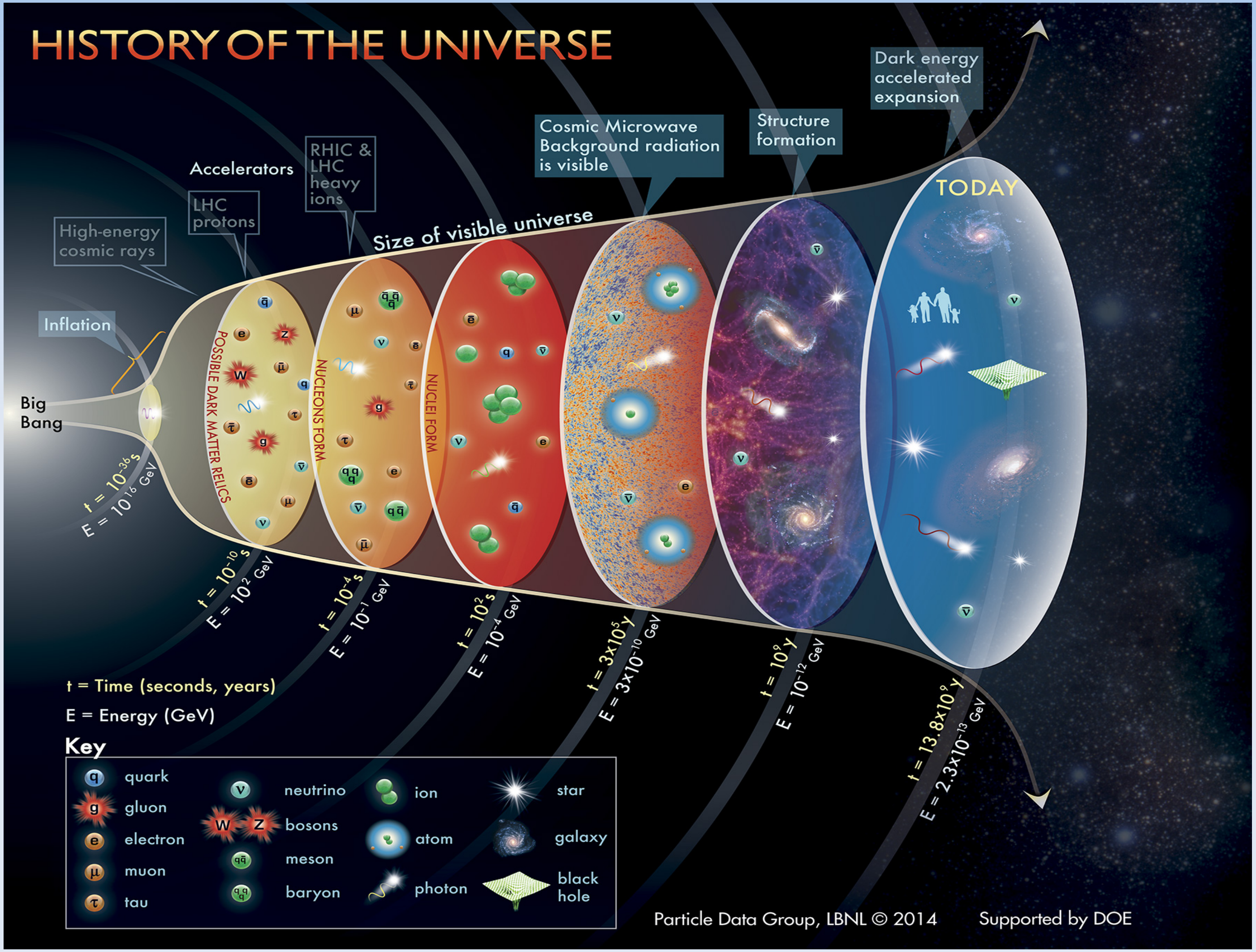
Cosmological probes of electroweak symmetry breaking

Thomas Konstandin

DESY, March 3./4., 2015

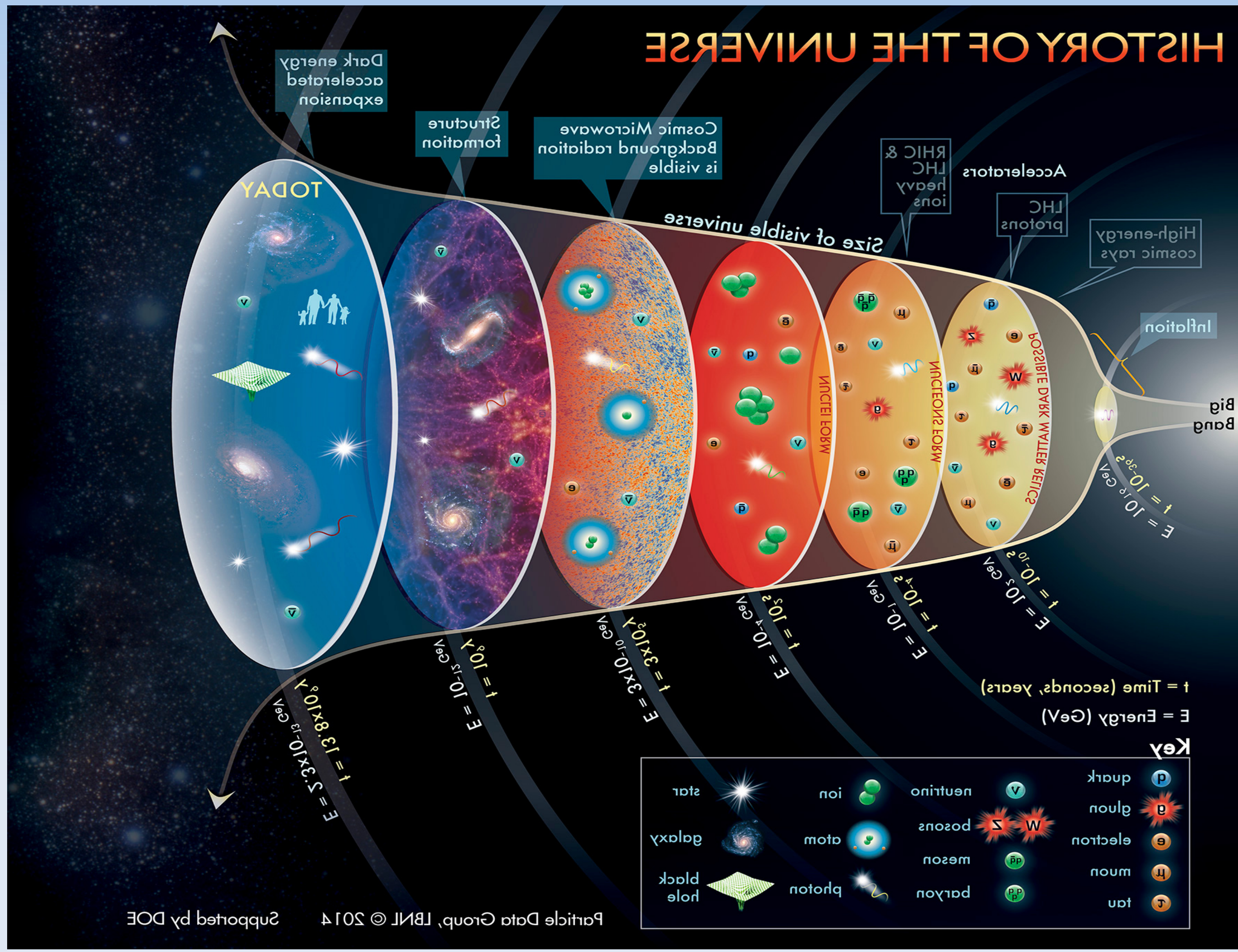
Standard Cosmology



time

temperature

Standard Cosmology



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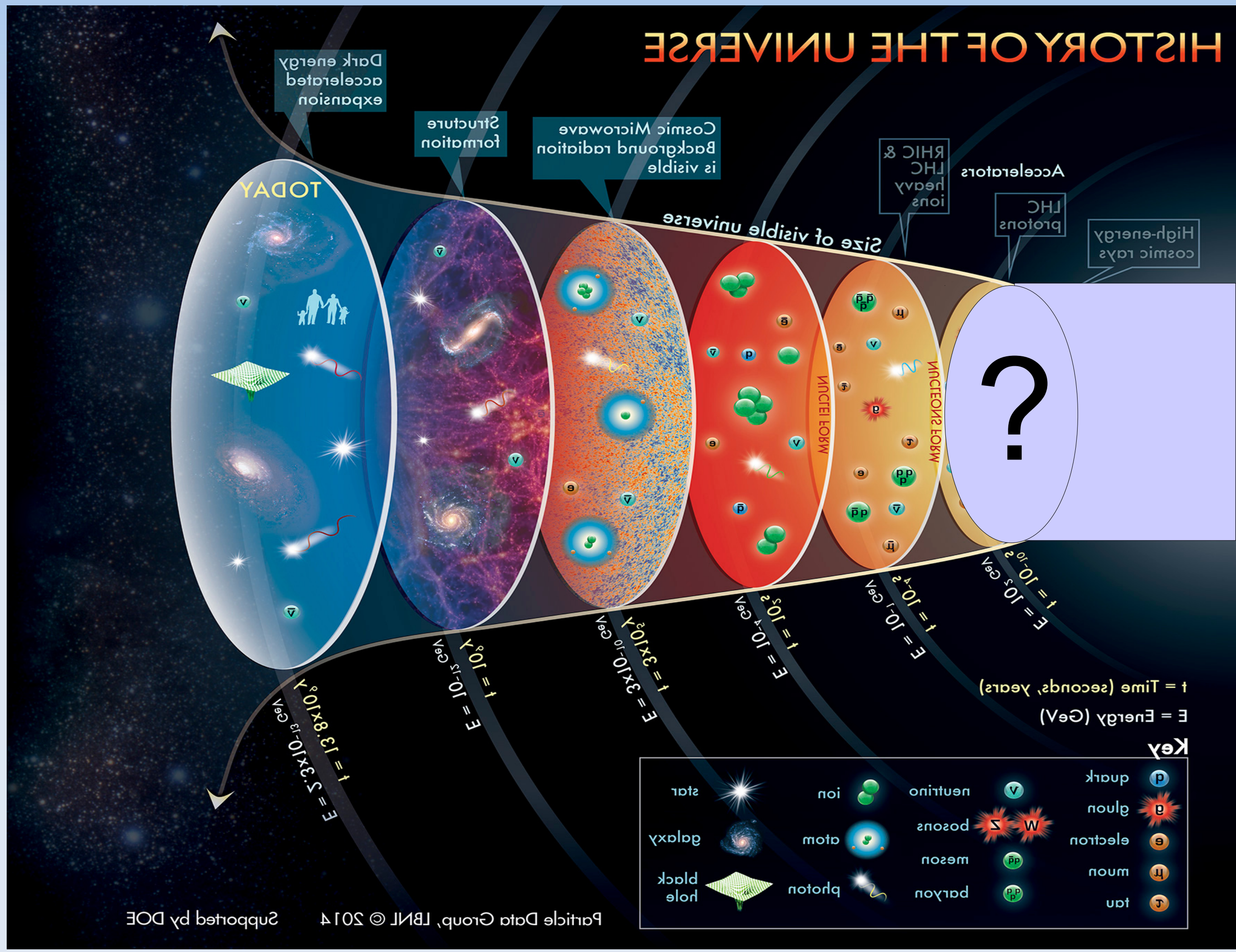

