Neutrinos, The Standard Model, and Beyond

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INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS
IN SEARCH FOR THE UNEXPECTED
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Outline

- Setting up the scene: the Standard Model and the LHC
- Problems of the Standard Model
  - Neutrino masses and oscillations
  - Dark Matter
  - Baryon asymmetry of the Universe
- Heavy Neutral Leptons (HNL’s or sterile neutrinos)
- Dark matter from HNL
- Baryon asymmetry of the Universe from HNL
- How to search for HNL
- Conclusions
Setting up the scene: the Standard Model and the LHC
The Standard Model was invented back in 1967 and completed with the discovery of the Higgs boson at the LHC 45 year later.

![Diagram of the Standard Model](Image)
## Searches for new physics, SUSY

**ATLAS SUSY Searches** - 95% CL Lower Limits

**Status:** ICHEP 2014

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell_e \ell_\mu \ell_\tau \gamma$</th>
<th>Jets</th>
<th>$E_T^{\text{miss}}$</th>
<th>Mass limit</th>
<th>Reference</th>
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<td>2-6</td>
<td>Yes</td>
<td>20.3 GeV</td>
<td>1405.1441</td>
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**Table:**

- **Model:** Various models for supersymmetric physics.
- **$\ell_e \ell_\mu \ell_\tau \gamma$:** Lepton flavors.
- **Jets:** Number of jets.
- **$E_T^{\text{miss}}$:** Missing transverse energy.
- **Mass limit:** Lower limit on the mass of new particles.
- **Reference:** Literature references for each model.

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1$\sigma$ theoretical signal cross section uncertainty.*
Searches for new physics, exotics

CMS Exotica Physics Group Summary – ICHEP, 2014

CMS Preliminary

Leptoquarks

RS Gravitons

Long-Lived Particles

Dark Matter

Leptoquarks

RS Gravitons

Heavy Gauge Bosons

Excited Fermions

Multijet Resonances

CMS Exotica Physics Group Summary – ICHEP, 2014

Erice, June 2019 – p. 6
Marginal evidence (less than $2\sigma$) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling.

Vacuum is unstable at $\sim 1.5\sigma$.
Summary of the LHC findings

The Standard Model is now complete: the last particle - Higgs boson, predicted by the SM, has been found.
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The masses of the top quark and of the Higgs boson, the Nature has chosen, make the SM a self-consistent effective field theory all the way up to the quantum gravity scale $10^{19}$ GeV (15 orders of magnitude larger than the LHC energy!).
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End of high energy physics?
Theoretical prejudice for new physics beyond the Standard Model: WHY questions

Hierarchy problem: Why $M_W/M_{Pl} \ll 1$?

Stability of the Higgs mass against radiative corrections.

Cosmological constant problem: Why $\epsilon_{vac}/M_{Pl}^4 \ll 1$?

Strong CP-problem: Why $\theta_{QCD} \ll 1$?

Fermion mass matrix: Why $m_e \ll m_t$?

...
Experimental problems of the Standard Model
Neutrino masses and oscillations
SM: neutrinos are massless and lepton numbers are conserved!

Experiment: neutrinos have masses and lepton numbers are not conserved! Lectures by Alessandro Bettini, Sergio Bertolucci, Harald Fritzsch and Mikko Laine.

Solution: neutrinos have masses $\mathcal{O}(eV)$ and SM must be extended.
Baryon asymmetry of the Universe and baryogenesis
The birth of antimatter
The birth of antimatter

Before 1930: The only known elementary particles were protons, neutrons, electrons and photons
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Big theoretical issue: how to unify quantum mechanics and special relativity
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Big theoretical issue: how to unify quantum mechanics and special relativity.

