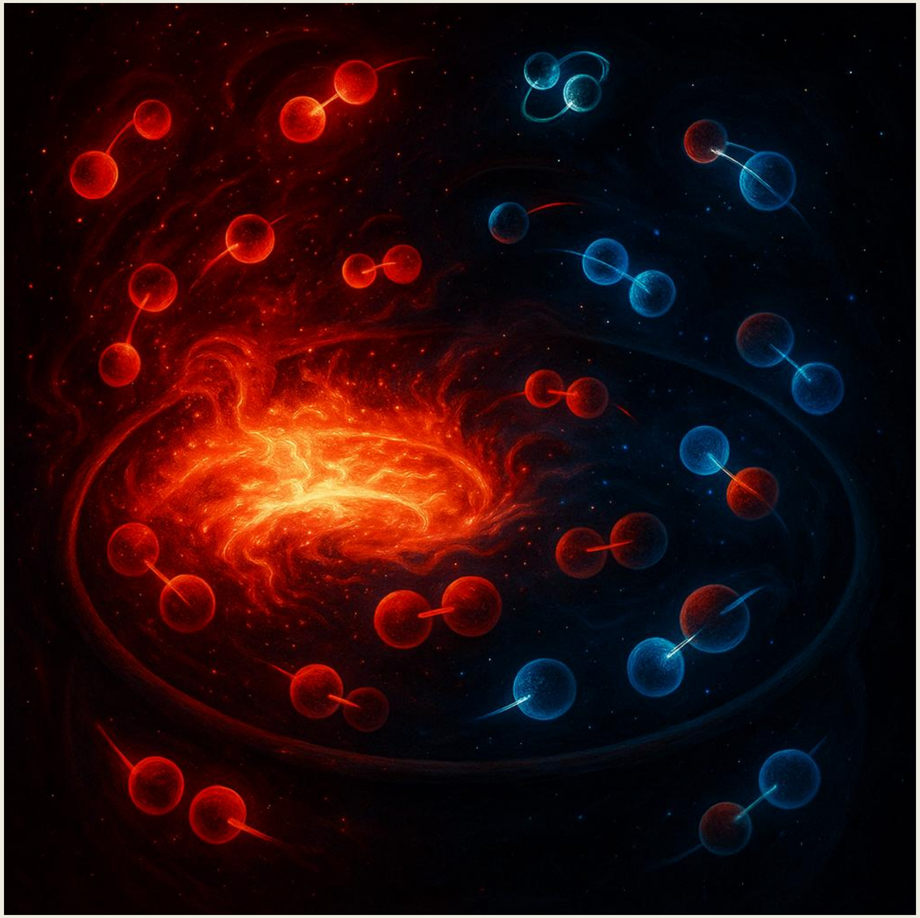
Baryogenesis



Credit: OpenAI

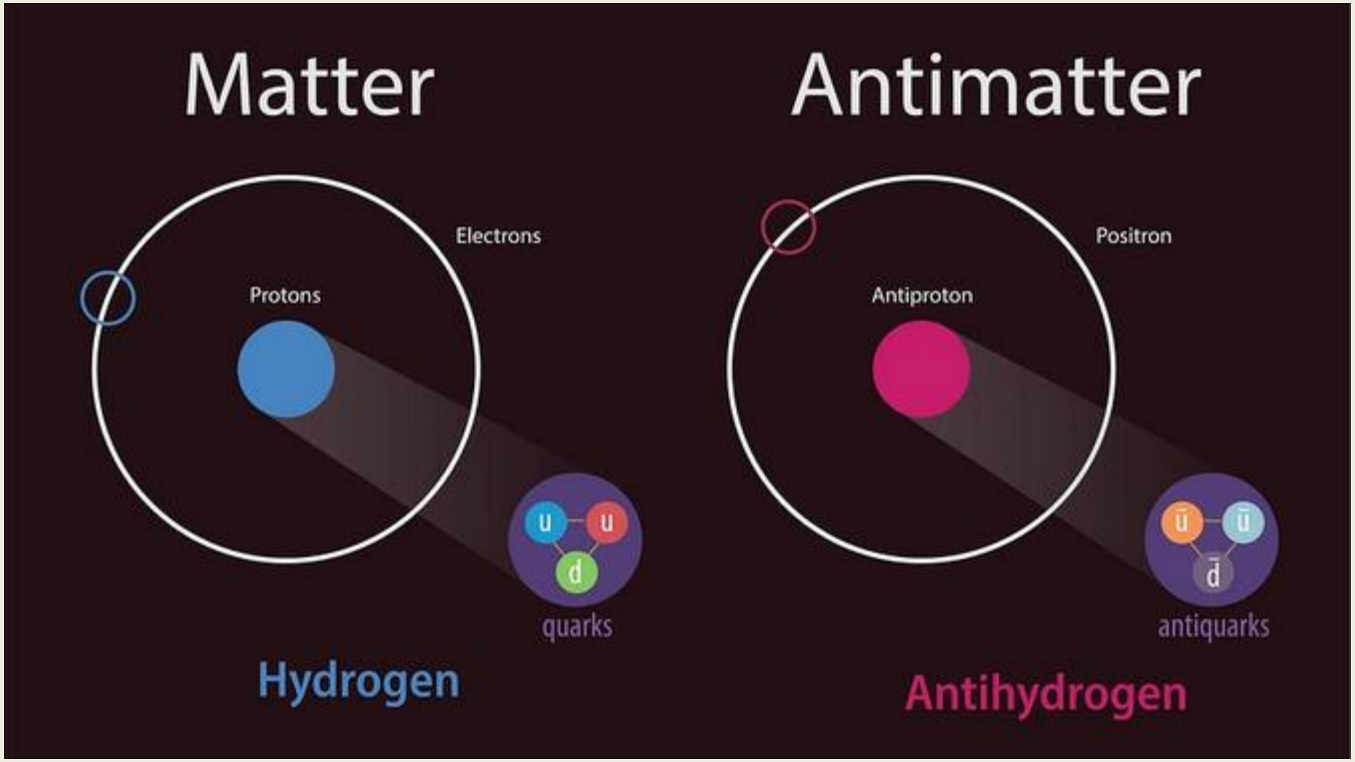
The Standard Model of Particle Physics

	Quarks (come in three colors)			Leptons		
	I	II	III	I	II	III
Fermions (half-integer spin)	u Up	c Charm	t Top	e Electron	μ Muon	τ Tau
	+2/3 charge			-1 charge		
	d Down	s Strange	b Bottom	ν_e Neutrino	ν_μ Neutrino	ν_τ Neutrino
	-1/3 charge			0 charge		
Hadrons (Made of Quarks)	Baryons Fermionic Hadrons (Three Quarks)	Mesons Bosonic Hadrons (Quark & Anti-Quark)	Quark Color Charge	Red / Anti-Red	Blue / Anti-Blue	Green / Anti-Green

Force	Electromagnetic	Strong	Weak		Gravity	Officially Gravity and the Graviton are not part of the Standard Model, but they are included here for completeness.
Vector Bosons (full-integer spin)	γ Photon	g Gluon (eight color combinations)	$W^{-/+}$ Boson	Z^0 Boson	Graviton (hypothetical)	
Scalar Boson (zero spin)	Higgs					

