Dark Matter-Baryogenesis Connection

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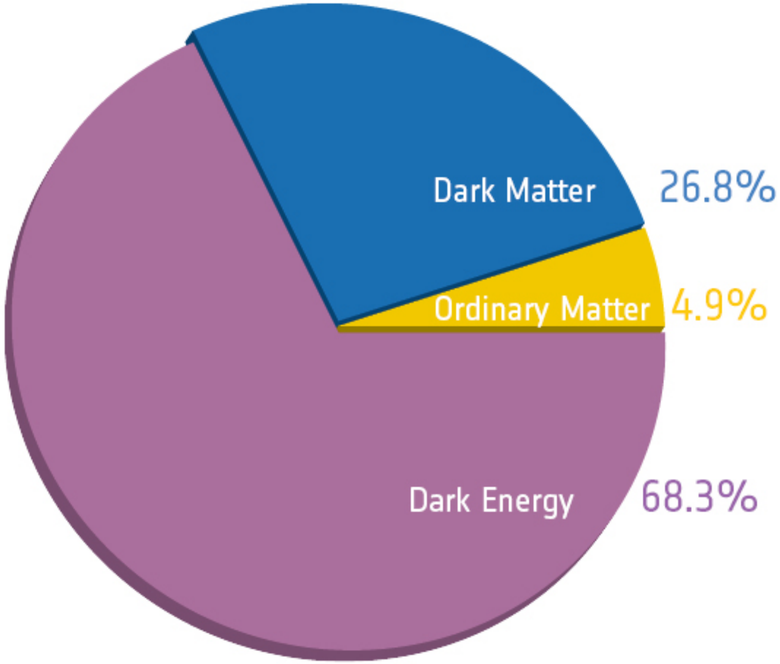
IFAE

Are the Dark Matter and baryon abundances related ?

$\Omega_{DM} \approx 5\ \Omega_{baryons}$



Atoms:	4.9 %
Photons:	0.0022 %
Neutrinos:	0.0016 %

Matter Anti-matter asymmetry:

characterized in terms of the baryon to photon ratio

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}$$

$$5.1 < \eta_{10} < 6.5 \text{ (95\% CL)}$$

The great annihilation

10 000 000 001
Matter

10 000 000 000
Anti-matter

▼

1
(us)

Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

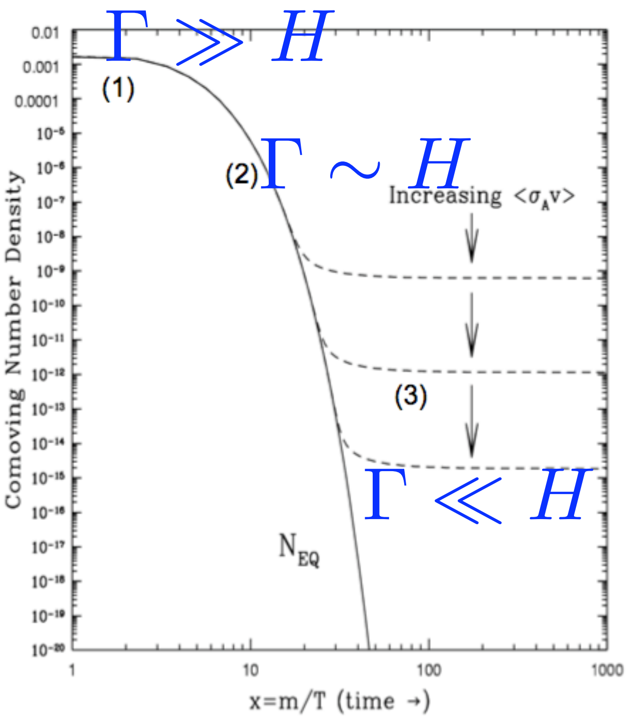
$$\boxed{\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}}$$

~ 6. 10^{-10}

The great annihilation between nucleons & anti-nucleons

$$n + \bar{n} \to \pi + \pi \to \gamma + \gamma + \ldots$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T}/m_\pi^2 \sim H \sim \sqrt{g_*} T^2/m_{Pl}$



corresponding to a freeze-out temperature T_F ~ 20 MeV

In absence of an asymmetry:

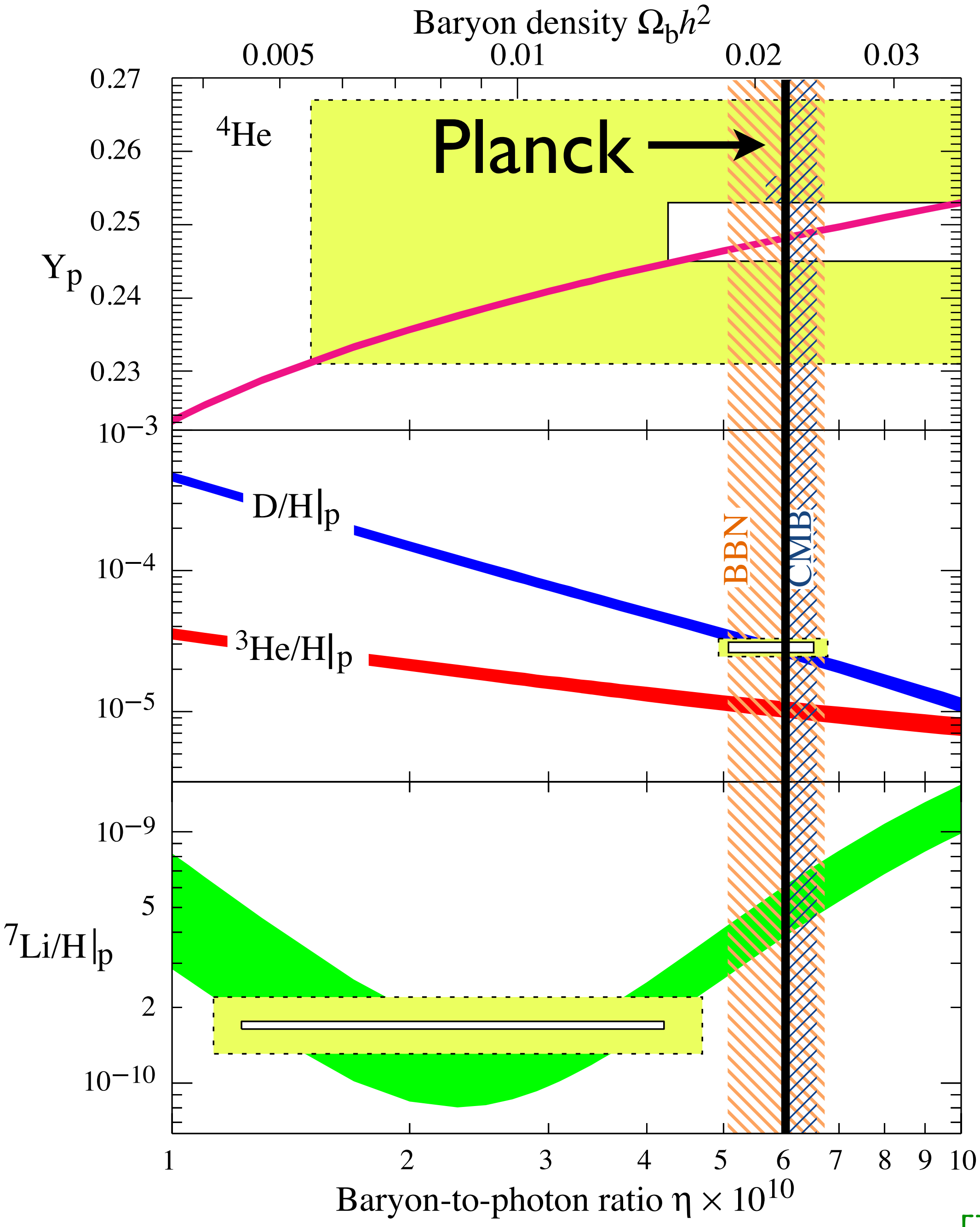
$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001
Matter

10 000 000 000
Anti-matter

1
(us)



The Baryon Asymmetry of the Universe (BAU) deduced from the Cosmic Microwave Background measurements is now more precise than the one deduced from Big Bang Nucleosynthesis (D/H abundance)

[PDG 2012]

η remains unexplained within the Standard Model

double failure:

- lack of out-of-equilibrium condition

- so far, no baryogenesis mechanism that works with only SM CP violation (CKM phase)

proven for standard
EW baryogenesis

Gavela, P. Hernandez, Orloff, Pene '94
Konstandin, Prokopec, Schmidt '04

unconclusive attempts in
cold EW baryogenesis

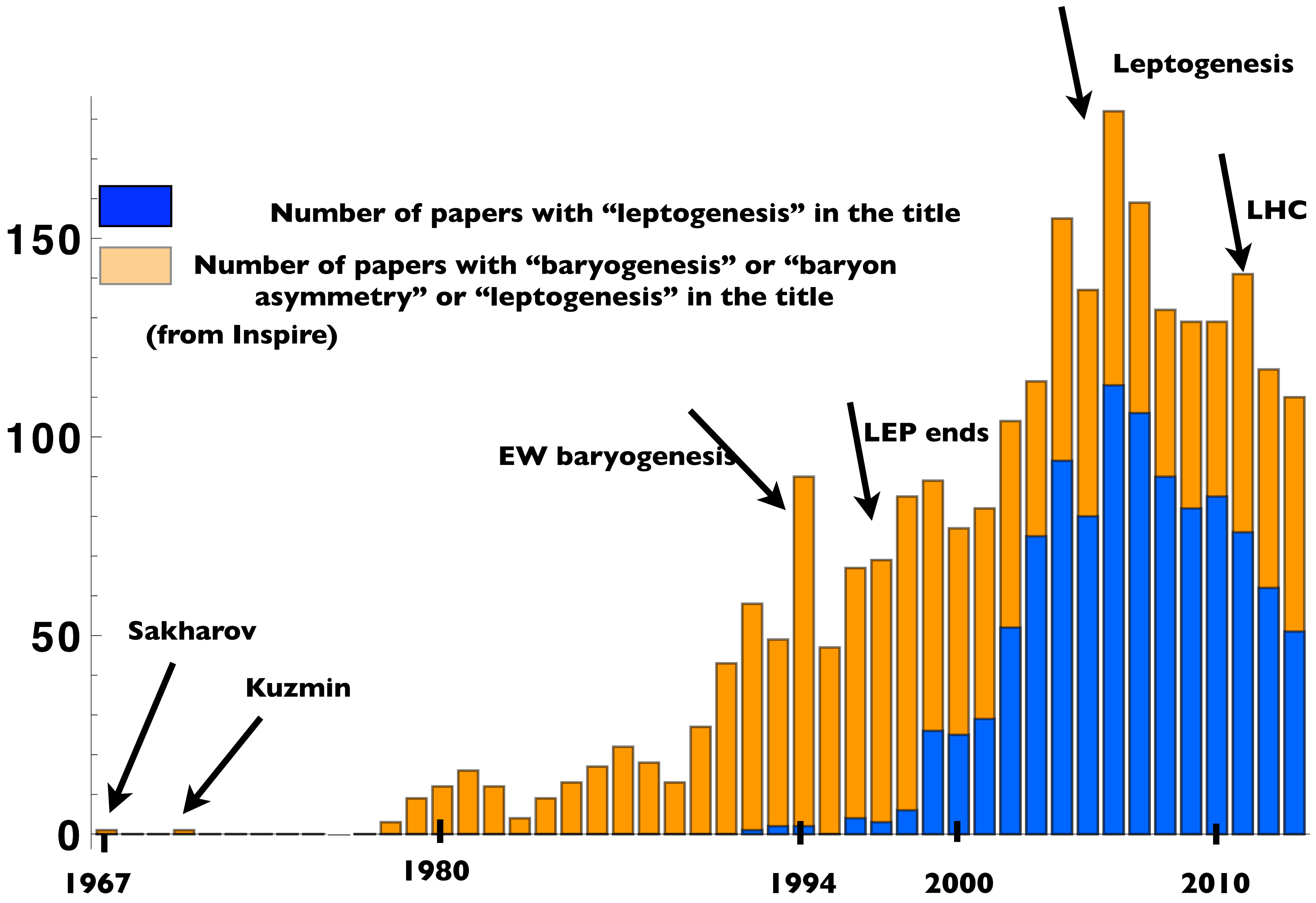
Tranberg, A. Hernandez, Konstandin, Schmidt '09
Brauner, Taanila,Tranberg,Vuorinen '12

Shaposhnikov,

Journal of Physics: Conference Series **171** (2009) 012005

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

History of baryogenesis papers



Two leading candidates for baryogenesis:

--> Leptogenesis by out of equilibrium decays of RH neutrinos before the EW phase transition

--> Baryogenesis at a first-order EW phase transition

Models of Baryogenesis

T

GUT baryogenesis

B washout unless B-L ≠ 0

requires SO(10)
requires too high reheat temperature to produce enough GUT particles

⟶ leptogenesis

Thermal leptogenesis

hierarchy pb -> embed in susy-> gravitino pb (can be solved if M_gravitino>100 TeV and DM is neutralino or gravitino is stable)

Affleck-Dine (moduli decay)

Non-thermal leptogenesis (via oscillations)

Asymmetric dark matter-cogenesis

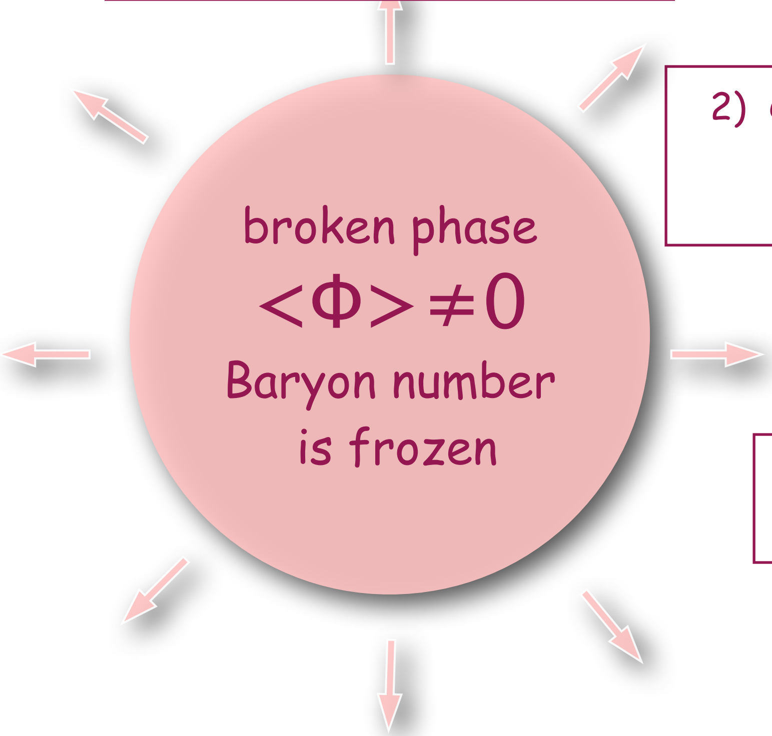
EW breaking, sphalerons freese-out

EW (non-local) baryogenesis

EW cold (local) baryogenesis

Baryon asymmetry and the EW scale

1) nucleation and expansion of bubbles of broken phase



broken phase

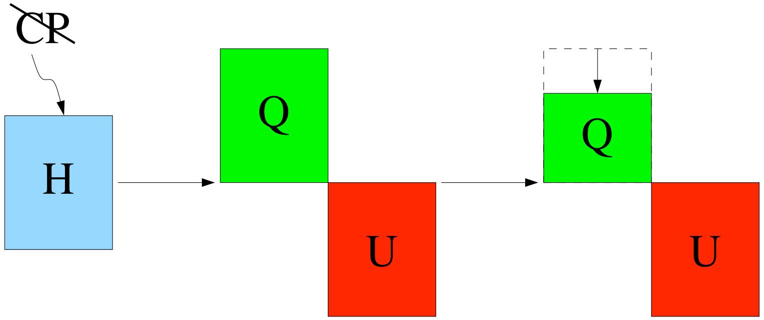
$\langle\Phi\rangle \neq 0$

Baryon number is frozen

2) CP violation at phase interface responsible for mechanism of charge separation

