Status of cosmology and the Higgs boson: Lectures #1-2

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow, Russia

The Helmholtz International School
"Cosmology, Strings, and New Physics"

Main points of the lecture course:

Since we got no signals of Physics beyond the SM (so far. . .)

And nevertheless we need New Physics

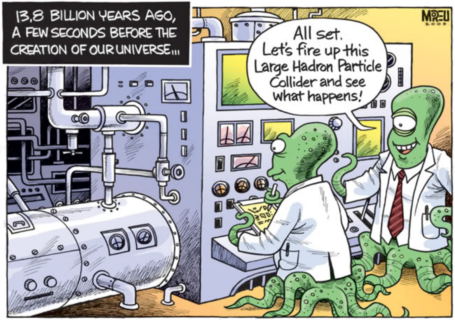
- Higgs boson mass of about 126 GeV is close to be very special: second degenerate with EW minimum at Planck scale !
  $\Longrightarrow$
  great desert upto Planck scale and smooth unification there...?
- The recently descovered at LHC Higgs sector is not explored yet: it can be responsible for (play some part in):
  - neutrino oscillations
  - (baryo)leptogenesis
  - dark matter production
  - early-time inflation
  - post-inflationary reheating

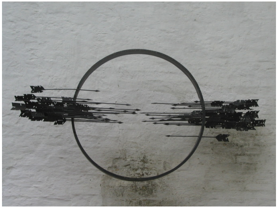
Outline

1. Higgs in SM
2. Unexplained phenomena
3. Possible roles of the Higgs in all above

Outline

LHC in numbers





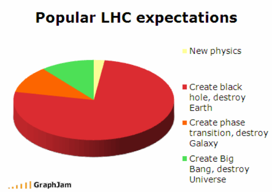
Achieved in *pp*-collisions

- E_{pp} : 7 TeV (2011), 8 TeV (2012)
- $\int \mathscr{L}_{pp}\, dt \sim 30$ fbarn^{-1}

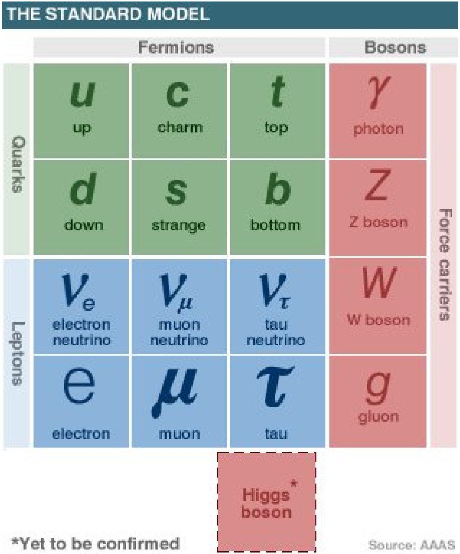
Plans: from 2015

- $E_{pp} = 13$ TeV
- $\mathscr{L}_{pp} = 30$ fbarn^{-1}year^{-1}
- $\sim 10^9$ *pp*-collisions in second

NB: $E_{pp} \nearrow \quad \Longrightarrow \quad \mathscr{L}_{pp} \nearrow$



LHC for Particle physics



Most expected?

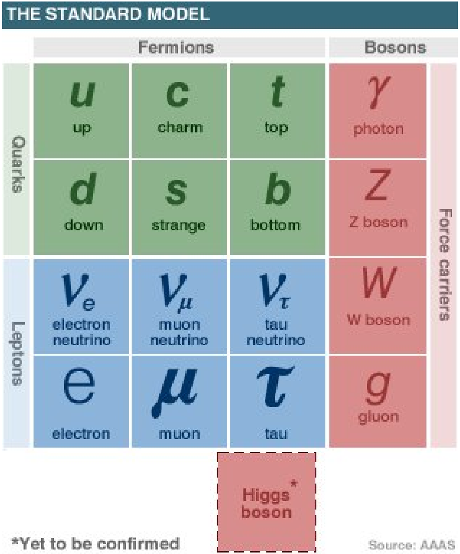
- Higgs boson!
- Higgs sector!

Other tasks in the SM

- Unitarity of CKM-matrix:
  - Absence of FCNC
  - Absence of new CP-phases
- EW-parameters
- t-quark physics
- Physics of B_s, B_c, b-baryons
- QCD
- . . .

NB: All things

LHC for Particle physics



Most expected?

- Higgs boson!
- Higgs sector!

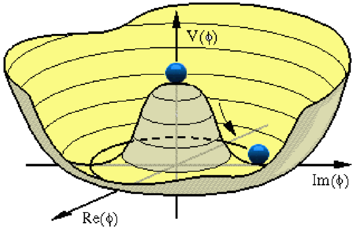
Other tasks in the SM

- Unitarity of CKM-matrix:
  - Absence of FCNC
  - Absence of new CP-phases
- EW-parameters
- t-quark physics
- Physics of B_s, B_c, b-baryons
- QCD
- ...

