Some new developments in Electroweak baryogenesis

Thomas Konstandin

***KEK-PH* meeting**, Tsukuba
February 18, 2020

[1911.12342] *with* Hall, McGehee,
[1910.08068] Murayama, Servant

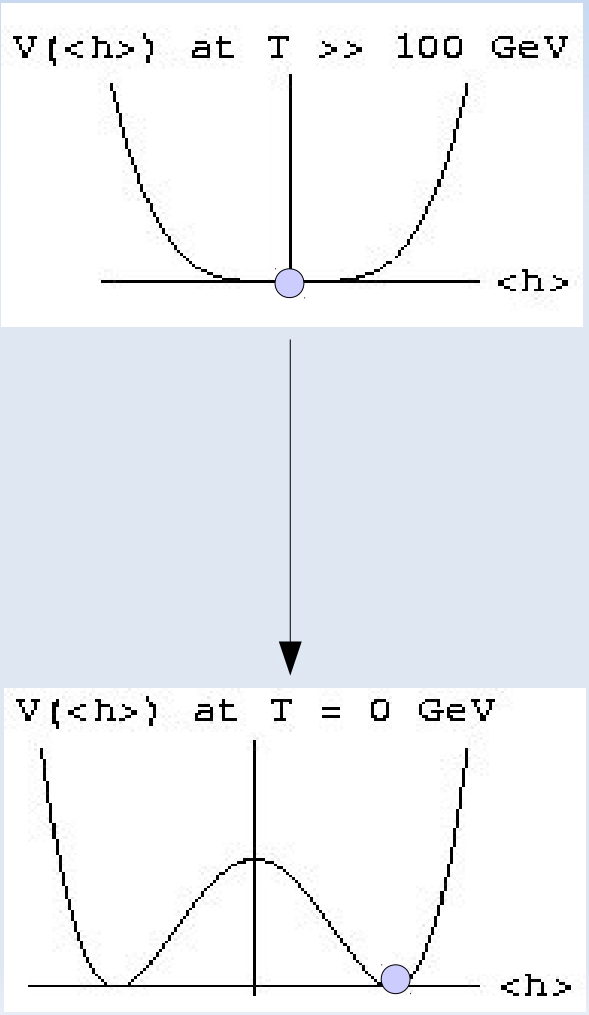
1st order electroweak phase transition

gravitational waves

baryogenesis

First-order phase transition

The free energy (as a function of the Higgs vev) decides the nature of the phase transition → connection to Higgs physics



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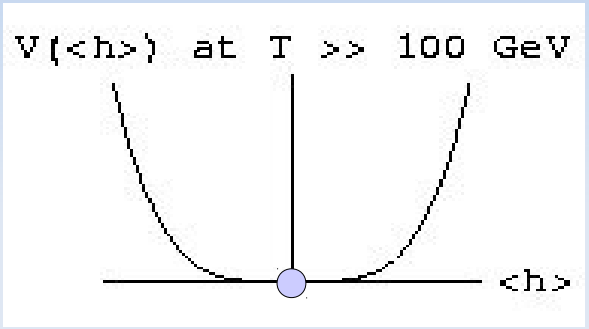

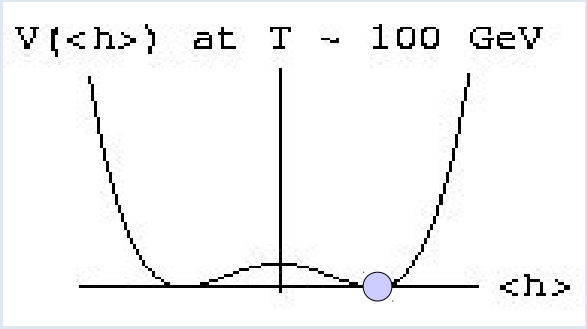

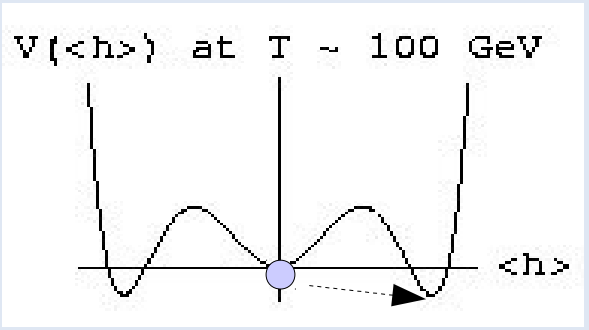

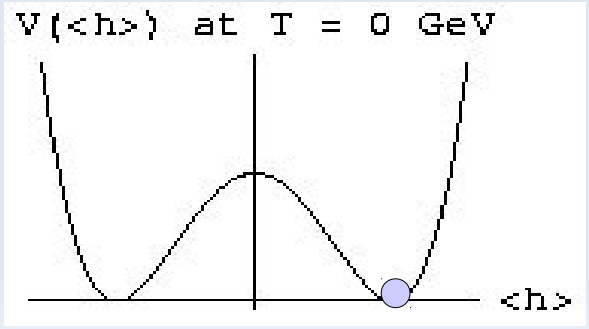

higher-order PT
or crossover

first-order PT

First-order phase transitions

- first-order phase transitions proceed by bubble nucleations

- in case of the electroweak phase transition, the ”Higgs bubble wall” separates the symmetric from the broken phase

- this is a violent process ($v_b = O(1)$) that drives the plasma out-of-equilibrium
  $\rightarrow$ GW signal?

- SM has a crossover - bosons that are strongly coupled to the Higgs tend to make the phase transition stronger

Baryogenesis

[Sakharov '69]

Baryogenesis aims at explaining the observed asymmetry between matter and antimatter abundances.

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 10^{-10}$$

The main ingredients for viable baryogenesis are stated by the celebrated Sakharov conditions:

- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium

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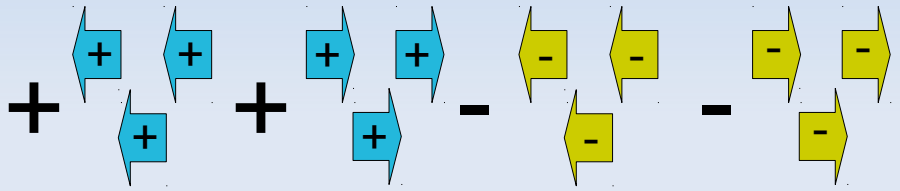

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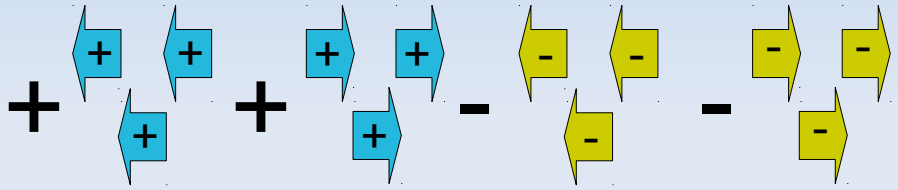

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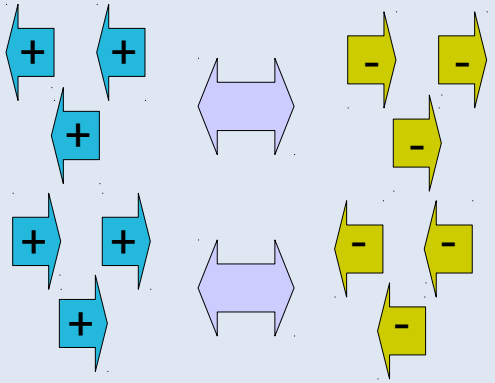

$$n_B \leftrightarrow n_{\bar{B}}$$

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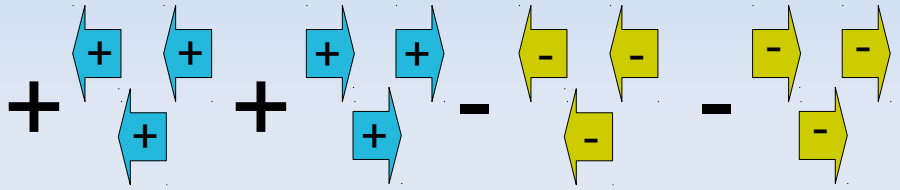

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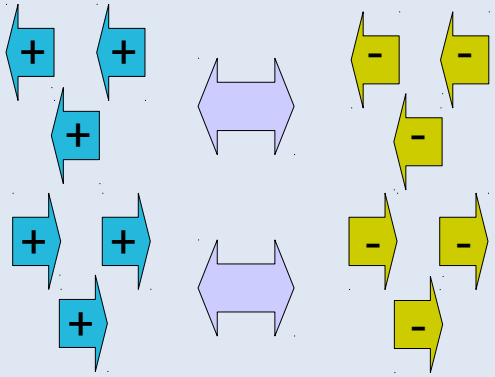

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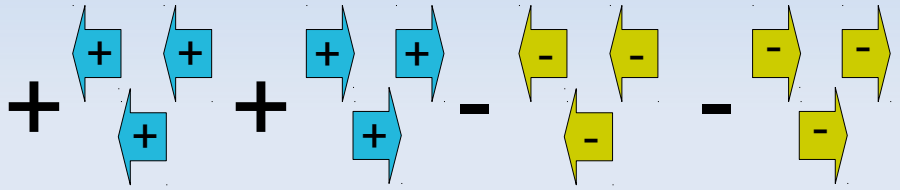

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$$n = n(m/T)$$

$$m = \bar{m}$$

$$n_B = n_{\bar{B}}$$

Baryogenesis

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$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 10^{-10}$$

SM @ EW temp

C

B

CP

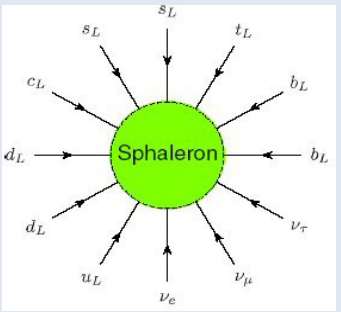
eq

B+L anomaly

Jarlskog invariant

expansion slow EW PT?

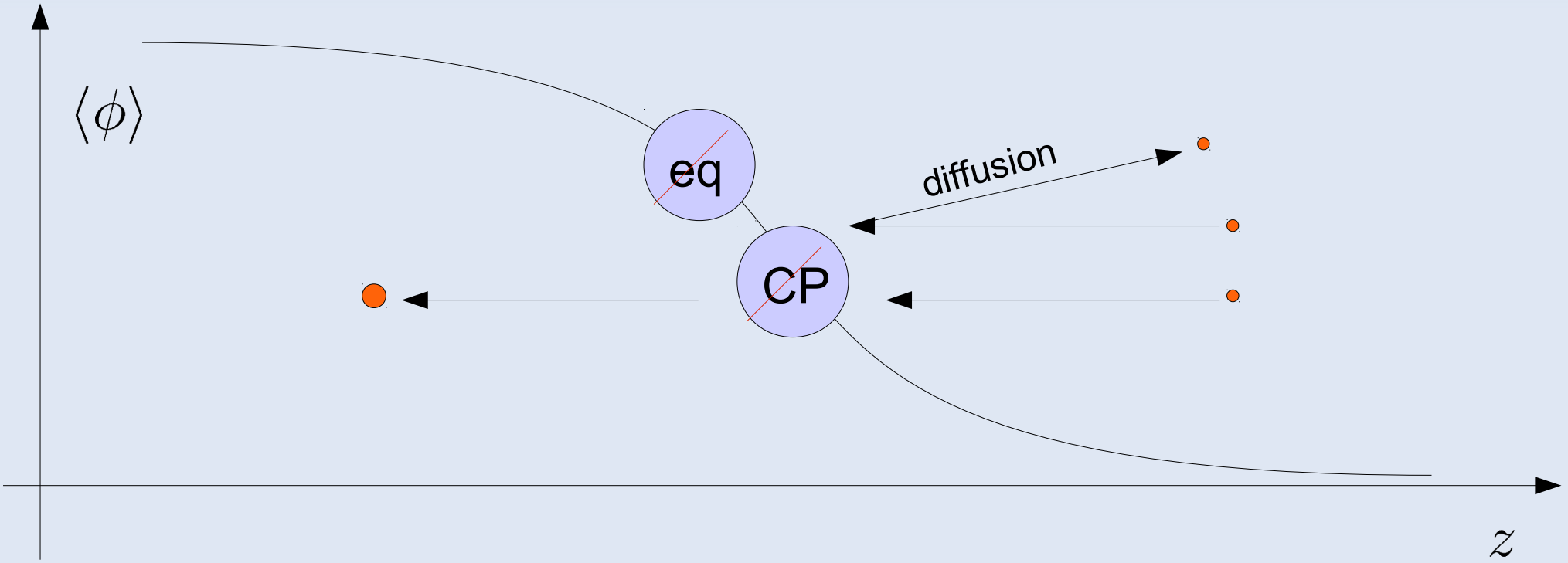
sphaleron



beyond the SM physics essential

Electroweak baryogenesis

[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]



