Как искать новую физику и что делать со старой

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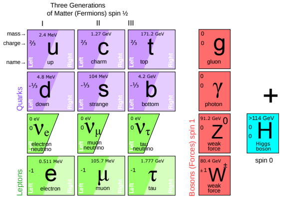
Standard Model – perturbative field theory up to M_P



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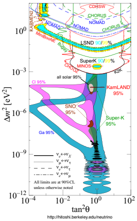
Einstein gravity

Describes

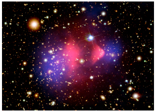
- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$ sec)

Experimental problems:

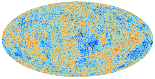
- Laboratory
  - ? Neutrino oscillations



- Cosmology
  - ? Baryon asymmetry of the Universe
  - ? Dark Matter



  - ? Inflation



  - ? Dark Energy

Possible solutions

New physics above EW scale

- SUSY (Hierarchy problem, Dark Matter, neutrino masses, GUT)
- Extra Dimensions (low scale gravity, hierarchy)
- …

No new physics above EW scale

- Standard Model up to Planck scale

Do we have experimental indications of the scales where new physics should appear?

Most things do not really point to a definite scale above EW

- Neutrino masses ans oscillations (absent in SM)
  - Right handed neutrino between 1 eV and 10^{15} GeV
- Dark Matter (absent in SM)
  - Models exist form 10^{-5} eV (axions) up to 10^{20} GeV (Wimpzillas, Q-balls)
- Baryogenesys (absent in SM)
  - Leptogenesys scenarios exist from $M \sim 10$ MeV up to 10^{15} GeV

It's physics

The question can be answered only by experiment!

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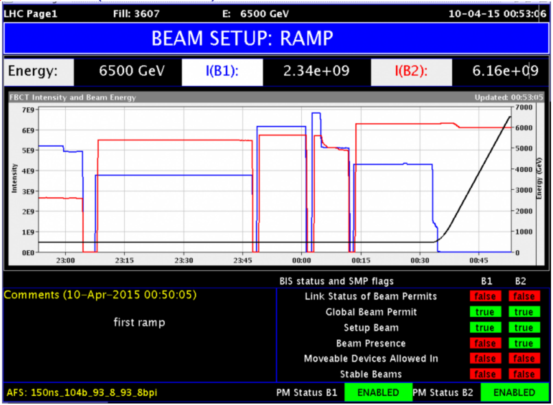
LHC – Started again

Searching for "high" scale (about TeV)



- Great way to see if there are something around TeV
  - If something is found – celebrate, and forget most of what I am talking about today

If nothing is found?

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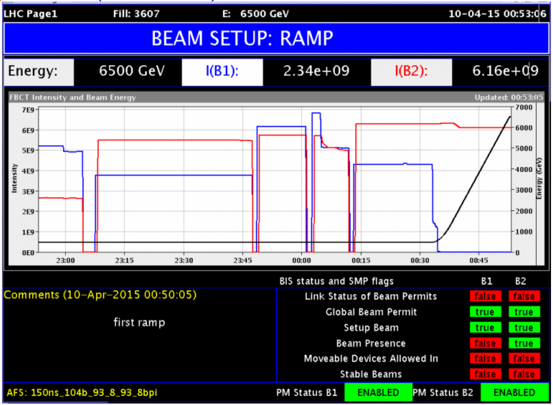

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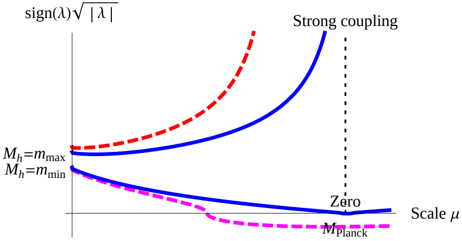
Standard Model – can it be unchanged up to Planck scale?

- Higgs self coupling λ constant changes with energy due to radiative corrections.