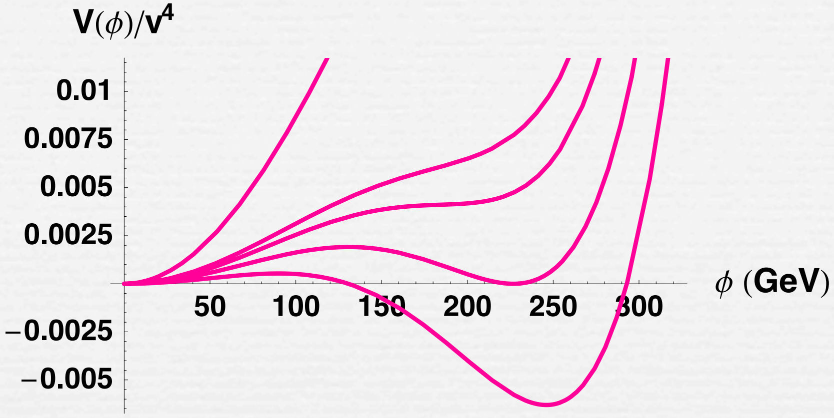
Chirality Flux in front of the wall

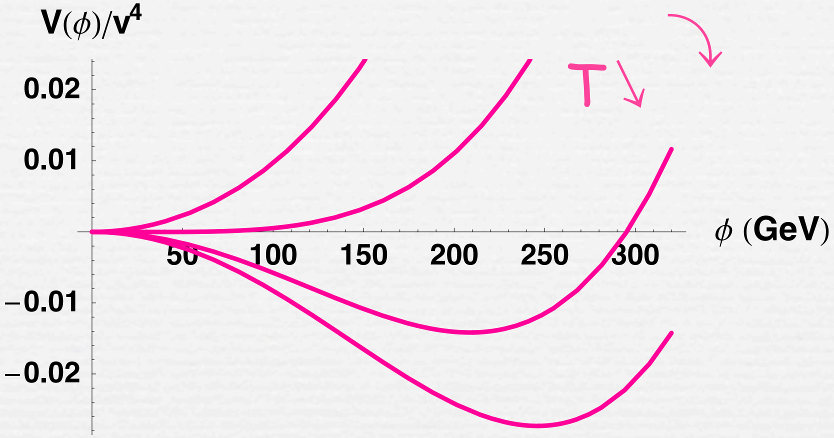
3) In symmetric phase, $\langle\Phi\rangle = 0$, very active sphalerons convert chiral asymmetry into baryon asymmetry



Electroweak baryogenesis mechanism relies on a first-order phase transition

first-order or second-order?





In the SM, a 1rst-order phase transition can occur due to thermally generated cubic Higgs interactions:

$$V(\phi,T) \approx \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^4 - ET\phi^3$$

$$-ET\phi^3 \subset -\frac{T}{12\pi}\sum_i m_i^3(\phi)$$

Sum over all bosons which couple to the Higgs

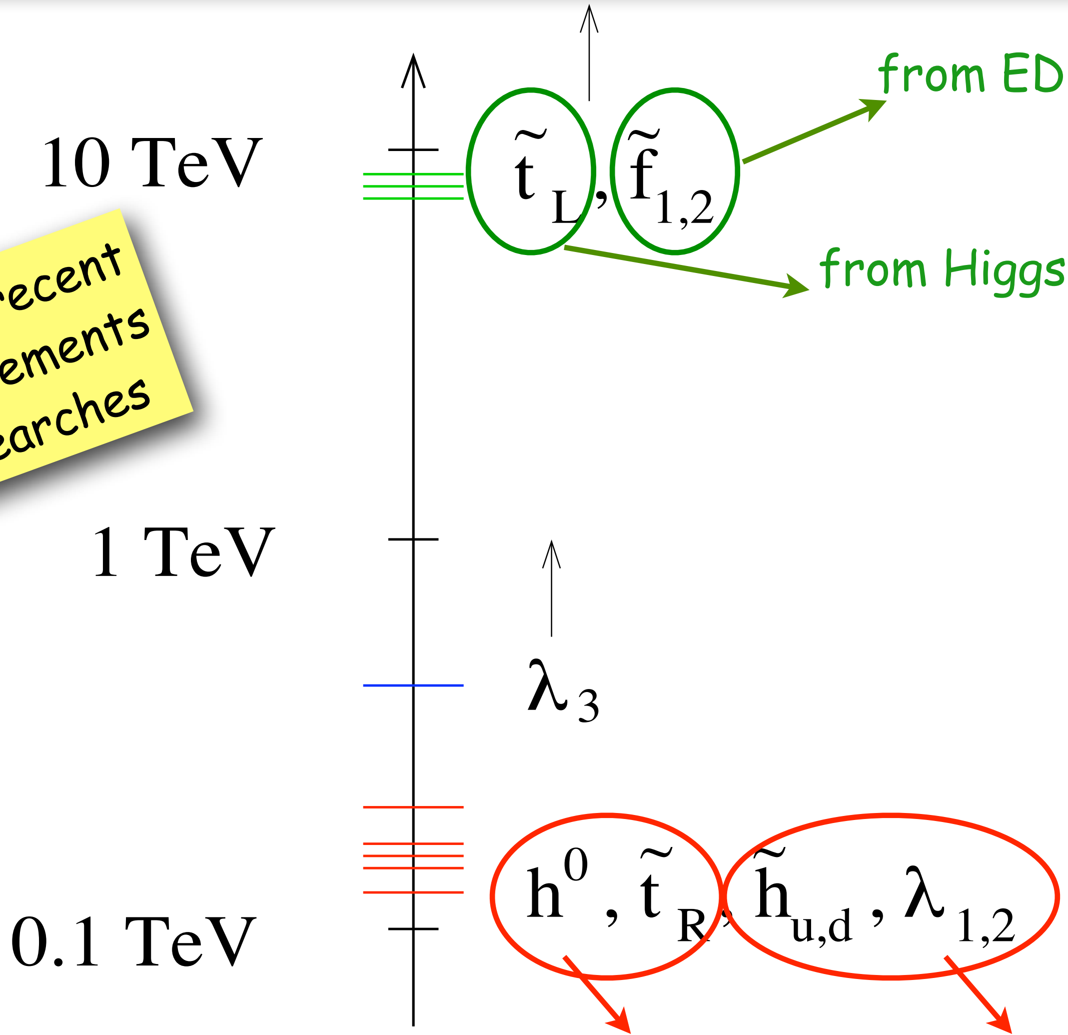
In the SM: $\sum_i \simeq \sum_{W,Z}$ → not enough

for mh>72 GeV, no 1st order phase transition

In the MSSM: new bosonic degrees of freedom with large coupling to the Higgs

Main effect due to the stop

The (fine-tuned) EW baryogenesis window in the Minimal Supersymmetric Standard Model: A Stop-split supersymmetry spectrum



10 TeV

$\tilde{t}_L, \tilde{f}_{1,2}$

from EDM bounds

from Higgs mass bound

1 TeV

λ_3

0.1 TeV

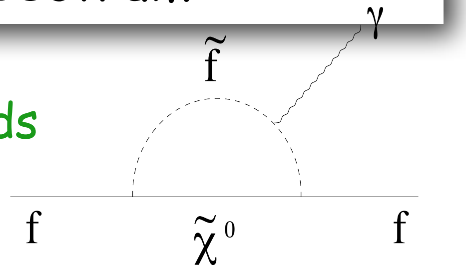
$h^0, \tilde{t}_R, \tilde{h}_{u,d}, \lambda_{1,2}$

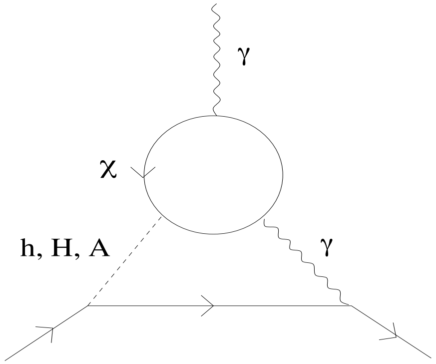
for strong 1st order phase transition

for sufficient CP violation $\propto Im(\mu M_2)$

excluded by recent higgs measurements and stop searches

see 1207.6330





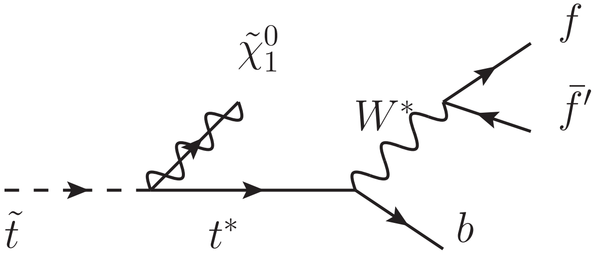
The light stop scenario: testable at the LHC

bounds get relaxed when adding singlets or in BSSM

Very light stop searches at the LHC

The 2 decay channels that have been studied in most detail:

$$\tilde{t}_1 \to t\tilde{\chi}_1^0$$

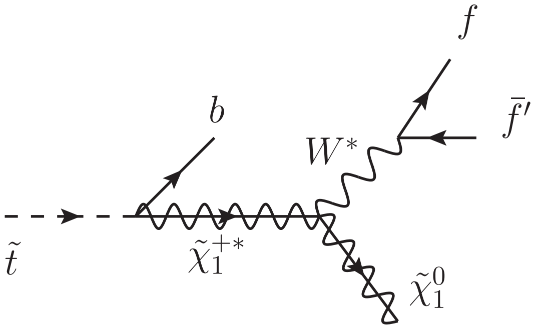


$$\tilde{t}_1 \to b\tilde{\chi}_1^+$$

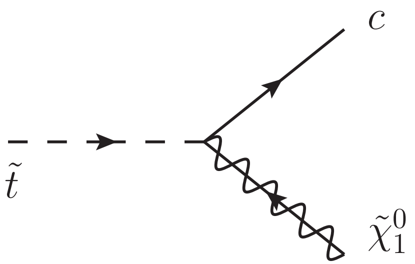
When stop is very light we have instead:

$$\tilde{t}_1 \to b\tilde{\chi}_1^0 W^+$$ **3-body**

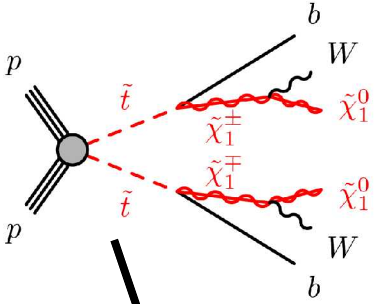
$$\tilde{t}_1 \to b\tilde{\chi}_1^0 f\bar{f}'$$ **4-body**



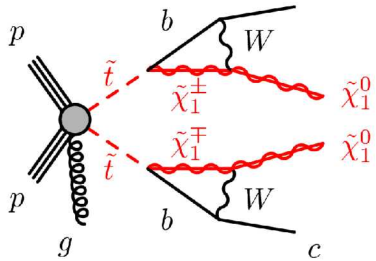
$$\tilde{t}_1 \to c\tilde{\chi}_1^0$$ **flavour-violating**

