Beyond the Standard Model

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on c-τ factory

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Outline

1. Introduction to BSM
2. Neutrino oscillations
3. Cosmology
   - Neutrino sector
   - Dark Matter
   - Matter-antimatter asymmetry
4. Theoretical problems
   - Supersymmetry
   - Portals

Outline

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, M_W, ...)
- Does not describe (PHENO) (THEORY)

(PHENO)

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

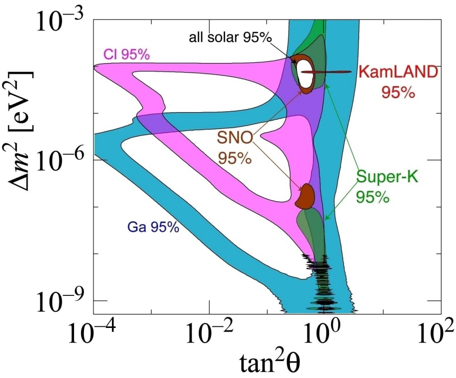
(THEORY)

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

Outline

Neutrino oscillations: masses and mixing angles

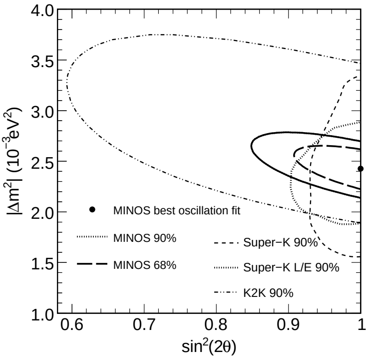
Solar 2×2 "subsector"



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, T2K: $\sin^2 2\theta_{13} \approx 0.08$

Description of neutrino oscillations (I)

- Two bases: gauge $|\nu_\alpha\rangle$, $\alpha = e,\ \mu,\ \tau$ and mass $|\nu_i\rangle$, $i = 1,2,3$

$$|\nu_i\rangle = U_{\alpha i}|\nu_\alpha\rangle \qquad \text{with unitary PMNS } 3\times 3 \text{ matrix} \quad U_{\alpha i}$$

- Neutrino mass matrix is then

$$M_{\alpha\beta} = \langle\nu_\alpha|M|\nu_\beta\rangle = (UM^{(m)}U^\dagger)_{\alpha\beta}\ , \quad \text{where} \quad M^{(m)}_{ij} = m_i\delta_{ij}\ .$$

- Free neutrino evolution in time and space

$$|\nu_j(t)\rangle = \mathrm{e}^{-im_jt}|\nu_j(0)\rangle \quad \to \quad |\nu_j(t,L)\rangle = \mathrm{e}^{-i\left(E_jt - p_jL\right)}|\nu_j(0)\rangle\ ,$$

in ultrarelativistic case

$$p_j = \sqrt{E^2 - m_j^2} = E - m_j^2/2E \quad \to \quad |\nu_j(L)\rangle = \mathrm{e}^{-i\frac{m_j^2}{2E}L}|\nu_j(0)\rangle\ .$$

Description of neutrino oscillations (II)

- Neutrino effective Hamiltonian

$$|\nu_j(L)\rangle = \mathrm{e}^{-i\frac{m_j^2}{2E}L}|\nu_j(0)\rangle \quad \to H_{eff} = \frac{M^2}{2E}$$

- Transition amplitude of neutrino ν_α to neutrino ν_β is

$$A(\alpha\to\beta) = \sum_j \langle\nu_\beta|\nu_j(L)\rangle\langle\nu_j(0)|\nu_\alpha\rangle = \sum_j \langle\nu_\beta|\nu_j\rangle \mathrm{e}^{-i\frac{m_j^2}{2E}L}\langle\nu_j|\nu_\alpha\rangle = \sum_j U_{\beta j}\mathrm{e}^{-i\frac{m_j^2}{2E}L}U^*_{\alpha j}$$

- and the transition probability $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$

$$P(\nu_\alpha\to\nu_\beta) = |A(\alpha\to\beta)|^2$$
$$= \delta_{\alpha\beta} - 4\sum_{j>i}\mathrm{Re}[U^*_{\alpha j}U_{\beta j}U_{\alpha i}U^*_{\beta i}]\sin^2\left(\frac{\Delta m_{ji}^2}{4E}L\right)$$
$$+2\sum_{j>i}\mathrm{Im}[U^*_{\alpha j}U_{\beta j}U_{\alpha i}U^*_{\beta i}]\sin\left(\frac{\Delta m_{ji}^2}{2E}L\right),$$

Description of neutrino oscillations (III)

- Two-neutrino oscillations: transition probability

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E}L\right) ,$$

- Two-neutrino oscillations: survival probability

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

- Oscillation length

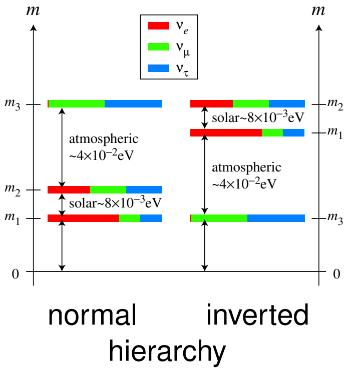
$$L_{osc} = \frac{4\pi E}{\Delta m^2} = (2.5\ \mathrm{km}) \cdot \frac{E}{\mathrm{GeV}}\frac{\mathrm{eV}^2}{\Delta m^2}$$

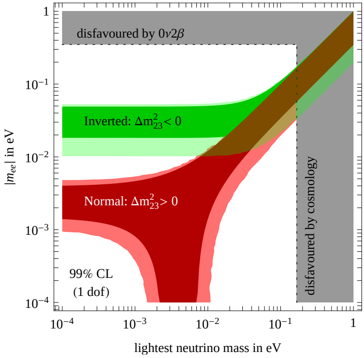
Active neutrinos: normal and inverted hierarchy

Only mass squared are fixed, neutrino masses are model-dependent

to be determined by T2K&Novaνae

CP ??





$|m_{ee}| = \left|\sum U_{ei}^2 m_i\right|$, if Majorana masses 1205.3867

Physics behind the neutrino oscillations is still elusive

- nature of neutrino mass (Dirac vs Majorana)
- neutrino mass hierarchy
- *CP*-violation
- relevance for the matter-antimatter asymmetry
- neutrino anomalies — do not fit to 3ν
  - LSND $\to$ MiniBooNE
  - SAGE & GALLEX & BEST(gallium anomaly)
  - reactor antineutrinos $\to$ DANSS, NEUTRINO-4, etc

Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

$$\mathscr{L}^{(5)} = \frac{\beta_L}{4\Lambda} F_{\alpha\beta} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$; in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$ and

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{\beta_L v^2}{4\Lambda} \frac{F_{\alpha\beta}}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

hence

$$\Lambda \sim 3 \times 10^{14}\,\text{GeV} \times \beta_L \times \left(\frac{3 \times 10^{-3}\,\text{eV}^2}{\Delta m^2_{\text{atm}}} \right)^{1/2}$$

The model has to be UV-completed at the neutrino scale $\Lambda_\nu < \Lambda$

What is beyond the neutrino scale Λ_ν ?

Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

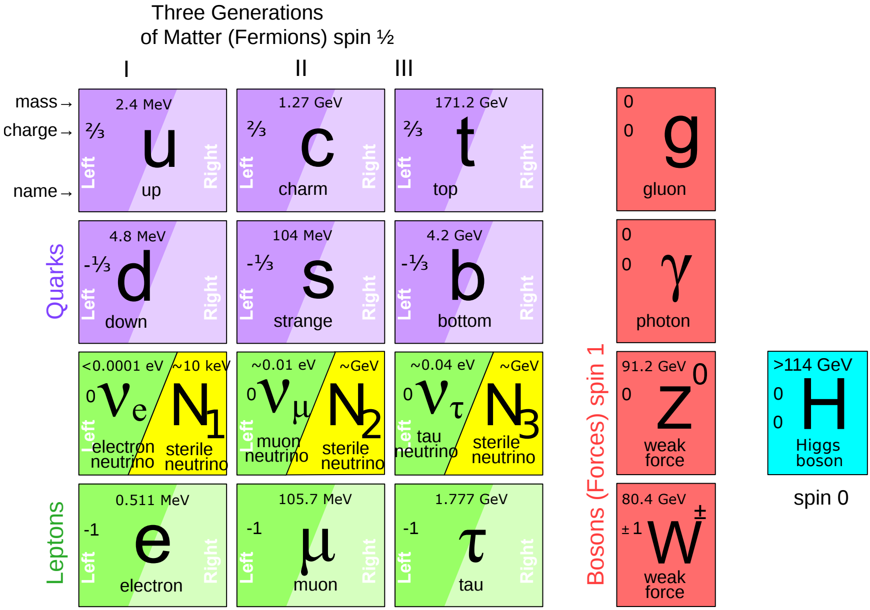
sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

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)
- light(?) sterile neutrinos might be responsible for neutrino anomalies. . . ?

Disappointing feature:

Major part of parameter space is UNTESTABLE


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
0
νe
electron neutrino
~10 keV
N1
sterile neutrino
~0.01 eV
0
νμ
muon neutrino
~GeV
N2
sterile neutrino
~0.04 eV
0
ντ
tau neutrino
~GeV
N3
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
Z0
weak force
80.4 GeV
±1
W±
weak force
>114 GeV
0
0
H
Higgs boson
spin 0

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
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9 new parameters in total

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

Sterile neutrino lagrangian

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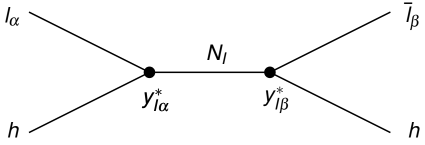
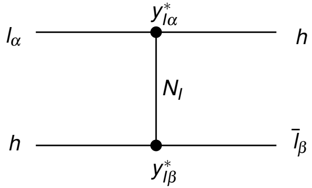
9 new parameters in total
check number!

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

Producing the effective dim-5 operator at $M_N \to \infty$

i.e., integrating out the Heavy Sterile neutrinos





thus we obtain

$$\propto \frac{y^2}{M_N} lhlh \quad \to \quad \frac{(LH)(LH)}{\Lambda}$$

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

see Lecture by S.Bilenky and Lectures by A.Smirnov

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

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

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

Violation of L, C and CP symmetries

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

- $f = 0 \quad \longrightarrow \quad$ free fermion, no need to call 'sterile'
- $M_N = 0 \quad \longrightarrow \quad$ N and ν form pure Dirac neutrino,
  the most boring case, worth than we have with the Higgs boson
  one may refuse to call it 'new physics'
- $f \neq 0, \quad M_N \neq 0 \quad \longrightarrow \quad$ introduces new massive parameter,
  violates lepton symmetry L see Lecture by G.Mitselmakher
  (and C- and CP-symmetry with several N's)

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

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

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

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

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 $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I}N_I$ — neither $U_{\alpha i}$ nor $\theta_{\alpha I}$ is unitary

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

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

Seesaw mechanism: sterile neutrino scale

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

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SEESAW says nothing about the sterile neutrino scale M_I !

Unitarity: $f \lesssim 1 \quad \Longrightarrow \quad M_N \lesssim 3 \times 10^{14}\,\text{GeV} \times \left(\frac{3{\cdot}10^{-3}\,\text{eV}^2}{\Delta m^2_{atm}}\right)^{1/2} \longrightarrow \Lambda$ in $(LH)^2/\Lambda$

At given M_N without fine tuning the scale of Yukawas $\hat{f}$ and strength of active-sterile mixing $\theta_{\alpha I} = \frac{(M^D)^T_{\alpha I}}{M_I} \propto \hat{f}^T \frac{v}{M_N} \ll 1$ are fixed

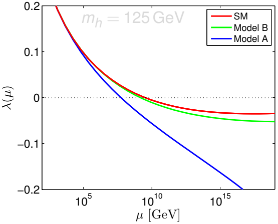
1203.3825

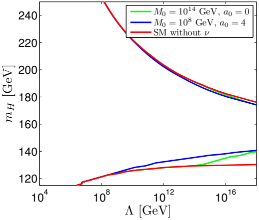
With fine tuning in $\hat{f}^T \hat{M}^{-1} \hat{f}$ can have larger f:

and change the Higgs mass window

$$\frac{d\lambda}{d\log\mu} \propto \lambda^2 + \lambda\, tr(\hat{f}^\dagger \hat{f}) - tr(\hat{f}^\dagger \hat{f} \hat{f}^\dagger \hat{f})$$

$$m_h^2 = 2\lambda v^2$$





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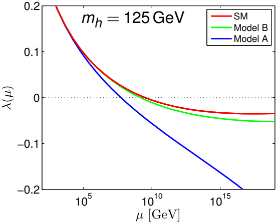
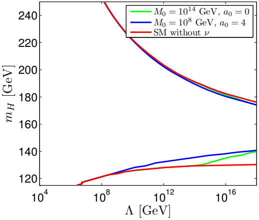




Where is sterile neutrino scale?

eigenvalues: $\simeq \hat{M}_N$ and $\hat{M}^\nu = -\hat{M}^{D\,T}\frac{1}{\hat{M}_N}\hat{M}^D \propto f^2\frac{v^2}{M_N} \lll M_N$

SEESAW says nothing about the sterile neutrino scale M_N !

Unitarity: $f \lesssim 1 \quad \Longrightarrow \quad M_N \lesssim 3\times 10^{14}\ \text{GeV} \times \left(\frac{3\cdot 10^{-3}\ \text{eV}^2}{\Delta m^2_{atm}}\right)^{1/2} \longrightarrow \Lambda$ in $(LH)^2/\Lambda$

Integrating out sterile neutrinos get dim-5 operator $\quad -f_{\alpha I}\bar{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I \to f^2 (LH)^2/M_N$

SM Higgs without NP at EW-scale favors sterile neutrinos at EW-scale (or below) !

- Majorana mass violates scale-invarinace $\Longrightarrow$ finite corrections $\quad \delta m_h^2 \propto f^2 M_N^2$
- Scale invariance helps to abandon infinite corrections $\quad \delta m_h^2 \propto f^2\Lambda^2$
- In SM scale invariance is broken by the Higgs mass and running of coupling constants
  $T^\mu_\mu \propto \beta(\alpha)\times\hat{O} + \left(m_h^2 + \alpha\Lambda^2\right)\times h^2 \quad \Longrightarrow$ quadratic divergences are irrelevant

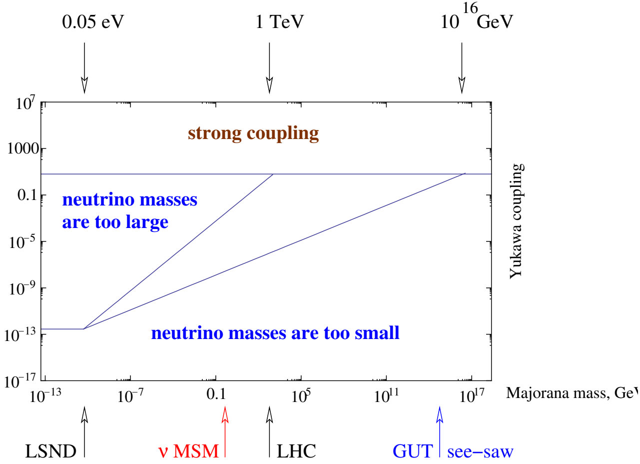
$\delta m_h^2 \lesssim m_h^2$ then $M_N \lesssim 10^7$ GeV $\qquad$ W.Bardeen (1995)

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

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

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

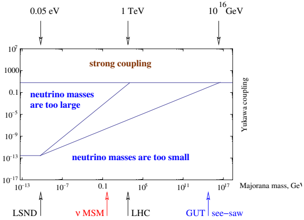
9 new parameters in total

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
- Neutrino anomalies (1 eV sterile neutrinos?)

direct searches!

$M_N \sim 100$ GeV-5 TeV

- BAU via leptogenesis

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

but with fine tuning or new global or gauge symmetries (e.g. $SU(2)_L \times SU(2)_R$)

direct searches at colliders

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

- BAU via leptogenesis

$f \simeq 0.01 - 1$

Untestable. . . ?
or already confirmed?

prefered by many theorists

Outline

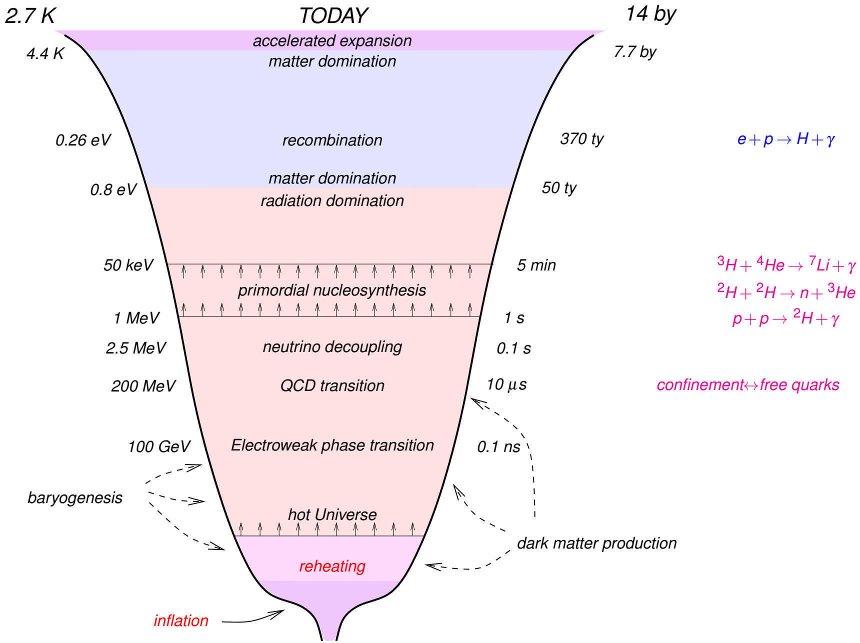
Standard cosmological model $ds^2 = dt^2 - a^2(t)dx^2$

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = H_0^2 \left[\Omega_\Lambda + (\Omega_{DM} + \Omega_B + \Omega_{\nu,m\neq 0})\left(\frac{a_0}{a}\right)^3 + (\Omega_\gamma + \Omega_{\nu,m=0})\left(\frac{a_0}{a}\right)^4\right]$$

- $T_\gamma = 2.735\,\mathrm{K}, \quad \Longrightarrow \quad \Omega_\gamma \sim 10^{-5}$
- $N_\nu \approx 3, \quad \sum m_\nu < 0.2\,\mathrm{eV} \quad \Longrightarrow \quad \Omega_{\nu,\neq 0},\, \Omega_{\nu,0} \sim 10^{-5}$?
- $\Omega_B = 4.5\% \quad \Longrightarrow \quad \eta_B \equiv n_B/n_\gamma = 6 \times 10^{-10}$
- $\Omega_{DM} = 27.5\%$
- $l_{s,rec} \sim l_{H,rec}/\sqrt{3} \to \quad H_0 = 67\,\mathrm{km/s/Mpc} \quad \Longrightarrow \quad \rho_0 = 5\,\mathrm{GeV/m^3}$
- $\Omega_\Lambda = 68\% \quad \Longrightarrow$ flat space
- adiabatic, gaussian matter perturbations

$$\langle \left(\frac{\delta\rho}{\rho}\right)^2 \rangle \sim A_S \int \frac{dk}{k} \left(\frac{k}{k_*}\right)^{n_S - 1}$$

  with $A_S = 3 \times 10^{-9}$ and $n_S = 0.97$
- no tensor perturbations, $r \equiv A_T/A_S < 0.03$
- reionization at $z_{rei} \equiv a_0/a = 8$


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

New Physics in Cosmology: any energy scales…

Cosmology constrains the time-scale, rather than energy-scale

- Dark energy — be present by $T \gg 5\,\mathrm{K}$
- Dark matter (if particles) — be produced by $T \gg 1\,\mathrm{eV}$
- Baryon asymmetry — be generated by $T \gg 1\,\mathrm{MeV}$

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

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

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

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

Why do we think it is most probably new particle physics
(new gravity if any is not enough) ?

– BAU requires baryon number violation
– DM evidences at various spatial scales and epochs

World-wide accepted problems. . .

Origins of...?

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- Matter-antimatter asymmetry
- Dark Energy
- matter perturbations (inflation?)
- . . .
- extragalactic magnetic field
- superheavy black holes in the galaxy centers

Coincidences

- $\Omega_{DM} \sim \Omega_B$
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- $(\delta\rho/\rho)^2 \simeq n_B/n_\gamma$
- $T_d^n \sim (m_n - m_p)$
- $\tau_U \approx H_0^{-1}$
- . . .