time

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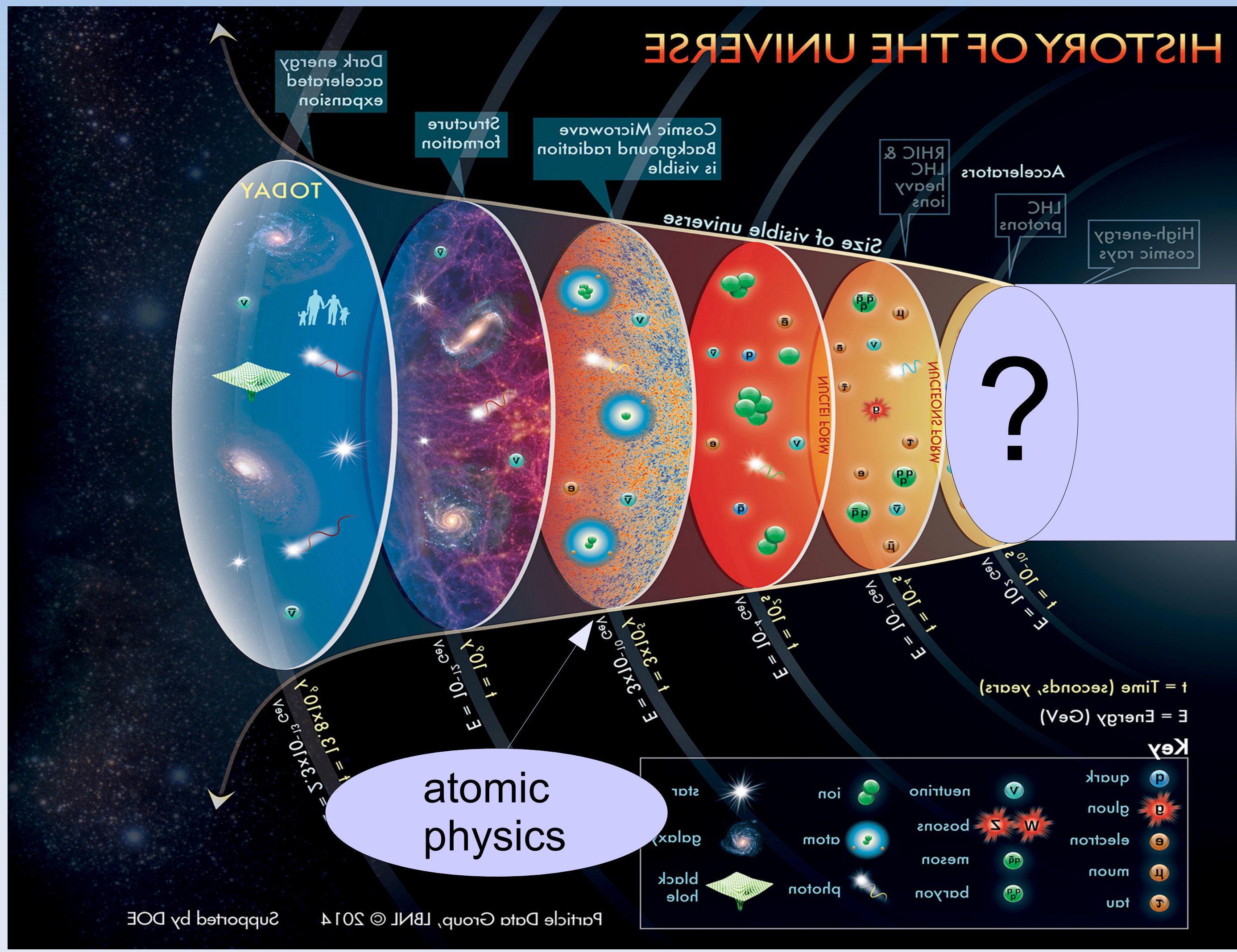
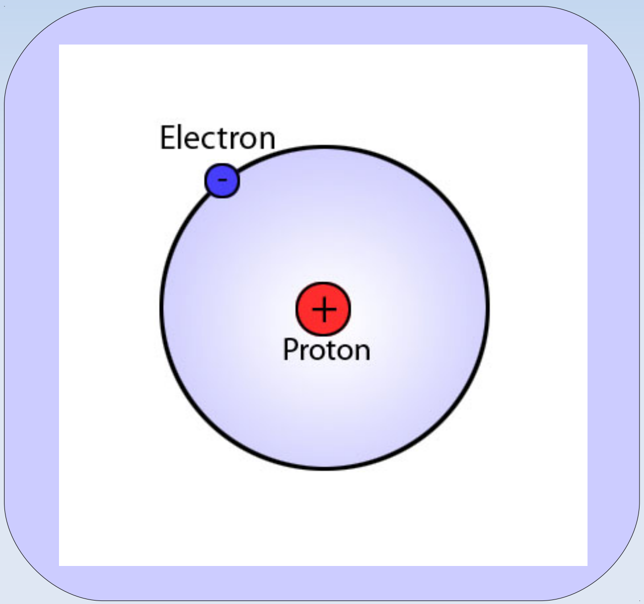
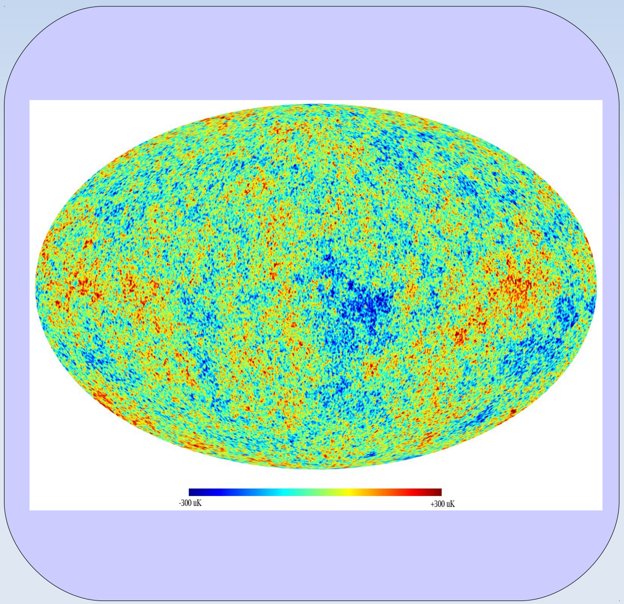


time ←

→ temperature

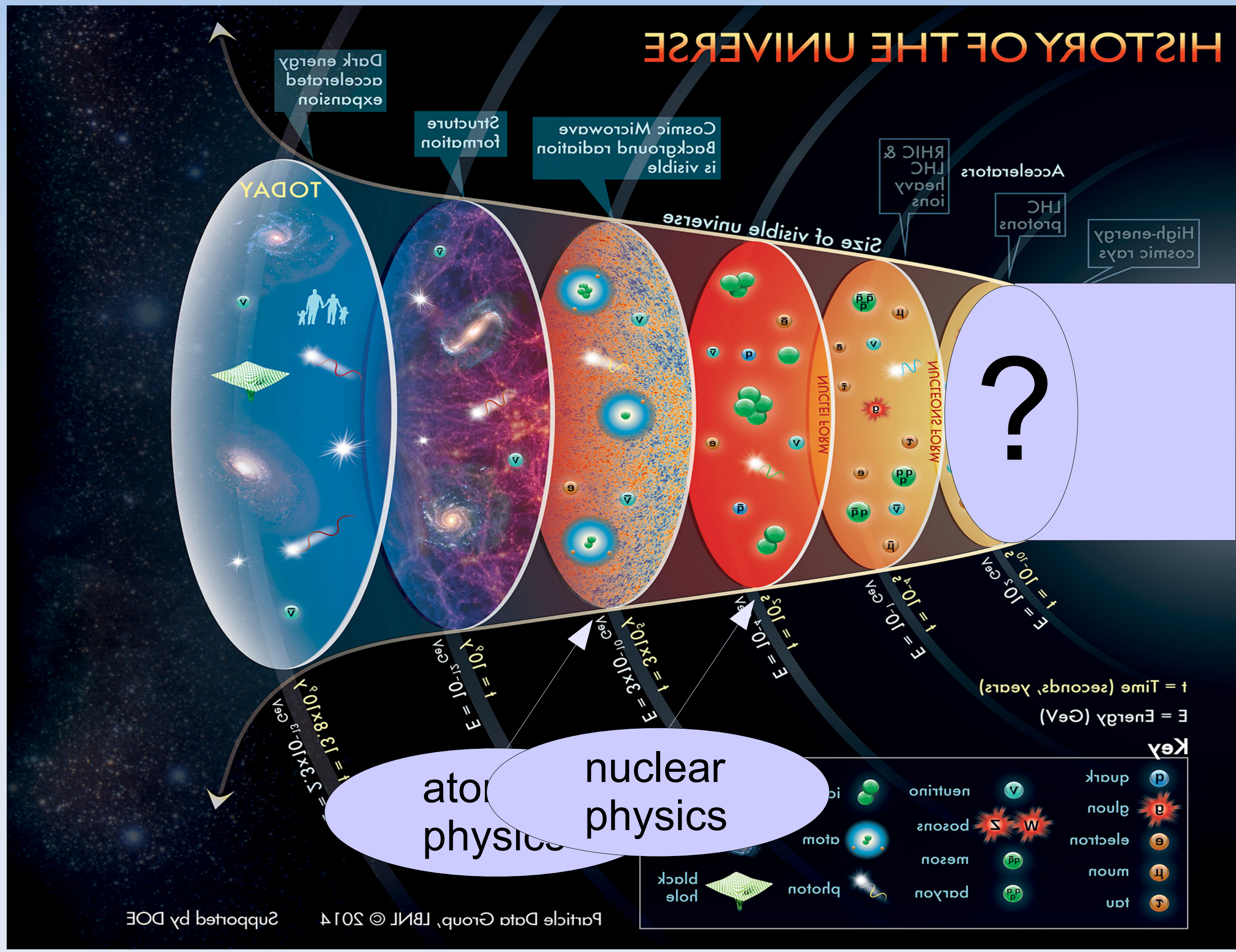
Atomic physics at T~eV





The Cosmic Microwave Background **links** atomic physics to cosmology at temperature T~eV

