Perturbative Unitarity in the Dark Sector

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Based on 1412.5660, 1501.03153, and ongoing work with Matthew Cahill-Rowley, Sonia El-Hedri, and Devin Walker

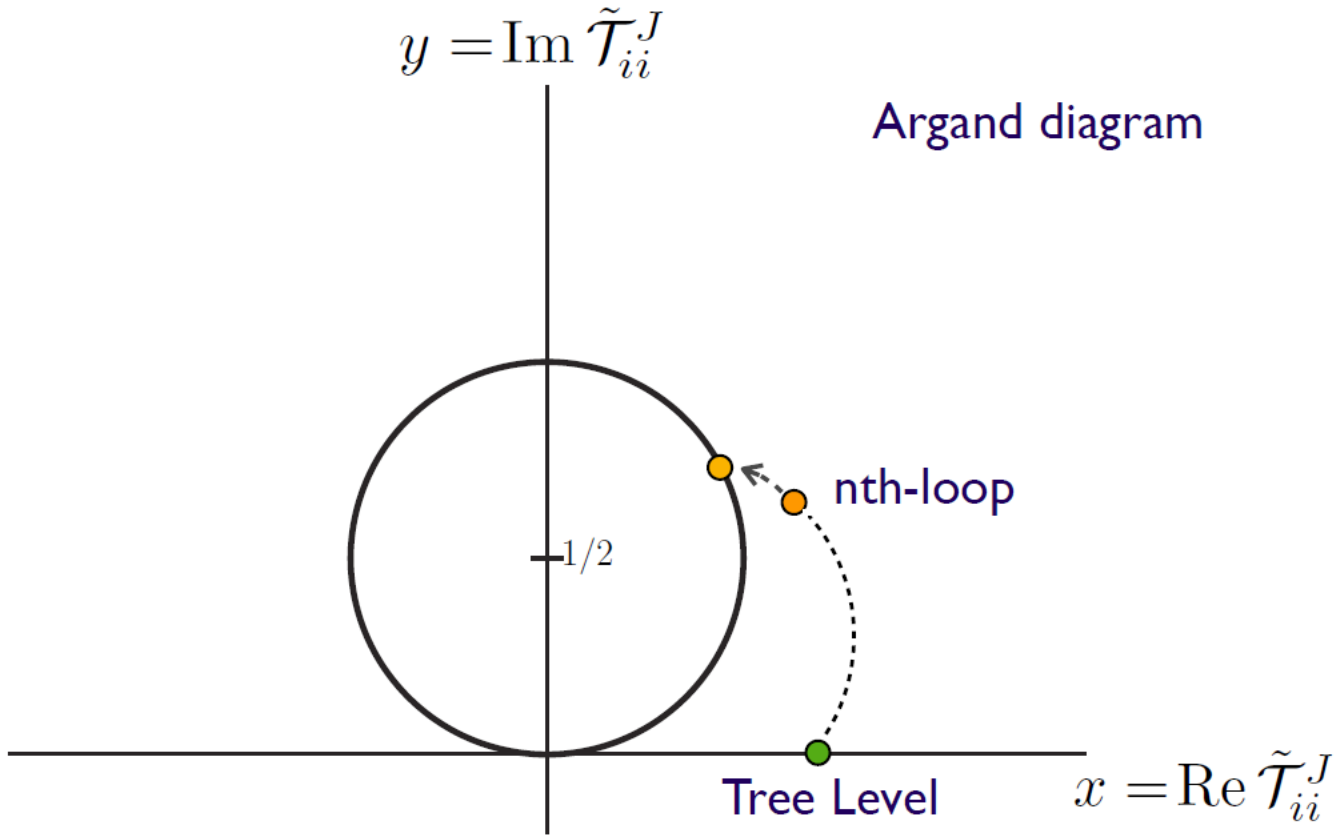
The Scale of New Physics

- Historically in HEP, we've often known where we were going
  - Fermi theory of weak decays needed new bosons
  - Precision measurements pointed to the top quark
  - Heavy bosons needed symmetry breaking
- After the Higgs discovery, we have no map
  - The Standard Model is stubbornly good
- Where are we going, and how far away is it?

