DM searches at the LHC
+
The Higgs potential in the Early Universe

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DESY Theory Fellow Meeting
31/10/2016

About me…

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Education: SNS Pisa (2007-12)
Thesis on flavour physics with "less minimal" flavour violations (with R. Barbieri)
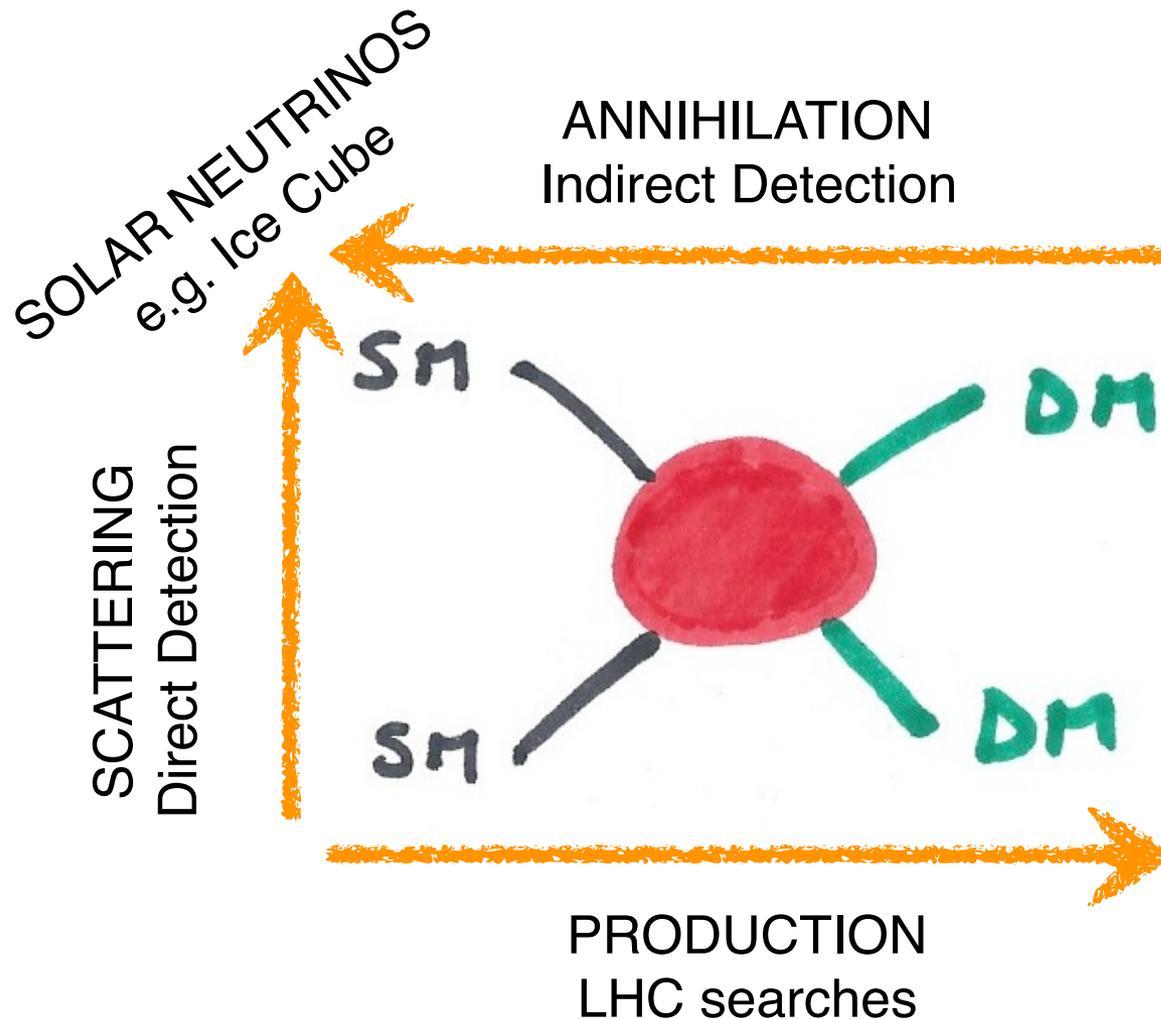
Lots of hard work…

About me…

PhD at Geneva University (2013-16). Thesis: DM searches at colliders and other probes (with Toni Riotto)

Meanwhile, my life changed a lot…

WIMP Dark Matter searches

How can we test WIMP DM interactions with the Standard Model?

SOLAR NEUTRINOS
e.g. Ice Cube

ANNIHILATION
Indirect Detection

SCATTERING
Direct Detection

PRODUCTION
LHC searches

Different searches cover different portions of parameter space

⇒ Importance of

COMPLEMENTARITY

DM at the LHC

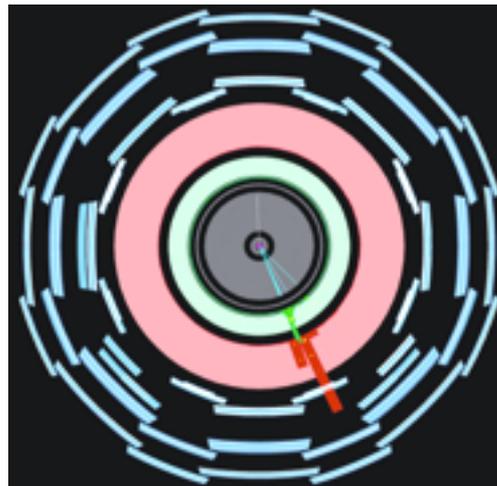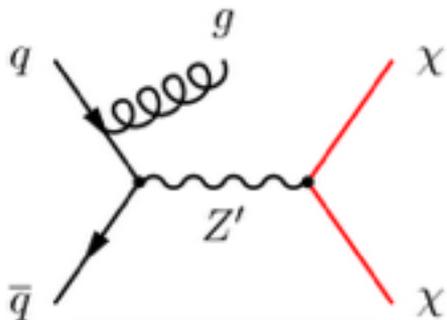Trivial observation: WIMP particles do not interact with the detectors

