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Collider & Cosmology: discussion

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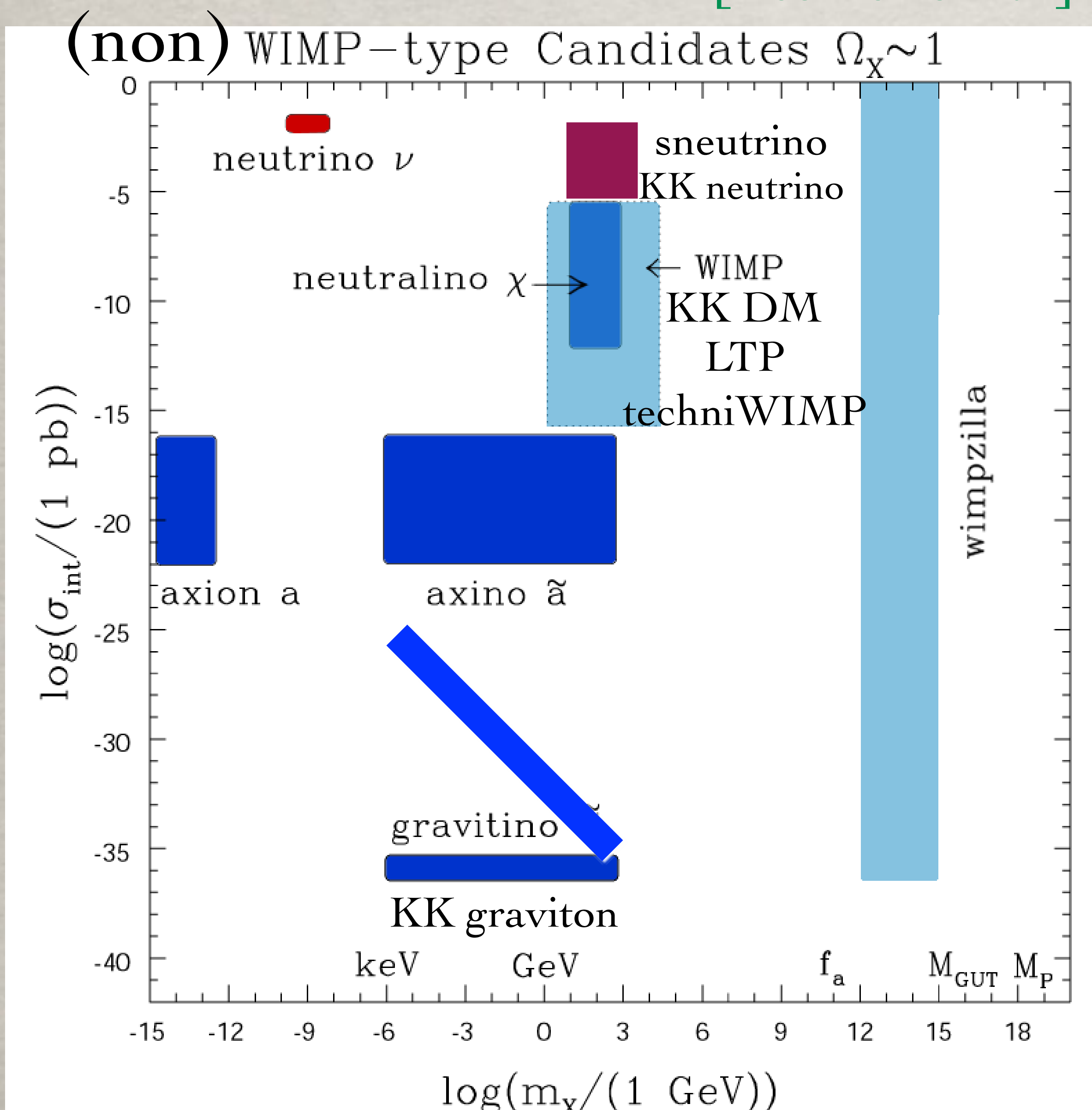
neutrinos, dark matter & dark energy physics

Open Questions

- Dark Matter: Coupling and Mass ???
- Inflationary phase: simple single field inflation still OK with all data…
  - Higgs inflation ?
- Baryogenesis: EW baryogenesis ??? Stop mass in MSSM ?
  - Leptogenesis ??? CP violation in the neutrino sector ?

DARK MATTER CANDIDATES

[Roszkowski 04]



Too many different candidates...

"Standard" DM production paradigms:

WIMPs

(i.e. neutralino)

&

"FIMP/SuperWIMPs"

(i.e. gravitino)

&

Misalignment

(i.e. axion/condensate)

10+Billion$ Question: How does Dark Matter interact ?

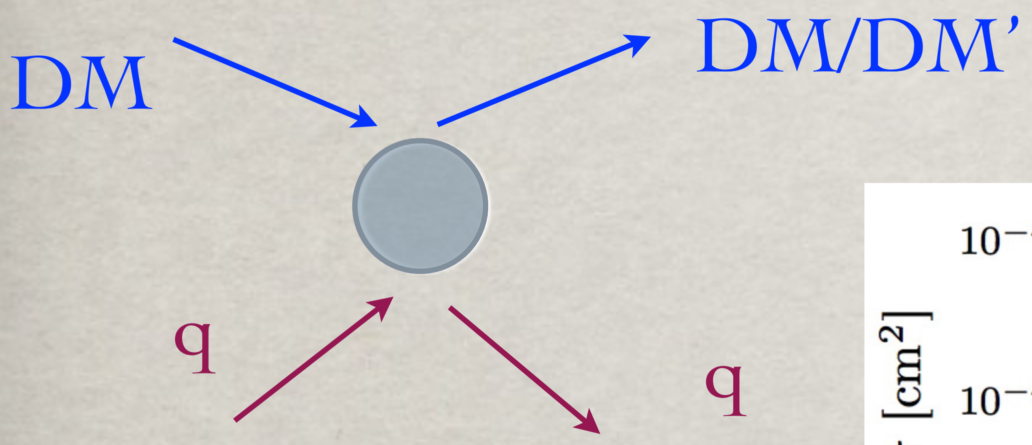
We detected DM so far only through its gravitational interaction... Unfortunately gravity is democratic, it does not tell us what DM is !
BUT probably we some other interaction is needed to produce DM since gravity is not very effective.

How can we explore DM (non-gravitational) interactions ???

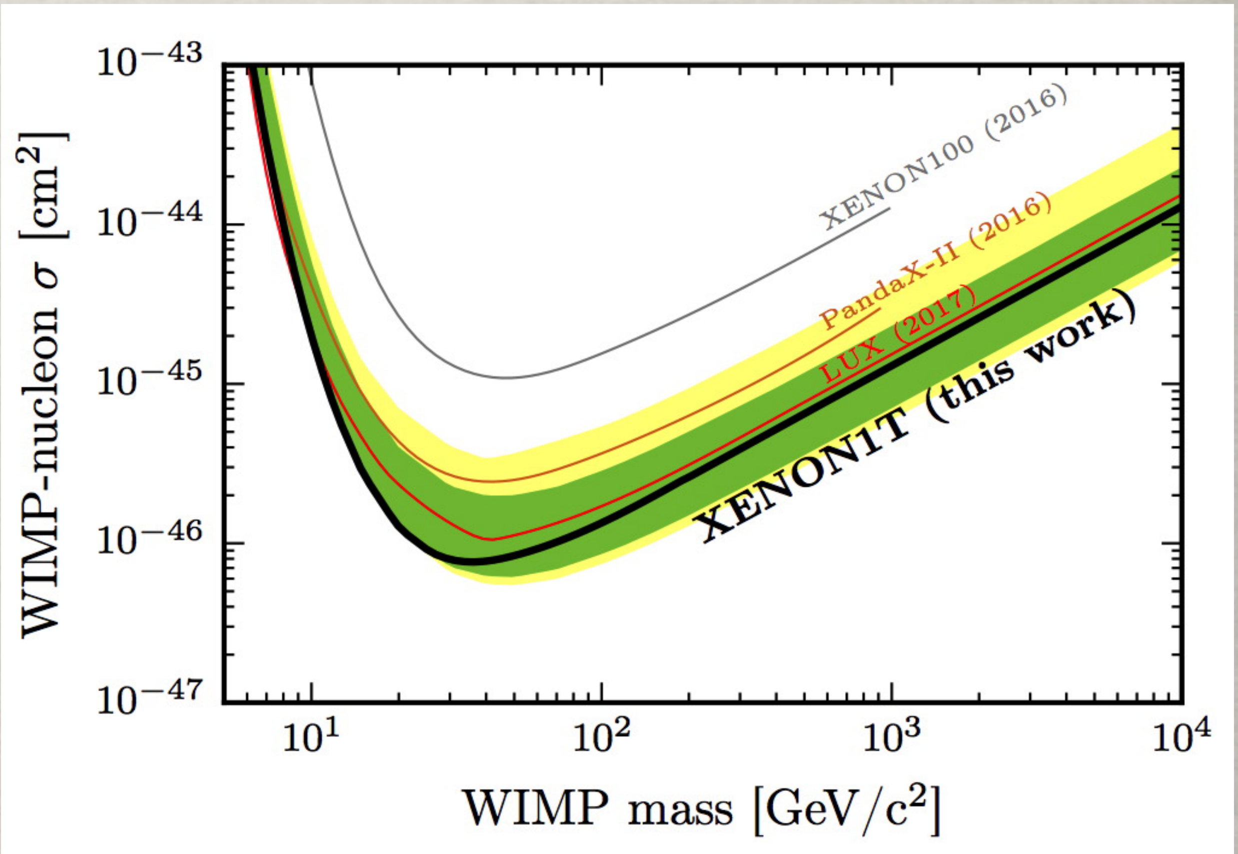
Going beyond the CDM/(SUSY) WIMP paradigms !

DM-Matter Interaction

Elastic/inelastic scattering



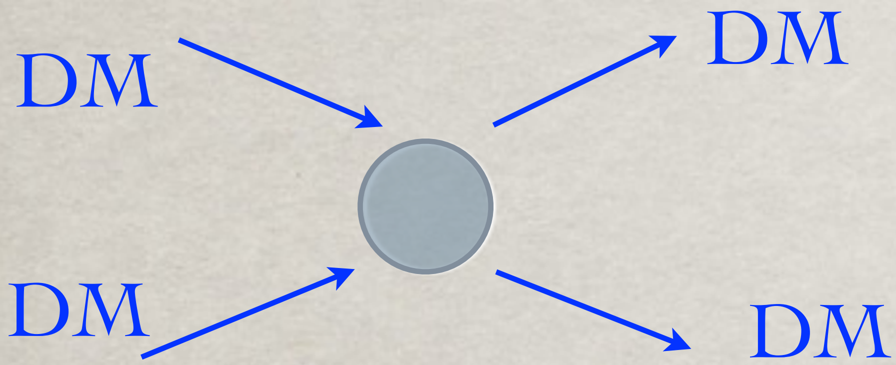
Direct detection:
elastic spin independent cross-section



Also other interactions can be tested, e.g. with SM neutrinos

DM-DM INTERACTION

Self-interaction:



Bullett cluster bound on self-interaction:

$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb \quad (m = 1\,\mathrm{GeV})$$

[Markevitch et al 03]

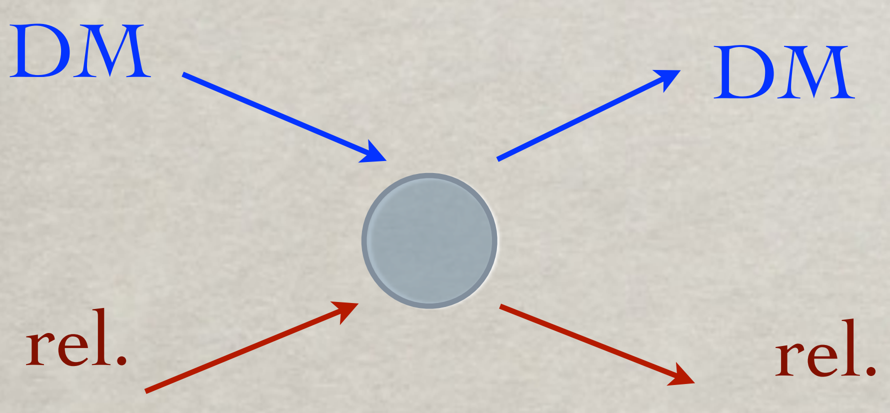
Slightly stronger constraint by requiring a sufficiently large core & from sphericity of halos... [Yoshida, Springer & White 00]

But at the boundary maybe some effect on small scales: SIMP

Interacting Dark Matter

Apart for chemical decoupling of DM, also the kinetic decoupling is important as it sets the cut-off in the power spectrum at small scales. ANY interaction of the DM, even with a hidden (relativistic) Dark Sector can influence the DM kinetic decoupling and structure formation at small scales.

[Hofmann, Schwarz & Stecker 2001, Green, Hofmann & Schwarz 2005, Bringmann & Hofmann 2007, ...]