The Scale of New Physics

- Naturalness
  - The Higgs mass is subject to corrections from new physics, these corrections are potentially huge
  - The SM as a UV theory requires cancellations in these corrections to 1 part in $10^{\sim 30}$
  - New symmetry could enforce this if it happens low enough, but bounds on scale depend on amount of tuning deemed acceptable
- New Phenomena
  - Neutrino masses need at least the Weinberg operator, but that can be at scales far beyond what we'll see
  - Dark matter is the other new particle we need experimentally

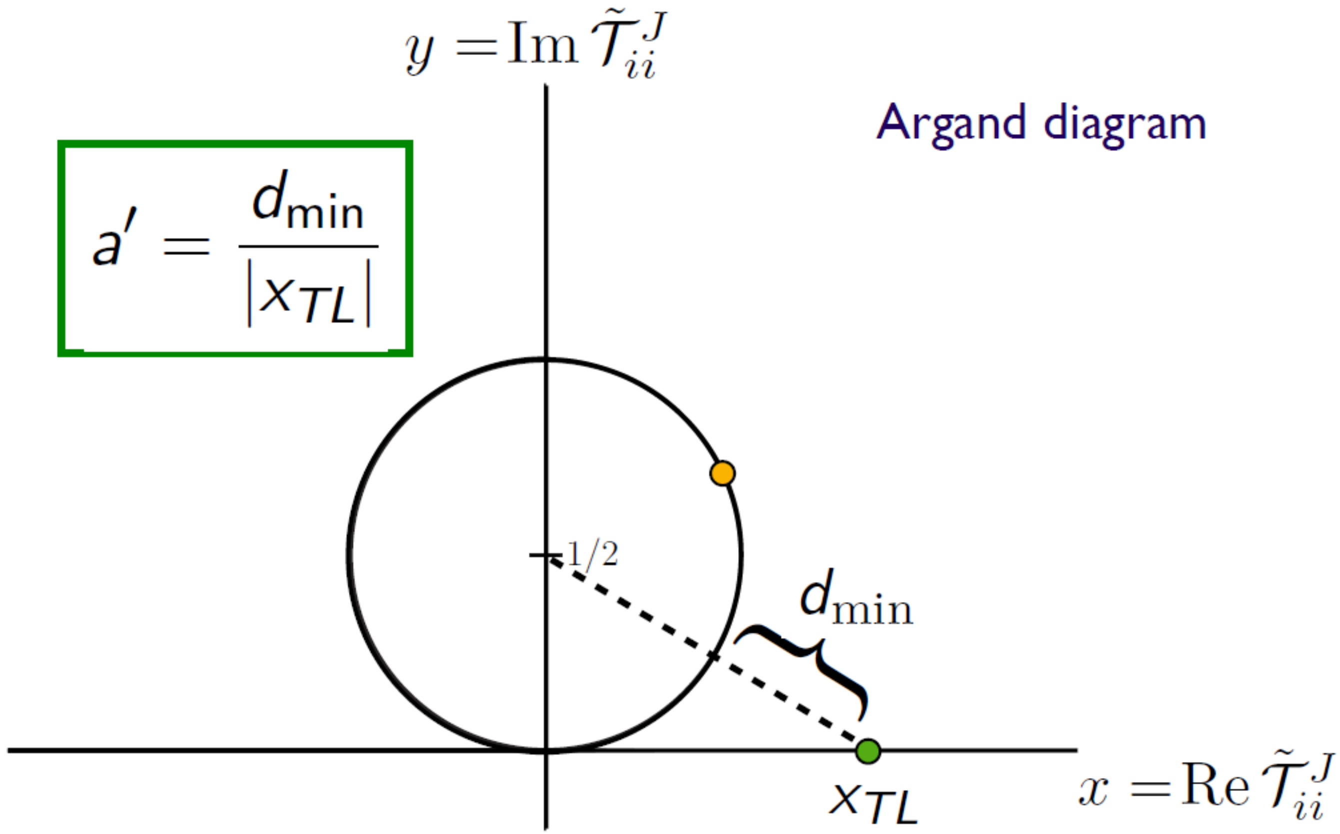
A Picture of Unitarity



Schuessler and Zeppenfeld 0710.5175
Aydemir, Anber, Donoghue 1203.5153

A Picture of Unitarity

