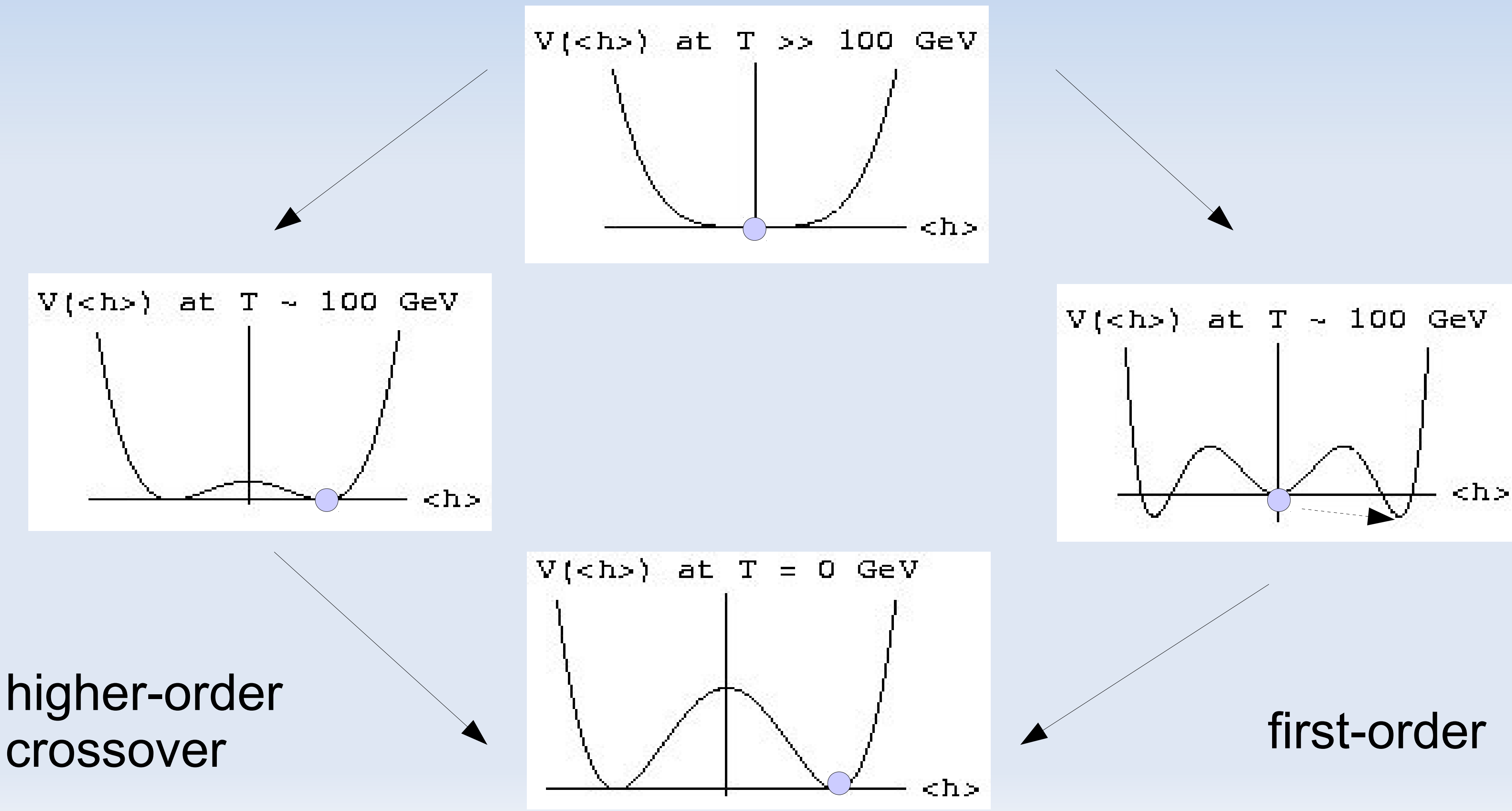
Cosmology on Electroweak Scales

Thomas Konstandin

Osaka, February 19, 2019

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 (**HPNP**):



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

- 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:

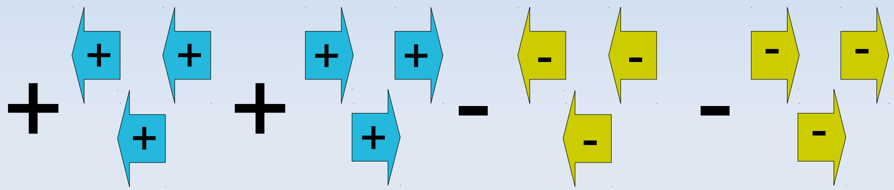
- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium

Baryogenesis

[Sakharov '69]

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

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



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

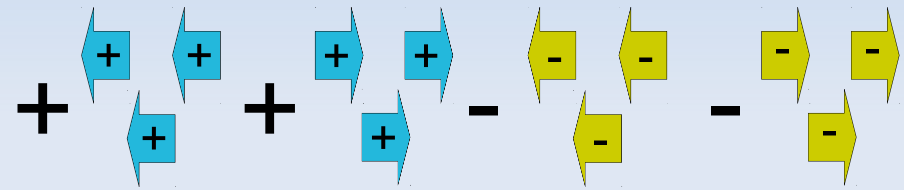
- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium

Baryogenesis

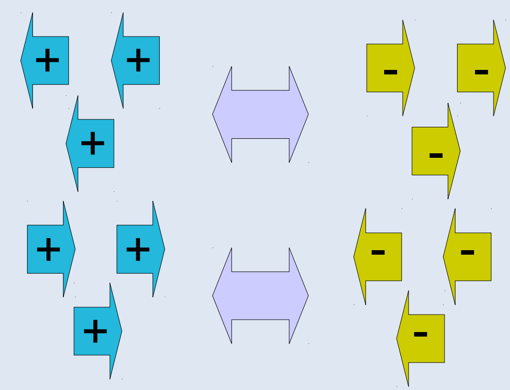
[Sakharov '69]

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

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



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



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

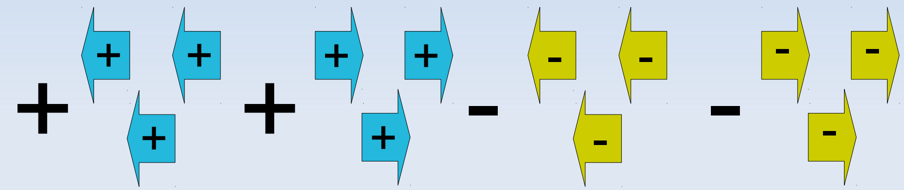
- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium

Baryogenesis

[Sakharov '69]

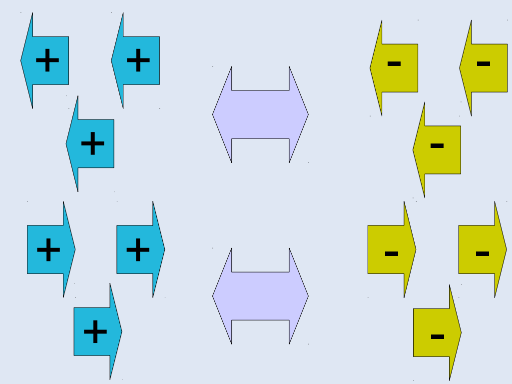
Baryogenesis aims at explaining the observed asymmetry between matter and antimatter abundances.

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



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



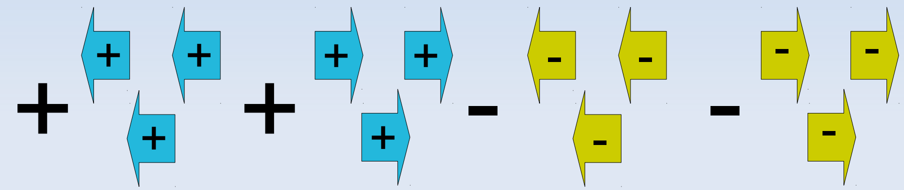
$$n_B \leftrightarrow n_{\bar{B}}$$

Baryogenesis

[Sakharov '69]

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

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



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

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

$$m = \bar{m}$$

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

Baryogenesis

[Sakharov '69]

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

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

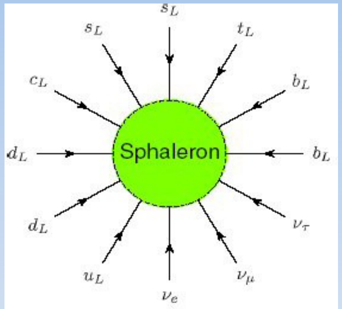
$\not{C}$ $\not{B}$ $\not{CP}$ $\not{eq}$

