Searching for particle physics signals in the cosmological collider via gravitational wave surveys

蔡一夫 Yi-Fu Cai

the KIAA/DoA Colloquium @ Peking U

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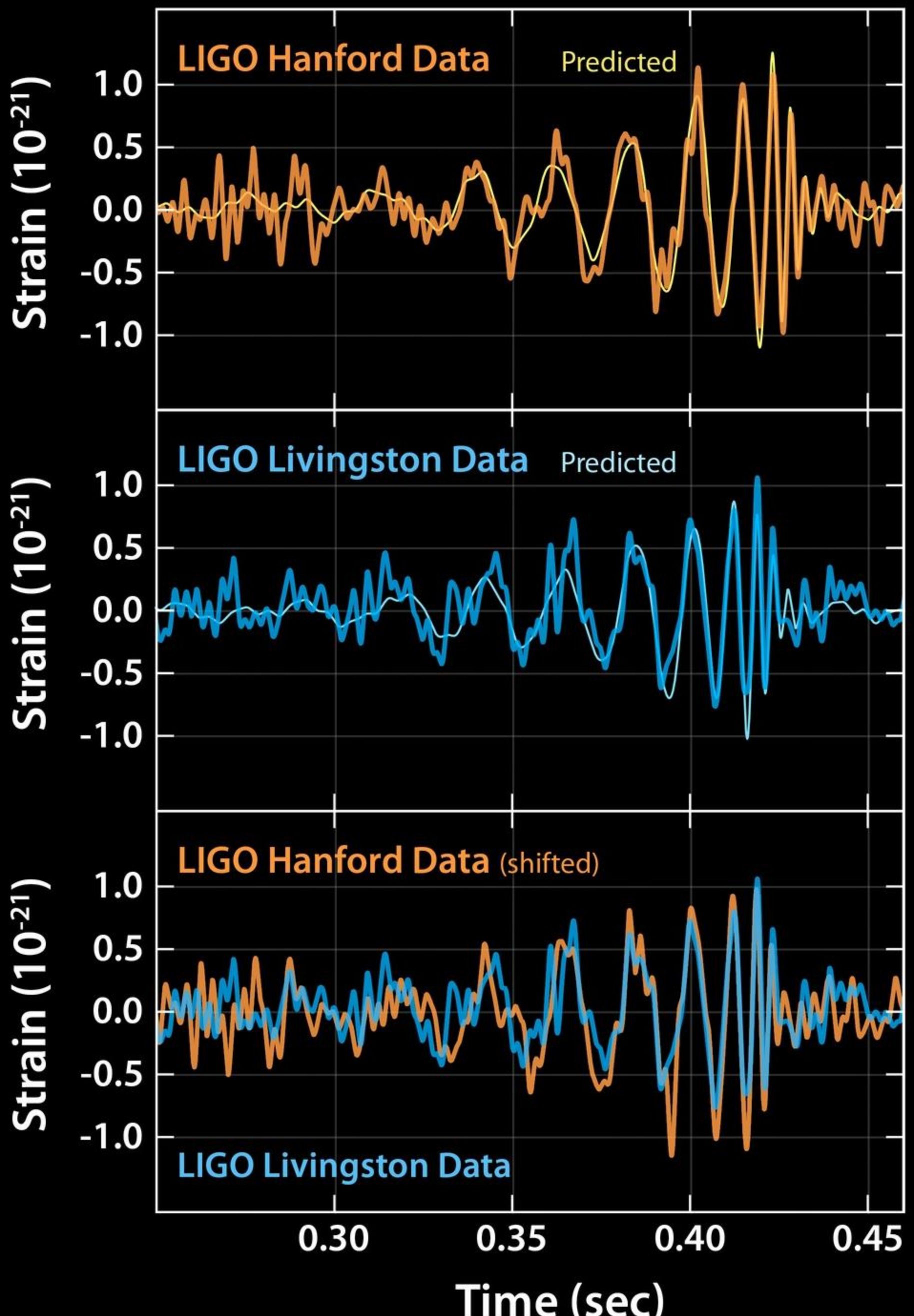
中国科学技术大学
Department of Astronomy, University of Science and Technology of China



On Feb 11 2016

LIGO Executive Director

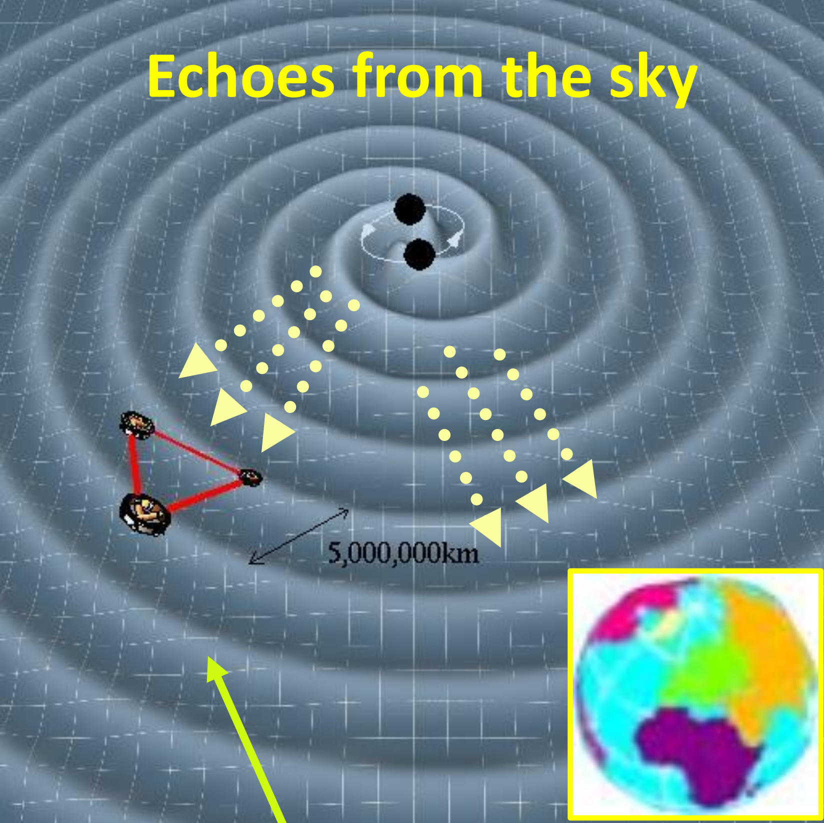
David Reitze:

“We have detected

gravitational waves.

We did it.”

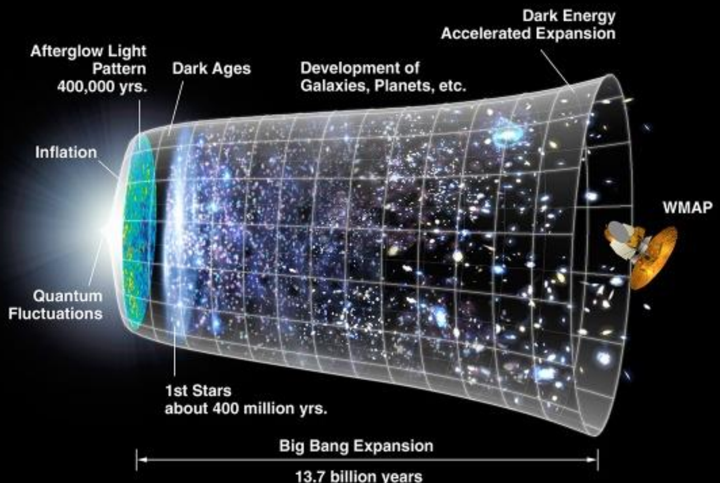
Age of GW astronomy



Ground based:
LIGO, Virgo, …

CMB detectors:
BICEP, SPT, Ali, …

Space telescopes:
eLISA, 天琴, 太极
…



The Age of GW astronomy has come!

