Steps beyond the Standard Model: searching for simplicity

Mikhail Shaposhnikov

April 19, 2018

Motivation: the hierarchy problem
42 years soon, dob June 15, 1976

PHYSICAL REVIEW D VOLUME 14, NUMBER 6 15 SEPTEMBER 1976

Gauge-symmetry hierarchies*

Eldad Gildener
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 June 1976)

It is shown that one cannot artifically establish a gauge hierarchy of any desired magnitude by arbitrarily adjusting the scalar-field parameters in the Lagrangian and using the tree approximation to the potential; radiative corrections will set an upper bound on such a hierarchy. If the gauge coupling constant is approximately equal to the electromagnetic coupling constant, the upper bound on the ratio of vector-meson masses is of the order of $\alpha^{-1/2}$, independent of the sclar-field masses and their self-couplings. In particular, the usual assumption that large scalar-field mass ratios in the Lagrangian can induce large vector-meson mass ratios is false. A thus far unsuccessful search for natural gauge hierarchies is briefly discussed. It is shown that if such a hierarchy occurred, it would have an upper bound of the order of $\alpha^{-1/2}$.

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

Hierarchy of Interactions in Unified Gauge Theories*

H. Georgi,† H. R. Quinn, and S. Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 May 1974)

We present a general formalism for calculating the renormalization effects which make strong interactions strong in simple gauge theories of strong, electromagnetic, and weak interactions. In an SU(5) model the superheavy gauge bosons arising in the spontaneous breakdown to observed interactions have mass perhaps as large as 10^{17} GeV, almost the Planck mass. Mixing-angle predictions are substantially modified.

GUTs

Proposal, going back to 70ties: Strong, weak and electromagnetic interactions are part of the same gauge force and are unified at high energies:

$$\boldsymbol{SU(3) \times SU(2) \times U(1) \in G}$$

- 1973 - Pati, Salam: $\boldsymbol{G = SU(4) \times SU(2) \times SU(2)}$. Lepton number as 4th colour, left-right symmetry
- 1974 - Georgi, Glashow $\boldsymbol{G = SU(5)}$
- 1975 - Fritzsch, Minkowski $\boldsymbol{G = SO(10)}$. All fermions of one generation are in one representation $\underline{16}$!

GUTs

Generic features of GUTs:

- charge quantisation is automatic
- quantum numbers of SM fermions can be understood
- $\sin^2\theta_W$ can be predicted: gauge coupling unification.
- some relations between quark and lepton masses (e.g. bottom quark and τ lepton) can appear
- common prediction: instability of matter, proton decay

Looks great!

Main trouble: hierarchy problem

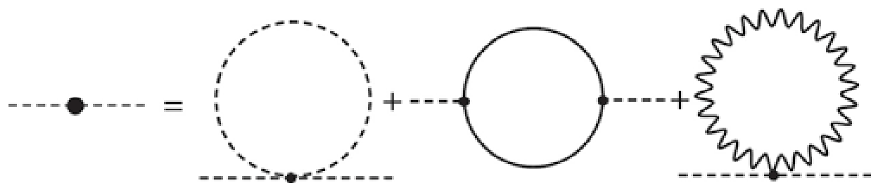
Extra particles beyond the SM – leptoquarks (vector and scalar) must be very heavy, $M_X > 10^{15}$ GeV

- this is required by the gauge coupling unification
- this is needed for stability of matter, proton lifetime $\tau_p > 10^{34}$ years

Hierarchy: $\left(\frac{M_X}{M_W}\right)^2 \simeq 10^{28}$

Two faces of hierarchy

- Ad hoc tuning between the parameters (masses and couplings of different multiplets) at the tree level with an accuracy of 26 orders of magnitude
- Stability of the Higgs mass against radiative corrections Gildener, '76



$$\delta m_H^2 \simeq \alpha_{GUT}^n M_X^2$$

Tuning is needed up to 14th order of perturbation theory!

Proposed solutions

Stability of EW scale – requirement of “naturalness”: absence of quadratic divergencies in the Higgs mass

- Low energy SUSY: compensation of bosonic loops by fermionic loops
- Composite Higgs boson - new strong interactions
- Large extra dimensions

All require new physics right above the Fermi scale, which was expected to show up at the LHC

The LHC has discovered something quite unexpected : the Higgs boson and nothing else, confirming the Standard Model.

The LHC has discovered something quite unexpected : the Higgs boson and nothing else, confirming the Standard Model.

No low energy SUSY, no large extra dimensions, no new strong interactions.

The LHC has discovered something quite unexpected : the Higgs boson and nothing else, confirming the Standard Model.

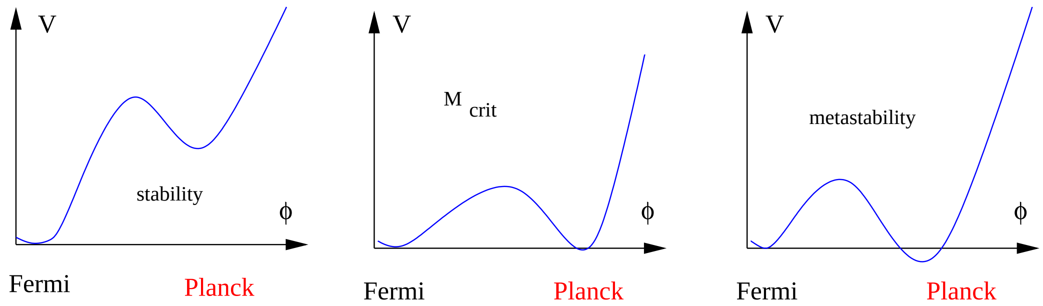
No low energy SUSY, no large extra dimensions, no new strong interactions.

For $\mathbf{125}$ GeV Higgs mass the Standard Model is a self-consistent weakly coupled effective field theory for all energies up to the quantum gravity scale $M_P \sim 10^{19}$ GeV

The LHC results must be reconciled with experimental evidence for new physics beyond the Standard Model:

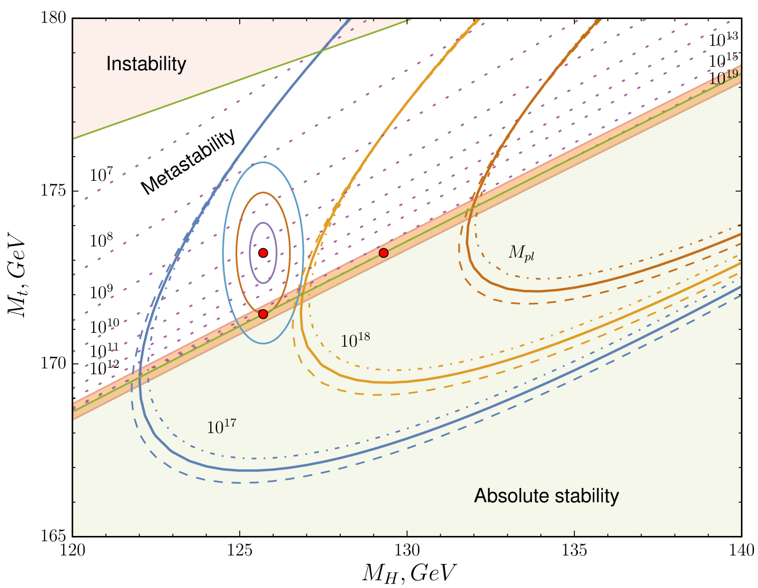
- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM).
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)
- Cosmological inflation is absent in canonical variant of the SM
- Accelerated expansion of the Universe (?) - though can be “explained” by a cosmological constant.

