Searches for New Physics at Fixed-target experiments

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Yuryfest 'from... to Hyper-K'
on occasion of his 70th Birthday

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Widely accepted statements

- Standard Model nicely explains
  almost all results of particle physics experiments
- We definitely need New particle Physics
  - neutrino oscillations
  - baryon asymmetry
  - dark matter
  - inflation-like stage in the early Universe

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- New Heavy particle contribution to the Higgs boson mass lifts it up
  but miraculously $m_h \sim E_{EW}$

Guesswork: a logically possible option

- All the new particles are at (below) E_{EW}
  then quantum contributions to $m_h \sim E_{EW}$ are safe
- Why so far no evidences for such light New Particles ?
- They are only feebly coupled to the Standard Model
  - they are SM gauge singlets (not a GUT)
  - new Yukawa-type couplings ?
  - portal-like couplings ?

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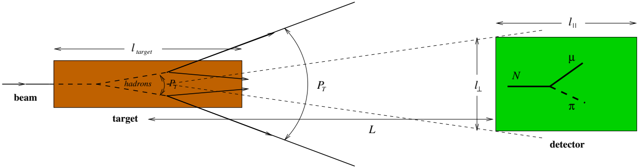
Disclaimer

There are no general theoretical motivation for the New Particles to be of (sub)GeV mass

Fixed target and similar

However for the feebly coupled light particle best place to show up is
the intensity frontier fixed target experiment



Variations and specifics

- dedicated (e.g. NA64) or working as by-product (e.g. T2K)
- thin target (e.g. T2K) or dump (e.g. NA64)
- decays or hits as the signature
- production by cosmic rays
- ...

Fundamental physics behind the FIMPs

Feebly Interacting Massive Particles

- Dark (pseudo)scalars, fermions, photons as thermal Dark Matter
  recall WIMPs
  or non-thermal Dark Matter
- Heavy Neutral Leptons with seesaw type I for neutrino masses
- Axion from solutions to strong-CP problem
- HNL, dark scalars, Axion-Like Particles, dark photons involved in generation of matter-antimatter asymmetry
- Dark scalars, ALP in solutions to the gauge hierarchy problem
- Dark scalars as inflatons
- FIMPs to solve issues (if any) in astrophysics

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

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

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

  sterile neutrino !!

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

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

  hidden photon

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

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector:

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

e.g. with Dark matter Ψ

0711.4866

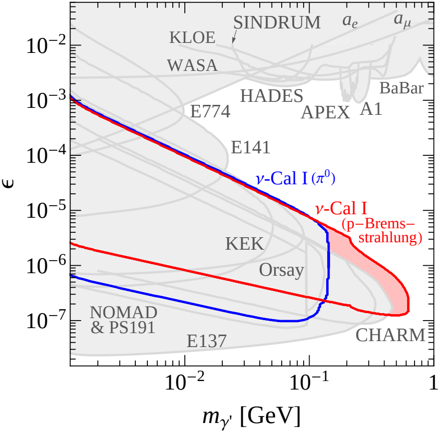
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu \partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

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



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

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

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

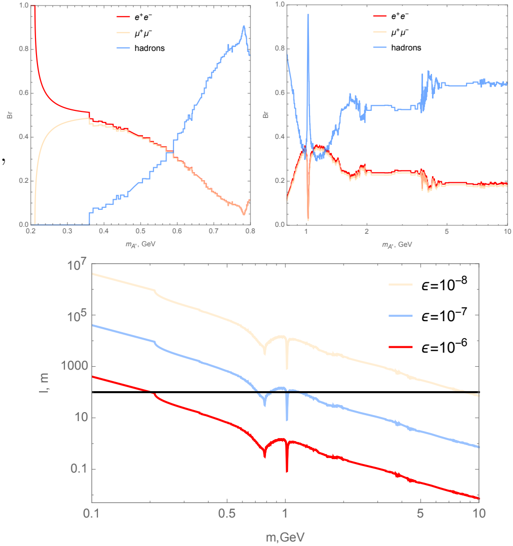
$$\Gamma_{A'}^{\rm hadrons} = \frac{1}{3}\alpha_{\rm QED}\, m_{A'}\, \varepsilon^2 \cdot R(m_{A'}),$$

where

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

and

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



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Massive vectors: production by protons