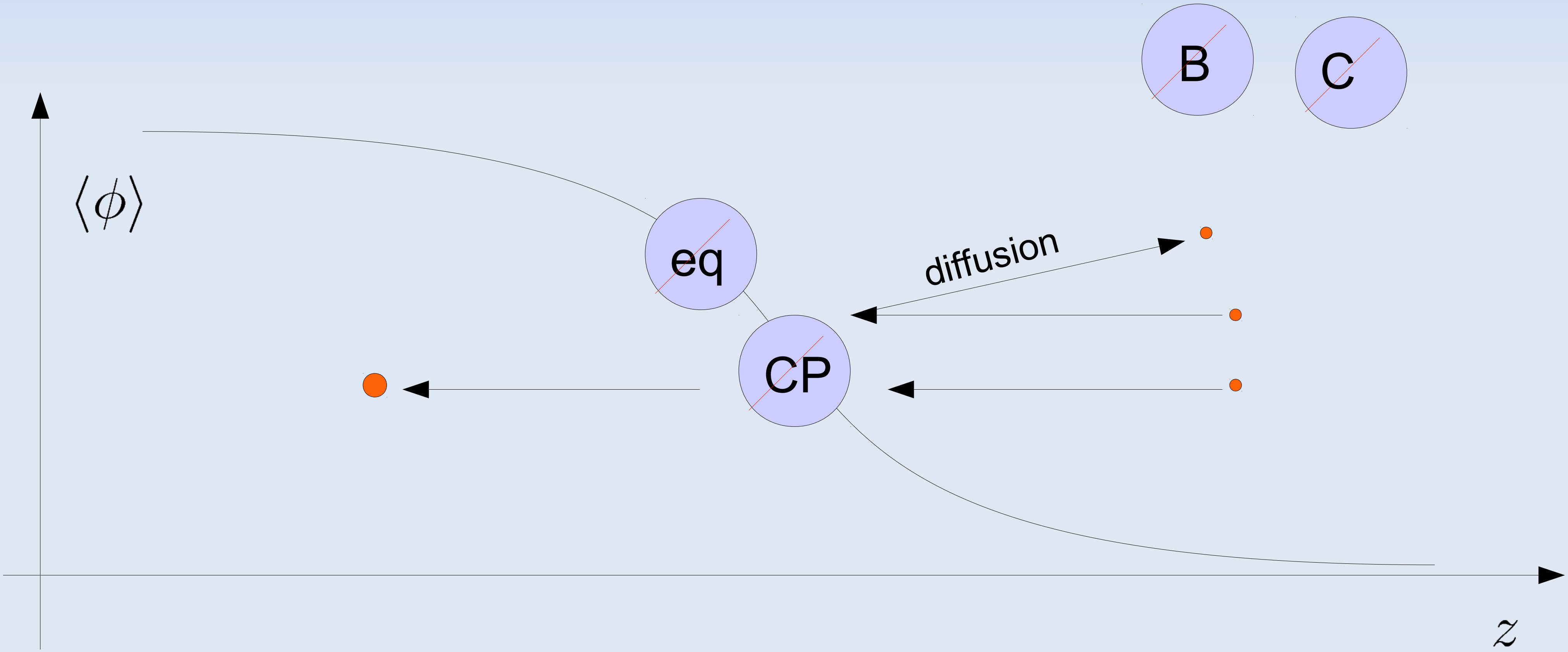
SM @ EW temp

✓	B+L anomaly	sphaleron
✗	Jarlskog invariant	beyond the SM physics essential
✗	expansion slow EW PT?	

Electroweak baryogenesis

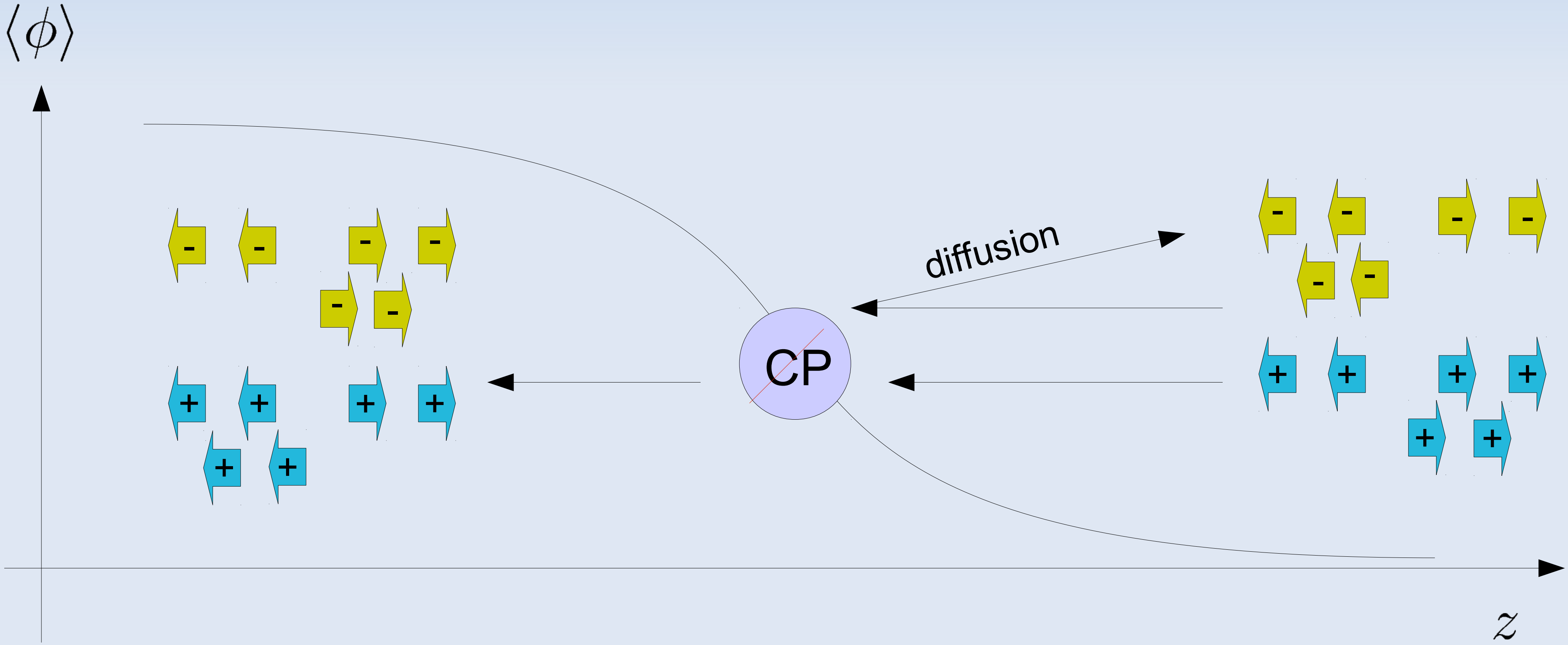
[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]





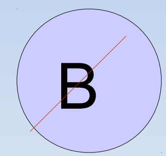
Electroweak baryogenesis

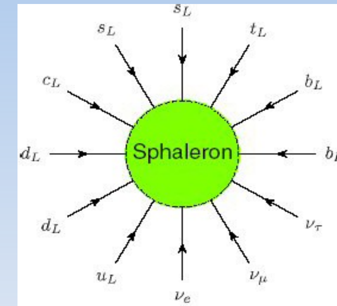
[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]