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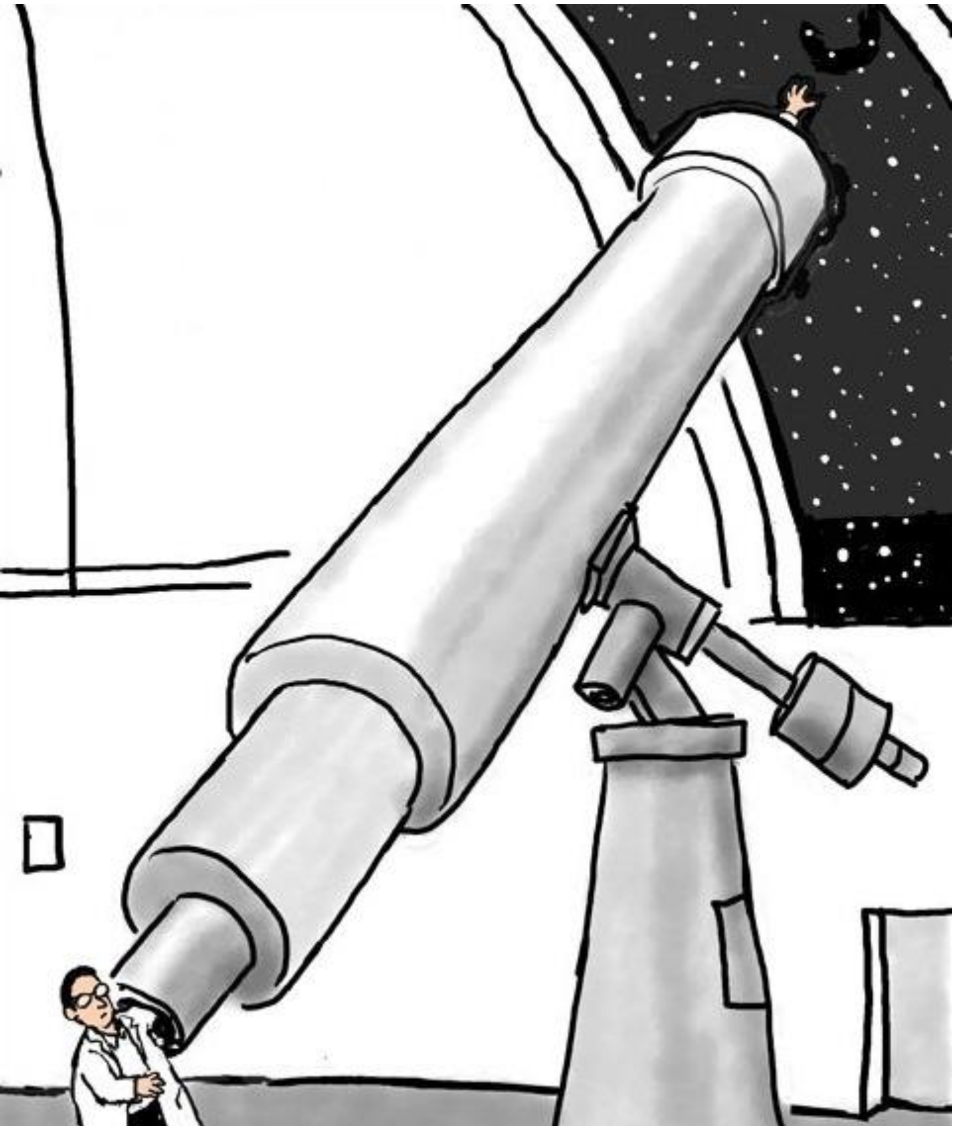
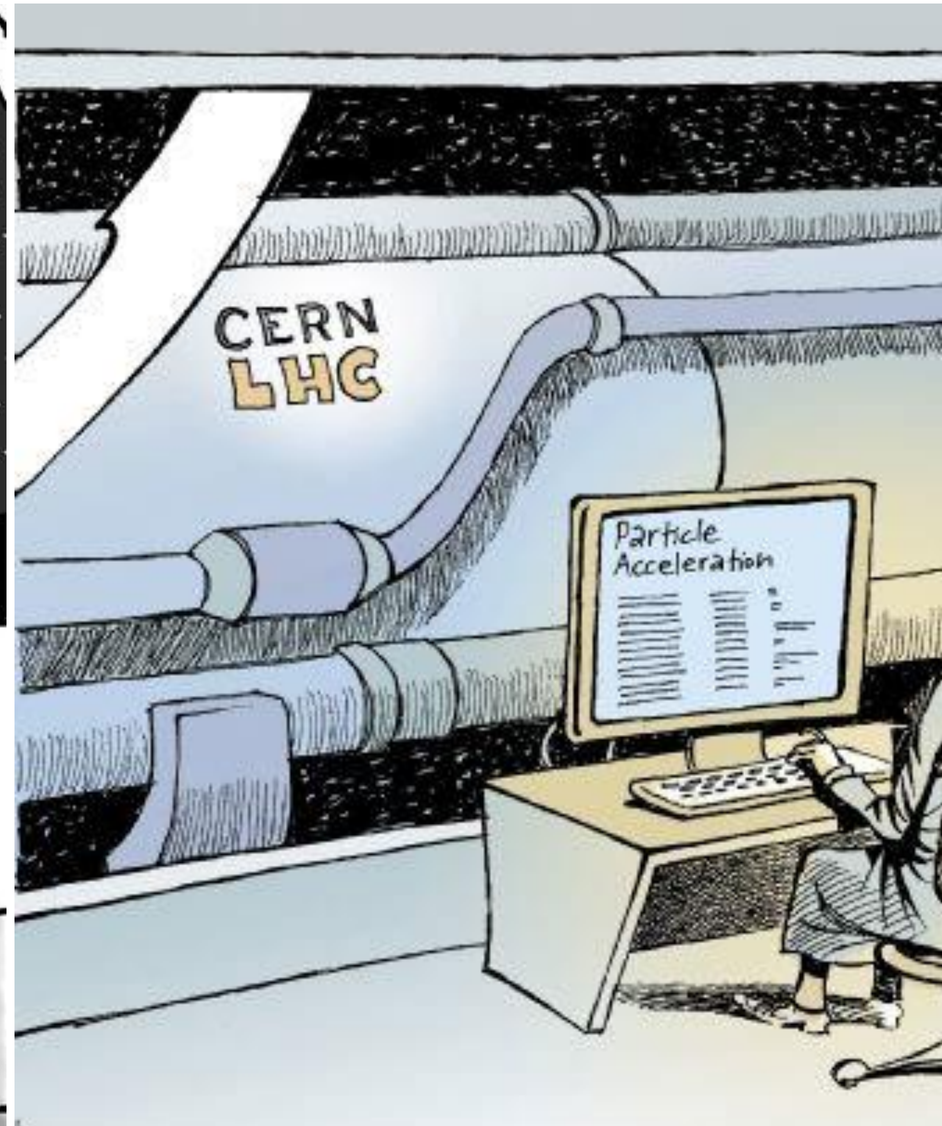
重要的事情说三遍 ☺