Anomalies

- BBN: Lithium
- CMB: multipole statistics
- Planck: low and high multipoles
- Planck: lensing, SZ-clusters
- Hubble measurements
- σ_8

Microscopic processes in the expanding Universe

A competition between scattering, decays, etc and expansion

for general processes one should solve kinetic equations

$$\frac{dn_{X_i}}{dt} + 3Hn_{X_i} = \sum(production - destruction)$$

Boltzmann equation in a comoving volume: $\frac{d}{dt}\left(n\, a^3\right) = a^3 \int \dots$

production:

$$\sigma(A+B \to X+C)n_A n_B, \quad \Gamma(D \to E+X)n_D \cdot M_D/E_D, \quad \text{etc}$$

destruction:

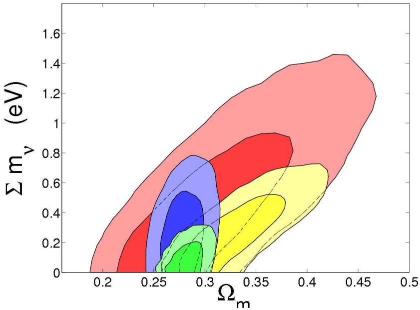
$$\sigma(A+X \to C+B)n_A n_X, \quad \Gamma(X \to F+G)n_X \cdot M_X/E_X, \quad \text{etc}$$

Fast processes, $\Gamma \gtrsim H$, are in equilibrium, $\sum(\ ) = 0$

and thermalize particles

no history-dependence

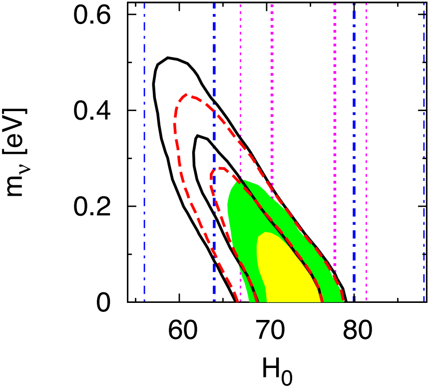
Cosmological limits on active neutrino masses



LRG+BAO+WMAP5+SNe+BAO

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

0911.5291



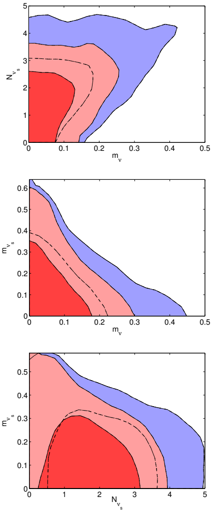
CMB+Hubble measurements

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

0911.0976

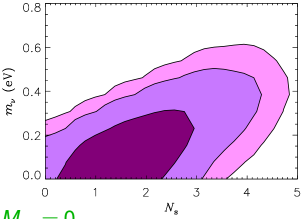
Combined analysis for sterile and active neutrinos

WMAP7+LRG+HST

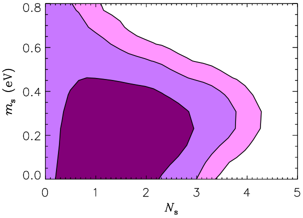


flat ΛCDM 1102.4774

CMB+SDSS+HST



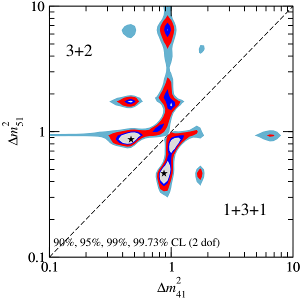
$M_{\nu_s} = 0$



$m_\nu = 0$

flat ΛCDM 1006.5276

LSND+MiniBooNE



1103.4570

"3+1" :

$\Delta m^2_{41} = 1.76\,\text{eV}^2$, $|U_{e4}| = 0.151$

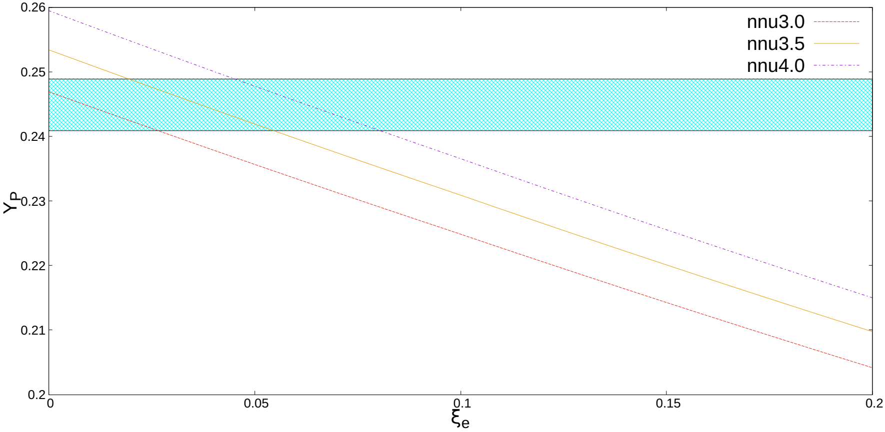
"3+2" :

$\Delta m^2_{41} = 0.46\,\text{eV}^2$, $|U_{e4}| = 0.108$

$\Delta m^2_{51} = 0.89\,\text{eV}^2$, $|U_{e5}| = 0.124$

BBN: extra-radiation and lepton asymmetry

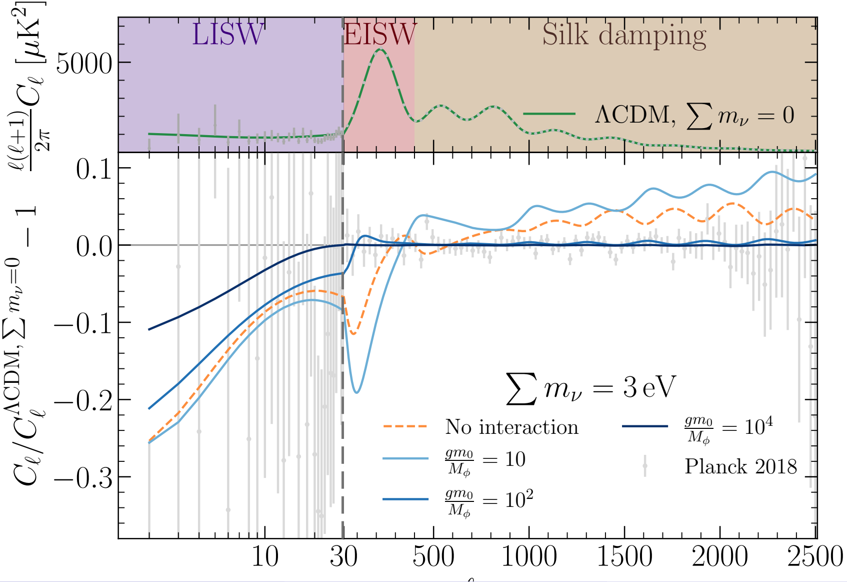
2104.04381



$$n_n \propto e^{-\frac{\mu_\nu}{T}}\,, \qquad H^2 \propto (\dots \Delta N_\nu)\, T^4$$

CMB: 'heavy' neutrinos with long-range force

2101.05804



World-wide accepted problems. . .

Origins of...?

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- matter perturbations (inflation?)
- . . .
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- Planck: lensing, SZ-clusters
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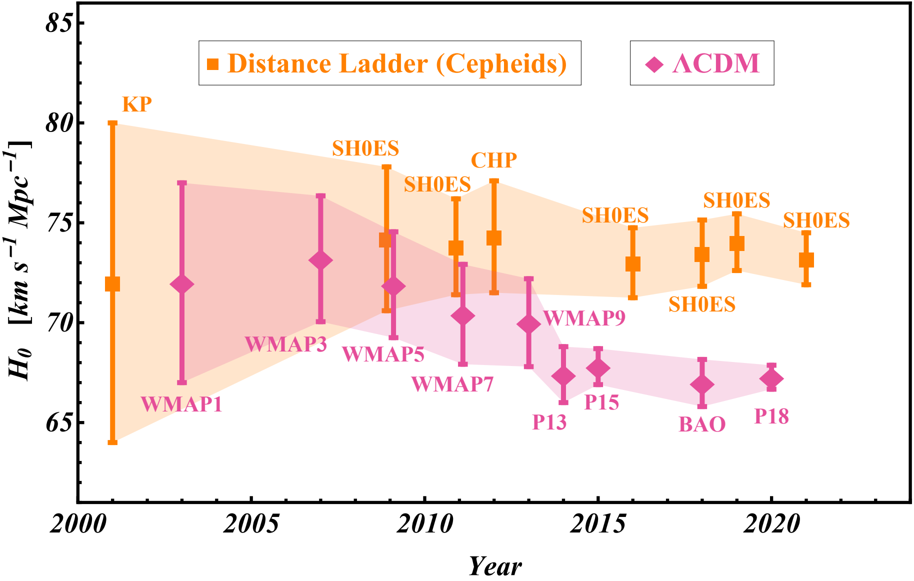
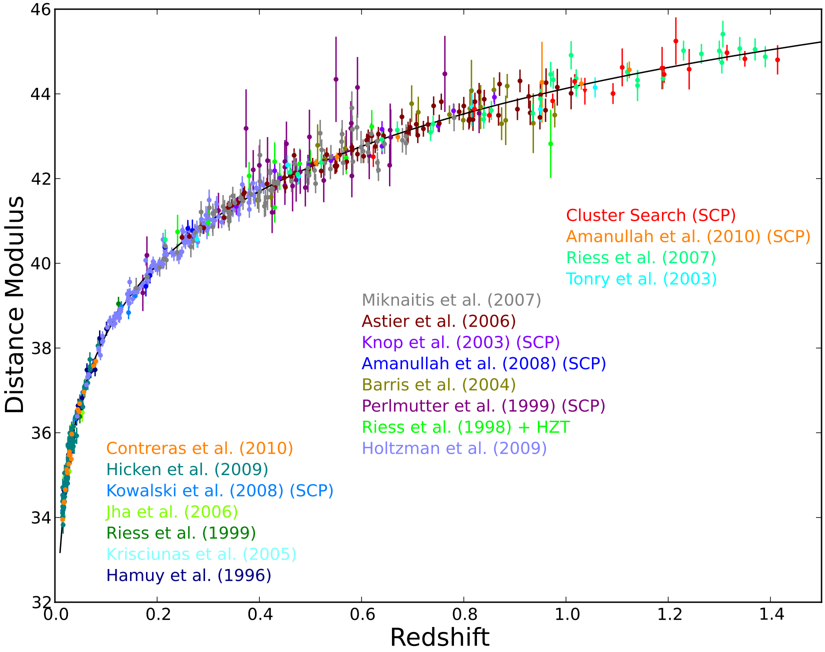
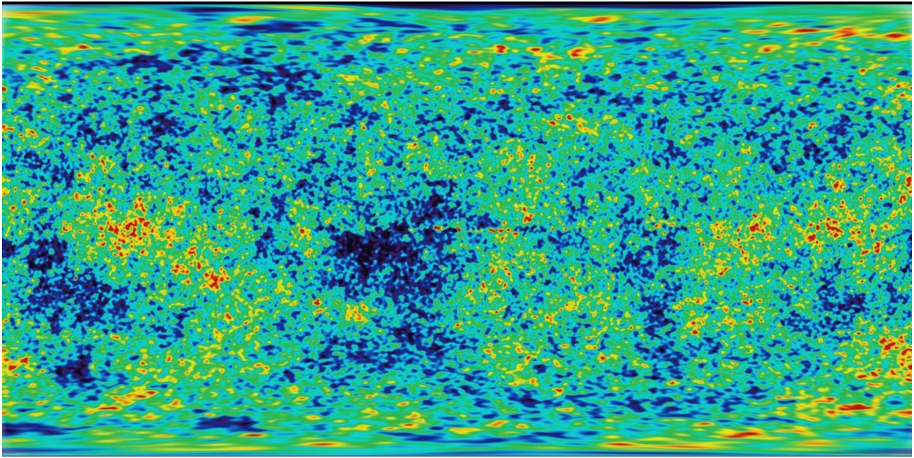

Distance Ladder (Cepheids)
ΛCDM
KP
SH0ES
CHP
SH0ES
SH0ES
SH0ES
SH0ES
SH0ES
SH0ES
WMAP1
WMAP3
WMAP5
WMAP7
WMAP9
P13
P15
BAO
P18
85
80
75
70
65
H_0 [km s^{-1} Mpc^{-1}]
2000
2005
2010
2015
2020
Year

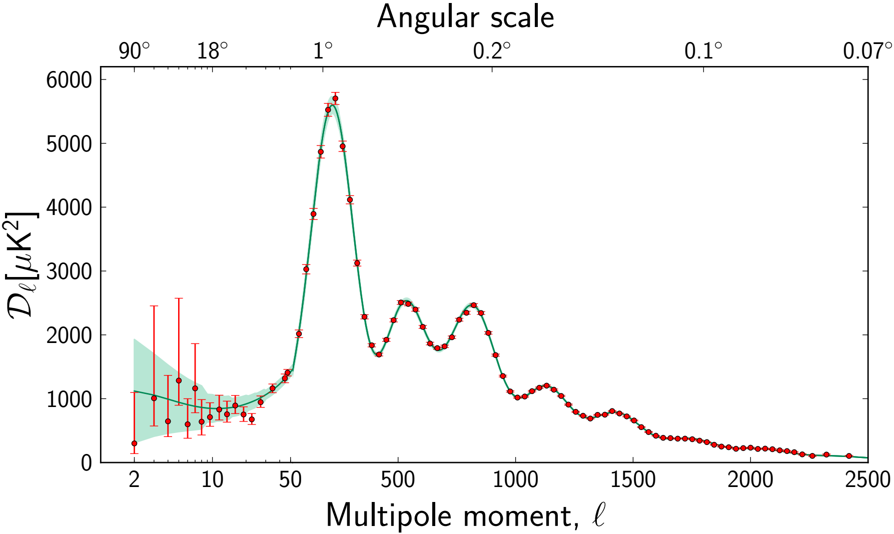
2105.05208

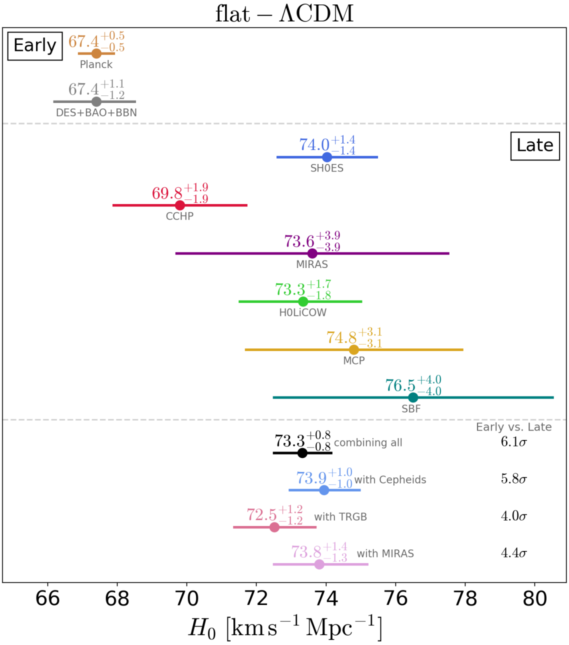

Distance Modulus
Redshift
46
44
42
40
38
36
34
32
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)

CMB map

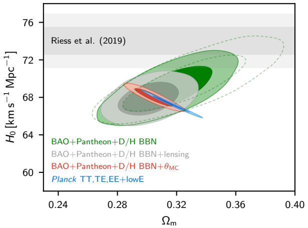


fit to ΛCDM model $\theta_{rec}, \Omega_{DM}h^2, \Omega_B h^2, z_{rei}, A_S, n_s$

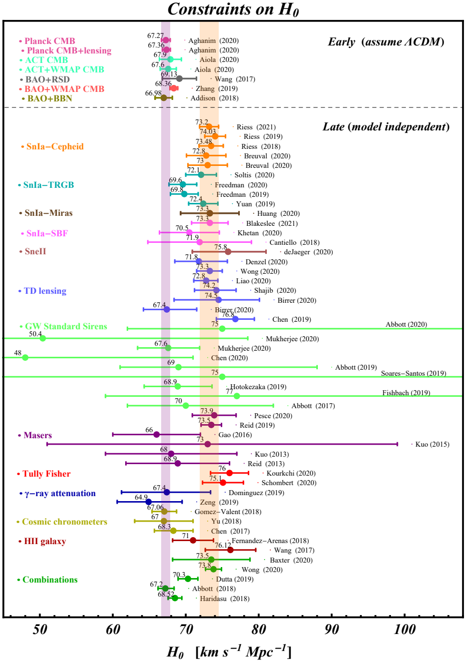




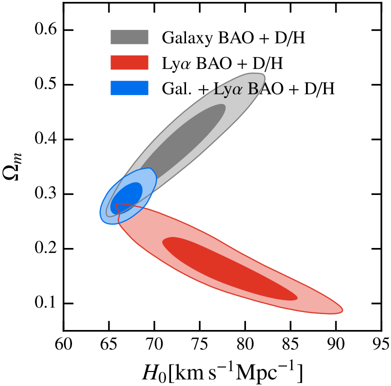
1807.06209



1907.10625

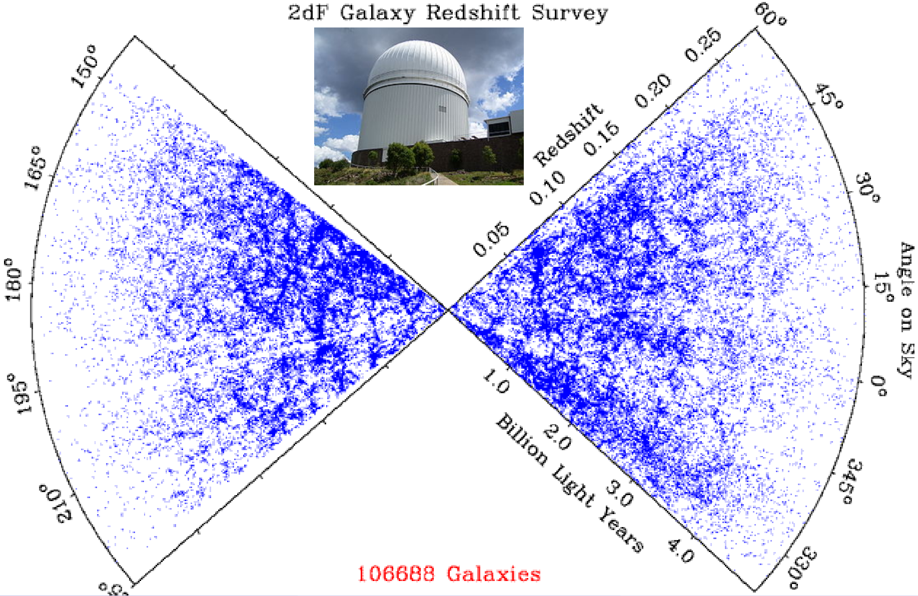


2105.05208

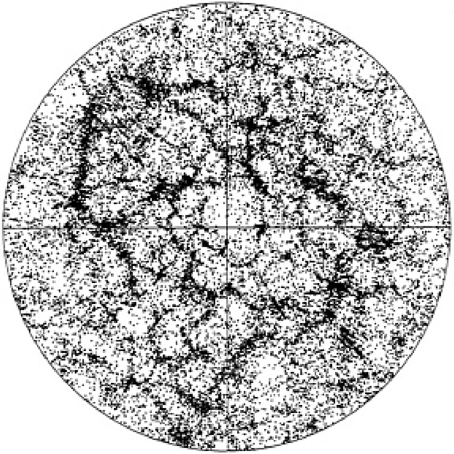


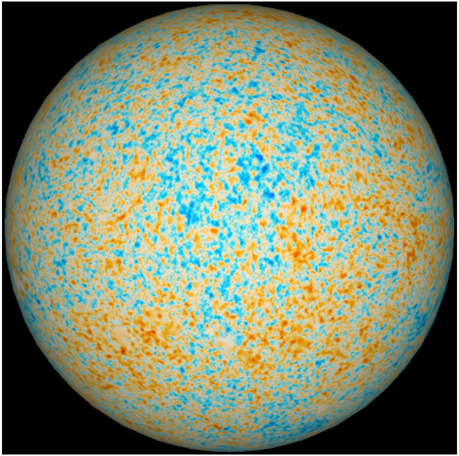
1707.06547

Very large scales: homogeneity and isotropy



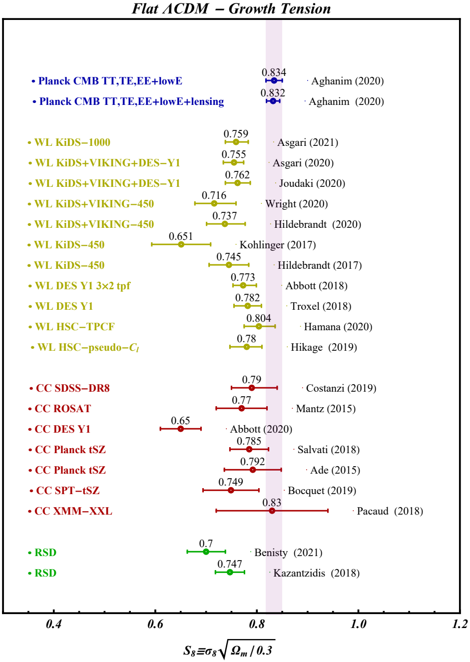
Inhomogeneous Universe



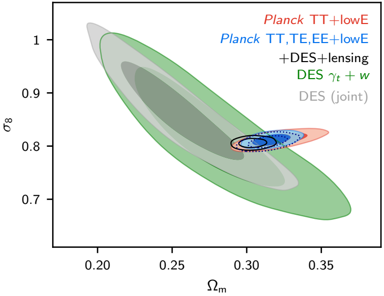


Large Scale Structure

CMB anisotropy



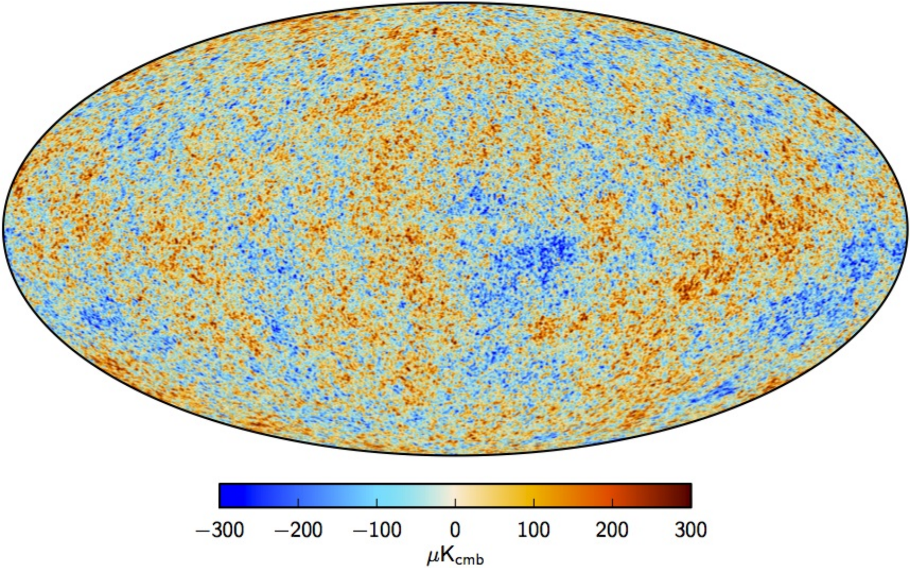
2105.05208



1807.06209

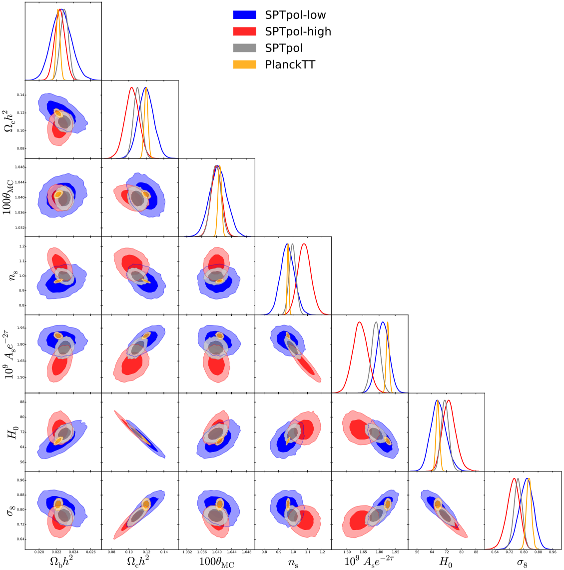
CMB map (Planck)