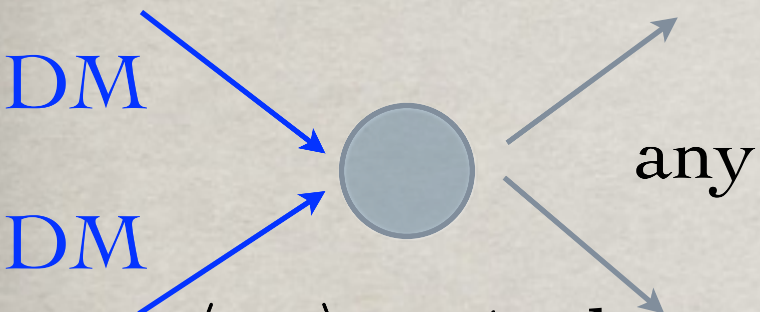


Probes ANY interaction with a relativistic species !

A lot of activity for different interactions/mediators !
Not clear if it can always resolve the small scale crises,though...

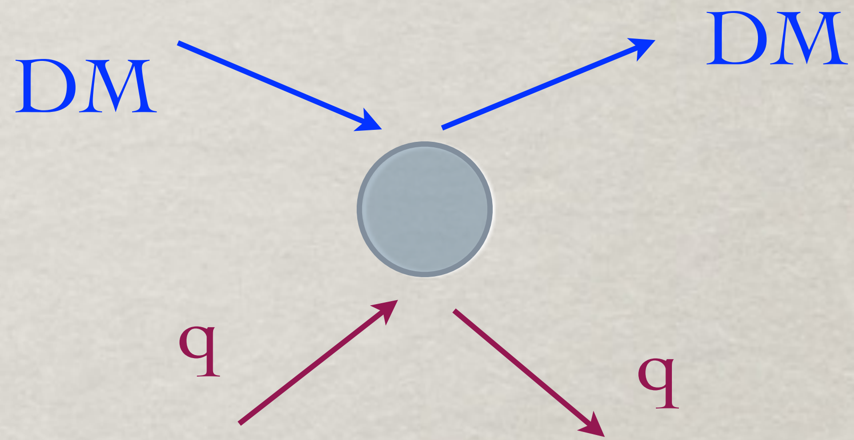
THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$

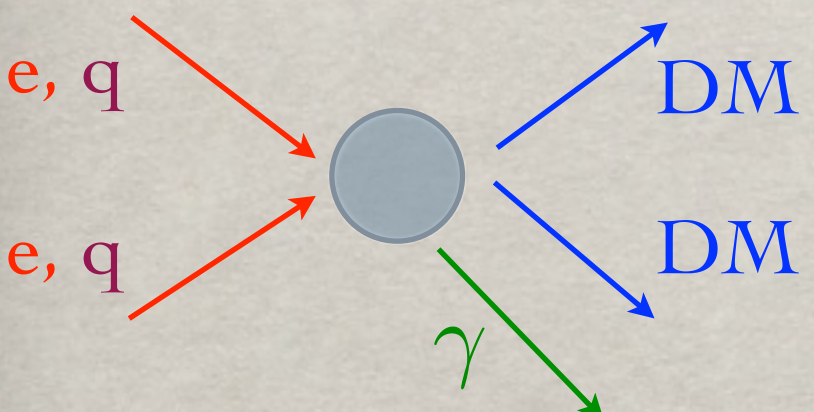


$\langle \sigma v \rangle \sim 1$ pb

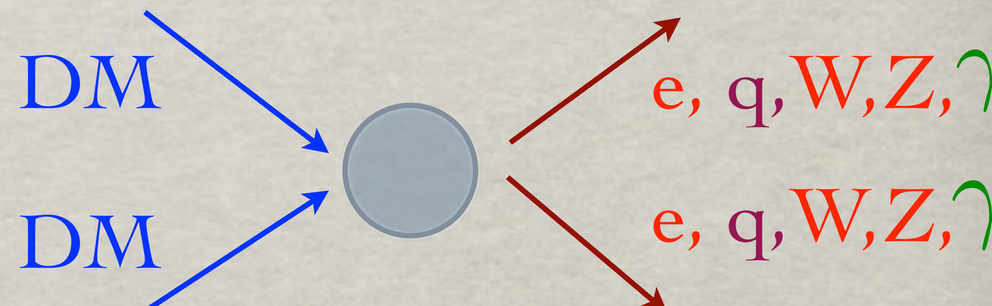
Direct Detection:



Colliders: LHC/ILC



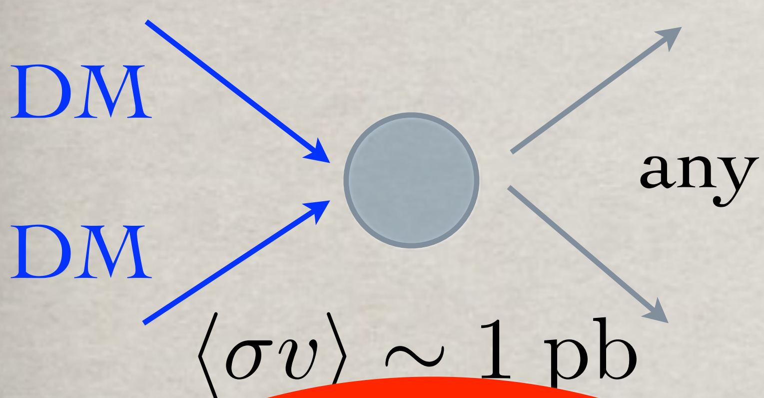
Indirect Detection:



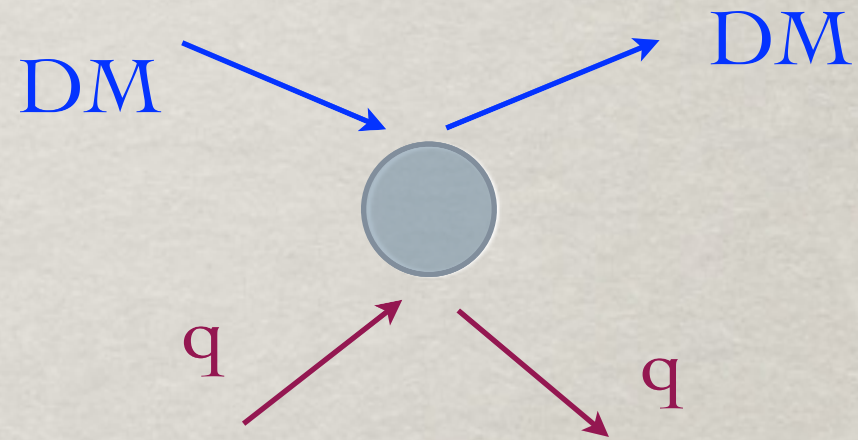
3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$



Direct Detection:



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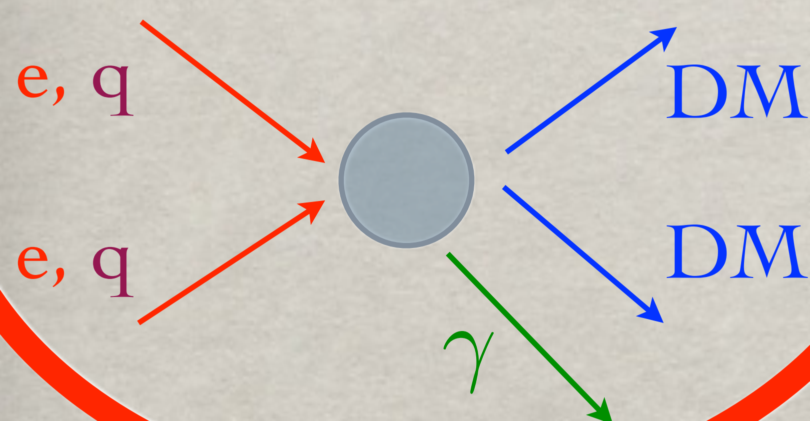
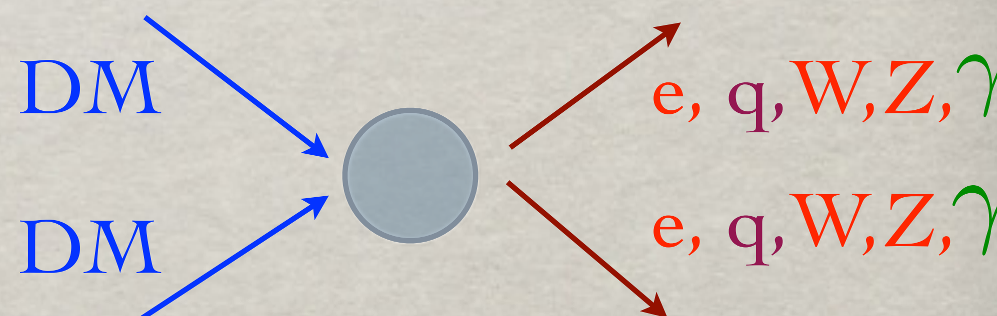


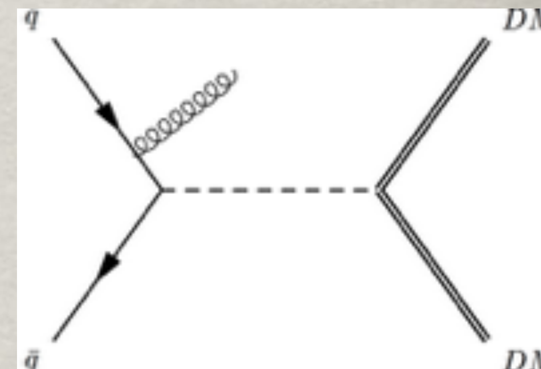
Indirect Detection:

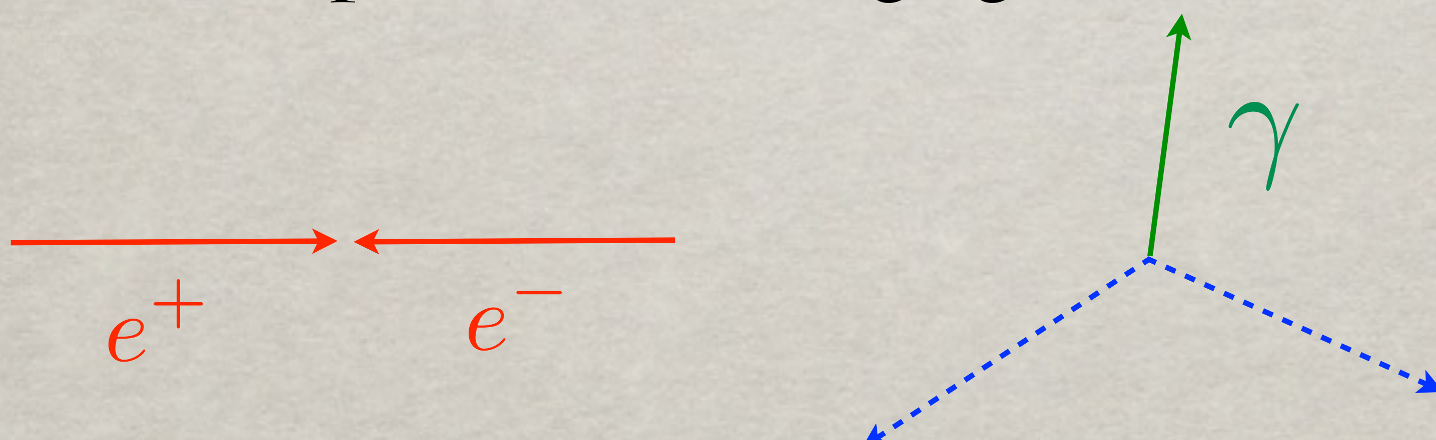


3 different ways to check this hypothesis !!!

