FIMP DM at KOTO

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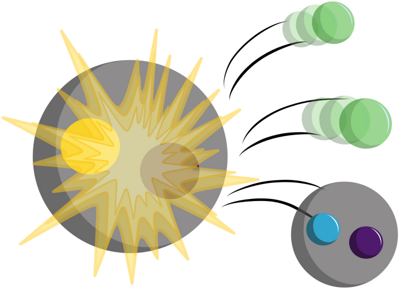
The Grossman–Nir Bound [1]

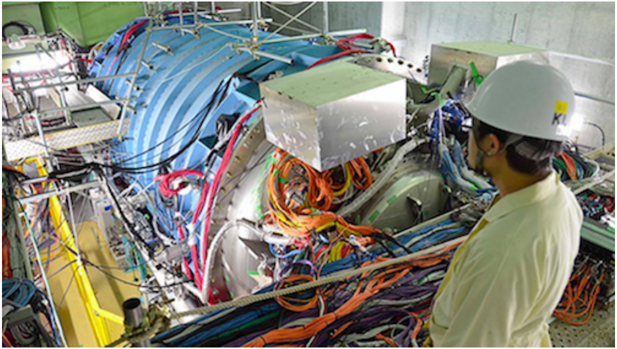
A **clean prediction** for a **clean channel**



$$\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \leq 4.3\,\mathrm{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$$

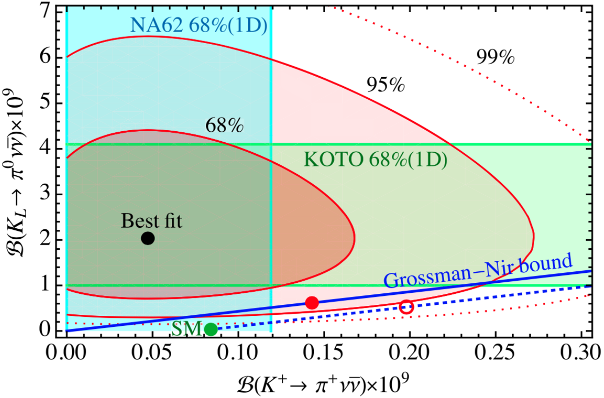
Holds in a broad class of BSM models

The KOTO experiment



The KOTO experiment

[2]



4 events $\gg 0.10 \pm 0.02$ events [3]

. . . Dark matter?

Enhancing $\mathrm{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$ is hard. But **we don't need to** if

$$\text{“}\nu\bar{\nu}\text{”} = X_1 X_2$$

New ball game: account for KOTO excess with $K_L \to \pi^0 X_1 X_2$, and suppress $K^+ \to \pi^+ X_1 X_2$ kinematically

Does a minimal model also give us dark matter?

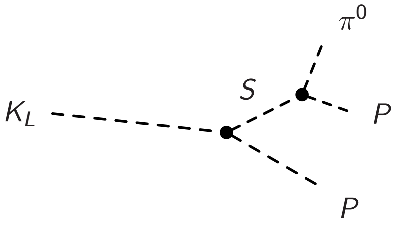
What do we need?

1. Kinematics must resemble KOTO signal
2. Choose masses and interactions to prevent K^+ decay
3. For dark matter, stability and production mechanism

A simple model

Start with an effective theory of two new particles[1]

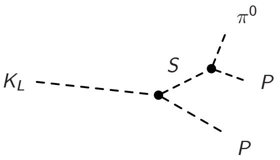
- Scalar S, pseudoscalar P with $m_{K_L} > m_S > m_{\pi^0} > m_P$



