Neutrino and cosmology

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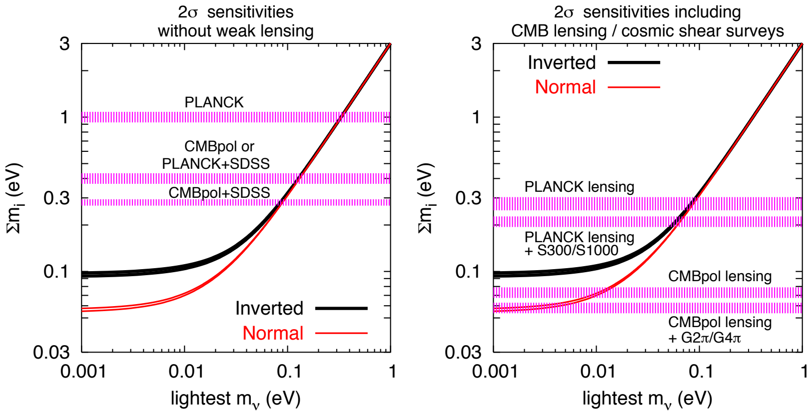
6-15 September 2012, Alushta

Summary of future sensitivities



Lesgourgues & Pastor, Phys. Rep. 429 (2006) 307

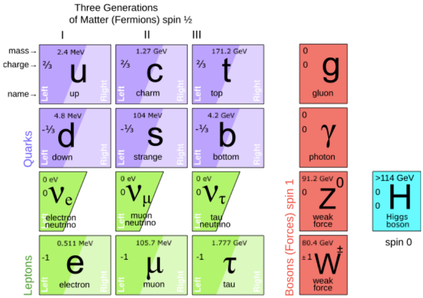
Summary of future sensitivities

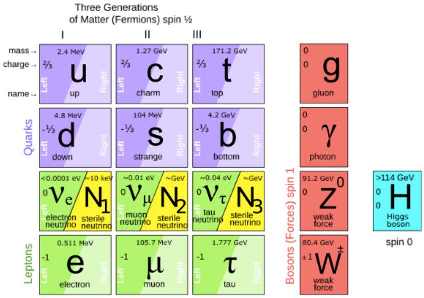
- Planck by itself will be able to constrain N_{eff} at the 0.2 level with 68% confidence
- CMBR experiments alone are insensitive to $m < \mathbf{0.3\ eV}$ (this value corresponds to recombination temperature)
- With Planck + LSST or EUCLID, a 68% sensitivity to $m < \mathbf{0.05\ eV}$ may be possible
- The same for Planck + future galaxy cluster surveys

Light Sterile Neutrinos: A White Paper, 2012

- SRG, Russian-German space mission, launch planned for 2013.
- Large Synoptic Survey Telescope (LSST), Chile. First light at the beginning of 2020.
- EUCLID, European space mission, launch planned for 2019.

Sterile Neutrino





Sterile Neutrino

Consider Standard Model with minimal extention to include right handed neutrino N_j, ($j = 1, 2, 3$)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\bar{N}_j \partial_\mu \gamma^\mu N_j - \left[\lambda_{ji} N_j (H L_i) + \frac{M_{ji}}{2} N_j N_i + \mathrm{h.c.} \right]$$

Here M - Majorana mass of sterile neutrino,
$m_D = \lambda v$ - Dirac mass, $v = \langle H \rangle = 174\ \mathrm{GeV}$.

If $\lambda v \ll M$ the see-saw formula works

$$m_\nu = -m_D \frac{1}{M} m_D^T$$

Scale of M cannot be extracted from low-energy experiments: multiply m_D by x and M by x^2, m_ν does not change.

