

**Generation and constraints  
of cosmological magnetic  
fields (and gravitational  
waves) during early phase  
transitions**

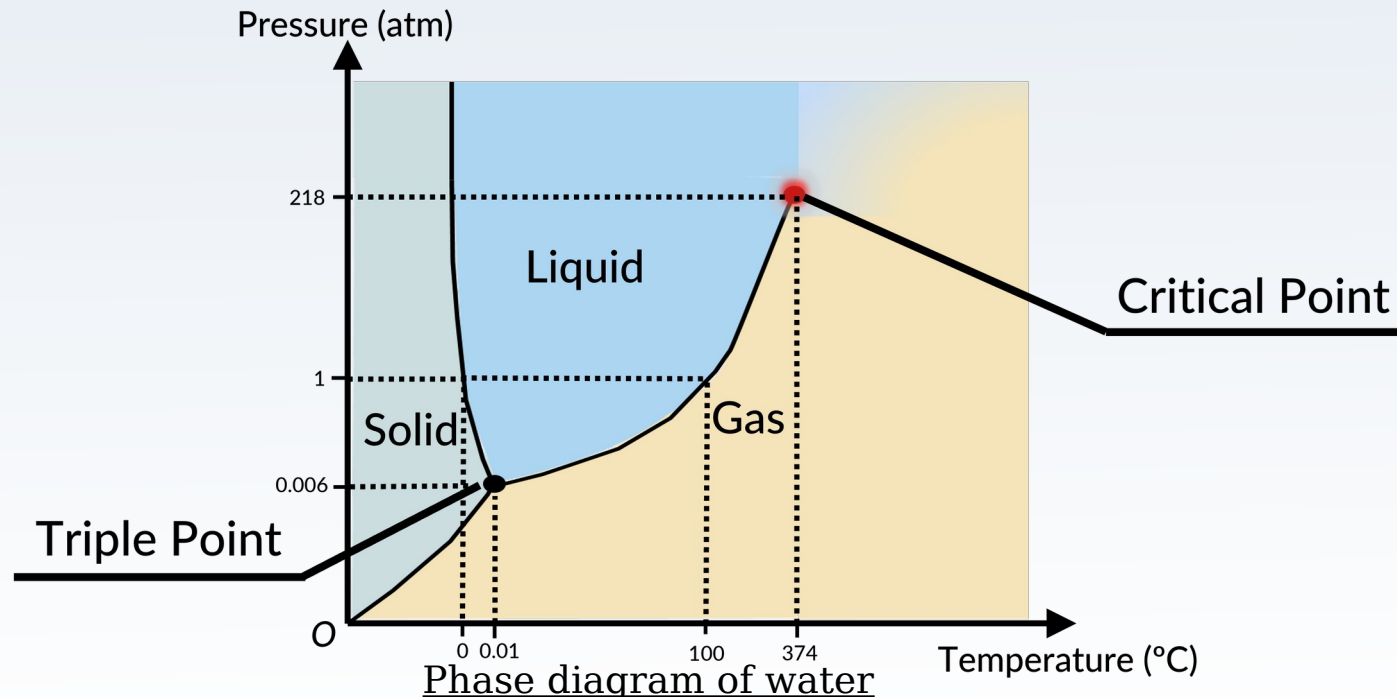
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What is a phase  
transition ?

# *What is a phase transition ?*

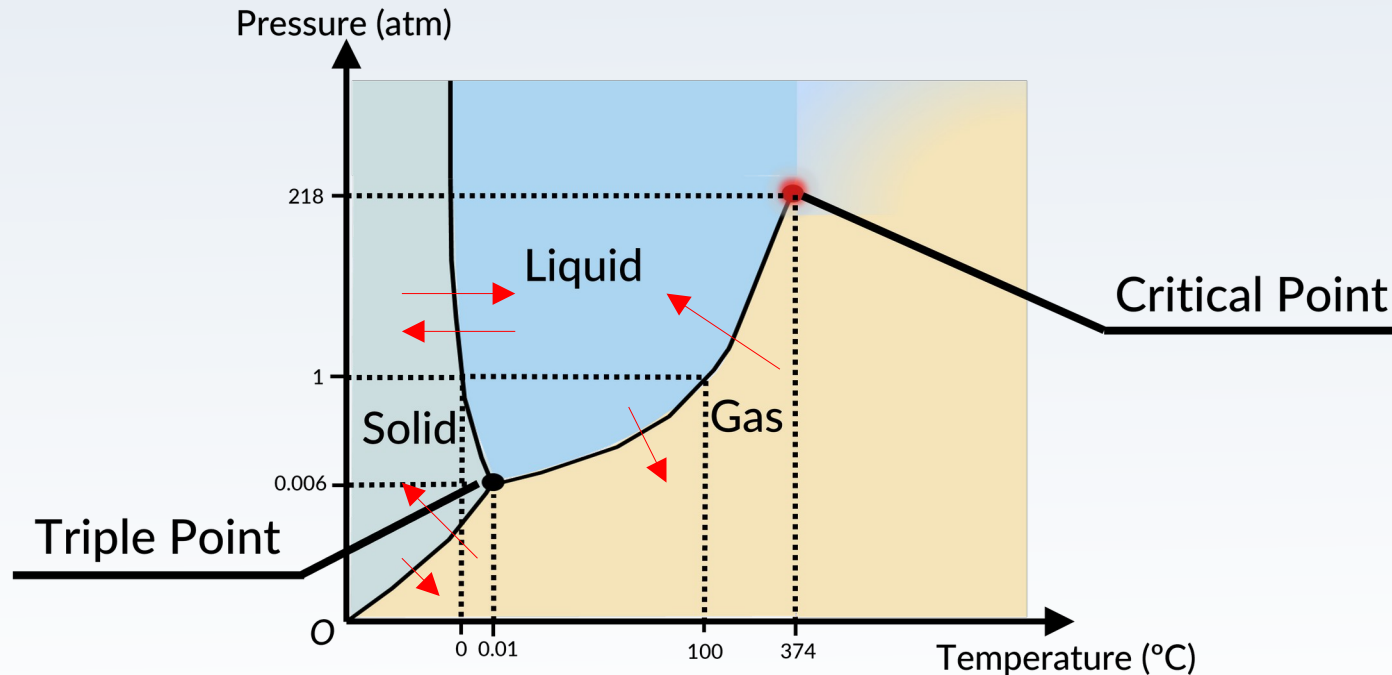
Transition between states of matter

Ex : solid to liquid, liquid to gas ...