1930, Dirac: construction of relativistic equation describing quantum mechanics of electron (particle with spin $\frac{1}{2}$)
“If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regards it rather as an accident that the Earth (and presumably the whole solar system), contains a predominance of electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.”
Baryon asymmetry in the present universe

Dirac was perfectly correct that the solar system is constructed from matter!
However, how can we know whether distant stars and galaxies consist of matter or antimatter?
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There are several methods for detection of antimatter:

- The search of antinuclei in cosmic rays: the probability of the process

\[ pp \rightarrow \text{antinuclei} + \text{etc} \]

is very small!
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There are several methods for detection of antimatter:

- The search of antinuclei in cosmic rays: the probability of the process

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is very small!

Result: no antinuclei in cosmic rays have been found!
Detection of antimatter

Annihilation: particles and antiparticles annihilate:

\[ p\bar{p} \rightarrow \pi^+ \pi^- \pi^0 \rightarrow \gamma\gamma \]

\[ \nu_\mu \mu^+ \leftrightarrow \mu^- \bar{\nu}_\mu \]

\[ e^+ \nu_e \bar{\nu}_\mu \leftrightarrow e^- \bar{\nu}_e \nu_\mu \]

Detection of $\gamma$-rays?
Detection of antimatter

Annihilation: particles and antiparticles annihilate:

\[ p\bar{p} \rightarrow \pi^+ \pi^- \pi^0 \rightarrow \gamma\gamma \]

\[ \nu_\mu \mu^+ \quad \mu^- \bar{\nu}_\mu \]

\[ e^+ \nu_e \bar{\nu}_\mu \quad e^- \bar{\nu}_e \nu_\mu \]

Detection of γ-rays?

However, this has not been observed!
Our universe is asymmetric!
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Dirac was wrong: cosmological observations do not support the hypothesis that the distant stars and galaxies may consist of antimatter.
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The problem
Our universe is asymmetric!

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The problem

Where is antimatter?
Our universe is asymmetric!

Dirac was wrong: cosmological observations do not support the hypothesis that the distant stars and galaxies may consist of antimatter.

The problem

Where is antimatter?

Its absence looks really strange, as the properties of matter and antimatter are very similar!
Sakharov Proposal: Universe is asymmetric because of

- Baryon number non-conservation (otherwise symmetric state cannot evolve to asymmetric state) - present in the SM
- CP-violation (otherwise there is no difference between matter and antimatter) - present in the SM, but very small
- Substantial deviations from thermal equilibrium (otherwise there is no arrow of time and asymmetry cannot be created) - absent in the SM
Dark matter in the universe
Problem since 1933, F. Zwicky.
Most of the matter in the universe is dark

**Evidence:**
- Rotation curves of galaxies
- Big Bang nucleosynthesis
- Structure formation
- CMB anisotropies
- Supernovae observations

Non-baryonic dark matter:
\[ \Omega_{DM} \approx 0.22 \]
Standard Model: no particle physics candidate for Dark Matter

- The only neutral stable objects - atoms and neutrinos
- **if atoms**: contradiction with BBN - so many baryons are not admitted
- **if neutrinos - hot DM**: contradiction with structure formation - small scale inhomogeneities are erased

**Dark Matter : new particle (?)**
What do we know for sure about DM particles
They must have a lifetime exceeding the age of the Universe - otherwise they would have decayed.

Relatively light particles ($M < \text{ few TeV}$) must be neutral and very weakly interacting - otherwise we would easily detect their cosmic flux.

The DM particles should form the cold or warm DM – they must not be relativistic at the onset of structure formation, Lyman-$\alpha$ data puts $\lambda_{FS} < 150$ kpc.

If they are fermions, their mass should not be below 400 eV – Tremaine-Gunn bound.
Ben Moore simulations
Number of satellites of the Milky way

CDM versus WDM, Carlos Frenk et al.
The smaller is the DM mass the bigger is the number of particles in an object with the mass $M_{\text{vir}}$.

