ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

What is the scale of new physics?

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3rd KIAS phenomenology workshop

New physics enters for sure at the Planck scale, associated with Newton constant of gravitation G_N:

energies $E \sim M_P \sim 10^{19}$ GeV

distances $l \sim 10^{-33} cm$

time intervals $\delta t \sim 10^{-43} s$

However, we do not know if there is any new particle physics scale between the Fermi and Planck scales

If yes

- proton decay yes (?)

$$\tau_p \sim \frac{\Lambda_{new}^4}{m_p^5}$$

Current limit $\tau_p > 10^{32}$ years;

- new physics at LHC yes (?)

  Electroweak scale solution to the hierarchy problem - stability of the weak scale against quantum radiative corrections.

  Supersymmetry, composite Higgs boson, large extra dimensions, etc. Scale of new physics hundreds of GeV.

If yes

- searches for Dark Matter Weakly Interacting Massive Particles (WIMPS) yes (?)
  SUSY relic - neutralino
- searches for Dark Matter annihilation yes (?)
  SUSY relic - neutralino
- searches for axions yes (?)
  Axion is a hypothetic particle used for solution of the strong CP problem

If no

- proton decay no

  $\tau_p \simeq 10^{45}$ years for $\Lambda_{new} \simeq M_P$
- Higgs and nothing else at LHC
- searches for Dark Matter Weakly Interacting Massive Particles (WIMPS) no
- searches for Dark Matter annihilation no
- searches for axions no

  Interacts too weakly if $\Lambda_{new} \simeq M_P$

Outline

- Hierarchy problem and the scale of new physics
- Cosmological constant problem and the scale of new physics
- Strong CP problem and the scale of new physics
- Higgs mass and the scale of new physics
- Cosmological inflation and the scale of new physics
- Baryogenesis and the scale of new physics
- Dark matter and the scale of new physics
- Neutrino masses and the scale of new physics
- New physics below the Fermi scale
- Conclusions

Hierarchy problem and the scale of new physics

Higgs mass hierarchy problem

Actually, two different problems:

- 1. Why $M_W \ll M_{Planck}$?
- 2. Quantum corrections to the Higgs mass M_H are (from power counting) quadratically divergent. What is the mechanism of their cancellation? Naturalness problem.

Only the second problem will be discussed.

Consider first theories without gravity

Hierarchy problem and the mass of new particles

- Theories with just one scale (like the SM, apart from the problem with Landau poles) - no any hierarchy problem, in-spite of quadratic divergences. All physical masses are of the same order. The UV cutoff is an unphysical quantity.

- Theories with several mass scales, such as GUTs may have a hierarchy problem: for $M_{GUT} \gg M_H$ one has to choose carefully counter-terms up to $N \simeq \log(M_{GUT}^2/M_W^2)/\log(\pi/\alpha_W) \simeq 13$ loop level to get $M_H \ll M_{GUT}$! This is enormous fine-tuning and is an argument for existing of new physics right above the EW scale, if one insists that there is the GUT scale $M_{GUT} \ll M_P \simeq 10^{19}$ GeV.

- New particles with masses below Fermi scale:
  Do not lead to any hierarchy problem

Possible solutions

- Compensation of divergent diagrams by new particles at TeV scale (supersymmetry, composite Higgs boson, large extra dimensions). Consequence: new physics at the LHC.
  This solution is now challenged by experiments: no signs of new physics at the LHC, no indication of wimps, no rare processes that are not consistent with predictions of the SM.
- There are no particles with masses between the Planck scale and the Fermi scale. There is no Grand Unification or it happens at the Planck scale (easy to realize with higher-dimensional operators).
  Consistent with all experiments

Theory with gravity

The gravity scale $M_P \gg M_H$. Hierarchy problem? Not necessarily: M_H is the mass of the particle but M_P is associated with the strength of the gravitational interaction. The graviton is massless.

Perturbative computations of gravitational corrections to the Higgs mass in scale-invariant regularisation such as dimensional regularisation: all corrections are suppressed by M_P, and there are no corrections proportional to M_P!

What happens non-perturbatively is an open question.

So, there may be no problem of stability of the Higgs mass against radiative correction, only the problem why $M_H \ll M_P$ remains.

Cosmological constant problems and the scale of new physics

Quadratic and quartic divergences

One can hear sometimes: since the quantum corrections M_H diverge as Λ^2, one must introduce new physics which cancels these divergences, and that new physics should appear close to the EW scale.

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In fact, besides the problem of Landau poles, the EW theory itself is known to be a perfectly valid theory without any new physics!

Strong CP problem and the scale of new physics

Strong CP-problem

Invisible axion solution to strong CP-problem: Peccei-Quinn scale is bounded from above and below by cosmology and astrophysics to be in the region 10^8 GeV $\lesssim M_{PQ} \lesssim 10^{12}$ GeV.

New intermediate scale ?

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Is there space at all at short distances if gravity is included?

Is the topology of space always non-trivial?

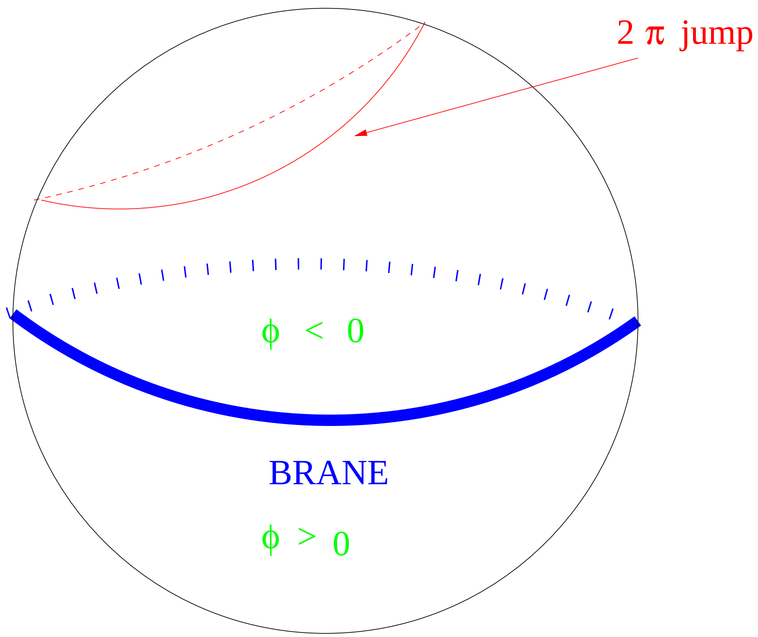
Topology

If extra dimensions have topology such that the mapping

$$\mathbf{D - dim\ Space} \rightarrow \boldsymbol{S_3}$$

is trivial no θ angle exists! Planck scale compactification is sufficient - the solution to the strong CP-problem may occur at M_{Pl} (Khlebnikov, M.S., 1988, 2004)

$2 + 1$ U(1) example, brane-world



Maxwell equations do not admit existence of source-less static electric field.

Brane-world compactification, $S^2 \to U(1) = S^1$ - trivial mapping $\to$ no N-vacua $\to$ no θ vacua.

Extra dimensions are not seen if we live on a brane.

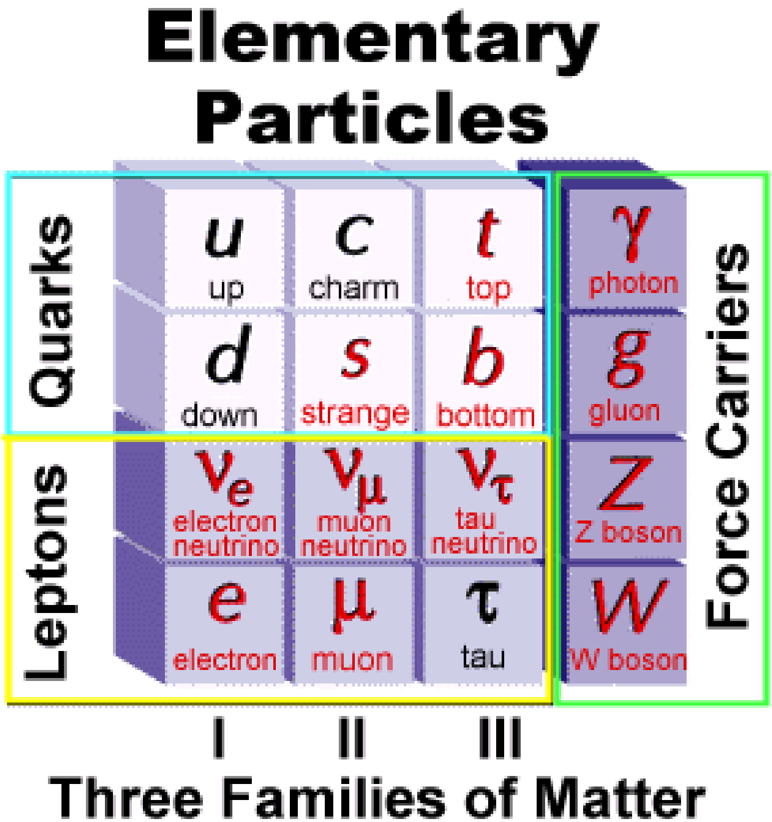
Major ingredients:

(i) compactness of the space

(ii) non-factorizable geometry

Higgs mass and the scale of new physics

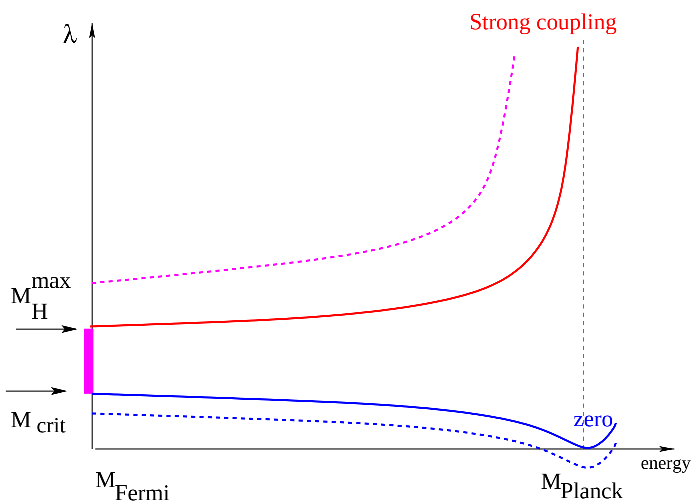
The Standard Model of particle interactions is in great shape: no convincing deviations from it were seen in any of accelerator experiments

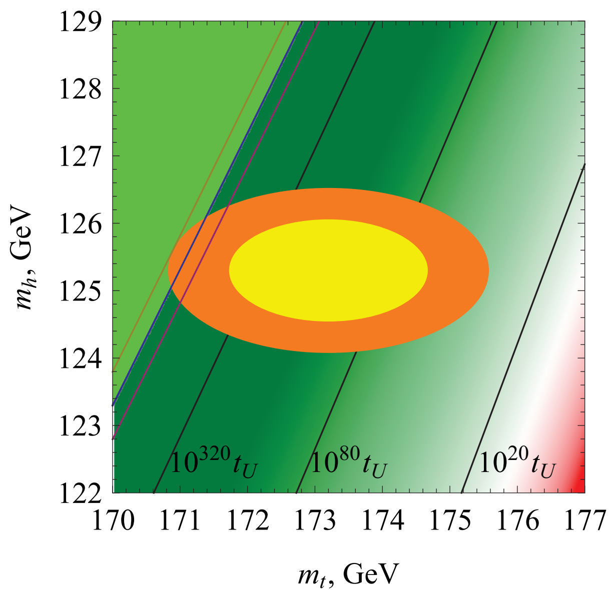


The discovery the Higgs boson with the mass $125 - 126$ GeV has been made recently by Atlas and CMS collaborations at LHC.

