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SUPERWEAK EXTENSION OF THE STANDARD MODEL

based on
arXiv:1812.11189 (*Symmetry*), 1911.07082 (*PRD*), 2104.11248 (*JCAP*), 2104.14571 (*PRD*), 2105.13360 (*J.Phys.G*), 2204.07100 (*PRD*), 2301.07961 (*JHEP*), 2305.11931
with S. Iwamoto, T.J. Kärkkäinen, I. Nándori, Z. Péli, K. Seller, Zs. Szép

FFK2023

International Conference on Precision Physics and Fundamental Physical Constants
23 May 2023

OUTLINE

1. Motivation: status of particle physics
2. Superweak $U(1)_z$ extension of SM
3. Neutrino masses
4. Dark matter candidate
5. Vacuum stability and scalar sector constraints
6. Contribution to M_W (see the excellent poster by Zoltán Péli)
7. Conclusions

MOTTO

Rough estimates of BSM effects
can easily be deceptive

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example: discovery of the Higgs particle came much faster than expected at the time of construction of the LHC because the

- detector performance was
- theoretical prediction for Higgs production was significantly

underestimated

Status of particle physics: energy frontier

- Colliders: SM describes final states of particle collisions precisely
- No proven sign of new physics beyond SM at colliders*
- SM vacuum is metastable

[Bezrukov et al, arXiv:1205.2893; Degrassi et al, arXiv:1205.6497]

*Exciting news keep pupping up, all below discovery significance

Status of particle physics: cosmic and intensity frontiers

- Universe at large scale described precisely by cosmological SM: ΛCDM (Ω_m =0.3)
- Neutrino flavours oscillate
- Existing baryon asymmetry cannot be explained by CP asymmetry in SM
- Inflation of the early, accelerated expansion of the present Universe

[https://pdg.lbl.gov]

Established observations require physics beyond SM, but do not suggest rich BSM physics

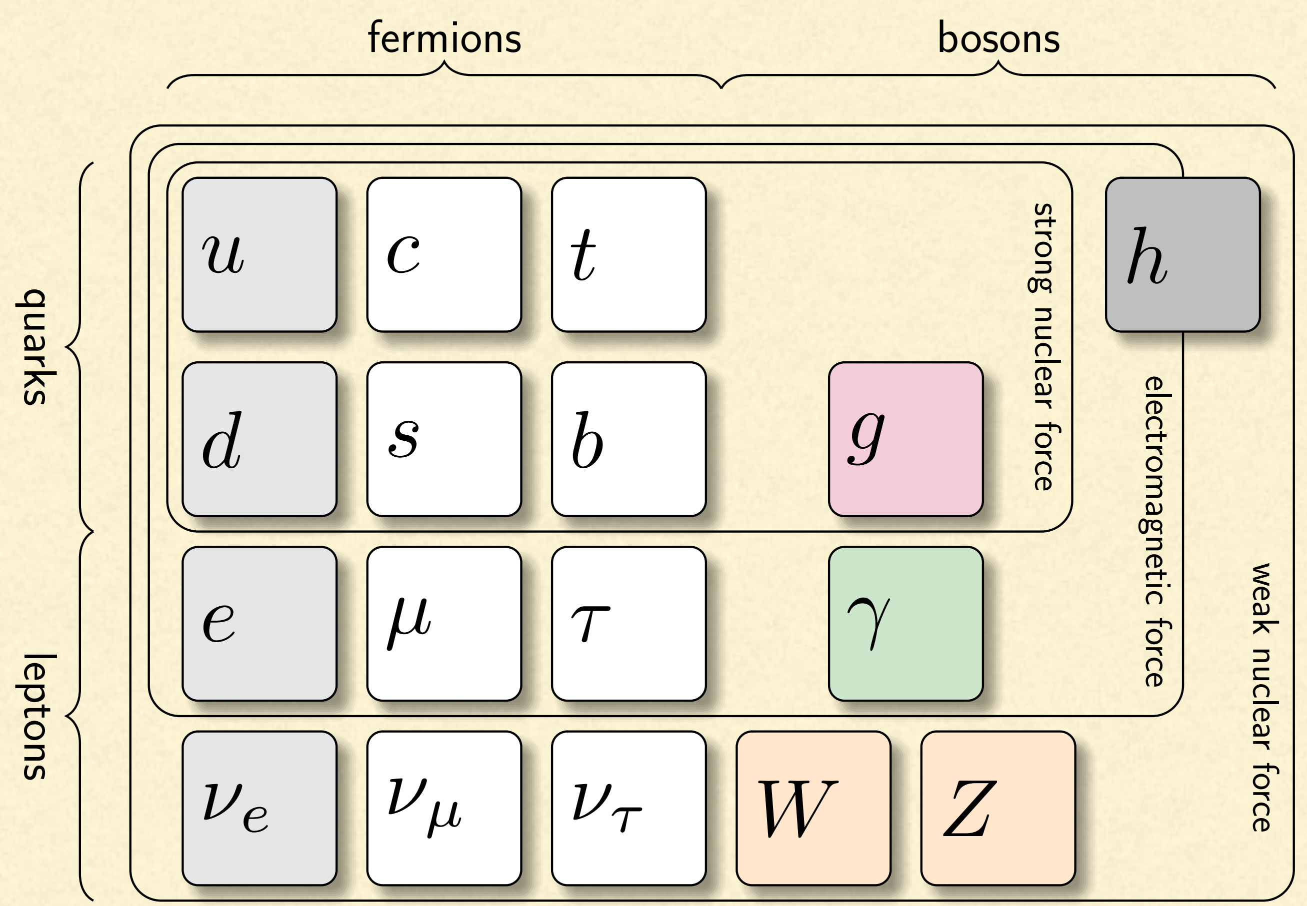
Extension of SM: three alternatives with different strength and weaknesses