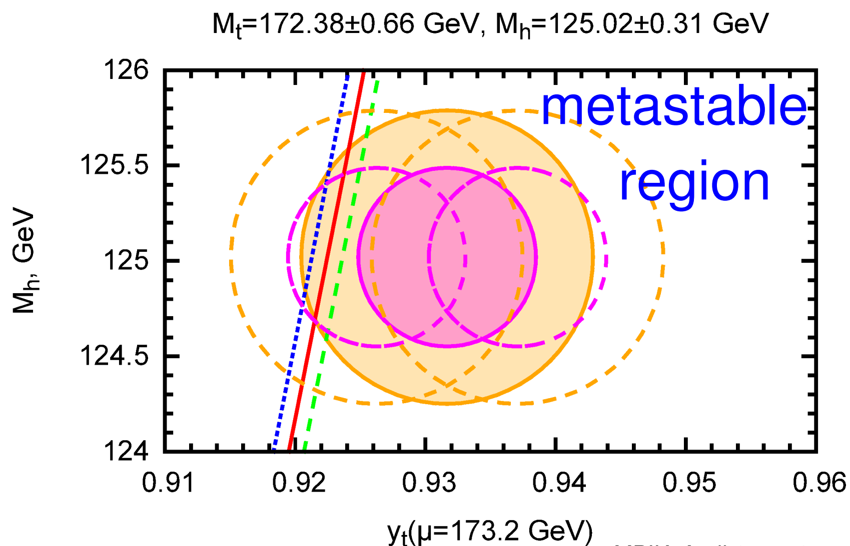
- Marginal evidence (less than 2σ) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling



Bednyakov et al, '15

Vacuum is unstable at $\mathbf{1.3\sigma}$





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 $\epsilon_{vac}/M_{Pl}^4 \lll 1$?
- Strong CP-problem: Why $\theta_{QCD} \ll 1$?
- Fermion mass matrix: Why $m_e \ll m_t$?
- ...

Where is new physics?

Only at the Planck scale?

Does not work: neutrino masses from five-dimensional operator

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

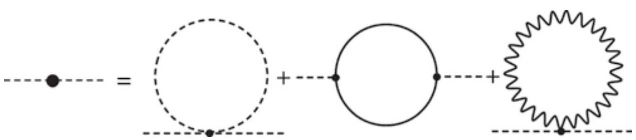
suppressed by the Planck scale are too small, $m_\nu < 10^{-5}$ eV.

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

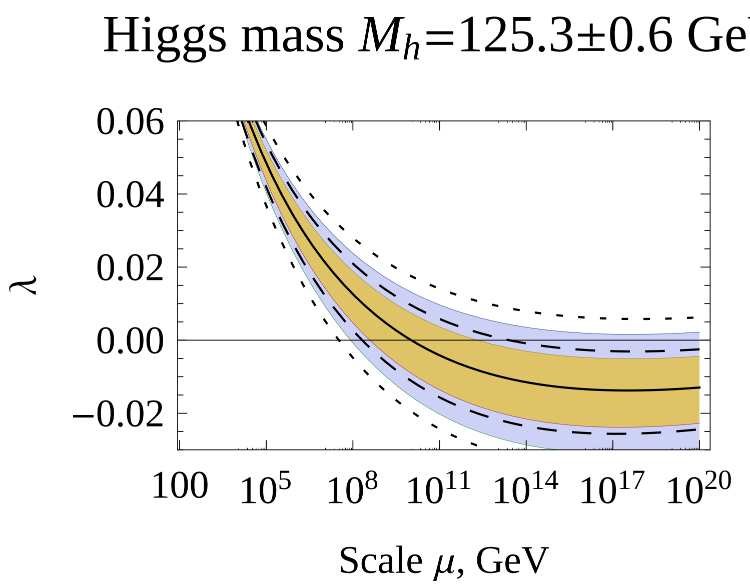
- Stability of the Higgs mass against radiative corrections



$$\delta m_H^2 \simeq \alpha_{GUT}^n M_{heavy}^2$$

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?). This is violated if new particles contribute to the evolution of the SM couplings.



Naturalness:

“Physics at the electroweak scale or right above it should be organised in such a way that quadratic divergencies in the Higgs boson mass are eliminated”.

Naturalness:

“Physics at the electroweak scale or right above it should be organised in such a way that quadratic divergencies in the Higgs boson mass are eliminated”.

Possible consequences: low energy SUSY, composite Higgs, large extra dimensions, etc.

Naturalness:

“Physics at the electroweak scale or right above it should be organised in such a way that quadratic divergencies in the Higgs boson mass are eliminated”.

Possible consequences: low energy SUSY, composite Higgs, large extra dimensions, etc.

Change of paradigm ?

Naturalness:

"Physics at the electroweak scale or right above it should be organised in such a way that quadratic divergencies in the Higgs boson mass are eliminated".

Possible consequences: low energy SUSY, composite Higgs, large extra dimensions, etc.

Change of paradigm ?

UV physics (gravity?) should be organised in such a way that the Fermi scale is much smaller than the Planck scale

Naturalness:

"Physics at the electroweak scale or right above it should be organised in such a way that quadratic divergencies in the Higgs boson mass are eliminated".

Possible consequences: low energy SUSY, composite Higgs, large extra dimensions, etc.

Change of paradigm ?

UV physics (gravity?) should be organised in such a way that the Fermi scale is much smaller than the Planck scale

Then all the experimental BSM problems should be explained by light particles! (dark matter, neutrinos, baryon asymmetry of the Universe). And heavy particles better not to exist, to avoid hierarchy problem.

New Physics without new energy scale

New Physics without new energy scale

Should we abandon Grand Unification?

New Physics without new energy scale

Should we abandon Grand Unification?

Should we accept fine tunings in many orders of perturbation theory?

New Physics without new energy scale

Should we abandon Grand Unification?

Should we accept fine tunings in many orders of perturbation theory?

How do we solve BSM problems?

Main problem of the stability of the Higgs mass against radiative corrections: existence of superheavy particles, $\delta m_H^2 \propto M_X^2$.

Do we need lepto-quarks for GUTs?

Yes, if the Nature we know at EW scale repeats itself at the gauge coupling unification scale!

Physics at EW scale $\equiv$ dynamical Higgs mechanism $\equiv$ true Higgs boson

Perhaps, the physical meaning of the GUT scale is different from that of EW scale?

A lesson from gravity

Gauging of Poincaré group Einstein-Cartan-Sciama-Kibble theory
Covariant field strengths

$$\text{torsion (shifts):}\quad T^A_{\mu\nu} = \partial_\mu e^A_\nu - \partial_\nu e^A_\mu - \omega^A_{\mu B} e^B_\nu + \omega^A_{\nu B} e^B_\mu \ ,$$

$$\text{curvature (Lorentz):}\quad \omega^{AB}_{\mu\nu} = \partial_\mu \omega^{AB}_\nu - \partial_\nu \omega^{AB}_\mu - \omega^{AC}_\mu \omega^B_{\nu C} + \omega^{AC}_\nu \omega^B_{\mu C}$$

20 physical degrees of freedom = graviton + heavy states + ghosts (for generic action).
Gauge covariant constraint: vanishing of torsion

$$T^A_{\mu\nu} = 0 \ ,$$

We end up with the relation between the connection and the metric $\omega = \bar{\omega} \sim \partial e$ and

Einstein gravity with 2 degrees of freedom!

$\Rightarrow$ Poincaré group can be gauged with the vielbein only if (gauge invariant) constraints are added!