Credit: https://www.fas37.org

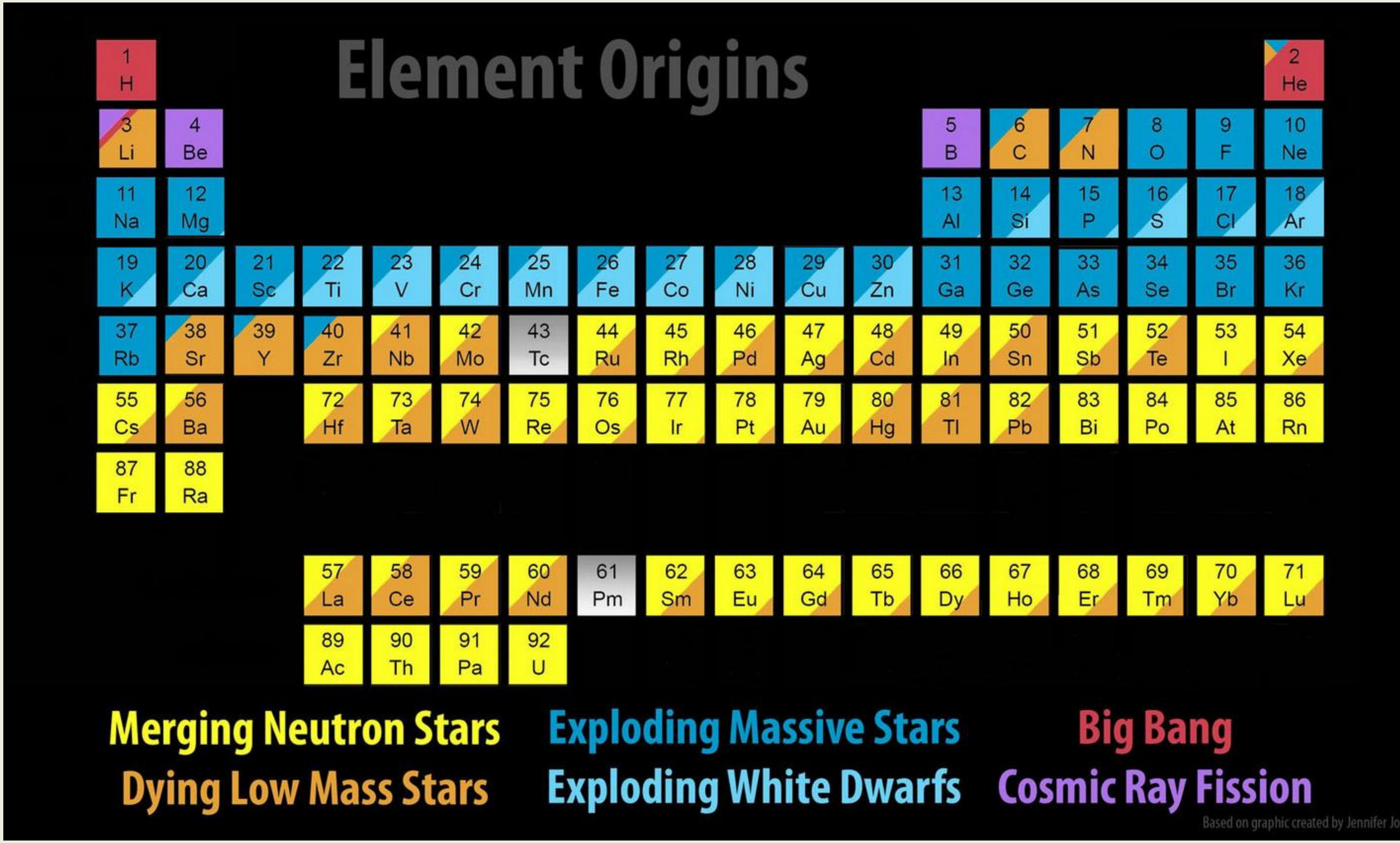
The Standard Model of Particle Physics



Credit: zombiu26 / Adobe Stock

CP-symmetry - charge conjugation parity ("mirror") symmetry.

