Gravitational Wave Spectra from Cosmological Phase Transitions

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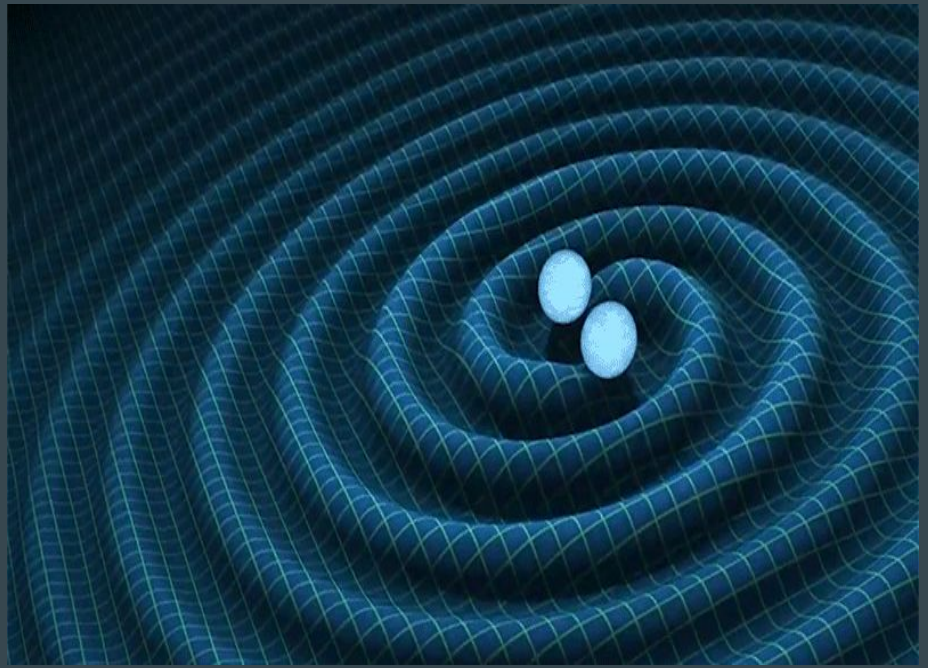
Gravitational Waves

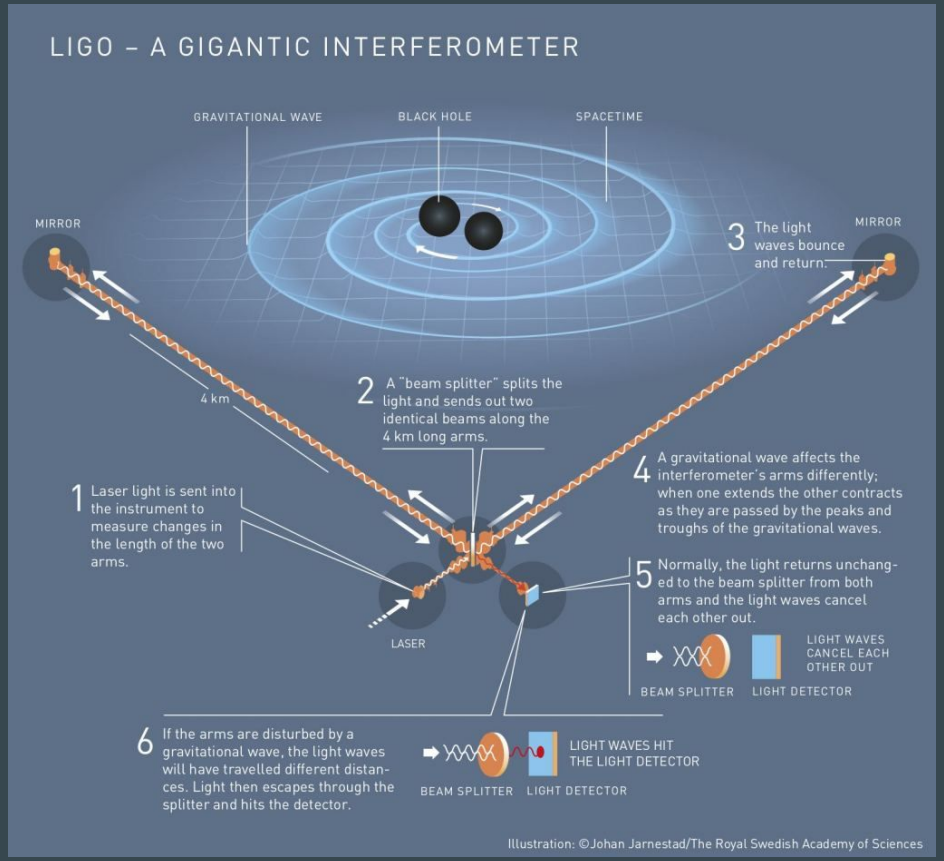
Gravitational Waves, What are they ?

