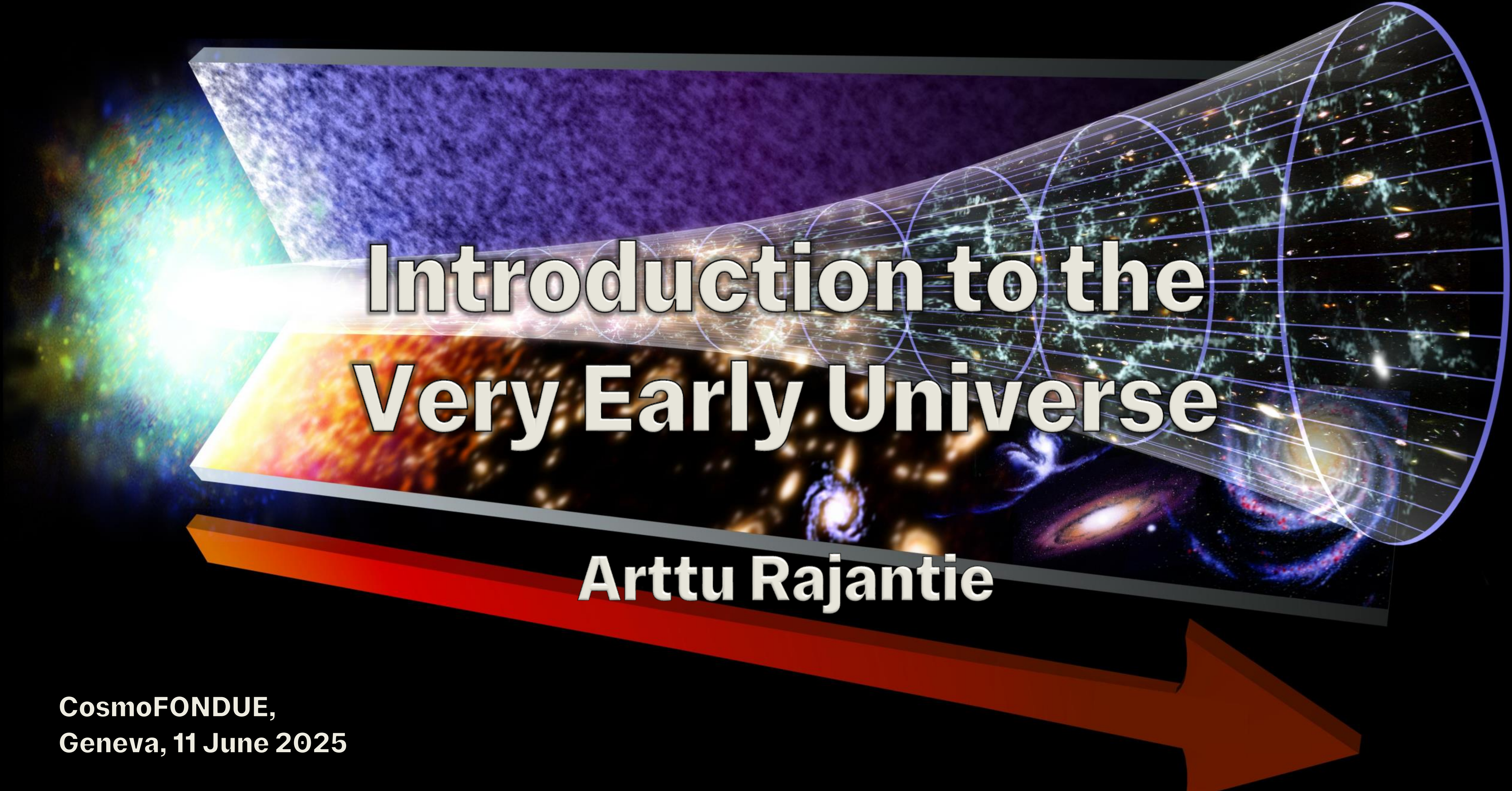
IMPERIAL

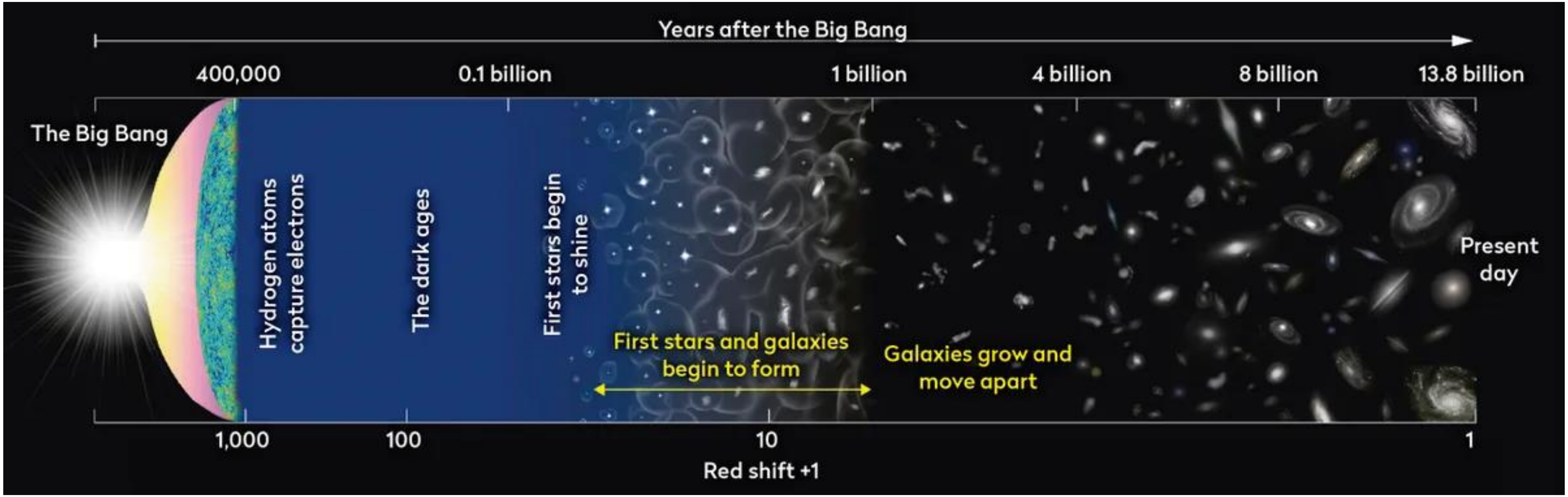
Introduction to the Very Early Universe



Arttu Rajantie

CosmoFONDUE,
Geneva, 11 June 2025

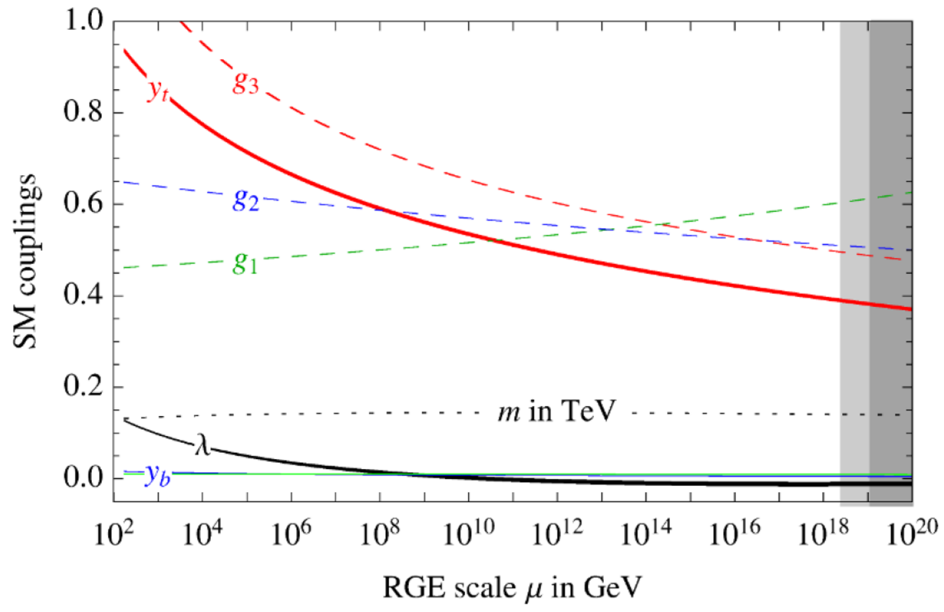
Timeline



- This talk: “Very Early Universe”
  = before Big Bang nucleosynthesis (~ 1 min after Big Bang)

Ultimate Particle Physics Experiment

- Temperature $T \approx 1 \text{ MeV} \left(\frac{t}{\text{s}}\right)^{-\frac{1}{2}}$
  $\Rightarrow$ very early Universe = very high temperature
- Above LHC energies when $t \lesssim 10^{-14}\text{s}$
- Test particle physics theories:
  - beyond the Standard Model
  - or even the Standard Model itself



(Buttazzo et al 2013)

