Electroweak baryogenesis and GWs at electroweak scales

Thomas Konstandin

SGW Mini-workshop, Brussels
November 14, 2019

Outline

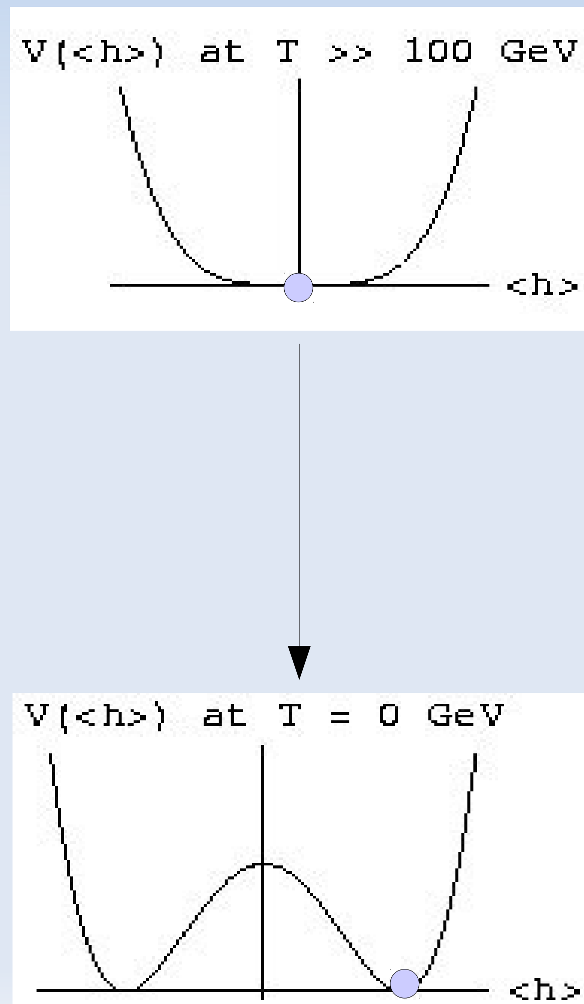
Cosmological phase transitions

Baryogenesis

GWs

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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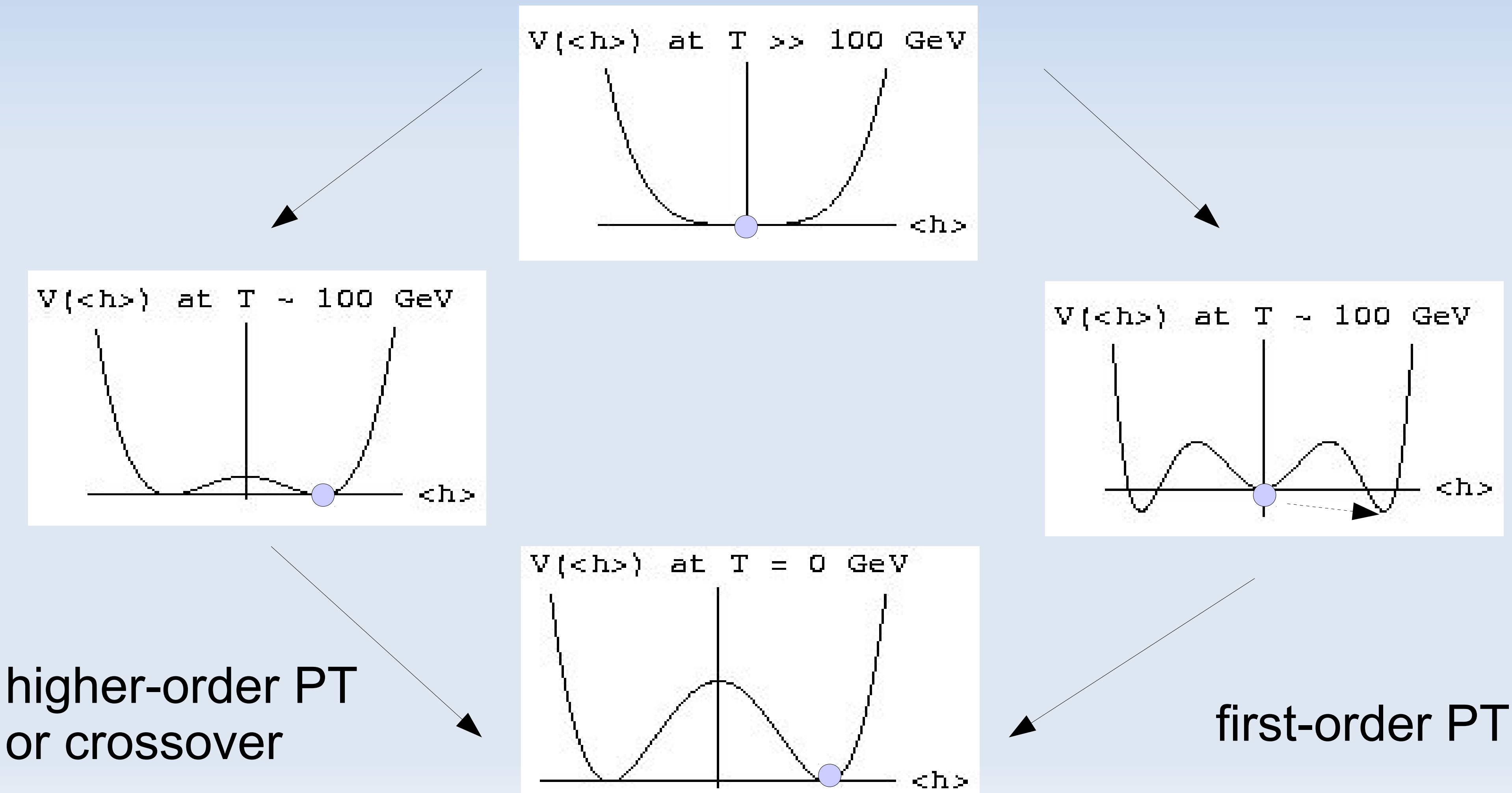

First-order phase transitions

- 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

1st order electroweak phase transition

gravitational waves

baryogenesis

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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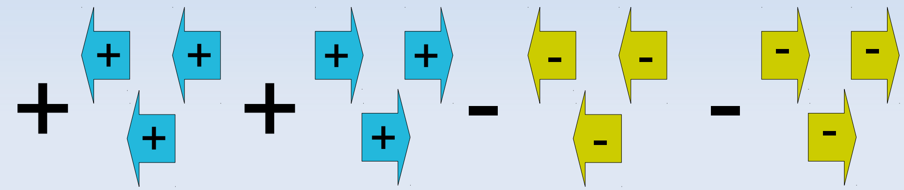

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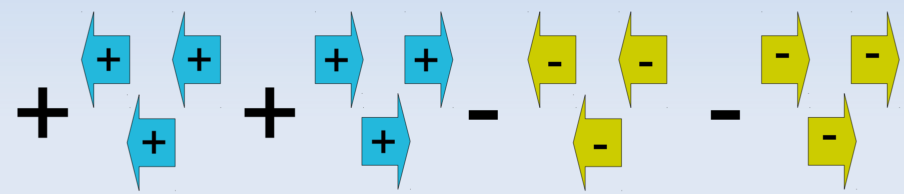

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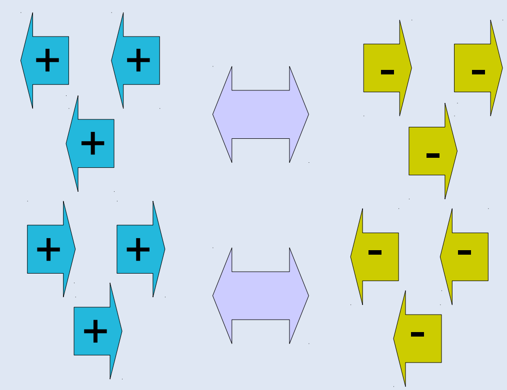

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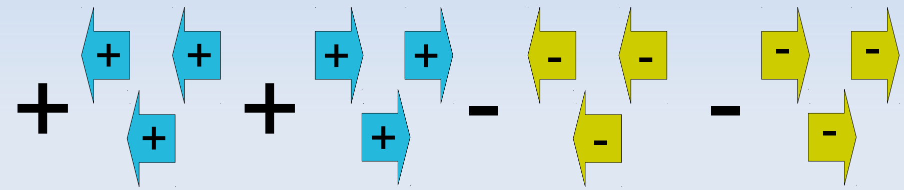

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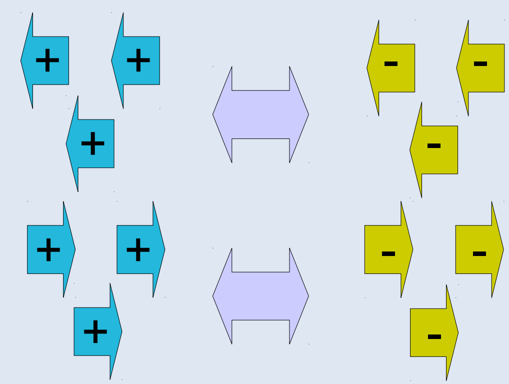

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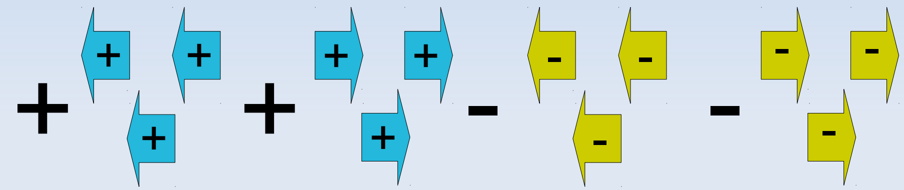

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- out-of-equilibrium

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

$$m = \bar{m}$$

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

Baryogenesis

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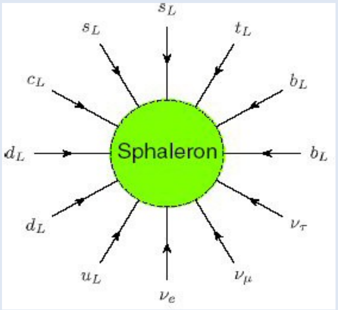
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 10^{-10}$$

SM @ EW temp

~~C~~ ~~B~~ ~~CP~~ ~~eq~~


B+L anomaly

sphaleron



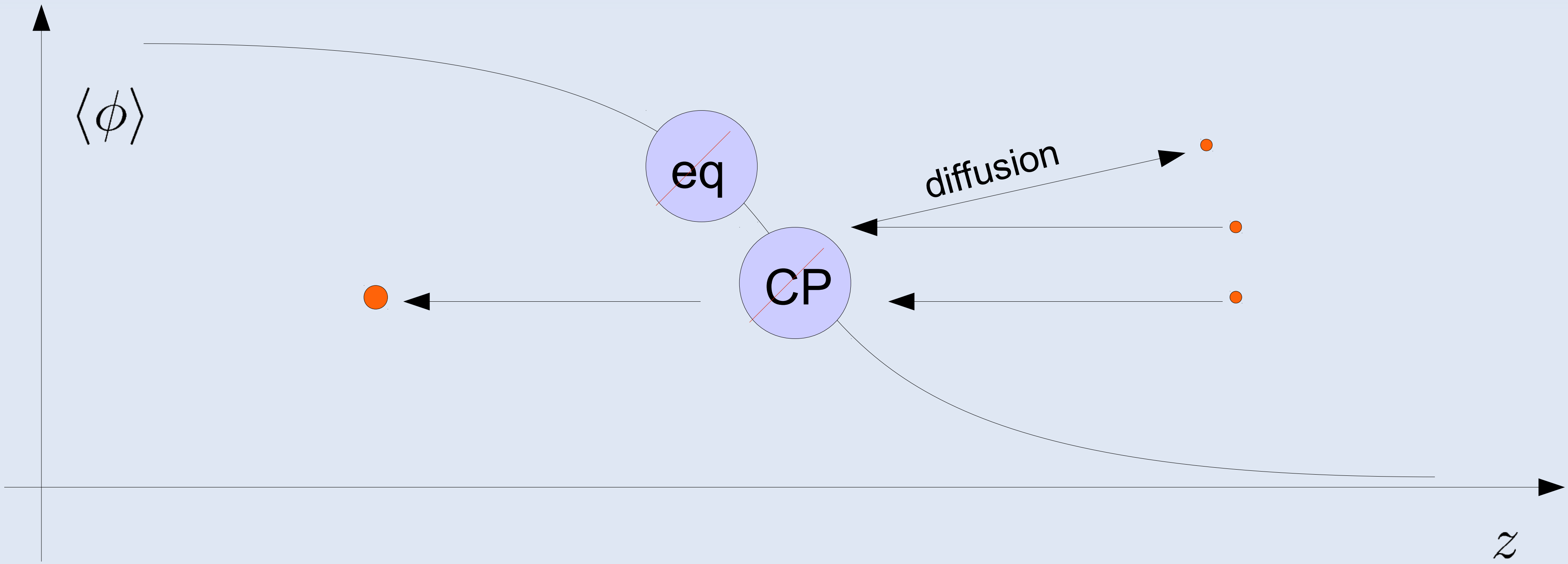

Jarlskog invariant


expansion slow EW PT?