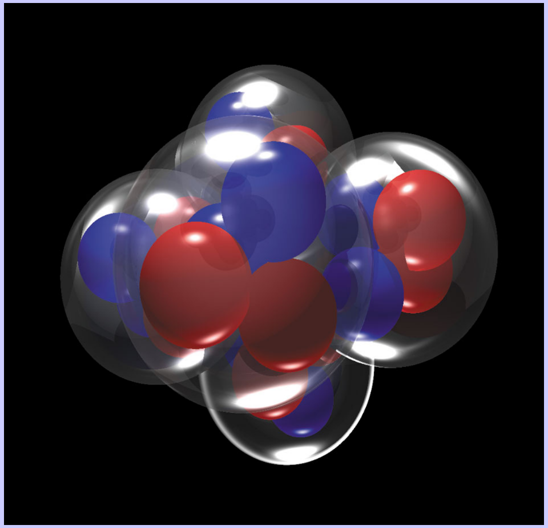
Standard Cosmology

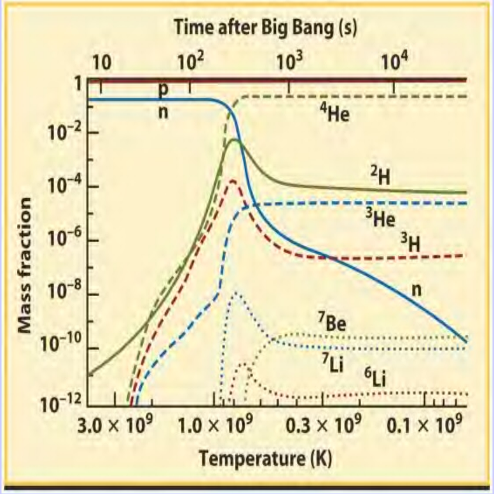


time

temperature

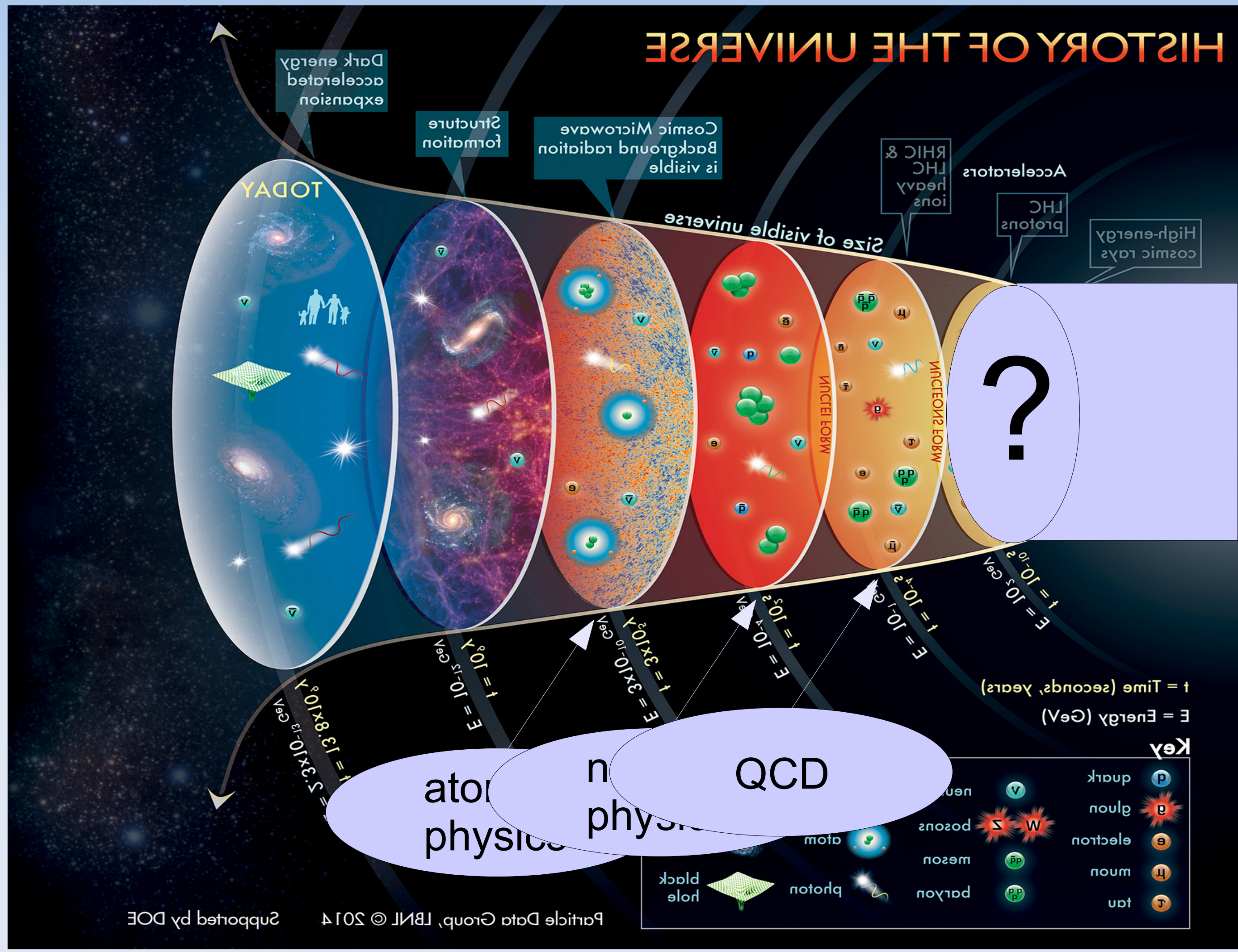
Nuclear physics at T~MeV





Big bang nucleosynthesis **links** nuclear physics to cosmology at temperature T~MeV

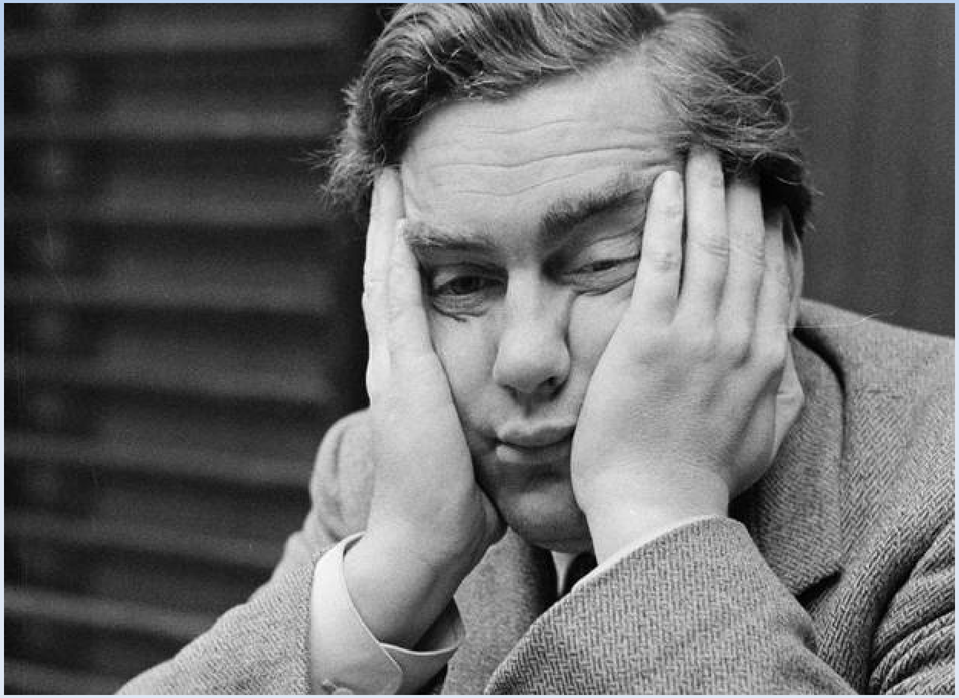
Standard Cosmology



time

temperature

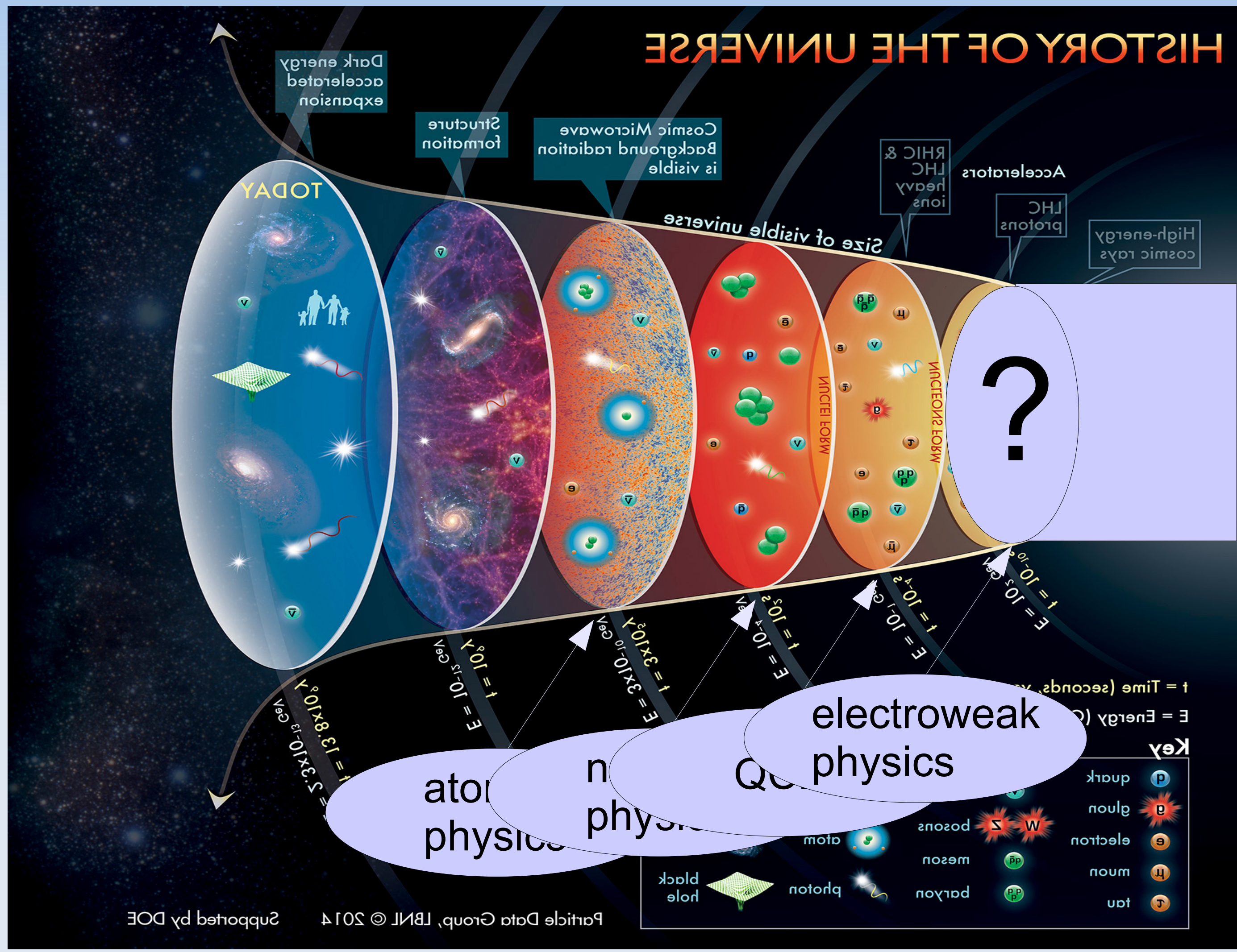
QCD at T~100 MeV



At temperatures of QCD scale T~100 MeV, **protons and neutrons** form from **quarks**.

But the Universe stays close to **equilibrium** and **no relics** remain from this epoch that could be observed today.

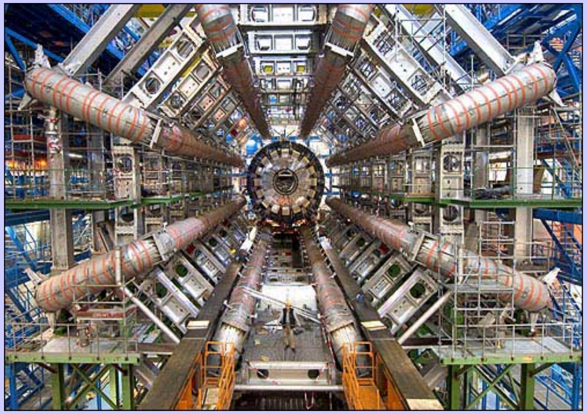
Standard Cosmology

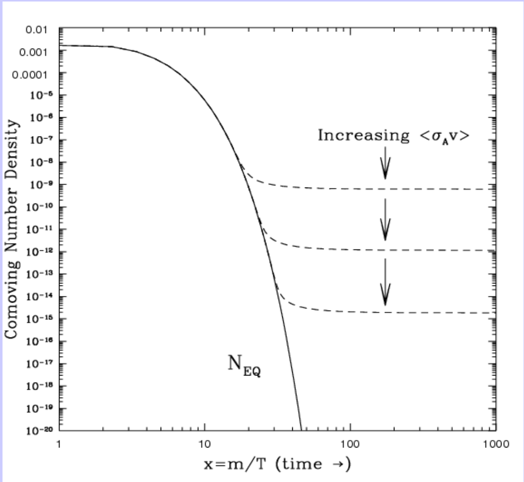


time

temperature

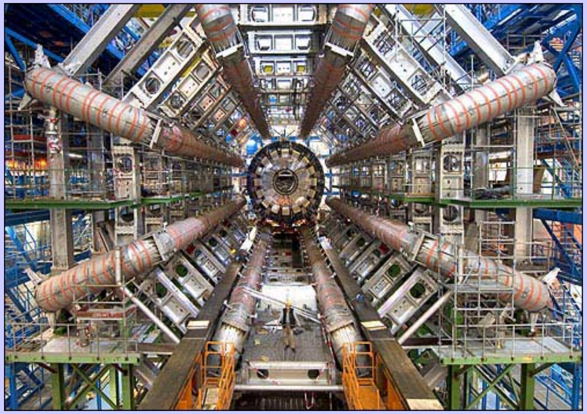
DM freeze-out at T~100 GeV?

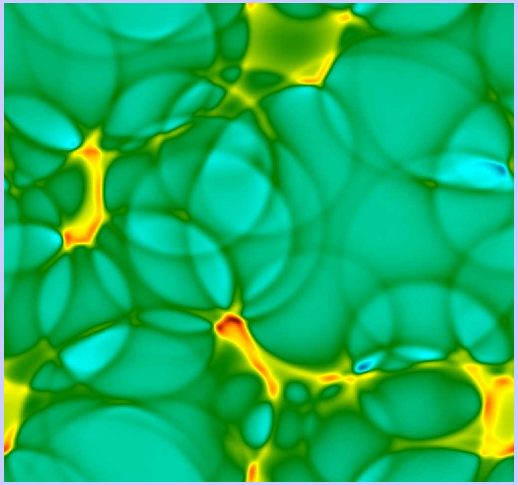




Possibly, a WIMP dark matter candidate froze out at electroweak temperatures T~100 GeV

Phase transition at T~100 GeV?