The main message from the LHC: SM is a consistent effective theory all the way up to the Planck scale

- No signs of new physics beyond the SM are seen
- $M_H < 175$ GeV : SM is a weakly coupled theory up to Planck energies
- $M_H > 111$ GeV: Our EW vacuum is stable or metastable with a lifetime greatly exceeding the Universe age. Espinosa et al





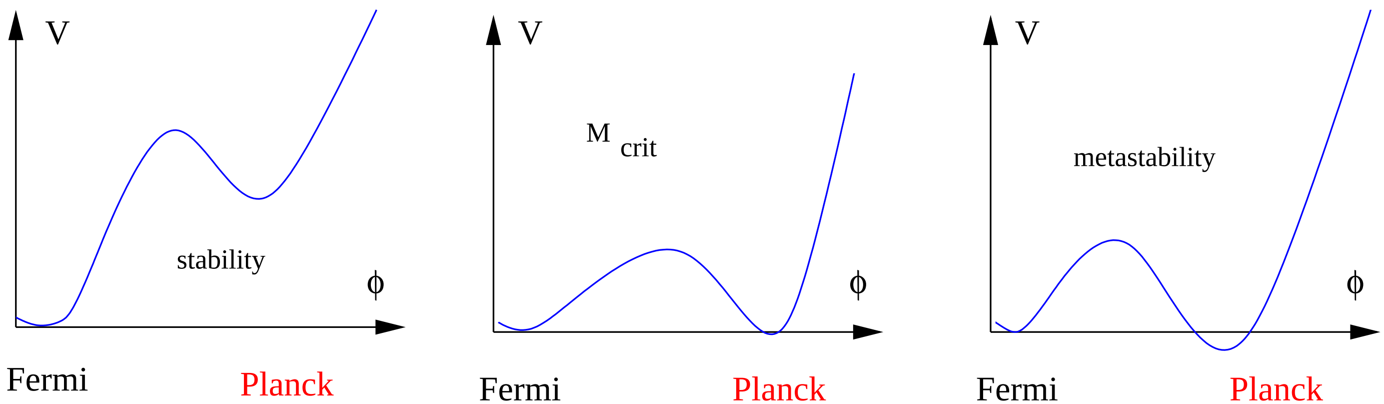
The mass of the Higgs boson is very close to the stability bound on the Higgs mass* (95'), to the Higgs inflation bound** (08'), and to asymptotic safety value for M_H*** (09'):

$$M_{crit} = [129.3 + \frac{y_t(M_t) - 0.9361}{0.0058} \times 2.0 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.5]\ \mathrm{GeV}$$

$y_t(M_t)$ - top Yukawa in $\overline{\mathrm{MS}}$ scheme

Matching at EW scale	Central value	theor. error
Bezrukov et al, $\mathcal{O}(\alpha\alpha_s)$	129.4 GeV	1.0 GeV
Degrassi et al, $\mathcal{O}(\alpha\alpha_s, y_t^2\alpha_s, \lambda^2, \lambda\alpha_s)$	129.6 GeV	0.7 GeV
Buttazzo et al, complete 2-loop	129.3 GeV	0.07 GeV

Chetyrkin et al, Mihaila et al, Bednyakov et al, 3 loop running to high energies



* Froggatt, Nielsen

** Bezrukov et al, De Simone et al

*** Wetterich, MS

What does it mean for for the scale of new physics, if cosmological considerations are included?

Two possibilities

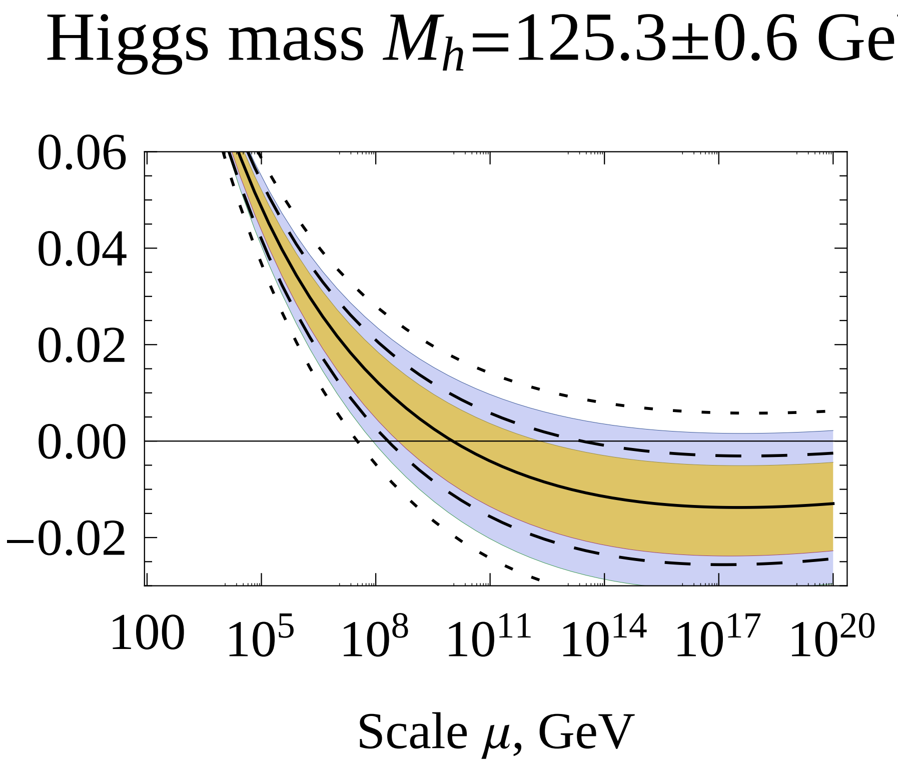
- Higgs self coupling crosses zero at energy scale $M_\lambda \ll M_P$. M_λ can be as "small" as 10^8 GeV.
  - The Universe after inflation finds itself in our vacuum, reheating temperature is below M_λ. Example - R^2 inflation Gorbunov, Panin;....
  - Some kind of new physics makes our vacuum unique. Giudice et al,Hyun Min Lee, Lebedev et al, Barroso et al, Baek et al., Datta et al., Anchordoqui et al.,...

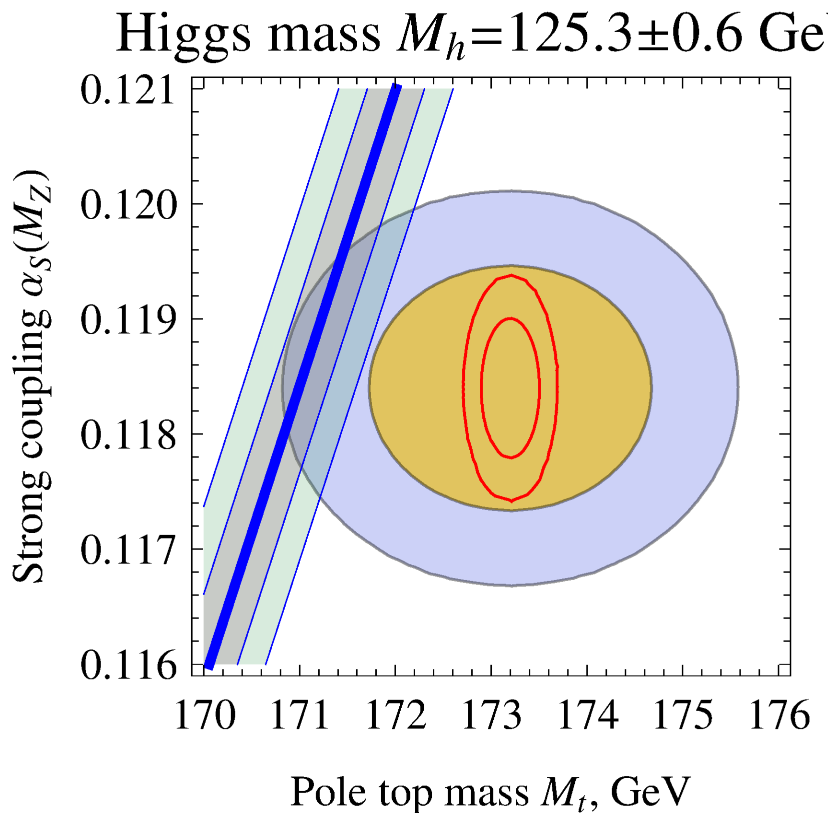
In both cases the scale of new physics is around $M_\lambda \ll M_P$

or

- Higgs self coupling never crosses zero or does that close to the Planck scale. Then no new physics at high energies is needed.

We do not know which possibility is realised!





errors in y_t: theory + experiment

Tevatron: $M_t = 173.2 \pm 0.51 \pm 0.71$ GeV

ATLAS and CMS: $M_t = 173.4 \pm 0.4 \pm 0.9$ GeV

$\alpha_s = 0.1184 \pm 0.0007$

Main uncertainty - top Yukawa coupling.

- 1 GeV experimental error in M_t leads to 2 GeV error in M_{crit}.
- Perturbation theory, $\mathcal{O}(\alpha_s^4)$. Estimate of Kataev and Kim: $\delta y_t/y_t \simeq -750(\alpha_s/\pi)^4 \simeq -0.0015$, $\delta M_{crit} \simeq -0.5$ GeV
- Non-perturbative QCD effects, $\delta M_t \simeq \pm\Lambda_{QCD} \simeq \pm 300$ MeV, $\delta M_{crit} \simeq \pm 0.6$ GeV
- Alekhin et al. Theoretically clean is the extraction of y_t from $t\bar{t}$ cross-section. However, the experimental errors in $p\bar{p} \to t\bar{t} + X$ are quite large, leading to $\delta M_t \simeq \pm 2.8$ GeV, $\delta M_{crit} \simeq \pm 5.6$ GeV.

Precision measurements of m_H, y_t and α_s are needed.