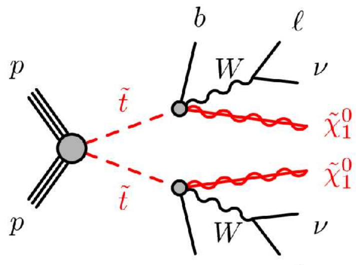


branching ratios depend on flavour structure

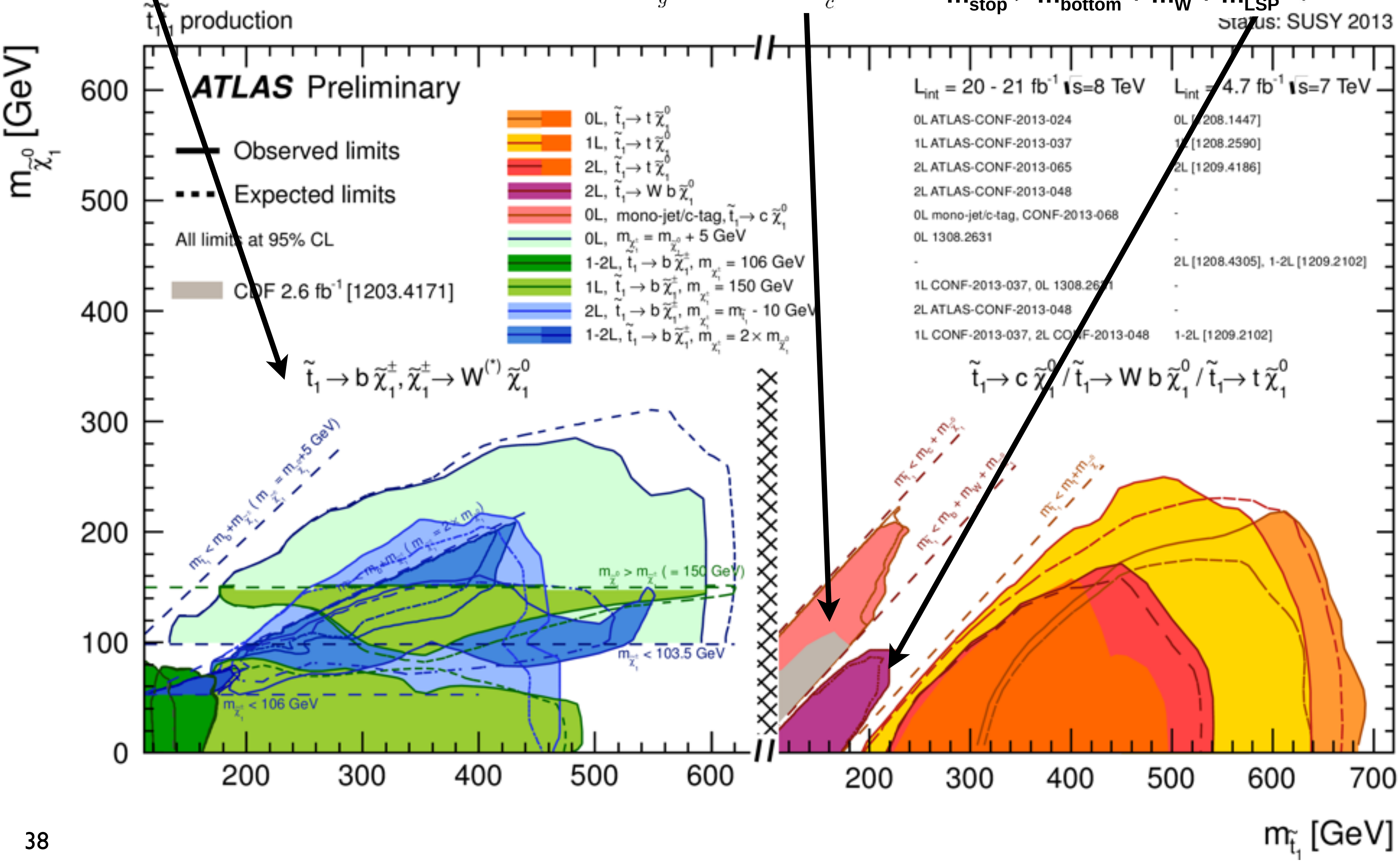


$m_{stop} > m_{charm} + m_{LSP}$

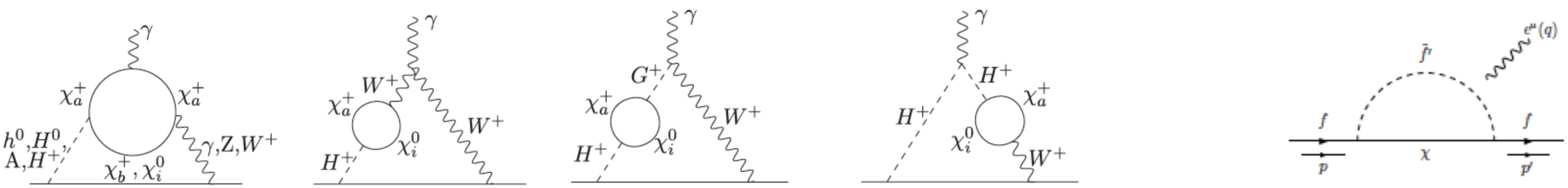


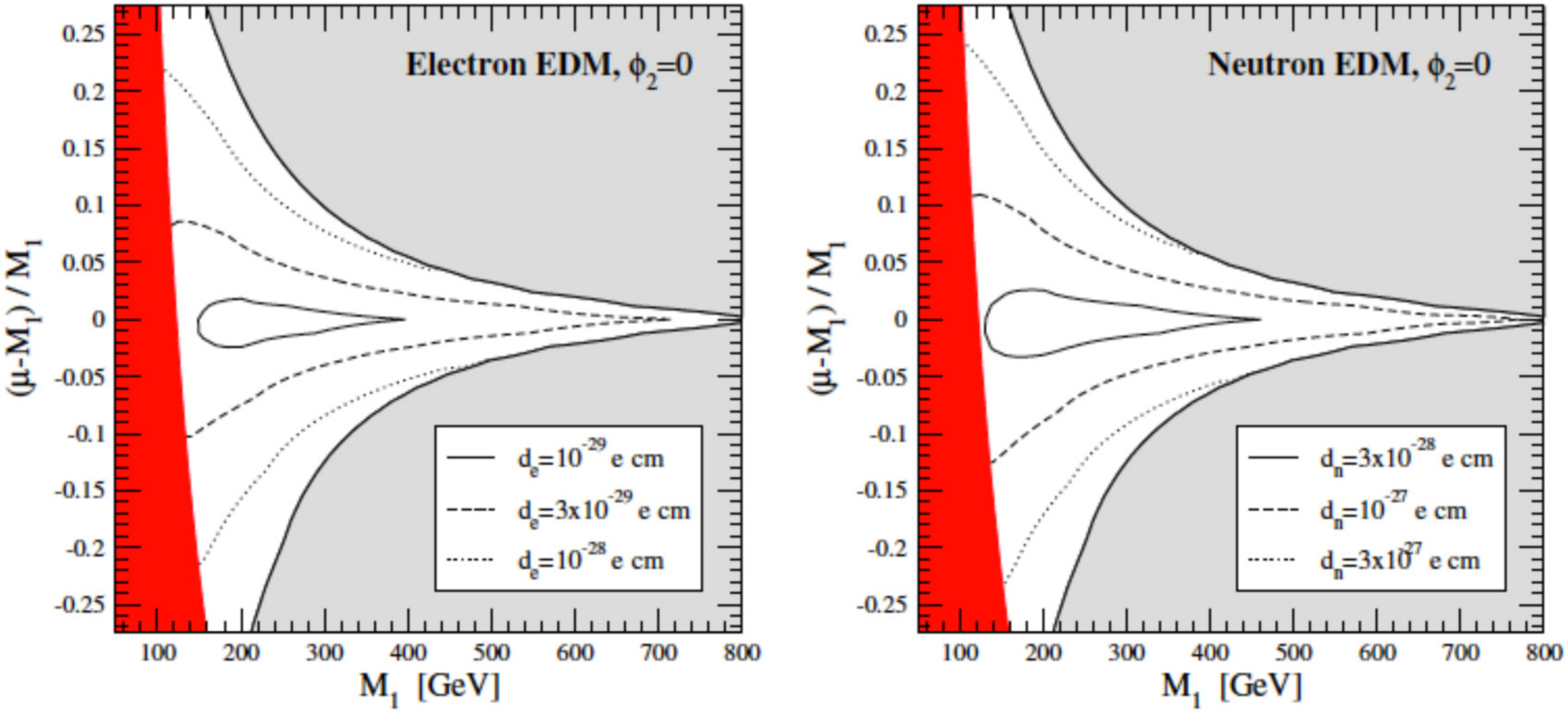


$m_{stop} > m_{bottom} + m_W + m_{LSP}$



and in addition... EDM constraints !





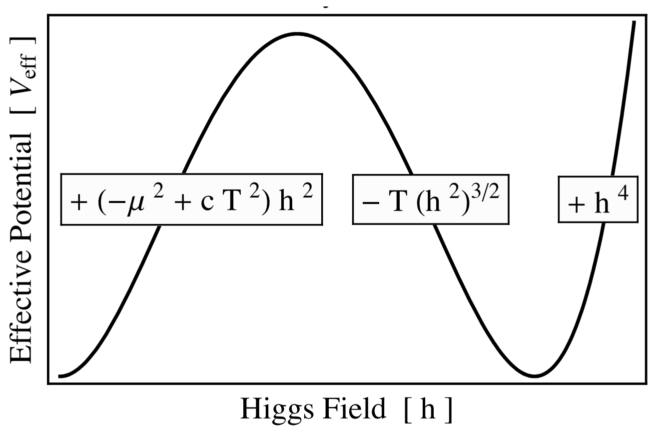
Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration*: J. Baron[1], W. C. Campbell[2], D. DeMille[3], J. M. Doyle[1], G. Gabrielse[1], Y. V. Gurevich[1,**], P. W. Hess[1], N. R. Hutzler[1], E. Kirilov[3,#], I. Kozyryev[3,†], B. R. O'Leary[3], C. D. Panda[1], M. F. Parsons[1], E. S. Petrik[1], B. Spaun[1], A. C. Vutha[4], and A. D. West[3]

versus

$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$$ @ 90%CL [1310.7534]

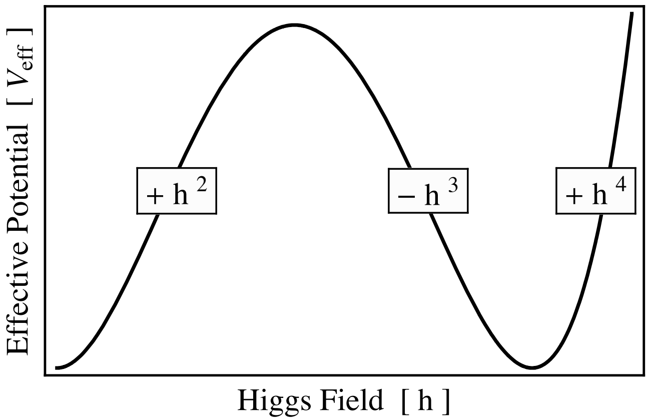
Three ways to obtain a strongly 1st order phase transition by inducing a barrier in the thermal effective potential



thermally driven

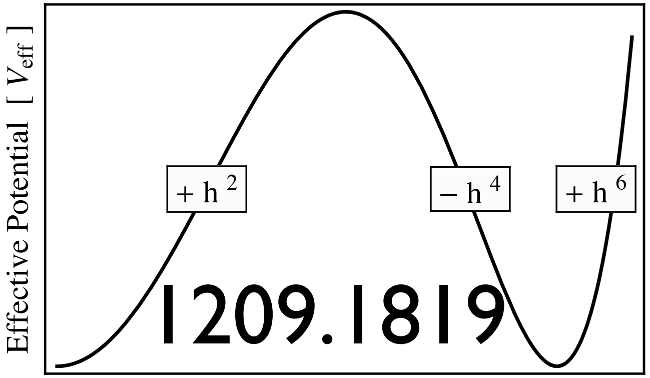
(thermal loop of bosonic modes)

(example:stop loop in MSSM)



tree-level driven

(competition between renormalizable operators)



tree-level driven

(competition between renormalizable and non-renormalizable operators)

1) Scenario where the 1st order phase transition is thermally driven

following [1401.1827]

most famous example: light stop scenario in MSSM

consider effect of new scalar coupled to the Higgs via

$$V \propto \kappa |\Phi|^2 |H|^2 \ .$$

Its effect on the thermal Higgs effective potential is:

$$V_{\rm eff}(\varphi;T) = V_0(\varphi) + V_T(\varphi;T) \approx \frac{1}{2}\left(-\mu^2 + \frac{g_\Phi \kappa T^2}{24}\right)\varphi^2 - \frac{g_\Phi \kappa^{3/2} T}{24\sqrt{2}\pi}\varphi^3 + \frac{\lambda}{4}\varphi^4.$$

as the mass of Φ in presence of background higgs field φ is:

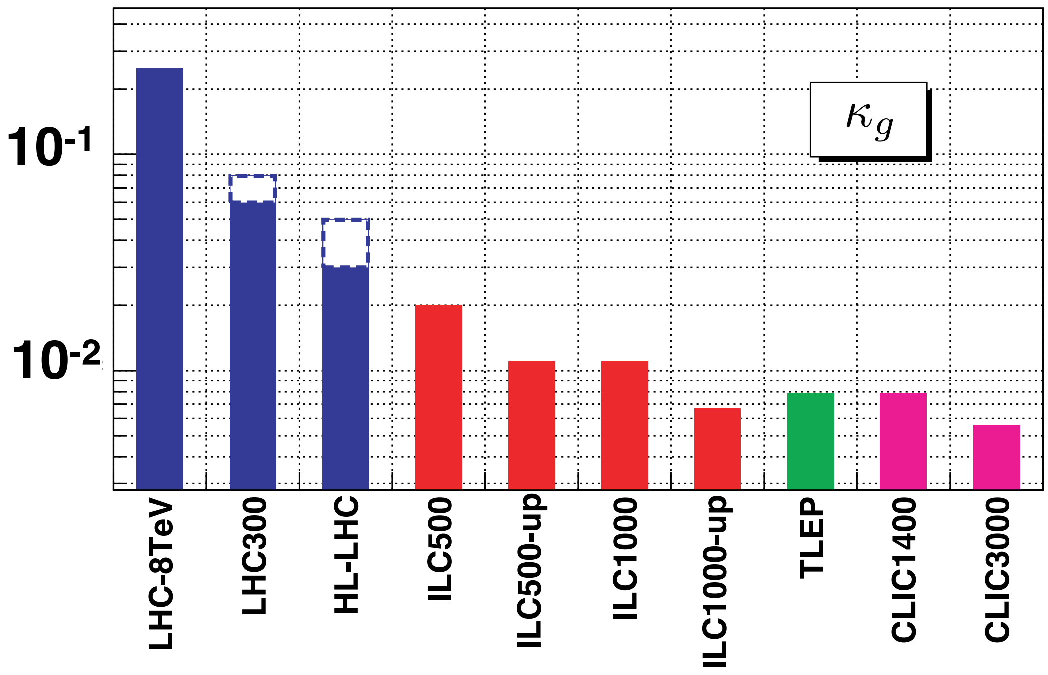
$$m_\Phi^2(\varphi) = m_0^2 + \frac{\kappa}{2}\varphi^2.$$

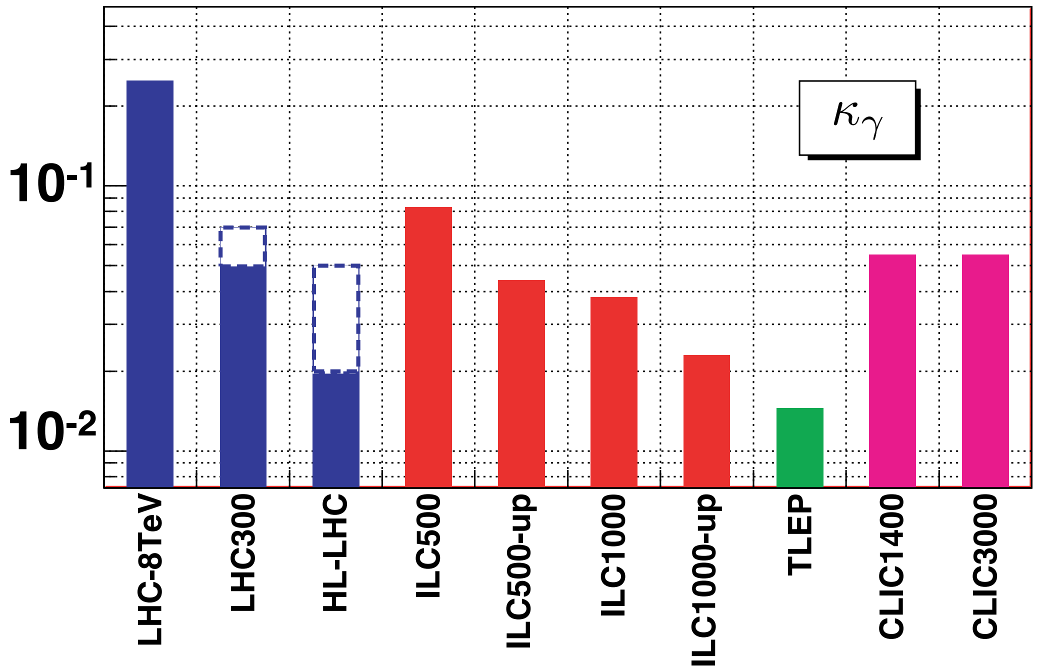
At the same time the Φ loop contributes
to the Higgs-gluon coupling

-> A strong 1st order PT leads to sizable deviations in Higgs production rate and decays in $\gamma\gamma$

-> typically excluded

Measurement precision on hgg and hγγ couplings





And if BSM scalar is neither colored nor electrically charged?