Average phase-space density of fermion DM particles should be smaller than density of degenerate Fermi gas:

$$\frac{M_{\text{vir}}}{\frac{4\pi}{3} R_{\text{vir}}^3} \frac{1}{\frac{4\pi}{3} v_{\infty}^2} \leq \frac{2m_{\text{DM}}^4}{(2\pi \hbar)^3}$$

Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the lower bound on the fermionic DM mass $m_{\text{DM}} \gtrsim 400$ eV

"Tremaine-Gunn bound"
What we **do not know** about DM particles
Mass: the range from $10^{-33}$ eV (stringy axions) to $10^{24}$ GeV (supersymmetric Q-balls) was considered

Spin: both fermions and bosons are OK

Interaction strength and interaction type

Production mechanism

How they are embedded into Big Picture of particle physics
How to reconcile the evidence for new physics without spoiling the success of the Standard Model?
Where is new physics?
Only at the Planck scale?

Does not work: neutrino masses from five-dimensional operator

\[
\frac{1}{M_P} A_{\alpha\beta} \left( \bar{L}_\alpha \tilde{\phi} \right) \left( \phi^\dagger L^c_\beta \right)
\]

suppressed by the Planck scale are too small, \( m_\nu < 10^{-5} \) eV.
Below the Planck scale, but where?

- Neutrino masses and oscillations: the masses of right-handed see-saw neutrinos can vary from $\mathcal{O}(1)$ eV to $\mathcal{O}(10^{15})$ GeV.

- Dark matter, absent in the SM: the masses of DM particles can be as small as $\mathcal{O}(10^{-22})$ eV (super-light scalar fields) or as large as $\mathcal{O}(10^{20})$ GeV (wimpzillas, Q-balls).

- Baryogenesis, absent in the SM: the masses of new particles, responsible for baryogenesis (e.g. right-handed neutrinos), can be as small as $\mathcal{O}(10)$ MeV or as large as $\mathcal{O}(10^{15})$ GeV.

- Higgs mass hierarchy: models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale, whereas the models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales.
Arguments for absence of new heavy particles above the Fermi scale

- Stability of the Higgs mass against radiative corrections

\[ \delta m_H^2 \sim \alpha^n_{\text{GUT}} M_{\text{heavy}}^2 \]

- No heavy particles - no large contributions - no fine tuning

Higgs self coupling \( \lambda \approx 0 \) at the Planck scale (criticality of the SM - asymptotic safety? Astrid Eichhorn lectures). This is violated if new particles contribute to the evolution of the SM couplings.

Higgs mass \( M_h = 125.3 \pm 0.6 \) GeV
New Physics without new energy scale
Outline of a possible answer

Right handed neutrinos (other names: Majorana fermions, heavy neutral leptons – HNLs, sterile neutrinos)

- Minimal physics for neutrino masses
- Baryogenesis
- Dark Matter
- Conclusions
the SM

Three Generations of Matter (Fermions) spin \( \frac{1}{2} \)

<table>
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<th>II</th>
<th>III</th>
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<tr>
<td>name</td>
<td>u</td>
<td>c</td>
<td>t</td>
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</table>

Quarks:
- u: up, mass 2.4 MeV
- c: charm, mass 1.27 GeV
- t: top, mass 171.2 GeV
- d: down, mass 4.8 MeV
- s: strange, mass 104 MeV
- b: bottom, mass 4.2 GeV

Leptons:
- e: electron, mass 0.511 MeV
- \( \nu_e \): electron neutrino
- \( \mu \): muon, mass 105.7 MeV
- \( \nu_\mu \): muon neutrino
- \( \tau \): tau, mass 1.777 GeV
- \( \nu_\tau \): tau neutrino

Bosons (Forces) spin 1:
- \( \gamma \): photon, mass 0 GeV
- W\( ^\pm \): weak force, mass 80.4 GeV

Bosons (Forces) spin 0:
- Z\( ^0 \): weak force, mass 91.2 GeV
- H: Higgs boson, mass 0 GeV
The missing piece: sterile neutrinos

Most general renormalizable (see-saw) Lagrangian

\[ L_{\text{see-saw}} = L_{\text{SM}} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \Phi - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}, \]

Assumption: all Yukawa couplings with different leptonic generations are allowed.