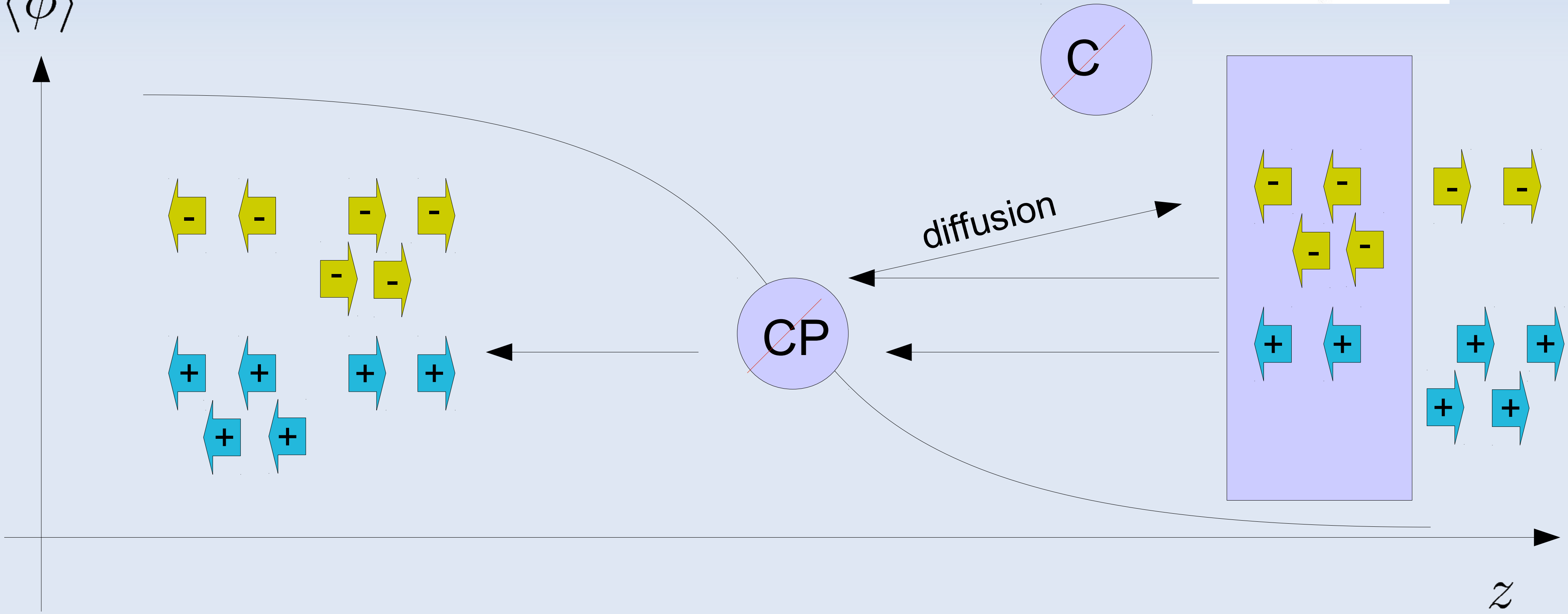


Electroweak baryogenesis

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

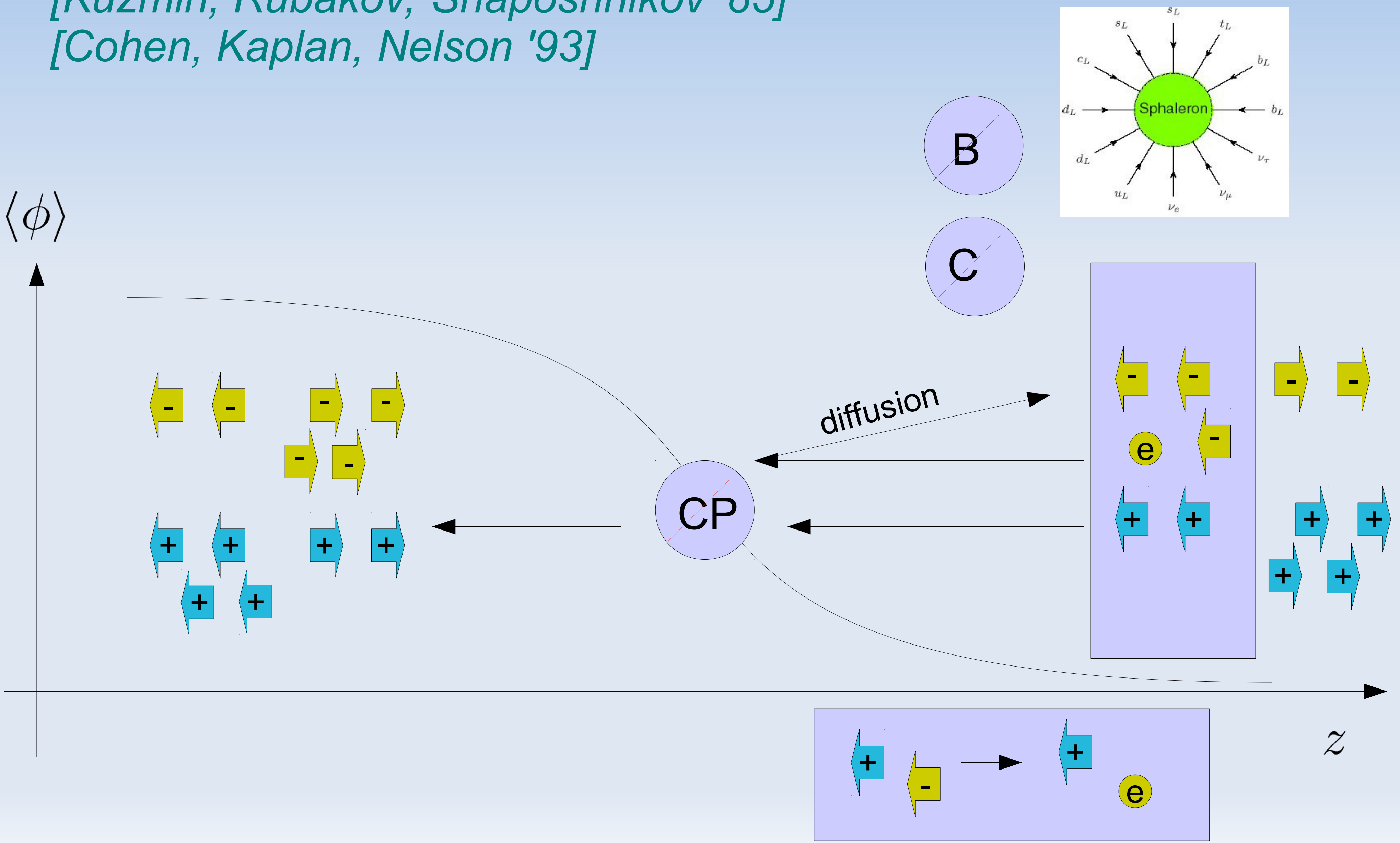






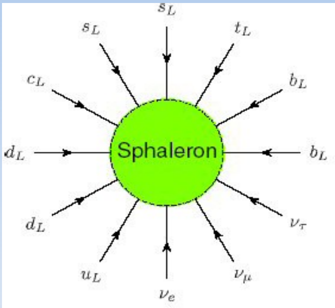
Electroweak baryogenesis

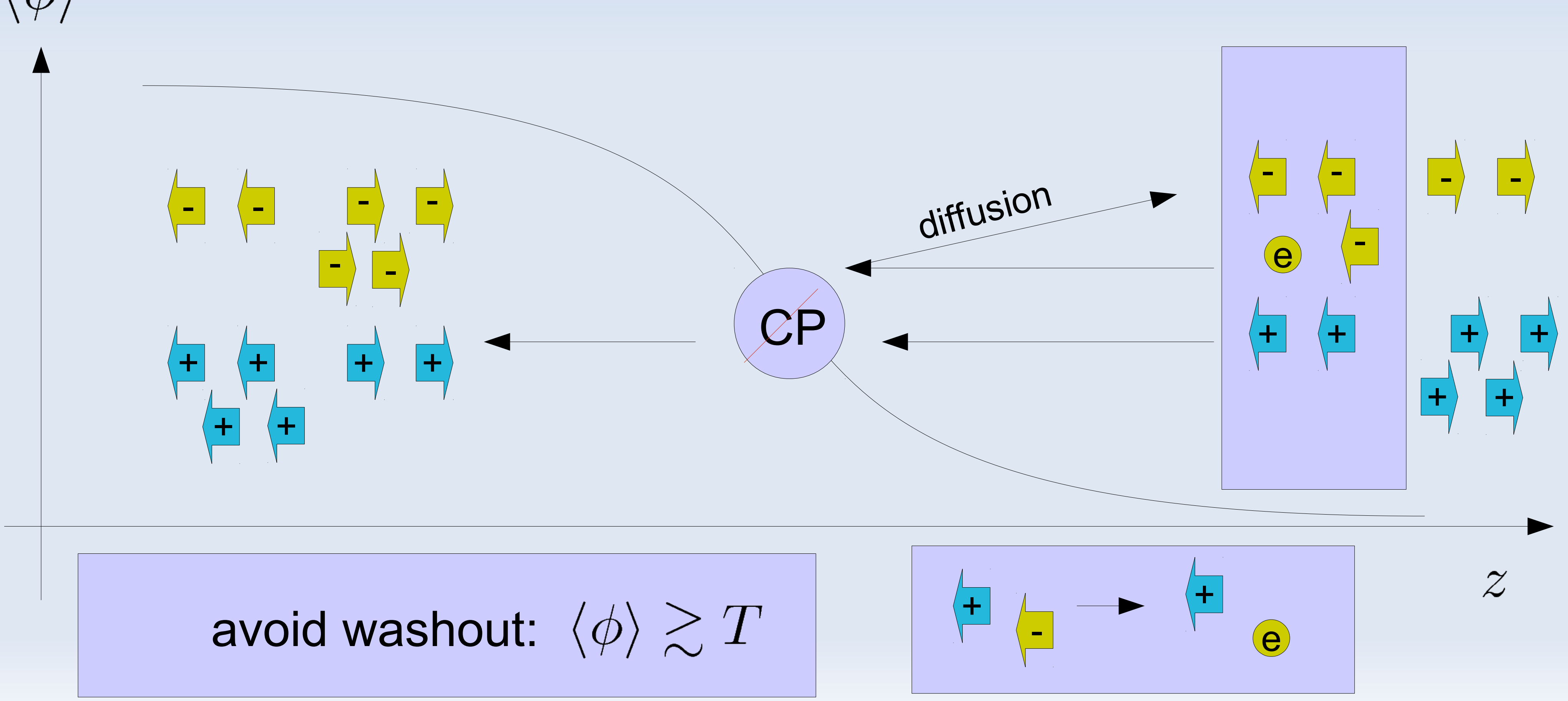
[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]



Electroweak baryogenesis

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





Ingredients

1 ~~eq~~ Strong first-order electroweak phase transition $\phi > T$

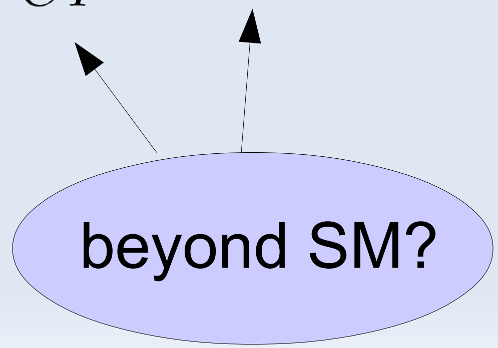
→ modifications in the Higgs sector

2 ~~CP~~ Some fermion species that is reflected in a CP violating way at the Higgs bubble
→ EDMs

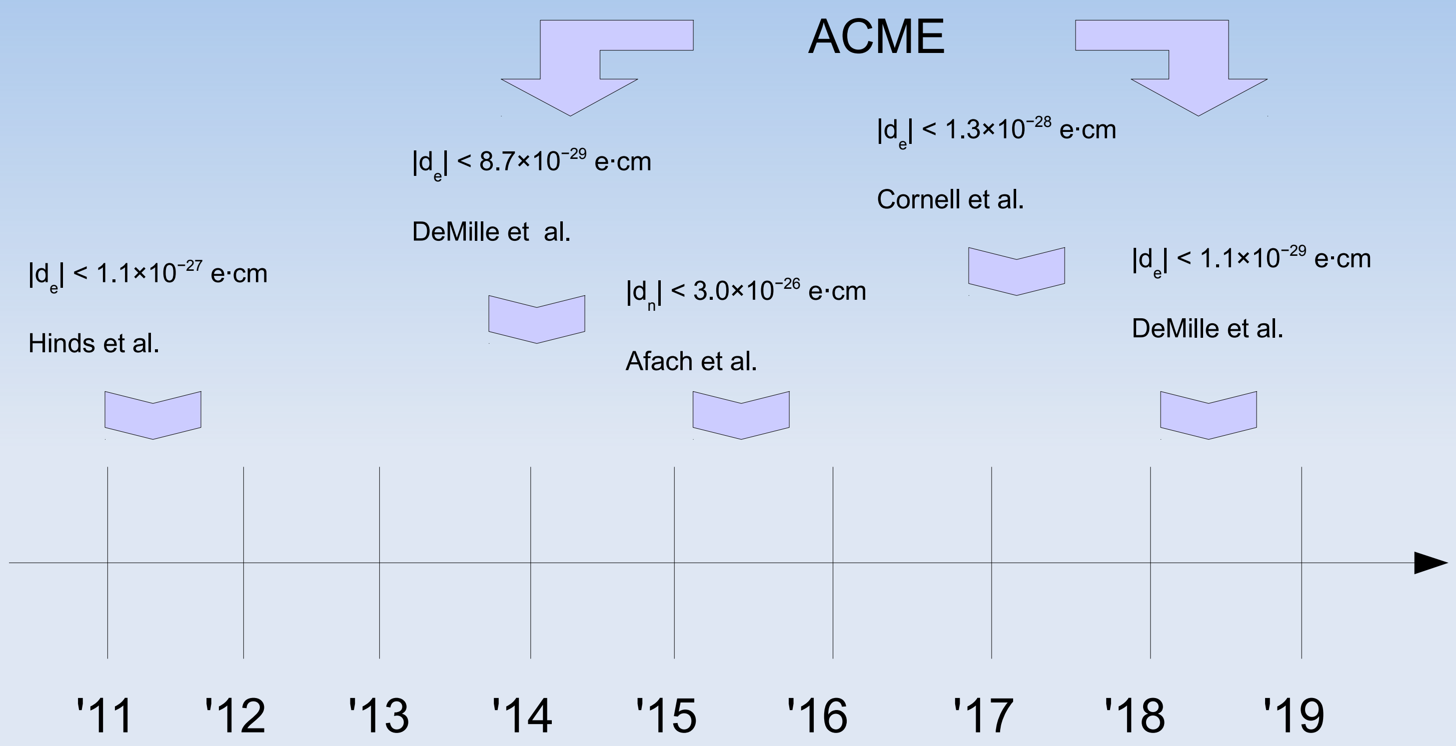
Why is this interesting?