beyond the SM physics essential

Electroweak baryogenesis

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



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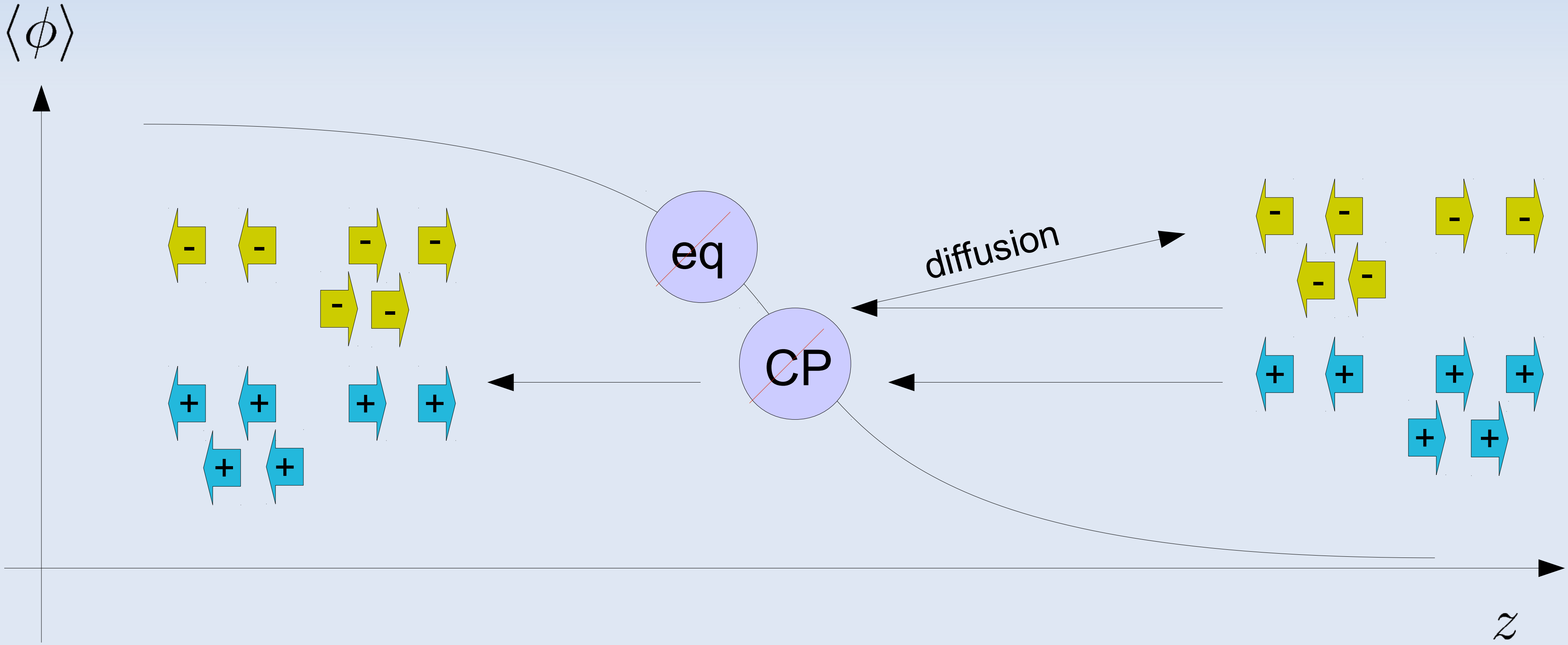

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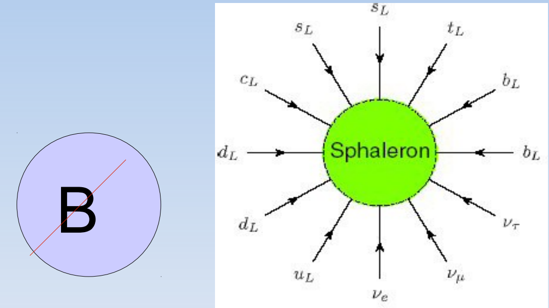

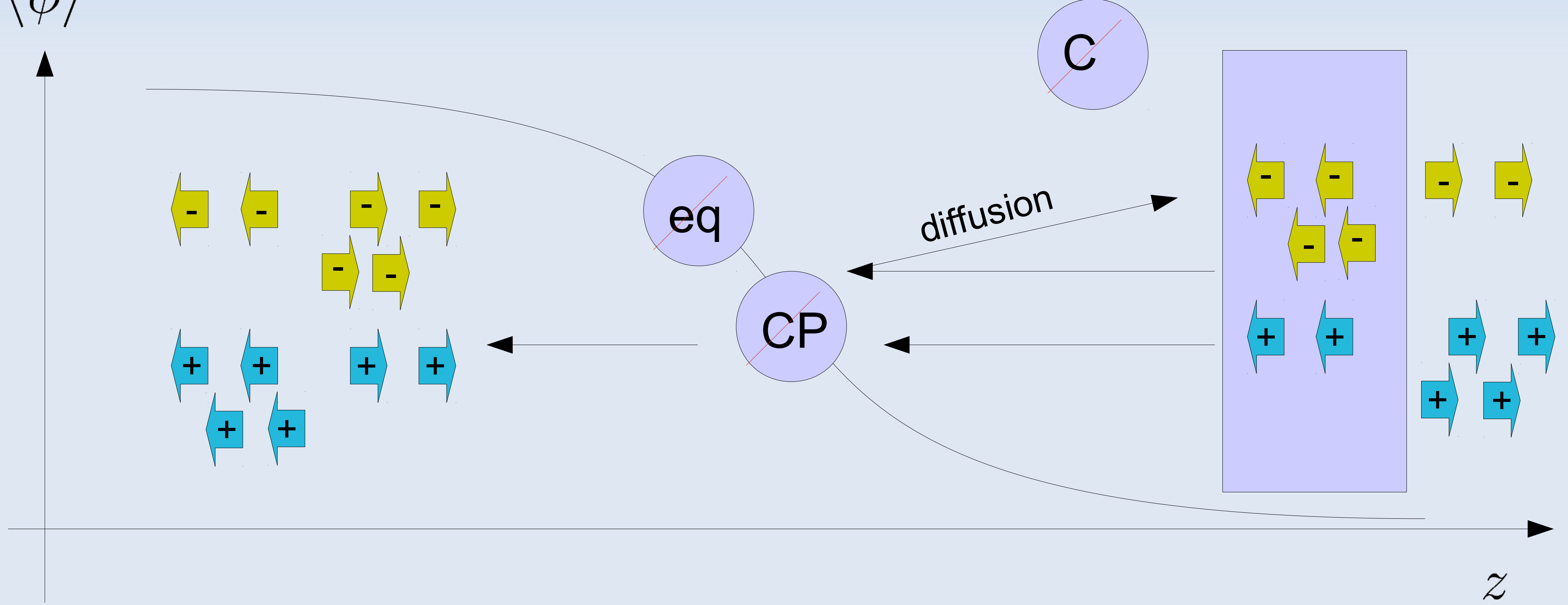

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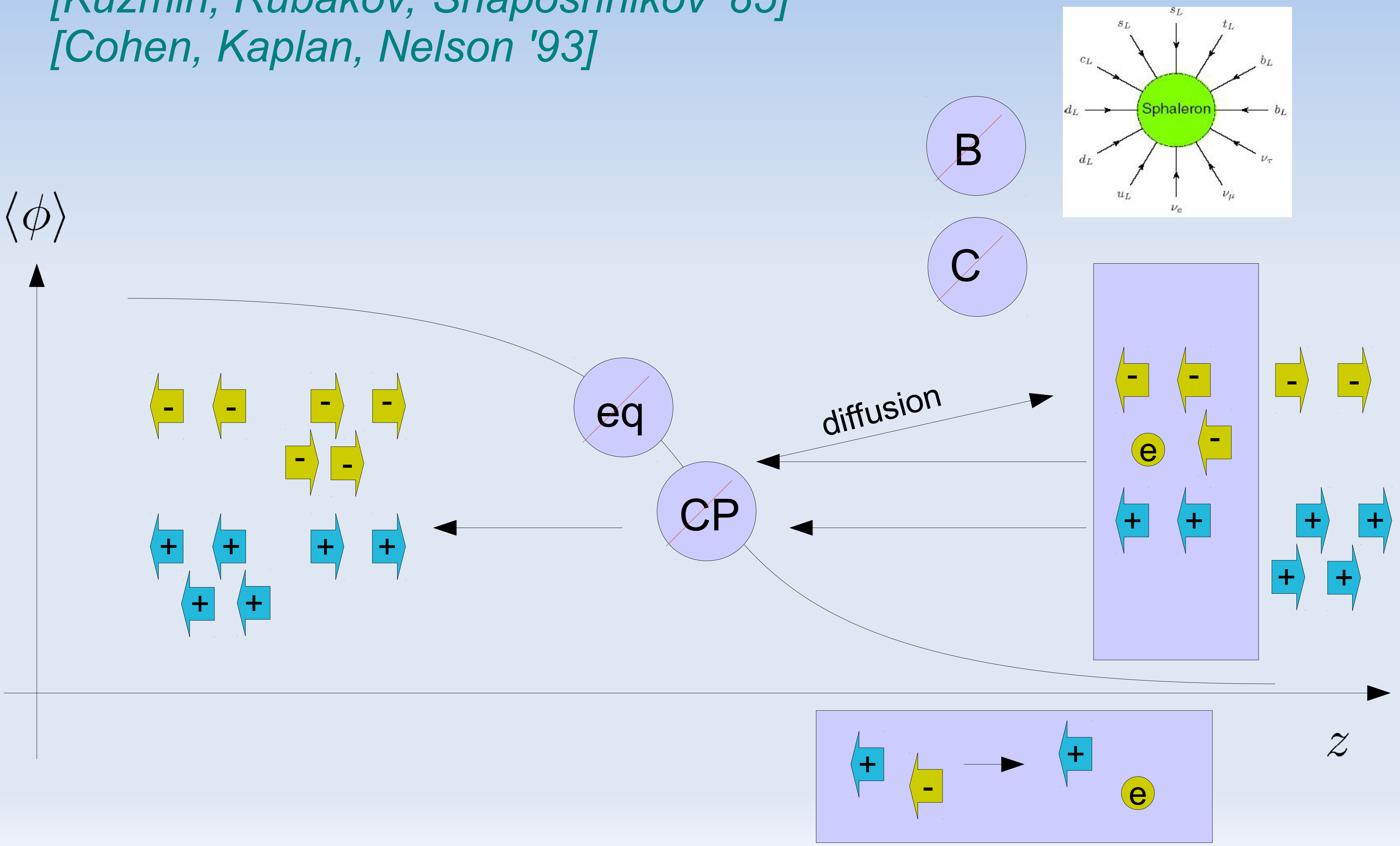

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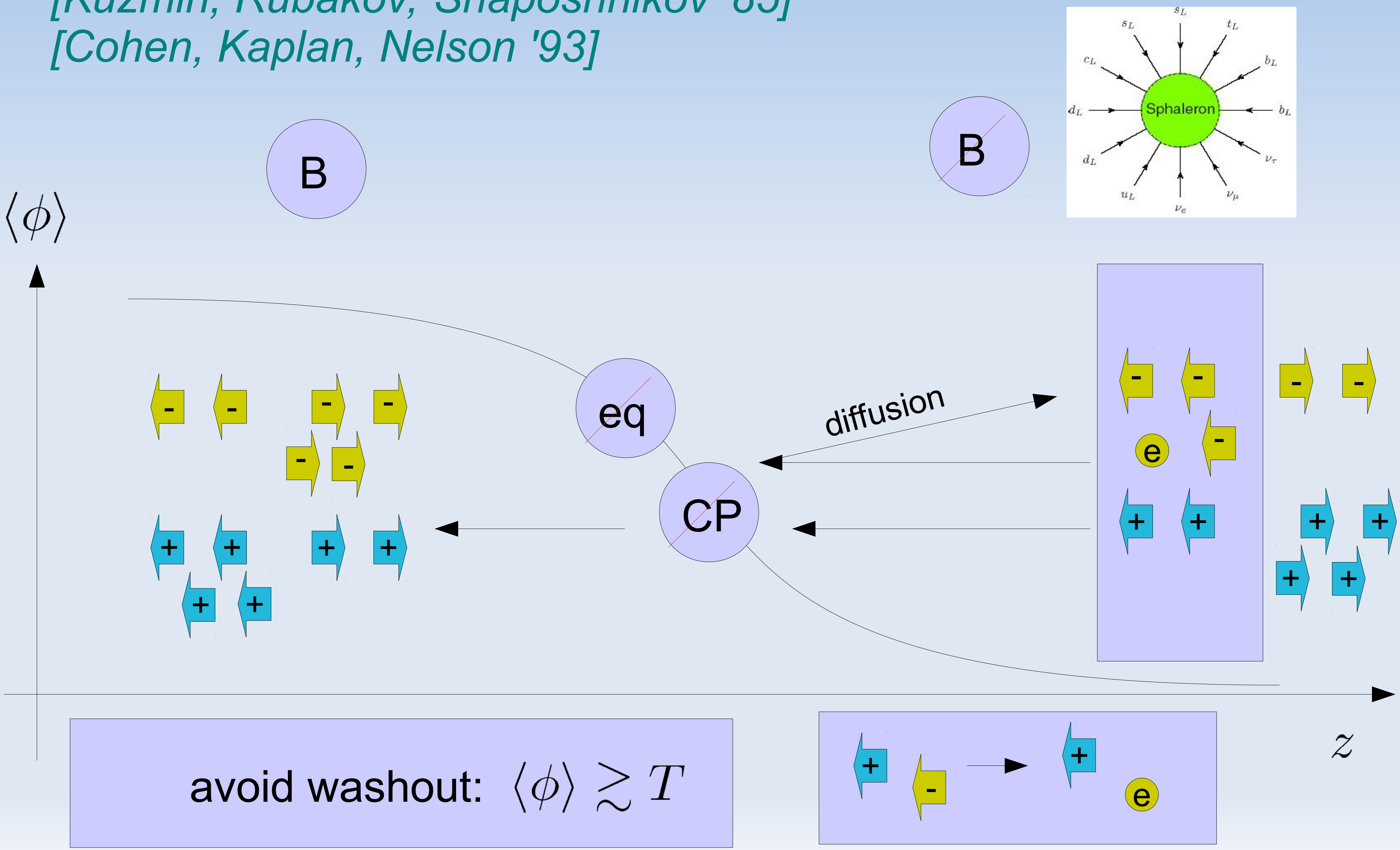