NB: All things

Higgs mechanism: spontaneous symmetry breaking

$$SU(3)_s \times SU(2)_w \times U(1)_Y \longrightarrow SU(3)_s \times U(1)_{em}$$



$$H \;:\quad (0,2,1) \longrightarrow \quad \langle H^\dagger H \rangle = \frac{\upsilon^2}{2}$$

$$\mathscr{L}^{self} = \mathscr{D}_\mu H^\dagger \mathscr{D}^\mu H - \lambda \left(H^\dagger H - \frac{\upsilon^2}{2} \right)^2$$

$$\mathscr{D}_\mu H \equiv \left(\partial_\mu - ig \frac{\tau^a}{2} V^a_\mu - ig' \frac{Y_H}{2} A_\mu \right) H$$

unitary gauge: $H = \begin{pmatrix} 0 \\ \frac{\upsilon}{\sqrt{2}} + \frac{h}{\sqrt{2}} \end{pmatrix}$

Role of the Higgs boson in SM: particle masses

unitary gauge: $$H = \begin{pmatrix} 0 \\ \frac{\upsilon}{\sqrt{2}} + \frac{h}{\sqrt{2}} \end{pmatrix}$$

$$\mathscr{D}_\mu H^\dagger \mathscr{D}^\mu H \longrightarrow \frac{g^2 \upsilon^2}{4} W_\mu^+ W^{\mu -} + \frac{\left(g^2 + g'^2\right) \upsilon^2}{8} Z_\mu Z^\mu$$

$$Y_j^l \bar{L}_j H E_j + h.c. \longrightarrow m_j \left(\bar{e}_{L_j} e_{R_j} + \bar{e}_{R_j} e_{L_j} \right)$$

$$L_1 \equiv \begin{pmatrix} \nu_e \\ e \end{pmatrix}_{\mathrm{L}} , \quad E_1 \equiv e_{\mathrm{R}} , \quad m_j = Y_j \frac{\upsilon}{\sqrt{2}}$$

$$M_W = \frac{g\upsilon}{2} \approx 80\,\mathrm{GeV} \longrightarrow \upsilon \approx 250\,\mathrm{GeV}$$

Checks

$$\text{unitary gauge:} \quad H = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} + \frac{h}{\sqrt{2}} \end{pmatrix}$$

$$\mathscr{D}_\mu H^\dagger \mathscr{D}^\mu H \longrightarrow \frac{g^2}{4} h^2 |W_\mu^-|^2 + \frac{g^2 + g'^2}{8} h^2 Z_\mu Z^\mu + \frac{g^2}{2} v h |W_\mu^-|^2 + \frac{g^2 + g'^2}{4} v h Z_\mu Z^\mu$$

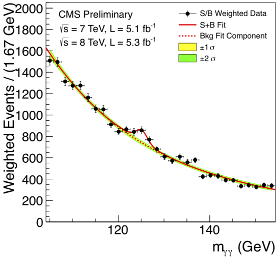
$$Y_f H \bar{f} f \longrightarrow Y_f h \bar{f} f / \sqrt{2} = \frac{m_f}{v} h \bar{f} f$$

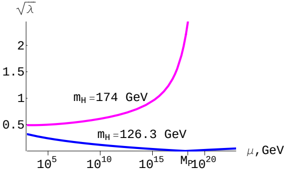
Numerically:

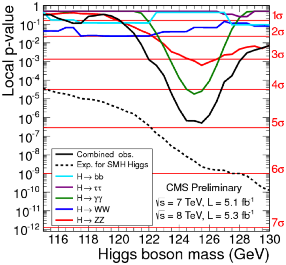
$$g \approx 0.5,\ g' \approx 0.3,\ Y_f = 10^{-6} - 10^{-2},\ Y_b \approx 1/40,\ Y_t \approx 1$$

1. New (5th) short-range force: Yukawa potential between massive particles!
2. Unitarity in $WW \to WW$
3. Unitarity in $f\bar{f} \to WW$

LEPII, TeVatron & LHC: . . . Higgs of 126 GeV?

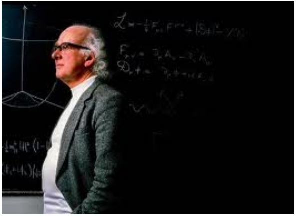






- LEPII: $m_h > 114\,\text{GeV}$
- fit to EW data: $m_h \sim 90 < 114\,\text{GeV}$
- TeVatron: not in $156 < m_h < 177\,\text{GeV}$
- CMS: not in $127 < m_h < 600\,\text{GeV}$
- ATLAS: not in 114-115, 131-237, 251-453 GeV

$$m_h = \sqrt{2\lambda}\,v$$



$$\lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2$$

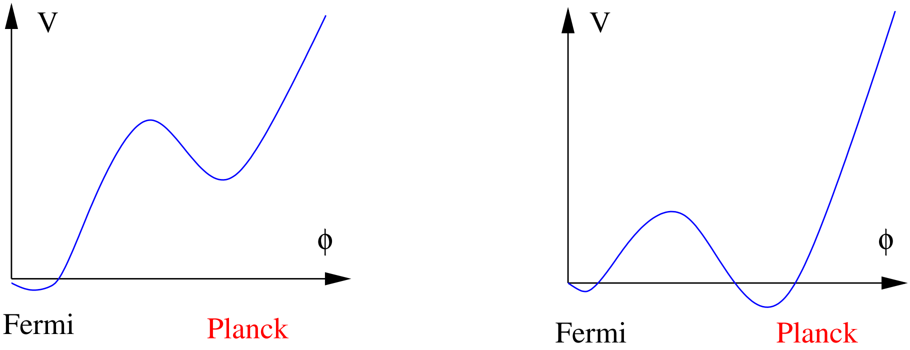
$$\to \frac{\lambda}{4}h^4 + \lambda v^2 h^2$$

$$\mathcal{L}_Y \propto Y_f h \bar{f} f/\sqrt{2}$$

- renormgroup equation
$$\frac{d\lambda}{d\log\mu} \propto +\#\lambda^2 - \#Y_t^4$$
- 126 GeV: Looks as the SM Higgs. . . ?

