The Higgs boson and its (plausible) history: from LHC to the early Universe

UnivEarthS 2015 Fall School

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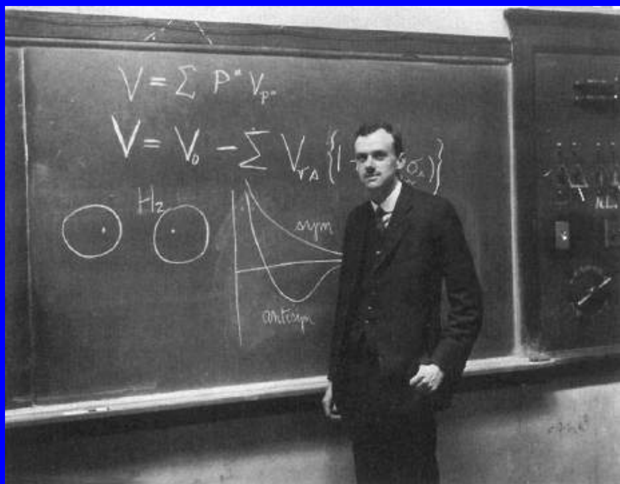
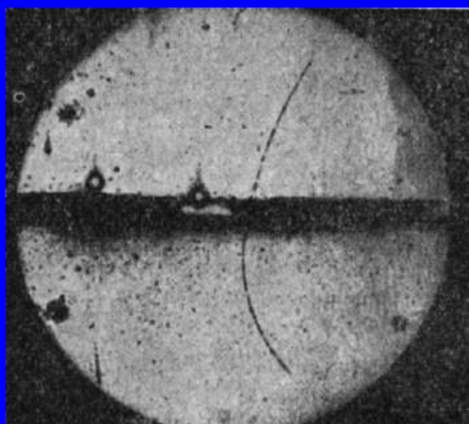
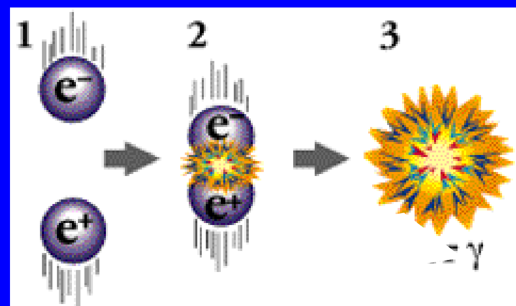
DESY - University of Bern

ANTI-ELECTRONS EXIST

Paul Dirac 1902-1984

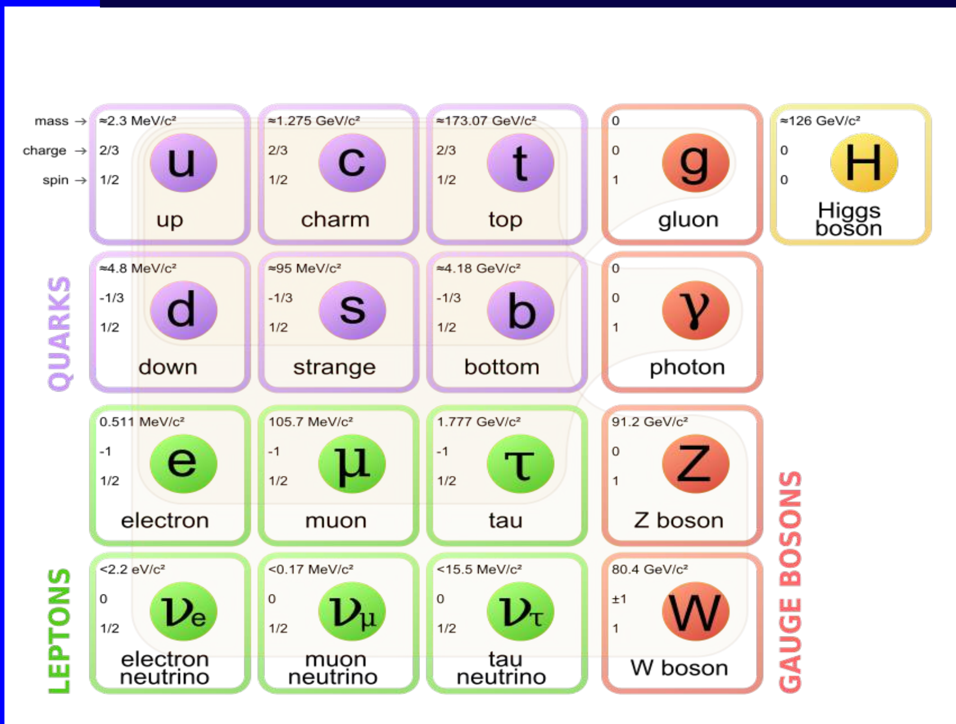


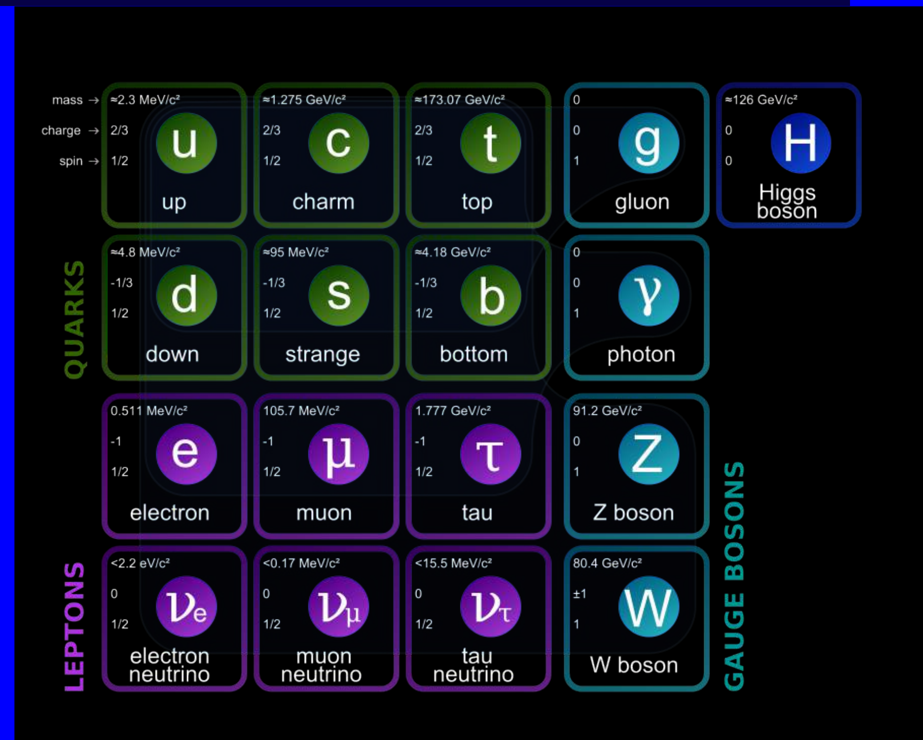




Electrons and positrons annihilate into photons ($E=mc^2$)

ANTI-PARTICLES EXIST





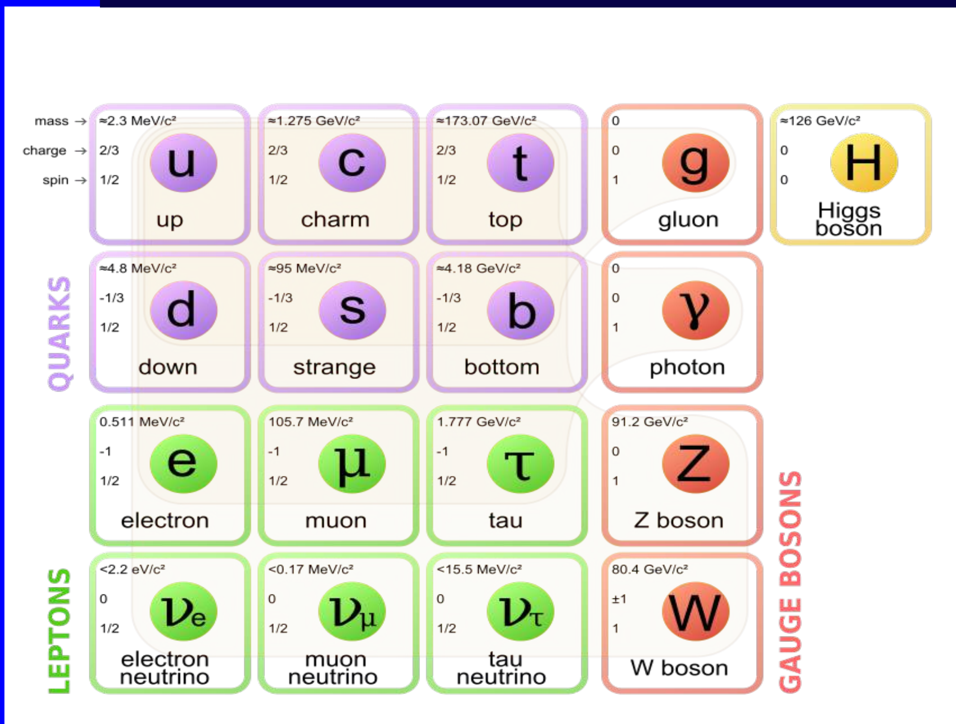
Examples: electron – positron

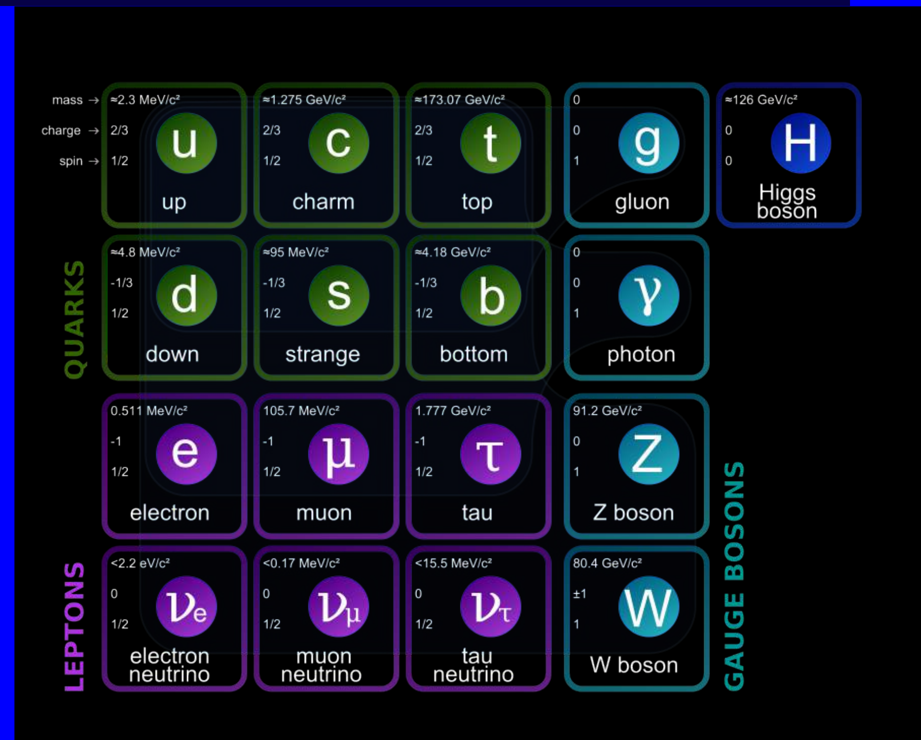
proton – antiproton

up-quark – anti-up quark

photon – photon (its own antiparticle)

ANTI-PARTICLES EXIST





The symmetry “C” is said to be conserved if whatever happens to the particle X occurs also to its antiparticle $\bar{X}$

The antimatter of the early universe has completely disappeared. Only the primordial matter have survived.

Incompatible ?

At the beginning of the Universe there was the same baryons and antibaryons.

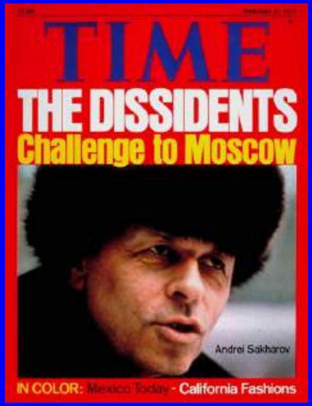
Recipe for a baryon asymmetry

Under what conditions could a baryon asymmetry emerge („baryogenesis“)?

1) Baryon number must be violated (predicted at high T)

2) Particles and antiparticles cannot behave exactly the same („CP violation“, discovered in neutral kaons 1964)

3) The universe must be out of thermal equilibrium (there must be some arrow of time)



by Andrei Sakharov (1921-1989) in 1967; Soviet nuclear physicist; dissident (against the nuclear program); 1975 Nobel Peace Prize

Recipe for a baryon asymmetry

Bottle of (cheap) wine for including CP!!!