Possibly, the electroweak phase transition drove the Universe **out-of-equilibrium.**

Outline

Phase transition

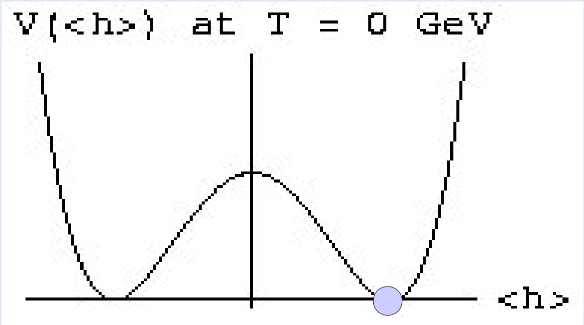
Gravitational waves

Electroweak baryogenesis

Electroweak symmetry breaking

The **Mexican hat** potential is designed to lead to a finite Higgs vacuum expectation value (VEV) and break the electroweak symmetry

$$V(h) = \frac{\lambda}{4}\left(h^2 - v^2\right)^2$$

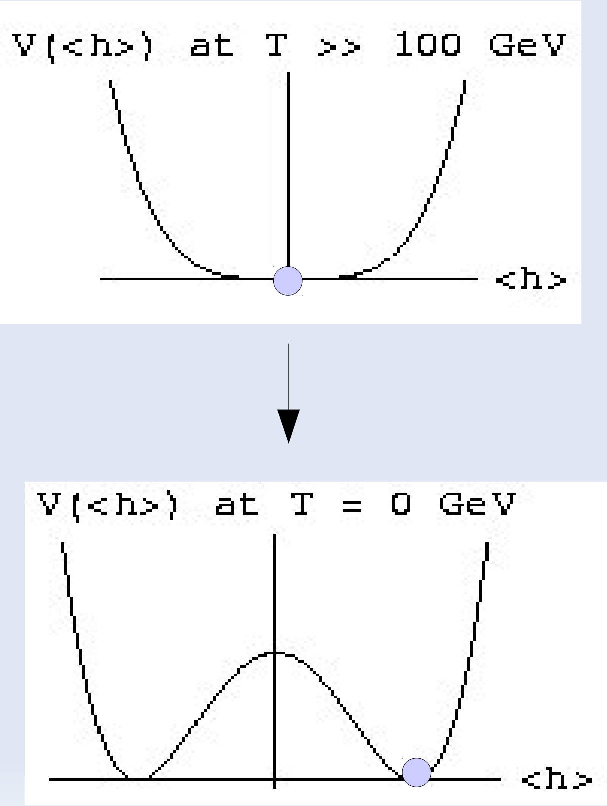


Electroweak symmetry breaking

[Weinberg '74]

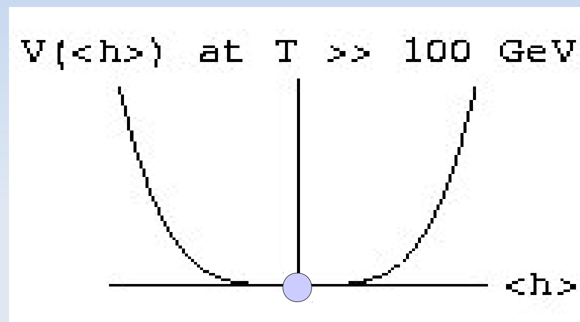
At large temperatures the symmetry is restored

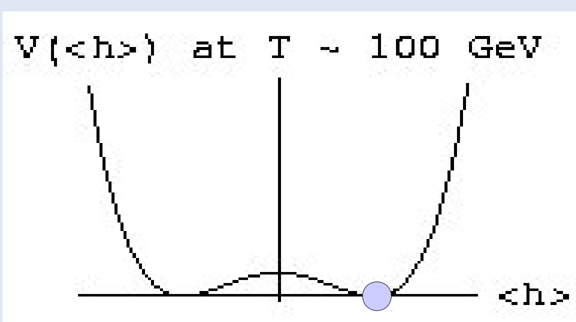
$$V(h,T) = \frac{\lambda}{4}\left(h^2 - v^2\right)^2 + \mathrm{const} \times h^2 T^2 + \mathrm{details}$$

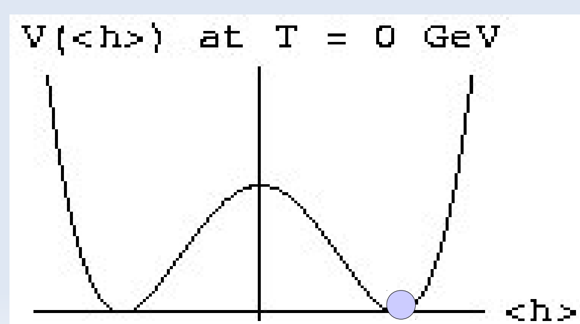


Electroweak symmetry breaking

Depending on the details, the phase transition can be very weak or even a cross over



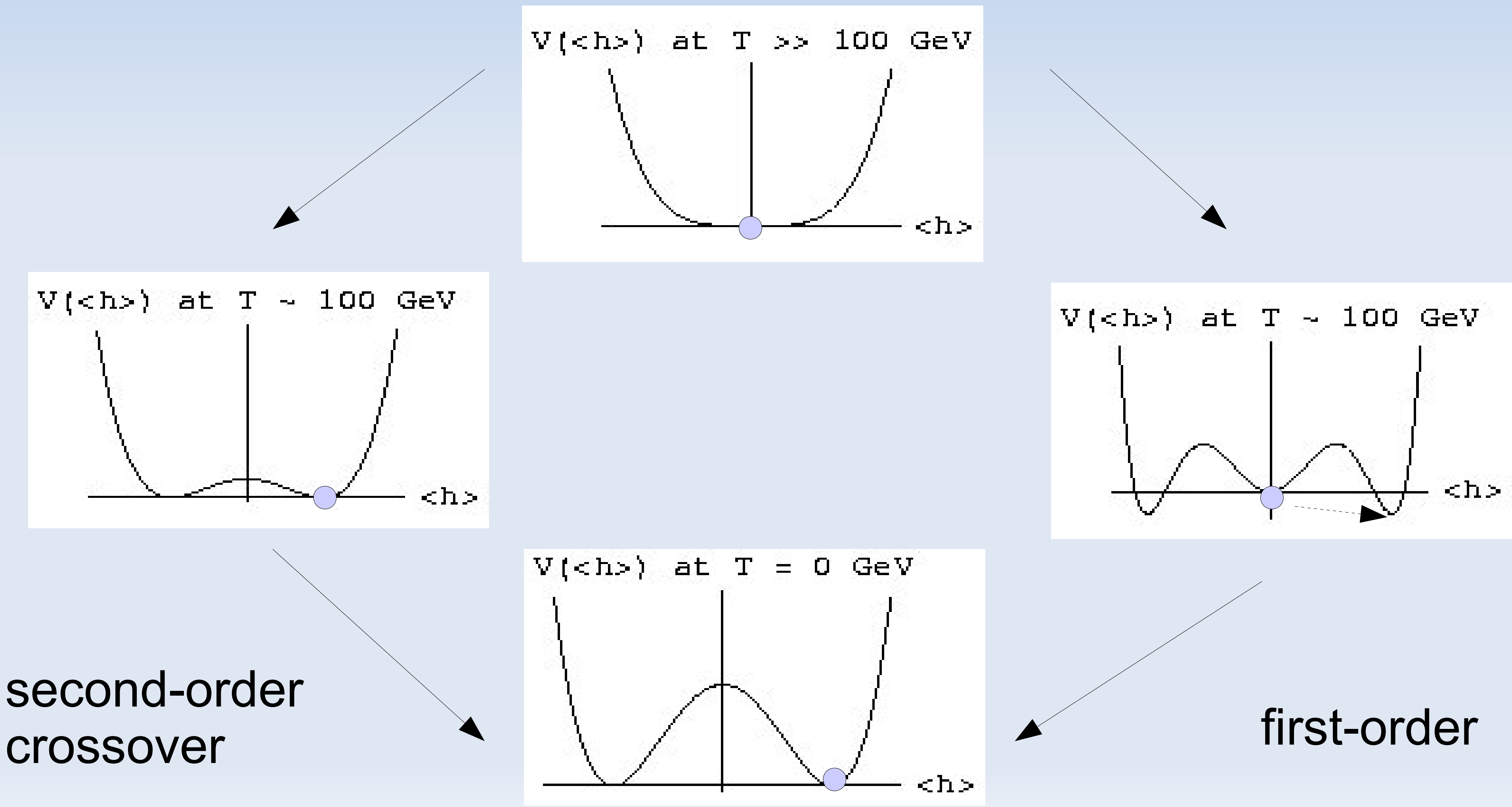




second-order
crossover

Electroweak symmetry breaking

It can also be a strong phase transition if a **potential barrier** seperates the new phase from the old phase



Electroweak symmetry breaking

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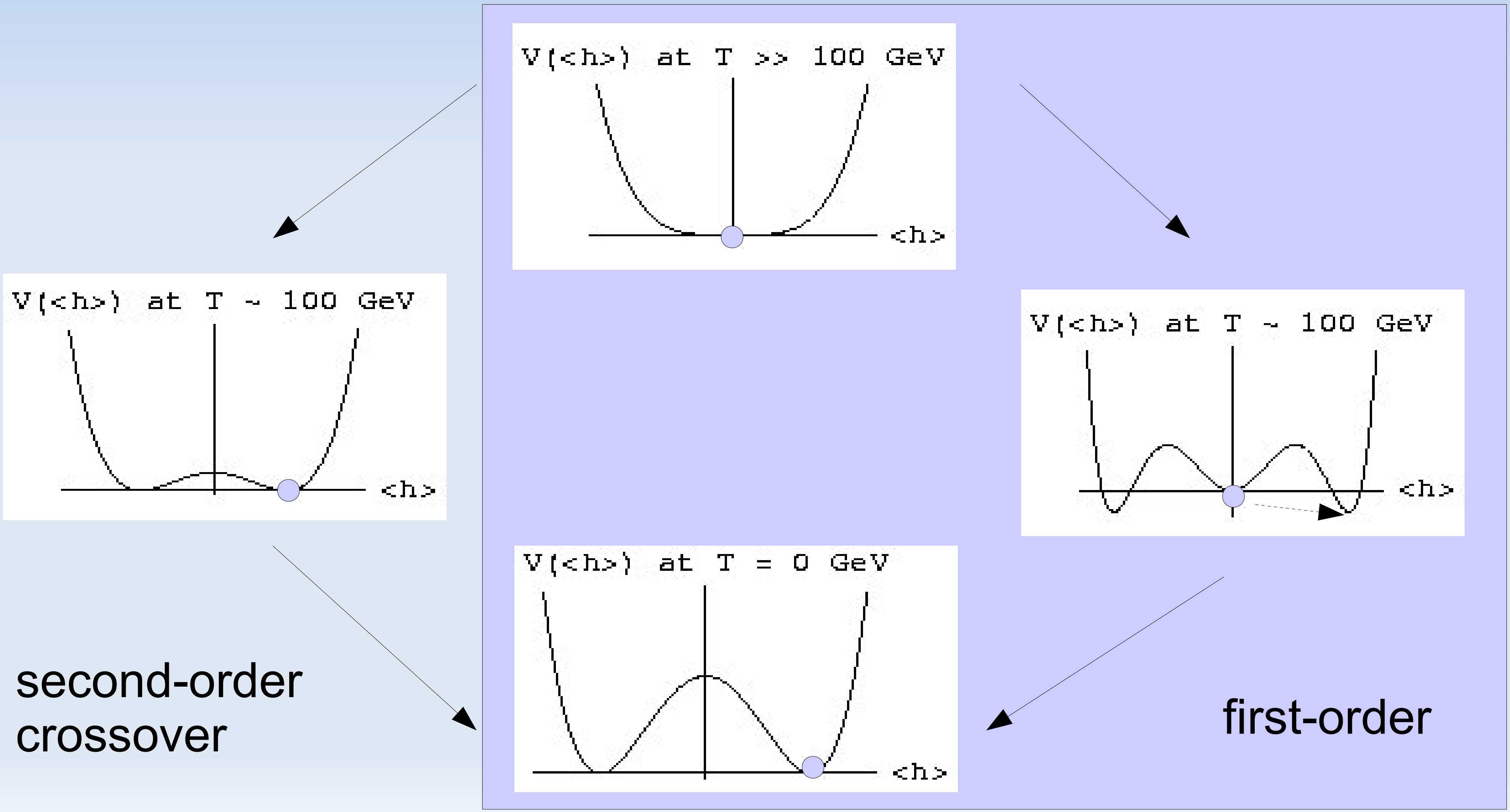


First-order phase transitions

• first-order phase transitions proceed by bubble nucleations

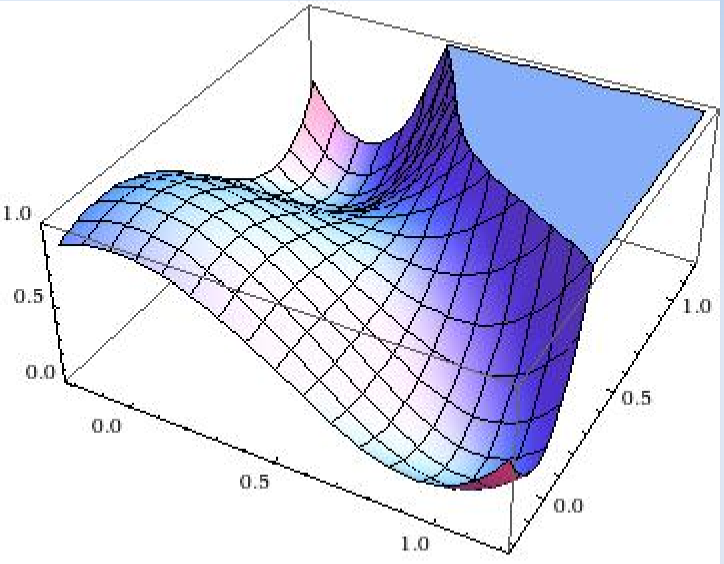
• in case of the electroweak phase transition, the ”Higgs bubble wall” separates the symmetric from the broken phase

• this is a violent process ($v_{wall} \simeq O(c)$) that drives the plasma out-of-equilibrium

Singlet extension

The Standard Model only features a electroweak crossover.

