Towards the minimal effective theory for leptogenesis, dark matter, and neutrino masses

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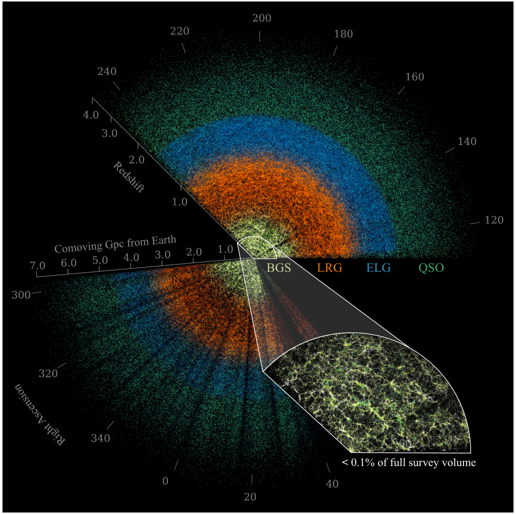
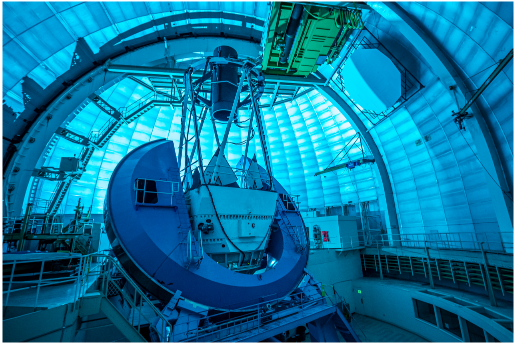
MATFYZ CONNECTIONS

The expanding universe as we see it today



Thin slice of the 2025 DESI data showing nearby bright galaxies (yellow), luminous red galaxies (orange), emission-line galaxies (blue), and quasars (green). Credit: Claire Lamman/DESI collaboration.



The Dark Energy Spectroscopic Instrument maps the universe by collecting spectra from millions of galaxies and quasars. Credit: Marilyn Sargent/Berkeley Lab.

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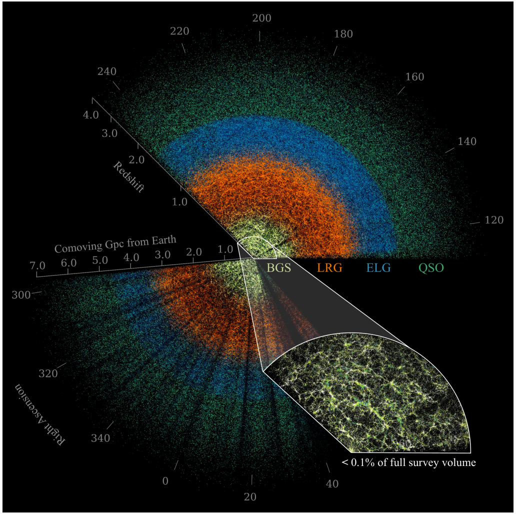

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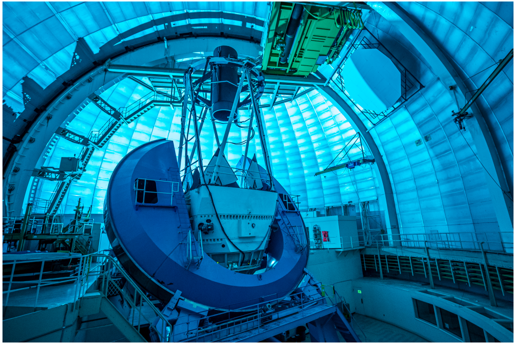

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At cosmological scales, the universe is homogeneous and isotropic . . .

The expanding universe as we see it today

$$\mathbf{r}(t) = \mathbf{r}(t_0)a(t)$$

$$\left(\frac{\mathrm{d}a/\mathrm{d}t}{a}\right)^2 = \frac{8\pi G}{3}\rho(a)$$

- ... and its only dynamics are the expansion or collapse.

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- … and its only dynamics are the expansion or collapse.
- The universe expands, but galaxies themselves do not.
- The expansion slows massive particles down. For photons, it causes a redshift, which is not due to the Doppler effect.
- By measuring a galaxy's redshift, we gain insight into the universe's expansion rate in the past.

