Updating Sterile Neutrino Dark Matter Using Scale Invariance

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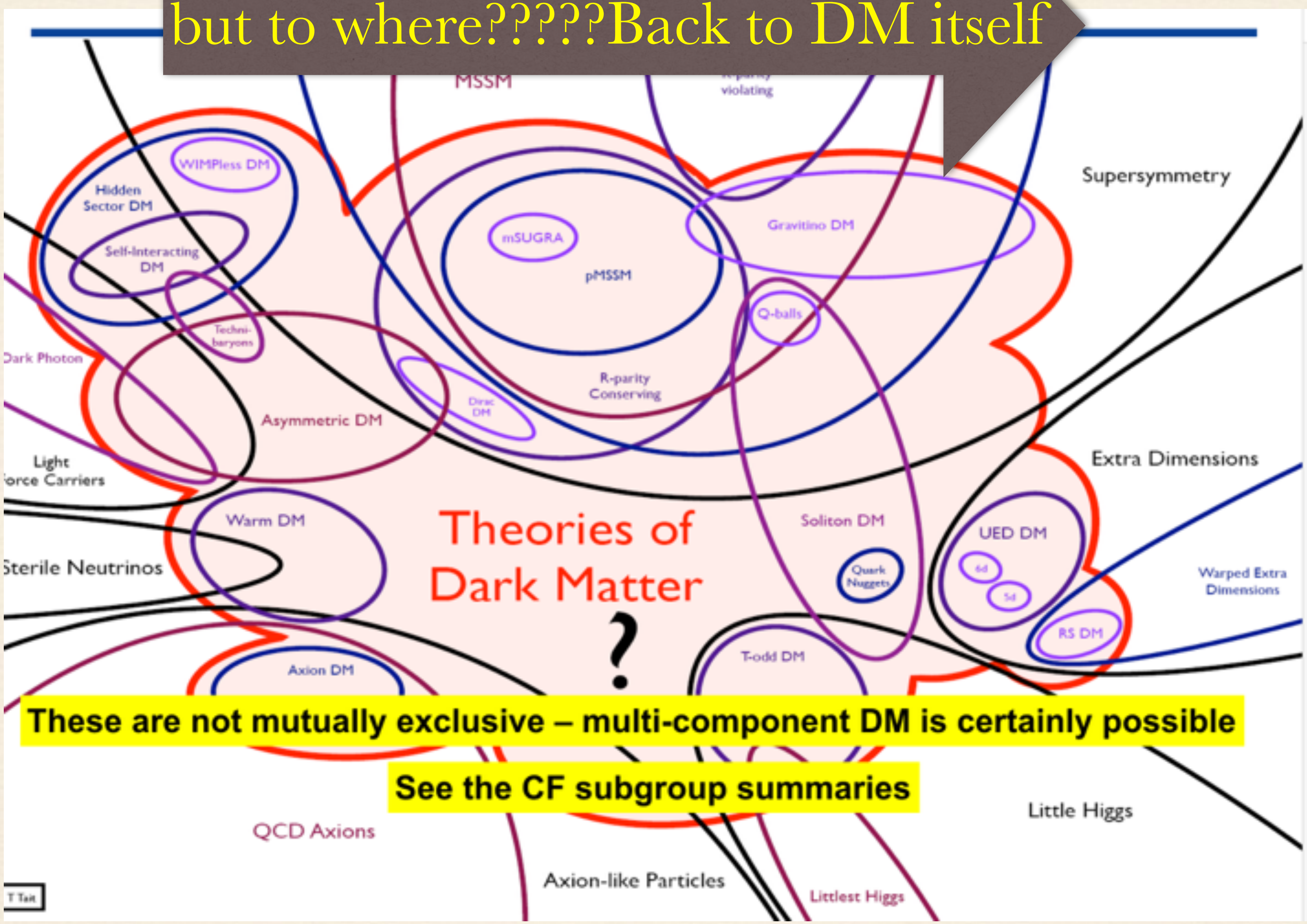
Outline

- Basic questions on dark matter
- FI*m*P, a new paradigm for 2,3nd Q
- Ex: Sterile neutrino as a FI*m*P
- View FI*m*P in DM self-interactions
- Conclusions

Basic questions on dark matter

- Dark Matter: Roadmap to new physics?

but to where?????Back to DM itself



Basic questions on dark matter

- Q1: Why is it there?