Ingredients

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

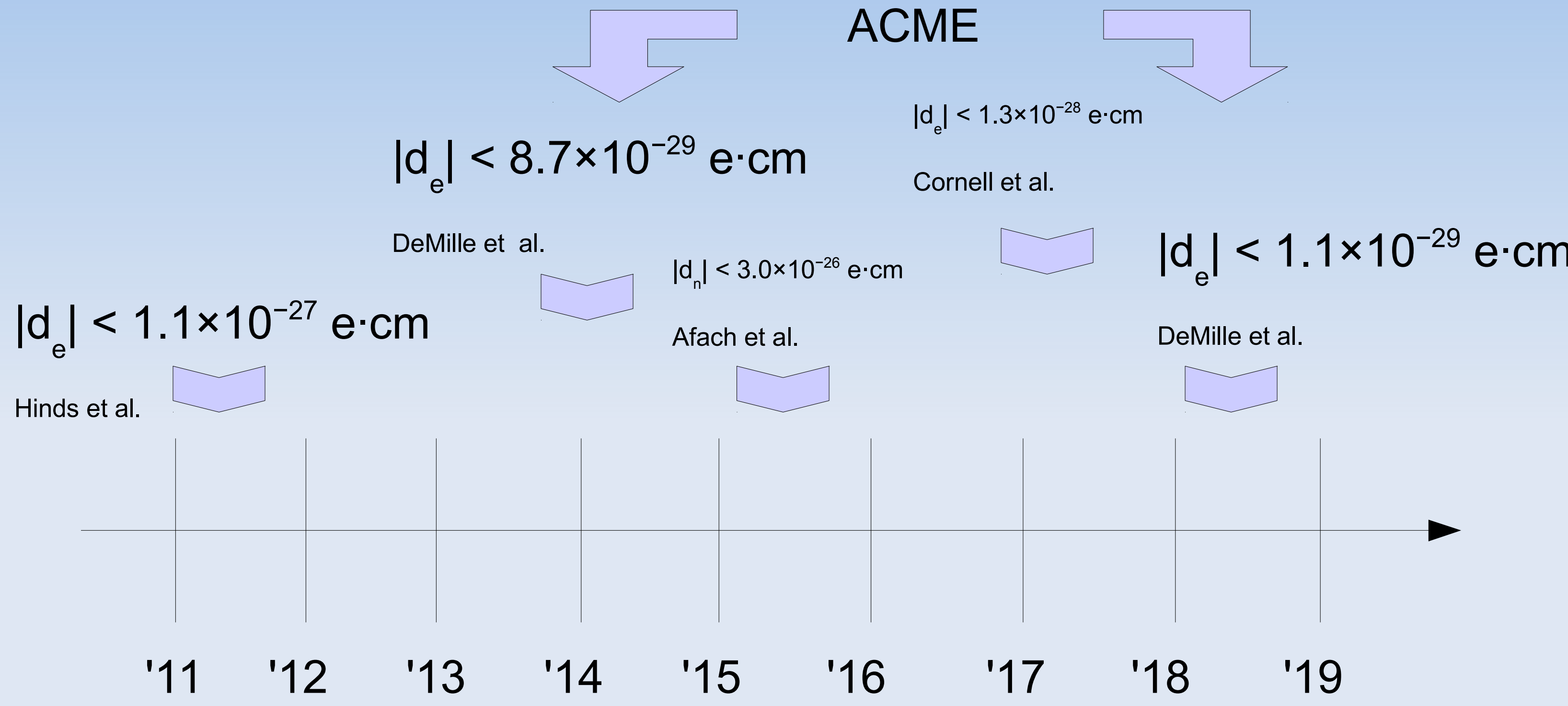
Why is this interesting?

- 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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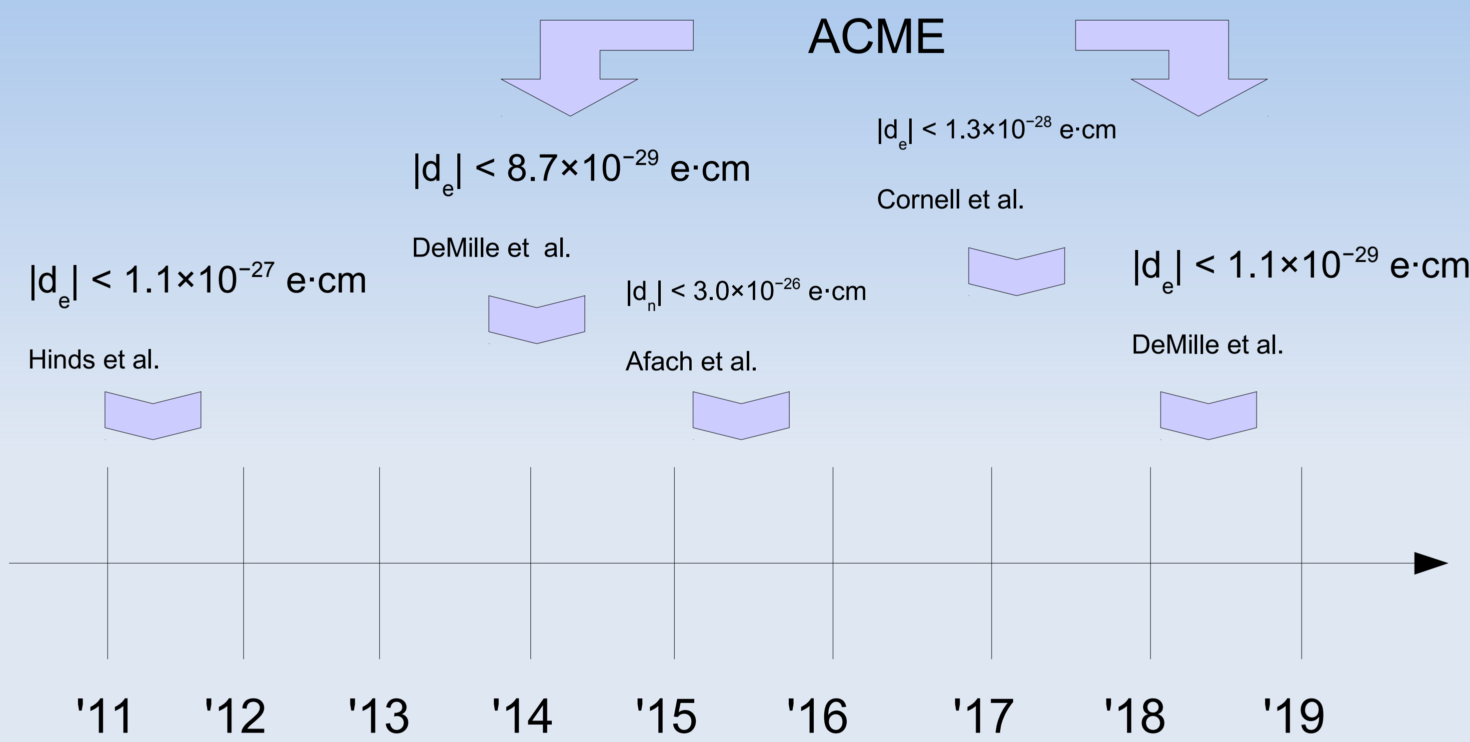
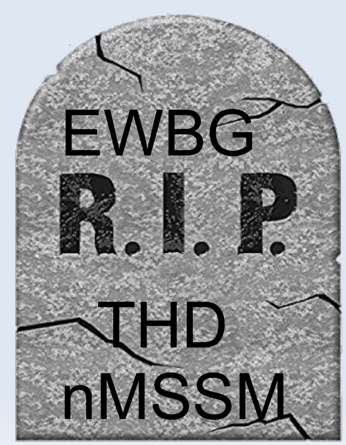
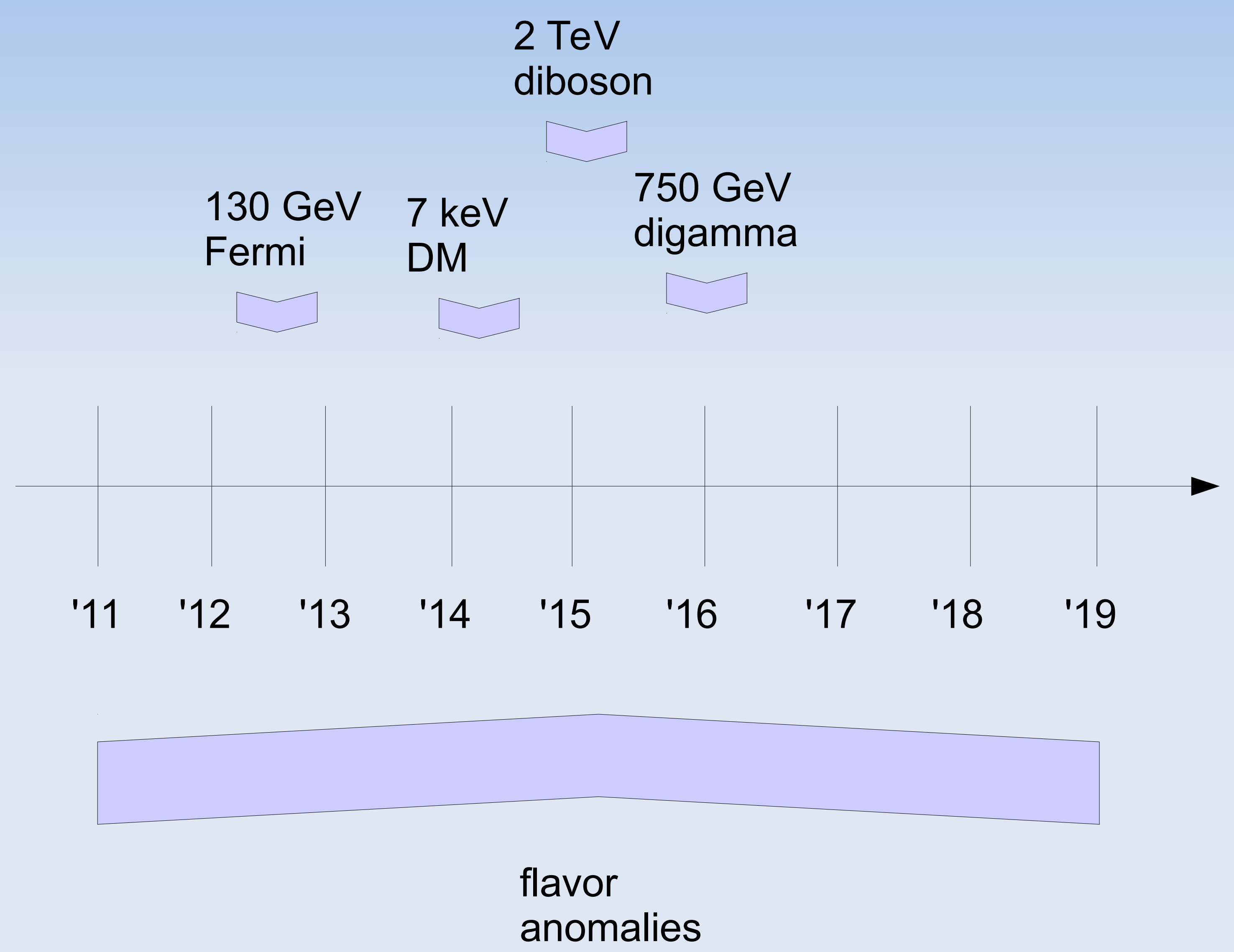


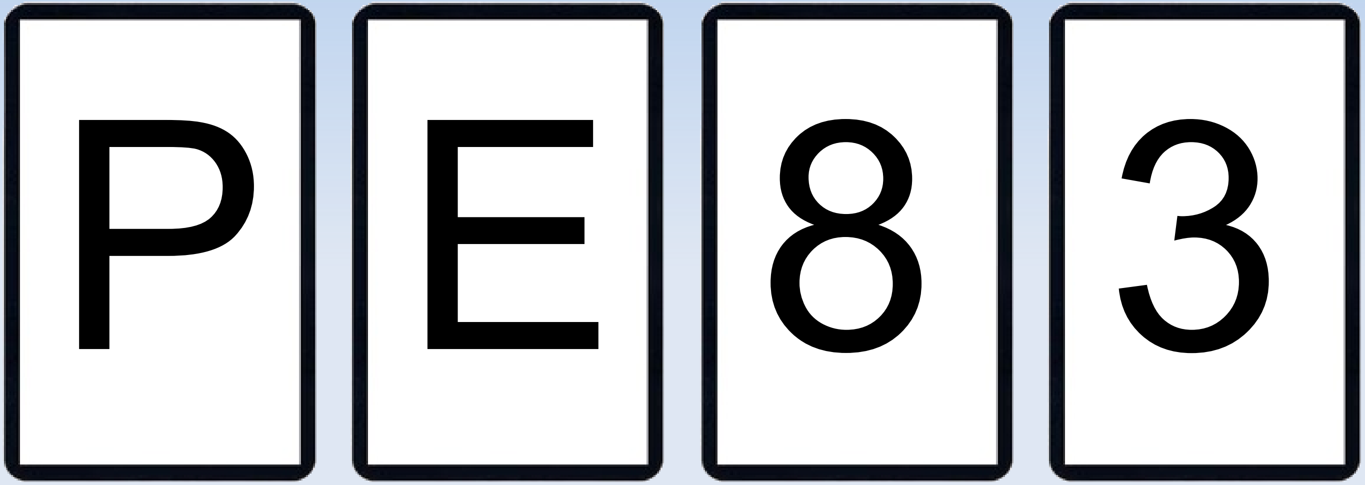


Time line of BSM discoveries



Wason selection task

You have a deck of cards with **letters** on one side and **numbers** on the other side.



