FLAVORS OF DARK MATTER

In honor of Ernest Ma's retirement

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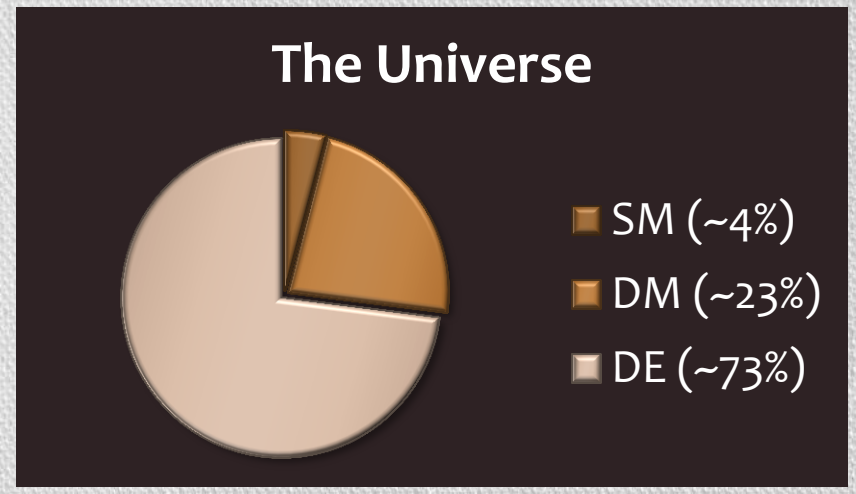
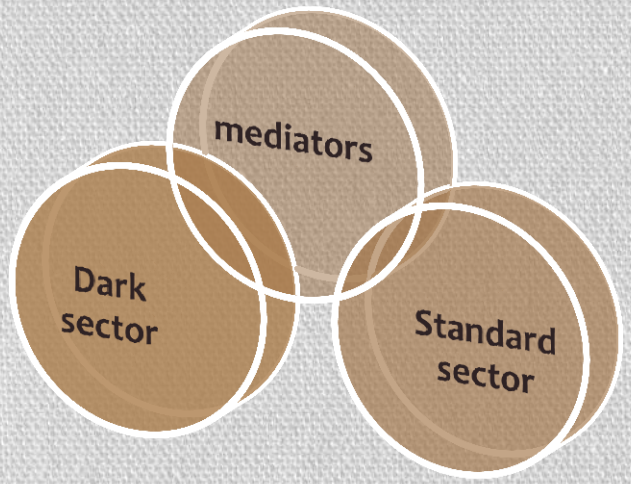
DM paradigm





Assumptions:

- standard & dark sectors interact via the exchange of heavy mediators
- DM stabilized against decay by some symmetry G_{DM}
- SM particles: G_{DM} singlets
- Dark particles: G_{SM} singlets
- Weak coupling

Effective theory of DM-SM interactions

Within the paradigm:

$$\mathcal{L}_{\text{eff}} \sim \frac{1}{M^k}\mathcal{O}_{SM} \times \mathcal{O}_{DM}$$

Mediator mass

Leading interactions:

Lowest dimension (smallest M suppression)

Tree generated (no loop suppression factor)

Leading interactions (dim ≤ 6)

Simplifications:

- Scalar or fermions mediators
- Leading observable effects (≤ 1 loops)

dim.	
4	$\lvert\phi\rvert^2(\Phi^\dagger\Phi)$
5	$\lvert\phi\rvert^2\bar{\Psi}\Psi, \quad (\bar{\Psi}\Phi)(\phi^T\epsilon\ell)$
6	$\lvert\phi\rvert^2\bar{\Psi}\Phi\Psi', \ \lvert\phi\rvert^2 X_{\mu\nu}^2, \ \Phi^2\bar{\psi}\phi\psi', \ \Phi^2 B_{\mu\nu}^2, \ \Phi^2(W_{\mu\nu}^I)^2$ $J_{\rm SM}^{(i)} \cdot J_{\rm dark}^{(a)} \ (i = \ell, \phi; \ a = \Phi, L, R)$