The LSP such as neutralino predicted by supersymmetry in addressing the hierarchy problem, a symbol for cold really interacting massive particle (WIMP) DM~10^2 GeV

Sterile neutrino predicted by seesaw models in addressing neutrino mass, a symbol for warm DM~10^{-6} GeV

Axion predicted by PQ-models in addressing strong CP problem

a symbol for unbelievable light DM~10^{-15} GeV

All of them are SM neutral particles, crossing ~20 orders

Basic questions on dark matter

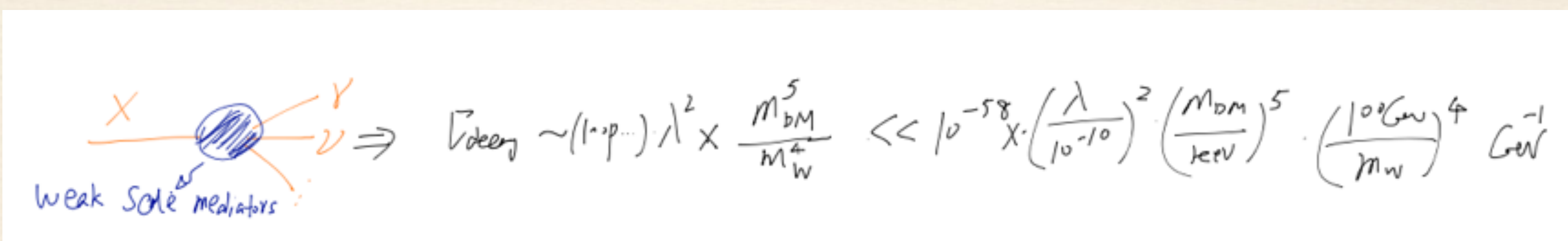
- Q2: Why is it stable?

For WIMP DM, by virtue of cheap ***X***-parity like $\boldsymbol{Z}_2$, $\boldsymbol{Z}_3$ and so on.

improvements: 1) gauged origin such as local U(1)→**Z**n
2) accidental due to the field content and gauge & space time symmetries
attempt in scale invariance models $-\mathcal{L} = \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + \frac{\lambda_{ij}}{2}\Phi^\dagger\Phi S_i S_j + \frac{\lambda_{ijkl}}{4!} S_i S_j S_k S_l,$

J. Guo and Z. K, "Higgs Naturalness and Dark Matter Stability by Scale Invariance," Nucl. Phys. B 898, 415 (2015)
J. Guo, Z. K, P. Ko and Y. Orikasa, "Accidental dark matter: Case in the scale invariant local B-L model," Phys. Rev. D 91, no. 11, 115017 (2015)

Symmetriless but accidentally long-lived due to extremely light & feebly interacting, such as the sterile DM. Cosmic age $\tau \gtrsim 10^{17}$s$\sim 10^{-42}$/GeV

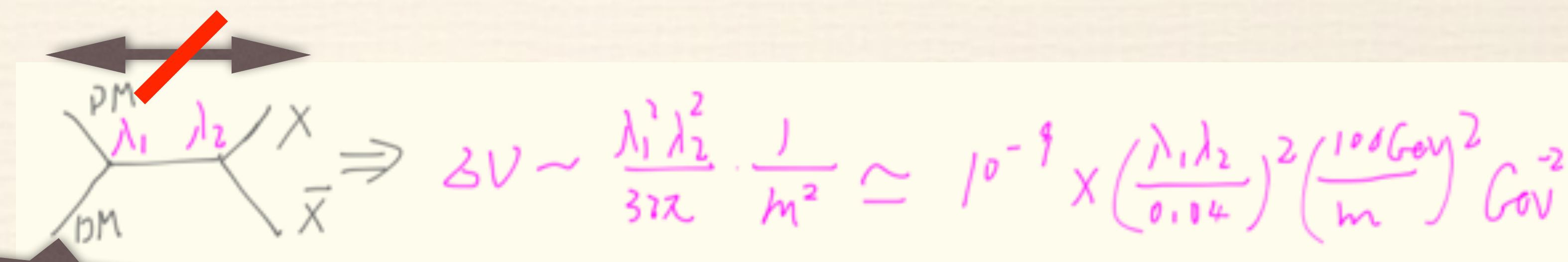


Purely light like the QCD axion, too light to decay away.