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

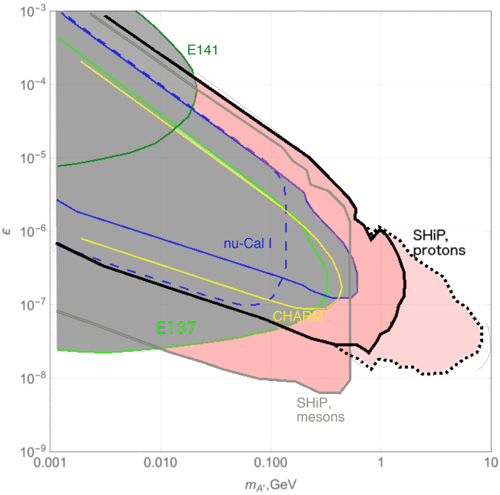
$$\mathrm{Br}_{\pi^0\to A'\gamma} \simeq 2\varepsilon^2 \left(1-\frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}_{\pi^0\to\gamma\gamma}$$

- 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...



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Searches for visible decays

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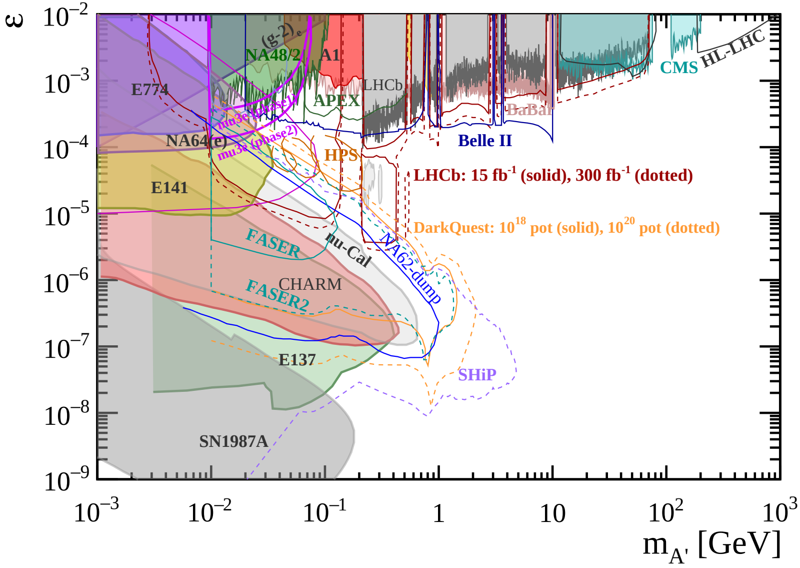

Searches for invisible mode

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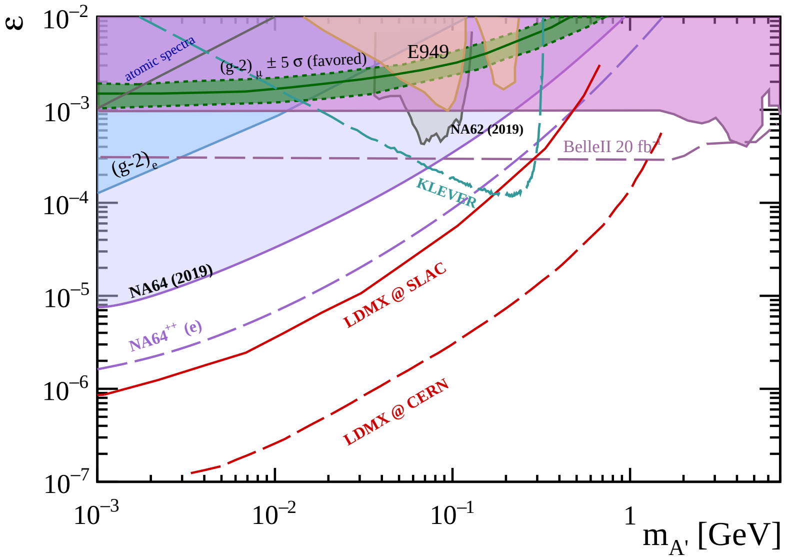