\( I \leq \mathcal{N} \) - number of new particles - HNLs - cannot be fixed by the symmetries of the theory.

Let us play with \( \mathcal{N} \) to see if having some number of HNLs is good for something.
\( N' = 1 \): Only one of the active neutrinos gets a mass
\[ \mathcal{N} = 1: \text{Only one of the active neutrinos gets a mass} \]
\[ \mathcal{N} = 2: \text{Two of the active neutrinos get masses: all neutrino experiments, except LSND-like, can be explained. The theory contains 3 new CP-violating phases: baryon asymmetry of the Universe can be understood} \]
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\[ \mathcal{N} = 3: \] All active neutrinos get masses: all neutrino experiments, can be explained (LSND with known tensions). The theory contains 6 new CP-violating phases: baryon asymmetry of the Universe can be understood. If LSND is dropped, dark matter in the Universe can be explained. The quantisation of electric charges follows from the requirement of anomaly cancellations (1-3-3, 1-2-2, 1-1-1, 1-graviton-graviton).
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\[ \mathcal{N} > 3: \text{Now you can do many things, depending on your taste - extra relativistic degrees of freedom in cosmology, neutrino anomalies, dark matter, different scenarios for baryogenesis, and different combinations of the above.} \]
New mass scale and Yukawas

\[ Y^2 = \text{Trace}[F^\dagger F] \]

- 0.05 eV
- 1 TeV
- \(10^{16}\) GeV

- Strong coupling
- No seesaw
- Neutrino masses are too small

- LSND
- v MSM
- LHC
- GUT
- See-saw

Majorana mass, GeV
$\mathcal{N} = 3$ with $M_I < M_W$: the $\nu$MSM

$\mathcal{N} =$ Heavy Neutral Lepton - HNL

Role of $\mathcal{N}_1$ with mass in keV region: dark matter

Role of $\mathcal{N}_2$, $\mathcal{N}_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe
What should be the properties of $N_{1,2,3}$ in the minimal setup - no any type of new physics between the Fermi and Planck scales?

How to search for them experimentally?
Baryon asymmetry

Sakharov conditions:

- Baryon number violation - OK due to complex vacuum structure in the SM and chiral anomaly
- CP-violation - OK due to new complex phases in Yukawa couplings
- Deviations from thermal equilibrium - OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

More in lecture by Mikko Laine
Creation of baryon asymmetry - a complicated process involving creation of HNLs in the early universe and their coherent CP-violating oscillations, interaction of HNLs with SM fermions, sphaleron processes with lepton and baryon number non-conservation

Akhmedov, Rubakov, Smirnov; Asaka, MS

Resummation, hard thermal loops, Landau-Pomeranchuk-Migdal effect, etc. Ghiglieri, Laine. How to describe these processes is still under debate, but the consensus is that it works and is testable.
Experimental challenges:

HNL production and decays are highly suppressed – dedicated experiments are needed:

- **Production**
  - via intermediate (hadronic) state
    
    \[
    p + \text{target} \rightarrow \text{mesons} + \ldots, \text{ and then hadron} \rightarrow N + \ldots.
    \]
  - via \(Z\)-boson decays: \(e^+e^- \rightarrow Z \rightarrow \nu N\)

- **Detection**
  - Subsequent decay of \(N\) to SM particles
Dedicated experiments

Common features of all relatively light feebly interacting particles:

- Can be produced in decays of different mesons ($\pi$, $K$, charm, beauty)
- Can decay to SM particles ($l^+l^-$, $\gamma\gamma$, $l\pi$, etc)
- Can be long lived

Requirements to experiment:

- Produce as many mesons as you can
- Study their decays for a missing energy signal: charm or B-factories, NA62
- Search for decays of hidden sector particles - fixed target experiments
  - Have as many pot as you can, with the energy enough to produce charmed (or beauty) mesons
  - Put the detector as close to the target as possible, in order to catch all hidden particles from meson decays (to evade $1/R^2$ dilution of the flux)
  - Have the detector as large as possible to increase the probability of hidden particle decay inside the detector
  - Have the detector as empty as possible to decrease neutrino and other backgrounds

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Energy and Intensity Frontiers
Most recent dedicated experiment - 1986, Vannucci et al

No new particles are found with mass below K-meson, the best constraints are derived
a discovery machine for weakly coupled LLPs, with a complementary detector for $\nu$ physics and LDM scattering signatures

- large geometrical acceptance: long volume close to dump
- zero background with spectrometry, PID and VETO taggers
MAssive Timing Hodoscope for Ultra-Stable Neutral Particles

An external LLP detector for the HL- or HE-LHC
FCC at $10^{13}$ $Z^0$ and decay length 0.01-500 cm
Dark Matter candidate: $N_1$

DM particle is not stable. Main decay mode $N_1 \rightarrow 3\nu$ is not observable.

Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$

Radiative decay width:

$$\Gamma_{\text{rad}} = \frac{9 \alpha_{\text{EM}} G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) M_s^5$$
Constraints on DM sterile neutrino $N_1$

- **Stability.** $N_1$ must have a lifetime larger than that of the Universe.

- **Production.** $N_1$ are created in the early Universe in reactions $l\bar{l} \rightarrow \nu N_1$, $q\bar{q} \rightarrow \nu N_1$ etc. We should get correct DM abundance. More in lecture by Mikko Laine.

- **Structure formation.** If $N_1$ is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-$\alpha$ forest spectra of distant quasars and structure of dwarf galaxies.

- **X-rays.** $N_1$ decays radiatively, $N_1 \rightarrow \gamma \nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).
Available X-ray satellites:
Suzaku, XMM-Newton, Chandra, INTEGRAL, NuStar

Life-time $\tau$ [sec]

$M_{DM}$ [keV]

$10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$

$10^{25}$ $10^{26}$ $10^{27}$ $10^{28}$ $10^{29}$

$10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$

PSD exceeds degenerate Fermi gas

$\tau = \text{Universe life-time } \times 10^8$

Future of decaying dark matter searches in X-rays

**Another Hitomi (around 2020)**
It is planned to send a replacement of the Hitomi satellite

**Microcalorimeter on sounding rocket (2019)**
- Flying time $\sim 10^2$ sec. Pointed at GC only
- Can determine line’s position and width

**Athena+ (around 2028)**
- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10 \times$ that of XMM)
- Super spectral resolution

“Dark matter astronomy era” begins?
Conclusions

Heavy neutral leptons can be a key to (almost all) BSM problems:
- neutrino masses and oscillations
- dark matter
- baryon asymmetry of the universe

They can be found in Space and on the Earth
- X-ray satellites
- proton fixed target experiment - SHIP, $M \lesssim 2$ GeV
- collider experiments at FCC-ee in Z-peak, $M \gtrsim 2$ GeV
Structure of the Universe at large scales and Inflation
**Universe at large scales**

Important cosmological problems:

**Horizon problem:** Why the universe is so uniform and isotropic?

\[ r \propto t^{1/2} \text{ (radiation)}, \quad r \propto t^{2/3} \text{ (matter)} \]

Expected fluctuations at \( \theta \sim 1^\circ \):

\[ \delta T/T \sim 1. \]

Observed fluctuations: \( \delta T/T \sim 10^{-5} \)

\[ t_U \sim 14 \text{ billion years}, \quad t_r \sim 2 \times 10^5 \text{ years} \]
Structure formation problem: What is the origin of cosmological perturbations and why their spectrum is almost scale-invariant?
Flatness problem: Why $\Omega_M + \Omega_\Lambda + \Omega_{\text{rad}}$ is so close to 1 now and was immensely close to 1 in the past?