- Einstein predicted Gravitational Waves in 1916.
- Gravitational Waves are ripples caused in the fabric of space-time.
- They are typically caused by **extreme** astronomical events.



Gif: bradlor/gifer.com

How are you even supposed to see them ?

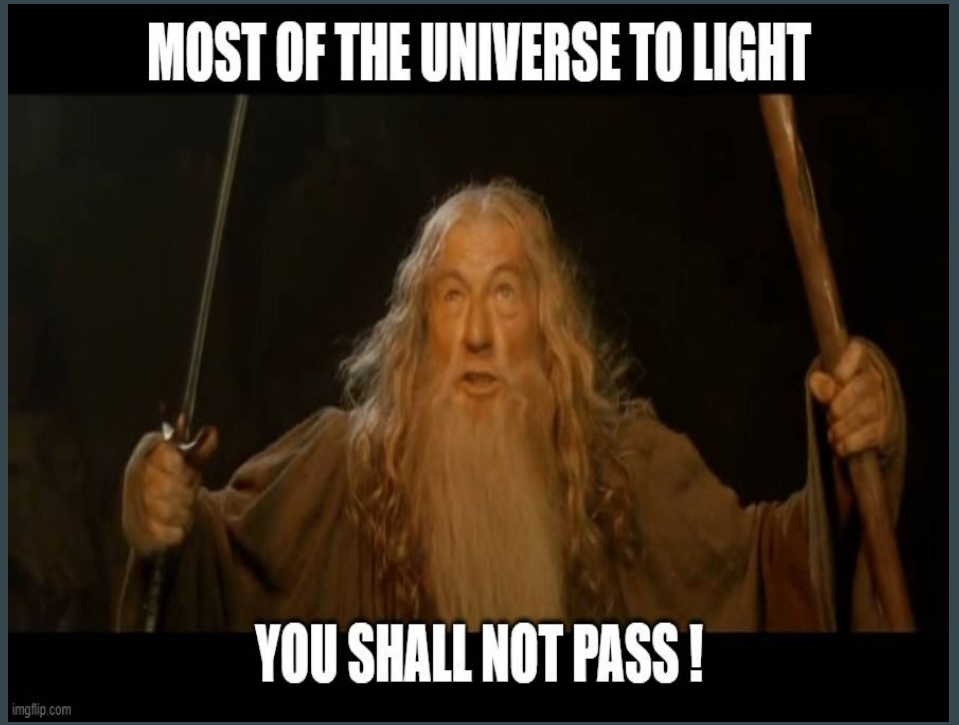


- Gravitational Waves cause distortions(~10^{-15} m) to planetary objects(Earth) that can be observed.
- Laser Interferometers(LIGO) were used to detect these events in 2016.

Video: LIGO/Caltech, image:universetoday

What do they tell us ? Can they tell us anything ?

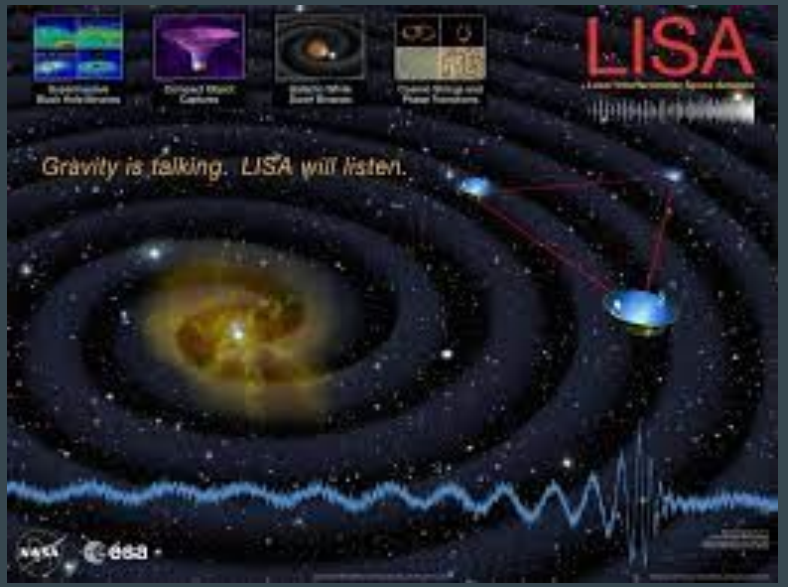
- Gravitational Waves are better than light in navigating a largely dark universe.
- Helps probe our understanding of the early universe(BSM,EWPT etc)
- Gives a different look at relatively recent extreme Cosmological Events



What can we do now ? What's Next ?