Searches for invisible mode

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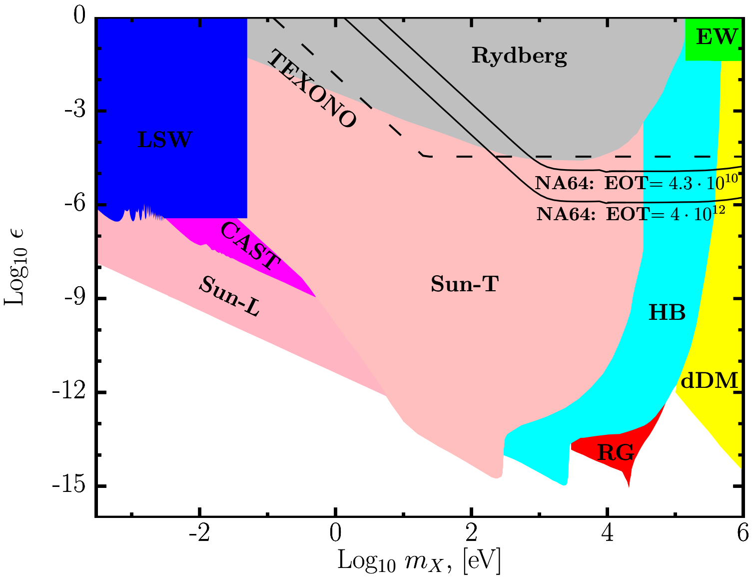

Searches for dark matter

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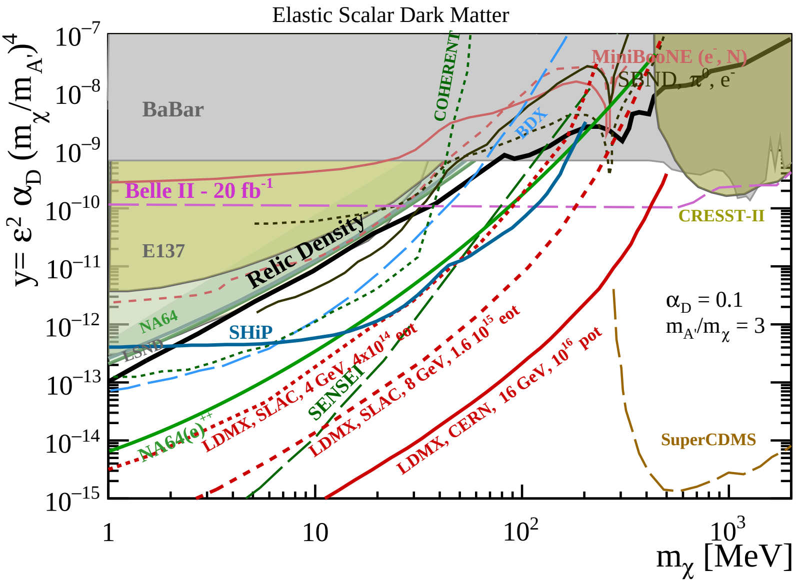

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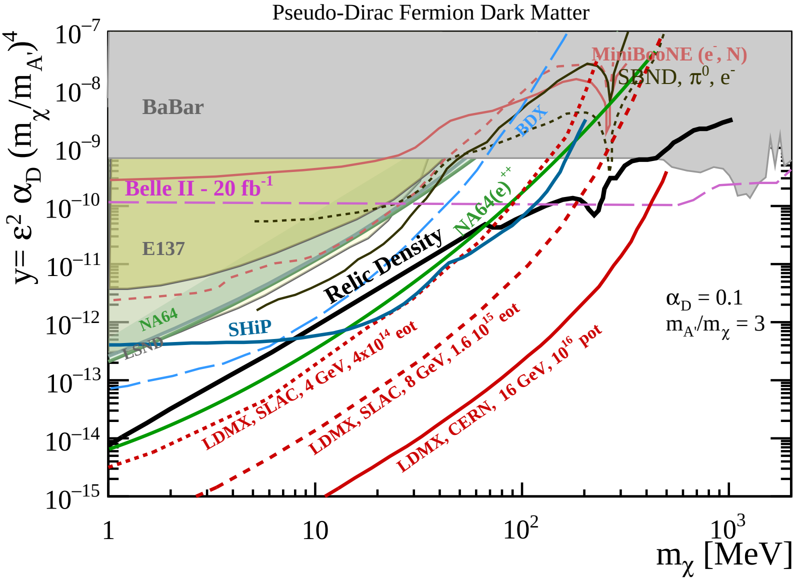

Exclusion plots: always check!