QCD-background, QCD-corrections, . . .

Multiple point principle: D.Bennett, H.Nielsen (1993), C.Froggatt, H.Nielsen (1995)

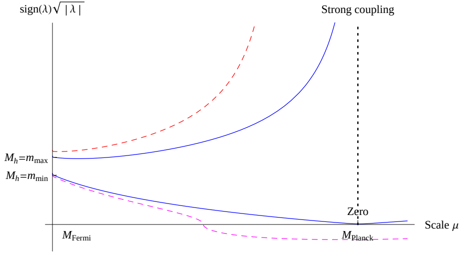


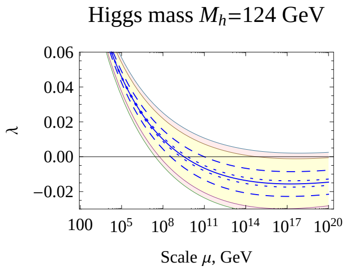
$$\Lambda \simeq 0 \;\Rightarrow V(\phi_{EW}) = V(\phi_{Planck}) = 0 \Rightarrow \lambda(\mu_{Planck}) = 0$$

Planck scale enters $\Rightarrow V'(\phi_{EW}) = V'(\phi_{Planck}) = 0 \Rightarrow \frac{d\lambda(\mu)}{d\log\mu}(\mu_{Planck}) = 0$

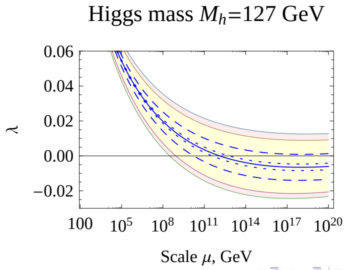
It gives $m_t \simeq 173$ GeV and $m_h \simeq 129$ GeV

Critical point: where EW-vacuum becomes unstable





F.Bezrukov, M.Shaposhnikov (2009)
F.Bezrukov, D.G. (2011)
F.Bezrukov, M.Kalmykov, B.Kniehl, M.Shaposhnikov (2012)
G. Degrassi et al (2012)



$$m_h^{cr} > \left[129.0 + \frac{m_t - 172.9\,\text{GeV}}{1.1\,\text{GeV}} \times 2.2 - \frac{\alpha_s(M_Z) - 0.1181}{0.0007} \times 0.56\right]\,\text{GeV}$$

present measurements at CMS and ATLAS:

$$m_h \simeq 125.8 \pm 0.9\,\text{GeV}$$

Upper limit on the Higgs boson mass

F.Bezrukov, M.Shaposhnikov (2009)
F.Bezrukov, D.G. (2011)
F.Bezrukov, M.Kalmykov, B.Kniehl, M.Shaposhnikov (2012)
G. Degrassi et al (2012)

$$m_h^{cr} > \left[129.0 + \frac{m_t - 172.9\,\text{GeV}}{1.1\,\text{GeV}} \times 2.2 - \frac{\alpha_s(M_Z) - 0.1181}{0.0007} \times 0.56\right] \text{GeV}$$

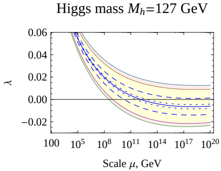
critical value refers to $\lambda(h \to M_P) \to 0$

May be important for pre-Big-Bang history...
say, at inflation naturally $h \sim H$

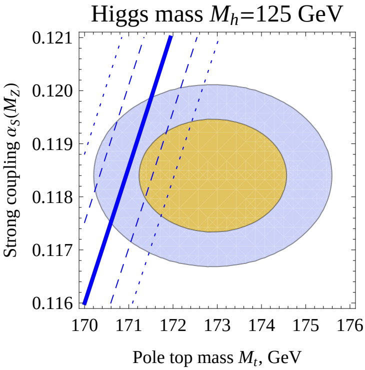
May be important for pre Hot-Big-Bang History

$$\frac{d\lambda}{d\log\mu} = +\#\lambda^2 - Y_t^4 + \alpha_W + \dots$$

Can end up in Wrong vacuum...



errors in M_W give uncertainties < 0.2 GeV

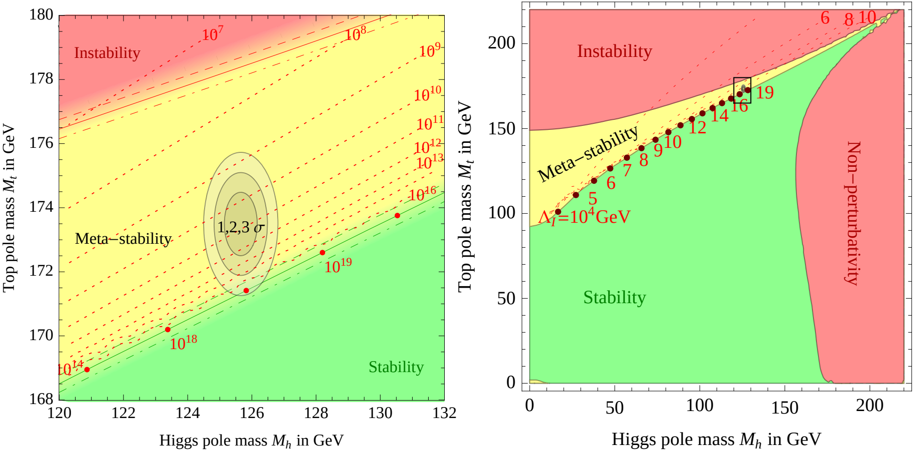


Experimental uncertainties: 2-3 GeV
Theoretical uncertainties: < 0.2 GeV

Important for further improvement:

- 3-loop matching and QCD for t
- measurement of α_s, m_t and m_h at LHC(?)