Gauge coupling unification without new particle thresholds

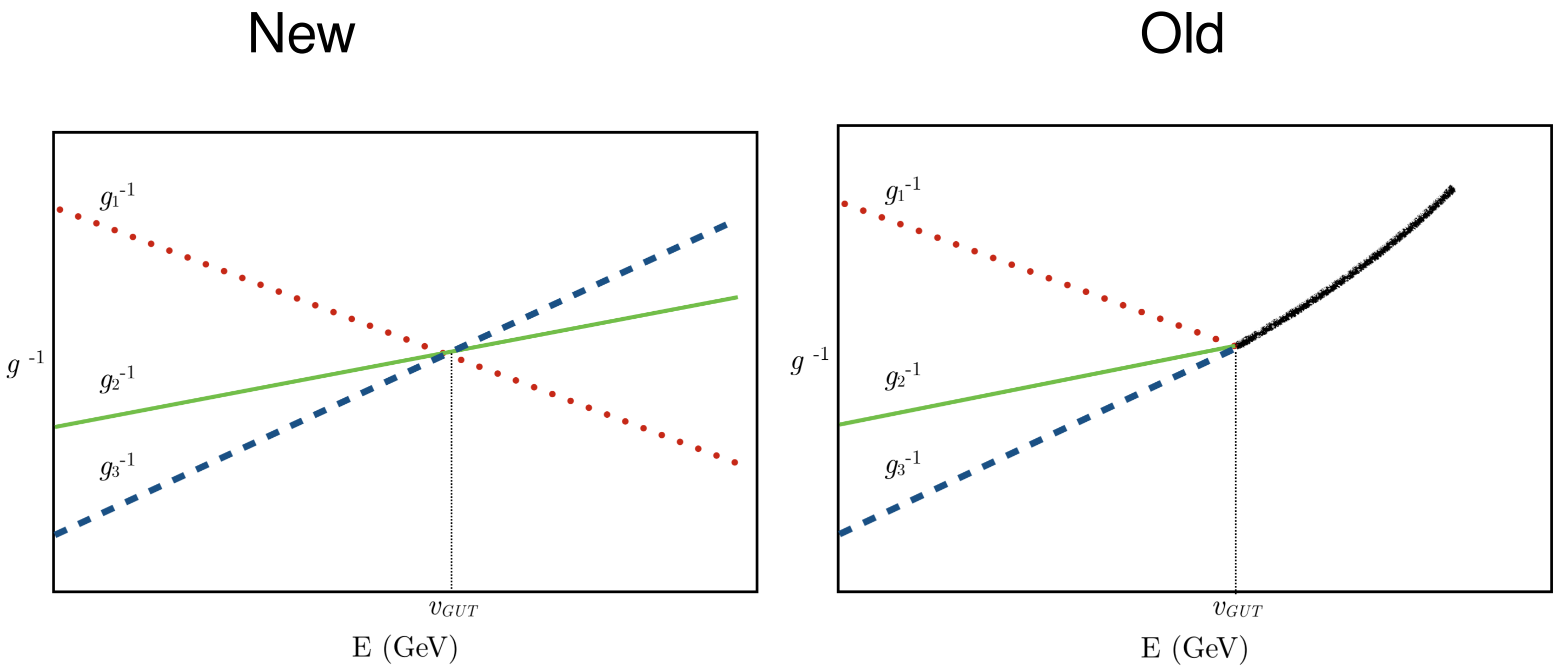
Karananas, MS' 2017

Idea: Take some GUT and remove all heavy degrees of freedom by imposing gauge-invariant constraints. From geometrical point of view, this operation confines the theory on a specific manifold in the field-space. Resulting theory: Renormalisable Standard Model which inherits from SU(5)

- fermion quantum numbers
- relations between the gauge couplings
- relations between the Yukawa couplings

The theory does contain a number of fine-tunings. However they are technically natural due to absence of superheavy particles.

Gauge coupling unification



As in the Minimal SU(5):

- $v_{GUT} \simeq 10^{14}$ GeV, but no problem with the proton decay (no leptoquarks !)
- $\sin^2\theta_W \simeq 0.2$ – too small

How to correct $\sin^2\theta_W$? Proposal goes back to Hill; Shafi and Wetterich: add to the theory higher-dimensional operators suppressed by the Planck scale. In our setup this results in

- Modification of the relation $g_1 = g_2 = g_3$ at the GUT scale
- Changing of the prediction of $\sin^2\theta_W$
- Changing of the gauge unification scale

The theory is still renormalisable and no new degrees of freedom are introduced!

A viable possibility: $v_{GUT} \simeq M_P$ – unity of all forces at the Planck scale?

The answer to the question: “Should we abandon Grand Unification?” is “no”:

- The gauge coupling unification scale may be not related to the mass of any particle
- “Constrained GUTs" provide a specific example of unified theories without leptoquarks
- In these theories the EW scale is stable against radiative corrections

Why the week scale is so much smaller than the Planck scale?

Why the week scale is so much smaller than the Planck scale?

Possible answer: due to non-perturbative effects at the Planck scale

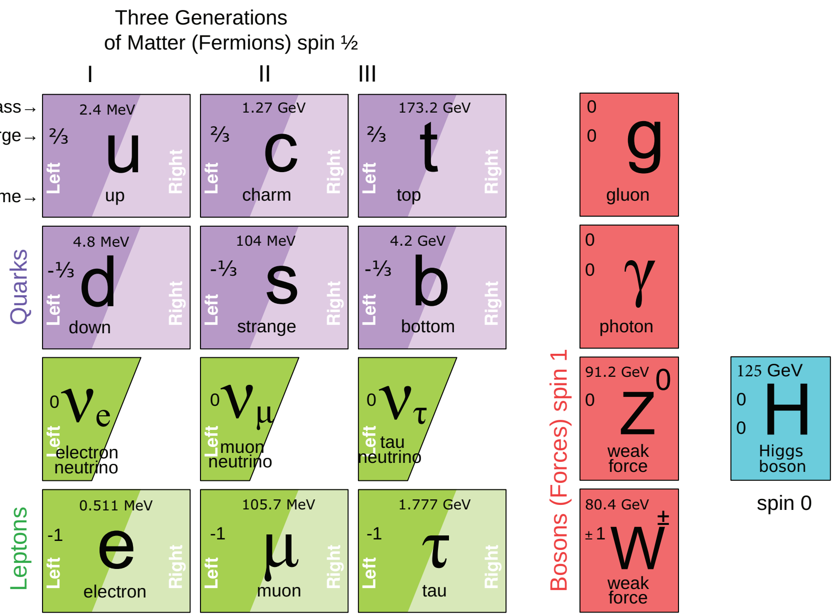
MS, Shkerin, arXiv:1803.08907; arXiv:1804.06376

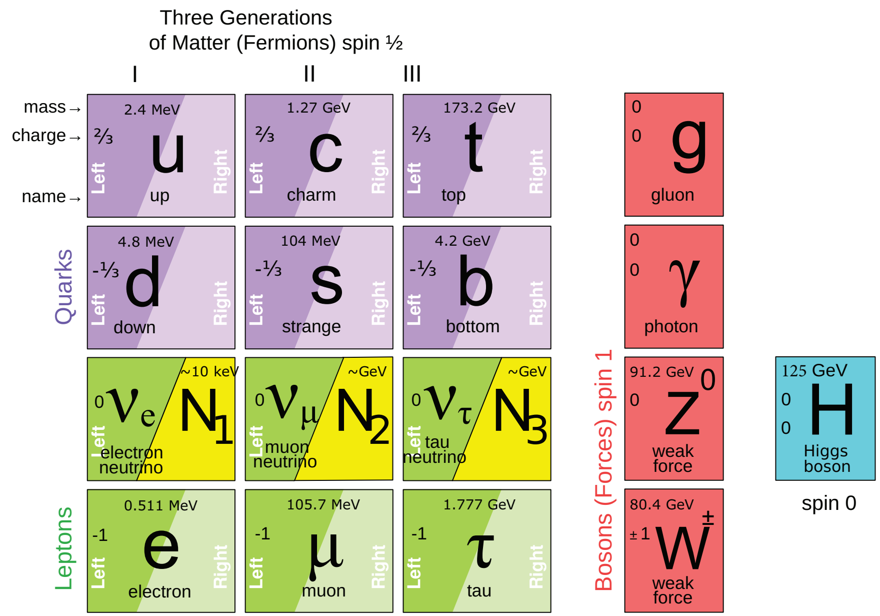
Ingredients

- SM is conformally invariant at the classical level, $m_H = 0$
- No new heavy degrees of freedom exist
  - This leads to perturbative stability of the Higgs mass against perturvative radiative corrections
- The Higgs field has non-minimal coupling to gravity Ricci scalar R: $\xi H^2 R$
  - This allows to construct an appropriate instanton solution with specific boundary conditions
- The theory is approximately Weyl invariant at large values of the Higgs field
  - This leads to the large instanton action $S \gg 1$ and generates a small scale out of the Planck mass, $m_H = e^{-S} M_P$

New Physics below the weak scale

Example of "complete" theory: the νMSM





νMSM $\equiv$ Neutrino minimal Standard Model

$\equiv$ Minimal low scale see-saw model with 3 singlet fermions

Role of $N_2, \; N_3$ with mass in 100 MeV – GeV region: "give" masses to neutrinos and produce baryon asymmetry of the Universe.