- Current events(LIGO) vs early universe(LISA)
- Others: BICEP and KECK arrays
- Theoretical Approaches are also important ! But how ?

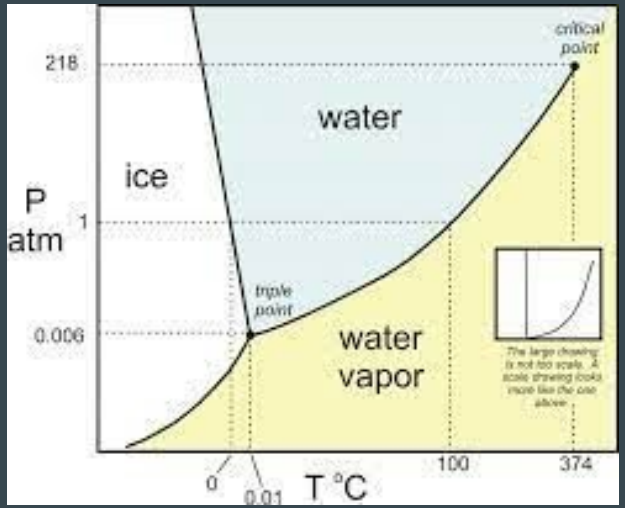
Image: left - BICEP; right - heap/usa



PHASE TRANSITIONS

What are Phase Transitions ?

- As the macroscopic variables(T,P,etc) of a system change, there are events where its properties will abruptly transform, in a rather dramatic fashion.
- Familiar Examples: I) Ice, Water, Steam ; II) Ferro-Para Magnet
- The Point at which this transition occurs is the critical point.



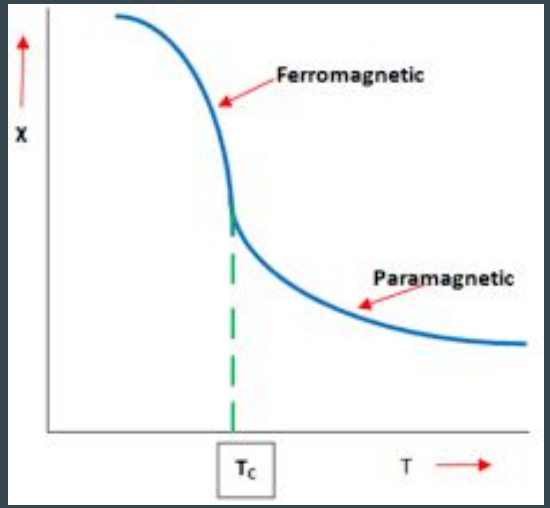
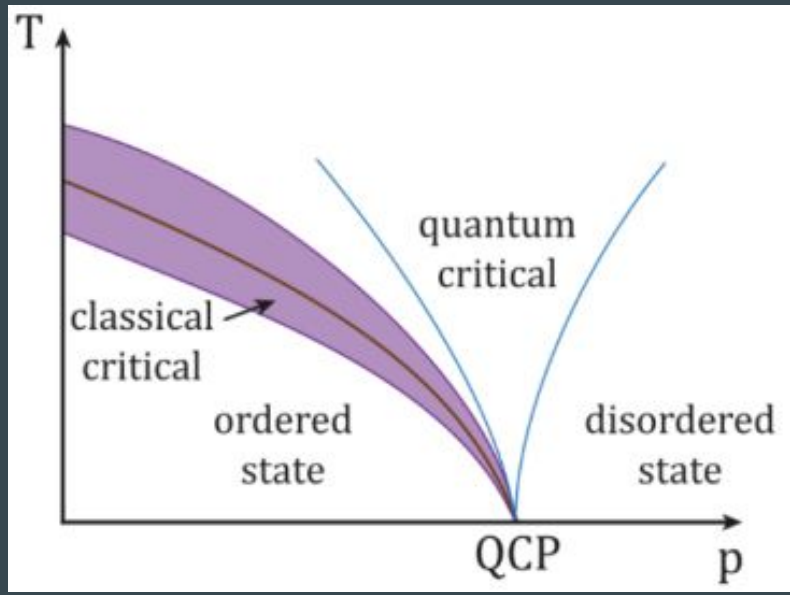


Image: left- stackoverflow; right: researchgate

Are all Phase transitions the Same ?