- Effective field theory, such as SMEFT: general but highly complex (2499 dim 6 operators), focuses on new physics at high scales

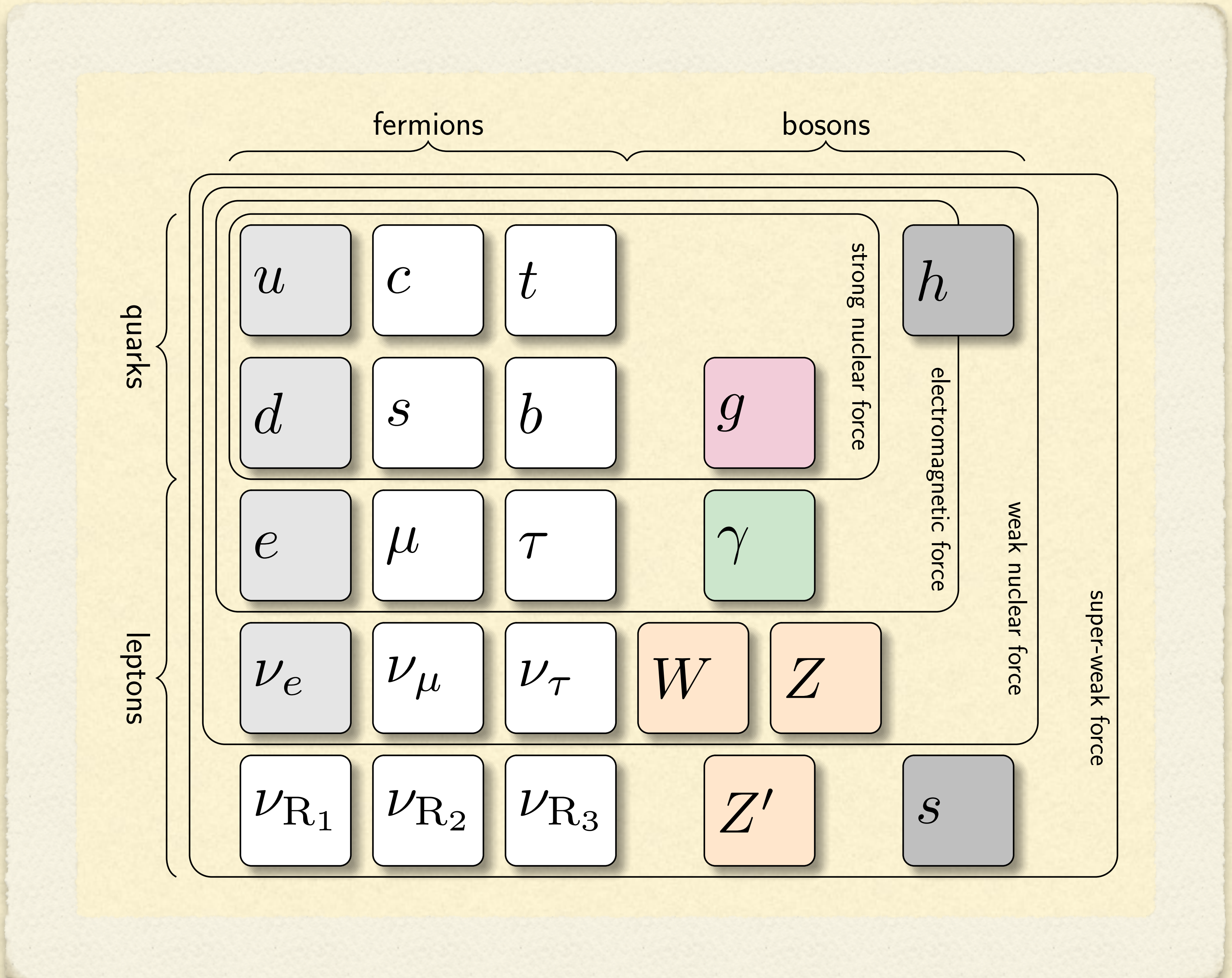
- Simplified models, such as dark photon, extended scalar sector or right-handed neutrinos: "easily accessible" phenomenology, but focuses on specific aspect of new physics, so cannot explain all BSM phenomena

- UV complete extension with potential of explaining BSM phenomena within a single model such as Superweak extension of the Standard Model: SWSM

Particle content of SM



Particle content of SWSM
(take-home picture)



Superweak extension of SM

- Symmetry of the Lagrangian: local $G = G_{SM} \times U(1)_z$ with $G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

renormalizable gauge theory, including all dim 4 operators allowed by G

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renormalizable gauge theory, including all dim 4 operators allowed by G

- *z*-charges fixed by requirement of
  - gauge and gravity anomaly cancellation and
  - gauge invariant Yukawa terms for neutrino mass generation

Expected consequences (take-home messages)