Two paths to explore our Universe





Motivations

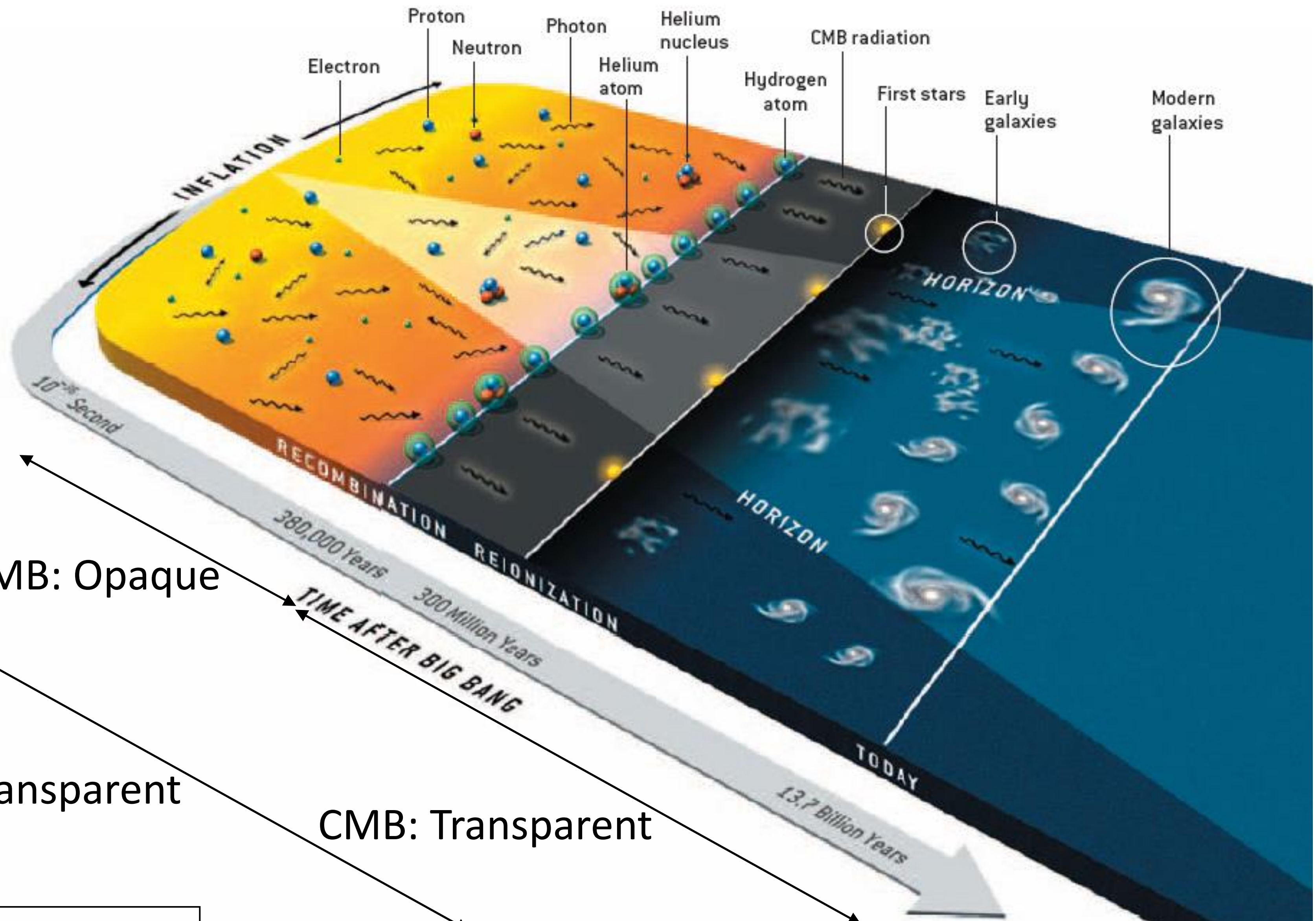
- Why search for particle physics signals via GW surveys?

- Our Universe was a super collider at early times

- Our Universe can be transparent to GW since very early moment:
    - Photon decoupling (CMB): $T = 0.3\text{eV}$
    - Graviton decoupling: $T \sim 10^{19}$ GeV

- GW propagate freely, can record every detailed info about the early universe directly

Evolution of the universe



CMB: Opaque

GW: Transparent

CMB: Transparent

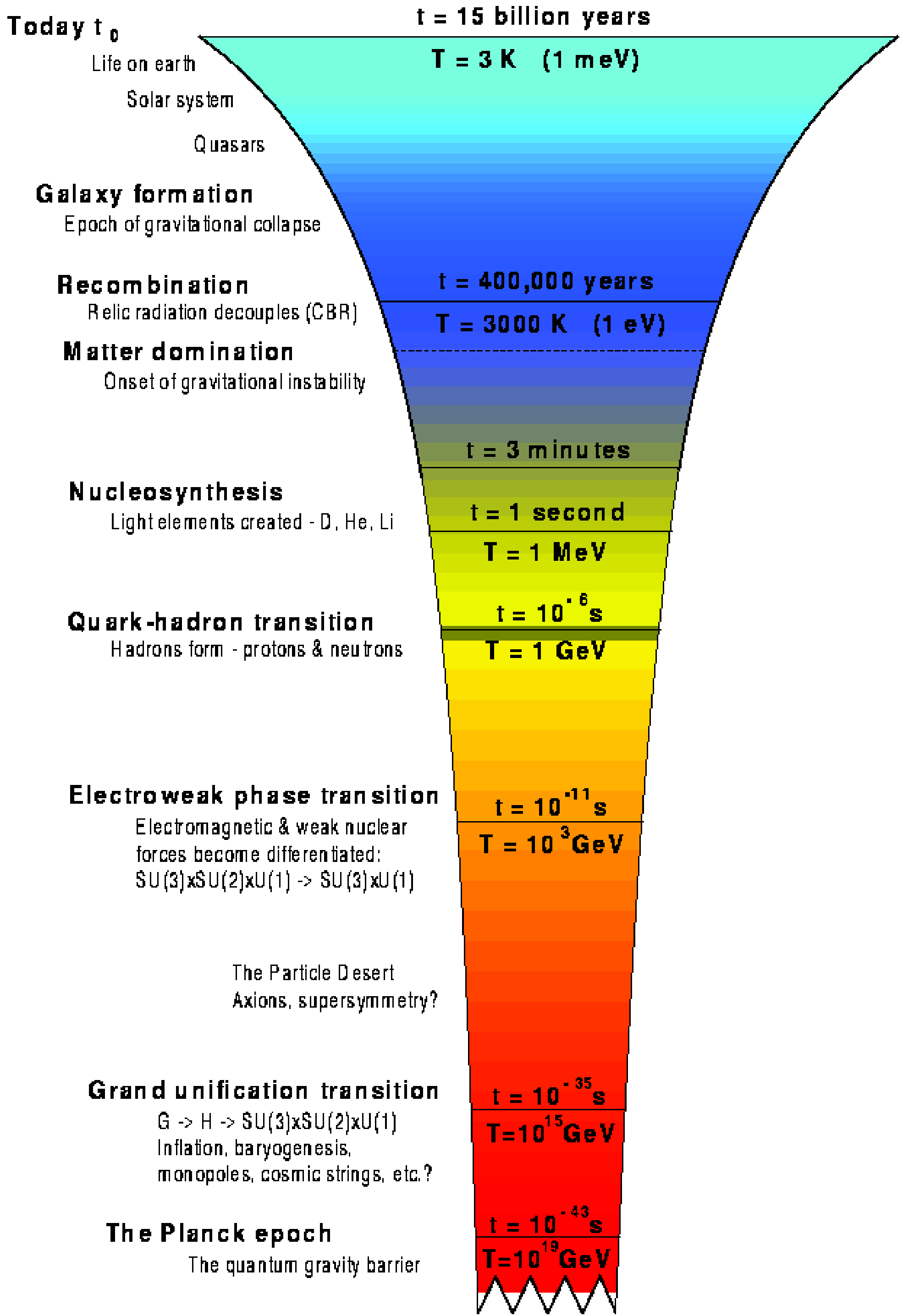
Hu & White (2004)

In the first several seconds after the Big Bang, many phase transitions could've taken place.