H portal

ν portal

Where:

Dark Side

- Φ — scalars
- Ψ — fermions
- X — vectors

SM:

- ϕ — scalar isodoublet
- l — left-handed lepton isodoublet
- ψ — fermion
- B — $U(1)_Y$ gauge field
- W — $SU(2)_L$ gauge fields

and

$$J_{\rm SM}^{(\psi)\,\mu} = \bar{\psi}\gamma^\mu\psi\,, \qquad J_{\rm SM}^{(\phi)\,\mu} = \frac{1}{2i}\phi^\dagger \overleftrightarrow{D^\mu}\,\phi\,,$$

$$J_{\rm dark}^{(L,R)\,\mu} = \bar{\Psi}\gamma^\mu P_{L,R}\Psi \qquad J_{\rm dark}^{(\Phi)\,\mu} = \frac{1}{2i}\Phi^\dagger \overleftrightarrow{\mathcal{D}^\mu}\,\Phi$$

Effective Lagrangian

Integrate all modes with energies > $\Lambda = \omega$ (mediator) mass

$$\mathcal{L}_{\rm eff}^{(\omega)} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm dark} + c_{\rm I}|\phi|^2|\Phi|^2 + \mathcal{L}^{(\omega-{\rm tree})} + \mathcal{L}^{(\omega-{\rm loop})}$$

Tree generated: from integrating the ω

Loop-generated from integrating out

- Dark modes with energies > Λ
- SM modes with energies > Λ
- The mediators

Neutrino portal scenario

Dark sector: at least Φ & Ψ

Fermion mediators (Dirac)

Ignored subleading effects

$$\mathcal{L}^{(\mathcal{F}-\text{tree})} = \frac{c_{\text{III}}}{\Lambda}(\bar{\Psi}\Phi)(\tilde{\phi}^\dagger \ell) + \cdots$$

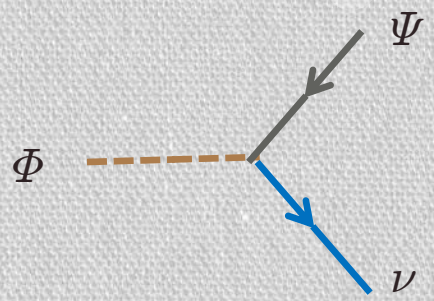
$$\mathcal{L}^{(\mathcal{F}-\text{loop})} = \frac{c_{\text{II}}}{16\pi^2\Lambda}|\phi|^2\bar{\Psi}\Psi + \sum_{a=\ell\,\phi;\, i=L,R,\Phi} \frac{c_{\text{VII}}^{(a|i)}}{(4\pi\Lambda)^2}\left(J_{\text{SM}}^{(a)} \cdot J_{\text{dark}}^{(i)}\right)$$

H – DM coupling

Z – DM coupling

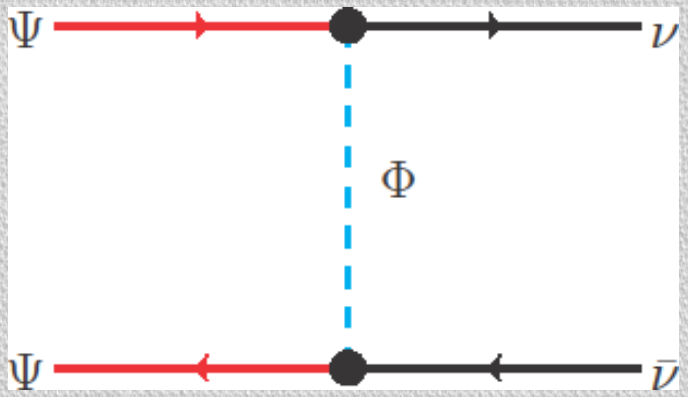
Assume: $m_{\Phi} > m_{\Psi} \Rightarrow$ all Φ's have decayed: fermionic DM.

