keV Warm Dark Matter and Composite Neutrinos

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Based on: 1009:2781 (Y. Grossman and DR, JHEP **1101** 132);
1205.0569 (DR and Y. Tsai).

Background

KeV Warm Dark Matter

- An alternative to CDM WIMP
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Today:

- keV *elementary* sterile neutrinos with correct mixing angles for 'resonantly produced' WDM are a natural component of composite neutrino scenario.
- Supercooled sudden confinement can produce entropy for production by entropy-diluted thermal freeze out.

Composite Neutrino Scenario

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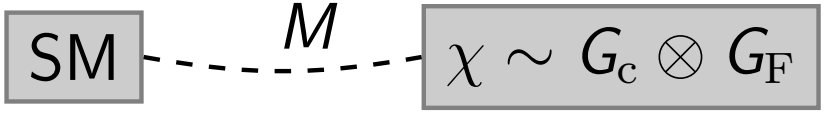

'ν-color' and hidden flavor

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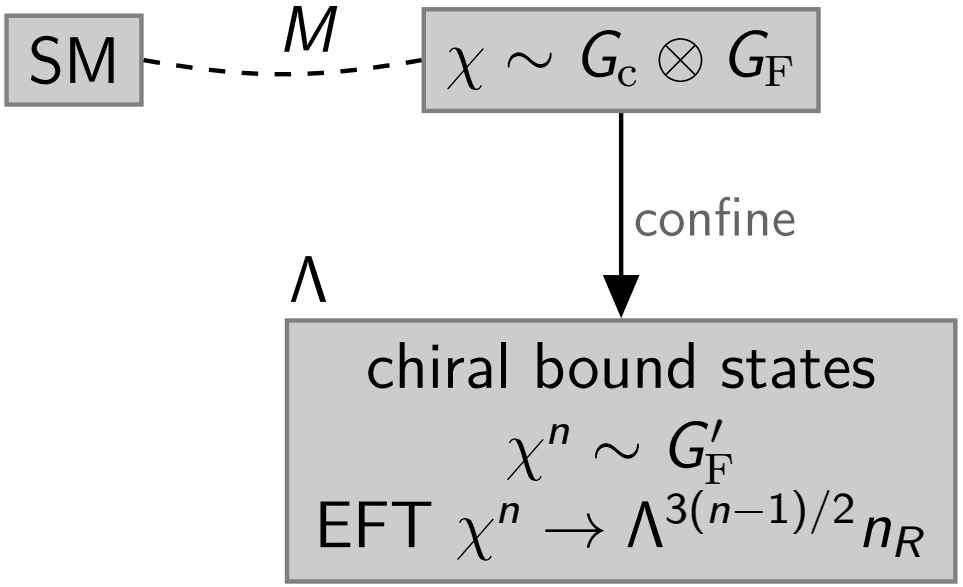

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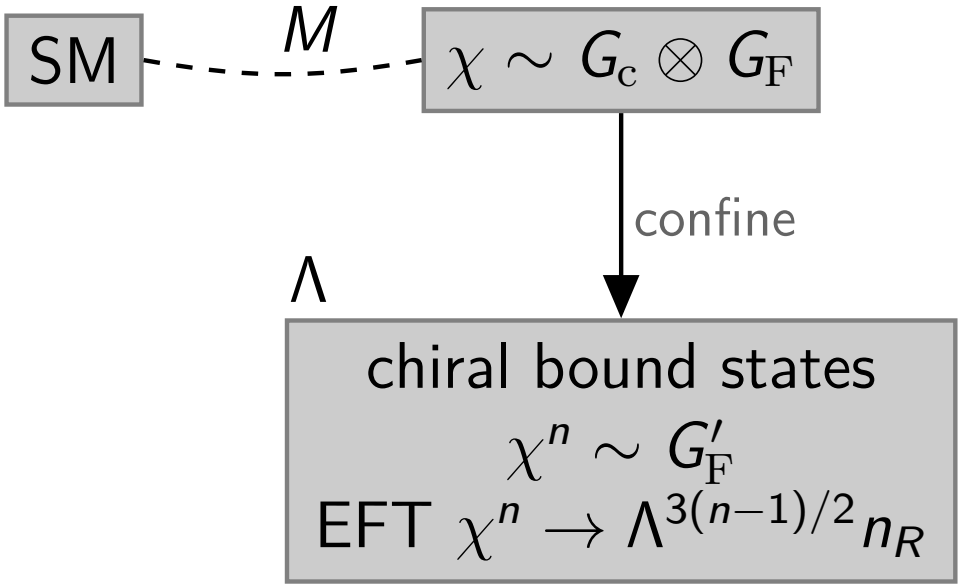