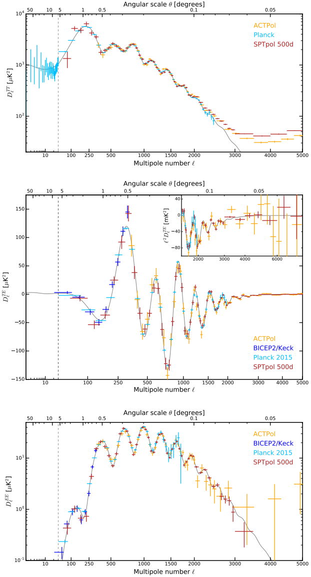
1502.01582

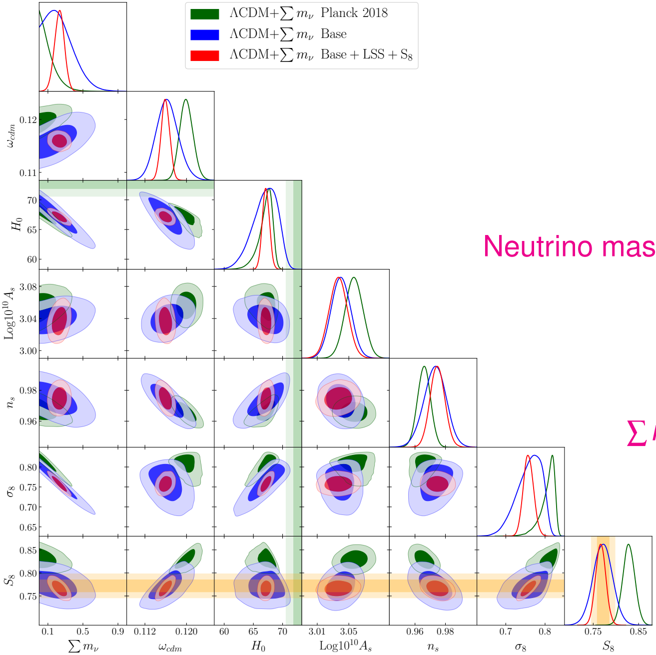


SPTPole with critical $l = 1000$

1707.09353







Neutrino masses: 4 σ evidence...

2203.03666

both H_0 and σ_8,

$$\sum m_\nu = 0.32 \pm 0.06\,\text{eV}$$

World-wide accepted problems...

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- ...
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- ...

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- Planck: lensing, SZ-clusters
- Hubble measurements
- σ_8

Dark Matter properties from cosmology: $p = 0$

(If) particles:

1. stable on cosmological time-scale

   requires new (almost) conserved quantum number

2. produced in the early Universe

   some time before RD/MD-transition ($T = 0.8\,\text{eV}$)

3. nonrelativistic particles long before RD/MD-transition ($T = 0.8\,\text{eV}$)
   (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
   Otherwise no small-size structures, like dwarf galaxies: $l_{fs} = a \int v(t)dt/a(t)$
   smoothed out by free streaming

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

4. (almost) collisionless $p = 0$, $v_{\text{sound}} = 0$

5. (almost) electrically neutral CMB distortion

6. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta\left(\frac{n_B}{n_{DM}}\right) = \delta\left(\frac{n_B}{n_\gamma}\right) = \delta\left(\frac{n_\nu}{n_\gamma}\right) = 0$$

Decoupling of nonrelativistic Dark Matter

Assumptions:

1. no $X - \bar{X}$ asymmetry — either $X = \bar{X}$ or $n_X = n_{\bar{X}}$
2. @ $T \lesssim M_X$ in thermal equilibrium with plasma — (e.g. neutrons)

$$n_X = n_{\bar{X}} = g_X \left(\frac{M_X T}{2\pi} \right)^{3/2} \mathrm{e}^{-M_X/T}$$

$$X\bar{X} \longrightarrow \text{light particles}$$

freeze-out temperature T_f — $H \equiv T^2/M_{Pl}^*$

$$n_X \langle \sigma_{ann} v \rangle = H(T_f) \longrightarrow T_f = \frac{M_X}{\ln\left(\frac{g_X M_X M_{Pl}^* \sigma_0}{(2\pi)^{3/2}} \right)} .$$

Bethe formula: — s-wave: $\sigma_{ann} = \frac{\sigma_0}{v}$

Weakly Interacting Massive Particles

density after freeze-out: $$n_X(T_f) = \frac{T_f^2}{M_{Pl}^* \sigma_0}$$

present density: $$n_X(T_0) = \left(\frac{a(T_f)}{a(T_0)}\right)^3 n_X(T_f) = \left(\frac{s_0}{s(T_f)}\right) n_X(T_f) \propto \frac{1}{T_f}$$

$X + \bar{X}$ contribution to critical density:

$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} = 7.6\frac{s_0 \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)}{\rho_c \sigma_0 M_{Pl}\sqrt{g_*(T_f)}}$$

$$= 0.1 \cdot \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0}\right) \frac{10}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

WIMPs: discussion

$$\Omega_X = 0.1 \cdot \left(\frac{(10\text{ TeV})^{-2}}{\sigma_0}\right) \frac{10}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

- natural DM: subweak-scale cross section $\sigma_0 \sim 0.01 \times \sigma_W$
  say, $M_X \sim 1$ TeV or X is not a weak gauge eigenstate
- naturaly "light" unitarity $\sigma_0 \lesssim \frac{4\pi}{M_X^2} \frac{g^4}{1} \longrightarrow M_X \lesssim 100$ TeV
- all stable particles with smaller σ_0 are forbidden !!
- WIMPs remain in kinetic equilibrium with plasma till $T \sim 10$ MeV

  this is Cold Dark Matter, $v_{RD/MD} \ll 10^{-3}$

  WIMPs may form dark halos (clumps) much lighter than dwarf galaxies

Weakly IMPs are mostly welcome (e.g. LSP in SUSY)

We can fully explore the model !!

- Direct searches for Galactic Dark Matter ($v \sim 10^{-3}$) a hit

$$X + \text{nuclei} \to X + \text{nuclei} + \Delta E$$

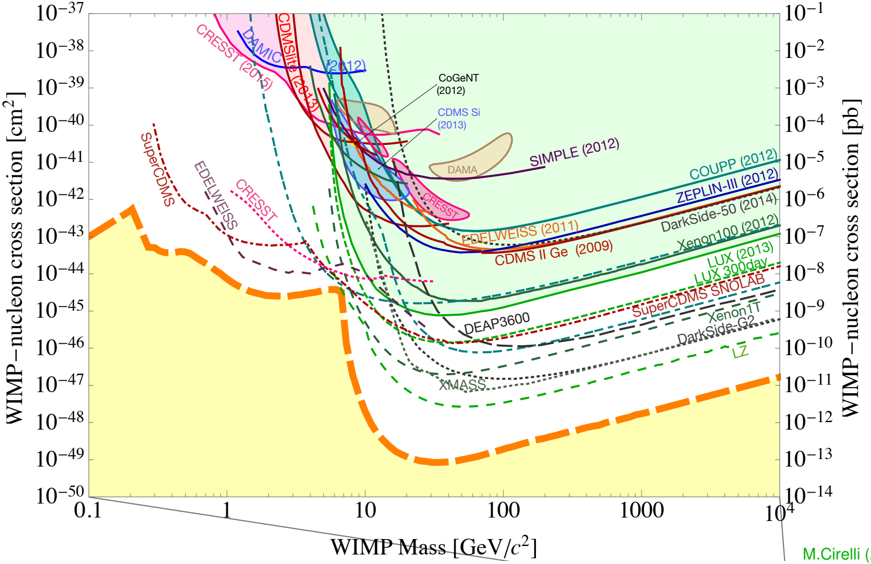
- Can search for WIMPs in cosmic rays: products of WIMPs annihilation (in Galactic center, dwarf galaxies, Sun) $\propto n^2$

$$X + \bar{X} \to p\bar{p}\,,\;\; e^+e^-\,,\;\; \nu, \gamma, \ldots$$

- Can search for WIMPs in collision experiments (LHC): missing

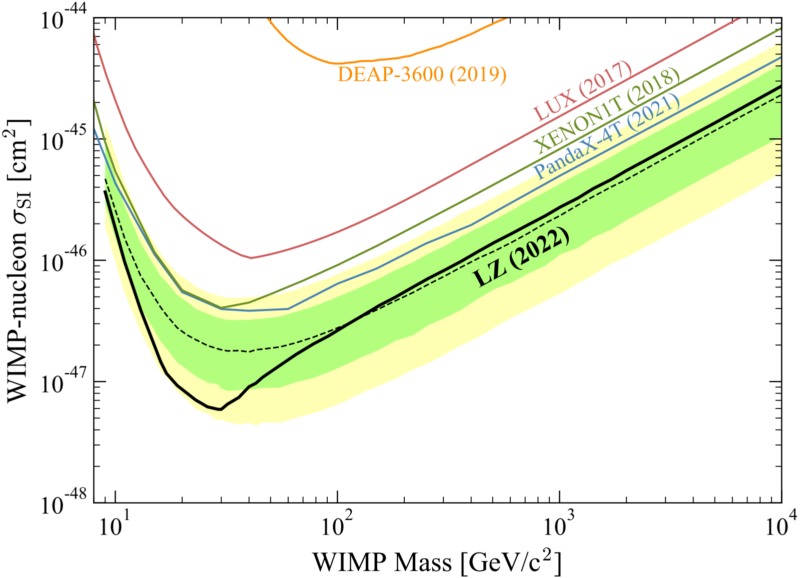
$$X + \bar{X} \leftrightarrow \text{SM} + \text{SM'} + \ldots$$

Prospects in WIMP searches



M.Cirelli (2015)

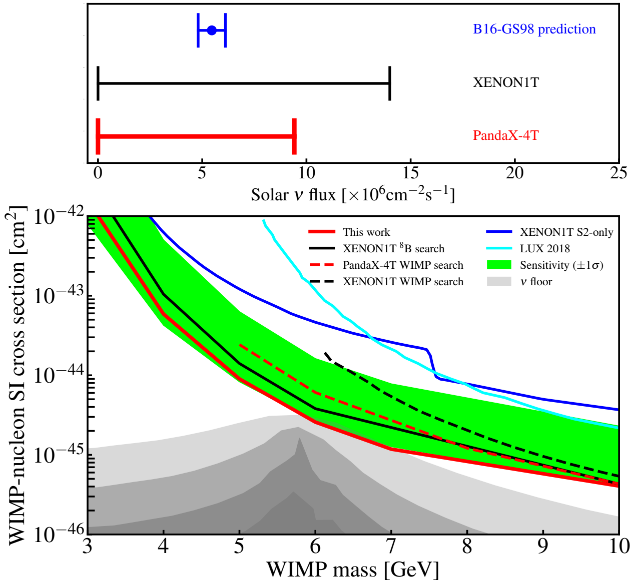
First results of next-gen experiments: LUX-ZEPLIN



2207.03764

Testing neutrino floor with PandaX-4T

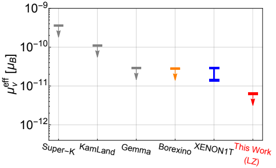
2207.04883



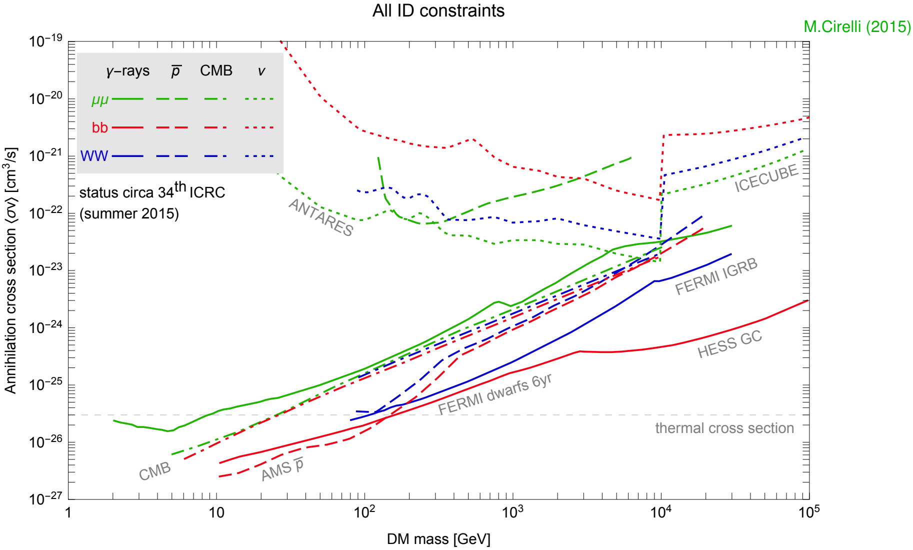
Other by-product results:

2207.05036

the strongest limit on μ_ν from LZ:

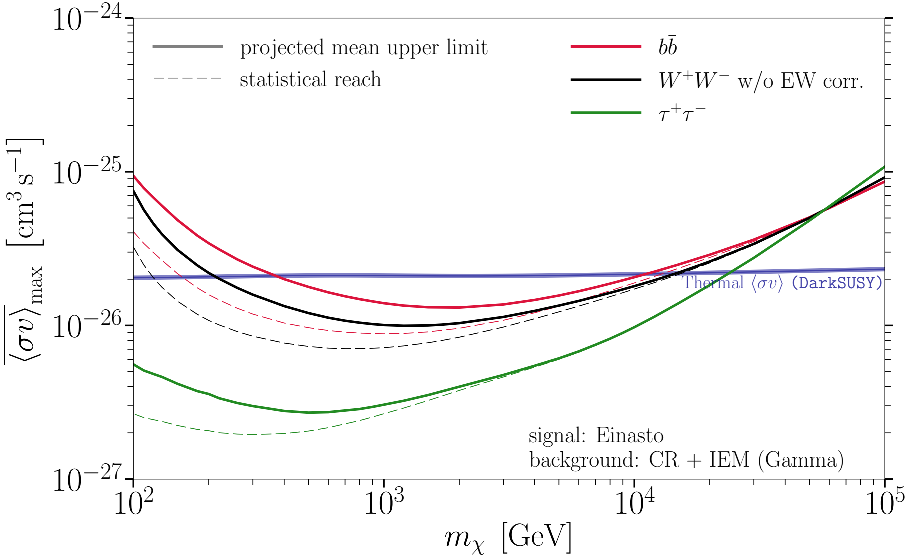


Indirect limits on DM annihilation (clumps..)



Next generation: CTA

2108.09078



If thermal CDM but not Weakly IMPs?

We still can study the model if DM annihilates (partly) into SM particles

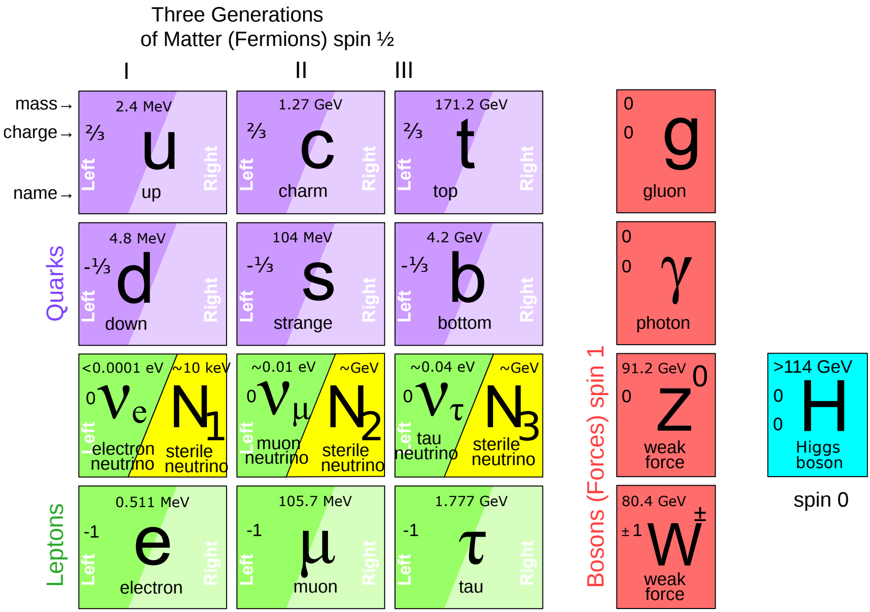
- But DM particle X can be light and feebly coupled (t-channel)

$$\sigma_0 \sim \frac{\xi^4}{M_X^2}$$

ξ is not a gauge coupling within GUT !