Which cards do you have to turn to test the following hypothesis:

vowel *on one side* → ***even*** *number on the other side*

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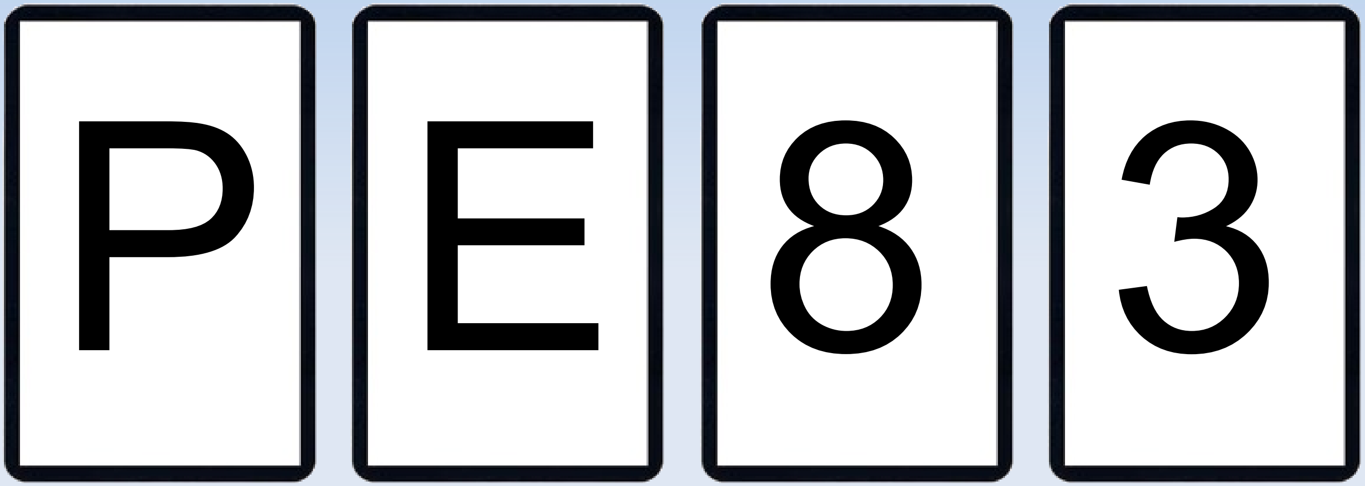


Which cards do you have to turn to test the following hypothesis:

> ***vowel*** *on one side →* ***even*** *number on the other side*

Only 10% of test subjects found the right solution.

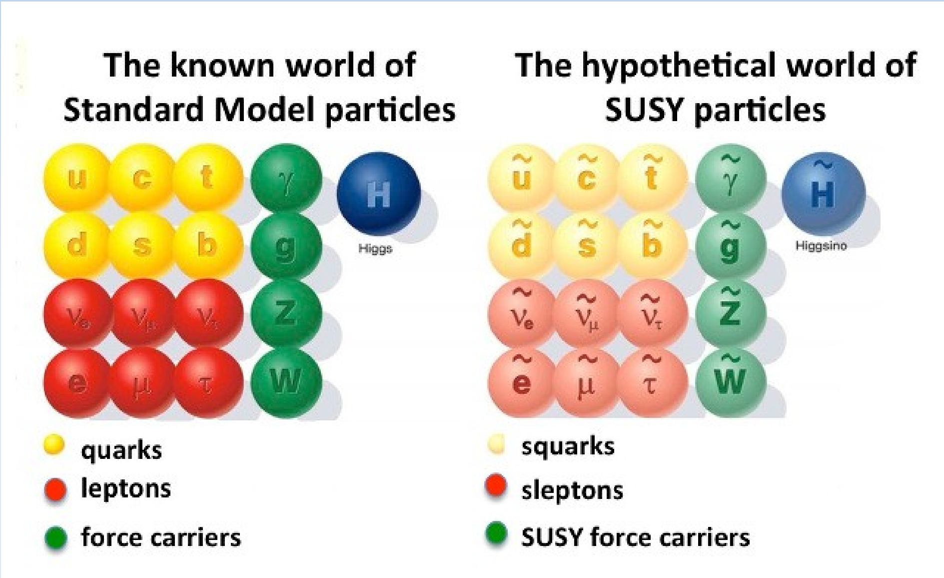
The human mind is design to see patterns. Often it sees a symmetry where there is none.

SUSY vs non-SUSY

In SUSY models, EWBG is strongly constrained

o the Higgs sector is strongly constrained
→ strong PT hard to achieve (light stops)

o 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

~~eq~~ Strong first-order electroweak phase transition

$$V(s,h)$$

~~CP~~ CP violation from dimension-five operators

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

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

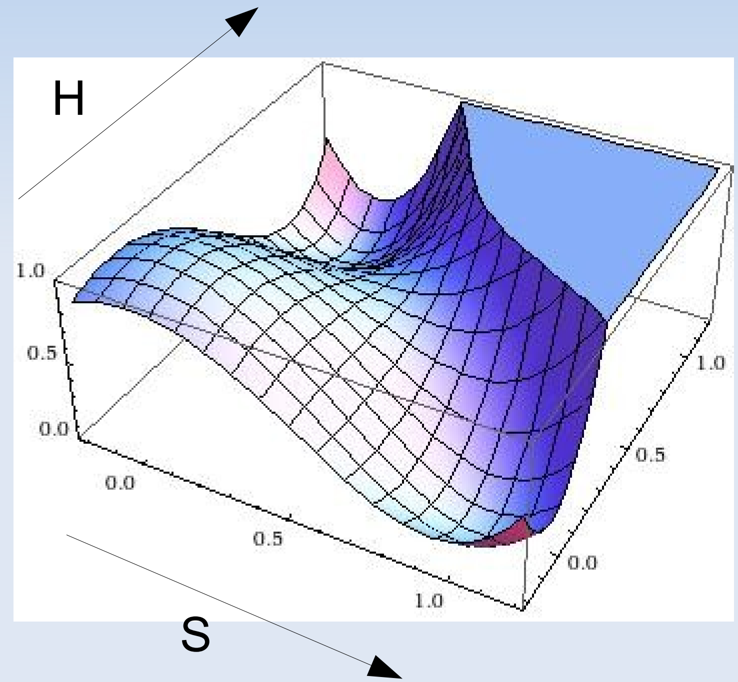
Both ingredients natural in composite Higgs models.

[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

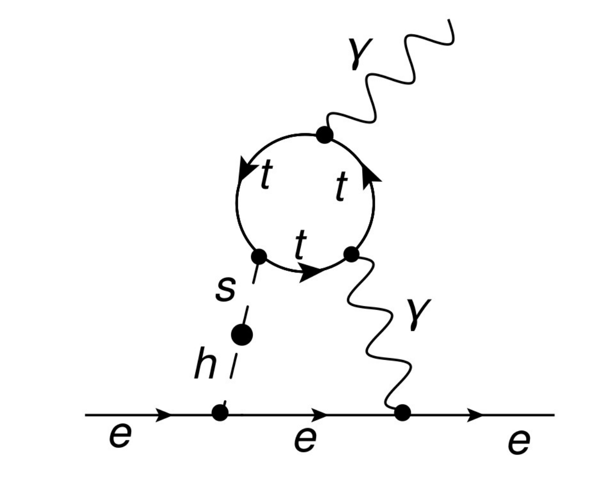
$$\mathcal{L} \ni y_t \bar{\psi}_t H \psi_t + \frac{\tilde{y}_t}{f} S \bar{\psi}_t H \psi_t$$

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

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

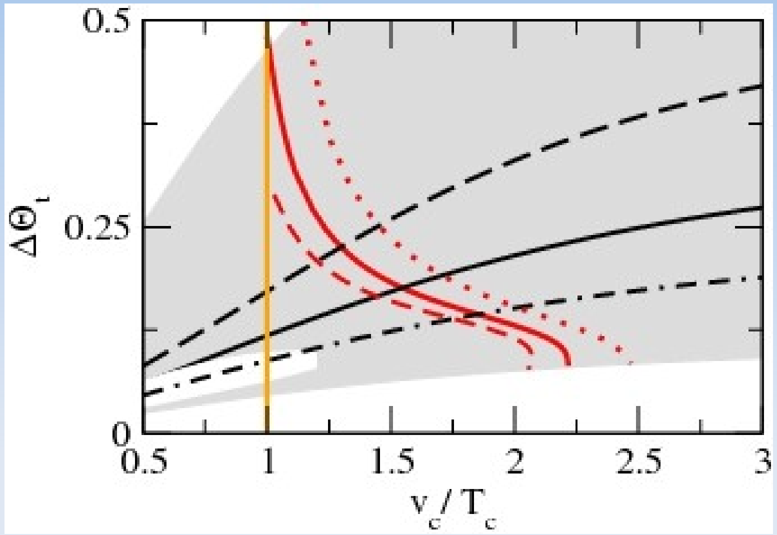
So, the complex phase during the phase transition behaves as

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



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

Baryogenesis



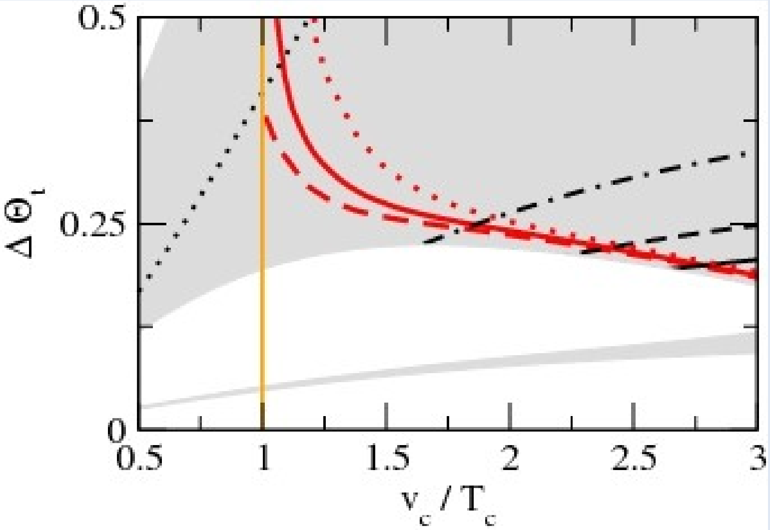
$$m_s = 130\,\mathrm{GeV}$$

$$\Delta\theta_t \gtrsim 0.15$$

strength of CP violation

strength of the phase transition

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



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

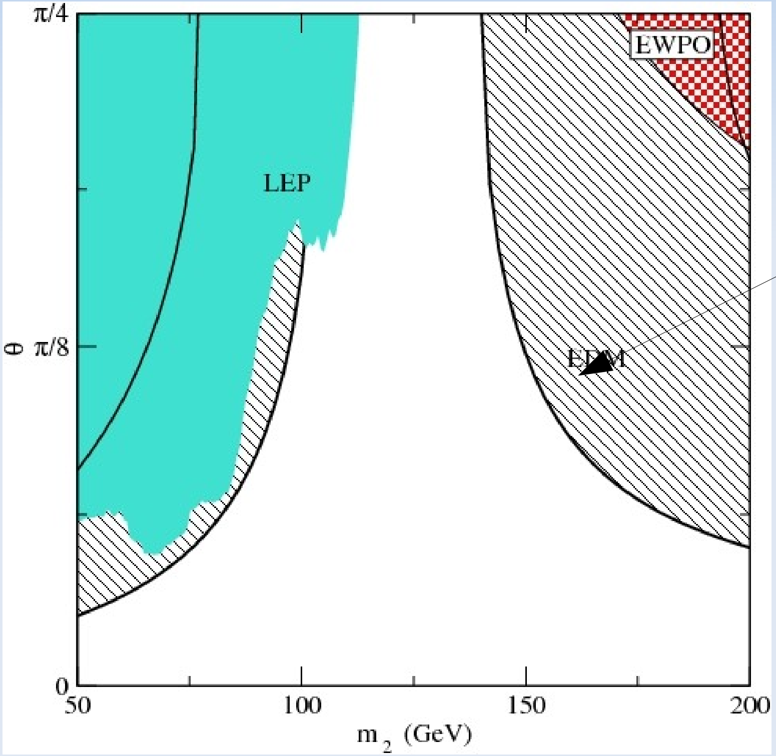
$$\Delta\theta_t \gtrsim 0.25$$

[Espinosa, Gripaios, TK, Riva '11]

Signals = nightmare

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

Higgs-singlet mixing ~ CP violation



old bounds!!

singlet mass

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

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

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.

