Valery Rubakov & contemporary status of cosmology

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“From quarks to galaxies: elucidating dark sides”

Institute of High Energy Physics, IHEP
Protvino, Russia

Standard Model + GR : Major Problems

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

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

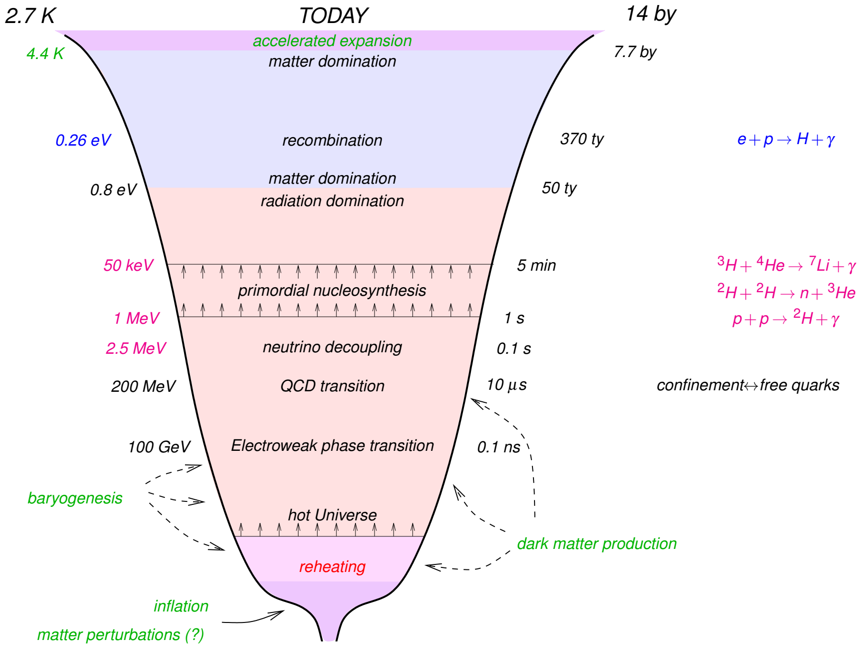
- Describes all experiments dealing with
  - electroweak and strong interactions (anomalies! $g-2$, B-physics, ...)
- Does not describe

(PHENO)

- Neutrino oscillations
- Dark matter (Ω_{DM})
- Baryon asymmetry (Ω_B)
- Why the Universe is flat and homogeneous?
- Where did the matter perturbations come from?

(THEORY)

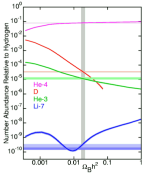
- Dark energy (Ω_Λ)
- Strong CP-problem
- Gauge hierarchy
- Quantum gravity
- Quantization of electric charge
- Why 3 generations?
- Why $Y_e \ll Y_\mu \ll .. \ll Y_t$



2.7 K
TODAY
14 by
accelerated expansion
4.4 K
matter domination
7.7 by
0.26 eV
recombination
370 ty
$e+p\to H+\gamma$
matter domination
0.8 eV
50 ty
radiation domination
50 keV
5 min
$^3H+{}^4He\to{}^7Li+\gamma$
primordial nucleosynthesis
$^2H+{}^2H\to n+{}^3He$
1 MeV
1 s
$p+p\to{}^2H+\gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation
matter perturbations (?)

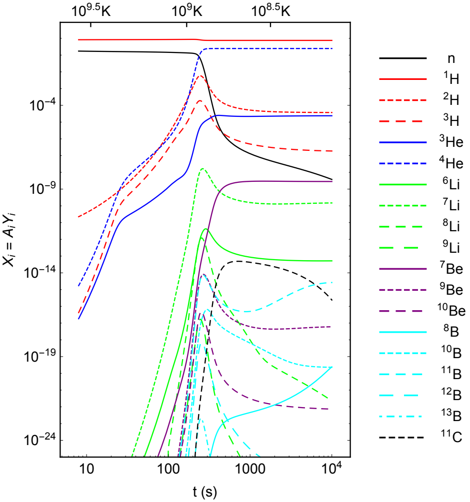
Present knowledge about the past: back to 2-3 MeV

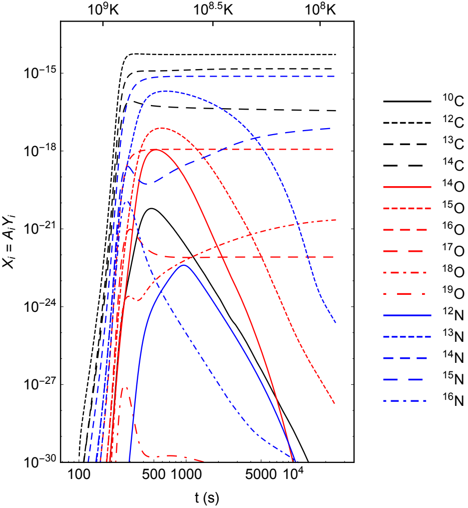
past stages		observables
deceleration/acceleration	$\ddot{a} = 0$	SN Ia, CMB, clusters
reionization	$\gamma + H \to p + e$	CMB, quasars, stars
recombination	$p + e \to \gamma + H^*$	CMB, BAO
RD/MD equality	$\rho_{\text{matter}} = \rho_{\text{radiation}}$	CMB, BAO
nucleosynthesis	$p + n \to D + \gamma,\ etc$	cold gas clouds
neutrino decoupling	$\nu_e + n \to p + e$	cold gas clouds



$$H^2 \propto \rho_\gamma + \rho_\nu$$

Nucleosynthesis





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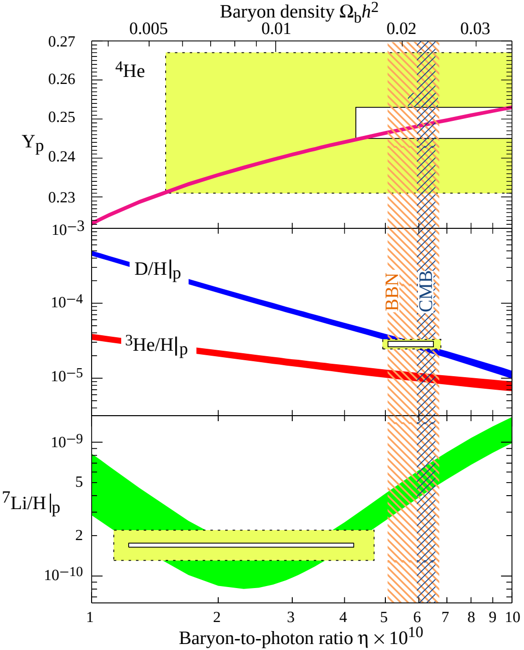


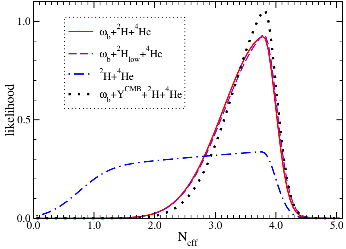
Measurement of $\eta_B = n_B/n_\gamma$
at $T \sim 1$ MeV

Lack of Lithium. . . Exotics needed?