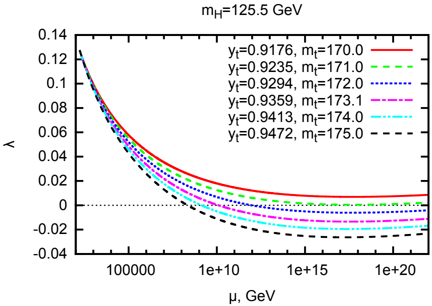


- Behaviour is determined by the masses of the Higgs boson and other heavy particles (top quark)
- If Higgs is heavy $M_H > 170$ GeV – the model enters *strong coupling* at some low energy scale – new physics required. Maiani, Parisi, Petronzio'77; Lindner'85; Hambye, Riesselmann'96

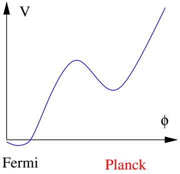
Lower Higgs masses: RG corrections push Higgs coupling to negative values

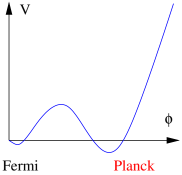
- For Higgs masses $M_H < M_{\text{critical}}$ coupling constant is negative above some scale μ_0.
  Krasnikov'78; Hung'79; Politzer, Wolfram'79; Altarelli, Isidori'94; Casas, Espinosa, Quiros'94; Ellis, Espinosa, Giudice, Hoecker, Riotto'09
- The Higgs potential may become negative!
  - Or world is not in the lowest energy state!
  - Problems at some scale $\mu_0 > 10^{10}$ GeV?

Coupling λ evolution:



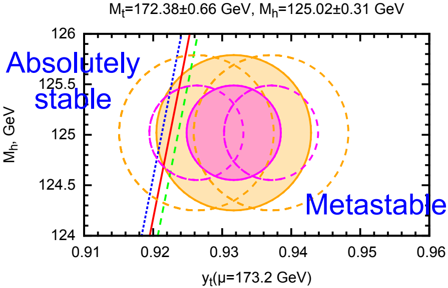
Higgs potential $V(\phi) \simeq \lambda(\phi)\frac{\phi^4}{4}$



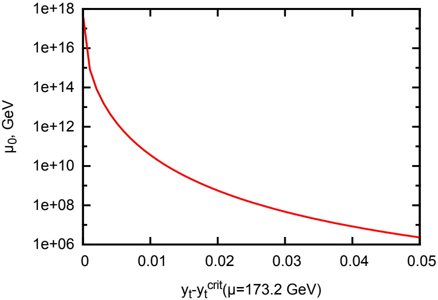


LHC major result: SM is perturbative up to Planck scale, and probably has metastable SM vacuum

Experimental values for y_t



Scale μ_0 for $\lambda(\mu_0) = 0$



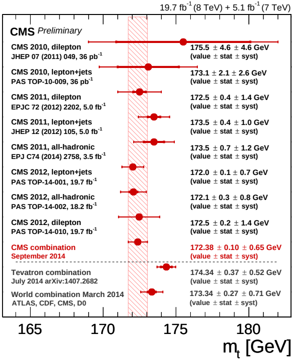
We live close to the metastability boundary – but on which side?!

Future measurements of top Yukawa and Higgs mass are essential!

FB, Kalmykov, Kniehl, Shaposhnikov'12; FB, Shaposhnikov'14

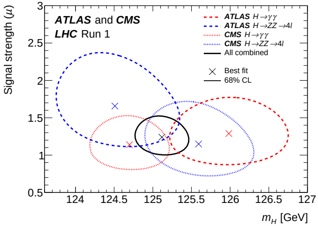
Measuring top quark Yukawa and Higgs boson mass

- Hard to relate the “pole” (the same for “Mont-Carlo”) mass to the $\overline{\text{MS}}$ top quark Yukawa
  - NLO event generators
  - Electroweak corrections – important at the current precision goals!



- Build a lepton collider (ILC, FCC)
- Improve analysis on a hadron collider?

- Higgs mass measurement may also change a bit…

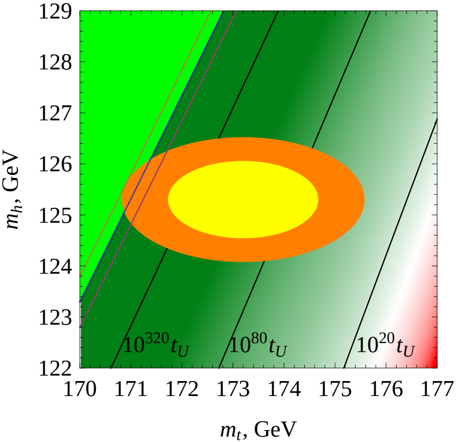


So, what are the consequences if the Standard Model electroweak vacuum is metastable?