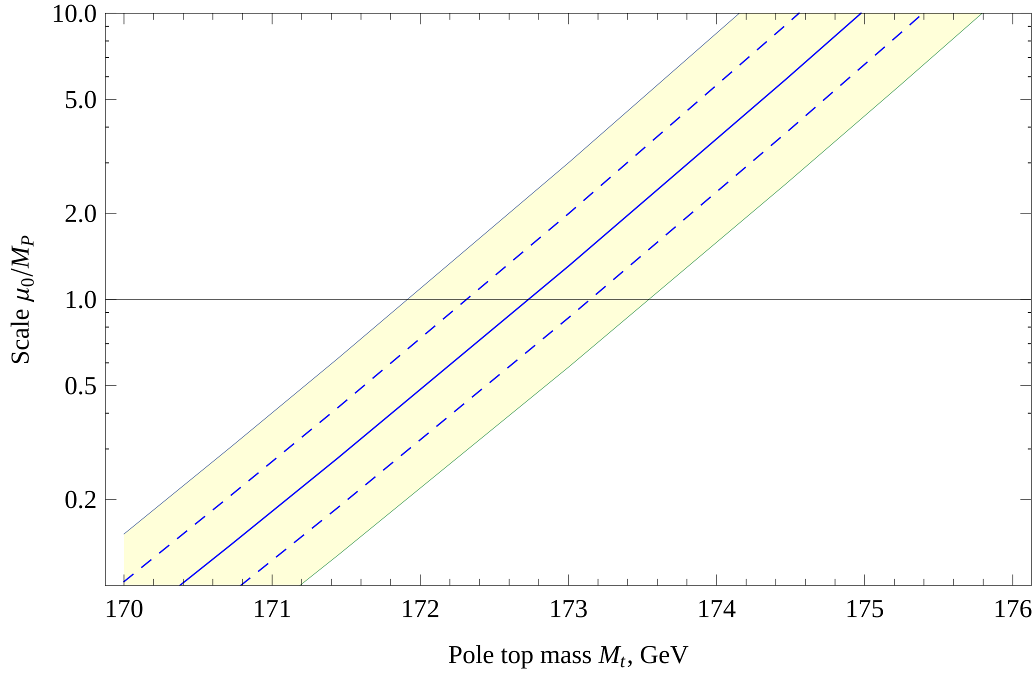
Suppose that in fact $M_H = M_{crit}$.

This was a prediction of the Higgs mass from asymptotic safety of the SM (Wetterich, MS) due to gravity. AS requirement leads to two conditions:

$$\lambda(\mu_0) = 0, \quad \beta_\lambda^{\mathrm{SM}}(\mu_0) = 0$$

and require that

μ_0 determined by the EW physics gives the Planck scale, $\mu_0 \simeq M_P$!



This relation is generically spoiled if new physics exists between the Fermi and Planck scales.

$$\Downarrow$$

Argument in favour of absence of new physics scales between Fermi and Planck.

Cosmological inflation and the scale of new physics

Can we get the mass of the inflaton from the theory of inflation?

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No

Example: Chaotic inflation

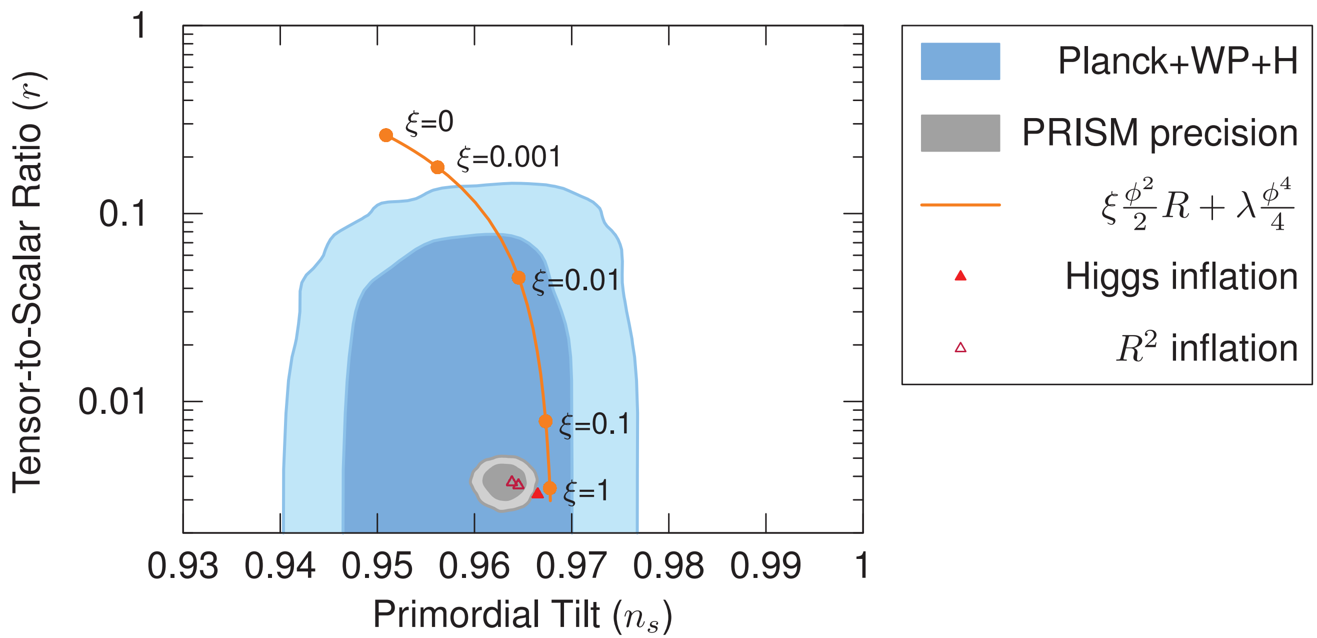
Take the inflaton potential in the simplest form

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

and add non-minimal coupling of the inflaton to gravity,

$$\xi\phi^2 R$$

Inflation works for any scalar mass from 0 to 10^{13} GeV and perfectly agrees with observations



Moreover, we do not need any new particle at all to make the Universe flat, homogeneous, and isotropic, and produce the necessary spectrum of fluctuations for structure formation Bezrukov, MS :

Higgs inflation

non-minimal coupling of Higgs field 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,...

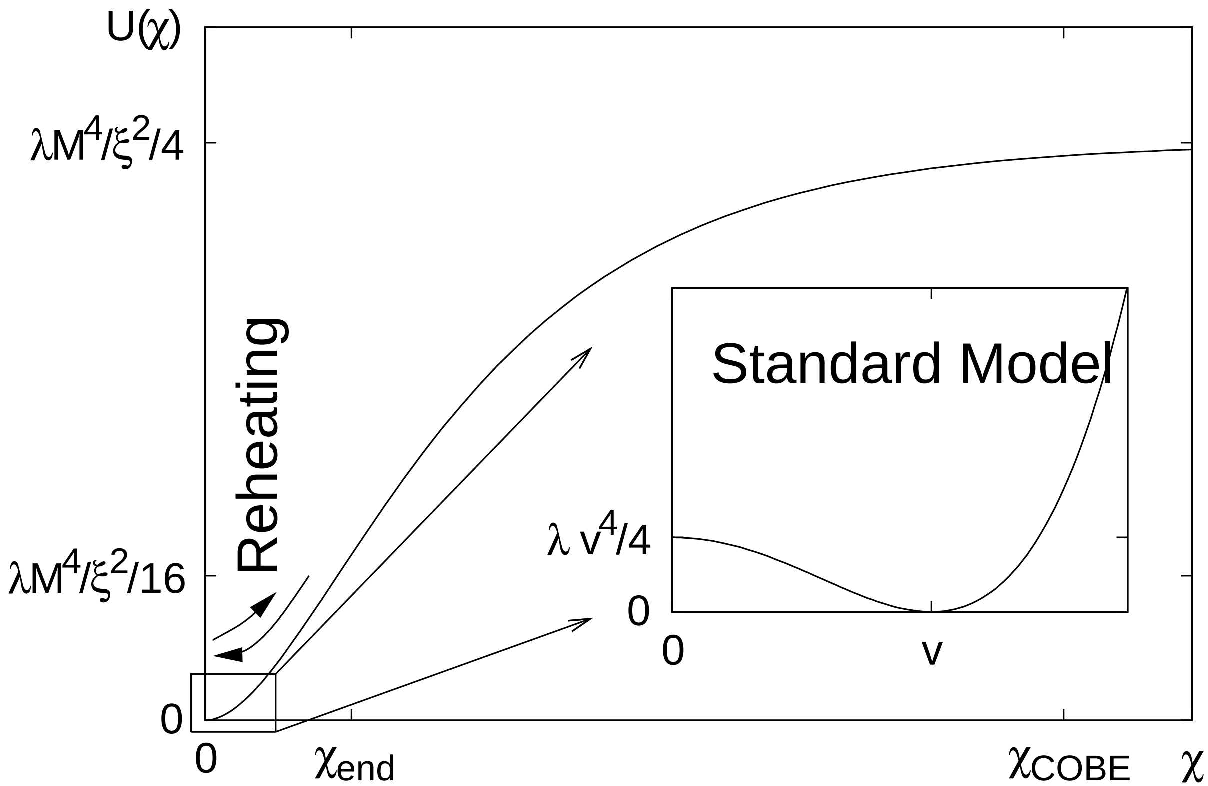
Consider large Higgs fields h.

- Gravity strength: $M_P^{\rm eff} = \sqrt{M_P^2 + \xi h^2} \propto h$
- All particle masses are $\propto h$

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

Existence of effective flat direction, necessary for successful inflation.