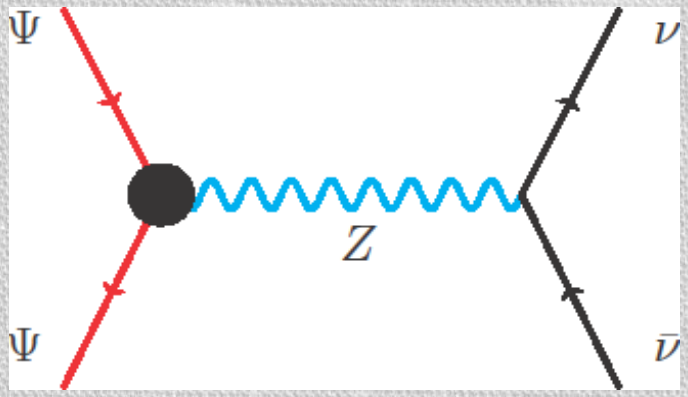
$$(\bar{\ell}\tilde{\phi})(\Phi^{\dagger}\Psi) \rightarrow \frac{v}{\sqrt{2}}\bar{\nu}_L\Phi^{\dagger}\Psi$$

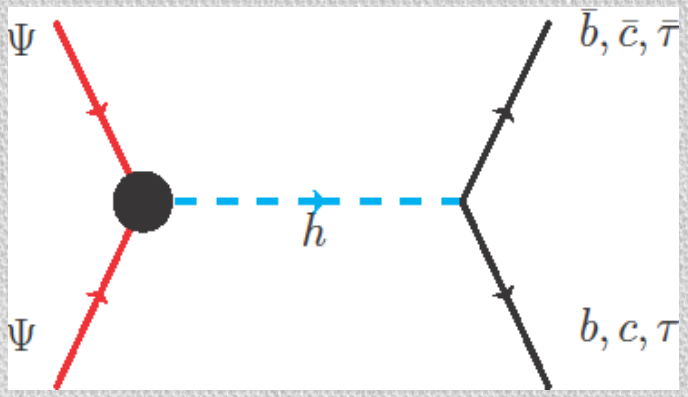


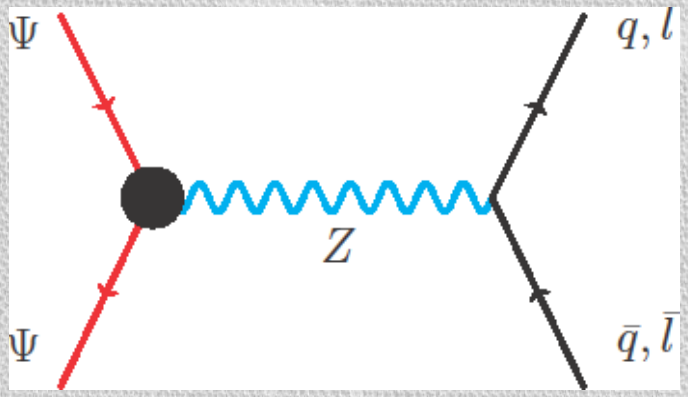
Relic abundance

Main processes (Z and H exchanges: 1 loop $\Rightarrow$ important on resonance)