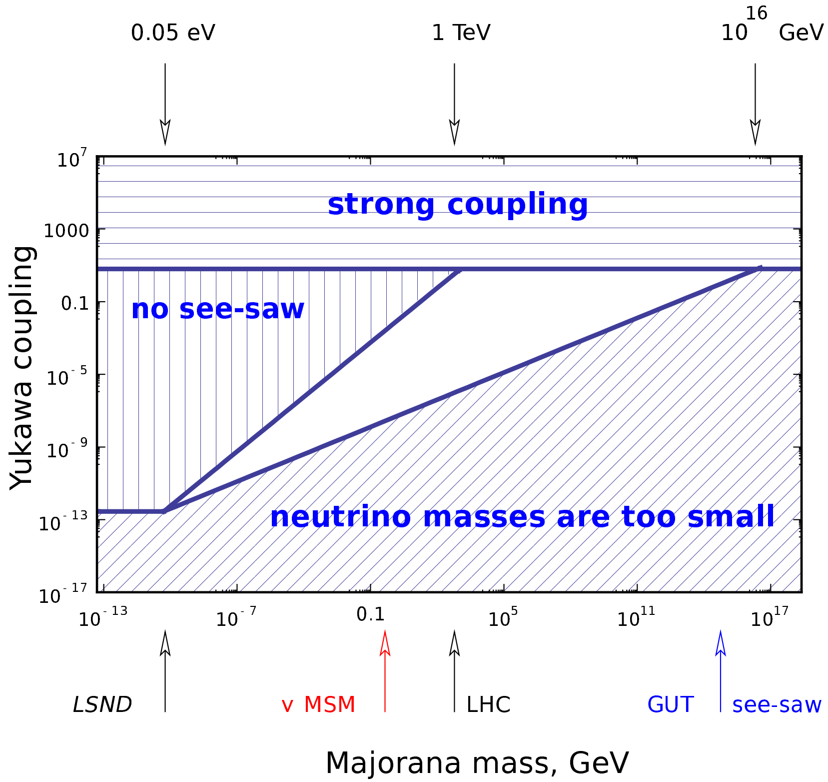
Role of N_1 with mass in keV region: dark matter.

Role of the Higgs boson: break the symmetry and inflate the Universe

Cosmology and phenomenology of a minimal model

Neutrino masses and Yukawa couplings

Yukawa couplings: $Y^2 = Trace[F^\dagger F]$



Baryon asymmetry

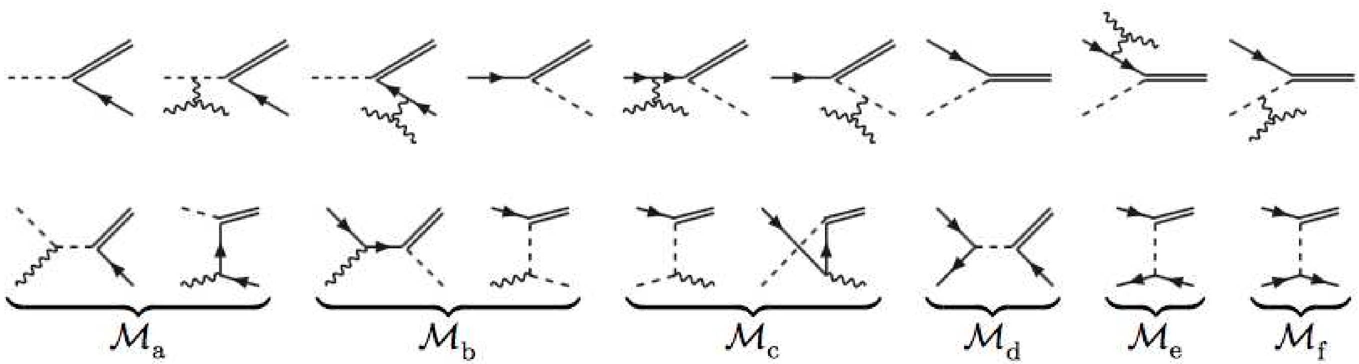
Sakharov conditions:

- Baryon number violation - OK due co 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

Baryon asymmetry

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



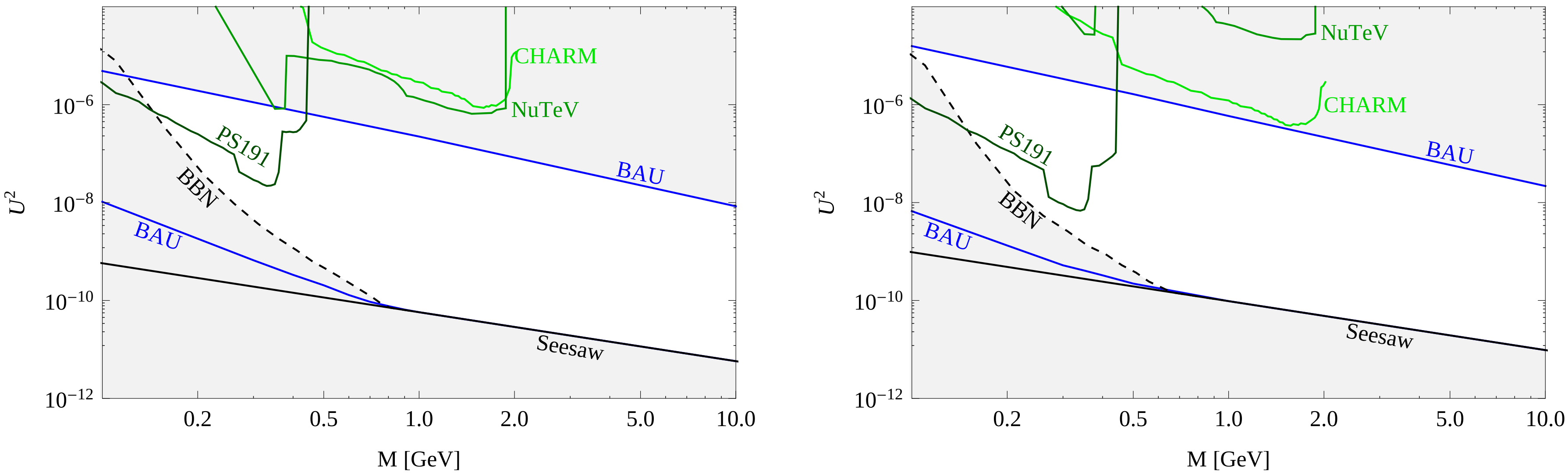
Resummation, hard thermal loops, Landau-Pomeranchuk-Migdal effect, etc. Ghiglieri, Laine. How to describe these processes is still under debate, but the consensus is that it works and is testable.

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- BAU generation requires out of equilibrium: mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too small
- BBN. Decays of $\boldsymbol{N_{2,3}}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $\boldsymbol{N_{2,3}}$ have not been seen

Baryon asymmetry: HNLs $N_{2,3}$



Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS ’12).

Baryon asymmetry: HNLs $N_{2,3}$

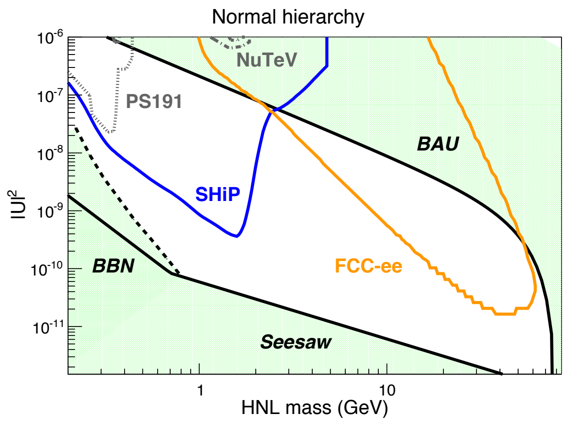
Similar results: recent works by

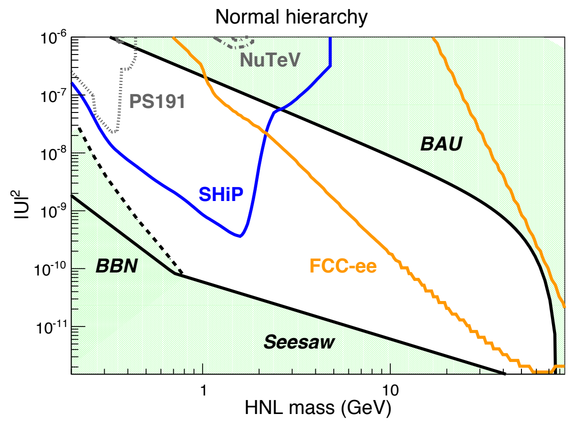
- Abada, Arcadia, Domcke, Lucente ’ 15
- Hernández, Kekic, J. López-Pavón, Racker, J. Salvado ’16
- Drewes, Garbrech, Guetera, Klarić ’16
- Hambye, Teresi ’17