Basic questions on dark matter

- Q3: How does it get relic density $\Omega_{DM} h^2 \sim 0.1$ (25% fraction)?

WIMP miracle: DM annihilates via weak scale particle with weak scale interaction strength



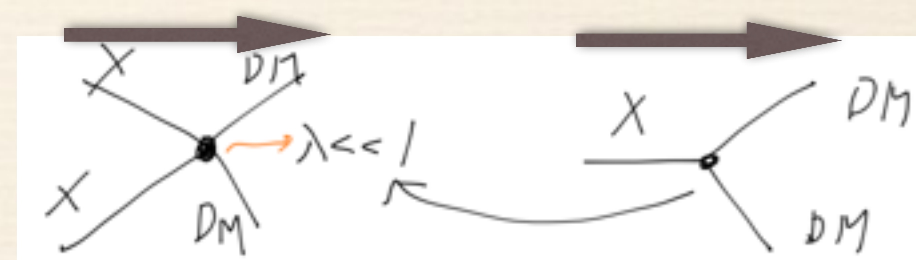
But actually most WIMP DM studied is far away from this miracle, distorted by tuning parameters resonant and coannihilation effects.

On the other hand, FIMP,

feebly interacting massive particle, also works

FIMP never enter thermal equilibrium (must couplings to plasma extremely weak), but it can be produced via bleeding

J. McDonald, Phys.Rev.Lett. 88, 091304 (2002); L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, JHEP 1003, 080 (2010), 0911.1120.



Basic questions on dark matter

- More on FIMP relic density

Simple Boltzmann equation (BE) without inverse term in the collision term

$$Y_X'(z) = \frac{z}{sH}\gamma(P.. \to X...), \quad \Rightarrow \quad Y_X(\infty) \approx \int_{m_P/T_R}^{\infty} dz \frac{z}{sH}\gamma(P.. \to X...)$$

UV-insensitive for renormalizable freeze-in processes, e.g., for decay

particles are effectively produced near the mass of thermal particles

$$Y_X(\infty) \approx \frac{45\, g_A}{1.66\pi^4 (g_* g_{*S})^{1/2}} \frac{\Gamma(7/2)\Gamma(5/2)}{16} \frac{M_{\rm Pl}}{m_P^2} \Gamma(P \to \bar{X} X).$$

$$\Omega_{\rm DM} h^2 = 2.82 \times 10^2 \left(\frac{m_{\rm DM}}{\rm keV}\right) Y_{\rm DM}(\infty)$$

For example, a 10 GeV FIMP from a 100 GeV thermal particle decay requires partial decay width as small as $\sim 10^{-20}$ GeV!

FI*m*P, a new paradigm for 2,3nd Q

- From FIMP to FI*m*P, by scale invariance (SI)

When FIMP ***X*** meets SI, extremely light FIMP, FI*m*P arises:

due to SI, *X* must gain mass via coupling to some Higgs-like field **Φ** with VEV (~ TeV?)

$$\frac{1}{2}\lambda_\phi X^2\Phi^2, \quad \frac{1}{2}y_\phi X^2\Phi,$$

As a FIMP, λ_ϕ, y_ϕ must be extremely small

Hence, the FIMP must be extremely light, ~ keV-MeV (thus M→*m*)

Lightness & feebly coupling guarantee FI*m*P must be sufficiently long-lived

- Remarks: the only known way to inherently address the basic properties of DM unifiedly, mass and relic density origins, implying the stability mechanism at the same time.