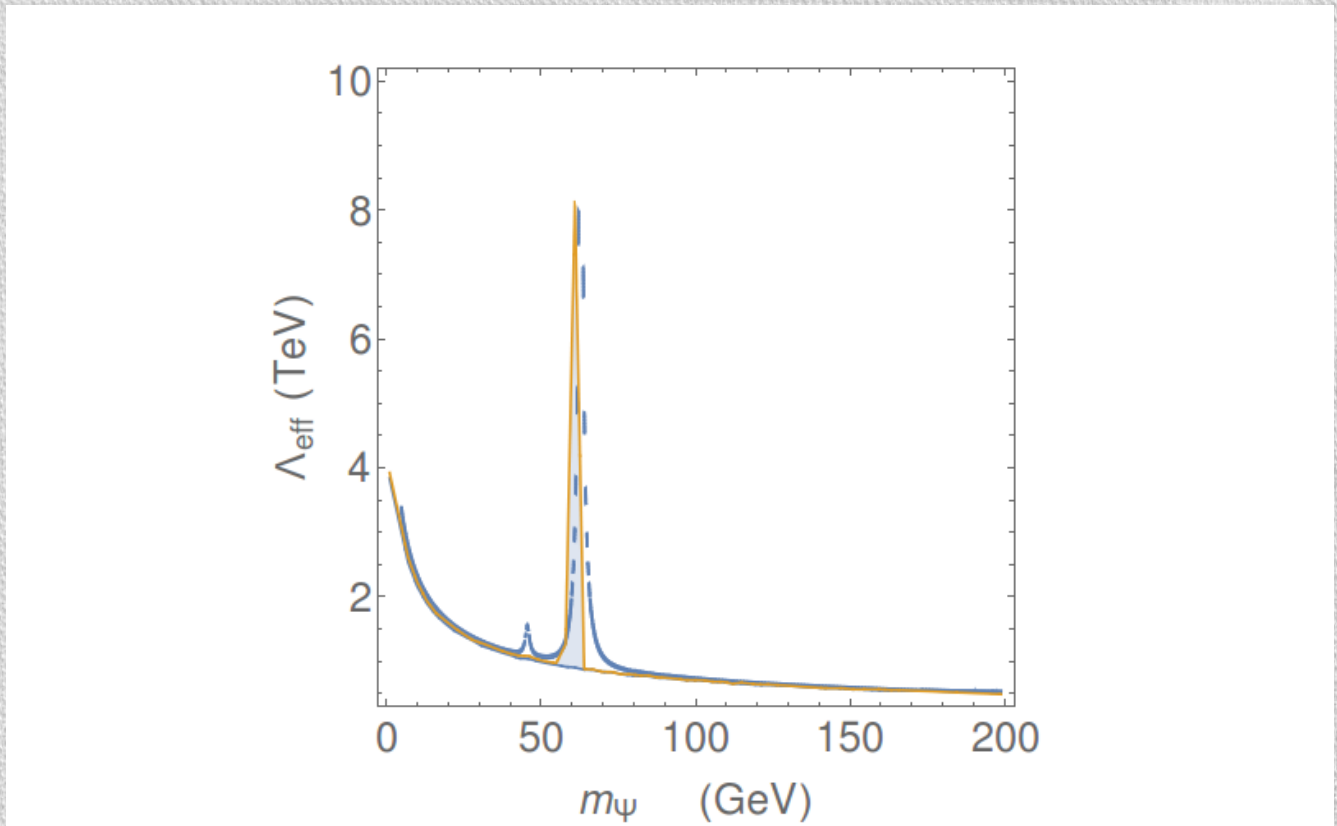








Constraint: - $\Omega_{\text{Planck}} h^2 = 0.1198 \pm 0.0026 \quad (3\,\sigma)$

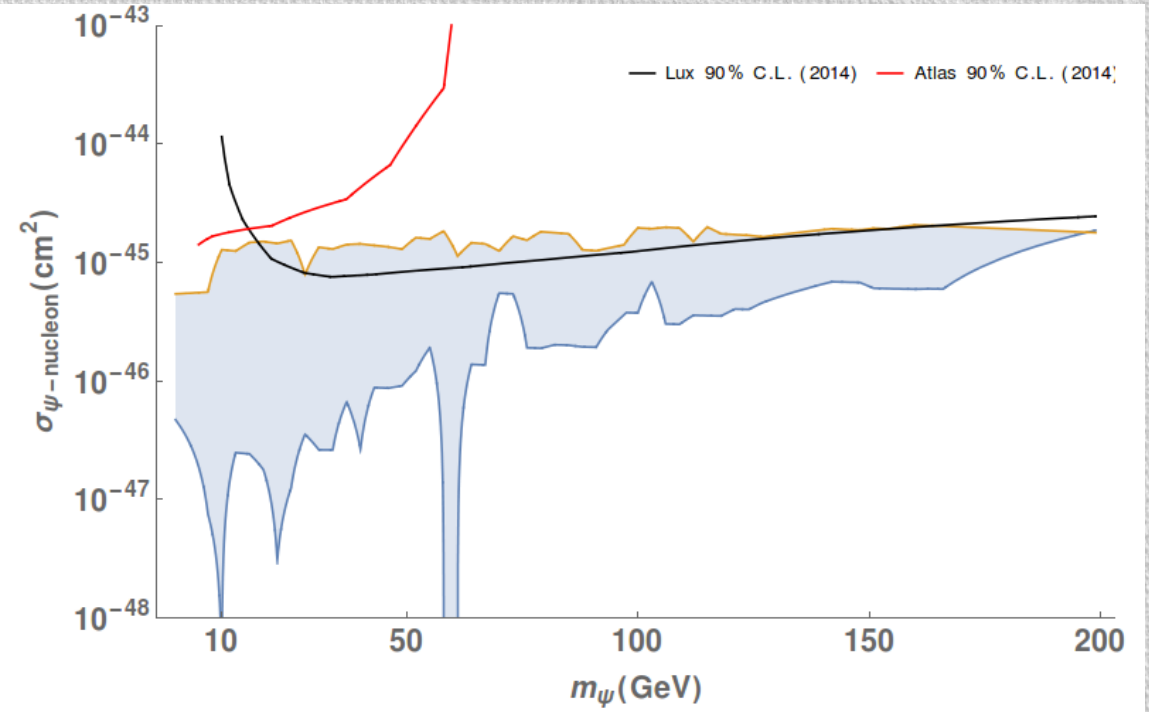


$$\Lambda_{\text{eff}} = \sqrt{1 + \frac{m_\Phi^2}{m_\Psi^2}\frac{\Lambda}{c_{\text{III}}}} \simeq \sqrt{\frac{m}{m_\Psi}}\,\text{TeV}; \quad m \simeq 74\text{GeV} \quad \text{(non-resonant region)}$$

Direct detection

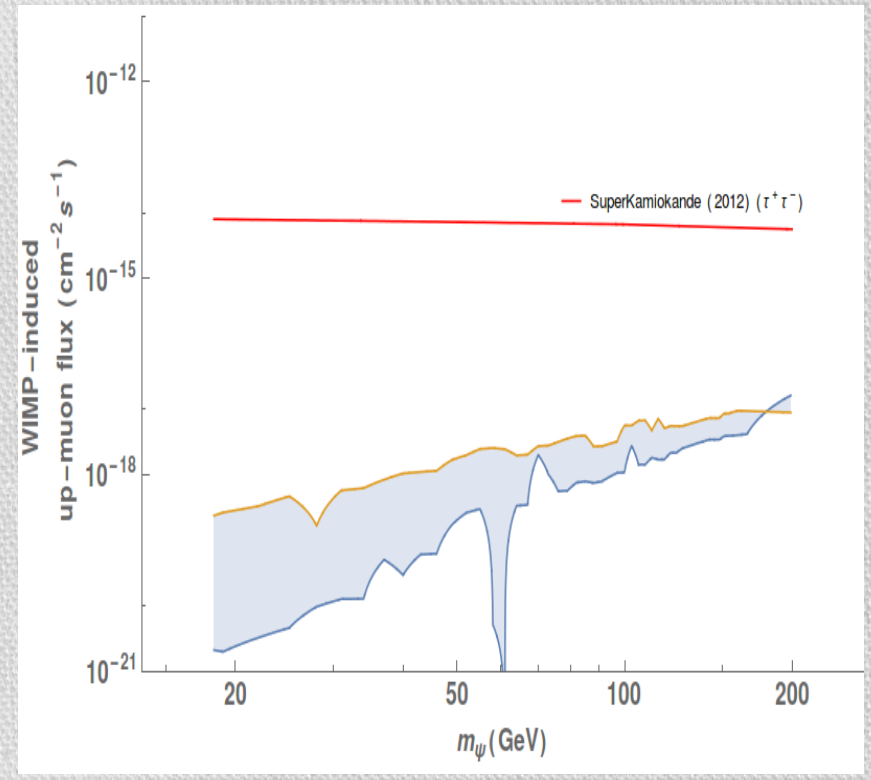
Main processes Z and H exchanges: 1 loop $\Rightarrow$ naturally suppressed