- flavor puzzle
- composite Higgs
- DM / dark sector
- GWs

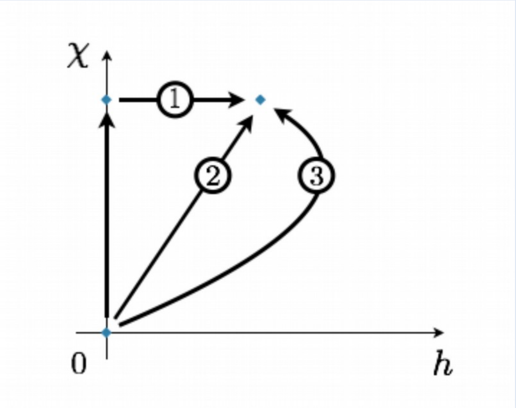
EWBG from varying Yukawas

Varying Yukawa couplings arise in different contexts.
Froggatt-Nielsen models are one possibility.
[Baldes, Bruggisser, TK, Servant ’16, ’18]
[Ellis, Ipek, White ’19]

In composite Higgs models, the Yukawa couplings are generated in the strong sector.
[Bruggisser, von Harling, Matsedonskyi, Servant ’18]

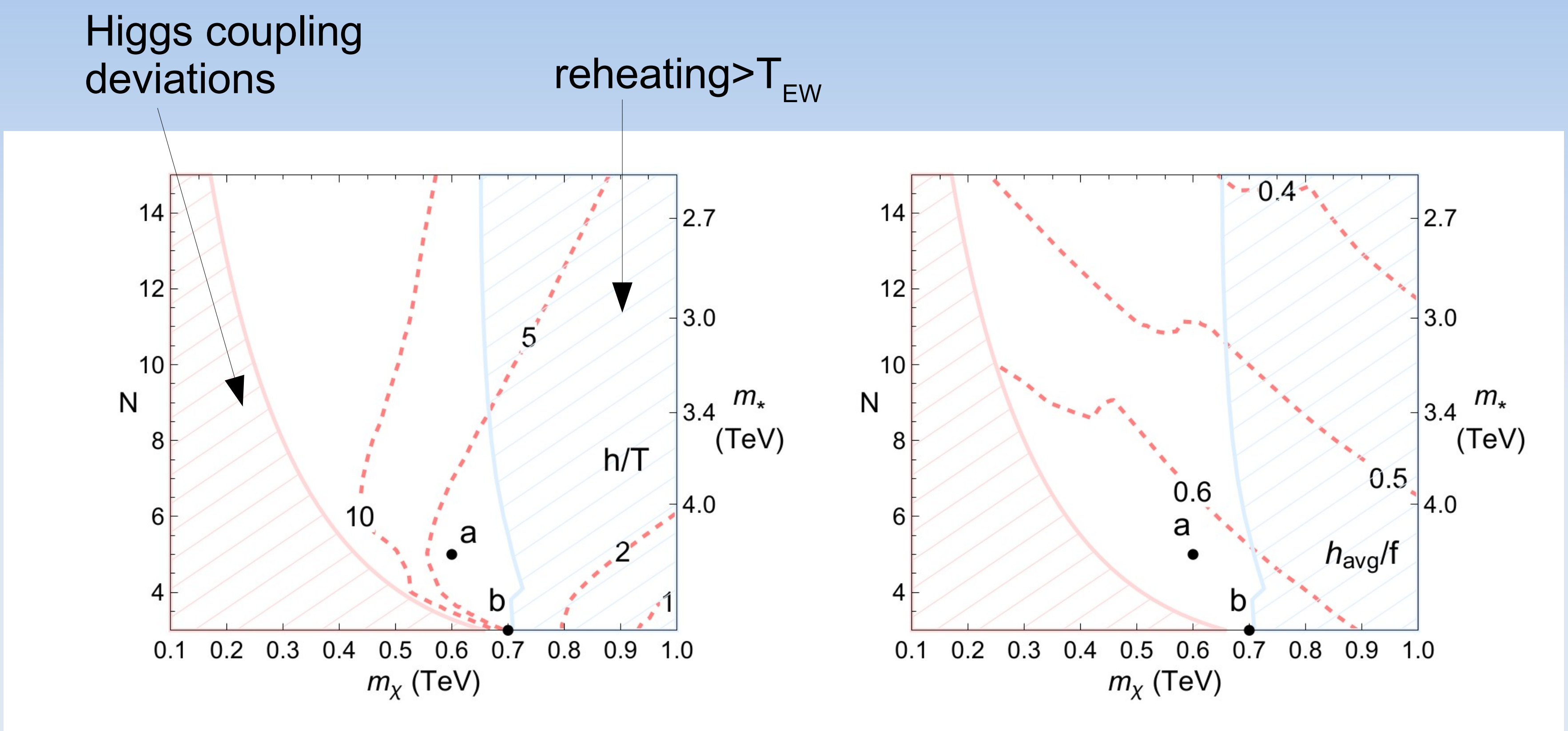
If the flavor puzzle is tied to electroweak symmetry

- o the electroweak phase transition can be stronger
- o new CP violating sources are induced by the varying Yukawa couplings



dilaton vs. Higgs

EWBG and composite Higgs



The phase transition and CPV is strong enough to make baryogenesis work.

[Bruggisser, von Harling, Matsedonskyi, Servant ’18]

EWBG in the dark sector

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

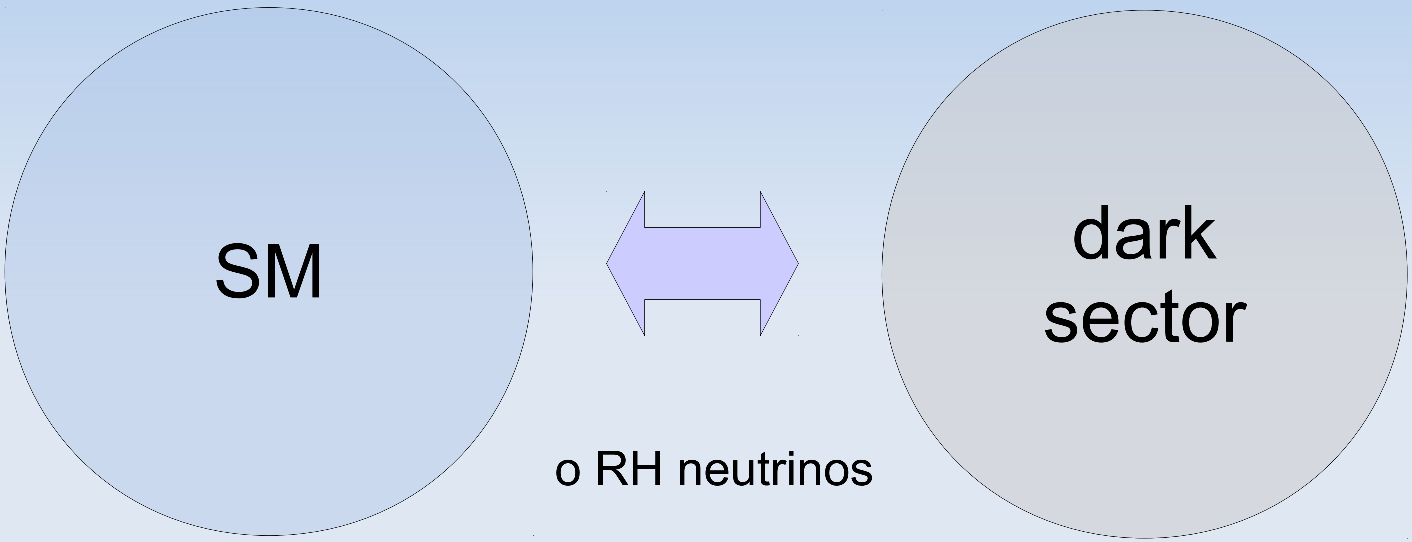
- o Higgs
- o kinetic mixing, Z'
- o higher dim Ops

EWBG in the dark sector
→ weak EDM constraints

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

EWBG in the dark sector II

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



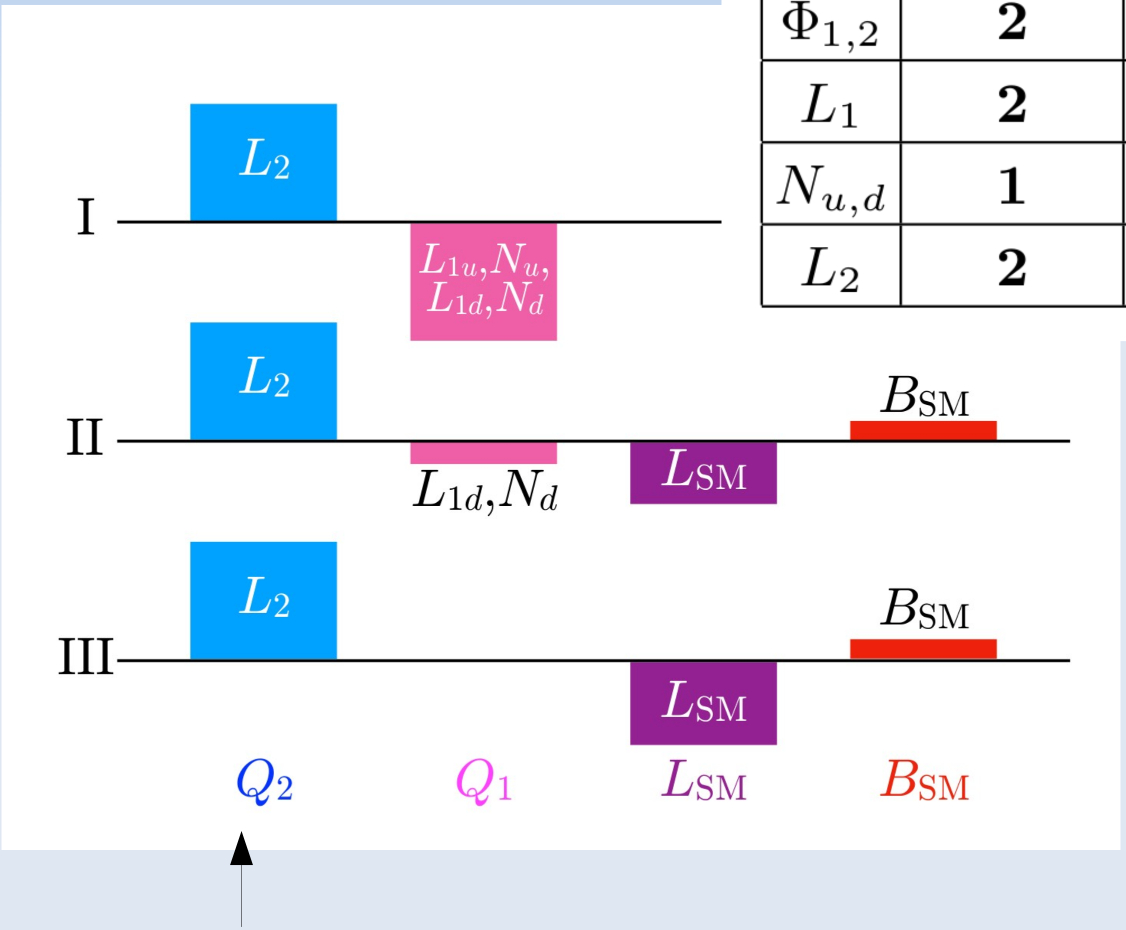
Nice features:
- minimal
- renormalizable

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

EWBG in the dark sector
$\rightarrow$ weak EDM constraints

Baryogenesis

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

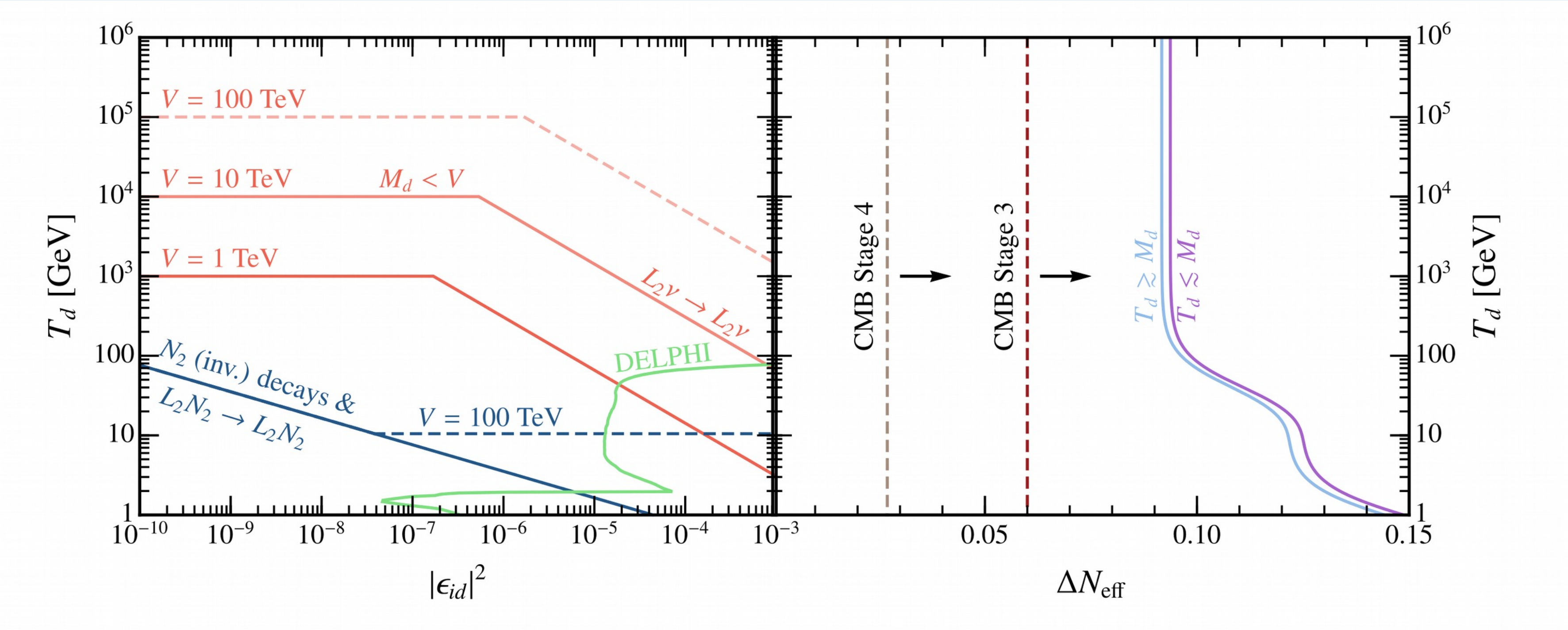


massless
symmetric component
→ excess radiation

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



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?