Missing energy signature

- The direct production of two DM particles in a collider gives unfortunately no signal ! The energy just disappears...
- How is it possible to tag such events: Thanks to Initial State Radiation !
  i.e. either a single photon or gluon emitted by the initial parton, recoiling against the DM particle(s)





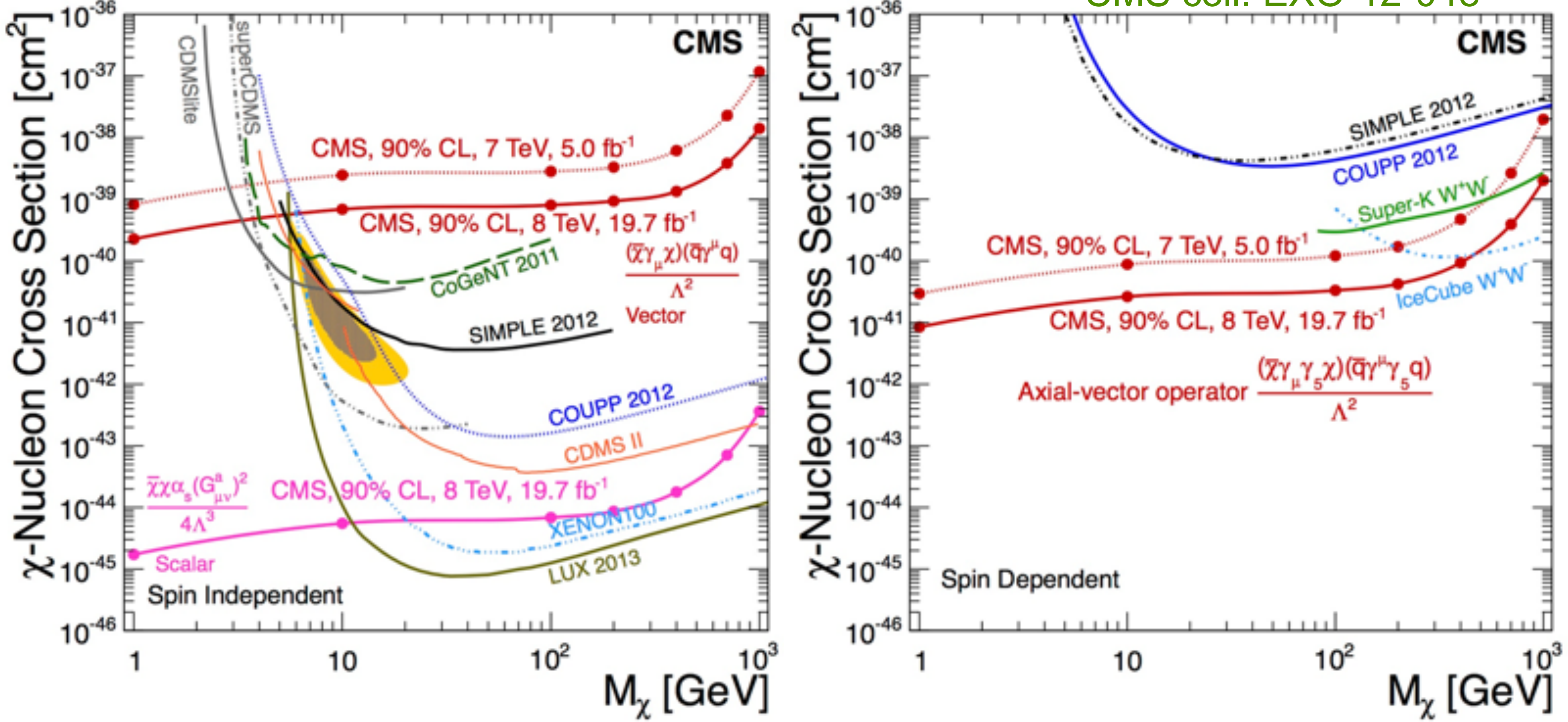
Dark Matter: Missing energy signature

Trouble: need sufficient rate of DM production...

COLLIDER BOUNDS

ATLAS & CMS have performed monojet/monophoton analysis for DM:

CMS coll. EXO-12-048



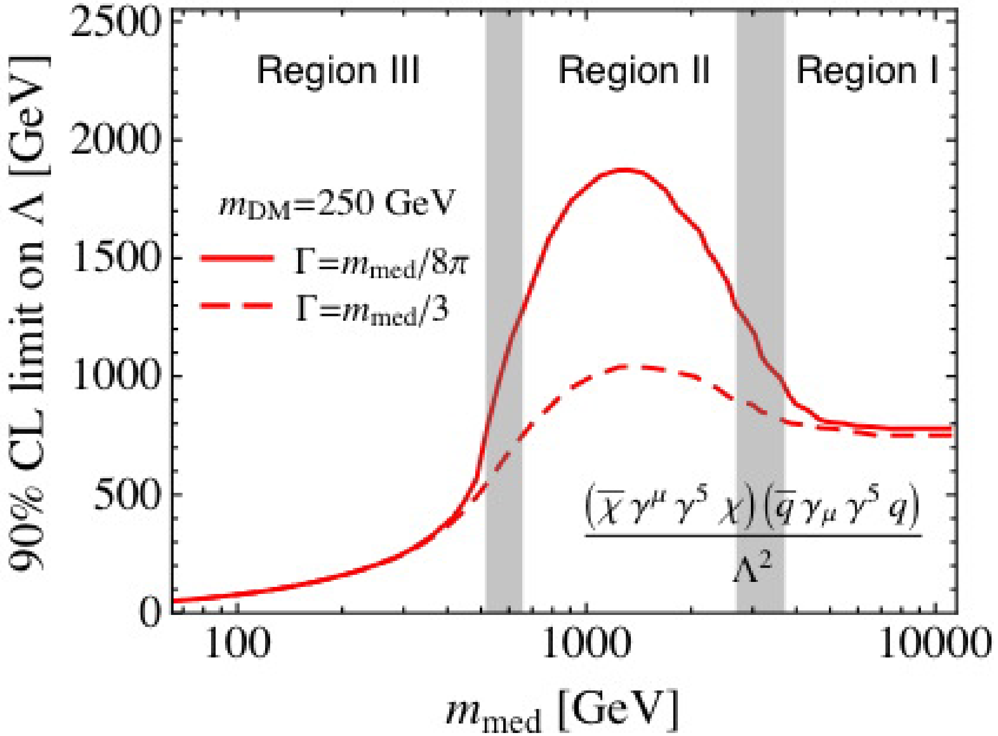
Strongest bound for low mass and for spin dependent case !

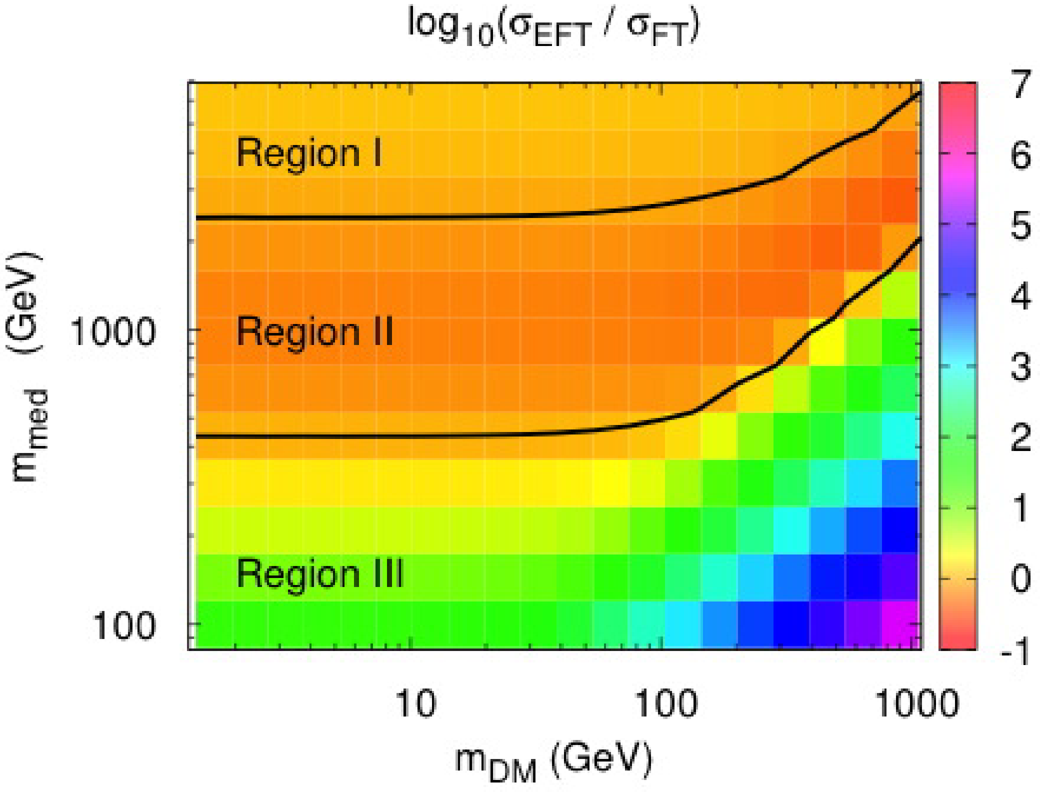
Caveat for the EFT: s

While the use of EFT for the case of non-relativistic scattering with matter in DM direct detection is well-justified, at LHC energies one has to be more careful...

[Fox et al 11, Busoni et al 13, O.Buchmuller et al 13, ...]

[O.Buchmuller et al 1308.6799]

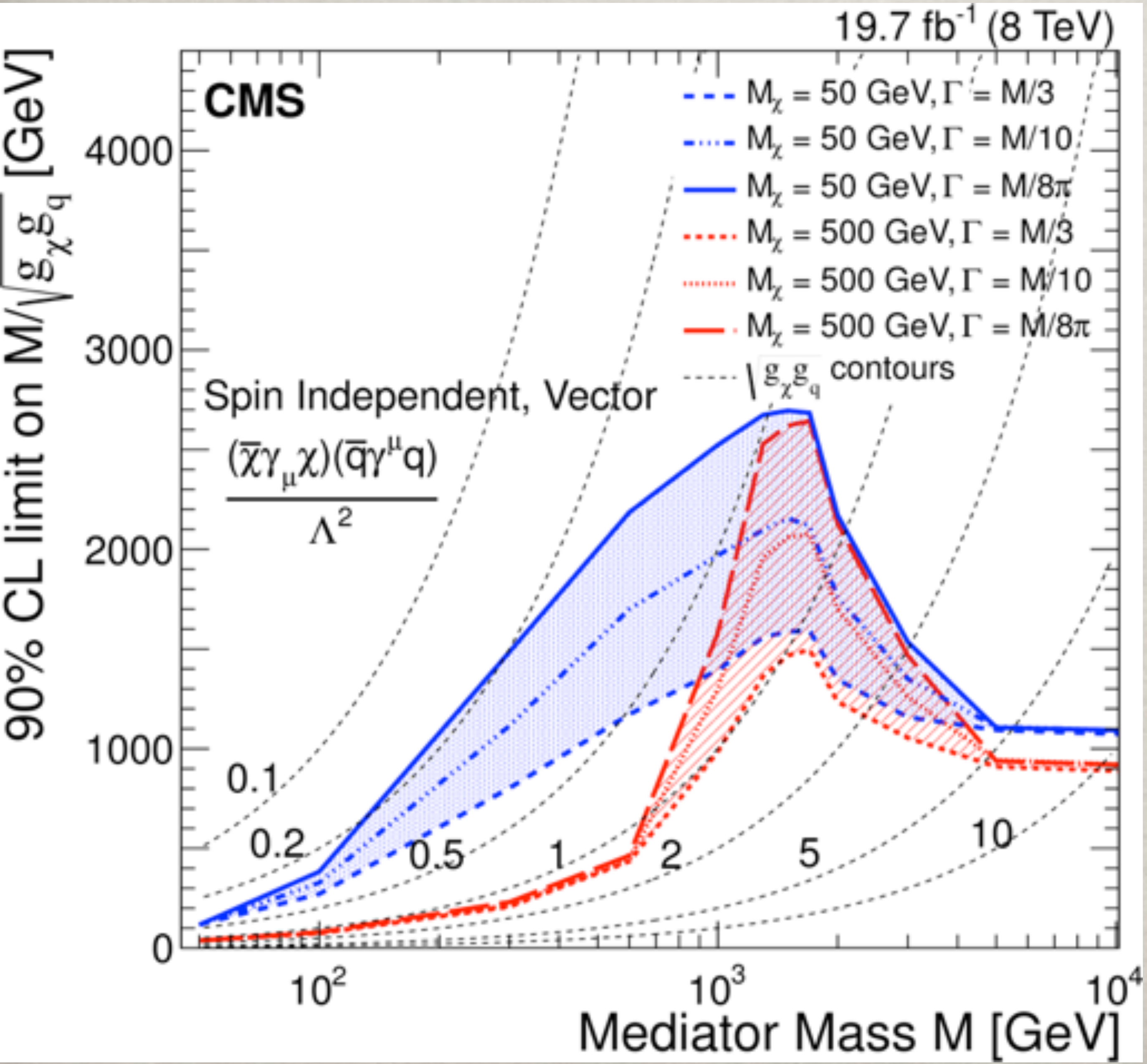




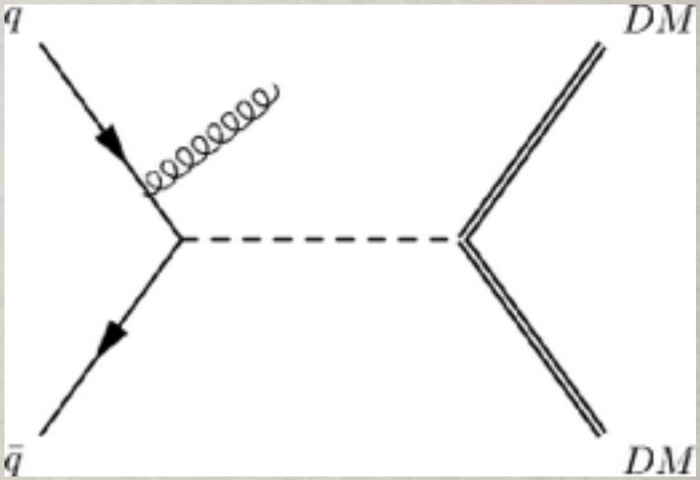
The bound is valid only for large mediator mass !

