A tour through time

Jack Shergold

Contents

- Particle physics and cosmology
- From the CMB to the Big Bang
- Some advice

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Particle physics

- Physics at the smallest scales

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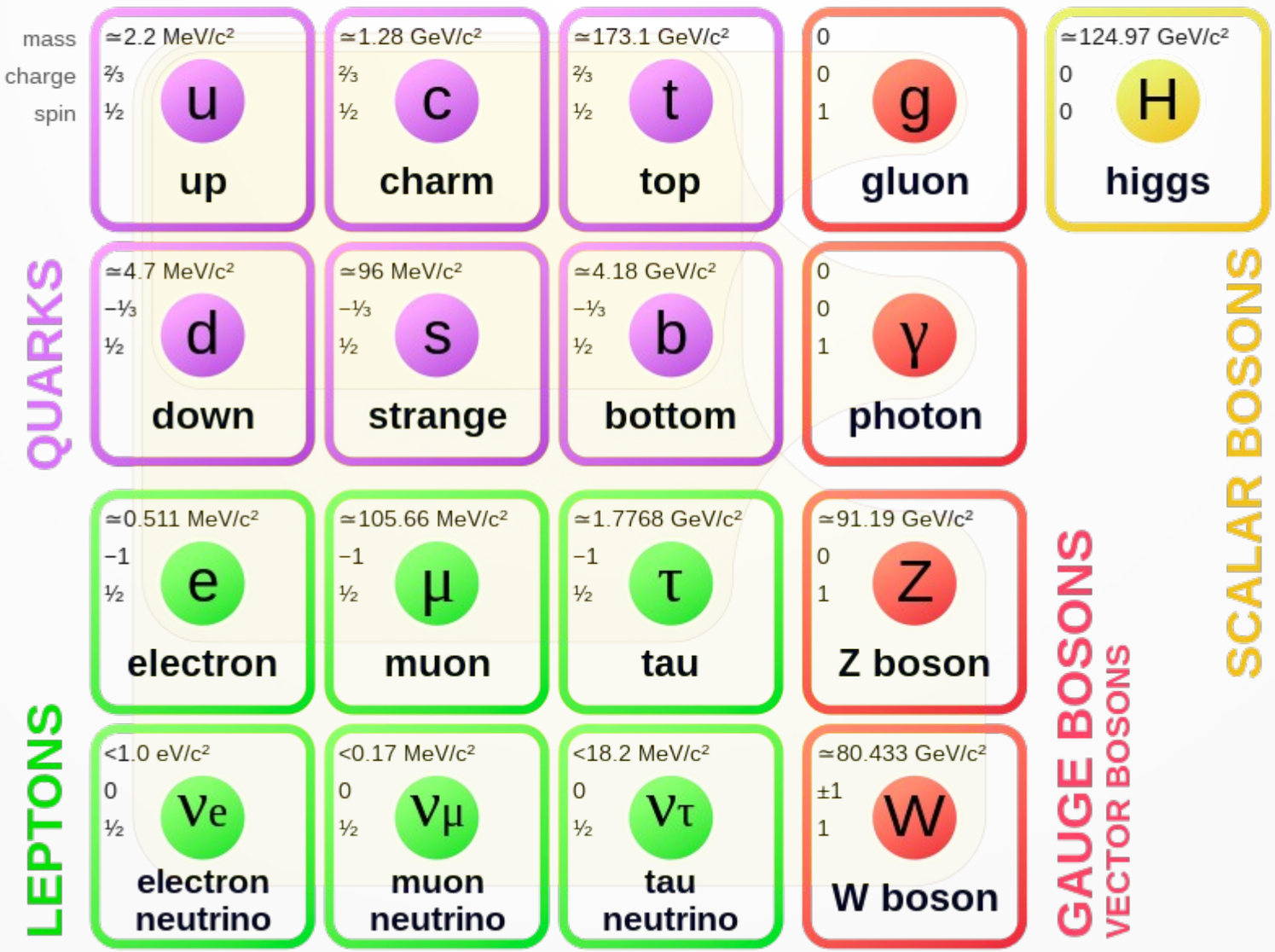
  - New particles? Dark matter? New forces?
  - Unification?

The Standard Model



Cosmology

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Cosmology

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- Seek to answer fundamental questions:
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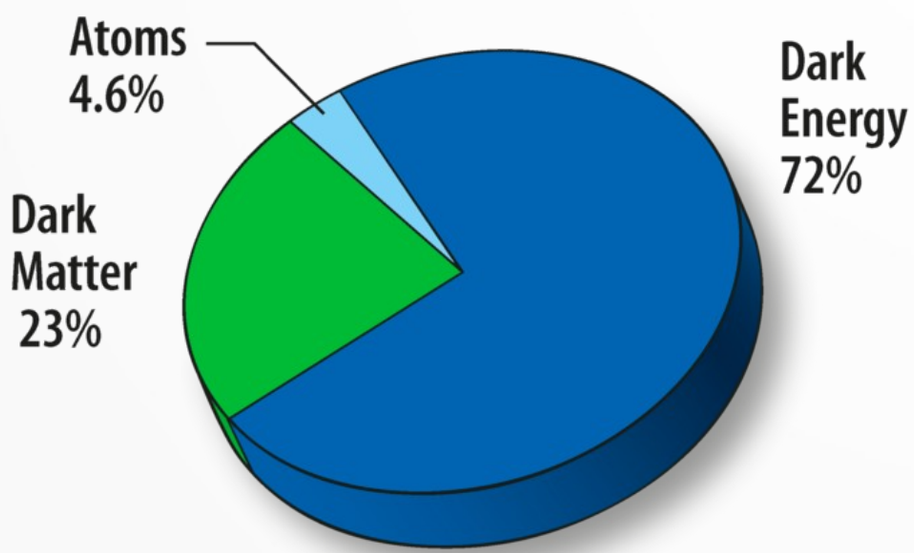
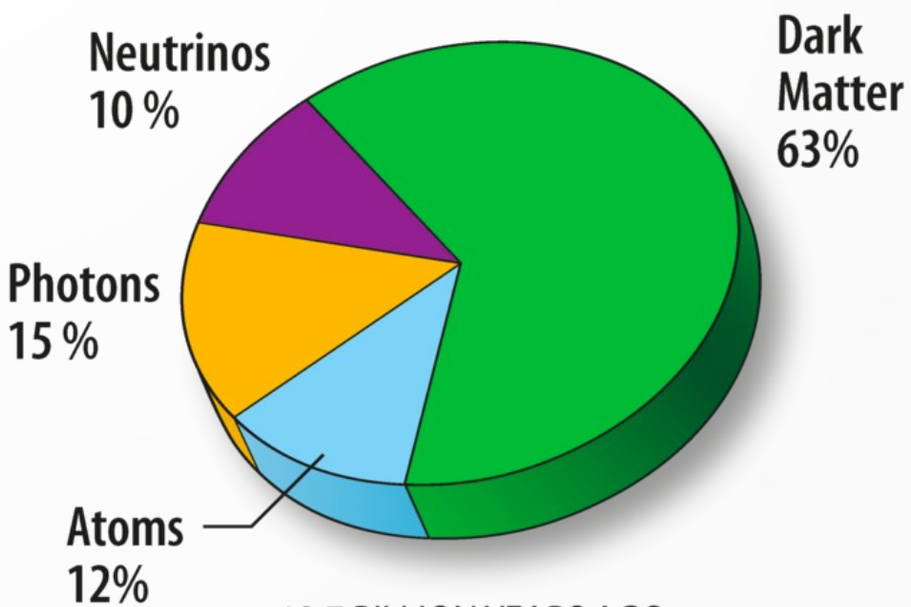
  - Origin of the universe?
  - Content of the universe? Where is all of the antimatter?

ΛCDM Model



TODAY



13.7 BILLION YEARS AGO

(Universe 380,000 years old)

Olber's paradox

- If the universe were infinitely old, and uniform:

$$\int_{r_0}^{\infty} L(r)N(r) \rightarrow \infty$$

Olber's paradox

- If the universe were infinitely old, and uniform:

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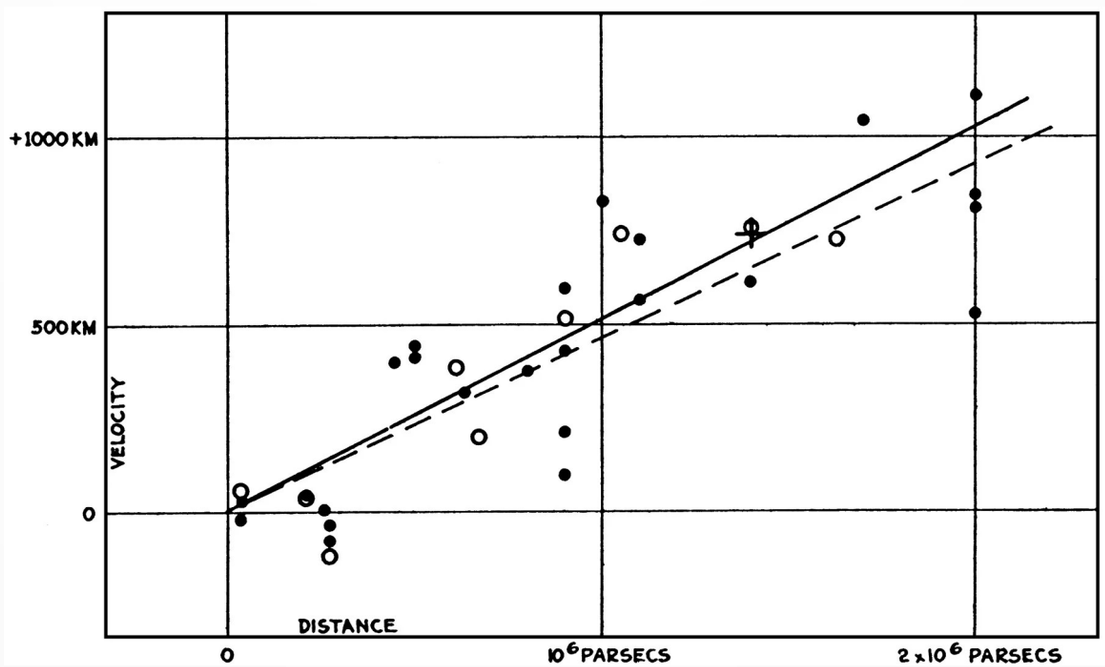
- But the sky is dark!