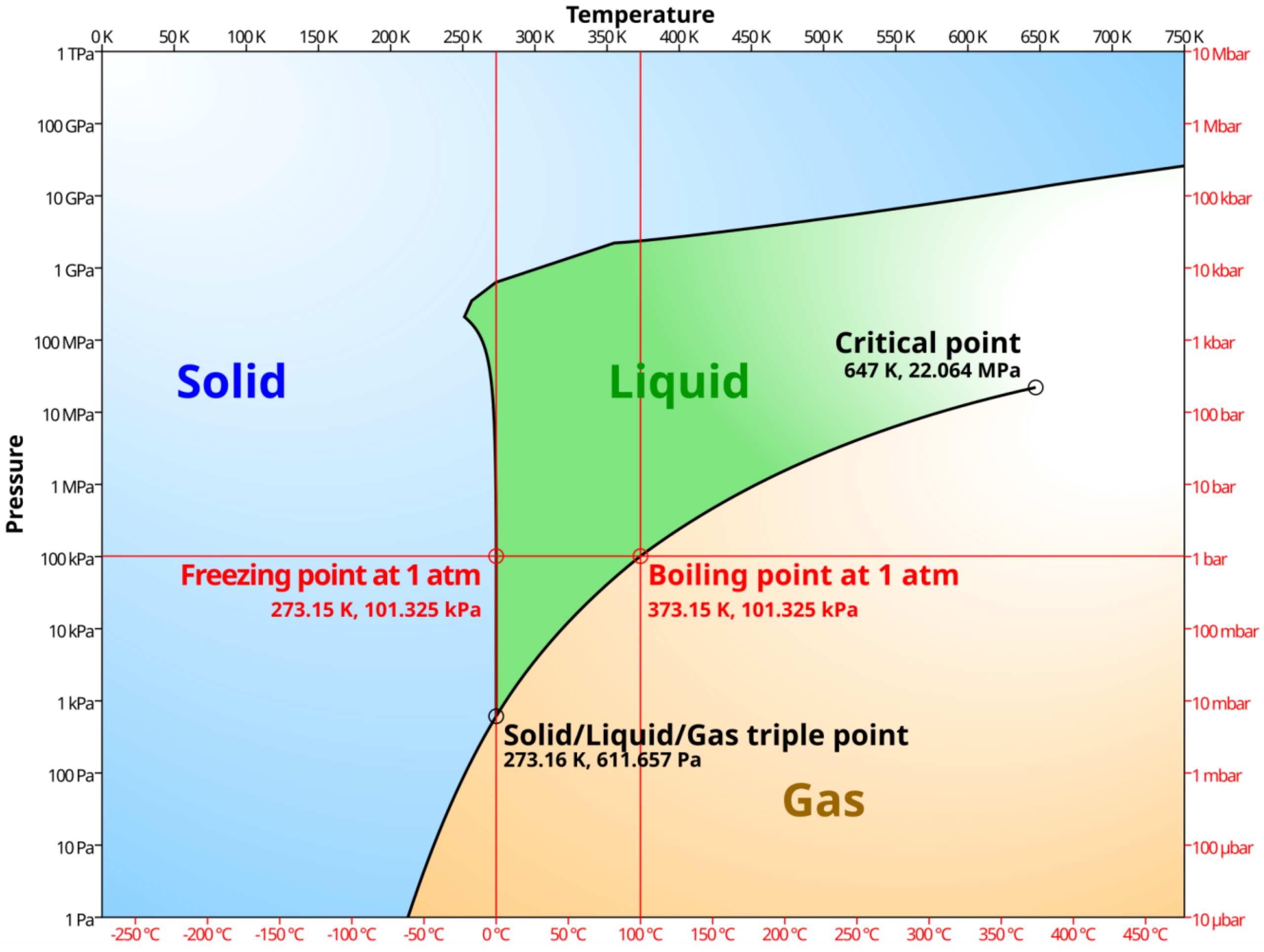
Non-Equilibrium Phenomena

- Phase transitions
- Parametric resonance
- etc

- Relic particles
- Baryon asymmetry
- Primordial black holes
- Curvature or isocurvature perturbations
- Primordial magnetic fields
- Vacuum decay

Phase Transitions

- First-order phase transition:
  - Discontinuous observables
  - Bubbles
    (See posters by Schicho, Bernardo)
- Second-order phase transition:
  - Continuous observables
  - Diverging correlation length
- Crossover
  - Smooth observables
  - No actual transition



(Wikimedia Commons / Cmglee)

QCD Phase Transition

- Temperature $T \sim 100\ \text{MeV}$, time $t \sim 10^{-5}\ s$
- Quark gluon plasma → protons and neutrons
- Lattice field theory simulations:
  crossover
  ⇒ No actual departure from equilibrium

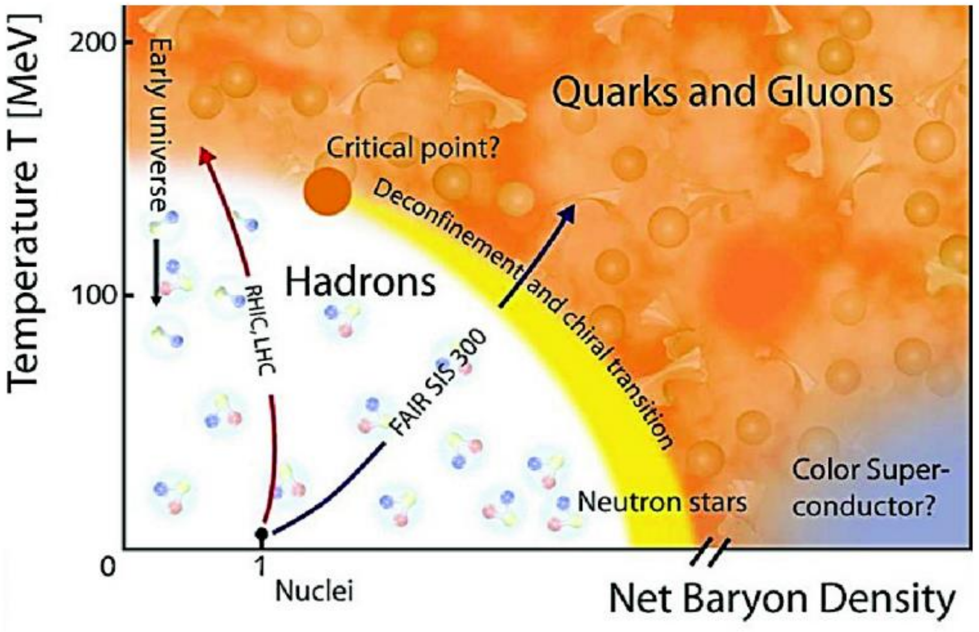
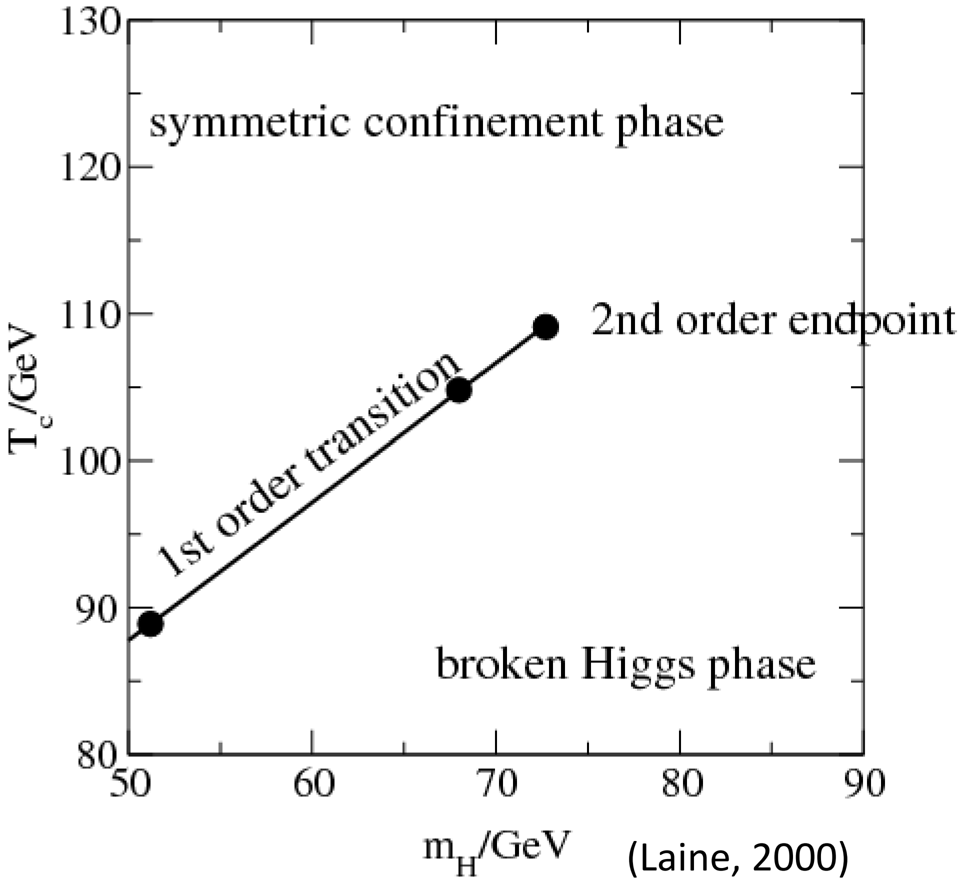