The SM Higgs of 126 GeV: naturality...?



1307.7879

The SM Higgs boson (?) found @ 126 GeV

- When the digit matters. . . !!
- Smooth incorporation of gravity @ M_{Pl}?

  – Great desert up to Gravity scale (asymptotic safety?)

  (no gauge hierarchy problem: all NP we need is either @ EW-scale or in gravity sector)

  – viable (ν, DM, BAU) SM extensions: R^2-inflation with νMSM, Higgs-inflation (can $S^2 H^\dagger H$ help?), . . .
- It's another scale: e.g. PQ-scale, or Leptogenesis, etc
- Just a coincidence, e.g. as GUT

  – gauge coupling unification $\to$ (gauge hierarchy problem, then not at a single point) $\to$ SUSY

  – there are other "hints":

  $m_h^2 \approx m_Z m_t$, $\quad m_h \approx v/2 \approx 3m_Z/2$, $\quad \lambda\,(m_h = 126 \text{ GeV}) \approx 0.126$

  Is Nature aware of GeV and decimal system?

Checks of the SM Higgs couplings

$$\mathscr{D}_\mu H^\dagger \mathscr{D}^\mu H \longrightarrow$$

unitary gauge: $H = \begin{pmatrix} 0 \\ \frac{\upsilon}{\sqrt{2}} + \frac{h}{\sqrt{2}} \end{pmatrix}$

$$\frac{g^2}{4} h^2 |W_\mu^-|^2 + \frac{g^2+g'^2}{8} h^2 Z_\mu Z^\mu + \frac{g^2}{2} \upsilon h |W_\mu^-|^2 + \frac{g^2+g'^2}{4} \upsilon h Z_\mu Z^\mu$$

$$Y_f H \bar{f} f \longrightarrow Y_f h \bar{f} f / \sqrt{2} = \frac{m_f}{\upsilon} h \bar{f} f$$

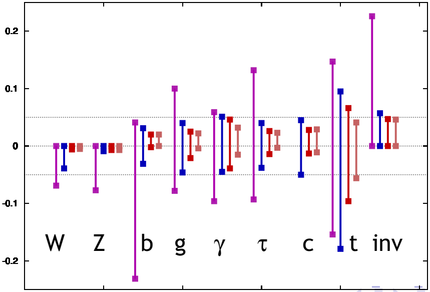
Numerically:

$g \approx 0.5,\ g' \approx 0.3,$

$Y_f = 10^{-6} - 10^{-2},$

$Y_b \approx 1/40,\ Y_t \approx 1$

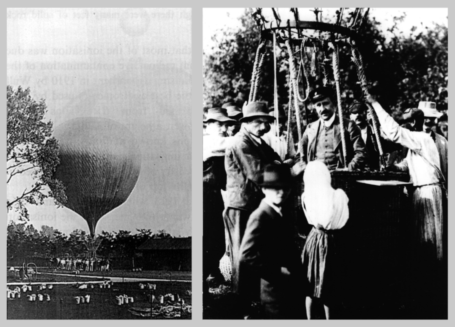
g(hAA)/g(hAA)|$_{SM}$-1 LHC/ILC1/ILC/ILCTeV



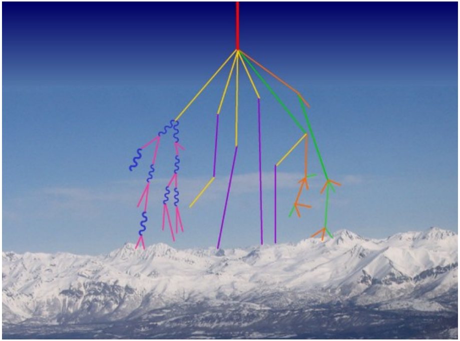
M.Peskin (2012)

century of Particle Physics ends with Nobel in 2013?

Discovery: Victor Hess, 1912



- Spontaneous discharge of electroscopes
- Even in a closed vessel!
- Rate drops with depth and grows with height! $\nearrow$5300m
- Penetrating radiation not from Sun!



- 1932: discovery of positron e^+ "anti"
- 1937: discovery of muons $\mu^+ \mu^-$ and their decays 2nd generation
- 1947: discovery of π-mesons hadrons, multiparticle production
- 1955: discovery of K-mesons and neutral hyperons "strangeness"

Checks in the SM Higgs sector

1. Gives masses to all particles, which at LHC can be proved only for vector bosons and 3rd generation fermions. . .
2. At which level of precision we have (want?) to check the Higgs boson couplings? Y_e is always unobservable
3. New (5th) short-range force: Yukawa potential between massive particles!
4. Unitarity in $WW \to WW$ $\varepsilon^\mu \propto p^\mu/M_W$
5. Unitarity in $f\bar{f} \to WW$ $gg \to t\bar{t}W^+W^-$
   needs both high energy and lumonosity!
6. Higgs mechanism: $\lambda h^4, \lambda \upsilon h^3$ . . . muon collider?
7. Higgs boson mass. . . last unknown CM parameter

Which couplings are most interesting?

Outline

Standard Model: Success and Problems

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP: ? (boundary terms, new topology, ...)
  - Gauge hierarchy: ? (No new scales!)
  - Quantum gravity

Try to explain all above

Planck-scale physics saves the day

Higgs sector can be not (exactly) like in SM. . .