- 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

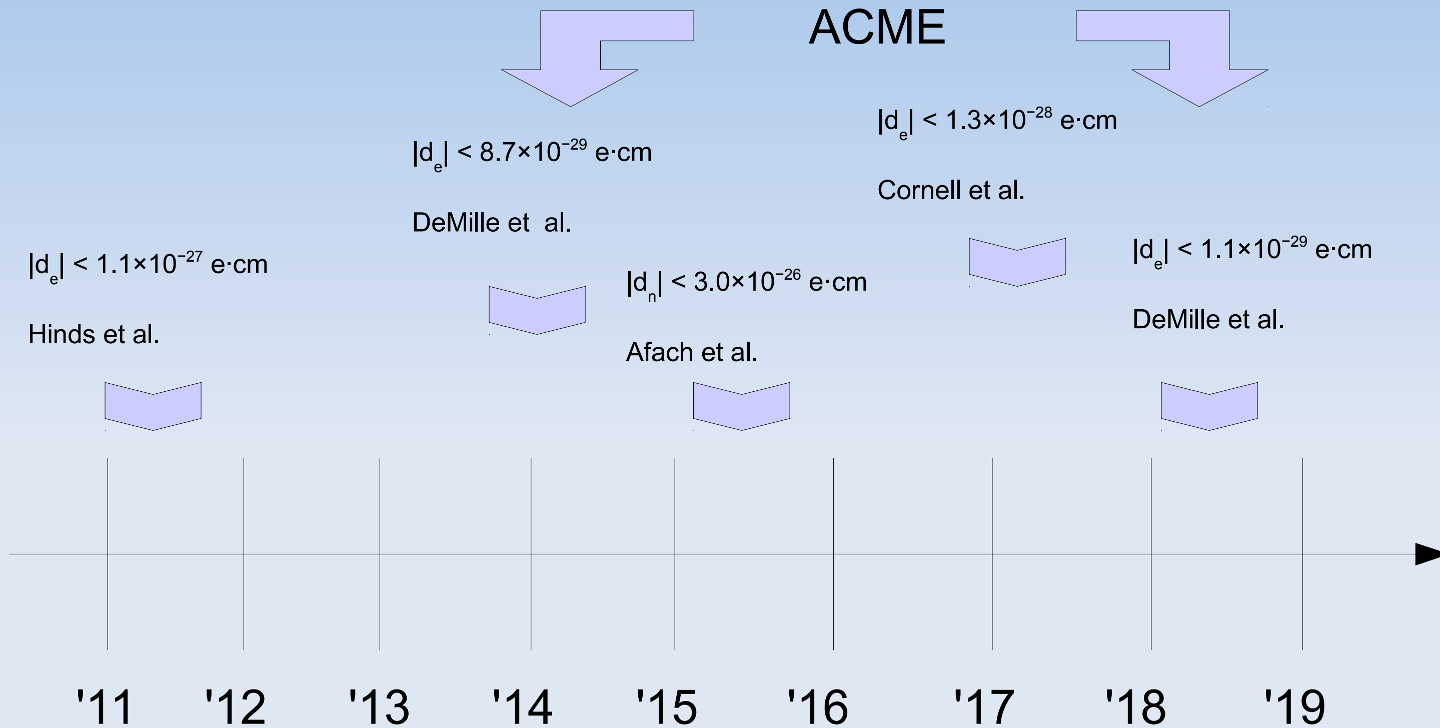
$$\eta_B \sim \frac{\Gamma_{ws}}{l_w T^2} \, \delta_{CP} \, e^{-m_\chi/T} \sim 10^{-11} - 10^{-9}$$

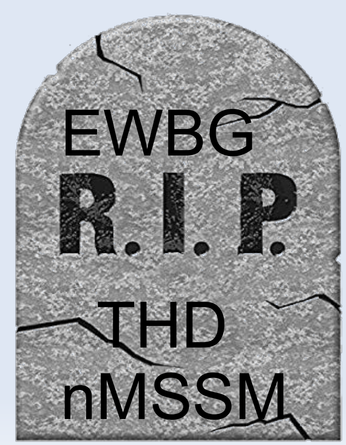


Time line of EDM bounds

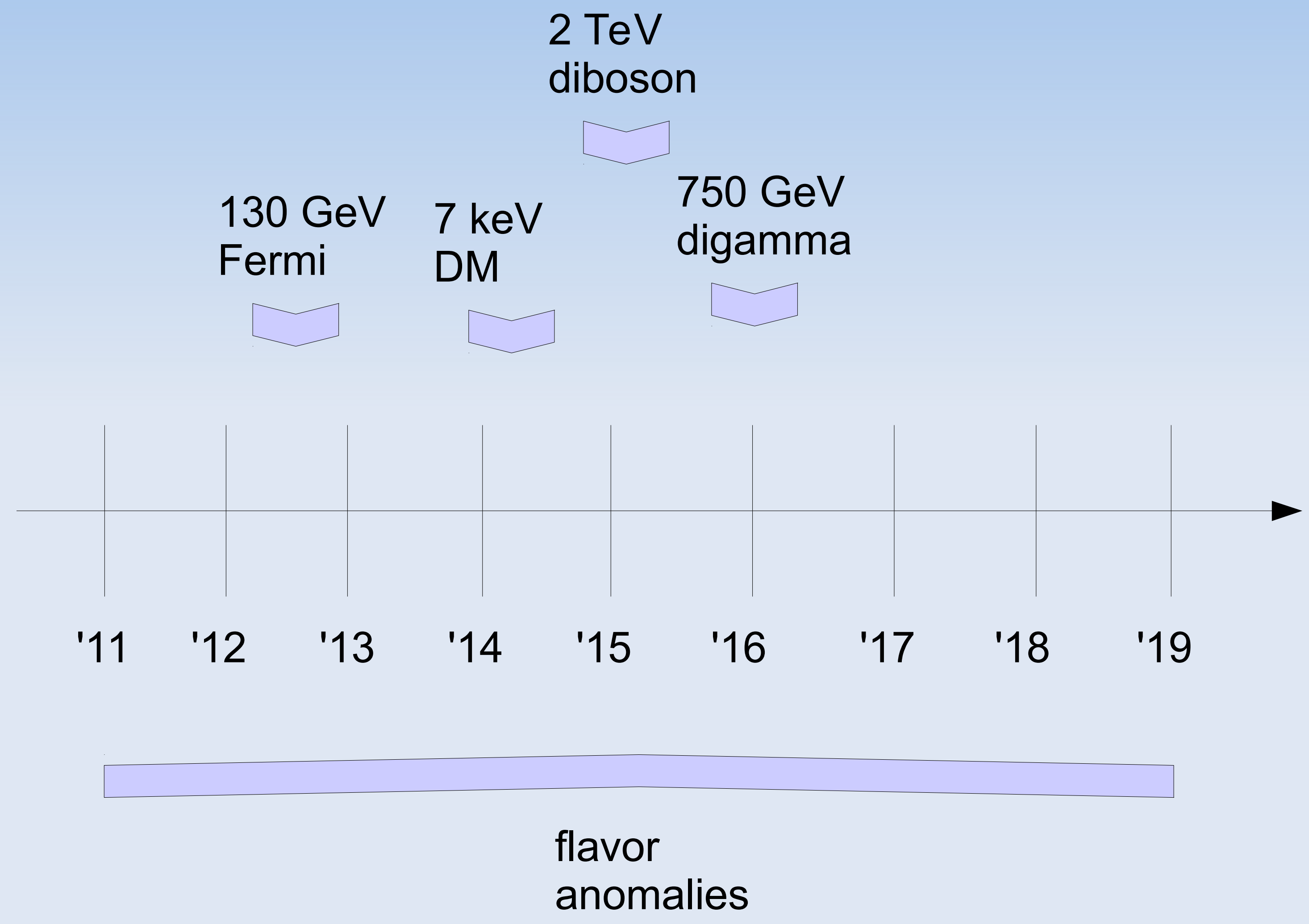


Time line of EDM bounds





Time line of BSM discoveries

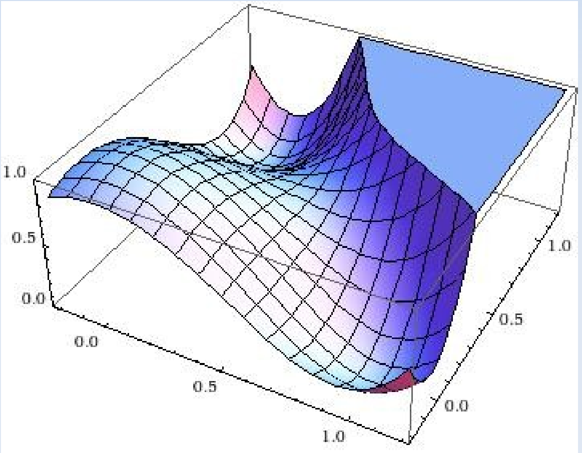


Minimal model

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

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

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

This model was also called the nightmare scenario.

Composite Higgs models

The broken symmetry will determine the light degrees of freedom and their quantum numbers

$$\frac{SO(5)}{SO(4)} \to H$$

[Kaplan, Georgi '84]

but also

$$\frac{SO(6)}{SO(5)} \to H + S \qquad \frac{SO(6)}{SO(4) \times SO(2)} \to 2H$$

In these models, Yukawa couplings are often generated dynamically, which helps to drive EWBG and to suppress EDM constraints at the same time.

Besides the strong coupling at ~TeV scales often makes the EW phase transition stronger.

→ talk by **S. Bruggisser**

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)

Working models

- need a mechanism that suppress observable EDMs
- often require a low cutoff:
  A) to introduce new SM CPV (higher dim operators)
  B) to make the PT strong

Falsifiability?