Sterile Neutrino

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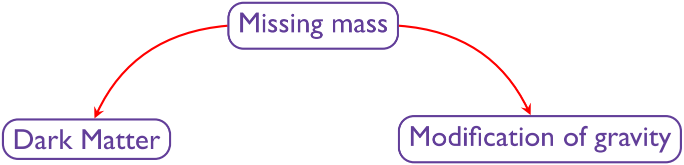
This model can explain a number of observations:

- Neutrino masses and oscillations;
- $M_1 \gtrsim 10^8\ \mathrm{GeV}$ - baryon asymmetry; *Fukugita & Yanagida, (86)*
- $M_1 \gtrsim 1\ \mathrm{keV}$ - dark matter; *Dodelson & Widrow (94)*
- $M_1 \gtrsim 1\ \mathrm{keV}$ and $M_2, M_3 \sim 1\ \mathrm{GeV}$ - baryon asymmetry and dark matter (NuMSM). *Asaka & Shaposhnikov (05)*

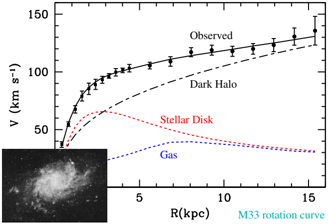
Missing mass: alternatives



Missing mass

Dark Matter

Modification of gravity



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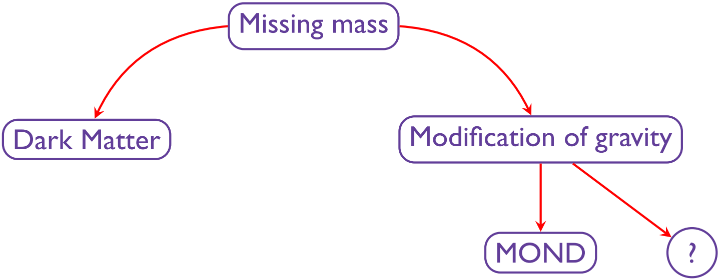

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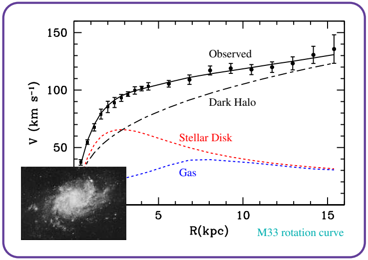
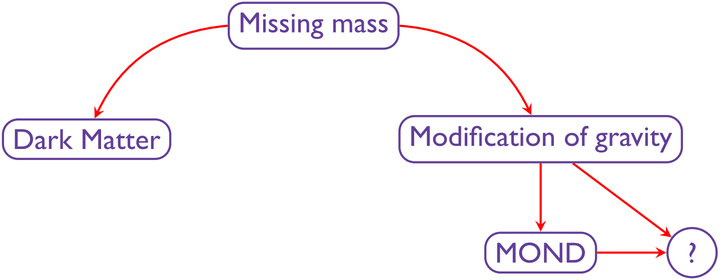
MOND

?



M33 rotation curve

Missing mass: alternatives



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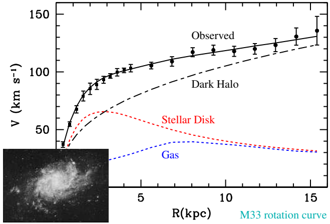

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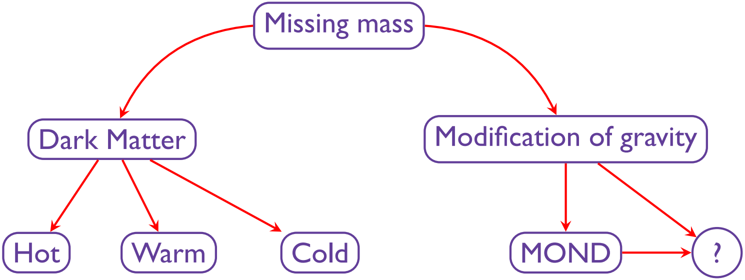


Missing mass

Dark Matter

Modification of gravity

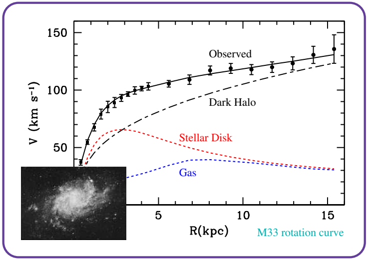
Hot

Warm

Cold

MOND

?