- Could be 2 Higgs doublets! 5 particles

  EW baryogenesis: $T \sim 100\,\text{GeV}$

  within SM: not enough CP, not I order phase transition

- enter two of the three SM portals to hidden sectors (=SM-gauge singlets)

  $$\varepsilon B^{\mu\nu}_{U(1)_Y} B^{\mu\nu}_{U(1)_{Y'}} \qquad \alpha H^\dagger H \cdot \Phi^\dagger \Phi \qquad \beta \bar{L}^c \tilde{H} N^c + \text{h.c.}$$

  dimensionless coupling constants β, α, renormalizable interactions

  Dark Matter candidate:

  Natural CDM thermally produced in primordial plasma

  Singlet scalar field:

  $$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_0^2}{2} S^2 - \lambda S^2 H^\dagger H + \ldots$$

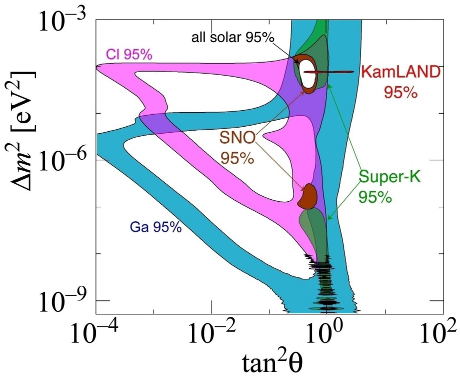
  direct searches for dark matter

- With additional scalars can avoid dimensionfull parameters in the SM:

  no v in (classical) Lagrangian

Neutrino oscillations: masses and mixing angles

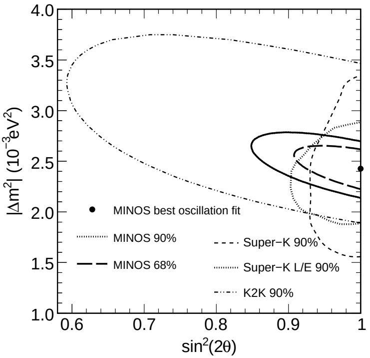
Solar 2×2 "subsector"



http://hitoshi.berkeley.edu/neutrino/

$m_1 > 0.008\,\text{eV}$

Atmospheric 2×2 "subsector"



arXiv:0806.2237

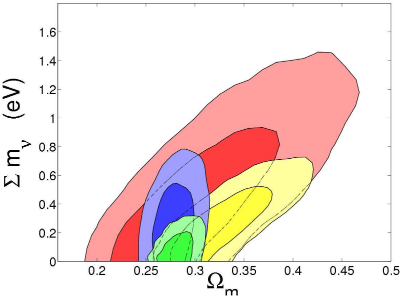
$m_2 > 0.05\,\text{eV}$

DAYA-BAY, RENO: $\sin^2 2\theta_{13} \approx 0.1$ also T2K

Cosmological limits on active neutrino masses

Neutrino contributions:
Start of structure formation
Gravity potentials at recombination
Late-time structure formation
Universe expansion

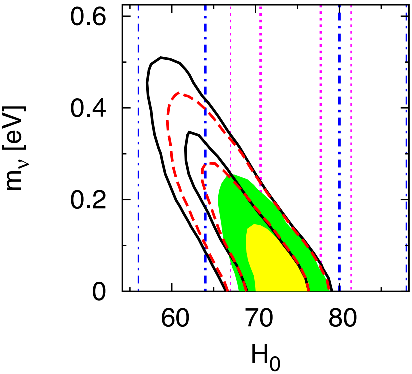
For $N_\nu = 3$ light neutrinos



LRG+BAO+WMAP5+SNe

$\sum m_\nu < 0.28$ eV (95% CL)

0911.5291, see also 1112.4940

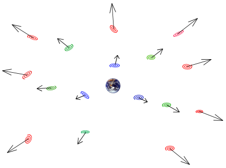


CMB+Hubble measurements

$\sum m_\nu < 0.20$ eV (95% CL)

0911.0976, see also 1202.2889

Conclusions from observations



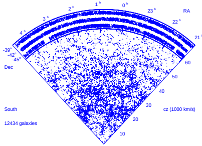
The Universe is homogeneous, isotropic, hot and expanding...

Conclusions

- interval between events gets modified

$$\Delta s^2 = c^2\,\Delta t^2 - a^2(t)\,\Delta \mathbf{x}^2$$

in GR expansion is described by the Friedmann equation



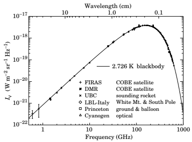
$$\left(\frac{\dot a}{a}\right)^2 = H^2(t) = \frac{8\pi}{3}\,G\rho^{\text{energy}}_{\text{density}}$$

$$\rho^{\text{energy}}_{\text{density}} = \rho_{\text{radiation}} + \rho_{\text{matter}} + \dots$$

- in the past the matter density was higher, our Universe was "hotter" filled with electromagnetic plasma

$$\rho_{\text{matter}} \propto 1/a^3(t)\,,\quad \rho_{\text{radiation}} \propto 1/a^4(t)\,,\quad \rho_{\text{curvature}} \propto 1/a^2(t)$$

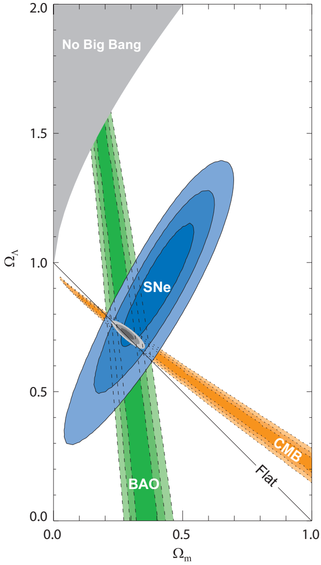
certainly known up to $T \sim 1\,\text{MeV} \sim 10^{10}\,\text{K}$



Why do we need dark components (within GR)?