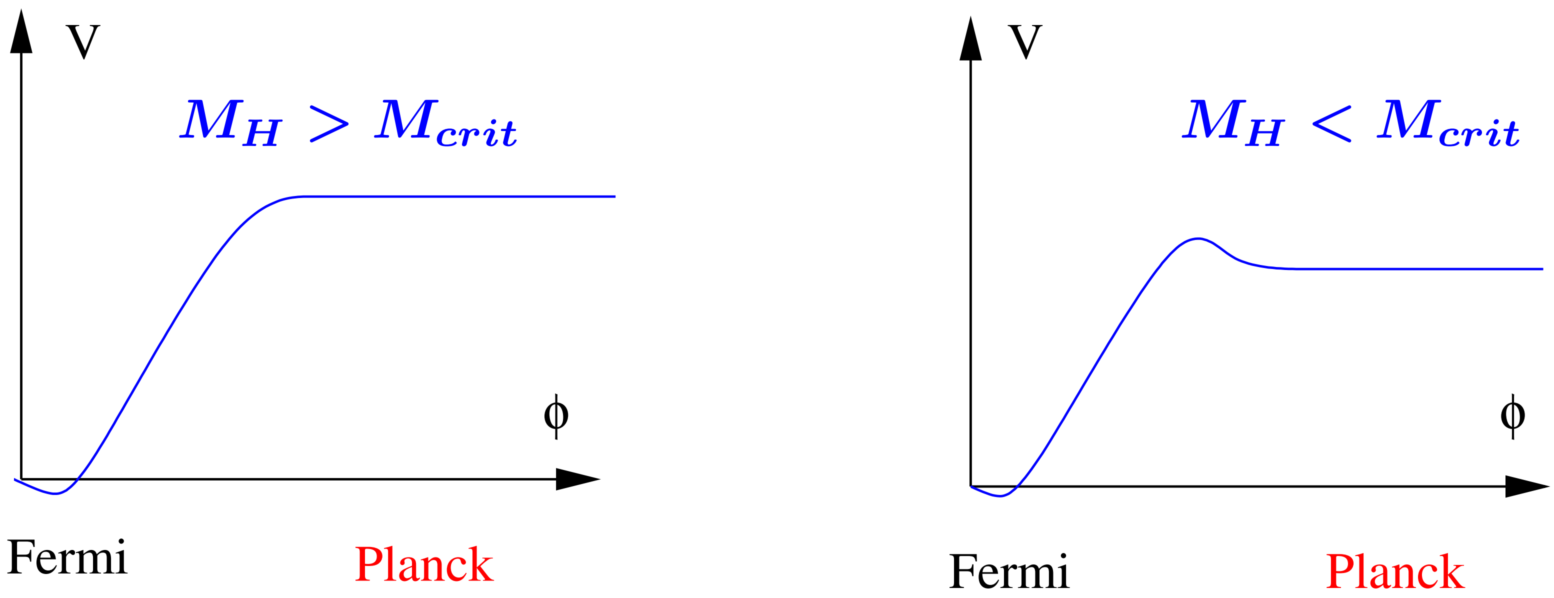
Potential in Einstein frame



χ - canonically normalized scalar field in Einstein frame.

Inflation and the Higgs mass

Radiative corrections to inflationary potential: Higgs inflation works only for $\lambda(M_P/\sqrt{\xi}) > 0$. Numerically, $M_H > M_{crit}$ with extra theoretical uncertainty of $\delta M_H \sim 1$ GeV.



Analysis of higher dimensional operators and radiative corrections: Higgs inflation occurs in the weak coupling regime and is self-consistent. Bezrukov et al

Inflaton potential and observations

If inflaton potential is known one can make predictions and compare them with observations.

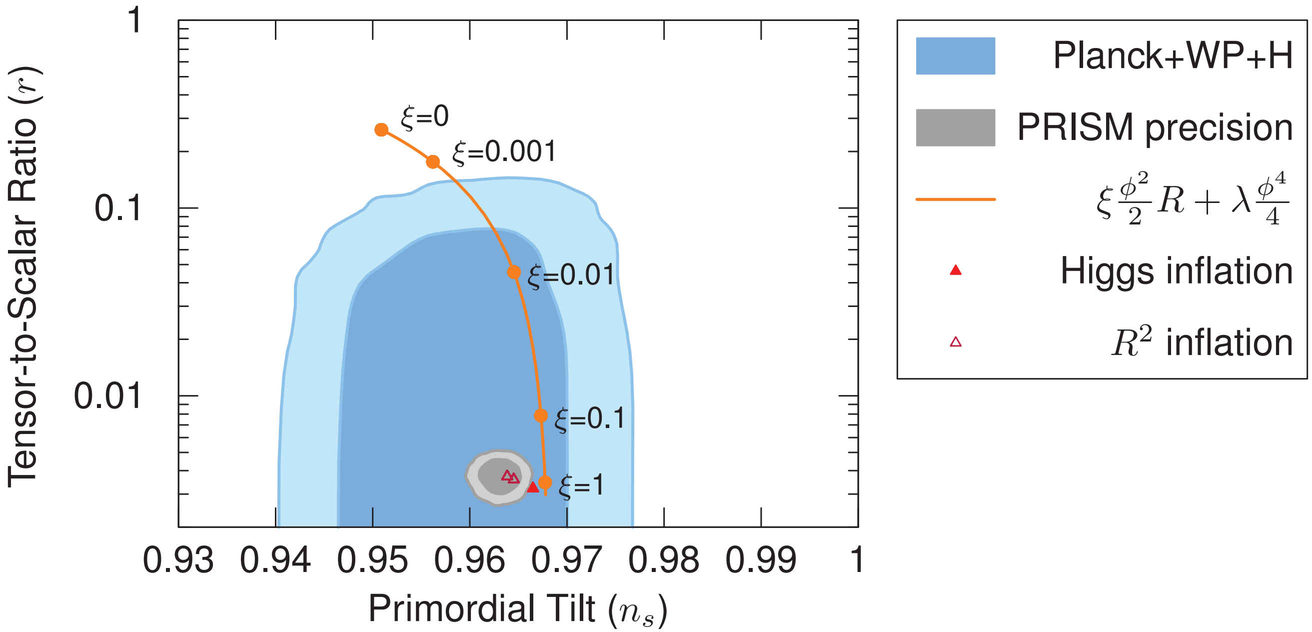
- $\delta T/T$ at the WMAP normalization scale $\sim \mathbf{500}$ Mpc.
- The value of spectral index n_s of scalar density perturbations

$$\left\langle \frac{\delta T(x)}{T} \frac{\delta T(y)}{T} \right\rangle \propto \int \frac{d^3k}{k^3} e^{ik(x-y)} k^{n_s-1}$$

- The amplitude of tensor perturbations $r = \frac{\delta\rho_s}{\delta\rho_t}$

These numbers can be extracted from WMAP observations of cosmic microwave background. Higgs inflation: one new parameter, $\xi \Longrightarrow$ two predictions. From WMAP normalization ξ can be as small as $\sim \mathbf{700}$.

CMB parameters—spectrum and tensor modes



- $T_{reh} \sim 10^{13-14}$ GeV, $N \simeq 58$
- Perturbations are Gaussian, in accordance with Planck.

Baryon asymmetry of the universe and the scale of new physics

Baryon asymmetry of the Universe I

Popular mechanism for baryogenesis:

- Electroweak baryogenesis. Idea (Cohen, Kaplan, Nelson): at high temperatures we are in the symmetric phase of the EW theory. During the universe cooling the first order EW phase transition (PT) goes through nucleation of bubbles of the new (Higgs) phase. Scattering of different particles on the domain walls leads to separation of baryon number and due to sphalerons to baryon asymmetry.

Challenged, but still possible in the MSSM: light stop is required for first order EW phase transition. Curtin et al, Cohen et al, Carena et al, Morrissey et al,...

Baryon asymmetry of the Universe II

Another popular mechanism for baryogenesis:

- Thermal leptogenesis. Idea (Fukugita, Yanagida): superheavy Majorana leptons with the mass $\sim 10^{10}$ GeV decay and produce lepton asymmetry, which is converted to baryon asymmetry by sphalerons.

Necessity of heavy particles $\Longrightarrow$ large radiative corrections to the Higgs mass (hierarchy problem) $\Longrightarrow$ SUSY at the electroweak scale. However, no signs of SUSY are seen... Way out: resonant leptogenesis with degenerate Majorana leptons with masses 1 TeV Pilaftsis et al

Thermal leptogenesis cannot be disproved, but will be fine tuned without new physics at Fermi scale

So, if the next LHC runs will confirm the SM, popular mechanisms for baryogenesis will be disfavored.

How the baryon asymmetry of the Universe has emerged?

Possibility: new physics below the Fermi scale

Dark matter and the scale of new physics

Dark matter

Most popular DM candidate: WIMP, associated with new physics solving the hierarchy problem at the electroweak scale. If no new physics is discovered at the LHC, this candidate is not that attractive anymore...

What is the Dark matter particle?

Possibility: new physics below the Fermi scale

Neutrino masses and the scale of new physics

Most probably, origin of neutrino masses - existence of new unseen particles; complete theory is renormalisable

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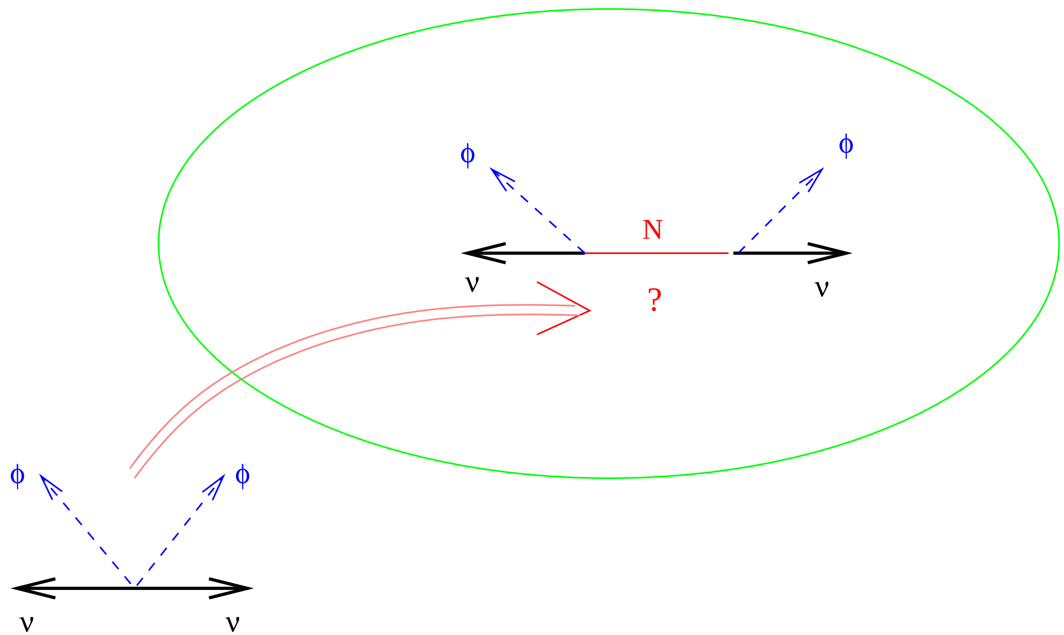


Realisation: SM + 3 right-handed neutrinos

Most general renormalizable Lagrangian

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

Extra coupling constants:

3 Majorana masses of new neutral fermions N_i,

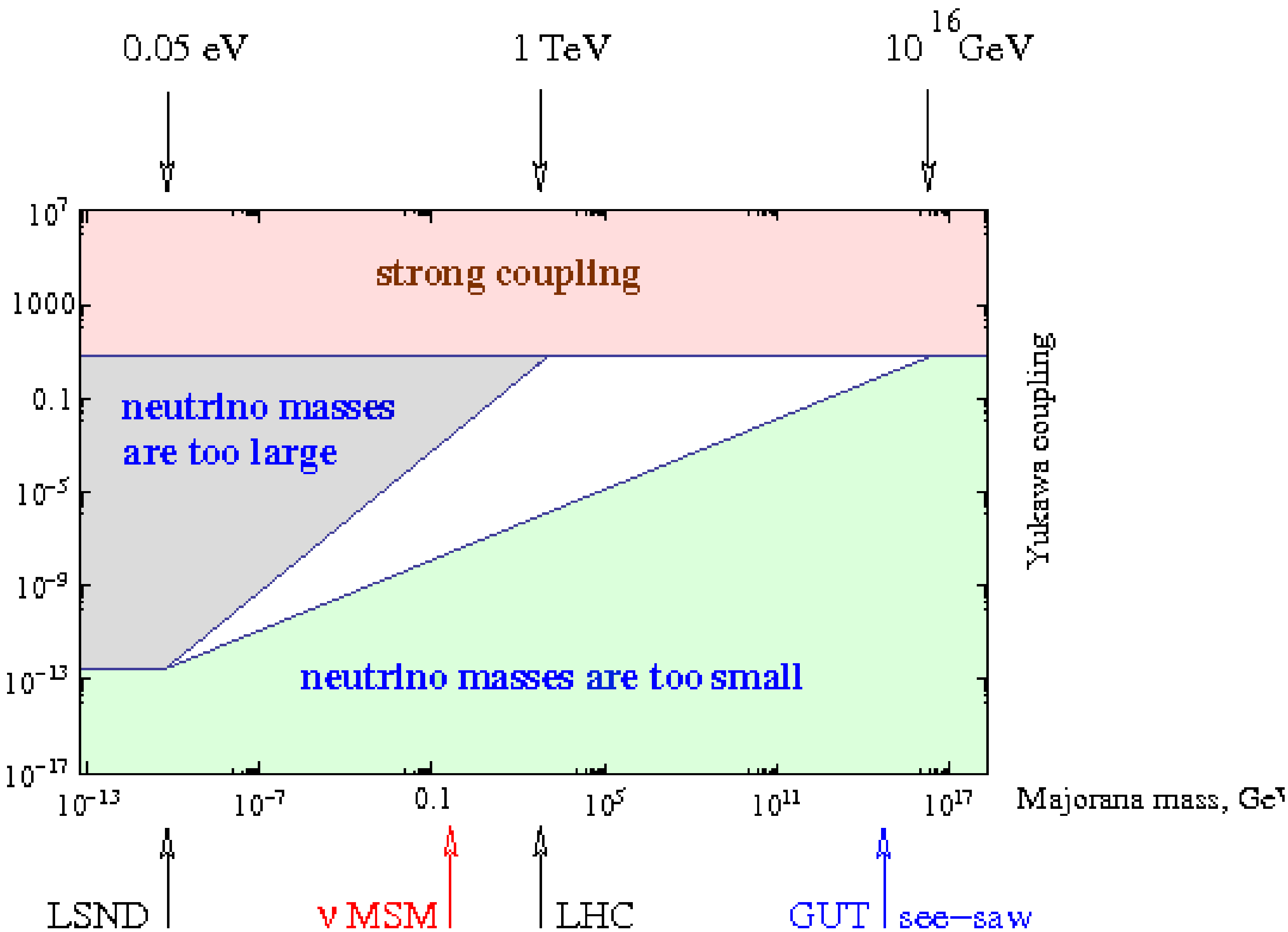
15 new Yukawa couplings in the leptonic sector

(3 Dirac neutrino masses $M_D = F_{\alpha I} v$, 6 mixing angles and 6 CP-violating phases),

18 new parameters in total. The number of parameters is almost doubled in comparison with the SM.

$$Y^2 = Trace[F^\dagger F]$$

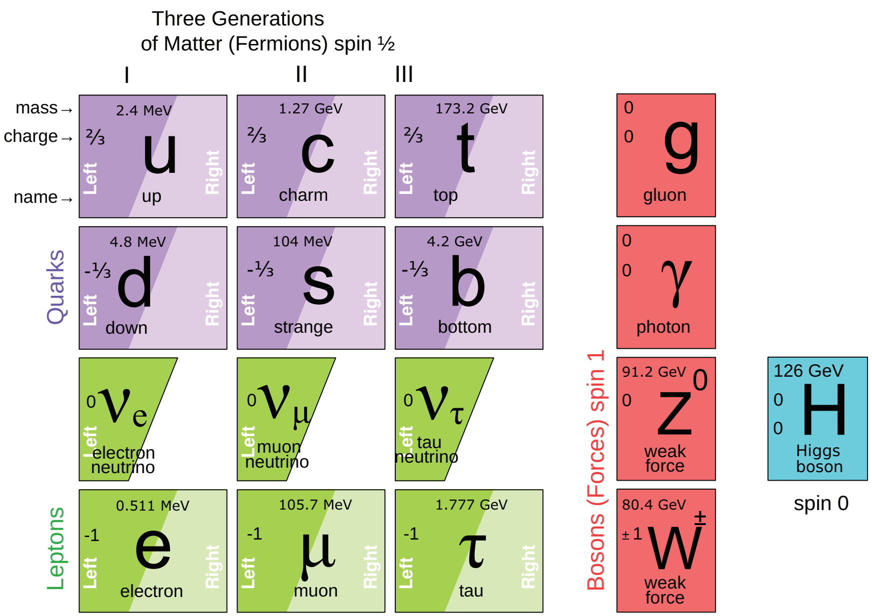
New mass scale and Yukawas

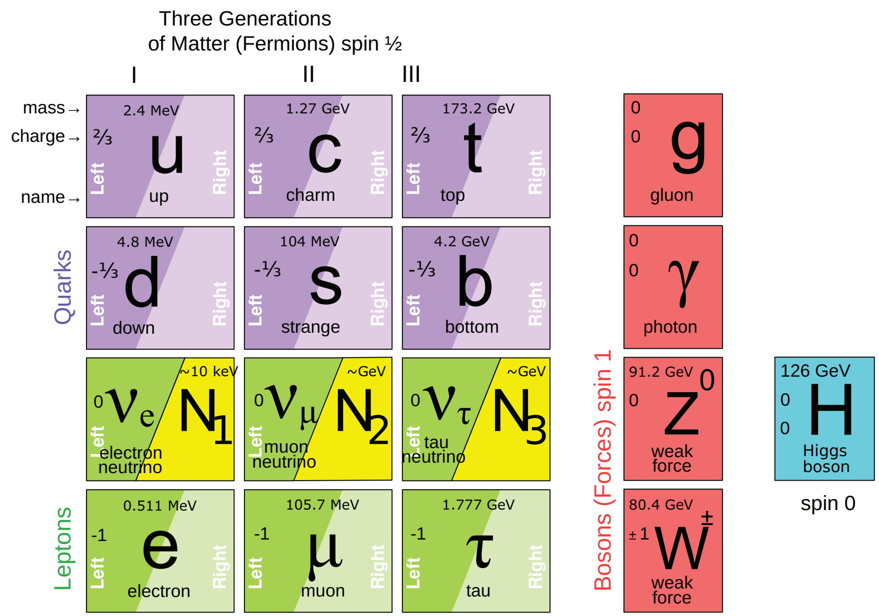


Physics case for different choices

	N mass	ν masses	eV ν anoma–lies	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

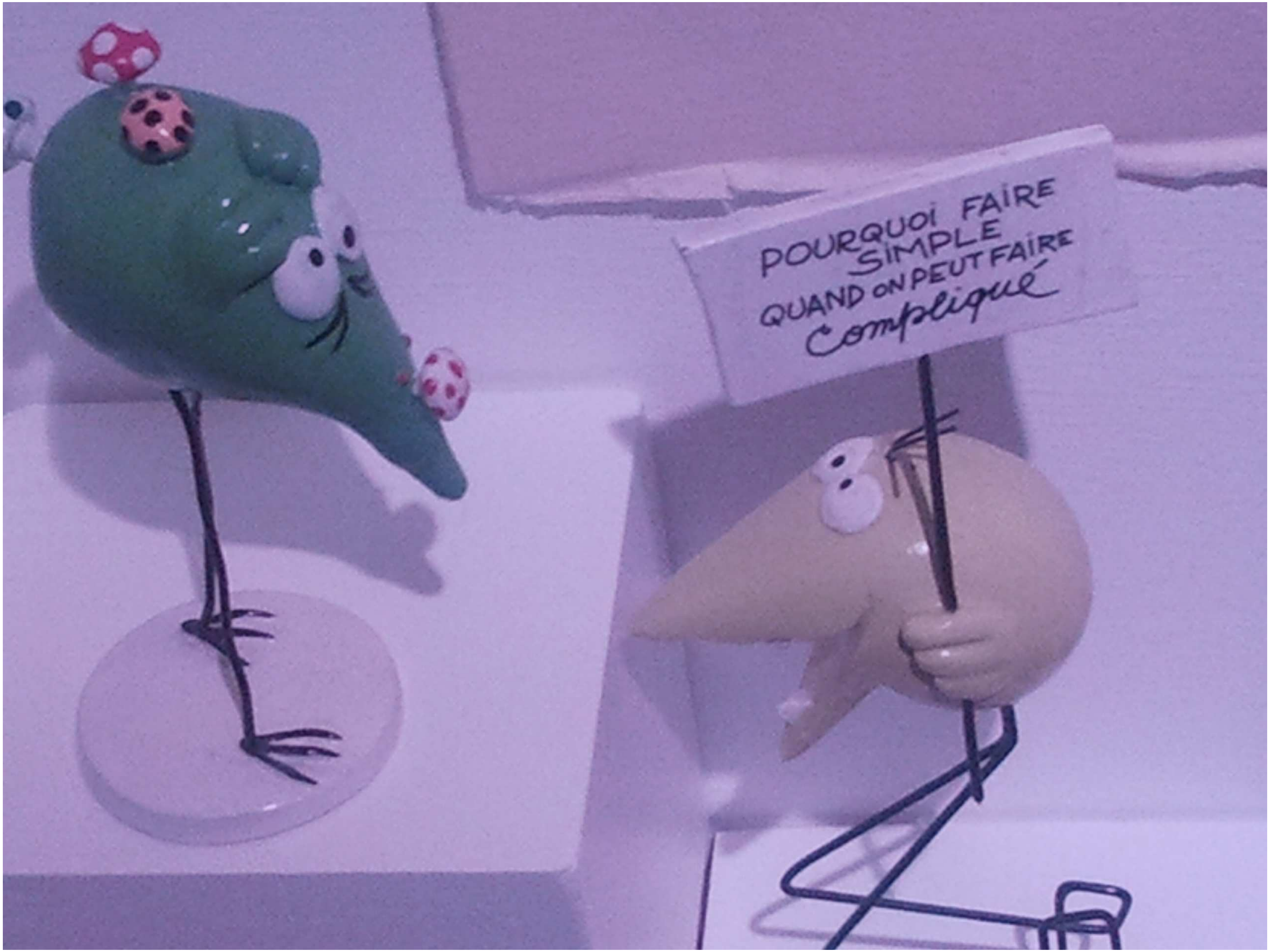
New physics below the Fermi scale: the νMSM