Expansion?

- More distant stars are redshifted:



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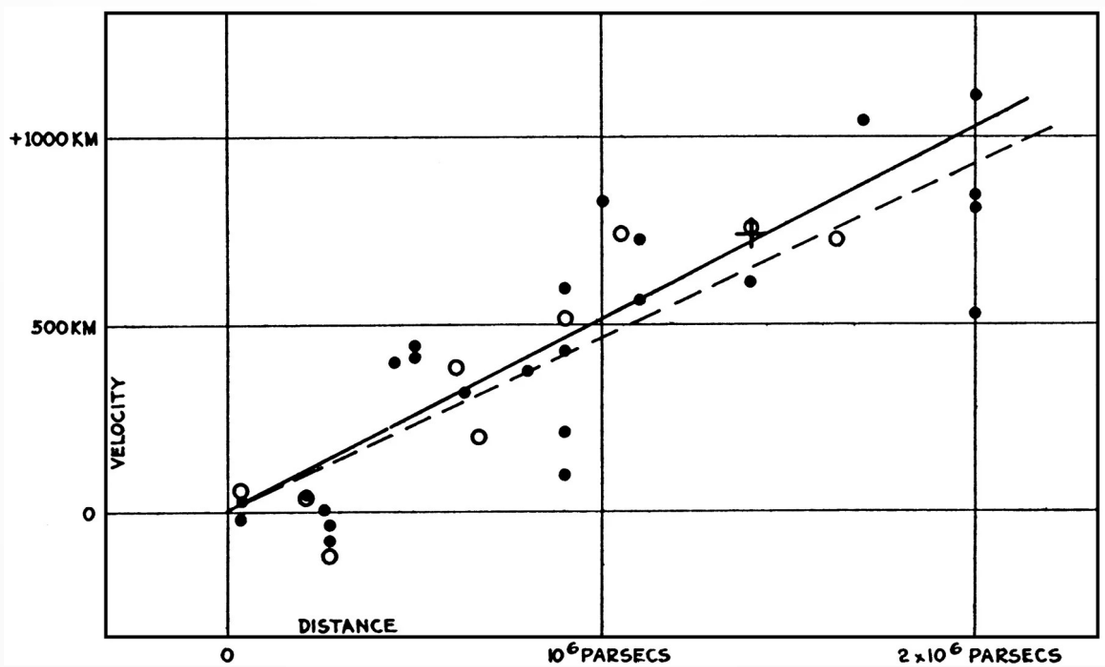

- The universe is expanding!

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A shrinking universe gets hotter!

- Recall that in quantum mechanics:

$$E = hf = \frac{hc}{\lambda}$$

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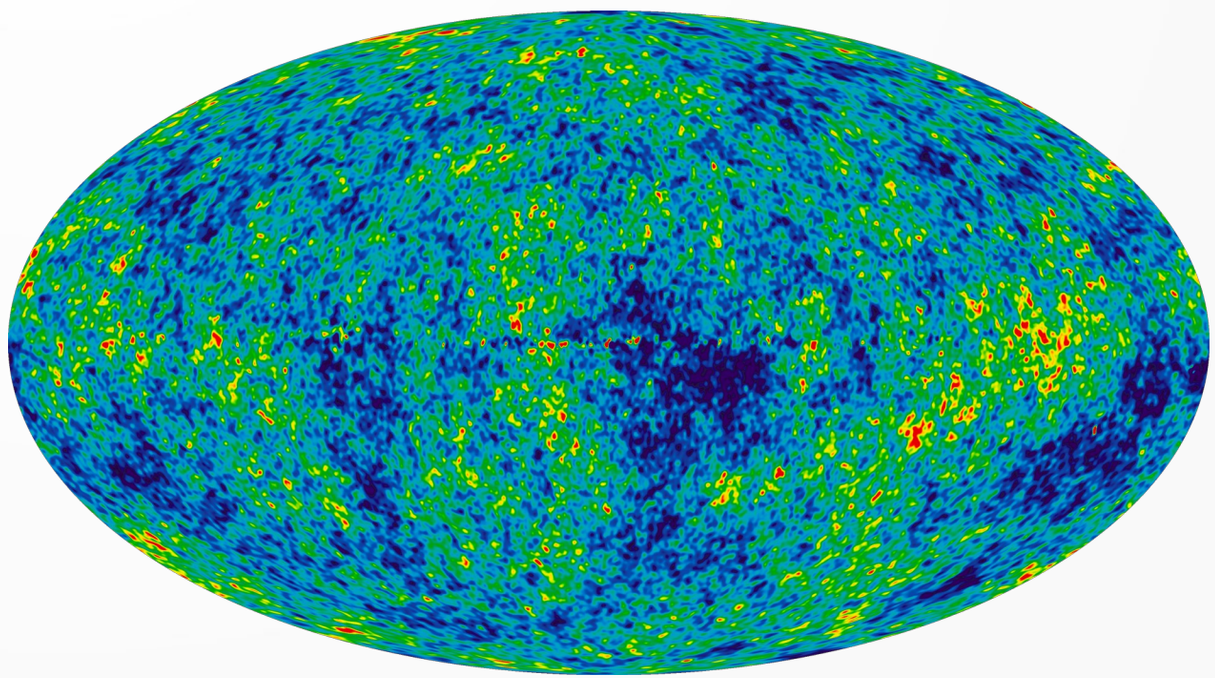
- If the universe contracts, wavelengths get shorter:

- The universe gets hotter!

Starting point: the CMB

- Photons from the early universe (~380,000 years)

$$T = 0.3\,\mathrm{eV}/3000\,\mathrm{K}$$
$$t = 10^5\,\mathrm{y}$$



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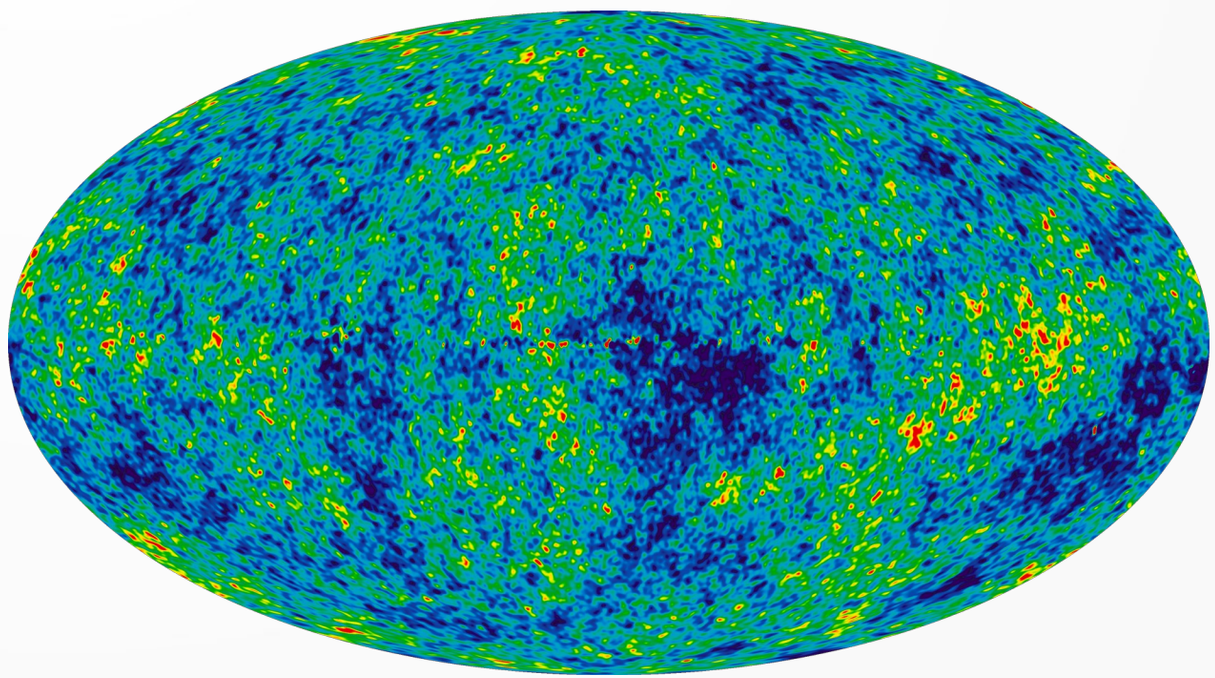