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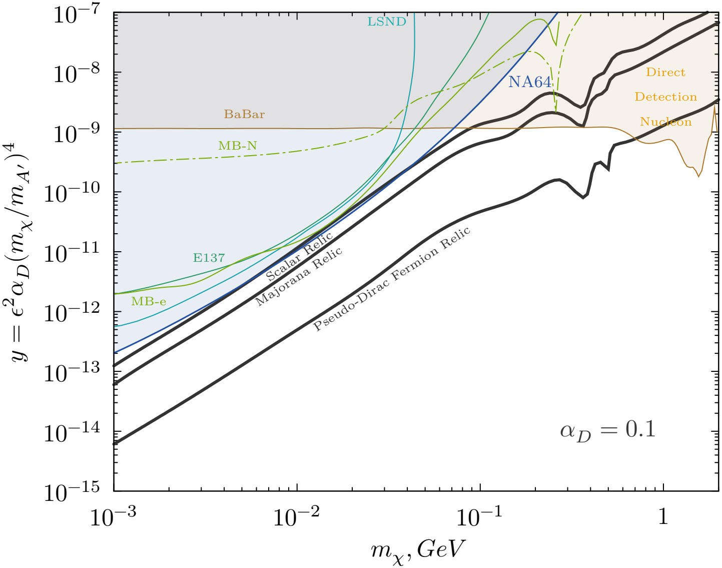
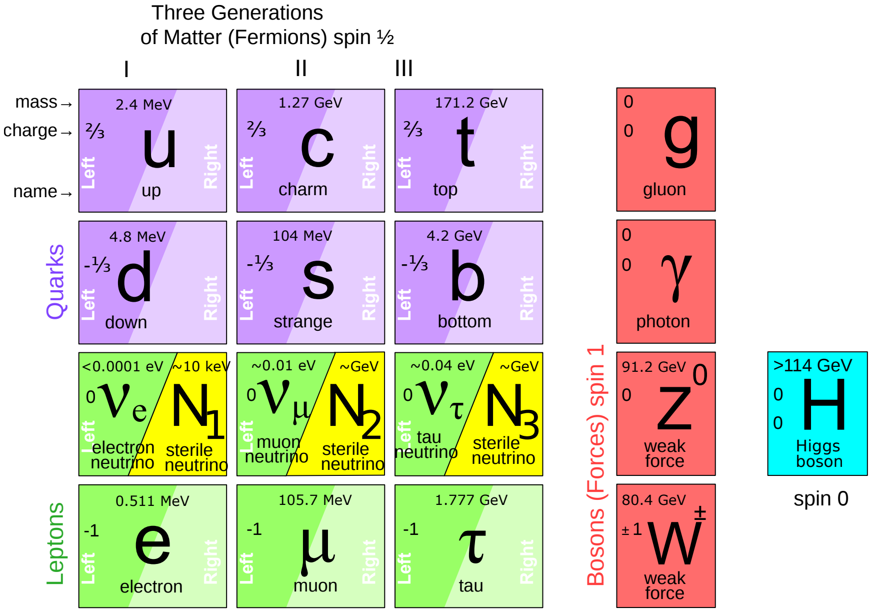



Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
γ
photon
<0.0001 eV
~10 keV
0
νe
N1
electron neutrino
sterile neutrino
~0.01 eV
~GeV
0
νμ
N2
muon neutrino
sterile neutrino
~0.04 eV
~GeV
0
ντ
N3
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
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
80.4 GeV
±1
W±
weak force
Bosons (Forces) spin 1
Left
Right

Seesaw type I mechanism: $M_N \gg m_{active}$

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

where $I = 1,2,3$ and $\alpha = e,\mu,\tau$ $\quad \tilde{H}_a = \varepsilon_{ab} H_b^*$

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

$$\mathscr{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \frac{1}{2}\left(\overline{\nu}_\alpha\,,\overline{N}_I^c\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_\alpha^c\,,N_I\right)^{\mathrm{T}} + \text{h.c.}$$

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

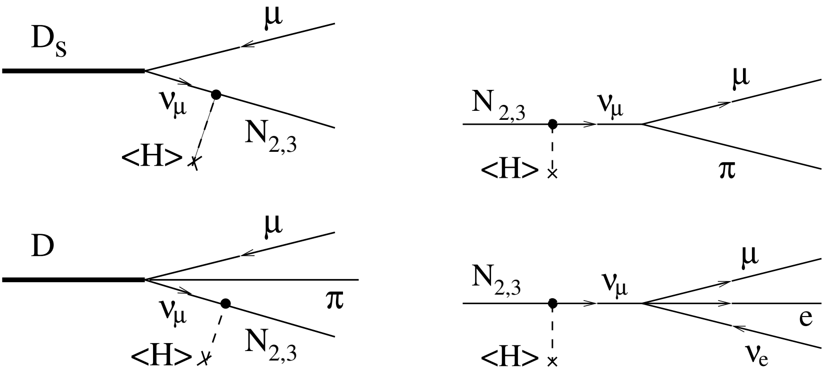
$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{M}^\nu = -\hat{M}_D\frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2\frac{v^2}{M_N} \lll M_N$$