LHC: simplified models

[CMS collaboration, EPJC 75 (2015) 235]

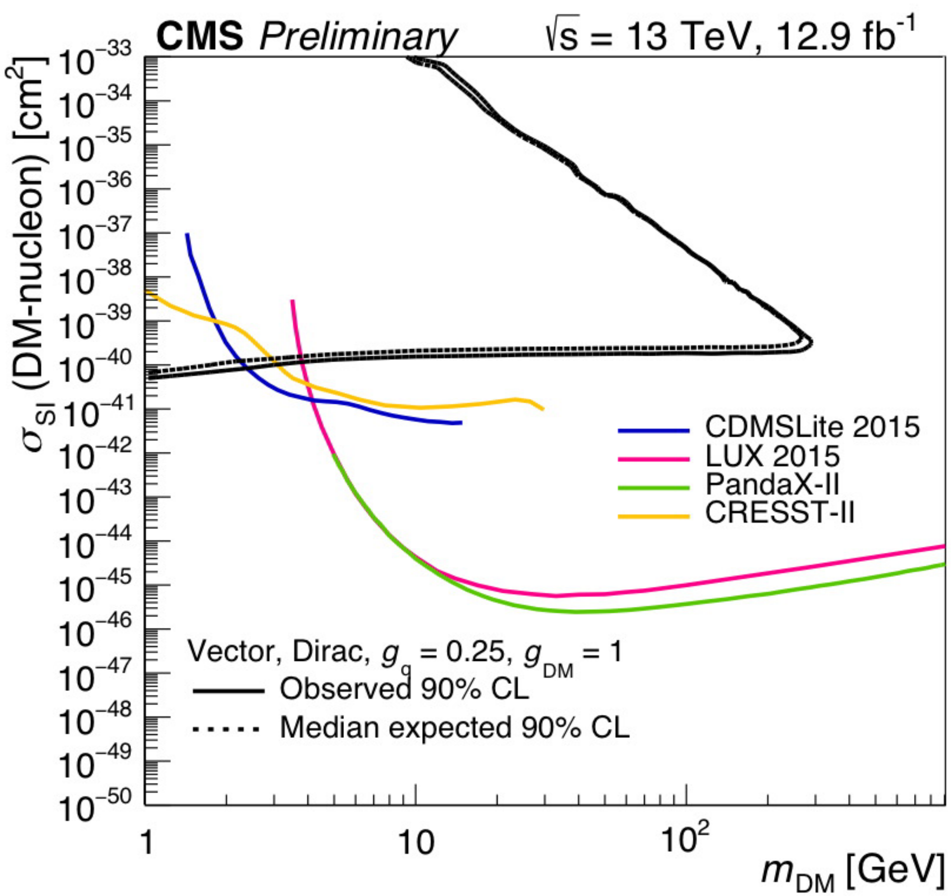


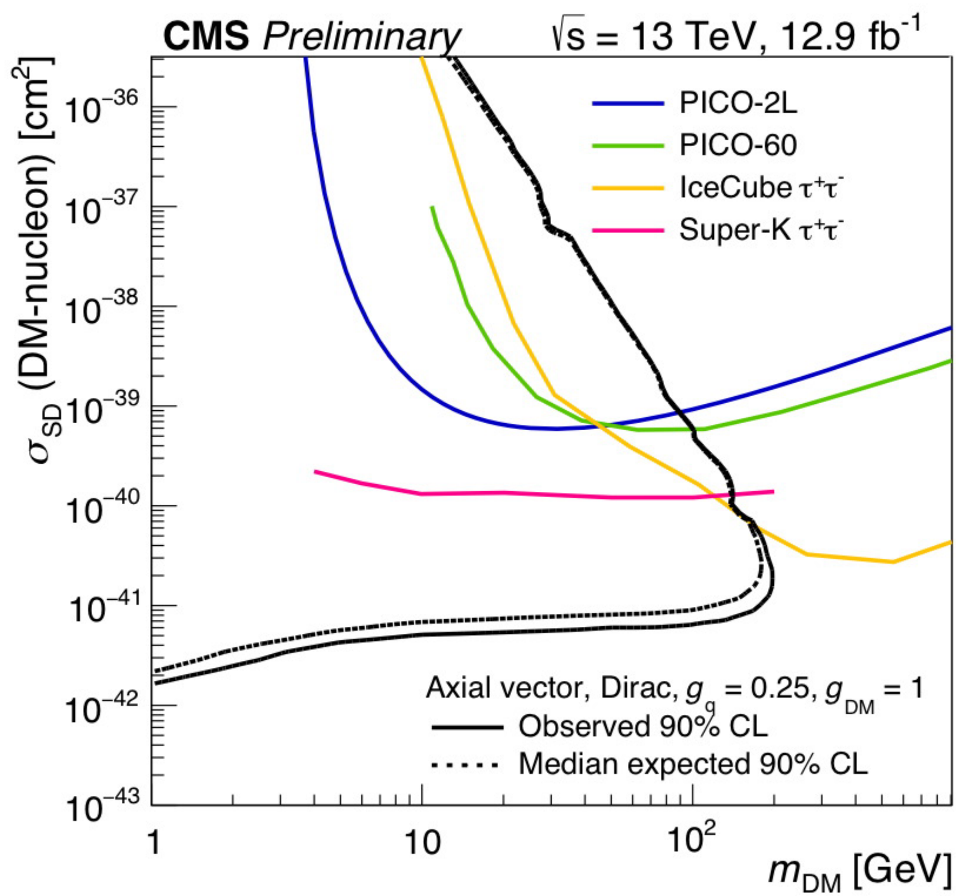
Vector mediator



LHC: SIMPLIFIED MODELS II

[CMS, EXO-16-039-pas]



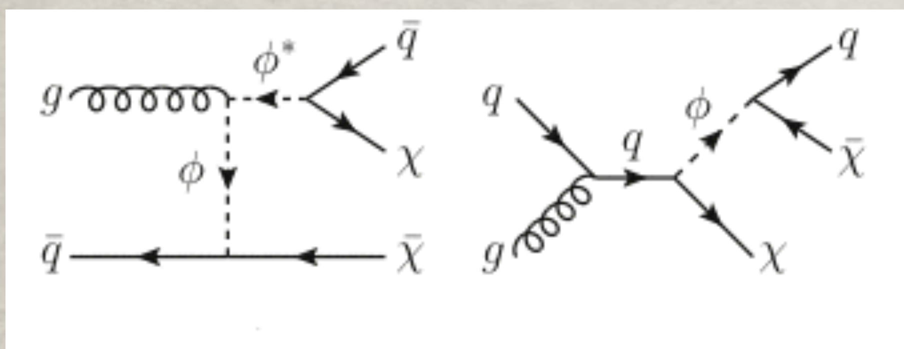


Very strong bounds for the axial vector case !

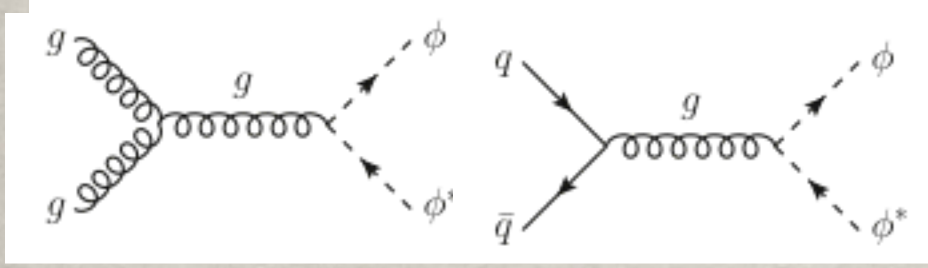
Caveat for the EFT: t

In the case of t-channel mediation, there is no resonant enhancement, but instead more channels for monojets as well as dijets show up, e.g. for scalar mediator:

[An et al. 2013, Papucci et al 2014]



Mono-jet without ISR



Dijet and MET

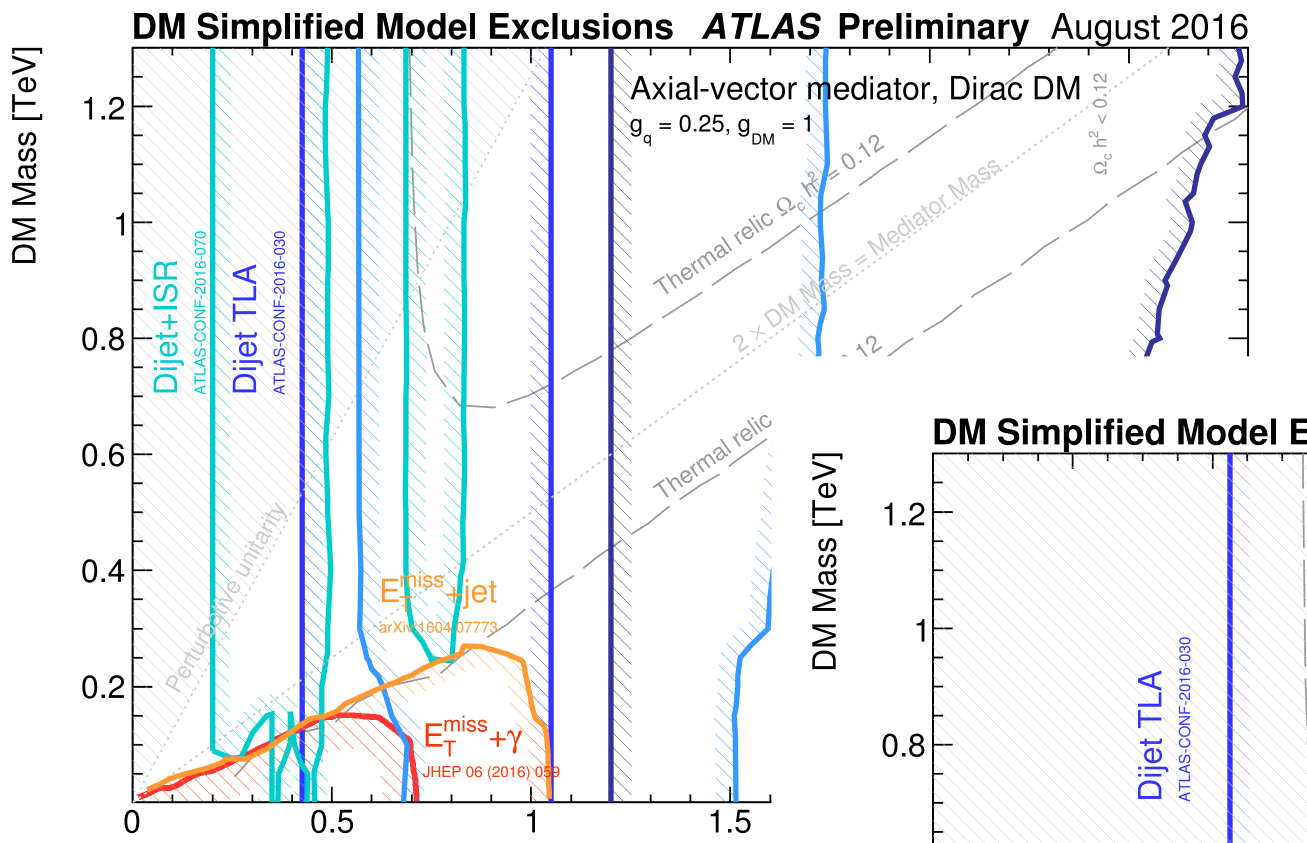
Complementary limits from Mono-jets & Di-jets !

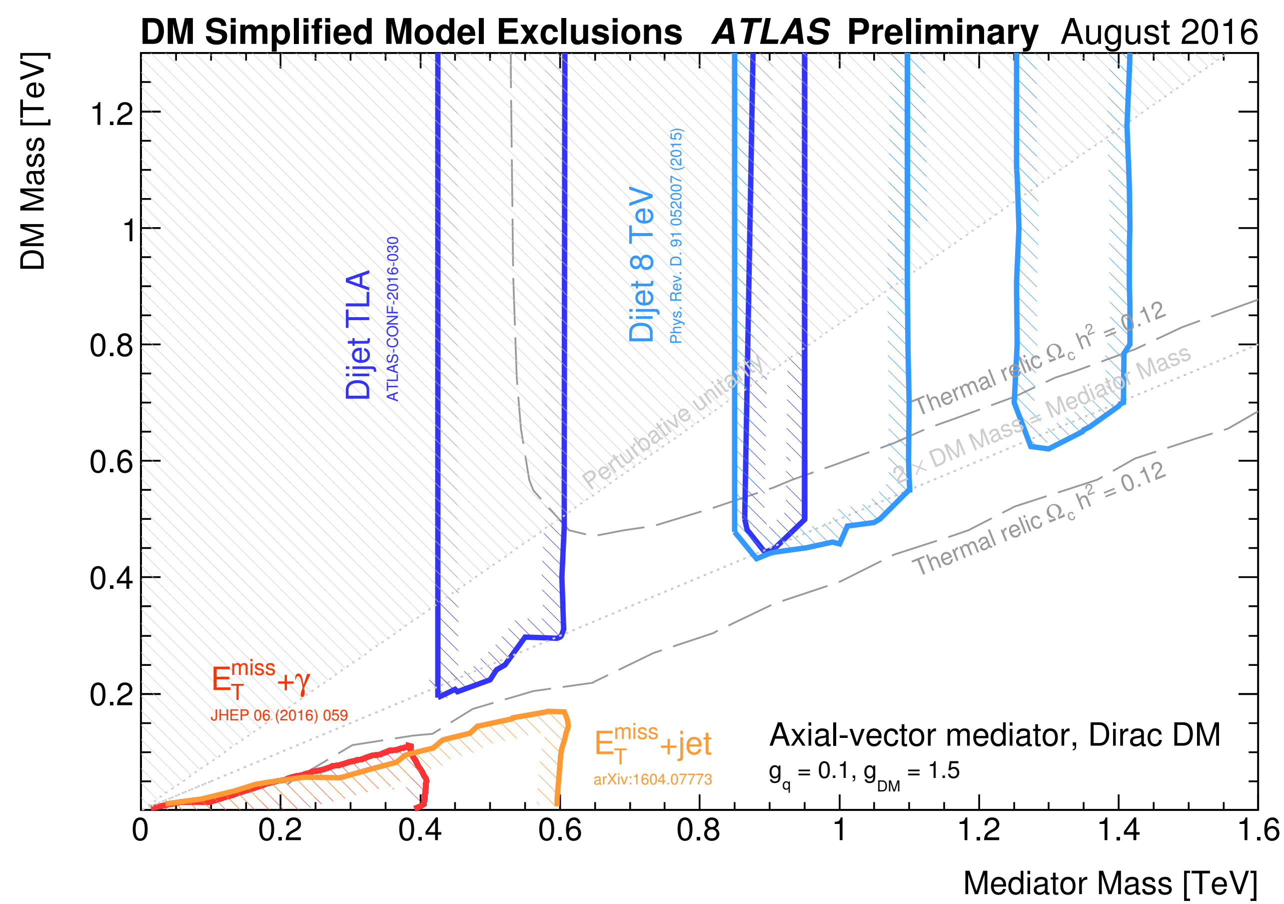
In some cases direct searches for the mediator or di-jets can be more effective than monojets (i.e. also for Z').