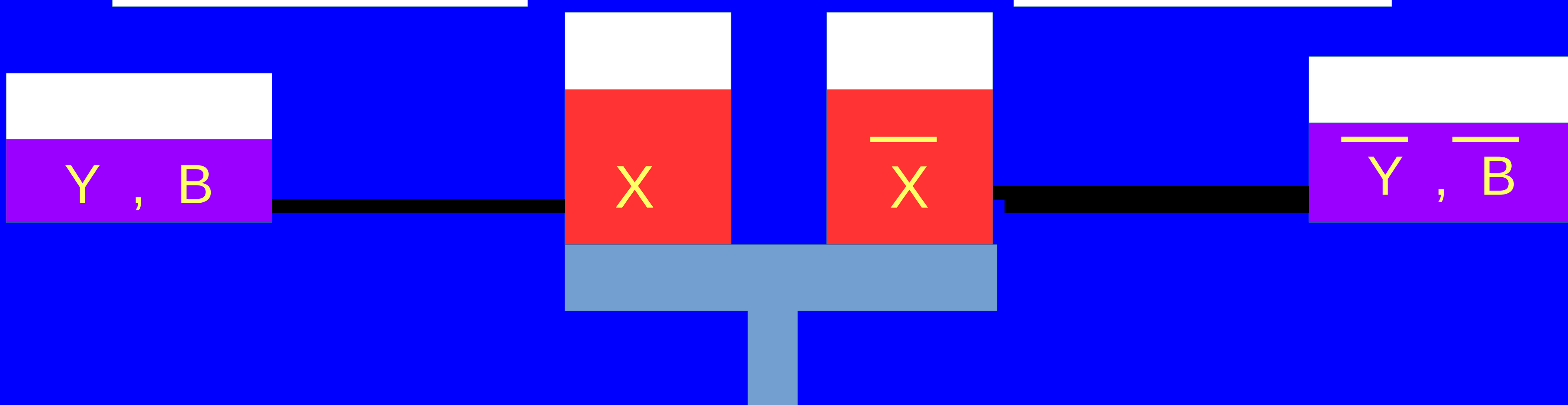
1) Baryon number violation   2) C and (CP) violation

3) The universe must be out of thermal equilibrium (there must be some arrow of time)

$$Aim: from \quad N_X = N_{\bar{X}}, \quad N_Y = N_{\bar{Y}}, \quad N_B = N_{\bar{B}}$$
$$to \quad N_B \neq N_{\bar{B}}$$

$$\Gamma(X \to Y + B)$$

$$\Gamma(\bar{X} \to \bar{Y} + \bar{B})$$



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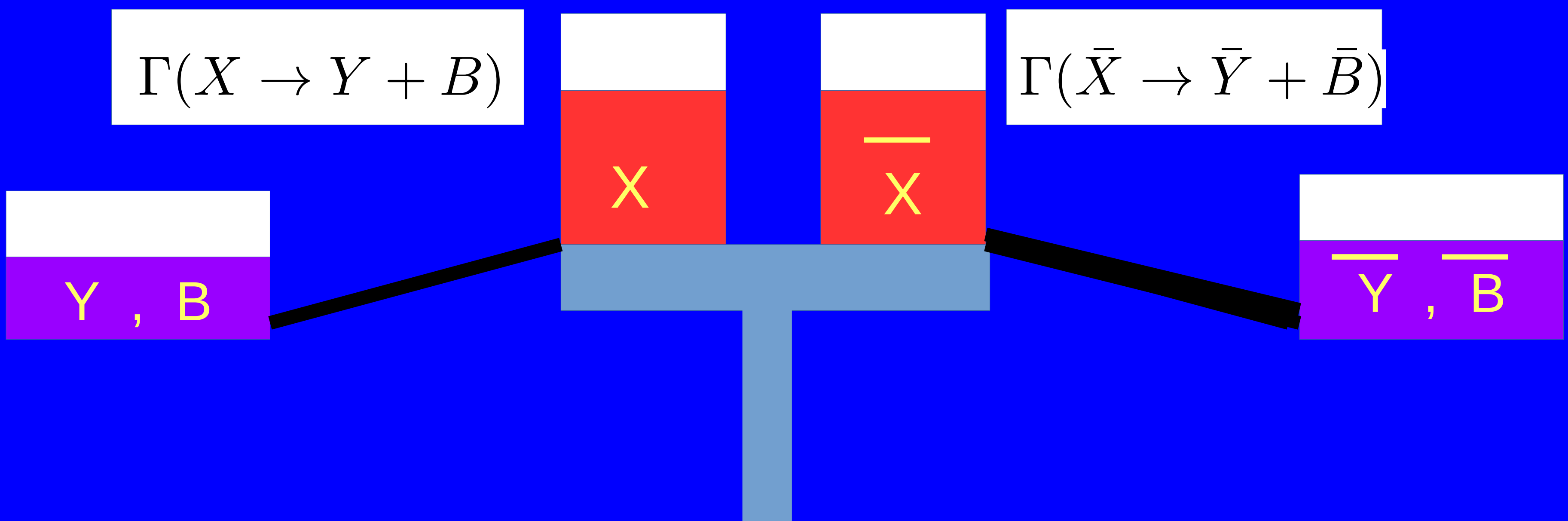


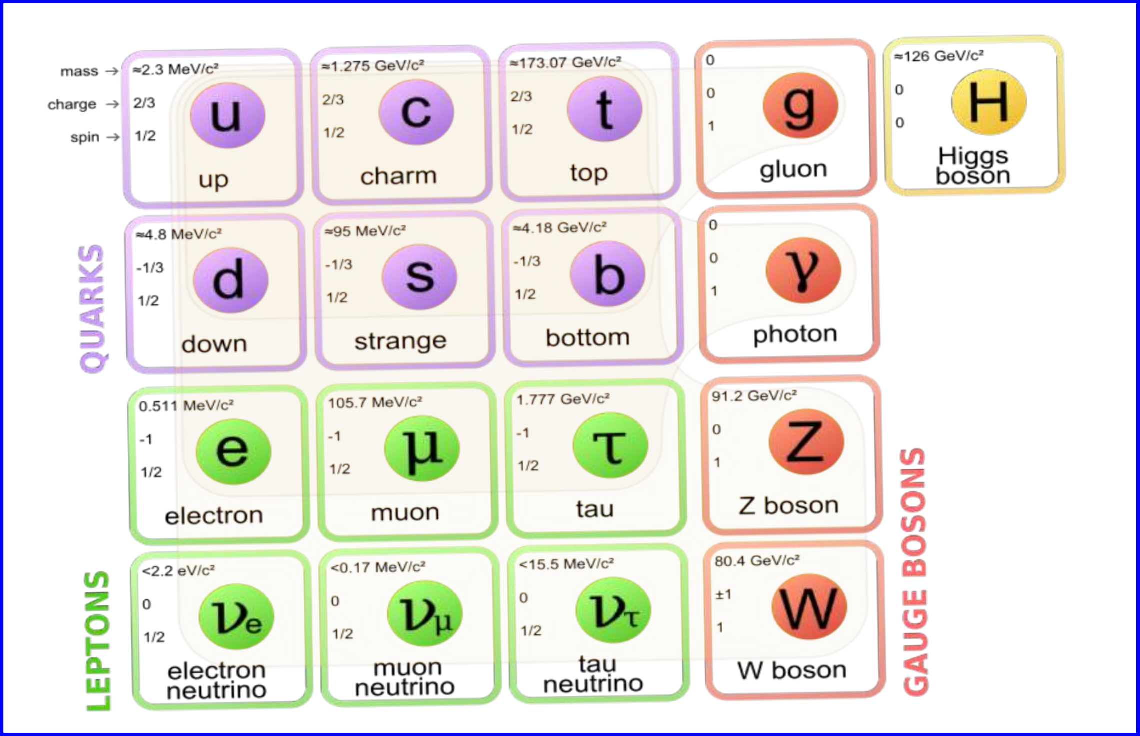
FACTS


FakTS


WINNER OF BEST ANIMATED SHORT FILM
2004 ACADEMY AWARDS
Harvie Krumpet
Some are born great, some achieve greatness, some have greatness thrust upon them ....and then there are others.

Summary of the FACTS

- We know that there exist (at least) these elementary particles:

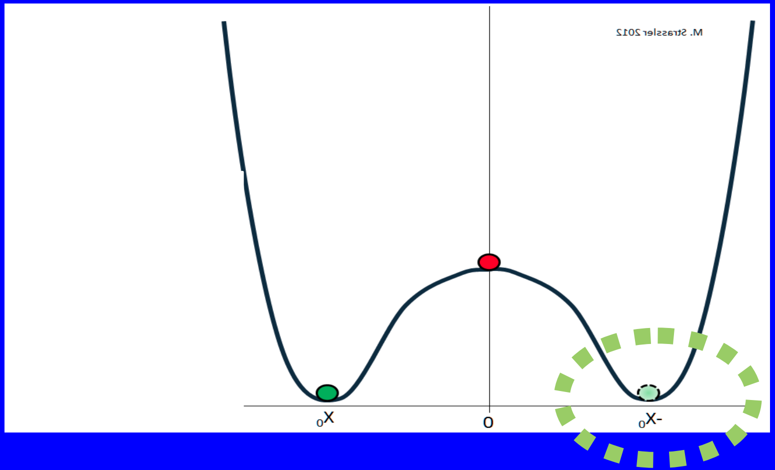


- These particles have a mass due to the interaction with the Higgs.

The larger the interaction, the larger the mass

Summary of the FACTS

- The Higgs boson (at present) has this kind of potential



- We do not know how the Higgs potential was in early Universe:

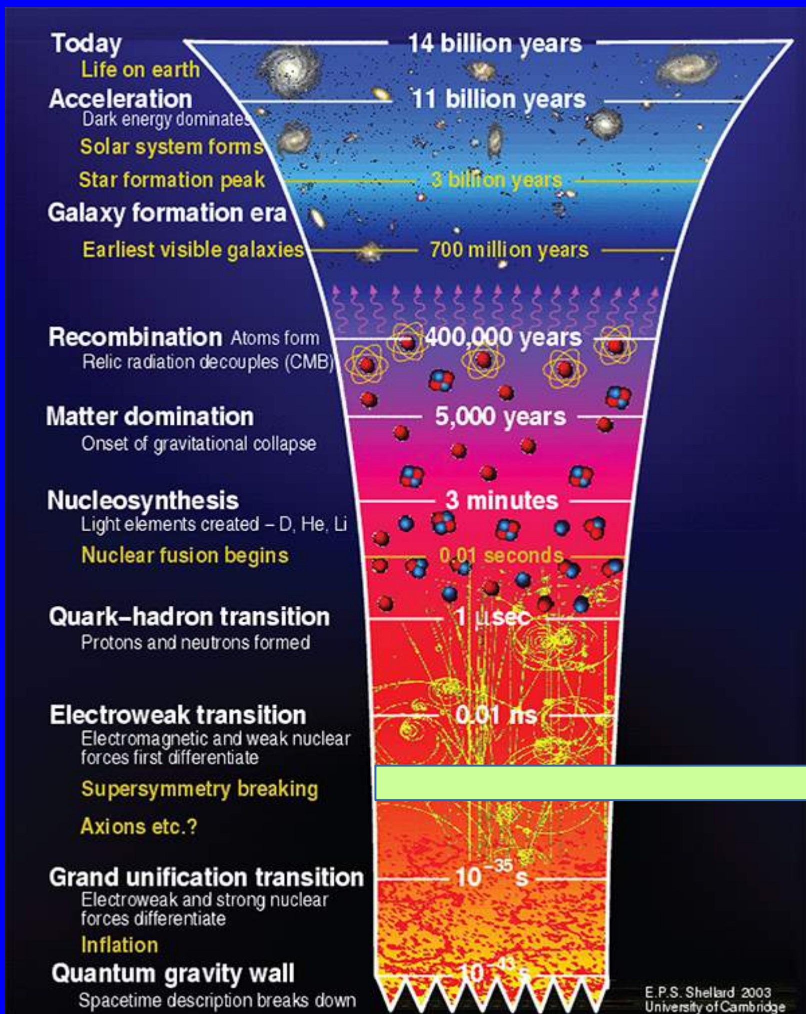
1) Its behaviour when the Universe was very hot

2) Its behaviour when the energy involved in the early Universe was much larger than the one we can test at the LHC

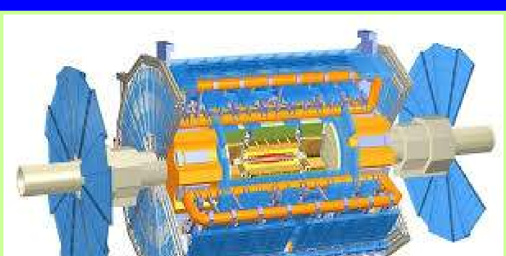
Summary of the FACTS

Temp.[K]	Density [gr/cm^3]	Energy [GeV]	Size
1	10^{-30}	10^{-12}	1
10^3	10^{-21} (>atom)	10^{-9}	10^{-3}
10^{10}	10 (>water)	10^{-3}	10^{-9}
10^{15}	10^{28}	10^3	10^{-15}

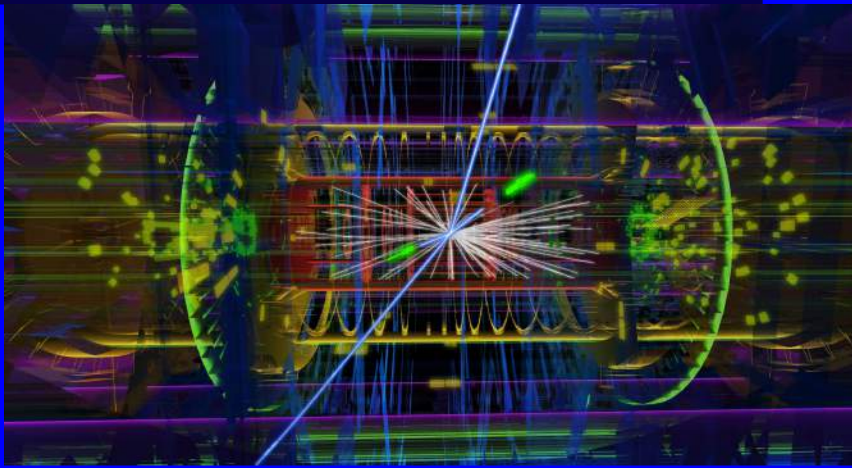
?