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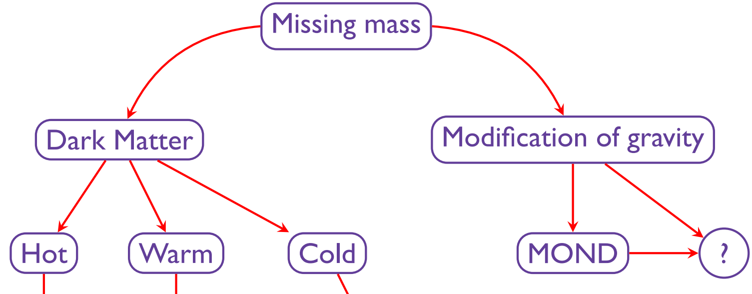


Missing mass

Dark Matter

Modification of gravity

Hot

Warm

Cold

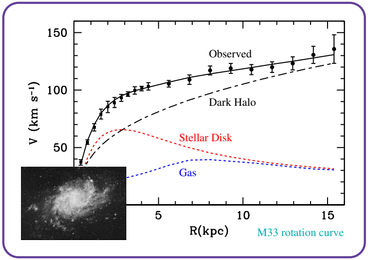
MOND

?

Ruled out

Best fit

Most popular



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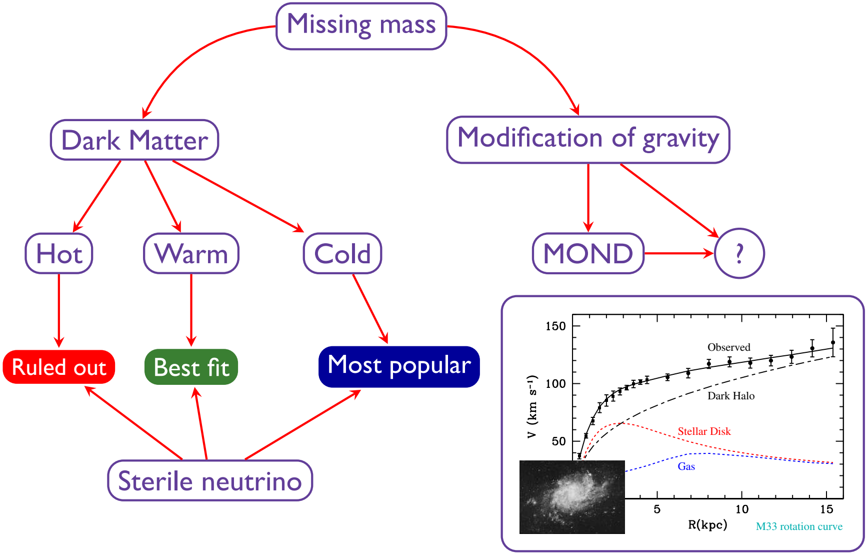

"Thermal" dark matter: some facts and definitions

- Cold if freeze-out temperature $< M_X$.
  Otherwise:
  - Hot if $M_X < 1\ \mathrm{eV}$
  - Warm if $M_X > 1\ \mathrm{eV}$

Free streaming length:

Horizon size at $T \sim M_X$ expanded to present epoch,

$$L_{fs} \sim \frac{M_{\mathrm{Pl}}}{T_0 M_X}$$

For $M_X \sim 1\ \mathrm{eV}$: $L_{fs} \sim 100\ \mathrm{Mpc}$.

Clearly ruled out.

For $M_X \sim 1\ \mathrm{keV}$: $L_{fs} \sim 0.1\ \mathrm{Mpc}$.