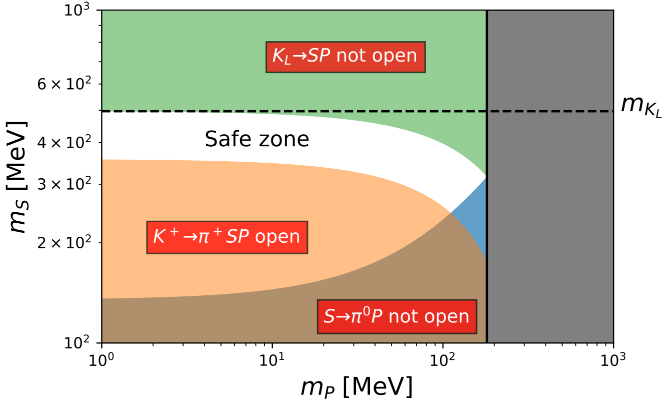
- $\mathcal{L} \supset \Lambda_{sd}^{-1} \bar{s}(i\gamma_5) dSP + \Lambda_{dd}^{-1} \bar{d}(i\gamma_5) dSP$
- No equivalent decay chain for $K^+ \to \pi^+ PP$

[1] via Maxim Pospelov

Kinematics



π^0
S
K_L
P
P

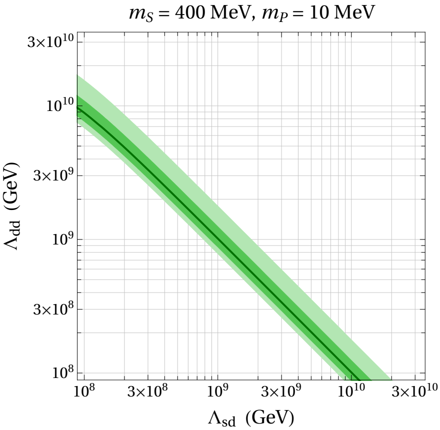


$K_L \to SP$ not open
m_{K_L}
Safe zone
$K^+ \to \pi^+ SP$ open
$S \to \pi^0 P$ not open
m_S [MeV]
m_P [MeV]

Accounting for the excess

KOTO measurement:

$\mathrm{Br}\left(K_L \to \pi^0 PP\right) \sim 2 \times 10^{-9}$

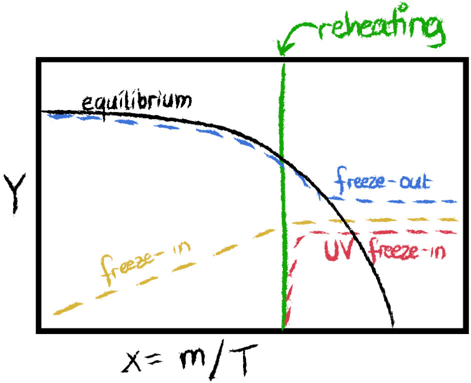


$$\mathcal{L} \supset \Lambda_{sd}^{-1}\bar{s}(i\gamma_5)dSP + \Lambda_{dd}^{-1}\bar{d}(i\gamma_5)dSP$$

Cosmological production

Scale of new physics is $\Lambda_{dd} \gg M_{\rm weak}$:
feebly interacting massive particle

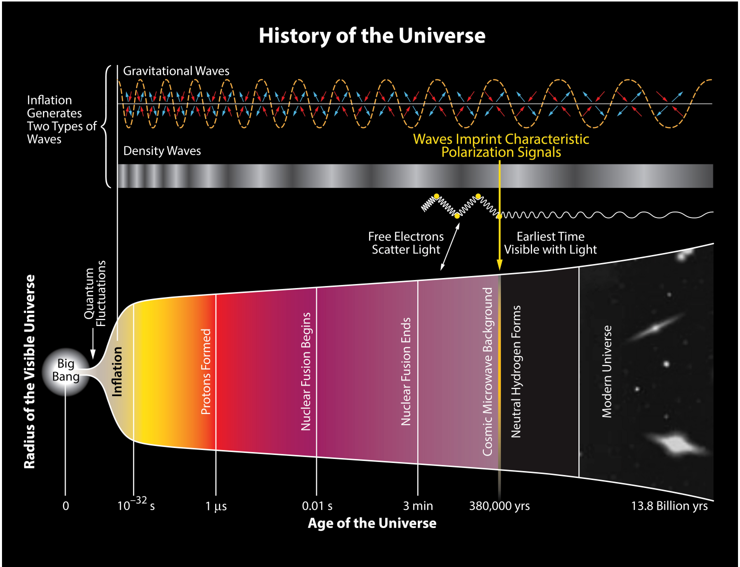
Normally, **FIMPs** freeze in



Nonrenormalizable:
UV freeze-in [4]