- Dirac and Majorana neutrino mass terms are generated by the SSB of the scalar fields, providing the origin of neutrino masses and oscillations
  [Iwamoto, Kärkäinnen, Péli, ZT, arXiv:2104.14571; Kärkkäinen and ZT, arXiv:2105.13360]
- The lightest new particle is a natural candidate for WIMP dark matter if it is sufficiently stable [Seller, Iwamoto and ZT, arXiv:2104.11248]
- Diagonalization of neutrino mass terms leads to the PMNS matrix, which in turn can be the source of lepto-baryogenesis
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- The second scalar together with the established BEH field may stabilize the vacuum and be related to the accelerated expansion now and inflation in the early universe
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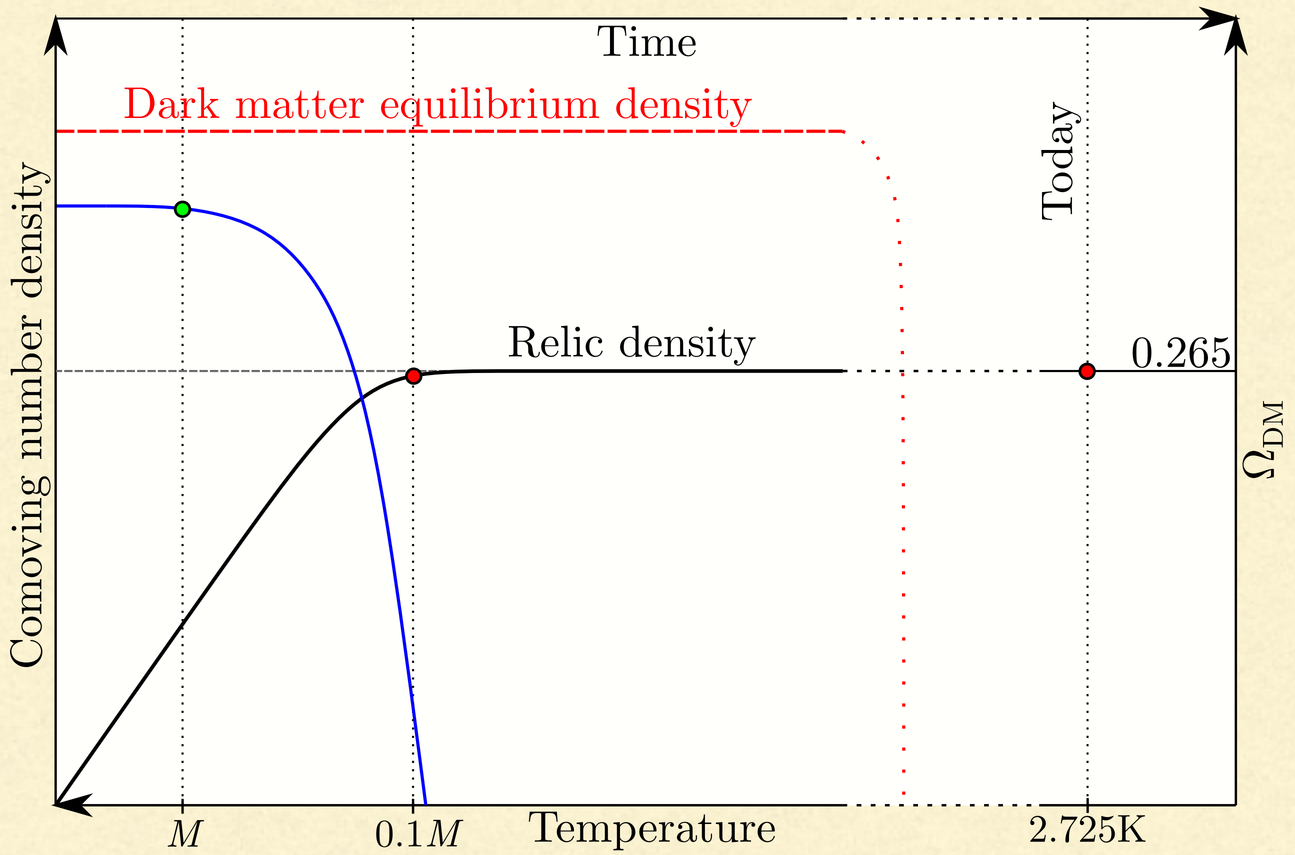
Dark matter candidate

- DM exists, but known evidence is based solely on the gravitational effect of the dark matter on the luminous astronomical objects and on the Hubble-expansion of the Universe
- Assume that the DM has particle origin
- Only chance to observe such a particle if it interacts with the SM particles, which needs a portal

In the superweak model the vector boson portal Z' with the lightest sterile neutrino ν_4 as dark matter candidate is a natural scenario (Higgs portal exists, but negligible)