FI*m*P, a new paradigm for 2,3nd Q

- A bird eye on scale invariance

A classical spacetime symmetry, forbidding massive couplings

But it is anomaly, violated radiatively, as is crucial for SI spontaneously breaking via the Colman-Weinberg (CW) mechanism:

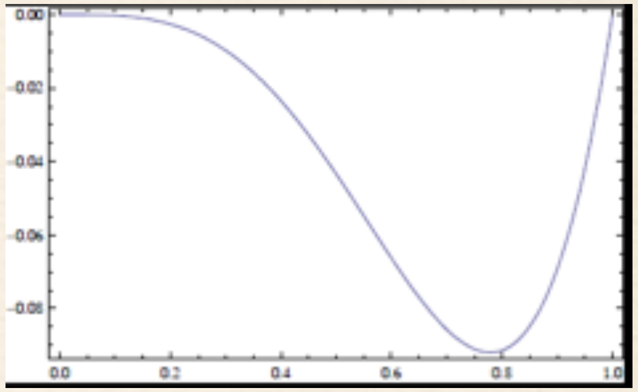
$$V_{\rm eff} = A\phi_{\rm cl}^4 + B\phi_{\rm cl}^4 \ln\frac{\phi_{\rm cl}^2}{Q^2},$$

$$A = \frac{\lambda}{8} + \frac{1}{64\pi^2}\sum_P n_P g_P^4\left(-A_P + \ln g_P^2\right),$$

$$B = \frac{1}{64\pi^2}\sum_P n_P g_P^4, \qquad m_\phi^2 = 8B\langle\phi_{\rm cl}\rangle^2.$$

encode quantum effect

PGSB of SI breaking, $B>0$



A "solution" to gauge hierarchy problem?

W. A. Bardeen, FERMILAB-CONF-95-391-T, C95-08-27.3 (1995).

In SI SM top quark makes $B<0$, so it fails and requires extensions, e.g., new bosons strongly couple to SM Higgs or a hidden sector breaking SI via $\mathbf{\Phi}$ which then is mediated to SM via $\mathbf{\Phi}^2|H|^2$.

Ex: Sterile neutrino as a FI*m*P

- *v*MSM version 1.0

T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett. B 631 (2005) 151.

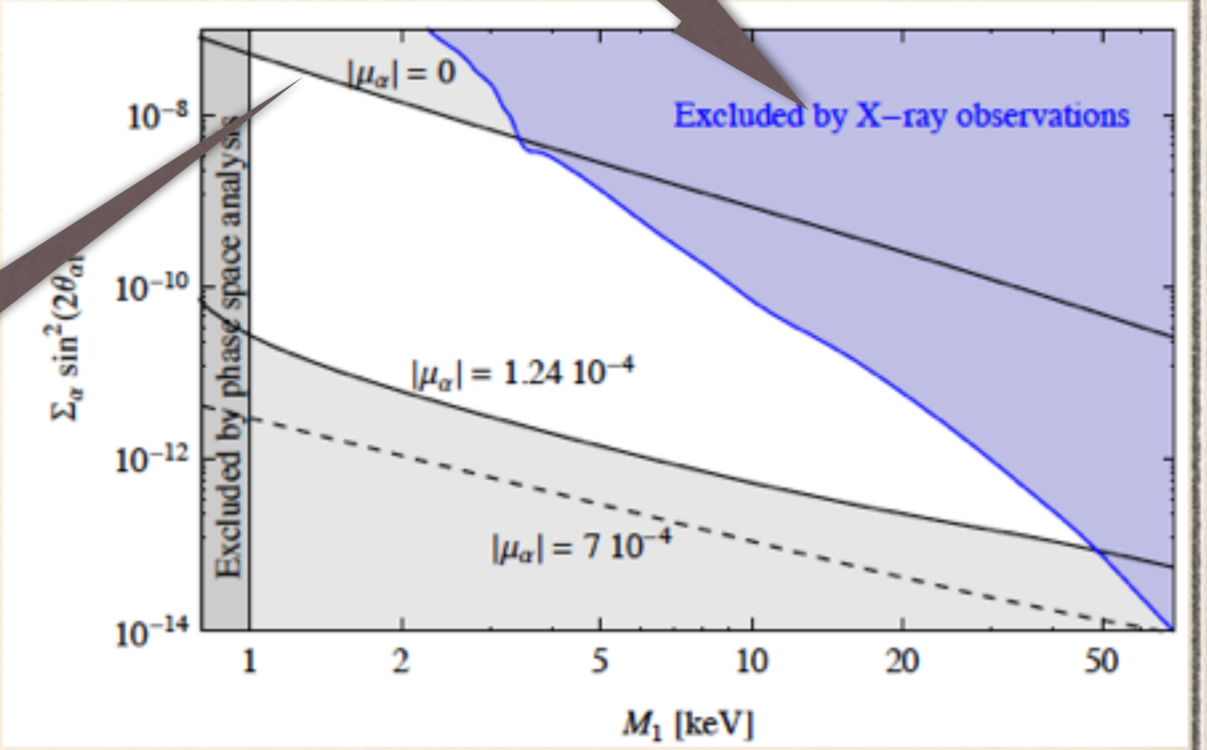
*v*MSM=SM+RHNs=the canonical seesaw with very low seesaw scale