A potential barrier and hence first-order phase transitions are quite common in extended scalar sectors:



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

The singlet field has an additional $\mathbb{Z}_2$ symmetry and is a viable DM candidate.

The phase transition proceeds via

$$(h,s) = (0,w) \to (h,s) = (v,0)$$

Summary

The electroweak phase transition can drive the plasma of the early Universe out-of-equilibrium if it is of **first-order**.

In the **Standard Model** and (almost all of) the **MSSM** there is only a **crossover**.

A **first-order** electroweak phase transition is common in singlet extensions of the SM or MSSM, composite Higgs models, 2HD models, ...

In any case **new degrees of freedom** that are **coupled strongly** to the Higgs field are required.

Outline

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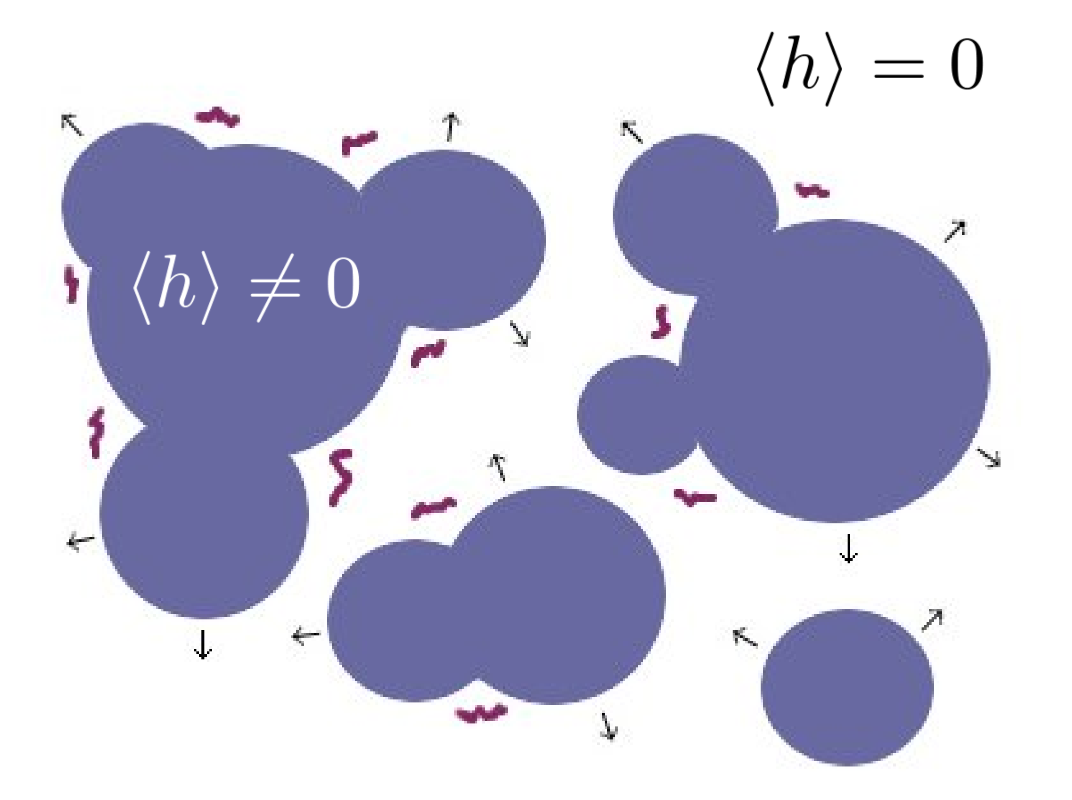
Gravitational waves



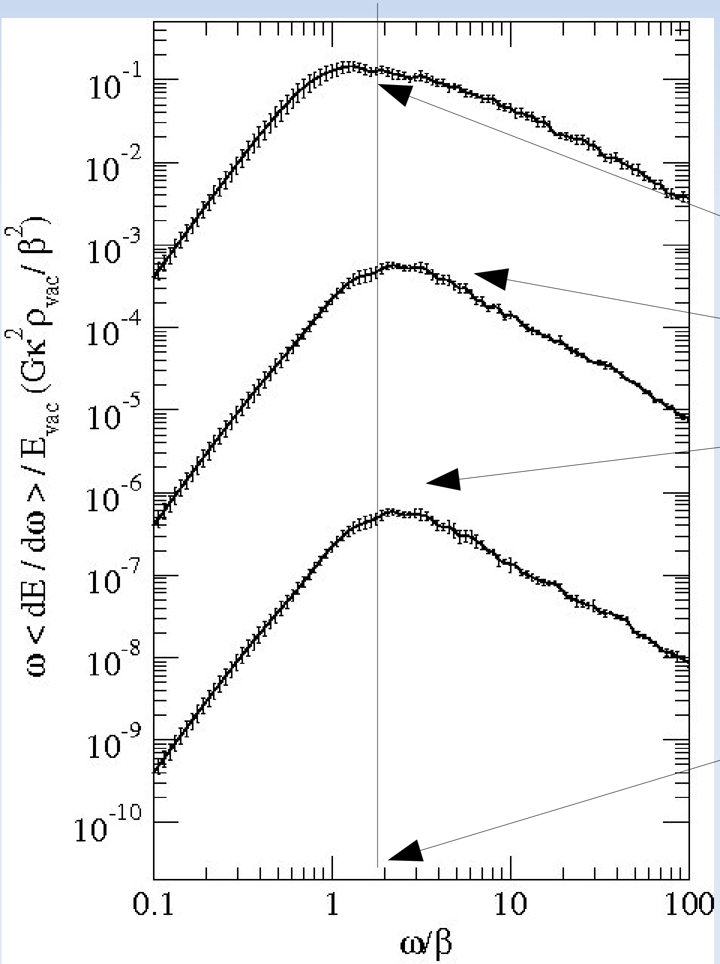
During the first-order phase transitions, the nucleated bubbles expand. Finally, the colliding bubbles generate **stochastic gravitational waves**.

(A) envelope approximation for large wall velocities
(B) hydrodynamics for small wall velocities

(A) Envelope approximation

[Huber&TK '08]

For large wall velocities, the system can be descibed using the envelope approximation. $v_{wall} \simeq c$



The amplitude depends mostly on the **wall velocity** and the ratio

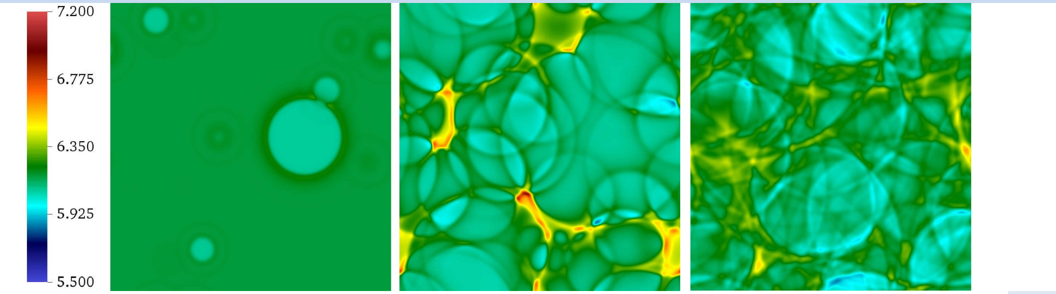
$$\alpha = \frac{\text{latent heat}}{\text{total energy}}$$

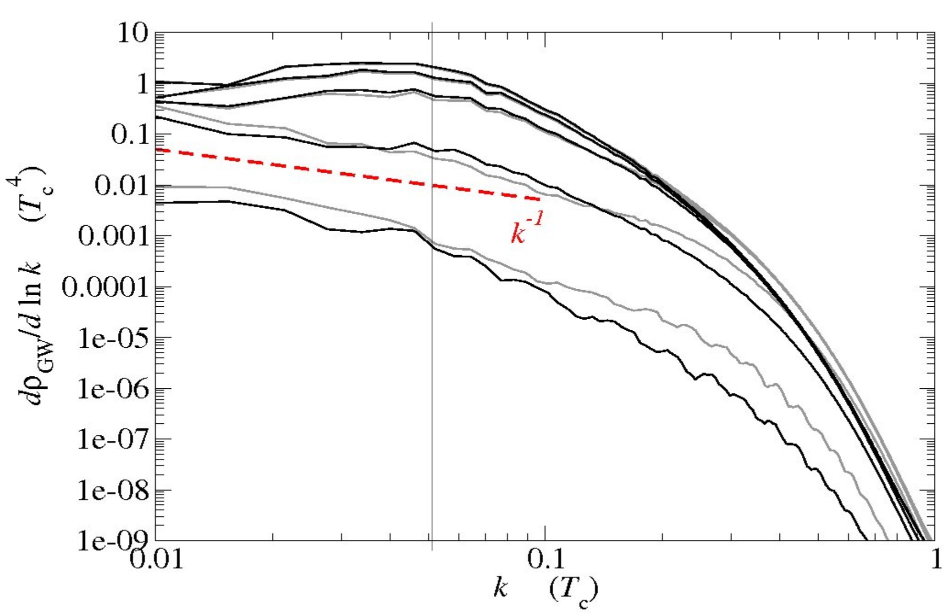
The peak frequency depends on the bubble size that is a few times smaller than the **Hubble horizon**

(B) Hydrodynamics

[Hindmarsh et.al. '13]

For small wall velocities, the system can be descibed using hydrodynamics. $v_{wall} \ll c$



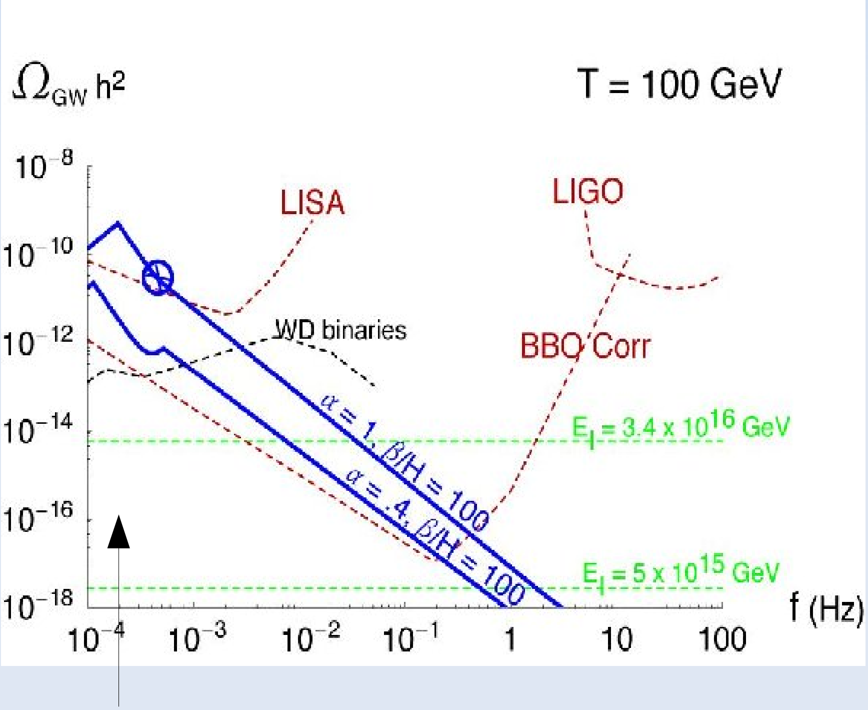


The overall features are quite similar to the envelope approximation.