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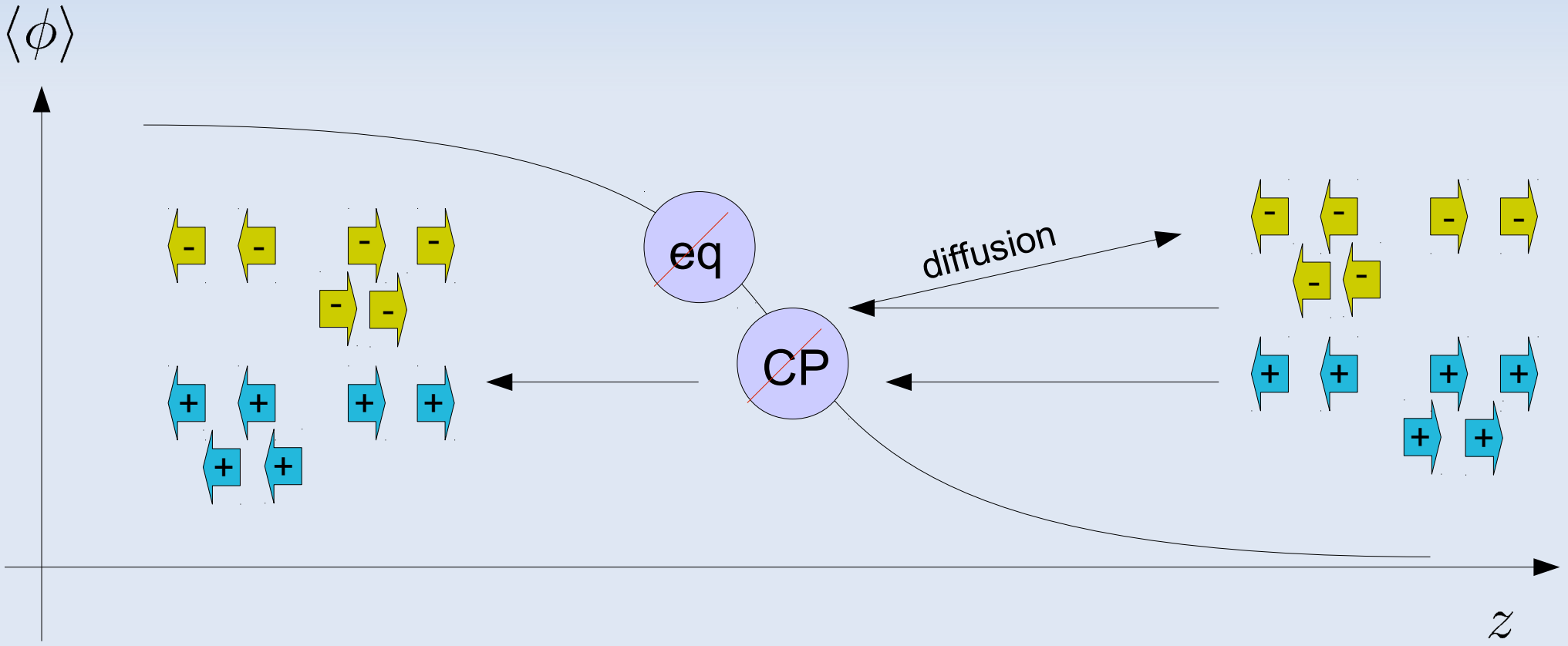

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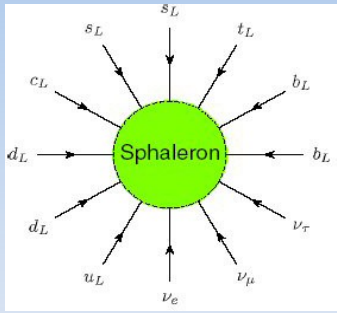

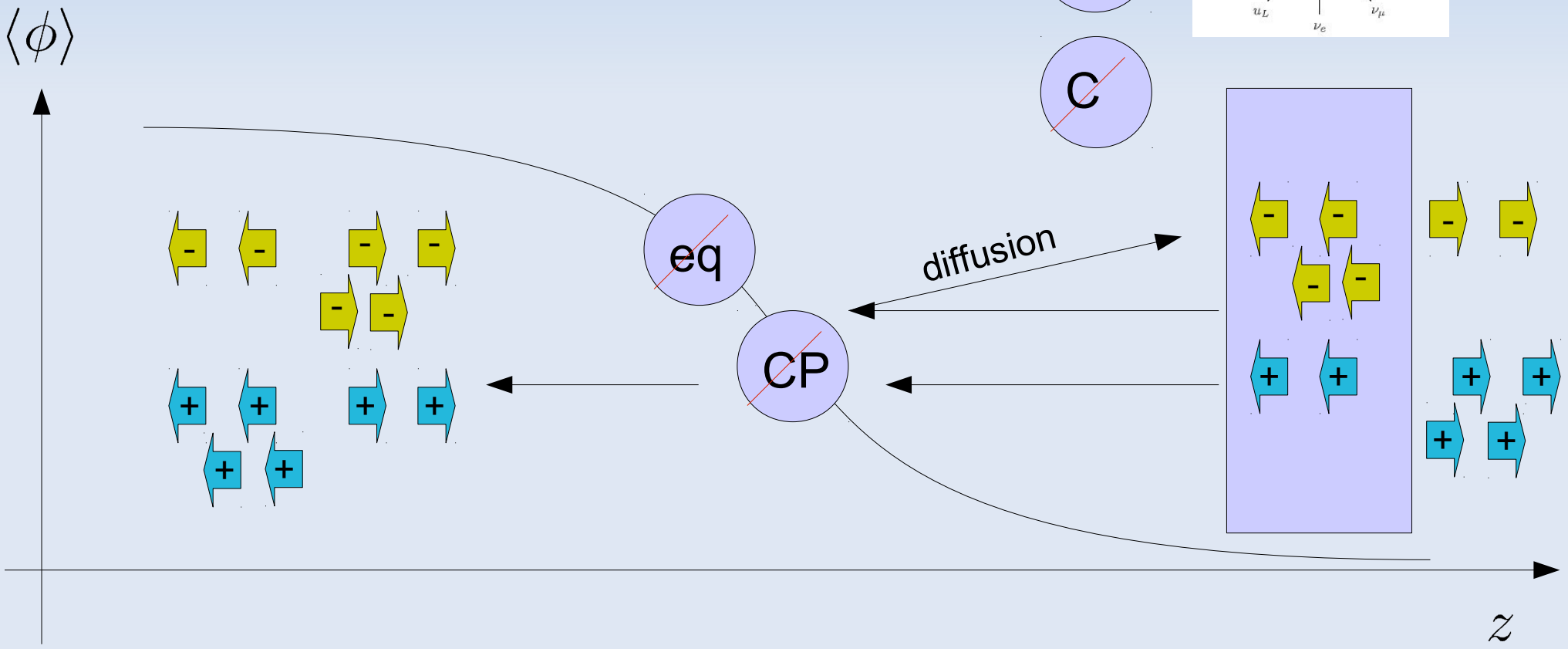

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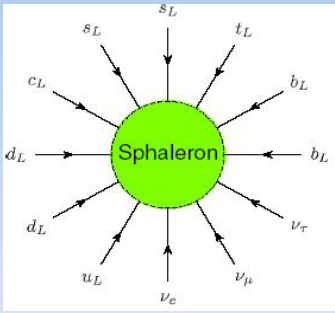

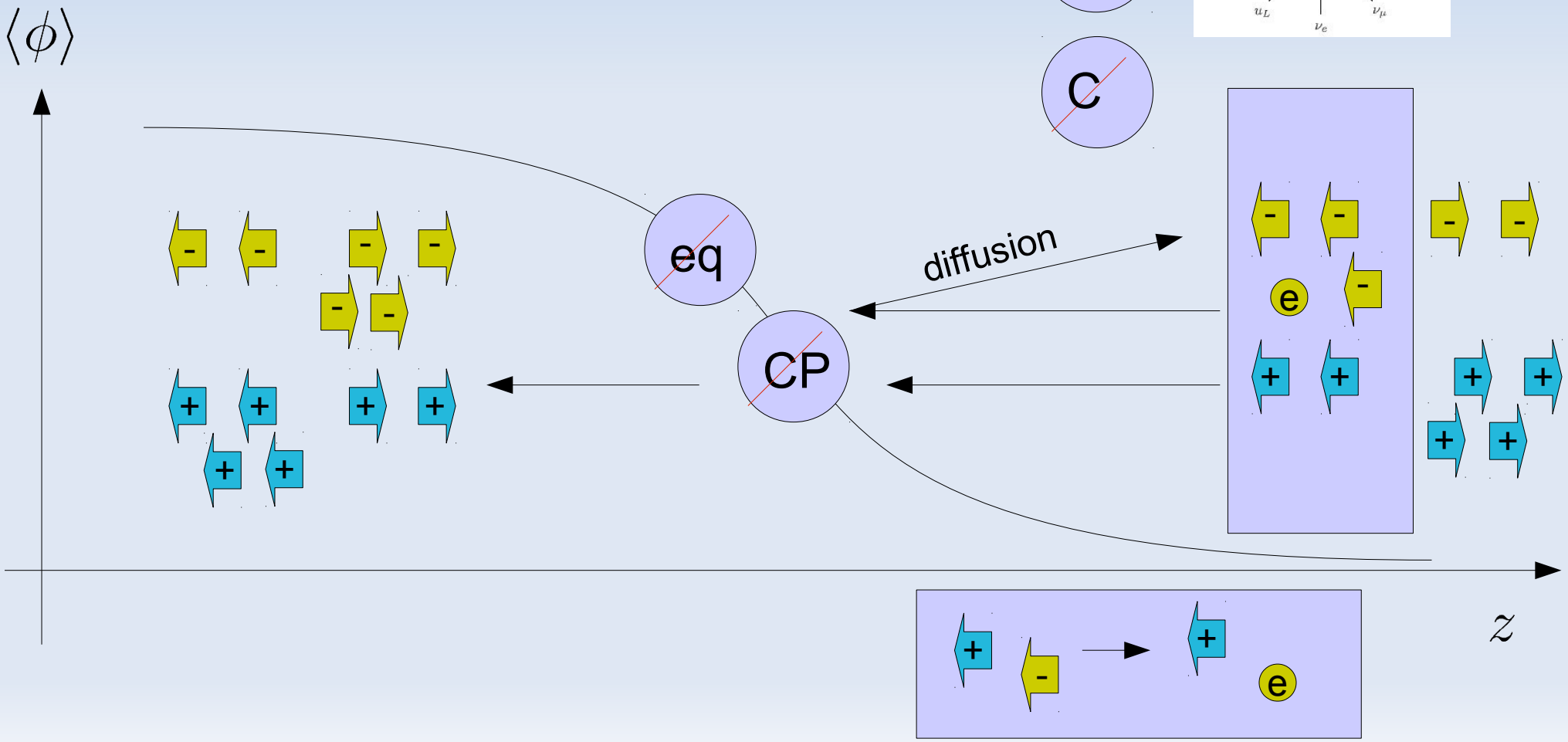

Electroweak baryogenesis

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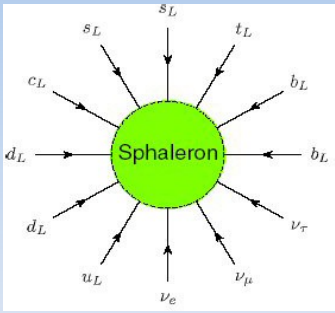
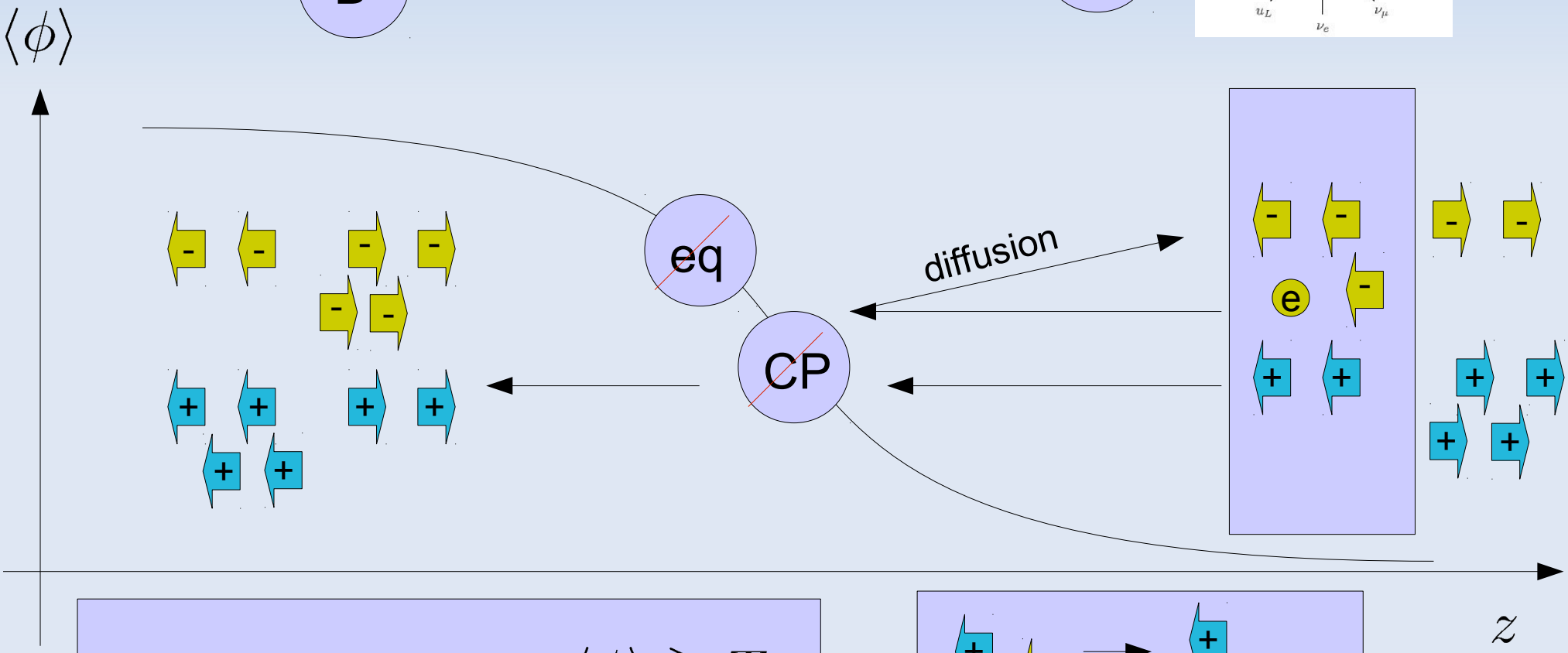
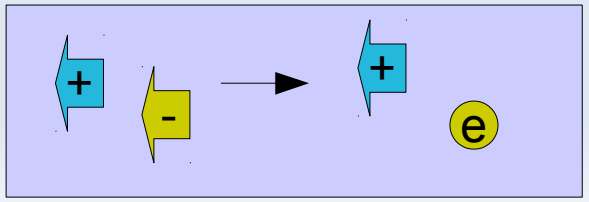