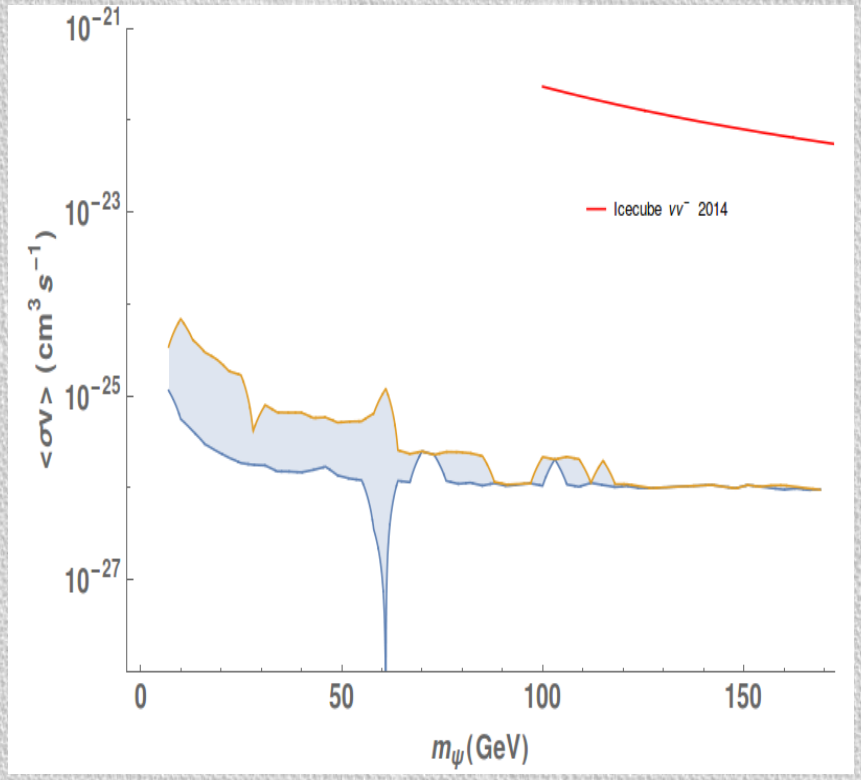
$$\mathcal{L}^{(\mathcal{F}-\text{loop})} \supset \frac{v c_{\text{II}}}{16\pi^2\Lambda} H\bar{\Psi}\Psi - \frac{g}{2c_{\text{w}}}\frac{v^2}{16\pi^2\Lambda^2}\bar{\Psi}\not{Z}\left(c_{\text{VII}}^{(\phi|L)}P_L + c_{\text{VII}}^{(\phi|R)}P_R\right)\Psi$$



Indirect detection

- No significant $\gamma\gamma$ signal
- Interesting $\nu\nu$ monochromatic signal @ E = m_{Ψ}
- Not enough experimental sensitivity