$$Y_p = 0.2581 \pm 0.025\,,$$

$$D/H\big|_p = (2.87 \pm 0.21) \times 10^{-5}$$

1103.1261



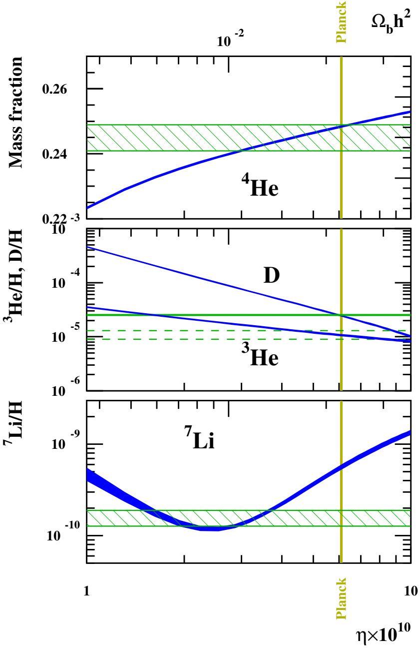
similar results from other recent studies including structure formation

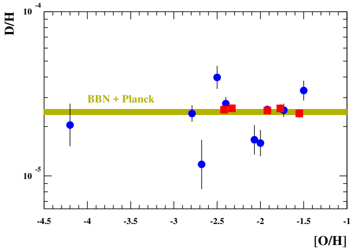
1001.4440, 1001.5218, 1202.2889

$N_{\nu,eff} < 4.2$ @ 95%CL

$N_{\nu,eff} < 4.0$ from D/H 1205.3785

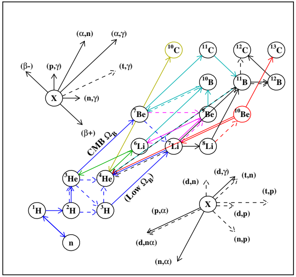
1707.01004 Measurement of $\eta_B = n_B/n_\gamma$ at $T \sim 1$ MeV





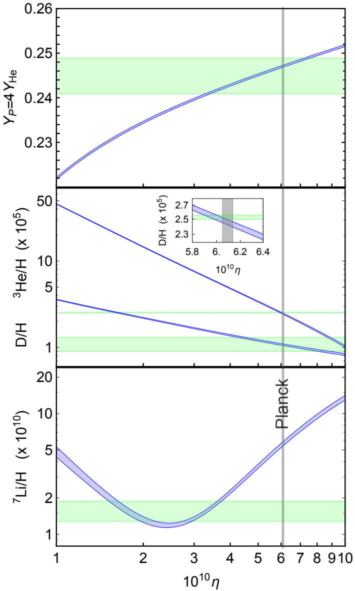
Lack of Lithium. . .

Exotics needed?

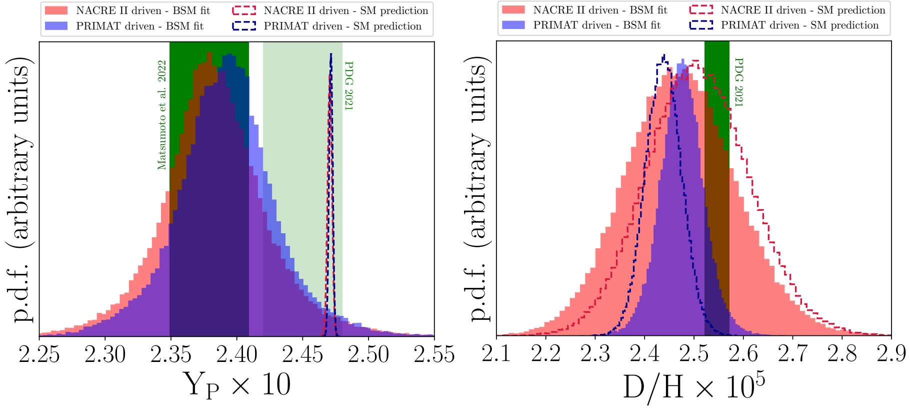


BBN $\eta = n_B/n_\gamma$

1. p + n $\to$ $\gamma + $ D
2. D + p $\to$ γ + ^{3}He
   D + D $\to$ n + ^{3}He
   D + D $\to$ p + T,
   ^{3}He+n $\to$ p+T
3. T + D $\to$ n^4 + He
   ^{3}He + D $\to$ p + ^{4}He
4. T + α $\to$ γ + ^{7}Li
   ^{3}He + α + γ $\to$ + ^{7}Be
   ^{7}Be + n $\to$ p + ^{7}Li
5. $^7\mathrm{Li} + p \to \alpha + {}^4\mathrm{He}$

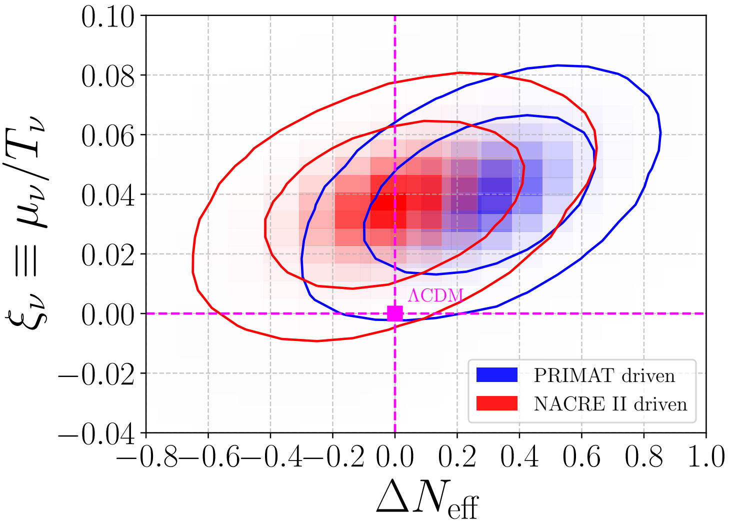


Nucleosynthesis: new measurements of D and He^4



2206.00693

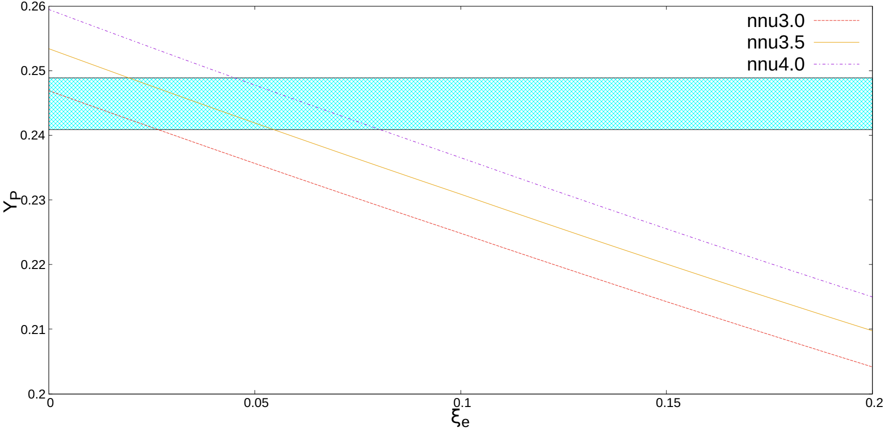
Nucleosynthesis: $n_n \propto e^{-\mu_\nu/T_\nu}$, $H_n^2 \propto (.. + \Delta N_\nu)$



2206.00693

BBN: extra-radiation and lepton asymmetry

2104.04381



Baryogenesis

Sakharov conditions of successful baryogenesis

- B-violation $(\Delta B \neq 0)\ XY\dots \to X'Y'\dots B$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)\ \bar{X}\bar{Y}\dots \to \bar{X}'\bar{Y}'\dots \bar{B}$
- processes above are out of equilibrium $X'Y'\dots B \to XY\dots$

Electroweak sphalerons & B by Kuzmin, Rubakov and Saposhnikov

$$\partial^\mu j_\mu{}^{\mathrm{B}} = 3\,\frac{g^2}{16\pi^2}\, V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\;,$$

$V^a{}_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + g\varepsilon^{abc} V^b_\mu V^c_\nu$ refer to $SU(2)_{\mathrm{W}}$, $\tilde{V}^a{}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\lambda\rho} V^{a\;\lambda\rho}$

Anomaly: only left fermions couple to fields V^a_μ.