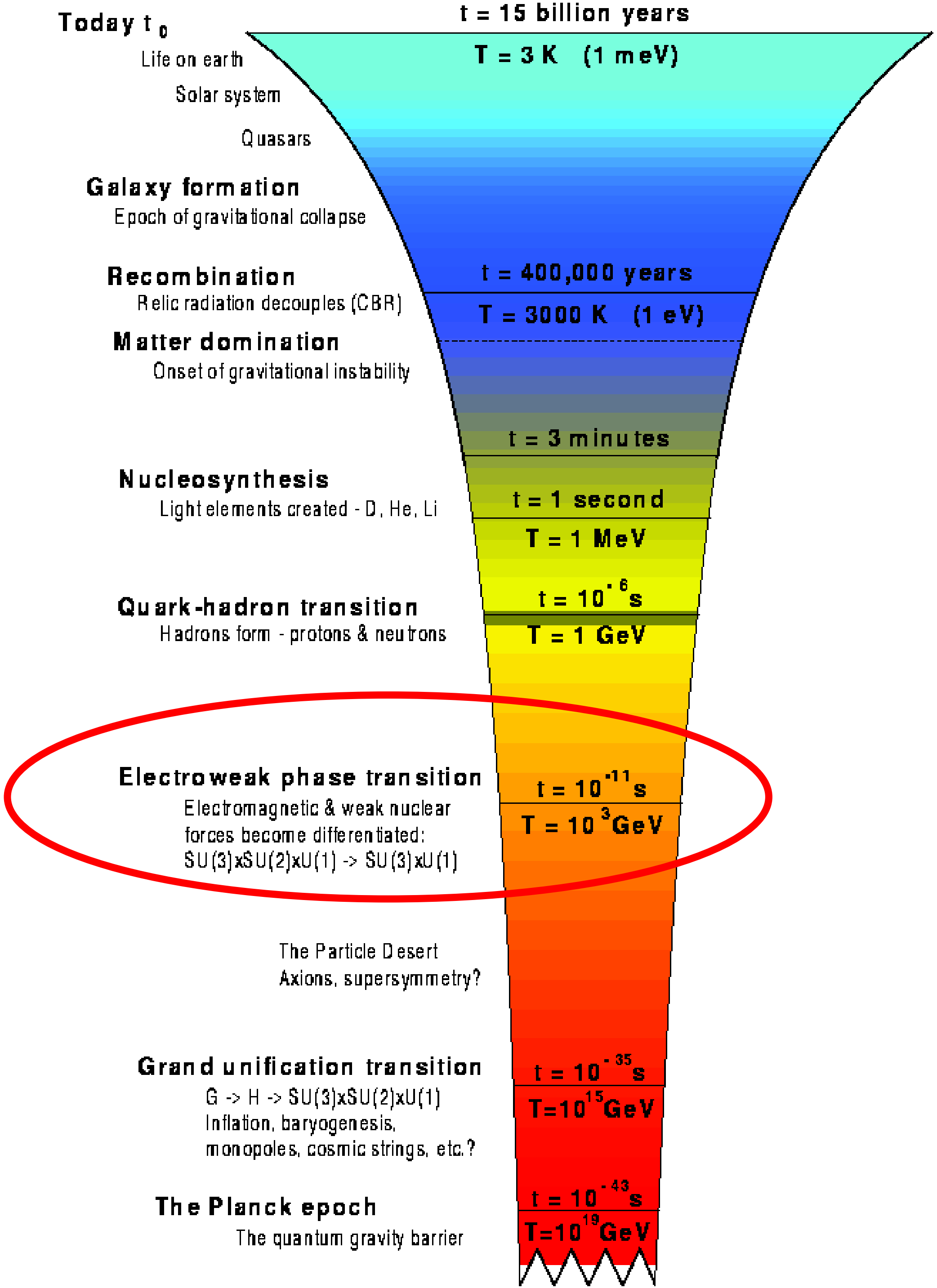
Why so important?

- These PTs can reveal the fundamental symmetry at high-energy scales;
- They affect the structure of the universe at large length scales;
- One amongst them, which is of collider interest, is the Electroweak phase transition.

Thermal history of our universe



Thermal history of our universe



Electroweak PT:

$T_{EW} \simeq 10^{2\text{-}3}$ GeV

$t_{EW} \simeq 10^{-10}$ sec

$\omega_{EW} \geq 10^{-5}$ Hz

Physics of Electroweak PT:

- **Details of the Higgs potential**
- **EW symmetry breaking**
- **EW baryogenesis**
- **Echoes of relic GW**

Kuzmin et al (1985); Zhang (1993); review by Trodden (1999); …

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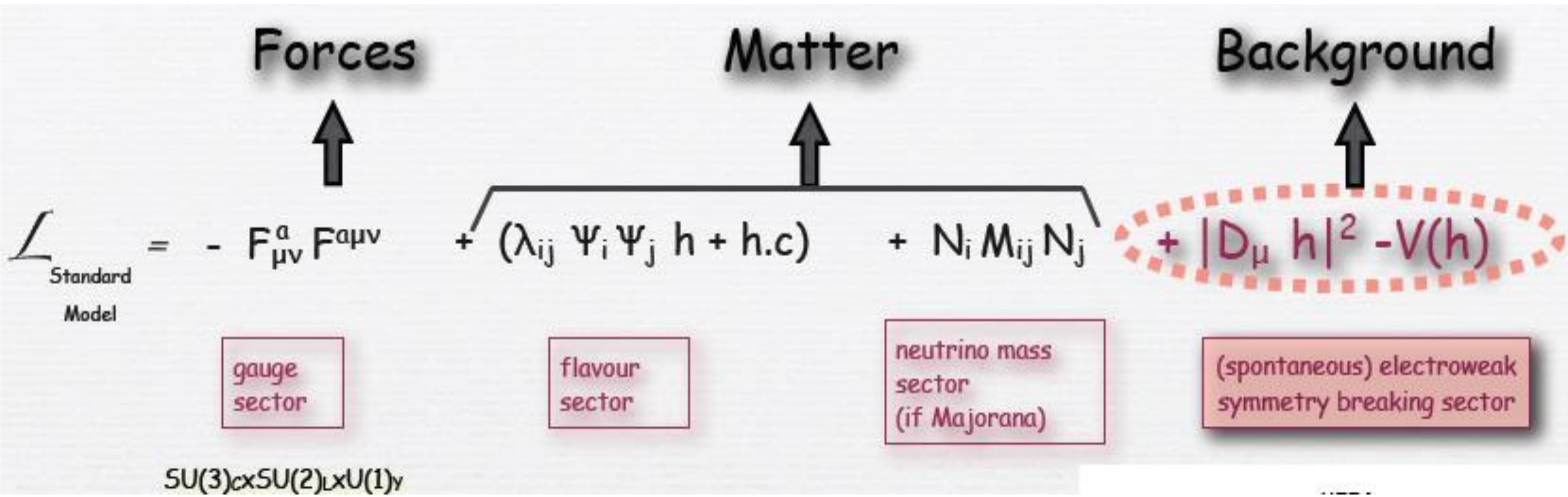
Standard Model of Particle Physics



- Decades to develop it
- Tested with impressive precision in colliders
- Accounts for all data in experimental particle physics up to TeV scales