- Classically, most phase transitions are thermally driven.
- Ist Order(Discontinuous) vs IInd Order (Continuous)

But what's this ? ->



- **Quantum Phase Transitions** are driven by competition and **uncertainty**.
- Keeping track of the Hamiltonian becomes important.

Image: Quantum scaling in many body

Systems- Contnetino

How to approach Phase Transitions ? - Scaling Theory

- Most transitions can be tracked by defining a length to the critical point and an order parameter and tracking how divergences occur in physical observables in relation to these parameters
- Example: 1D Ising model in a transverse magnetic field.

$$H = -J \sum_i S_i^z S_{i+1}^z - h \sum_i S_i^x - H \sum_i S_i^z,$$

- Given order parameter $\langle S^2 \rangle$, critical point at $(h/J)_c$
- Length g : $(h/j)-(h/j)_c$

1-D Ising Model - Scaling Relations

- Here, as $g \to 0$, the free energy density f_s, the correlation length ξ , the critical relaxation time τ , the order parameter $m = -\partial f_s/\partial H$, the order parameter susceptibility $\chi = -\partial^2 f_s/\partial H^2$, behave as shown.

$$f_s \propto |g|^{2-\alpha}$$
$$\xi \propto |g|^{-\nu}$$
$$m \propto |g|^{\beta}$$
$$\chi \propto |g|^{-\gamma}$$
$$\tau_\xi \propto |g|^{-\nu z}$$
$$m(H, g = 0) \propto H^{1/\delta},$$

- This gives rise to the equations between the critical exponents themselves - Scaling and Hyperscaling relations

$$\alpha + 2\beta + \gamma = 2$$
$$\beta + \gamma = \beta\delta$$
$$\nu(2 - \eta) = \gamma.$$
$$2 - \alpha = \nu d.$$

Does Scaling theory hold at the Quantum level ?

- The major change comes in relation to the ‘dynamic exponent’ **z**.
- Since in the quantum state time and Energy are coupled by Heisenberg uncertainty. You get different hyperscaling relations.
- That is to say the quantum system behaves classically at an effective dimension of $d_{eff}=d+z$.