LHC



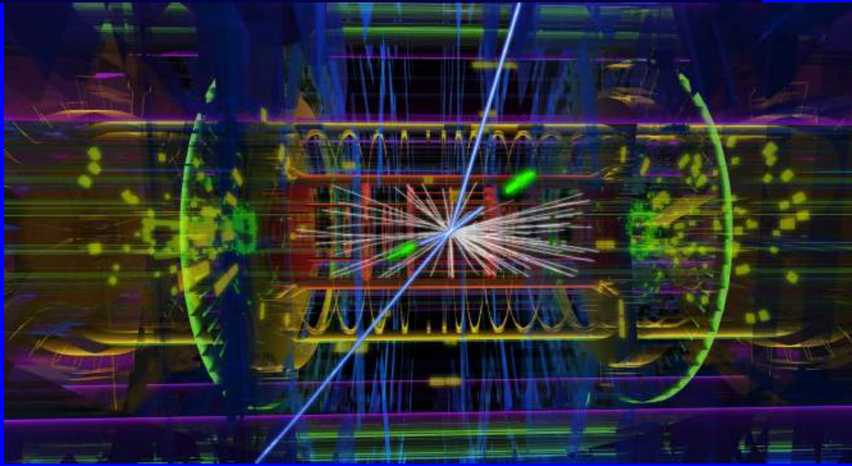
… further masses ...



In practice, at ATLAS and CMS the particles produced by a collision do not collide a second time

At high temperature and density, there are everywhere many particles. Therefore, to go from (a) to (b), a particle that interacts a lot with the other particles...

… further masses ...



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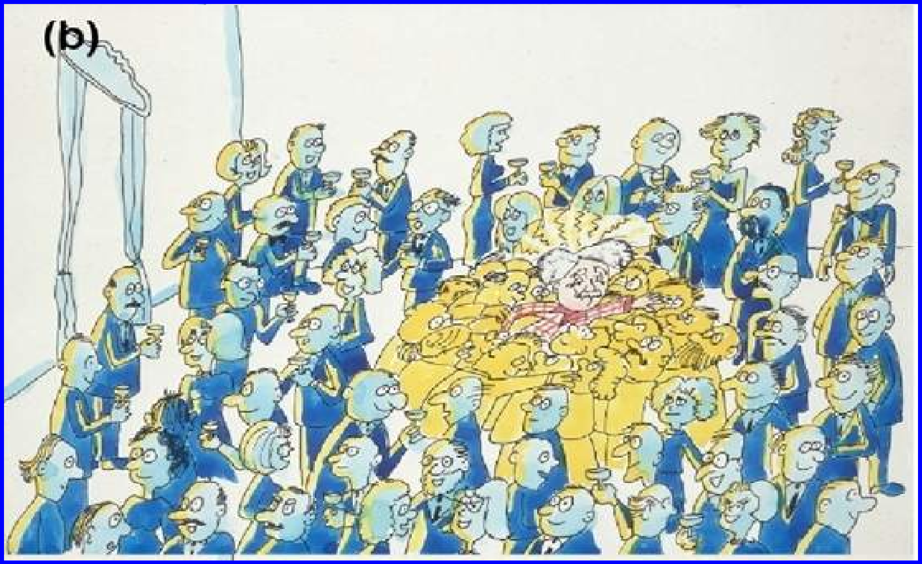


At high temperature and density, there are everywhere many particles. Therefore, to go from (a) to (b), a particle that interacts a lot with the other particles… must bump many times before reaching its destination.

This is equivalent to an effective mass !!!

Thermal mass

- This kind of scenarios involves an interplay of statistical mechanics and relativistic quantum mechanics, called thermal quantum field theory.
- A particle with a coupling g to the other particles of the thermal bath, has an effective mass (if m < 3 T ; Boltzman suppression)

$$m_{eff}^2(T) = m^2 + \Pi(T) \qquad \Pi(T) = \# g\, T^2$$

- The thermal effects can lead to a new dynamics.

Example: Assuming $m_X < 2\, m_Y$,

at T = 0 $\quad X \not\longrightarrow Y + Y$

at $T \neq 0$ $\quad X \longrightarrow Y + Y \quad$ if $m_X^{eff}(T) > 2\, m_Y^{eff}(T)$

The Higgs prediction (mass in gauge theory)

There is a strong similarity between the harmonic oscillators and the particles:

- Each already-known particle is the harmonic oscillator X
- There is an undiscovered particle (Higgs) which is the harmonic oscillator Y
- There is an interaction proportional to g_x between X and Y
- This interaction generates an effective mass, like in the oscillator case:

$$k_x^{eff} = k_x + g_x\, const \longrightarrow m_x^{eff} = m_x + g_x\, const$$

- The beautiful gauge symmetry forbids the mass term, i.e. it imposes $m_x = 0$,

thus all particles have masses proportional to the constant „const”. This means

$$m_x^{eff} = g_x\, const \qquad m_z^{eff} = g_z\, const \qquad m_\ell^{eff} = g_\ell\, const$$

The role of the Higgs boson

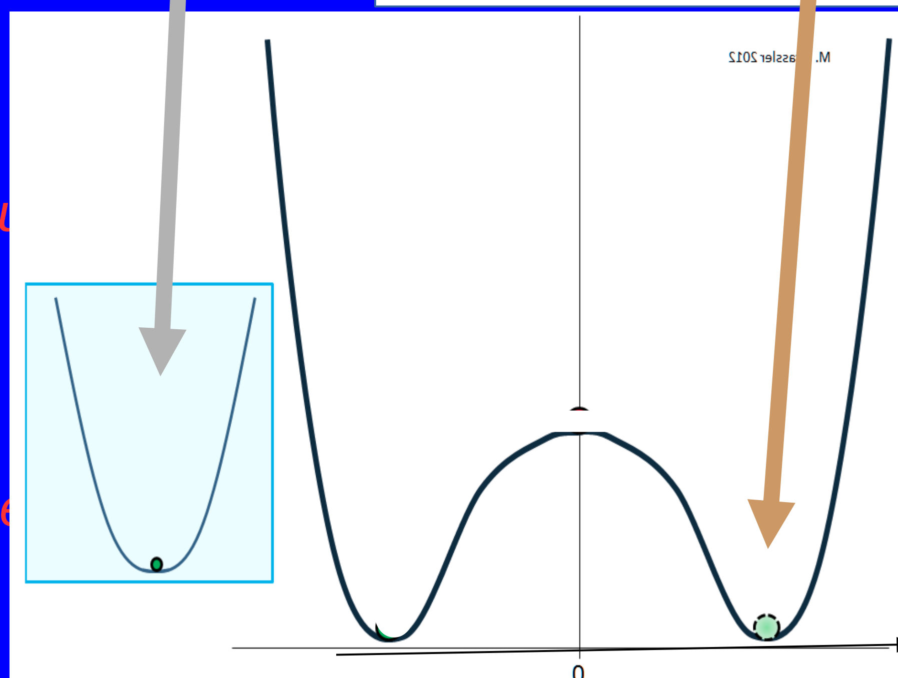
- We add a second oscillator Y that DOES interact with the oscillator X
- Again, how would you measure ω_x ? Is the result different? What about if y ≈ const ?

$$L = E_K - V = \frac{1}{2} m_x \left(\frac{dx}{dt}\right)^2 - \frac{1}{2} k_x x^2 + \frac{1}{2} m_y \left(\frac{dy}{dt}\right)^2 - \frac{1}{2} k_y y^2 - \frac{1}{2} g_x\, y\, x^2$$

$$k_x^{eff} = k_x + g_x\, const$$

$$f_x^{eff} = \sqrt{k_x^{eff} / m_x / (2\pi)}$$

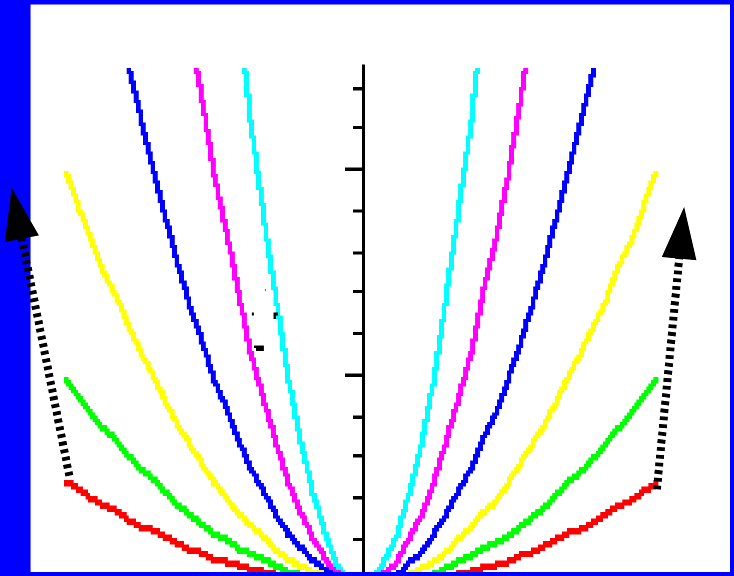
Even if you cou… X still behaves



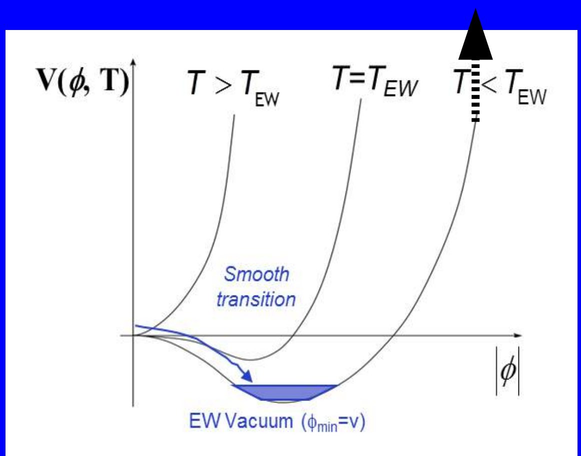
You just ne… e not seen)

Higgs potential at finite T

From the analogy of the harmonic oscillator we see that increasing the temperature T corresponds to deforming the usual potential of the particle as here.



By applying the same effect to the Higgs potential, what does it happen?