- Astrophysical data favor Dark Matter
  - Observations in galaxies
  - Observations in galaxy clusters
- Cosmological data favor Dark Matter and Dark Energy
  - Observation of objects at cosmological distances (far=early)
  - Baryonic Aciustic (Sakharov) Oscillations (BAO) in two-point galaxy correlation function
  - Evolution of galaxy clasters in the Universe
  - Anisotropy of Cosmic Microwave Background (CMB)

Astrophysical and cosmological data are in agreement



$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{density}}^{\text{energy}}$$

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}}^{\text{ordinary}} + \rho_{\text{matter}}^{\text{dark}} + \rho_\Lambda$$

$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

$$\rho_\Lambda = \text{const}$$

$$\frac{3H_0^2}{8\pi G} = \rho_{\text{density}}^{\text{energy}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5}\,\frac{\text{GeV}}{\text{cm}^3}$$

radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}$

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.046$

Neutrino: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

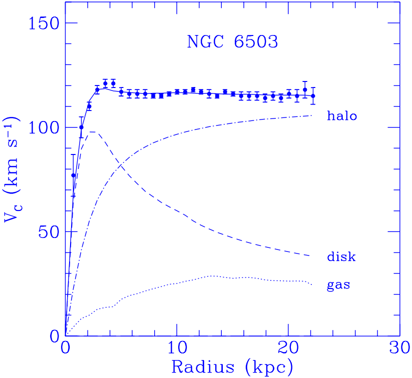
Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.23$

Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.73$

Galactic dark halos: flat rotation curves

$$v(R) = \sqrt{G\frac{M(R)}{R}}$$

$$M(R) = 4\pi\int_0^R \rho(r) r^2 dr$$



observations: $v(R) \simeq \text{const}$

visible matter: internal regions $v(R) \propto \sqrt{R}$

external ("empty") regions $v(R) \propto 1/\sqrt{R}$

Dark Matter in clusters

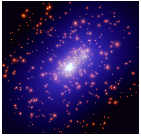
X-rays from hot gas in clusters SZ-effect in CMB

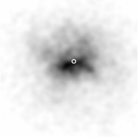
$$\frac{dP}{dR} = -\mu n_e(R) m_p \frac{GM(R)}{R^2}\ , \quad M(R) = 4\pi \int_0^R \rho(r) r^2 dr\ , \quad P(R) = n_e(R) T_e(R)$$

galaxies in clusters virial theorem

$$U + 2E_k = 0$$

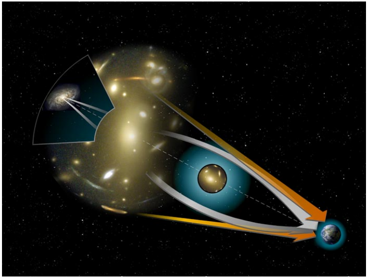
$$3M\langle v_r^2 \rangle = G\frac{M^2}{R}$$



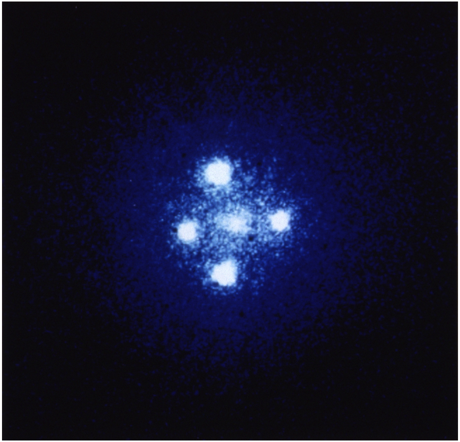


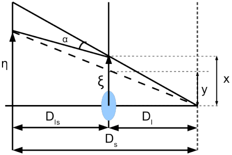
Milky Way: Virgo infall

Gravitational lensing in GR: $\alpha = 4GM/(c^2 b)$



Einstein Cross





$$\vec{\eta} = \frac{D_s}{D_l}\,\vec{\xi} - D_{ls}\,\vec{\alpha}\left(\vec{\xi}\right)$$

common lens
with specific
refraction
coefficient

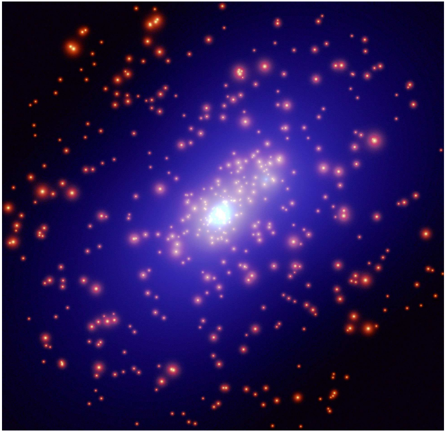
$$\vec{\alpha}\left(\vec{\xi}\right) = \frac{4G}{c}\int \frac{\vec{\xi}-\vec{\xi}'}{\left|\vec{\xi}-\vec{\xi}'\right|^2}\, d^2\xi' \int \rho\left(\vec{\xi}',z\right)dz$$