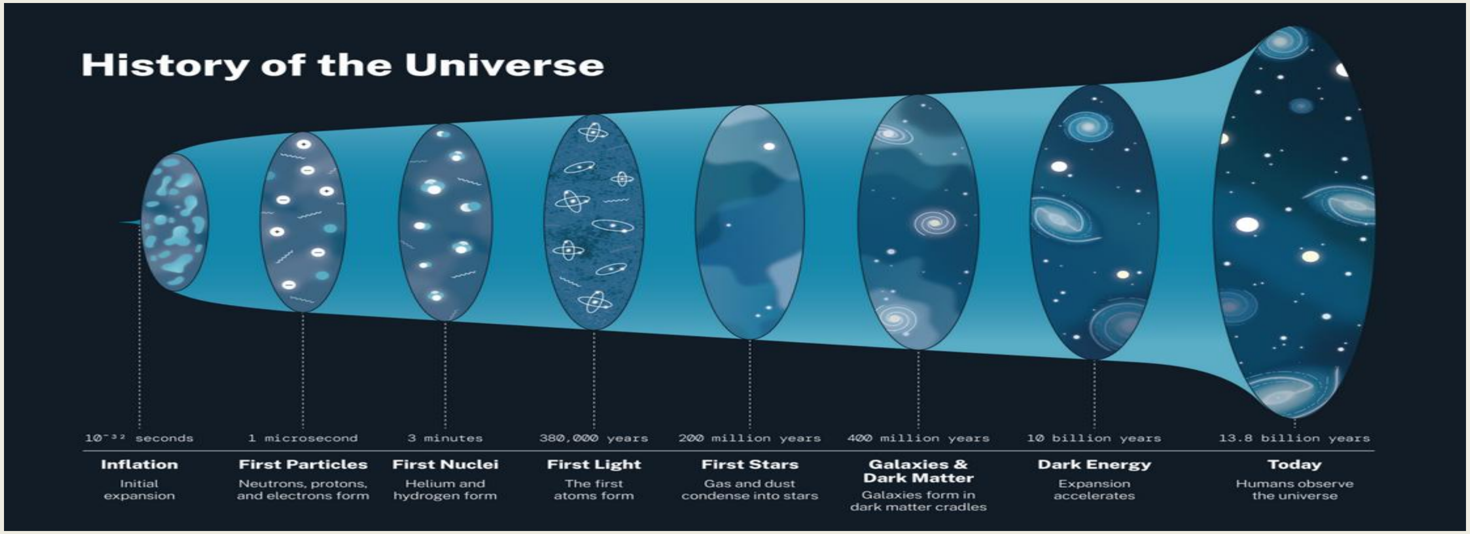
Element Origins

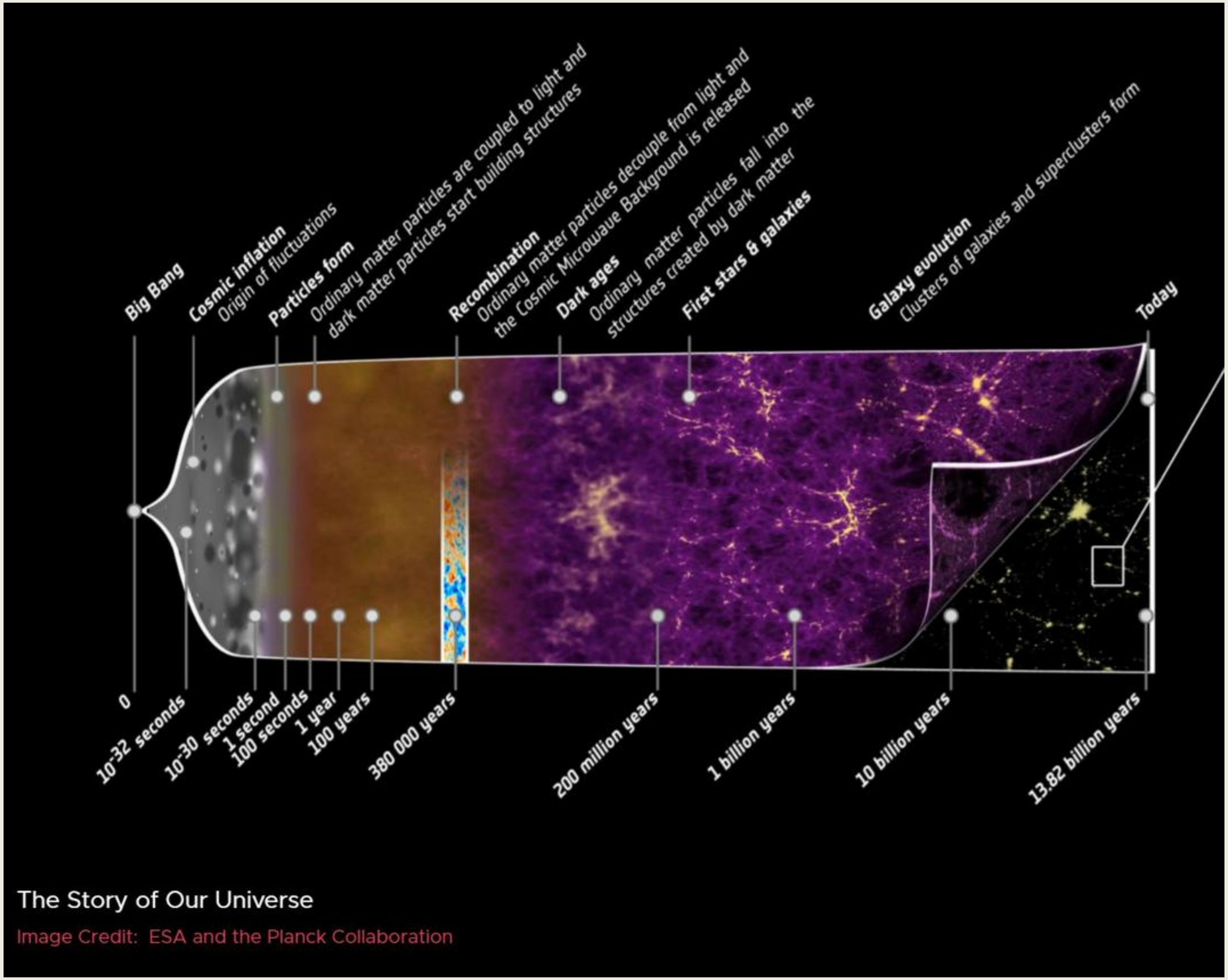


Credit: Jennifer Johnson

Era/Epoch	Beginning	Ending	Note
Planck	0	10^{-43} sec	All four forces are unified
GUT	10^{-43} sec	10^{-36} sec	Strong, weak, and electromagnetic forces are unified
Inflation	10^{-36} sec	10^{-32} sec	Rapid expansion in a fraction of a second
Electroweak	10^{-32} sec	10^{-12} sec	Weak and electromagnetic forces are unified
Particle: Quark	10^{-12} sec	10^{-6} sec	Quarks forms
Particle: Hadron	10^{-6} sec	10^{-3} sec	Protons and Neutrons form
Particle: Lepton	1 sec	10 sec	Electrons (Leptons) form
Nucleosynthesis	3 sec (10^{-3} sec)	20 min (3 min)	Hydrogen and Helium Nuclei form
Photon	10 min	380,000 years	Energetic photons bounce around the universe
Recombination	≈240,000 years	380,000 years	Nuclei bond with electrons to form atoms
CMB		380,000 years	Light escapes and the universe becomes transparent
Dark Ages	≈400,000 years	½ to 1 billion years	Few stars to create light
Reionization	400 million years	1 billion years	Energetic photons knock electrons off atoms creating ions
Stars	100 to 250 million years		Stars form from hydrogen nuclei and atoms
Galaxies	½ to 1 billion years		Stars are pulled together into galaxies

Credit: https://www.fas37.org




Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years
The Story of Our Universe
Image Credit: ESA and the Planck Collaboration

Sakharov Conditions

In 1967, Andrei Sakharov identified three necessary ingredients for any process that starts from zero net baryon number and produces a nonzero surplus of baryons over antibaryons:

1. Baryon number violation ($\Delta B \neq 0$)
2. Charge conjugation (C) and charge–parity (CP) violation
3. Departure from thermal equilibrium

No single one of these is sufficient; together they allow a tiny asymmetry to develop and then survive.