What to do if we are metastable?

$$p_{\text{decay}} \propto e^{-S_{\text{bounce}}} \sim e^{-\frac{8\pi^8}{3\lambda(h)}}$$

Even if the vacuum is metastable, it lives *much* longer than the Universe

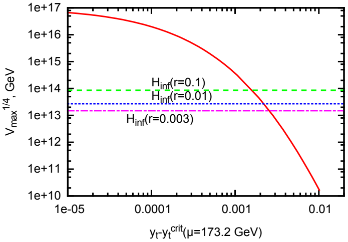


- No danger today (and, with a bit more analysis, neither there are problems at early hot stages)
- And at higher energies, at inflation?

Metastable vacuum during inflation *is* dangerous

- Let us suppose Higgs is *not at all* connected to inflationary physics
- All fileds have vacuum fluctuation
- Typical momentum $k \sim H_{\text{inf}}$ is of the order of Hubble scale

$$H_{\text{inf}} \sim 8.6 \times 10^{13}\,\text{GeV} \left(\frac{r}{0.1}\right)^{1/2}$$



- If typical momentum is greater than the potential barrier – SM vacuum would decay

$$H_{\text{inf}} > V_{\text{max}}^{1/4}$$

Most probably, fluctuations at inflation lead to SM vacuum decay…

- Observation of any tensor-to-scalar ratio *r* by CMB polarization missions would mean great danger for metastable SM vacuum!

Two most important measurements to test for SM validity up to the highest scales

- Precise value of the top quark Yukawa y_t
  - Best – lepton collider at $E \gtrsim 2m_t$ (ILC, FCC)
- (Ok, a bit more than two measurements – Higgs boson mass, α_s)
- Scale of inflation
  - Primordial gravity waves – or B-modes of CMB (QUIJOTE, QUBIC, GroundBIRD, BICEP3, ...)

All other SM experimental problems can be solved by changes at low scales

Definintly need new particles

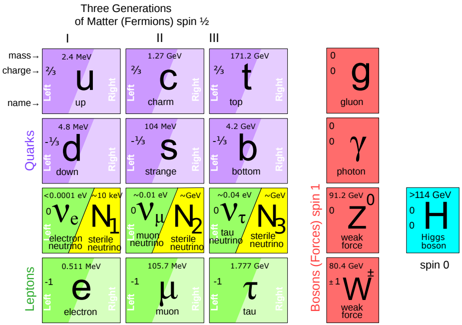
- Neutrino oscillations
- Dark Matter
- Baryon asymmetry of the Universe

all can be solved at low energies

Three sterile neutrinos –

νMSM

New physics only at low scales



Role of sterile neutrinos

N_1 $M_1 \sim 1 - 50$keV: (Warm) Dark Matter,

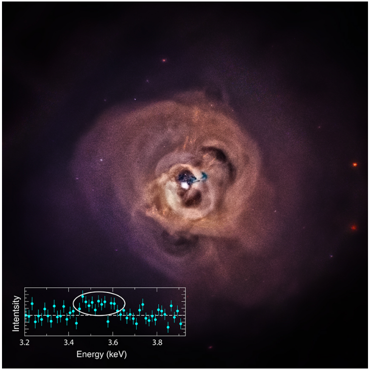
$N_{2,3}$ $M_{2,3} \sim$ several GeV:
Gives masses for active neutrinos, Baryogenesys

Asaka, Shaposhnikov'05; Asaka, Blanchet, Shaposhnikov'05

N_1 has been seen! (probably)

Line in the X-ray signal can mean 7 keV DM

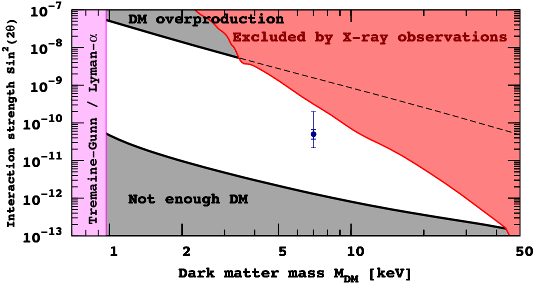
Signal in Perseus cluster



Data by Chandra and XMM-Newton,

Bulbul et.al’13, Boyarsky et.al’13

Required parameters of sterile neutrino N_1



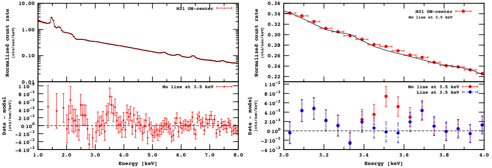


FIG. 1: *Left:* Folded count rate (top) and residuals (bottom) for the MOS spectrum of the central region of M31. Statistical Y-errorbars on the top plot are smaller than the point size. The line around 3.5 keV is *not added*, hence the group of positive residuals. *Right:* zoom onto the line region.