For nontrivial gauge fields in vacuum or plasma

$$\Delta B = B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3\mathbf{x}\, \partial^\mu j^{\mathrm{B}}_\mu = 3\int_{t_i}^{t_f} d^4x\, \frac{g^2}{16\pi^2}\, V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\;,$$

Strong fields are needed: $V^a{}_{\mu\nu} \propto \frac{1}{g}$, (integral is a natural number!).

Energies of such configurations $\propto \frac{1}{g^2}$.

At temperatures 100 GeV $\lesssim T \lesssim 10^{12}$ GeV they are in equilibrium in primordial plasma !!

B gets violated

Electroweak sphalerons & $B-L$ by Kuzmin, Rubakov and Saposhnikov

$$\partial^\mu j_\mu{}^{B} = 3\,\frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\;,$$

$$\partial^\mu j_\mu{}^{Ln} = \frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\;,\quad n=1,2,3\;,$$

$V^a{}_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + g\varepsilon^{abc}V^b_\mu V^c_\nu$ refer to $SU(2)_W$, $\tilde{V}^a{}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\lambda\rho}V^{a\;\lambda\rho}$

Anomaly: only left fermions couple to fields V^a_μ.

For nontrivial gauge fields in vacuum or plasma

$$\Delta L_e = L_e(t_f) - L_e(t_i) = \int_{t_i}^{t_f} dt \int d^3\mathbf{x}\,\partial^\mu j^{Le}_\mu = 3\int_{t_i}^{t_f} d^4x\,\frac{g^2}{16\pi^2}\,V^{a\;\mu\nu}\,\tilde{V}^a{}_{\mu\nu}\;,$$

Strong fields are needed: $V^a{}_{\mu\nu} \propto \frac{1}{g}$, (integral is natural number!). Energies of such configurations $\propto \frac{1}{g^2}$.

$$\Delta B = 3\,\Delta L_e = 3\,\Delta L_\mu = 3\,\Delta L_\tau$$

At temperatures 100 GeV $\lesssim T \lesssim 10^{12}$ GeV sphalerons violate all four, but any 3 keep intact, e.g.

$$B-L\;,\quad L_e - L_\mu\;,\quad L_e - L_\tau$$

where $$L \equiv L_e + L_\mu + L_\tau$$

Baryogenesis $\to$ Leptogenesis by Kuzmin, Rubakov and Saposhnikov

Sakharov conditions of successful baryogenesis

- B(L)-violation $(\Delta B(L) \neq 0)\ XY \dots \to X'Y' \dots B(L)$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)\ \bar{X}\bar{Y} \dots \to \bar{X}'\bar{Y}' \dots \bar{B}(L)$
- processes above are out of equilibrium $X'Y' \dots B(L) \to XY \dots$

At 100 GeV$\lesssim T \lesssim 10^{12}$ GeV nonperturbative processes (EW-sphalerons) violate B, L_α, so that only three charges are conserved out of four, e.g.

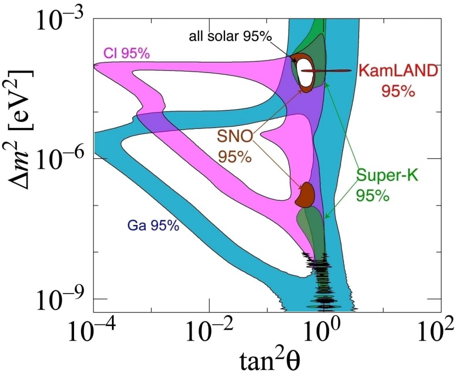
$$B - L\,, \quad L_e - L_\mu\,, \quad L_e - L_\tau$$

and $B = \alpha \times (B - L),\ L = (\alpha - 1) \times (B - L)$

Leptogenesis: Baryogenesis from lepton asymmetry of the Universe ... due to sterile neutrinos

Neutrino oscillations: masses and mixing angles

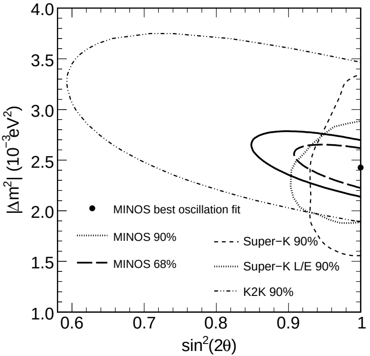
Solar 2×2 "subsector"



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

$m_{\rm sol}^2 \approx 7.4 \times 10^{-5}\,{\rm eV}^2$

Atmospheric 2×2 "subsector"



arXiv:0806.2237

$m_{\rm atm}^2 \approx 2.5 \times 10^{-3}\,{\rm eV}^2$

DAYA-BAY, RENO, T2K: $\sin^2 2\theta_{13} \approx 0.08$

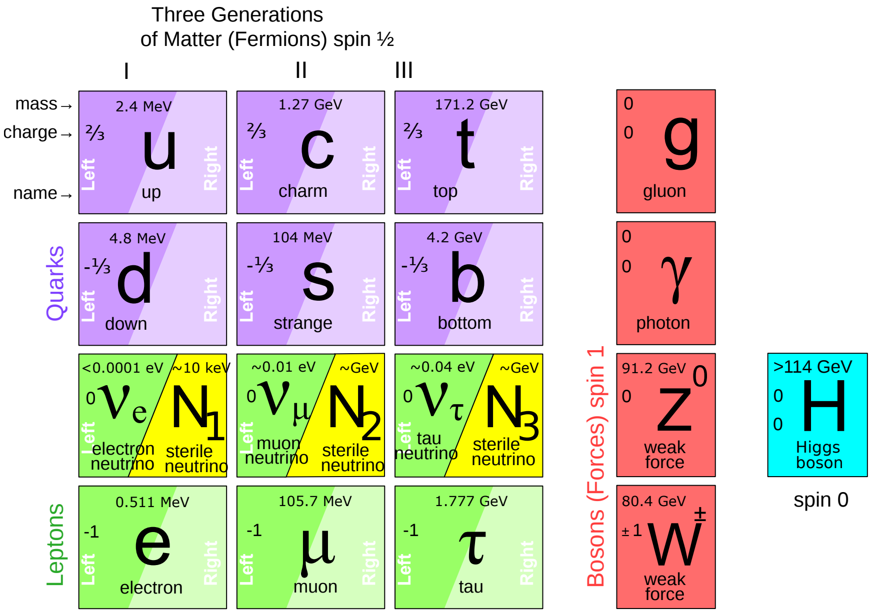
Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