Falsifiability?

Electroweak phase transition

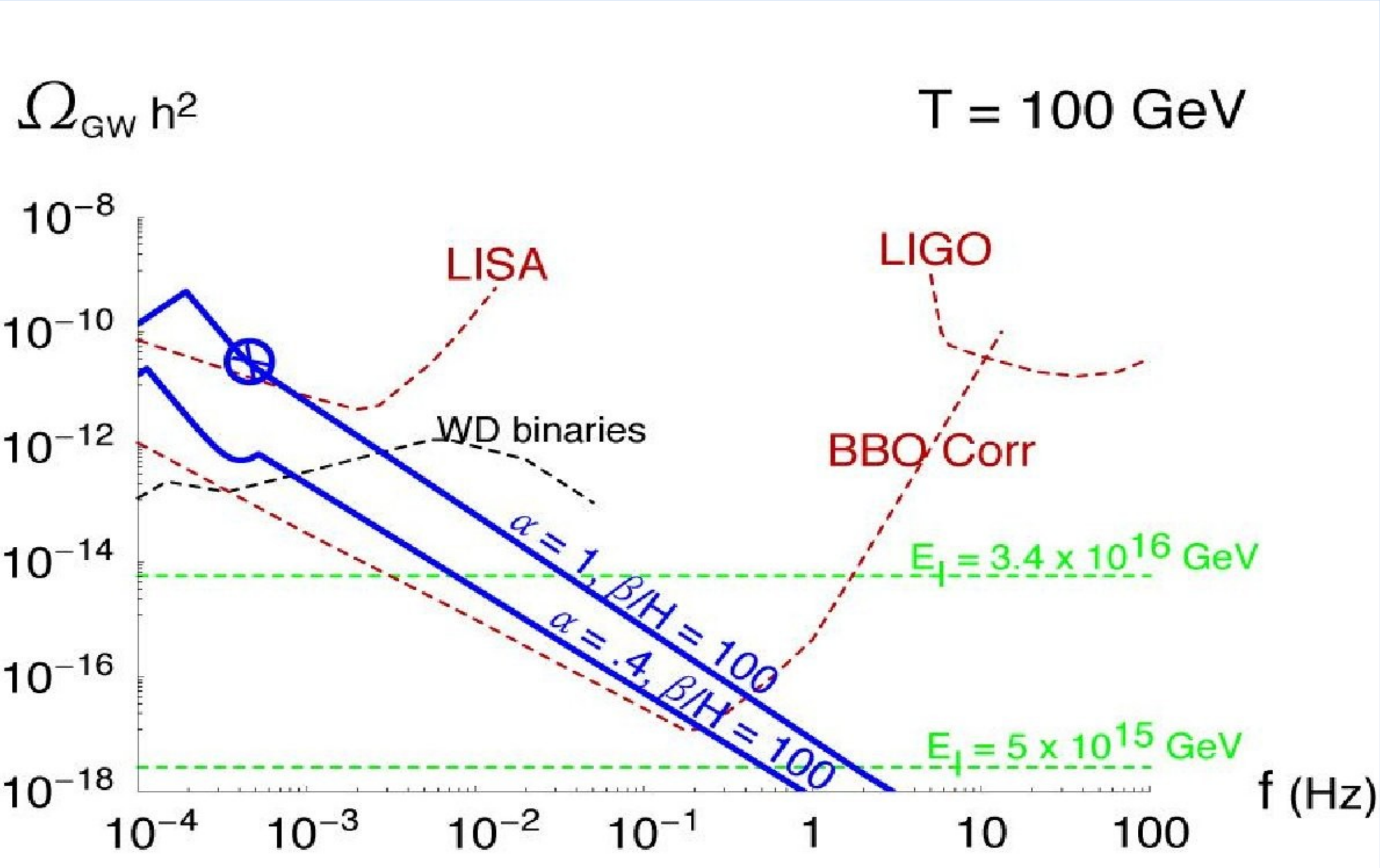
gravitational waves

baryogenesis

Cosmological phase transition

Gravitational waves from the phase transition

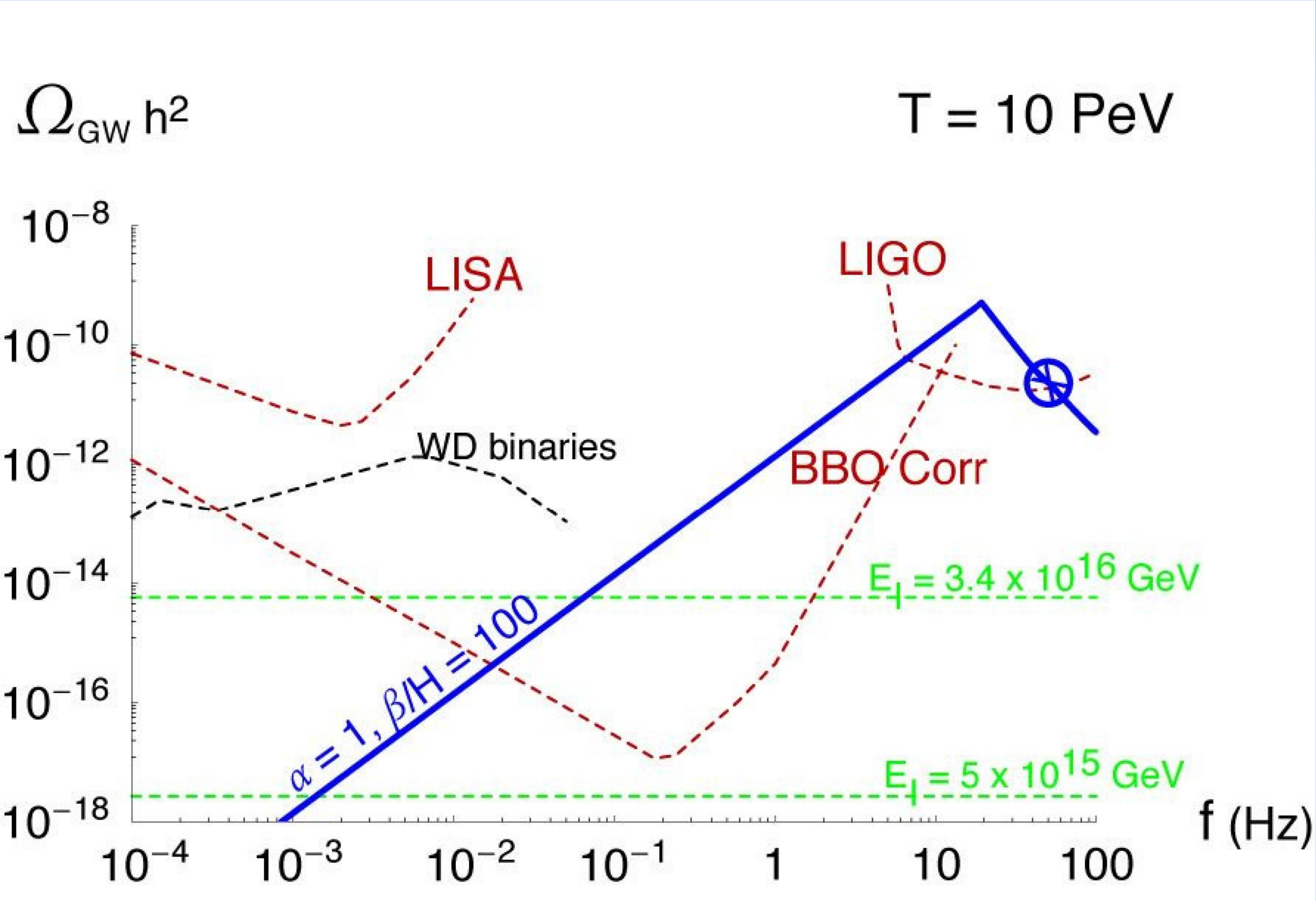
$$\alpha = \rho_{vac}/\rho_{rad}, \quad \beta \sim \tau^{-1}, \quad v_b, \quad T$$



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

Gravitational waves from the phase transition

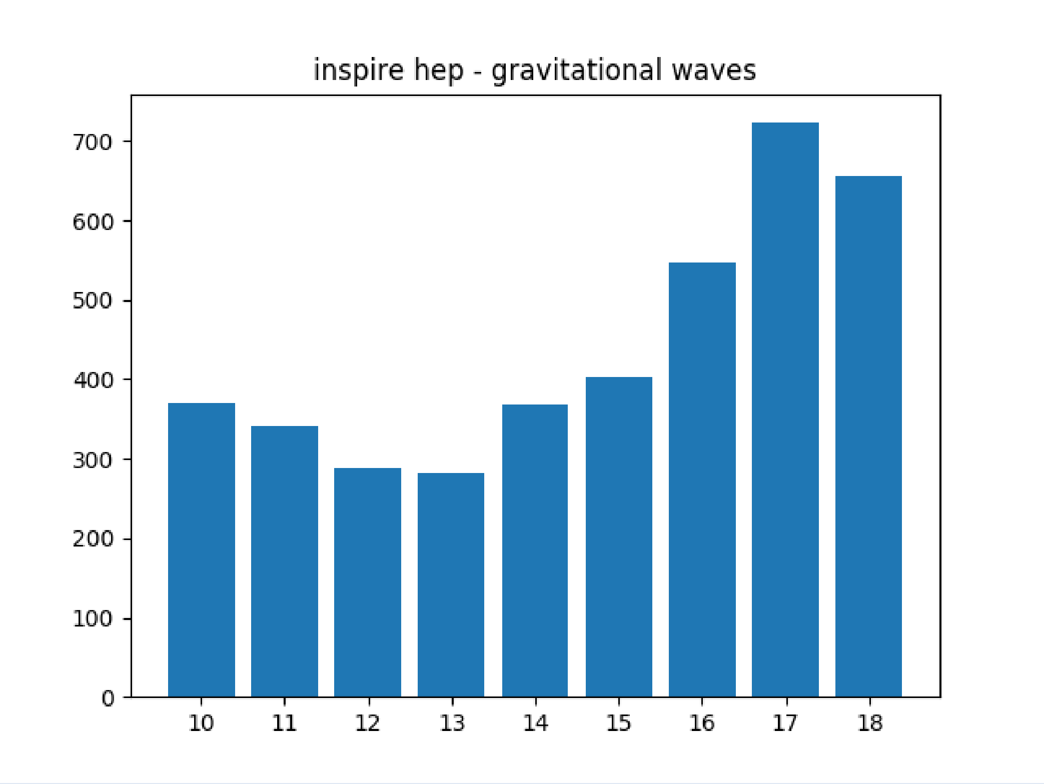
[Grojean, Servant '06] $\alpha = \rho_{vac}/\rho_{rad}, \quad \beta \sim \tau^{-1}, \quad v_b, \quad T$

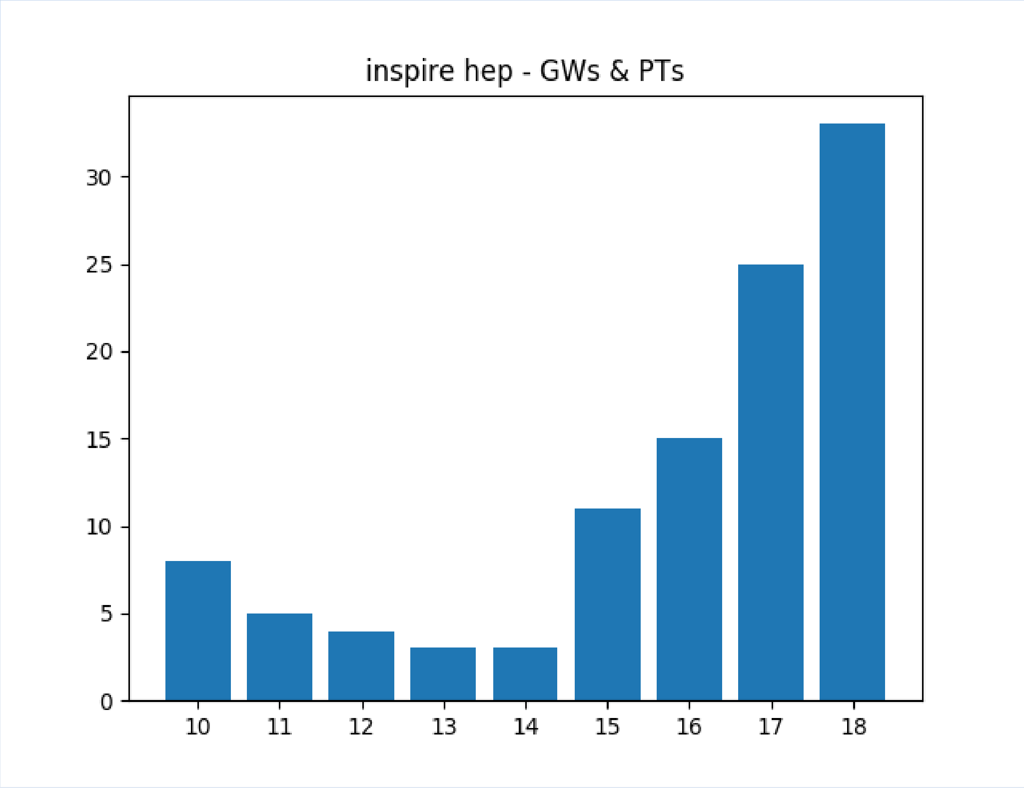


In principle, GW observations can test cosmological phase transitions up to very high scales ~10^6 GeV. E.g. before EM decoupling and beyond LHC.