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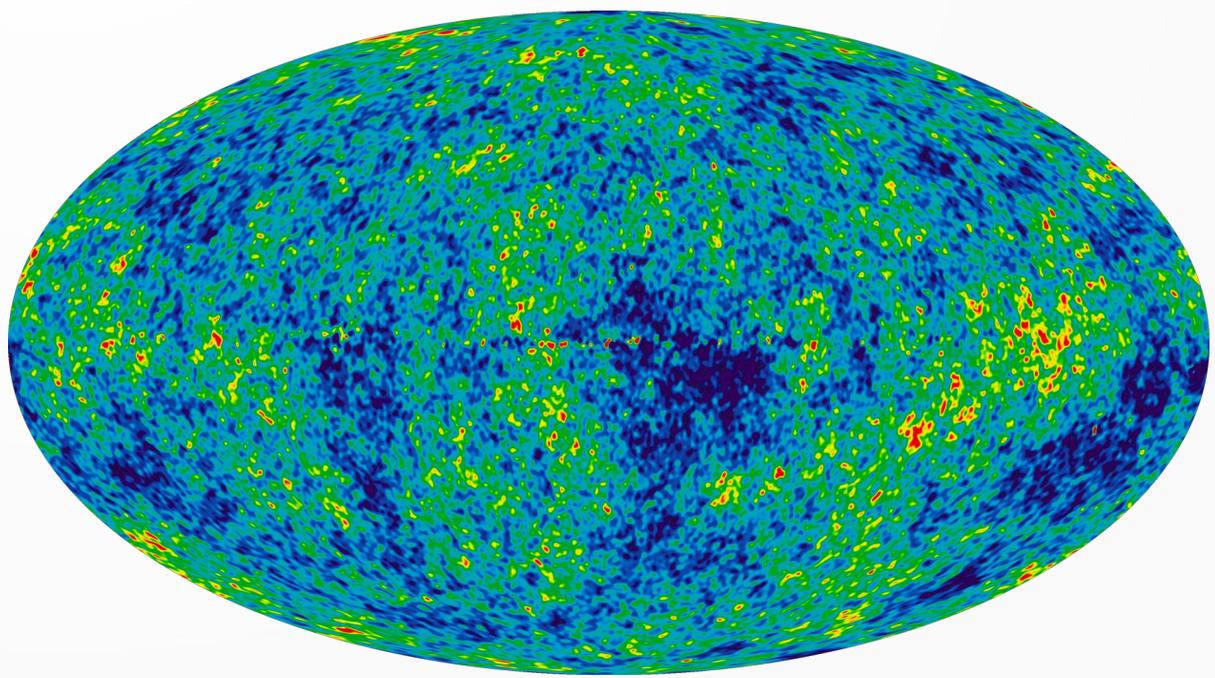
- Furthest that we can look back through time
- Almost completely uniform (~10^{-4})



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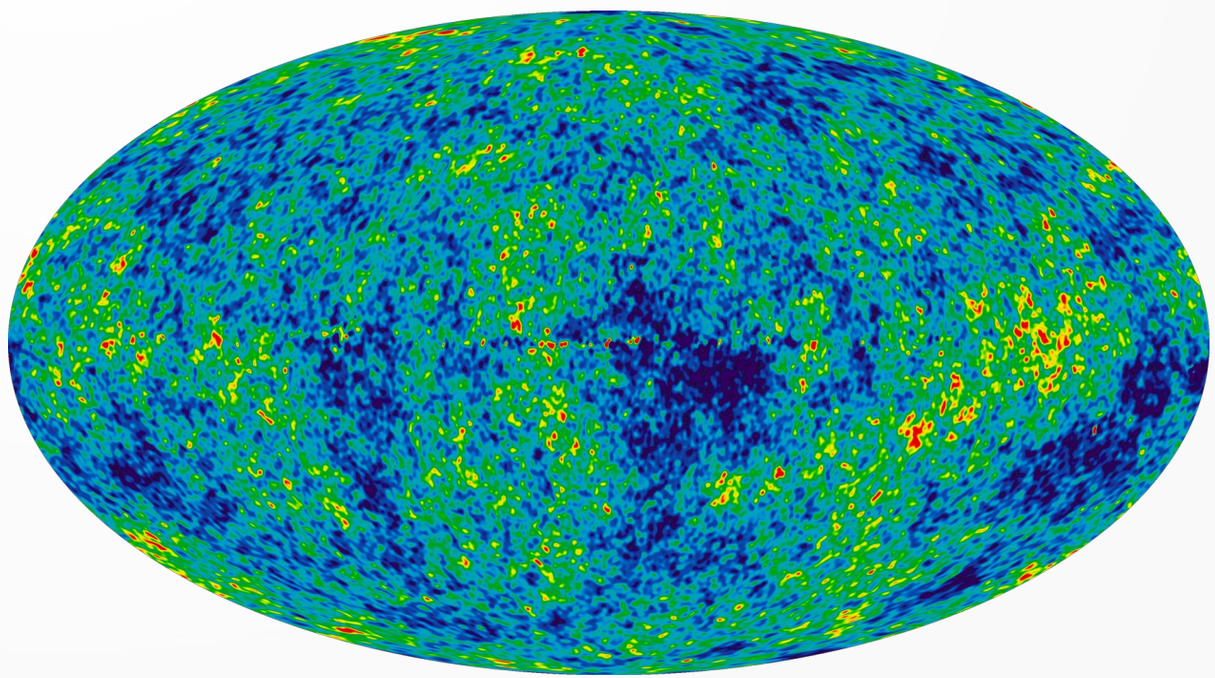

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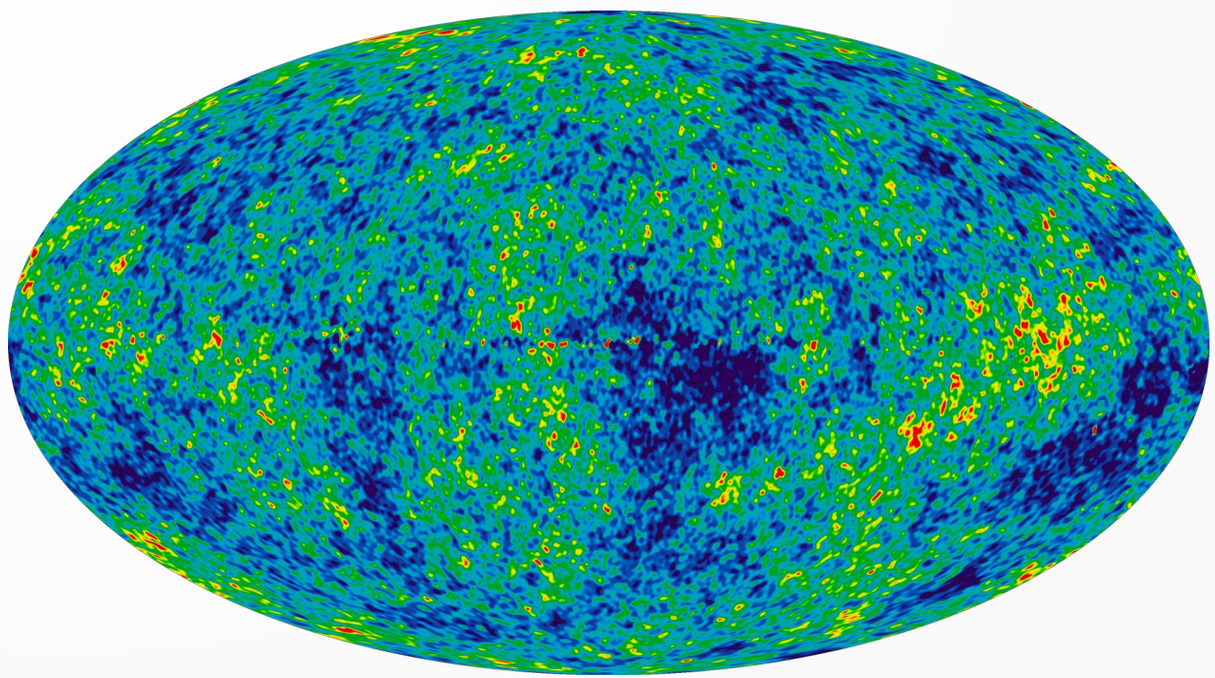
- Contains information about components of the universe
- Definitely not made of pigeons!



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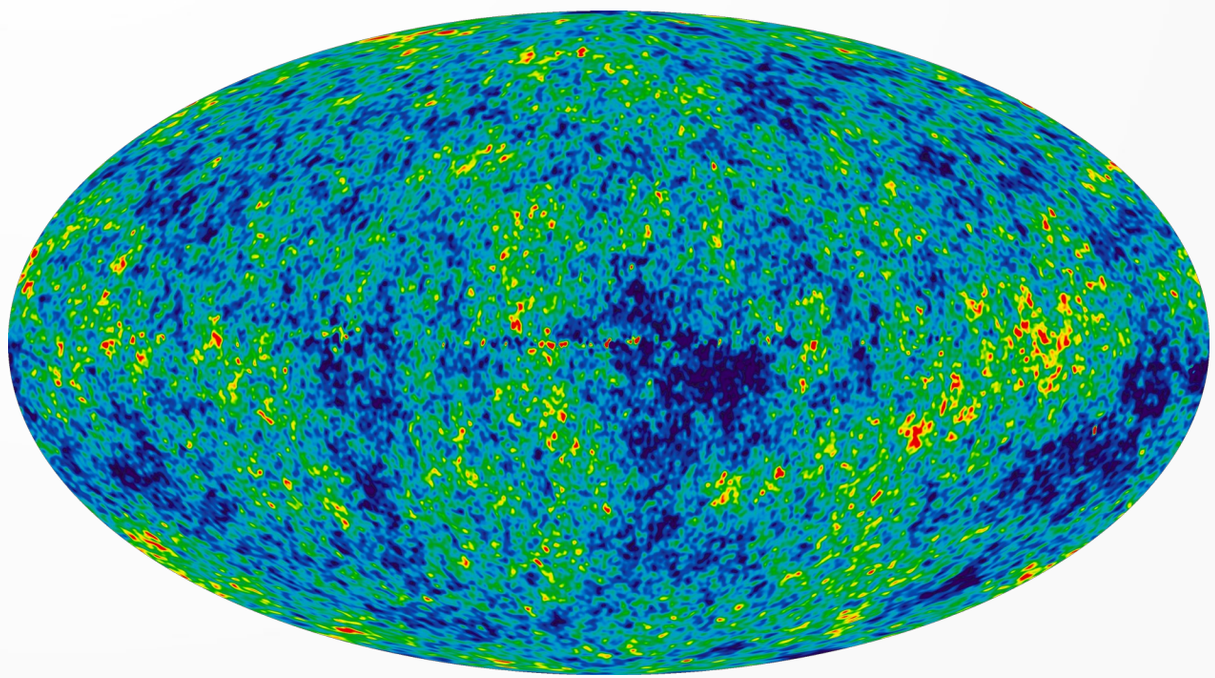