Observation

[Grojean&Servant '06]

The produced gravitational waves can be observed with laser interferometers in space



redshifted **Hubble horizon** during a phase transition at T ~ 100 GeV

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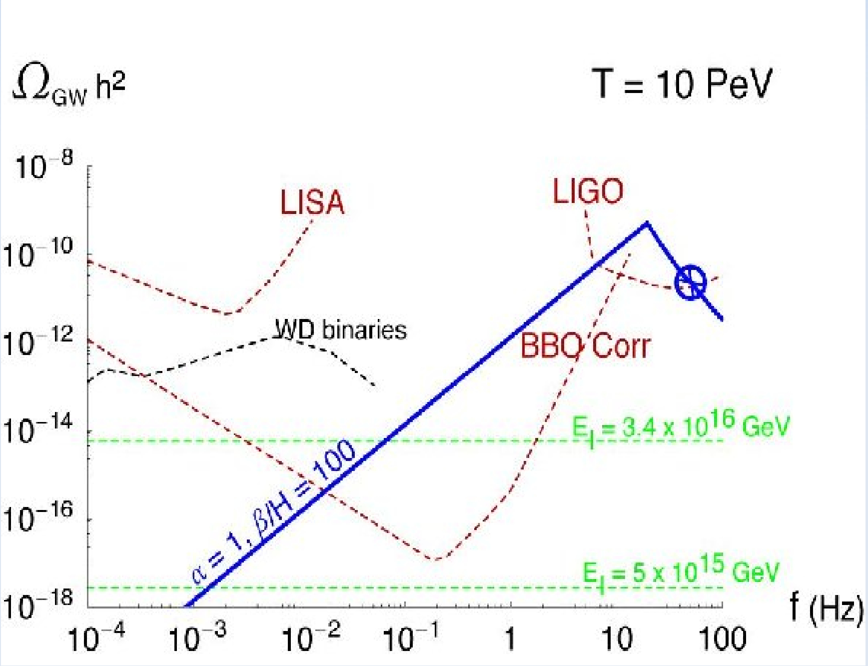

Strong phase transition at **larger temperatures** produce the same energy fraction of gravitational waves but at **higher frequencies**.

Summary

Gravitational waves from an electroweak phase transition can be observed in several decades.

They are interesting because

- The information is complementary to collider experiments (latent heat, bubble size, ..)
- Gravitational wave experiments have a very large reach (multi-PeV)

Outline

Phase transition

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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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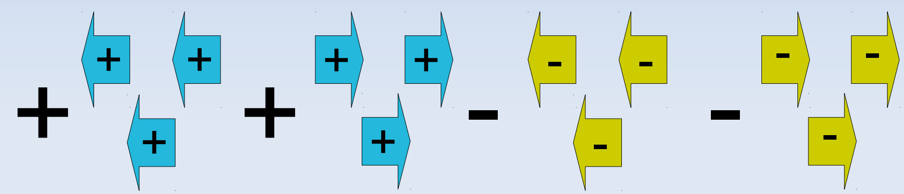

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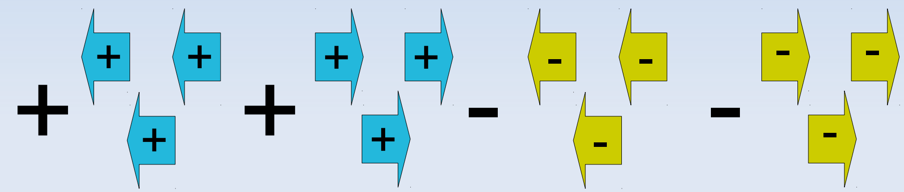

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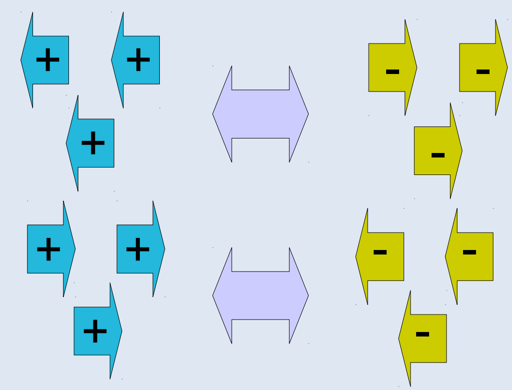

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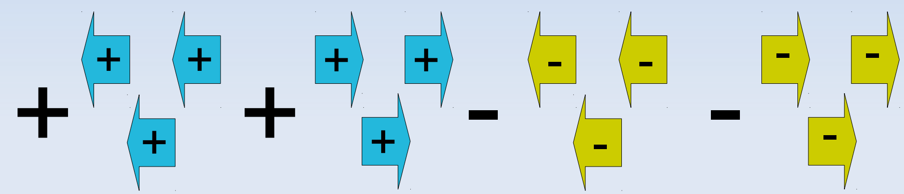

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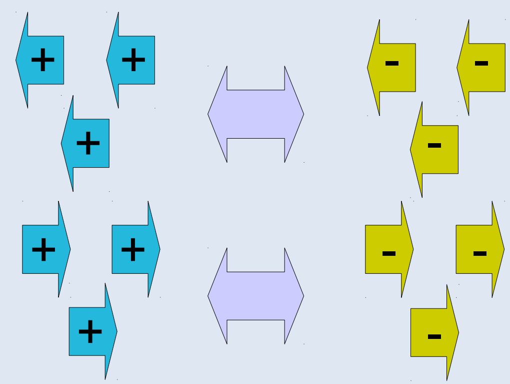

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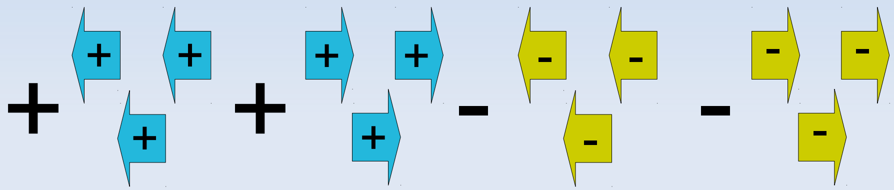

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- B-number violation (baryon-number)
- C and CP violation (charge/parity)
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$$n = n(m/T)$$

$$m = \bar{m}$$

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

Baryogenesis

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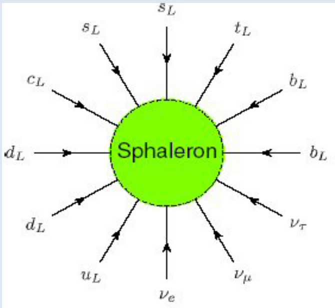