avoid washout: $\langle\phi\rangle \gtrsim T$



Ingredients

1 eq

Strong first-order electroweak phase transition

$$\phi > T$$

→ modifications in the Higgs sector

→ GWs

2 CP

Some fermion species that is reflected in a CP violating way at the Higgs bubble

→ EDMs

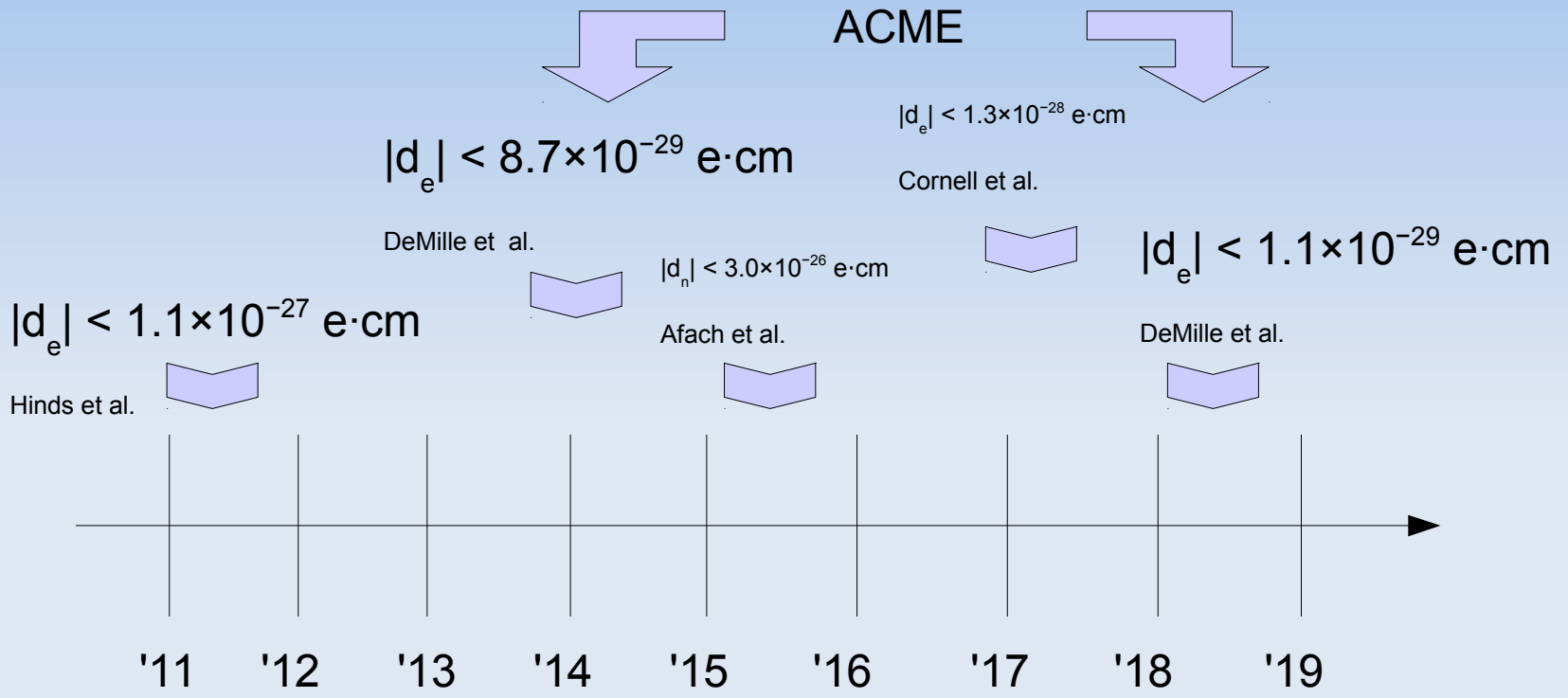
Why is this interesting?

- The hierarchy problem indicates that there is some BSM physics at EW scales
- Electroweak baryogenesis involves only physics at the electroweak scale that is accessible to EDM and collider experiments
- Electroweak baryogenesis leads naturally to the observed baryon asymmetry

$$\eta_B \sim \frac{\Gamma_{ws}}{l_w T^2}\,\delta_{CP}\, e^{-m_\chi/T} \sim 10^{-11} - 10^{-9}$$

beyond SM?

Time line of EDM bounds



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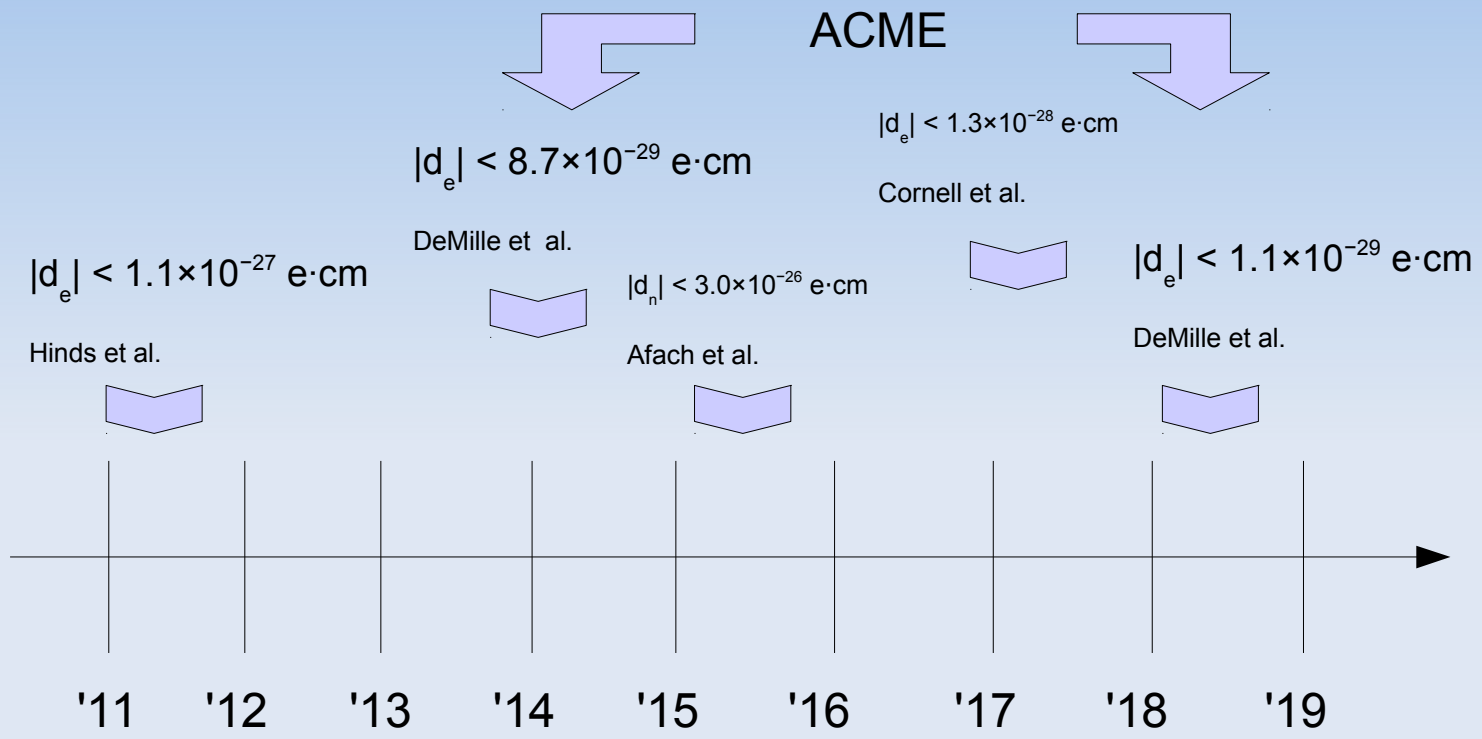
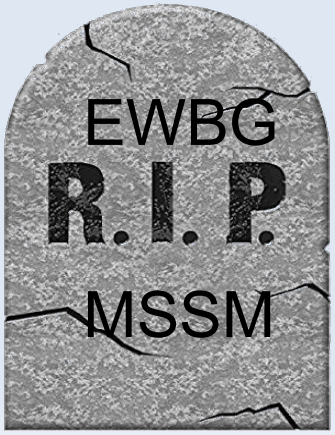
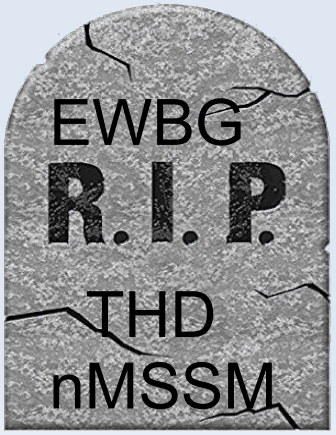
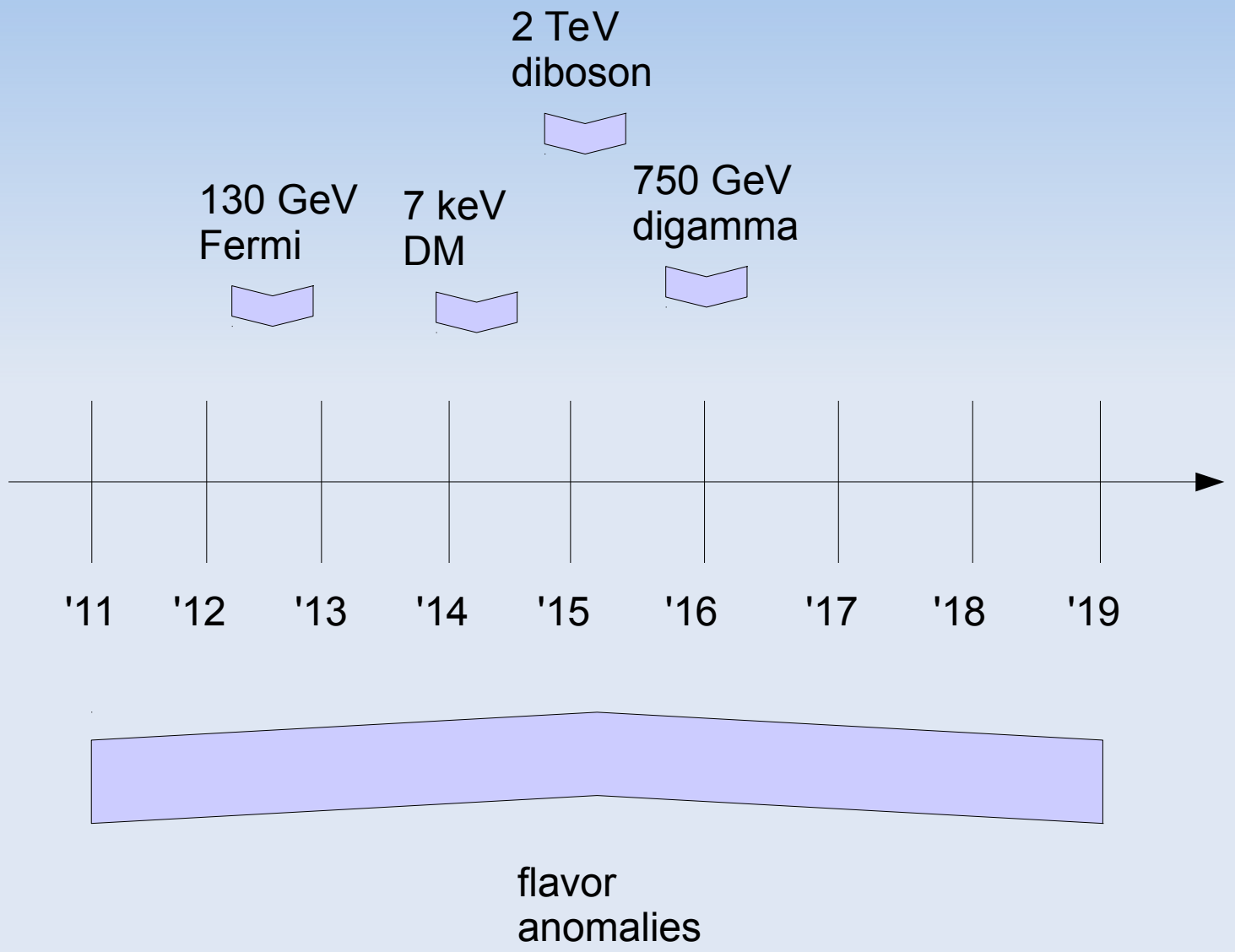