- With small σ_0 one needs entropy production
- σ_0 may be increased by s-channel resonance, $M_Y \approx 2M_X$
- annihilation can be amplified by co-annihilation channels, $X + A \to SM$
- With light messangers between Dark and Visible sectors many estimates change, say $\sigma_0 = \sigma_0(v)$
- DM interaction at freeze-out and now are not the same
say, Sommerfield enhancement of the annihilation of slow particles $v \sim 10^{-3}$

- In this way we may fully explore the model parameter space of the Weakly interacting Massive Particles
- Similar case with another 'light' and physically well-motivated candidate: sterile neutrino


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

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

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

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 $M_N < M_W$)

$$\theta^2 < 1.5 \times 10^{-7} \left(\frac{50\,\text{keV}}{M_N}\right)^5$$

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

$$\tau_{N\to3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\text{yr}\,(10\,\text{keV}/M_N)^4$$

Sterile neutrino: indirect searches

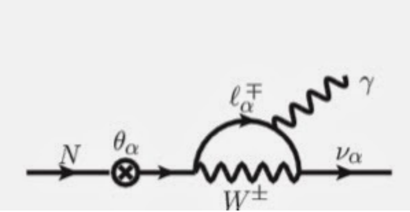
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- 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

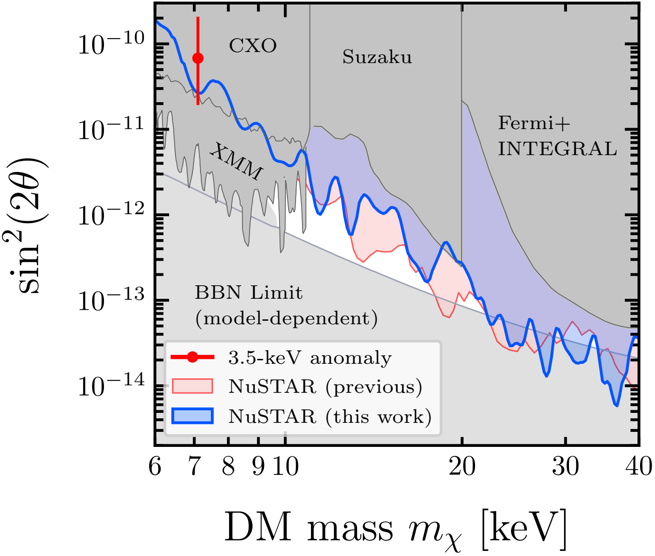


a narrow line $(\delta E_\gamma/E_\gamma \sim v \sim 10^{-3})$
at photon frequency $E_\gamma = M_N/2$

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

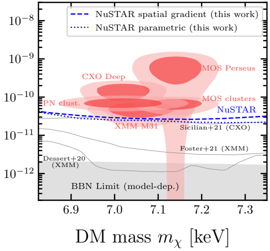
. . . present searches: NuSTAR

2207.04572

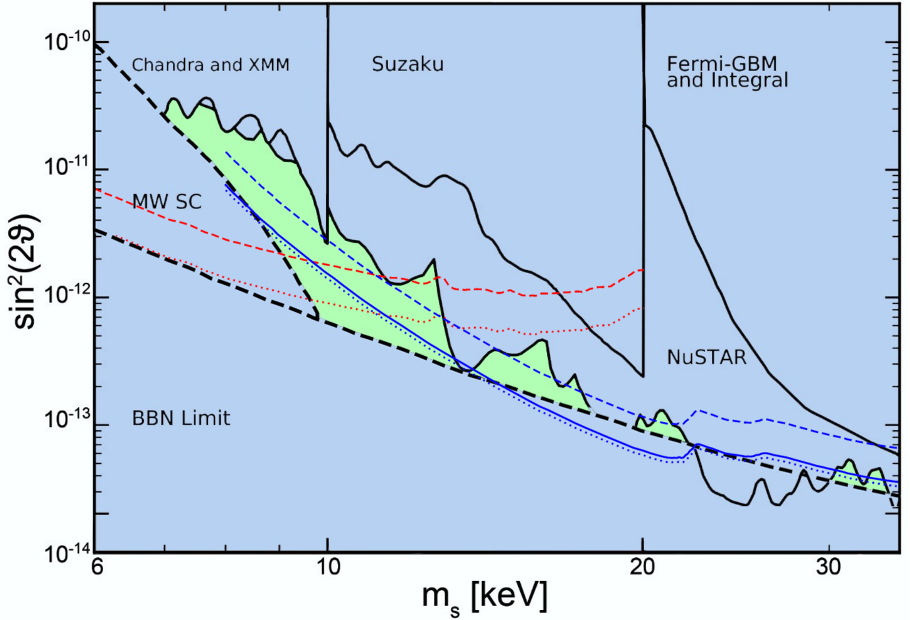


- upper limits on mixing: from *X*-ray searches
- lower limits on mass: from structure formation

and BBN predictions



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



1908.09037 2007.07969 (V. Barinov, R. Burenin, D.G., R. Krivonos)

Production in oscillations, $p_X \approx p_T$, except resonances

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

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

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

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

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

and effective plasma potential for active neutrinos

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

resonant production in the lepton asymmetric plasma

- In this way we may fully explore the model parameter space of the Weakly interacting Massive Particles
- Similar case with another 'light' and physically well-motivated candidate: sterile neutrino
- But some DM models, even the simplest ones, can be incredibly elusive

Illustration with a simple example of scalar DM

most general renormalizable coupled to SM:

Z_2-invariant Higgs (Φ) portal

$$\Delta\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu S\partial_\nu S - \frac{1}{2}m^2S^2 + g^2S^2\Phi^\dagger\Phi - \frac{\lambda}{4}S^4$$

Options:

- freeze-out: sufficiently large g^2

$$\sigma_{hh\to SS}\times n_h \gtrsim H \;\;\to\;\; \sigma_{SS\to\ldots} = \sigma_0, \text{ e.g. } \frac{g^4}{(4\pi\ldots)^2 m_S^2} = \sigma_0$$

- freeze-in: intermediate g^2

$$\dot{n}_S + 3Hn_S = \sigma_{hh\to SS}n_h^2 \;\;\to\;\; \frac{n_S}{s} = \#\int dT\,\frac{n_h^2}{sHT}\times\frac{g^4}{T^2} \sim g^4\frac{M_{Pl}}{m_S} \;\;\to$$

$\Omega_S \propto g^4 \;\;\to\;\; g^2 \approx 10^{-11}$ still natural...

Free massive scalar field $g^2 = 0$

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} m_\phi^2 \phi^2$$

Homogeneous scalar field in the expanding Universe

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

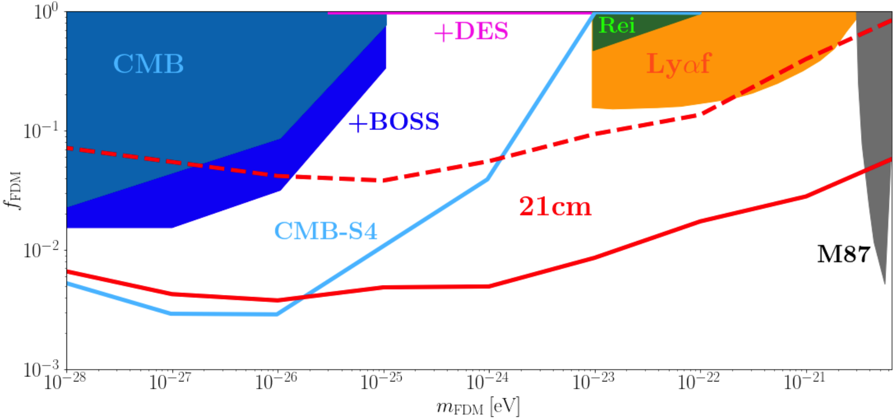
Two-stage evolution:

$$m_\phi < H(t) \quad \Longrightarrow \quad \phi = \phi_i = \text{const}$$

$$m_\phi > H(t) \quad \Longrightarrow \quad p = \langle E_k \rangle - \langle E_p \rangle = 0\,, \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3$$

- dust-like substance in the late Universe, $\Omega \propto m_\phi^{1/2} \phi_i^2$
  depends on initial conditions
- presureless at spatial scales $l > M_{Pl}^{1/2}/\rho^{1/4} m_\phi^{1/2}$ fuzzy DM
- isocurvature mode: $\delta\rho_\phi \propto \delta H\,,\ \delta f_i$

HERA sensitivity to Fuzzy DM (quantum pressure)



new observable to test the model...

2207.05083

scalar DM without dependence on initial field

$0 \neq g^2 < 10^{-11}$

Z_2-invariant Higgs (Φ) portal

$$\Delta\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu S \partial_\nu S - \frac{1}{2} m^2 S^2 + g^2 S^2 \Phi^\dagger \Phi - \frac{\lambda}{4} S^4$$

Higgs particles in plasma change the potential:

$$g^2 S^2 \Phi^\dagger \Phi \;\rightarrow\; g^2 S^2 T^2/3$$

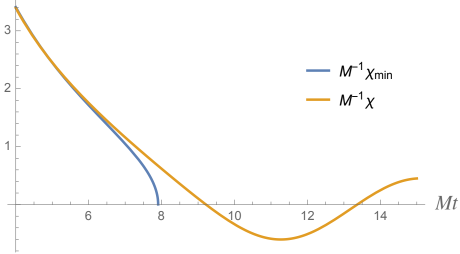
Z_2 symmerty is broken after reheating by the plasma contribution

Temperature decrease restores Z_2

2004.03410

$$\Delta\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu S\partial_\nu S - \frac{1}{2}m^2S^2 + g^2S^2T^2/3 - \frac{\lambda}{4}S^4$$

S starts from the false vacuum



at $g^2T_*^2 \simeq m^2$ sign changes and S starts to oscillate

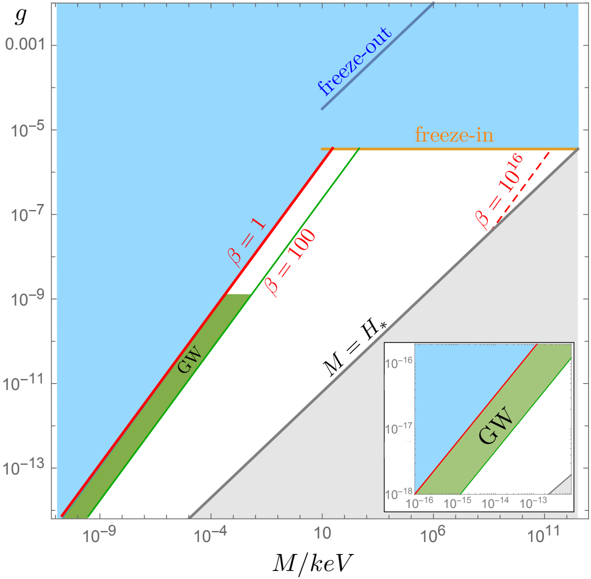
gravitational misalignment

$$\rho_{DM}(t_*) = \frac{m^2 \cdot S_*^2}{2} \simeq \frac{\left(m^5H_*\right)^{2/3}}{4\lambda}$$

And the correct amount of DM by classical oscillating field

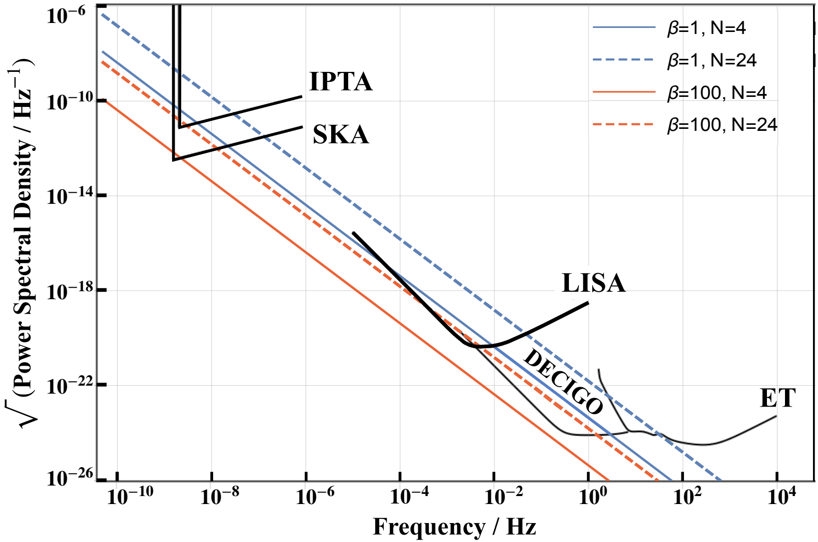
$$g^2 \simeq 10^{-12} \times \left(\frac{\lambda}{10^{-6}}\right)^{6/5} \times \left(\frac{10^6\,\text{GeV}}{m}\right)^2$$

DM and Gravitational Waves from Domain Walls 2104.13722



GW signals from dissipating DM ...

2104.13722



Freeze in via gravitational scatterings..?

any particles in plasma

$$\sigma_{XX\to SS} \propto \frac{T^2}{M_{Pl}^4} \;\to\; \frac{n_S}{s} \sim \frac{T_i^3}{M_{Pl}^3} \cdots$$

assuming $m \ll T_i$

World-wide accepted problems. . .

Origins of...?

- Dark Matter
- Matter-antimatter asymmetry
- Dark Energy
- matter perturbations (inflation?)
- . . .
- extragalactic magnetic field
- superheavy black holes in the galaxy centers

Coincidences

- $\Omega_{DM} \sim \Omega_B$
- $\Omega_M \sim \Omega_{DE}$
- $(\delta\rho/\rho)^2 \simeq n_B/n_\gamma$
- $T_d^n \sim (m_n - m_p)$
- $\tau_U \approx H_0^{-1}$
- . . .

Anomalies

- BBN: Lithium
- CMB: multipole statistics
- Planck: low and high multipoles
- Planck: lensing, SZ-clusters
- Hubble measurements
- σ_8

Baryogenesis

– Need BAU $\eta_B \equiv n_B/n_\gamma \approx 6 \times 10^{-10}$ starting from BBN epoch, $T \lesssim 1$ MeV
– The same number at recombination and later

Sakharov conditions of successful baryogenesis

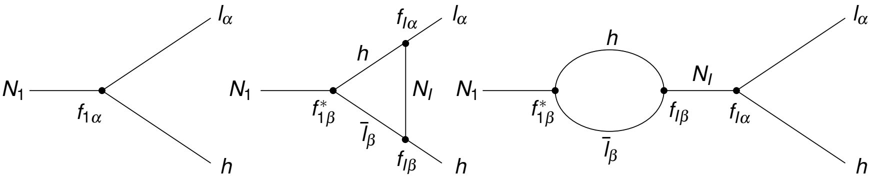
- B-violation $(\Delta B \neq 0)\; XY \dots \to X'Y' \dots B$
- C- & CP-violation $(\Delta C \neq 0,\, \Delta CP \neq 0)\; \bar{X}\bar{Y} \dots \to \bar{X}'\bar{Y}' \dots \bar{B}$
- processes above are out of equilibrium $X'Y' \dots B \to XY \dots$

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.

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

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

Lepton asymmetry δ at 1-loop level $\quad f_{l\alpha}\bar{L}_\alpha N_I \widetilde{H}$



$$\Gamma(N_1 \to lh) = \frac{M_1}{8\pi} \cdot \sum_\alpha \left| f_{1\alpha} + \frac{1}{8\pi} \sum_{\beta,l} F\left(\frac{M_1}{M_l}\right) \cdot f^*_{1\beta} f_{l\alpha} f_{l\beta} \right|^2 , \quad m_\nu \ll M_l$$

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = -\frac{1}{8\pi} \sum_{l=2,3} \mathrm{Im}\left[F\left(\frac{M_1}{M_l}\right)\right] \cdot \frac{\mathrm{Im}\left(\sum_\alpha f_{1\alpha} f^*_{l\alpha}\right)^2}{\sum_\gamma |f_{1\gamma}|^2} .$$

for $M_{2,3} \gg M_1$, $f\left(\frac{M_1}{M_l}\right) = -\frac{3}{2}\frac{M_1}{M_l}$, $\delta = \frac{3\,M_1}{16\pi} \frac{1}{\sum_\gamma |y_{1\gamma}|^2} \sum_{\alpha\beta l} \mathrm{Im}\left[y_{1\alpha} y_{1\beta} \left(y^*_{l\alpha} \frac{1}{M_l} y^*_{l\beta}\right)\right]$.

Superheavy sterile neutrinos: $M_N \simeq 10^9$-10^{14} GeV

- Motivation: close to GUT scales, e.g. $SO(10)$
- Bad fact: huge finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \gg m_H^2 (\Rightarrow M_N < 10^7\,\text{GeV})$
  SUSY solution? (New fileds...new problems: e.g. gravitino overproduction with high T_{reh} for leptogenesis)
- Good fact: If $T > M_N$ decays of thermal sterile neutrino yield the lepton asymmetry in the early Universe: M.Fukugita, T.Yanagita (1986)

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = \frac{1}{8\pi} \sum_{l=2,3} f\left(\frac{M_{N_1}}{M_{N_l}}\right) \cdot \frac{\text{Im}\left(\sum_\alpha f_{1\alpha} f_{l\alpha}^*\right)^2}{\sum_\gamma |f_{1\gamma}|^2} \,.$$

  Needs $M_{N_1} \gtrsim 10^9\,\text{GeV}$ or $M_{N_1} \gtrsim 10^{12}\,\text{GeV}$ without fine tuning in $\hat{f}$
- Exciting fact: to avoid washing out of Δ_L in $hl_\alpha \leftrightarrow h\bar{l}_\beta$ we need ...
  $M^\nu < 0.1 - 0.3\,\text{eV}$!!!
- Cooling down: No way to test further. Can get $\Delta_B \sim 10^{-10}$ even with
  $\theta_{13} = \delta_{\text{CP}} = 0$!

NB: can work for nonthermal case as well

production by inflaton decay G.Lazaridies, Q.Shafi (1991) e.g. in R^2-inflation D.G., A.Panin (2010)

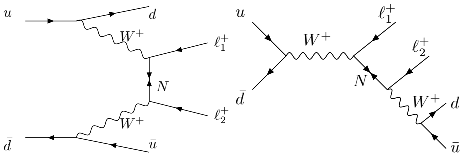
Very heavy sterile neutrinos: $M_N \simeq 100\,\text{GeV-}5\,\text{TeV}$

- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  No hierarchy between Λ_ν and Λ_{EW}
- Bad fact: Without extra symmetries, fine tuning or new interactions generation of lepton asymmetry and hence No BAU
- Way out: fine tunning can help: e.g. resonant enhancement of CP-violation in out-of-equilibrium sterile neutrino decays:
  leptogenesis for $M_N \gtrsim 1\,\text{TeV}$ if $\Delta M_N \sim \Gamma_N$ Pilaftsis (1997,...)
- Further cooling down:
  can be directly produced but at a tiny amount only: as small as $f \sim 10^{-6}$!
- Conclusion: Seesaw type I is generally untestable in direct searches:
  Yuakawa couplings are too small, while sterile neutrinos are quite heavy.

To make interesting either NEW fields or fine tuning (larger f)
or symmetries, e.g. $SU(2)_L \times SU(2)_R$ are required!!!

Very heavy sterile neutrinos: $M_N \simeq 50\,\text{GeV-5 TeV}$

- Without fine tuning or extra symmetries:
  can be directly produced but @ tiny amount: $f \sim 10^{-6}$!
- With extra symmetries and/or interactions, e.g. $SU(2)_L \times SU(2)_R$
  can be studied at LHC $\quad pp \to W_R \to \mu N$
- Indirect searches ... $\Delta L = 2$ processes $\quad pp \to \dots \mu^+\mu^+ \dots,\ t \to b\mu^+\mu^+ W^-$
  $D^+ \to \mu^+\mu^+K^-,\quad K^+ \to \mu^+\mu^+\pi^-$
  see Lectures by B.Kayser



$$\sigma\left(pp \to W^{\pm *}W^{\pm *} \to \ell_1^{\pm}\ell_2^{\pm}X\right) = \left(2-\delta_{\ell_1\ell_2}\right)\left|\theta_{\ell_1 N}\theta_{\ell_2 N}\right|^2 \sigma_0(WW)$$

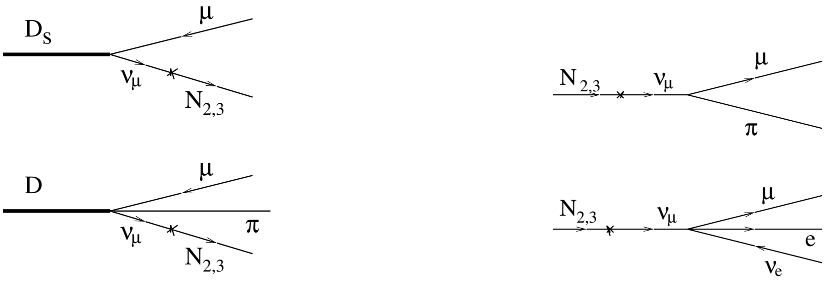
$$\sigma(pp \to W^{+*} \to \ell_1^{\pm}\ \ell_2^{\pm}\ W^{\mp}) \approx \left(2-\delta_{\ell_1\ell_2}\right)\sigma(pp \to \ell_1^{\pm}N)Br(N \to \ell_2^{\pm}W^{\mp})$$

- Conclusion: Seesaw type I is testable only indirectly for this range of masses. To make interesting NEW fields (symmetries) are required!!!

Heavy sterile neutrinos: $M_N \simeq 1\,\text{keV-}100\,\text{GeV}$

- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  True low-energy scale modification of the SM
- Good fact: At $T > 100\,\text{GeV}$ active-sterile neutrino oscillations produce lepton asymmetry in the early Universe, if $\Delta M_N \ll M_N$ E.Akhmedov, V.Rubakov, A.Smirnov (1998)
- can be directly produced !!

Weak decays due to mixing



More on direct searches

Weak decays due to mixing

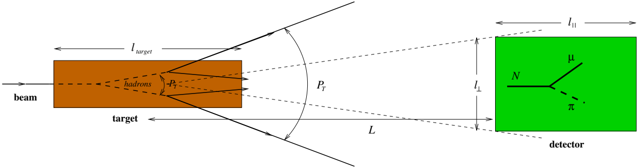
$$\Gamma(A \to N + \dots) \propto \theta^2 \qquad \Gamma(N \to B + \dots) \propto \theta^2$$

- Searches for production of N: $S \propto \theta^2$ — e.g. peaks in p_μ
- Searches for decays of N:
  If the decay length is shorter than the detector size, $S \propto \theta^2$
  but with $\theta^2 \to 0$ arrive at $S \propto \theta^2 \times \theta^2$

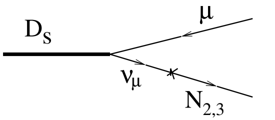
Heavy sterile neutrinos: direct searches

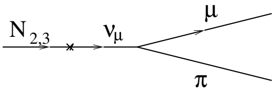
Weak decays due to mixing

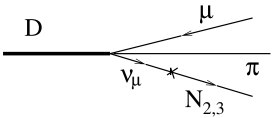
Production in beam-dump experiments

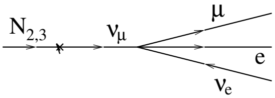


And More. . .