➡ still induces a 1-loop contribution to Higgs wave function renormalization and affect e+e- -> hZ cross section

$$\delta_{hZ} = -\frac{g_\Phi \kappa^2 v^2}{24\pi^2 m_h^2}\left(1 + F(\tau_\Phi)\right)$$

1305.5251

expected deviation: ~0.6%

can be probed at upgraded ILC-500 and at TLEP

(similarly for colored and/or electrically charged BSM scalars)

➡ still induces a deviation in the Higgs cubic self-coupling

expected deviation: ~10-20%

difficult to test with proposed facilities

Estimated per-experiment precision on Higgs triple self-coupling λ (1310.8361)

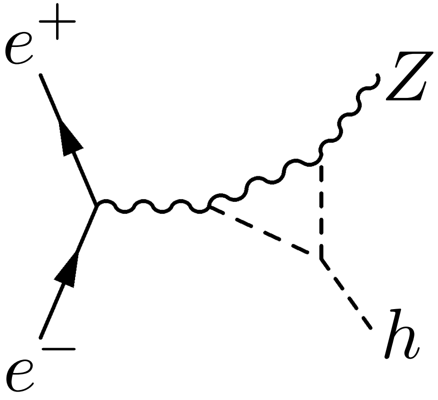
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

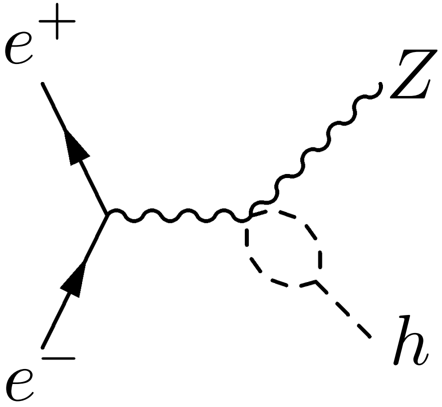
Estimated precision from combined facilities (1310.8361)

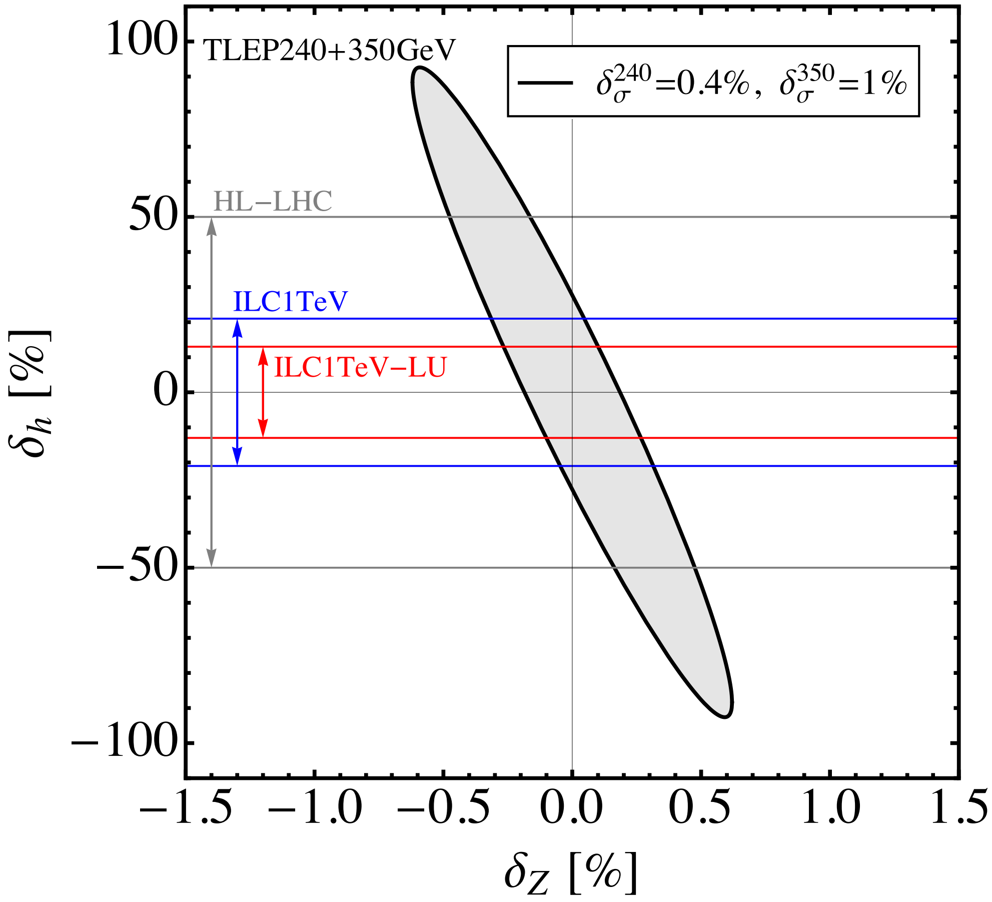
LHC	HL-LHC							
+ILC	+ILC-up	+(TLEP)			+ILC-up		+CLIC	
		+CLIC	+HE-LHC	+VLHC	+HE-LHC	+VLHC	+HE-LHC	+VLHC
21%	12.6%	15.2/9.8%	18.6%	7.9%	10.9%	6.8%	12.5/8.9%	7.2/6.2%

Indirect constraints on Higgs self-coupling at TLEP via its contribution to Higgsstrahlung

1312.3322







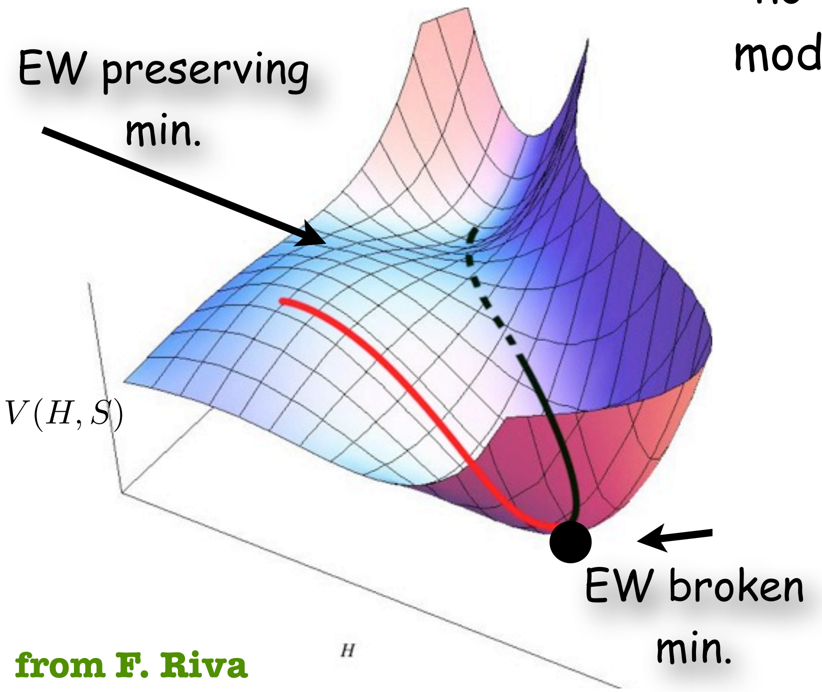
constrains deviations of order ~ 30%

2) Tree level modifications of the Higgs potential:

the SM+ a real scalar singlet: the nightmare scenario?

1409.0005

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4.$$



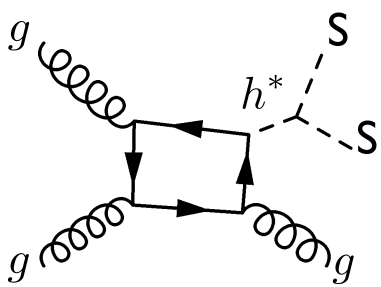
from F. Riva

S has no VEV today:
no Higgs-S mixing-> no EW precision tests , no modifications of higgs couplings as experimental probes of the EW phase transition
m_S>m_H/2: no modified Higgs decay

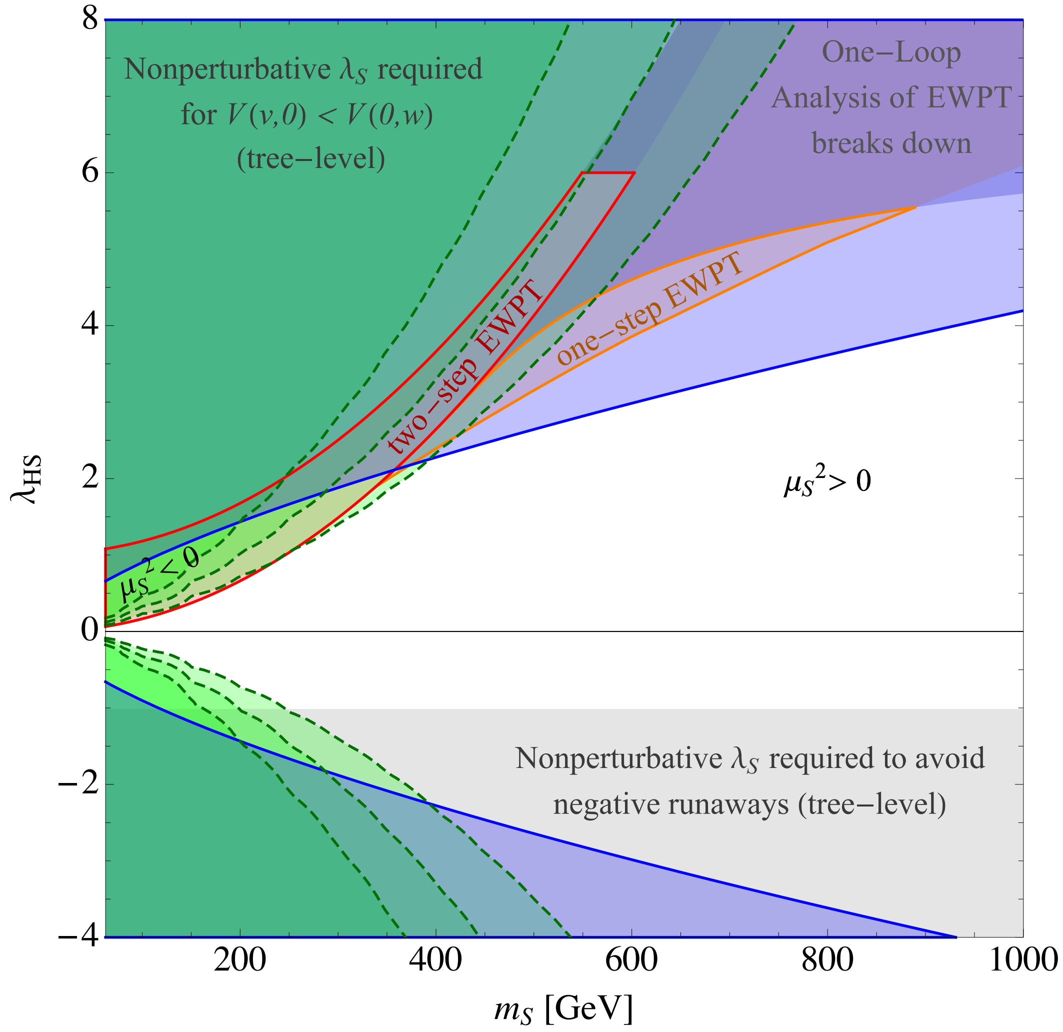
-> Espinosa et al, 1107.5441

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4.$$

singlet pair production via off-shell Higgs:



h*->SS testable at 100 TeV collider



higgs triple coupling deviation >16% and can be excluded at 100 TeV collider

$$\lambda_3 = \frac{m_h^2}{2v} + \frac{\lambda_{HS}^3 v^3}{24\pi^2 m_S^2} + \ldots$$

(loop level)

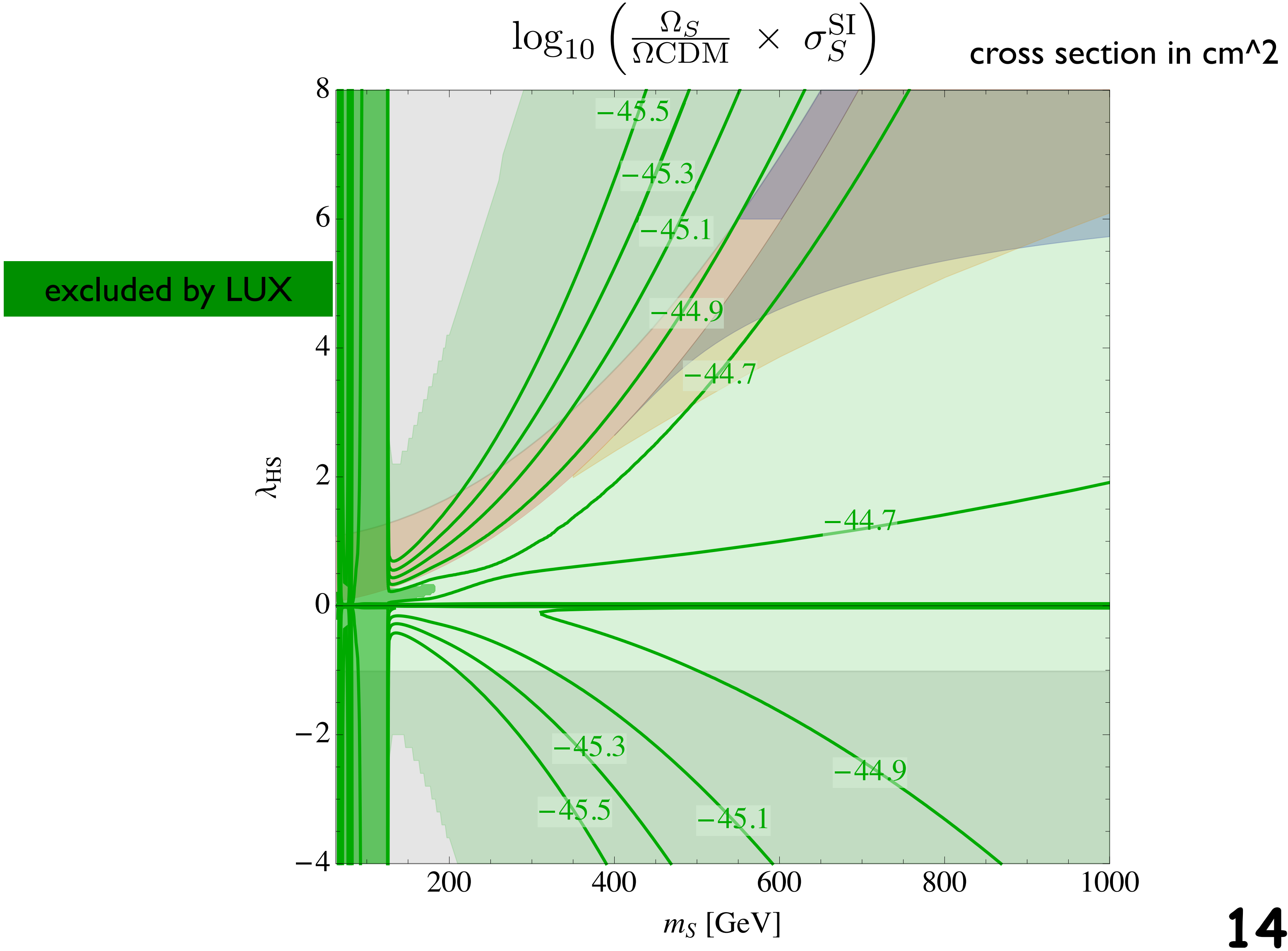
1409.0005

Besides:

$$\delta\sigma_{Zh} = \frac{1}{2}\frac{|\lambda_{HS}|^2 v^2}{16\pi^2 m_h^2}\left[1 + F(\tau_\phi)\right]$$ <0.5% in relevant region

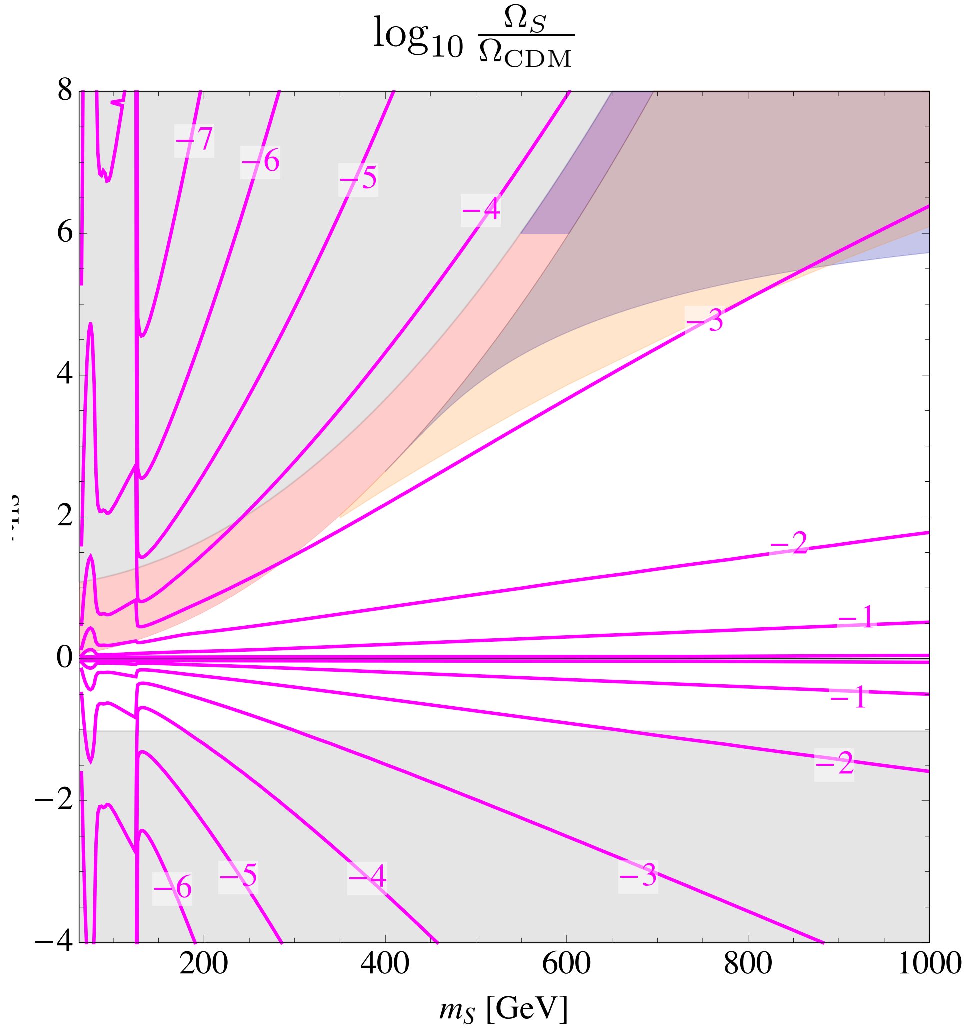
(at 1 loop)

very difficult to test at colliders but Xenon 1T can test all relevant parameter space!