source: quasar $D_s = 2.4$ Gpc

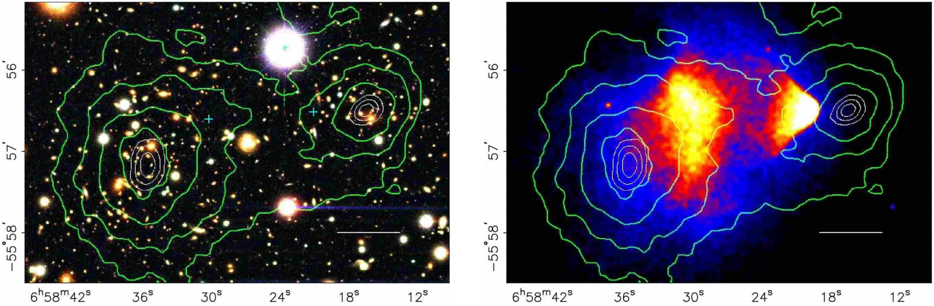
lens: galaxy $D_l = 120$ Mpc

Dark Matter in clusters

gravitational lensing $\rho_B \approx 0.25\rho_{DM}$



Colliding clusters (Bullet clusters 1E0657-558)



gravitational lensing

Observations in X-rays

$M \simeq 10 \times m$

scale is 200 kpc

clusters are at 1.5 Gpc

Dark Matter Properties $p = 0$

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

If were in thermal equilibrium: $M_X \gtrsim 1$ keV

If not: for bosons

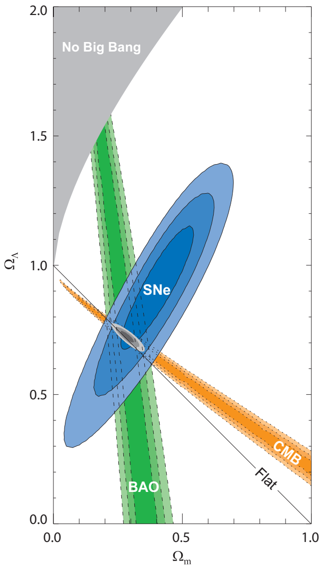
$\lambda = 2\pi/(M_X v_X)$, in a galaxy $v_X \sim 0.5 \cdot 10^{-3} \longrightarrow M_X \gtrsim 3 \cdot 10^{-22}$ eV

for fermions

Pauli blocking: $M_X \gtrsim 750$ eV

$$f(\mathbf{p}, \mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}} \Bigg|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Astrophysical and cosmological data are in agreement



$$\left(\frac{\dot a}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G\rho_{\text{density}}^{\text{energy}}$$

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}}^{\text{ordinary}} + \rho_{\text{matter}}^{\text{dark}} + \rho_\Lambda$$

$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

$$\rho_\Lambda = \text{const}$$

$$\frac{3H_0^2}{8\pi G} = \rho_{\text{density}}^{\text{energy}}(t_0) \equiv \rho_c \approx 0.53\times 10^{-5}\,\frac{\text{GeV}}{\text{cm}^3}$$

radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5\times 10^{-4}$

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.046$

Neutrino: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.23$

Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.73$

Determination of $a(t)$ reveals the composition of the present Universe

$\Delta s^2 = c^2 \Delta t^2 - a^2(t) \Delta \vec{x}^2 \rightarrow ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

Light propagation changes...

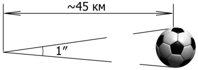
How do we check it?

by measuring distance L to an object!

- Measuring angular size θ of an object of known size d

single-type galaxies

$$\theta = \frac{d}{L}$$



- Measuring angular size $\theta(t)$ corresponding to physical size $d(t)$ with known evolution

$$\theta(t) = \frac{d(t)}{L}$$

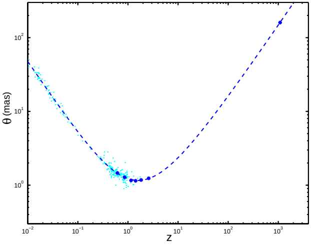
- Measuring brightness J of an object of known luminosity F

"standard candles"

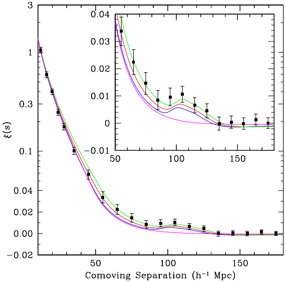
$$J = \frac{F}{4\pi L^2}$$

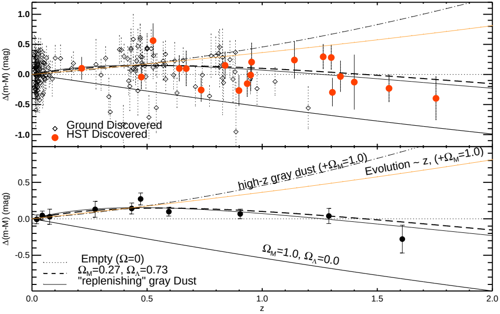
In the expanding Universe all these laws get modified

Results of distance measurements



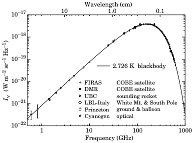
$$\Delta(m-M) = 5\log\frac{r_{ph}}{r_{ph}(\Omega_c = 0.8, \Omega_M = 0.2)}$$