→ talk by **S. Bruggisser:** today @ 9:30
→ poster by **F. P. Huang:** today
→ talk by **M. Ramsey-Musolf:** Wed @ 9:00
→ talk by **K. Fuyuto:** Wed @ 10:00
→ talk by **E. Senaha:** Yesterday

Electroweak phase transition

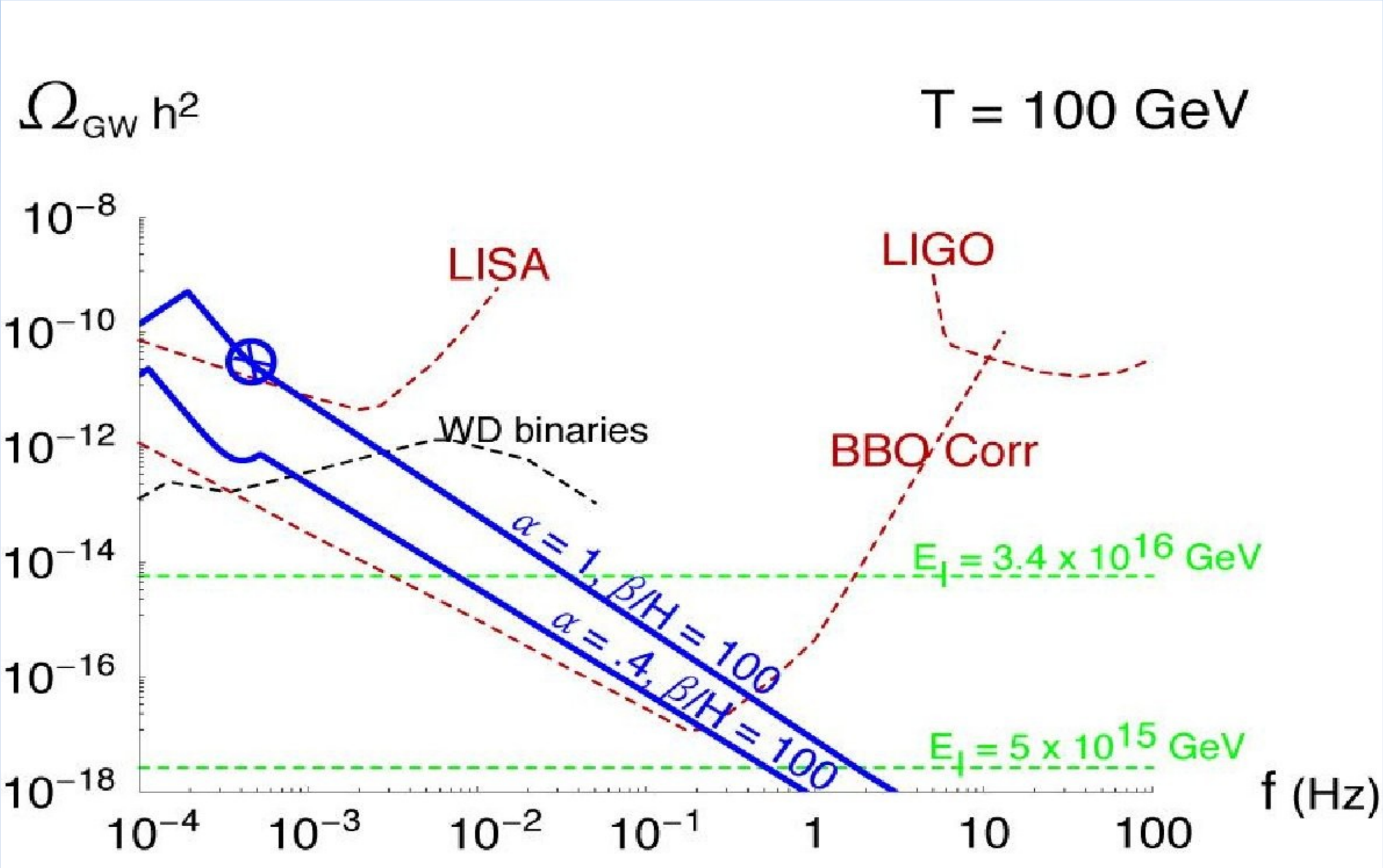
gravitational
waves

baryogenesis

Cosmological phase transition

Gravitational waves from the phase transition

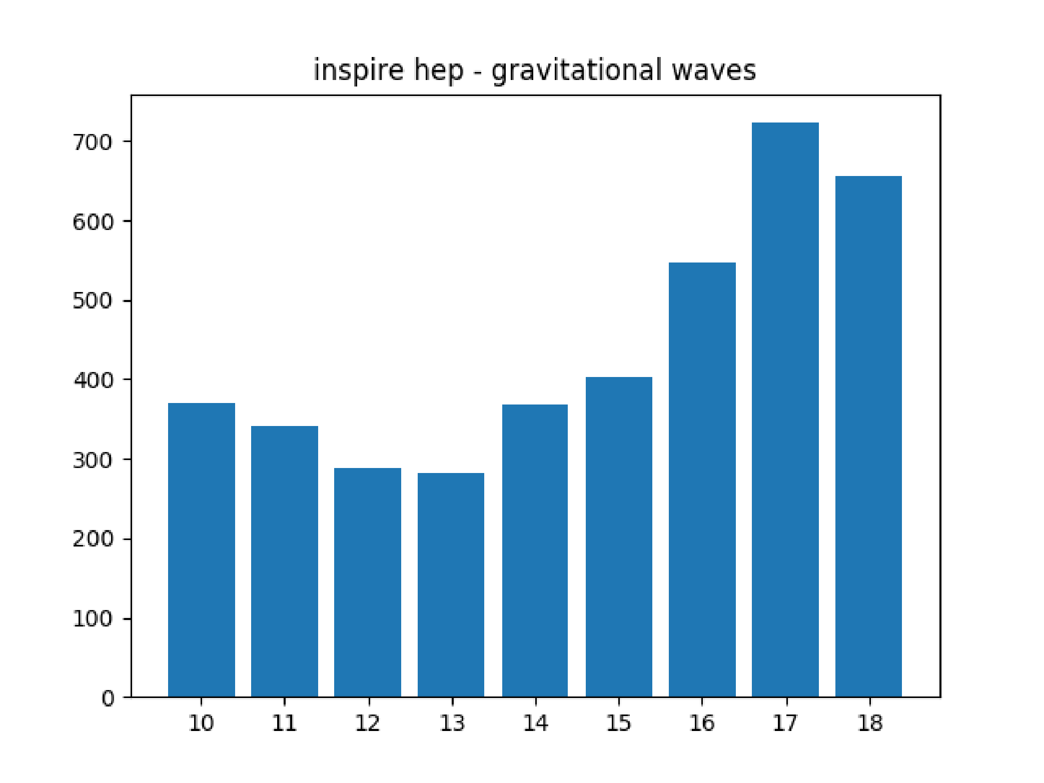
[Grojean, Servant '06] $\alpha = \rho_{vac}/\rho_{rad}, \quad \beta \sim \tau^{-1}, \quad v_b, \quad T$

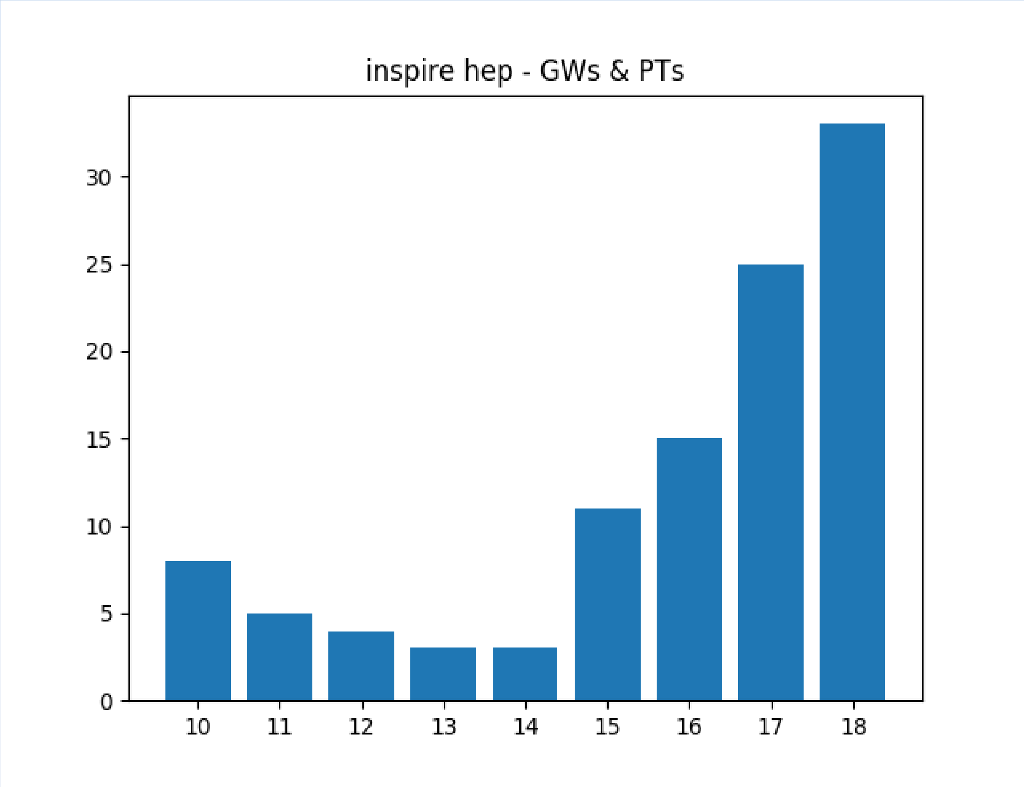


In principle, GW observations can test cosmological phase transitions up to very high scales ~10^6 GeV. E.g. before EM decoupling and beyond LHC.