# *What is a phase transition ?*

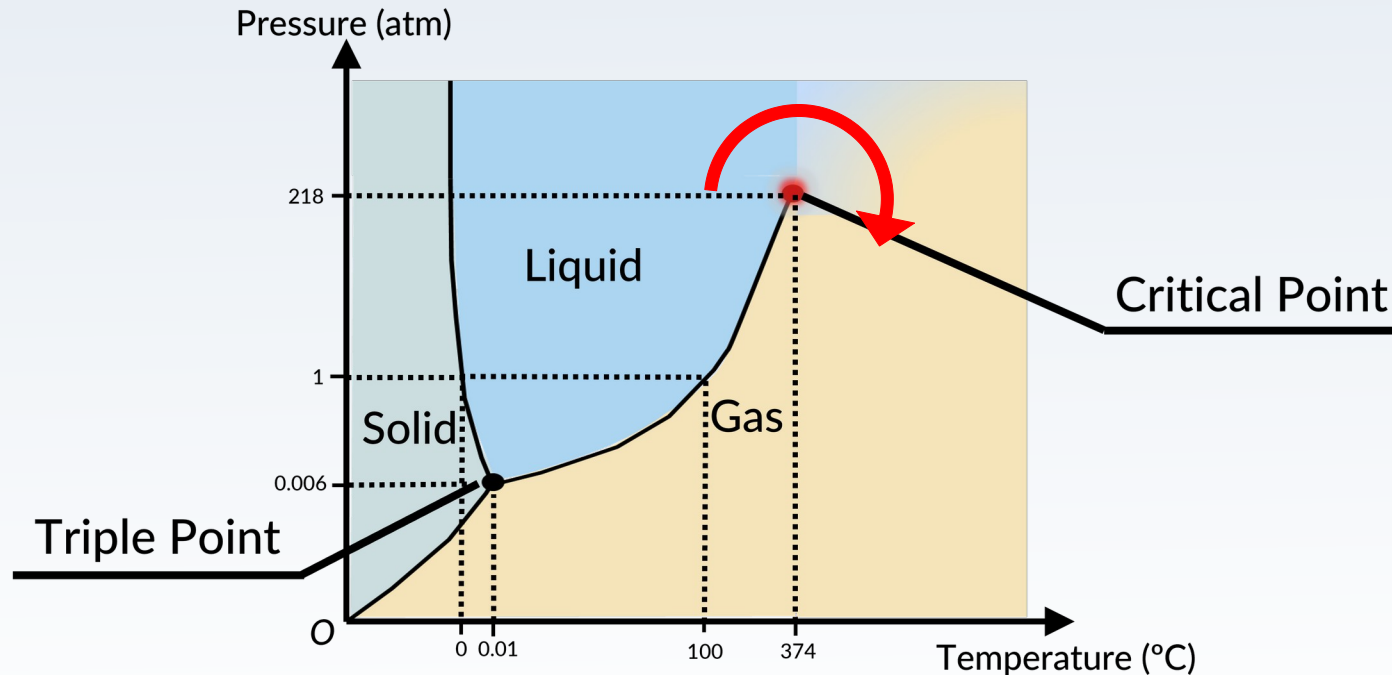
2 types of phase transition : 1st order type



Phase diagram of water

# *What is a phase transition ?*

2 types of phase transition : 2nd order type / crossover



Phase diagram of water

# *What is a phase transition ?*

1st order : releasing or absorbing latent heat

2nd order/crossover : no latent heat

ORDER PARAMETER : =0 in one phase and  $\neq 0$  in the other

1st order : discontinuous evolution of the order parameter

2nd order/crossover : continuous evolution of the order parameter

Ex : density for ice/water, viscosity for glass ...

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What is an early phase transition ?



# *What is an early phase transition ?*

A brief history of  
our Universe (for  
now)