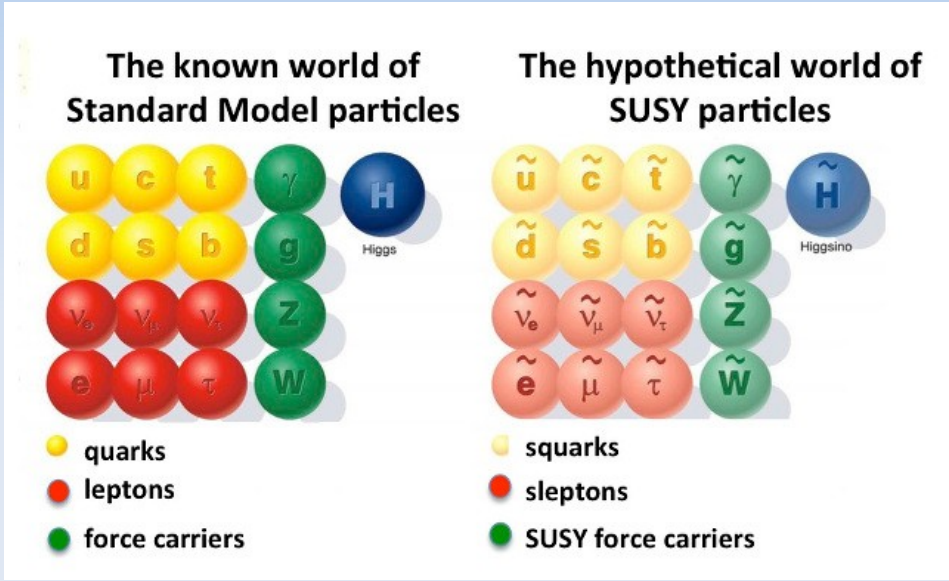
Time line of BSM discoveries



SUSY vs non-SUSY

In SUSY models, EWBG is strongly constrained

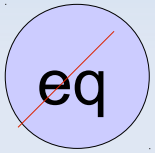
- the Higgs sector is strongly constrained
  → strong PT hard to achieve (light stops)
- CPV is strongly constrained
  → EWBG often ruled out by EDM bounds (mixing charginos)



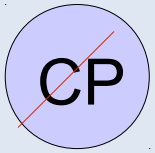
EWBG is much easier to realize in BSM models without SUSY.

SM + singlet scalar

Two ingredients of baryogenesis are missing in the Standard Model. These are provided in models that have an additional singlet in the low energy effective description



Strong first-order electroweak phase transition $V(s,h)$



CP violation from dimension-five operators

$$\mathcal{L} \ni y_t \bar{\psi}_Q H \psi_t + \frac{\tilde{y}_t}{f} S \bar{\psi}_Q H \psi_t + h.c.$$

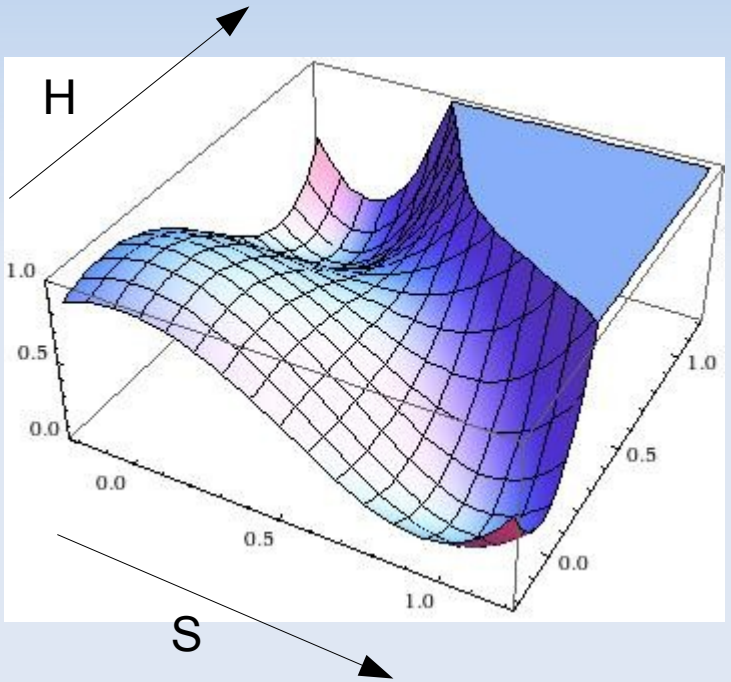
$$\Im(y_t \tilde{y}_t^*) \neq 0$$

Both ingredients natural in composite Higgs models.
[Espinosa, Gripaios, TK, Riva '11]
[Beniwal, Lewicki, Wells, White, Williams '17]
[Grzadkowski, Huang '18]

Phase transition

The construction of a potential barrier and hence first-order phase transitions are easily achieved in extended scalar sectors:

$$V(h,s) = \frac{\lambda}{4}(h^2 - v^2)^2 + m_s^2 s^2 + a_s s^3 + \lambda_s s^4 + a_m s\, h^2 + \lambda_m s^2 h^2$$



For example consider deformations of the $\mathbb{Z}_2$ - symmetric "super-Mexican-hat"

$$V(s,h) = \frac{\lambda}{4}(h^2 + s^2/\alpha^2 - v^2)^2 + \lambda_m h^2 s^2$$

that has a phase transition (two-stage phase transition)

$$(h,s) = (0,\alpha v) \rightarrow (h,s) = (v,0)$$

CP violation

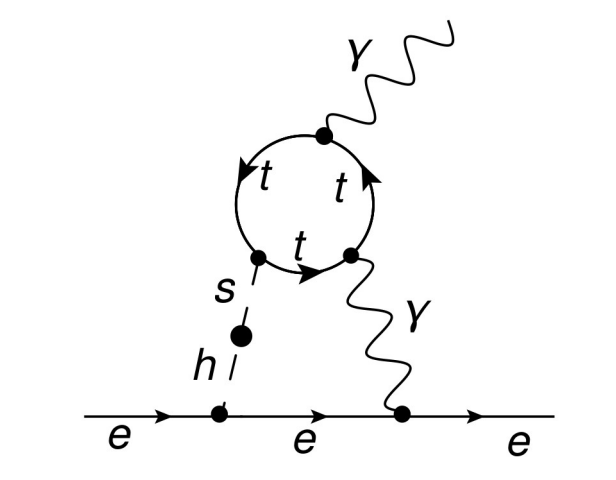
$$\mathcal{L} \ni y_t \bar{\psi}_t H \psi_t + \frac{\tilde{y}_t}{f} S \bar{\psi}_t H \psi_t$$

During the phase transition this leads to a top mass of the form

$$m_t = |m_t| e^{i\theta_t} = \frac{y_t h}{\sqrt{2}} \left(1 + \frac{\tilde{y}_t}{y_t} \frac{s}{f} \right)$$

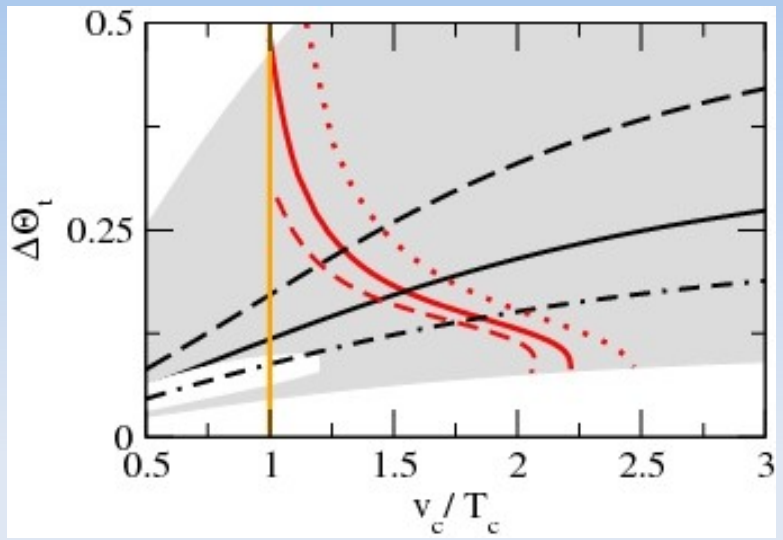
So, the complex phase during the phase transition behaves as

$$\theta_t \simeq \frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{s}{f}$$



This is a one flavor system and the BAU can be reliably determined with the semi-classical force approach.

Baryogenesis



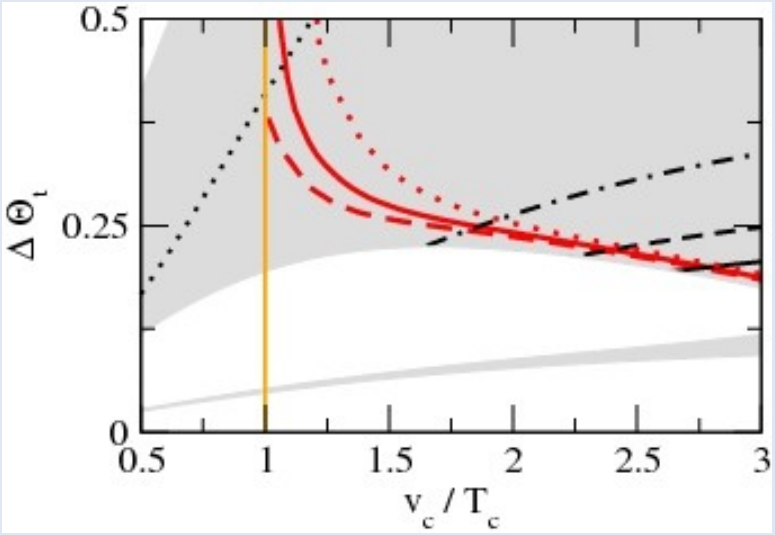
$$m_s = 130\,\mathrm{GeV}$$

$$\Delta\theta_t \gtrsim 0.15$$

strength of CP violation

strength of the phase transition

$$\Delta\theta_t \simeq \frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{\Delta s}{f}$$



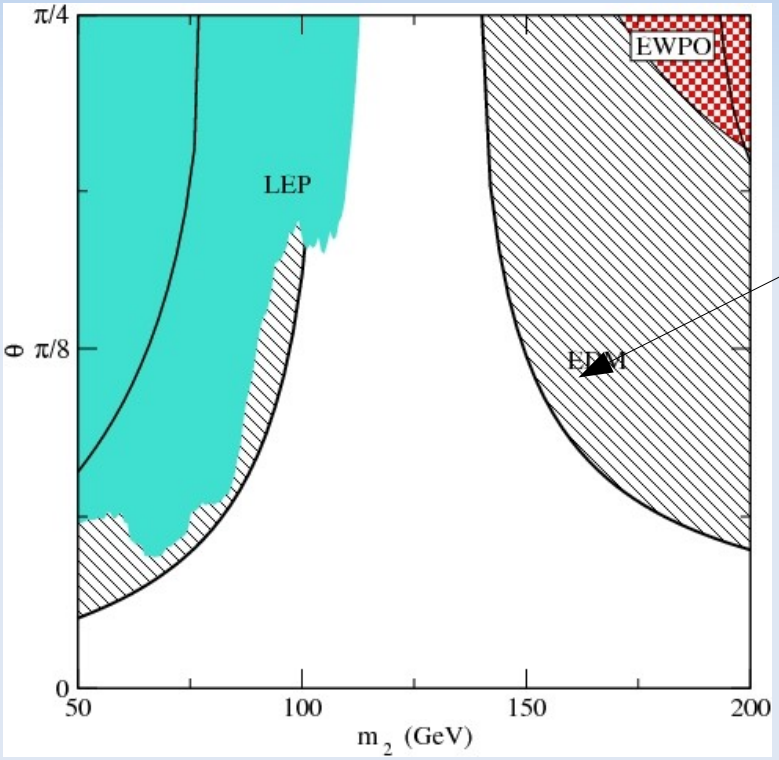
$$m_s = 80\,\mathrm{GeV}$$

$$\Delta\theta_t \gtrsim 0.25$$

[Espinosa, Gripaios, TK, Riva '11]