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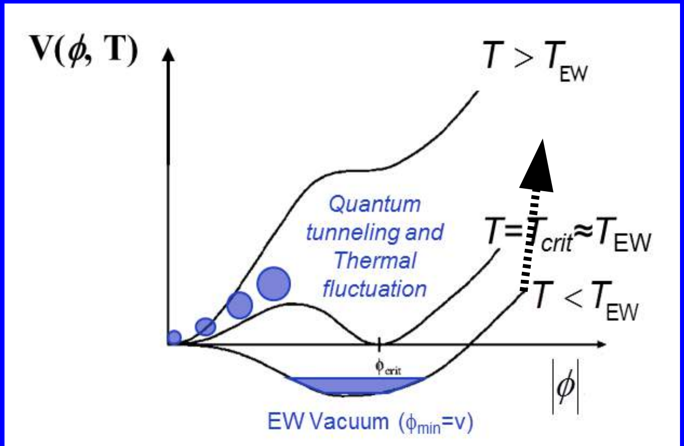
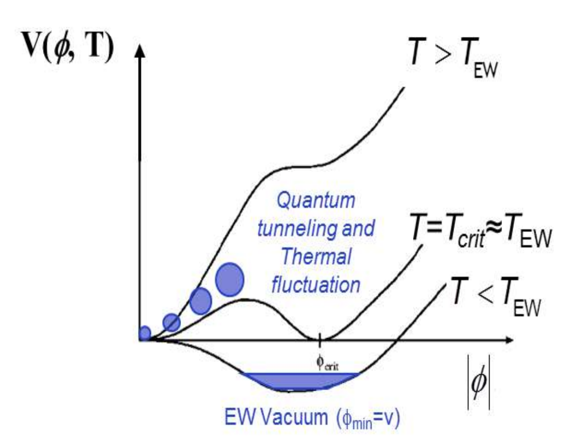


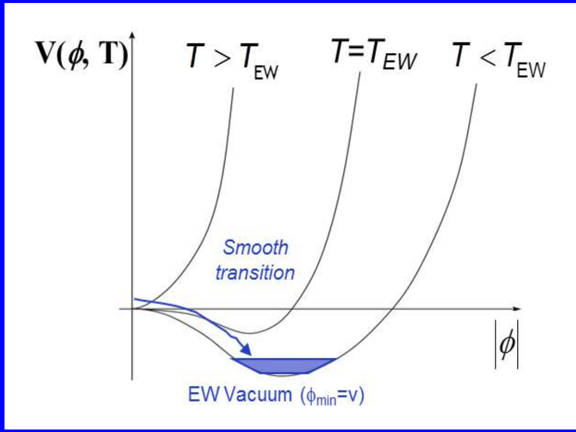
Higgs potential at finite T

Depending on the particle content, (perturbative) TQFT gives:



$$V(\phi) = D(T^2 - T_0^2)\phi^2 - 3E(T)\phi^3 + 4\lambda\phi^4$$

$$\phi_{const}(T) = \cdots$$



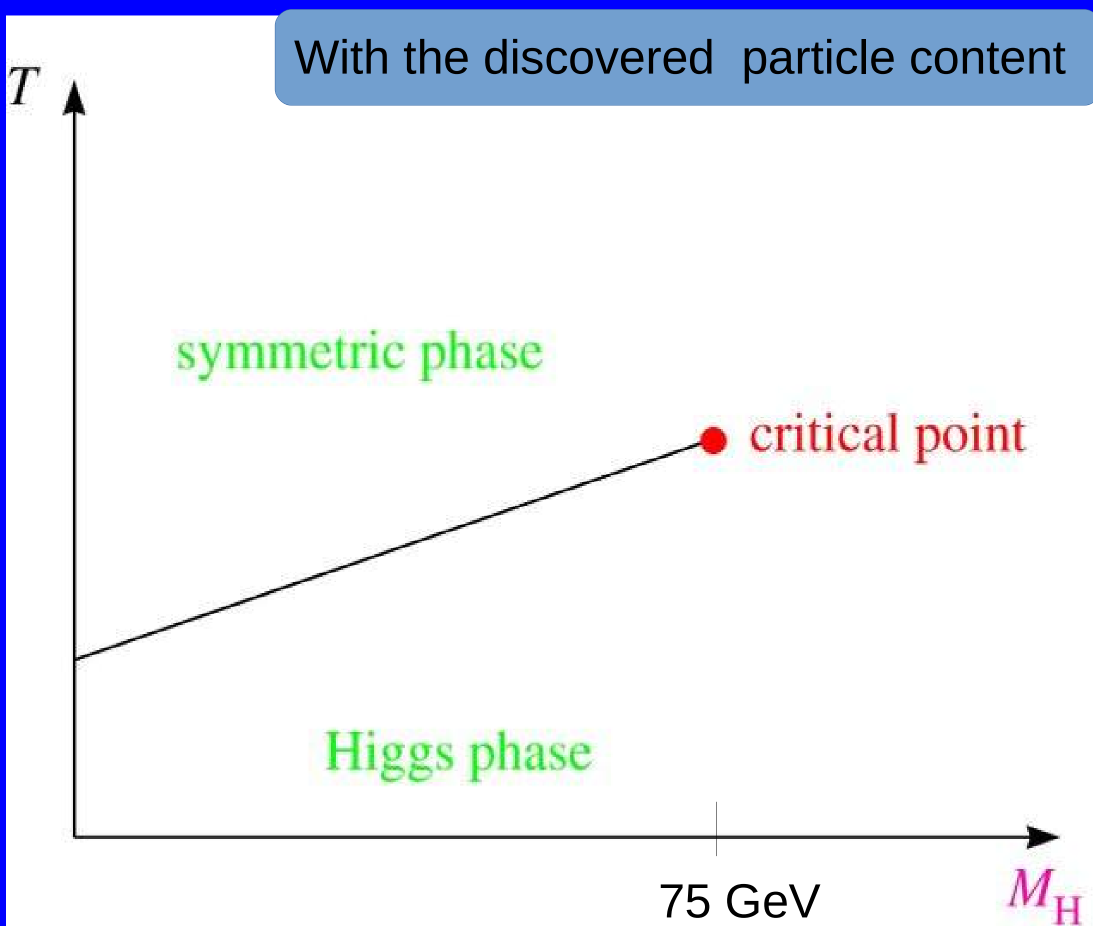
$$V(\phi) = D(T^2 - T_0^2)\phi^2 + 4\lambda\phi^4$$

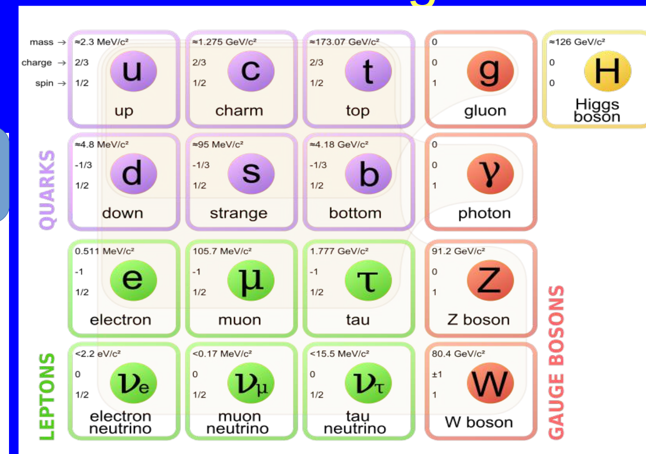
$$\phi_{const}(T) = D\frac{T^2 - T_0^2}{2\lambda}$$

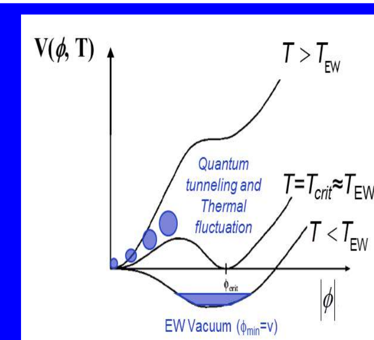
Q: Order of these transitions? Definition?

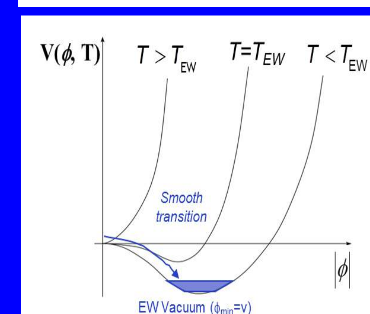
Higgs potential at finite T

… but the case of the particle content we have discovered till know, is unlucky. Indeed calculations including non-perturbative effects give



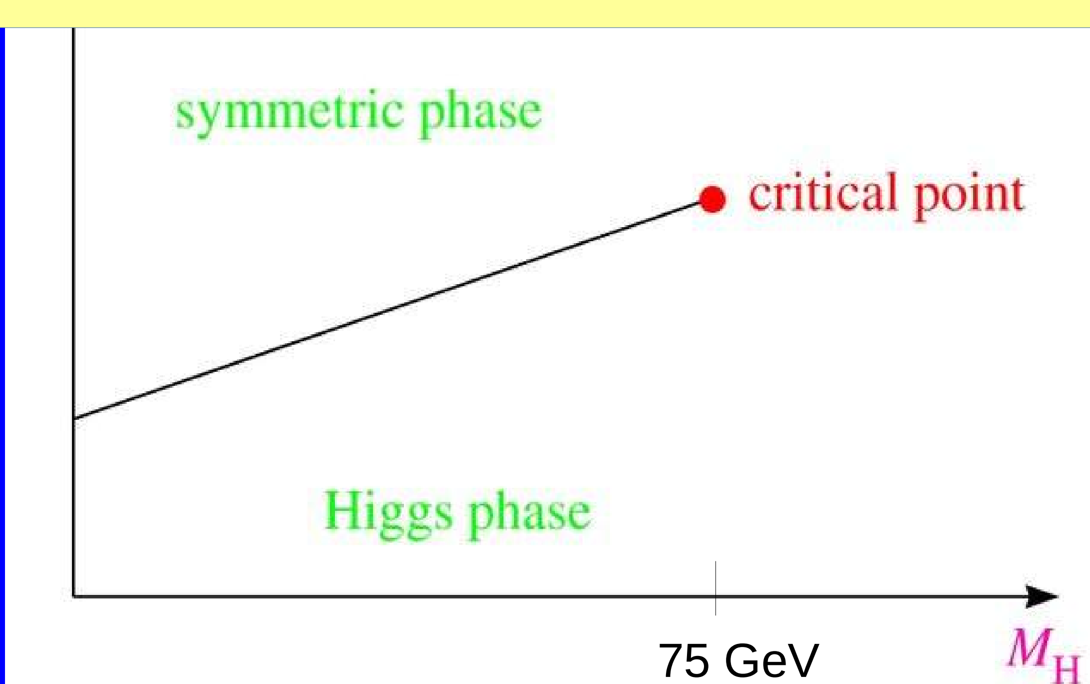


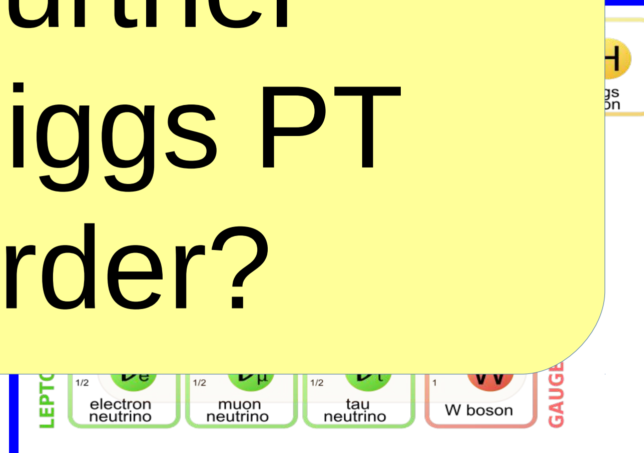


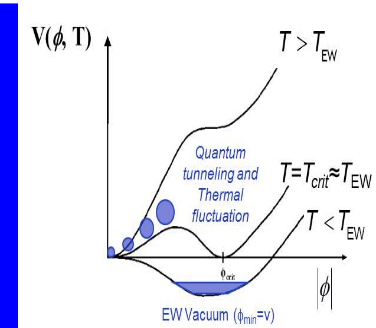


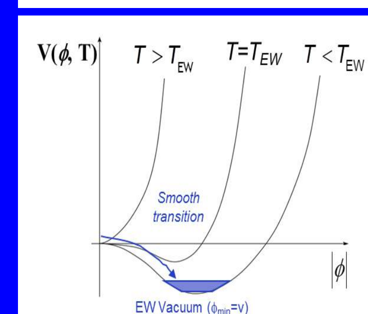
Higgs potential at finite T

But if there exist further particles, can the Higgs PT become of first order?