This is size of a dwarf galaxy. Therefore this is lower bound for M_X,

$$M_X > 1\ \mathrm{keV}$$

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Lightest sterile neutrino as dark matter

We have to find models and parameter ranges where this creature:

- Produced in correct amounts
- Is relatively stable
- Does not contradict cosmological and astrophysical constants

Lightest sterile neutrino as dark matter

Production mechanisms

- Directly in inflaton decays. *Shaposhnikov & I.T. (06)*

- Active-sterile oscillations. *Dodelson & Widrow (94)*

  Important parameter - mixing of active and sterile neutrino

$$\theta^2 = \frac{1}{M_1^2} \sum_{i=e\mu\tau} |\lambda^{1i} v|^2$$

Resulting abundance:

$$\Omega_s \sim \Omega_m \frac{\sin^2(2\theta)}{10^{-7}} \left(\frac{M}{1\ \mathrm{keV}} \right)^2$$

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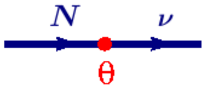

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$$\Omega_s \sim \Omega_m \frac{\sin^2(2\theta)}{10^{-7}} \left(\frac{M}{1\ \mathrm{keV}}\right)^2$$

Estimate of abundance

Production rate:

$$\Gamma = \theta^2 \Gamma_W \approx \theta^2 \sigma_W n \sim \theta^2 G_F^2 T^2 \cdot T^3$$

Multiply this by time, $t \sim H^{-1} \sim M_{\rm Pl}/T^2$ to get total number produced

$$\frac{n_1}{n_\gamma} = \theta^2 \, G_F^2 T^3 M_{\rm Pl}$$

Caveat:

Active sterile neutrino mixing is temperature dependent

$$\theta \to \theta_M = \frac{\theta}{1 + 2.4(T/200 \text{ MeV})^6 (\text{keV}/M_1)^2}$$

Dolgov, Hansen

Production temperature of sterile neutrino

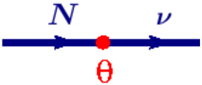
$$T \sim 130 \left(\frac{M_1}{1 \text{ keV}} \right)^{1/3} \text{ MeV}$$

Lightest sterile neutrino as dark matter

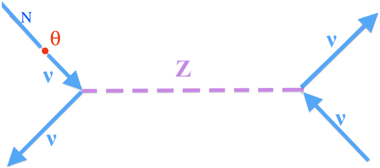
Lifetime

Important parameter - mixing of active and sterile neutrino

$$\theta^2 = \frac{1}{M_1^2}\sum_{i=e\mu\tau}|\lambda^{1i}v|^2$$



Main decay mode $N \to 3\nu$



Sterile neutrino can be long-living

Lifetime:

$$\tau_{N_1} = 5\times10^{26}\,\mathrm{sec}\left(\frac{1\ \mathrm{keV}}{M}\right)^5\left(\frac{10^{-8}}{\theta^2}\right)$$

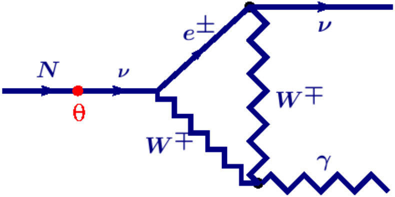
Light from dark matter

- Photon energy:

$$E_\gamma = \frac{M_1}{2}$$

- Radiative decay width

$$\Gamma = \frac{9\alpha_{\rm EM} G_F^2}{256\pi^4}\,\theta^2\, M_1^5$$



Dark matter made of sterile neutrino is not completely dark

Dolgov & Hansen (2000)

Where to search for sterile neutrinos?

$$F_{\rm dm} = \frac{\Gamma_{\rm rad}\, d\Omega\; I}{8\pi}, \qquad I = \int_{\text{line of sight}} \rho_{\rm dm}(r)\, dr$$

Strategy:

- Select objects with maximal value of I
- Select objects with minimal background
- Look for narrow emission line

Boyarsky, Neronov, Ruchayskiy, Shaposhnikov & I. T. (2006)

Where to search for sterile neutrinos?

$$F_{\mathrm{dm}} = \frac{\Gamma_{\mathrm{rad}}\, d\Omega\; I}{8\pi}, \qquad I = \int_{\text{line of sight}} \rho_{\mathrm{dm}}(r)\,dr$$

Value of I is approximately equal for various objects from dwarf galaxies to galaxy clusters

- Signal (value of I) from Milky Way halo is comparable to the signal from Virgo or Coma cluster
- Signal from Draco или Ursa Minor dwarfs is 3 times larger

Boyarsky, Neronov, Ruchayskiy, Shaposhnikov & I. T. (2006)

Where to search for sterile neutrinos?