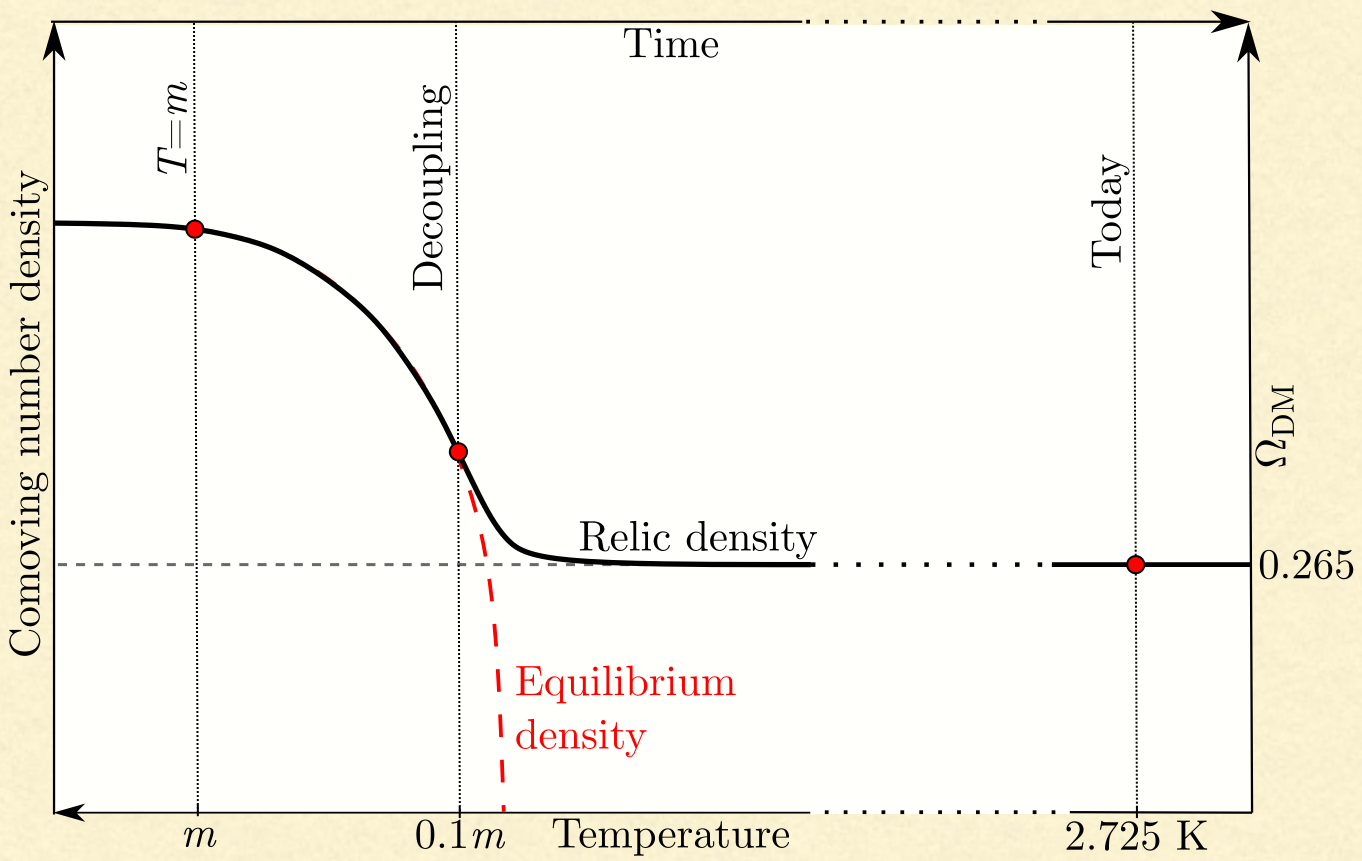
Freeze-in:
Possible in SWSM, but we skip now

- increases from vanishing initial abundance, but never reaches equilibrium
- Possible scenario in SWSM, but
- requires very small couplings (cannot be tested in particle physics, only in cosmology)



main production channel in SWSM : $Z' \to N_1 N_1$

Freeze-out



main production channel in SWSM : $f\bar{f} \to Z' \to N_1 N_1$

- DM particle decouples from the other particles in the cosmic soup at some temperature $T_{\rm dec}$
- DM particles of mass m are in equilibrium with others before decoupling ($T > T_{\rm dec} \sim m/10$)
- Decoupling is a result of scattering processes becoming slow compared to Hubble expansion, so the estimation of the rate of possible scattering processes is needed

Freeze-out

- Current exclusion limits on Z' vector boson portal leave room for $M_{Z'} \gtrsim 20$ MeV
- But a sufficiently heavy Z' can change Big-Bang Nucleosynthesis (BBN) dramatically through the production of SM particles, so we focus on the mass window with upper end below the pion mass, $M_{Z'} \lesssim 140$ MeV
- DM particles are produced by the decay of Z', so we consider $m_4 \in [10,50]$ MeV, hence $T_{\rm dec}$ is $O(1)$ MeV
- electrons and active neutrinos are abundant in the cosmic soup, heavier fermions are negligible.

Resonant enhancement

- in freeze-out mechanism the smaller the coupling (⇒ the smaller interaction rate ⇒ the earlier decoupling), the larger the relic density, can easily be too large in the superweak region ⇒ we need enhanced rates at small coupling