Attractive features:

- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)



Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
Quarks
Leptons
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
<0.0001 eV
~10 keV
0
ν_e
N_1
electron neutrino
sterile neutrino
~0.01 eV
~GeV
0
ν_μ
N_2
muon neutrino
sterile neutrino
~0.04 eV
~GeV
0
ν_τ
N_3
tau neutrino
sterile neutrino
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Left
Right
Bosons (Forces) spin 1
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
0
Z
weak force
80.4 GeV
±1
$W^\pm$
weak force
>114 GeV
0
0
H
Higgs boson
spin 0

Seesaw mechanism: $M_N \gg 1$ eV

With $m_{active} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - f \overline{L}_e^c \tilde{H} N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.}$$

Higgs gains $\langle H \rangle = v/\sqrt{2}$ and then

$$\mathscr{V}_N = \frac{1}{2} \left(\overline{\nu}_e \,, \overline{N}^c \right) \begin{pmatrix} 0 & v \frac{f}{\sqrt{2}} \\ v \frac{f}{\sqrt{2}} & M_N \end{pmatrix} \begin{pmatrix} \nu_e \\ N \end{pmatrix} + \text{h.c.}$$

For a hierarchy $M_N \gg M^D = v \frac{f}{\sqrt{2}}$ we have

flavor state $\nu_e = U \nu_1 + \theta N$ with $U \approx 1$ and

active-sterile mixing: $$\theta = \frac{M^D}{M_N} = \frac{v f}{2 M_N} \ll 1$$

and mass eigenvalues

$$\approx M_N \quad \text{and} \quad -m_{active} = \theta^2 M_N \lll M_N$$

Seesaw mechanism: $M_N \gg 1\,\text{eV}$

With $m_{active} \lesssim 1\,\text{eV}$ we work in the seesaw (type I) regime:

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}^c_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}^c_I N_I + \text{h.c.}$$

When Higgs gains $\langle H\rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathscr{V}_N = \frac{1}{2}\left(\overline{\nu}_1, \ldots \overline{N}^c_1 \ldots\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_1, \ldots N_1 \ldots\right)^{\mathrm{T}} + \text{h.c.}$$

Then for $M_N \gg \hat{M}^D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues:

$$\simeq \hat{M}_N \quad \text{and} \quad \hat{M}^\nu = -(\hat{M}^D)^T \frac{1}{\hat{M}_N}\hat{M}^D \propto f^2\frac{v^2}{M_N} \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

active-active mixing: $U^\dagger \hat{M}^\nu U = diag\,(m_1, m_2, m_3)$

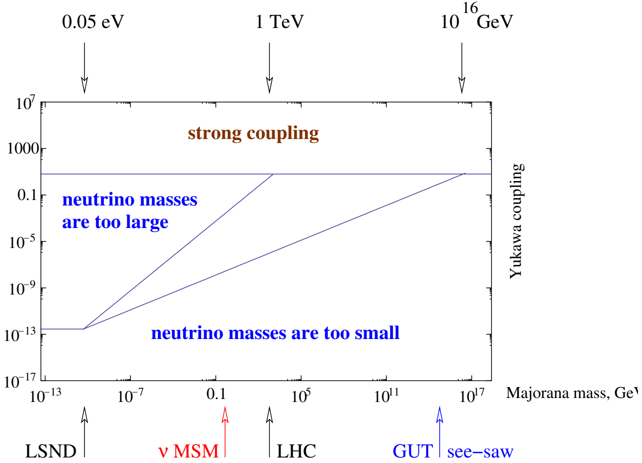
active-sterile mixing: $\theta_{\alpha I} = \frac{(M^D)^T_{\alpha I}}{M_I} \propto \hat{f}^T \frac{v}{M_N} \ll 1$

Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw



Seesaw diagram

Sterile neutrino lagrangian

Most general renormalizable with 2(3...) right-handed neutrinos N_I

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

Parameters to be determined from experiments

9(7): active neutrino sector

- 2 Δm_{ij}^2: oscillation experiments
- 3 θ_{ij}: oscillation experiments
- 1 CP-phase: oscillation experiments
- 2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$
- 1(0) m_ν: $^3\text{H} \to {}^3\text{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

- 2: Majorana masses M_{N_I}
- 9: New Yukawa couplings $f_{\alpha I}$ which form
  - 2: Dirac masses $M^D = f\langle H\rangle$
  - 3+1: mixing angles
  - 2+1: CP-violating phases

4 new parameters in total

18: $N = 3$ sterile neutrinos:

- 3: Majorana masses M_{N_I}
- 15: New Yukawa couplings $f_{\alpha I}$ which form
  - 3: Dirac masses $M^D = f\langle H\rangle$
  - 3+3: mixing angles
  - 3+3: CP-violating phases

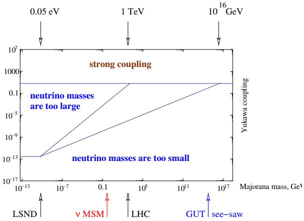
9 new parameters in total

Profit: can suggest why neutrinos are so light, $m_\nu \sim 0.1 - 0.01$ eV

Bonus: depends on the sterile neutrino mass range

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism
Extended seesaw



There are different regions:

$M_N \sim$ 1 eV-100 GeV

- keV-scale dark matter
- BAU via leptogenesis

Via AN-SN oscillations

Akhmedov, Rubakov, Smirnov

direct searches!

$M_N \sim$ 100 GeV-...