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Ionisation

- Photons hot enough to ionise atoms

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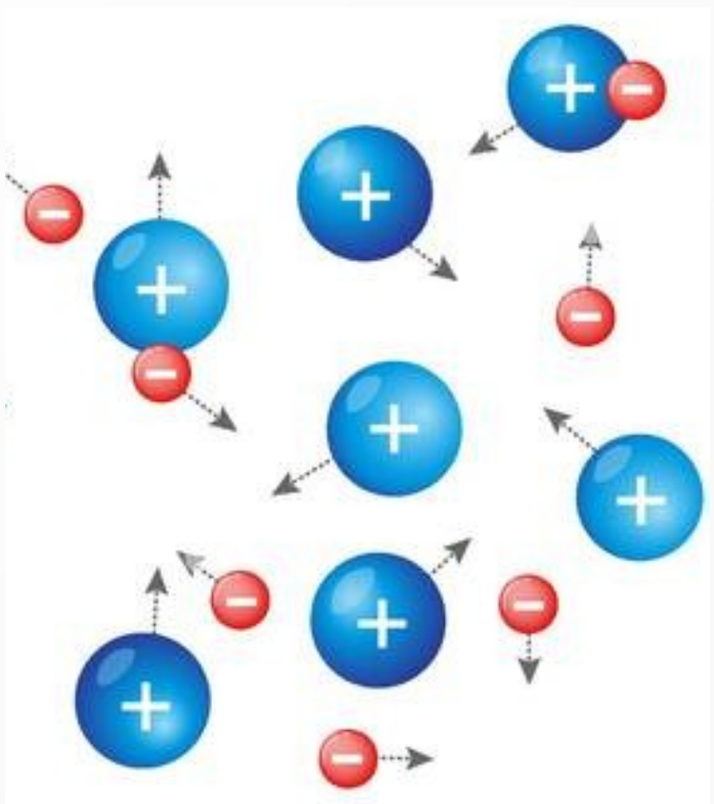

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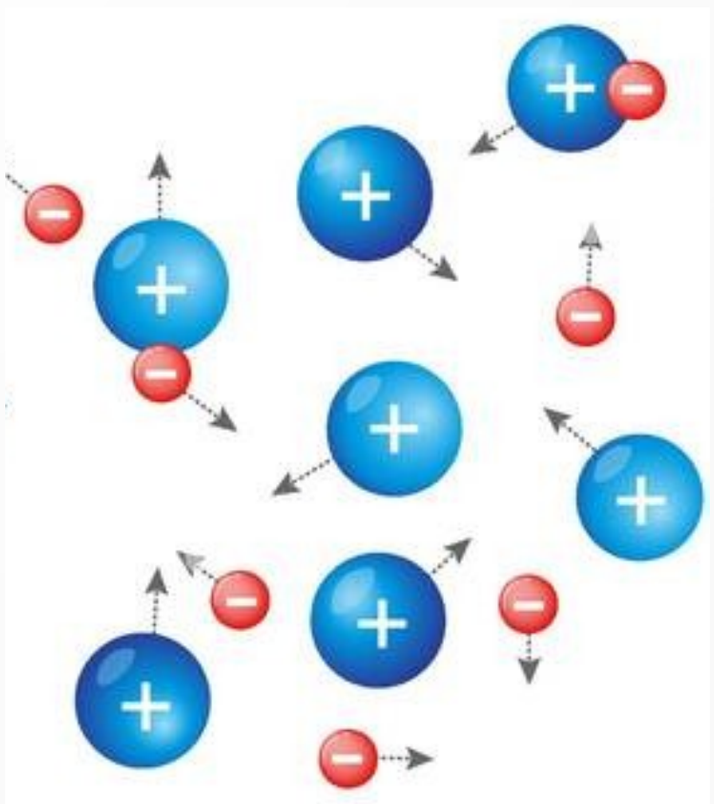
- Free electrons, atomic nuclei and photons



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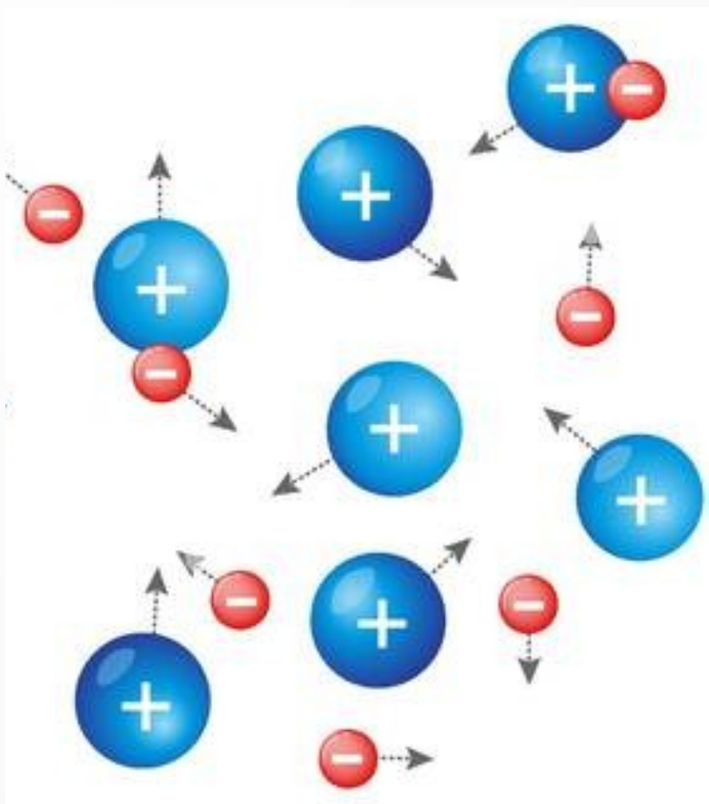

- Universe becomes opaque!

Big Bang nucleo-destruction

- Universe too hot to support atomic nuclei

$$T = 10\,\mathrm{keV}/10^8\,\mathrm{K}$$
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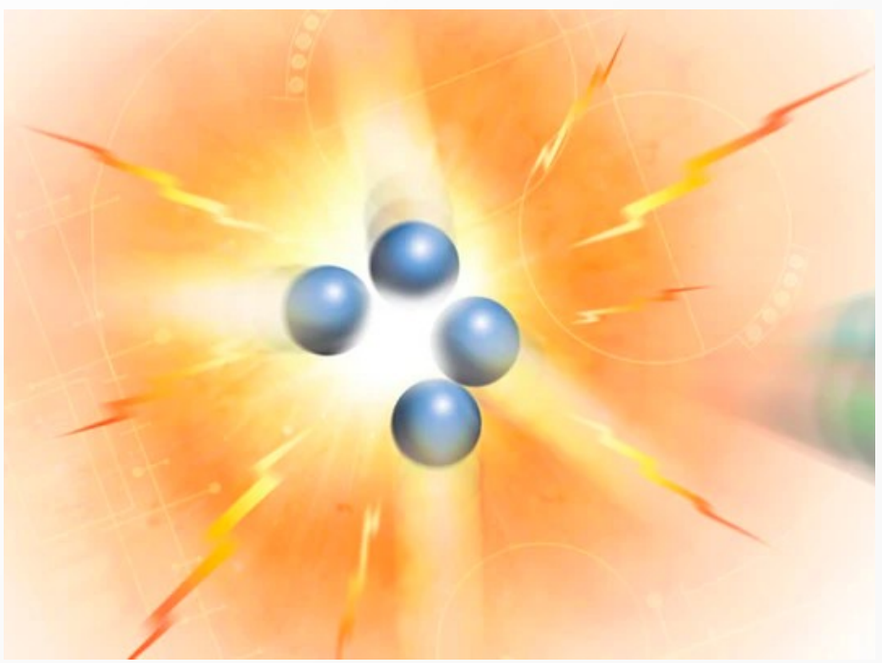

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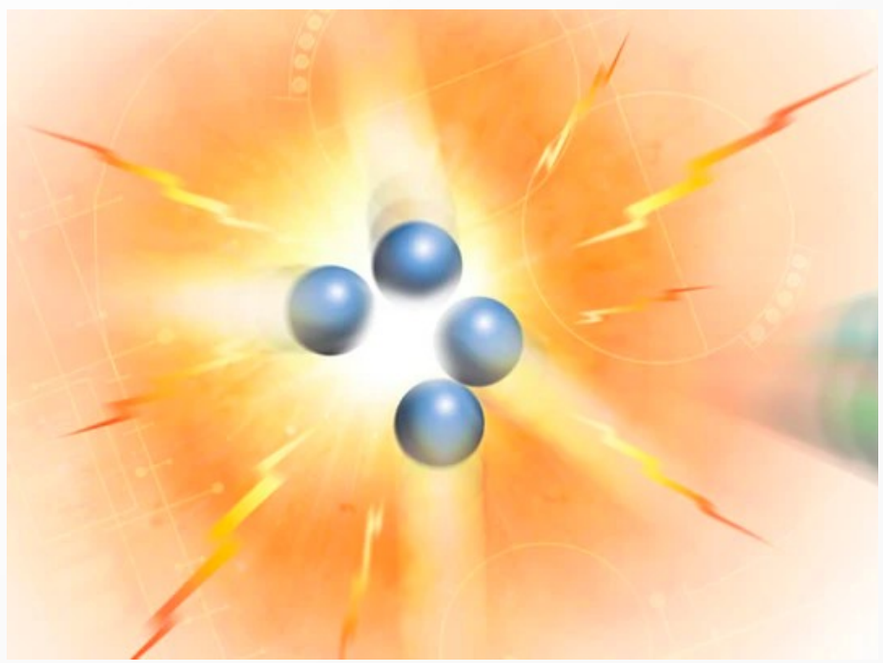