$$pp \rightarrow \cancel{DM\ DM}$$

Tag DM events with some recoiling SM particle

e.g. "mono-X + MET" searches

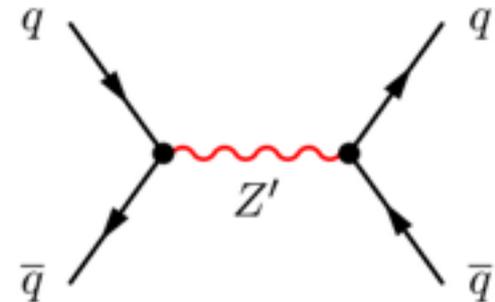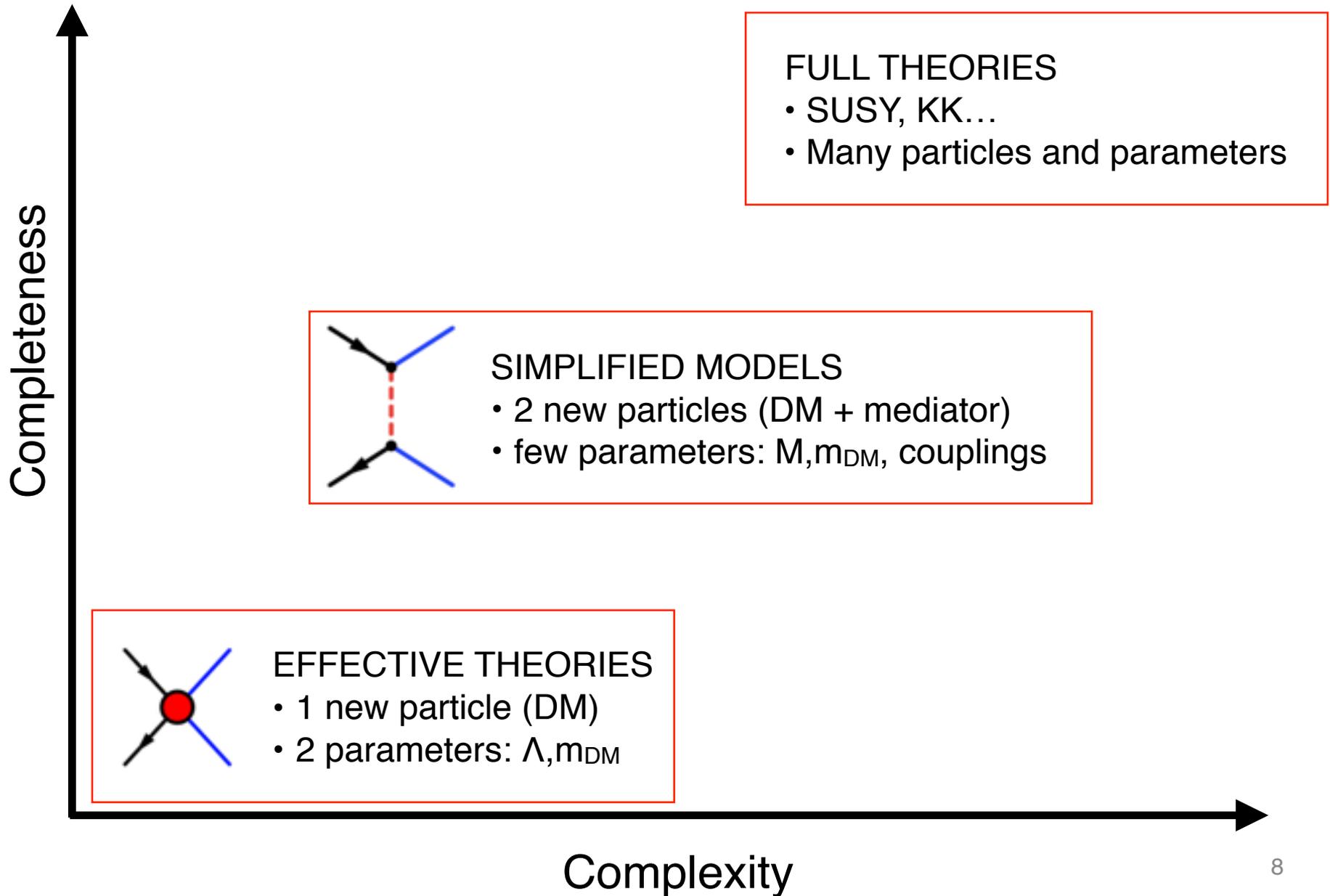a single SM object recoiling against some unpaired momentum in the transverse plane

Study the "dark sector" independently of DM

e.g. "di-jet" searches

the mediator is produced and decays back into a quark - antiquark pair

ATLAS mono-jet event, CERN courier

DM "models"

Completeness

FULL THEORIES
• SUSY, KK…
• Many particles and parameters

SIMPLIFIED MODELS
• 2 new particles (DM + mediator)
• few parameters: M, m_{DM}, couplings

EFFECTIVE THEORIES
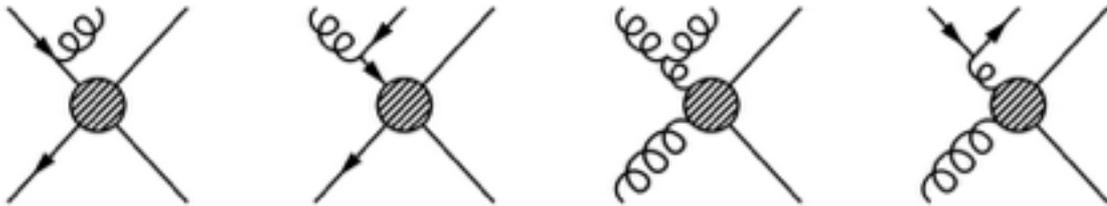• 1 new particle (DM)
• 2 parameters: Λ, m_{DM}