- Amplification of production in $1 \to 2$ (chirality)

$$\Gamma(M \to N + l) \propto \theta^2 M_N^2$$

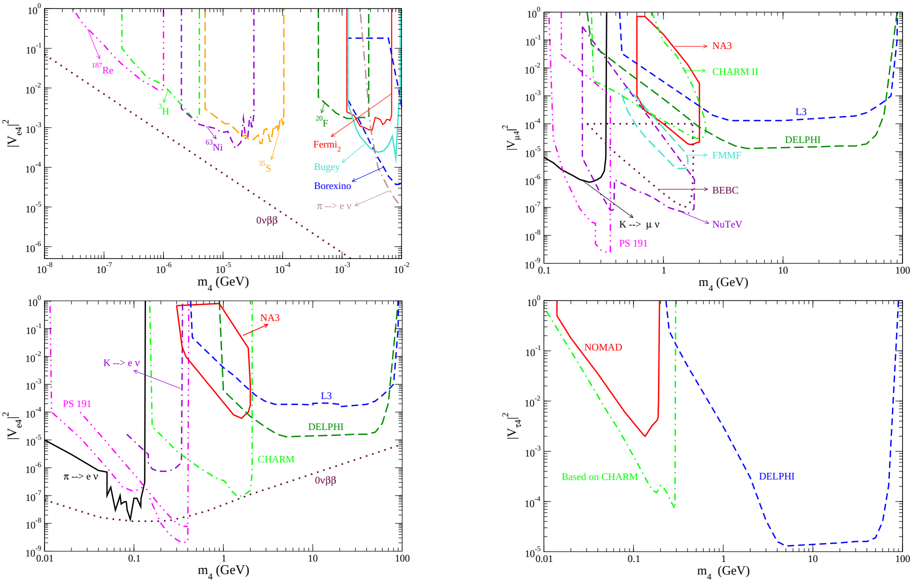
- heavy N decay is fast

$$\tau = \frac{\tau_\mu}{\theta^2} \times \left(\frac{m_\mu}{M_N}\right)^5 = 10^{-10}\,\mathrm{s} \times \frac{10^{-6}}{\theta^2} \times \left(\frac{10\,\mathrm{GeV}}{M_N}\right)^5$$

tends to decay inside the detector

Limits 10 years ago. . .

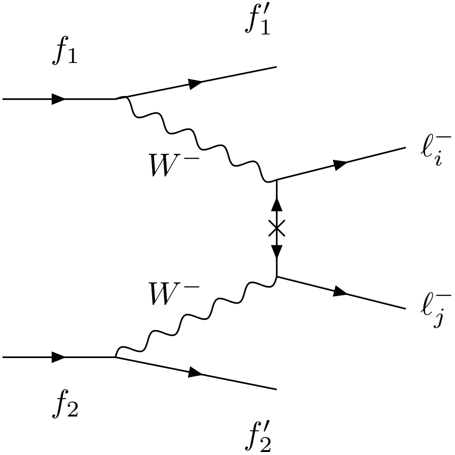
0901.3589



Indirect searches: $\Delta L = 2$ processes

$0\nu\beta\beta$

limits are only for one sterile neutrino...



for light sterile neutrinos

$$\langle m \rangle^2_{\ell_i \ell_j} = \left| \sum_I U_{\ell_i I} U_{\ell_j I} M_{N_I} \right|^2$$

for heavy sterile neutrinos

$$\left| \sum_I \frac{V_{\ell_i I} V_{\ell_j I}}{M_{N_I}} \right|^2 ,$$

How far we should go? νMSM

T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

see Lectures by A.Smirnov

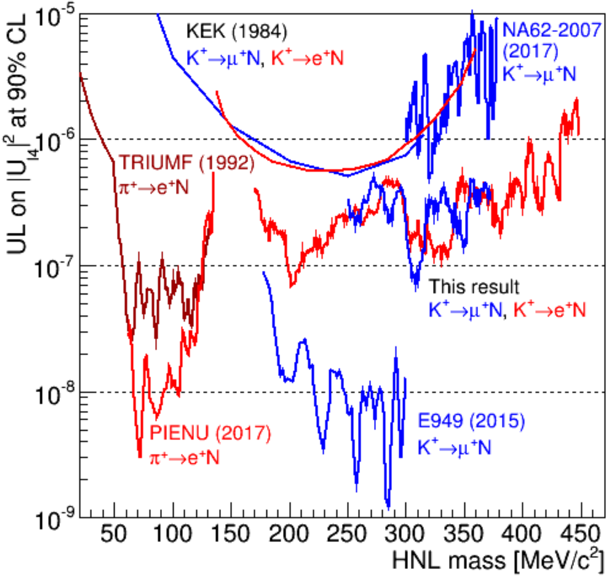
- Seesaw mechanism is provided mostly by two 'heavy' sterile neutrinos
  lightest active is almost massless
- They are (highly) degenerate in mass, $\Delta M_N \ll M_N$ producing matter-antimatter asymmetry of the Universe via leptogenesis in primordial plasma at $T > 100\,\text{GeV}$ E.Akhmedov, V.Rubakov, A.Smirnov (1998)
  mixing is constrained from above and from below !!
- The third 'light' sterile neutrino, $M_N \simeq$ 1-10 keV, is almost decoupled and serve as dark matter
  mixing is constrained from above and from below !!

the model explain while the previous experiments fail...

the model can be fully explored

Present limits from production

1904.09124



Present limits and expectations

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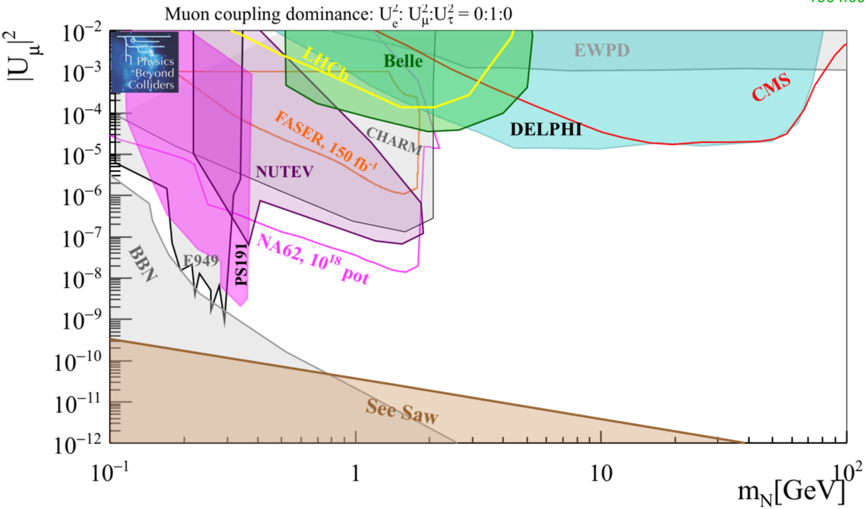
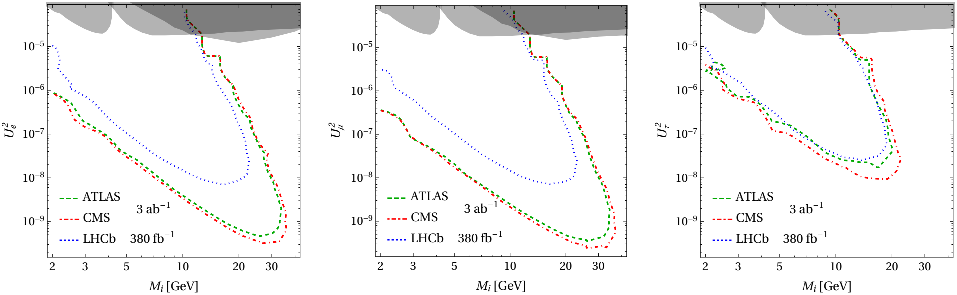


LHC-HL: expectations for a displaced vertex

1903.06100



Outline

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, M_W, ...)
- Does not describe

(PHENO)

- Neutrino oscillations (and anomalies...)
- 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/gauge unification?
- Why 3 generations?
- Why $Y_e \ll Y_\mu \ll .. \ll Y_t$

Theoretical guideline: gauge hierarchy problem

Quantum corrections to the SM Higgs boson mass

quadratic divergences regularized by a cut in loop 4-momentum

$$\delta m_h^2 \propto \Lambda^2 + m_X^2 + \ldots$$

Physical meaning? Bardeen's argument: regularization violates scale invariance

$$T_{\mu\nu} \propto \Lambda^2 \phi^2 + \ldots$$

Becomes convincing with some heavy states involved. . .

Theoretical guideline: gauge hierarchy problem

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More severe problem in cosmology

Contribution to dark energy

Higgs vev and quartic divergences regularized by a cut in loop 4-momentum

$$(0.002\,eV)^4 = Cosmological\ Constant = \frac{\lambda}{4}v^4 + (..)\Lambda^4$$

there must be a mechanism to cancel them

The solutions involve cosmological evolution
and some (relaxation, etc.)
pretend to cancel the δm^2 as well...

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pretend to cancel the δm^2 as well...

Other solutions within particle physics

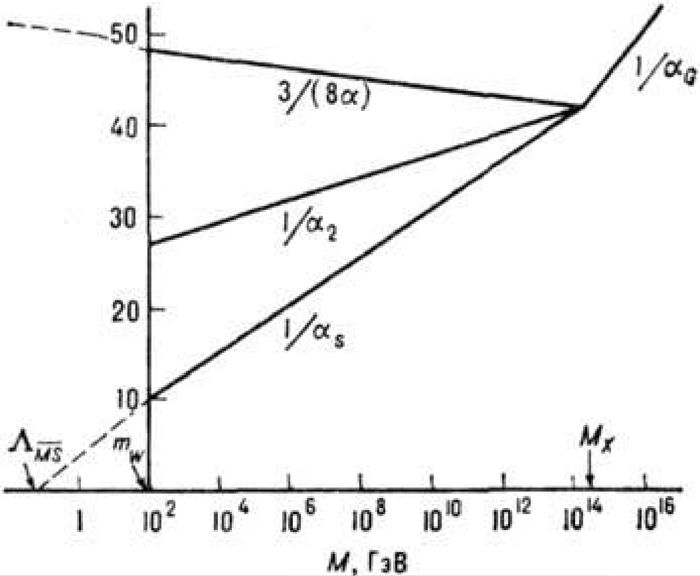
- Supersymmetry (but with heavy superpartners)
- Technicolor
- ...

Predicts new ingredients in the early Universe !!

Predicts higher order non-renormalizable operators...
the lowest one is dim-5 and gives neutrino masses !!

$$\mathscr{L} = \frac{1}{\Lambda}\bar{L}\tilde{H}L\tilde{H}^\dagger \longrightarrow \frac{v^2}{\Lambda}\bar{\nu}\nu$$

New physics at high energies...



– Gauge coupling unification
– Wilsonian approach: solid state physics lattice supersymmetry
– gauge coupling unification supersymmetry
– LHC: nothing at TeV scale...

Supersymmetry is a symmetry of bosons and fermions

supercharge $\hat{Q}_{SUSY}$

- SUSY exhanges bosons and fermions:

$$\hat{Q}_{SUSY}\ \text{boson} \longrightarrow \text{fermion}$$
$$\hat{Q}_{SUSY}\ \text{fermion} \longrightarrow \text{boson}$$

  they become superpartners

- In supersymmetric theory

$$\text{bosonic d.o.f.} == \text{fermionic d.o.f.}$$

- $$\left[\hat{Q}_{SUSY}\,,\,\hat{H}\right] == 0$$

  superpartners
  are of the same mass and exhibit the same interactions

How does it work? Supersymmetric QED

- the same number of d.o.f. in bosonic and fermionic sectors

$$\text{Dirac fermion } \Psi : 4\, d.o.f. \longrightarrow \text{complex scalars } \phi_+ , \phi_-$$
$$\text{massless vector } A_\mu : 2\, d.o.f. \longrightarrow \text{Majorana fermion } \lambda$$

- superpartners are of the same masses

$$m\bar{\Psi}\Psi \longrightarrow m^2 \phi_+^* \phi_+ + m^2 \phi_-^* \phi_- \,, \qquad M_A = M_\lambda = 0 \,,$$

- and exhibit the same interactions

$\mathscr{L}$ is a scalar !!

$$e A_\mu \bar{\Psi} \gamma^\mu \Psi \longrightarrow ie A^\mu \left(\phi_+ \partial_\mu \phi_+^* - \phi_+^* \partial_\mu \phi_+ \right) - ie A^\mu \left(\phi_- \partial_\mu \phi_-^* - \phi_-^* \partial_\mu \phi_- \right)$$
$$e A_\mu \bar{\psi}_+ \bar{\sigma}^\mu \psi_+ - e A_\mu \bar{\psi}_- \bar{\sigma}^\mu \psi_- \longrightarrow -ie\sqrt{2} \left(\phi_+ \bar{\psi}_+ \bar{\lambda} - \phi_- \bar{\psi}_- \bar{\lambda} \right) + \text{h.c.}$$
$$\text{total derivative} \longleftarrow e^2 A_\mu A^\mu \phi_+^* \phi_+ + e^2 A_\mu A^\mu \phi_-^* \phi_-$$
$$\text{total derivative} \longleftarrow -e^2 \frac{1}{2} \left(\phi_+^* \phi_+ - \phi_-^* \phi_- \right)^2$$

Most attractive features

- Theory: bosonic loops cancel fermionic ones

  only logarithmic divergences remain:

  stability of the hierarchical structure of energy scales, e.g. $M_W \ll M_{Pl}$ is stable

- Phenomenology: number of particles gets doubled !!

  get new interactions but with the same coupling constants !!

SUSY: a couple is more stable and promising

Supersymmetrizing the Standard Model MSSM

gluons, g	$\longleftrightarrow$	gluino, $\tilde{g}$
photon, γ	$\longleftrightarrow$	photino, $\tilde{\gamma}$
weak gauge bosons, $W^{\pm}, Z$	$\longleftrightarrow$	winos, zino, $\tilde{W}^{\pm}, \tilde{Z}$
quarks, leptons, q, l	$\longleftrightarrow$	squarks, sleptons, $\tilde{q}, \tilde{l}$
	e.g.	
r.h. electron, e_R	$\longleftrightarrow$	r.h. selectron, $\tilde{e}_R$
l.h. top, t_L	$\longleftrightarrow$	l.h. stop, $\tilde{t}_L$
neutrino, ν	$\longleftrightarrow$	sneutrino, $\tilde{\nu}$
SM Higgs boson	$\longleftrightarrow$	higgsino
to avoid the anomaly		due to higgsino set
two Higgs doublets, $h, H, A, H^{\pm}$	$\longleftrightarrow$	neutral $\tilde{h}$, $\tilde{H}$ and charged $\tilde{H}^{\pm}$ or $\chi^0_{1,2}$ and $\chi^{\pm}$ higgsinos
graviton, G	$\longleftrightarrow$	gravitino, $\tilde{G}$

Problems of a supersymmetric extension

there are no superpartners of the same mass with the same couplings

$\longrightarrow$ SUSY must be spontaneously broken

- superpartners are heavy bases are not aligned
  Higgs makes SM particles (and superpartners) massive
  hundred new parameters $\Longleftarrow$ mixing and FCNC

At least a huge gap is between us

SUSY is broken and thereby even more attractive

- Higgs mass gets corrections of the types

$$\propto \log(m_t^2/m_{\tilde{t}}^2), \quad \text{and} \quad \propto \left(m_{\tilde{t}}^2 - m_t^2\right),$$

  the superpartners must be not far from the EW-scale
- Massive, emerge in pairs $\Longrightarrow$ lightest superpartner is stable (LSP)
  R-parity most natural DM candidate (WIMPs) we have
- 2 Higgs doublets can arrange EW phase transition of the I order
  additional sources of CP-violation
  $\Longrightarrow$ prospects for EW baryogenesis
- There are several anomalies in particle physics (and closely related) experiments: $\text{Br}(B \to K^*\mu^+\mu^-)$
  $(g-2)$, $\Gamma(B \to D^{(*)}\tau\nu)/\Gamma(B \to D^{(*)}l\nu)$,
  $\Gamma(B \to K\mu^+\mu^-)/\Gamma(B \to Ke^+e^-)$

Problems of a supersymmetric extension

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$\longrightarrow$ SUSY must be spontaneously broken

- superpartners are heavy — bases are not aligned
  Higgs makes SM particles (and superpartners) massive
  handred new parameters $\Longleftarrow$ mixing and FCNC
- in local SUSY — supergravity (SUGRA)
  super Higgs mechansim works:
  gravitino eats Goldstone field, goldstino, and becomes massive

$$m_{\tilde{G}} = \frac{\Lambda_{SUSY}^2}{\sqrt{3}\,M_{Pl}}\,, \qquad \mathscr{L}_{int} = \frac{1}{\Lambda_{SUSY}^2}\,J^{\mu}_{SUSY}\partial_\mu \tilde{G}$$

in many SUSY setups

gravitino production overcloses the Universe

Gravitino production in scatterings and decays

$$\tilde{X}_i \to \tilde{G} + X_i\,, \quad X_i + X_j \to \tilde{X}_k + \tilde{G}$$

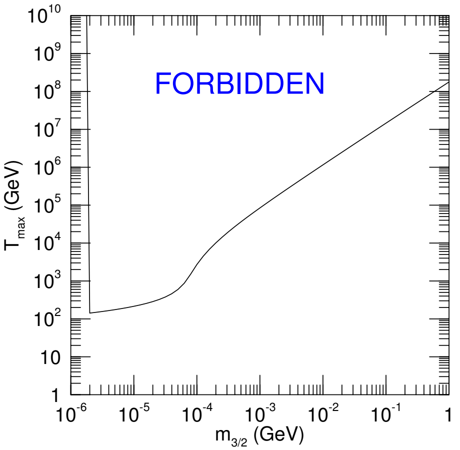
$$\Gamma \propto \frac{1}{F^2} \propto \frac{1}{m_{3/2}^2}\,, \qquad \sigma \propto \frac{1}{F^2} \propto \frac{1}{m_{3/2}^2}$$

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = \sum_i \Gamma_{\tilde{X}_i} \cdot \gamma_i^{-1} \cdot n_{\tilde{X}_i} + \sum_{i,j} \langle \sigma_{ij} \rangle \cdot n_{X_i} n_{X_j}\,,$$

$$\frac{d}{dT}\left(\frac{n_{3/2}}{s}\right) = -\sum_i \Gamma_{\tilde{X}_i} \cdot \frac{n_{\tilde{X}_i}}{\gamma_i \cdot sHT} - \sum_{i,j} \frac{\langle \sigma_{ij} \rangle \cdot n_{X_i} n_{X_j}}{sHT}\,,$$

$$\propto \frac{1}{T^3} \qquad\qquad \propto \text{const}$$

$$\Omega_{3/2} \sim \left(\frac{200\text{ keV}}{m_{3/2}}\right) \cdot \left(\frac{T_{max}}{10\text{ TeV}}\right) \times \left(\frac{M_S}{1\text{ TeV}}\right)^2 \cdot \left(\frac{15}{\sqrt{g_*(T_{max})}}\right) \cdot \frac{1}{2h^2}$$

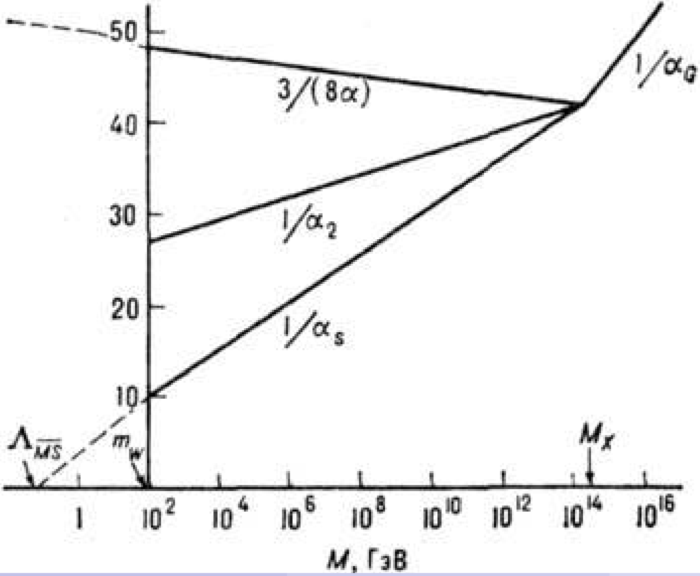


...issues of QFT description

of a gauge theory at finite temperature

Outcome depends on initial conditions !!!

Comments on SUSY GUTs



– Gauge coupling unification

– Dependence on the structure of soft terms

dim-5 operator violating baryon number

No Yukawa coupling unification

No unification for 1st and 2nd gen

anyway: no neutrino masses

NMSSM ?

Why NMSSM ?