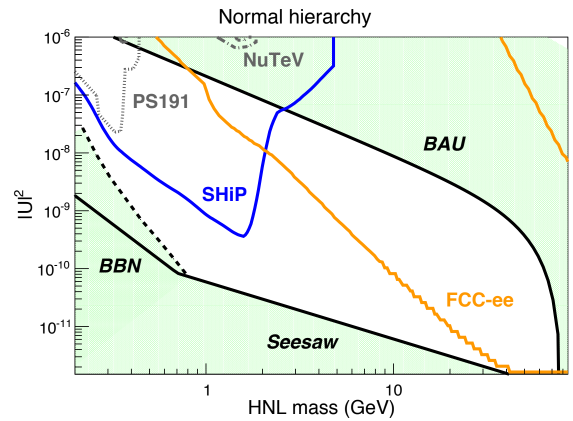
Experimental challenges:

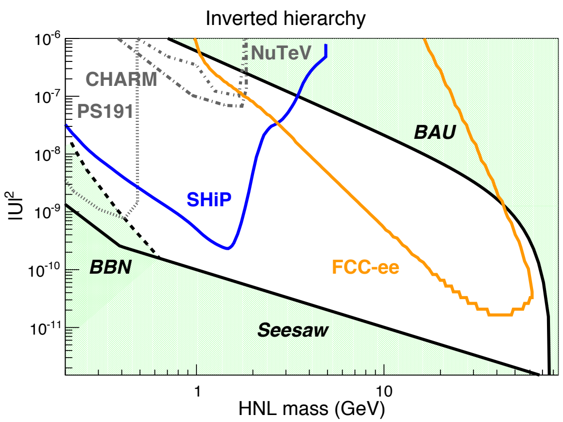
- HNL production and decays are highly suppressed – dedicated experiments or analyses are needed:
  - Mass below $\sim \mathbf{2}$ GeV - Intensity frontier, CERN SPS.
  - Mass above $\sim \mathbf{2}$ GeV - FCC in e^+e^- mode in Z-peak, LHC
  - HNL's in beauty and charm decays: Belle, LHCb

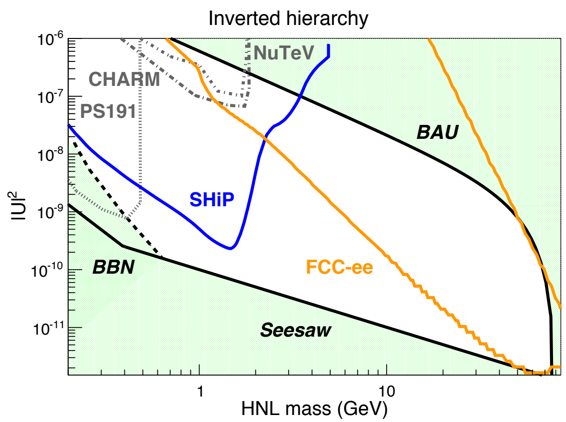
SHiP and FCC-ee sensitivity

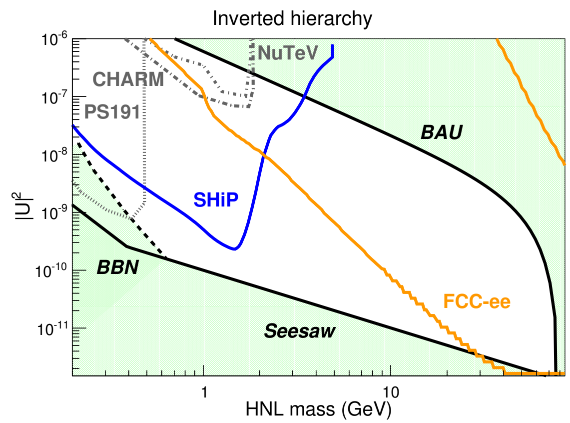












Decay length: 10-100 cm | 10-100 cm | 0.01-500 cm

$10^{12}\ Z^0$ | $10^{13}\ Z^0$ | $10^{13}\ Z^0$

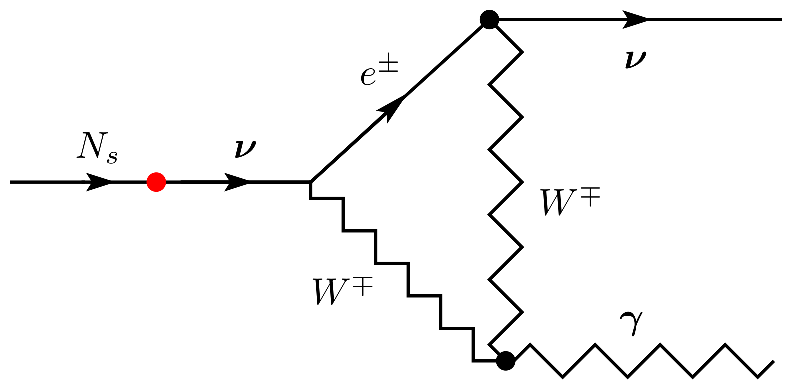
Dark Matter candidate: N_1

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

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

Photon energy:

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

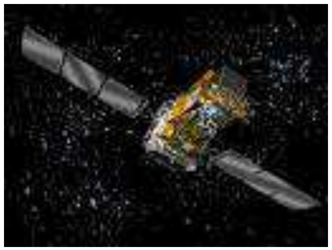


Radiative decay width:

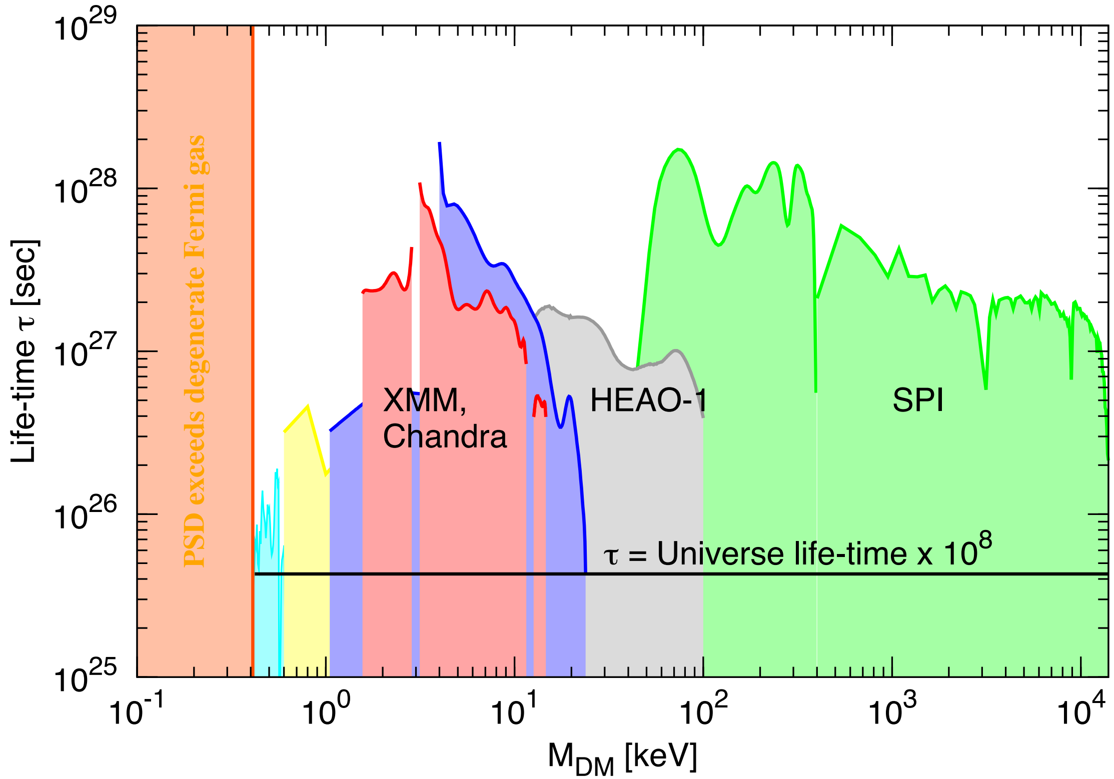
$$\Gamma_{\mathrm{rad}} = \frac{9\,\alpha_{\mathrm{EM}}\,G_F^2}{256\cdot 4\pi^4}\,\sin^2(2\theta)\,M_s^5$$