Complexity

EFT description

The simplest description is
EFT with initial state radiation

- Write a complete set of operators (*e.g.* in the s-channel)

- Suppose DM production happens only through one of these

- Derive bounds on the plane (m_{DM}-Λ) for that operator

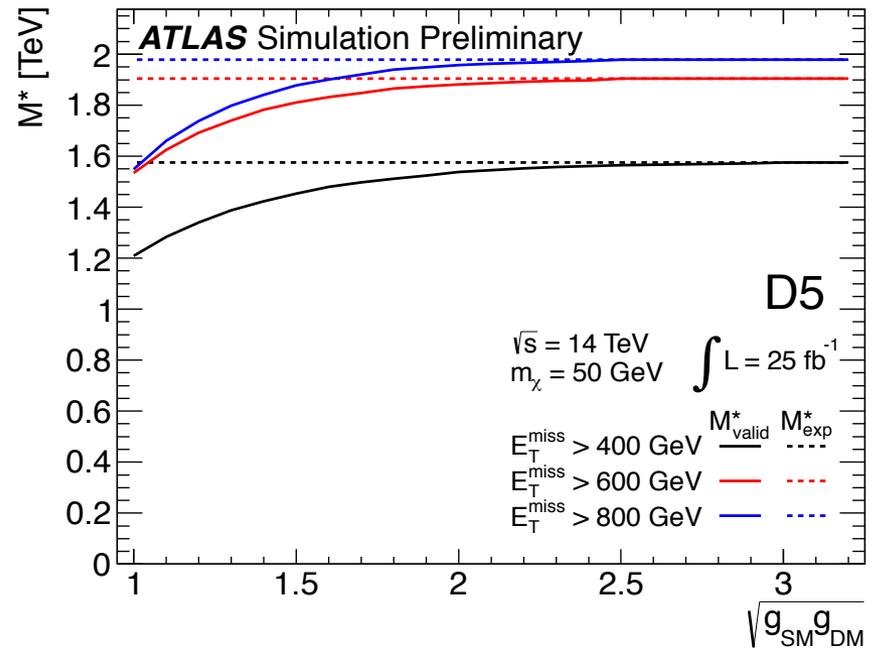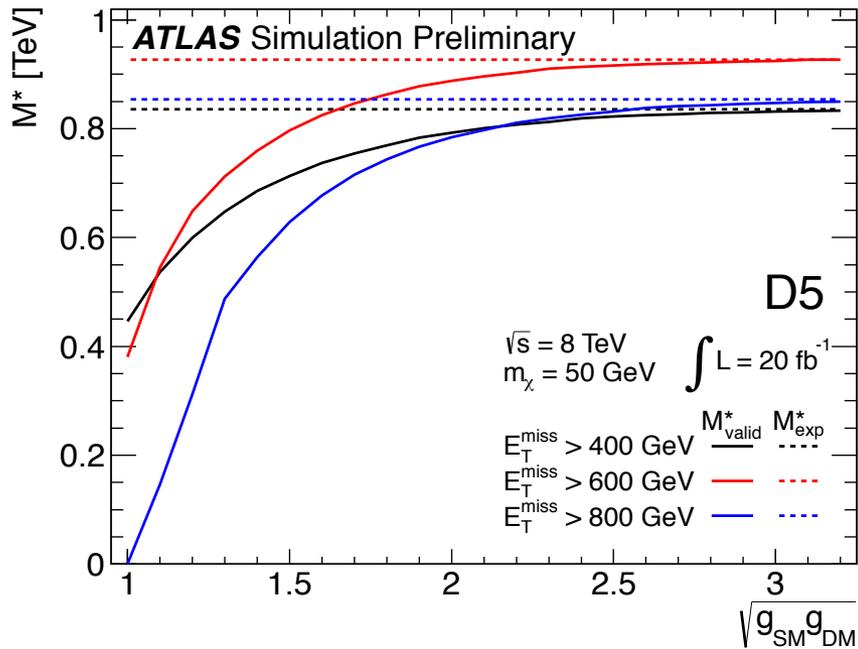| Name	Operator	Coefficient
D1	$\bar{\chi}\chi\,\bar{q}q$	m_q/Λ^3
D1'	$\bar{\chi}\chi\,\bar{q}q$	$1/\Lambda^2$
D2	$\bar{\chi}\gamma^5\chi\,\bar{q}q$	im_q/Λ^3
D2'	$\bar{\chi}\gamma^5\chi\,\bar{q}q$	i/Λ^2
D3	$\bar{\chi}\chi\,\bar{q}\gamma^5 q$	im_q/Λ^3
D3'	$\bar{\chi}\chi\,\bar{q}\gamma^5 q$	i/Λ^2
D4	$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$	m_q/Λ^3
D4'	$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$	$1/\Lambda^2$
D5	$\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q$	$1/\Lambda^2$
D6	$\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu q$	$1/\Lambda^2$
D7	$\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu\gamma^5 q$	$1/\Lambda^2$
D8	$\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu\gamma^5 q$	$1/\Lambda^2$
D9	$\bar{\chi}\sigma_{\mu\nu}\chi\,\bar{q}\sigma^{\mu\nu}q$	$1/\Lambda^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\,\bar{q}\sigma^{\mu\nu}q$	i/Λ^2
D11	$\bar{\chi}\chi\,G^{\mu\nu}G_{\mu\nu}$	$\alpha_s/4\Lambda^3$
D12	$\bar{\chi}\gamma^5\chi\,G^{\mu\nu}G_{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D13	$\bar{\chi}\chi\,G^{\mu\nu}\tilde{G}_{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D14	$\bar{\chi}\gamma^5\chi\,G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\alpha_s/4\Lambda^3$