- BAU via leptogenesis

$f \sim 10^{-6} \simeq Y_e$

Degeneracy between HNLs is needed

Pilaftis

$M_N \sim 10^{12}$-10^{14} GeV

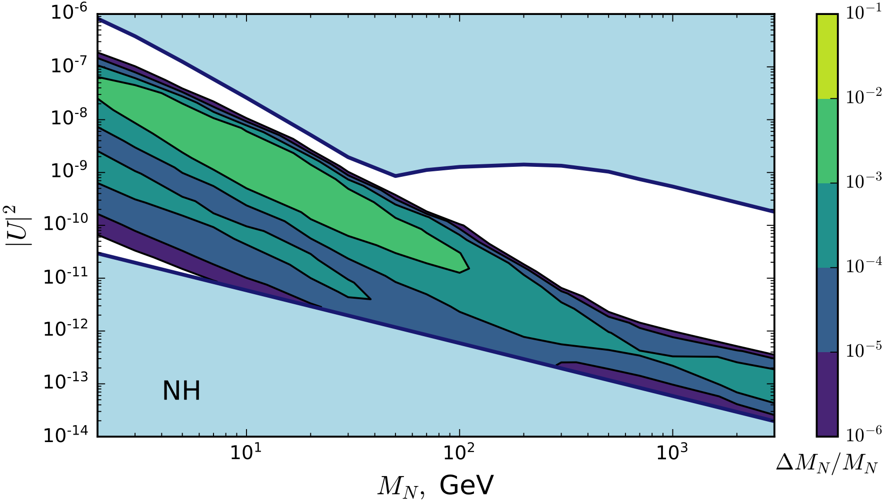
- BAU via leptogenesis

$f \simeq 0.01 - 1$

In decays of heavy leptons
Fukugita and Yanagida

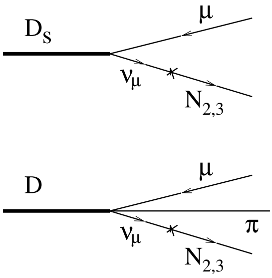
Degeneracy for Leptogenesis

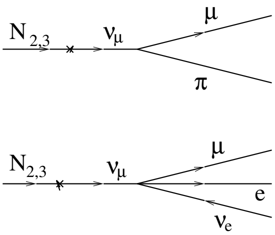
2008.13771



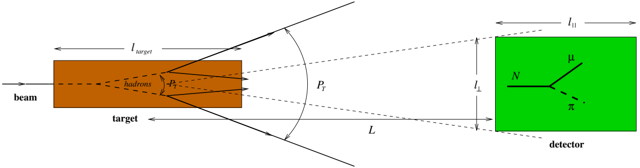
Heavy sterile neutrinos: direct searches

Weak decays due to mixing

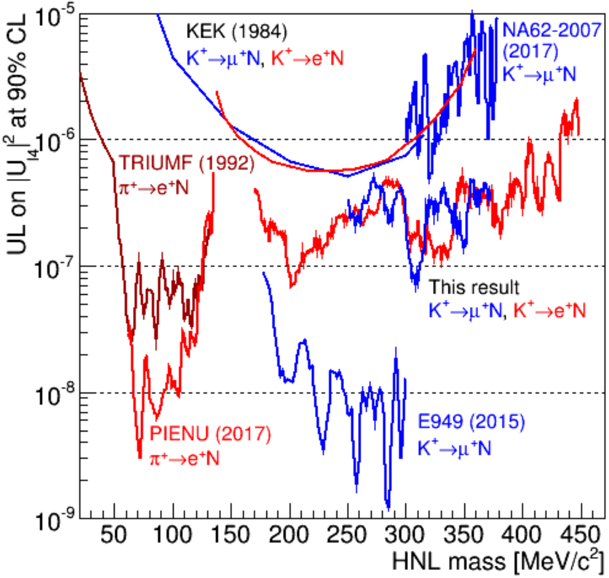




Production in beam-dump experiments

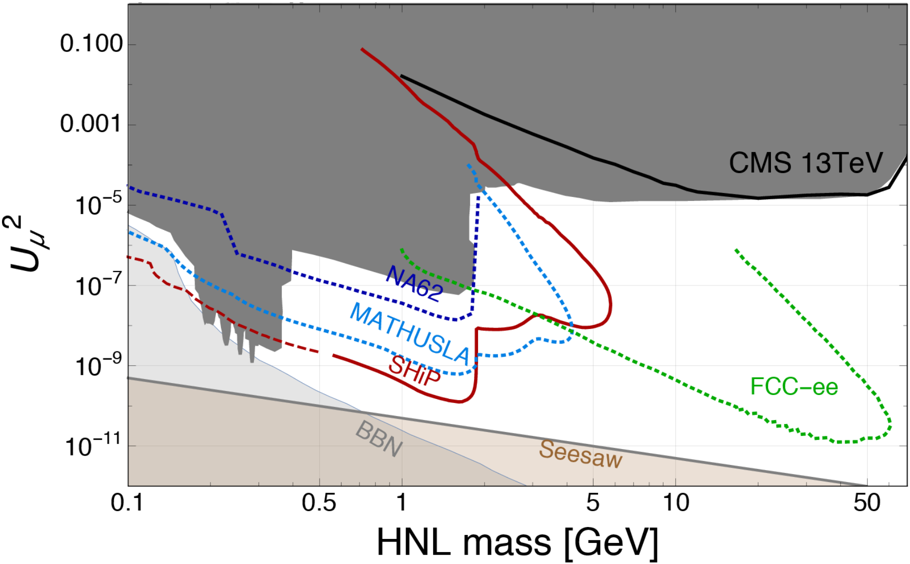


Present limits from production



New projects. . .

1904.09124



Sterile neutrino: well-motivated keV-mass Dark Matter

- massive fermions giving mass to active neutrino through mixing (seesaw)

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, $N \to \nu\nu\nu$ is always open
  but exceeding the age of the Universe if

(applicable for $M_N < M_W$)

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \quad \Longrightarrow \quad \theta^2 < 1.5 \times 10^{-7} \left(\frac{50\,\text{keV}}{M_N}\right)^5$$

- with seesaw constraint $m_a \sim \theta^2 M_N$

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\text{yr}\,(10\,\text{keV}/M_N)^4$$

Sterile neutrino: indirect searches

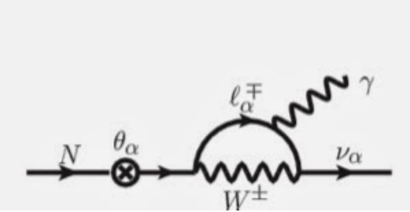
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, but exceeding the age of the Universe if

$$\frac{\theta^2}{3 \times 10^{-3}} < \left(\frac{10\,\text{keV}}{M_N}\right)^5$$

- DM sterile neutrinos can be searched at X-ray telescopes because of two-body radiative decay

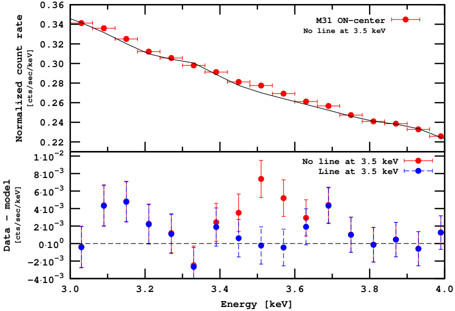
give limits in absence of the feature



a narrow line $\quad (\delta E_\gamma / E_\gamma \sim v \sim 10^{-3})$
at photon frequency $\quad E_\gamma = M_N/2$

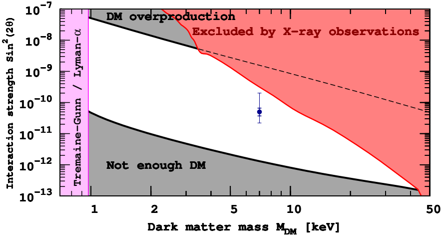
$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\text{ keV}}{M_N}\right)^4$$

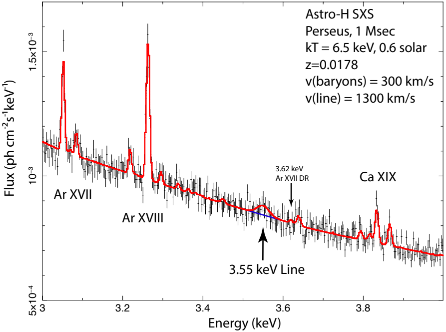
. . . 8 years ago: Dark Matter decay observed in X-ray?