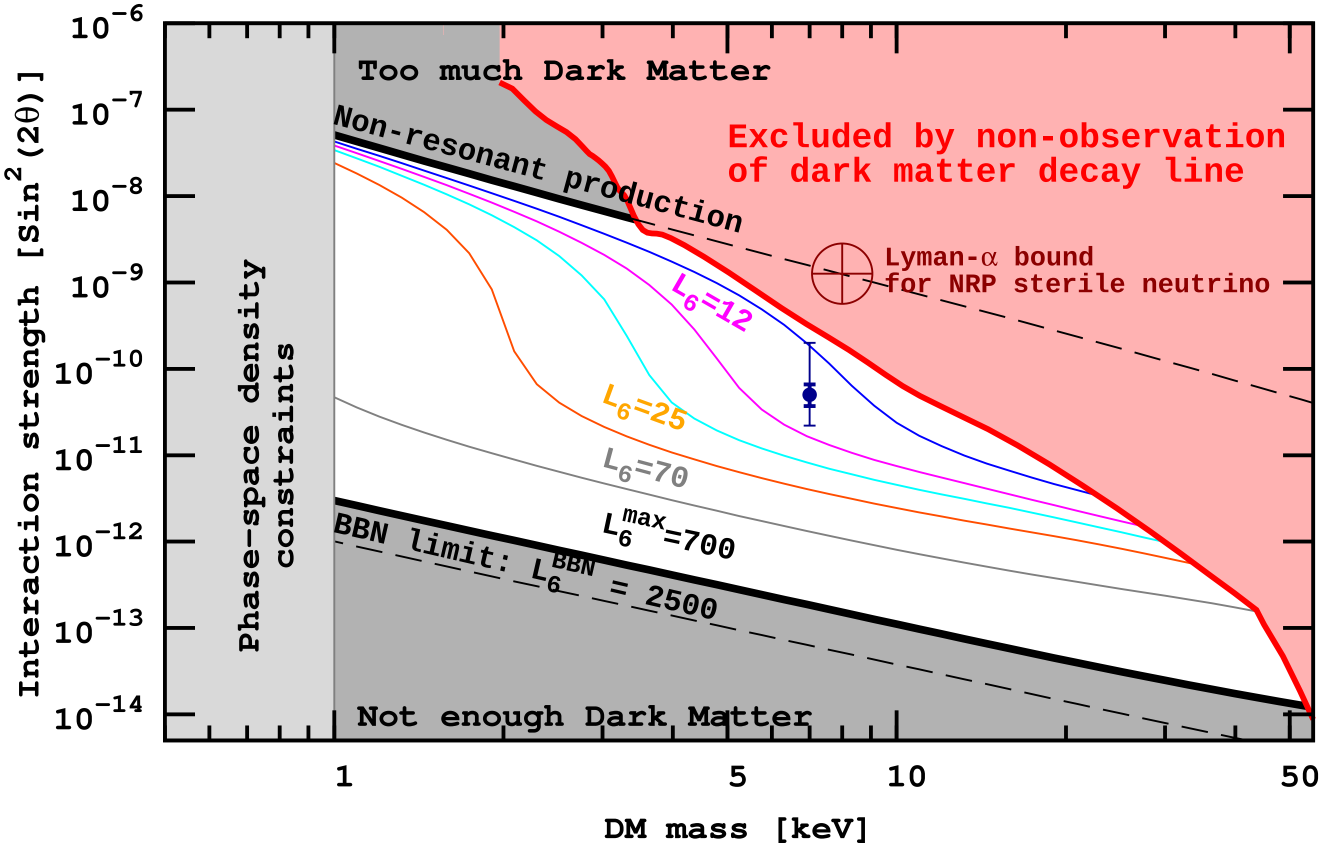
Constraints on DM sterile neutrino N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \;\; q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- 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-α forest spectra of distant quasars and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, 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





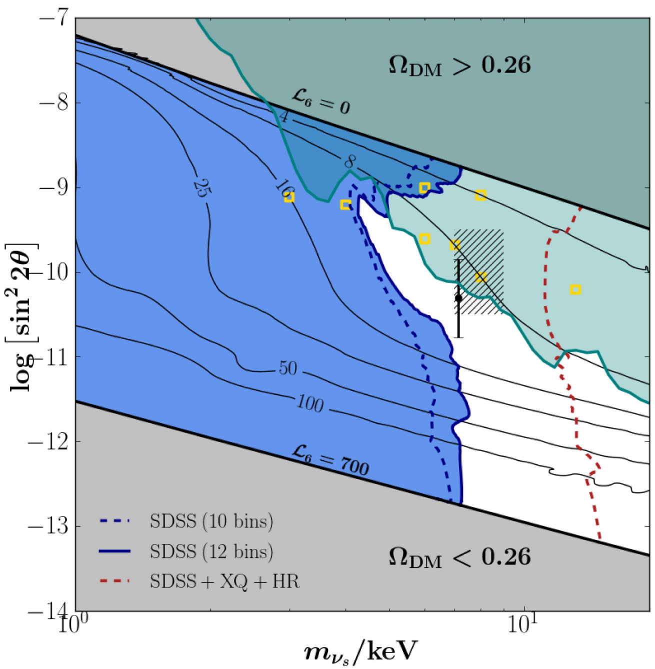
Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

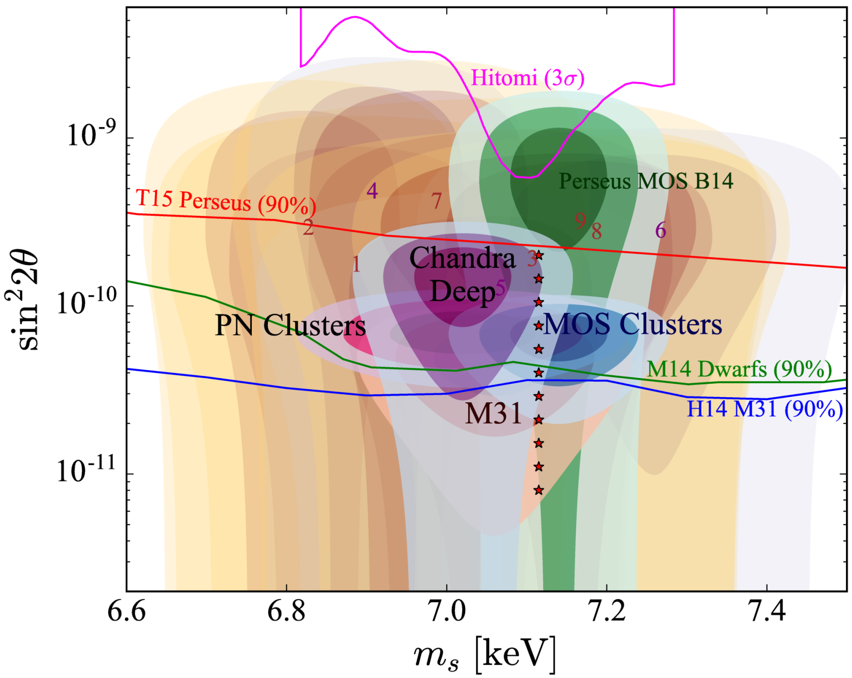
An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

Status of sterile neutrino dark matter N_1

Decaying DM: $N_1 \to \gamma\nu$

3.5 keV line: E. Bulbul et al, Boyarsky et al





1706.03118, Baur et al.