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

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

active-sterile mixing: $\qquad \theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$

Sterile neutrinos: production and decays



Interaction via neutral and charged weak hadronic currents

mixing with ν_e

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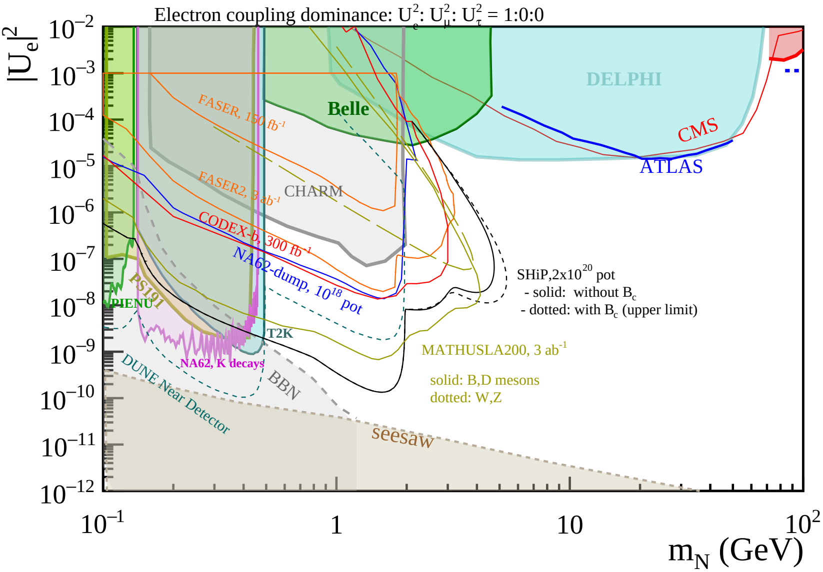

mixing with ν_μ

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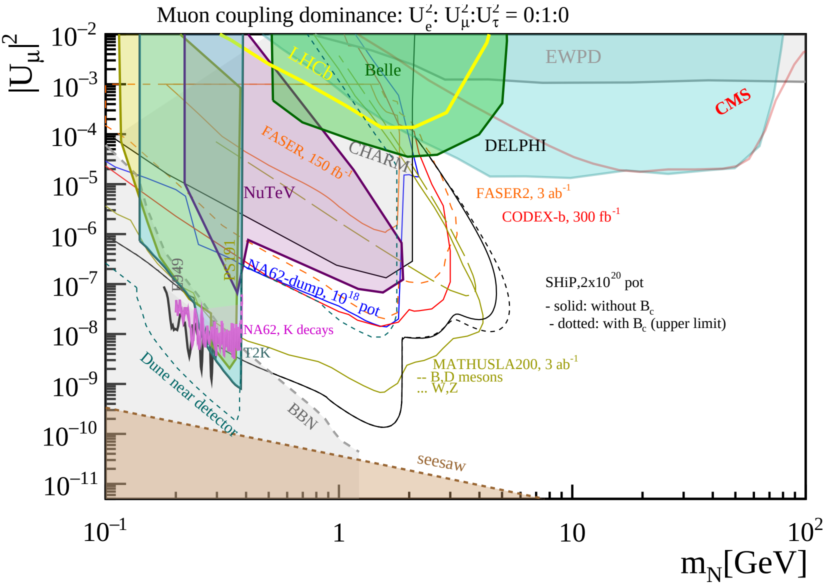