1409.0005

In the parameter space relevant for EW baryogenesis, the singlet scalar is a subdominant dark matter component.



the large singlet-higgs coupling annihilates away the relic density

Conclusion 1:

The minimal scalar extension to the SM (adding a real singlet) leads to strong first-order EW phase transition as needed for EW baryogenesis

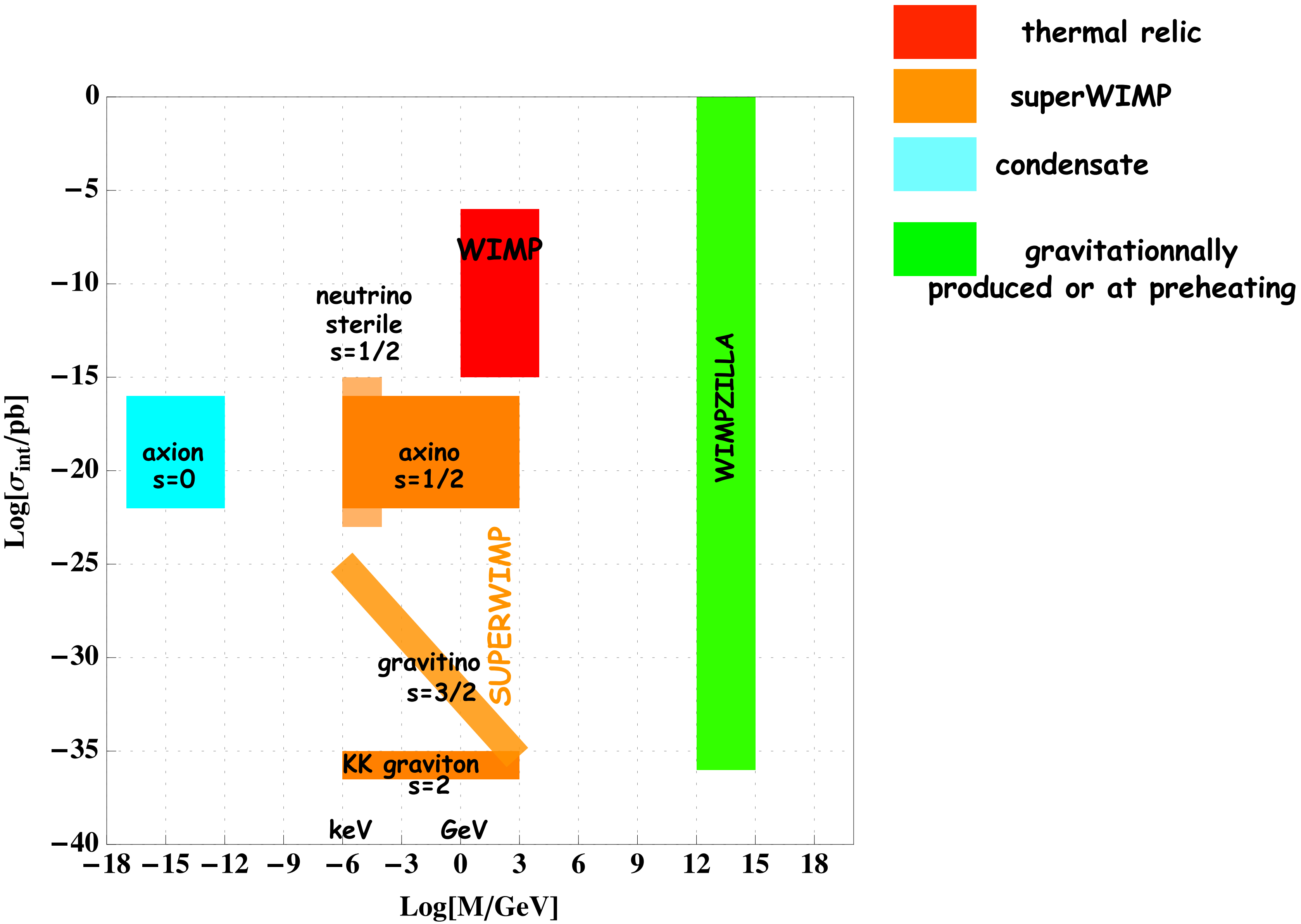
Very challenging to test at future colliders (100 TeV collider needed)

Relevant region of parameter space for baryogenesis cannot account for dark matter

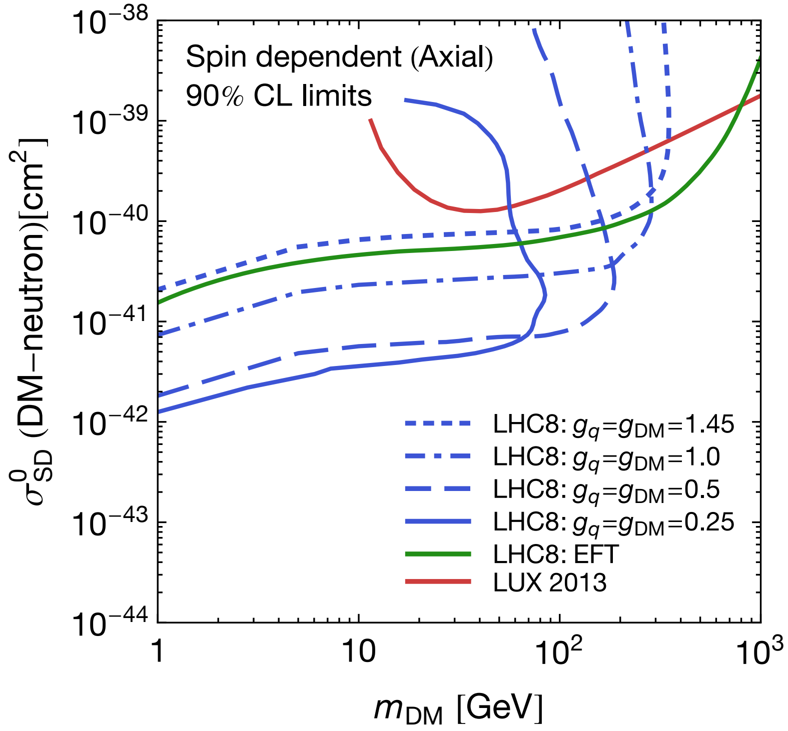
Still, large Higgs-singlet interactions enable to test the relevant region with Xenon 1 T.

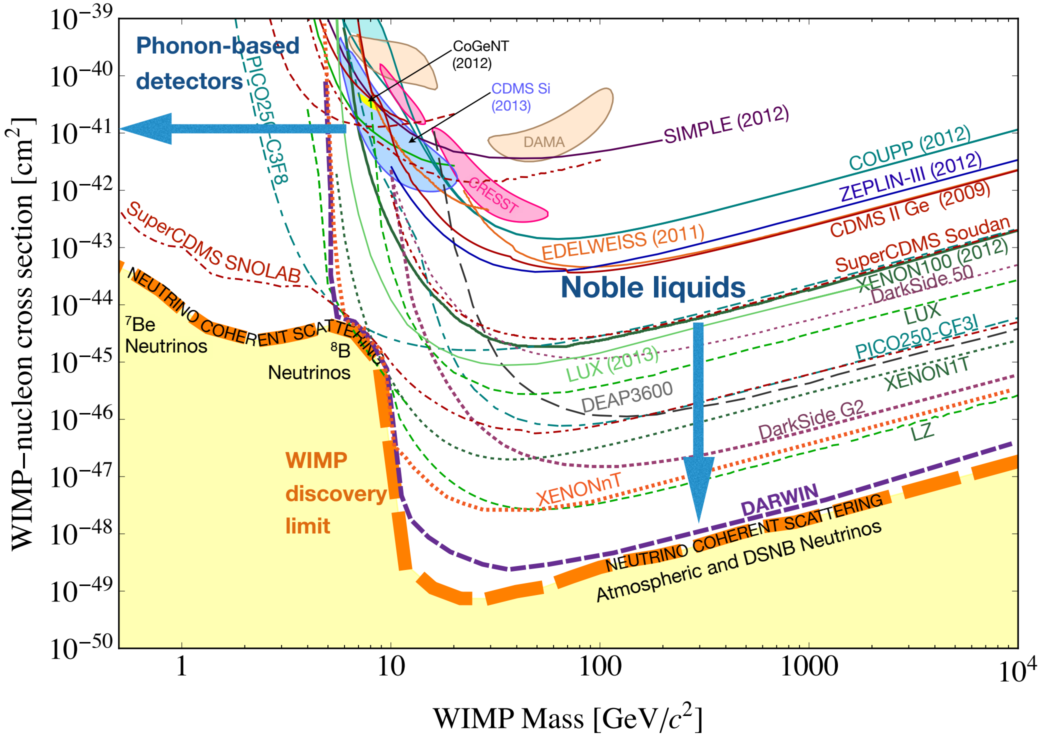
Standard EW baryogenesis is essentially disconnected from the problem of dark matter generation and does not try to find a unified explanation for dark and visible matter densities.

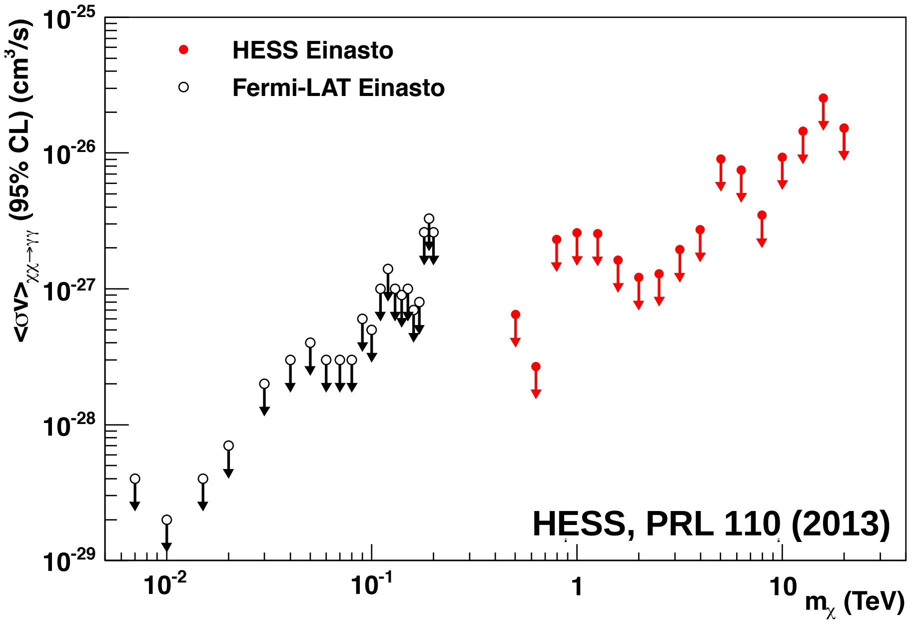
Dark Matter Candidates



Wimps under pressure
from the LHC, Fermi, Xenon, LUX ...

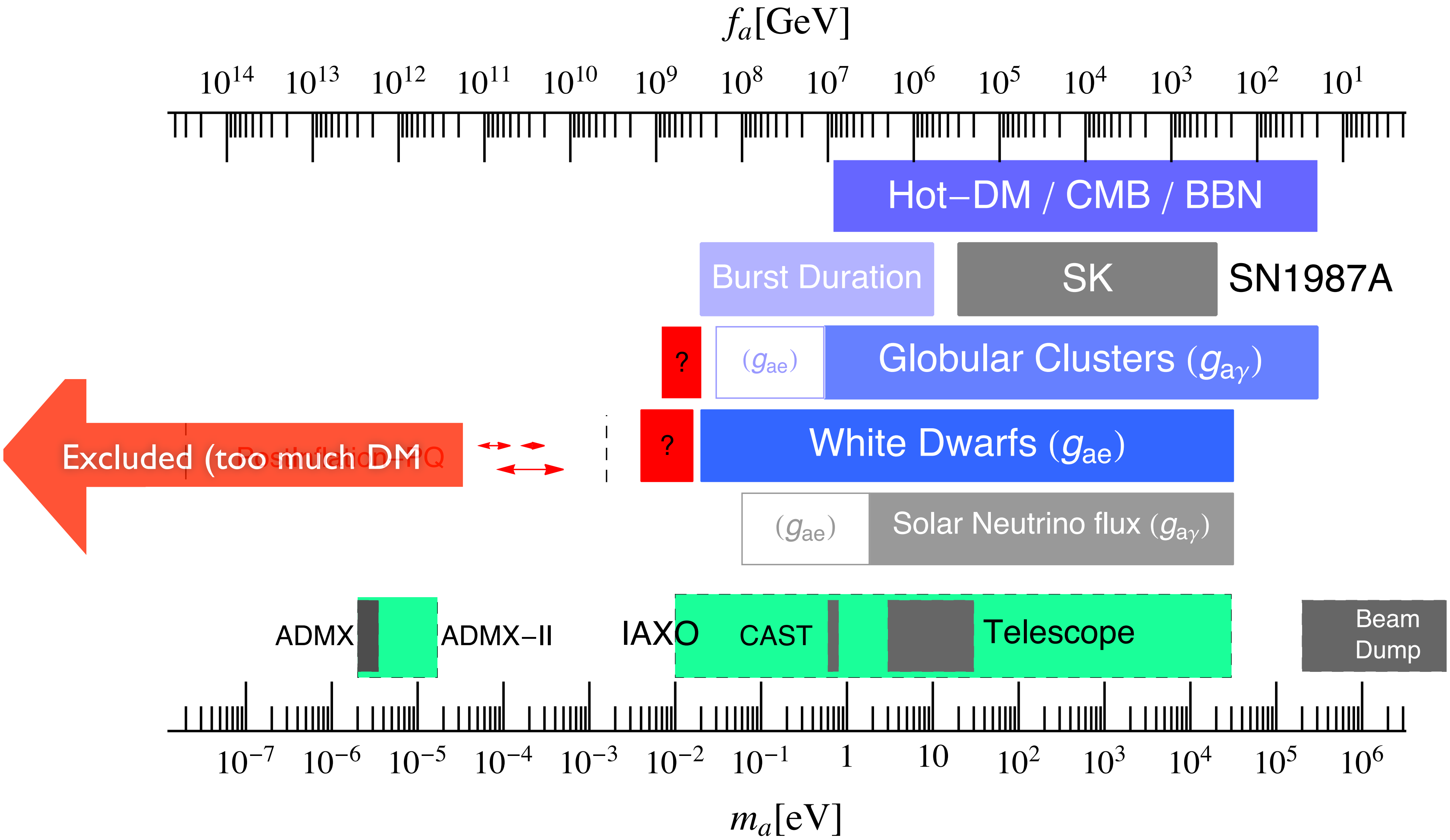






HESS, PRL 110 (2013)

constraints on axion



WIMP-baryogenesis Connection?