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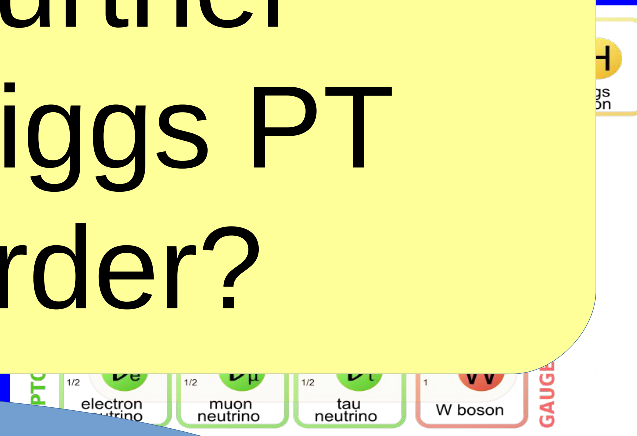
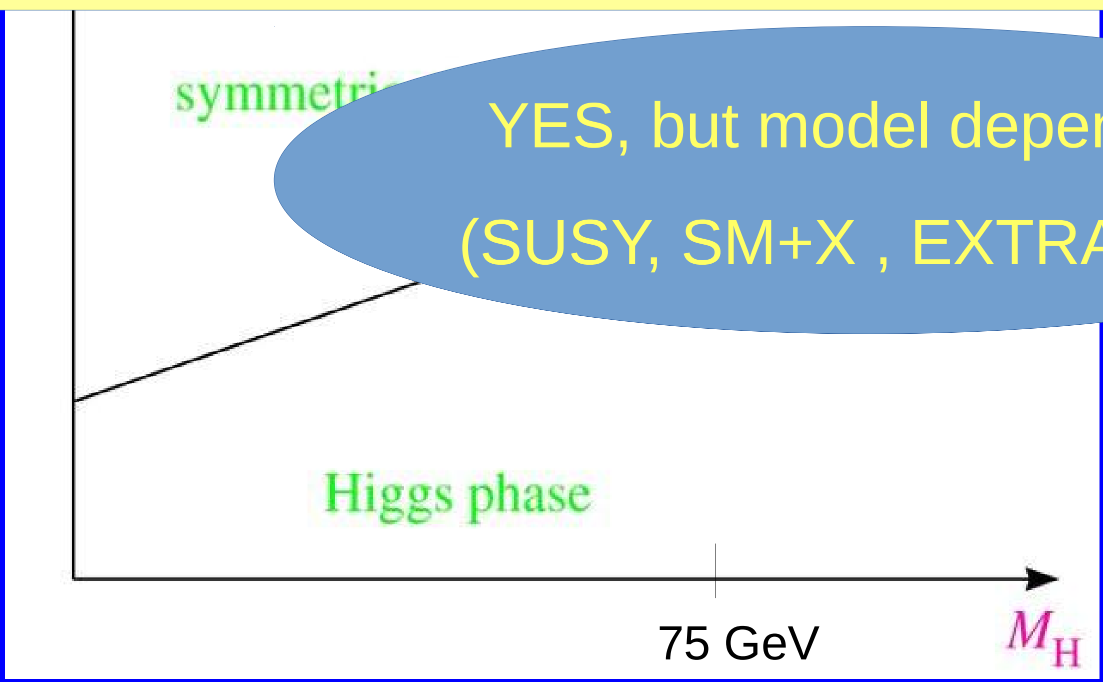
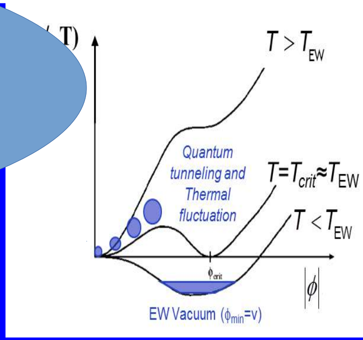
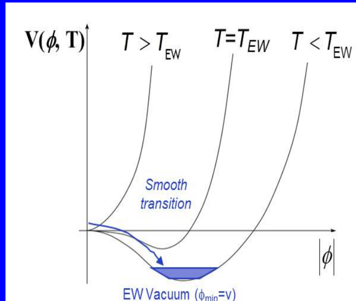




YES, but model dependent

(SUSY, SM+X , EXTRADIM.)





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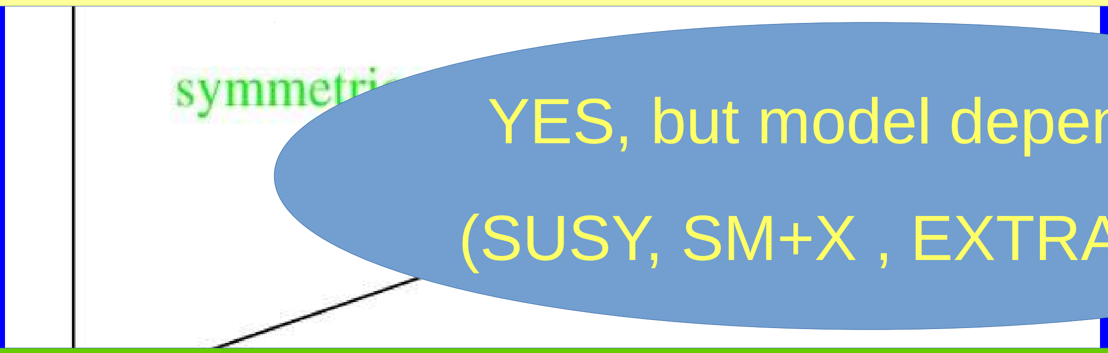

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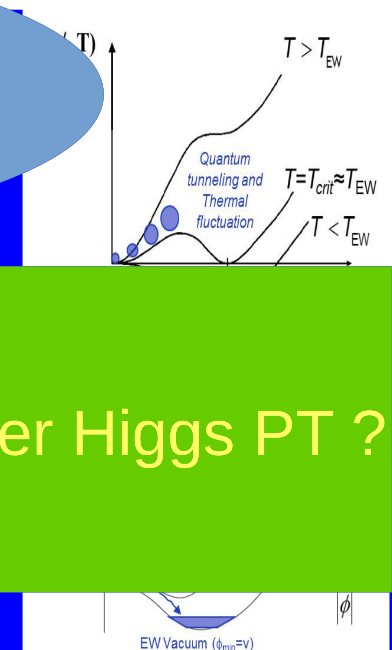
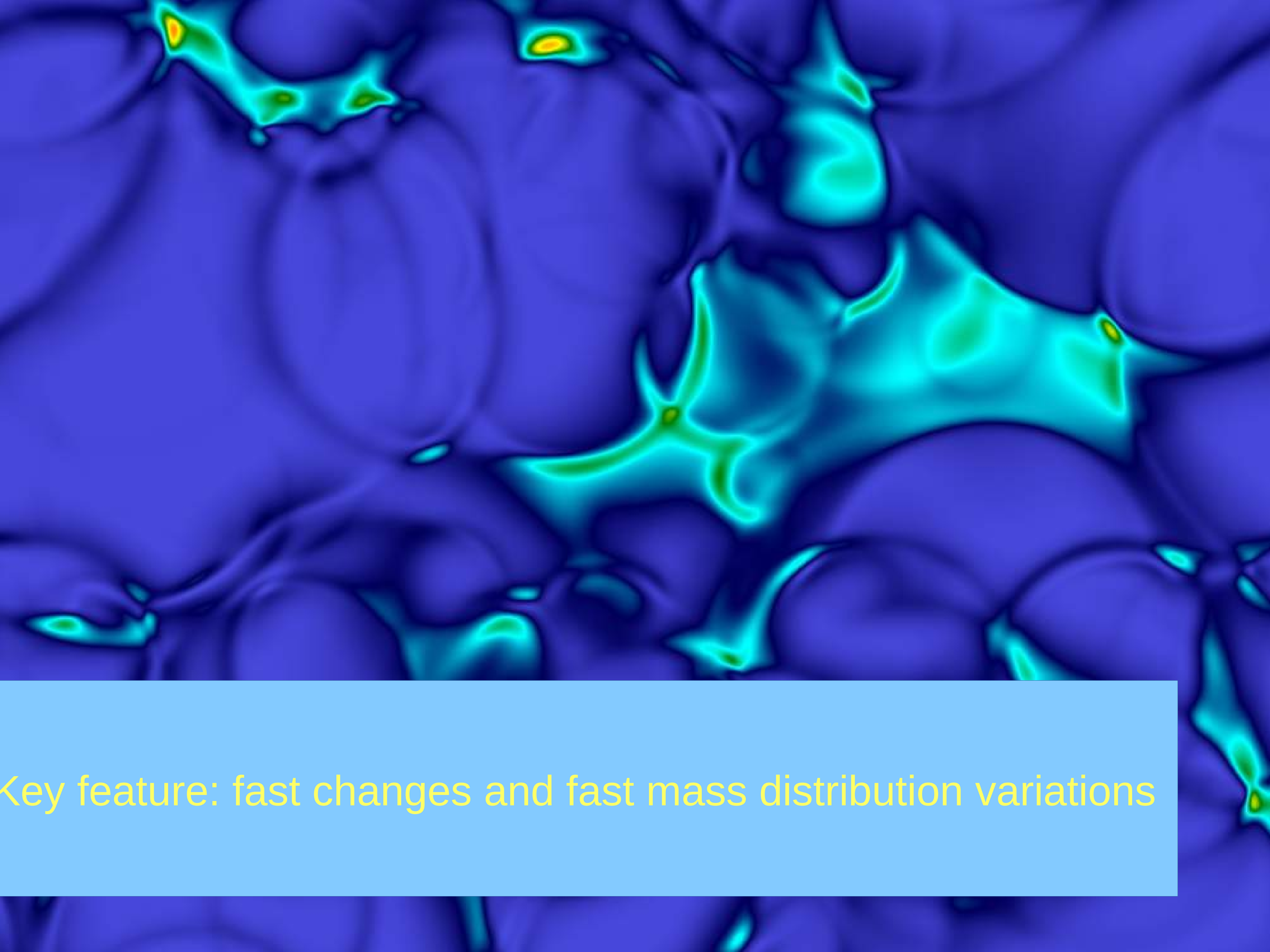
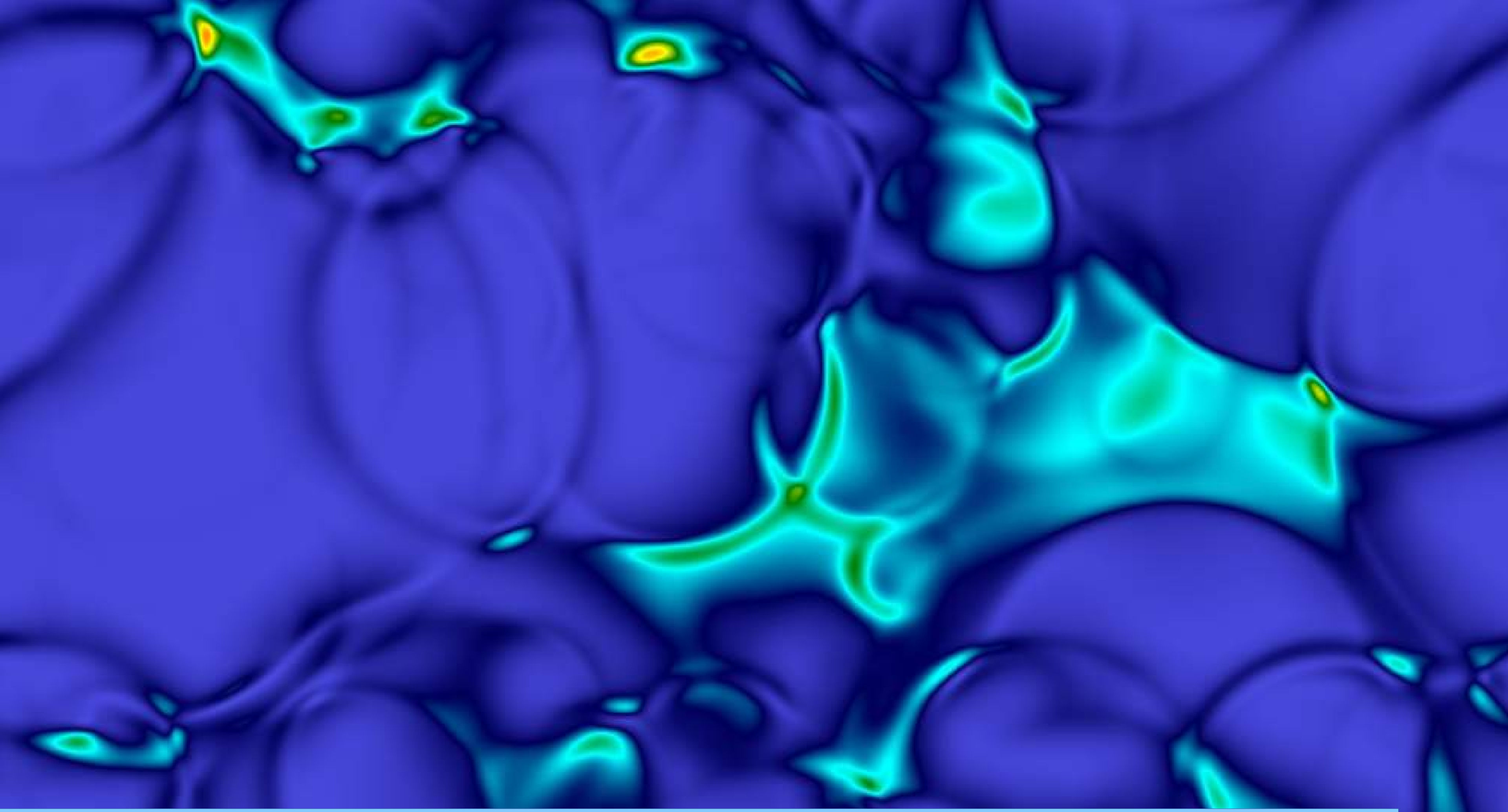


Besides LHC, what are the predictions of a 1st order Higgs PT ?