Goodman *et al.*, 1008.1783

Validity of the EFT

At the LHC, the typical momentum exchanged is close to the scales that are probed

$$\langle Q_{\mathrm{tr}}^2 \rangle \sim \mathcal{O}(1\,\mathrm{TeV})^2 \sim \Lambda^2$$
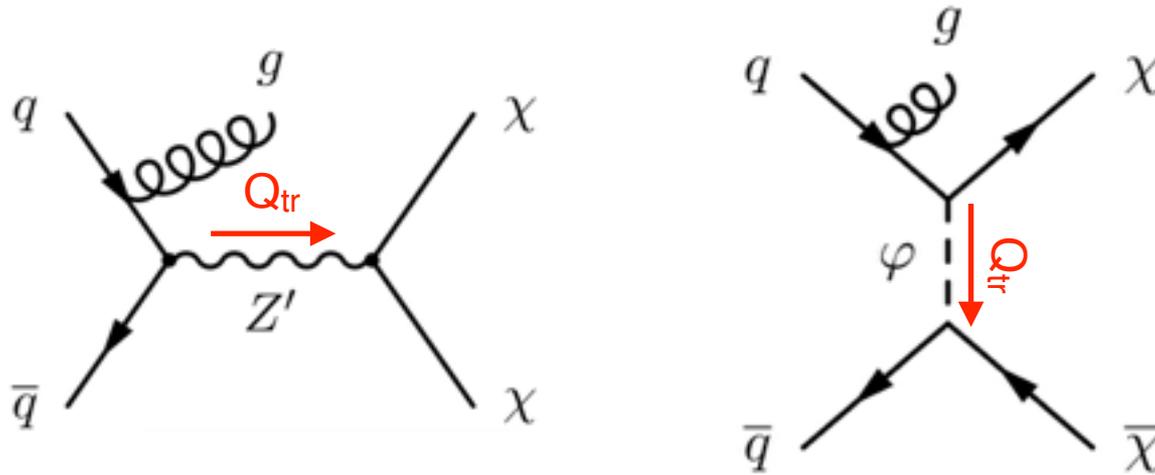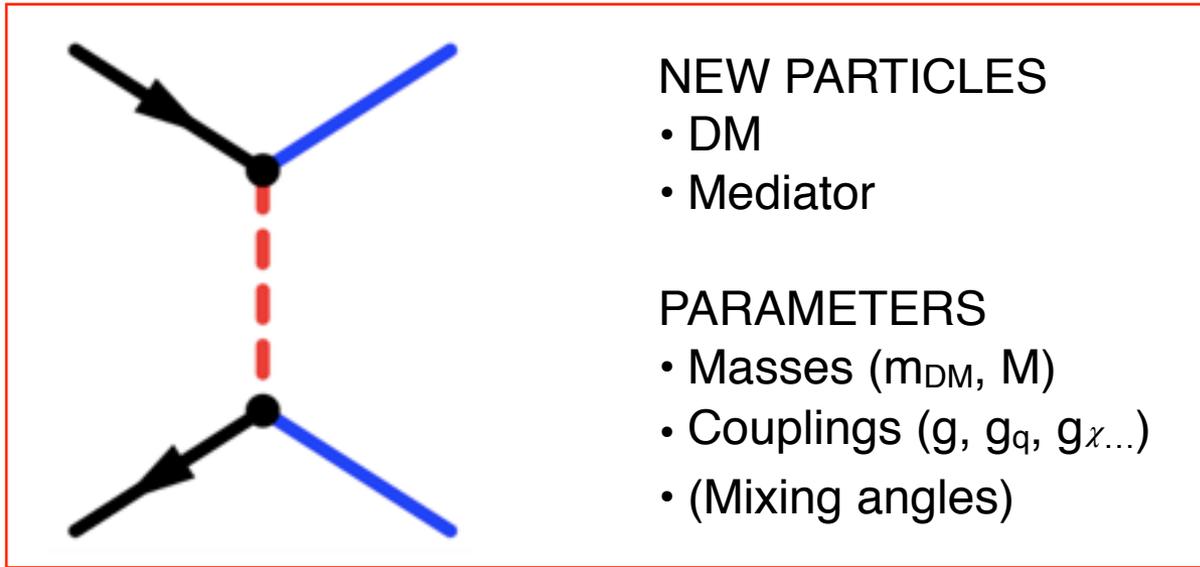

The effective description is expected to fail

[Busoni, EM, *et al.*, 1307.2253, 1402.1275, 1405.3101]

Implications for LHC searches

Simplified Models

Beyond EFT: consider a set of simple toy models

NEW PARTICLES
- DM
- Mediator

PARAMETERS
- Masses (m_{DM}, M)
- Couplings (g, g_q, $g_{\chi...}$)
- (Mixing angles)

Implementation in LHC searches for DM still in progress (DM@LHC working group)

Simplified Models
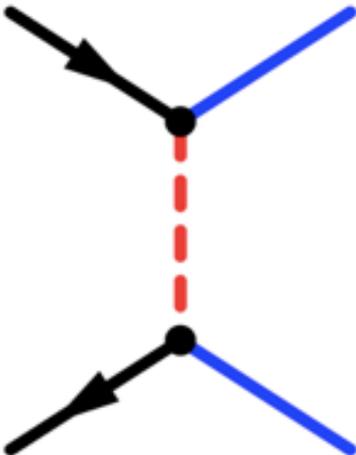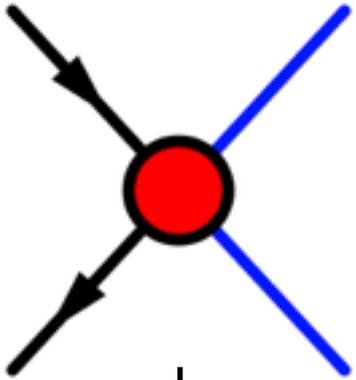
✓ Can grasp the most relevant physical features of a full theory including DM

✓ Theoretically consistent

✓ Richer phenomenology: other channels and searches complementary to mono-X

✗ More parameters (couplings) → higher dimensional space to constrain

✗ How to present constraints?

Interesting questions

- How to build simple but consistent simplified models

  - ✤ experimental constraints;
  - ✤ perturbative unitarity;
  - ✤ anomalies?