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{MSM}} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\, \bar{N}_I^c N_I + \mathrm{h.c.}\,,$$

Accidental stability of the lightest RHN, N_1: $\Gamma_{N_1 \to \nu\gamma} \simeq \frac{9 G_F^2 \alpha M_1^5}{256\pi^4} \times \sin^2\theta_1,$

Relic density, a problem: sterile-active neutrino oscillation with(out) resonant effect

Lyman-alpha bound excludes the region above a few keV



without resonant effect it has been excluded; while resonant effect requires anomalously large lepton asymmetry.

Ex: Sterile neutrino as a FI*m*P

- *v*MSM version 2.0

*v*MSM 2.0=*v*MSM 1.0 with classical SI

$$\mathcal{L} = \frac{\lambda_1}{2}|H|^4 + \frac{\lambda_2}{2}|S|^4 + \lambda_3|H|^2|S|^2 + \lambda_4|H|^2\left(S^2 + S^{*2}\right) + \lambda_5|S|^2\left(S^2 + S^{*2}\right) + \frac{\lambda_6}{2}\left(S^4 + S^{*4}\right)$$
$$+ \left(\frac{\lambda_{sn}}{2} S N^2 + y_N \bar{\ell} H N + c.c.\right).$$

impose CP-invariance to reduce parameters

SI demands singlets with VEVs to give Majorana masses of RHNs; One complex singlet (two real singlets) is required to accommodate Higgs phenomenology. Potential in real components

$$S = \frac{J + i\sigma}{\sqrt{2}}$$

$$V(J, \sigma, h) = \frac{\lambda_J}{4!} J^4 + \frac{\lambda_\sigma}{4!} \sigma^4 + \frac{\lambda_h}{4!} h^4 + \frac{\lambda_{J\sigma}}{4} J^2 \sigma^2 + \frac{\lambda_{hJ}}{4} h^2 J^2 + \frac{\lambda_{h\sigma}}{4} h^2 \sigma^2$$

three-d field space, using the Gilderner-Weinberg approach

PGSB of SI is dominated by singlet with largest VEV~TeV, with mass around 100 GeV

Ex: Sterile neutrino as a FI*m*P

- FI*m*P miracle? Extremely light particle with extremely weak interactions just have correct relic density:

$$\frac{1}{2}\lambda_S S N^2 \xrightarrow{S=\frac{1}{\sqrt{2}}(\langle s\rangle+s)} \begin{cases} M_N=\lambda\langle s\rangle \Rightarrow \lambda=\frac{M_N}{\langle s\rangle}\sim 10^{-8} \\ \frac{1}{2\sqrt{2}}\lambda\cdot sN^2 \end{cases}$$

EWSB favors singlets with VEVs~TeV, so a keV RHN means

$$\Omega_{\rm DM}h^2 = 0.11\times\sum_{H_a=\mathcal{P},H_2}\left(\frac{m_{\rm DM}}{10\,{\rm keV}}\right)^3\left(\frac{\rm TeV}{v_J}\right)^2\left(\frac{100\,{\rm GeV}}{m_{H_a}}\right)\left(\frac{10^3}{g_*^S\sqrt{g_*^\rho}}\right),$$

At the same time, RHN gains a feeble interaction, which is too weak to thermalize it. However, it is just at the correct order to freeze-in RHN:

By scale invariance, RHN mass and relic density share the same origin, strengthened miracle?