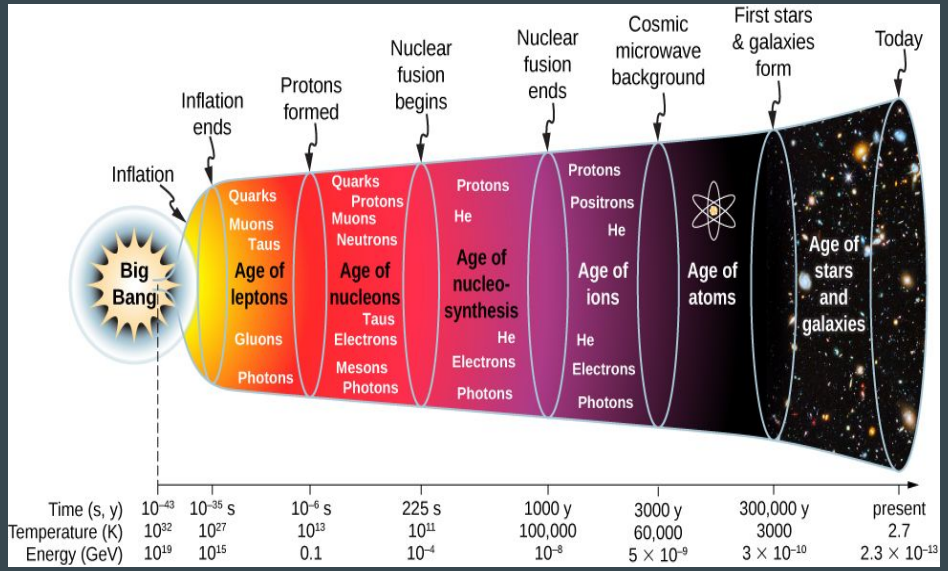
$$2-\alpha = \nu(d+z),$$

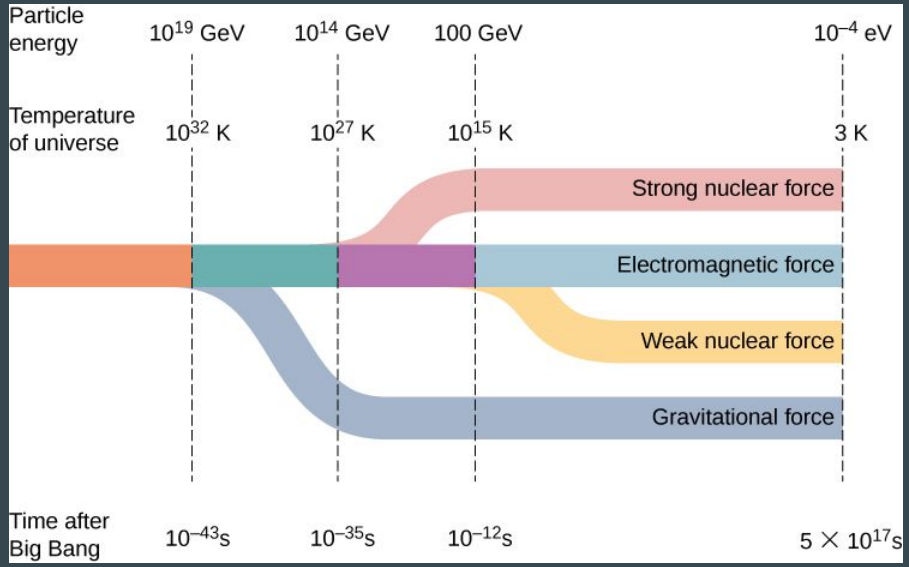
$$2\beta = \nu(d+z-2+\eta),$$

- Caveat: Scaling theories are very well defined for smooth transitions. In the case of first order phase transitions, interesting effects arise due to the discontinuity. More on that later.

Our Early Universe

A Timeline of how we Blew up !



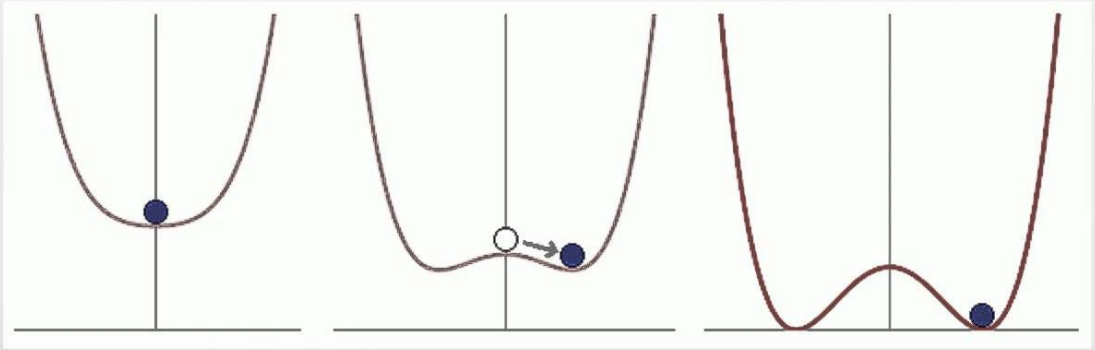


- Too many things happened before a second - notable events : **Breaking of the forces, inflation**

Image courtesy: LibreTexts/Physics/BigBangCosmology

A Closer Look after the Bang - How the forces split up ?