UV completion

Add neutral Dirac fermions ***N*** to the SM (the mediators):

$$\mathcal{L} = \bar{N}(i\,\partial\!\!\!/ - m_o)N + (y\,\bar{\ell}\tilde{\phi}N + \mathrm{H.c}) + (z\bar{N}\Phi^\dagger\Psi + \mathrm{H.c})$$

Mass eigentsates: $\boldsymbol{n_L}$ (mass=0), and $\boldsymbol{\chi}$ (mass=***M***)

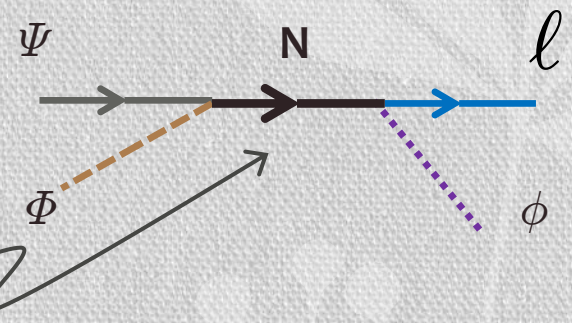
$$N = -s_\theta\, n_L + (c_\theta P_L + P_R)\chi\,, \qquad \nu = c_\theta\, n_L + s_\theta\, \chi_L$$

$$\tan\theta = yv/m_o\,; \quad \Lambda = \sqrt{m_o^2 + (yv)^2}$$

(easy to generate a Majorana mass for the $\boldsymbol{n_L}$: add one for the ***N***

~ inverse see-saw)

Effective couplings:



$$\mathcal{L}^{(\mathcal{F}-\text{tree})} \supset \frac{c_{\text{III}}}{\Lambda}(\bar{\Psi}\Phi)(\tilde{\phi}^\dagger \ell)$$

$$\mathcal{L}^{(\mathcal{F}-\text{loop})} \supset \frac{v c_{\text{II}}}{16\pi^2\Lambda} H\bar{\Psi}\Psi - \frac{g}{2c_{\text{w}}}\frac{v^2}{16\pi^2\Lambda^2}\bar{\Psi}\not{Z}\left(c_{\text{VII}}^{(\phi|L)}P_L + c_{\text{VII}}^{(\phi|R)}P_R\right)\Psi$$

where

$$\begin{aligned} c_{\text{III}} &= \sqrt{2}\,y\,z \\ c_{\text{II}} &= -c_{\text{III}}^2 - 2z^2 c_{\text{I}} \ln\left(\frac{\Lambda}{m_\Phi}\right) \end{aligned}$$

$$\begin{aligned} c_{\text{VII}}^{(\phi|L)} &= \frac{1}{2}c_{\text{III}}^2 \\ c_{\text{VII}}^{(\phi|R)} &= \frac{1}{2}c_{\text{III}}^2 \ln\left(\frac{\Lambda}{m_\Phi}\right) \end{aligned}$$

End matters

- Neutrino portal scenario works quite well, but difficult to confirm.
- Collider constraints mainly from H and Z invisible widths: weak
- The clearest signature: monochromatic neutrino line

- Other flavors of dark-standard interactions besides Higgs and neutrino portals might also be of interest. For example