mixing with ν_τ

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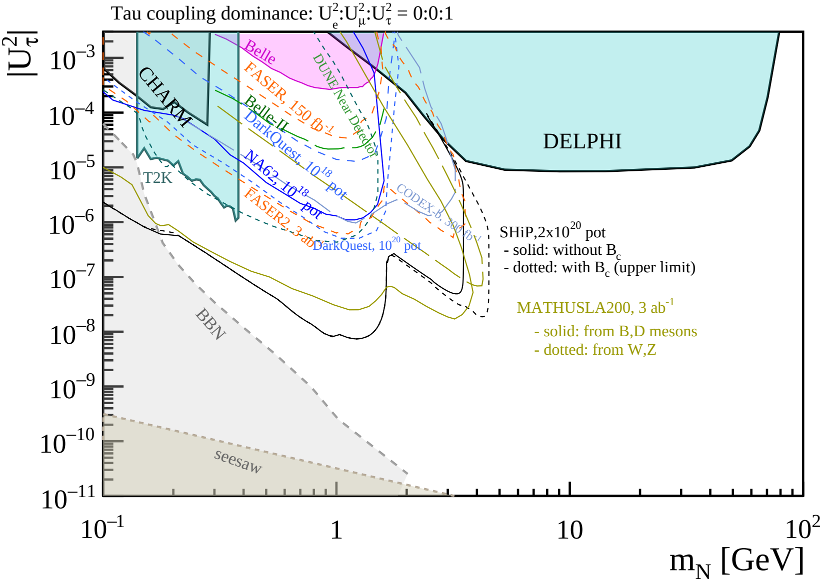


Renormalizable inflaton at GeV scale

0912.0390

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

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

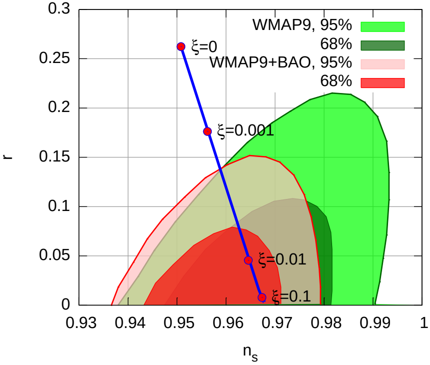
$$\mathscr{L}_{grav} = -\frac{M_P^2 + \xi X^2}{2} R,$$

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

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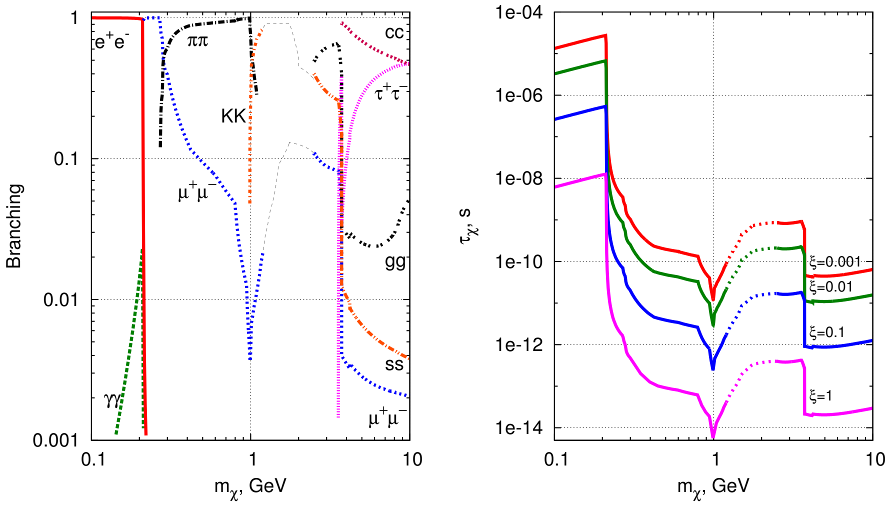
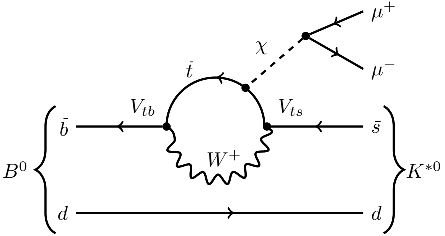


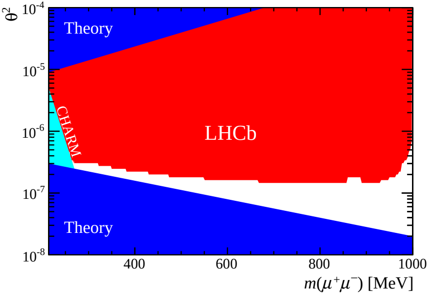
Interaction among the final hadronic states