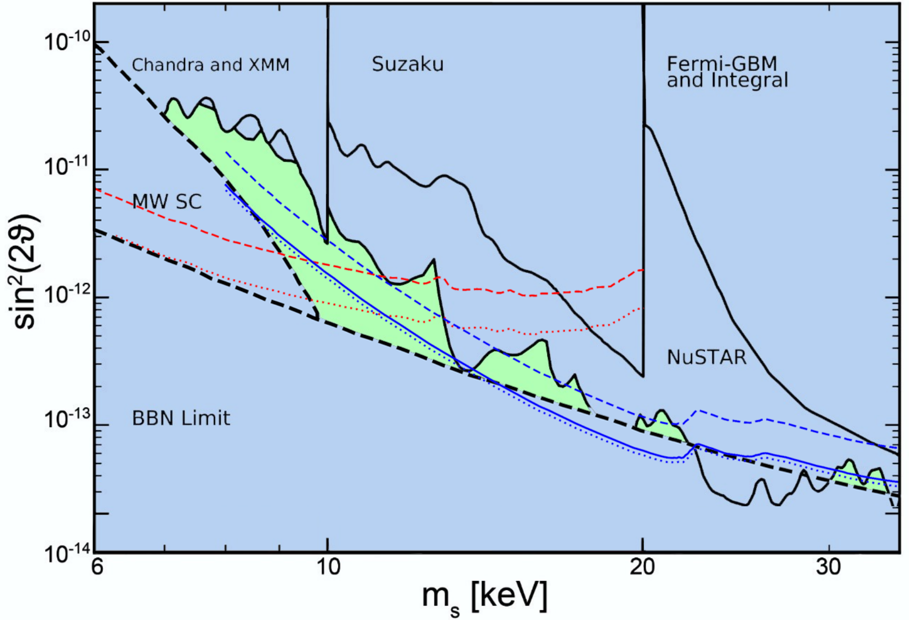
Stacking signals from many galaxies, especially Perseus cluster, then Andromeda

1402.2301, 1402.4119





Spektr-RG: eROSITA (0.2-10 keV), ART-XC (4-30 keV)



2007.07969 (V. Barinov, R. Burenin, D.G., R. Krivonos)

Production in oscillations

$$\frac{\partial}{\partial t} f_s(t,\mathbf{p}) - H\mathbf{p}\frac{\partial}{\partial \mathbf{p}} f_s(t,\mathbf{p}) = \Gamma_\alpha P(\nu_\alpha \to \nu_s)\, f_\alpha(t,\mathbf{p}).$$

$\Gamma_\alpha \propto G_F^2 T^4 E$ is the weak interaction rate in plasma

$$P(\nu_\alpha \to \nu_s) = \sin^2 2\theta_\alpha^{\text{mat}} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\text{mat}}}\right),$$

$$t_\alpha^{\text{mat}} = \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha}\cdot t_\alpha^{vac})^2}},$$

$$\sin 2\theta_\alpha^{\text{mat}} = \frac{t_\alpha^{\text{mat}}}{t_\alpha^{vac}} \cdot \sin 2\theta_\alpha, \quad t_\alpha^{vac} = \frac{2E}{M_N^2}$$

sign of the effective plasma potential matters: as compared to vacuum

$V_{\alpha\alpha} < 0 \implies$ mixing gets suppressed

$V_{\alpha\alpha} > 0 \implies$ amplification via resonance

DM from oscillations: (DW & ShF)

$$\left(\cos 2\theta_\alpha - V_{\alpha\alpha}\cdot t_\alpha^{vac}\right)^2$$

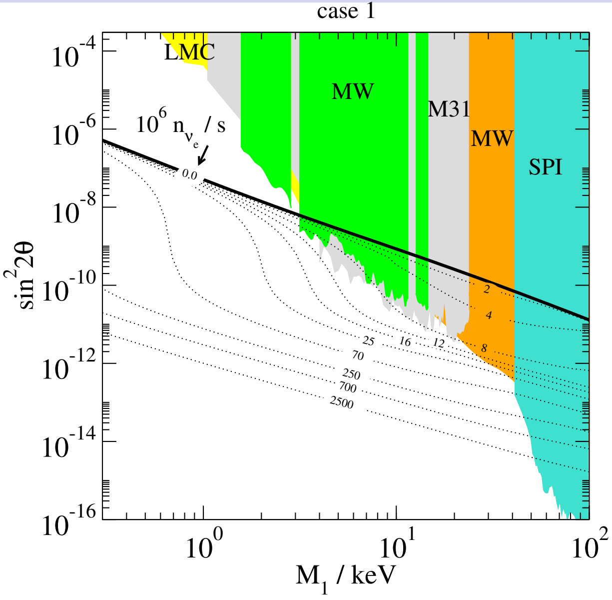
non-resonant:

$$V_{\alpha\alpha} \sim -\# G_F^2 T^4 E$$

resonant production in the lepton asymmetric plasma

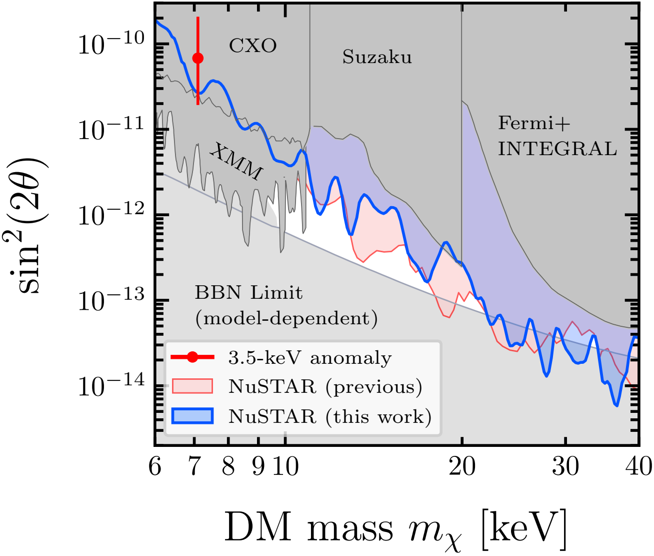
$$V_{\alpha\alpha} \sim +\# G_F T^2 \mu_{L_\alpha}$$

1601.07553



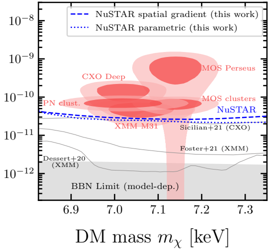
...present searches: NuSTAR

2207.04572

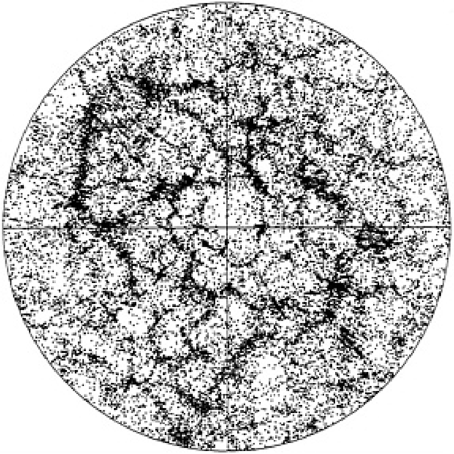


- upper limits on mixing: from *X*-ray searches
- lower limits on mass: from structure formation