Big Bang nucleo-destruction

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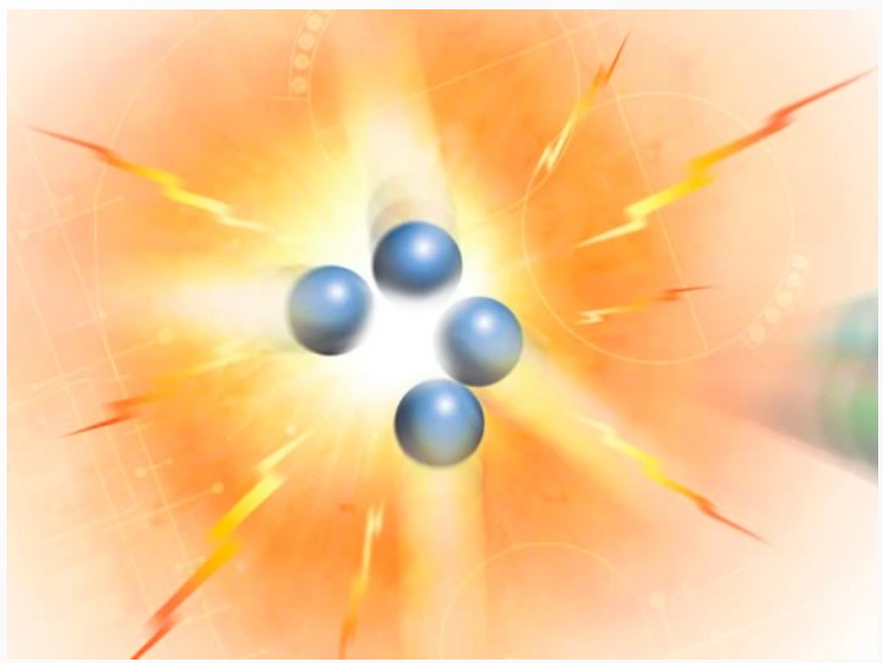
- Observable universe has radius ~300 ly!



Pair production

$$T = 1\,\mathrm{MeV}/10^{10}\,\mathrm{K}$$
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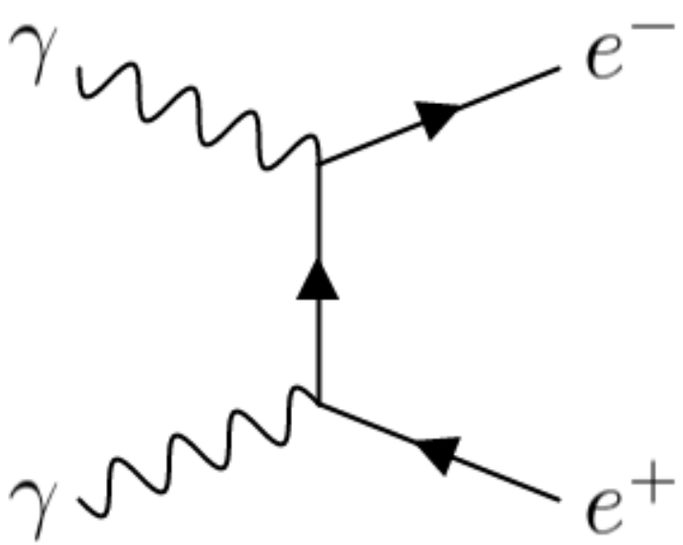

Pair production

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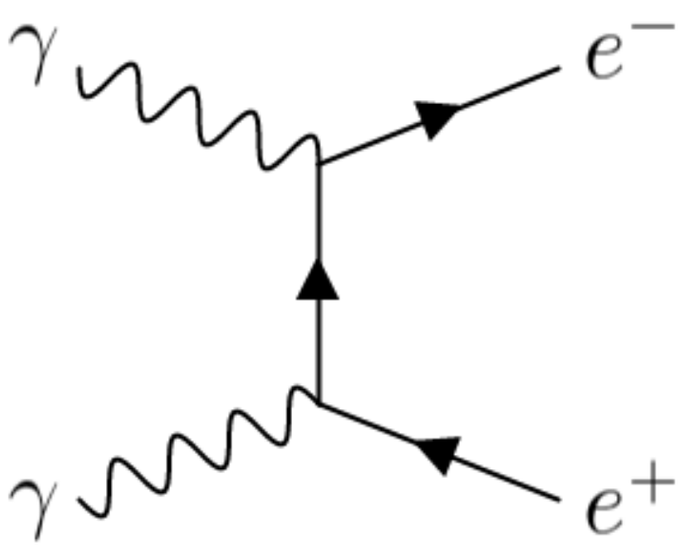
- Photons are now energetic enough to pair produce!
- First time that antimatter is produced!



Neutrino recoupling

- Weak interactions become significant

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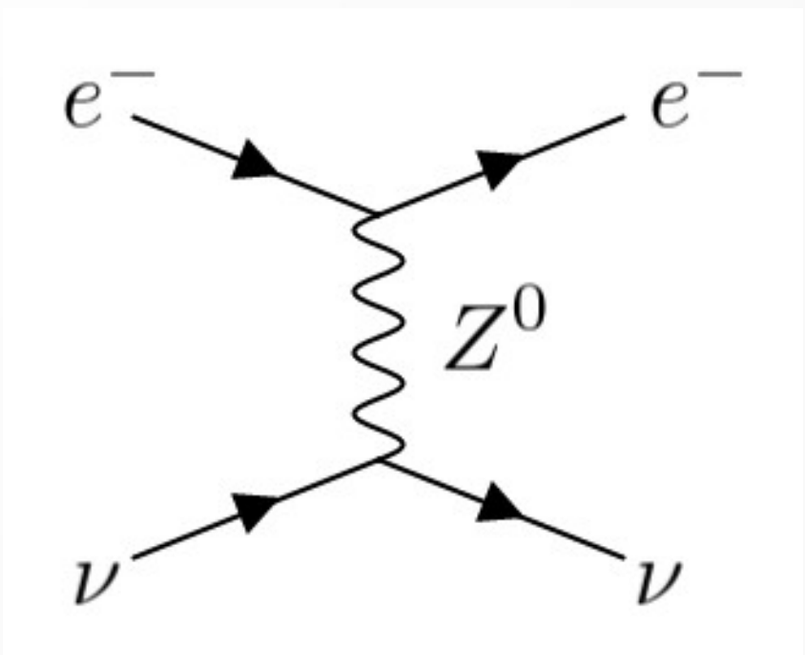

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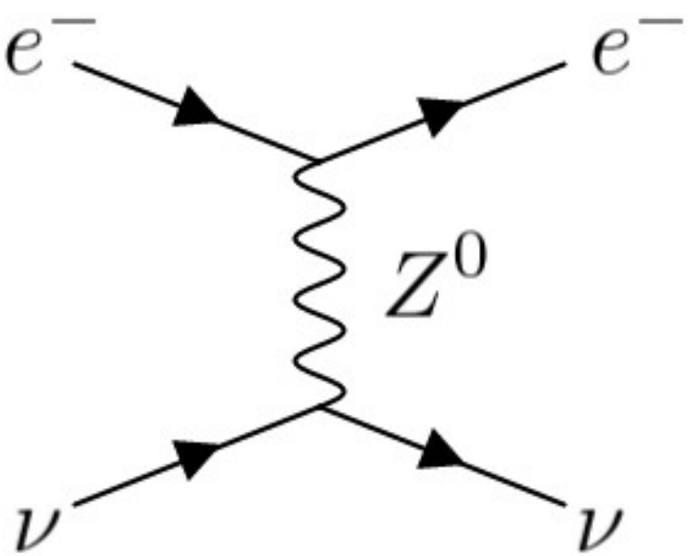

Neutrino recoupling

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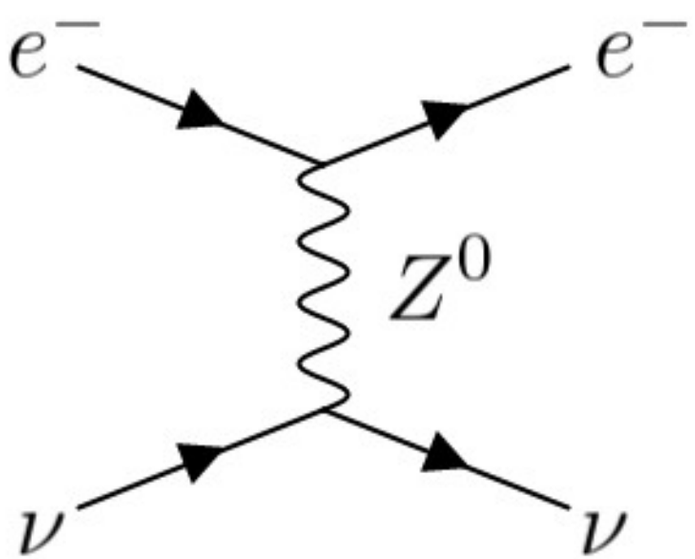
- Weak interactions become significant
- Neutrinos come into equilibrium
- In the forward-universe, these neutrinos are important!