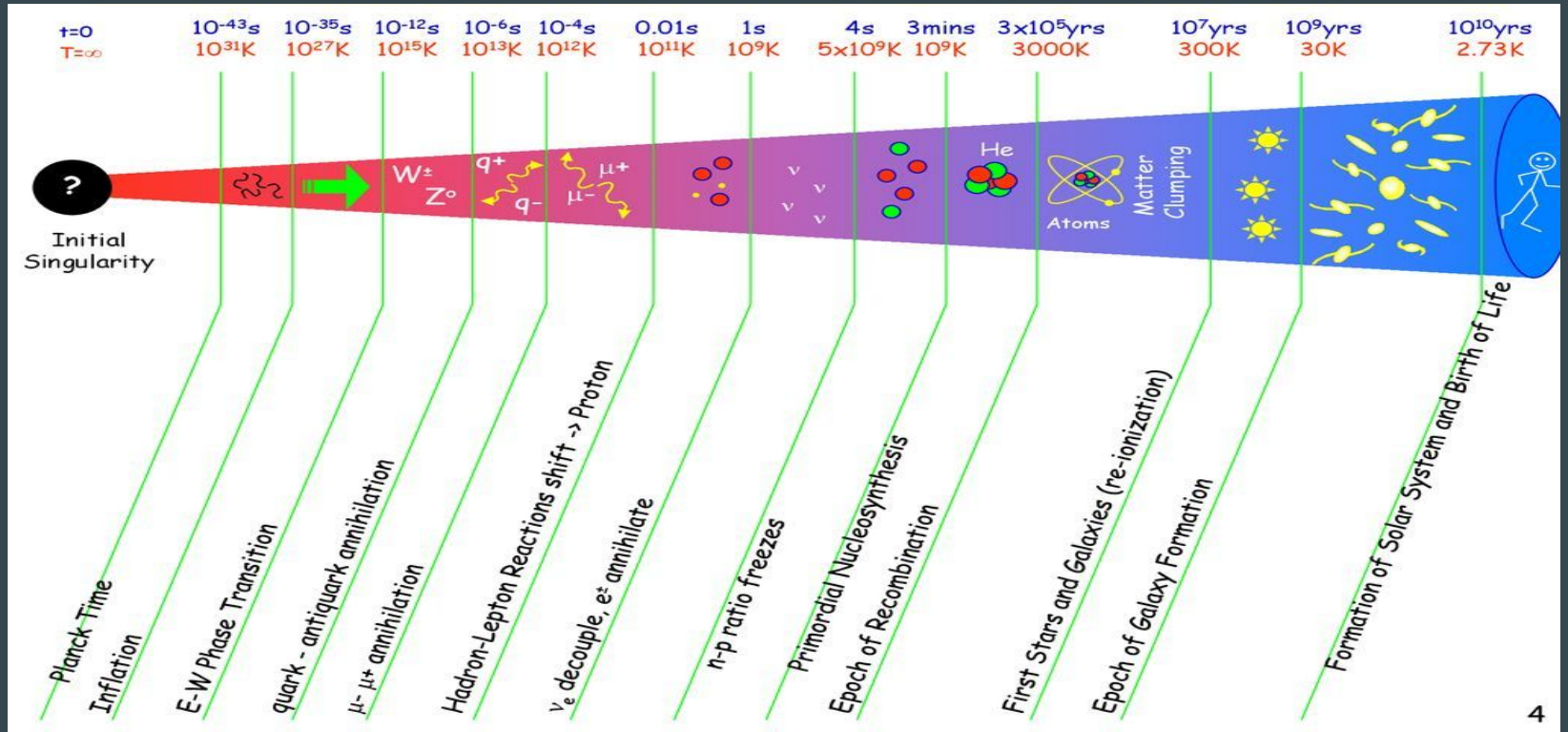
- It was posited and then since proved that the forces split up through a process called ***Spontaneous Symmetry Breaking.***
- This is a process, in which due to changes in the temperature of the universe, radical shifts are occurring in the very fabric of our reality. Sounds familiar?



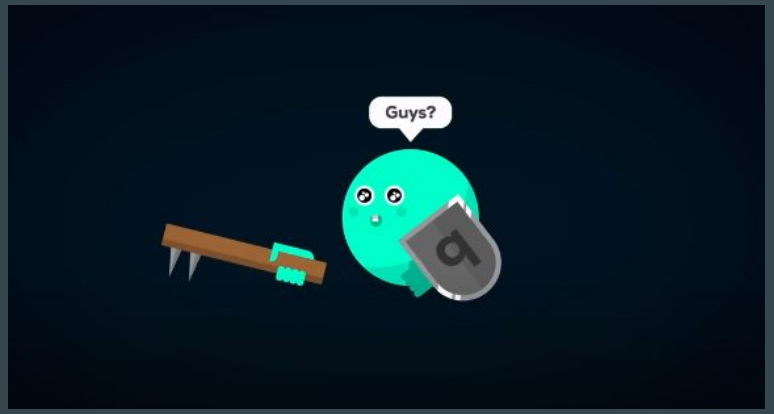
https://en.wikipedia.org/wiki/File:Spontaneous_symmetry_breaking_(explanatory_diagram).png

A Phase Transitioning Universe !

Image: Chris Pearson : Fundamental Cosmology 7: Big Bang Cosmology ISAS -2003



An Interesting Problem - An Uneven universe ?