Figure 1: The phase diagram of QCD.

(Reinhardt et al 2015)

Electroweak Phase Transition

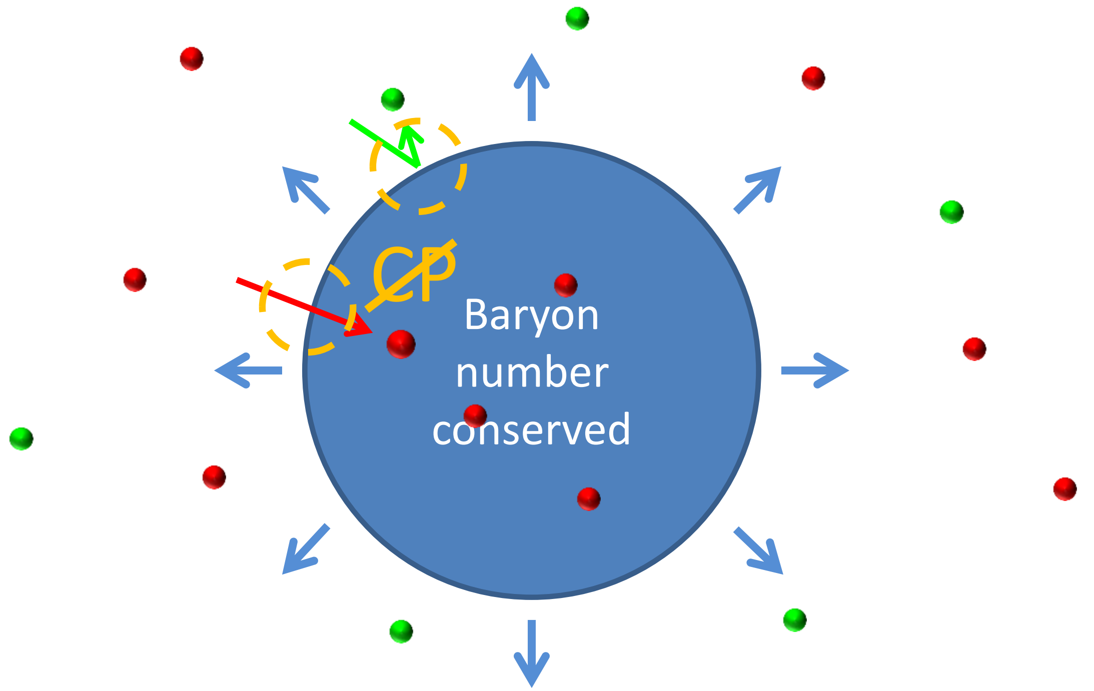
- Temperature $T \sim 100\ \text{GeV}$, time $t \sim 10^{-11}\ s$
- Electroweak force
  → electromagnetic + weak nuclear force
- Naively, the Higgs field acquires a non-zero vacuum expectation value
- Standard Model: crossover
  (Kajantie et al. 1996)
- Beyond the Standard Model: can be first order
  ⇒ Non-equilibrium process



(Laine, 2000)

Electroweak Baryogenesis

- In principle, the Standard Model can satisfy the Sakharov conditions needed to explain the baryon asymmetry (Kuzmin et al. 1985):
  - Baryon number violation:
    Chiral anomaly $B \leftrightarrow L$ √
  - C and CP violation:
    CKM matrix (but not enough) X
  - Deviation from equilibrium:
    If phase transition is 1st order (but it isn't) X
- Some BSM physics needed!