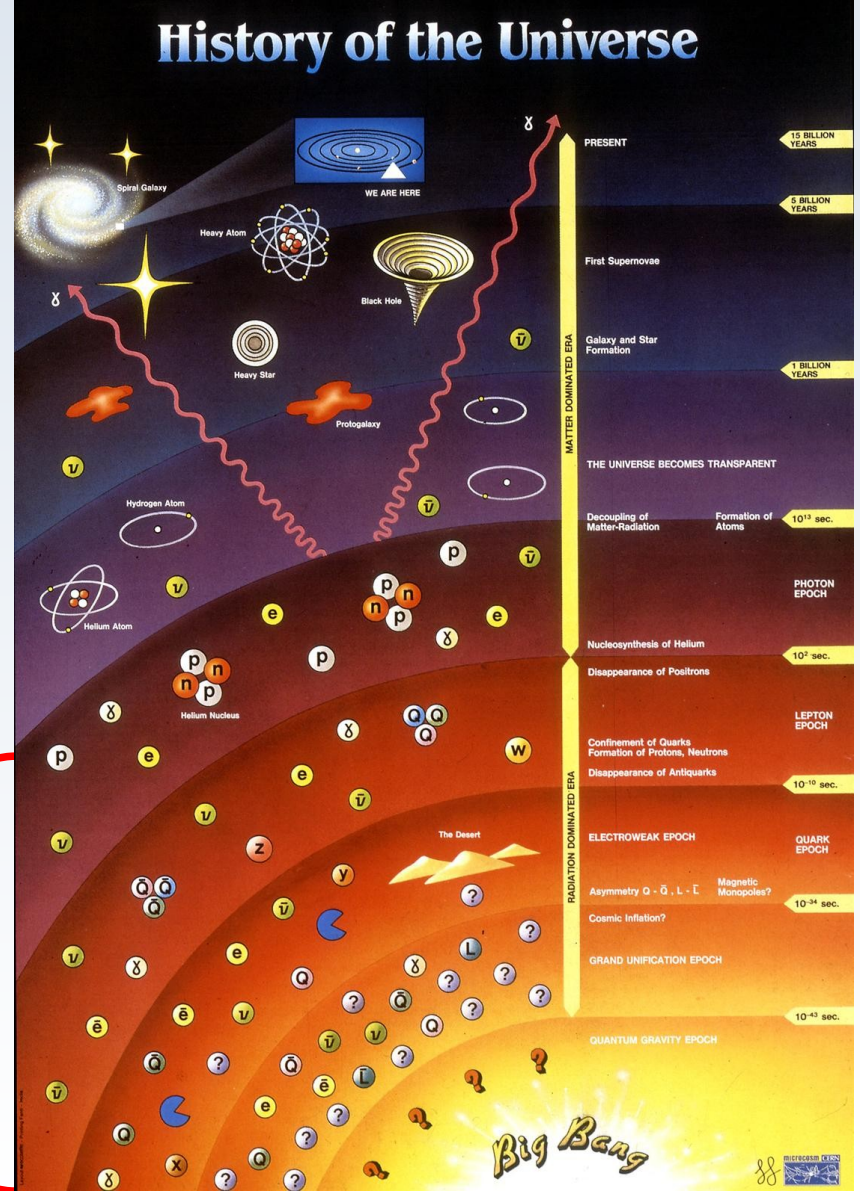


# What is an early phase transition ?

A brief history of our Universe (for now)

« Early »

= the first 400 000 years after the Big Bang



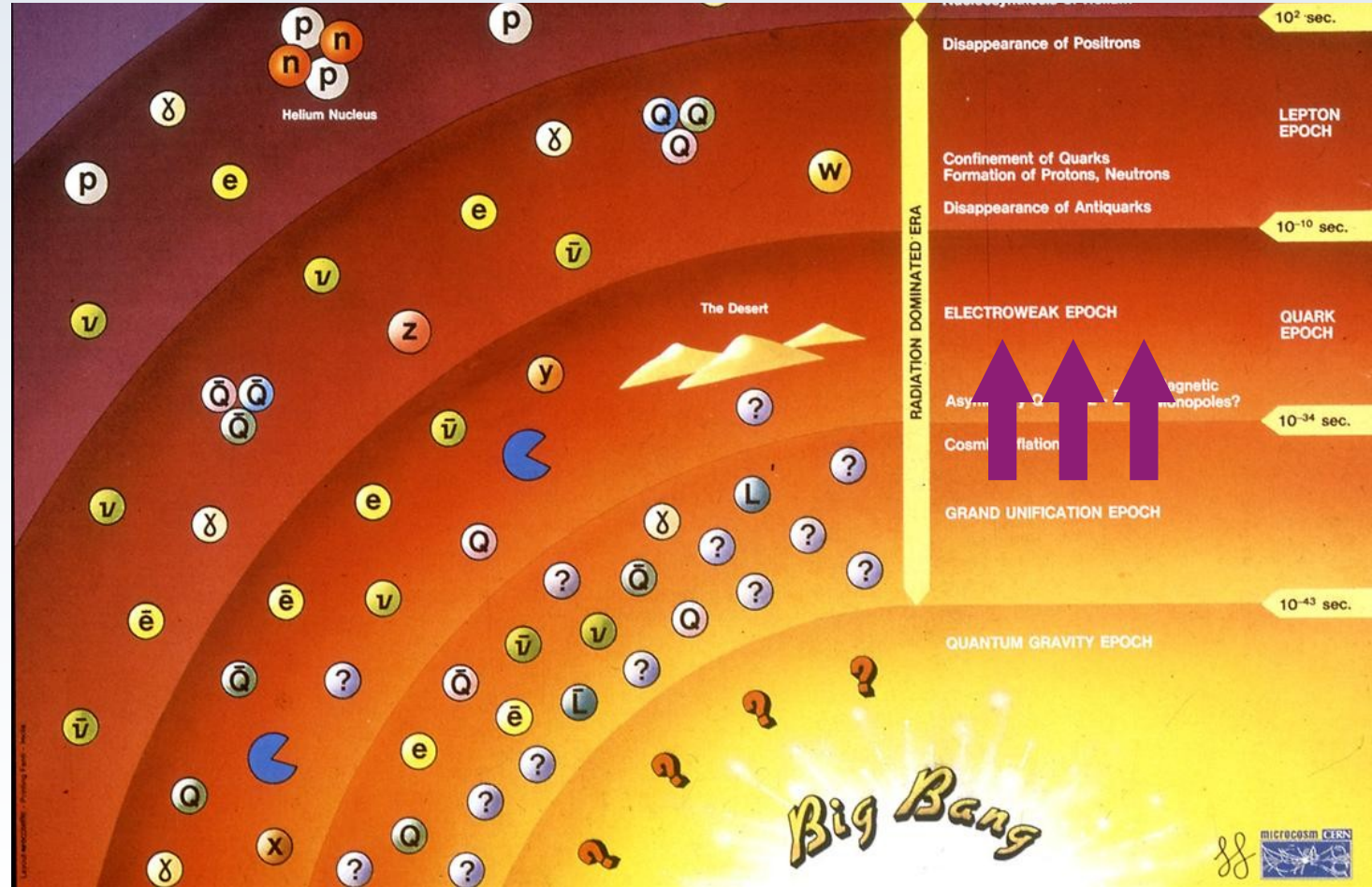


# What is an early phase transition ?

A brief history of our Universe (for now)