asymmetric dark matter

Matter Anti-matter asymmetry of the universe:

characterized in terms of the
baryon to photon ratio

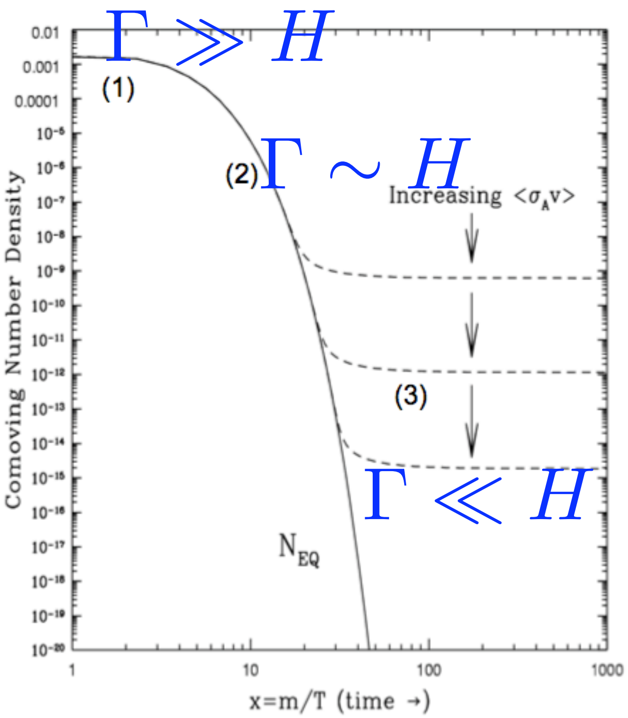
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10^{-10}

The great annihilation between nucleons & anti-nucleons

$$n + \bar{n} \to \pi + \pi \to \gamma + \gamma + \ldots$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T}/m_\pi^2 \sim H \sim \sqrt{g_*} T^2/m_{Pl}$



corresponding to a freeze-out temperature T_F ~ 20 MeV

In absence of an asymmetry:

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001
Matter

10 000 000 000
Anti-matter

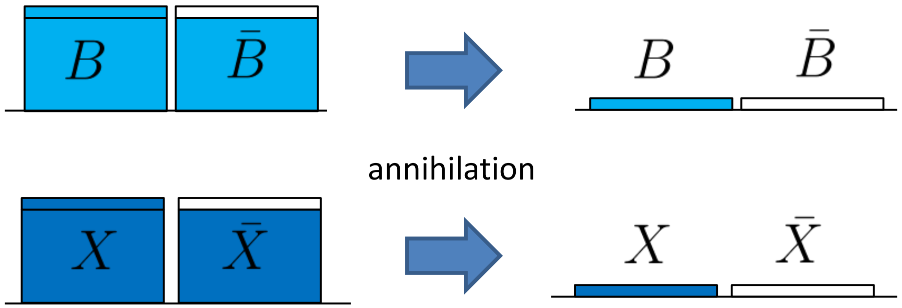
1
(us)

Similarly, Dark Matter may be asymmetric

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

Does this indicate a common dynamics?

If $n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$



Initial B asymmetry

Initial DM asymmetry

annihilation

Residual asymmetric component remains

conservation of global charge:

$$Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\bar{b}})$$

if efficient annihilations:

$$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}} \frac{m_{dm}}{m_b} \longrightarrow$$

typical expected mass ~ GeV

two possibilities:

1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors

Crucial role played by the Higgs in the 2 major theories of baryogenesis

- in EW baryogenesis: Higgs bubbles provide out-of-equilibrium dynamics

- in leptogenesis: Decay into the Higgs of RH neutrinos produce lepton asymmetry

New proposal

Servant & Tulin, PRL 111, 151601 (2013)

-Use the Higgs to mediate the asymmetries between the visible and dark sector

Starting observation:

In the early universe, at T>~ 100 GeV, before the EW phase transition, the thermal bath contains both Higgs particles and anti-Higgs particles since (since the Higgs doublet is a complex scalar)

We can therefore define an asymmetry between H and H*, particles and anti-particles of the Higgs field, like we do for leptons and quarks.

If the Higgs couples to the dark sector, it can transfer the asymmetry in the dark sector.

Standard Model equations describing chemical equilibrium in the hot plasma relate chemical potentials of the different species :

EW Sphalerons convert asymmetries between baryon and lepton number

$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$$

Yukawa interactions can induce a Higgs asymmetry

$$\begin{aligned} \mu_{q_i} - \mu_H - \mu_{d_j} &= 0 \ , \\ \mu_{q_i} + \mu_H - \mu_{u_j} &= 0 \ , \\ \mu_{\ell_i} - \mu_H - \mu_{e_j} &= 0 \ . \end{aligned}$$

Total hypercharge of the plasma

$$\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + \frac{2}{N_f}\mu_H) = 0 \ .$$

a primordial asymmetry, say in leptons, induces a Higgs asymmetry though the equations of chemical equilibrium

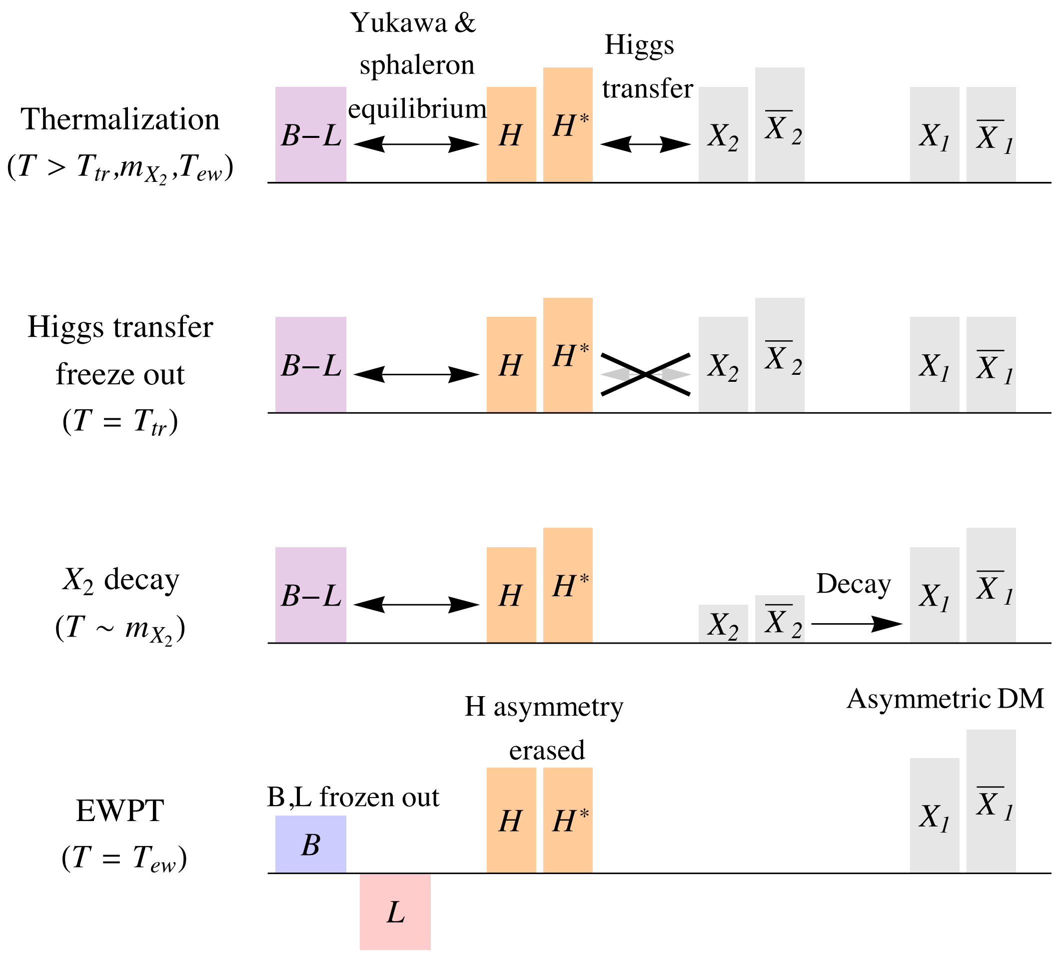
Minimal illustrative example

Just add to the Standard Model 2 vector-like fermions: a singlet X_1 (Dark matter) and one EW doublet X_2 whose role is to transfer the asymmetries between the visible and dark sectors

$$\mathcal{L} \supset \frac{1}{\Lambda_2}(H^\dagger X_2)^2 + y_H \bar{X}_2 X_1 H + h.c$$

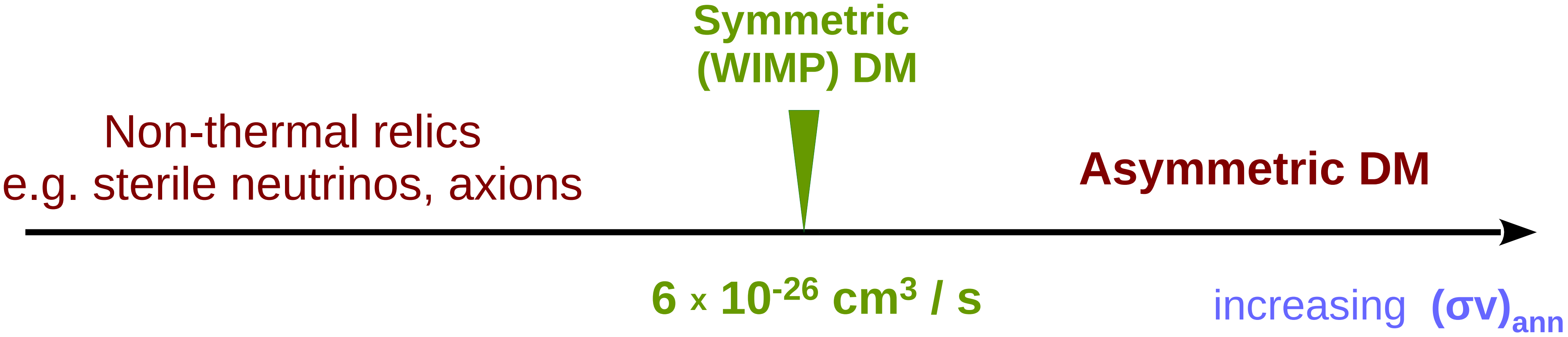
Case 1: Asymmetric Dark Matter from Lepto/Baryogenesis

Assume a primordial B-L asymmetry. It induces a Higgs asymmetry which flows into the dark sector



Such a scenario does not require new states that carry baryon or lepton number, unlike other Asymmetric DM models.

To get $\Omega_{DM} \sim 25\%$:



Non-thermal relics
e.g. sterile neutrinos, axions

Symmetric (WIMP) DM

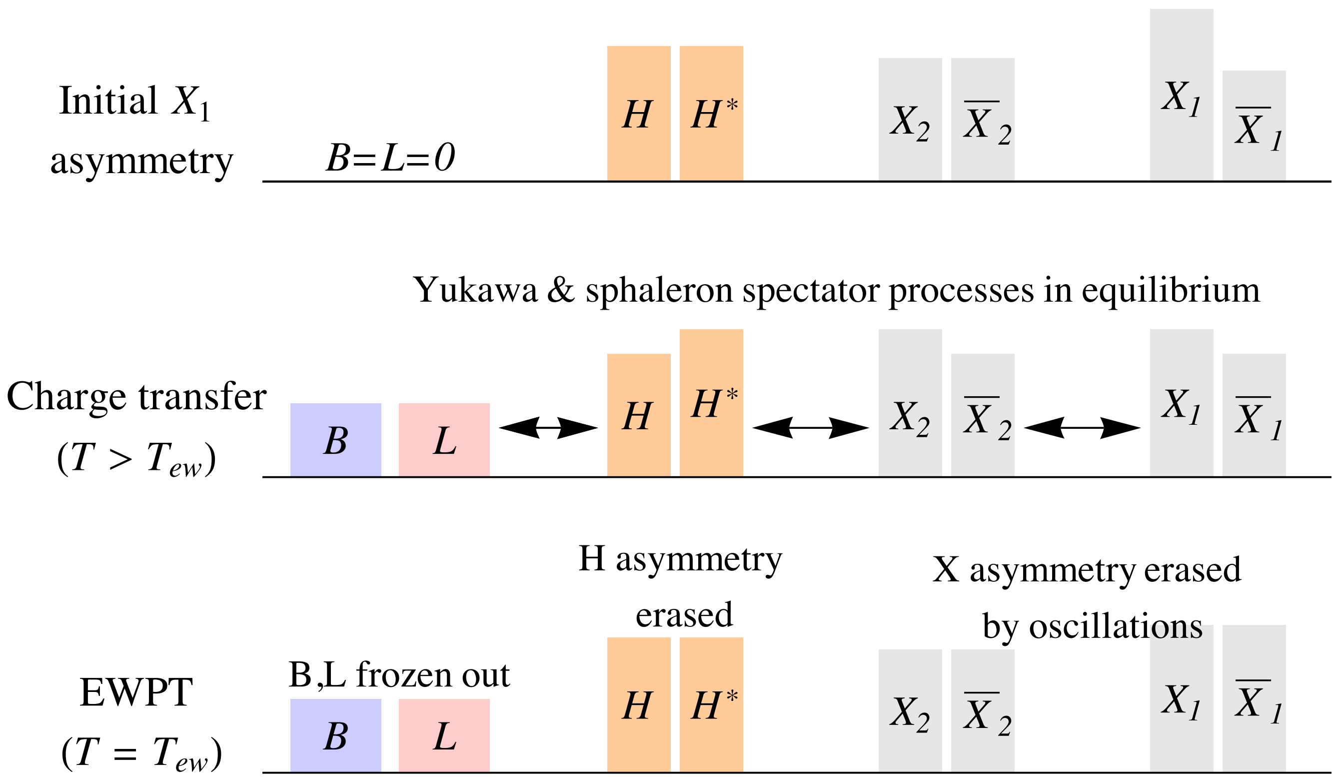
6×10^{-26} cm^3 / s

Asymmetric DM

increasing **$(\sigma v)_{ann}$**

[Petraki]

Case 2: Baryogenesis from a primordial dark matter asymmetry



DM is no longer asymmetric today

A theory of baryogenesis that does not require B nor L violation beyond the SM but by having an asymmetry trapped in spectator X_2 we bias sphalerons into generating B+L.

Tests?

	Case 1	Case 2
indirect detection	✔	✔
direct detection	✔ only for heavy DM	✔
invisible higgs decay	✖	✔
LHC searches of X2	✔	✔

Visible and WIMP Dark Matter abundances could be explained and related through the asymmetric Dark Matter paradigm

And what if dark matter is the axion, can it play any role in baryogenesis?