[Fradsen et al. 2012, Chala et al. 2015]

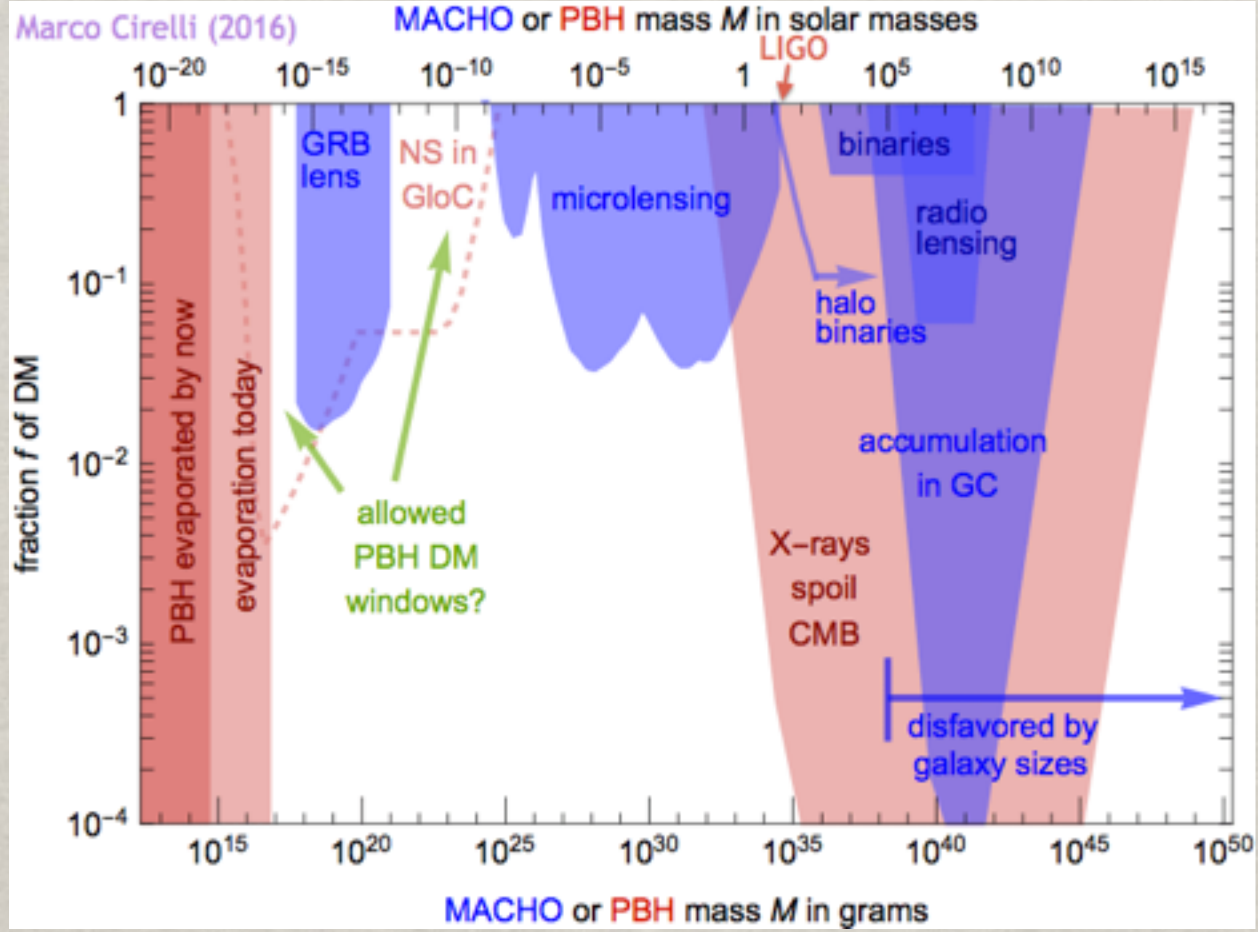
LHC limits from dijets

[ATLAS coll. 2016]





Black Hole DM



Not easy to produce them in the Early Universe..., e.g. need funny power spectra from inflation for primordial Black Holes

Axions as Dark Matter

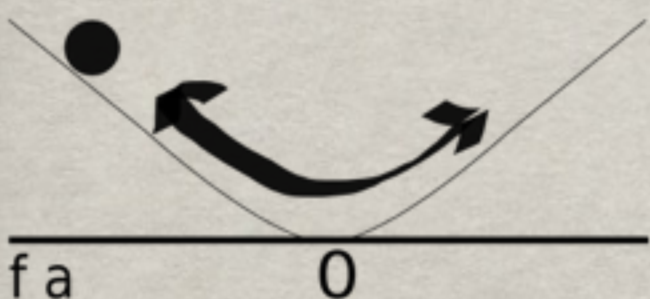
The axion is also a very natural DM candidate, but in this case in the form of a condensate, e.g. generated by the misalignment mechanism:

Before the QCD phase transition the potential for the axion is flat

After the QCD phase transition a potential is generated

$$V(a) = \Lambda^4_{QCD}\left(1 - \cos\left(\theta + \frac{a}{f_a}\right)\right)$$

by instantons effects and the axion starts to oscillate coherently around the minimum:



zero momentum particles >> CDM !

Axions as Dark Matter

Their energy density by misalignment is

$$\Omega_a h^2 = 0.5 \left(\frac{f_a}{10^{12}\mathrm{GeV}} \right)^{7/6} \theta_i^2$$

Axions can contribute to star/SN cooling and so

$$0.5 \times 10^{10}\mathrm{GeV} \leq f_a \leq 10^{12}\mathrm{GeV}$$

[Raffelt 98]

Therefore the mass for axion DM is very small:

$$m_a = \Lambda_{QCD}^2 / f_a \sim 6 \times 10^{-5}\mathrm{eV} \left(\frac{f_a}{10^{11}\mathrm{GeV}} \right)^{-1}$$

AXION DM SEARCHES

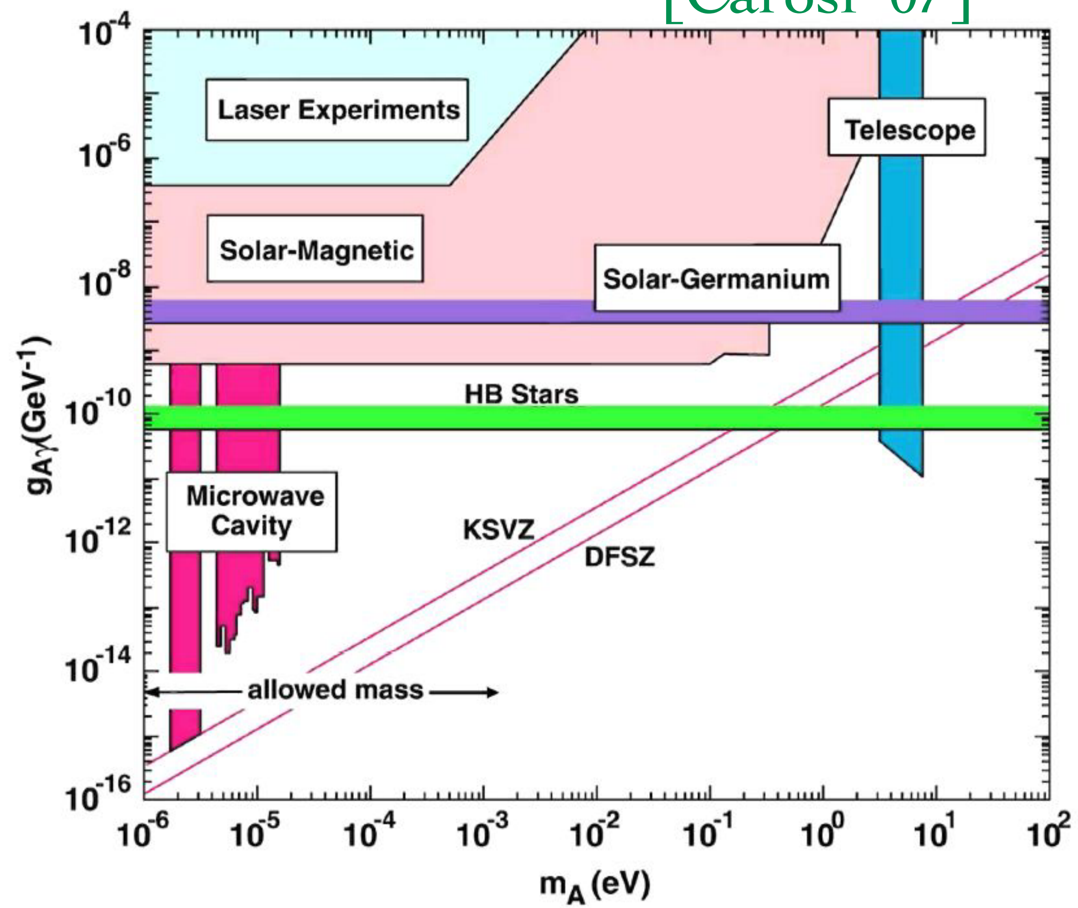
The right abundance can be obtained if the Peccei-Quinn scale is of the order of 10^{11-12} GeV and the mass in the μeV.

ADMX is finally touching the expected region.

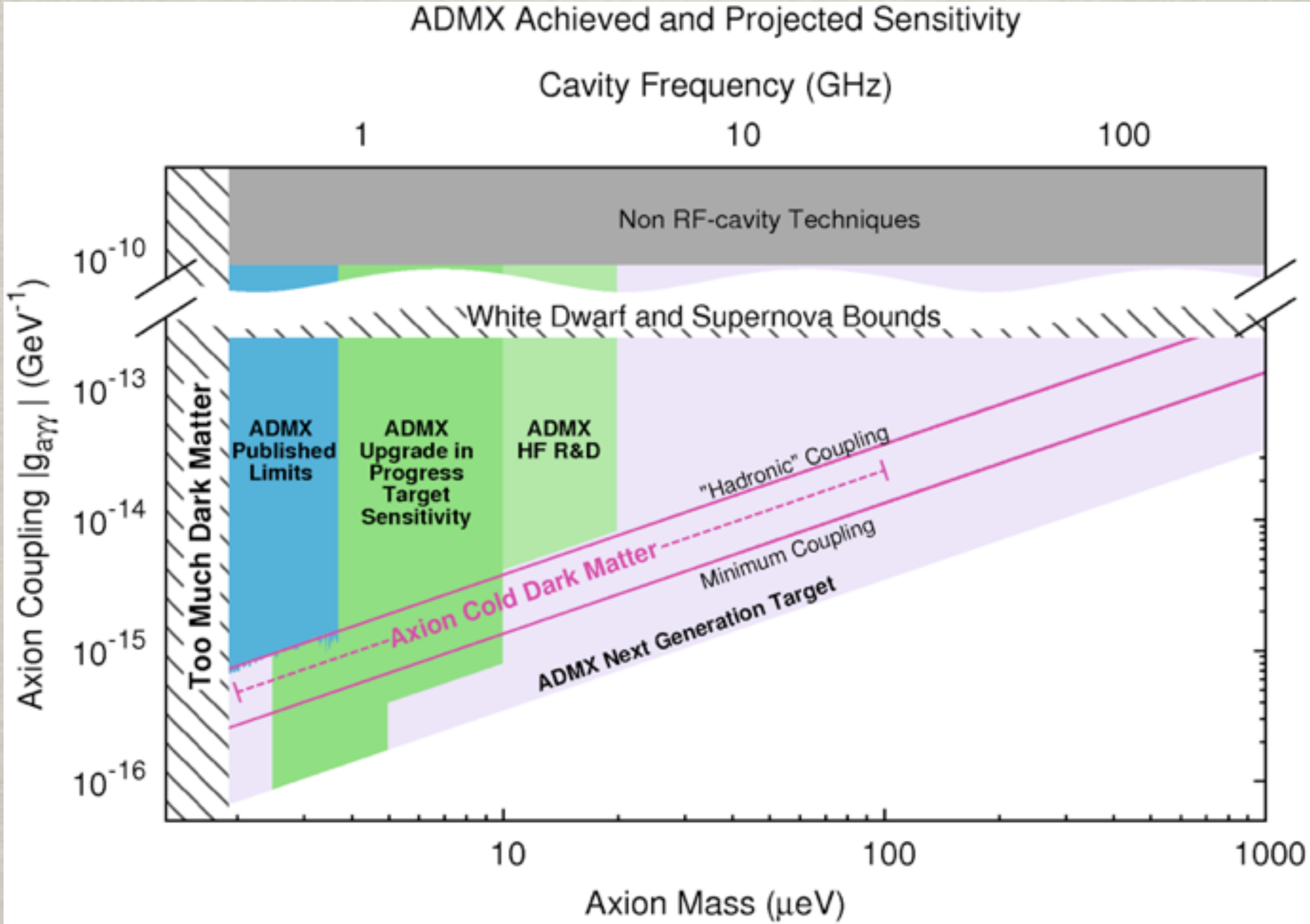
But it could be much wider for non-standard cosmologies...