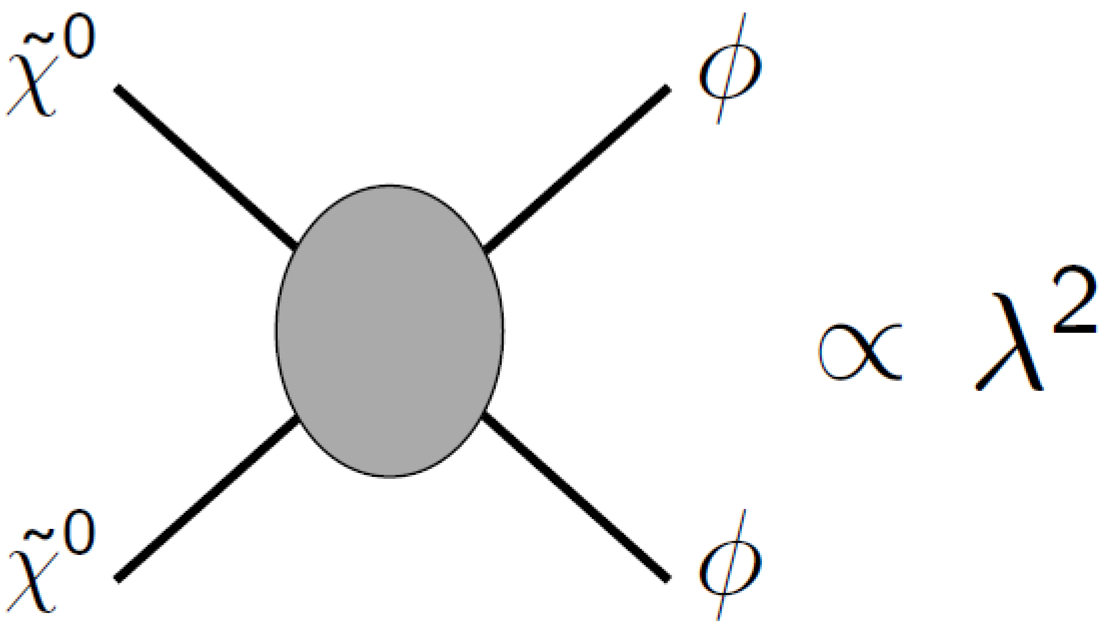
$$a' = \frac{d_{\min}}{|x_{TL}|}$$



Schuessler and Zeppenfeld 0710.5175

Unitarity and Dark Matter

- By insisting on unitarity in a general dark matter scenario, we can bound dark matter to be lighter than 120 TeV for coupling below 4π



Griest and Kamionkowski, 1990

Gauge Portal Dark Matter

- This model is characterized by the Lagrangian

$$\mathcal{L}_{DM} \supset g' \bar{\chi}\gamma^\mu\gamma_5 Z'_\mu \chi - \lambda_\chi \bar{\chi}\Phi\chi$$

$$\mathcal{L}_{gauge} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{\sin\delta}{2}Z'_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{L}_{Higgs} \supset |D_\mu\Phi|^2 + V(H,\Phi;\lambda_1,\lambda_2,\lambda_3)$$