Standard Model of Particle Physics

The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

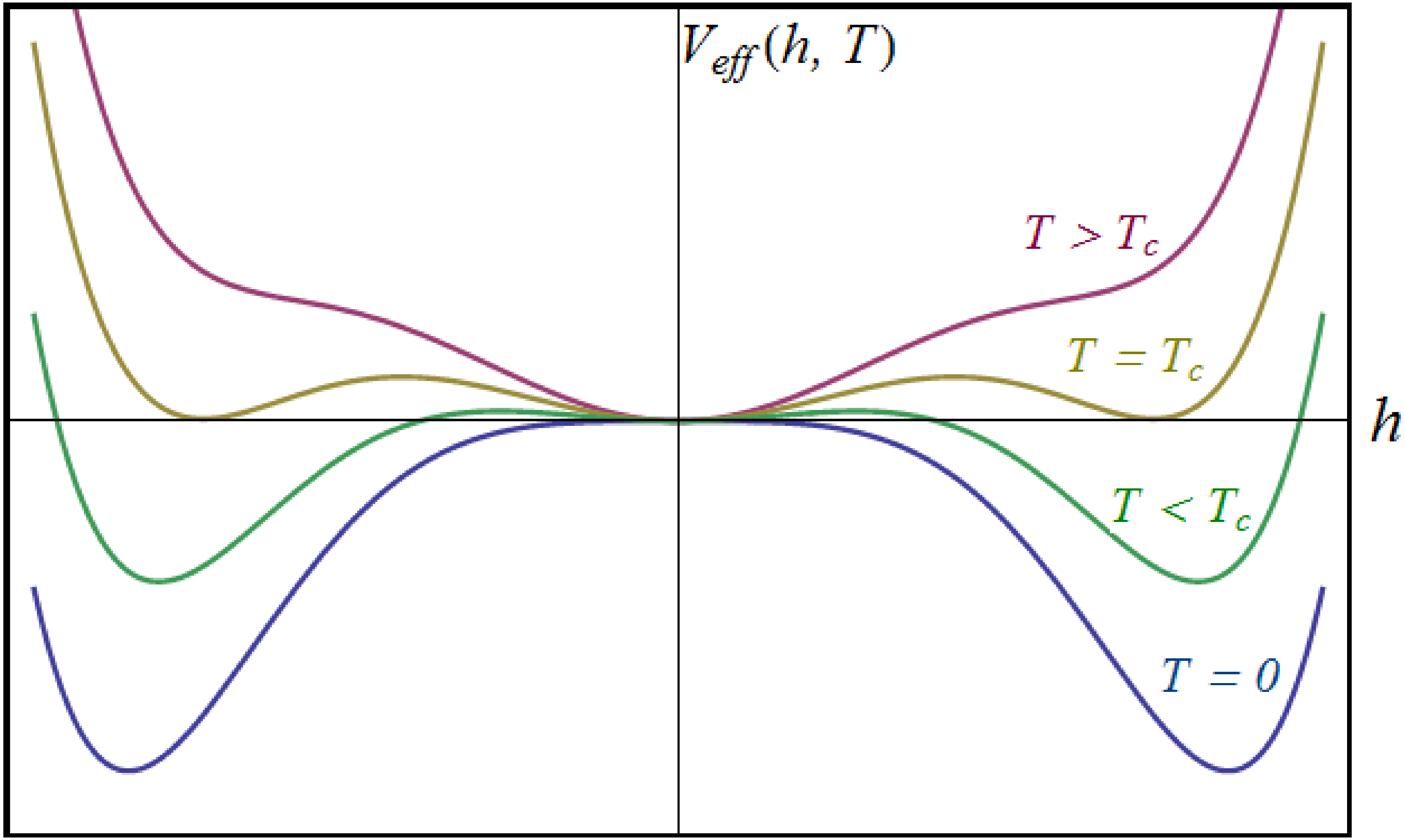
Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

- The discovery of the Higgs boson with a mass about 125 GeV was announced in July 2012

- It is viewed as a portal to new physics of hidden sectors

Finite-temperature corrected effective potential of the SM Higgs boson:



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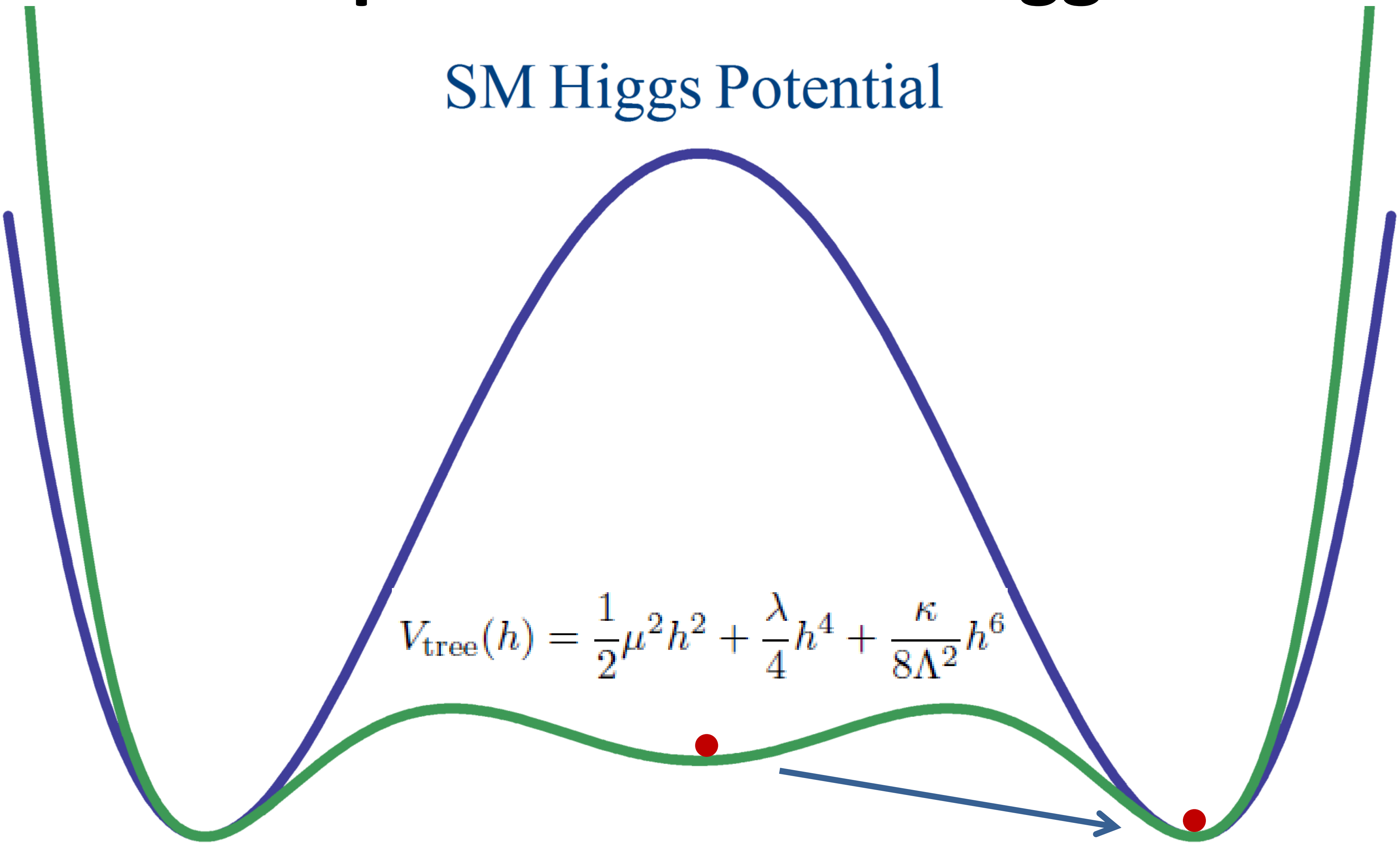
Effective potential of the Higgs boson



$$V_{\rm tree}(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6$$

If 1st order PT, it will be crucial for the EW baryogenesis.

Physics of Electroweak PT:

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Matter Anti-matter asymmetry of our Universe

Characterized in terms of the baryon-to-photon ratio: $$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$ $\sim 10^{-9}$

Sakharov's Golden Conditions for Baryogenesis:

Sakharov (1967)

- Baryon number violation
  (need a process which can turn antimatter into matter)

- C(charge conjugation) and CP(charge conjugation & Parity) violation
  (need to prefer matter over antimatter)

- Off thermal equilibrium
  (any preexisting asymmetry will be erased by interactions)

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- Off thermal equilibrium ← EWPT: 1st order
  (any preexisting asymmetry will be erased by interactions)

Physics of EWPT:

- A novel consequence of the above EWPT theory is A modification of the trilinear Higgs coupling

$$\mathcal{L}_{hhh} = -\frac{m_h^2}{2v}(1+\delta_h)h^3$$

- It can be tested in colliders through the $\delta_{\sigma_{hZ}}$ channel, namely, by the proposed CEPC, ILC, etc.

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- Q: any connection between these two stories?