The expanding universe as we see it today

$$\rho(a) = \rho_{\mathrm{crit},0} \times \left(\Omega_{\Lambda,0} + \frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{r,0}}{a^4} \right)$$

$$\boxed{\left(\frac{\mathrm{d}a/\mathrm{d}t}{a} \right)^2 = \frac{8\pi G}{3} \rho(a)}$$

- Our universe is almost flat and has a critical density of 8.6×10^{-27} kg/m^3.
- The expansion rate today, known as the Hubble constant, is

$$H_0 = \left. \frac{\mathrm{d}a/\mathrm{d}t}{a} \right|_{\mathrm{today}} = (67.7 \pm 0.4) \times \mathrm{km\,s^{-1}\,Mpc^{-1}}.$$

S. Navas *et al.* (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

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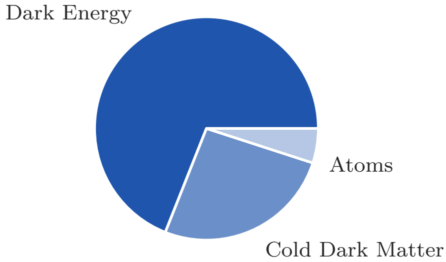

$$\Omega_{\Lambda,0} = (68.9 \pm 0.60)\%$$

$$\left.\begin{aligned} \Omega_{c,0} &= (26.0 \pm 0.36)\% \\ \Omega_{b,0} &= (4.89 \pm 0.07)\% \end{aligned}\right\} \Omega_{m,0} = (31.1 \pm 0.6)\%$$

$$\Omega_{r,0} = (5.38 \pm 0.15) \times 10^{-5} + \text{neutrinos}$$

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accelerates the expansion — $\Omega_{\Lambda,0} = (68.9 \pm 0.60)\%$

relative motion of galaxies, rotational curves, … — $\Omega_{c,0} = (26.0 \pm 0.36)\%$

mostly hydrogen — $\Omega_{b,0} = (4.89 \pm 0.07)\%$

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Radiation-dominated universe

$$\rho(a) = \rho_{\text{crit},0} \times \left(\Omega_{\Lambda,0} + \frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{r,0}}{a^4} \right) \approx \rho_{\text{crit},0} \times \frac{\Omega_{r,0}}{a^4} \quad \text{for} \quad a \ll 10^{-4}$$

$$\left.\begin{array}{c} t \ll t_{\text{eq}} \approx 50000 \text{ y} \\ T \gg T_{\text{eq}} \approx 0.25 \text{ eV} \simeq 10^4 \text{ K} \end{array}\right\} a(t) \propto t^{1/2}$$

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- No large-scale structures have formed yet.

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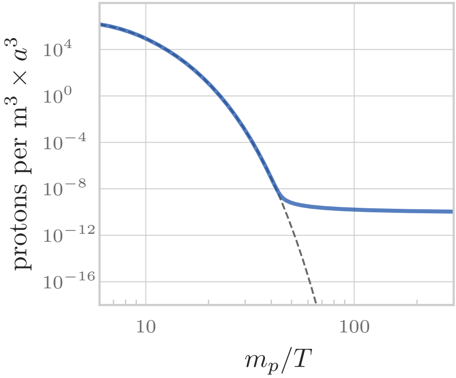
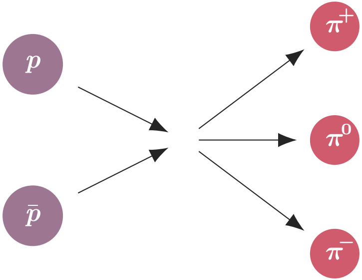
The radiation-dominated universe is a homogeneous, hot, and dense mixture of particles.

Proton anti-proton annihilation symmetric freeze-out





- Baryons (protons and neutrons) form at $T \approx 150$ MeV (1.7×10^{12} K)
- Annihilation and production remain in equilibrium until $T \approx 20$ MeV (2.3×10^{11} K).
- The resulting density today would be approximately 10^{-10} protons/m^3.

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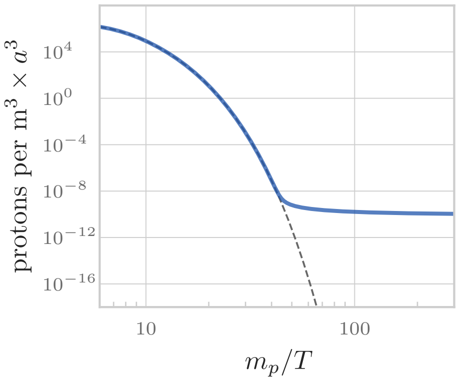
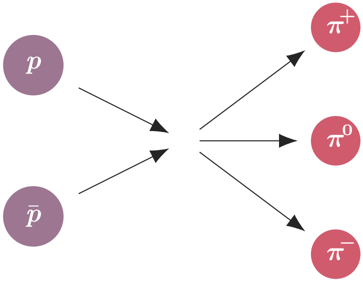
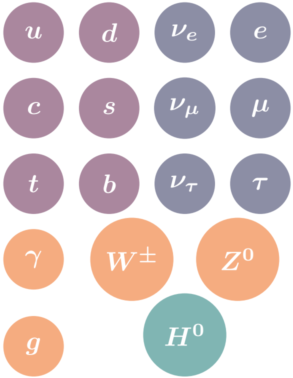




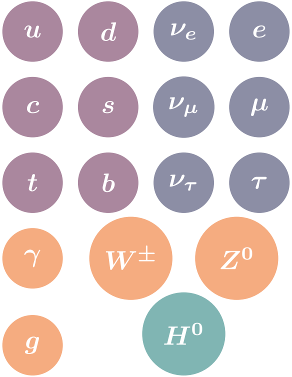
We need an excess of protons over antiprotons!
For every 10^{10} antiprotons, there must be one extra proton.