QCD phase transition

$$T = 100\,\mathrm{MeV}/10^{12}\,\mathrm{K}$$
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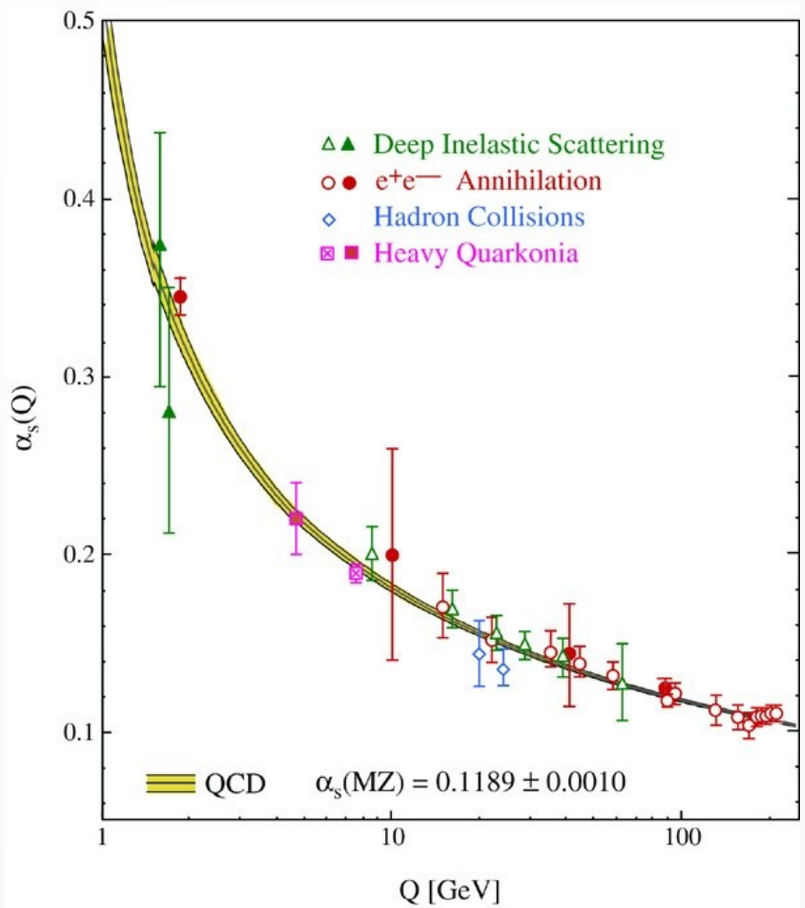
- At high energies, the strong force becomes weak



QCD phase transition

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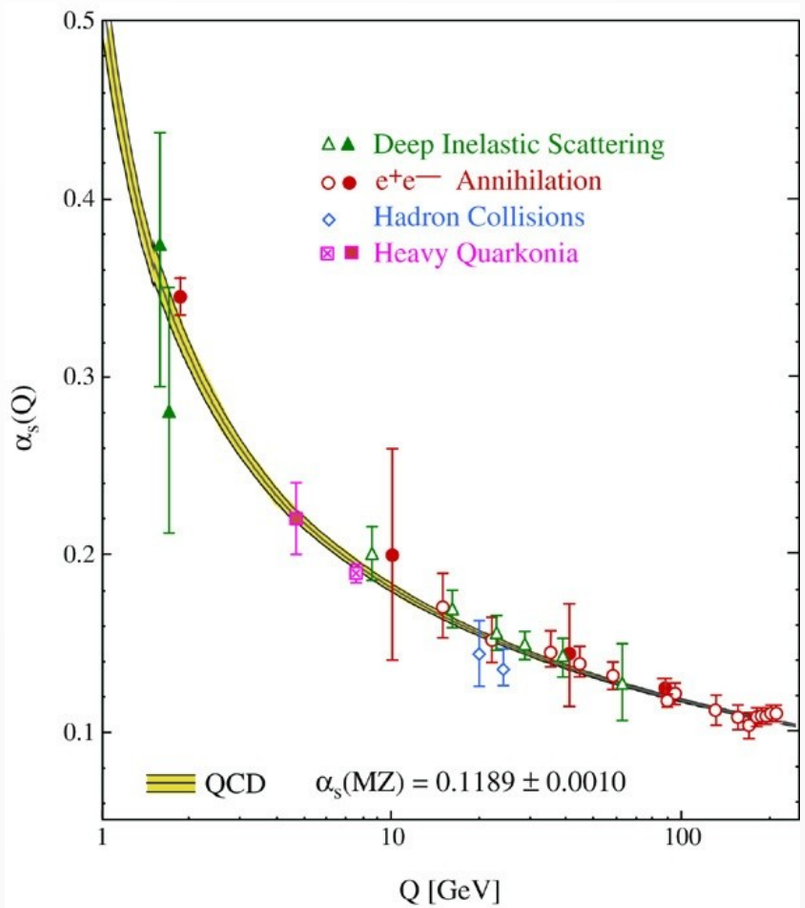
- At high energies, the strong force becomes weak
- Even protons and neutrons begin to break down!



Electroweak epoch

- Electromagnetism and the weak force merge

$$T = 150\,\mathrm{GeV}/10^{15}\,\mathrm{K}$$
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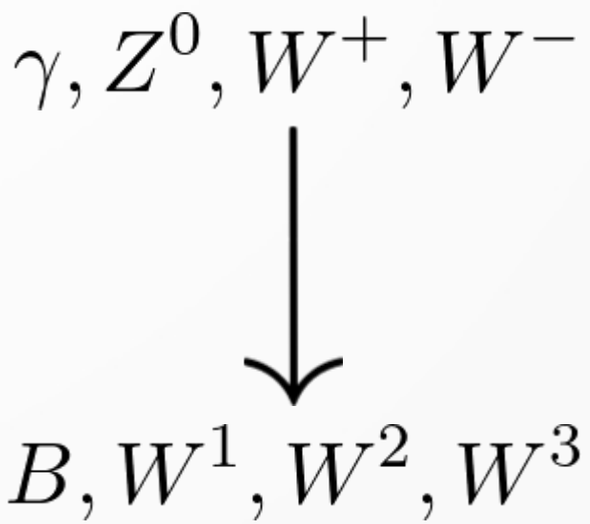

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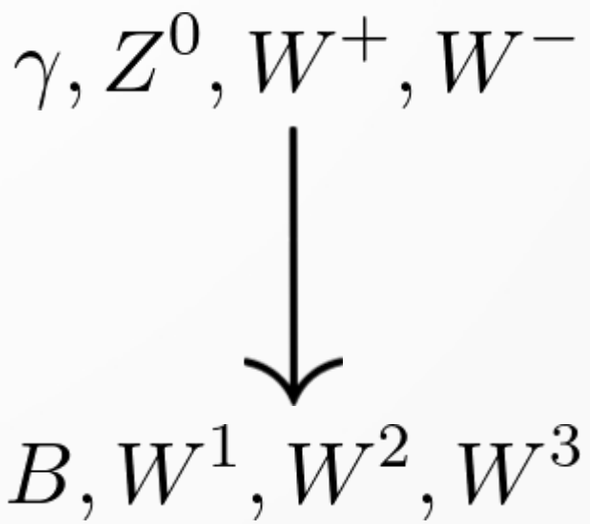

Electroweak epoch

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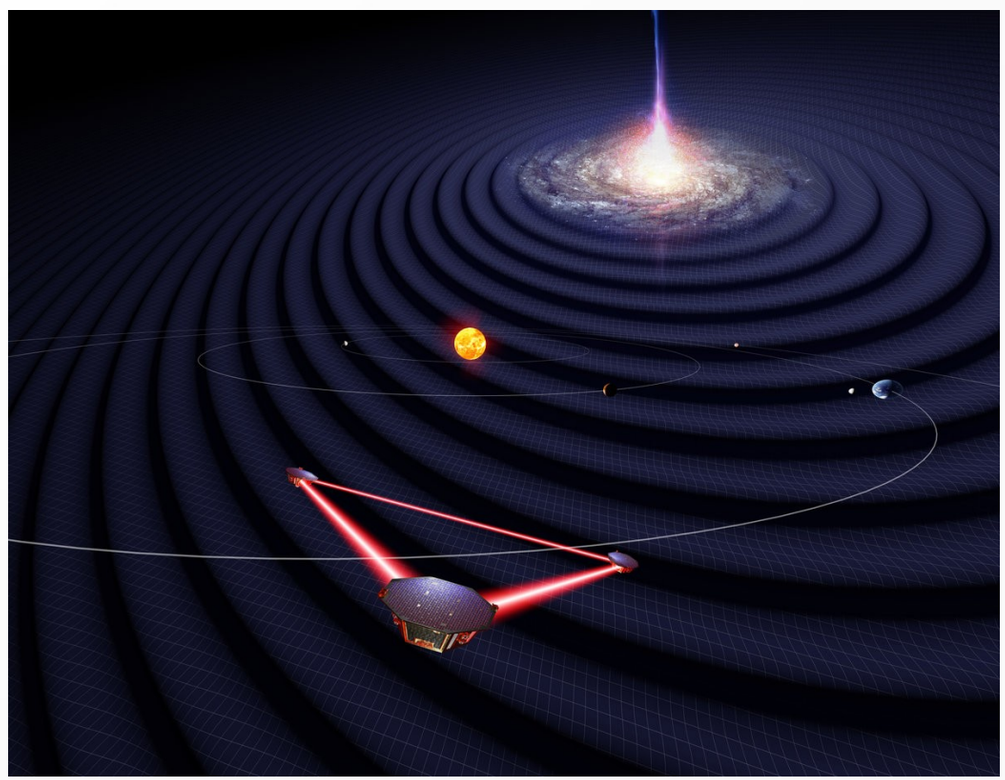
- Electromagnetism and the weak force merge
- "Electroweak symmetry is restored"
- Everything becomes massless!

$$\gamma, Z^0, W^+, W^-$$

$$B, W^1, W^2, W^3$$

How do we know all of this?