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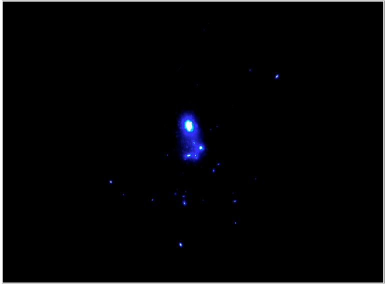
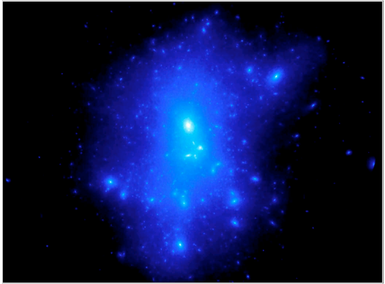
Annihilation

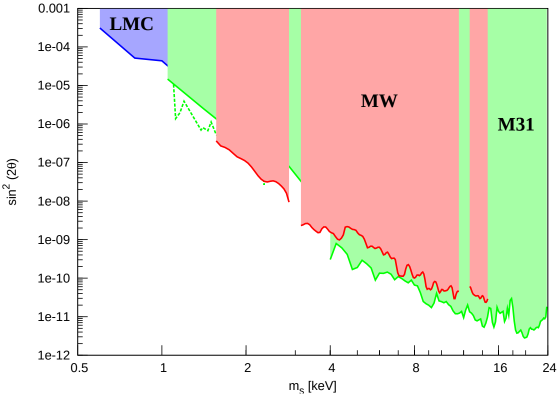


Decay



Ben Moore simulations for cold Dark Matter

Constraints on sterile neutrino parameters

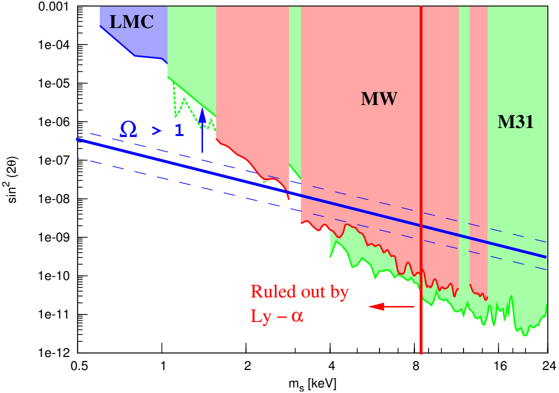


Constraints from X-rays

Best place to look for the decay line - dwarf satellites

Boyarsky, Neronov, Ruchayskiy, Shaposhnikov & I. T. (2006)

Constraints on sterile neutrino parameters

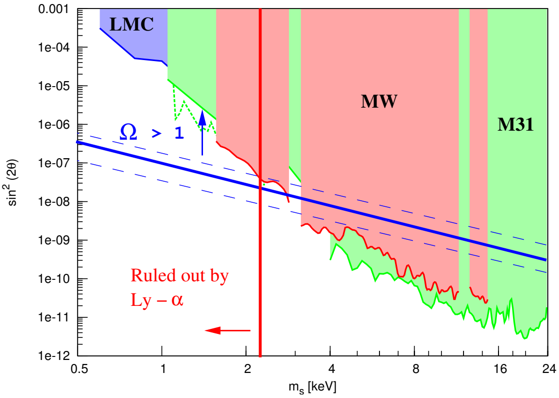


Above blue line: $\Omega_{\nu_s} > 1$ in active-sterile neutrino oscillations.