[Gondolo et al 09]

[Carosi '07]



AXION DM SEARCHES



http://www.phys.washington.edu/groups/admx/home.html

Higgs Inflation

[Bezukov & Shaposhnikov 09]

Couple the Higgs field non-minimally to gravity:

$$\mathcal{L}_\xi = -\frac{\xi}{2}\phi^2 R$$

The term combines with the usual Einstein-Hilbert term and changes the strength of gravity at large field:

$$(M_P^{eff})^2 = M_P^2 + \xi\,\phi^2$$

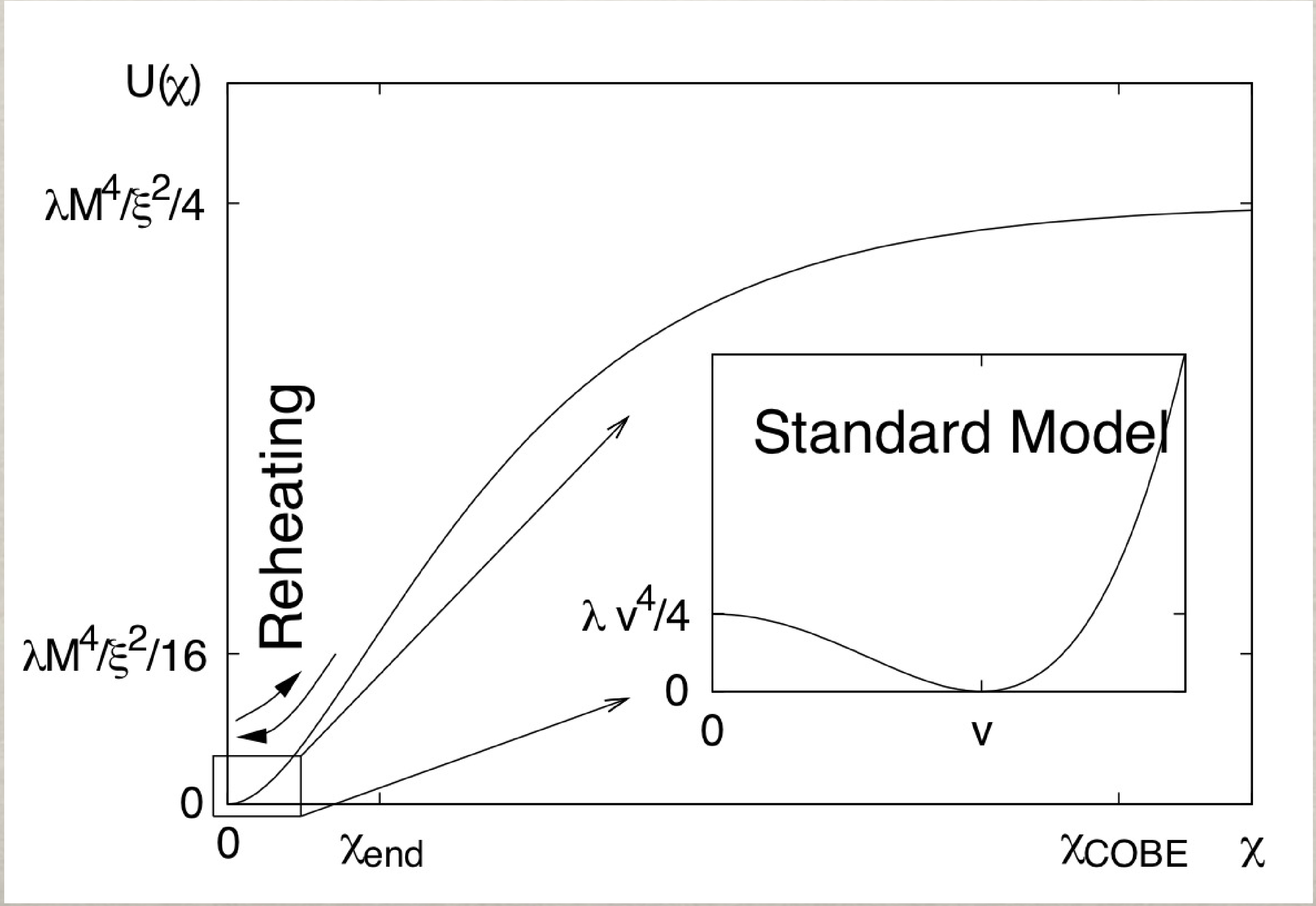
At large field values all the mass scales are proportional to the field and this can be "rescaled" away >> flat direction ! Indeed in the Jordan frame (via conformal transformation)

$$\tilde{g}_{\mu\nu} = \left(1 + \frac{\xi\phi^2}{M_P^2}\right) g_{\mu\nu} \qquad \frac{d\chi}{d\phi} = \frac{1}{\Omega}\sqrt{1 + \frac{6\xi^2\phi^2}{\Omega^2 M_P^2}}$$

Higgs Inflation

[Bezukov & Shaposhnikov 09]

In the redefined canonically normalized field the potential is:



Higgs Inflation

[Bezukov & Shaposhnikov 09]

Inflation is possible, BUT

- the normalization of the CMB power spectrum requires $$\xi \sim 5 \times 10^4 \sqrt{\lambda} \gg 1$$

  Very large non-minimal coupling to gravity !

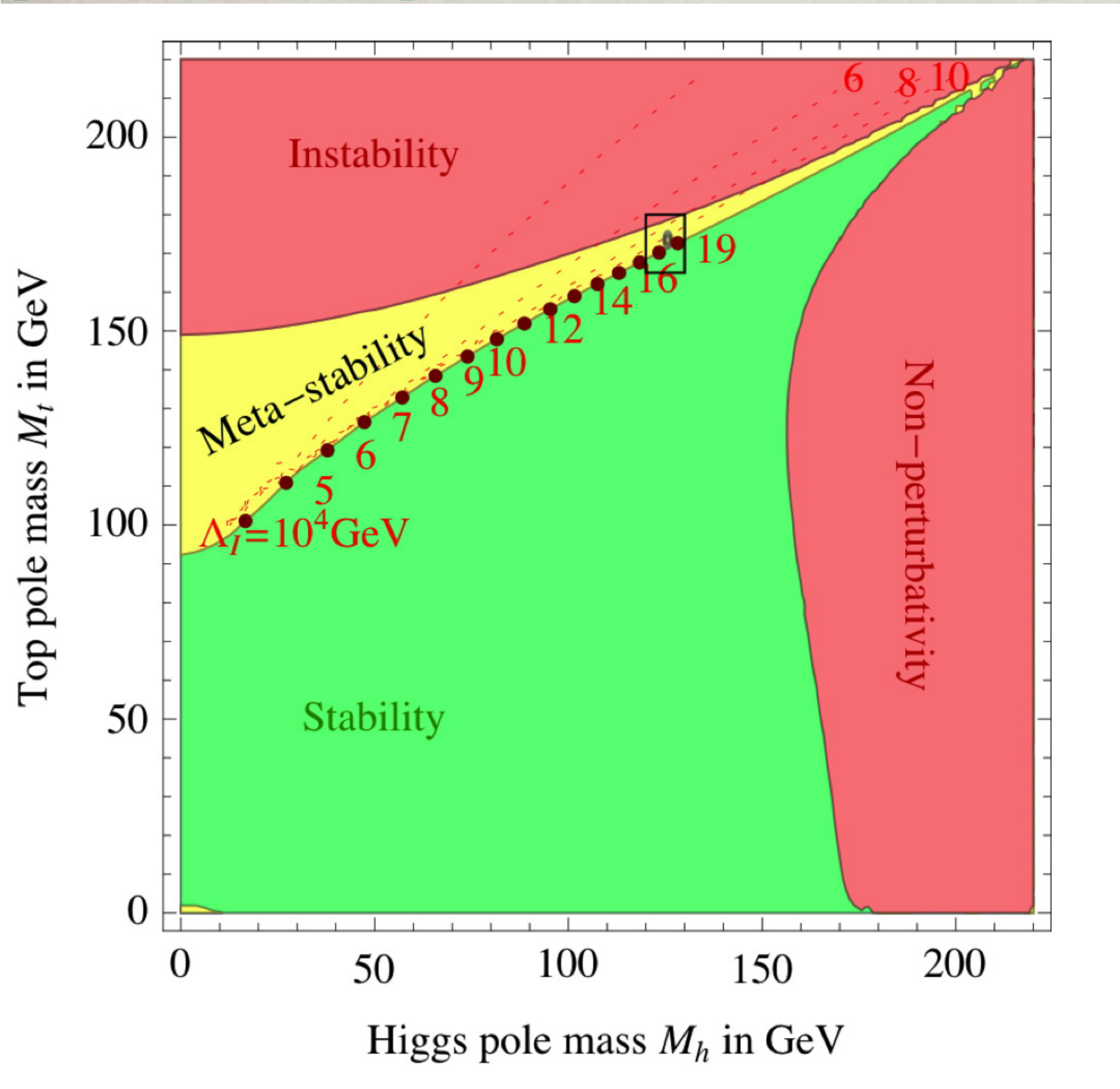
- connection to the Higgs coupling and therefore the Higgs mass as well by requiring consistency to the inflationary scale: $130\,\mathrm{GeV} \leq m_H \leq 194\,\mathrm{GeV}$
  ... now a bit on the boundary due to Higgs mass !

- Possible trouble: unitarity bound saturated at a scale

$$M_P/\sqrt{\xi} < M_P$$

Higgs Potential at M_Pl?

[Buttazzo & al. 14]



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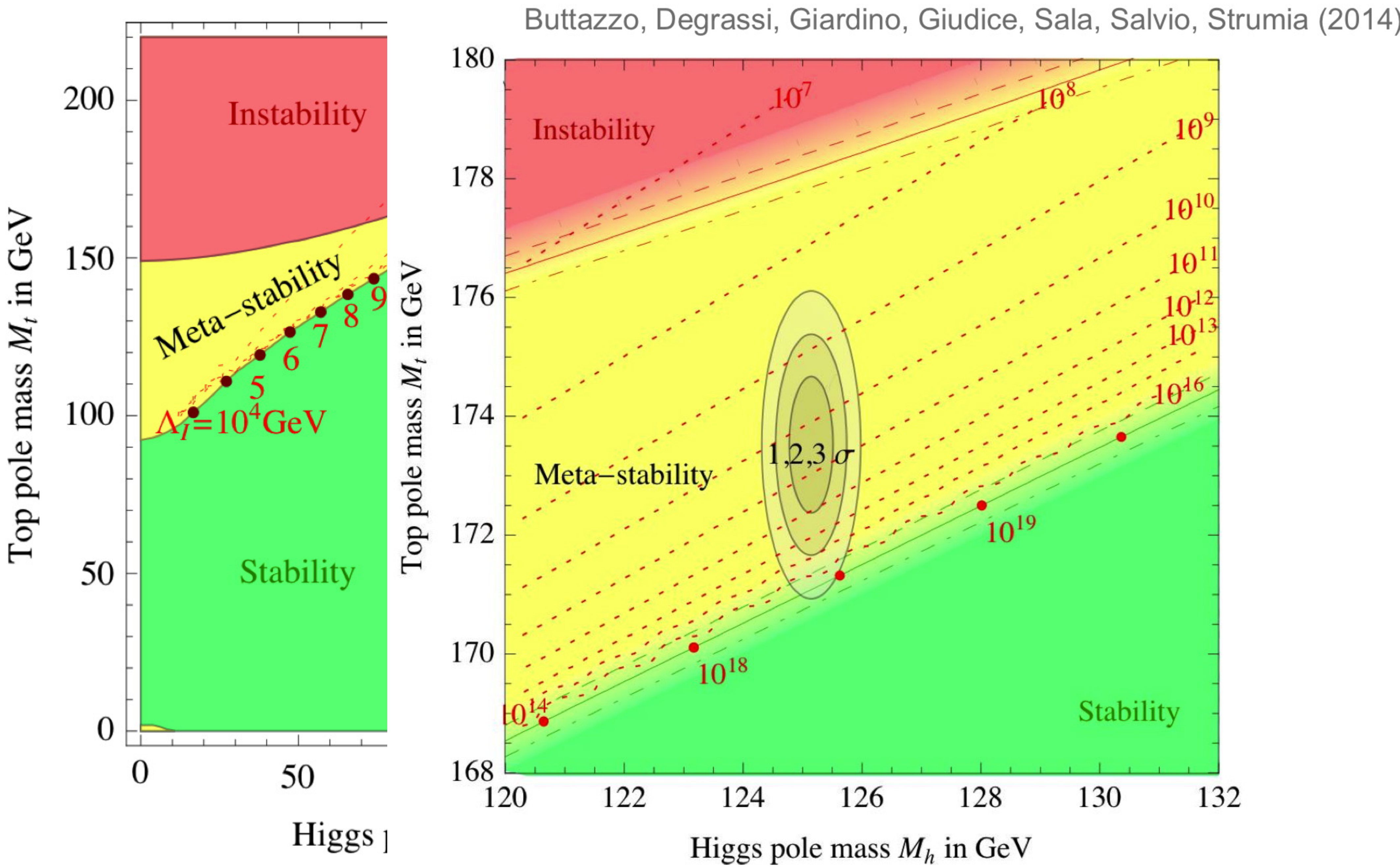