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No renormalizable operators coupling G_c singlets to SM below M. Leads to light Dirac masses after confinement.

$$\frac{\lambda}{M^{3(n-1)/2}} \overline{L}_L \widetilde{\phi} \chi^n \xrightarrow{\text{confine}} \lambda \left[\frac{\Lambda}{M}\right]^{3(n-1)/2} \overline{L}_L \widetilde{\phi} n_R \; . \to \equiv \varepsilon$$

Light Dirac Neutrinos

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- EWSB pattern

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- Light Dirac neutrinos! Mass $\sim v\epsilon^{3(n-1)/2}$.

Extended Hidden Sector

- Extended hidden sector of chiral $G_{\rm c}$ singlets, $\xi \sim G_{\rm F}$, are a generic feature.
- Scalar condensate $\langle \chi^m \rangle$ induces $G_{\rm F} \to G'_{\rm F}$. Suppose decomposition of ξ yields Dirac $\xi_{L,R}$ with $\mathrm{U}(1)_{\rm F}$ charge same as n_R.

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- ξ_R SM coupling just like n_R

$$\frac{1}{M^{3m/2}} \overline{L}_L \widetilde{\phi} \chi^m \xi \xrightarrow{\langle \chi^m \rangle} \epsilon^{3m/2} \overline{L}_L \widetilde{\phi} \xi_R \ .$$

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Spectrum

composite	SM	extended	composite
pions	active ν	ξ sterile ν	everything else
0	$v\epsilon^{3(n-1)/2} \sim 0.05$ eV	$m_d \sim \Lambda\epsilon^{(3m-2)/2}$	Λ

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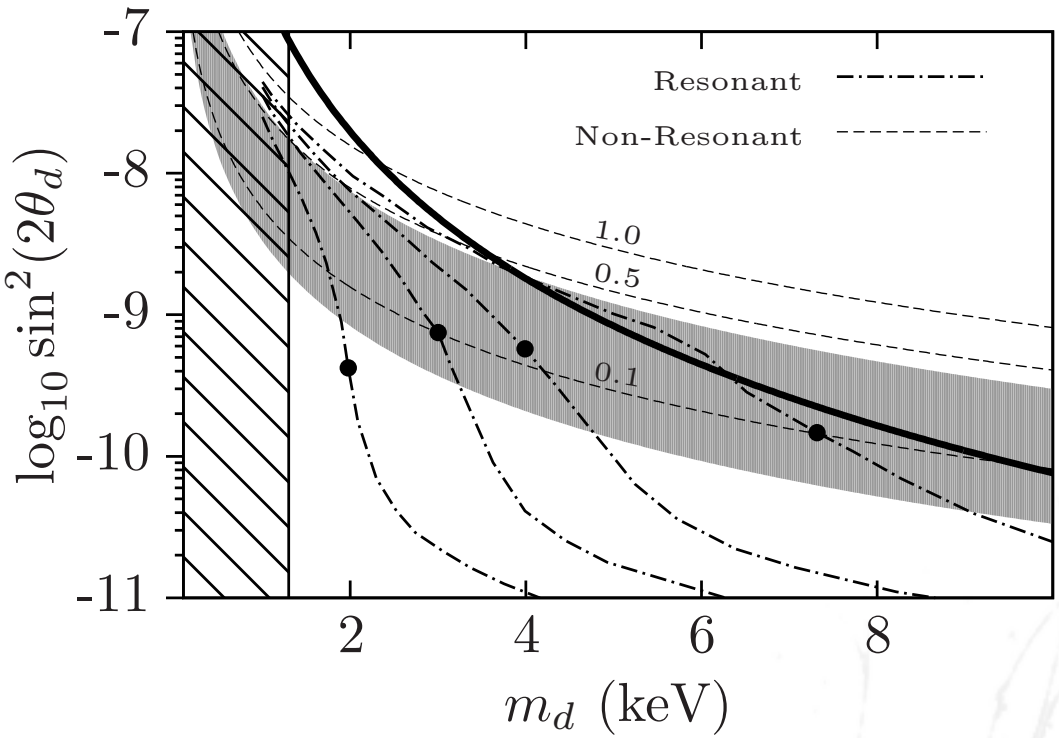