Dodelson & Widrow (94)
Asaka, Laine & Shaposhnikov (06)

Region to the left of red line is ruled out from Ly$_\alpha$
Seljak et al (06); Viel et al (06)

Constraints on sterile neutrino parameters



- Ω_{ν_s} и $\langle p \rangle$ are not determined by θ if lepton asymmetry is non-zero

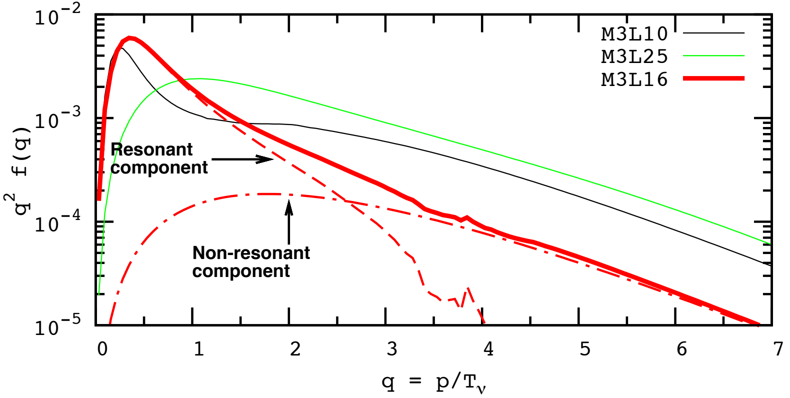
  Shi & Fuller (99)

- In inflaton decays correct Ω_{ν_s} can be obtained regardless of θ.

  Shaposhnikov & I.T. (06)

Resonant production

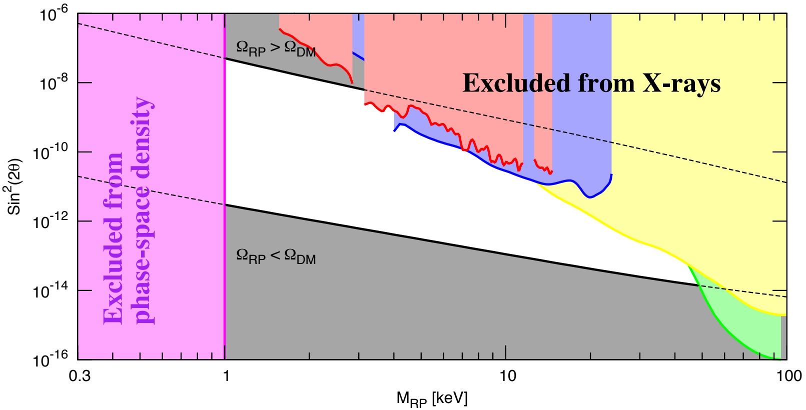
Requires large lepton asymmetry.



Phase space distribution function

Boyarsky et al 2009

Constraints on sterile neutrino parameters



Window corresponds to resonant production

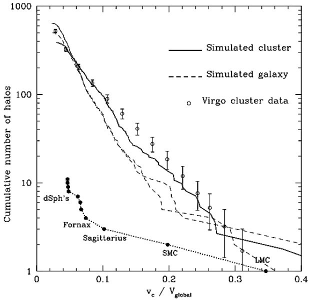
Upper boundary - zero lepton asymmetry

Lower boundary - maximal lepton asymmetry

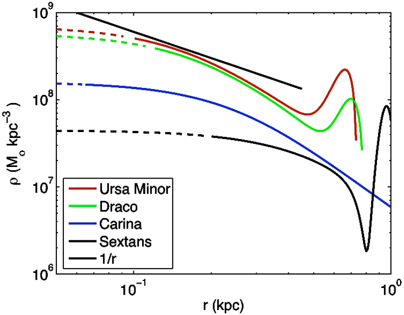
Boyarsky et al 2009

Cold Dark matter puzzles

CDM problems at small scales



Small number of dSph



Absence of cusps in density profiles of dSph

Warm dark matter

Galaxy halo:

CDM

WDM

2 keV non-thermal strile neutrino gives better fit to data

Lovell et al, 2011

Baryon asymmetry

In a comoving volume, at late times, entropy and the number of baryons are conserved. This gives important cosmological parameter, baryon asymmetry:

$$\Delta_B \equiv \frac{n_B - n_{\bar{B}}}{s} = \frac{n_\gamma}{s}\eta = 0.14\,\eta, \quad \text{where } \eta = \frac{n_B}{n_\gamma}$$

Observationally $\eta = (6.1 \pm 0.25) \times 10^{-10}$
This quantity should and can be understood dynamically within frameworks of the Big Bang.