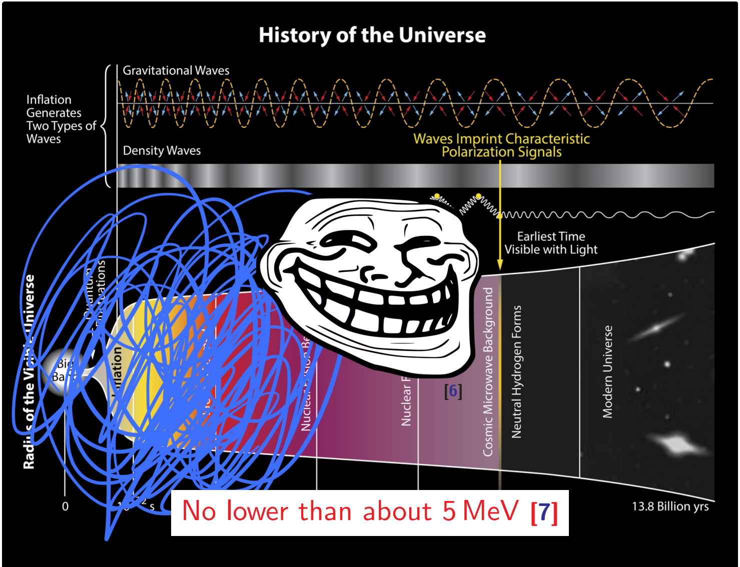
$T_{\rm RH}$ is a parameter of the model

When can reheating happen?



[5]

When can reheating happen?

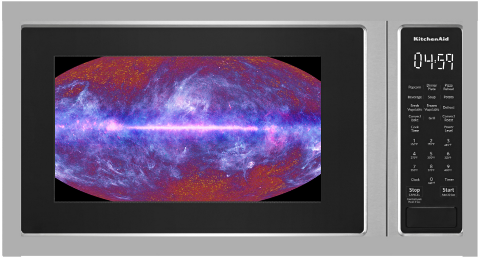


[5]

When does reheating need to happen?

$$Y(\infty) \simeq \frac{180 M_{\rm Pl}}{1.66(2\pi)^7 g_\star^{1/2} g_{\star S}} \frac{T_{\rm RH}}{\Lambda^2}$$

- For $\bar{d}d \to SP$, relic density requires $T_{\rm RH} \approx 100\,\text{MeV} < \Lambda_{\rm QCD}$



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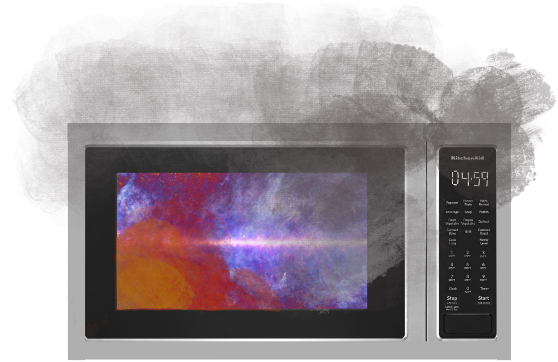
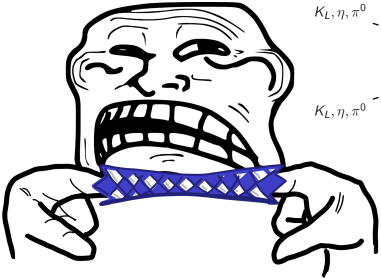
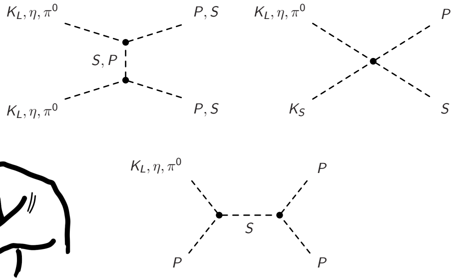
- For $\bar{d}d \to SP$, relic density requires $T_{\rm RH} \approx 100\,\text{MeV} < \Lambda_{\rm QCD}$
- Still easy to overproduce DM without any dilution mechanism