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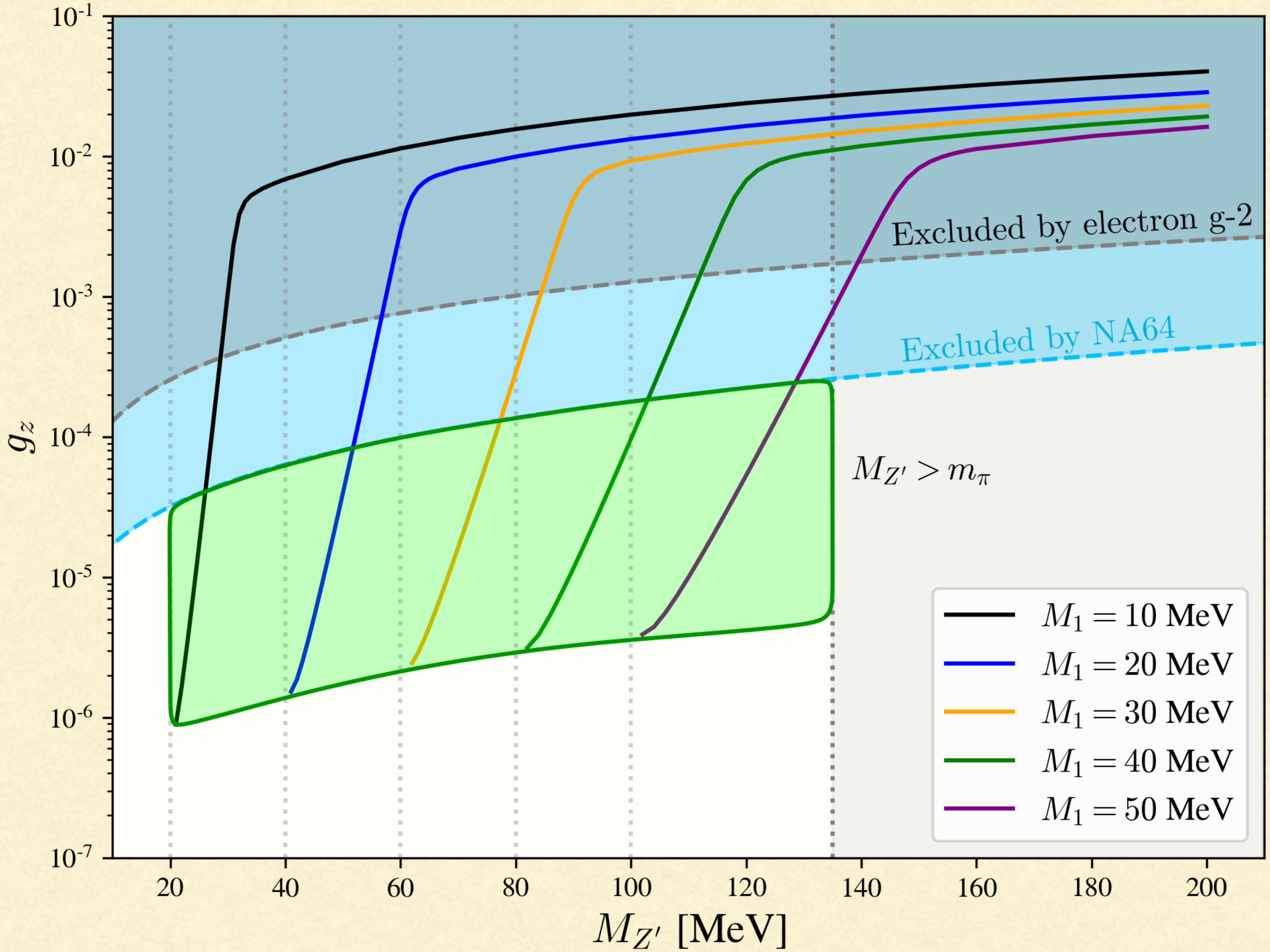
- in freeze-out mechanism the smaller the coupling (⇒ the smaller interaction rate ⇒ the earlier decoupling), the larger the relic density, can easily be too large in the superweak region ⇒ we need enhanced rates at small coupling
- s-channel resonance in $\sigma(s)$ dominates the integral in

$$\langle \sigma v_{\mathrm{M\o l}} \rangle \propto \int_{4\mu^2}^{\infty} \mathrm{d}s\ \sigma(s)(s-4m_{\mathrm{in}}^2)\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right)$$

if $m_4 \sim \dfrac{M_{Z'}}{2}$, which maintains the same interaction rate with smaller coupling

It is essential for the superweak model DM candidate that the resonance can dominate the integral in the rate

Parameter space for the freeze-out scenario of dark matter production in the supeweak model



Experimental constraints

- Anomalous magnetic moment of electron and muon
  - Z′ couples to leptons modifying the magnetic moment
  - Constraints on $(g-2)$ translate to upper bounds on the coupling $g_z(M_{Z'})$
- NA64 search for missing energy events
  - Strict upper bounds on $g_z(M_{Z'})$ for any U(1) extension (dark photons)
- Supernova constraints based on SN1987A
  - Constraints are based on comparing observed and calculated neutrino fluxes
- Big Bang Nucleosynthesis provides constraints on new particles
  - New particles should have negligible effects during BBN
  - Meson production can be dangerous close to BBN
- Further constraints are due to CMB, solar cooling, beam dump experiments etc.