Signals = nightmare

$$m_h = 120\,\mathrm{GeV}$$



Higgs-singlet mixing ~ CP violation

old bounds!!

singlet mass

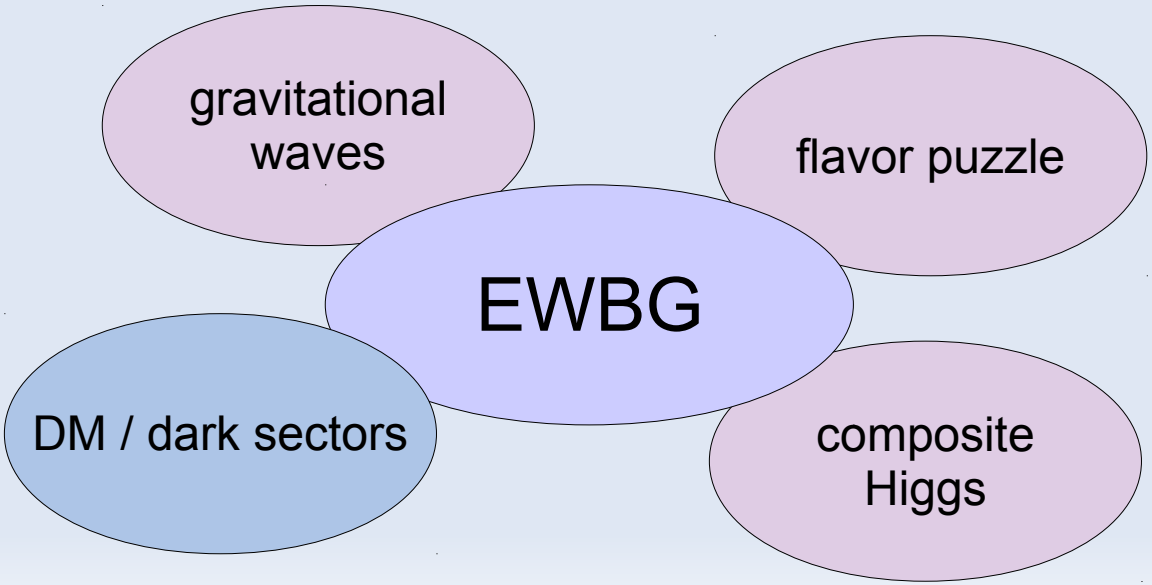
[Espinosa, Gripaios, TK, Riva '11]
[Curtin, Maede, Yu '14]

$$\frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{1}{f} = (500\,\mathrm{GeV})^{-1}$$

New developments

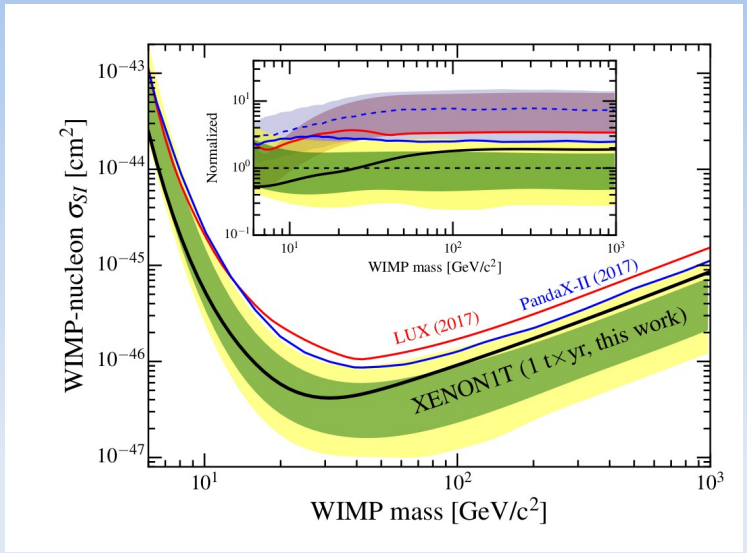
There are several ways of realizing EWBG and to avoid EDM and collider bounds.

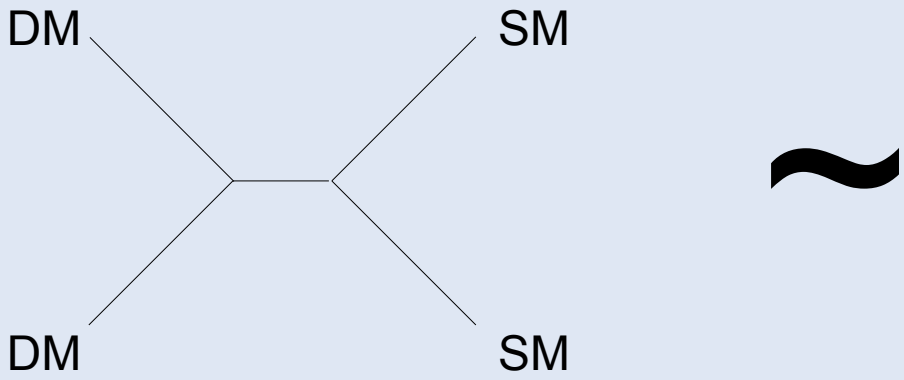
Recent developments aim at linking EWBG to other problems. This can lead to new signatures.

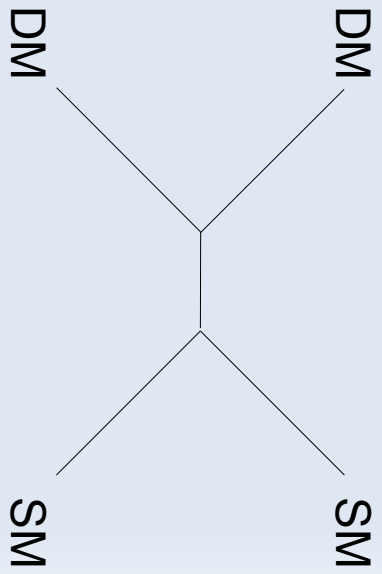


Dark Sector motivation

The WIMP miracle is somewhat under pressure since it links the DM annihilations to direct and indirect detection experiments

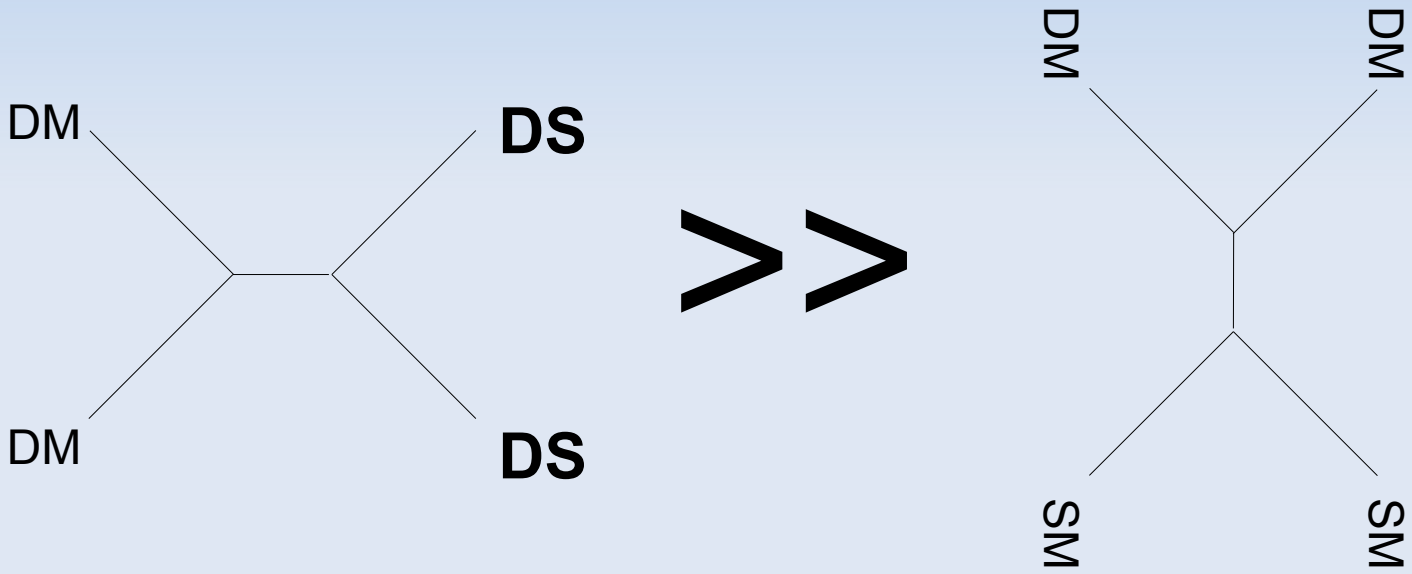






Dark Sector motivation

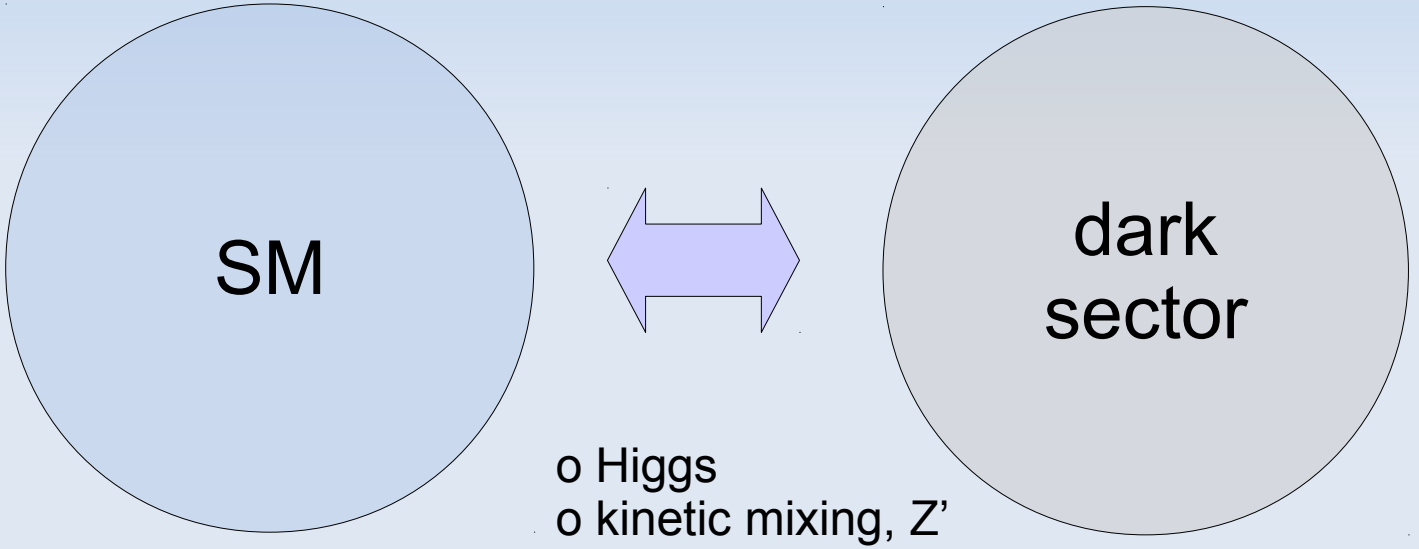
One way of sanitizing the WIMP miracle is to let the DM annihilate into a dark sector and decouple direct detection from the DM abundance



Likewise, electroweak baryogenesis in the dark sector occludes CP violation and suppresses SM EDM contributions

Darkogenesis

[Shelton, Zurek ’10] [Petraki, Trodden, Volkas ’12]
[Servant, Tulin ’13] [Cline, Kainulainen, Tucker-Smith ’17]
[Baldes ’17] [Carena, Quiros, Zhang ’19] + many more



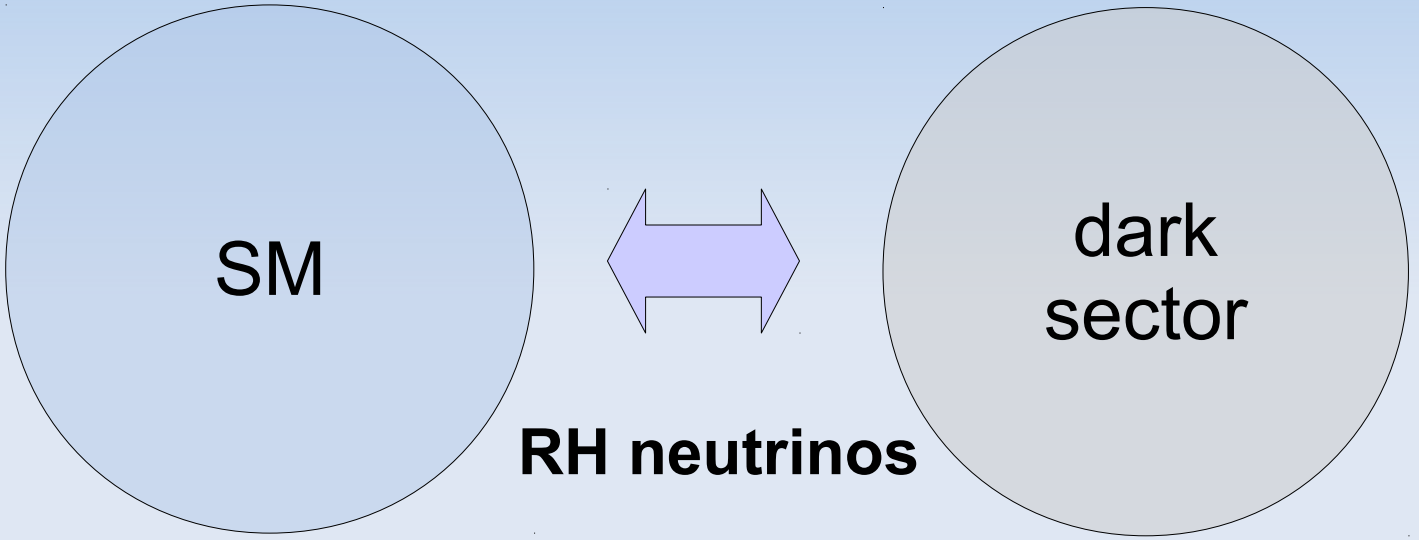
o Higgs
o kinetic mixing, Z’
o higher dim Ops

BG in the dark sector
→ weak EDM constraints

Darkogenesis works in the context of asymmetric dark matter. GWs from dark PT?