Production in the confined phase



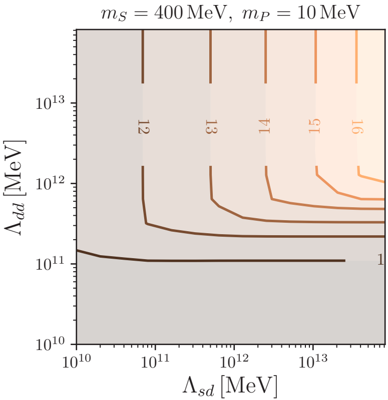


Quark-level EFT $\longrightarrow$ chiral perturbation theory

Production is now driven by *non-relativistic* mesons

$$Y(\infty) \simeq \frac{90 M_{\rm Pl}\sigma_0}{(2\pi)^{11/2} g_{\star S}} M_+^{5/2} T_{\rm RH}^{-3/2} \exp\left(-M_+ / T_{\rm RH}\right)$$

Producing all of dark matter



$$\mathcal{L} \supset \Lambda_{sd}^{-1} \bar{s}(i\gamma_5) dSP + \Lambda_{dd}^{-1} \bar{d}(i\gamma_5) dSP$$

- Max reheating temperature is logarithmic in Λ_{dd}, Λ_{sd}
- Minimal model requires a **low but safe** reheating scale
- Enlarged low-energy dark sector can allow for higher $T_{\rm RH}$

Other signatures

- X Indirect detection — *no*
- X Direct detection — *no*
- X Self-interaction — *no*
- $\sim$ New cosmology probes — *possibly*
- $\sim$ Other rare decays — *possibly*

But parameter space is already nicely boxed

Conclusions

Our goal: a minimal DM model accounting for the KOTO excess

- Easy to build and UV-complete
- Very robust DM candidate
- Non-thermal production works with late reheating

Hard to beat a golden channel.
But model already requires:

$$245\,\text{MeV} \lesssim m_S \lesssim 497\,\text{MeV}$$

Will the anomaly persist?

References

[1] Yuval Grossman and Yosef Nir. $K_L \to \pi^0 \nu \bar{\nu}$ beyond the standard model. *Phys. Lett. B*, 398:163–168, 1997. doi: 10.1016/S0370-2693(97)00210-4.

[2] Teppei Kitahara, Takemichi Okui, Gilad Perez, Yotam Soreq, and Kohsaku Tobioka. New physics implications of recent search for $K_L \to \pi^0 \nu \bar{\nu}$ at KOTO. *Phys. Rev. Lett.*, 124(7):071801, 2020. doi: 10.1103/PhysRevLett.124.071801.

[3] S. Shinohara. Search for the rare decay $K_L \to \pi^0 \nu \bar{\nu}$ at J-PARC KOTO experiment. Talk at KAON2019, 2019.

[4] Fatemeh Elahi, Christopher Kolda, and James Unwin. UltraViolet Freeze-in. *JHEP*, 03:048, 2015. doi: 10.1007/JHEP03(2015)048.

[5] BICEP2 Collaboration. http://bicepkeck.org/visuals.html.

[6] Carlos Ramirez. https://www.deviantart.com/whynne/art/Comic-Trolls-98357844, 2008.

[7] Steen Hannestad. What is the lowest possible reheating temperature? *Phys. Rev. D*, 70:043506, 2004. doi: 10.1103/PhysRevD.70.043506.

[8] Koji Ishiwata, Zoltan Ligeti, and Mark B. Wise. New Vector-Like Fermions and Flavor Physics. *JHEP*, 10:027, 2015. doi: 10.1007/JHEP10(2015)027.