Baryon asymmetry can be generated if

- Baryon number is not conserved
- C- and CP- are violated
- There are deviations from thermal equilibrium

Sakharov (1967), Kuzmin 1970)

Baryogenesis

Mechanisms:

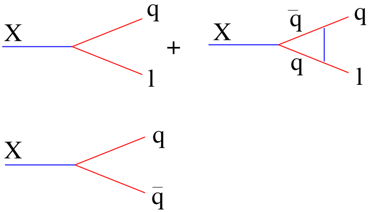
- Grand Unified Baryogenesis
- Electroweak baryogenesis
- Afflec-Dine mechanism
- Leptogenesis
    - thermal
    - at preheating
    - νMSM model
    - . . .
- . . .

Too many theories for a single number

Baryogenesis

Grand Unified Baryogenesis:

- Grand Unified Theories violate B



Out of equilibrium decays of heavy leptoquarks.

If C- and CP- are violated
$\Gamma(X \rightarrow q, l) \neq \Gamma(\bar{X} \rightarrow \bar{q}, \bar{l})$

- Most models based on SU(5) preserve $(B - L)$

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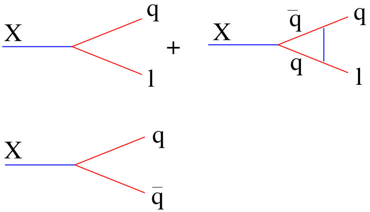

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Baryogenesis

Triangle anomalies in Standard Model violate the baryon and lepton numbers

$$\partial_\mu j_L^\mu = \partial_\mu j_B^\mu = \frac{g^2 n_F}{16\pi^2} W\tilde{W}$$

G. t'Hooft (1976)

- B-L is conserved
- At zero temperature violation is negligibly small
- W and Z bosons are massless at high temperatures
- W field fluctuates just like in thermal plasma

- Estimate of B-violating transition rate is $\Gamma \approx 20\alpha_W^5 T$.
- In thermal equilibrium at $T \gg M_W$ all preexisting B is washed out if B–L=0

Kuzmin, Rubakov, Shaposhnikov (1985)

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Baryogenesis

Choices:

- produce $(B\text{–}L)$ asymmetry above T_{EW}
  - e.g. leptogenesis from heavy ν_R
- produce $B = L$ at T_{EW}
  - e.g. electroweak baryogenesis
- produce B below T_{EW}

  e.g. exotic scalar field decays
- produce L below T_{EW}

  e.g. $\nu\mathrm{MSM}$

Sterile Neutrino

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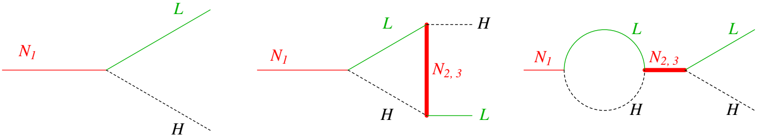
It can explain a number of observations:

- Neutrino masses and oscillations
- Dark matter in the Universe
- Baryon asymmetry of the Universe

Leptogenesis

- Presumably three ν_R
- One of them lives long and decays late
- Majorana: $\nu_R = \bar{\nu}_R$
- At tree-level, decays 50:50 to $L + H$ and $\bar{L} + H^*$
- At one-loop $\Gamma(\nu_R \to L + H) \neq \Gamma(\nu_R \to \bar{L} + H^*)$

How does it work?



$$\Gamma(N_1 \to LH) \propto \sum_i |\lambda_{1i} + \sum_{j,k} A\lambda^*_{1j}\lambda_{ki}\lambda_{kj}|^2,$$

To get $N_1 \to \bar{L}H^*$ make substitution $\lambda_{ij} \to \lambda^*_{ij}$.