$\xi_{L,R}$ mass and active-sterile mixing angle (light grey) for $m = n - 1$ theories

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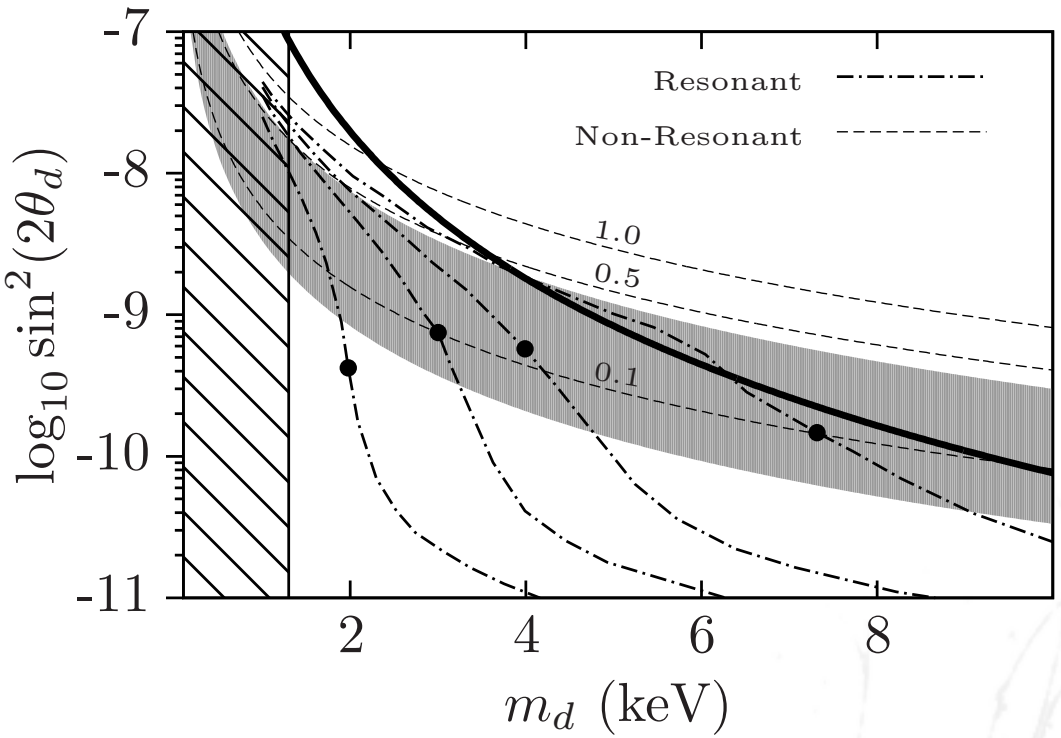

$\xi_{L,R}$ mass and active-sterile mixing angle (light grey) for $m = n - 1$ theories

- Bound state-ξ-SM decouplings are complete by TeV scale.
- If post-inflation reheating $\sim$ TeV; natural resonantly produced WDM.
- For $n = 3$ and $m = 2$: $\Lambda \sim$ TeV and $M \sim 10^4$ TeV.