Standard Model and the early universe



Does the Standard Model of elementary particles describe the early universe?

Standard Model and the early universe



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- A viable dark matter candidate is missing, so we cannot account for $\Omega_{c,0}$.

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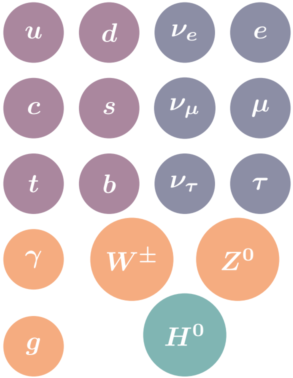

Does the Standard Model of elementary particles describe the early universe?

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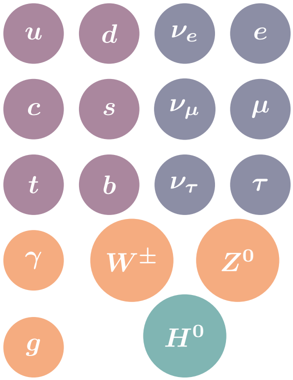

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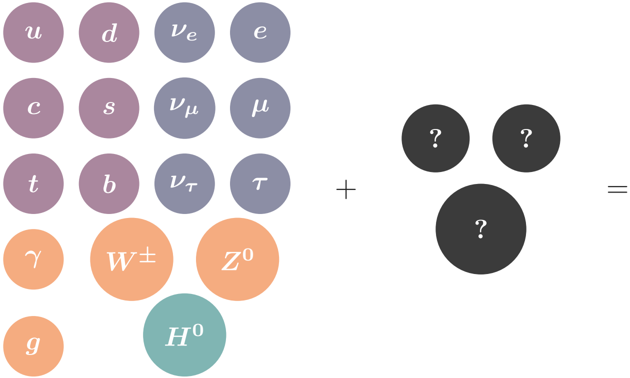
New physics needed to explain the matter in the universe!

Standard Model and the early universe



Observed dark matter and baryon density.

Baryogenesis and leptogenesis

- Processes violating baryon number.
- Independent C- and CP-symmetry violation.
- Interactions out of thermal equilibrium.

A.D. Sakharov, 1991 Sov. Phys. Usp. 34 392

$$C : \text{particle} \leftrightarrow \text{antiparticle}, \quad P : \text{left} \leftrightarrow \text{right}, \quad T : \text{past} \leftrightarrow \text{future}.$$

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Under reasonable assumptions (space-time symmetries, causality), any theory of particle interactions must be CPT-invariant.

J. Schwinger, Phys. Rev. 82, 914 (1951)

Baryogenesis and leptogenesis

- In **leptogenesis**, a lepton number asymmetry is generated first and then converted into a baryon asymmetry through Standard Model interactions.

M. Fukugita, T. Yanagida, Phys. Lett. B 174(1), 45 (1986)

$$\gamma_{N\to\ell H} = \frac{\#\text{ of } N \to \ell H \text{ decays}}{\text{unit volume} \times \text{unit time}}$$

- We require $\gamma^{\text{eq}}_{N\to\ell H} > \gamma^{\text{eq}}_{N\to\bar{\ell}\bar{H}}$ and this necessarily implies $\gamma^{\text{eq}}_{\ell H\to\bar{\ell}\bar{H}} > \gamma^{\text{eq}}_{\bar{\ell}\bar{H}\to\ell H}$.
- In thermal equilibrium, decay and scattering asymmetries cancel each other, so a departure from equilibrium is required.
- Stable dark matter candidate still missing.

Leptogenesis and dark matter in a minimal model

Top-down approach

- Well-motivated (neutrino masses, naturalness).
- Built upon new symmetries.
- Examples: SUSY, GUTs, extended Higgs sectors, ...

Bottom-up approach

- Minimal in terms of new particles and interactions.
- Effective theory below some energy scale Λ (power series in T/Λ).

How minimal can an effective theory be?

- Two new particles (a heavy neutral fermion f, a light neutral scalar S) stabilized by a $\mathbb{Z}_2$ symmetry.

- One portal operator and the Weinberg operator (leads to neutrino masses),

$$L_{\text{eff}} = \frac{\lambda}{\Lambda} S\bar{f} P_L \ell H + \frac{\lambda'}{\Lambda} H\bar{\ell}^c P_L \ell H + \text{H.c.}$$

- Apart form asymmetric decays and scatterings, the model implies asymmetries in non-standard reactions including spectator particles, such as $\ell HS \to \bar{\ell}\bar{H}S$ (with no change in state of S).

T. Blažek, P. Maták, J. Ramaj, M. Sabová, Eur. Phys. J. C 85 (2025) 801

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Thank you for your attention!