Theory of gravitational waves

- Small perturbations around the background metric:

$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

- These tensor perturbations evolve as

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G \Pi_{ij}$$

- Π_{ij} is the transverse-traceless part of the energy-stress tensor

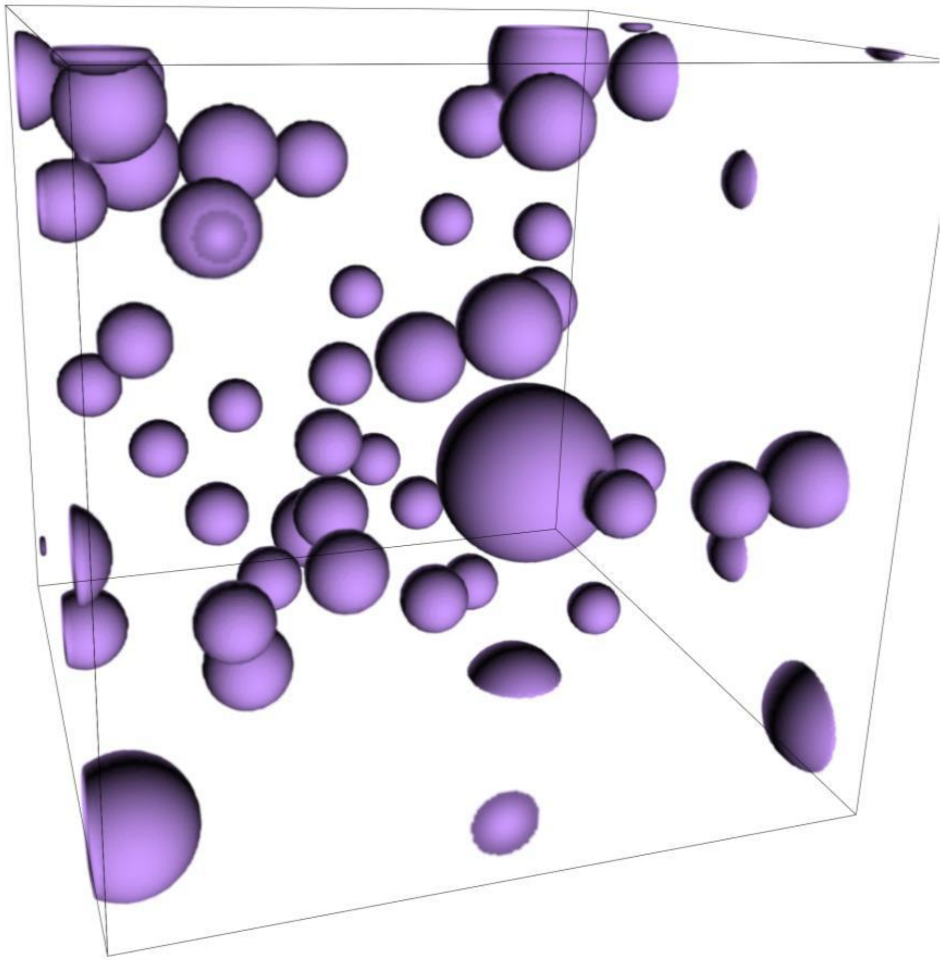
- How to generate Π_{ij} in EWPT?

Three Major sources for generating GW from the EWPT:

- Bubble Collisions
- Acoustic wave effects
- Magnetohydrodynamic turbulence

Bubble collisions - Little bangs after the Big Bang

- 1st order transition proceeds by nucleation of bubbles of Higgs phase
- Expanding bubbles generate shear stresses in hot cosmic fluid
- Leading to GW



Steinhardt (1982); Gyulassy et al (1984);
Witten (1984); Enqvist et al (1992); Kamionkowski et al (1993); …

Bubble collisions - Little bangs after the Big Bang

- PT parameters are determined by the underlying model:
  - α = Vacuum energy / Total energy
  - v_b = Bubble wall speed
  - H_* = Hubble rate at transition
  - β = Bubble nucleation rate
  - ε = Conversion efficiency of vacuum energy to fluid energy
  - g^t_* = Total d.o.f at transition
- The peak frequency is given by

$$f^*_{\rm co} = 0.62\beta/(1.8 - 0.1v_b + v_b^2)$$

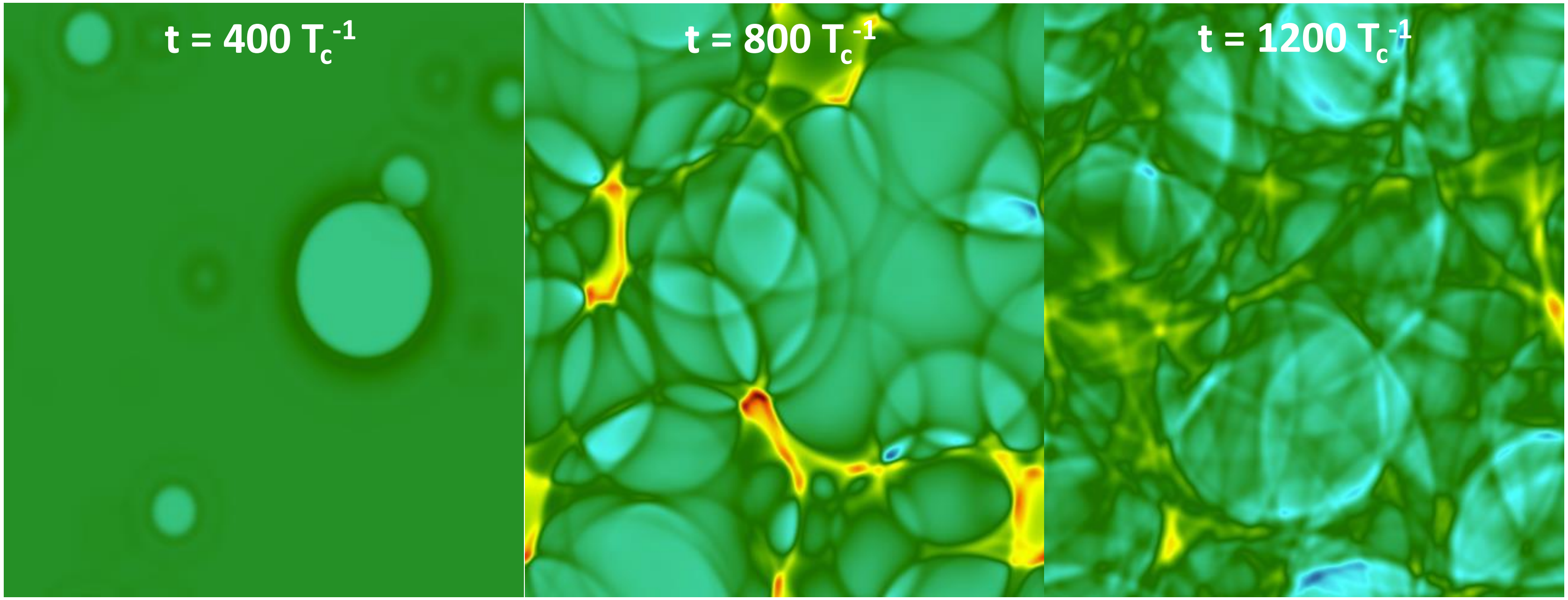
- The GW intensity spectrum takes

$$\Omega_{\rm co}(f)h^2 \simeq 1.67\times 10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\varepsilon\alpha}{1+\alpha}\right)^2\left(\frac{100}{g^t_*}\right)^{\frac{1}{3}} \times\left(\frac{0.11v_b^3}{0.42+v_b^3}\right)\left[\frac{3.8(f/f_{\rm co})^{2.8}}{1+2.8(f/f_{\rm co})^{3.8}}\right].$$

Bubble collisions - Little bangs after the Big Bang

- The GW intensity spectrum due to bubble collisions:
  - Increases as $f^{2.8}$ in the low frequency regime
  - Decreases as f^{-1} in the high frequency regime
- Therefore, a particular pattern can be obtained for this contribution

Acoustic wave effects - sound waves in the plasma



- Latent heat of PT transfers into fluid compression waves – sound
- They can survive long after the transition is complete
- Thus they play continuous sources for GW

Hogan (1986); Giblin et al (2013); Hindmarsh et al (2013); Caprini et al (2015)