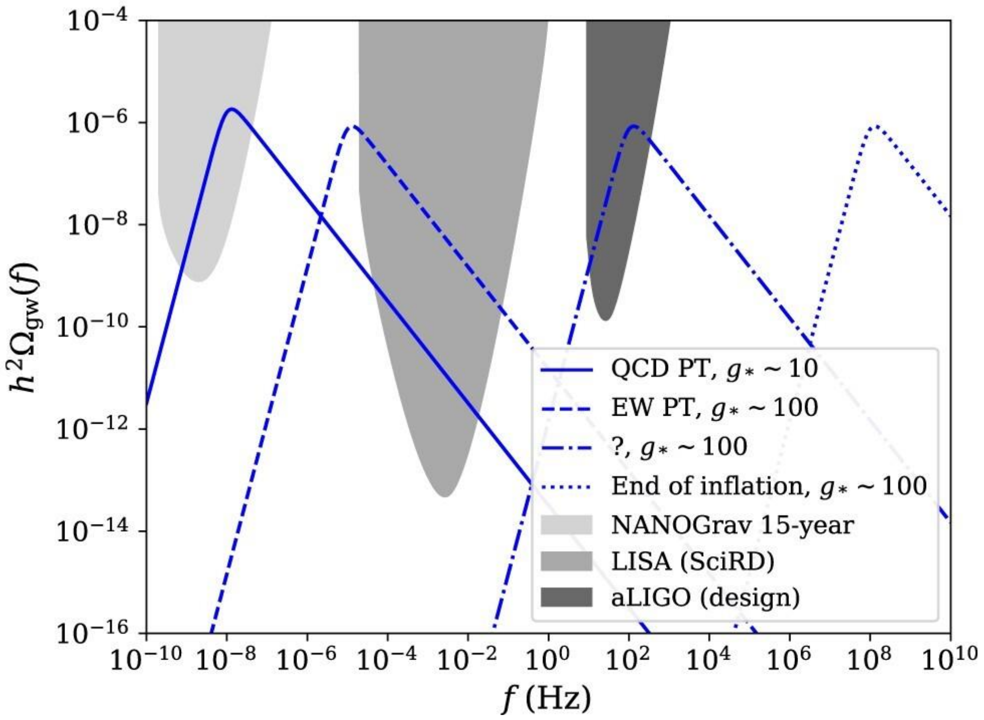


Leptogenesis

- Fukugita&Yanagida 1986:
  Alternative to EW baryogenesis
- Neutrinos violate CP and lepton number
- Heavy neutrinos produced thermally in the early Universe,
  decay out of equilibrium ⇒ Lepton asymmetry
- Chiral anomaly converts to baryon asymmetry
- Typically temperature $T \sim 10^9 - 10^{13}$ GeV, time $t \sim 10^{-33} - 10^{-25}$ s
- Some variants work at lower temperatures,
  e.g., Resonant leptogenesis (Pilaftsis&Underwood 2003)

Gravitational Waves

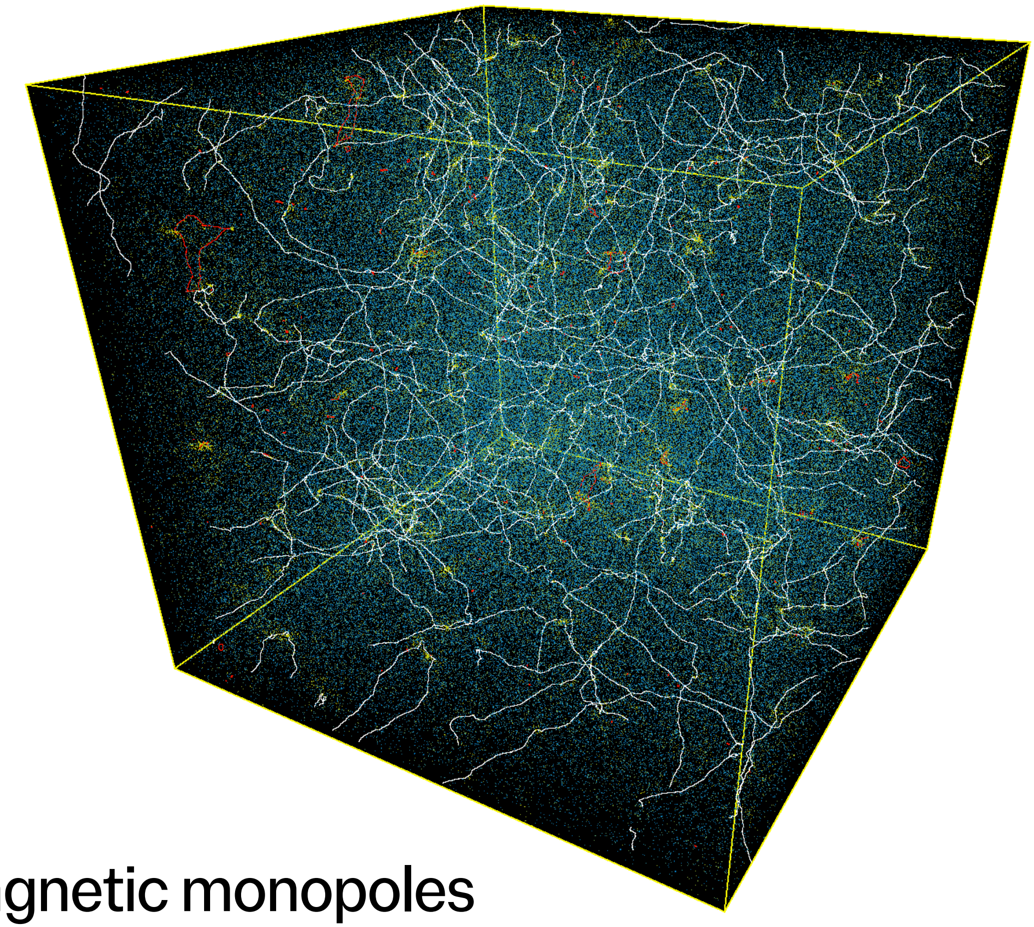
- First order phase transition:
  Bubbles collide, produce sound waves
  ⇒ Gravitational waves
- Peak frequency $f \sim 10^{-5}\ \mathrm{Hz} \left(\frac{T}{100\ \mathrm{GeV}}\right)$
- EW phase transition:
  Detectable with LISA?
- Beyond the Standard Model,
  Grand Unified Theory phase transitions:
  Higher frequency
- See Dani Figueroa's talk



(Croon&Weir, 2025)