Baryogenesis from Strong CP violation

Servant'14, 1407.0030

$$\mathcal{L} = -\bar{\Theta}\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a}$$

today $|\bar{\Theta}| < 10^{-11}$ as explained by Peccei-Quinn mechanism:

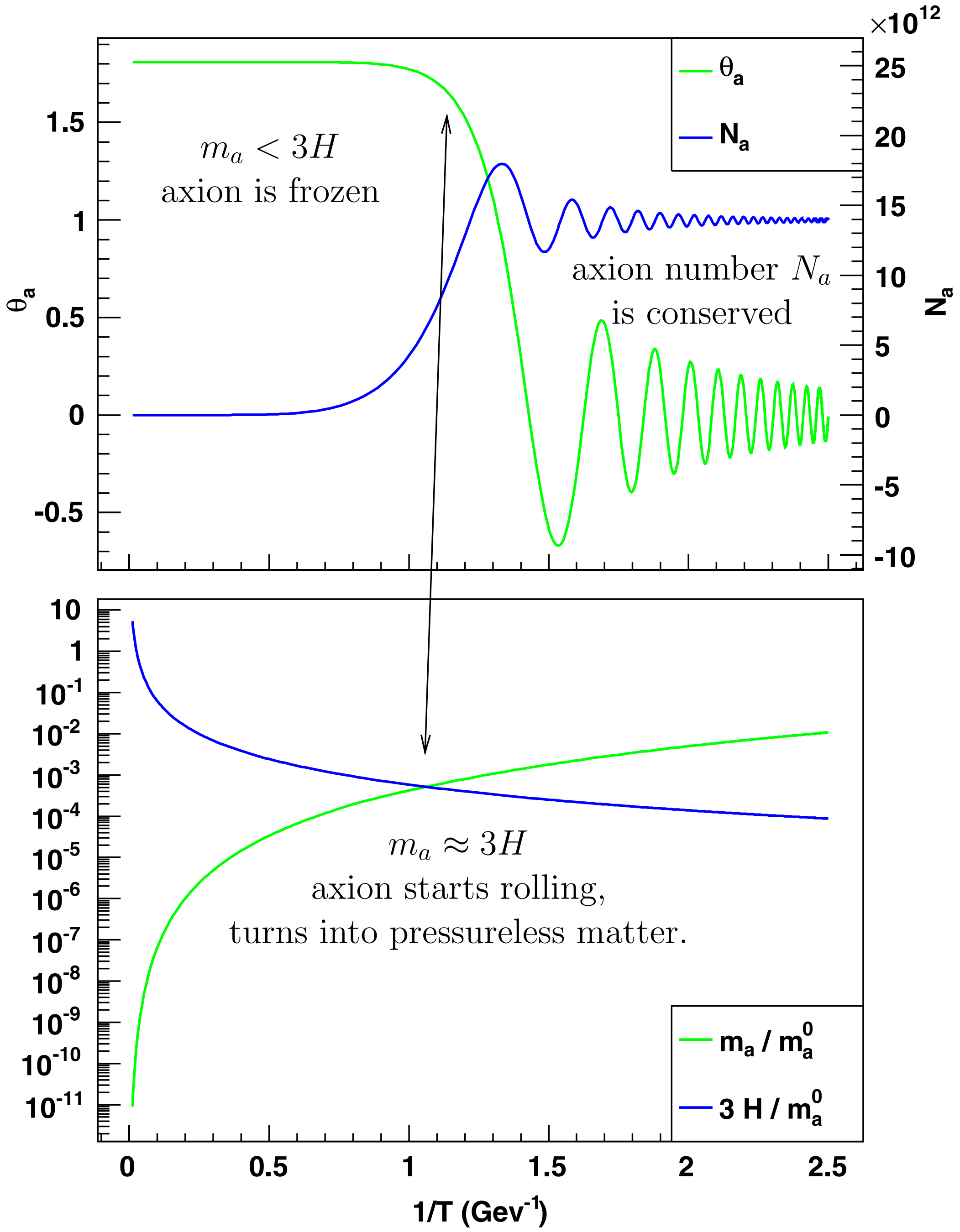
$$\bar{\Theta} \rightarrow \frac{a(x)}{f_a}$$

promoted to a dynamical field which relaxes to zero, to minimize the QCD vacuum energy.

in early universe, before the axion gets a mass around the QCD scale

$$|\bar{\Theta}| \sim 1$$

Could $\bar{\Theta}$ have played any role during the EW phase transition?



$m_a < 3H$
axion is frozen

axion number N_a
is conserved

$m_a \approx 3H$
axion starts rolling,
turns into pressureless matter.

Wantz, Shellard '10

Baryogenesis from Strong CP violation

Effective lagrangian generated by SU(3) instantons

Kuzmin, Shaposhnikov, Tkachev '92

$$\mathcal{L}_{eff} = \frac{10}{F_\pi^2 m_{\eta'}^2} \frac{\alpha_s}{8\pi} G\tilde{G} \quad \frac{\alpha_w}{8\pi} F\tilde{F}$$

A condensate for $G\tilde{G}$ induces a mass for the axion :

$$\frac{\alpha_s}{8\pi}\langle G\tilde{G}\rangle = m_a^2(T) f_a^2 \sin\theta$$

this leads to:

$$\mathcal{L}_{eff} = \underbrace{\frac{10}{F_\pi^2 m_{\eta'}^2} \sin\theta \; m_a^2(T) f_a^2}_{\equiv \zeta(T)} \; \frac{\alpha_w}{8\pi} F\tilde{F}$$

time variation of axionic mass and field is source for baryogenesis

$$\boxed{\mu = \frac{d\zeta}{dt} = \frac{f_a^2}{M^4} \frac{d}{dt}[\sin\bar{\Theta} \; m_a^2(T)]}$$

Operator relevant for baryogenesis:

$$\boxed{\mathcal{L}_{eff} = \frac{\alpha_W}{8\pi}\,\zeta(\varphi)\mathrm{Tr}\;F\tilde{F}}$$

EW field strength

↑

time-varying function

$$\int d^4x \frac{\alpha_W}{8\pi}\,\zeta\;\mathrm{Tr}\;F\tilde{F} = \int d^4x\;\zeta\;\partial_\mu j^\mu_{CS} = -\int dt\;\partial_t\zeta\int d^3x j^0_{CS}$$

$$N_{CS} = \int d^3x j^0_{CS}$$

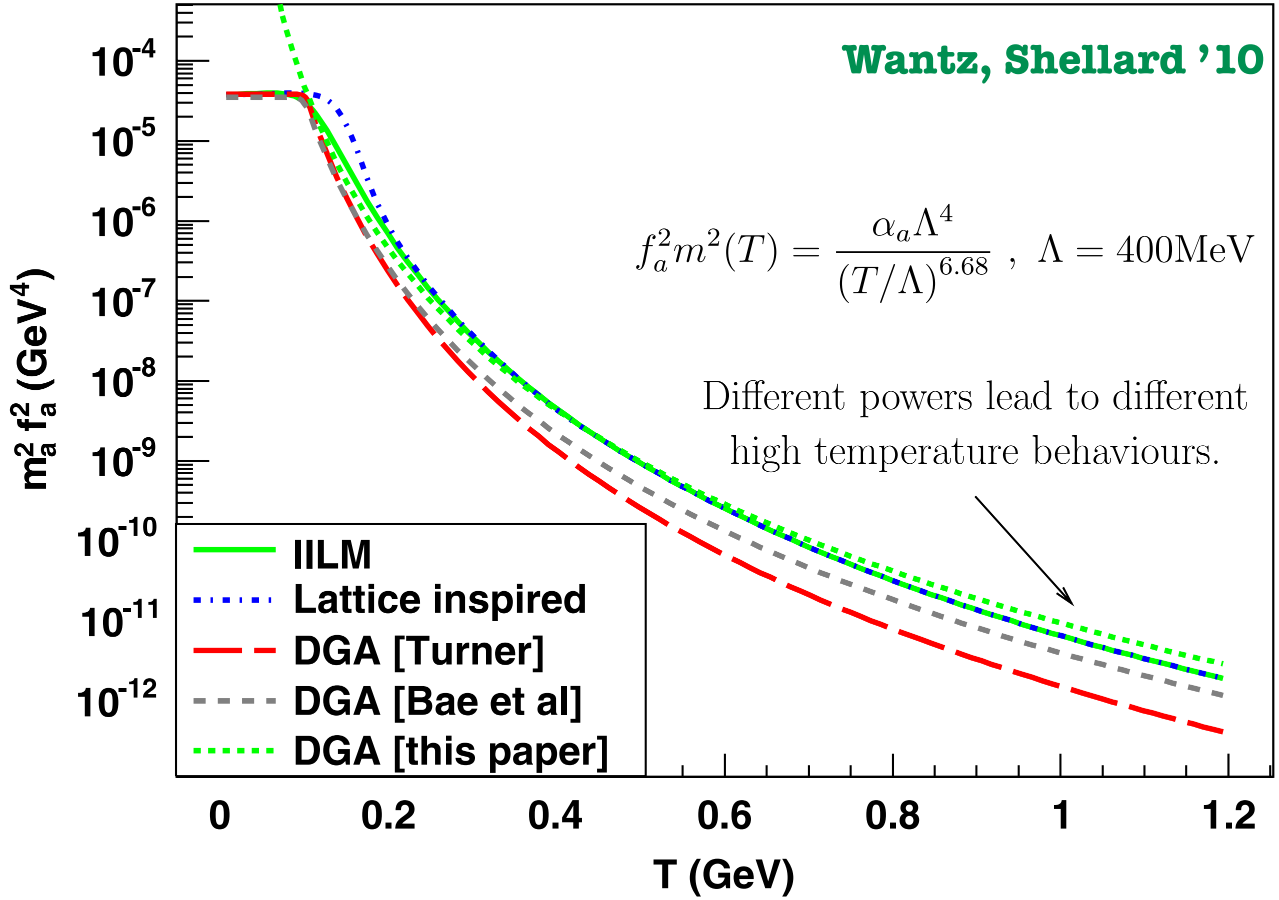
⇒ $$\mathcal{L}_{eff} = \mu\;N_{CS}$$

$$\boxed{\mu \equiv \partial_t\zeta}$$

the time derivative of ζ can be interpreted as a time-dependent chemical potential for Chern-Simons number

this operator has been used with $\zeta = \frac{8\pi}{\alpha_W}\frac{\Phi^\dagger\Phi}{M^2}$

Temperature dependence of axion mass



For T > T_t =0.1 GeV

$$m^2(T) = m^2(T=0) \times \left(\frac{T_t}{T}\right)^{6.68}$$

$$\delta m^2(T) \sim m^2(T)$$

$$\Delta\zeta \gtrsim 10^{-3} \rightarrow T \lesssim 0.3 \text{ GeV}$$

B-violation and time-variation of axion mass should occur at the same time...

$$n_B \propto \int dt \frac{\Gamma(T)}{T} \frac{d}{dt}[\sin\bar{\Theta}\ m_a^2(T)]$$

1) For the axion to be the source of baryogenesis, the EW phase transition should be delayed down to ~ 1 GeV. Fine ... but

$$\frac{n_B}{s} = n_f \alpha_w^4 \left(\frac{T_{eff}}{T_{reh}}\right)^3 \Delta\zeta \frac{45}{2\pi^2 g_*} \sim 10^{-7} \left(\frac{T_{eff}}{T_{reh}}\right)^3 \boxed{\Delta\zeta} \nearrow \sim \bar{\Theta}(T_{eff})$$

$$\left(\frac{T_{eff}}{T_{reh}}\right)^3 \sim \left(\frac{0.1}{100}\right)^3$$ killing factor

2) and there should not be any reheating -> unacceptable as $T_{reh} \sim m_h$.

Kuzmin, Shaposhnikov, Tkachev '92

Conclusion of the authors:
This kills baryogenesis from strong CP violation.

However,

in 1992, the mechanism of cold baryogenesis was not yet known

Cold baryogenesis cures it all as $\frac{T_{eff}}{T_{reh}} \sim [20-30]$

--> large enough baryon asymmetry even for $\bar{\Theta}(T) \gtrsim 10^{-6}$

$$\frac{n_B}{s} \sim 10^{-8} \left(\frac{T_{eff}}{T_{reh}}\right)^3 \sin\bar{\Theta}\Big|_{EWPT}$$

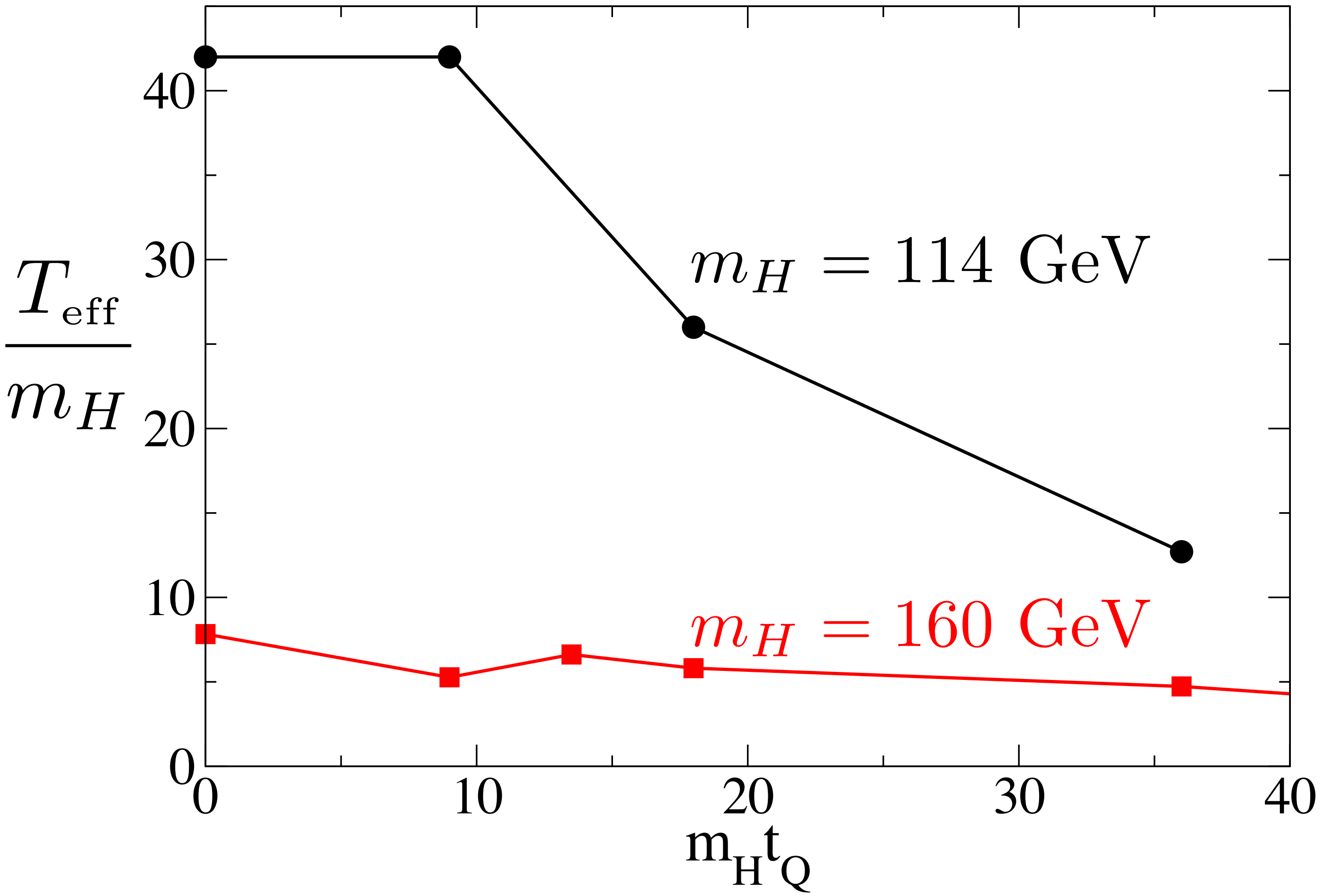
key point: $T_{eff} \neq T_{EWPT}$

So even if $T_{EWPT} \lesssim \Lambda_{QCD}$ we can have $T_{eff} \gtrsim T_{reh} \sim m_H$

Cold baryogenesis arises naturally in models where EW symmetry breaking is induced by the radion/dilaton vev.