- How to be as model independent as possible: what is the best set of models? How not to miss interesting phenomenologies?

- Complementarity with other experiments: more assumptions are needed
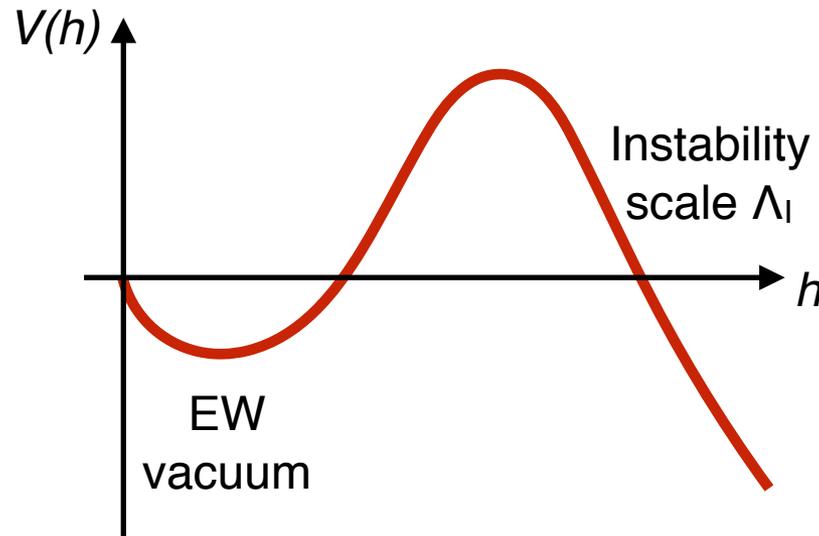
- Large parameter space: can we do a clever sampling?
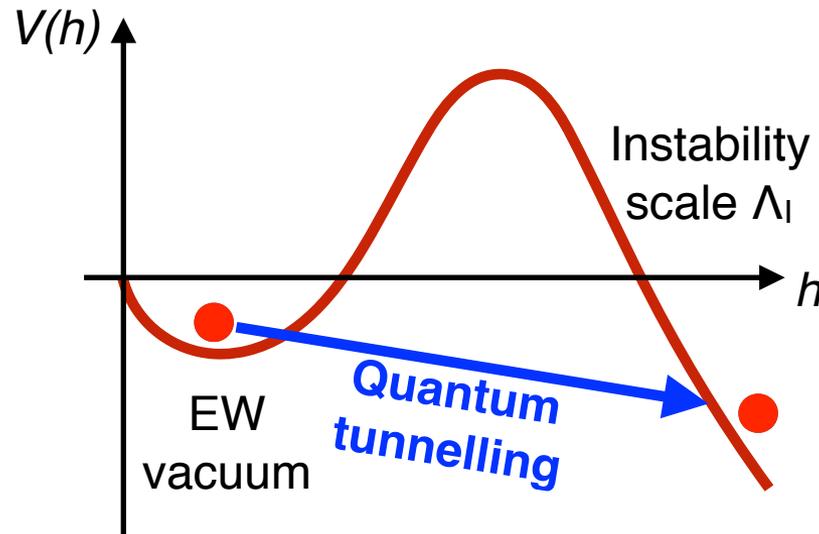
The Higgs potential in the early universe

The Higgs vacuum instability

Extrapolate SM up to Planck scale. We assume Higgs is SM like, no BSM physics.