- With breaking of the new symmetry by

$$\Phi = \frac{1}{\sqrt{2}}(\mathbf{u} + \phi^0)$$

Babu, Kolda, March-Russell hep-ph/9710441

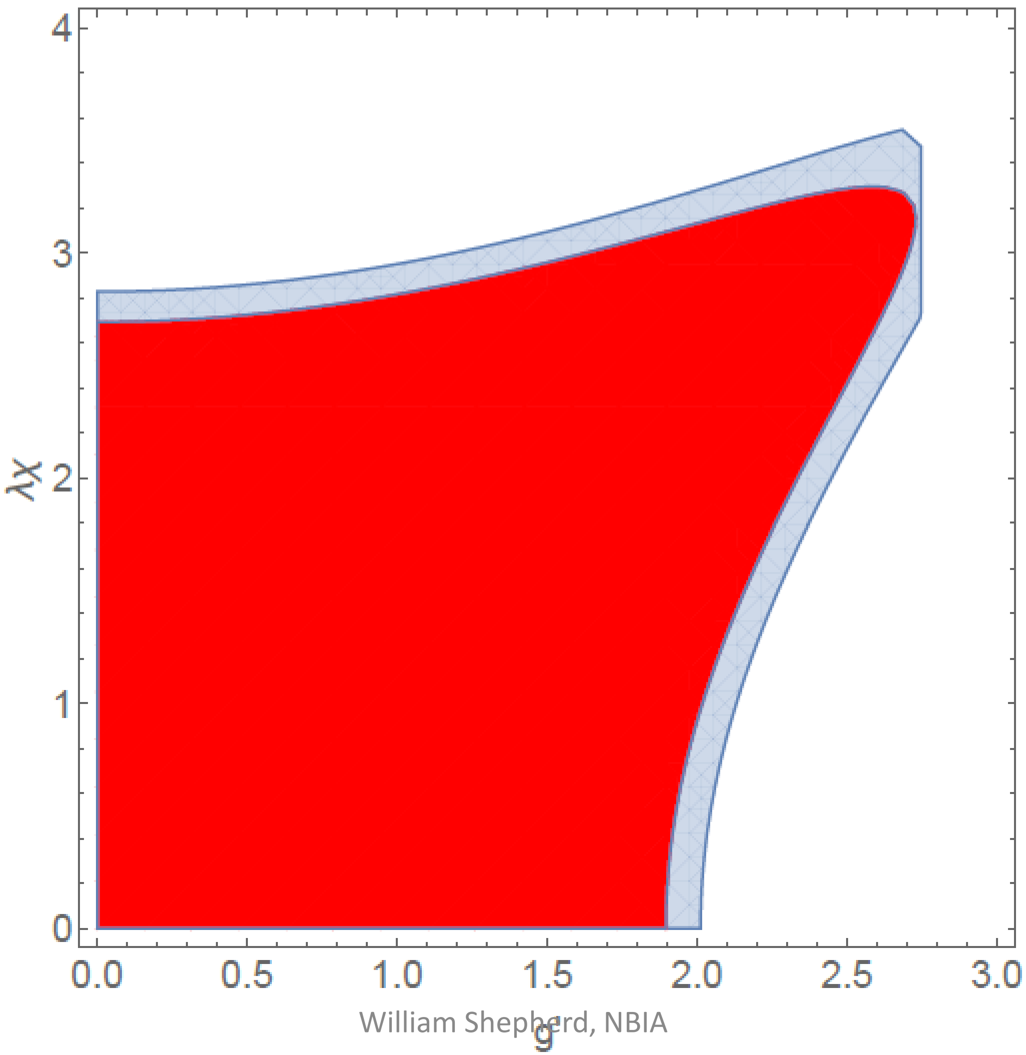
Gauge Portal Dark Matter

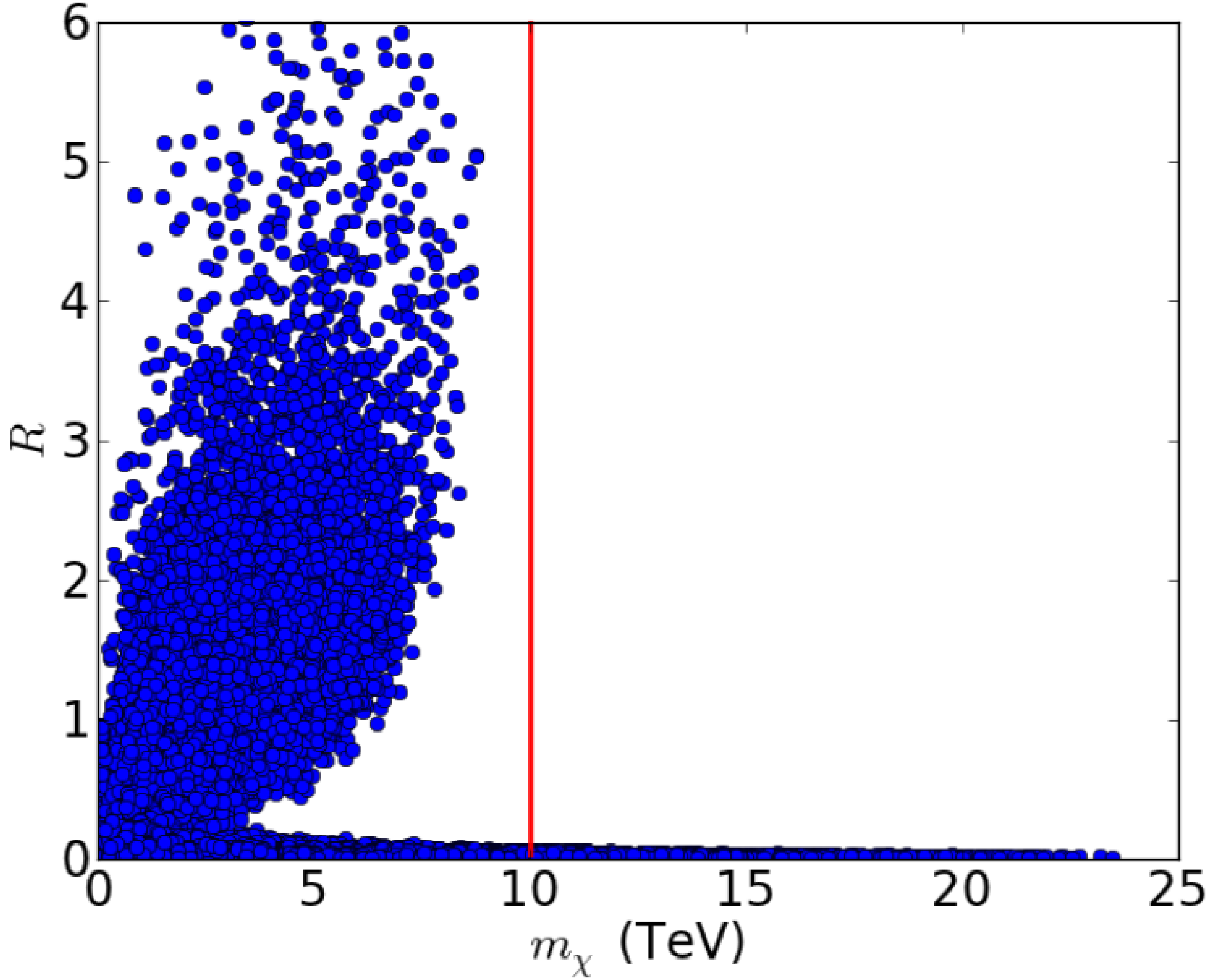
- This gives us 6 parameters and 1 new scale:

$$g', \lambda_\chi, \lambda_1, \lambda_2, \lambda_3, \sin\delta, \mathbf{u}$$

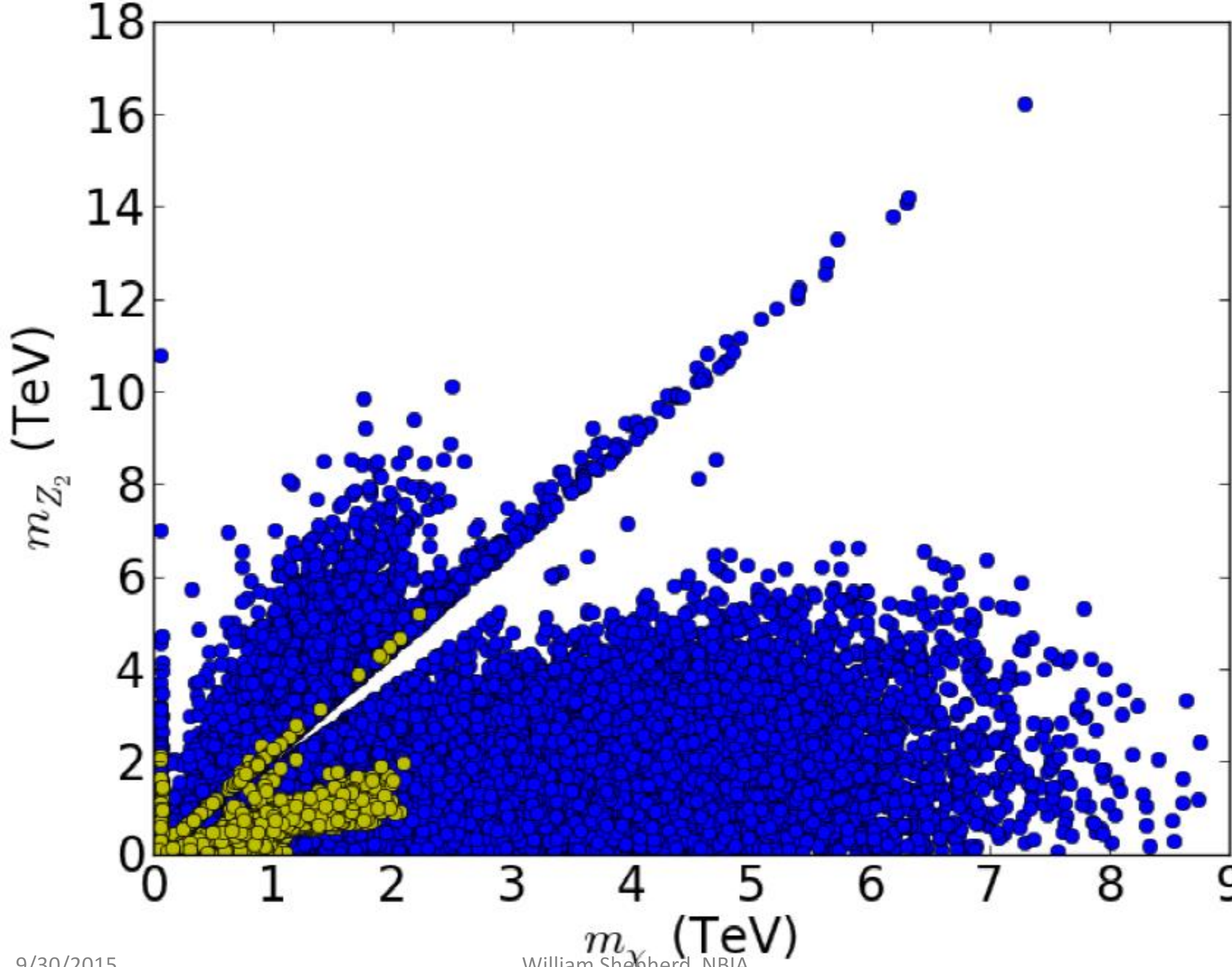
- The dimensionless couplings can be constrained directly from unitarity, but only ratios of scales can be constrained
- Here, the annihilation rate will set upper bounds on the scale of symmetry breaking

Dark Matter Coupling Bounds





$$R = \min\left\{ \frac{|m_{DM} - m_{Z'}|}{m_{DM}}, \frac{|m_{DM} - m_{\phi^0}|}{m_{DM}} \right\}$$


18
16
14
12
10
8
6
4
2
0
m_{Z_2} (TeV)
0
1
2
3
4
5
6
7
8
9
m_χ (TeV)