1705.01837 Abazajian

Future of decaying dark matter searches in X-rays

Another Hitomi (around 2020)

It is planned to send a replacement of the Hitomi satellite

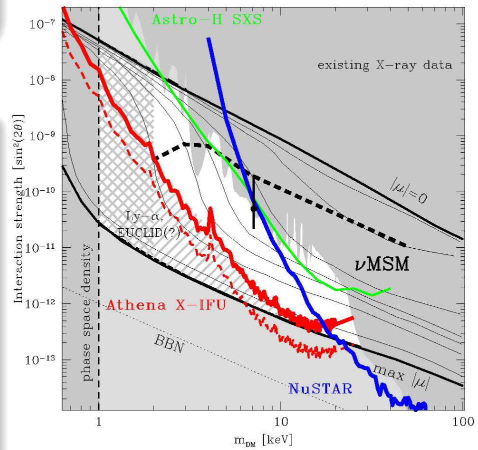
Microcalorimeter on sounding rocket (2019)

- Flying time $\sim 10^2$ sec. Pointed at GC only
- Can determine line's position and width

Athena+ (around 2028)

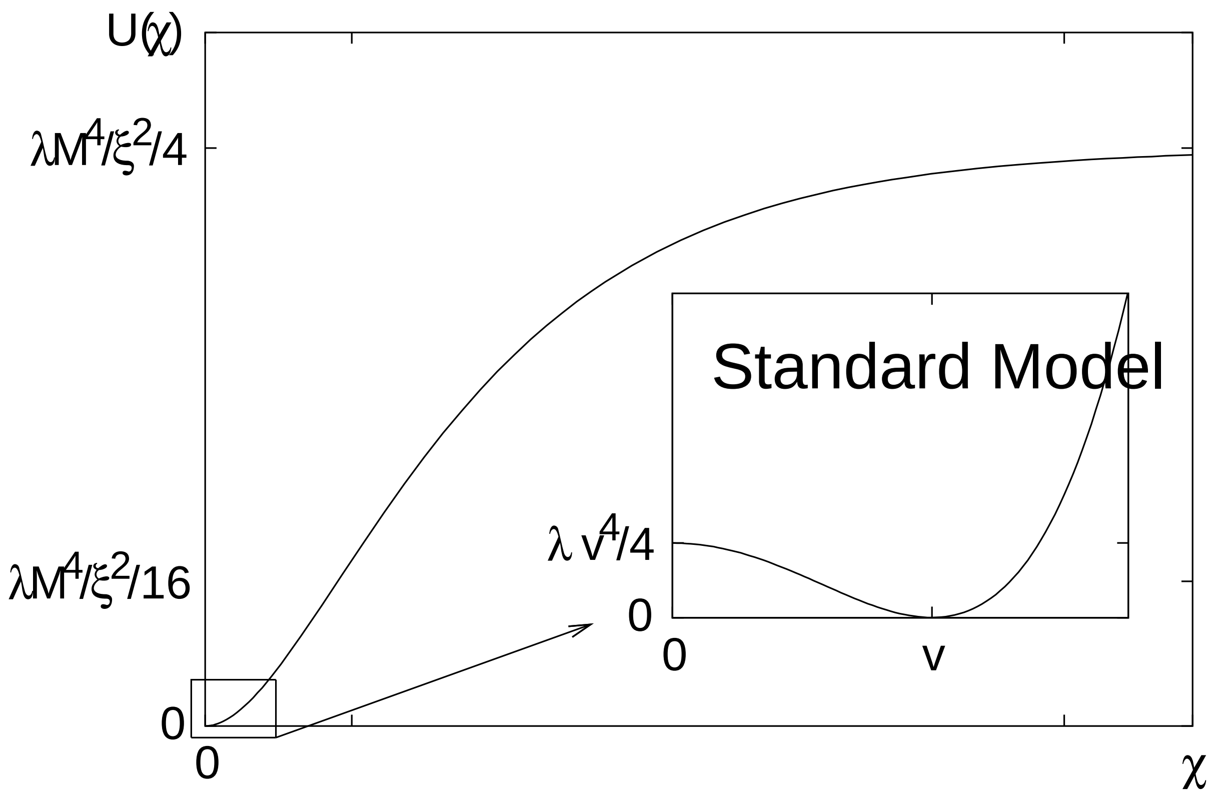
- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)
- Super spectral resolution

"Dark matter astronomy era" begins?



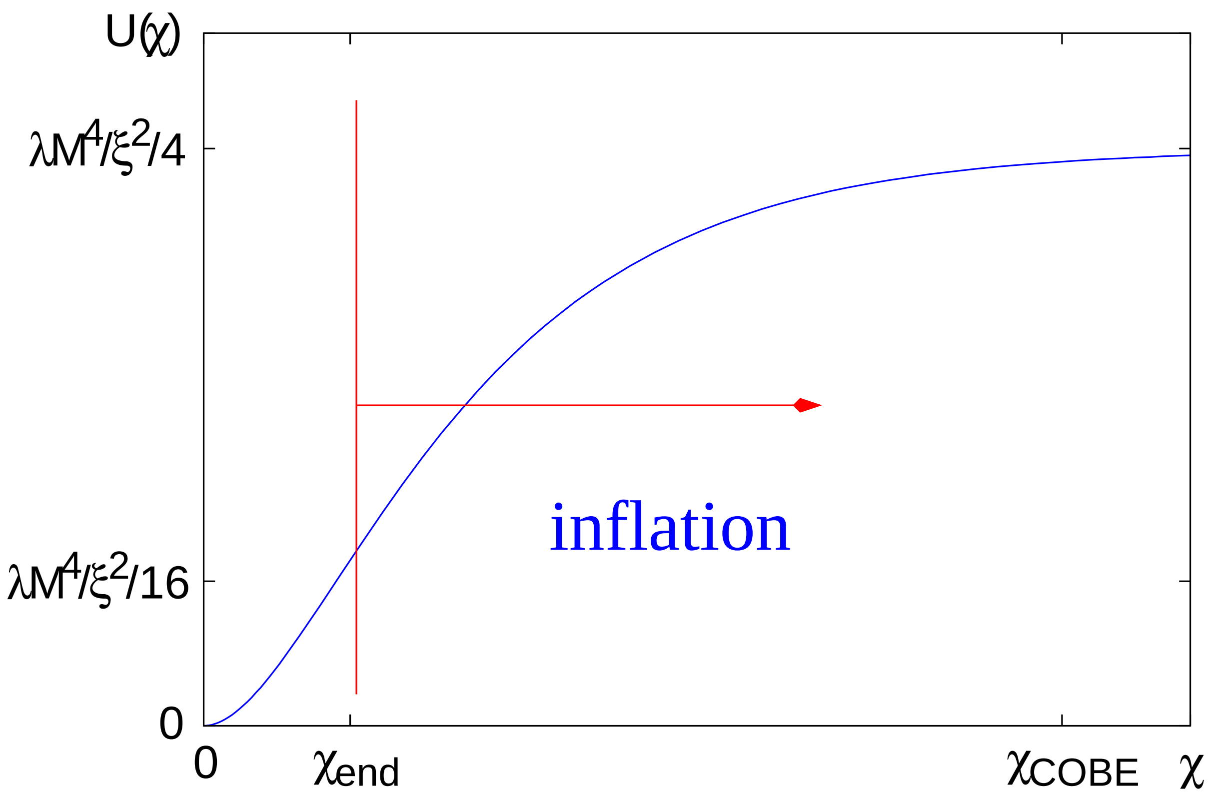
Inflation: Higgs boson

Potential in Einstein frame for non-minimally coupled Higgs, $\xi R h^2$



χ - canonically normalised scalar field in Einstein frame.