Phase transitions :

- Electroweak phase transition

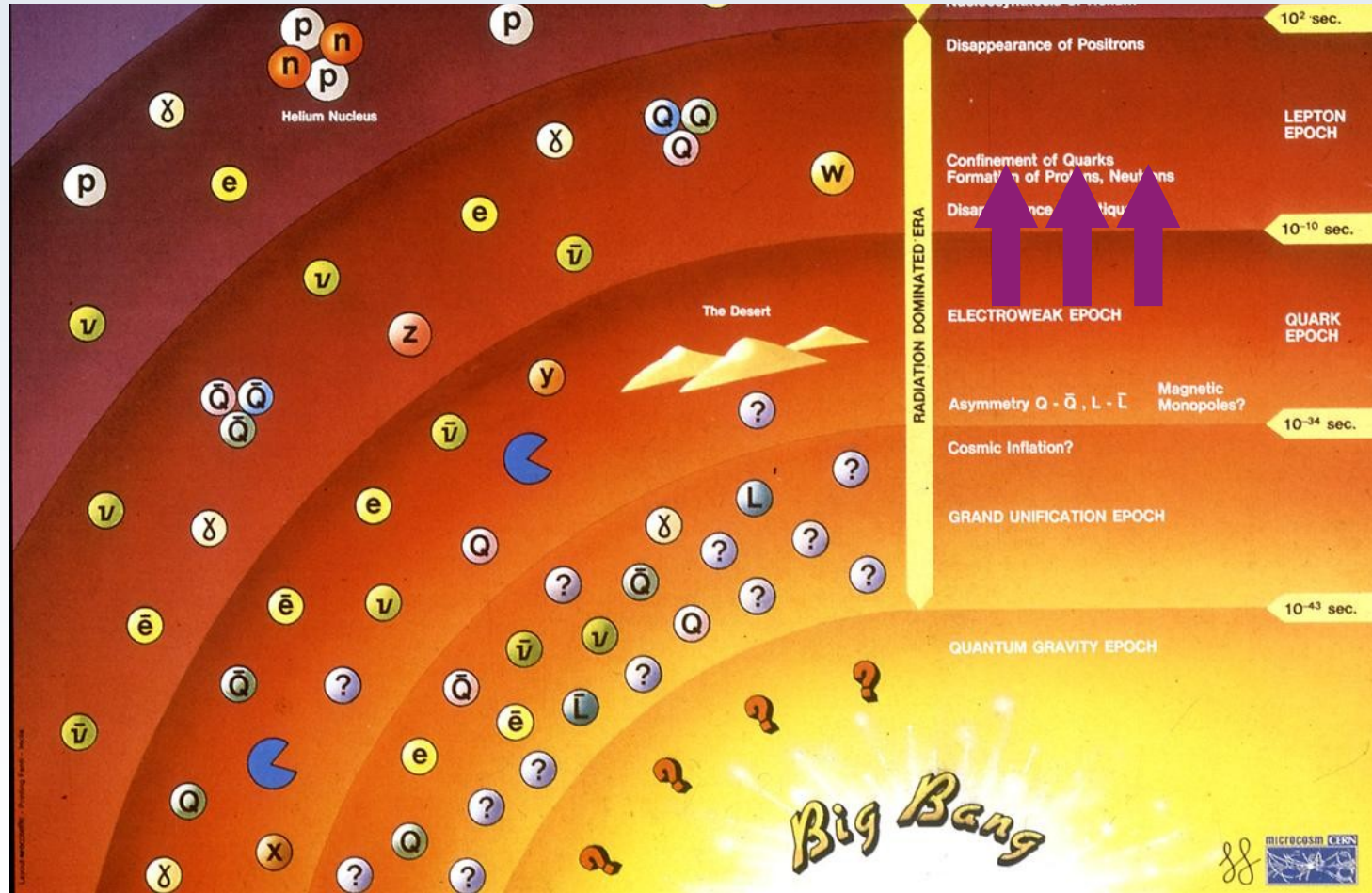


# What is an early phase transition ?

A brief history of our Universe (for now)

Phase transitions :

- Electroweak phase transition
- QCD phase transition



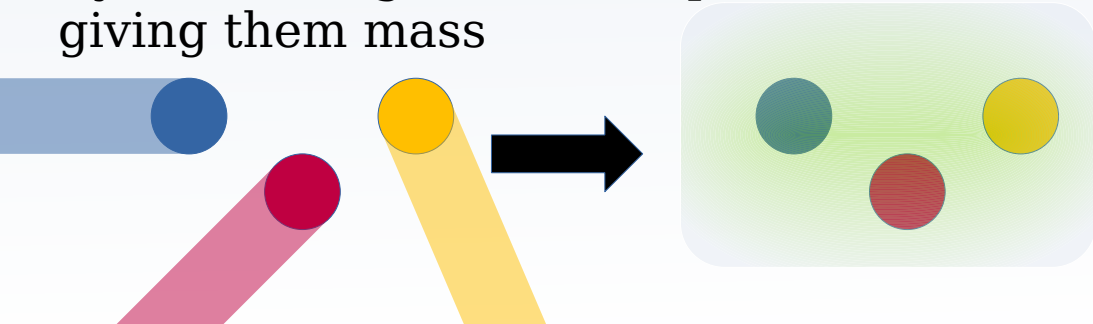
# *The Electroweak phase transition*

How do the particles acquire their inertial mass ?

Answer : Higgs mechanism !