$$V(h) = \lambda(h)\frac{h^4}{4}$$

RG running makes the potential negative at some scale $10^{10} \div 10^{11}$ GeV

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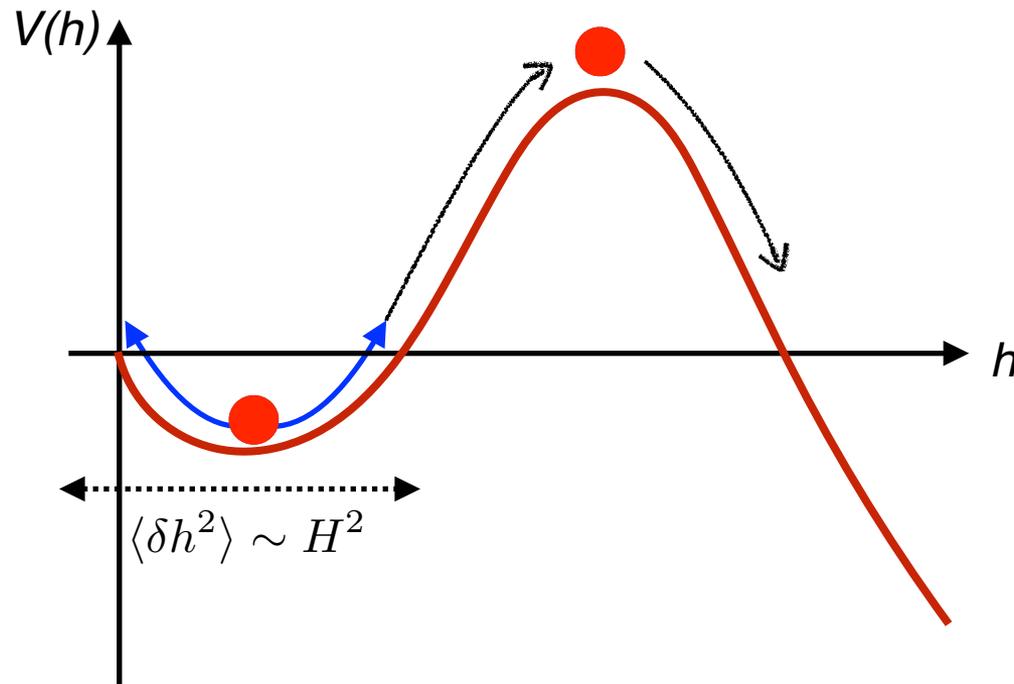
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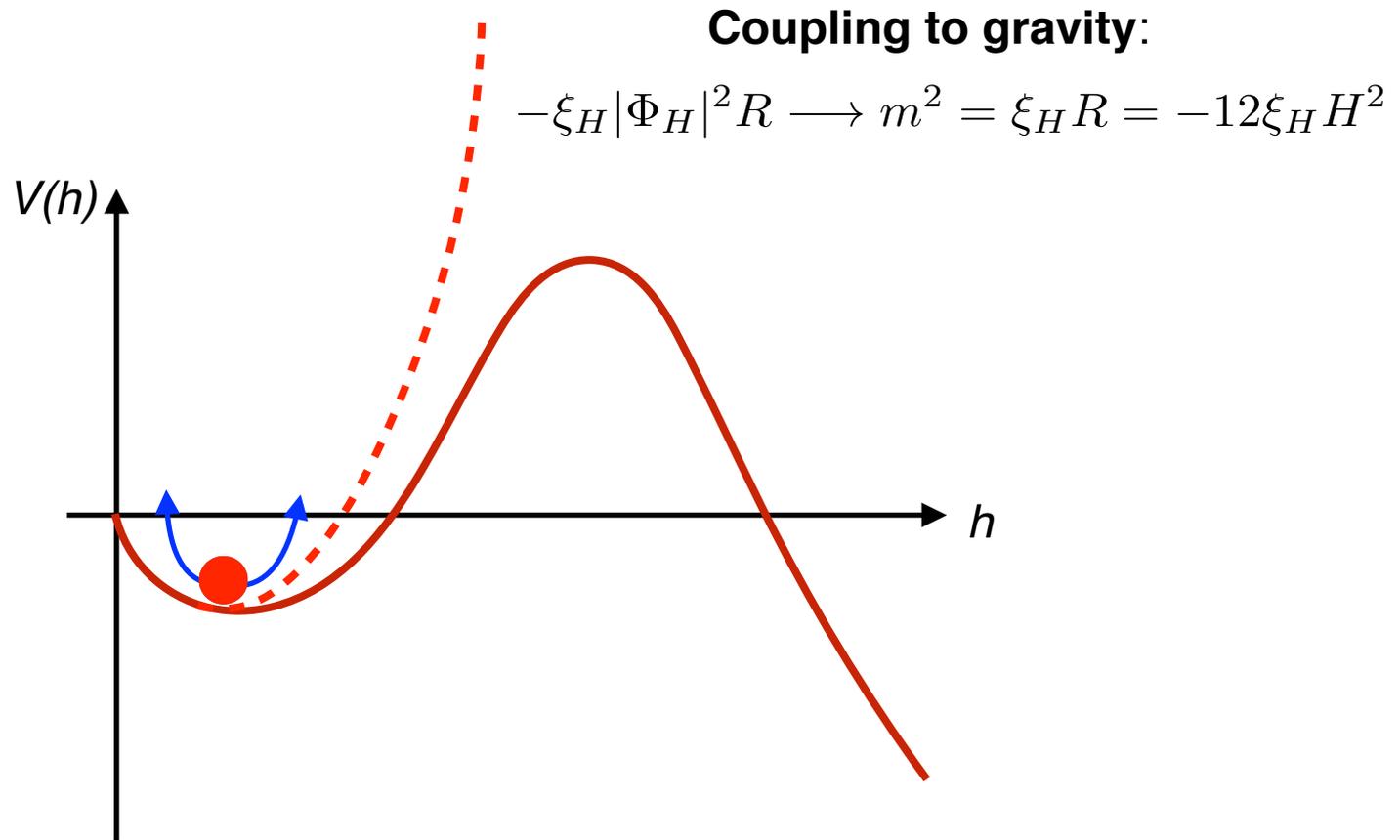
Metastability: EW vacuum lifetime is larger than the age of the Universe

Buttazzo & al.1307.3536

Instability in the early universe

Many effects can change the situation in the early universe:
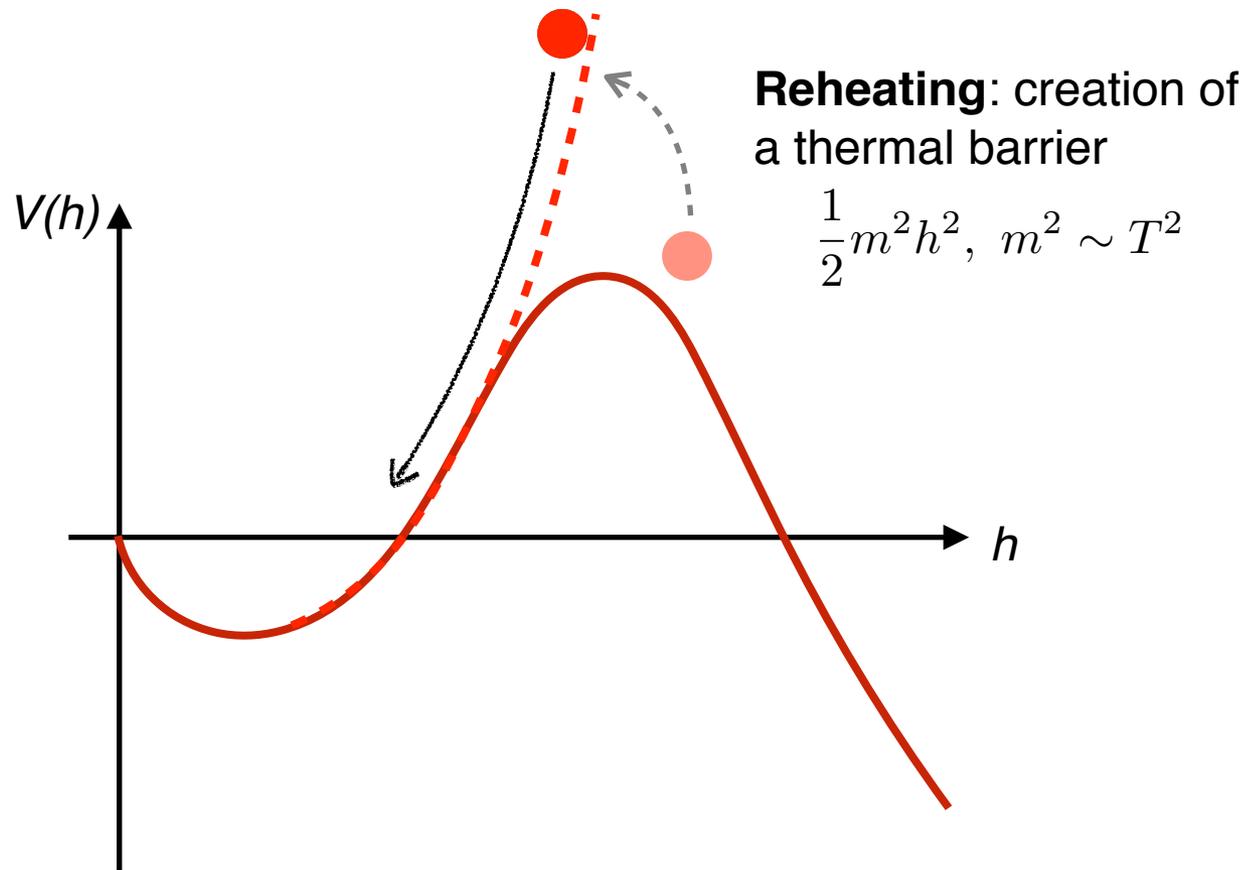
Inflation: quantum fluctuations