- Spontaneous symmetry breaking chooses one of it's possible choices randomly. An ideally equal world
- But a war broke out around 10^{-12} s (EWPT) But doesn't a war have winners ?
- Matter won ! - ***Baryon Asymmetry of the Universe.*** **Why** ?

Image:youtube/ Kurzgesagt – In a Nutshell

BaryoGenesis: Hunt for A Possible Solution.

Where do we start ?

- Physicists hoping to gain better understanding of what kind of Phase transition occurred in the early universe, invoked a ***Sphaleron.***
- The Sphaleron has the ability to convert a baryon to an antileptons/antibaryon to a lepton and thus unbalance the baryon number in the universe.
- We require Baryon excess in Unbroken phase but conservation in broken phase i.e, discontinuous. - 1st Order !

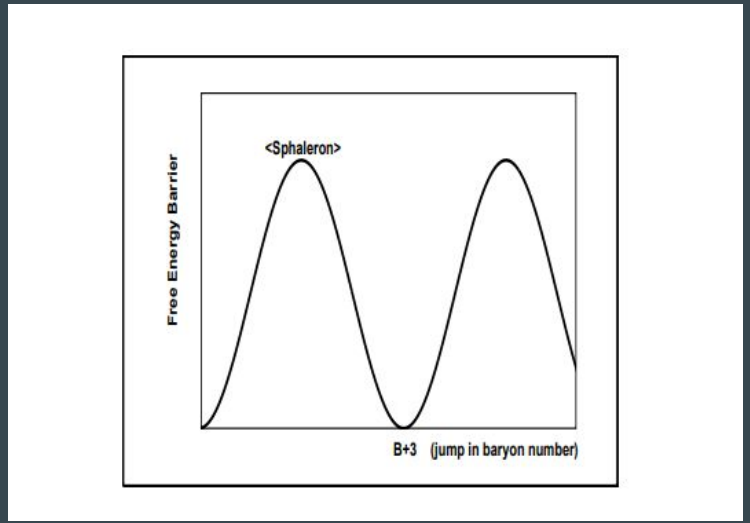
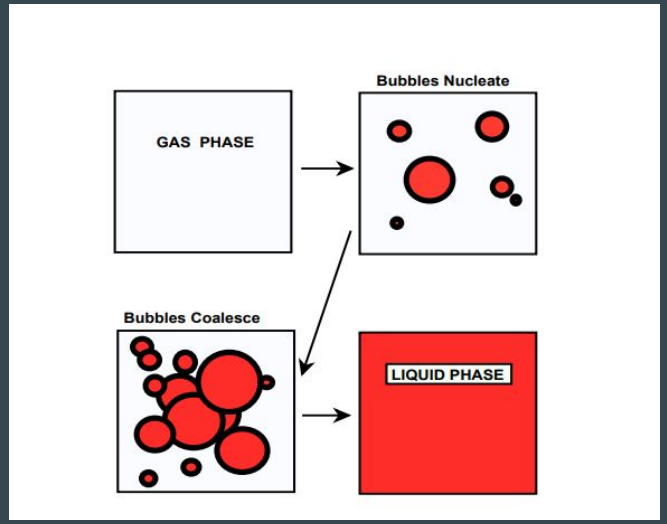


Image courtesy: arXiv:hep-ph/9803291v1 9 Mar 1998

Aren't First Orders Weird ? Can you even use Scaling ?

- Although there is no diverging length or time in these transitions, scaling ideas have proved to be very useful for discontinuous, temperature-driven transitions.
- When the temperature decreases at the critical point bubbles of characteristic length ξ_L are nucleated
- These Bubbles percolate, collide and eventually populate the phase.