Colored Scalars and Dark Matter

- In a SUSY-inspired model, we add

$$\tilde{u}_R = (\tilde{u}_R, \tilde{c}_R, \tilde{t}_R)$$

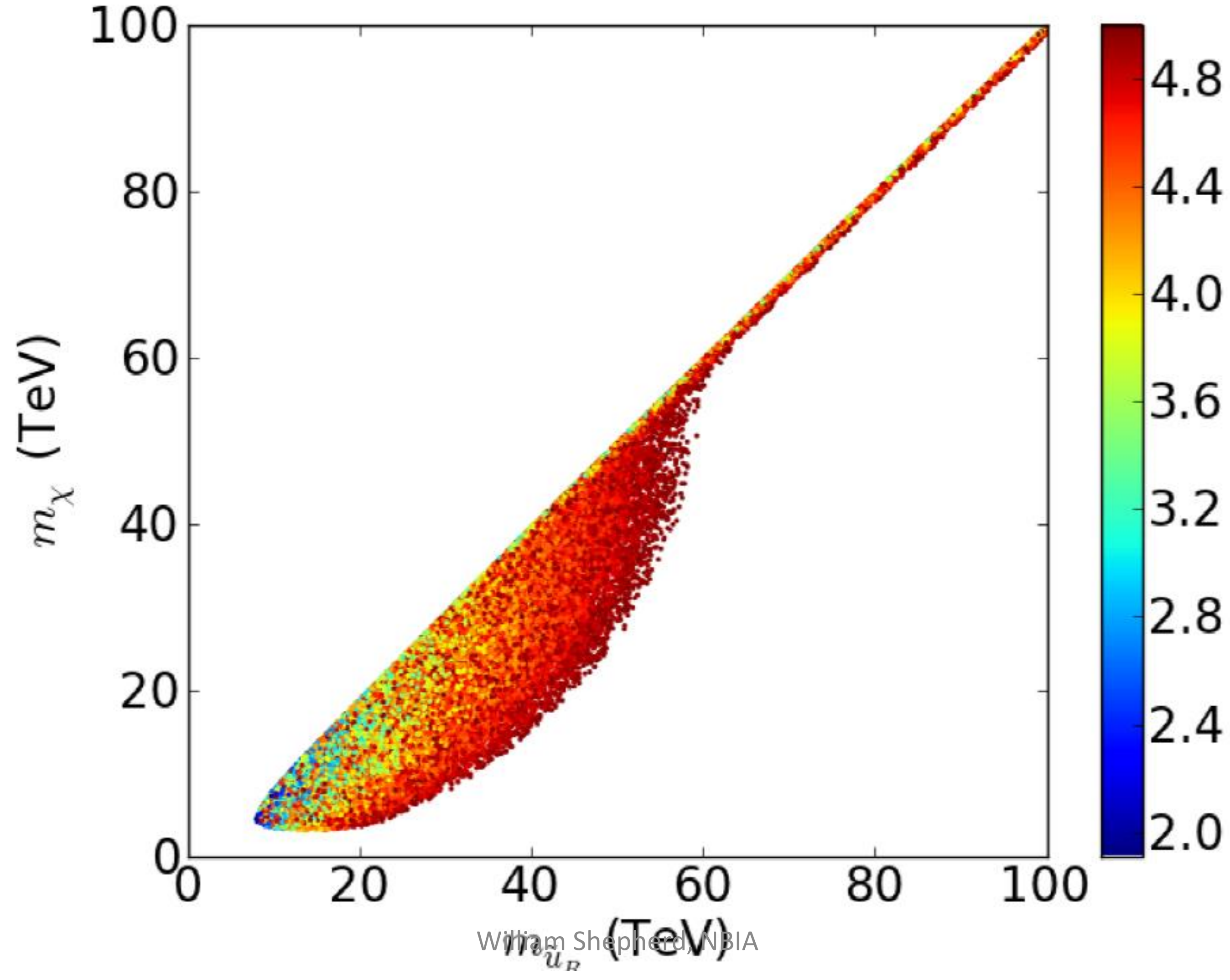
- And the Lagrangian terms

$$\mathcal{L} \supset \frac{1}{2} M_\chi \bar{\chi} \chi + \frac{1}{2} M_{\tilde{u}}{}^2 \tilde{u}^* u + \lambda_{\mathrm{dark}} \tilde{u}^* \bar{\chi} P_R u$$