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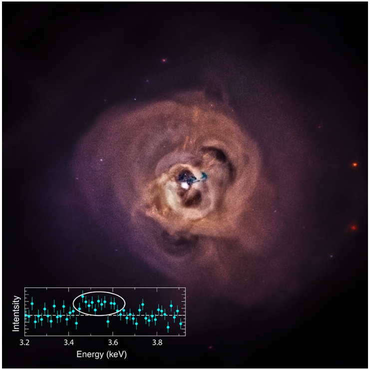

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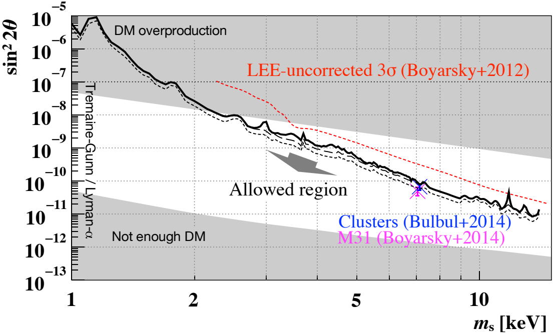
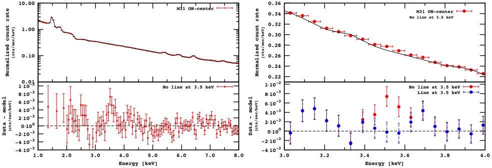
Suzaku strongly bounds the allowed region





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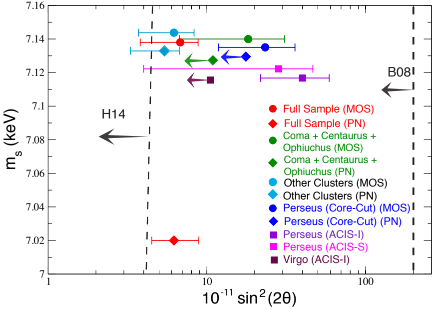
Testing that the 3.5 keV line is DM

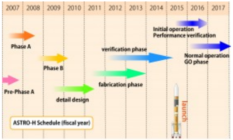
Verify, that

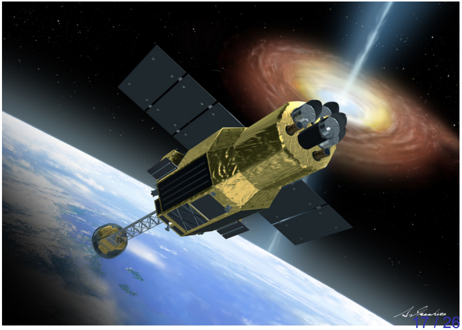
- all DM dominated objects emit the line
- and all do this in proper amount
- the feature is really a narrow line



Near future: ASTRO-H

- Good energy resolution
- Excellent sensitivity





Sterile neutrino is not the only candidate for light WDM

There are

- axion like particles
- split dark matter

How to test which is right?

Start searching and testing for other predictions

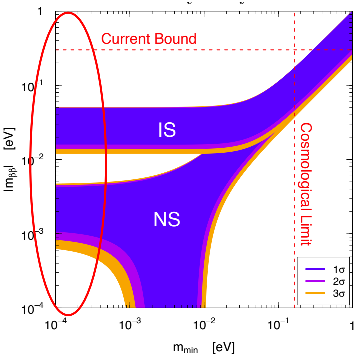
νMSM with DM means hierarchical active neutrino masses

Active neutrino masses

- X-rays require very small N_1 mixing angle θ_1, so
$$m_1 < 10^{-5}\text{eV}$$

Neutrinoless double beta decay

- Additional contributions are negligible
  - N_1 – X-ray constraints
  - $N_{2,3}$ – mass $> 100\,\text{MeV}$
- Mass spectrum strongly hierarchical – X-ray constraints
$$m_{0\nu\beta\beta} < 50 \times 10^{-3}\ \text{eV}$$