We assume the existence of a quantum field, whose vacuum expectation value (or its ground state) is  $\neq 0$  for  $T < T_c$  and  $= 0$  for  $T > T_c$

By interacting with other particles, it's giving them mass

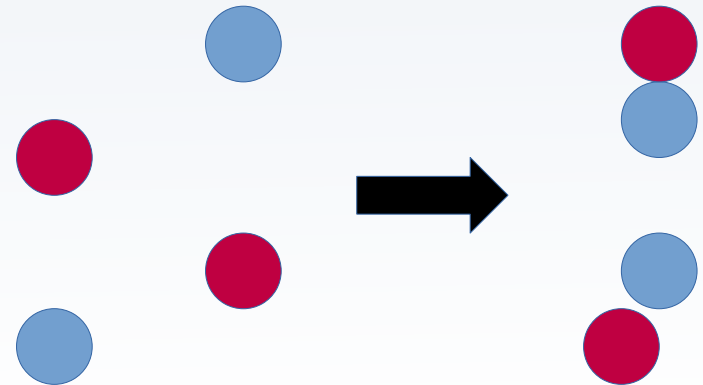


# *The QCD phase transition*

Before the QCDPT : quark gluon plasma

Phase transition : confinement of quark  $\Leftrightarrow$  quarks bound to form mesons

After the phase transition :



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# *What are gravitational waves ?*

- Theory of general relativity : describes gravity as a deformation of the geometry of space-time.
- Summarized in Einstein equation : matter can deform space-time and space-time geometry affect trajectory of matter

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Prediction : if high density matter at high velocities it can generate perturbation waves in the geometry of space-time : gravitational waves

# *What are cosmological magnetic fields ?*

- Magnetic fields exist on different scales : planets, stars, galaxies ...
- Magnetic fields on cosmological scales ?

Yes : Intergalactic Magnetic Fields (IGMF) !

- Constraints on their 2 parameters : amplitude  $B$  and correlation length  $\Lambda_B$
- Detectable effects : Faraday rotation and secondary gamma-ray emission

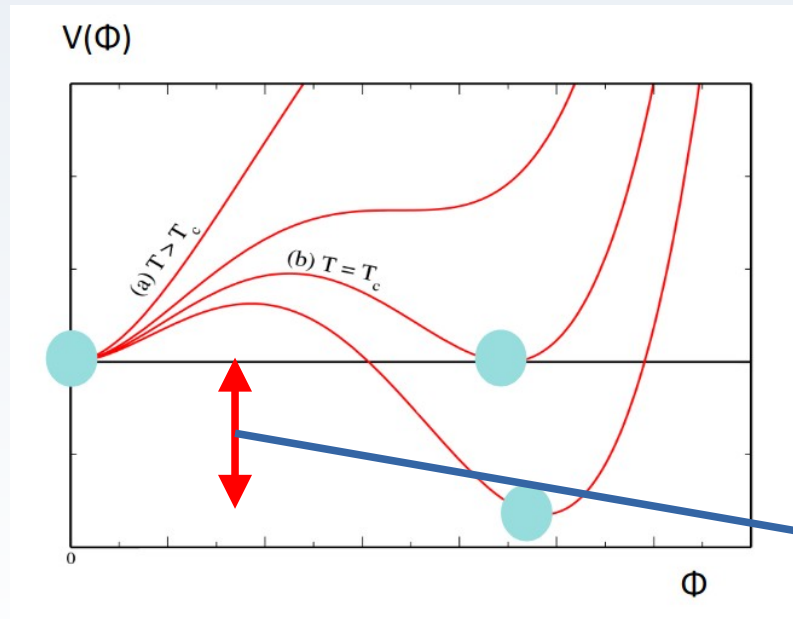
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How can phase transition generate IGMF  
and gravitational waves ?

# How can phase transition generate IGMF and gravitational waves ?

We need 1st order phase transition ! Because we need to be out of thermodynamic equilibrium

Exemple of the electroweak phase transition



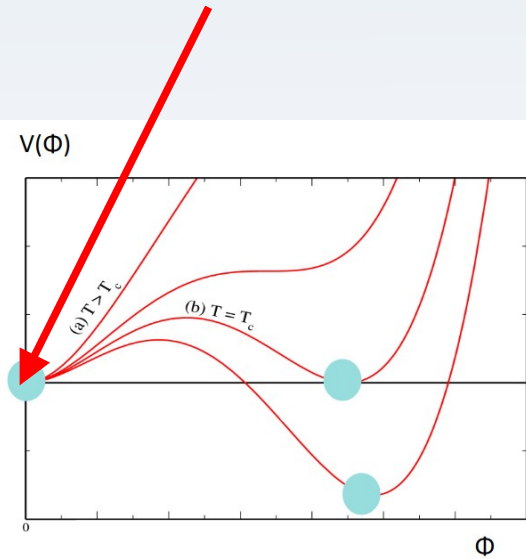
**order parameter** : Higgs vacuum expectation value (minimum of the potential)

Effective potential of the higgs field for a 1st order phase transition

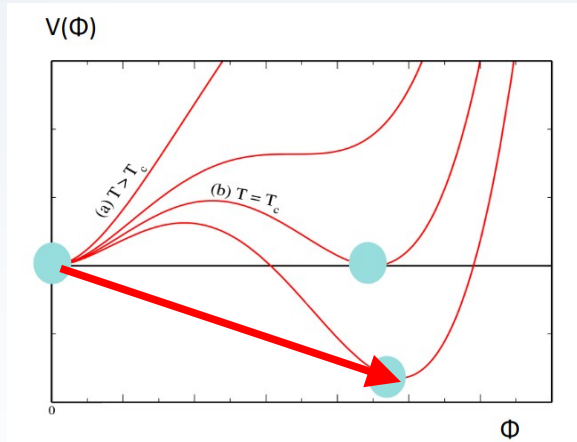
Latent heat

# How can phase transition generate IGMF and gravitational waves ?

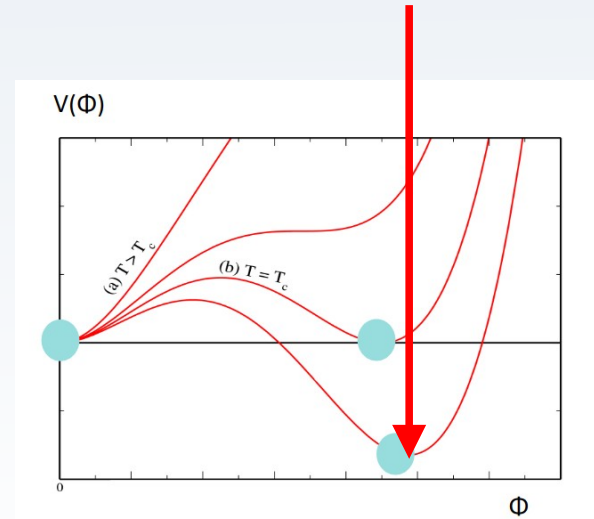
Step 1 : Universe is stuck in the  $\Phi=0$  ground state