Topological Defects

- Symmetry breaking phase transitions
  - Direction of symmetry breaking uncorrelated at long distances
    ⇒ Topological defects (Kibble 1976)
- Depending on symmetry breaking pattern:
  - Two-dimensional domain walls
  - One-dimensional cosmic strings
  - Pointlike monopoles
- Features on CMB, gravitational waves, etc.
- GUT phase transition would always produce magnetic monopoles
  Not observed = "monopole problem"



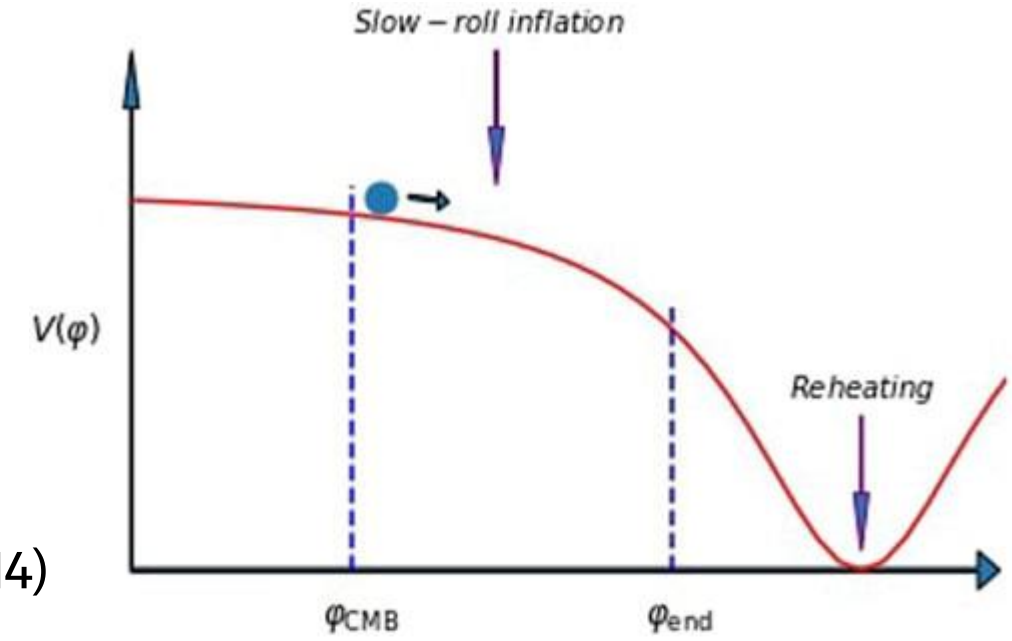
(Cunha et al, 2022)

Inflation

- Period of accelerating expansion in the early Universe:
  - Solve horizon, flatness and monopole problems (Guth 1981)
  - Avoids initial singularity (or at least makes it unobservable)
  - Quantum fluctuations of the inflaton field produce curvature perturbations
- Other light scalars ⇒ perturbations, dark matter (e.g. Markkanen et al 2018)
- Theoretical challenges: See Blachier's talk, Rogelj's poster!
- Tensor/scalar ratio $r \lesssim 0.036$ (Planck/BICEP 2022)
  - Inflationary Hubble rate $H \lesssim 5 \times 10^{13}$ GeV
  - Reheat temperature after inflation $T \lesssim 5 \times 10^{15}$ GeV
- Single-field models with monomial potential ruled out, but many others are ok, e.g., Higgs inflation (Bezrukov&Shaposhnikov 2008) predicts $H \approx 7 \times 10^{12}$ GeV