GWs from PTs

ArXiv activity:





GWs from PTs

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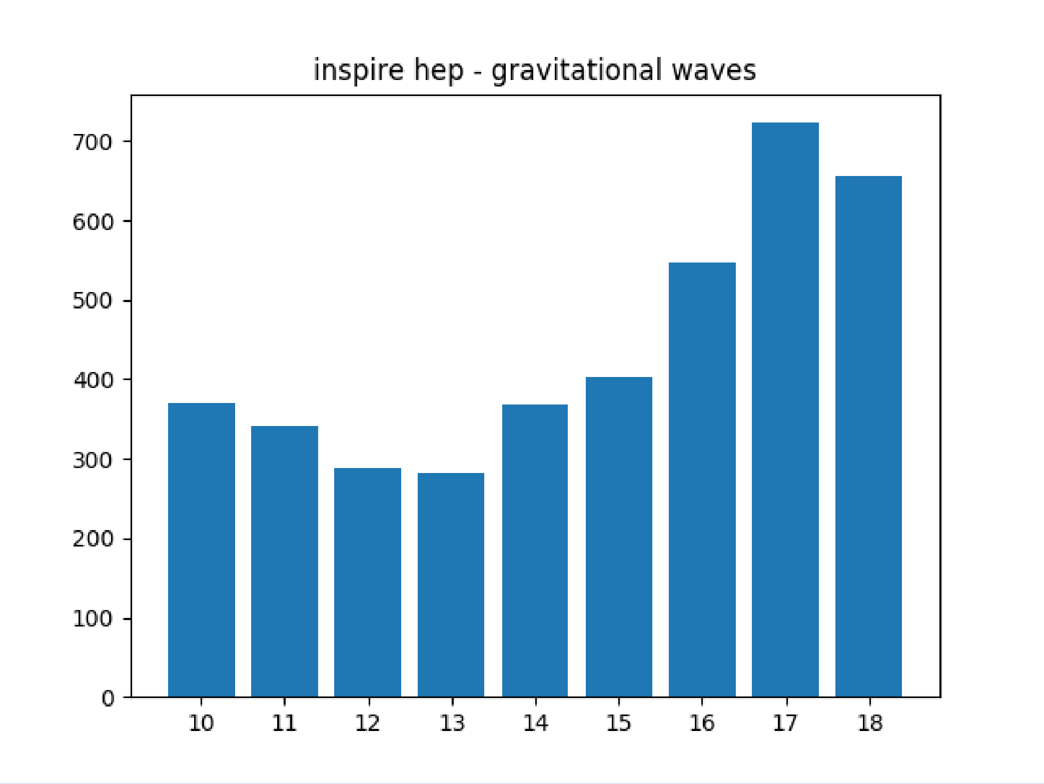
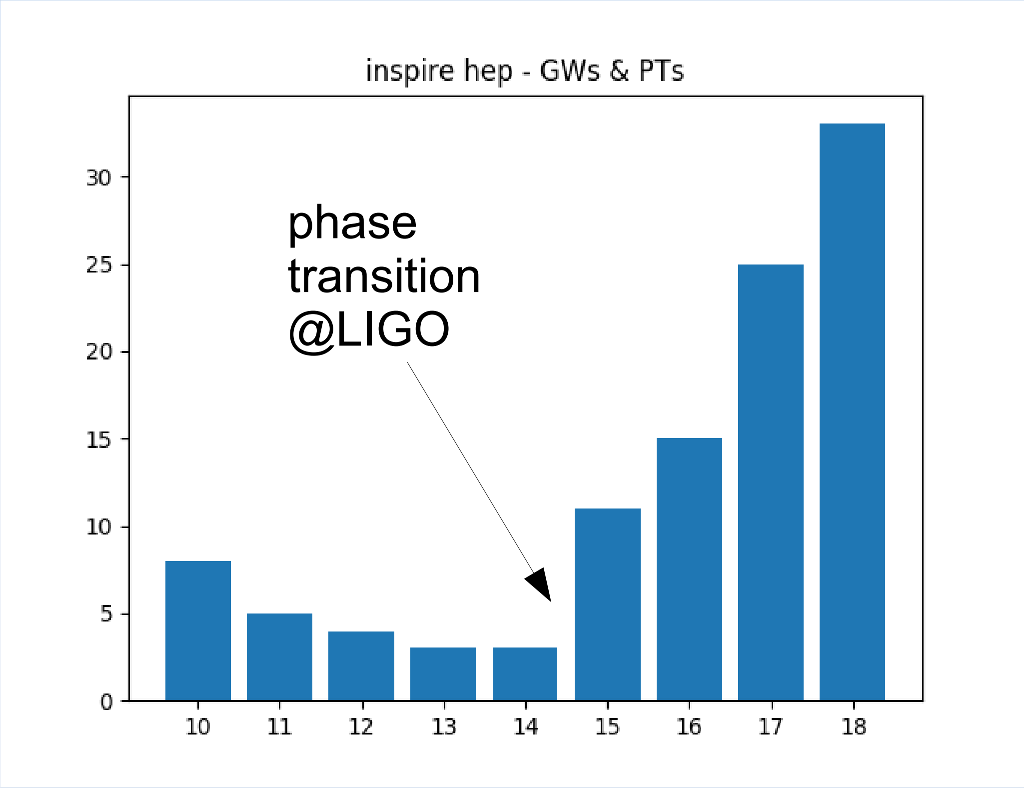
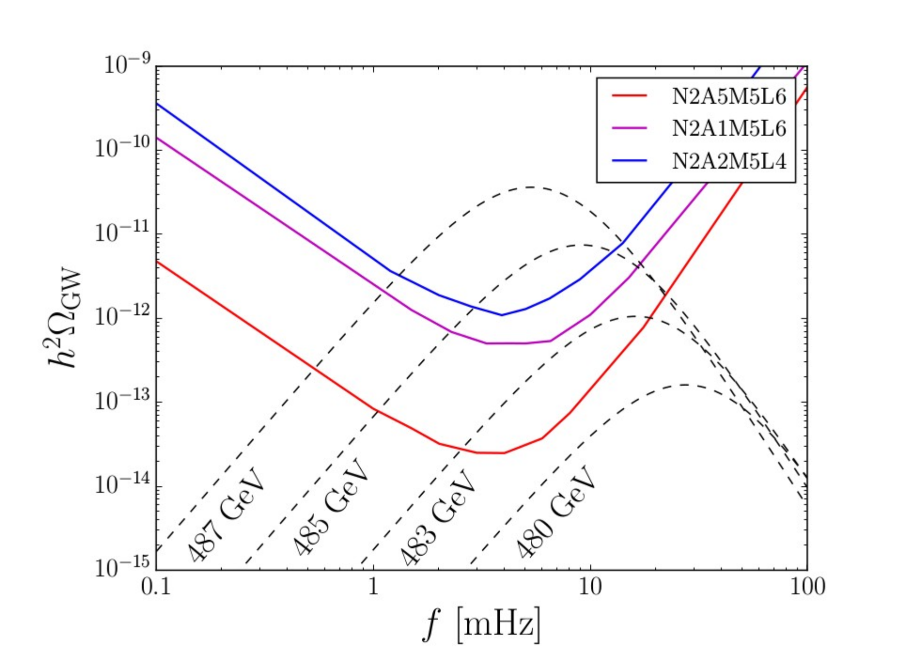




Update on sensitivity to stochastic GW background



m_{A^0} [GeV]	T_n	v_n/T_n	$L_w T_n$	$\Delta\Theta_t$	α_n	β/H_*	v_w
450	83.665	2.408	3.169	0.0126	0.024	3273.41	0.15
460	76.510	2.770	2.632	0.0083	0.035	2282.42	0.20
480	57.756	3.983	1.714	0.0037	0.104	755.62	0.30
483	53.549	4.349	1.556	0.0031	0.140	557.77	0.35
485	50.297	4.668	1.441	—	0.179	434.80	0.45
487	46.270	5.120	1.309	—	0.250	306.31	$\approx c_s$

[Dorsch, Huber, TK, No. '16]

[A. Petiteau, unpublished]

A dedicated analysis of the LISA analysis team for stochastic sources increases the sensitivity. **Long lasting, broad** spectra are easier to observe than localized, short-lived sources. LISA **pathfinder** measured the noise.

Sources of GWs from PTs

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

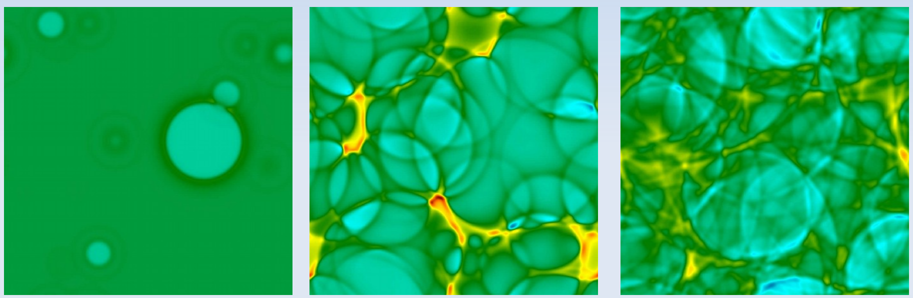
- Collisions of the scalar field configurations / initial fluid shells
- Sound waves after the phase transition (long-lasting)
- Turbulence
- Magnetic fields

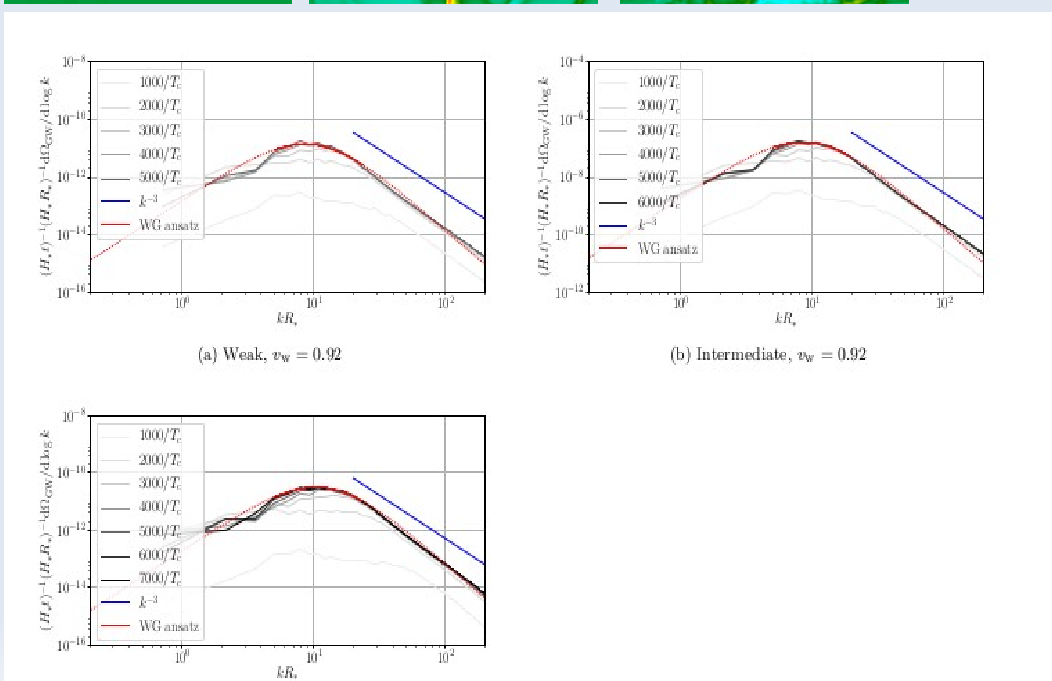
Which source dominates depends on the characteristics of the PT

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)