- μ-problem : $\mu^2 \left(H_U^\dagger H_U + H_D^\dagger H_D \right)$

  MSSM: $\hat{W} = \mu \hat{H}_u \hat{H}_d$ NMSSM: $\hat{W} = \hat{N} \hat{H}_u \hat{H}_d$

- mechanism of baryogenesis:

  MSSM: Affleck-Dine NMSSM : Electroweak

EWB does not work in SM:

- *CP*-violating processes are too weak
- crossover, so no departure from termal equilibrium

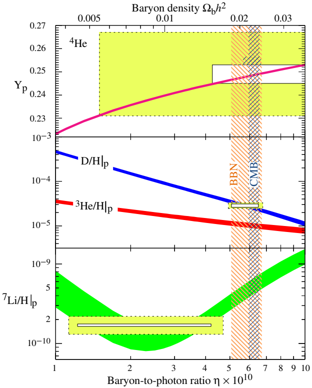
MSSM: new sources of *CP*-violation
NMSSM: + the strongly first order phase transition

Electroweak baryogenesis is attractive:
both ingredients can be directly tested

Baryogenesis

Sakharov conditions of successful baryogenesis

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



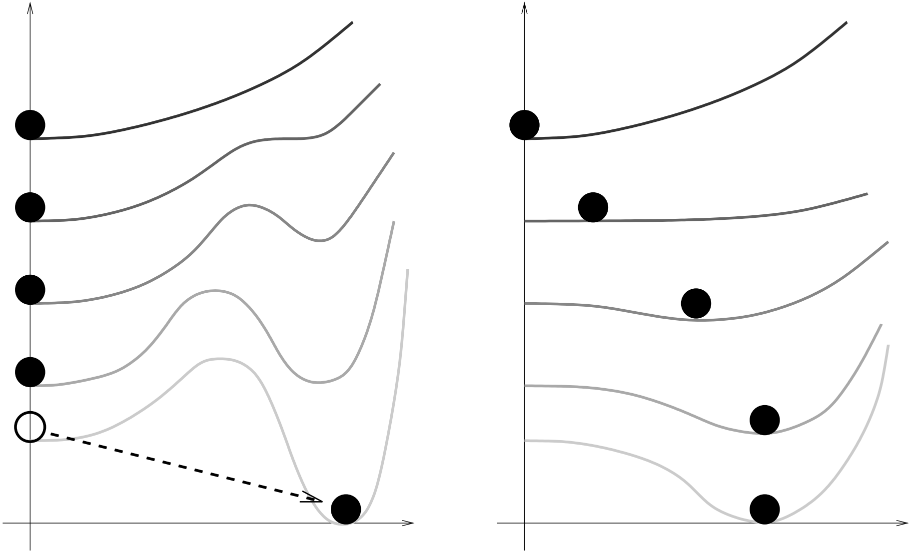
At 100 GeV$\lesssim T \lesssim 10^{12}$ GeV nonperturbative processes (EW-sphalerons) violate B, L_α, so that only three charges are conserved out of four, e.g.

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

Find similar estimates from BBN, CMB and LSS data

need baryon asymmetry production before $T \simeq 1$ MeV

Phase transitions of the I and II orders



EW phase transition

strongly first order: $v_c/T_c \gtrsim 1.1$ (otherwise erasure by sphalerons)
FTFT:

$$V_T(v, v_S, v_P) = V_{tree}(v, v_S, v_P) + V^{(1)}(v, v_S, v_P) + V_T^{(1)}(v, v_S, v_P).$$

$$V_T^{(1)} = \sum_i (\pm) \frac{T^4}{2\pi^2} n_i \int_0^\infty dx x^2 \log\left(1 \mp e^{-\sqrt{x^2 + (m_i(\phi)/T)^2}}\right),$$

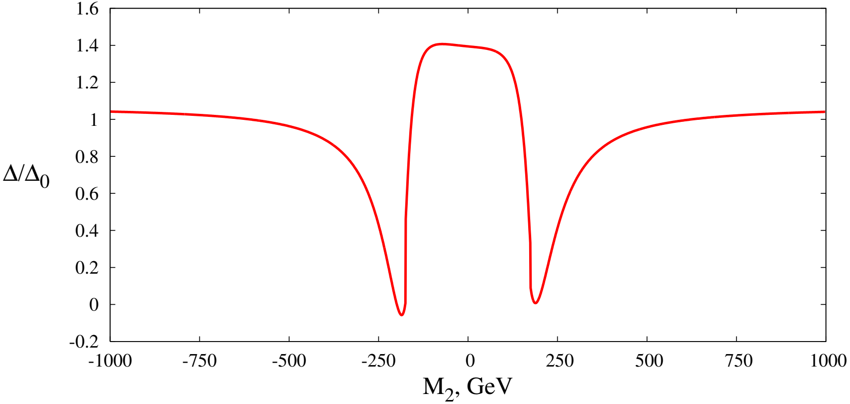
@ T_c first bubbles begin to nucleate: $S_3(T_c)/T_c \sim 130 - 140$
critical bubble is a saddle point of the free energy functional

$$S_3(T) = 4\pi \int_0^\infty dr r^2 \left[\left(\frac{dh}{dr}\right)^2 + \left(\frac{dS}{dr}\right)^2 + \left(\frac{dP}{dr}\right)^2 + V_T(h, S, P) \right].$$

The baryon asymmetry

EWB works perfectly (only μ is switched on)

Set (2), $\Delta_0 = 8.7 \times 10^{-11}$ or $\eta_B \equiv n_B/n_\gamma = 6.5 \times 10^{-10}$



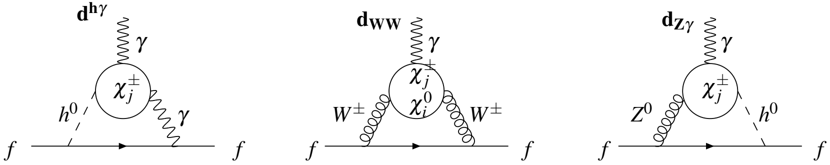
Electric dipole moments of electron and neutron

CP-source: the same contributions to EDMs as in Split MSSM
but here one has generally two additional phases,

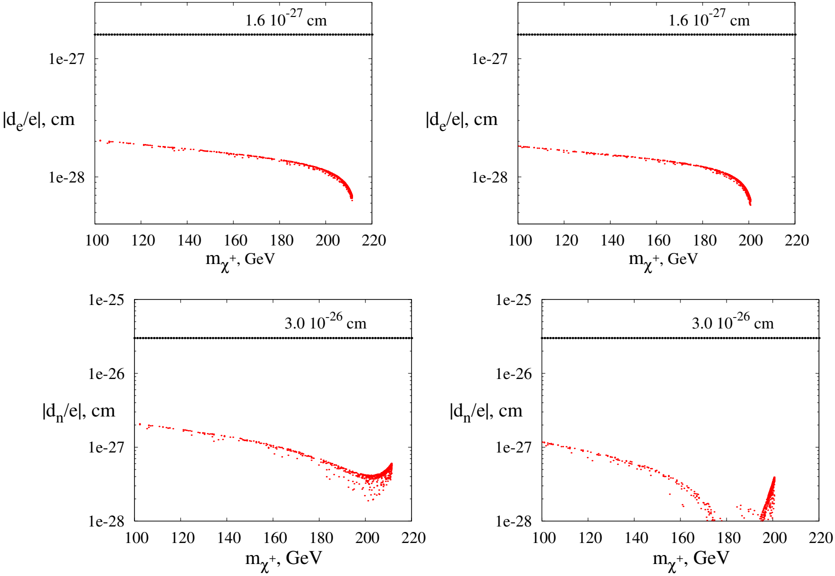
$$\phi_1 = \arg(\tilde{g}_u{}^* \tilde{g}_d{}^* M_2 \tilde{\mu})\,, \quad \phi_2 = \arg\left(\kappa k^* \lambda_u \lambda_d (\tilde{\mu}^*)^{-2}\right)\,, \quad \phi_3 = \arg(\lambda_u \lambda_d^* \tilde{g}_u^* \tilde{g}_d)$$

$$\tilde{\mu} = \mu + \kappa (v_s + i v_P)/\sqrt{2}$$

$$\mathrm{d_f} = \mathrm{d_{h\gamma}} + \mathrm{d_{WW}} + \mathrm{d_{hZ}}$$



Electric dipole moments . . . (2007)



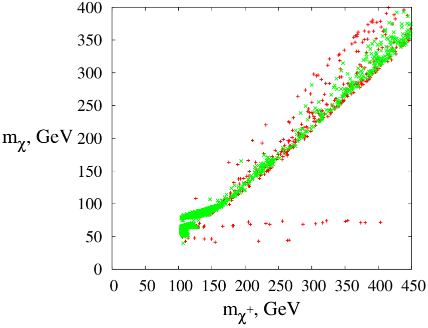
Dark Matter: WIMPs made of neutralino or singlino

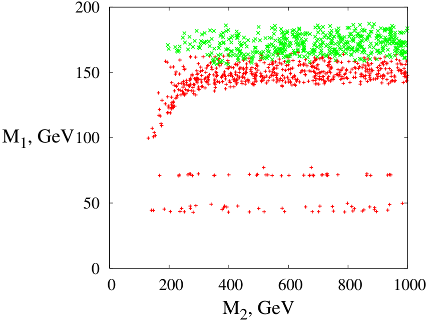
$$\chi = N_{51}\tilde{B} + N_{52}\tilde{W} + N_{53}\tilde{H}_u + N_{54}\tilde{H}_d + N_{55}\tilde{N}$$

$$\frac{m_\chi}{T_F} = x_F = \log\left(\frac{m_\chi}{2\pi^3}\sqrt{\frac{45}{2g_* G_N x_F}}\langle\sigma v\rangle_{\text{Møl}}\right)$$

$$\langle\sigma v\rangle_{\text{Møl}} = \frac{1}{8m_\chi^4 T K_2^2(m_\chi/T)}\int_{4m_\chi^2}^{\infty} ds\sigma(s)(s-4m_\chi^2)\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right)$$

$$\Omega_\chi h^2 = \frac{(1.07\times 10^9\text{GeV}^{-1})}{M_{Pl}}\left(\int_{x_F}^{\infty} dx\frac{\langle\sigma v\rangle_{\text{Møl}}(x)}{x^2}g_*^{1/2}\right)^{-1}.$$





Split NMSSM in 2017

S.Demidov, D.G., D.Kirpichnikov (2016)

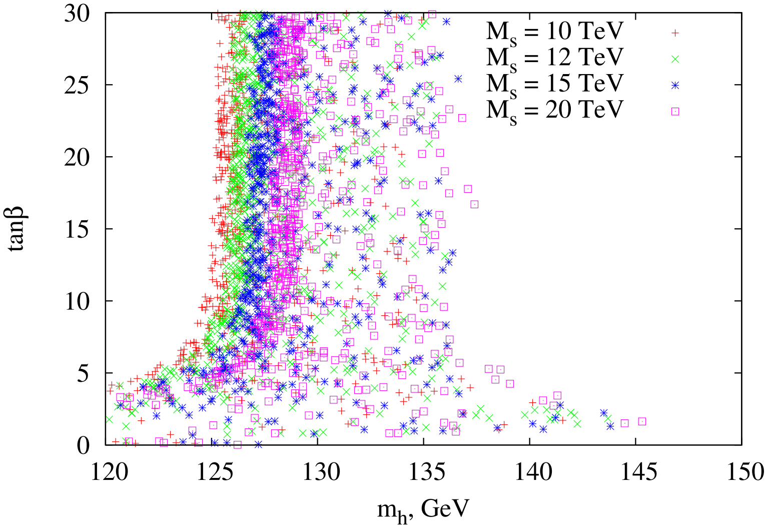
10 years passed

- Higgs of 125 GeV has been discovered
- LHC bounds on superpartner masses
- new bounds on EDMs
- stronger bounds on WIMPs from direct and indirect searches

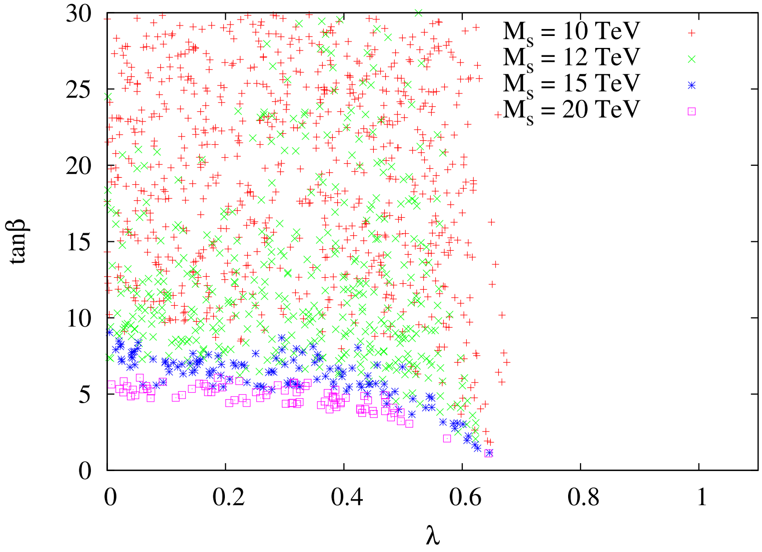
Is it still interesting? Yes. Why?

- Heavy higgs, heavy squarks are natural in Split SUSY
- Neither DM nor BAU problems are solved

The main concern: SM Higgs



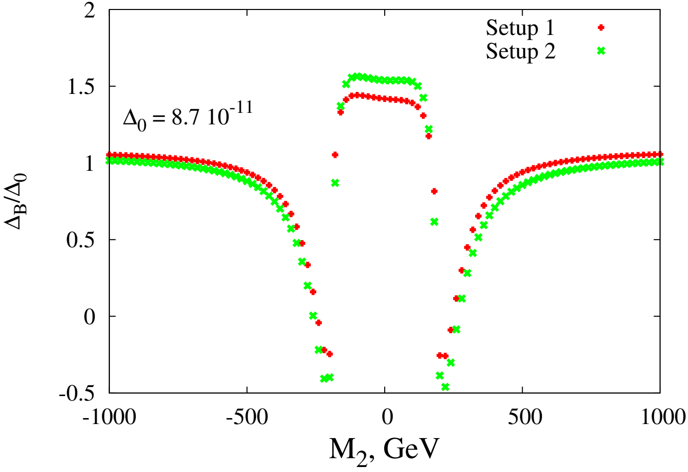
125 GeV SM Higgs with $\tan\beta \simeq 10$, $M_s \simeq 12$ TeV



BAU in Split NMSSM (2017)

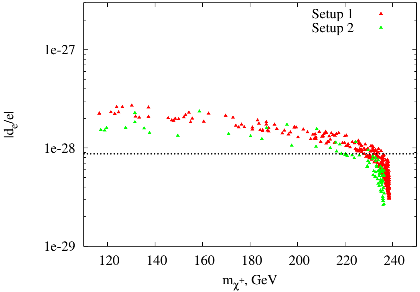
still EWB works (only μ is switched on)

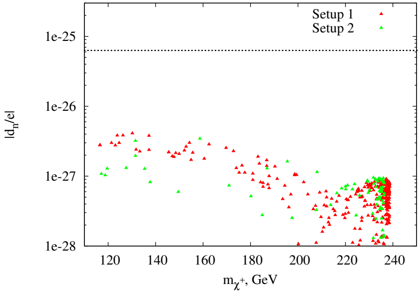
2 Setups $\Delta_0 = 8.3 \times 10^{-11}$ or $\eta_B \equiv n_B/n_\gamma = 6.2 \times 10^{-10}$



EDMs in Split NMSSM (2017)

a factor of 30 improvement in electron EDM for last 10 eyars

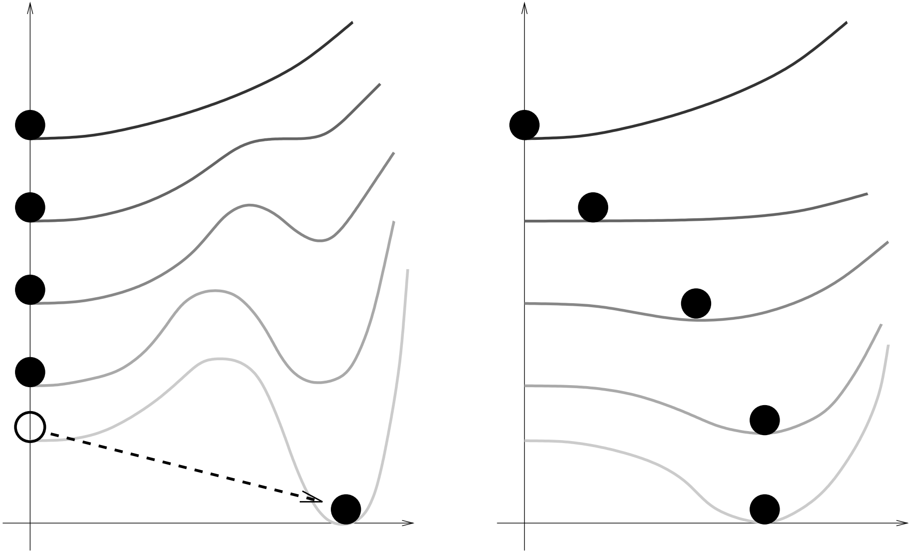




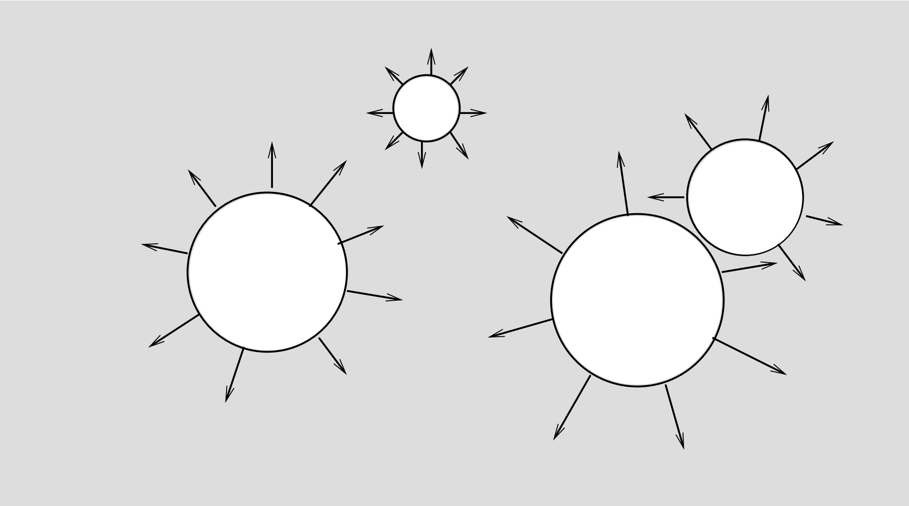
Also light charginos are disfavored from LHC

the rest ($m_{\chi^+} \simeq 200 - 240\,\text{GeV}$) can be tested in $\chi_1^+ \to \chi_1^0 + W^+$

Phase transitions of the I and II orders



Gravitational waves are produced at the transition

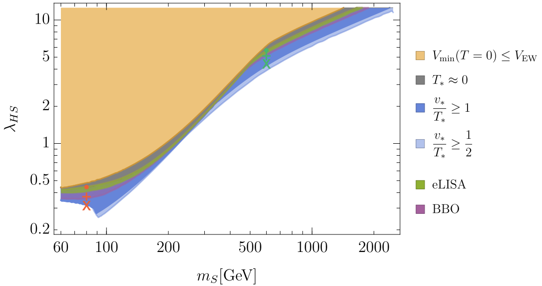


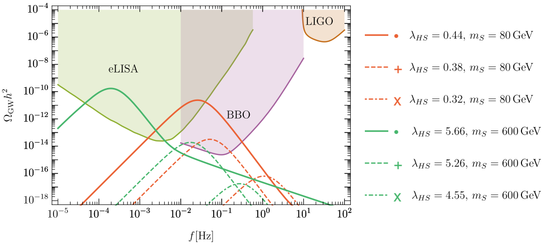
Minimal extension with one real scalar

$$\Delta V = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\lambda_{HS} S^2 H^\dagger H$$

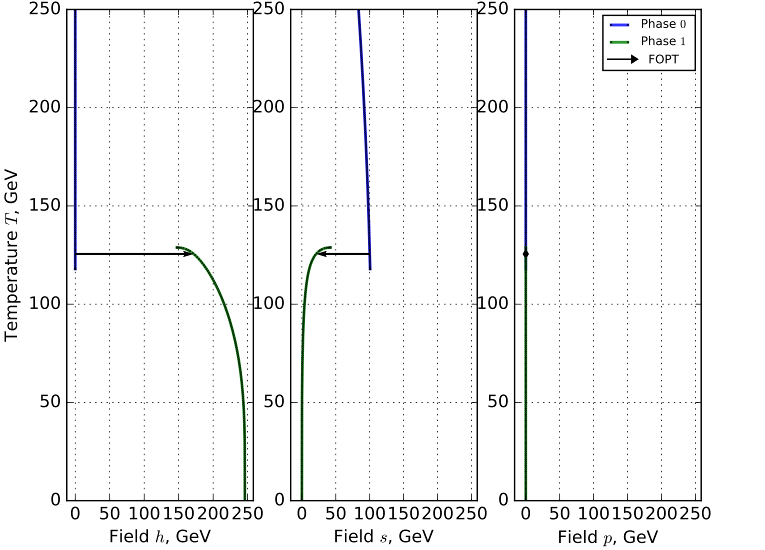
- EW phase transition of the strongly I order
- Gravitational waves production by the new phase bubbles