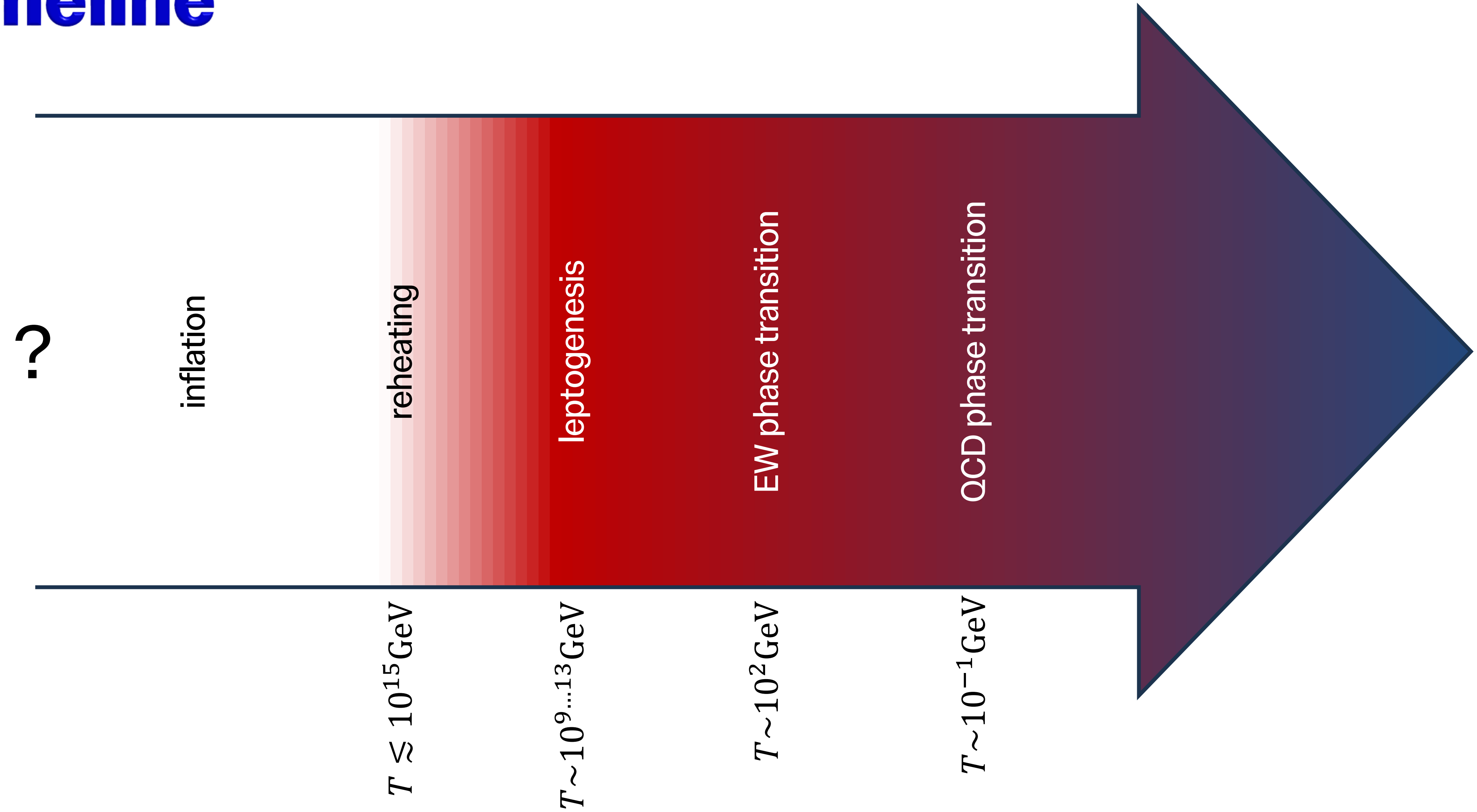
End of Inflation

- Transition from acceleration to radiation domination
  - Energy transferred from inflaton to other fields
- Often a rapid non-equilibrium process:
  - Parametric resonance (Kofman et al. 1994)
  - Tachyonic instability (Felder et al. 2001)
  - Very model-dependent
- Possible signatures:
  - Curvature perturbations (Chambers&AR, 2007)
  - Gravitational waves (Kamionkowski et al 1994) with large-scale anisotropy (Bethke et al 2013, 2014)
  - Primordial black holes (Green&Malik 2000) (See poster by Joana)
  - etc



(Padilla et al, 2024)

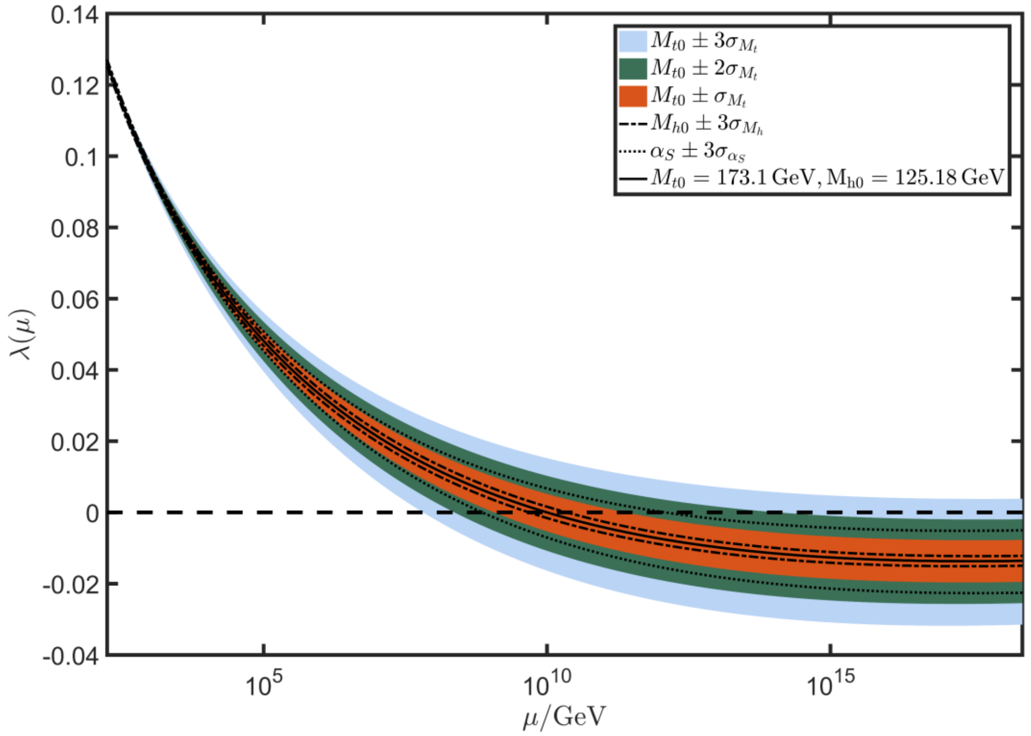
Timeline



?
inflation
reheating
leptogenesis
EW phase transition
QCD phase transition
$T \lesssim 10^{15}\text{GeV}$
$T \sim 10^{9\ldots13}\text{GeV}$
$T \sim 10^{2}\text{GeV}$
$T \sim 10^{-1}\text{GeV}$