[9] George W. S. Hou. Loophole in $K \to \pi \nu \bar{\nu}$ Search & $K_L \to \pi^0 \nu \bar{\nu}$ Beyond Grossman-Nir Bound. *J. Phys. Conf. Ser.*, 800(1):012024, 2017. doi: 10.1088/1742-6596/800/1/012024.

[10] Cover image: https://space.desktopnexus.com/wallpaper/1096729/ and https://commons.wikimedia.org/wiki/File:Japanese_Koto.jpg.


Hidden sector
Now with extra slides!

Possibilities in the UV

Vector-like quarks [e.g. 8, 9]

$$\mathcal{L} \supset g_{QD}\bar{Q}DH + g_{Qq}\bar{Q}q(S+P) + g_{Dd}\bar{D}d(S+P)$$

(schematic)

- $\Lambda_{dd} \sim \Lambda_{sd} \sim M^2_{Q,D}/v$
- Additional interactions constrained by P stability
- Gives rise to effective $\bar{d}dPP$ interaction useful for direct detection!

New Higgs with no vev

$$\mathcal{L} \supset g_{dd}H_{\rm BSM}\bar{d}d + g_{sd}H_{\rm BSM}\bar{s}d + H^\dagger_{\rm BSM}H_{\rm SM}SP$$

(schematic)

- Very simple extension of the SM
- No mixing of S, P with Higgs: P is stable
- Kaon mixing constraints from $(\bar{s}d)^2$ interaction

ChiPT Lagrangian

$$\mathcal{L}_{\text{chiPT}}/(Bv_h) \supset \sqrt{2} f_\pi g_{sd} \Lambda_{sd}^{-1} M_s^{-1} K_L^0 SP + \sqrt{\frac{2}{3}} f_\pi g_{dd} \Lambda_{dd}^{-1} M_d^{-1} \eta SP$$
$$- \sqrt{2} f_\pi g_{dd} \Lambda_{dd}^{-1} M_d^{-1} \pi^0 SP + i \left(\frac{1}{\sqrt{3}} - \frac{1}{\sqrt{8}} \right) g_{sd} \Lambda_{sd}^{-1} M_s^{-1} \eta K_S^0 SP$$
$$- i g_{sd} \Lambda_{sd}^{-1} M_s^{-1} \pi^0 K_S^0 SP + 2i g_{dd} \Lambda_{dd}^{-1} M_d^{-1} K_L^0 K_S^0 SP.$$

$$i\mathcal{M}(H_1 H_2 \to \chi\chi) = -g_{H_1 SP} g_{H_2 SP} \left((t - m_{\chi'}^2)^{-1} + (u - m_{\chi'}^2)^{-1} \right)$$
$$i\mathcal{M}(H_1 K_S^0 \to SP) = -i g_{H_1 K_S^0 SP}$$
$$i\mathcal{M}(H_1 P \to PP) = -\frac{g_{H_1 SP} g_{SPP}}{s - m_S^2}$$

$$\begin{cases} g_{K_L^0 SP} = \sqrt{2} B v_h f_\pi g_{sd} \Lambda_{sd}^{-1} M_s^{-1}, \\ g_{\eta SP} = \sqrt{\frac{2}{3}} B v_h f_\pi g_{dd} \Lambda_{dd}^{-1} M_d^{-1}, \\ g_{\pi^0 SP} = -\sqrt{2} B v_h f_\pi g_{dd} \Lambda_{dd}^{-1} M_d^{-1}, \end{cases} \qquad \begin{cases} g_{K_L^0 K_S^0 SP} = 2i B v_h g_{dd} \Lambda_{dd}^{-1} M_d^{-1}, \\ g_{\eta K_S^0 SP} = i \left(\frac{1}{\sqrt{3}} - \frac{1}{\sqrt{8}} \right) B v_h g_{sd} \Lambda_{sd}^{-1} M_s^{-1}, \\ g_{\pi^0 K_S^0 SP} = -i B v_h g_{sd} \Lambda_{sd}^{-1} M_s^{-1}. \end{cases}$$