Laboratory tests for νMSM and DM

Indirect

- Search for $0\nu\beta\beta$
  - GERDA

Direct

- Search for creation of N_1 in kinematics of beta decay (most probably only for extensions of νMSM)
  - Troitsk
  - KATRIN
  - PTOLEMY

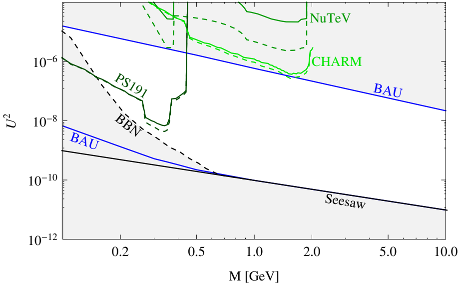
Search for $N_{2,3}$ is possible

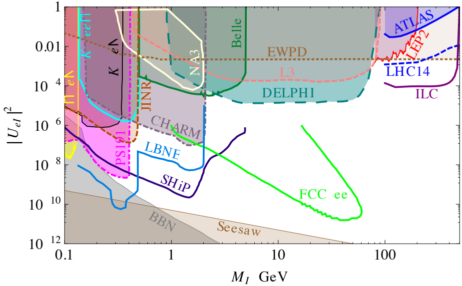
- Leptogenesys by $N_{2,3}$

  $$\Delta M/M \sim 10^{-3}$$

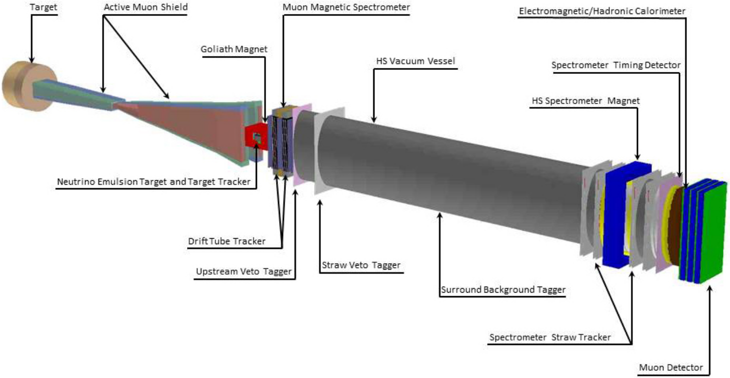
- Experimental searches
  - $N_{2,3}$ production in hadron decays (LHCb):
    - Missing energy in K decays
    - Peaks in Dalitz plot
  - $N_{2,3}$ decays into SM
    - Beam target: SHiP
    - High luminosity lepton collider at Z peak

Note: Other related models (e.g. scalars for DM generation, light inflaton) also show up in such experiments





SHiP – Beam Target experiment



- Protons – target – shield – empty space – detector
- N – created in the target
  - N – decays in the empty detector
    - decay products detected

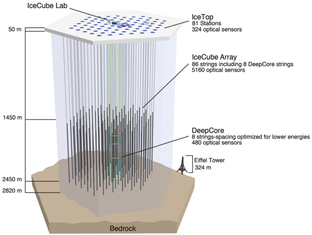
Neutrino oscillations require new physics

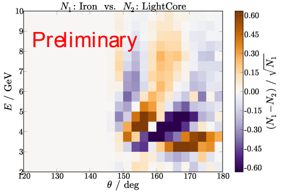
But knowing their parameters does not help much at the moment to fix its properties

- E.g. in type I see-saw (or in νMSM) all the interesting new physics effects – sterile N masses, sterile-active mixings, CP for leptogenesys – are independent on active ν parameters.

Using neutrino oscillations to measure something

- Using PINGU, ORCA to check the composition of the Earth
- Measuring active neutrino mass hierarchy+$0\nu\beta\beta$ – constraints νMSM?





Conclusions

The scale of new physics is unknown!

- Can be solved only by experiment:
- High scale – LHC "energy frontier"
- Ultra high scale – interplay between
  - top quark Yukawa (lepton collier)
  - inflationary scale (CMB properties, B-modes)
- Low scale
  - Rare physics – rare decays (LHCb), dedicated beam dump experiments (SHiP)
  - Astrophysics – X-rays

Use SM for something useful

- Neutrino oscillations for Earth study
- Neutrinos for – supernova explosions, reactor monitoring…

Happy Birthday, dear Dad!