Ex: Sterile neutrino as a FI*m*P

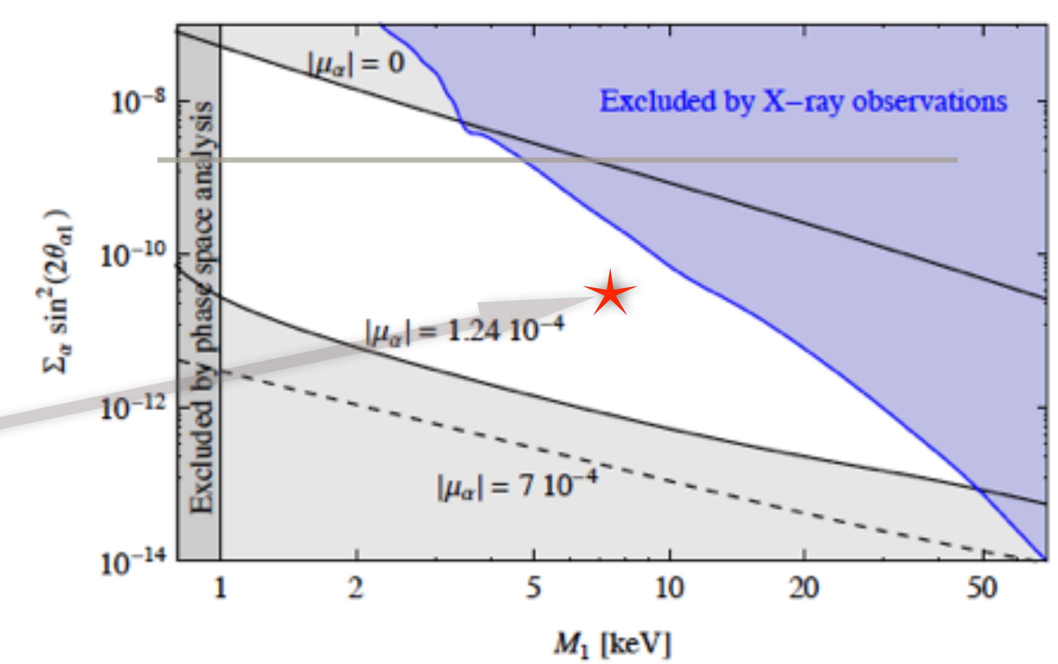
- FI*m*P miracle shines in the *X*-ray line?

The *X*-ray line at 3.5 keV reported this year is explained by RHN

$$\Gamma_{\nu\gamma} \simeq 1.62 \times 10^{-28} s^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right) \left(\frac{m_{\tilde{X}}}{7\mathrm{keV}}\right)^5$$

But it has been excluded for RHN with conventional productions, even for resonant production which has been excluded by Lyman-alpha bound

A. Merle and A. Schneider, arXiv:1409.6311



The RHN from freeze-in with colder spectrum thus being favored!

View FImP in DM self-interactions

- Why self-interaction? Or why not?