Key feature: fast changes and fast mass distribution variations



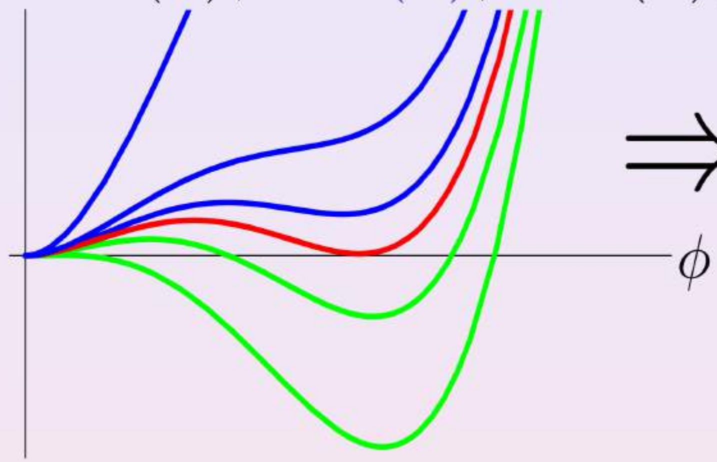
Key feature: fast changes and fast mass distribution variations

↓

Baryogenesis

1^{st}-order Higgs PT → Baryogenesis

$$V(\phi,T) \simeq m^2(T)\phi^2 + E(T)\phi^3 + \lambda(T)\phi^4$$



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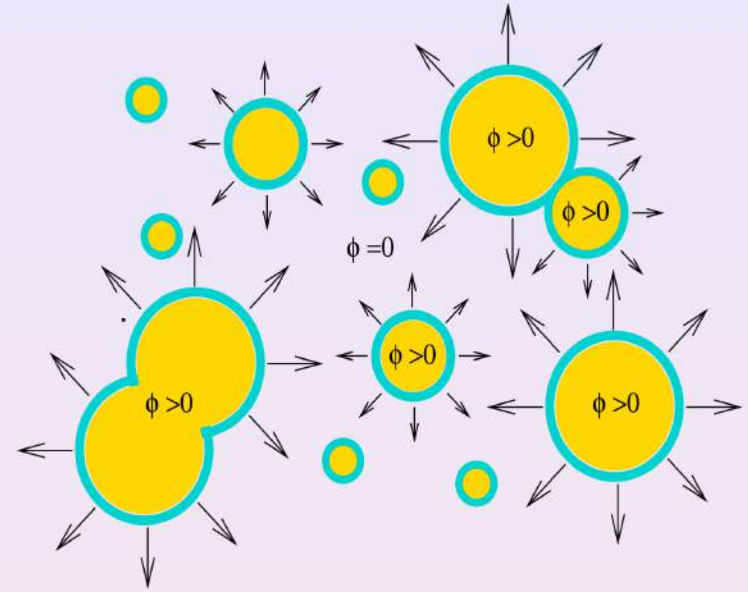
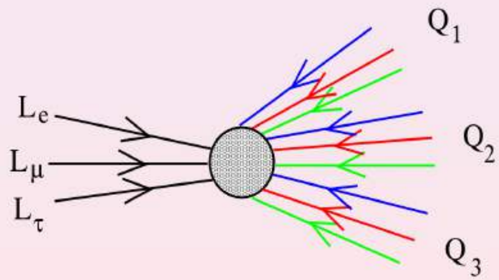


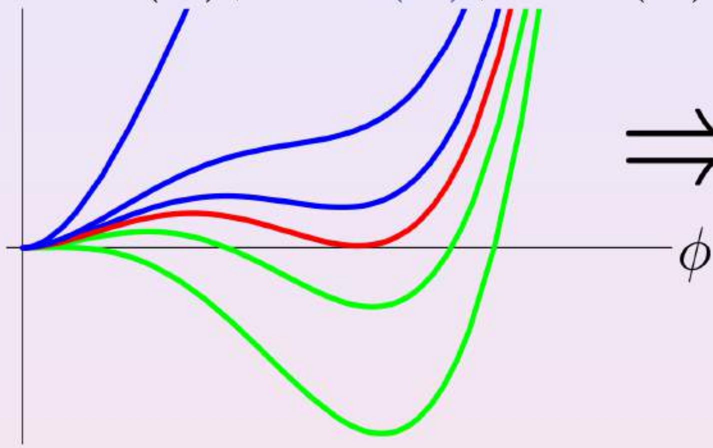
The SM contains the Sakharov conditions:

1. B number is non-perturbative violated at $T \neq 0$ (sphalerons) ['t Hooft,76]
2. CKM matrix contains CP violation
3. EWPT (when of 1^{st} order) proceeds by bubble nucleation. Expanding bubbles break the thermal equilibrium.

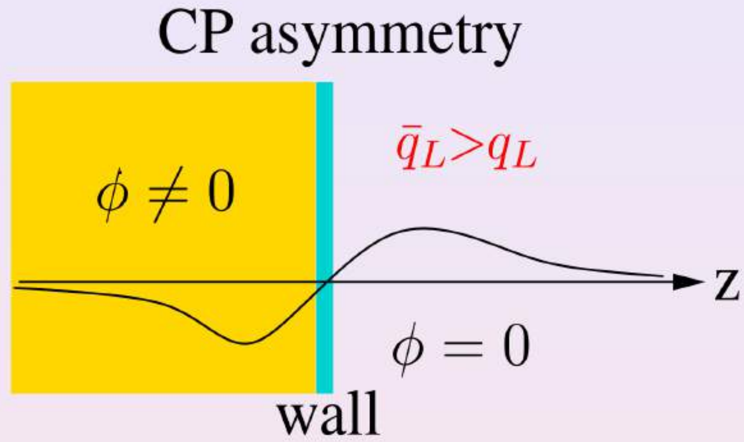


1^{st}-order Higgs PT $\rightarrow$ Baryogenesis

$$V(\phi,T) \simeq m^2(T)\phi^2 + E(T)\phi^3 + \lambda(T)\phi^4$$



$\Rightarrow$



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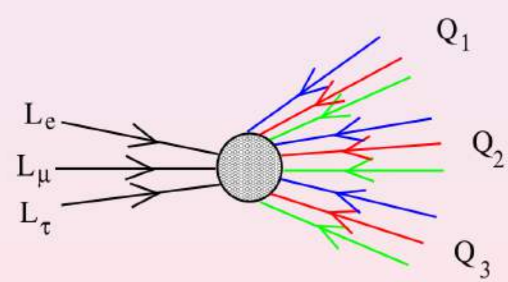

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1st-order Higgs PT → Baryogenesis

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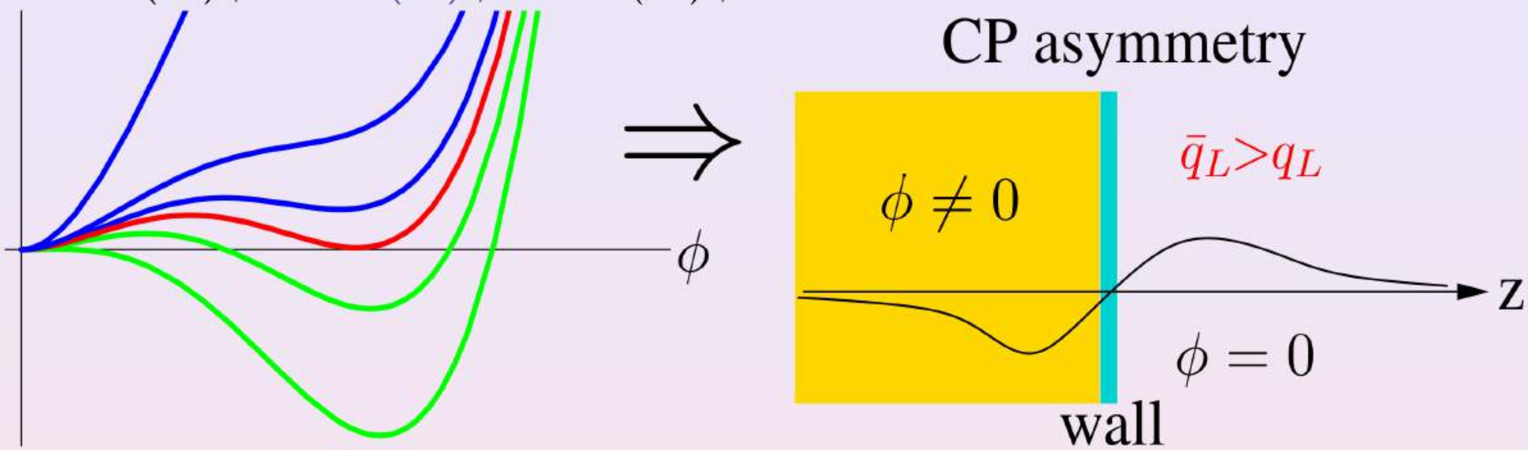
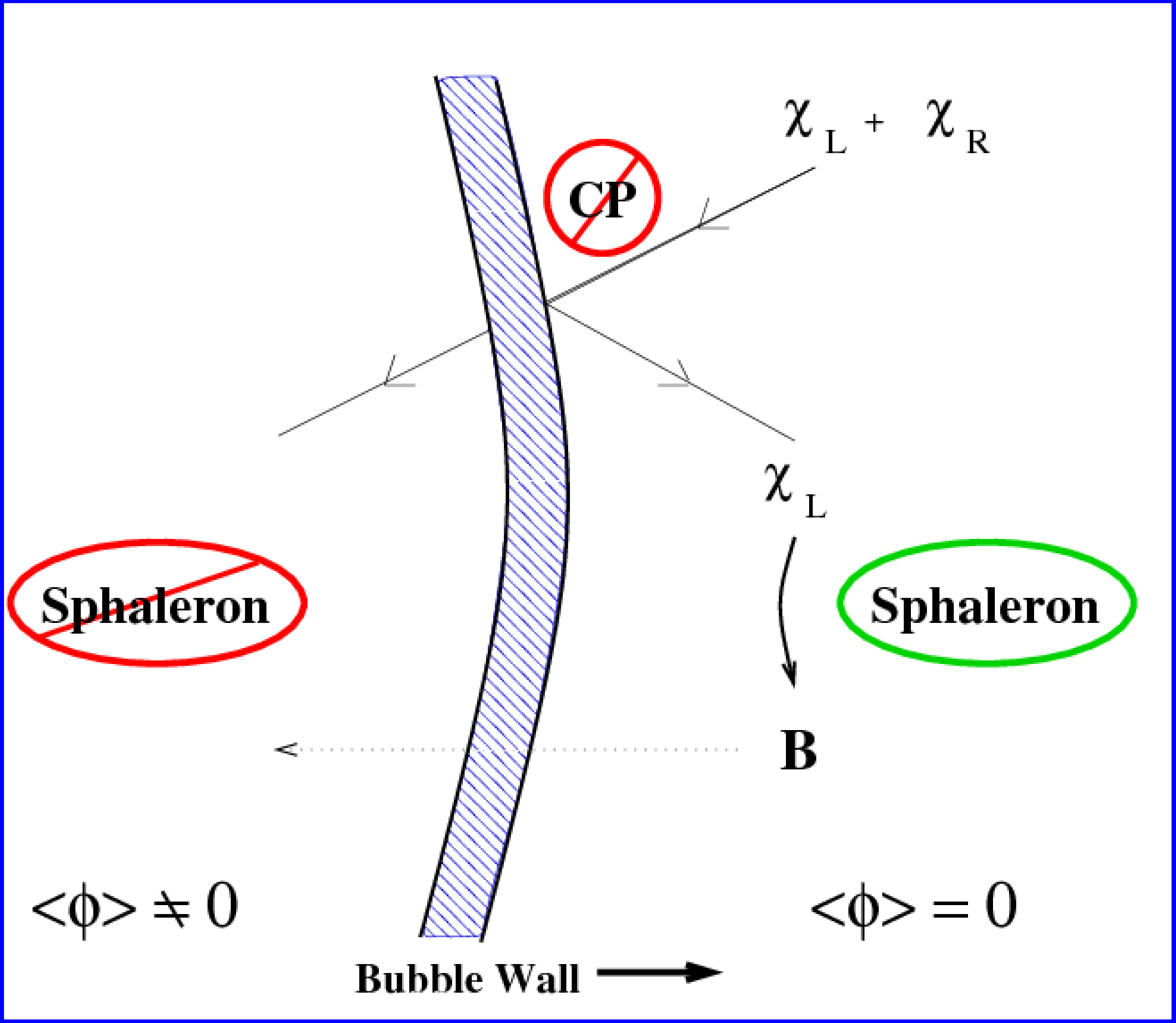