Vacuum Metastability

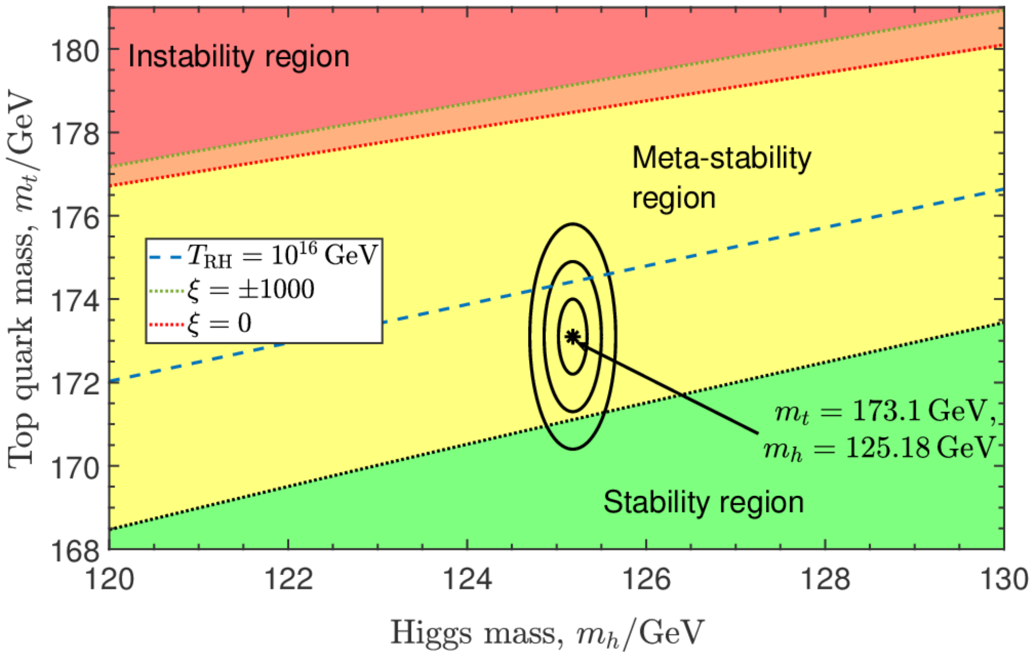
- Higgs self-coupling becomes negative at $\sim 10^{10}$ GeV
  - The current vacuum state is metastable
  - First order phase transition to a negative-energy true vacuum $\Rightarrow$ Gravitational collapse
- Today: Very long lifetime $\propto e^{1800}$
- However, even a single bubble in our whole past light cone would mean we could not exist



(Markkanen et al, 2018)

Vacuum Metastability in the Early Universe

- High temperature ⇒ Higher transition rate
  - Ok even up to $T = 10^{16}$ GeV (Delle Rose et al, 2016)
- Small black holes would catalyse (Hiscock 1987; Berezin et al 1991)
  - With evaporation, would rule out primordial BH for up to $M \sim 10^{12}$ GeV (Burda et al. 2016)
  - However, see Zell's talk!
- Spacetime curvature during inflation:
  - Vacuum decay if $H \gtrsim 10^{10}$ GeV (Espinosa 2008)

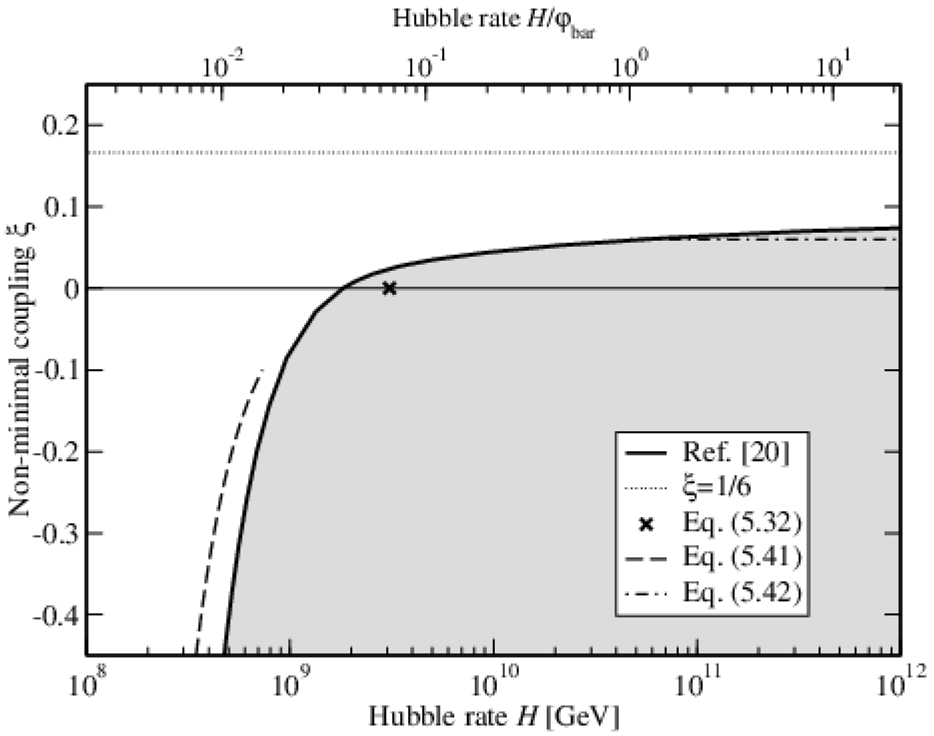


(Markkanen et al, 2018)

Non-Minimal Gravitational Coupling

$$\mathcal{L} = \cdots + \xi R \phi^\dagger \phi$$

- Describes how the Higgs field couples to spacetime curvature (Chernikov&Tagirov 1968)
- Last unknown parameter in the Standard Model: LHC $|\xi| \lesssim 2.6 \times 10^{15}$ (Atkins&Calmet 2012)
- If $H \gtrsim 10^{10}$ GeV,
  - $\xi \gtrsim 0.1$ would stabilise the vacuum during inflation (Herranen et al. 2014) , and
  - $\xi \lesssim 9$ would be needed to avoid instability at the end of inflation (Herranen et al. 2015; Figueroa et al. 2018)



(Markkanen et al, 2018)

Outlook

- Observations
  - Gravitational waves: Figueroa's talk
  - Combine data from cosmology and particle physics
- Theoretical challenges
  - Quantum field theory in curved space time, finite temperature, out of equilibrium
  - Limited data $\Rightarrow$ need reliable calculations
- Prospects
  - Answer deep questions about the Universe, e.g., the origin of matter
  - Testing particle physics theories in new ways
  - Example: Non-minimal gravitational coupling