- CMB, astrophysical surveys, supernovae



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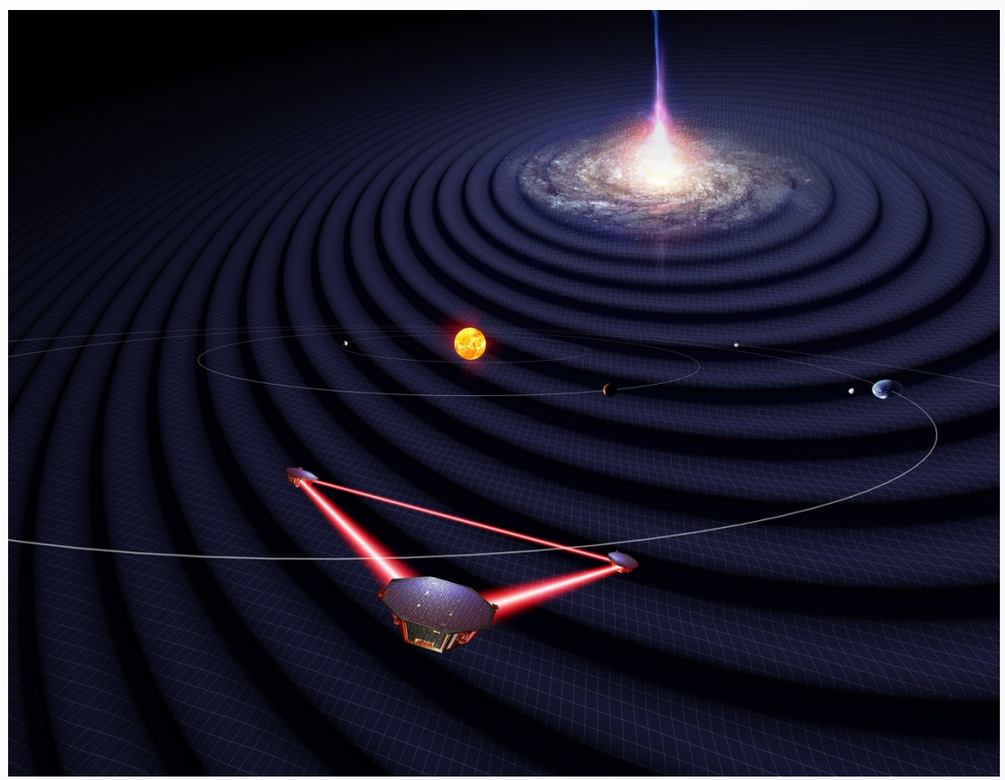

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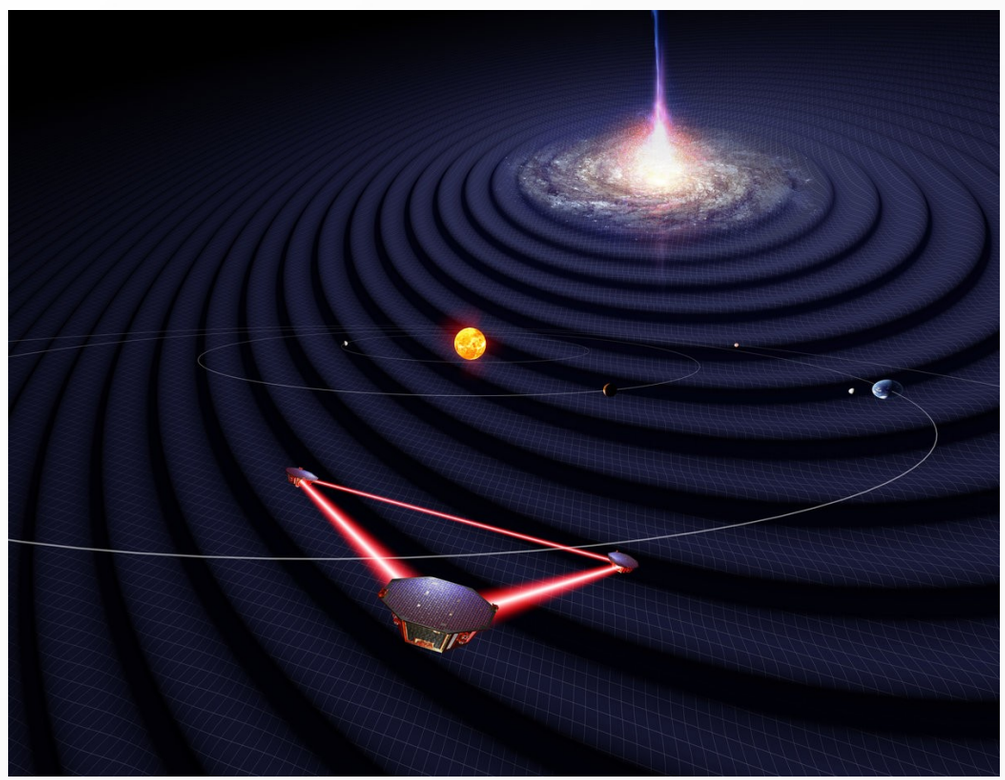
- CMB, astrophysical surveys, supernovae
- Particle accelerators!
- Gravitational waves? Neutrinos?



But what if we went further?

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- CMB homogeneity?
- New particles?
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- The universe rapidly shrinks! ($\sim 10^{-26}$)

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Deflation

- The universe rapidly shrinks! (~10^{-26})

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- Disconnected regions connect

- What causes this?

Grand unification

- Strong force merges with electroweak!

$$T = 10^{16}\,\mathrm{GeV}/10^{29}\,\mathrm{K}$$
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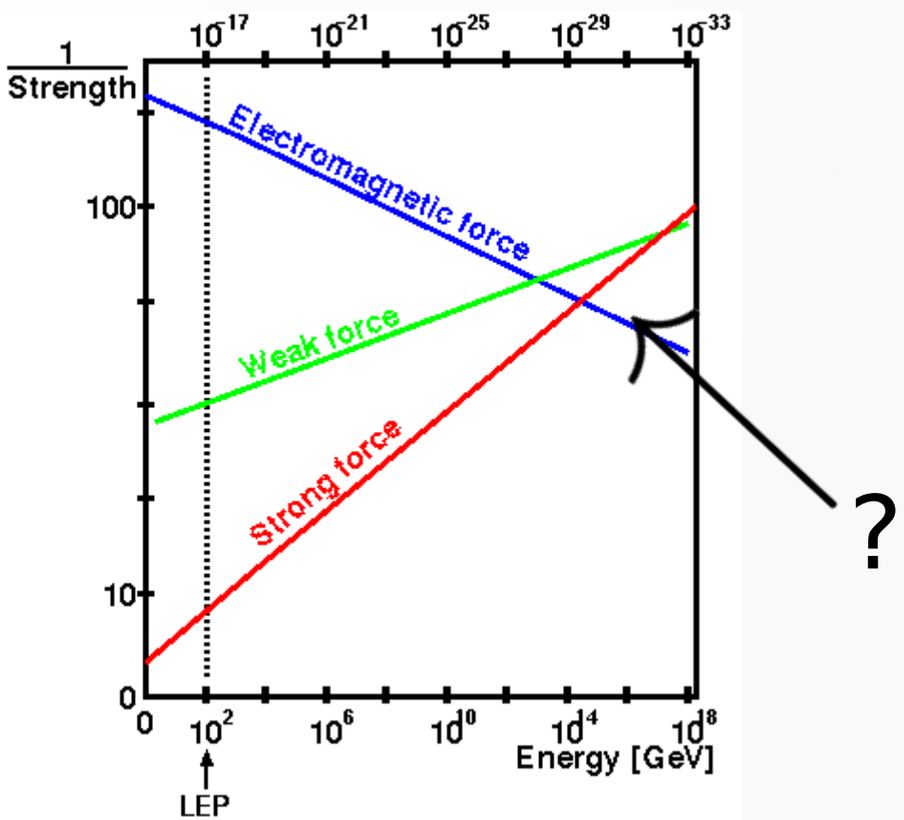

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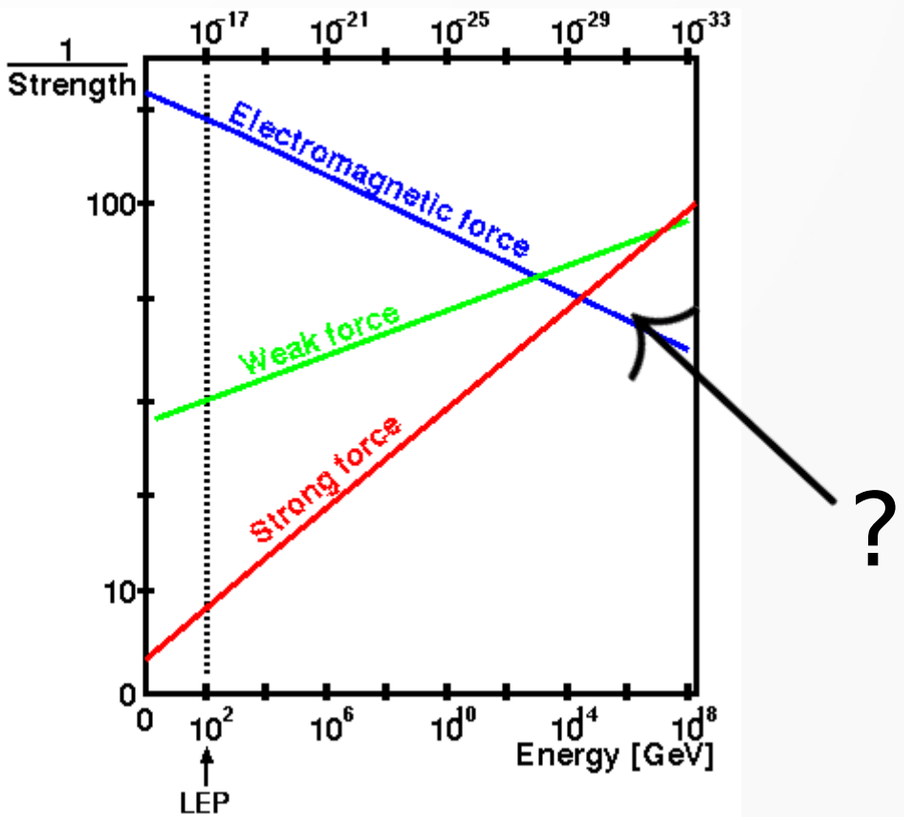

Grand unification

- Strong force merges with electroweak!
- Leptoquarks?
- But which theory?