GWs from PTs

Arxiv activity:





Sources of GWs from PTs

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

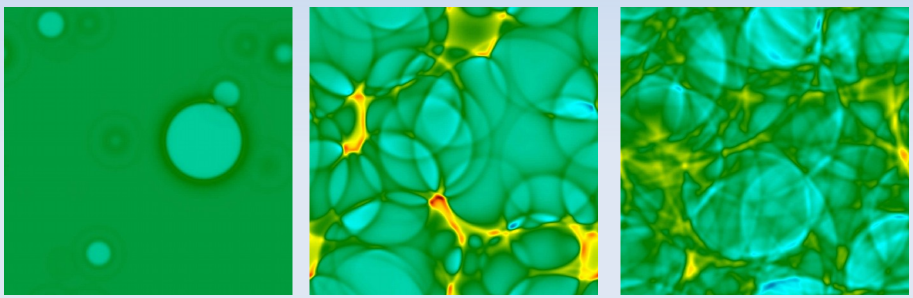
- Collisions of the scalar field configurations / initial fluid shells
- Sound waves after the phase transition
- Turbulence
- Magnetic fields

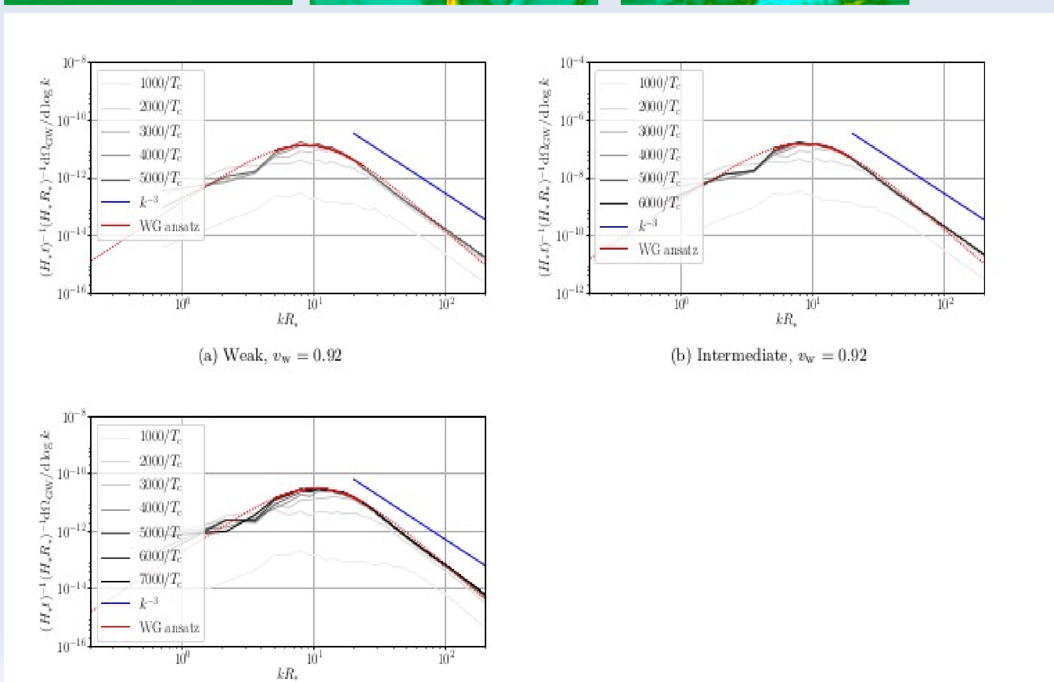
Which source dominates depends on the characteristics of the PT

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.

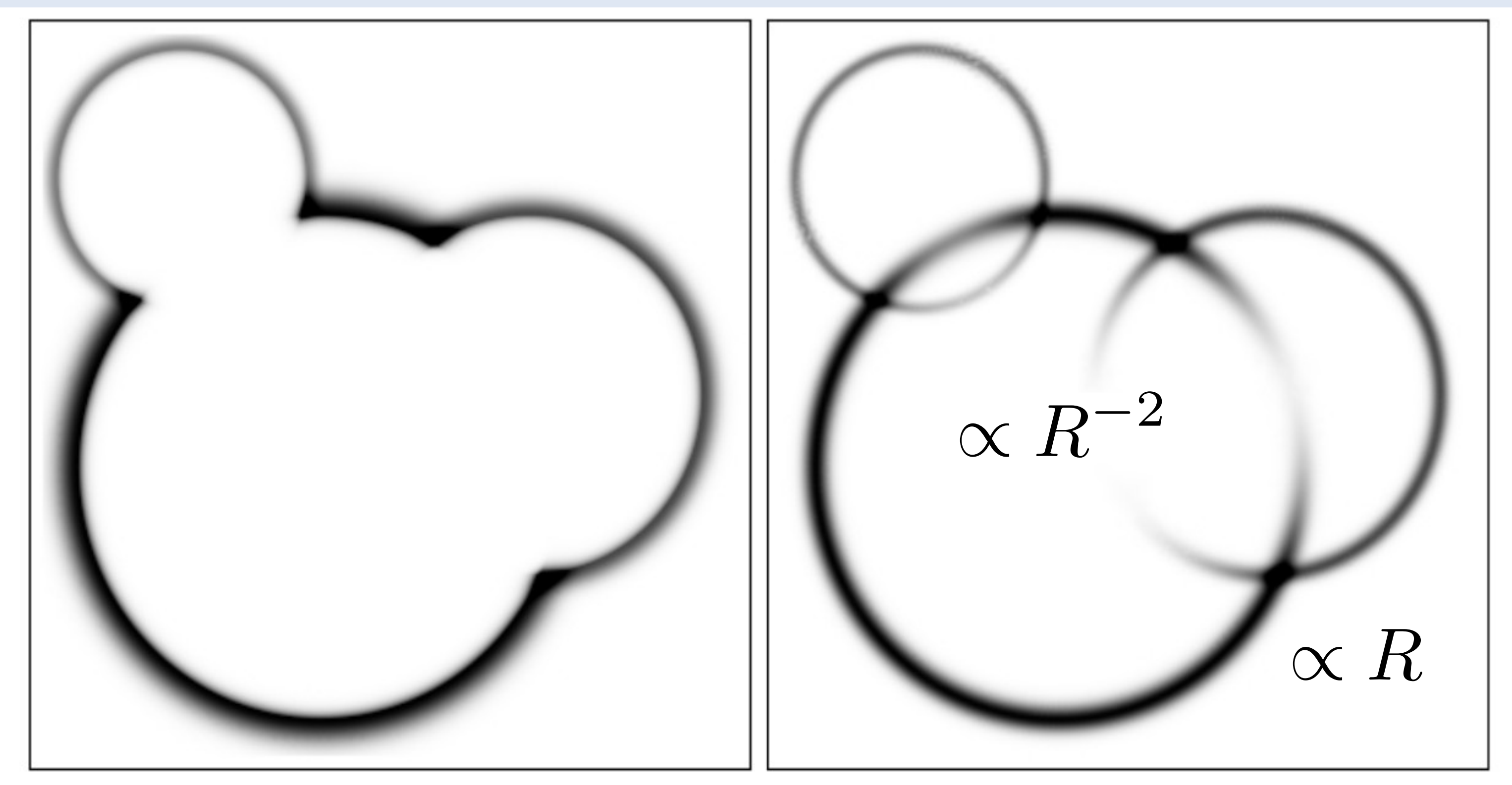
They predict reliably the produced spectrum of GWs for not too strong PTs with not too fast bubble wall velocities

Probably dominate in this regime (lifetime of waves).

Collisions

Gravitational waves from bubble dynamics: Beyond the Envelope

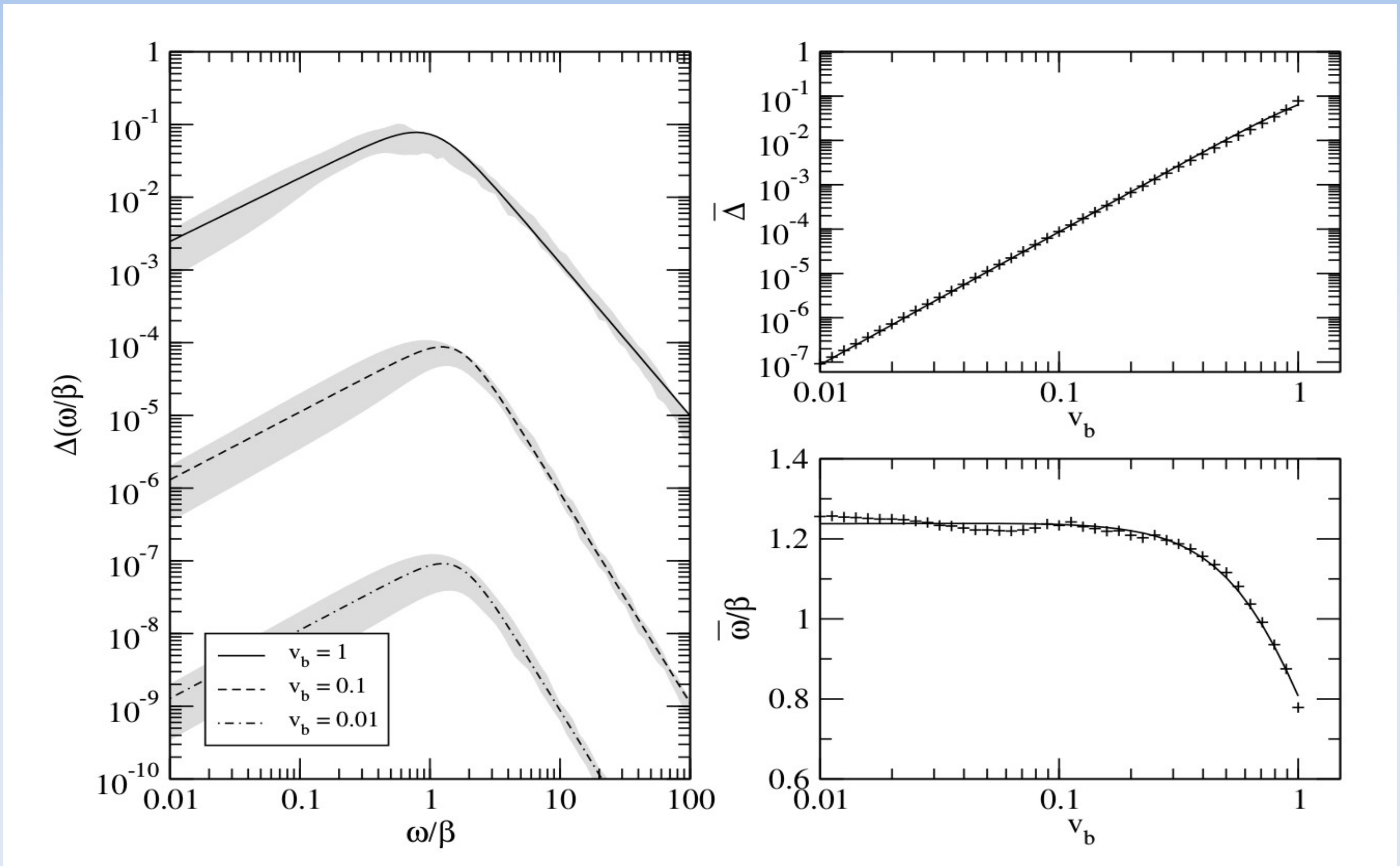
Ryusuke Jinno[a,b] and Masahiro Takimoto[b,c]