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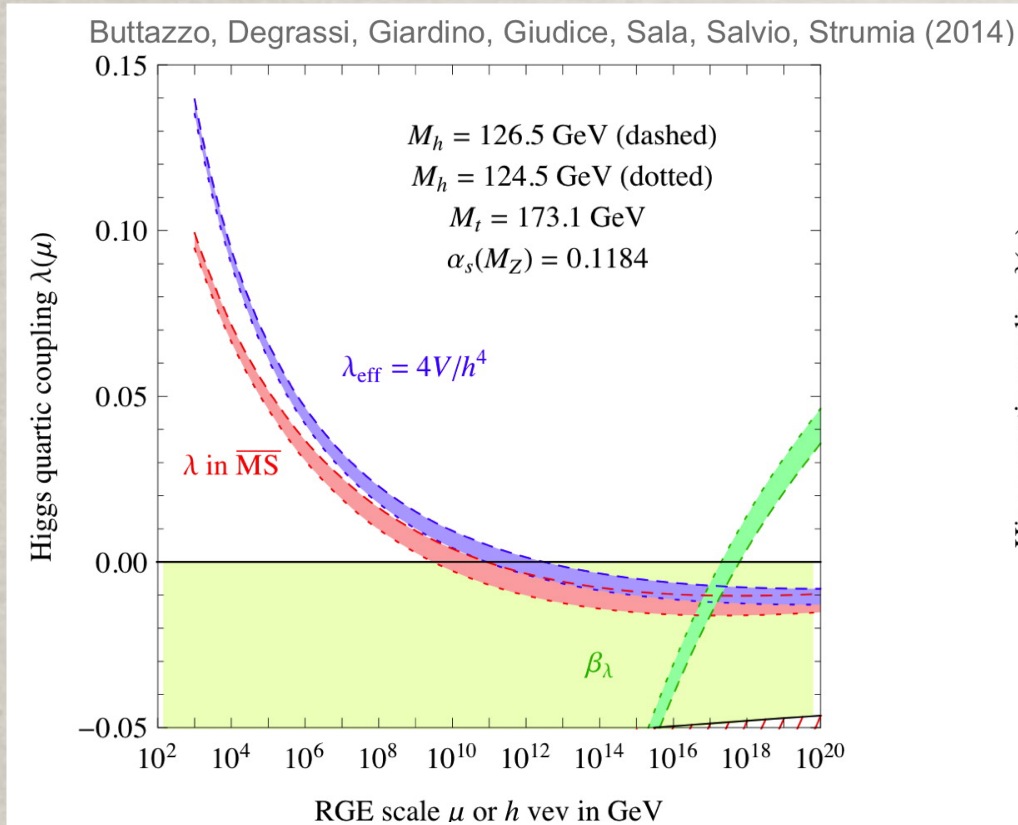
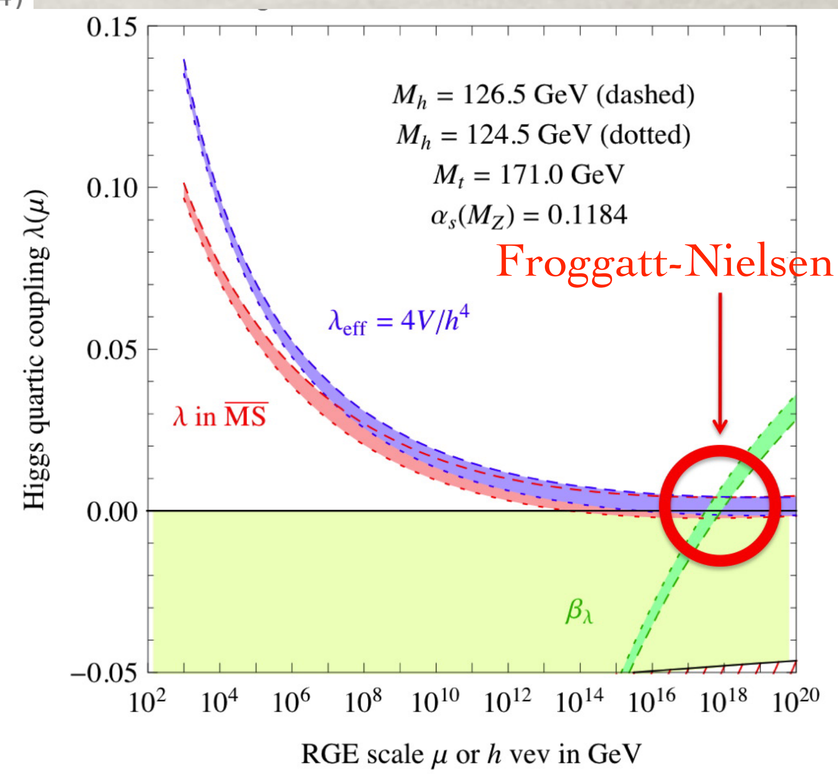
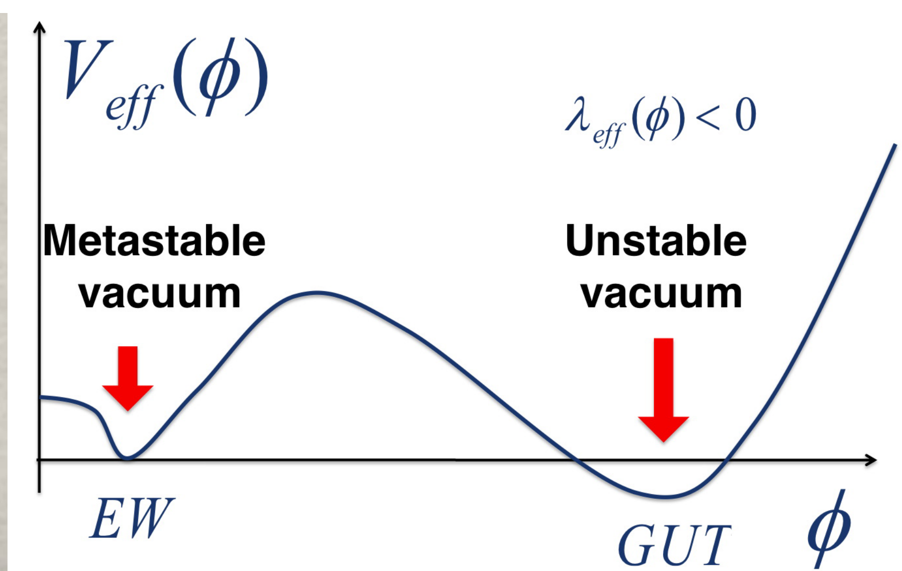
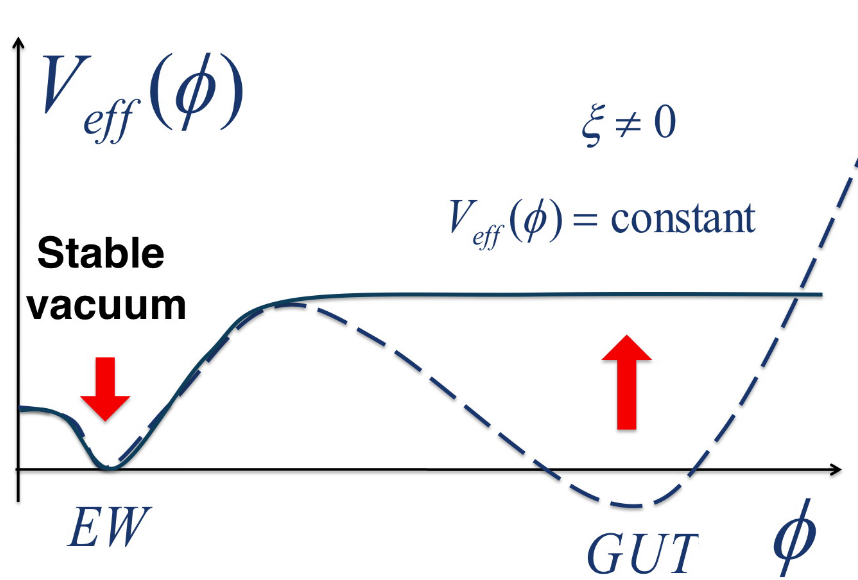