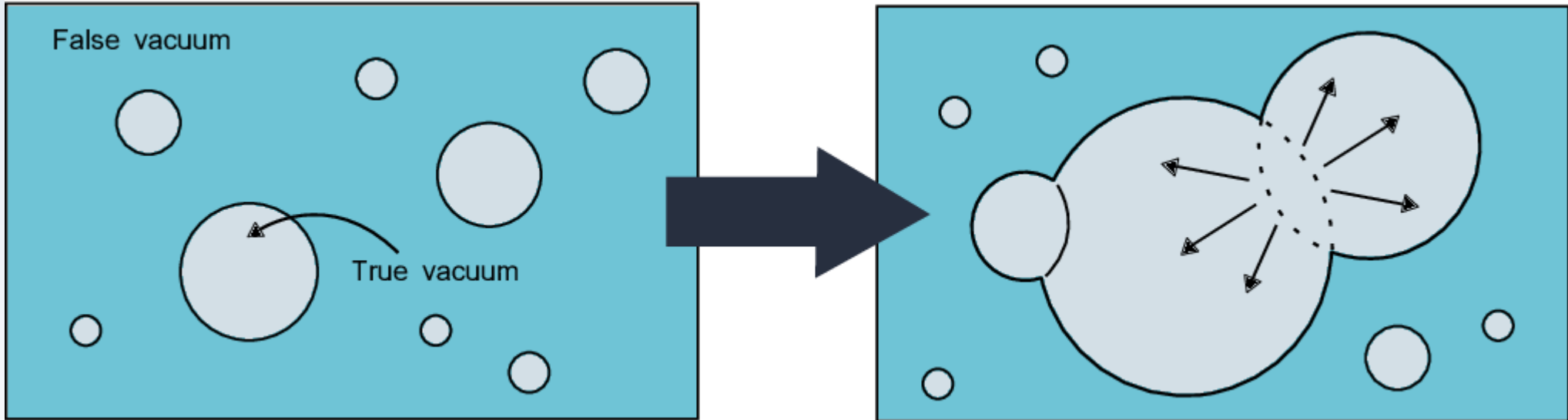
Step 2 : Universe is tunneling through the barrier to reach the true vacuum



Step 3 : Universe has transitioned totally into the true vacuum



# *How can phase transition generate IGMF and gravitational waves ?*



Bubbles of true vacuum expands in the old vacuum until they percolate : out of equilibrium  $\rightarrow$  generation of gravitational waves and magnetic fields

# *How can phase transition generate IGMF ?*

- Different mechanisms have been described : Higgs field gradient, charges separation at bubble wall ...
- Same « trick » often (not always) used to obtain and quantify huge magnetic fields and gravitational waves :

1- Generate a seed magnetic field using one of the many mechanisms proposed in the literature

2- Use the equipartition hypothesis saying that at bubble percolation we have :

$$\mathbf{E}_{\text{turb}} = \mathbf{E}_{\text{mag}}$$

→ amplification of the seed magnetic field



So, what is the problem ?

# *So, what is the problem ?*

- Standard model predicts that EWPT and QCDPT are crossovers ...
- And observed cosmological magnetic fields cannot be generated from crossovers.
- 3 ways to solve the issue :
  - we miss some hidden mechanism and crossovers can generate magnetic fields
  - there is some « new physics » to be discovered that transforms phase transition into 1st order
  - Magnetic fields don't come from phase transitions ...

# *So, what is the problem ?*

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**My job (partially) !**

- 3 ways to solve the issue :

- we miss some hidden mechanism and crossovers can generate magnetic fields
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- Magnetic fields don't come from phase transitions ...

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# What are the current constraints on IGMF ?

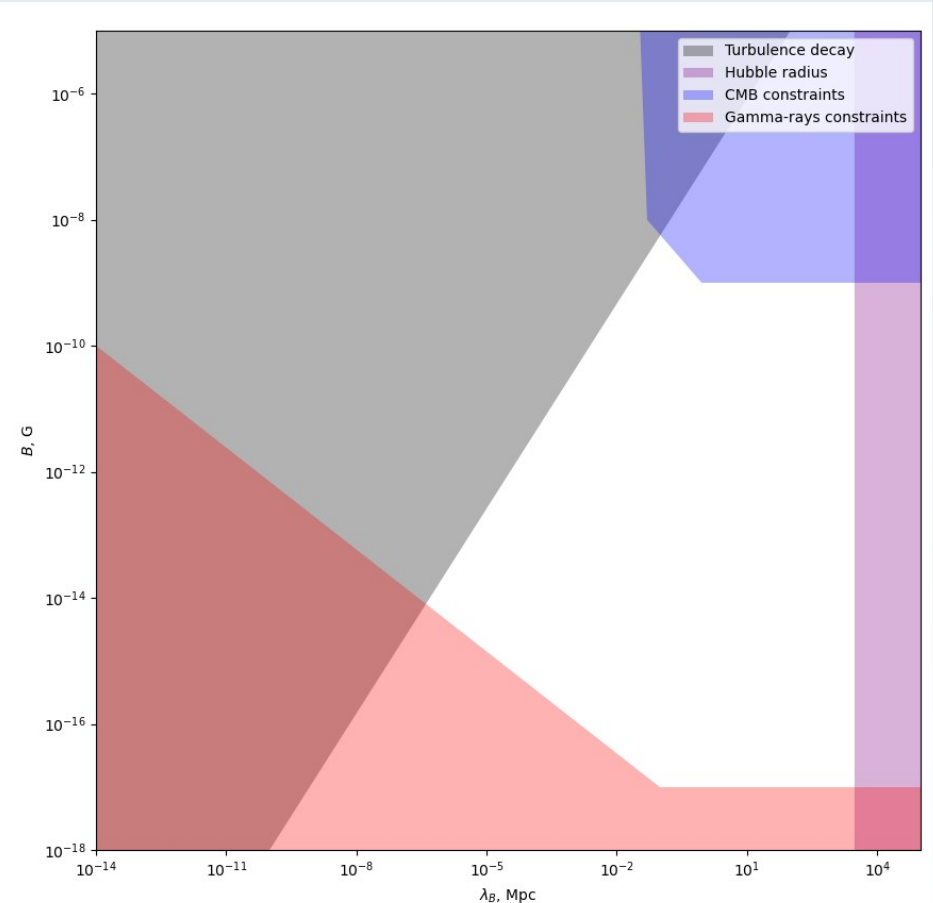
Turbulence decay : magnetic energy is converted into heat at smaller scales