FImP is very hard to be observed neither directly nor indirectly (may leave hints in X-ray line), not mentioning the colliders searches

But **FImP self-interaction may be sizable, as a result of its lightness**. This may heave astrophysical observable effects via DM self-scattering

DM self-scattering may lead to an observable separation between the DM halo and the stars of a galaxy, which is moving through a region with large DM density

Ex, recently such separation is observed in the elliptical galaxies falling into the core of galaxy cluster Abel 3827, pointing to

$$\sigma_{\rm DM}/m_{\rm DM} \sim (1.0 - 1.5)\text{cm}^2/\text{g} \sim (4.7 - 7.0) \times 10^3 \text{GeV}^{-3}.$$

Massey R., Williams L. L. R., Smit R., Swinbank M.,Kitching T., et al., 2015, MNRAS, 449, 3393

View FImP in DM self-interactions

- Easy self-interactions for scalar FImP

A scalar FImP tends to have large self-interactions due to its lightness and a sizable quartic coupling S^4. In the simplest model

accidental Z_2-parity

$$-\mathcal{L}_{DM} = \frac{\lambda_{sh}}{2} S^2 |H|^2 + \frac{1}{2} m_S^2 S^2 + \frac{\lambda_S}{4!} S^4$$

Freeze-in DM relic density determines the single free parameter

$$\Omega_X h^2 \simeq 0.12 \times \left(\frac{\lambda_{sh}}{10^{-10.5}}\right)^{5/2} \left(\frac{v/m_h}{2.0}\right)^3 \left(\frac{10^3}{g_*^S \sqrt{g_*^\rho}}\right) \Rightarrow m_S = 1.0\ \mathrm{MeV}.$$

Contact self-interaction leads to large velocity-independent self-scattering

$$\frac{\sigma_{DM}}{m_S} = \frac{1}{128\pi} \frac{\lambda^2}{m_S^3} \simeq 7.9 \times 10^3 \left(\frac{\mathrm{MeV}}{m_S}\right)^3 \left(\frac{\lambda}{0.1}\right)^2 \mathrm{GeV}^{-3}.$$

By contrast, a scalar WIMP has negligible velocity-independent self-scattering rate

$$\frac{\sigma_{DM}}{m} \sim \frac{1}{32\pi} \frac{\lambda^2}{m^3} \simeq 10^{-10} \times \left(\frac{\lambda}{0.1}\right)^2 \left(\frac{100\mathrm{GeV}}{m}\right)^3 \mathrm{GeV}^{-3},$$

View FImP in DM self-interactions

- Self-interactions for fermionic FImP

A fermonic FImP can have self-interactions in the presence of a force carrier like a scalar or gauge boson, which however is not built-in.

But a light scalar S_0 (also a FImP) may be a part of the FImP sector and it interacts with the fermonic FImP DM via $-\lambda S_0 NN$

Dark force limit: Light S_0 leads to velocity-dependent scattering

$$V = -\frac{\alpha_\lambda}{r} e^{-m_{S_0} r} \quad \Rightarrow \quad \sigma_T^{\rm Born} = \frac{8\pi\alpha_\lambda^2}{M_N^2 v^4}\left[\log\left(1+\xi_v^2\right) - \frac{\xi_v^2}{1+\xi_v^2}\right] \quad \xi_v \equiv M_N v/m_{S_0}.$$

$\xi_v \ll 1$, it becomes $\frac{\sigma_T^{\rm Born}}{M_N} = 7.9\times 10^3 \left(\frac{M_N}{0.1\,{\rm MeV}}\right)\left(\frac{0.002\,{\rm MeV}}{m_{S_0}}\right)^4 \left(\frac{\alpha_\lambda}{10^{-8}}\right)^2 {\rm GeV}^{-3}$ velocity-independent

Contact 4-fermion limit: Heavy S_0 leads to velocity-independent scattering

$$\frac{\sigma_{\rm DM}}{M_N} = \frac{3\lambda^4}{8\pi}\frac{M_N}{m_{S_0}^4} \simeq 6.0\times 10^3 \left(\frac{M_N}{0.1\,{\rm MeV}}\right)\left(\frac{\rm MeV}{m_{S_0}}\right)^4 \left(\frac{\lambda}{0.15}\right)^4 {\rm GeV}^{-3}.$$

Conclusions

- FImP is a framework from the nontrivial combination FIMP with scale invariance
- FImP can address DM stability, relic density and mass origins inherently.
- The sterile neutrino from νSISM is a very attractive example of FImP. Updating the sterile neutrino to FImP can resolve the relic density problem
- FImP, in particular scalar FImP easily leave hints in DM self-interactions because of its lightness

Thank you!