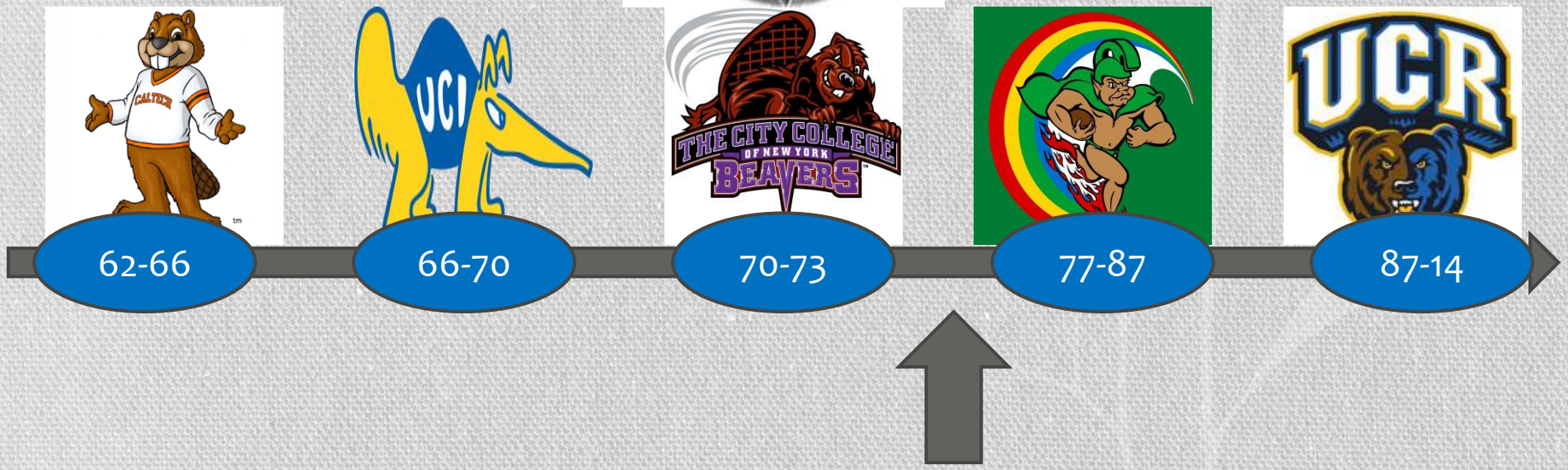
$$B_{\mu\nu}\,\Phi\,X^{\mu\nu} \qquad B_{\mu\nu}\,\Psi\,\sigma^{\mu\nu}\,\Psi$$

(in the second the DM symmetry could be a non-Abelian gauge one with Φ in the adjoint representation)

Ernest ma

441 papers
14119 citations

2 papers w > 500 citations
5 papers w > 250 citations
27 papers w > 100 citations



What happened here?

The ‘lost’ years

Explored the Amazon

Climbed the Everest

Discovered Atlantis

And took-up extreme surfing

… briefly

From Sandip Pakvasa

Dear Ernest:

Congratulations on your retirement!

I suppose this is not going to slow down the steady flow of ideas and papers from you. In fact, now that you will have even more time to devote to research, it might accelerate!

I am sorry Heide and I could not be there on this occasion to welcome you to this new life!

Best wishes

Sandip

From G Rajasekaran

I know Ernest for more than 25 years, but my association with him became closer only after I started visiting him at UCR almost every summer starting from the late 90's. We began to collaborate on neutrino masses and mixing and build models thereof. It proved to be a very fruitful and long-lasting collaboration. I can count more than ten papers. In all the papers one can see the hallmark of Ernest. The brevity and terseness of language... almost reaching the Dirac limit: not a single extra word anywhere!

In almost all of our collaborations, the story is the same. We start discussing an idea. I try to work out the details in my own way, but before I go far, Ernest has either thrown away the idea or has completed the construction of the full model and the calculations and has sent the draft to me for my comments.

Usually the paper is short, but contains the idea and the full model and the predictions that follow from the model. Of course, enough attention is paid to check that the model does not contradict any known data. Ernest is a Master Model Builder. During his career he has constructed a wide variety of models each exhibiting his ingenuity and skill as a model builder. Surely Nature must have used one or more of his models in designing this Universe and hopefully experiments will reveal it soon.

During these years I have learnt a lot of physics not only through the collaboration but also from his single- author papers, many of which are masterpieces.

Ernest's unbounded enthusiasm and infinite capacity for hard work have led to the large number of collaborations with physicists from all parts of the world. This is a major contribution to world science and I salute him for that.

I wish Ernest a long, happy, healthy and active life.


I'm Retired,
You're Not -
Nah-nah-nah-
nah-nah....