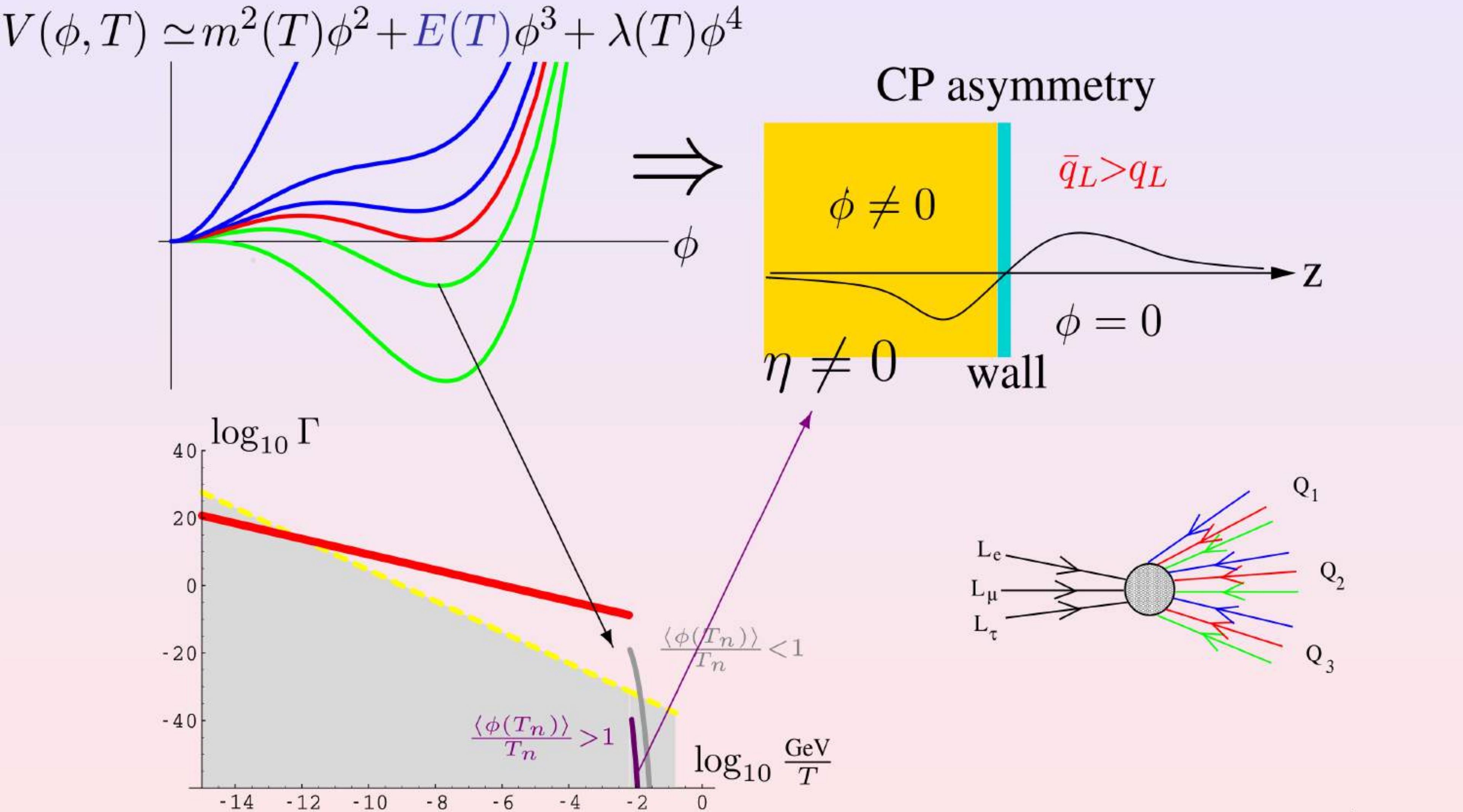
In front of the wall CP asymm. generates temporally $\bar{q}_L > q_L$
$\Rightarrow$ There are more sphalerons $B\uparrow$ than those $B\downarrow$
$\Rightarrow$ Temporally B asymm. is present beyond the wall $\Rightarrow$ The wall expansion accumulates $B > 0$ inside the bubble, where

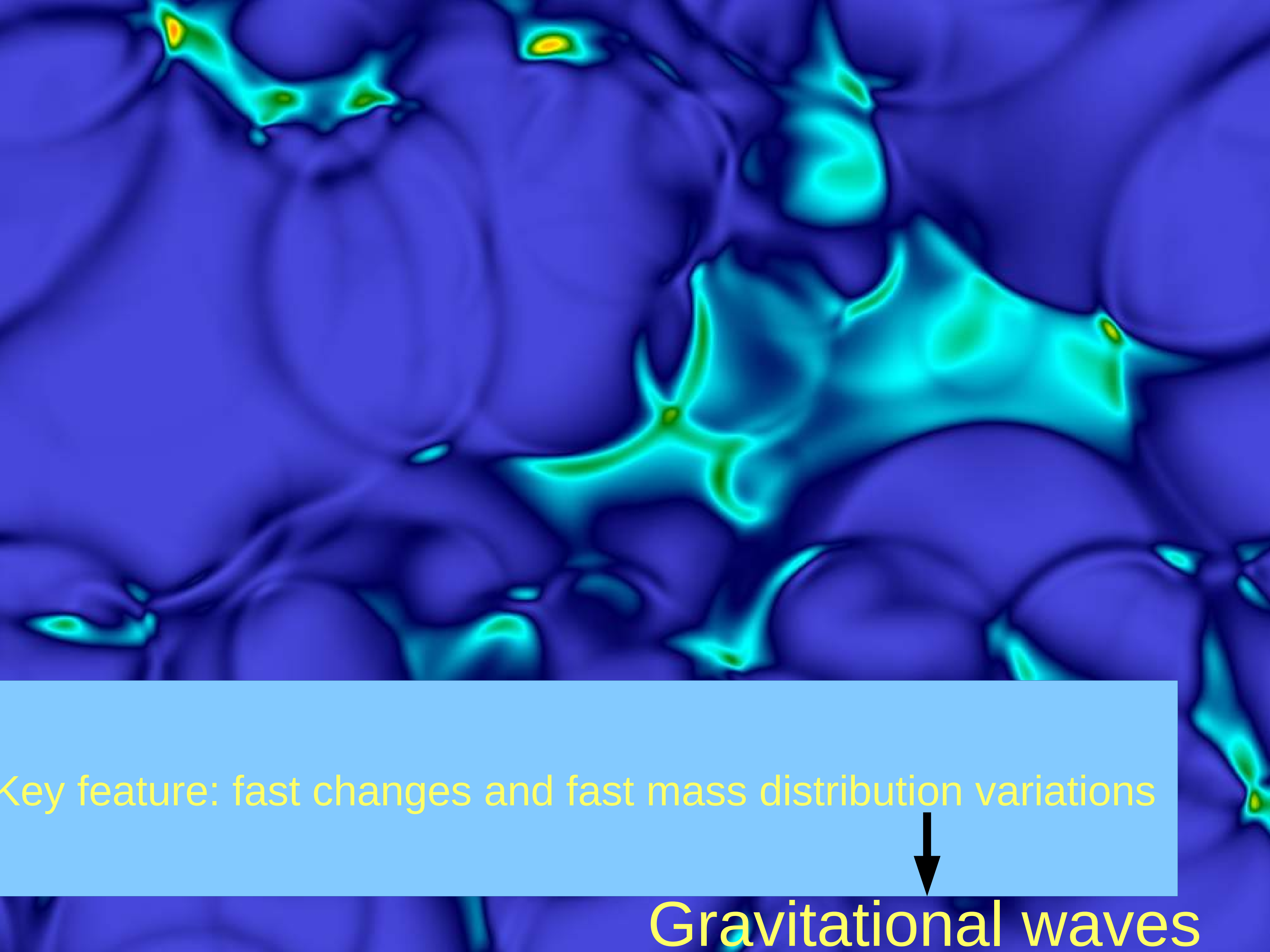
> If broken-phase sphalerons are in therm. equilibrium, $B \to 0$.
> Otherwise *(strong EWPT)* WE HAVE PRODUCED $B \neq 0$.

1^{st}-order Higgs PT → Baryogenesis



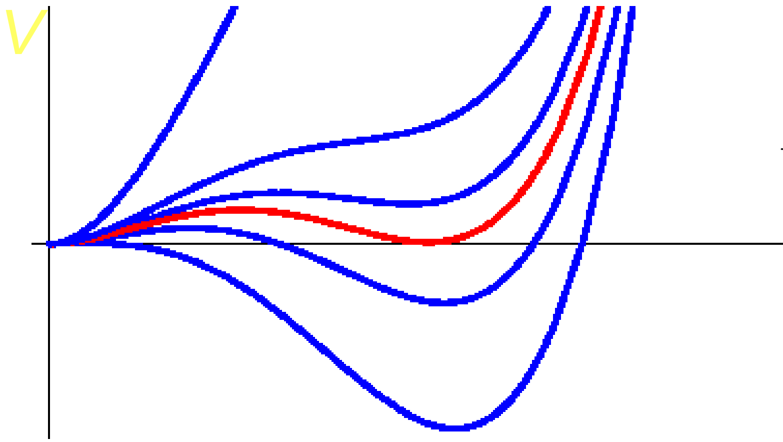
1st-order Higgs PT → Baryogenesis




Key feature: fast changes and fast mass distribution variations
Gravitational waves

1st-order Higgs PT → Gravitational Waves

Let us assume that the EWPT is of first order, i.e.



$$V(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \lambda(T)\phi^4$$

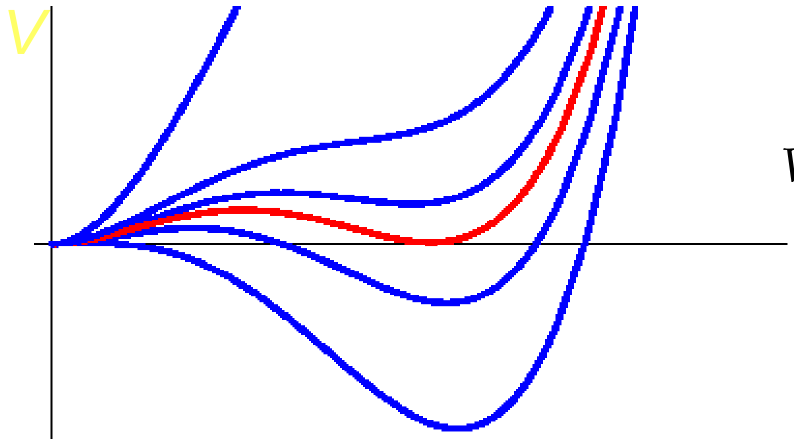
The phase transition occurs via tunneling. In the place where the tunneling happens, a bubble of EW broken phase ($\langle\phi\rangle = \phi_{brok}$ ucleates.

Conventionally, the EWPT starts in the Universe when statistically we have 1 nucleated bubble per Hubble volume and time. The temperature of the Universe at this time is called T_n

The tunneling rate is $\Gamma(t) = \Gamma_0 \exp[-S(t)]$ If $\beta = -dS/dt|_{t=t_n}$ large (small), many (a few) bubbles have nucleated by the time the first bubbles have expanded, i.e. the phase transition ends with many little (a few large) bubbles.

1^{st}-order Higgs PT → Gravitational Waves

Let us assume that the EWPT is of first order, i.e.



$$V(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \lambda(T)\phi^4$$

When bubbles collide, they convert part of their kinetic energy (of the expanding wall + turbulent fluid) into gravitational waves (GWs)!

So, the more energy is available, the stronger the GW signal

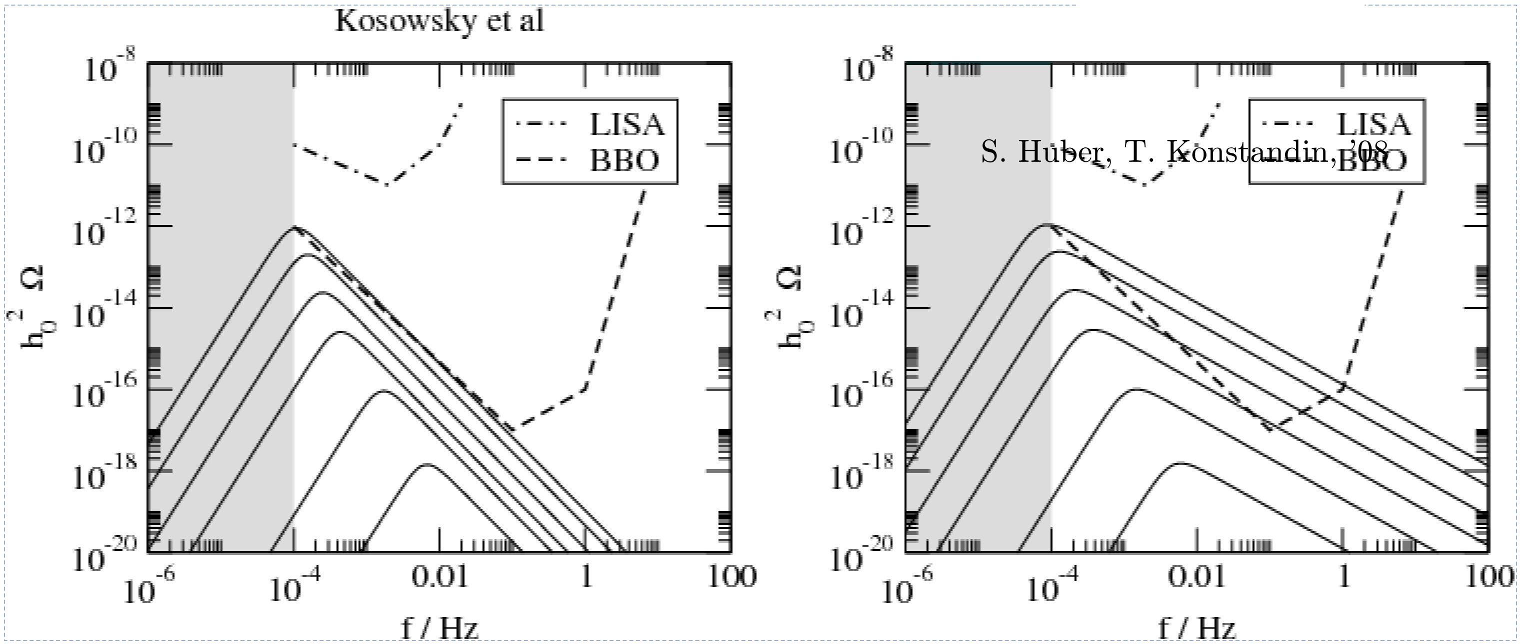
This available energy is the latent heat

$$\epsilon(T_n) = \Delta V(T_n) - T\frac{\partial \Delta V(T_n)}{\partial T} \quad , \qquad \Delta V(T_n) = V(\phi_{sym}, T_n) - V(\phi_{brok}, T_n)$$

which we normalize to the radiation energy: $\alpha = \epsilon(T_n) / \left(\frac{\pi^2}{30} g_* T_n^4\right)$