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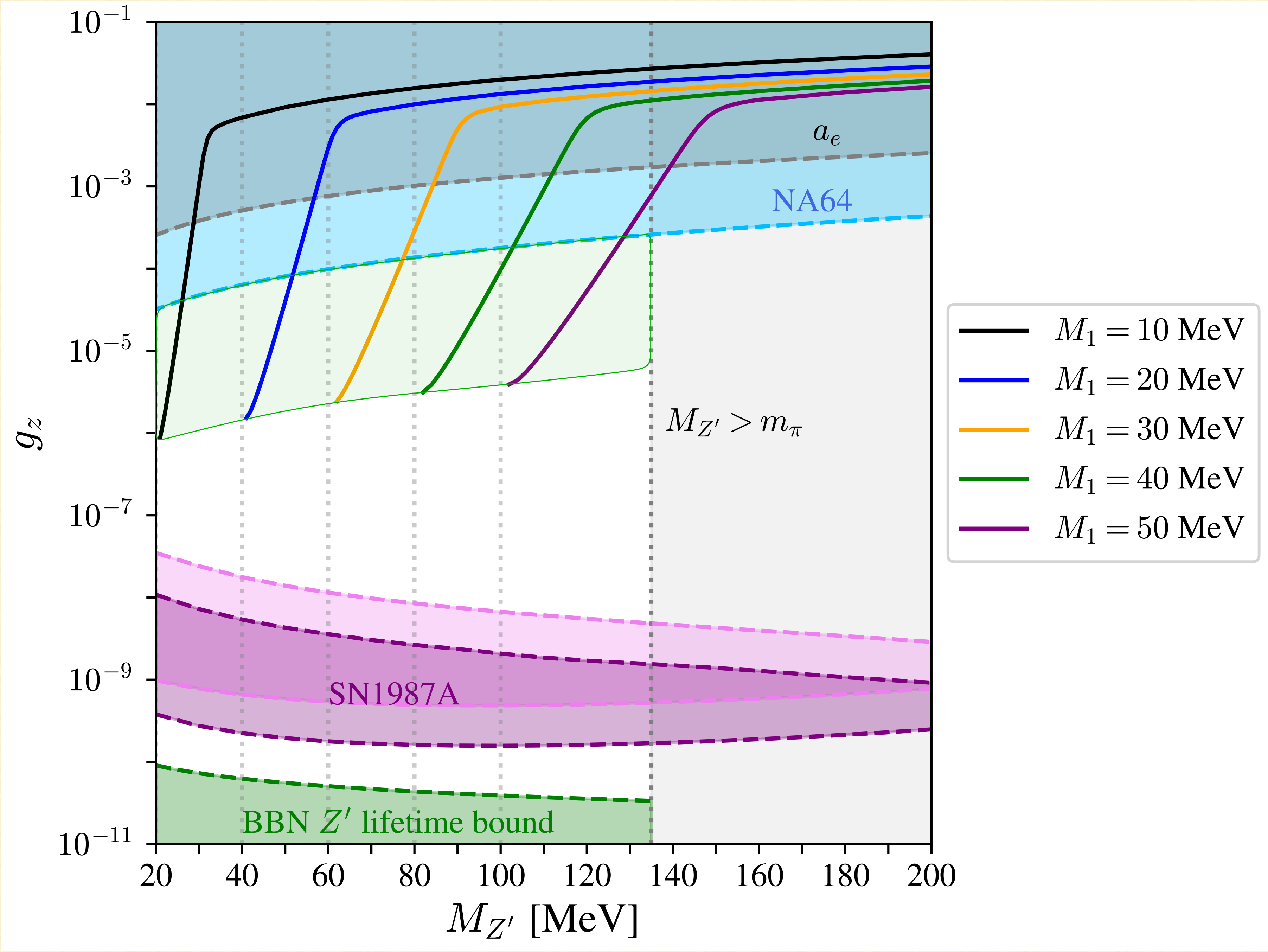

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has the potential of explaining all known results beyond the SM

Main questions

Is there a non-empty region of the parameter space where all these promises are fulfilled?

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Can we predict any new phenomenon observable by present or future experiments?

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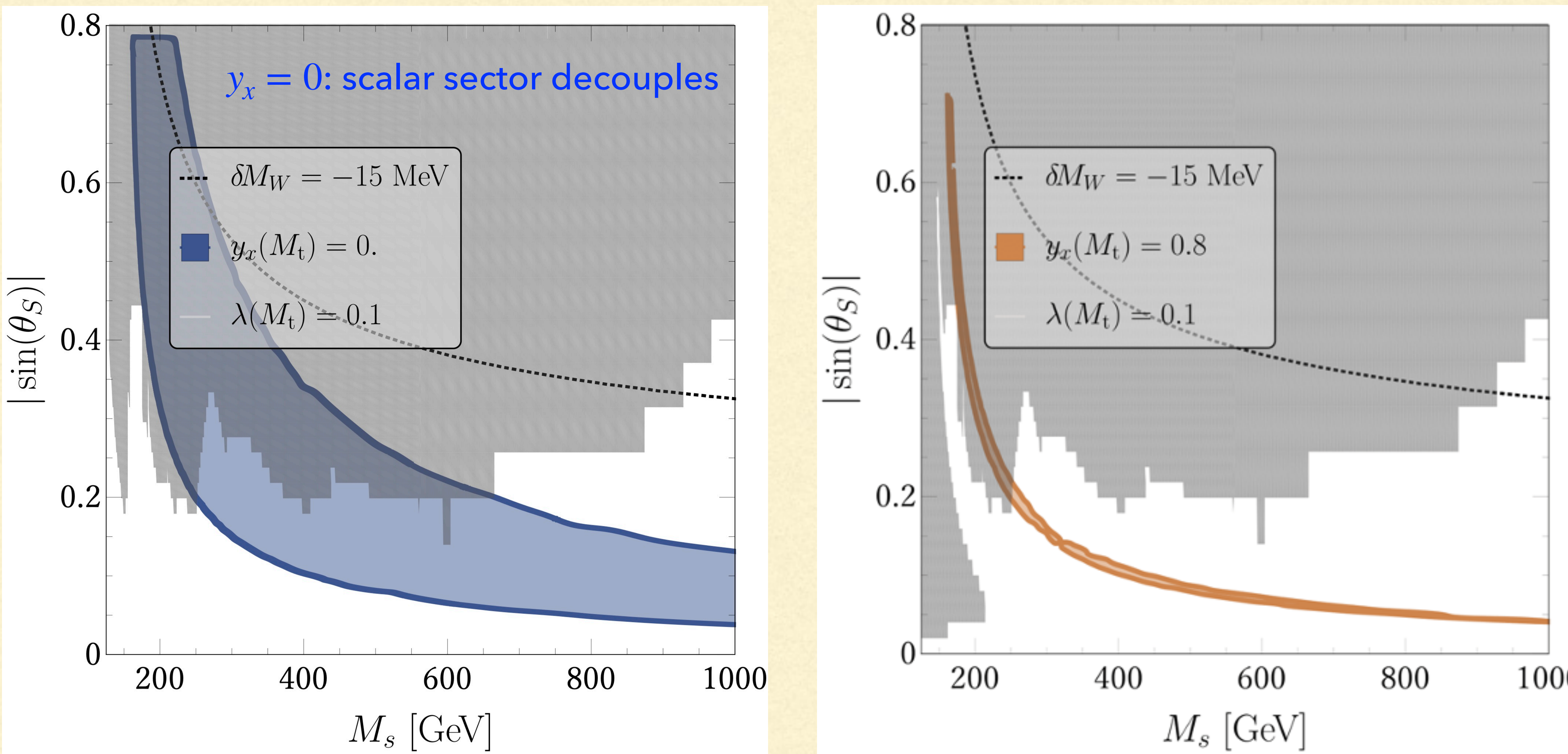
Present focus:

Is there a non-empty region of the parameter space where all these promises are fulfilled?

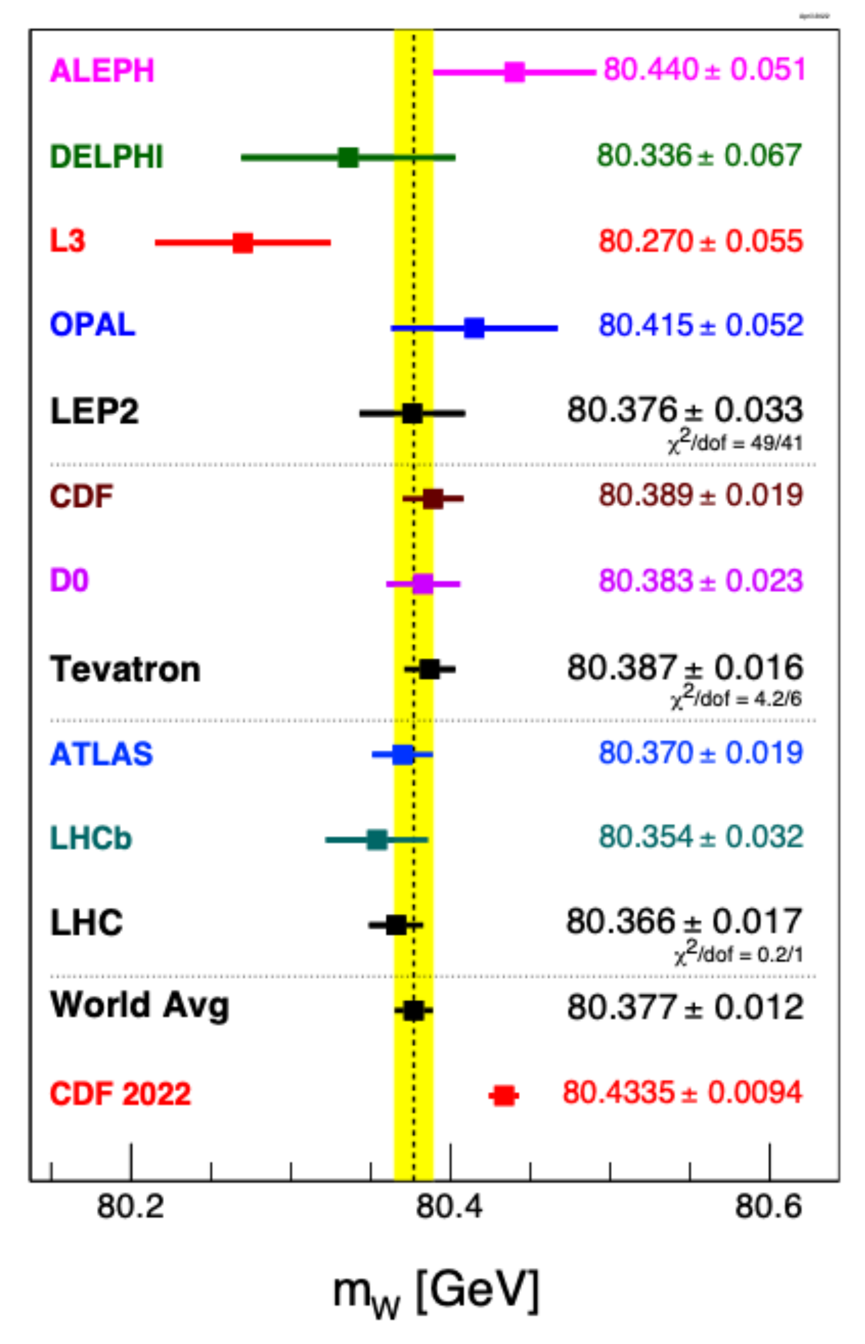
Can we predict any new phenomenon observable by present or future experiments?