1407.0030

cold baryogenesis: production of baryon number at T=0 from out-of equilibrium dynamics



Tranberg et al, hep-ph/0610096

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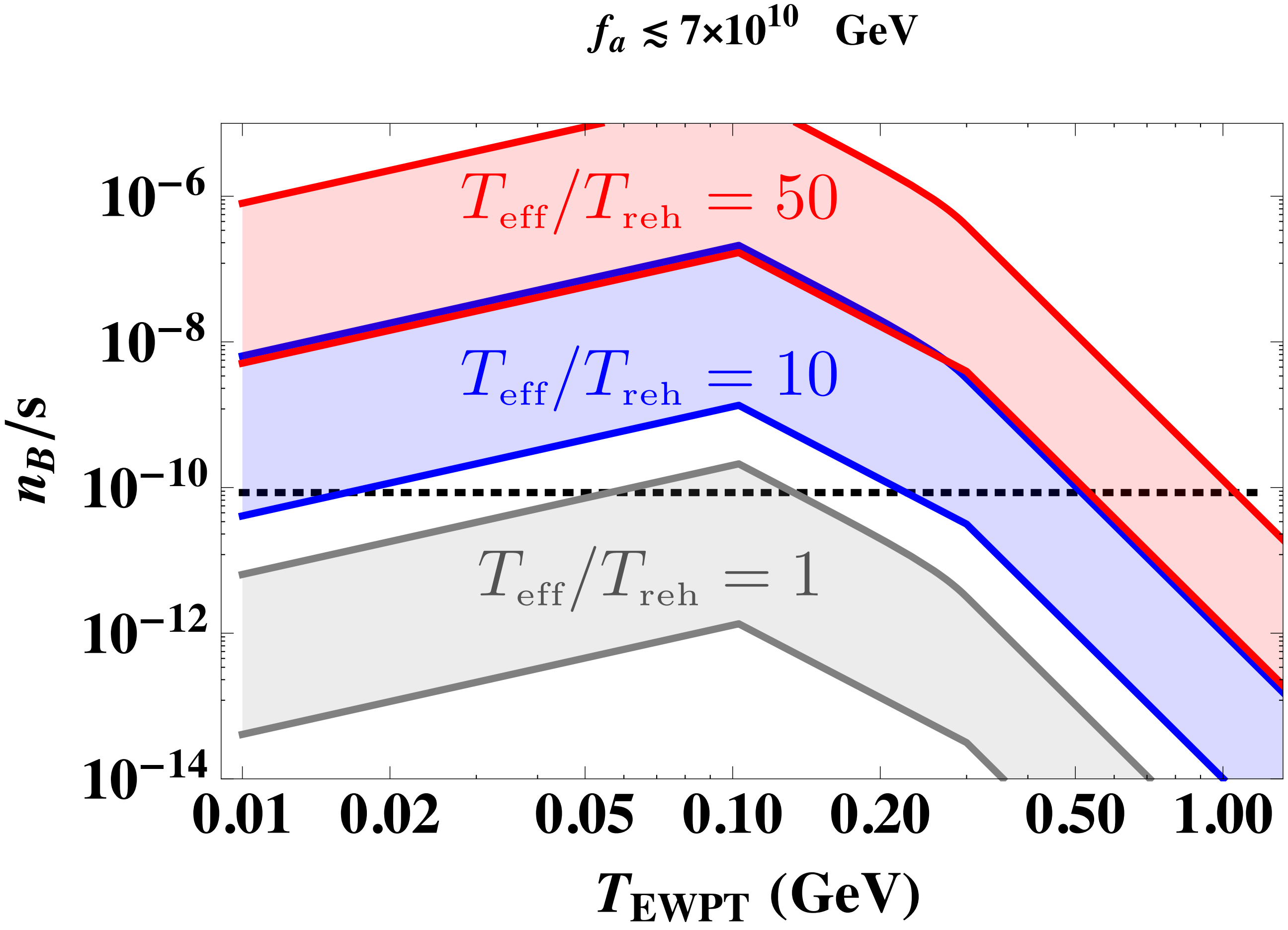
1407.0030

Axion dynamics during a supercooled EW phase transition can lead to baryogenesis

Servant, 1407.0030



$f_a \lesssim 7\times10^{10}$ GeV

requires a coupling between the Higgs and an additional light scalar

Summary

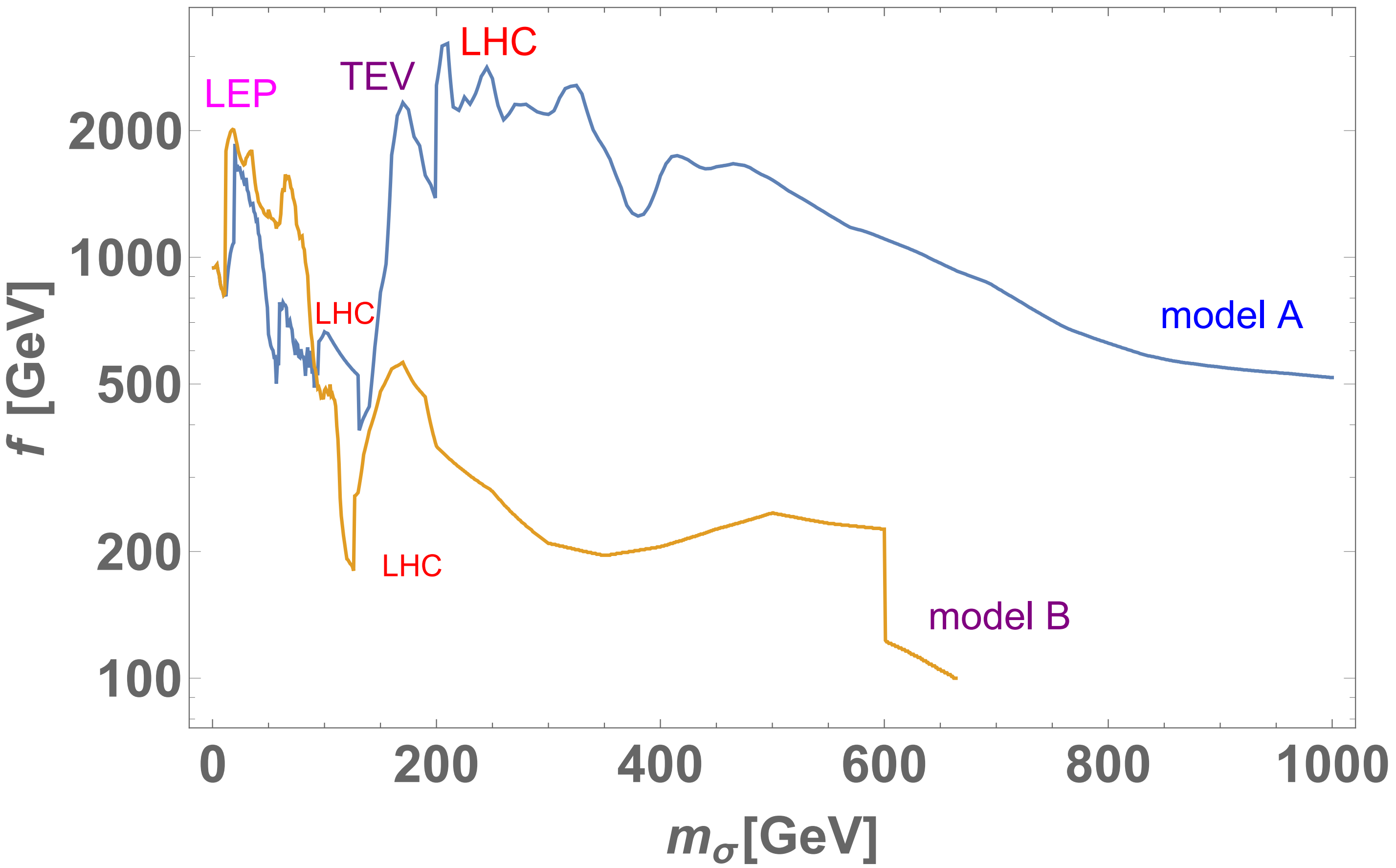
Strong CP violation from the QCD axion can be responsible for the matter antimatter asymmetry of the universe in the context of cold baryogenesis

if the EW phase transition is delayed down to the QCD scale

These conditions can arise naturally in models with a light dilaton (e.g Goldberger-Wise radion stabilisation mechanism)

scenario testable at LHC : existence of a O(100) GeV Higgs-like dilaton

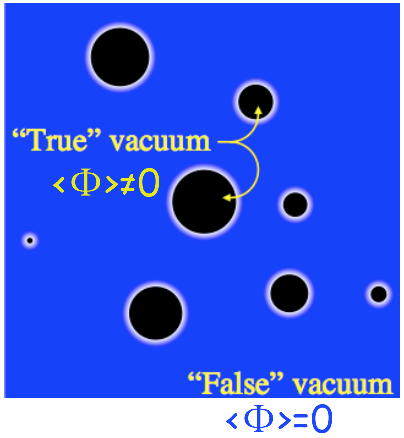
LHC constraints on the scale of conformal symmetry breaking (dilaton)



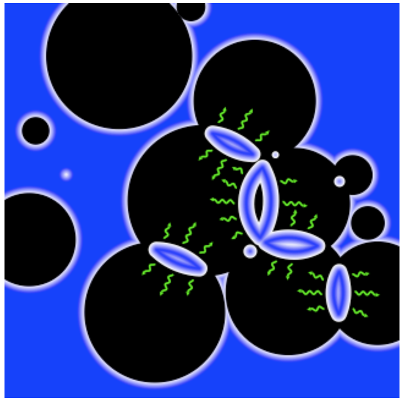
[1410.1873]

Smoking gun signature of a strongly first-order phase transition

Bubble nucleation



Bubble percolation

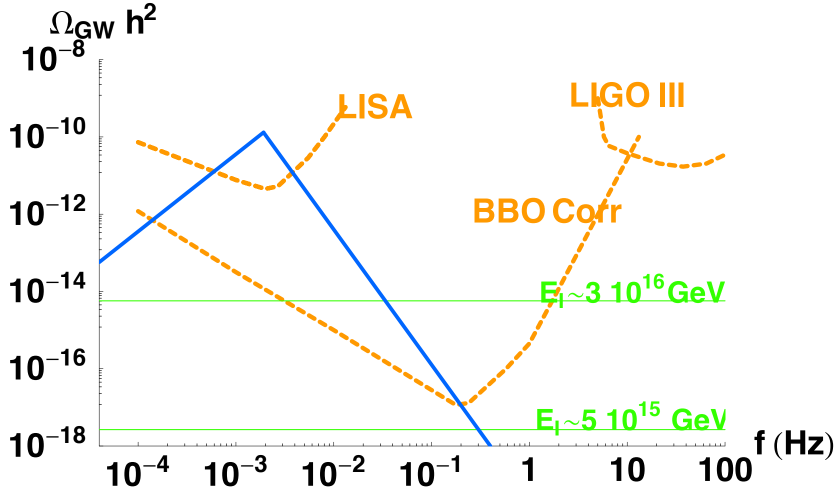


Fluid flows

turbulence

Magnetic fields

Stochastic background of gravitational radiation



$$\Omega_{GW} \sim \frac{1}{(\beta/H)^2}\kappa^2$$

characterizes amount of supercooling

violent process if $v_b \sim O(1)$

$$f_{\rm peak} \sim 10^{-2}\,{\rm mHz}\left(\frac{g_*}{100}\right)^{1/6}\frac{T_*}{100\ {\rm GeV}}\ \frac{\beta}{H_*}$$

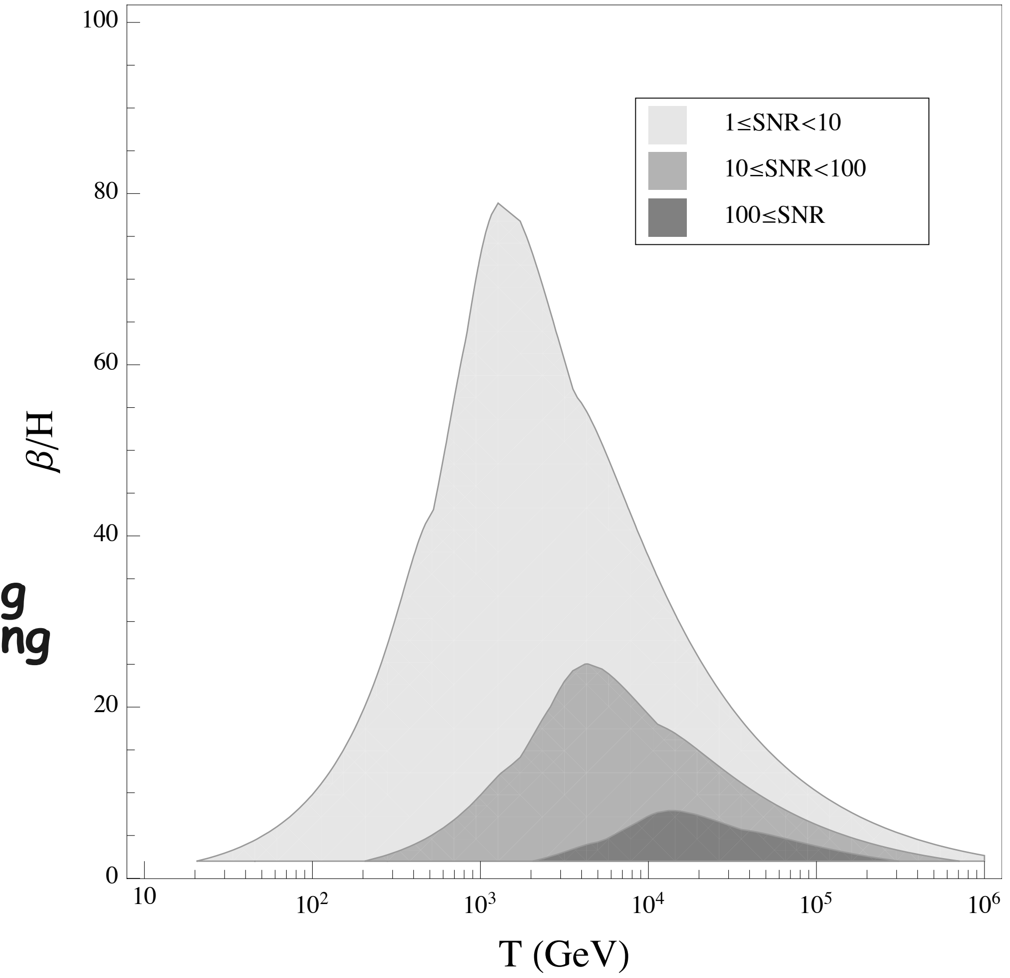
Grojean-Servant hep-ph/0607107

Detection of a GW stochastic background peaked in the milliHertz: a signature of near conformal dynamics at the TeV scale

Konstandin & Servant
1104.4791

Detection prospects for eLISA

increasing supercooling



Most sensitive in the region around 10TeV

It can detect GWs from strong PTs, occurring slow

[see review by Caprini et al, 1201.0983]

Conclusion

Baryogenesis and dark Matter:

No lack of theoretical ideas!

- For Standard EW baryogenesis through a Z_2 singlet, the connection to the EW phase transition does not make it necessarily easy to test at future colliders. Besides, no unified description of dark matter
- WIMP-baryogenesis connection through asymmetric dark matter: interesting but no model-independent generic prediction
- QCD axion-baryogenesis connection: easier to test at the LHC (relies on the existence of a light dilaton) and usual generic dark matter prediction of QCD axion remains unaffected