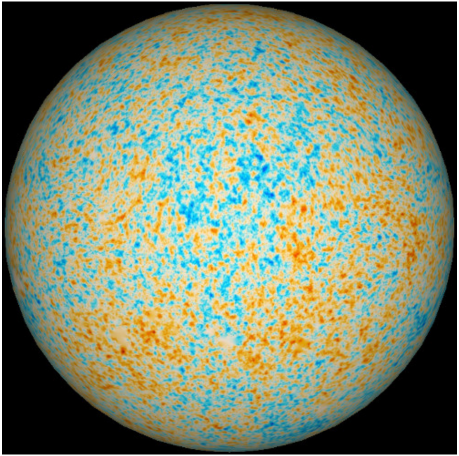
  and BBN predictions



Inhomogeneous Universe



Large Scale Structure



CMB anisotropy

Matter perturbations

originate from the initial matter density (scalar) perturbations

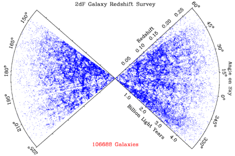
$\delta\rho/\rho \sim \delta T/T \sim 10^{-4}$, which are

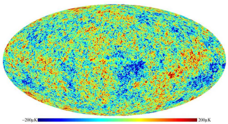
adiabatic $\delta\left(\frac{n_B}{s}\right) = \delta\left(\frac{n_{DM}}{s}\right) = \delta\left(\frac{n_L}{s}\right)$

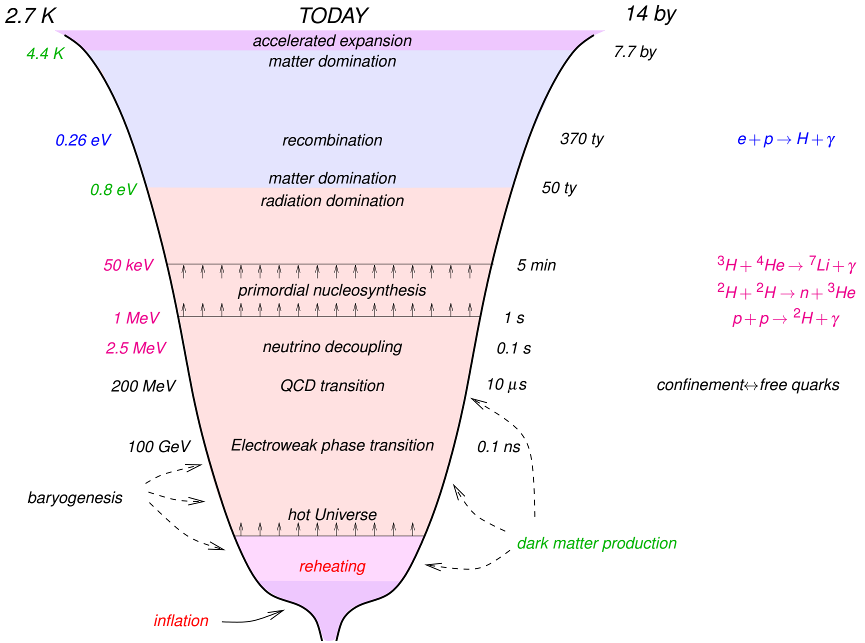
Gaussian $\langle\frac{\delta\rho}{\rho}(\mathbf{k})\frac{\delta\rho}{\rho}(\mathbf{k}')\rangle \propto \left(\frac{\delta\rho}{\rho}(\mathbf{k})\right)^2 \times \delta(\mathbf{k}+\mathbf{k}')$

flat spectrum $\langle\left(\frac{\delta\rho}{\rho}(\mathbf{x})\right)^2\rangle = \int_0^\infty \frac{\mathbf{dk}}{\mathbf{k}}\mathscr{P}_S(\mathbf{k})$ $\mathscr{P}_S(\mathbf{k}) \approx \text{const}$

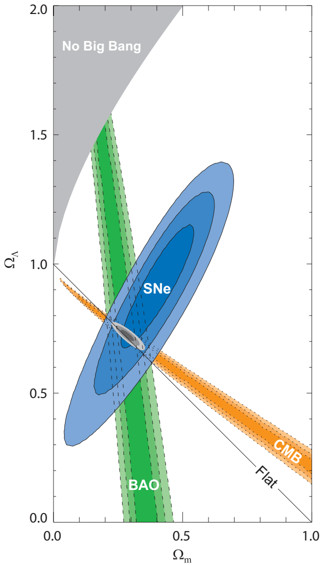
LSS and CMB $\mathscr{P}_S \equiv A_S \times \left(\frac{k}{k_*}\right)^{n_s-1}$ $A_S \approx 2.5\times 10^{-9}$, $n_S \approx 0.97$






2.7 K
TODAY
14 by
accelerated expansion
4.4 K
matter domination
7.7 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.8 eV
radiation domination
50 ty
50 keV
5 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD transition
10 µs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Cosmological data suggest . . . DM, DE, flatness, etc



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

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

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

$$\rho_\Lambda = \text{const}, \quad 1/a^2(t) \propto \rho_{\text{curvature}} = 0$$

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

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

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05$

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

Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.27$

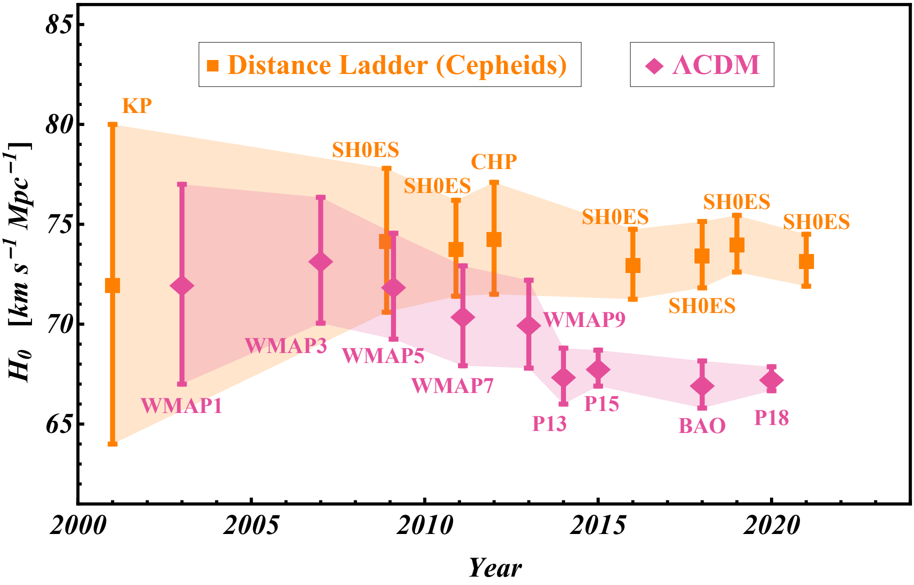
Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68$