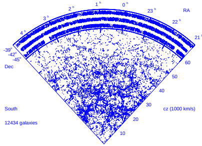


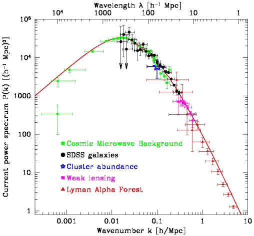


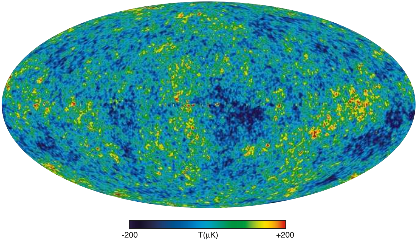
Key observable: matter perturbations

- CMB is isotropic, but "up to corrections, of course..."
  1. Earth movement with respect to CMB
     $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  2. More complex anisotropy!
     $$\frac{\Delta T}{T} \sim 10^{-4} - 10^{-5}$$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of recombination ($e + p \to \gamma + H^*$)
- Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow$ $\Longrightarrow$ galaxies (CDM halos)
-

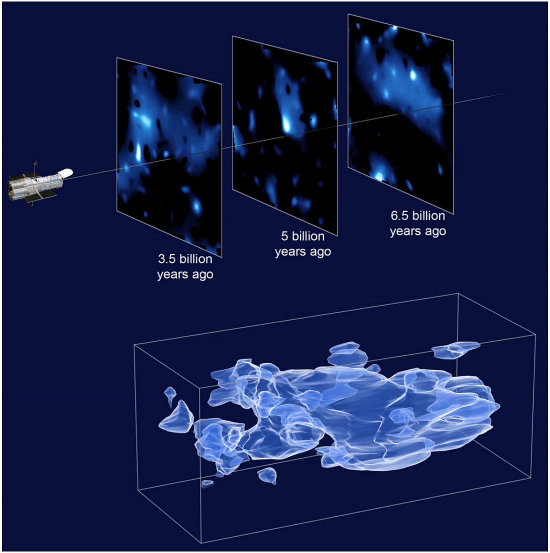








LSS: structure counts, weak lensing of CMB



Conclusions on (absence of) NP signal

- Let's wait for a while...
- If NP is discovered @ 1 TeV...
  – hint to some fundamental principle: why no FCNC?
  (conformal symmetry, etc)
  – careful study of the Higgs sector and CP-violation (EDMs):
  to test EW-baryogenesis in the SM-extension
- If we prove the SM @ 1 TeV...
  – Baryogenesis happened not @ EW-scale
  – DM-particles apparently are not WIMPs
  (axion $\to$ ADMX, sterile neutrinos $\to$ X-ray telescopes, mirror baryons $\to$ OPs$\to$nothing, etc)
  – May be, the minimal principle is at work (to be tested @ LHC):
  e.g., for DM: $V = m_X^2 X^2 + \beta X^2 H^\dagger H$

Future HL-LHC and HE-LHC may contribute to

- Higgs and top masses: . . . unification with gravity?
- Higgs sector:
- There are extensions of the SM capable of explaining ν, DM and BAU with NP below 100 GeV, but unreachable @ LHC
- But there are simple extensions (ν, DM and BAU) untestable (not only @ LHC) in the foreseeable future

Outline

Backup slides

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV… hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV... hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV… hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV… hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV... hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV... hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV… hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV… hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV... hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV... hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV... hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM

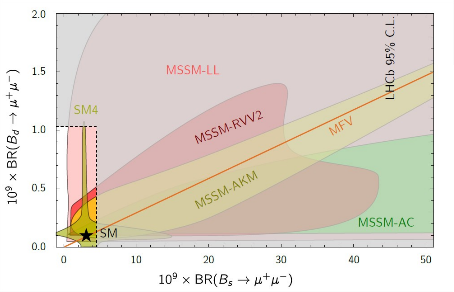
- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden $100\text{ GeV} < E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden $100\text{ GeV} < E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV... hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

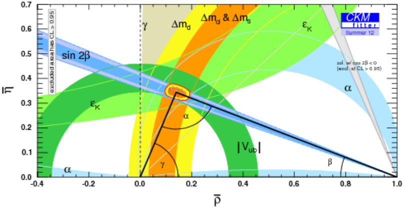
Physics beyond the SM

- neutrino oscillations: masses are needed
  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
- dark matter phenomena: Why $\Omega_B \sim \Omega_{DM}$? neutral stable particle
  a lack of gravity is observed: WIMPs @ EW? modified gravity?
- Hot Big Bang problems: inflation
  new scalars or interactions,
  but the scale is hidden 100 GeV $< E < M_{Pl}$
- strong CP-problem: axion
  requires NP @ $E > 10^{10}$ GeV... hierarchy problem?
- gauge hierarchy problem: NP @ EW-scale
  a) no new fields — no problem! b) already have to cancel Λ

Physics beyond the SM: no any signs in

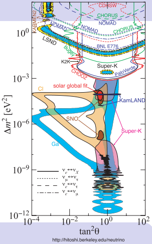
- direct production of new particles: superpartners, KK-excitations, techno-resonances, etc
- rare processes: quantum correction from new (heavy) particles





νMSM

- Use as little “new physics” as possible
- Require to get the correct neutrino oscillations
- Explain DM and baryon asymmetry of the Universe



Lagrangian

Most general renormalizable with 3 right-handed neutrinos N_I

$$\mathscr{L}_{\nu MSM} = \mathscr{L}_{MSM} + \overline{N}_I i \partial\!\!\!/ N_I - f_{I\alpha} H \overline{N}_I L_\alpha - \frac{M_I}{2} \overline{N}_I^c N_I + \text{h.c.}$$

Extra coupling constants:

3 Majorana masses M_i — T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

15 new Yukawa couplings — T.Asaka, M.Shaposhnikov (2005)

(Dirac mass matrix $M^D = f_{I\alpha}\langle H \rangle$ has 3 Dirac masses, 6 mixing angles and 6 CP-violating phases)