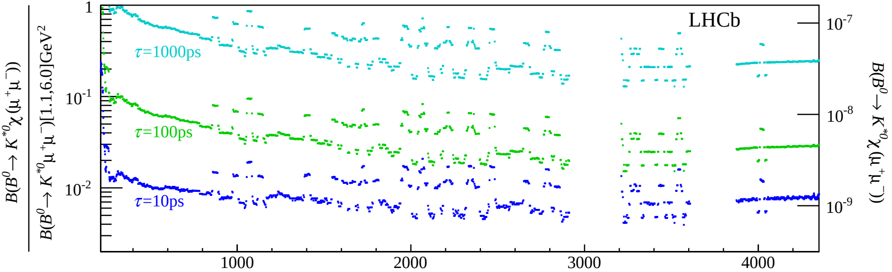
following J.Donoghue, J.Gasser and H Leutwyler (1990)

Limits from LHCb

1508.04094







direct limits on scalars

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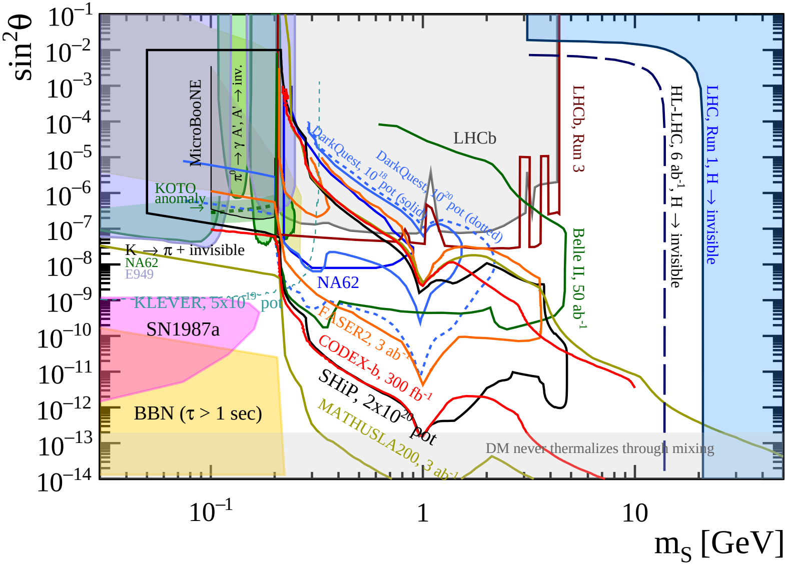

scalars in astrophysics

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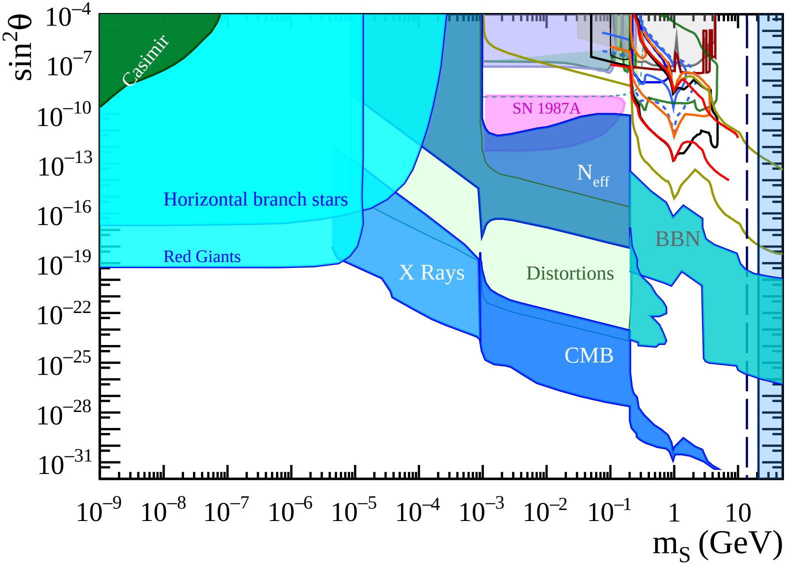

Summary on FIMPs

- Theoretically OK
- Experimentally promising
- Cosmologically and astrophysically interesting. . .
- We are waiting just for... discovery !!

Backup slides

Axion-like portal: Light sgoldstinos in SUSY

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)

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

SUSY is spontaneously broken

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: $\qquad \mathscr{L}_{S,P} \propto \frac{M_{soft}}{F}$ $\qquad F \sim$ (~~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

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

- 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...