Vacuum stability versus experimental constraints from HiggsBounds-5 and M_W

- $M_s > M_h$:



M_W is measured and computed precisely (with per myriad precision)



[PDG 2023]

Zoltán Péli's poster

Precise determination of the W-boson mass in U(1)z extensions of the standard modell

ELTE EÖTVÖS LORÁND UNIVERSITY

FFK2023

Zoltán Péli

The W-boson mass

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\,\alpha}{2\,M_W^2\,s_W^2}\frac{1}{1+\Delta r}$$

- Computed from the muon decay width
- Experiment and theory precision reached the per-myriad (1 to 10 000) level
- **How does BSM physics affect M_W?**

The $U(1)_z$ extensions of the SM

- Additional gauged $U(1)_z$ symmetry, a complex scalar field and right handed neutrinos. Rotation to mass eigenstates is defined as

$$\begin{pmatrix} B_\mu \\ W_\mu^3 \\ B'_\mu \end{pmatrix} = \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_Z & -s_Z \\ 0 & s_Z & c_Z \end{pmatrix}\begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

- **New particles: neutral gauge boson, a scalar and sterile neutrinos**
- Simple model, with a potential to explain several BSM phenomena
- **Precise corrections to electroweak observables?**

Free parameters

⇒ $M_{Z'}$ - mass of the new gauge boson

⇒ s_z - sine of the Z-Z' mixing angle

⇒ $\tan\beta$ - ratio of the VEV of the new scalar field and the BEH field

⇒ M_s - mass of the new scalar particle

⇒ s_s - sine of the scalar mixing angle

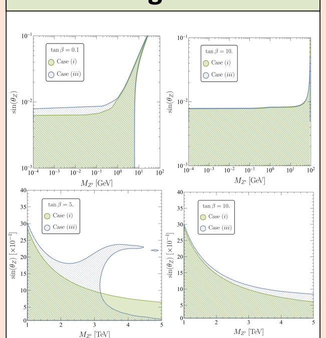
Tree level and one-loop corrections

- At **tree level** the mass of the new gauge boson and the Z-Z' mixing angle affects M_W:

$$\frac{M_W^2}{c_W^2} = M_Z^2 c_Z^2 + M_{Z'}^2 s_Z^2$$

- At **one-loop, Δr** can be split into two terms:
- **Δr_1** : formally the same as **Δr in the SM**, but **with BSM loops**
- **Δr_2** : completely unique correction to $U(1)_z$ extensions: **Z'-boson** and the **Z-Z' mixing angle**
- The **full prediction $\Delta r = \Delta r_1 + \Delta r_2$** is **finite** and **gauge independent**

Allowed region



$$\left|M_W^{\text{theo.}} - M_W^{\text{exp.}}\right| < 2\sigma$$

Approximations

- ***Can Δr_2 become important?***
- Compute M_W for different sets of input parameters to asses the effect of the new terms in Δr
- Include the two-loop SM corrections to Δr for precise numerical predictions for M_W
- Compare three cases in the numerical analysis
  - ***I. Tree level + ($\Delta r_1 + \Delta r_2$) + SM 2-loop***
  - *II. Tree level + (SM 1-loop) + SM 2-loop*
  - *III. Tree level + (Δr_1) + SM 2-loop*
- Present benchmarks and plot 2σ allowed bands for M_W (theory vs. experiment)
- Automated M_W calculators (such as SARAH/SPheno and FlexibleSusy) employ Case III.: **Is it justified to use Case III. and not Case I.?**

Conclusions

- The extension of the SM gauge group may have **profound effect** on the electroweak observables
- We computed the complete 1-loop correction to **Δr** in $U(1)_z$ extensions: **NEW RESULT**
- **Δr_2 becomes important if $M_{Z'}$ is much heavier than the Z-boson**
- Using a truncation, such as Case III. becomes unrealiable for computing the W-boson mass!

Benchmark and checking

- We use the 2022 PDG for the SM input values
- **The table shows the difference of the SM and the BSM predictions**
- In the table we use $M_{Z'}$ = 5 TeV, s_z = 0.0005 and s_s = 0.1
- **Cases I. and III. are very different!**

	$M_S = 50$ GeV						$M_S = 500$ GeV					
$\tan\beta$	ΔM_W [MeV]			Δs_W^2 [$\times 10^4$]			ΔM_W [MeV]			Δs_W^2 [$\times 10^4$]		
–	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
2	−165	43	−727	6	−2	39	32	43	−730	−6	−2	39
5	4	43	−83	−1	−2	4	34	43	−84	−2	−2	4
10	31	43	11	−2	−2	−1	37	43	10	−2	−2	−1

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Conclusions

- Established observations require physics beyond SM, but do not suggest rich BSM physics
- $U(1)_z$ extension has the potential of explaining all known results beyond the SM
- Neutrino masses are generated by SSB at tree level
- One-loop corrections to the tree-level neutrino mass matrix computed and found to be small (below 1‰) in the parameter space relevant in the SWSM
- Lightest sterile neutrino is a candidate DM particle in the [10,50] MeV mass range for freeze-out mechanism with resonant enhancement →predicts an approximate mass relation between vector boson and lightest sterile neutrino
- In the scalar sector we find non-empty parameter space for $M_s > M_h$
- Contributions to EWPOs (e.g. M_W, lepton g-2) are negligible in the superweak region and a systematic exploration of the parameter space is ongoing

the end

Appendix

M_W

- Can be determined from the decay width of the muon:

$$M_W^2 = \frac{\cos^2\theta_Z M_Z^2 + \sin^2\theta_Z M_{Z'}^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\alpha \big/ \left(\sqrt{2} G_F\right)}{\cos^2\theta_Z M_Z^2 + \sin^2\theta_Z M_{Z'}^2} \frac{1}{1 - \Delta r_{SM} - \left(\Delta r_{BSM}^{(1)} + \Delta r_{BSM}^{(2)}\right)}}\right)$$

  - θ_Z is the $Z - Z'$ mixing angle
  - Δr_{SM} collects the SM quantum corrections (known completely at two loops and partially at three loops)
  - $\Delta r_{BSM}^{(1)}$ collects the formally SM quantum corrections but with BSM loops
  - $\Delta r_{BSM}^{(2)}$ collects the BSM corrections to $M_{Z'}$ and θ_Z

See Zoltán Péli's poster for numerical effect