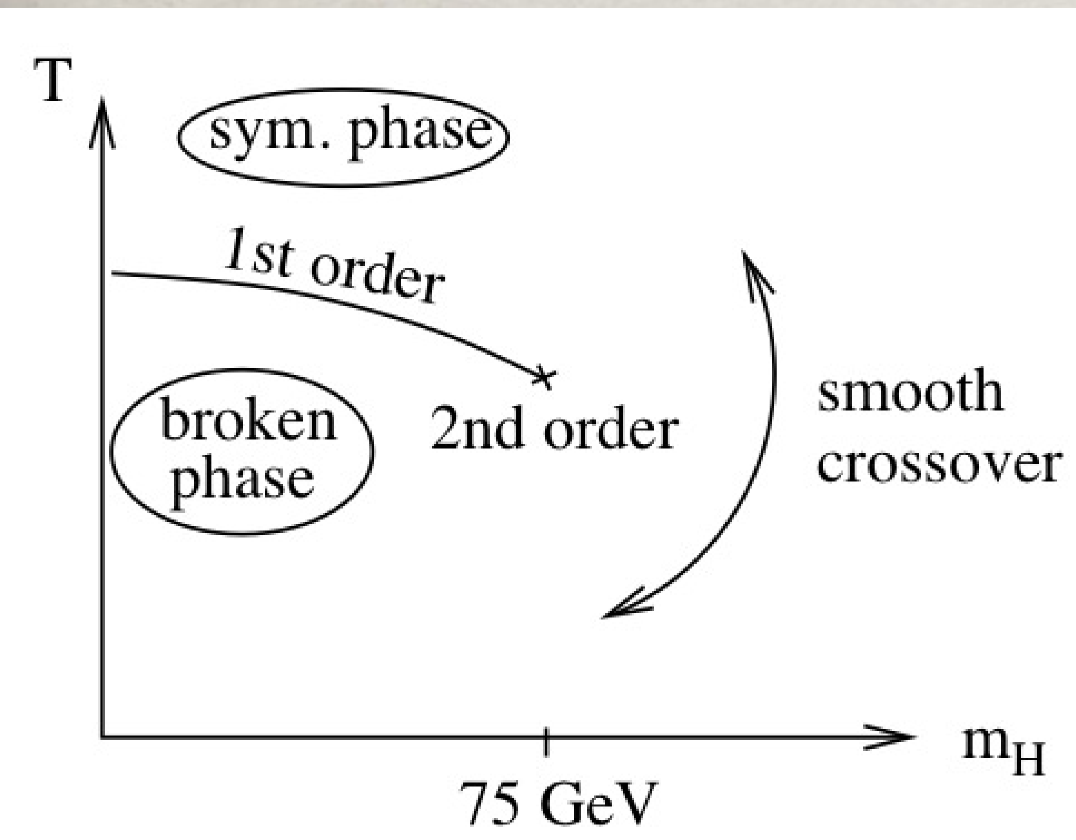




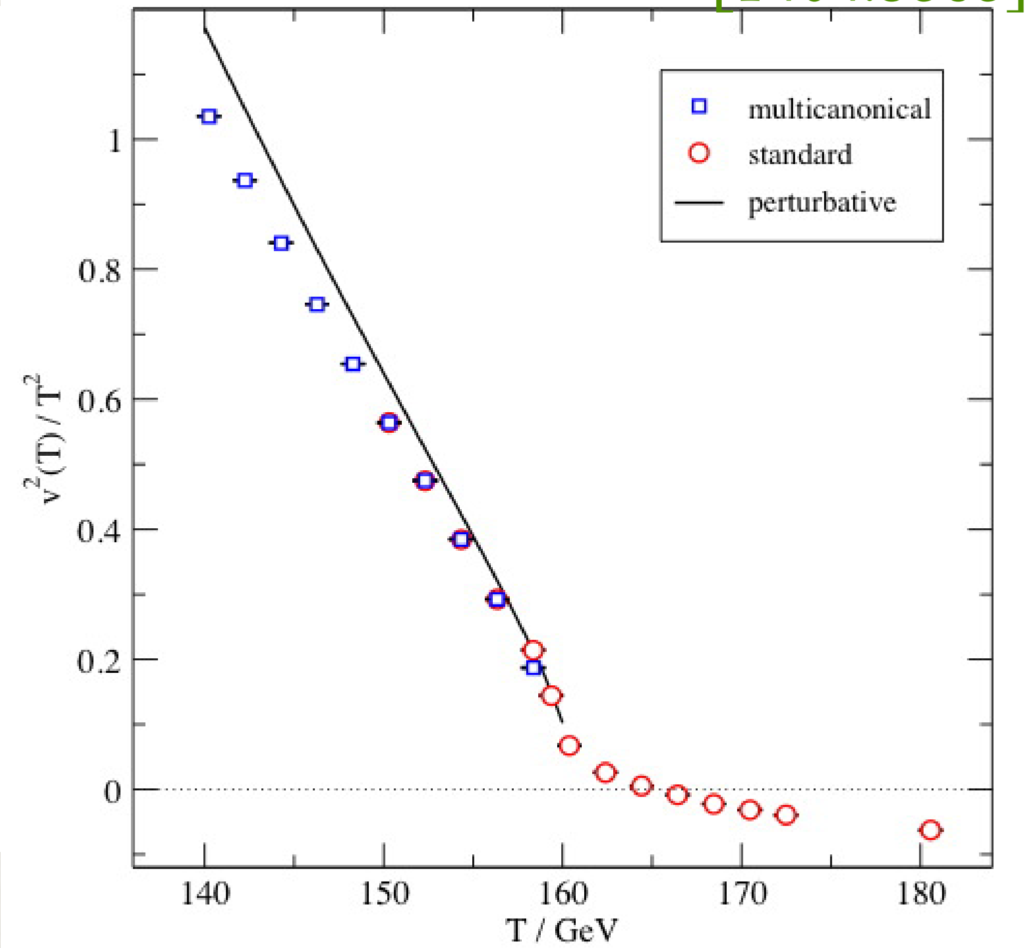


EW Phase Transition in SM

Compute the phase diagram for the EW phase transition:
for the physical Higgs mass it is a smooth cross-over !



[1404.3565]



NO EW baryogenesis in the SM !

EW Baryogenesis in SUSY

In SUSY extensions of the SM EW baryogenesis is possible if

- The phase transition is stronger: e.g. by enhancing the cubic term in the Higgs potential thanks to (light) scalars, e.g. in SUSY stops or singlets !
- There are additional CP violating phases to increase the amount of CP violation.
- Still the Higgs has to be light... in MSSM EW baryogenesis ~ 120 GeV with one stop state below the top... Is it possible with a 125 GeV Higgs ?

EW Phase Transition BSM

Again compute the effective potential at finite temperature:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

The cubic term determines mostly the presence of a barrier

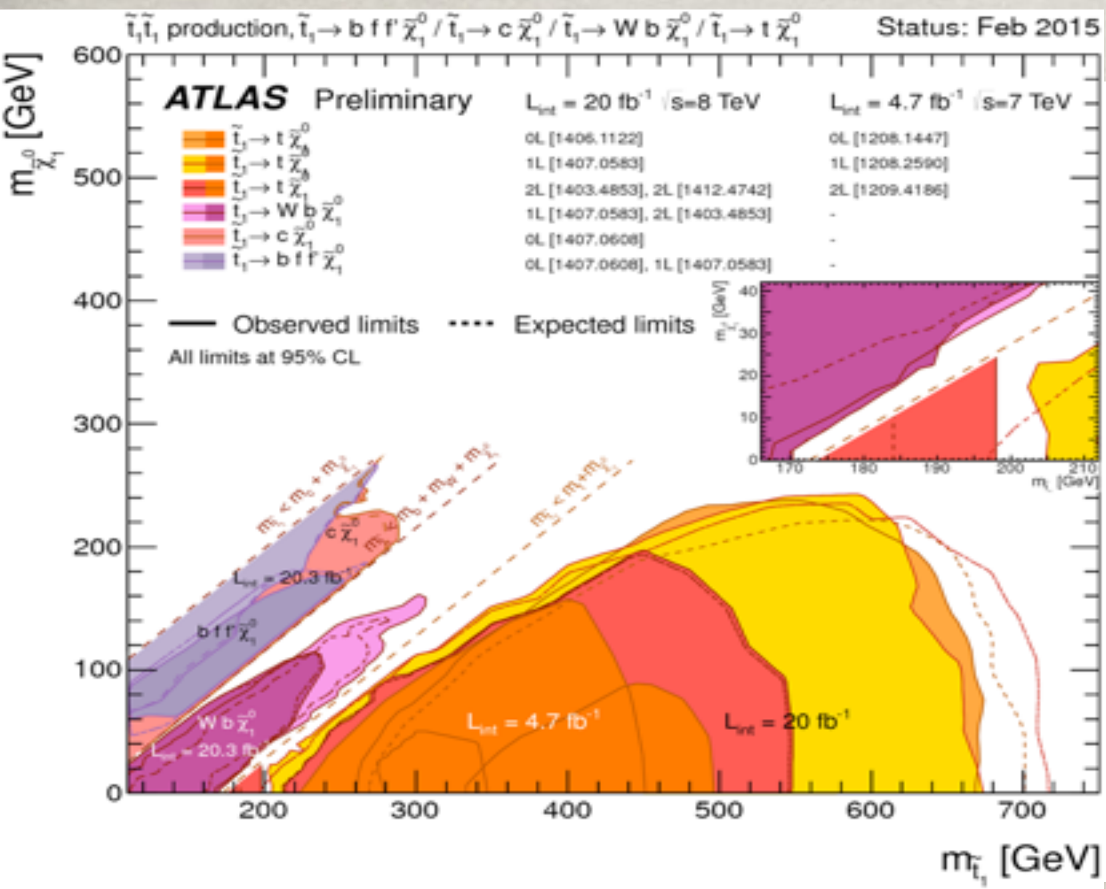
Bosonic Loops contribute to E(T), increasing the strength of the phase transition, so in order to make it first order increase the number of bosons in the model !

Many different possibilities, the simplest ones are:

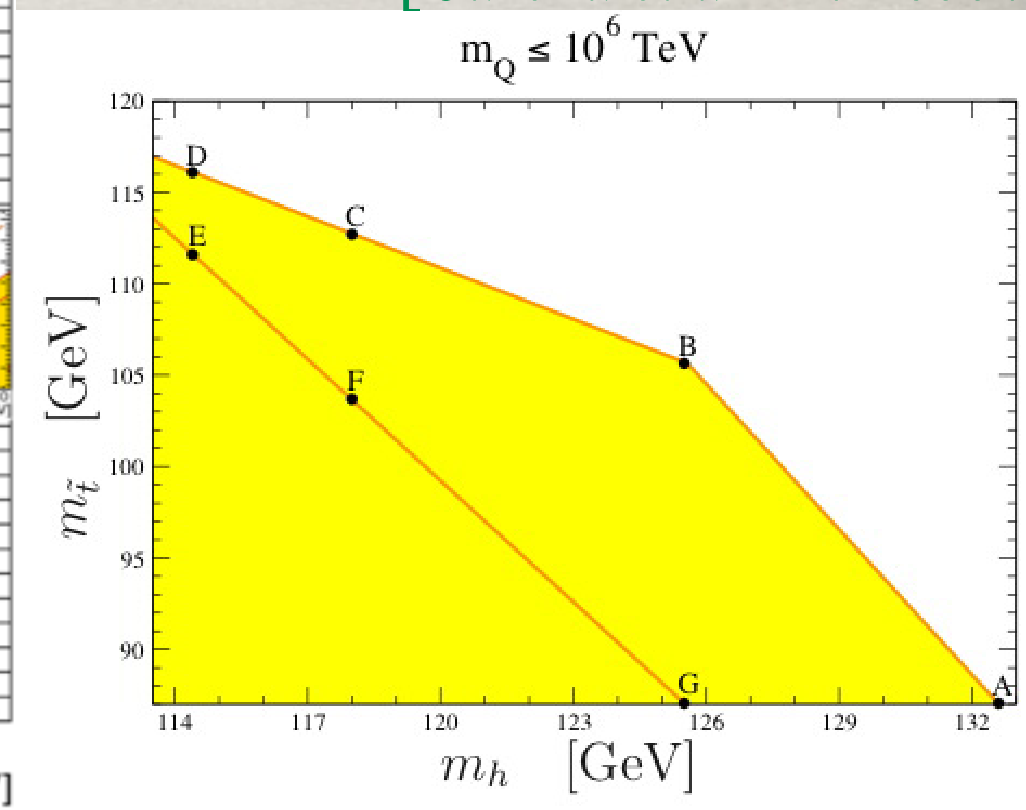
- extend the scalar/Higgs sector of the SM;
- add supersymmetry;
- add higher dimensional operators.

EW Baryogenesis in SUSY

In the MSSM a 125 GeV Higgs is still OK for heavy squarks. Still the light stop should be lighter than the top, some region of parameters is already probed by LHC...

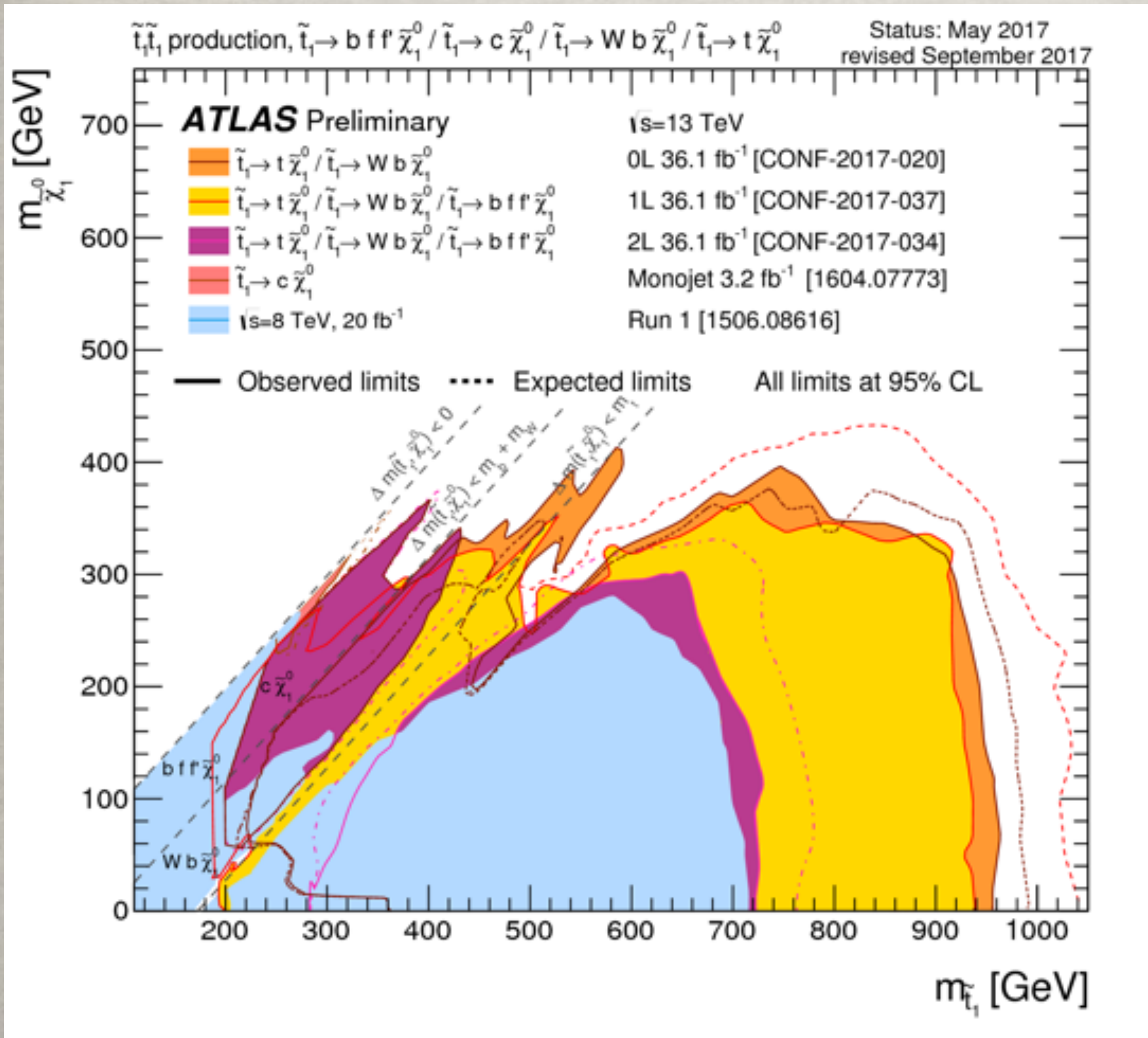


[Carena et al 1207.6330]



On the other hand, the light stop enhances ALL Higgs-VV couplings and seem not to be what LHC finds for the Higgs...

EW Baryogenesis in SUSY



New bounds on the stop mass seem to exclude nearly all the light stop mass region: probably need to go beyond MSSM for a 1st order phase transition !