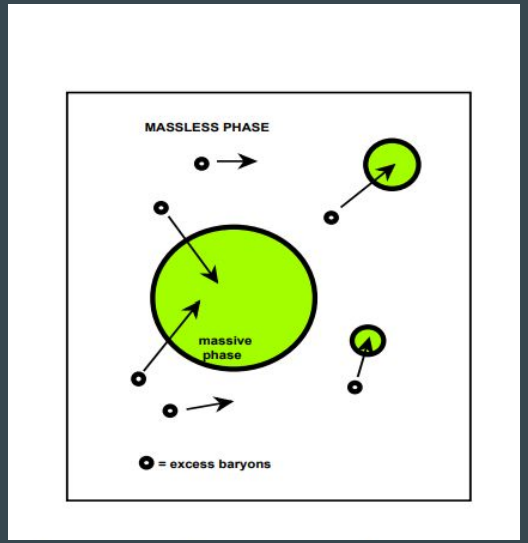
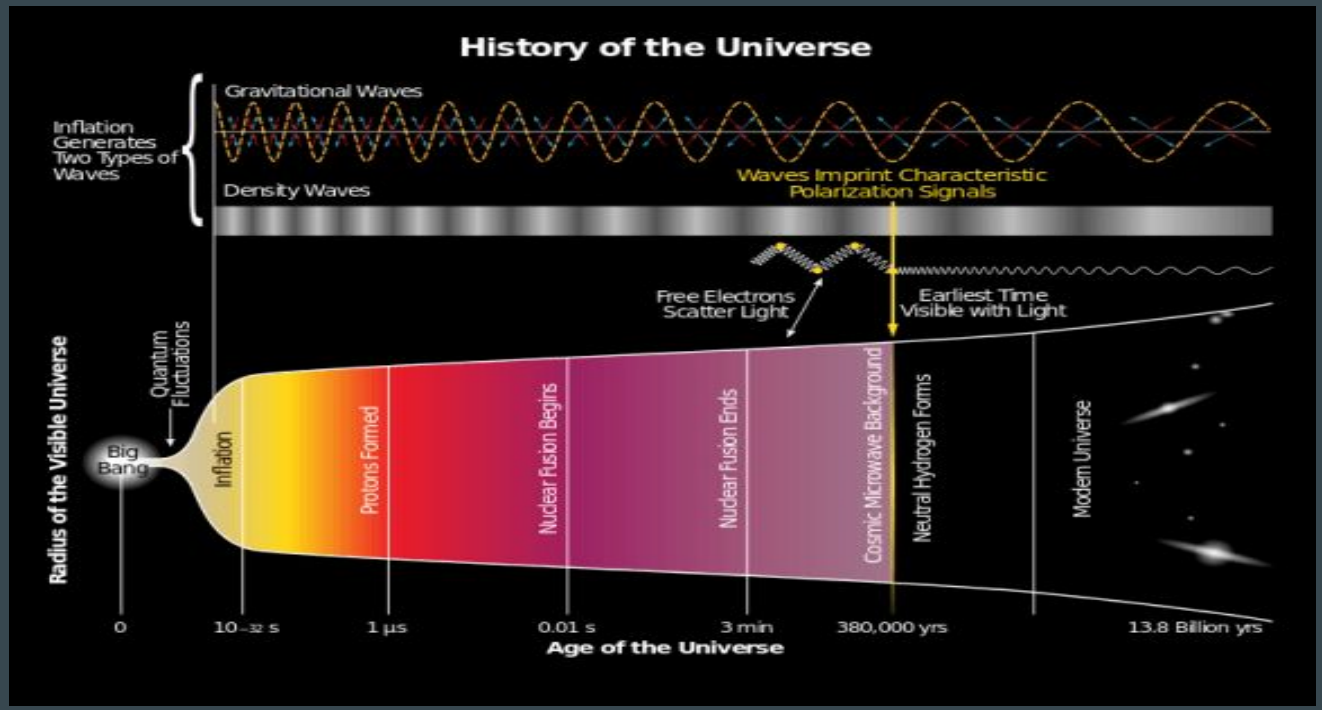


Image courtesy: arXiv:hep-ph/9803291v1 9 Mar 1998

Cosmological Bubble Collisions : Full Circle ?

- Bubble Collisions and related processes give rise to Gravitational Waves !

  Image: phys.org



An Effective Approach to Gravitational Waves

One can follow top down or bottom up approach.

- Design mechanism for Baryogenesis and include it in your model .
- Use Coleman/Weinberg or something similar to generate an effective potential from the Lagrangian.
- Apply scaling theory to generate bubble length, velocity, percolation rate etc.
- Generate gravitational wave spectra from calculations
- Compare with current data/Suggest signatures for searches.

CONCLUSION

- Gravitational waves are ripples in the space-time fabric and a discovery that will radically change how we view the universe .
- Understanding of phase transitions are essential when dealing with processes in the Early universe.
- Electroweak Baryogenesis models and other BSM models can be probed using gravitational waves generated from such phase transitions
- Theoretical and Experimental refinements in this field will dawn a new era of modern High Energy Physics/Cosmology.

Thank You