Entropy Dilution from Confinement

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- ξ freeze out relic density with entropy dilution γ

$$\frac{\Omega_d}{\Omega_{\rm DM}} \simeq \frac{Y_\xi m_d s_0}{\rho_c \Omega_{\rm DM}} = \frac{1.1 \times 10^4}{g_{*s}^d \, \gamma} \left(\frac{m_d}{5 \text{ keV}} \right) ,$$

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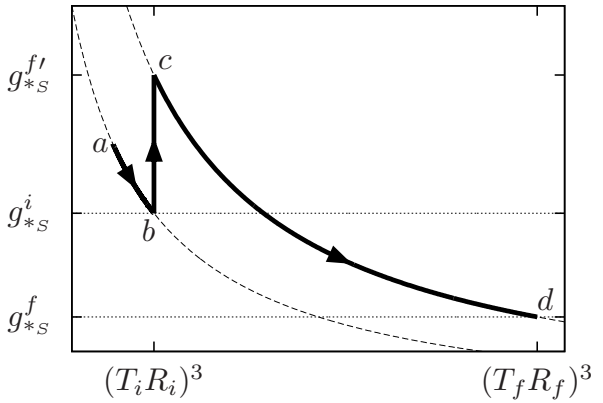
- Can choose ordering at TeV
  - ξ freeze out $\leftarrow$ Produce Ω_d
  - confinement $\leftarrow$ Source of entropy dilution γ
  - SM-bound state decoupling $\leftarrow$ Bound states and SM both warmer than DM.

Entropy Dilution from Confinement

Bounds

- Entropy production sufficient for WDM, if sudden supercooling

$$\frac{T_c}{T_i} \geq 6.3 \left(\frac{2 \times 10^2}{g^d_{*S}}\right)^{1/3} \left(\frac{m_d}{5\ \text{keV}}\right)^{1/3}$$



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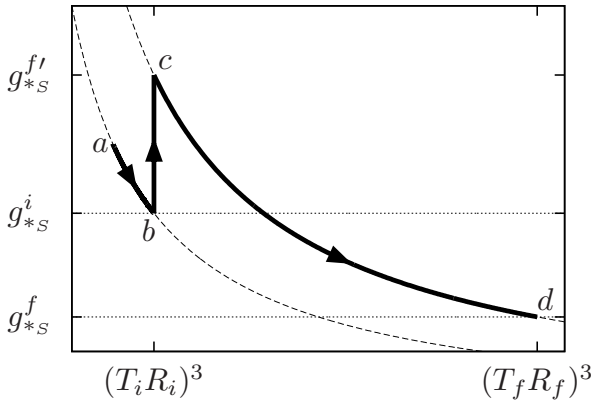

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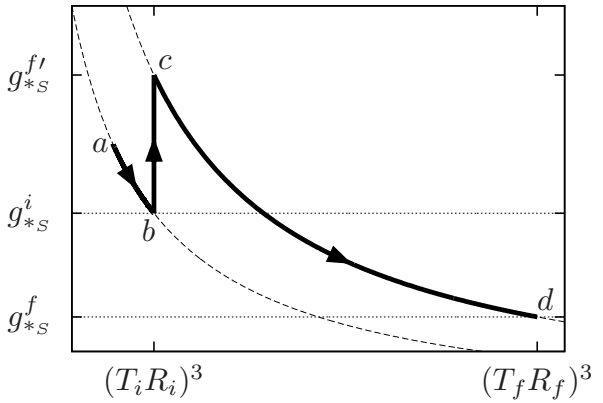

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- Lyman-α

$$m_d > 1.3 \text{ keV} \ .$$

Summary

- Active neutrinos can be light if RH neutrino is composite.
- Elementary keV sterile neutrinos with 'correct' mixing angles are natural ingredient of composite Dirac neutrino scenario.
- Could also have entropy-diluted thermal freeze out, with entropy from sudden supercooled confinement of composite neutrino sector.

Thank You!