envelope: vacuum/low temp

Jinno/Takimoto: relativistic bubble wall velocities

Numerical results

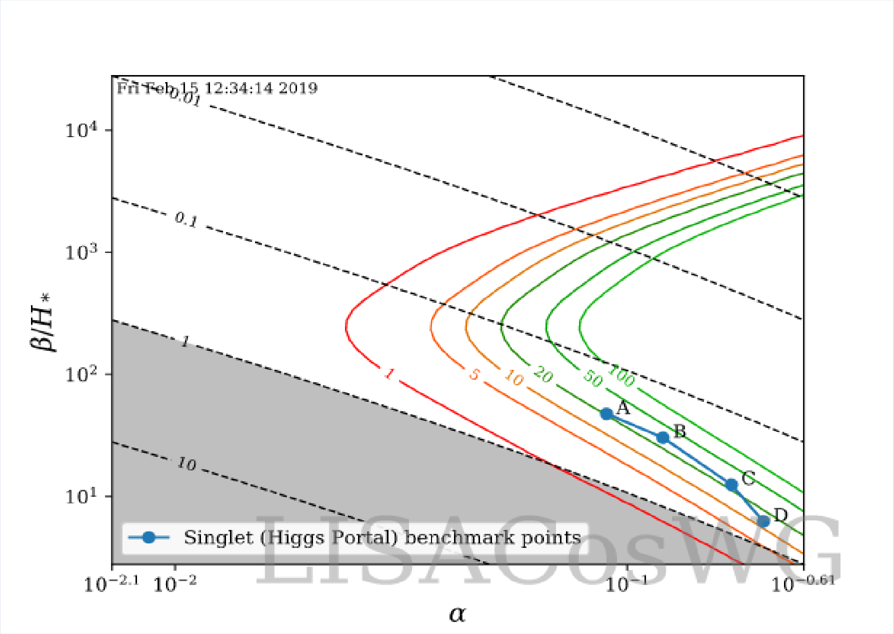


[Konstandin '17]

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:

web-tool by *David Weir*
http://still.secret.url.org



Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions

Caprini et al.
arxiv/1512.06239

Update is about to be published!

Summary

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

→ poster by **F. P. Huang:** today
→ poster by **K. Hashino:** today

The end

Thank you!

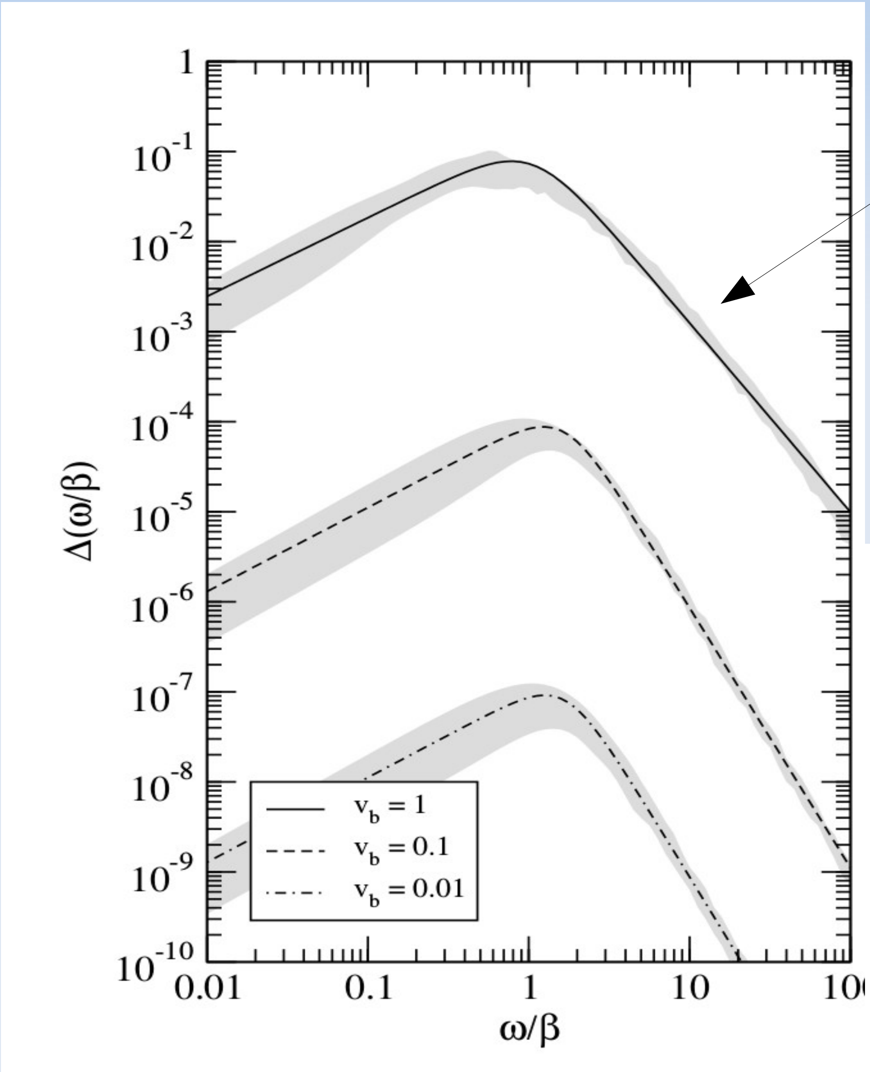
Electroweak phase transition

gravitational
waves

baryogenesis

computer games

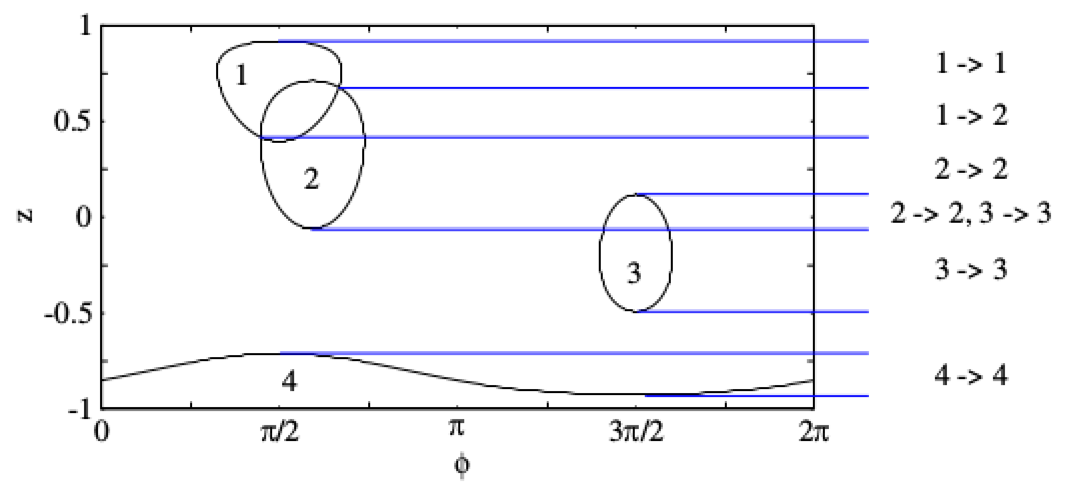
Integrations



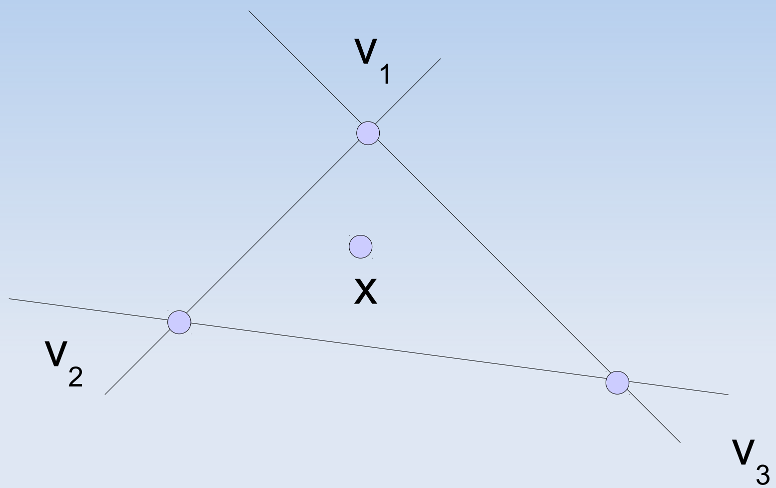
$$\Delta I/I \simeq 10^{-6}$$

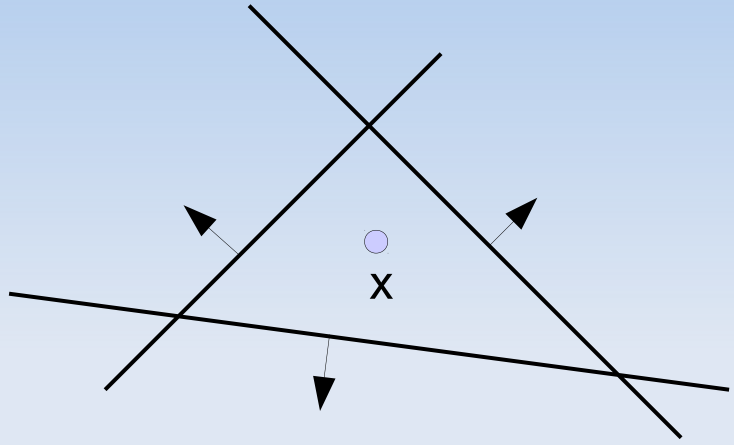
→ first integration analytical
→ second integration piece-wise

Border-crossings are problematic



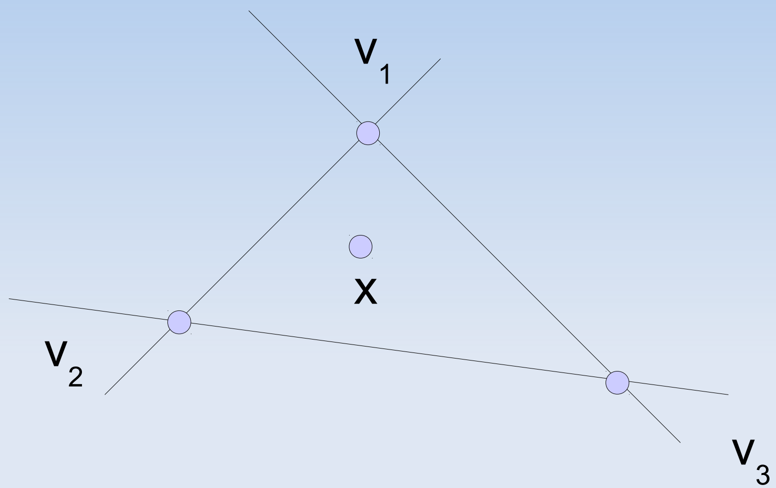
What is the best way to test inclusion?