All this requires enormous fine-tuning of initial conditions (at the Planck scale?) if the Universe was dominated by matter or radiation all the time!
Solution: Inflation = \textit{accelerated}

Universe expansion in the past
Flatness problem: Why $\Omega_M + \Omega_\Lambda + \Omega_{\text{rad}}$ is so close to 1 now and was immensely close to 1 in the past?

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Mechanism: scalar field dynamics
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Why scalar?

- Vector - breaking of Lorentz symmetry
- Fermion - bilinear combinations are equivalent to scalar fields
Mechanism: scalar field dynamics

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- Uniform scalar condensate has an equation of state of cosmological constant and leads to exponential universe expansion
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- Fermion - bilinear combinations are equivalent to scalar fields
- Uniform scalar condensate has an equation of state of cosmological constant and leads to exponential universe expansion
“Standard” chaotic inflation

\[ V(\phi) = \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} \phi^4 \]

Chaotic initial conditions: exponential expansion of the Universe at the beginning
self-reproducing inflationary universe. This theory is rather especially promising and leads to the most text of the chaotic inflation scenario. They first moved in all possible directions and then froze on top of one another. Each frozen wave slightly increased the scalar field in some parts of the universe and decreased it in others. Such regions are extremely rare, but still they do exist. And they can be extremely important. Those rare domains of the universe where the field jumps high enough begin exponentially expanding with ever higher the scalar field jumps, the faster.
Size of Universe

Age of Universe (Seconds)

Open
Flat
Closed

Inflation

Inflationary Universe Scenario

Space-Time Foam

Heating

Planck Length

10^{-43}
Closed

10^{-35}

10^{12}

STANDARD BIG BANG MODEL

10^{30}

10^{17}

UNIVERSE AT PRESENT TIME

Courtesy: Linde
Challenge for particle physics:

What kind of scalar field drives inflation?

Almost flat potential for large scalar fields is needed! Linde

Required for inflation: (to get $\delta T/T \sim 10^{-5}$)

- quartic coupling constant $\lambda \sim 10^{-13}$:
- mass $m \lesssim 10^{13}$ GeV,
Challenge for particle physics:

What kind of scalar field drives inflation?

Almost flat potential for large scalar fields is needed! Linde

Required for inflation: (to get $\delta T/T \sim 10^{-5}$)

- quartic coupling constant $\lambda \sim 10^{-13}$:
- mass $m \lesssim 10^{13}$ GeV,

Do we need new particles? New physics is required?
Higgs coupling to gravity

Higgs field in general must have non-minimal coupling to gravity:

\[ S_G = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2}R - \frac{\xi h^2}{2}R \right\} \]

Jordan, Feynman, Brans, Dicke,...

Consider large Higgs fields \( h > M_P/\sqrt{\xi} \), which may have existed in the early Universe

The Higgs field not only gives particles their masses \( \propto h \), but also determines the gravity interaction strength:

\[ M_{\text{eff}}^2 = \sqrt{M_P^2 + \xi h^2} \propto h \]

For \( h > \frac{M_P}{\sqrt{\xi}} \) (classical) physics is the same (\( M_W/M_{\text{eff}}^2 \) does not depend on \( h \))!

Physical effective potential does not depend on the Higgs field.
Potential in Einstein frame for non-minimally coupled Higgs, $\xi R h^2$

$\chi$ - canonically normalised scalar field in Einstein frame.
Stage 1: Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field

- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc
$n_s = 0.97, \ r = 0.003$
Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations

All particles of the Standard Model are produced

Coherent Higgs field disappears

The Universe is heated up to $T \propto \frac{M_P}{\xi} \sim 10^{14}$ GeV