Acoustic wave effects - sound waves in the plasma

- Acoustic parameters are with the fluid thermodynamics:
  - ε_v = Fractional latent heat transferred into the fluid

- The peak frequency is given by

$$f^*_{\rm sw} = 2\beta/\sqrt{3}v_b$$

- The GW intensity spectrum takes

$$\Omega_{\rm sw}(f)h^2 \simeq 2.65\times10^{-6}\Big(\frac{H_*}{\beta}\Big)\Big(\frac{\varepsilon_\nu\alpha}{1+\alpha}\Big)^2\Big(\frac{100}{g^t_*}\Big)^{\frac{1}{3}}v_b \times\Big[\frac{7(f/f_{\rm sw})^{6/7}}{4+3(f/f_{\rm sw})^2}\Big]^{7/2},$$

Acoustic wave effects - sound waves in the plasma

- The GW intensity spectrum due to acoustic wave effects:
  - Increases as f^3 in the low frequency regime
  - Decreases as f^{-4} in the high frequency regime
- Thus, another particular pattern can be obtained which manifestly differs from that of bubble collisions

MHD turbulence - propagations in the plasma

- The temperature of the cosmic plasma is around $T \sim 100\text{GeV}$, which is very high. Bubbles of the broken phase expanding into it can thus lead to turbulence

- In the broken phase the EM field does generically not vanish. The high conductivity rapidly damps the electric field so that the magnetic field is left in a turbulent plasma: MHD turbulence

- As both the vorticity and the magnetic field are divergence-free, causality requires both two spectra to be ~ k^2 for small k

Hogan (1986); Giblin et al (2013); Hindmarsh et al (2013); Caprini et al (2015)

MHD turbulence - propagations in the plasma

- MHD parameters:
  - ε_{tu} = Fractional latent heat damped due to turbulence
- The peak frequency is given by

$$f^{*}_{tu} = 3.5\beta/2v_b$$

- The GW intensity spectrum takes

$$\Omega_{\rm tu}(f)h^2 \simeq 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\varepsilon_{\rm tu}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g^t_*}\right)^{\frac{1}{3}} v_b \times \frac{(f/f_{\rm tu})^3}{(1+f/f_{\rm tu})^{11/3}(1+8\pi f a_0/(a_* H_*))},$$

MHD turbulence - propagations in the plasma

- The GW intensity spectrum due to the MHD turbulence:
  - Increases as f^3 in the low frequency regime
  - Decreases as $f^{-2/3}$ in the high frequency regime
- Thus, the third specific pattern can be obtained which is different from the previous two

MHD turbulence - propagations in the plasma

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→ The combination of these three parts leads to an energy spectrum for GW surveys, which is unique for every EWPT model!

Output: the GW signatures & the associated particle collider signals

Huang, Wan, Wang, ***CYF***, Zhang, 1601.01640

Our model - an effective h^6 Higgs potential

- Recall the effective potential at tree-level:

$$V_{\text{tree}}(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{\kappa}{8\Lambda^2} h^6$$

- The model parameters are set as follows:
  - κ = 1, Λ = 590 GeV
  - κ = 1, Λ = 600 GeV
  - κ = 1, Λ = 650 GeV
  - κ = 1, Λ = 700 GeV
  - κ = 1, Λ = 750 GeV

While, μ and λ are chosen to be consistent with the SM

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→

$$\delta_{\sigma_{hZ}} = 2.2\%$$
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  - κ = 1, Λ = 750 GeV → $\delta_{\sigma_{hZ}} = 1.3\%$

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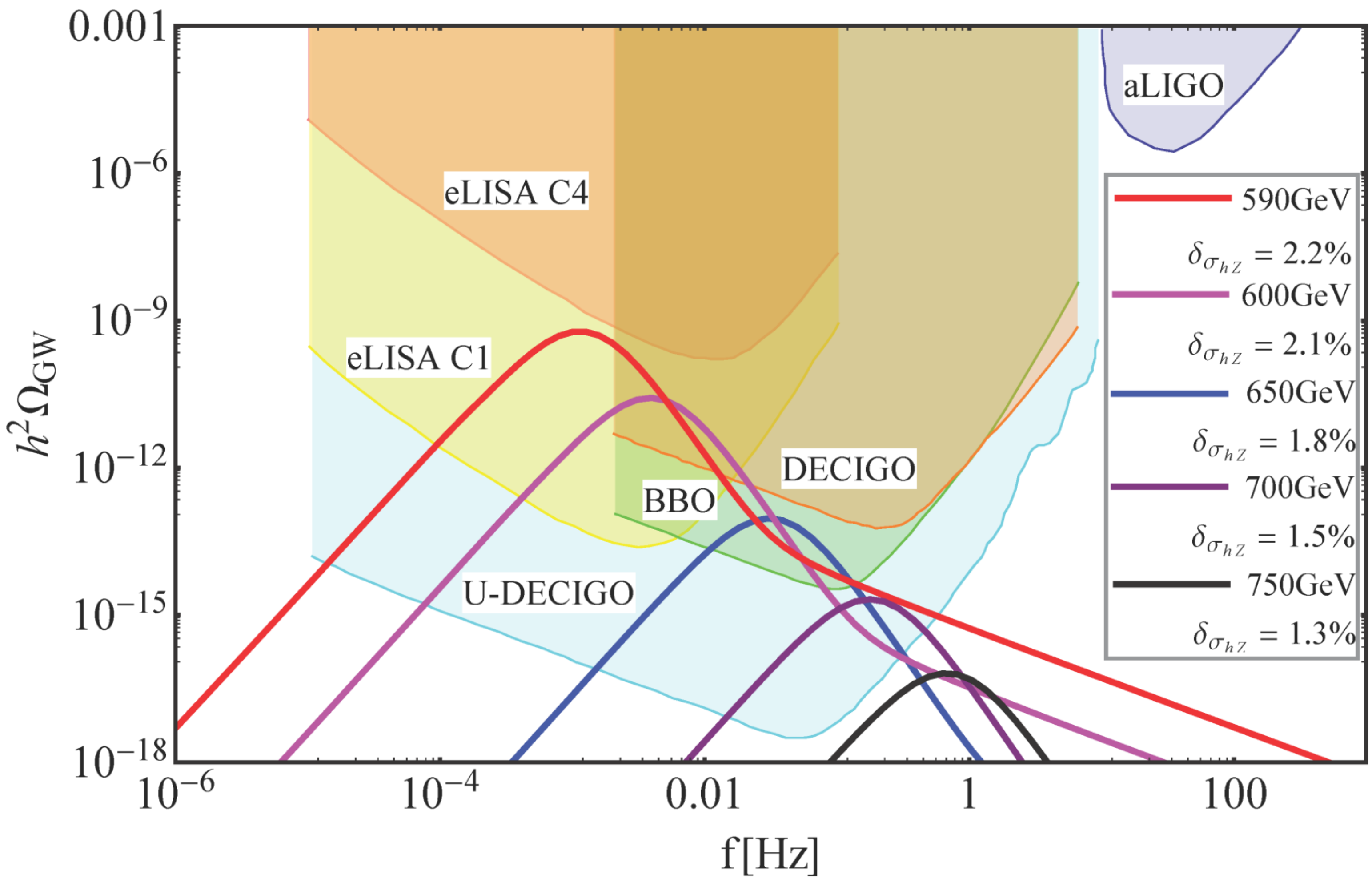
Predictions for colliders in next generation

Our model - an effective h⁶ Higgs potential

- The GW spectra are numerically calculated as follows,



Our model - an effective h^6 Higgs potential

- The observable frequency band is found within $[10^{-4},1]$ Hz, which highly overlaps with the eLISA