Hubble radius : maximal causal scale in the Universe

CMB constraints : lots of constraints ...

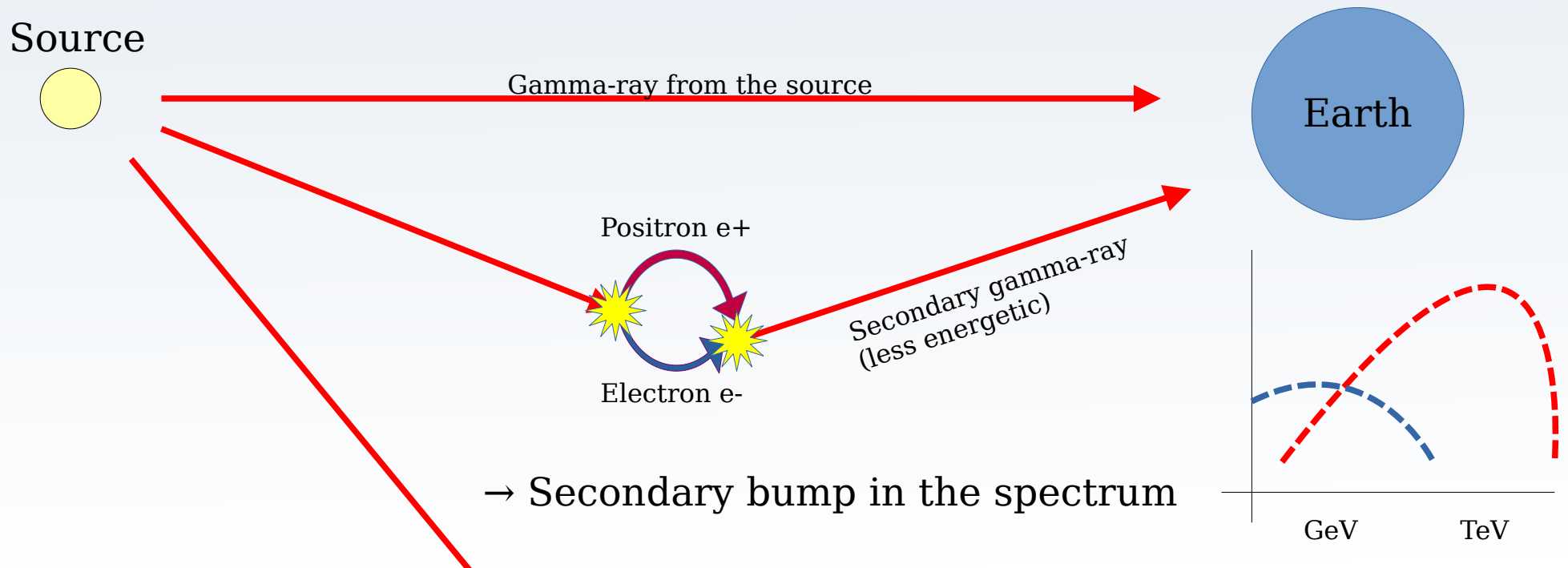
Gamma-rays constraints : the most important → non-zero magnetic fields « observed »

Finally a lower bound → we are (probably) not working on nothing !