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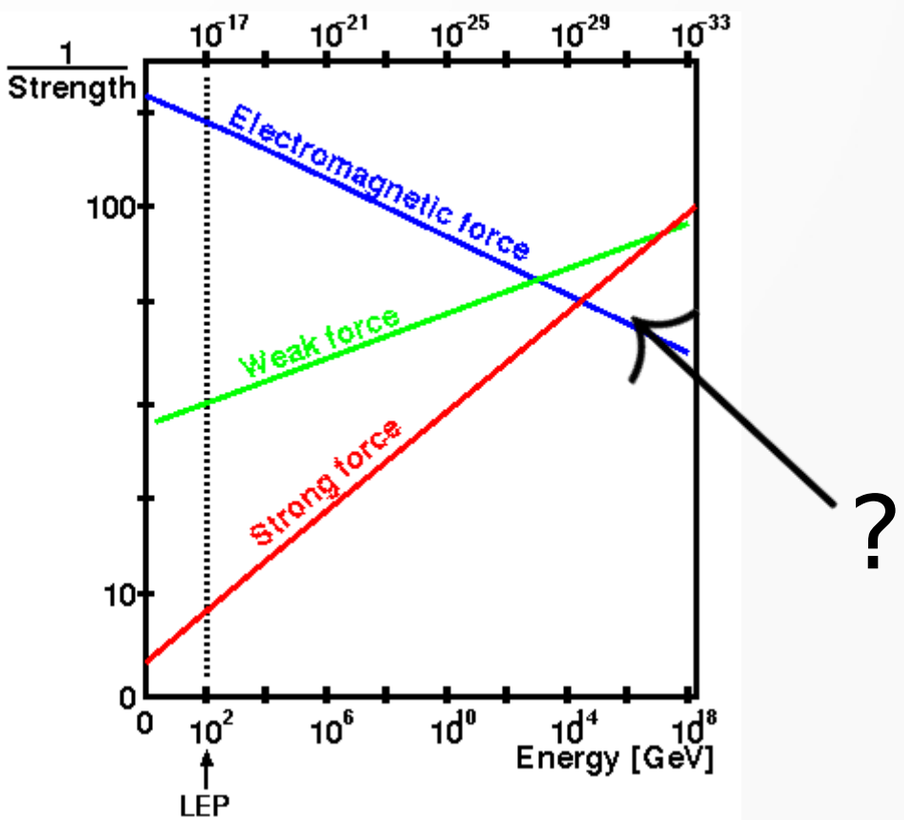

Quantum gravity

- Gravity becomes strong!
  Merges with other forces?

$$T = 10^{19}\,\mathrm{GeV}/10^{32}\,\mathrm{K}$$
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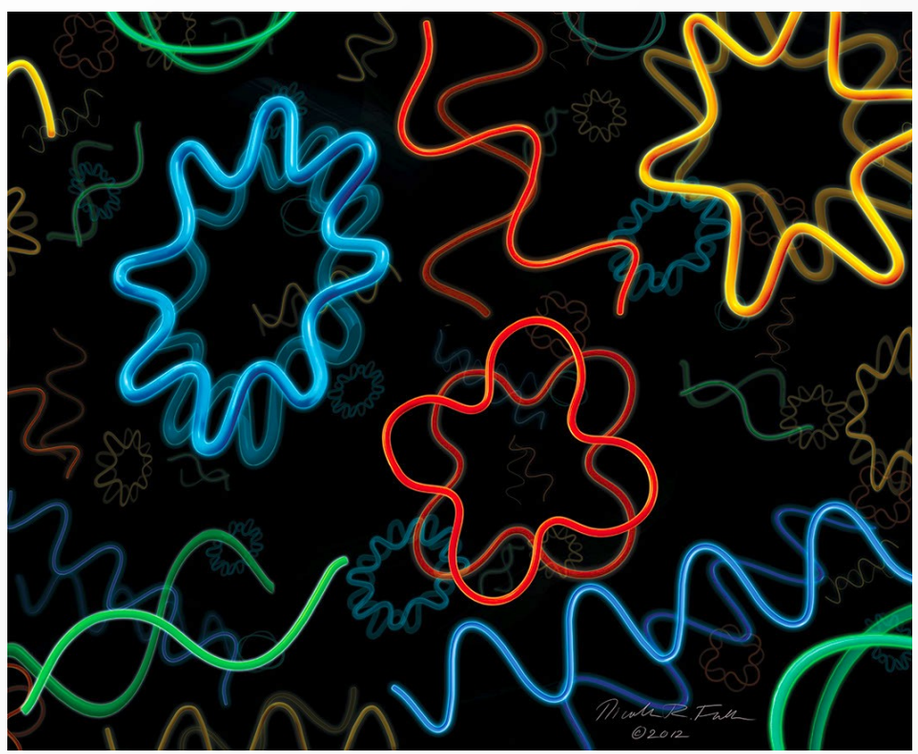

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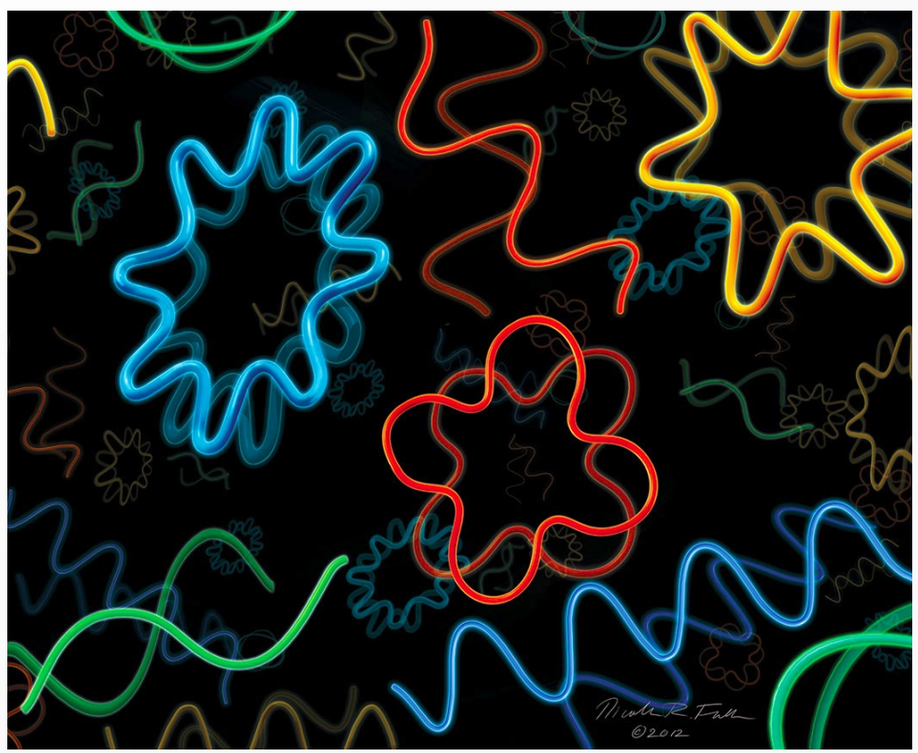

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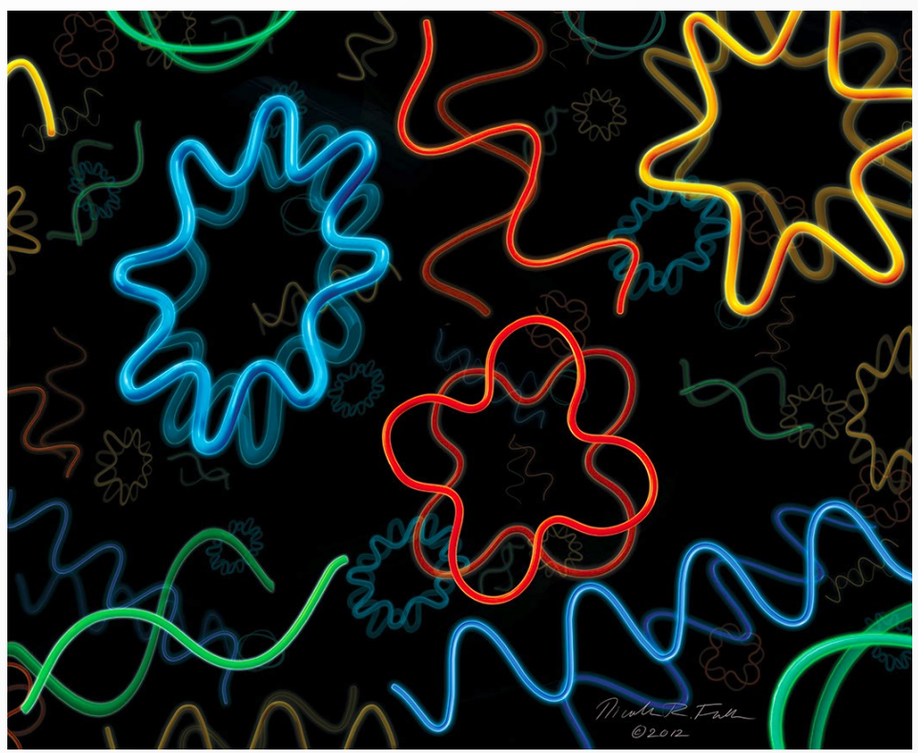
- String theory? Something else?



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- Early universe particle physics affects far future cosmology
- Several open questions in early universe
- Future experiments could probe further back in time!

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Some advice

- Ask questions!

Some advice

- Ask questions!
- Collaborate!

Some advice

- Ask questions!
- Collaborate!
- Enjoy yourself!

Thank you!
Questions?