1702.06124

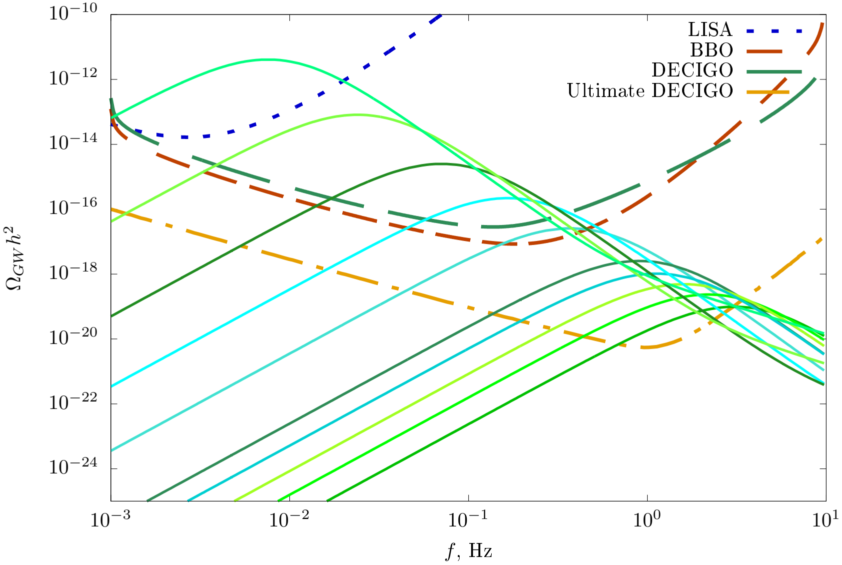




EW-I with one more scalar (S.Demidov, D.G., E.Kriukova (2021))



GW signals for sets of model parameters



More ingredients in the Higgs sector

With SM Higgs renormalizably coupled to Inert douplet

one can obtain

see e.g. 2205.06669

1. EW Ist order Phase transition (even in 2 steps !)
2. Gravitational waves (even with 2 peaks !)
3. Dark Matter

New physics is below EW scale and hidden so far

- Why no hints recognized at EW scale and below?

  couplings to the SM fields are tiny
- which certainly implies not a GUT-like new physics (all is $\propto g$)

  hence coupling to new gauge singlets
- that is usually nonrenormalizable interactions…

  however, there are exceptions…

  thus we arrive at the portals

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- that is usually nonrenormalizable interactions...
  however, there are exceptions...
  thus we arrive at the portals

Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet H and hidden scalar S

  the simplest dark matter

$$\mathcal{L}_{\text{scalar portal}} = -\beta H^\dagger H S^\dagger S$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion N

  sterile neutrino !!

$$\mathcal{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

$$\mathcal{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector:

e.g. with Dark matter Ψ

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector

0711.4866

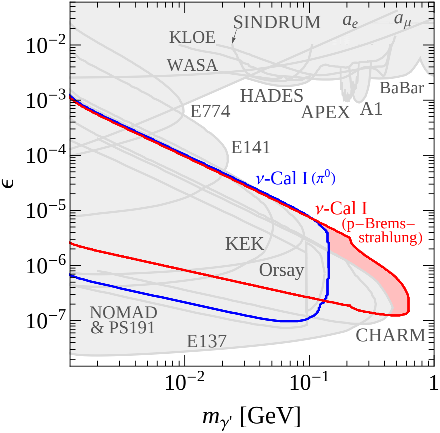
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu \partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

- limit from BBN:

$$\tau_V < 1\,\text{s}\,, \quad \Longrightarrow \varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

- light for $(g-2)$
- light for Pamela, Fermi, etc



1311.5104

Production by virtual photon $\sigma \propto \varepsilon^2$

Decay through virtual photon, $\Gamma \propto \varepsilon^2$

$V \to e^+e^-$, $\mu^+\mu^-$, etc

Massive vectors: decays are under control

Decay into SM via mixing with photon

into leptons

$$\Gamma_{A'}^{l^+l^-} = \frac{1}{3}\alpha_{\rm QED}\, m_{A'}\, \varepsilon^2 \sqrt{1-\frac{4m_l^2}{m_{A'}^2}}\left(1+\frac{2m_l^2}{m_{A'}^2}\right),$$

into hadrons

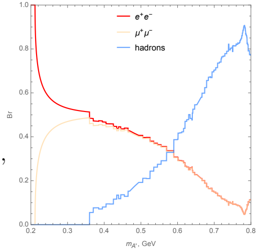
$$\Gamma_{A'}^{\rm hadrons} = \frac{1}{3}\alpha_{\rm QED}\, m_{A'}\, \varepsilon^2 \cdot R(m_{A'}),$$

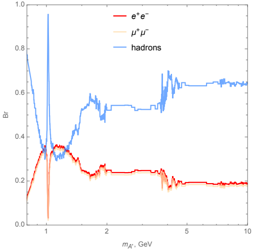
where

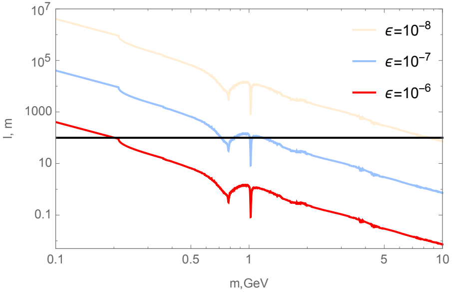
$$R(\sqrt{s}) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

and

$$\Gamma_{A'}^{\rm tot} = \Gamma_{A'}^{e^+e^-} + \Gamma_{A'}^{\mu^+\mu^-} + \Gamma_{A'}^{\rm hadrons}$$







1411.4007

Massive vectors: production by protons

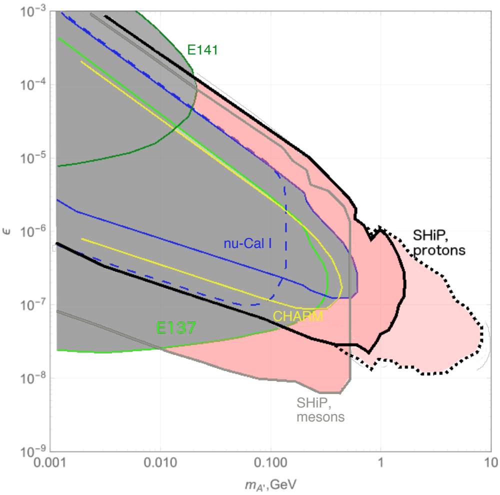
- decays of π^0, η^0 and $\rho^\pm$, ρ^0, ω

$$\mathrm{Br}_{\pi^0\to A'\gamma} \simeq 2\varepsilon^2 \left(1-\frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}_{\pi^0\to\gamma\gamma}$$

- proton bremsstrahlung
  concervatively corrected by
  the Dirac (electric) form factor of
  proton

$$F_1 = \frac{1}{\left(1+\frac{q^2}{m_D^2}\right)^2} \to \frac{1}{m_{A'}^4}$$

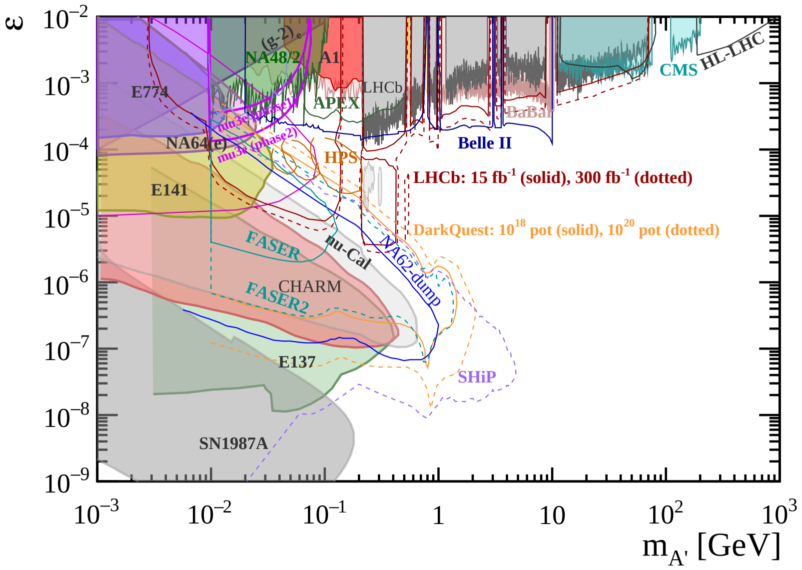
  with Dirac mass squared $m_D^2 = 12/r_D^2$
  and the Dirac radius $r_D \approx 0.8\,\mathrm{fm}$
- quark bremsstrahlung ??
  still under study...



1411.4007

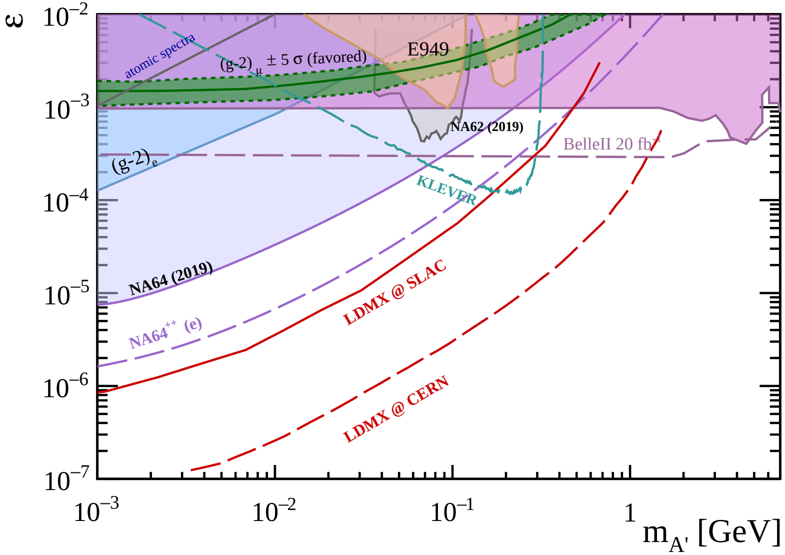
Searches for visible decays

2102.12143



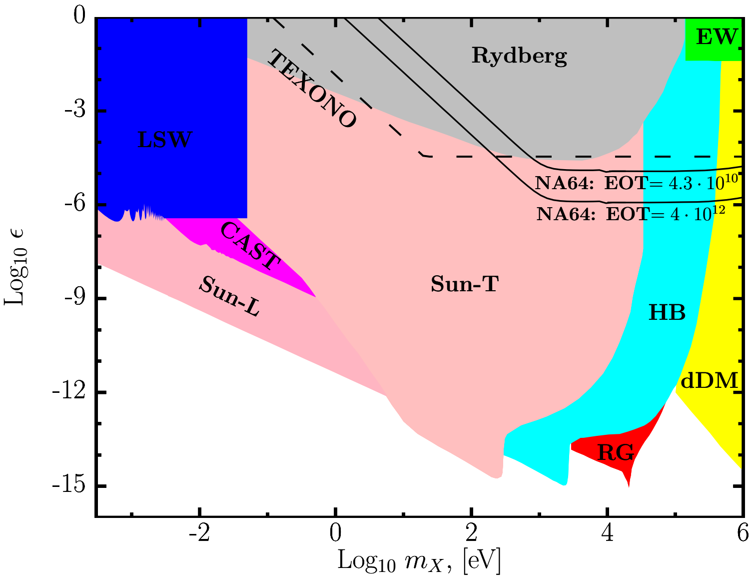
Searches for invisible mode

2102.12143



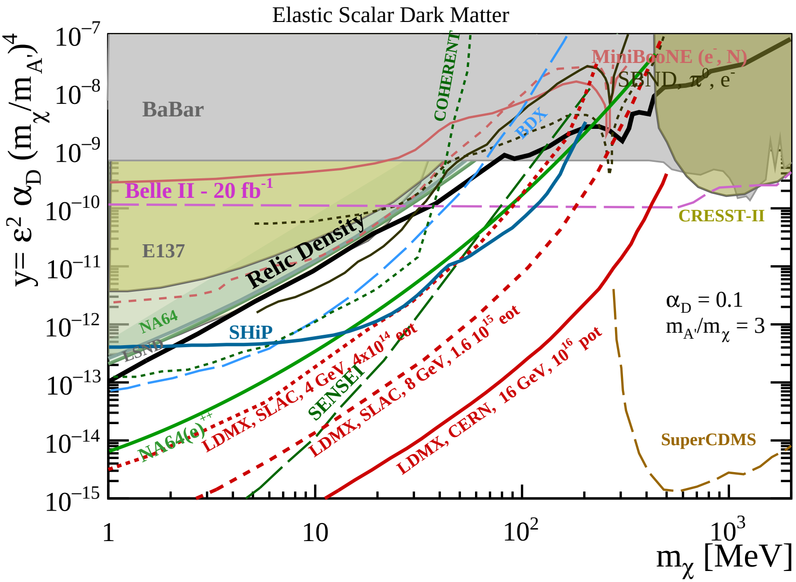
Searches for invisible mode

1812.02719



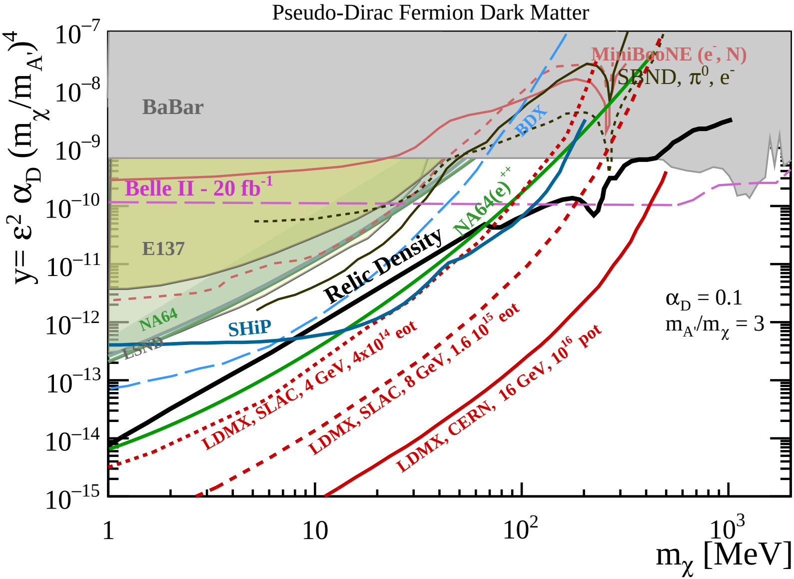
Searches for dark matter

2102.12143



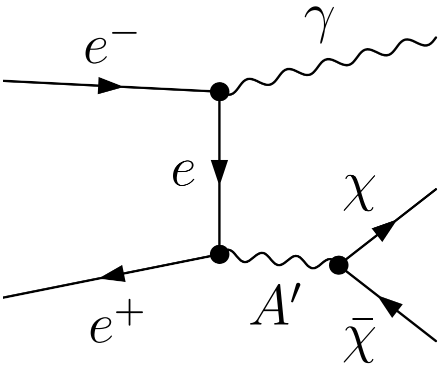
Searches for dark matter

2102.12143



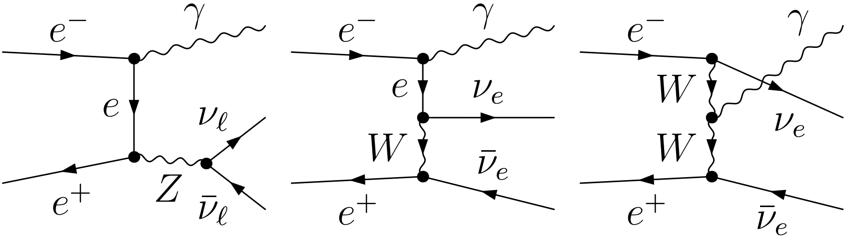
Searching for dark matter particles at STCF

1907.07046



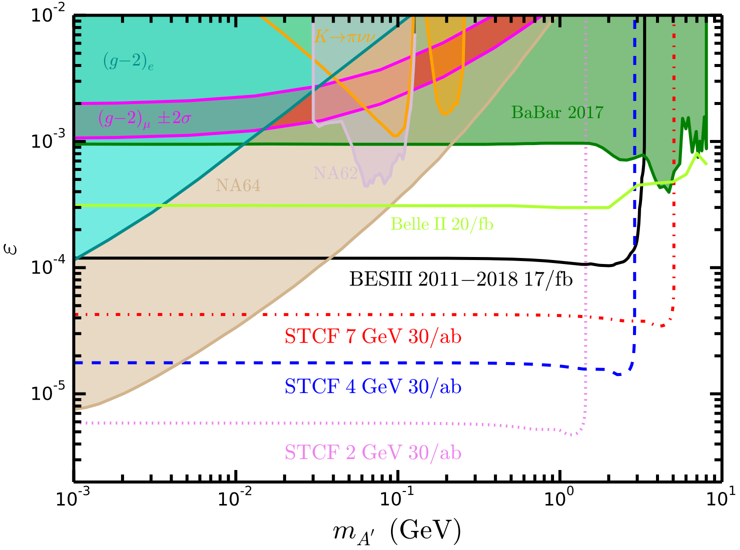
Searching for dark matter particles at STCF

1907.07046



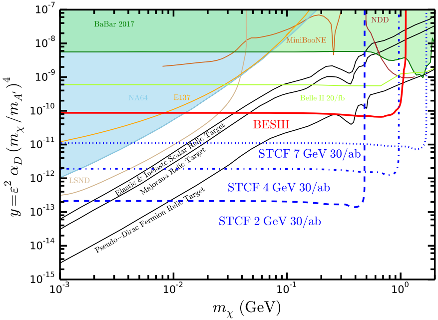
Searching for the messenger at STCF

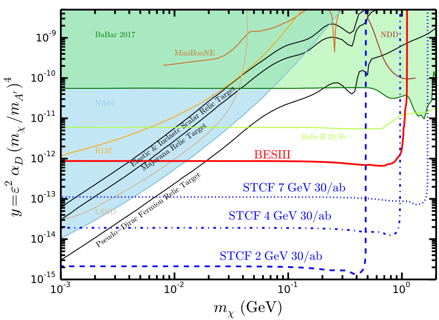
1907.07046



Searching for dark matter at STCF

1907.07046

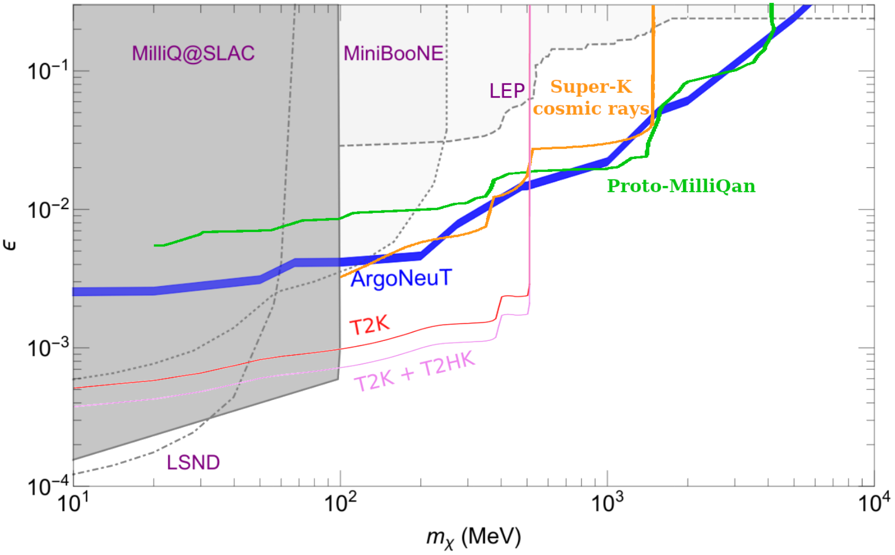




$m_{A'} = 3m_\chi\,, \ \ \alpha_D = 0.5$

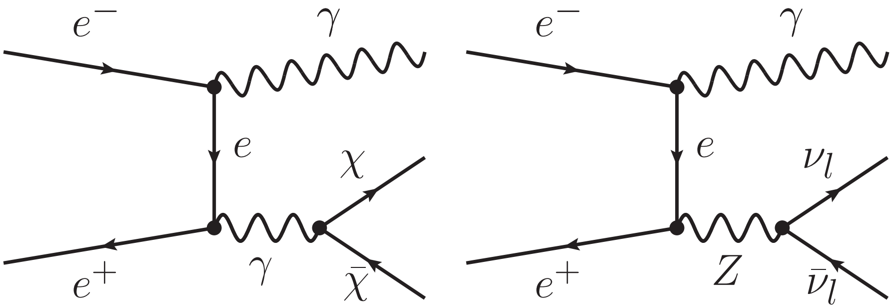
$\alpha_D = 0.005$

Heavy vector: leaving with millicharged particles 2103.11814



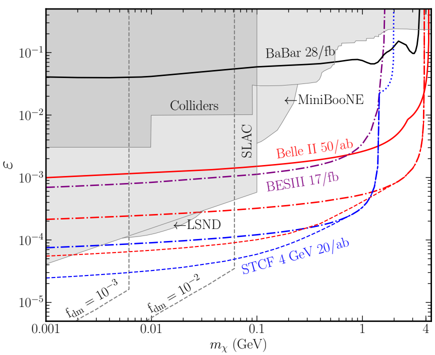
Searching for millicharged particles at STCF