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

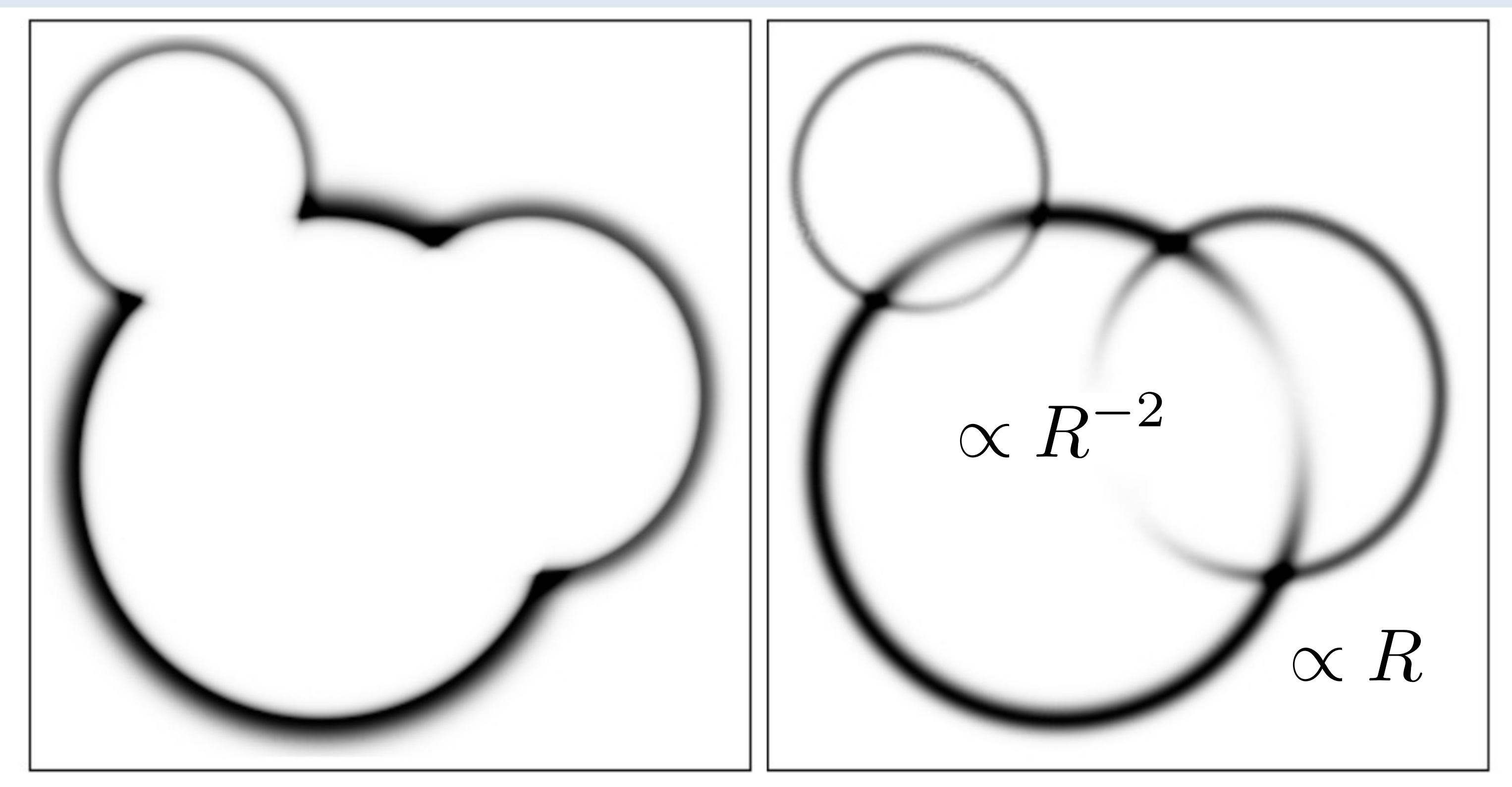
They predict reliably the produced spectrum of GWs for not too strong PTs with not too fast bubble wall velocities

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

Collisions

Gravitational waves from bubble dynamics: Beyond the Envelope

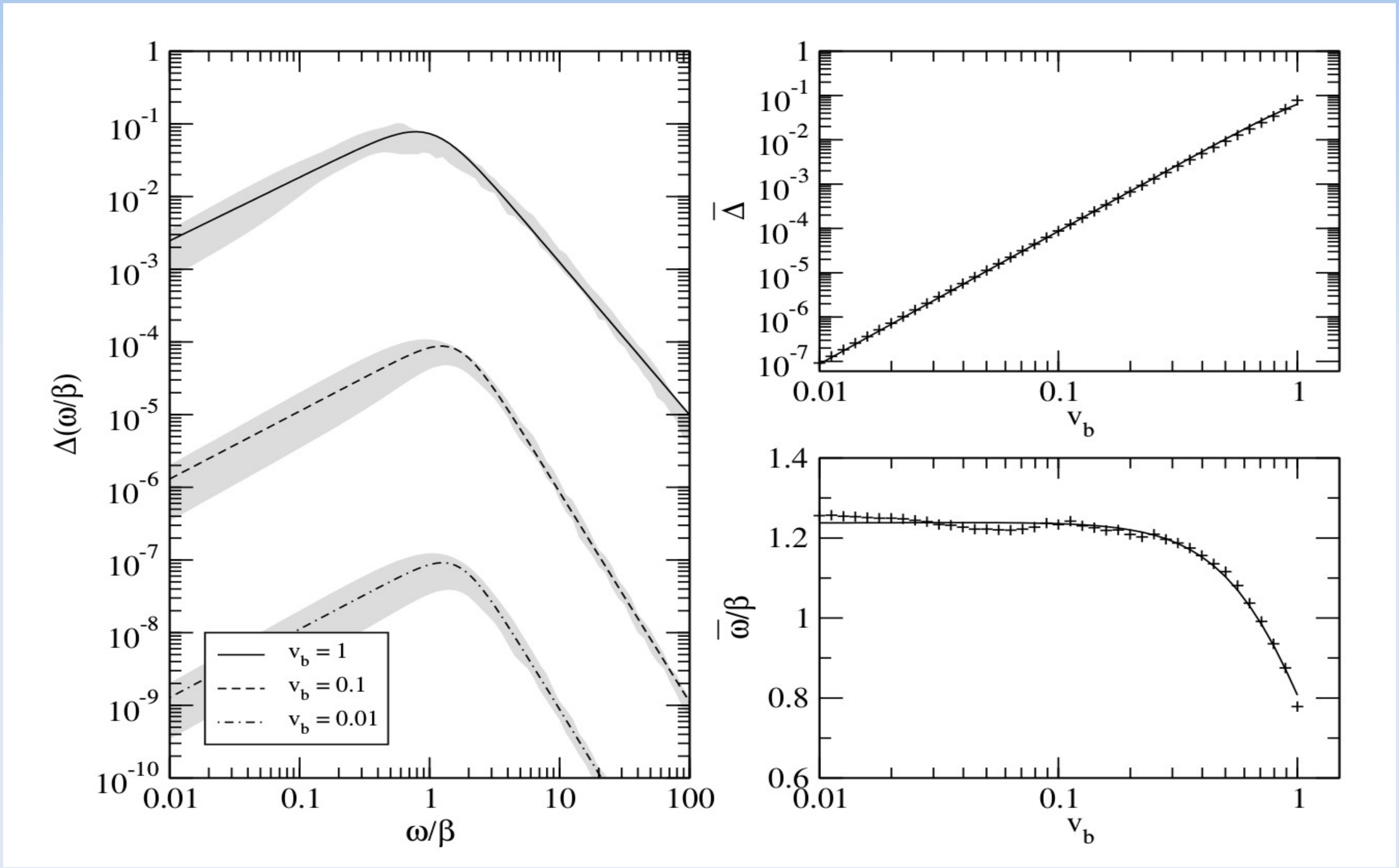
Ryusuke Jinno[a,b] and Masahiro Takimoto[b,c] 2017



envelope: vacuum/extreme supercooling

Jinno/Takimoto: relativistic bubble wall velocities

Numerical results



Simplistic models allow for very accurate predictions in limiting cases and easy parametric dependence

[Konstandin '17]

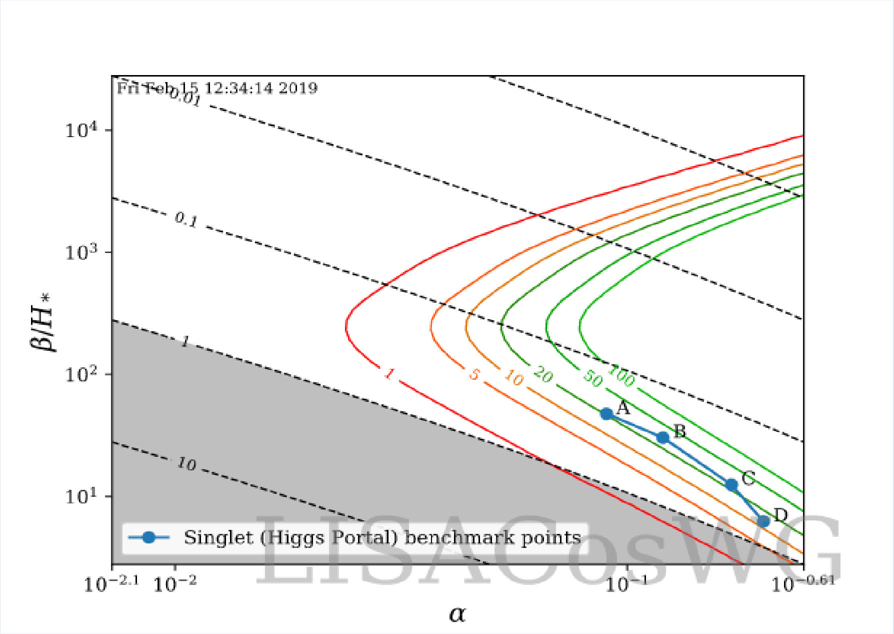
Putting it all together

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

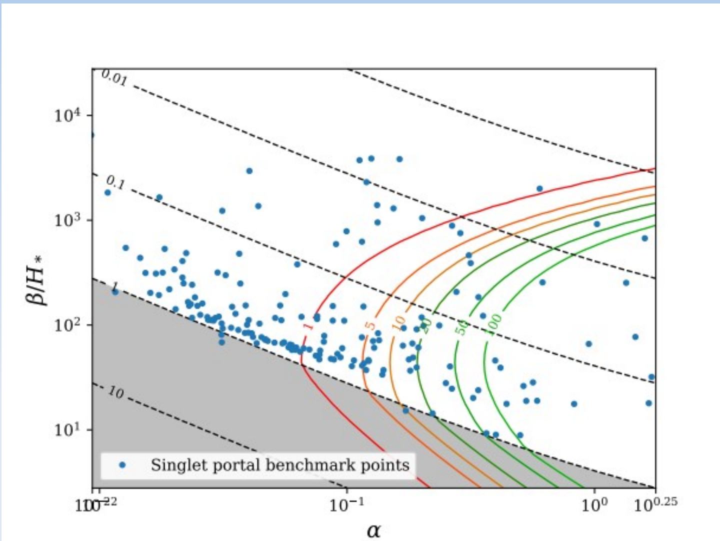
Detecting ravitational waves from cosmological phase transitions with LISA: an update
Caprini et al.
arxiv/1910.13125

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

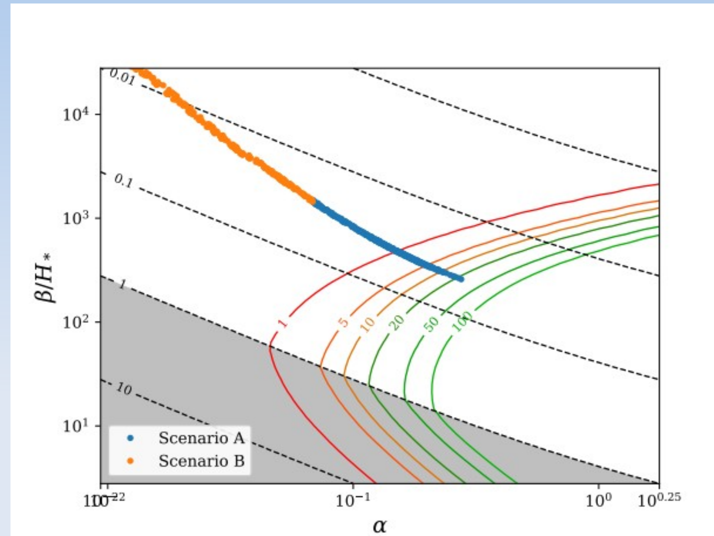


Models

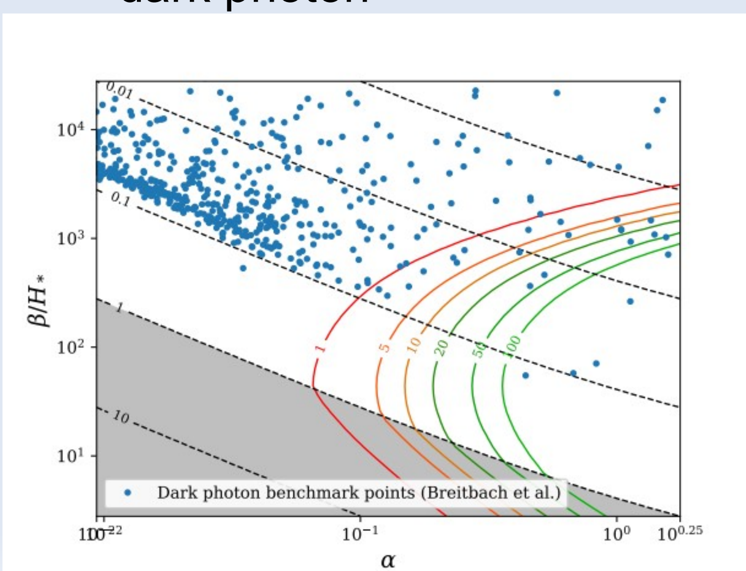
singlet portal model



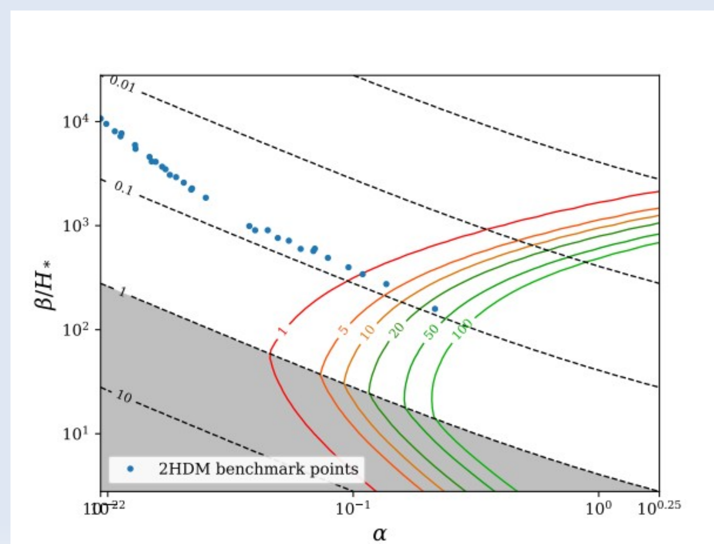
SM EFT



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.