Darkogenesis II

[Hall, TK, McGehee, Murayama, Servant '19]



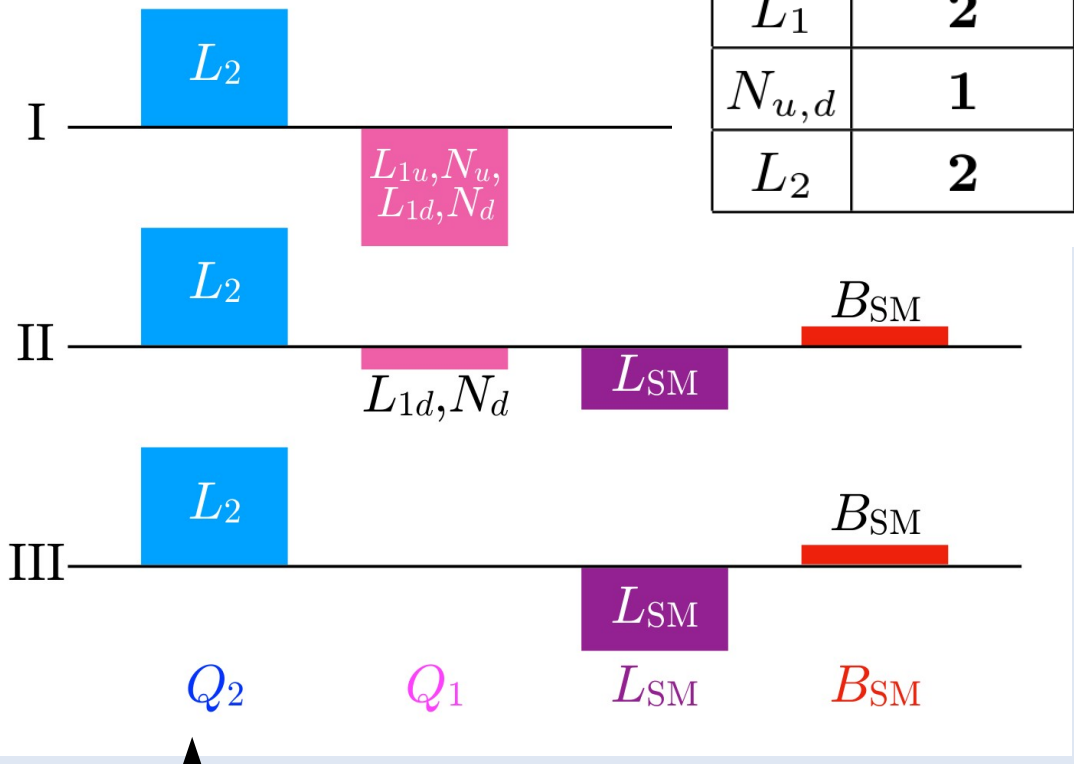
EWBG in the dark sector
→ weak EDM constraints

Nice features:
- EWBG → GWs?
- renormalizable
- directly translates
  chemical potentials

Three possible signatures
- exotic Higgs and Z decays
- GWs
- excess radiation?

Model A (minimality)

field	$SU(2)_D$	γ_5	Q_1	Q_2	$\mathbb{Z}_2$
$\Phi_{1,2}$	**2**	0	0	0	+
L_1	**2**	−1	+1	0	+
$N_{u,d}$	**1**	+1	+1	0	+
L_2	**2**	−1	0	+1	−



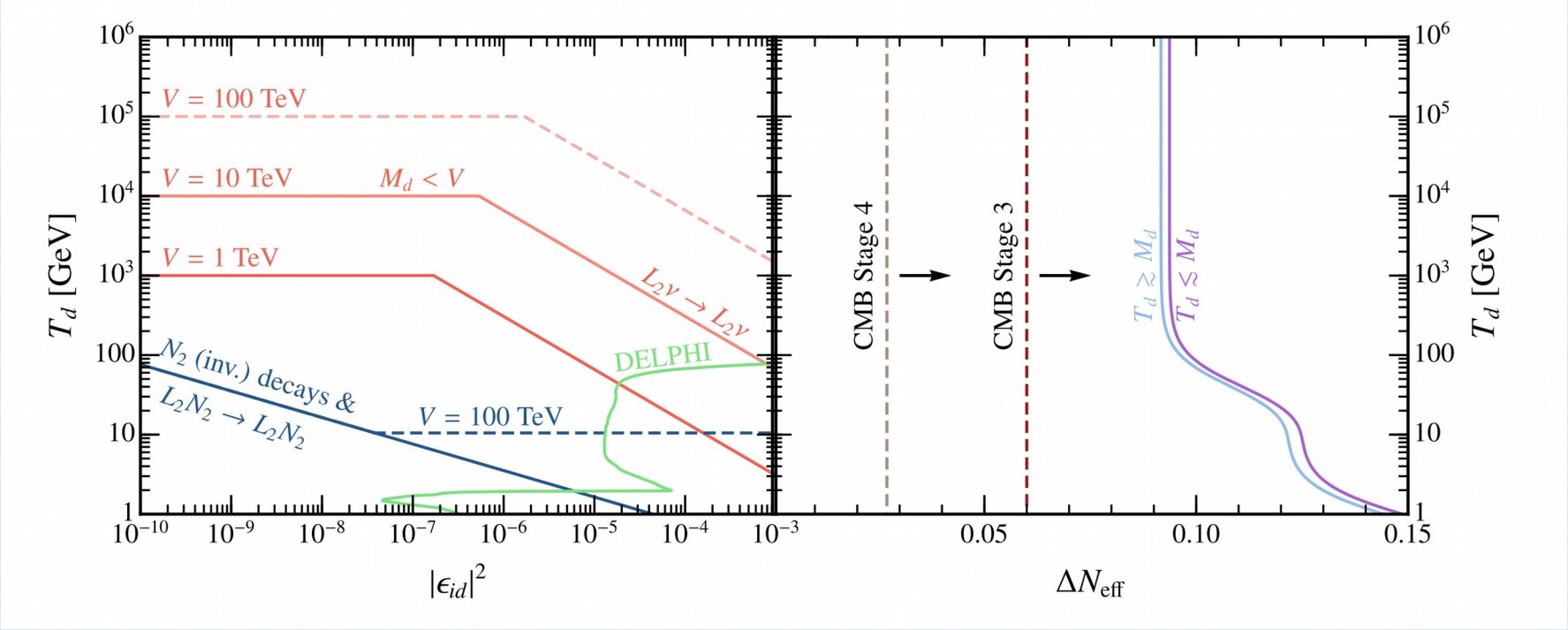
massless
symmetric component
→ excess radiation

[Hall, TK, McGehee, Murayama, Servant '19]

Excess radiation

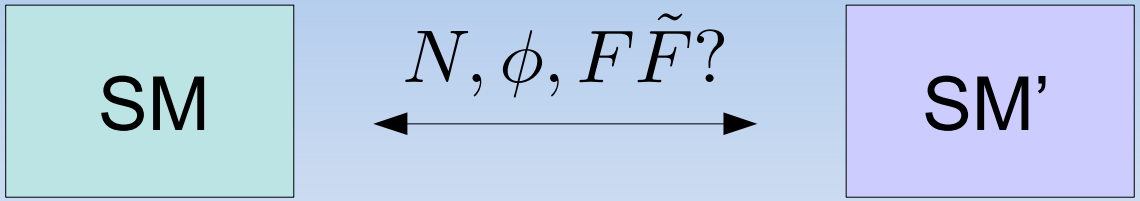
L2 is massless and annihilation of the symmetric component is relatively slow → excess radiation

- scatter on SM neutrinos (gauge coupling and mixing)
- equilibrate through dark down leptons



[Hall, TK, McGehee, Murayama, Servant '19]

Model B (symmetry)



$$m \neq m' , \quad g \neq g' , \quad m'_\gamma > 0$$

EWBG proceeds in the dark sector.
Dark matter is the dark proton or dark neutron.

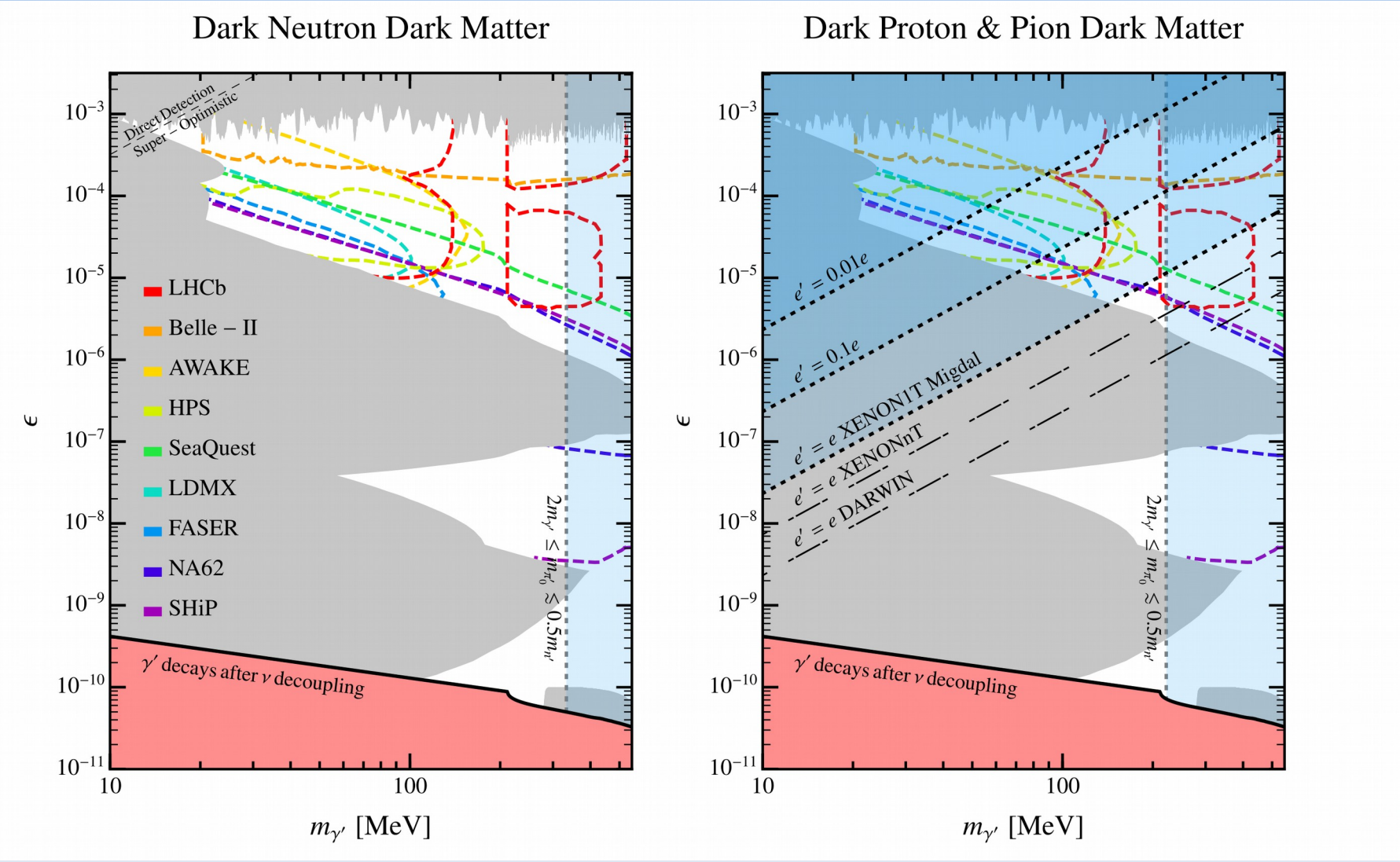
There are two sphalerons and if the two sectors are in equilibrium through the right-handed neutrinos, the asymmetries are related

$$\frac{\Omega_c}{\Omega_b} = \frac{B'}{B}\frac{m_{n'}}{m_p} = 5.238.$$

$$m_{n'} = 1.33\,\mathrm{GeV}.$$

[Hall, TK, McGehee, Murayama '19]

Kinetic mixing



[Hall, TK, McGehee, Murayama '19]

Summary

Electroweak baryogenesis is still a viable option but

- EDM bounds constrain many models tightly
- no collider hints what NP could make the PT strong
  (need Higgs couplings for model-ind. assessment)

Recent developments move away from SUSY models

- Link to GW observations
- EWBG with leptons
- EWBG and varying Yukawas → composite Higgs models
- EWBG in the dark sector → asymmetric dark matter?