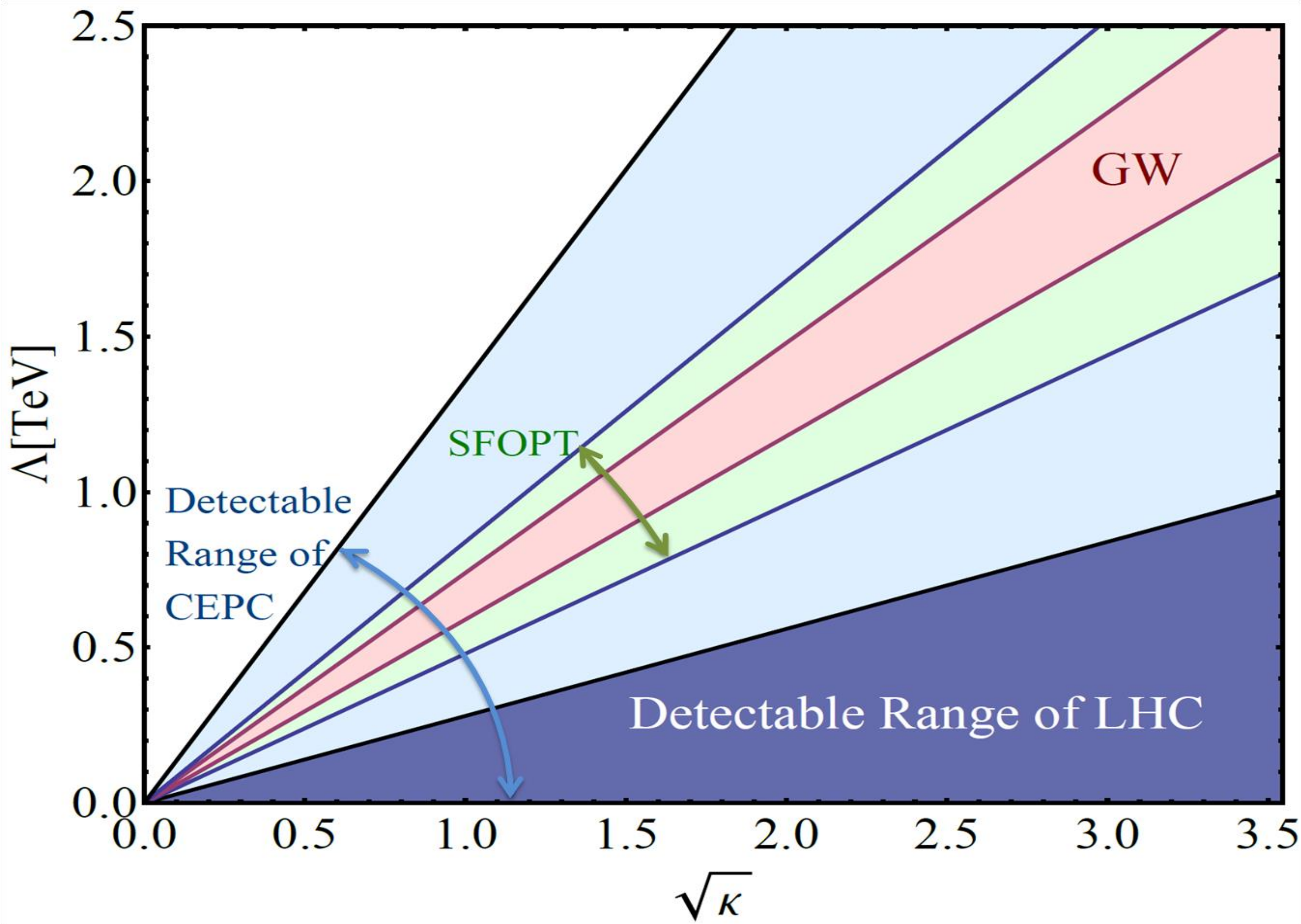
- The signals are sensitive to the eLISA, BBO and U-DECIGO

- Each GW spectrum curve corresponds to a specific value of σ_{hZ}

- Therefore, the EWPT bridges particle physics with the GW astronomy

Our model - an effective h^6 Higgs potential

- Comparing the observational abilities for experiments:



Conclusions

- The recent announced aLIGO observation has initiated a new window of exploring the nature

- The EWPT in the SM of particle physics does not lead to relic GWS

- But, if new physics modifies the Higgs potential, then the EWPT can become 1^{st} order and strong

- This process can realize the baryogenesis
  → to solve the matter/anti-matter asymmetry

- A large amount of GWs can be produced via the bubble collisions, acoustic waves and MHD turbulence

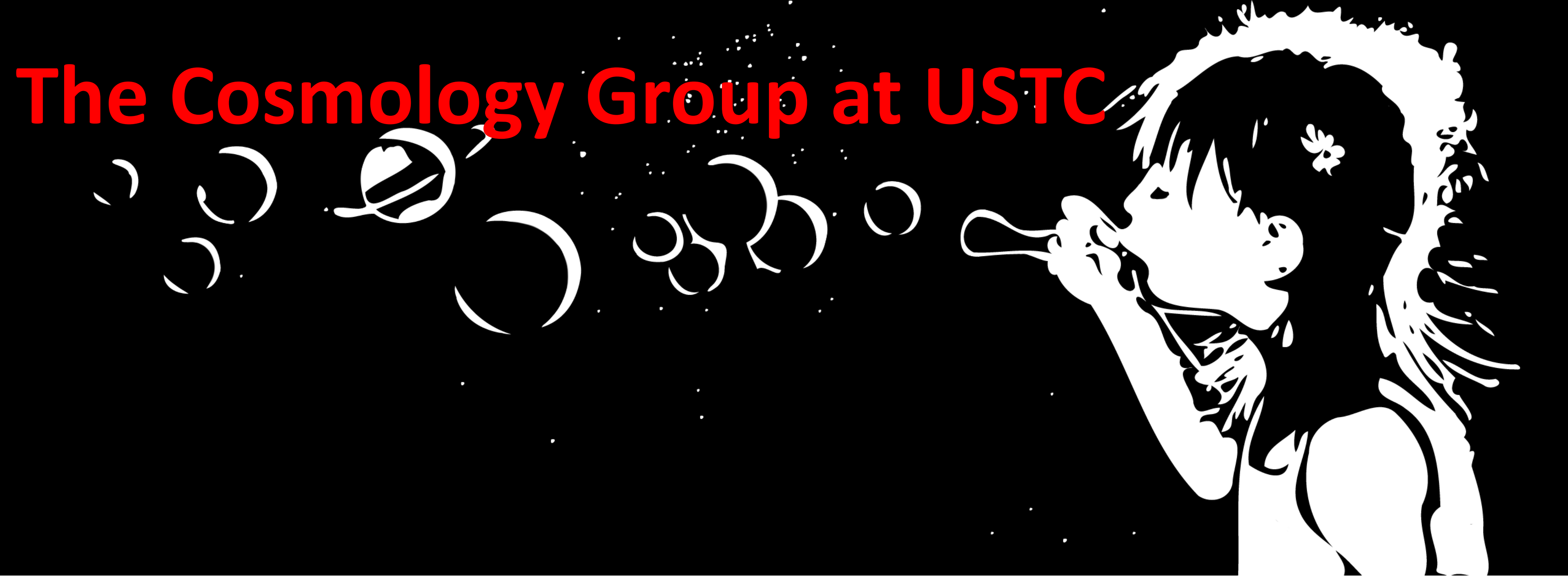
Conclusions

- Through this process, collider signals are correlated with the GW signatures via one-to-one correspondence
- A joint analysis that combines the collider & GW physics is able to discriminate theoretical models of EWPT
- Therefore, we are able to probe the Universe up to 10-10 sec after the birth!

Outlook into future

- A broader and more precise GW survey is expected to probe the early universe
- A bridge between particle physics and astronomy may be built upon the cosmological collider

The Cosmology Group at USTC



- The CAS key lab of Galaxy and Cosmology @ USTC welcome extensive interactions with other institutions. And there are postdocs positions in market. Our main research interests includes,
  - ✓ Cosmology (theory, numerics, observations)
  - ✓ Quantum/Classical Gravity physics
  - ✓ Dark Energy, Dark Matter
  - ✓ Galaxy formation and evolution
  - ✓ Supermassive black holes, AGN
- Email: yifucai@ustc.edu.cn

Thanks!