SGUT-Scale Baryogenesis

- Basic Idea
  - At temperatures $T \sim 10^{15\text{–}16}\,\mathrm{GeV}$, Grand Unified Theories predict heavy gauge or Higgs bosons, often called X and Y.
  - These bosons have baryon-number–violating decays such as

$$X \;\to\; q\,q \quad (\Delta B = +\tfrac{2}{3}), \qquad X \;\to\; \bar{q}\,\ell \quad (\Delta B = -\tfrac{1}{3}),$$

    resulting in a net baryon asymmetry if CP-violating phases make one channel slightly more probable.
- Pros
  - Naturally implements Sakharov's three conditions at very high energy.
  - Can produce a large asymmetry early, before any wash-out by later processes.
- Cons
  - **Experimental reach:** $10^{16}\,\mathrm{GeV}$ is far above collider or direct-detection capabilities.
  - **Monopole problem:** GUT phase transitions generically produce magnetic monopoles; their overabundance contradicts observations unless inflation dilutes them.
  - **Model dependence:** exact asymmetry depends sensitively on the GUT gauge group, Higgs sector, and its CP phases.

Electroweak Baryogenesis

- **Phase Transition**
  - Occurs at $T \sim 100\,\mathrm{GeV}$ when the Higgs field acquires its vacuum expectation value.
  - Needs to be a **strongly first-order** transition—like water boiling—so bubbles of the broken phase nucleate and expand in the symmetric plasma.
- **Standard Model Limitations**
  - Lattice studies show the SM Higgs at 125 GeV leads only to a smooth crossover, not a first-order transition.
  - SM CP violation (from the CKM matrix) is numerically too small ($\sim 10^{-20}$) to generate $\eta \sim 10^{-10}$.
- **Beyond the SM**
  - **Two-Higgs-Doublet Models (2HDM)** or the **Minimal Supersymmetric Standard Model (MSSM)** can strengthen the transition via additional scalar fields or stop squarks.
  - New CP-violating phases in the extended Higgs sector or gaugino–higgsino mixing can boost the asymmetry to observable levels.

Key Puzzles

Source of New CP-Violation

- We know the Standard Model's CP-violating rate is far too small.
- What additional CP-violating interactions exist? Possibilities include extra Higgs sectors, new fermions with complex Yukawa couplings, or heavy neutrino mixings. Identifying these sources is crucial both for baryogenesis and for explaining observed matter–antimatter imbalance.

Order of the Electroweak Phase Transition

- A strongly first-order transition is required to prevent wash-out of any generated asymmetry, but the SM predicts a smooth crossover.
- Does nature include additional scalar fields or new particles that modify the Higgs potential sufficiently to induce bubble nucleation?

Connection to Dark Matter

- Could the physics that generates the baryon asymmetry also explain dark-matter abundance?
- Scenarios like asymmetric dark matter posit a shared origin for both relic densities, linking CP-violation in the dark sector to visible-sector baryogenesis.

Future Experimental Directions

Electric Dipole Moment (EDM) Searches

- EDM experiments (neutron, proton, electron, and diamagnetic atoms) probe CP-violation far beyond collider reach.
- Next-generation sensitivities aim for orders-of-magnitude improvements, directly testing many beyond-SM baryogenesis models.

Gravitational Waves from First-Order Transitions

- A strongly first-order electroweak transition would produce a stochastic background of gravitational waves.
- Space-based detectors (e.g., LISA) and pulsar-timing arrays may detect these signals, offering a "smoking gun" for electroweak baryogenesis.

Neutrino Facilities and Leptogenesis Tests

- Long-baseline oscillation experiments (DUNE, Hyper-Kamiokande) will measure the Dirac CP phase in the PMNS matrix.
- Neutrinoless double-beta decay searches probe Majorana mass terms—key ingredients in thermal and resonant leptogenesis scenarios.