Model-independent falsifiability?

Electroweak phase transition

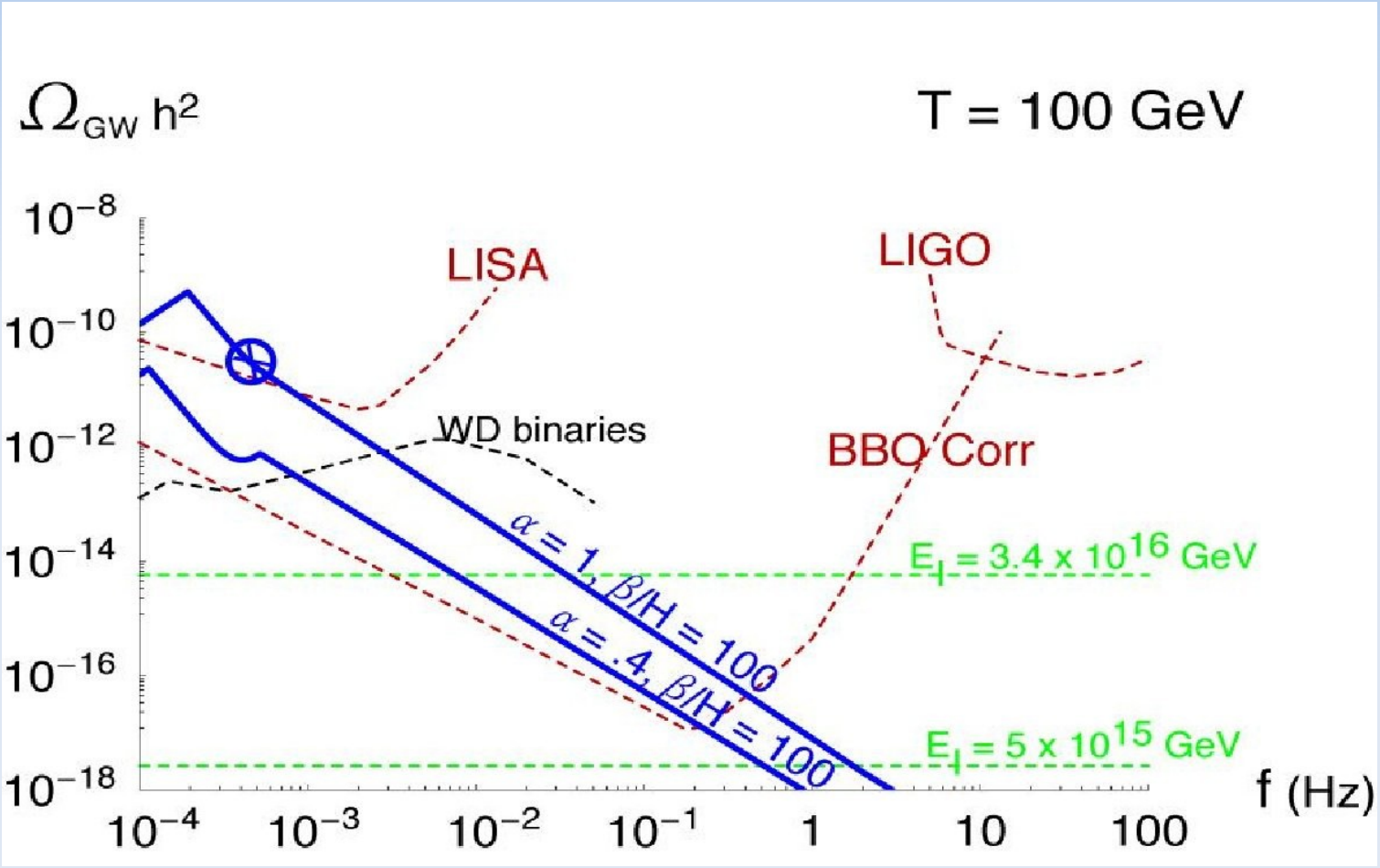
gravitational waves

baryogenesis

Cosmological phase transition

Gravitational waves from the phase transition

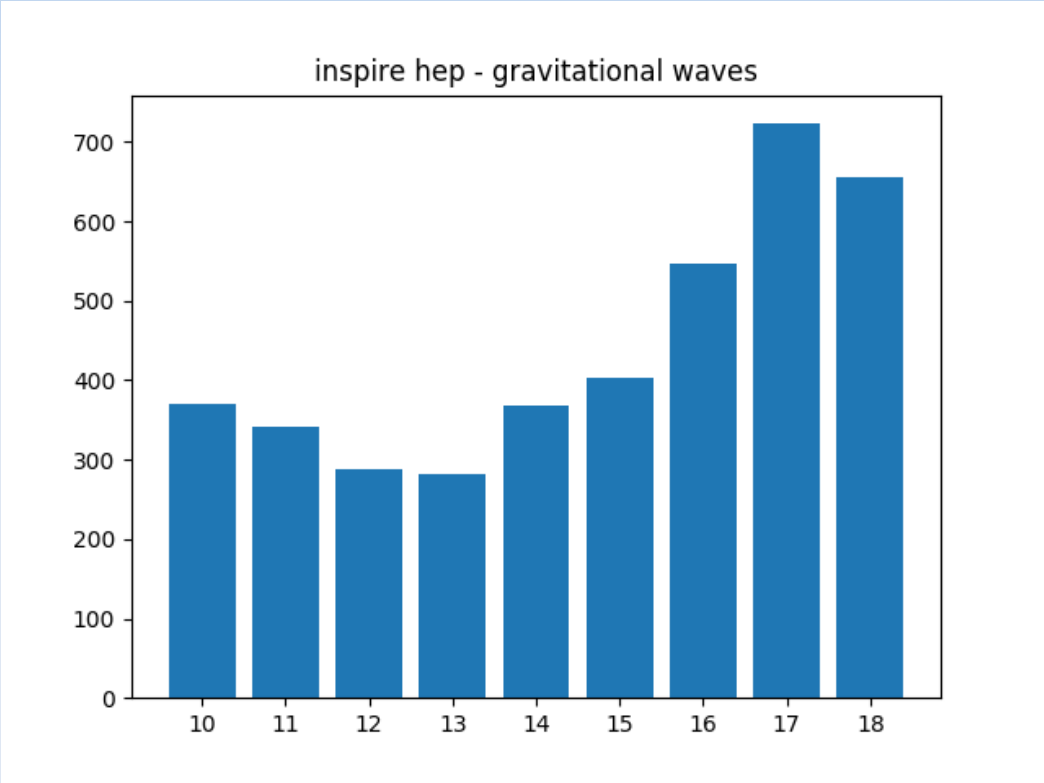
$$\alpha = \rho_{vac}/\rho_{rad}, \quad \beta \sim \tau^{-1}, \quad v_b, \quad T$$

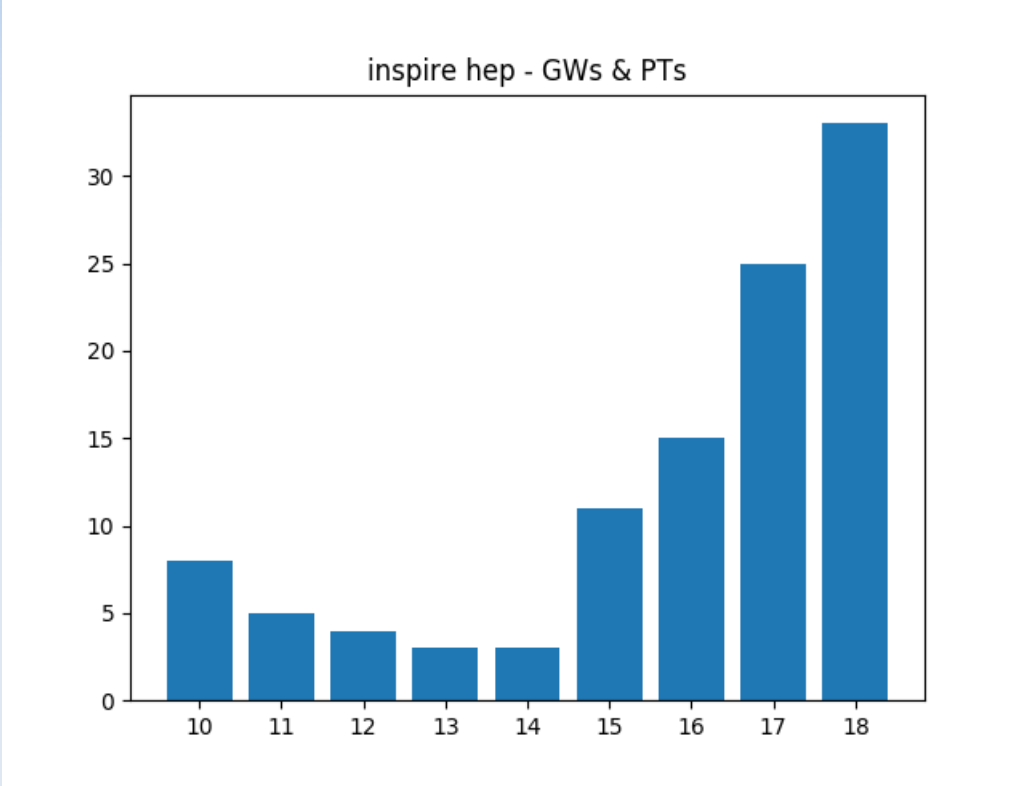


[Witten '84]
[Kosowsky, Turner, Watkins '92]
[Grojean, Servant '06]

GWs from PTs

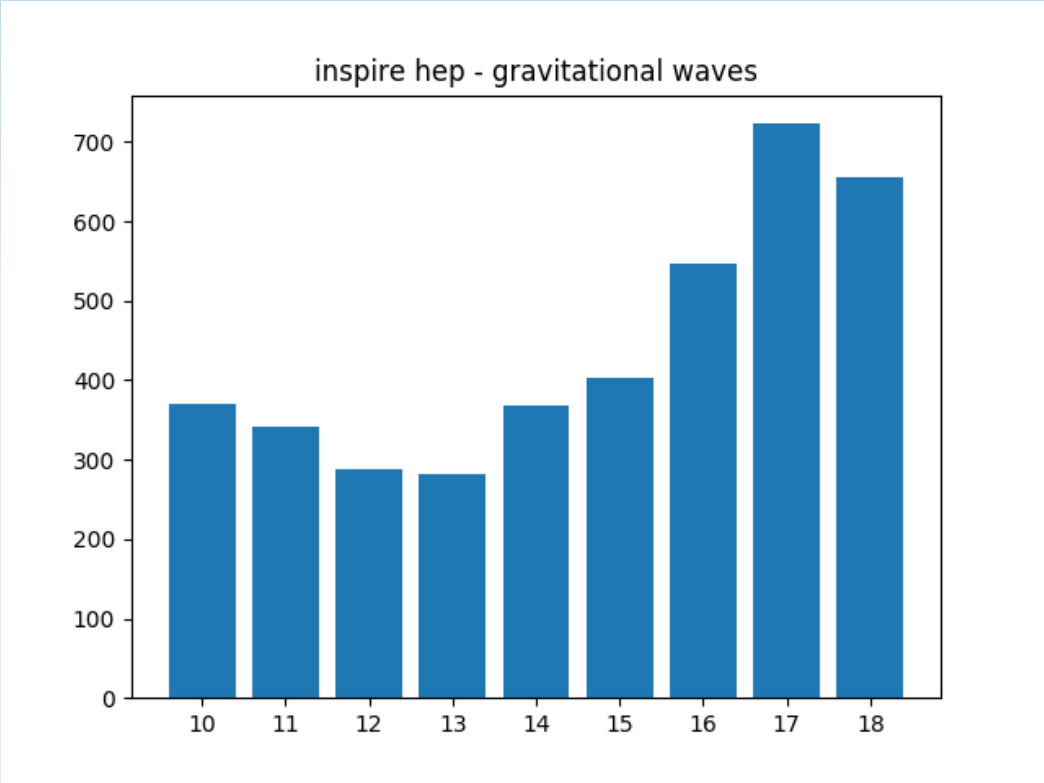
ArXiv activity:

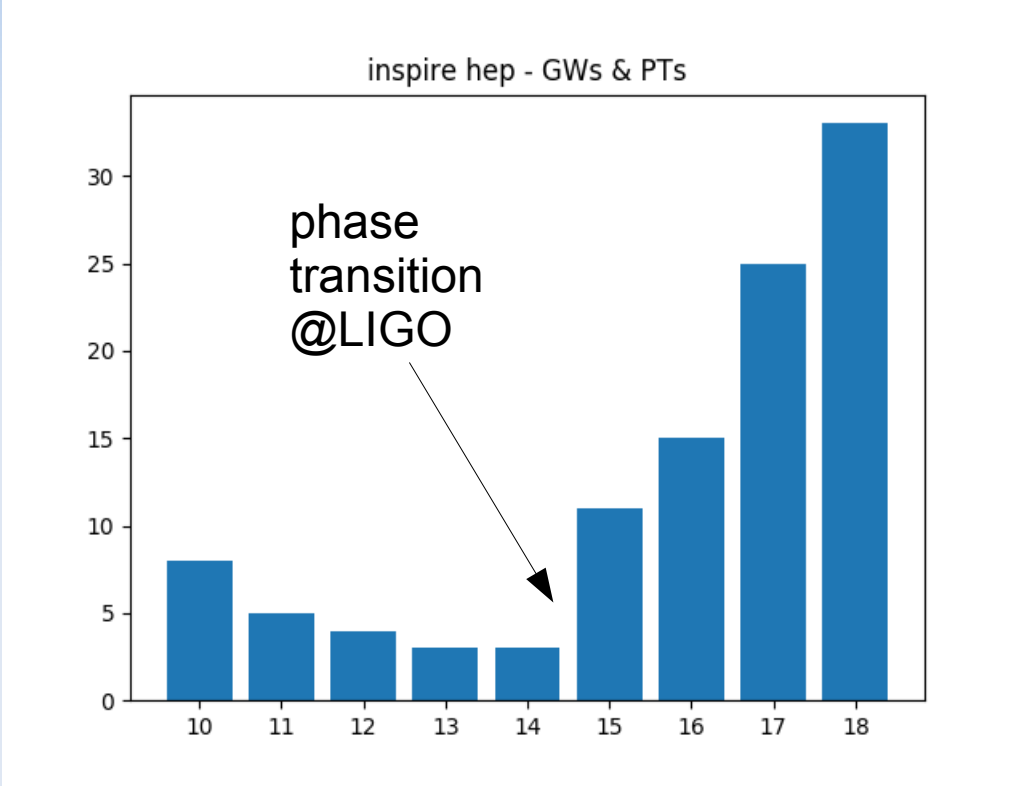




GWs from PTs

Arxiv activity:





Sources of GWs from PTs

During and after the phase transition, several sources of GWs are active

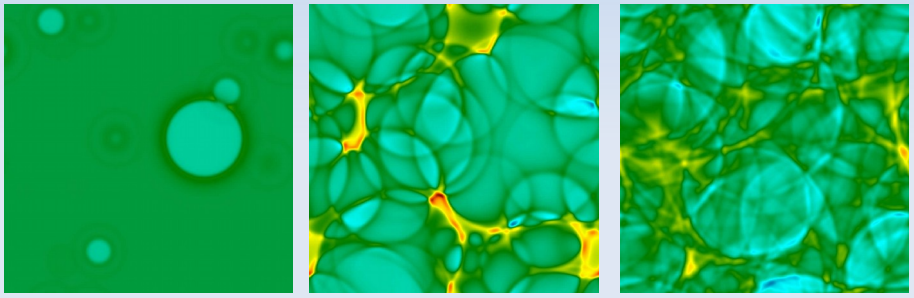
- Collisions of the scalar field configurations / initial fluid shells
- Sound waves after the phase transition (long-lasting)
- Turbulence
- Magnetic fields

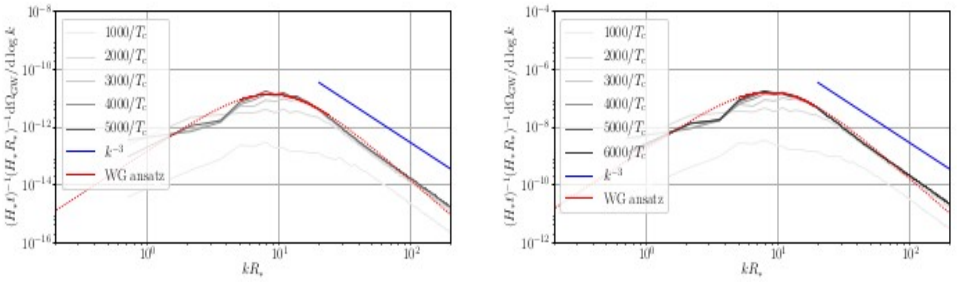
Which source dominates depends on the characteristics of the PT

State-of-the art

Shape of the acoustic gravitational wave power spectrum from a first order phase transition

Mark Hindmarsh,[1,2,*] Stephan J. Huber,[1,†] Kari Rummukainen,[2,‡] and David J. Weir[2,§]
[1] *Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, U.K.*
[2] *Department of Physics and Helsinki Institute of Physics, PL 64, FI-00014 University of Helsinki, Finland*
(Dated: April 20, 2017)





(a) Weak, $v_w = 0.92$

(b) Intermediate, $v_w = 0.92$

Lattice simulations of the hydrodynamics of the system fluid+scalar field are the state-of-the-art.

They predict reliably the produced spectrum of GWs for not too strong PTs with not too fast bubble wall velocities

Probably dominate in this regime (~lifetime of waves).

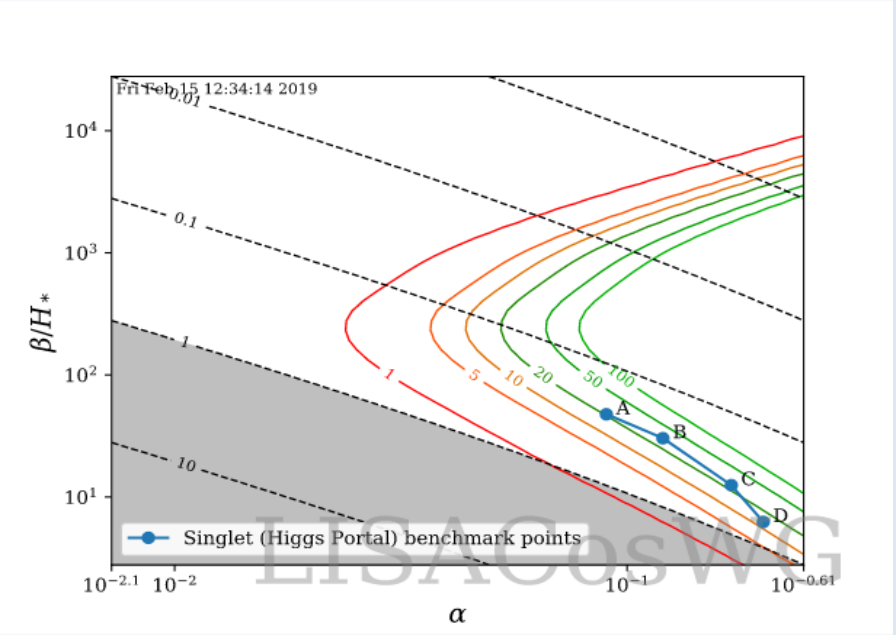
Putting it all together

The different sources and the relation to particlue physics model building is discussed in publications by the LISA cosmology working group on GWs from cosmological phase transitions:

Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions
Caprini et al.
arxiv/1512.06239

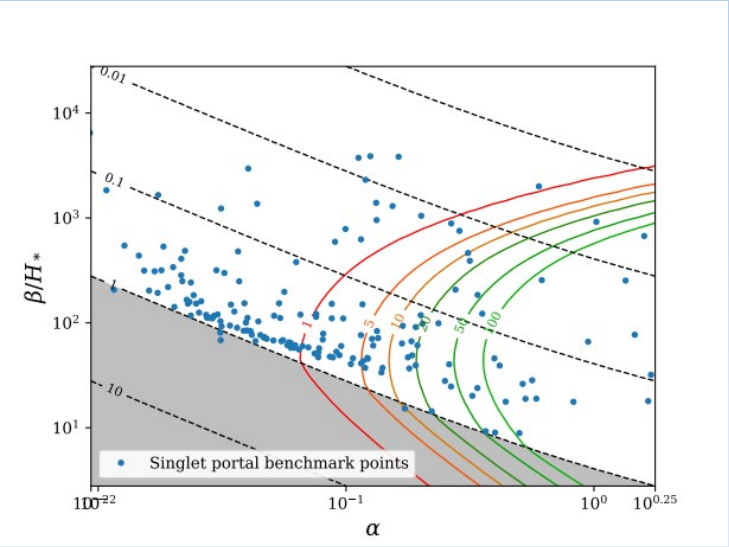
Detecting ravitational waves from cosmological phase transitions with LISA: an update
Caprini et al.
arxiv/1910.13125

web-tool by *David Weir*
http://www.ptplot.org

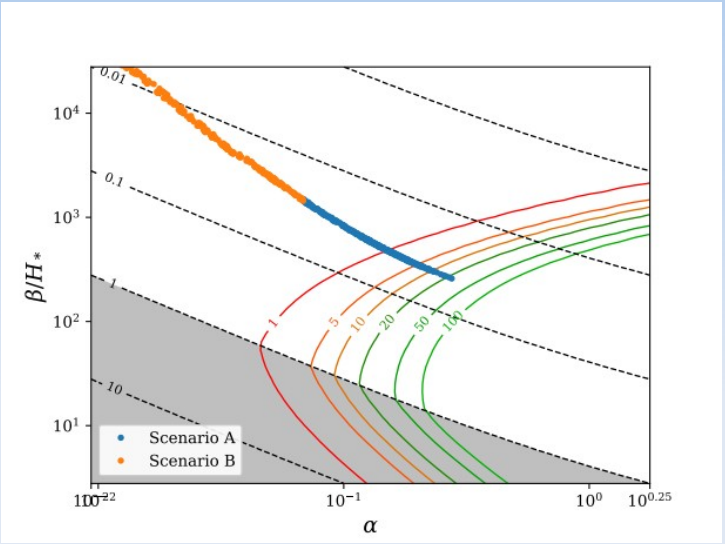


Models

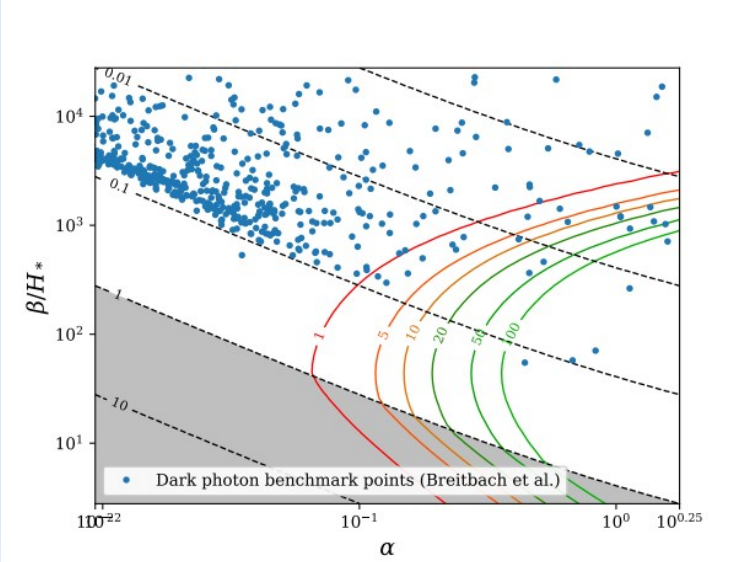
singlet portal model



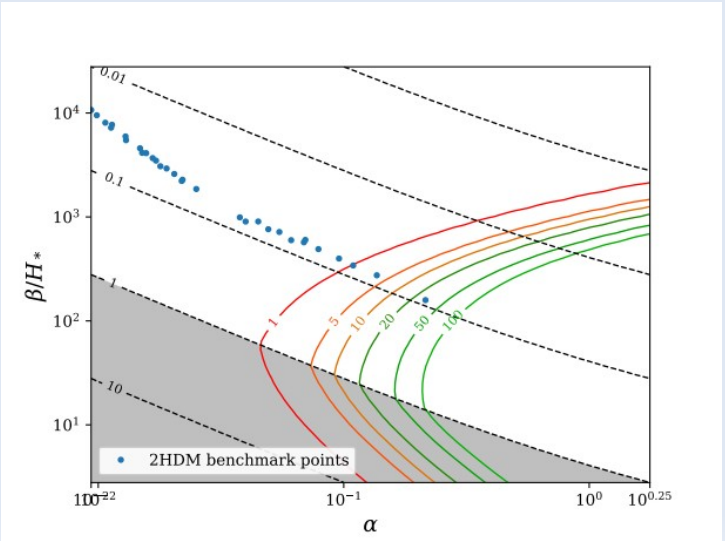
SM EFT



dark photon



THD



Summary

Gravitational waves from cosmological phase transitions are exciting because GWs are very exciting.

The main appeal of these observations is that one can probe the era before electromagnetic decoupling.

In principle, experiments as LISA/LIGO/DECIGO allow to test phase transitions (and hence particle physics) up to very high scales ~ 10^6 GeV.

LISA will fly in the 2030s and cover a large range of cosmological phase transitions in terms of strength and temperature close to electroweak scales.