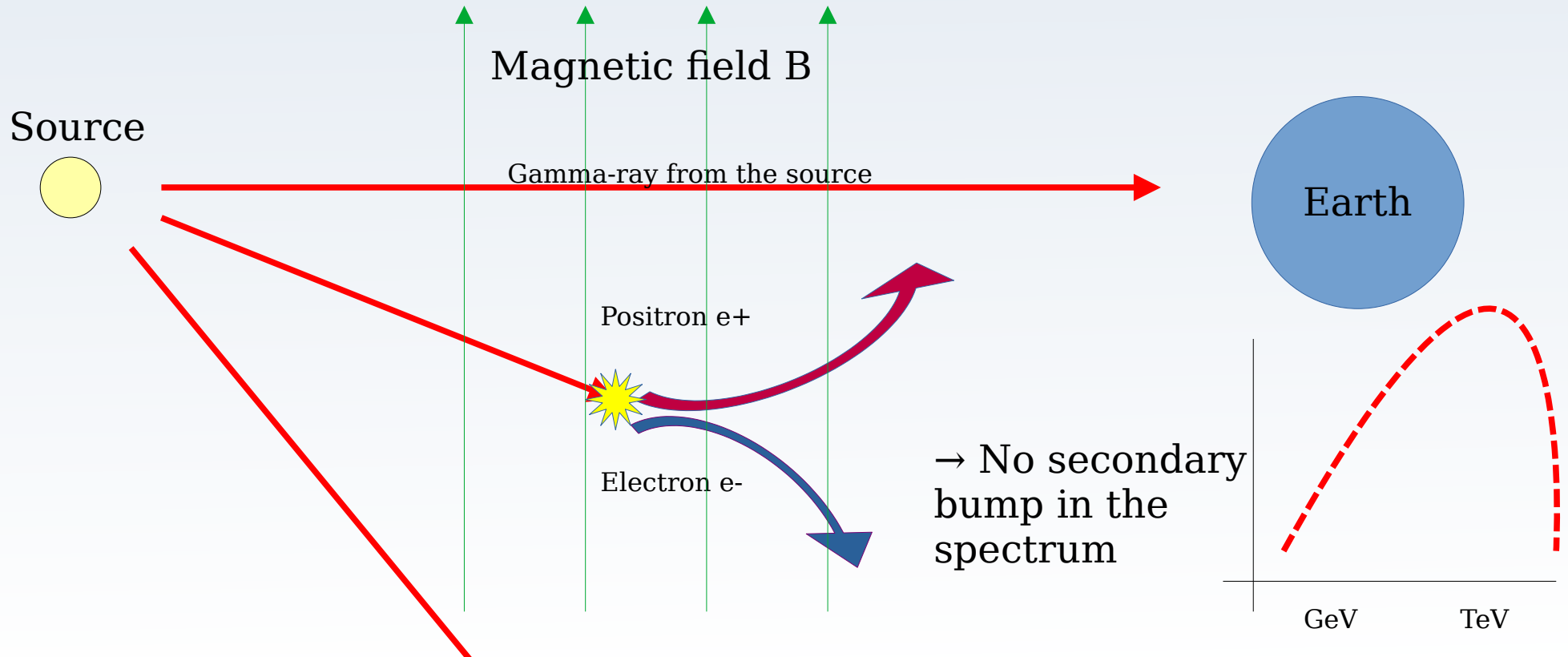
# What are the current constraints on IGMF ?

Gamma-rays constraints : how does it work ?



# What are the current constraints on IGMF ?

Gamma-rays constraints : how does it work ?





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In the early universe : matter is cooling down

→ phase transitions:  
EWPT and QCDPT

→ 1st order can  
generate IGMF and  
GW

Magnetic fields and  
gravitational waves  
have been indirectly  
observed

→ constraints on MF

→ must come from  
somewhere (probably  
the early Universe)



Problem : only 2nd order !

Thank you !

# *Is there new constraints on IGMF ?*

Pulsar Timing Array : using the pulsars as a galactic Interferometer (15 years survey in 2023)

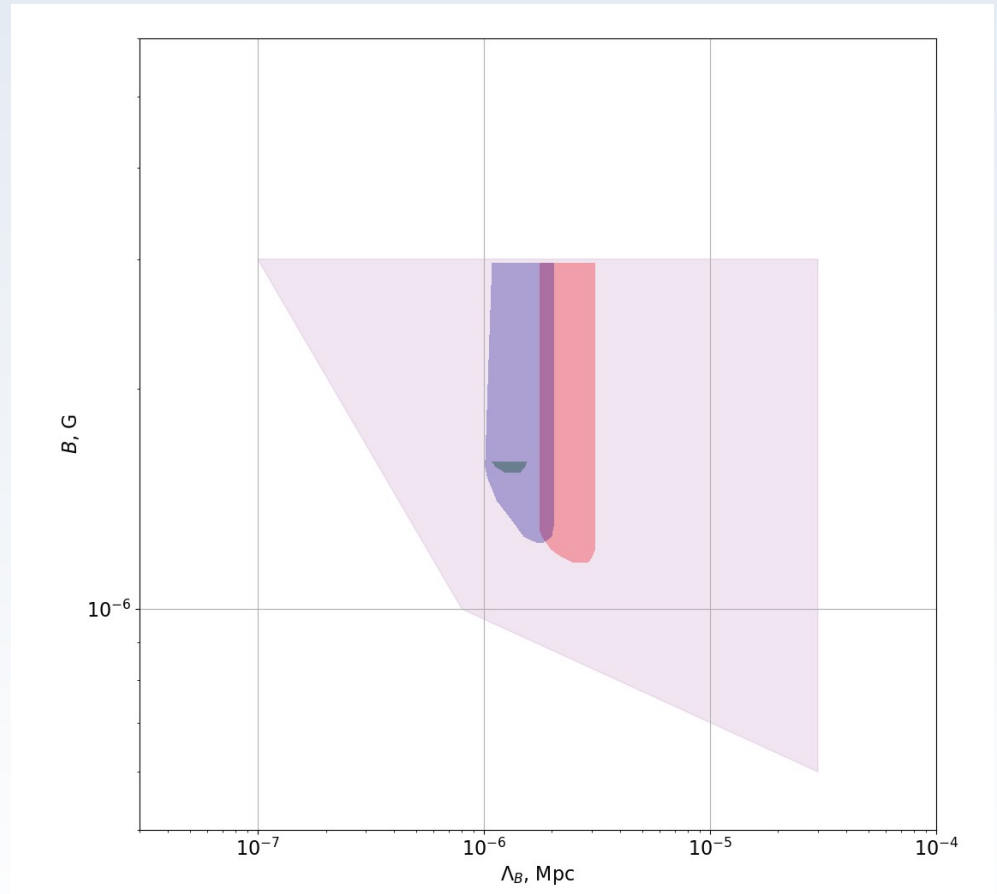
→ New constraints on the Stochastic Gravitational Waves Background (SGWB)

→ New constraints on the parameters of phase transitions

→ New constraints on intergalactic magnetic fields



*Is there new constraints on IGMF ?*



# *How can phase transition generate IGMF and gravitational waves ?*

- Phase transitions can be described by 5 parameters :
  - $\alpha$  the « strength » of the phase transition
  - $\beta$  the duration of the phase transition
  - $v_w$  the speed of the bubble wall
  - $T^*$  the temperature of the phase transition