Role of N_1 with mass in keV region: dark matter. Search - with the use of X-ray telescopes

Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe. Search - intensity and precision frontier, SPS at CERN.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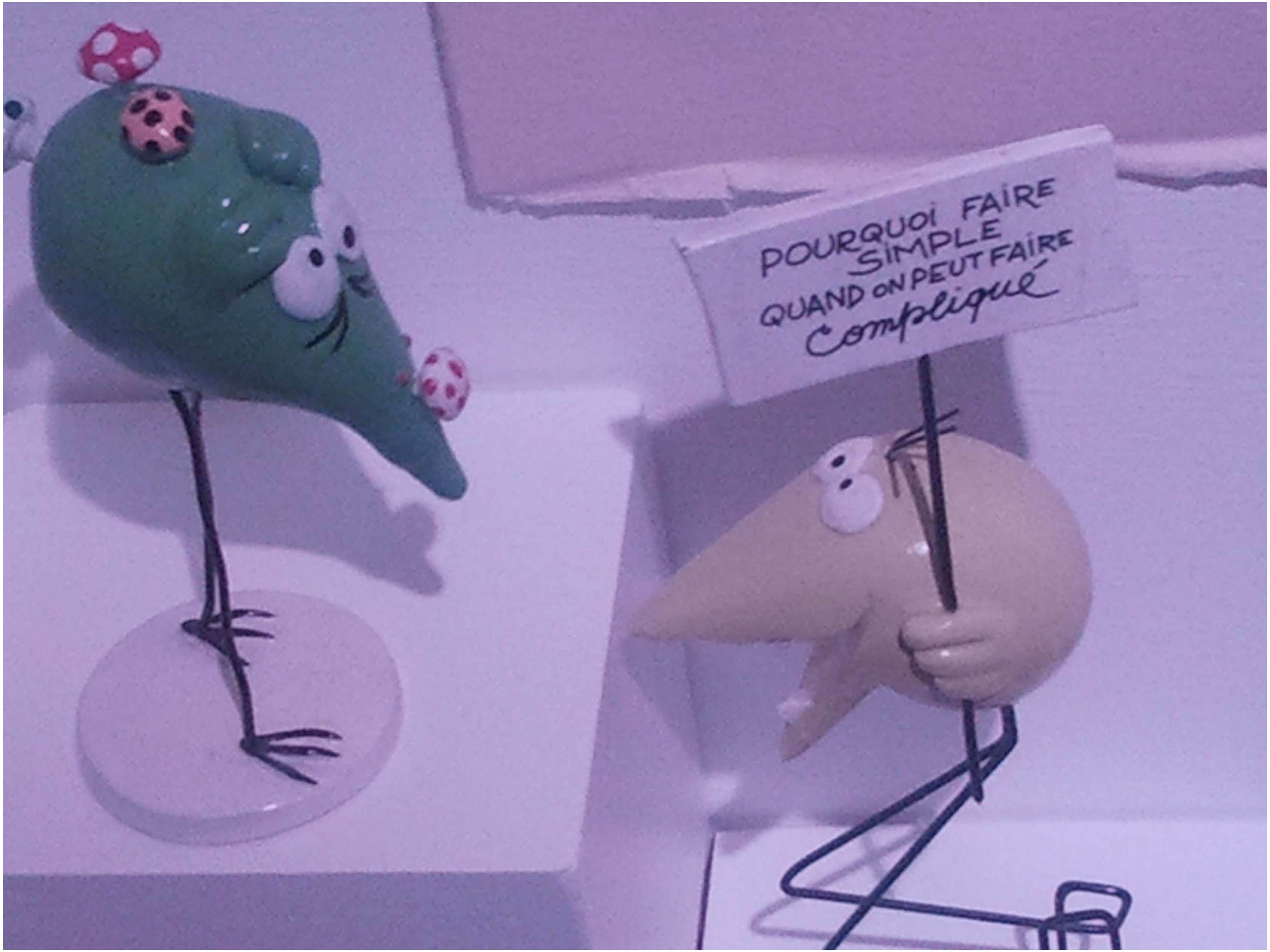
SIMPLE
QUAND ON PEUT FAIRE
Compliqué



Why make it simple when you can make it complicated?

Conclusions

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It may be above the Fermi scale -

challenged by experiments

It may be below the Fermi scale but very weakly coupled - consistent with experiments

Wish list

- Higgs mass with highest possible precision (LHC, $\mathbf{200}$ MeV?)
- Top Yukawa coupling with accuracy $\mathbf{5 \times 10^{-4}}$ ($\boldsymbol{\delta M_t \simeq} \mathbf{100}$ MeV) (LHC? future e^+e^- collider?)
- $\boldsymbol{\alpha_s}$ with uncertainty $\boldsymbol{\delta\alpha_s \simeq 2 \times 10^{-4}}$

Stability of EW vacuum? Higgs inflation? Asymptotic safety?

- Search for new particles producing baryon asymmetry of the Universe (below the Fermi scale, possible experiment at CERN-SPS?)

Wish list, cont

Cosmological and astrophysical experiments, which can elucidate the structure of the underlying theory.

To test Higgs inflation, and to distinguish it from R^2 inflation and other models:

- Precision in spectral index n_s of scalar perturbations at the level of 10^{-3} (PRISM?)
- Determination of tensor-to-scalar ratio down to values $r \simeq 0.003$ (COrE, PRISM?)
- Determination of the running of the spectral index $dn_s/dlogk$ down to values 5×10^{-4} (SKA?).

Wish list, cont

Dark matter

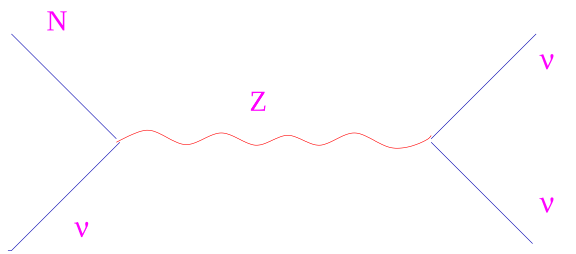
- Search for radiative decays of DM particles $N \to \gamma\nu$, alternative to WIMPS or axions with the help of high resolution X-ray telescopes.

*Prism: Polarized Radiation Imaging and Spectroscopy Mission
*DES: The Dark Energy Survey
*SKA: The Square Kilometer Array
*COrE: The Cosmic Origins Explorer

Back up slides

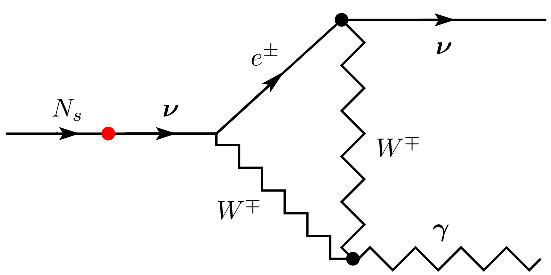
Dark Matter candidate: N_1

Yukawa couplings are small $\rightarrow$ N can be very stable.



Main decay mode: $N \to 3\nu$.

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



For one flavour:

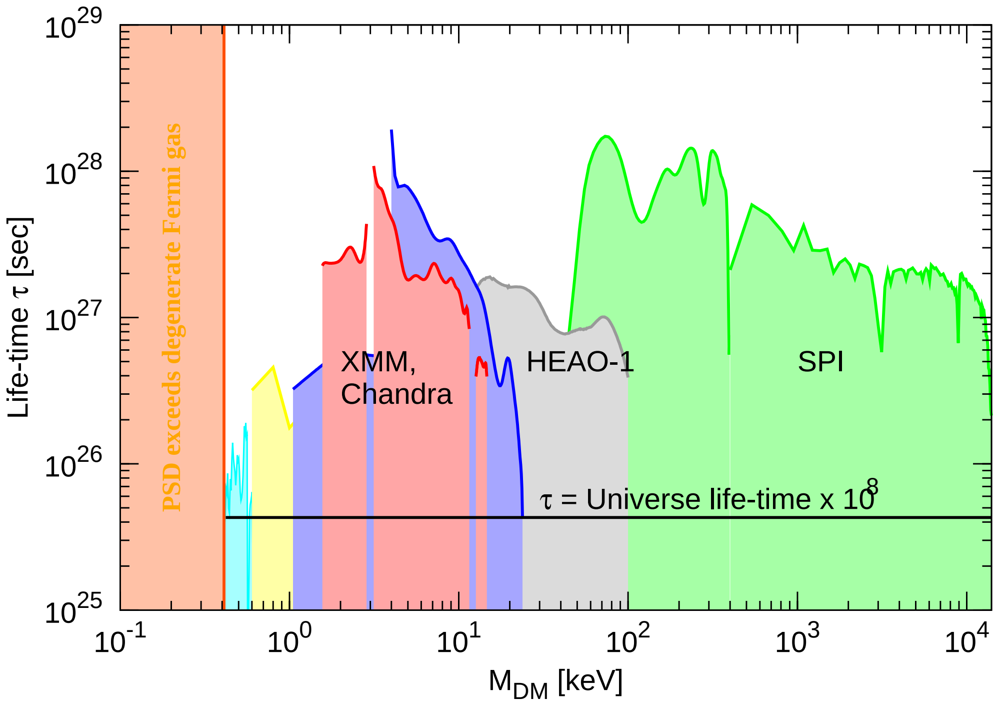
$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

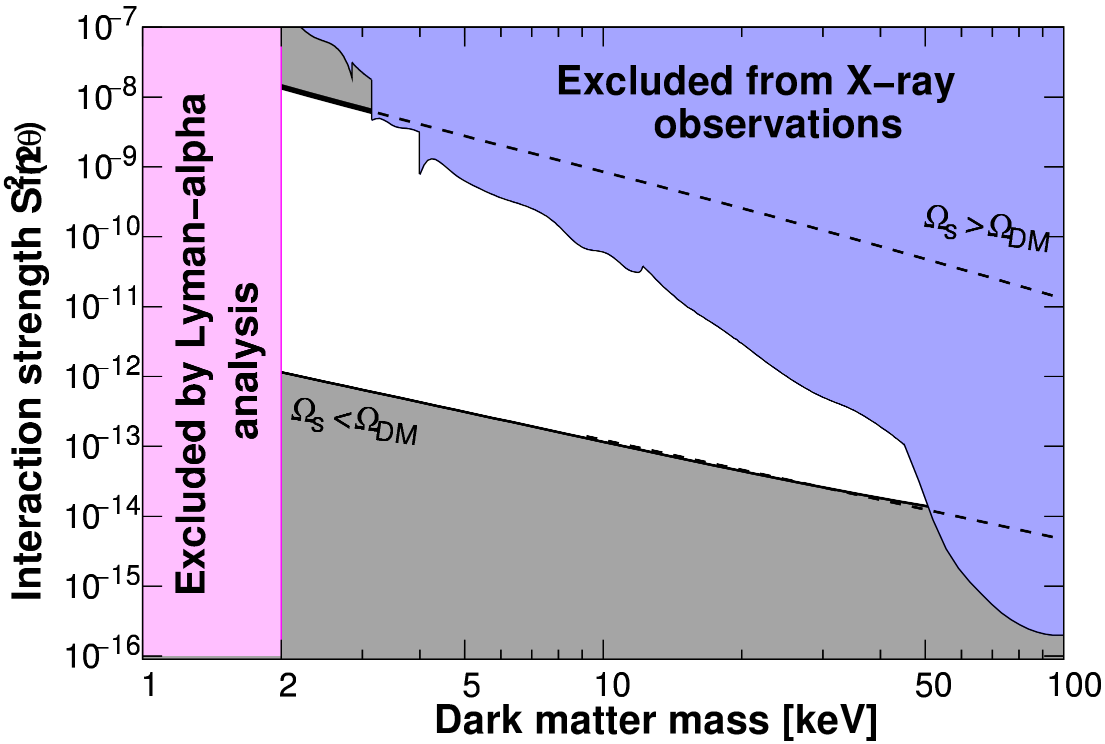
$$\theta_1 = \frac{m_D}{M_N}$$

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

Constraints on DM HNL 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 $l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1$ 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). This line has not been seen yet