Let's define:

$$[\lambda\lambda^\dagger]_{ij} \equiv \sum_k \lambda_{ik}\lambda^*_{kj}$$

$$\varepsilon_1 \equiv \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \bar{L}H^*)}{\Gamma_{tot}}$$

where

$$\Gamma_{tot} = \frac{M_1}{8\pi}[\lambda\lambda^\dagger]_{11}$$

How does it work?

In the limit

$$\varepsilon_1 = \frac{3}{16\pi} \frac{M_1}{[\lambda\lambda^\dagger]_{11}} \sum_{j\neq 1} \frac{\mathrm{Im}([\lambda\lambda^\dagger]_{1j})^2}{M_j}$$

Combinations of $[\lambda\lambda^\dagger]$ are not directly related to the light neutrino masses,

$$m_{ij} = -\frac{v^2}{2} \sum_k \frac{\lambda_{ki}\lambda_{kj}}{M_k}$$

although they look similar. In fact

$$|\varepsilon_1| \leq \frac{3}{16\pi} \frac{M_1}{v^2} (m_{\nu_3} - m_{\nu_1})$$

We need $\varepsilon_1 > 10^{-8}$. This gives $M_1 > 10^8\ \mathrm{GeV}$.

How does it work?

Resulting baryon asymmetry

$$\Delta_B = \frac{n_B}{s} = \frac{\varepsilon_1 n_{N_1}}{s}\gamma \approx \frac{\varepsilon_1}{g_*}\,\gamma.$$

$\gamma = 1$ for stronly out of equilibrium decays, $\Gamma_1 \ll H$. We have

$$\Gamma_{tot} = \frac{M_1}{8\pi}[\lambda\lambda^\dagger]_{11}, \qquad H = \frac{T^2}{M_{\rm Pl}^*}$$

Therefore, condition $\Gamma_1 \ll H$ at $T \sim M_1$ gives

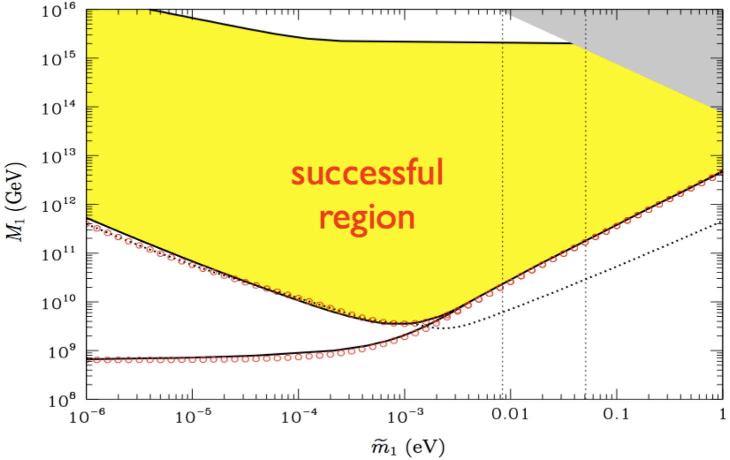
$$\tilde{m}_1 \ll \frac{4\pi}{M_{\rm Pl}^*}\,v^2 \sim 10^{-3}\ {\rm eV},$$

where

$$\tilde{m}_1 = \frac{[\lambda\lambda^\dagger]_{11}}{2M_1}\,v^2$$

is sum of |contributions| to the neutrino mass matrix due to N_1.

Non-trivial success!



di Bari, Plümacher, Buchmüller

Leptogenesis in NuMSM

Idea: sterile neutrino oscillations as source of baryon asymmetry.

- Sterile neutrino are created in the early universe and oscillate with CP breaking
- Total lepton number gets unevenly distributed between active and sterile neutrino
- The lepton number of active neutrinos is transferred to baryons due to sphalerons

Leptogenesis in NuMSM

Window for successful baryogenesis