$V(h)$

h

$$\langle \delta h^2 \rangle \sim H^2$$

Instability in the early universe

Many effects can change the situation in the early universe:

Coupling to gravity:

$$-\xi_H|\Phi_H|^2 R \longrightarrow m^2 = \xi_H R = -12\xi_H H^2$$

Instability in the early universe

Many effects can change the situation in the early universe:

Reheating: creation of a thermal barrier

$$\frac{1}{2}m^2h^2, \ m^2 \sim T^2$$

$V(h)$

h
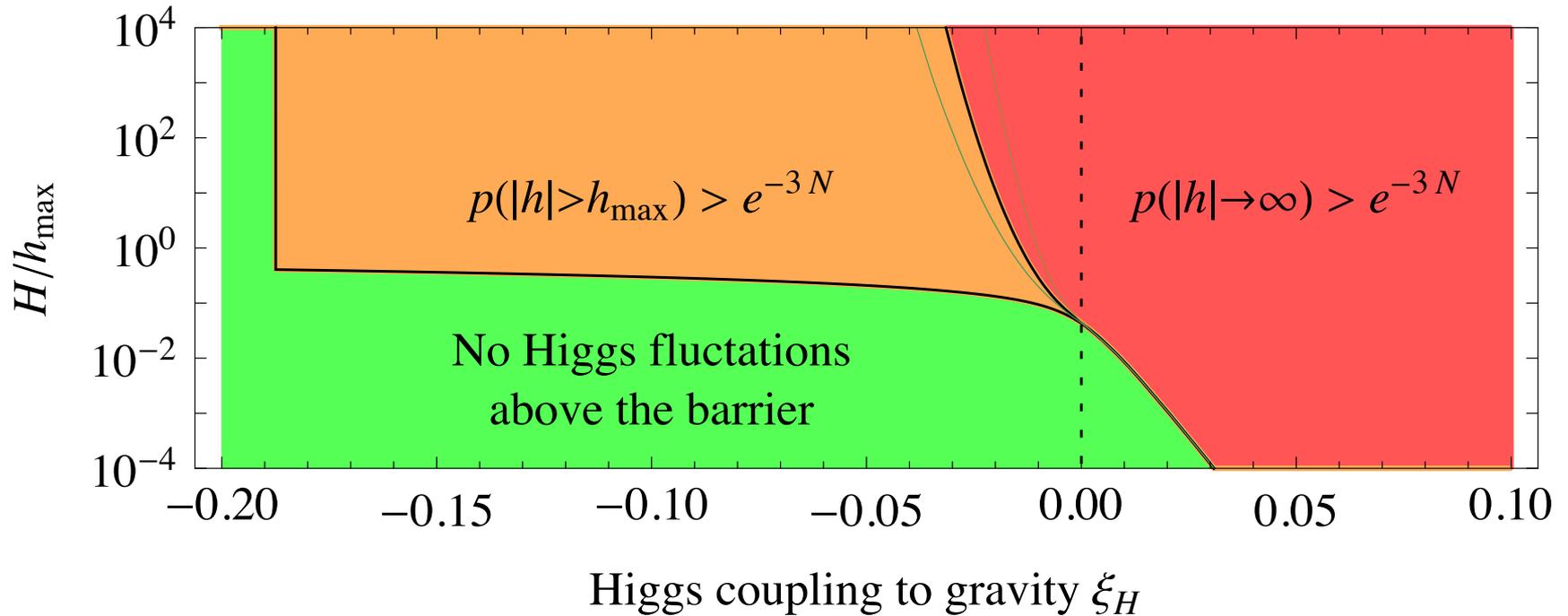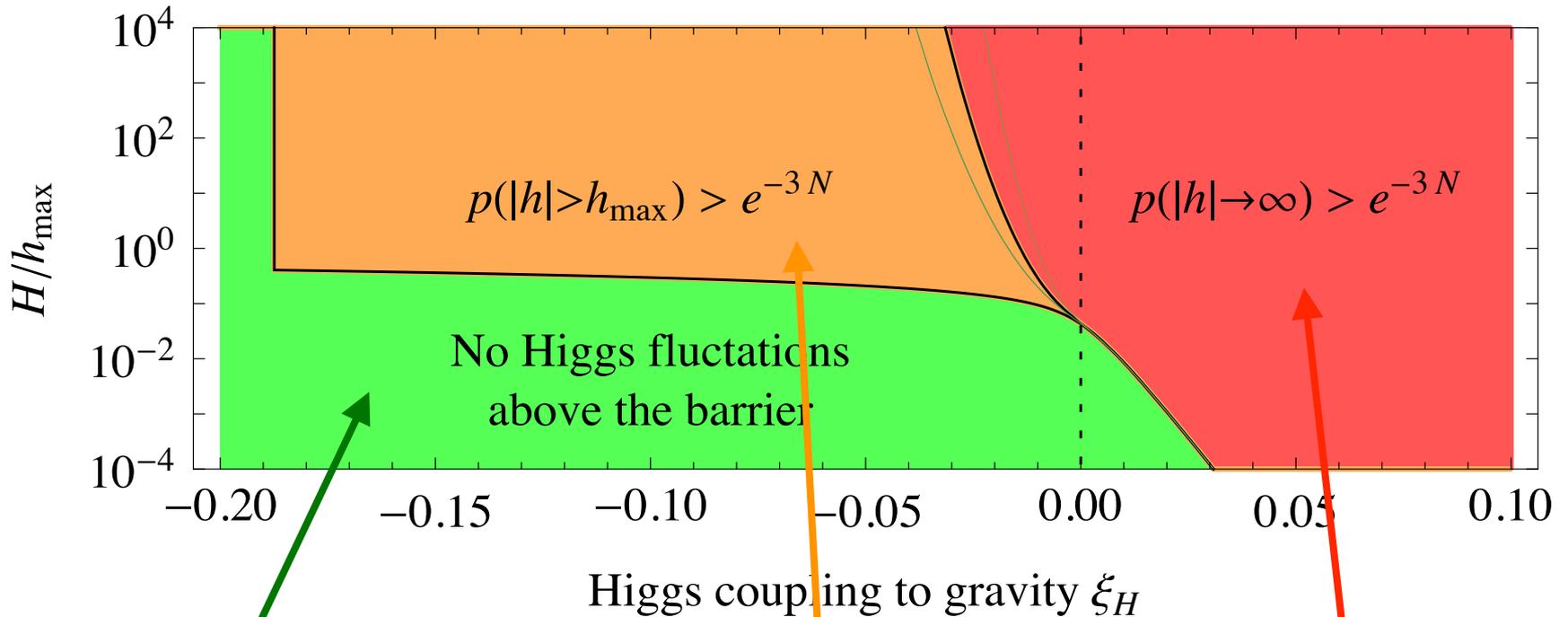
Instability in the early universe