PSD exceeds degenerate Fermi gas
XMM,
Chandra
HEAO-1
SPI
τ = Universe life-time x 10^8
Life-time τ [sec]
M_DM [keV]

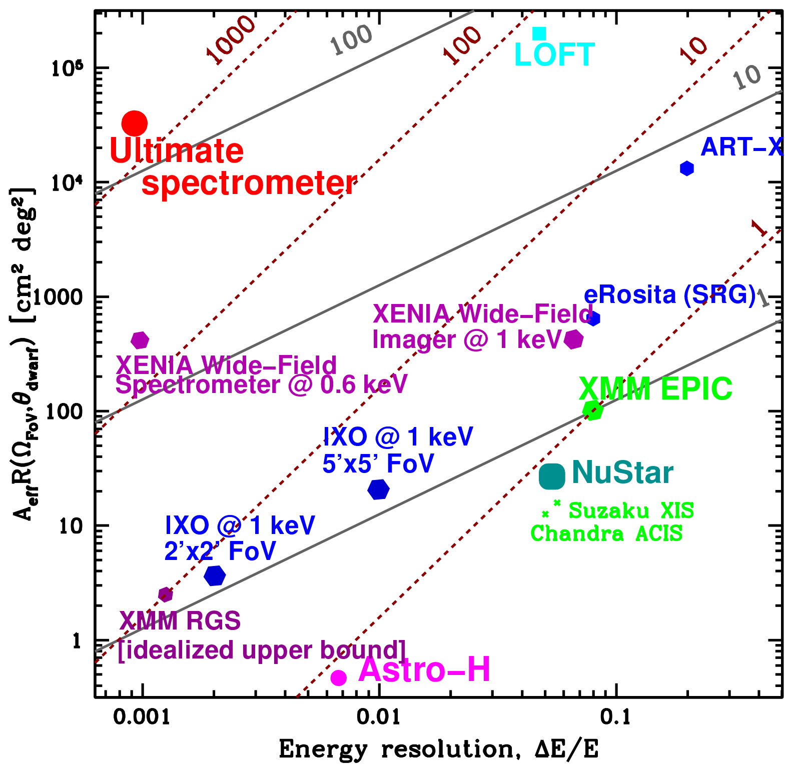

Excluded from X–ray observations
Excluded by Lyman–alpha analysis
Ω_s > Ω_DM
Ω_s < Ω_DM
Interaction strength Sin²(2θ)
Dark matter mass [keV]

How to find DM HNL?

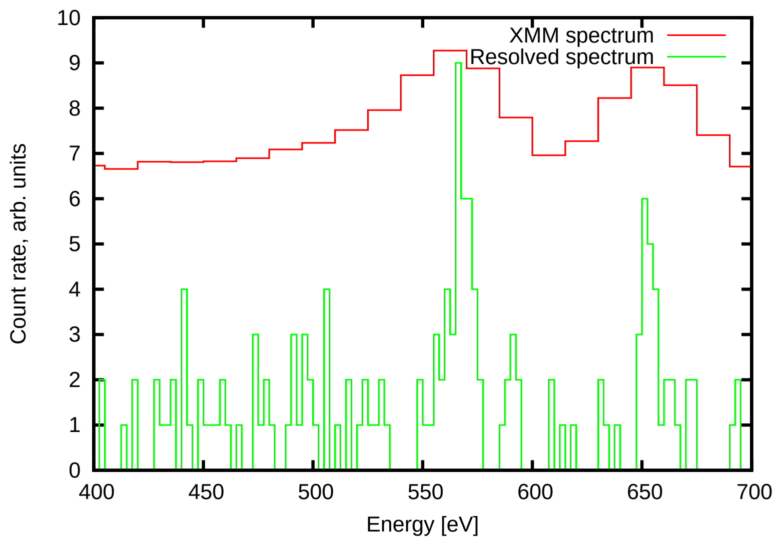
Strategy: Use X-ray telescopes (such as Chandra and XMM Newton) to look for a narrow γ line against astrophysical background. Choose astrophysical objects for which:

- The signal is maximal
- The X-ray background is minimal

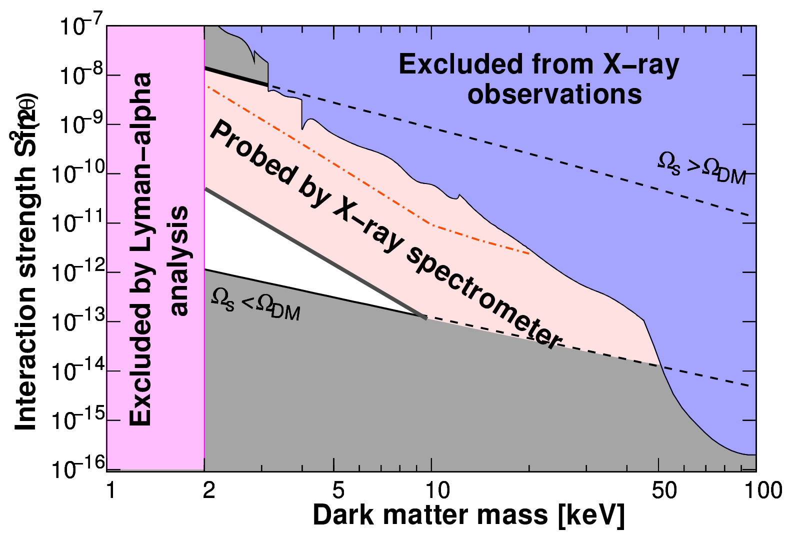
$\Longrightarrow$ Look at Milky Way and dwarf satellite galaxies



LOFT
Ultimate spectrometer
ART–X
eRosita (SRG)
XENIA Wide–Field Imager @ 1 keV
XENIA Wide–Field Spectrometer @ 0.6 keV
XMM EPIC
IXO @ 1 keV 5'x5' FoV
NuStar
Suzaku XIS
Chandra ACIS
IXO @ 1 keV 2'x2' FoV
XMM RGS [idealized upper bound]
Astro–H
1000
100
10
1
Energy resolution, ΔE/E



XMM spectrum
Resolved spectrum
Count rate, arb. units
Energy [eV]



Excluded from X–ray observations
Excluded by Lyman–alpha analysis
Probed by X–ray spectrometer
Interaction strength
Dark matter mass [keV]

Baryon asymmetry

CP is non-conserved in the νMSM:

6 CP-violating phases in the lepton sector and

1 Kobayashi-Maskawa phase in the quark sector.

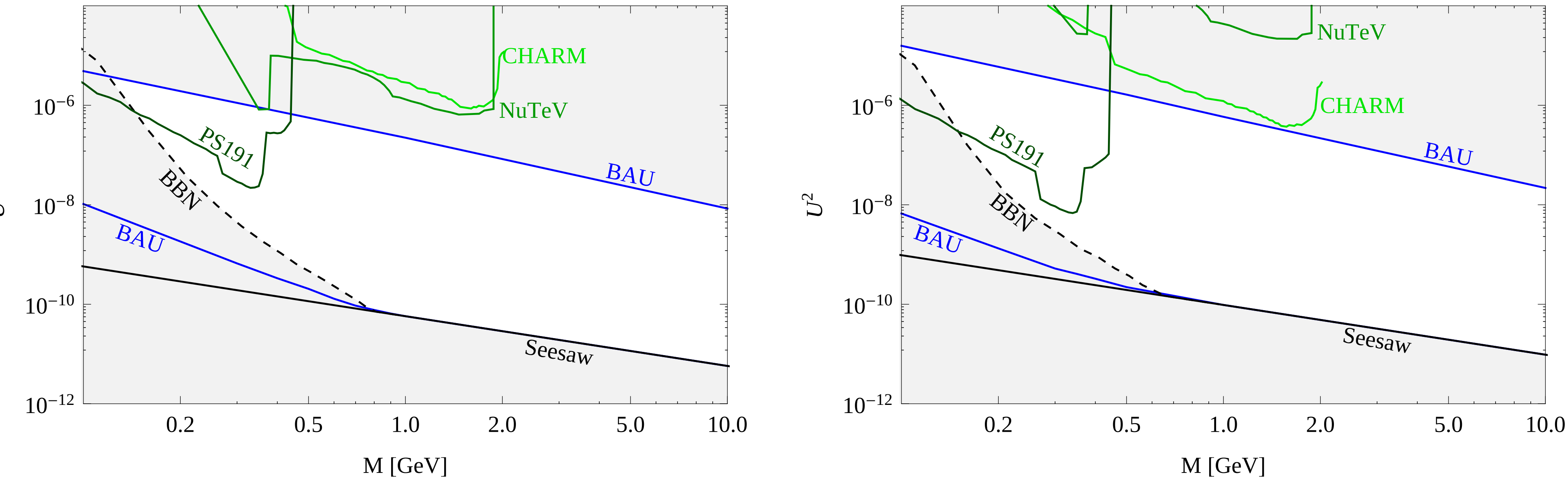
Deviations from thermal equilibrium:

very weakly coupled heavy neutral leptons.