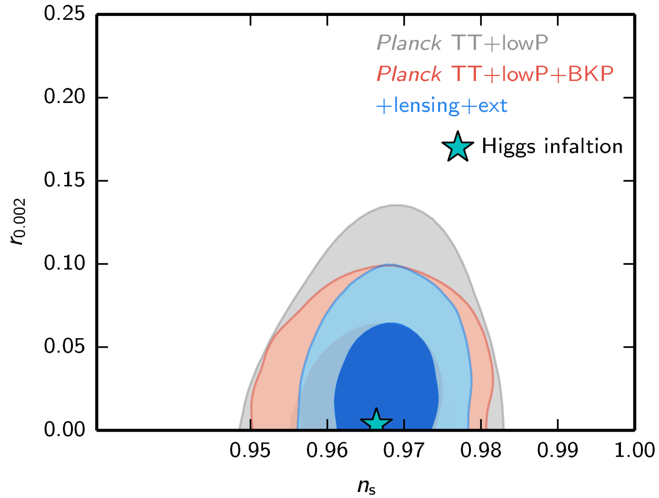
Stage 1: Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field

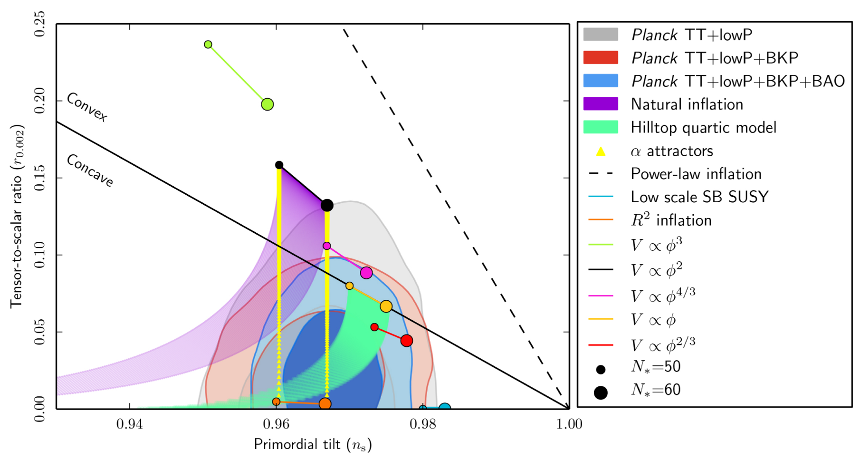


- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

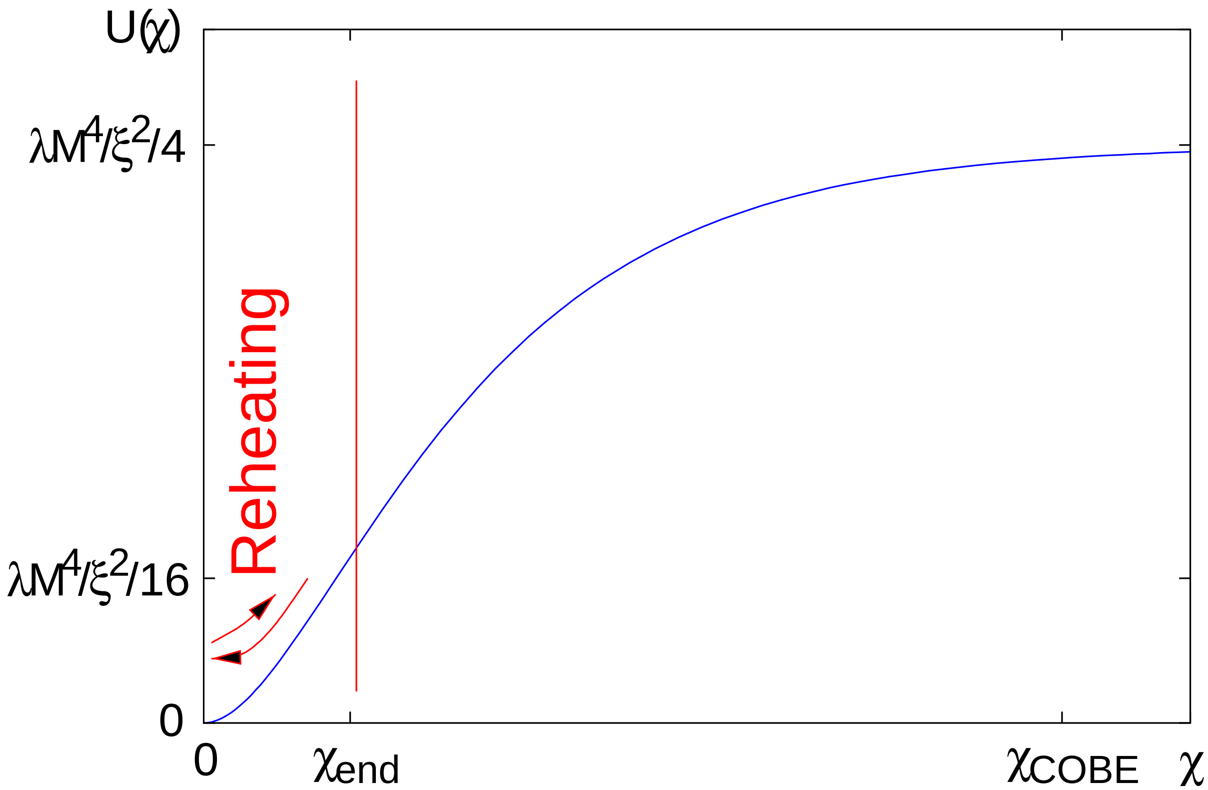
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$

$$n_s = 0.97, \quad r = 0.003$$





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 $T \propto M_P/\xi \sim 10^{14}$ GeV

Summary of predictions, 2005-2009

Prediction	assumptions	status
No deviations from SM at LHC	structure of νMSM	OK
SM Higgs boson with $M_H > 127 \pm 2$ GeV	Higgs inflation	OK within 2σ
SM Higgs boson with $M_H = 127 \pm 2$ GeV	asymptotic safety	OK within 2σ
No WIMPS	structure of νMSM	OK
DM is a keV scale HNL , $N \to \nu\gamma$	structure of νMSM	3.5 keV X-ray line?
New particles - HNL	structure of νMSM	constraints only
Unitarity of PMNS matrix	structure of νMSM	OK
no light sterile ν	structure of νMSM	OK
neutrino mass $m_1 \lesssim 10^{-5}$ eV	dark matter	constraints only
No visible $\mu \to e\gamma,\ \mu \to 3e, etc$	BAU	OK
$N_\nu = 3$	structure of νMSM	OK, Planck
spectral index $n_s = 0.967$	Higgs inflation	OK, Planck
small tensor to scalar ratio $r = 0.003$	Higgs inflation	Planck, constraints only
no non-Gaussianities	Higgs inflation	Planck, constraints only

Conclusions

- The absence of heavy particle thresholds may be a key for understanding of the hierarchy problem

- The absence of heavy particle thresholds may be a key for understanding of the hierarchy problem
- The gauge coupling unification is not necessarily related to existence of superheavy particles

- The absence of heavy particle thresholds may be a key for understanding of the hierarchy problem
- The gauge coupling unification is not necessarily related to existence of superheavy particles
- The generation of Fermi scale may be a non-perturbative gravity effect, leading to $M_W \ll M_P$

- The absence of heavy particle thresholds may be a key for understanding of the hierarchy problem
- The gauge coupling unification is not necessarily related to existence of superheavy particles
- The generation of Fermi scale may be a non-perturbative gravity effect, leading to $M_W \ll M_P$
- All observational drawbacks of the SM can be solved by the νMSM

- The absence of heavy particle thresholds may be a key for understanding of the hierarchy problem
- The gauge coupling unification is not necessarily related to existence of superheavy particles
- The generation of Fermi scale may be a non-perturbative gravity effect, leading to $M_W \ll M_P$
- All observational drawbacks of the SM can be solved by the νMSM
    - inflation - Higgs boson

- The absence of heavy particle thresholds may be a key for understanding of the hierarchy problem
- The gauge coupling unification is not necessarily related to existence of superheavy particles
- The generation of Fermi scale may be a non-perturbative gravity effect, leading to $M_W \ll M_P$
- All observational drawbacks of the SM can be solved by the νMSM
  - inflation - Higgs boson
  - neutrino masses, dark matter and baryogenesis - 3 HNLs

Theoretical challenges, similar to the Standard Model:

- UV completion, unification with gravity
- Why the cosmological constant (or dark energy) is so tiny?
- Why θ_{QCD} is so small?
- Origin and magnitude of Yukawa couplings
- ...