Instability in the early universe

Instability in the early universe

Lower bound on the reheating temperature
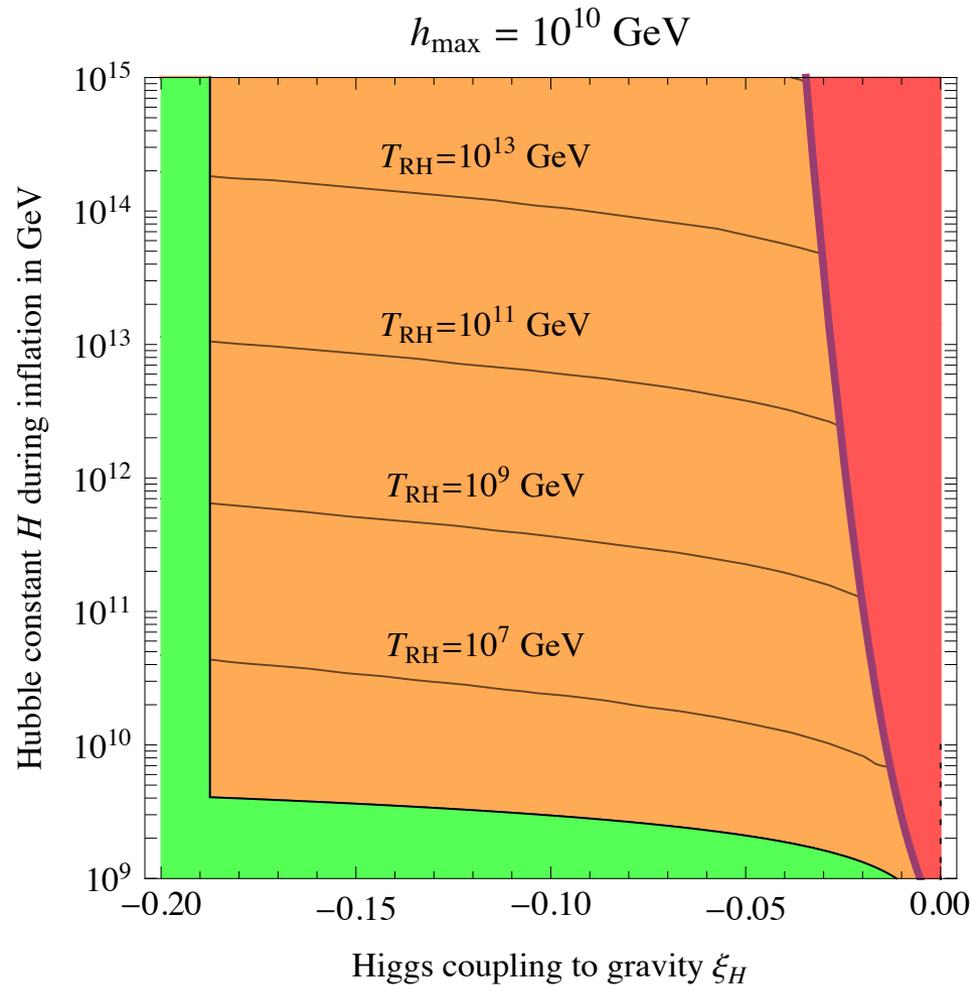
Interesting questions

- Is a gauge invariant treatment possible? What are the gauge invariant quantities involved in the process? Is the effective potential the best quantity to describe the physics?

- Sensitivity to new physics: can we use stability to exclude new physics models?

- New effects: particle productions after the tunnelling, bubble collisions, bubble formation triggered by black holes…

- Bounds on concrete realisations of cosmological history