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

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

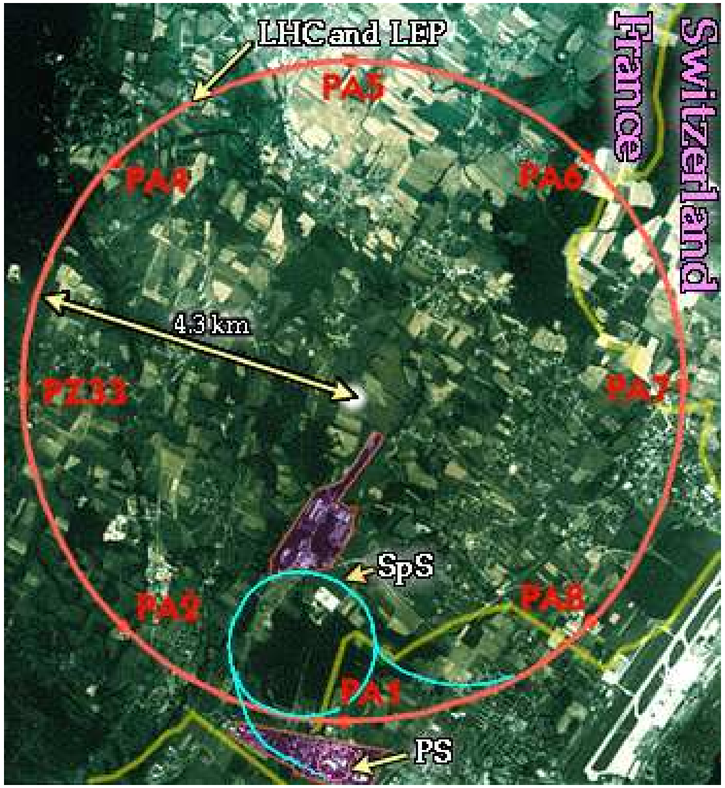
- BAU generation requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small
- BBN. Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{2,3}$ have not been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



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).

Experimental signature

- Two charged tracks from a common vertex, decay processes $N \to \mu^+\mu^-\nu$, etc. (sensitivity $U^4 = U^2 \times U^2$)
  First step: proton beam dump, creation of N in decays of $K,\ D$ or B mesons: U^2
  Second step: search for decays of N in a near detector, to collect all Ns: U^2
  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of PS.)
  - $M_N < M_D$: Best option: SPS beam + near detector
  - $M_N < M_B$: extremely hard
  - $M_N > M_B$: impossible



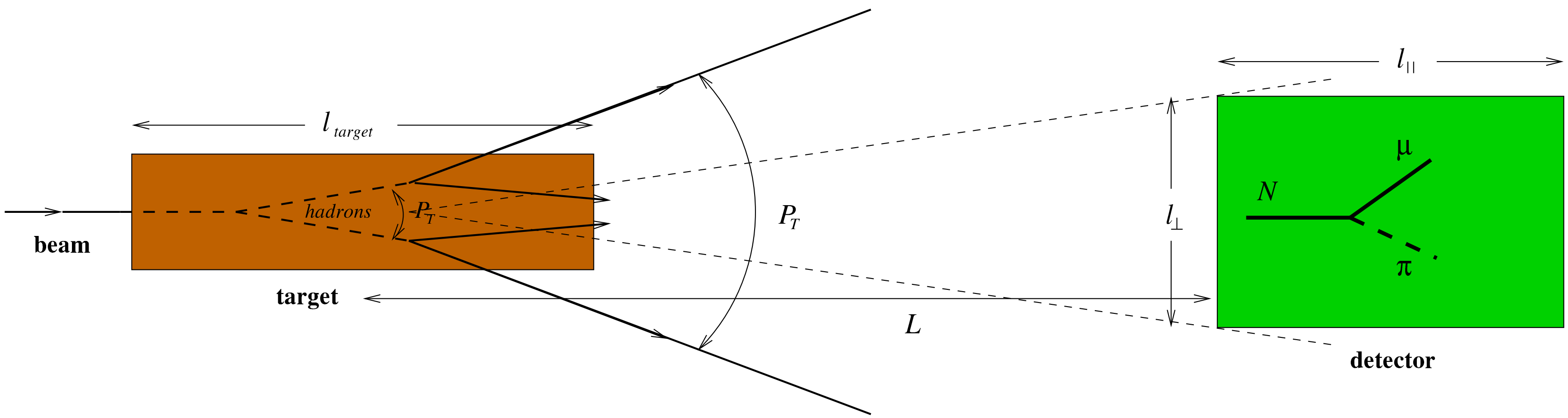
Energy: 400 GeV, power: 750 kW

$\mathbf{4.5 \times 10^{13}}$ protons per pulse (upgrade to $\mathbf{7 \times 10^{13}}$), every 6 s

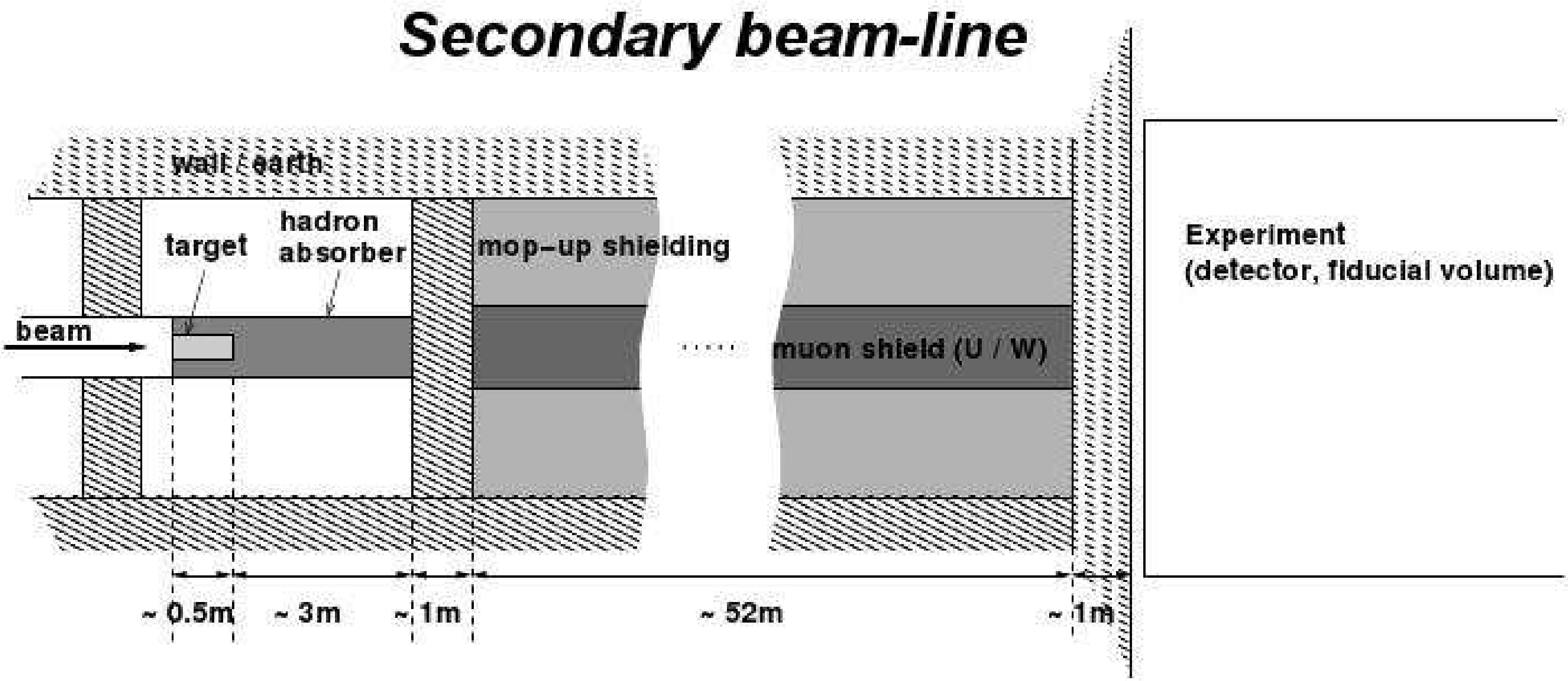
CNGS: $\mathbf{4.5 \times 10^{19}}$ protons on target per year (200 days, 55% machine availability, 60% of the SPS supercycle)

Proposal to Search for Heavy Neutral Leptons at the SPS arXiv:1310.1762

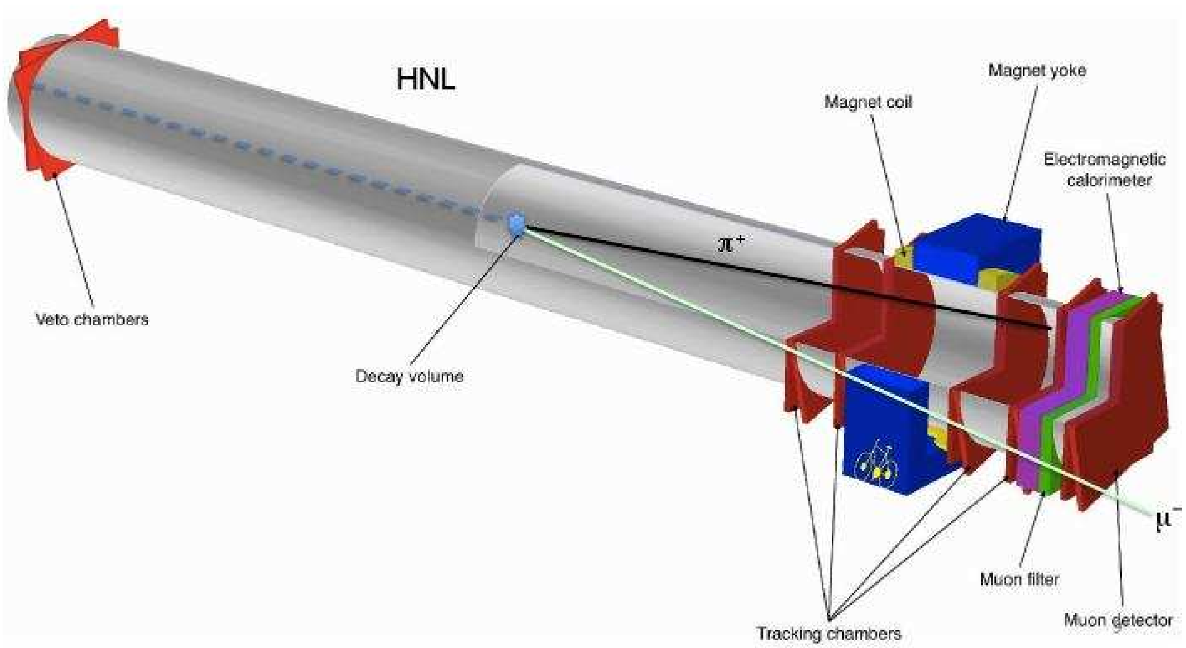
W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille



Target


Secondary beam-line
wall / earth
target
hadron
absorber
mop–up shielding
beam
muon shield (U / W)
Experiment
(detector, fiducial volume)
~ 0.5m
~ 3m
~ 1m
~ 52m
~ 1m

Detector


HNL
Magnet yoke
Magnet coil
Electromagnetic calorimeter
π+
Veto chambers
Decay volume
μ-
Muon filter
Muon detector
Tracking chambers

Sensitivity