SM @ EW temp

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

 weak gauge anomaly — sphaleron

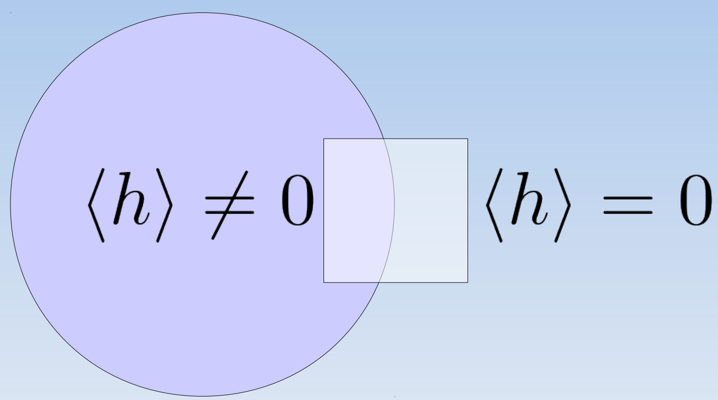
 Jarlskog invariant

 expansion slow EW crossover

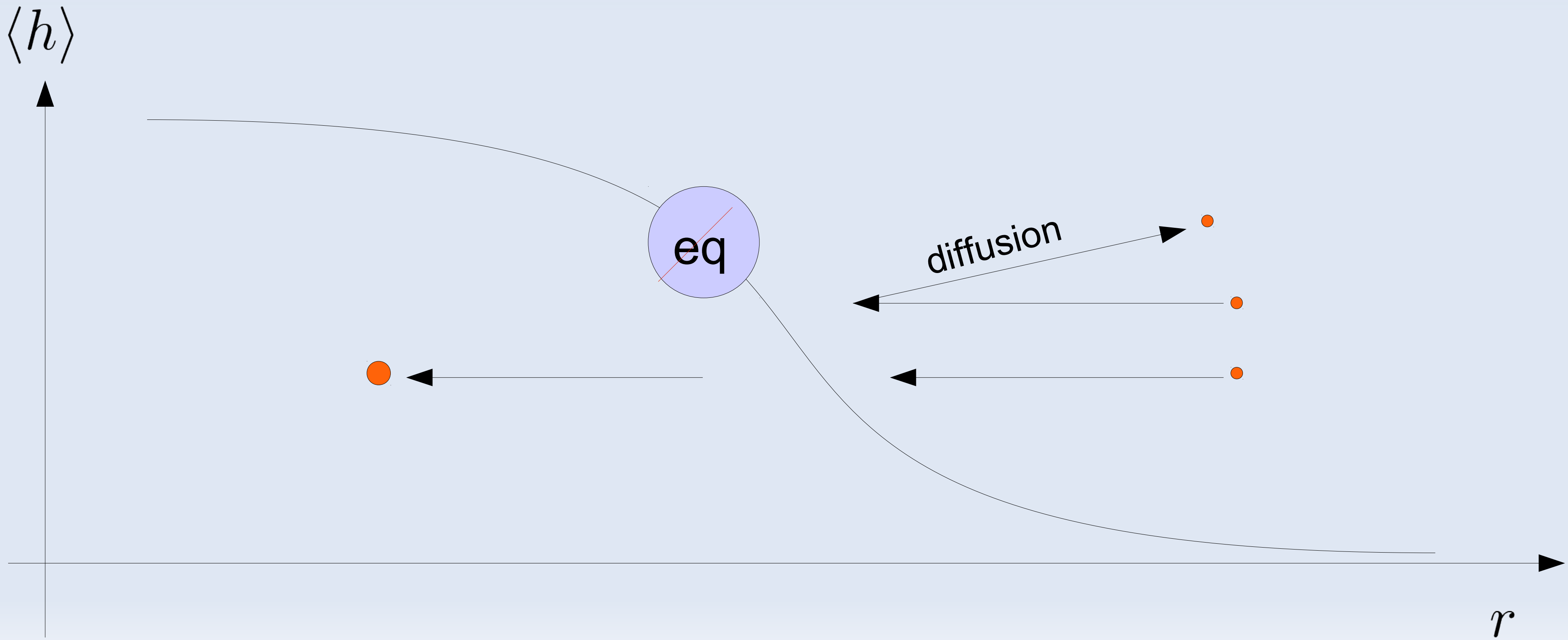
beyond the SM physics essential

first-order electroweak phase transition

Electroweak baryogenesis



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



Electroweak baryogenesis

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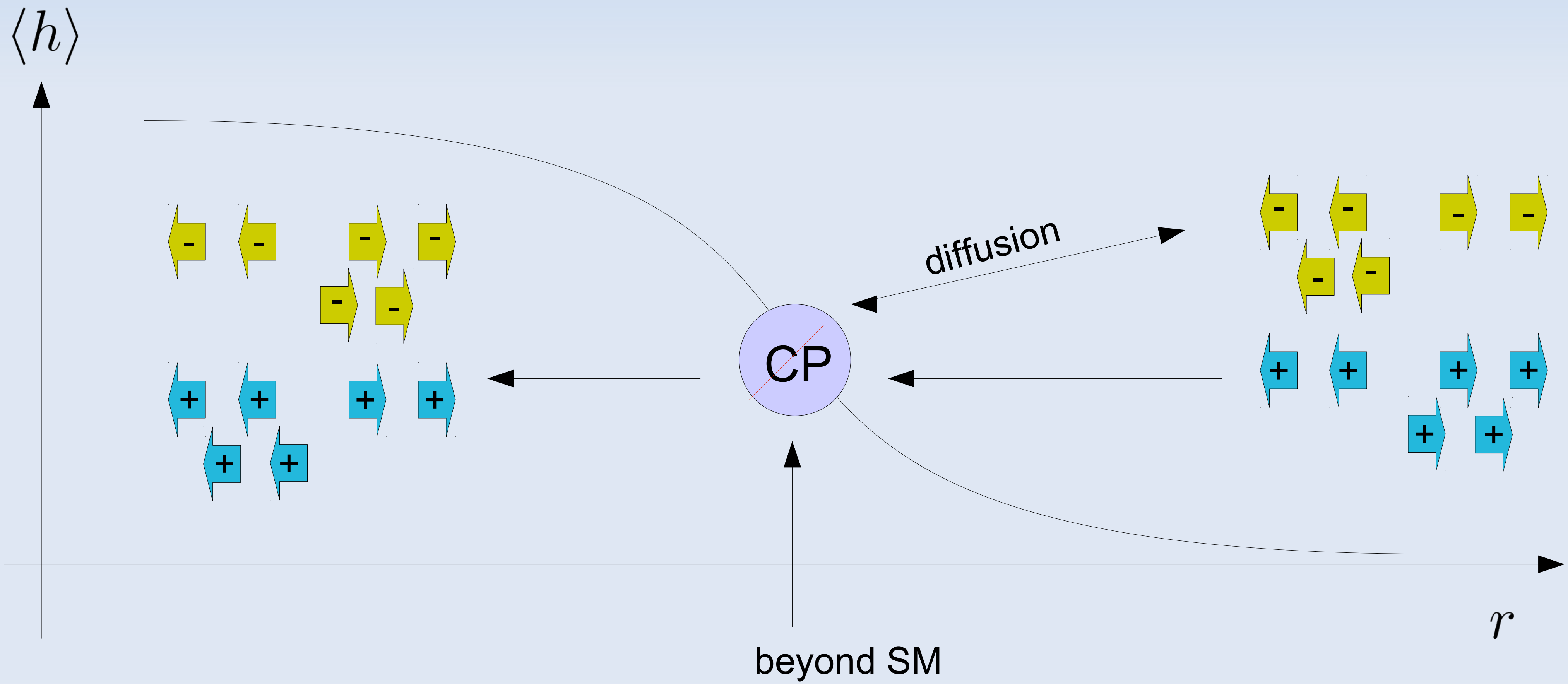

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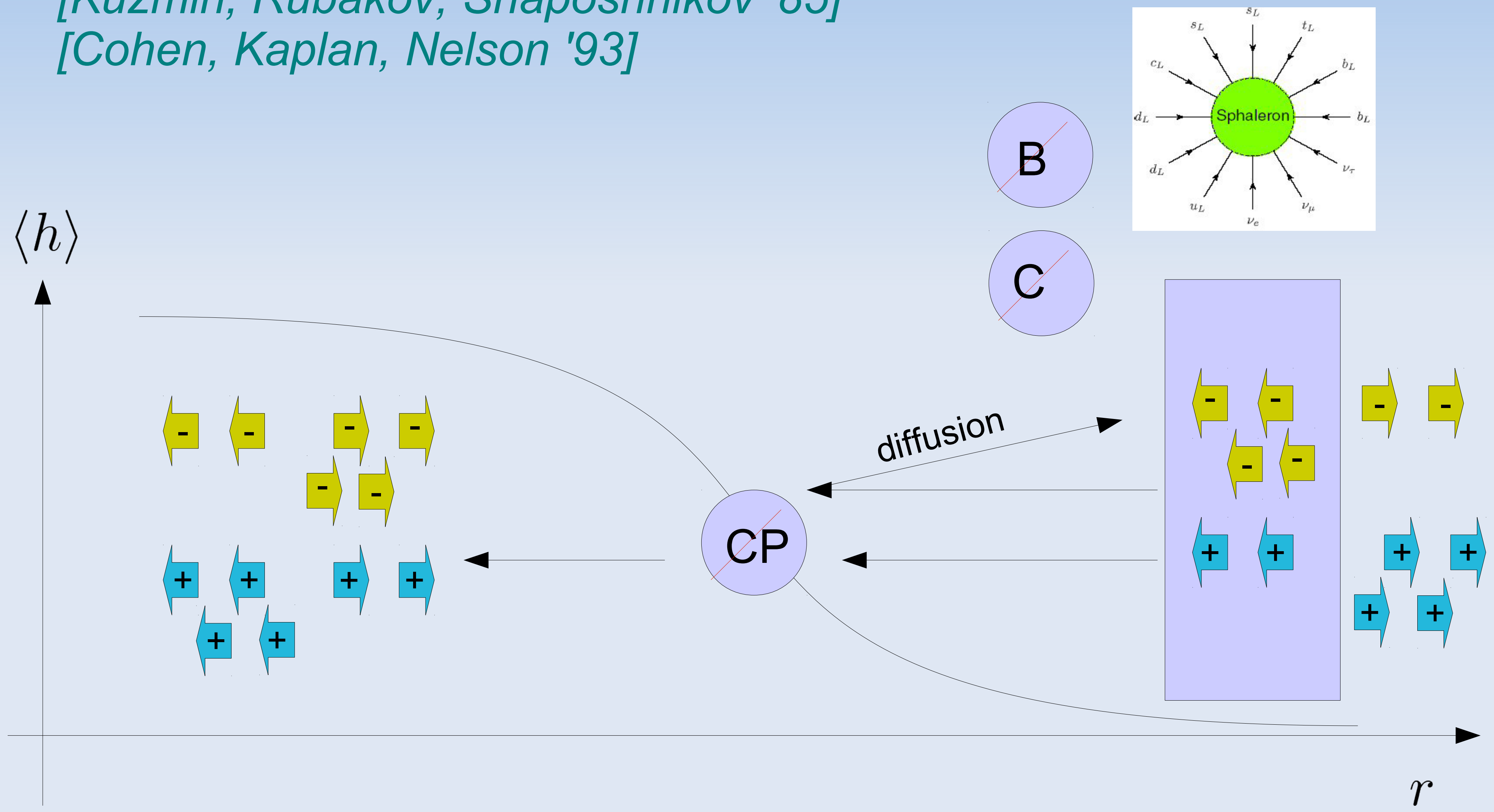

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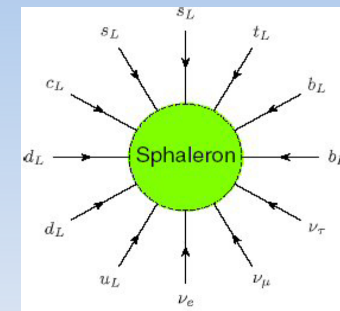

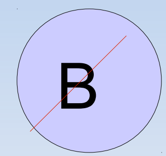

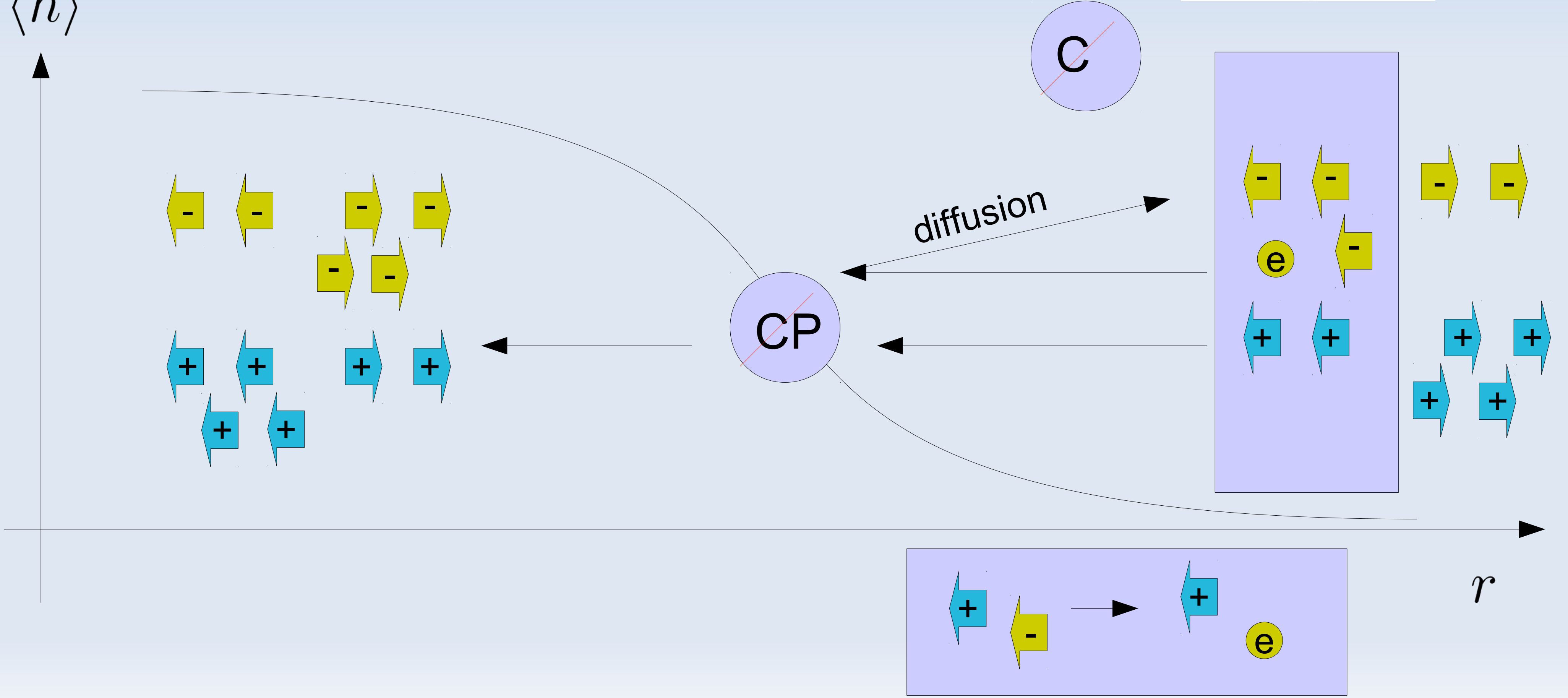

Electroweak baryogenesis

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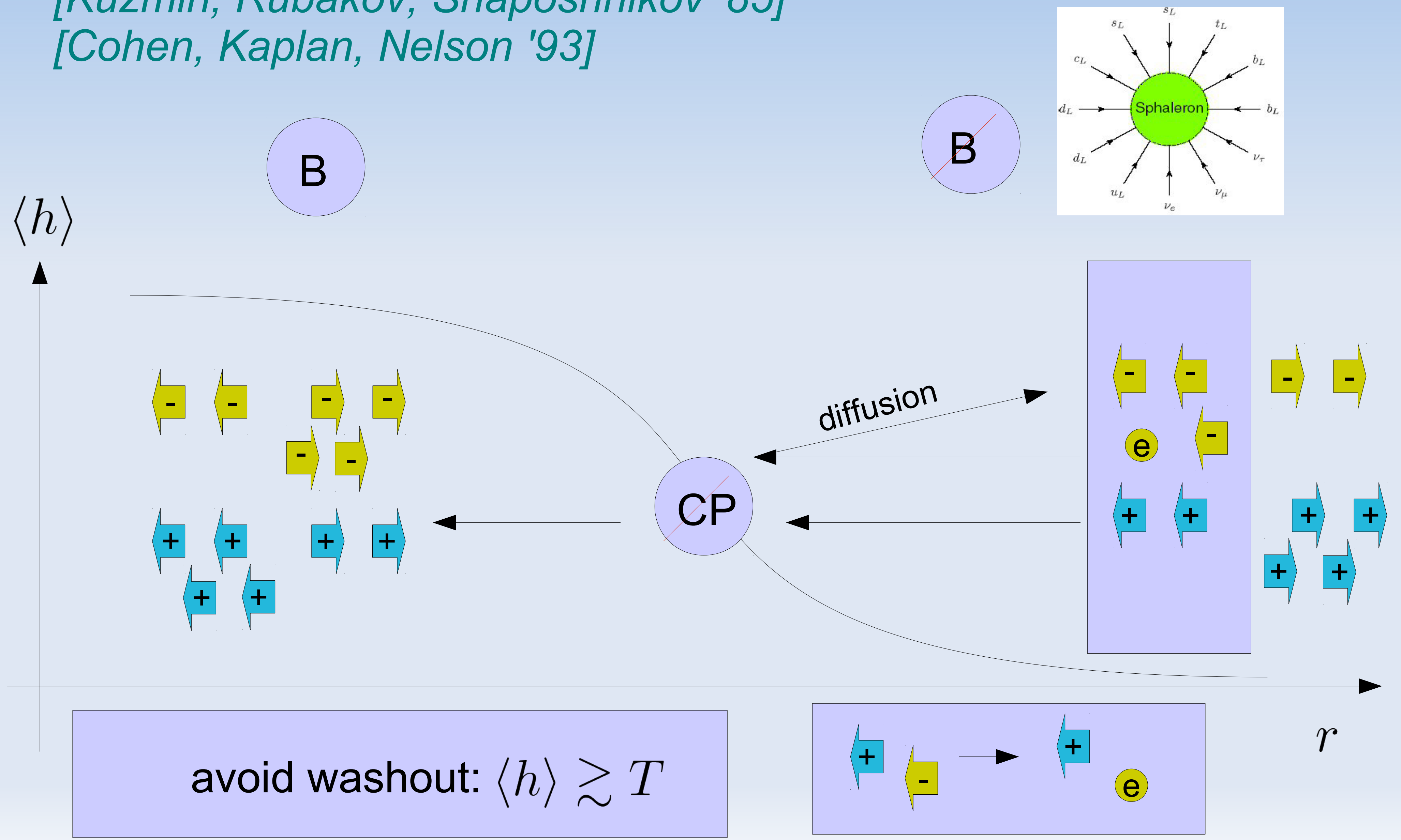


avoid washout: $\langle h \rangle \gtrsim T$

Ingredients

1 $\cancel{\text{eq}}$ Strong first-order electroweak phase transition $\langle h \rangle > T$

2 $\cancel{\text{CP}}$ Some fermion species that interacts with the Higgs in a CP violating way

Why is this interesting?