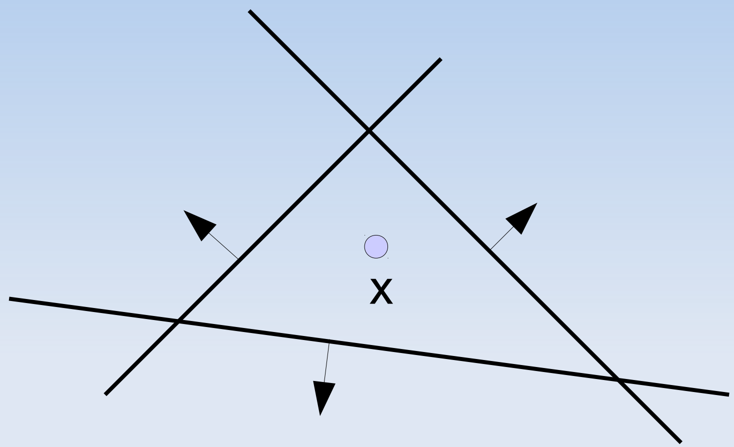




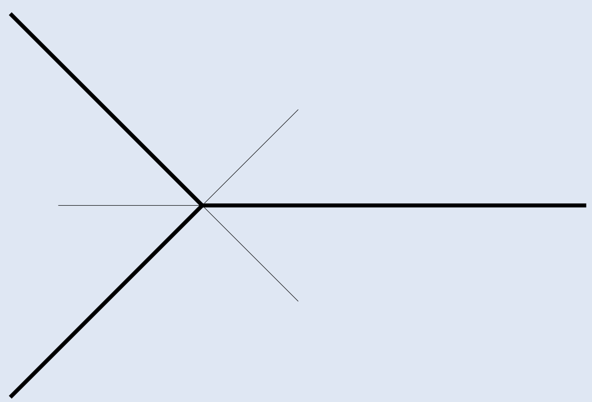
$$\vec{n}_i \cdot \vec{e} = b_i$$

What is the best way to test inclusion?



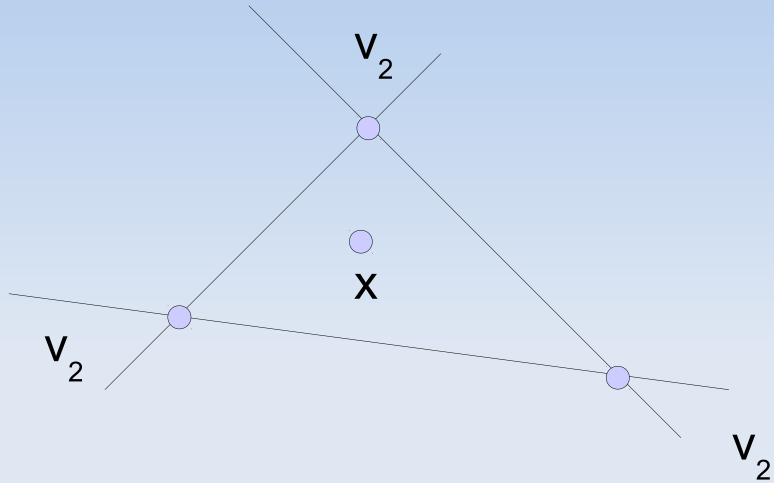


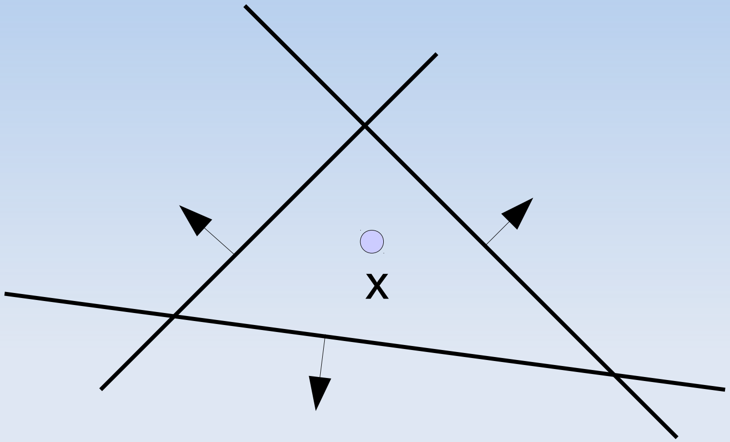
$$\vec{n}_i \cdot \vec{e} = b_i$$



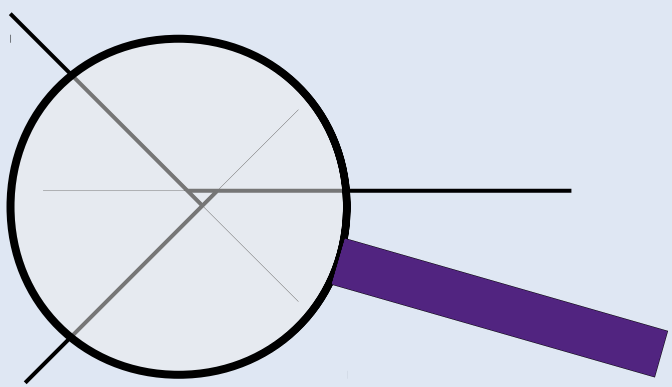
$$\vec{n}_i \cdot \vec{x} < b_i$$

What is the best way to test inclusion?





$$\vec{n}_i \cdot \vec{e} = b_i$$



$$\vec{n}_i \cdot \vec{x} < b_i$$

Nav and collision meshs

Visuals in computer games are tesselations in terms of triangles made from vertices

Collision detection is implemented using a navigation or collision mesh

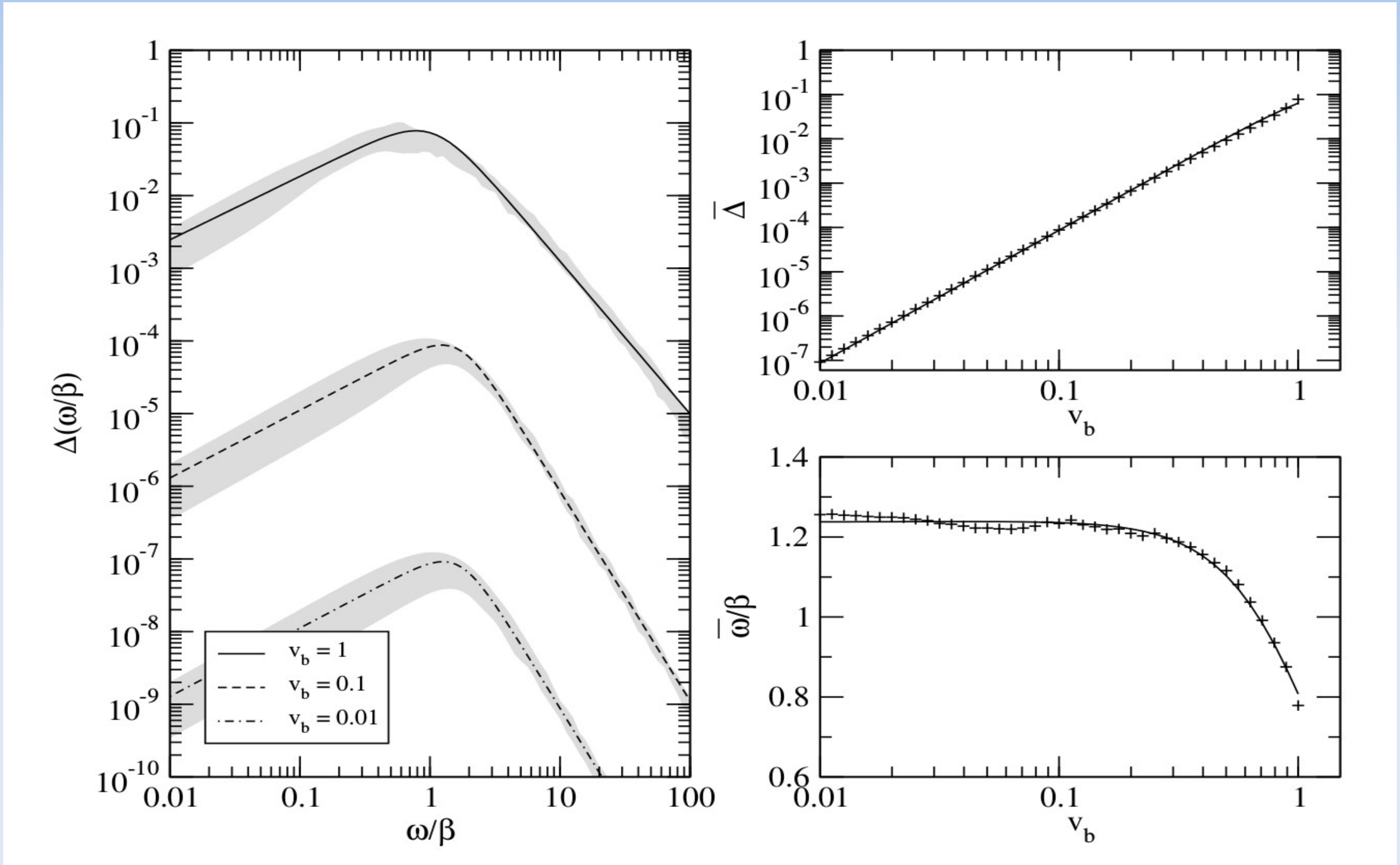
Often these meshes haves holes

Most expensive games cost ~200 M$ to produce

Google:
”out of bounds glitch”

Google:
”nav mesh algorithms blog”

Voila!



[Konstandin '17]