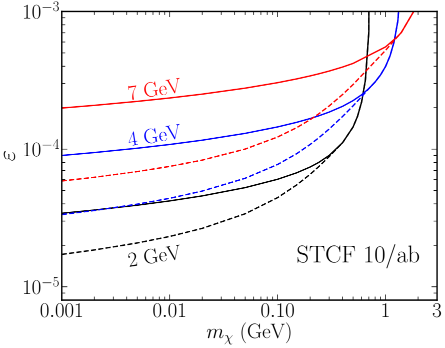
1909.06847



Searching for millicharged particles at STCF

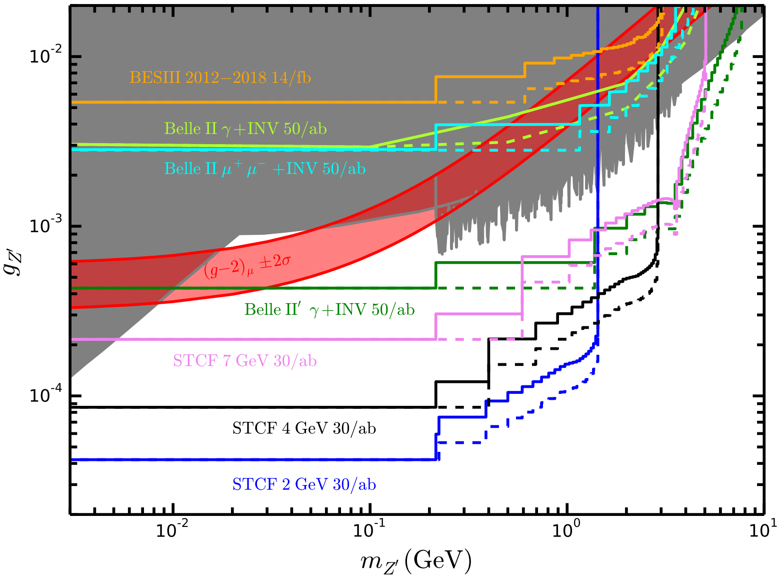
1909.06847





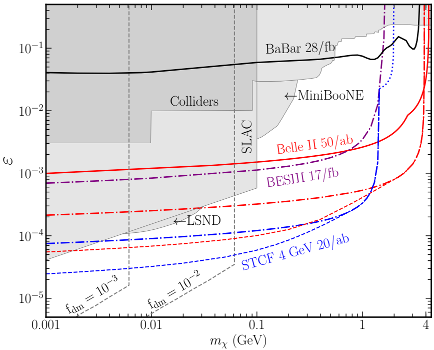
Searching for $L_\mu - L_\tau$ Z' at STCF

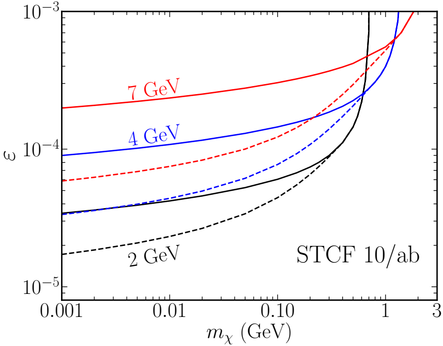
2012.10893



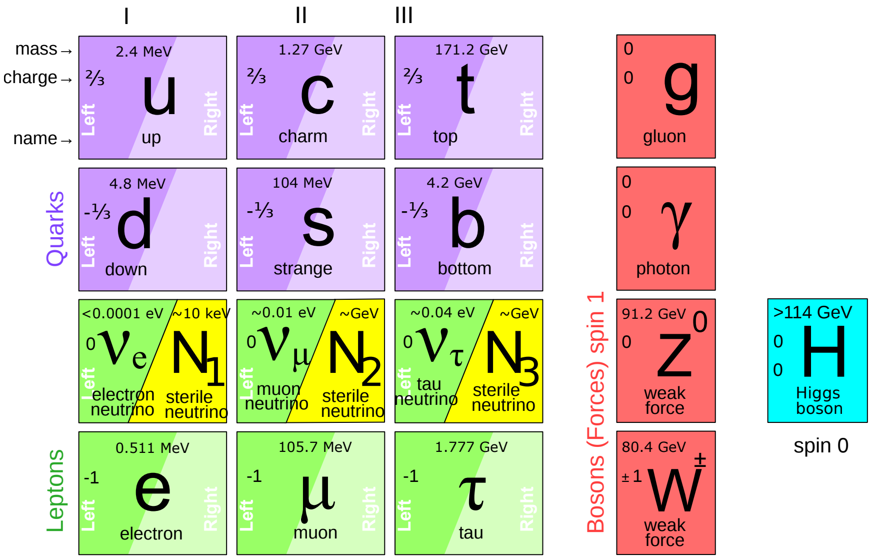
Searching for $L_\mu - L_\tau$ Z' at STCF

2012.10893

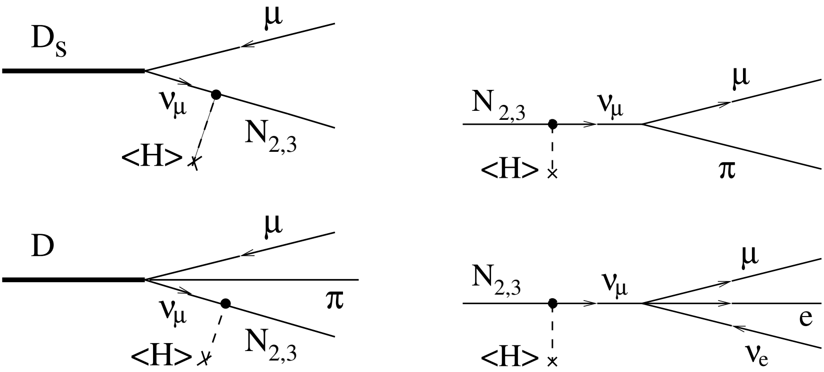




Three Generations
of Matter (Fermions) spin ½



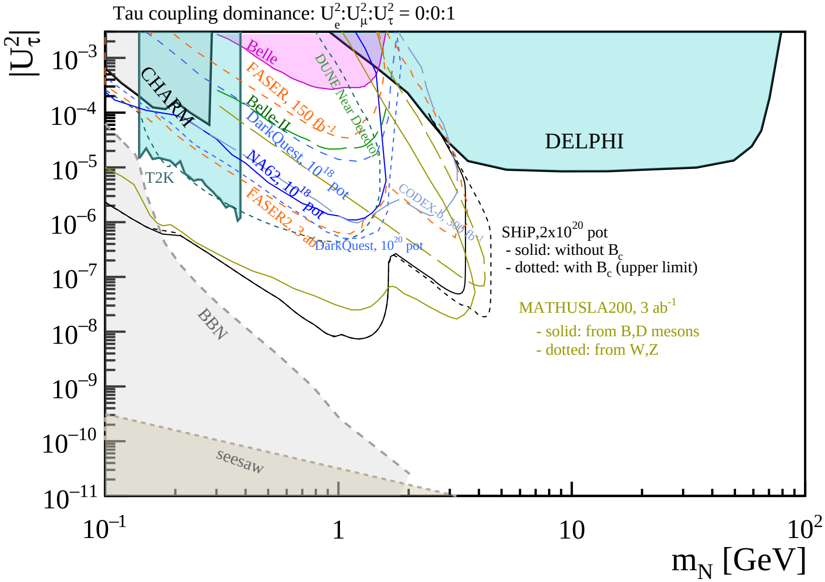
Sterile neutrinos: production and decays



Interaction via neutral and charged weak hadronic currents

mixing with ν_τ ... $\tau^\pm \to N + H^\pm$

2102.12143



Renormalizable inflaton at GeV scale

0912.0390

$$S_{XSM} = \int \sqrt{-g}\, d^4x \left(Ł_{SM} + Ł_{ext} + Ł_{grav} \right),$$

$$Ł_{ext} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2,$$

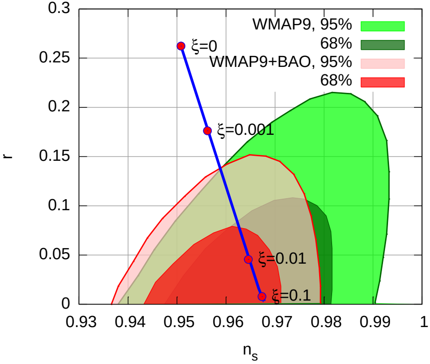
$$Ł_{grav} = -\frac{M_P^2 + \xi X^2}{2} R,$$

inflaton mass

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda \theta^2}}.$$

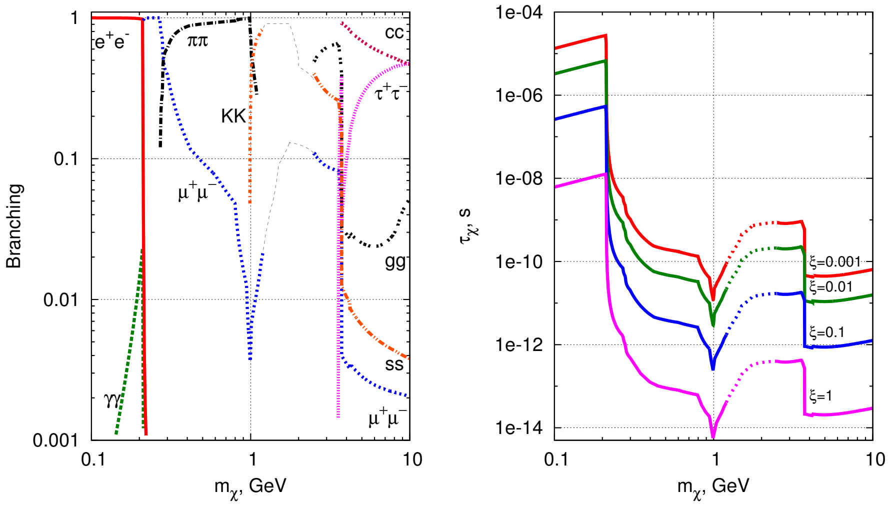
phenomenology is fixed by mixing with Higgs

$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}.$$



QCD modes: claimed uncertainties upto 10^2

1303.4395

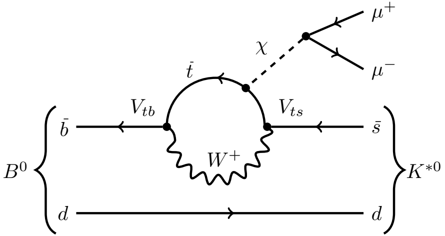


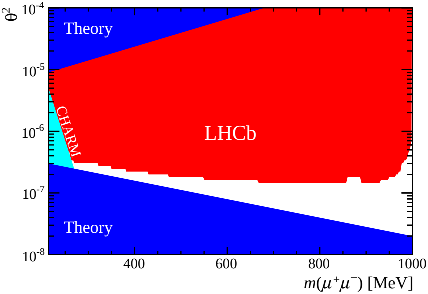
Interaction among the final hadronic states

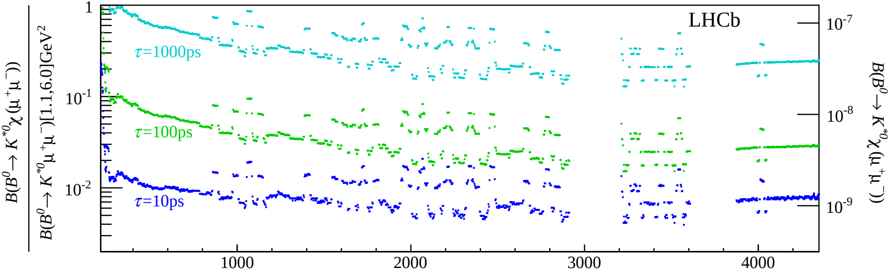
following J.Donoghue, J.Gasser and H Leutwyler (1990)

Limits from LHCb

1508.04094

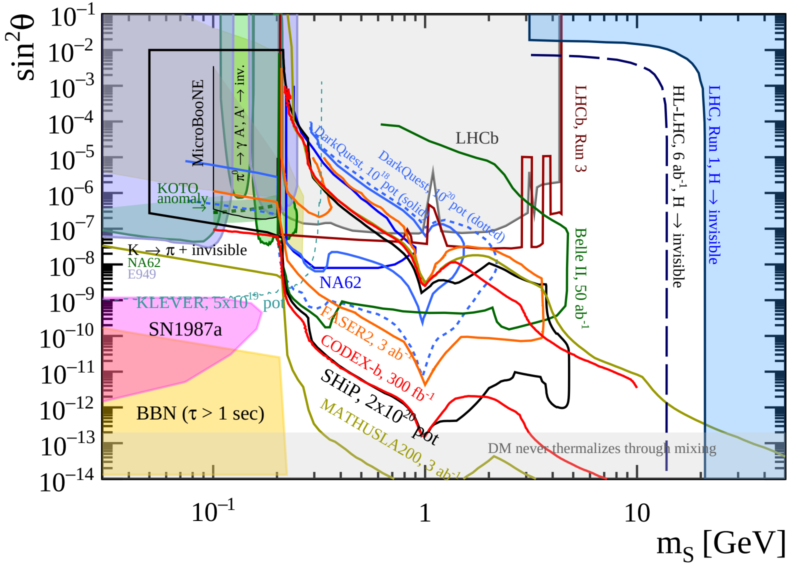






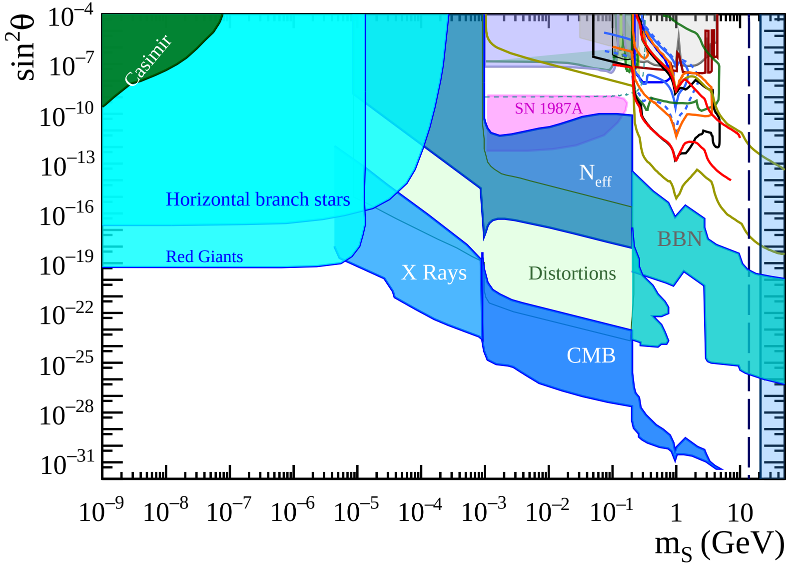
direct limits on scalars

2102.12143



scalars in astrophysics

2102.12143



Conclusions

We definitely need new physics

- There are many well-motivated BSM models
- Phenomenology, Theory, Anomalies...
- Not all the models can be presentky tested

for c-τ the viable field is BSM with portals: new light feebly coupled particles

Both experimental work (construction, background) and theoretical work (problems with QCD-calculus at the 1 GeV scale) are needed

Anomalies with matter structures at small scales

- Core-cusp problem

  Dark Matter density profiles in the centers of simulated halos are cusped
  while in observed dwarf galaxies are cored

- Lack of dwarf galaxies

  Matter perturbations of almost flat spectrum produce flat halo mass spectrum
  low abundance of small galaxies

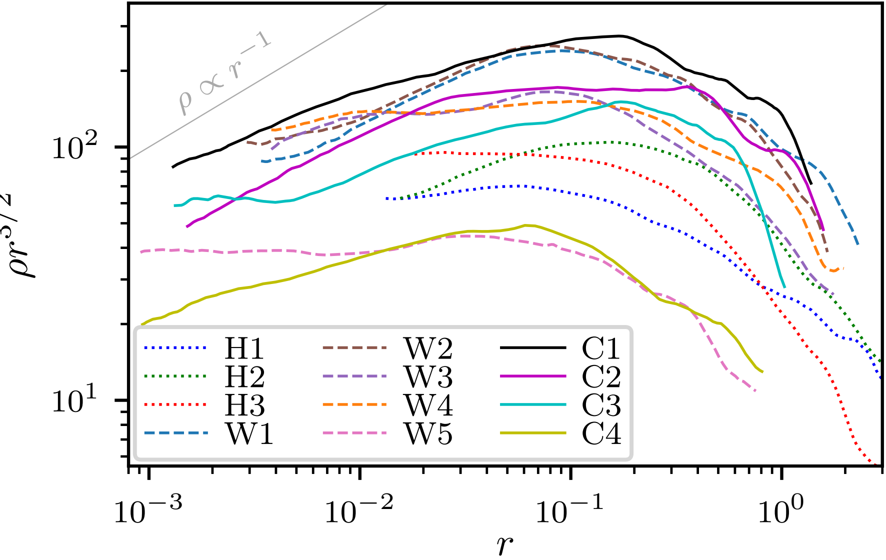
- Too-big-To-fail problem

  There must be galaxies heavy enough to keep baryons inside
  Milky Way hosts only two such galaxies

WDM, SIDM, Fuzzy DM etc: to suppress structures at small scales

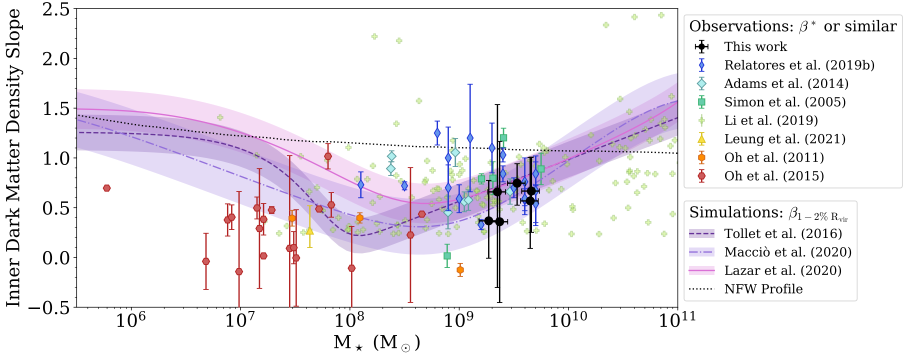
Cusps in simulations

2207.05082



Core vs cusp in a galaxy...

2203.00694



$$\rho(r) \propto \frac{1}{r^{\beta^*}}$$

Axion-like portal: Light sgoldstinos in SUSY

SUSY is spontaneously broken

breaking of $SU(2)_W \times U(1)_Y$ by the $\langle H \rangle = v$

Goldstones bosons couple to all massive fields

(Goldberger–Treiman formula like for pion)

$$\mathscr{L} = \frac{1}{v} J^{\mu}_{SU(2)_W \times U(1)_Y} \partial_\mu H$$

breaking of SUSY by $\langle F_\varphi \rangle = F$

Goldstone fermion: goldstino

$$\mathscr{L}_\psi \propto \frac{1}{F} J^{\mu}_{SUSY} \partial_\mu \psi$$

Goldstino supermultiplet: (boson φ (sgoldstino), fermion ψ (goldstino))

~~SUSY~~ $\longleftrightarrow$ $F \equiv \langle F_\varphi \rangle \neq 0$ $\qquad \Phi = \varphi + \sqrt{2}\theta\psi + F_\varphi \theta\theta$ $\qquad \frac{1}{\sqrt{2}}\left(\varphi + \varphi^\dagger\right) \equiv S$ — scalar

sgoldstino: $\mathscr{L}_{S,P} \propto \frac{M_{soft}}{F}$ $\qquad F \sim$ (~~SUSY~~ scale)^2 $\qquad \frac{1}{i\sqrt{2}}\left(\varphi - \varphi^\dagger\right) \equiv P$ — pseudoscalar

M_{soft}: MSSM soft terms

superpartner masses and trilinear couplings,

massless at tree level

naturally may be light...

gauginos:

$$M_\lambda \lambda\lambda \longrightarrow \frac{M_\lambda}{F} S F_{\mu\nu} F^{\mu\nu}\,, \quad \frac{M_\lambda}{F} P F_{\mu\nu} \tilde{F}^{\mu\nu}$$

squarks, sleptons:

$$A_{ij} h_u \tilde{q}_i \tilde{u}_j \longrightarrow \frac{A_{ij}}{F} S h_u q_i u_j\,, \quad \frac{A_{ij}}{F} P h_u q_i u_j$$

Direct coupling to gluonic tensor

- For $M_S \ll 1$ GeV estimate coupling to pions through the triangle anomaly in $T_{\mu\mu}$
  M.Voloshin, V.Zakharov (1980)

$$-\langle \pi\pi \left| \frac{bg_s^2}{32\pi^2} G^a_{\mu\nu} G^a_{\mu\nu} \right| 0\rangle = \langle \pi\pi | T_{\mu\mu} | 0\rangle = q^2 \varphi^\alpha_\pi \varphi^\alpha_\pi / 2$$

  hence we get an amplification 1511.05403

$$\Gamma(S \to \pi^0\pi^0) \approx \frac{\alpha_s^2(M_3)}{\beta^2(\alpha_s(M_3))} \frac{\pi m_S^3 M_3^2}{4F^2} \sqrt{1 - \frac{4m_{\pi^0}^2}{m_S^2}},$$

- For $M_S \gg 1$ GeV we have gluons and a suppression $g_s^2 G_{\mu\nu}^2$ is a renorm-invariant

$$\Gamma(S \to gg) = \left(\frac{\alpha_s(m_S)\beta(\alpha_s(M_3))}{\beta(\alpha_s(m_S))\alpha_s(M_3)} \right)^2 \frac{m_S^3 M_3^2}{4\pi F^2}.$$

- The two rates mismatch by orders...