- Electroweak baryogenesis involves only physics at the electroweak scale that is accessible to collider experiments

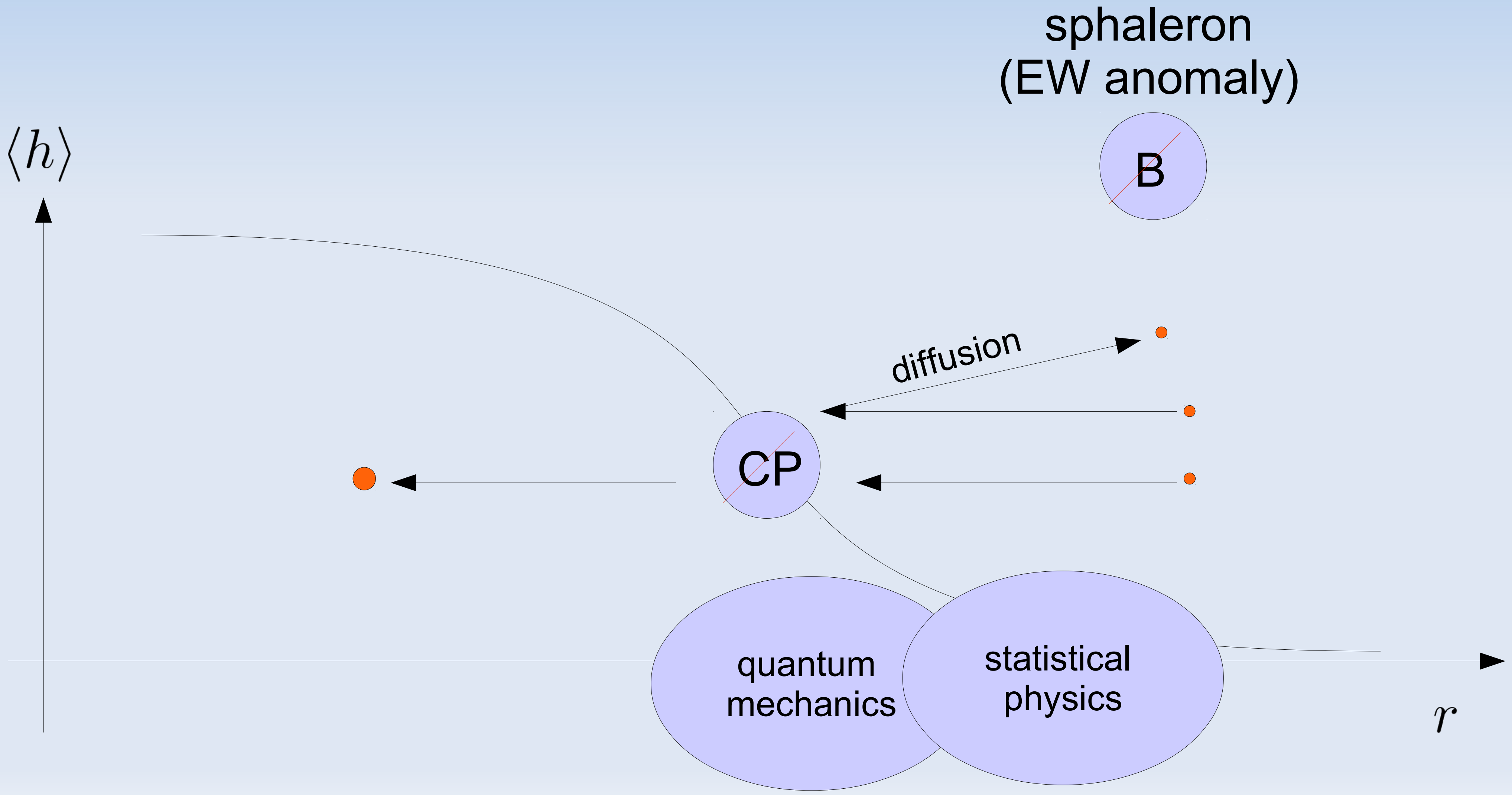
- Electroweak baryogenesis leads naturally to the observed baryon asymmetry

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

beyond SM?

What are the challenges?

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



Schwinger-Keldysh formalism

[Schwinger '61] [Kadanoff, Baym '61] [Keldysh '64]

In order to quantify electroweak baryogenesis one needs a formalism that includes **quantum** effects (CP violation) as well as **statistical** effects (diffusion/transport)

This is achieved by the Kadanoff-Baym equations that are a statistical generalisation of the Schwinger-Dyson equations of QFT (**Schwinger-Keldysh** formalism)

$$(\Box + m^2 + \Sigma)\, G(x, y) = \delta(x - y)$$

Formally the equation looks like SD, but

- The 2-point function depends on x and y seperately
  $\rightarrow$ X and p in Fourier (Wigner) space
- There is an additional 2x2 structure from the
  in-in-formalism

Ingredients

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Composite Higgs models

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 and a low cutoff $f \sim \mathrm{TeV}$

For example: **composite Higgs**

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

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

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

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

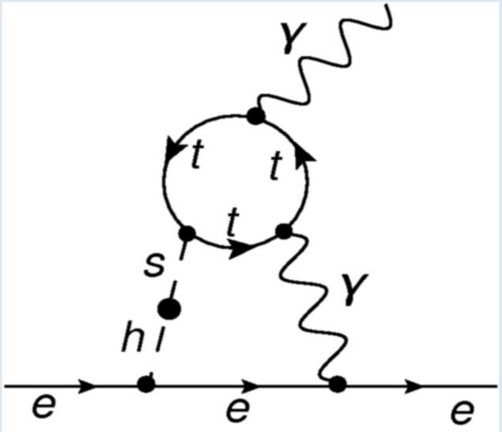
CP violation

The new source of CP violation leads to sizable **electric dipole mements**

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

The **complex phase of the top mass** during the phase transition behaves as

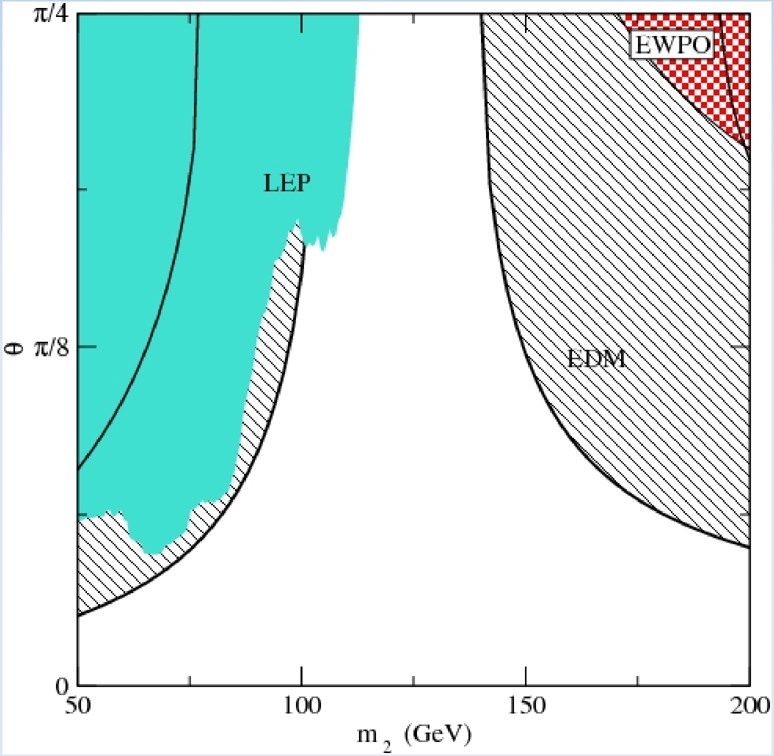
$$\theta_t \simeq \frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{s}{f}$$



Signals

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

Higgs-singlet mixing ~ CP violation

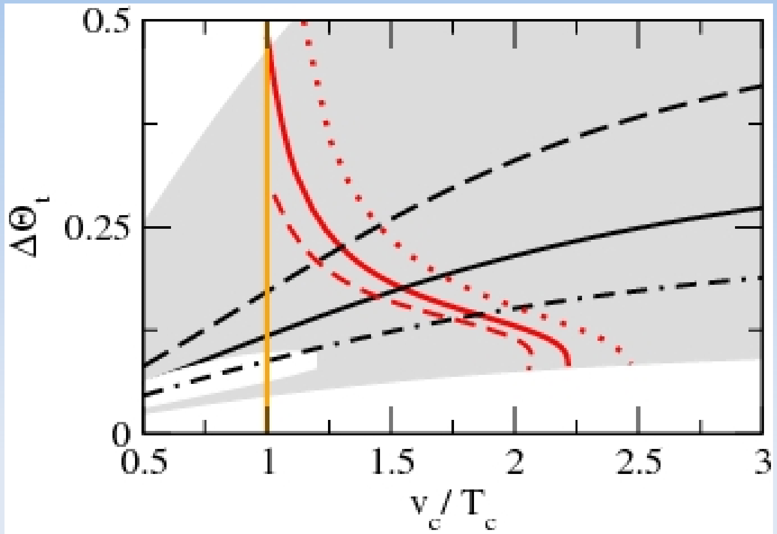


singlet mass

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

[Espinosa, Gripaios, TK, Riva '11]

Baryogenesis



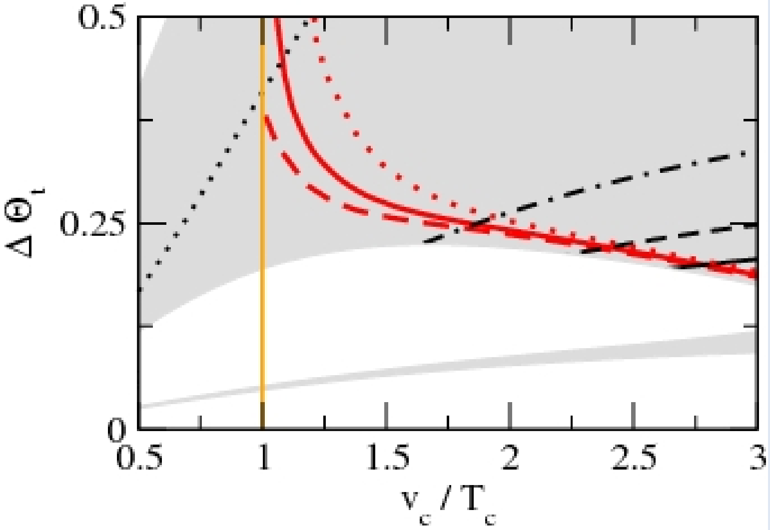
$$m_s = 130\,\mathrm{GeV}$$

$$\Delta\theta_t \gtrsim 0.15$$

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]

Summary

Electroweak baryogenesis is a predictive scheme to explain the baryon asymmetry.

It predicts/requires

- New light degrees of freedom that are strongly coupled to the Higgs (phase transition)
- New sources of CP violation that are observable by the next generation of EDM experiments

Conclusions

Understanding big bang cosmology requires to establish links between particle physics and expansion history of the Universe

So far, this is only possible up to nuclear energies.

At electroweak scale, possible links are

- a first-order electroweak phase transition
- dark matter freeze out