1^{st}-order Higgs PT → Gravitational Waves

Simulations on bubble collisions (based on the "envelope approx") show



where (for $v_w \simeq 1$)

$$h_0^2 \Omega_{GW} \approx 10^{-10} \kappa^2(\alpha) \left(\frac{100}{\beta/H}\right)^2 \left(\frac{\alpha}{\alpha+1}\right)^2$$

$$f_{peak} \approx \mathrm{mHz} \left(\frac{\beta/H}{100}\right) \left(\frac{T_n}{100\mathrm{GeV}}\right)$$

1^{st}-order Higgs PT → Gravitational Waves

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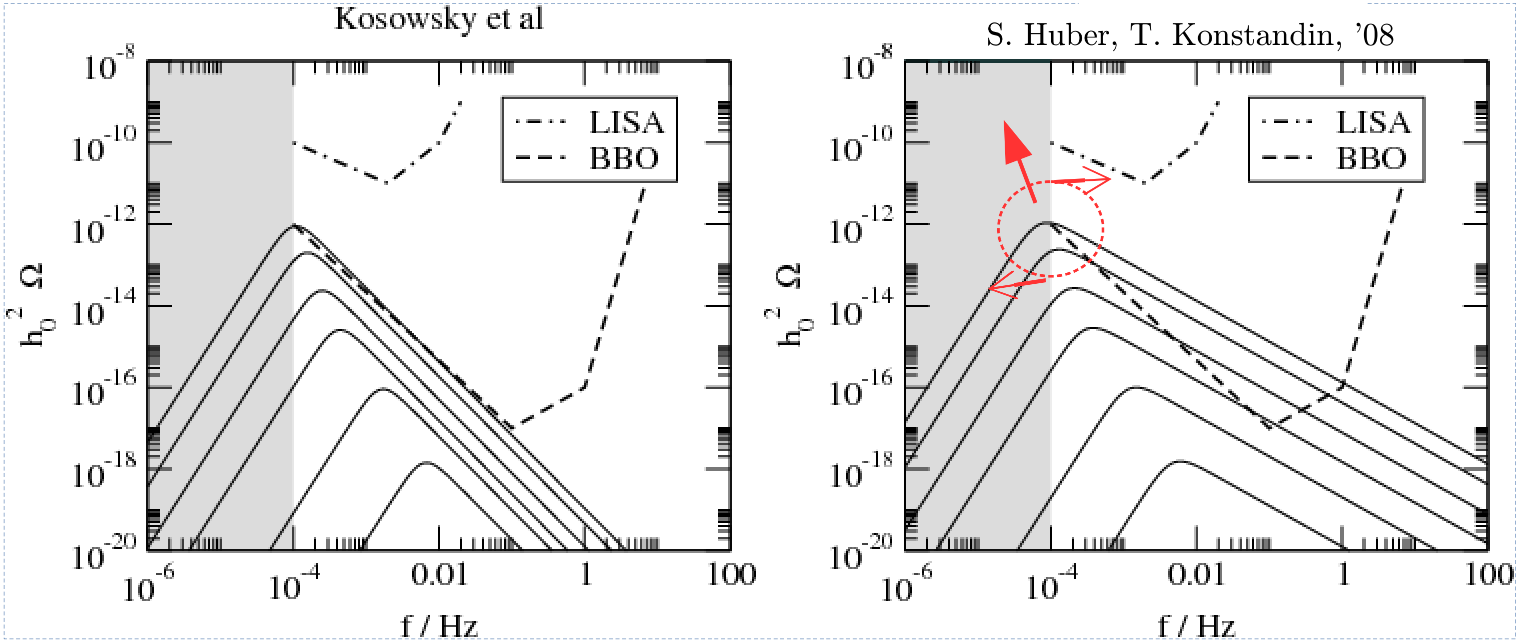

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$$f_{peak} \approx \text{mHz}\left(\frac{\beta/H}{100}\right)\left(\frac{T_n}{100\text{GeV}}\right)$$

- However some plasma dynamics can modify the spectrum: sound waves

1^{st}-order Higgs PT → Gravitational Waves

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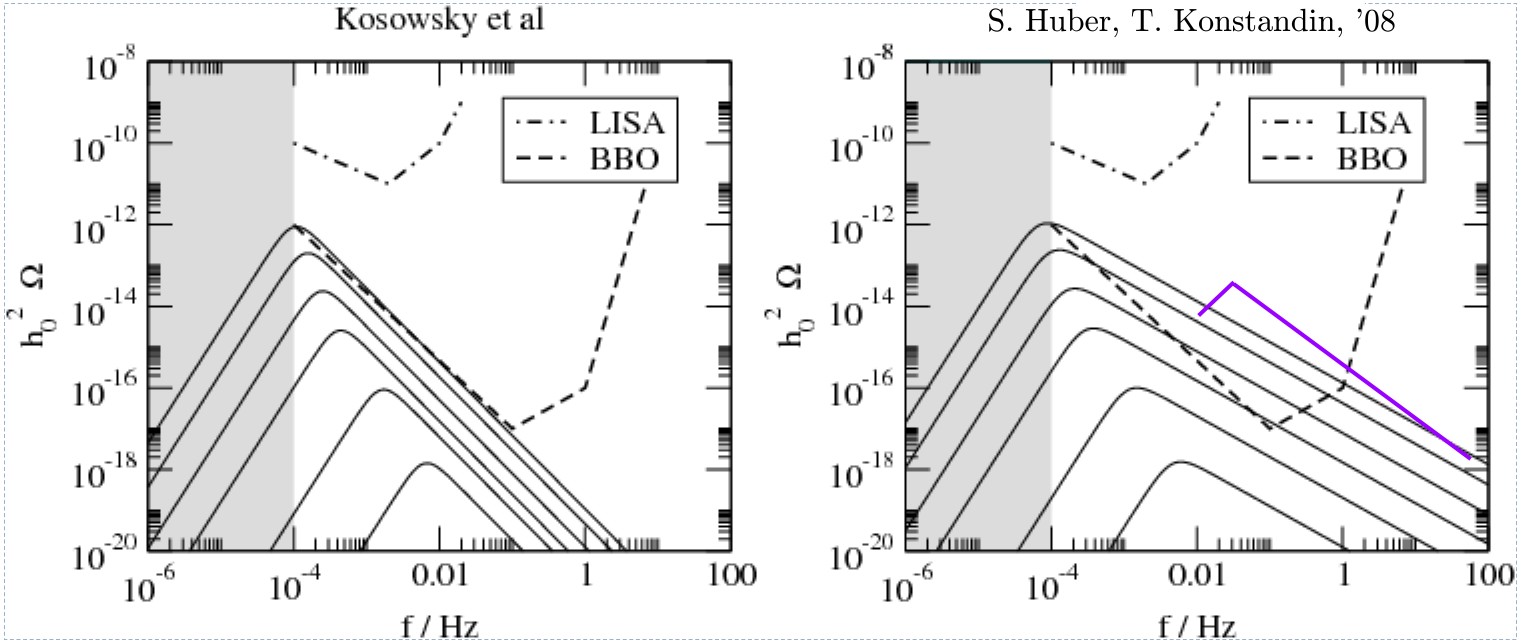

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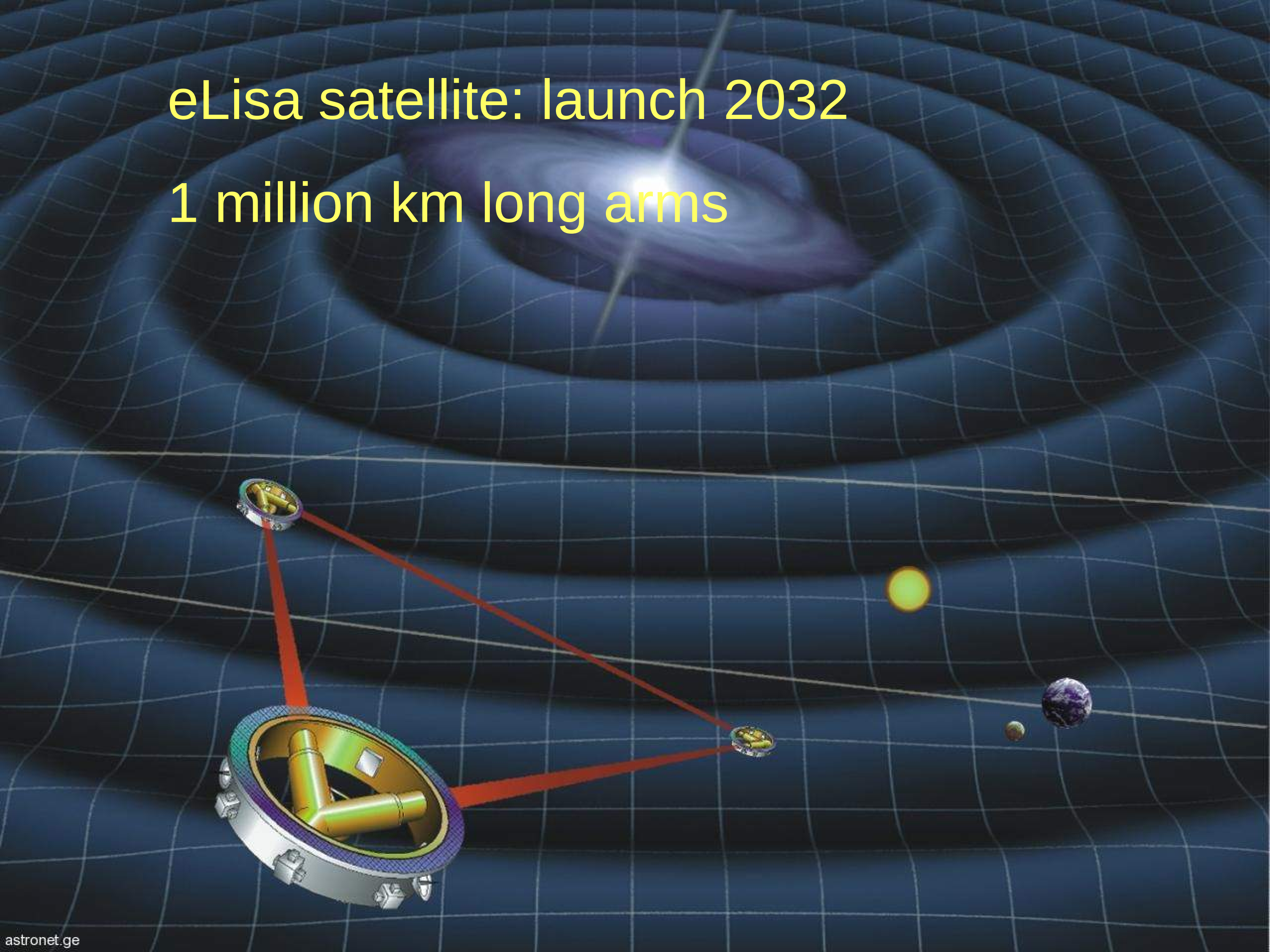
$$f_{peak} \approx \mathrm{mHz} \left(\frac{\beta/H}{100}\right) \left(\frac{T_n}{100\mathrm{GeV}}\right)$$

- However uncertainties due to the plasma dynamics: MHD turbulence

P.Binetruy,A.Bohe,C.Caprini,J.Dufaux,'12


eLisa satellite: launch 2032
1 million km long arms
astronet.ge

Lisa Pathfinder

Launch date

2 December 2015