vacuum: $T_{\mu\nu} = \rho_{vac}\eta_{\mu\nu}$ $p = -\rho$

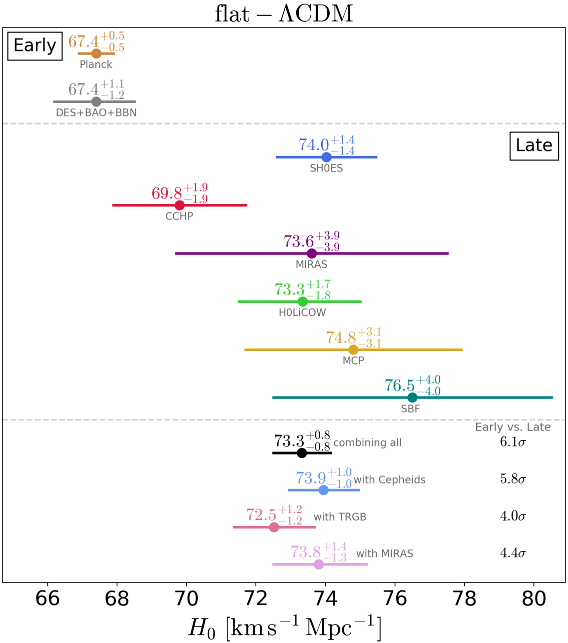
$$S_\Lambda = -\Lambda \int \sqrt{-g} d^4 x \, .$$

$$a = \mathrm{const} \cdot \mathrm{e}^{H_{\mathrm{dS}} t} \, , \quad H_{\mathrm{dS}} = \sqrt{\frac{8\pi}{3} G\rho_{vac}}$$

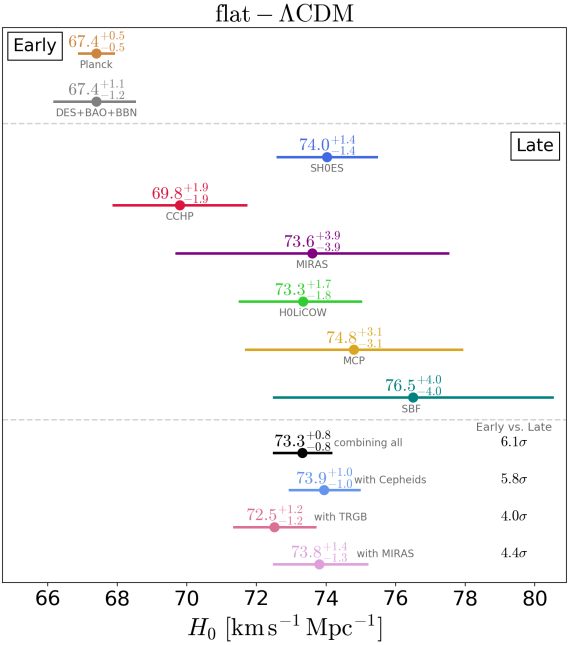
Rubakov suggested the ways to cancel Λ,
and consider some dynamical substance instead,
which may change future (and past) Universe
searching for bouncing (cyclic) cosmologies


Distance Ladder (Cepheids)
ΛCDM
85
80
75
70
65
H_0 [km s^{-1} Mpc^{-1}]
2000
2005
2010
2015
2020
Year
KP
WMAP1
WMAP3
SH0ES
WMAP5
SH0ES
CHP
WMAP7
WMAP9
P13
P15
SH0ES
SH0ES
SH0ES
BAO
P18
SH0ES

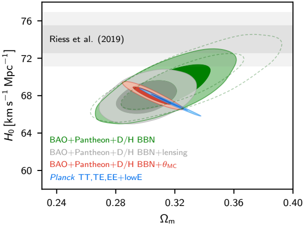
2105.05208


flat − ΛCDM
Early
67.4 +0.5 −0.5
Planck
67.4 +1.1 −1.2
DES+BAO+BBN
Late
74.0 +1.4 −1.4
SH0ES
69.8 +1.9 −1.9
CCHP
73.6 +3.9 −3.9
MIRAS
73.3 +1.7 −1.8
H0LiCOW
74.8 +3.1 −3.1
MCP
76.5 +4.0 −4.0
SBF
Early vs. Late
73.3 +0.8 −0.8 combining all
6.1σ
73.9 +1.0 −1.0 with Cepheids
5.8σ
72.5 +1.2 −1.2 with TRGB
4.0σ
73.8 +1.4 −1.3 with MIRAS
4.4σ
66
68
70
72
74
76
78
80
H0 [km s−1 Mpc−1]

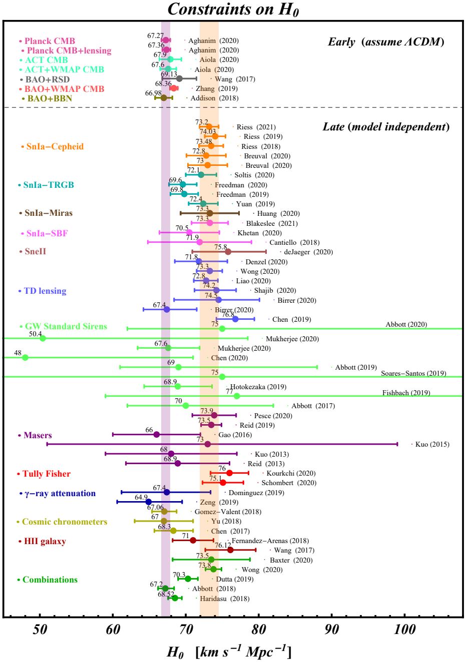
1907.10625



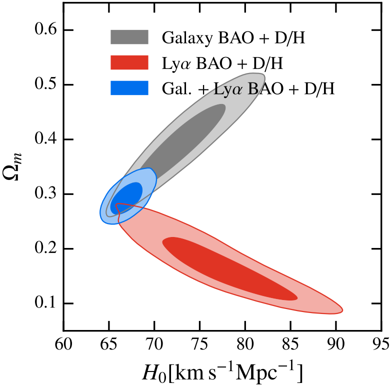
1807.06209



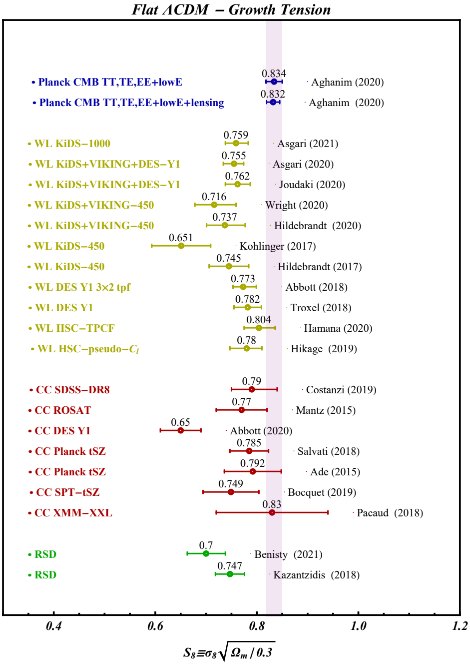
1907.10625



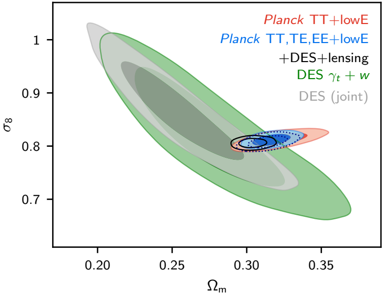
2105.05208



1707.06547



2105.05208



1807.06209

Conclusion

- Valery Rubakov contributed to all the major fields in cosmology
- Hubble puzzle and S_8-tension may point at the direction towards understanding the Nature of Dark Energy
- Alas, he will not learn it with us...