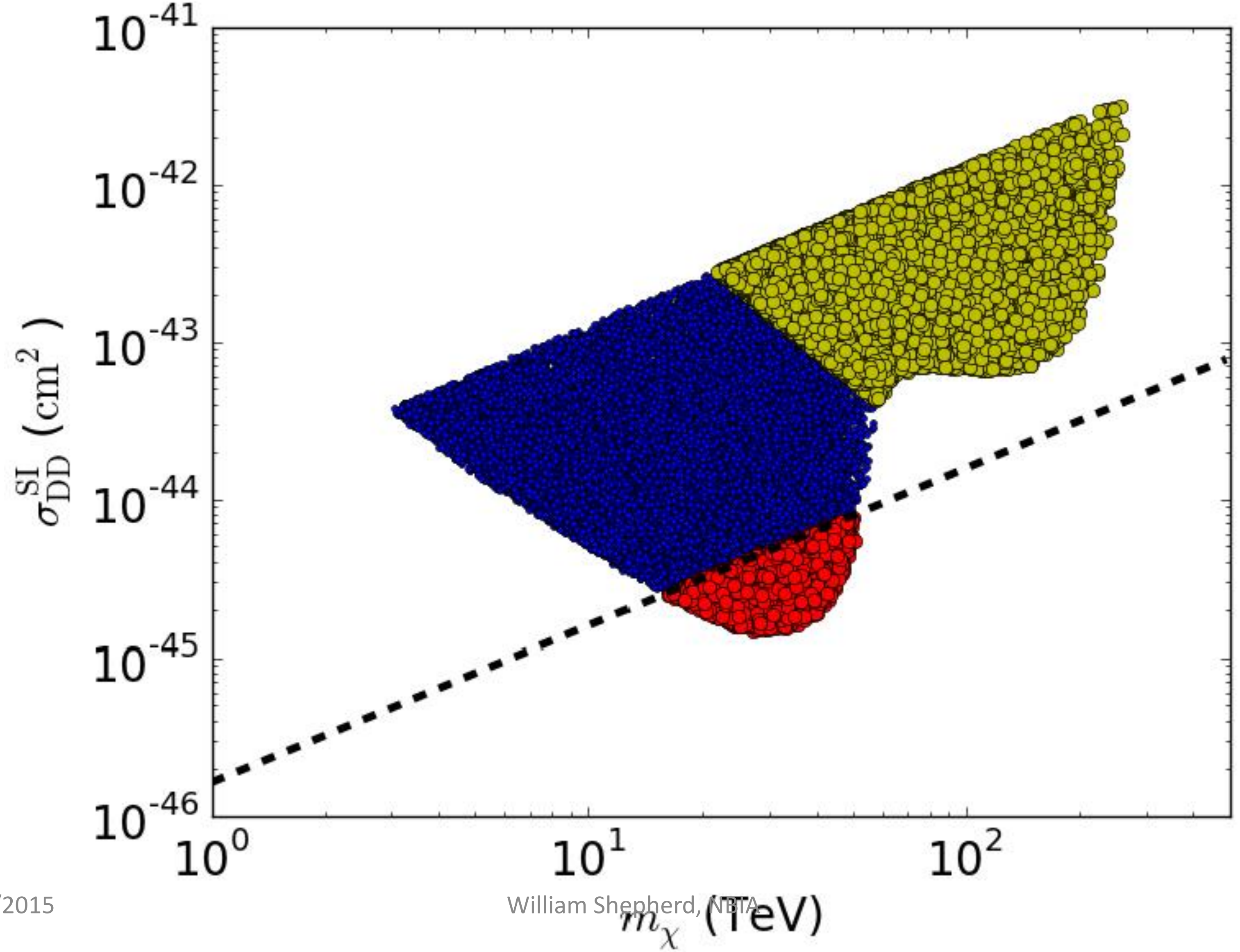
- This introduces the new parameter and scales

$$\lambda_{\mathrm{dark}},\ M_\chi,\ M_{\tilde{u}}$$

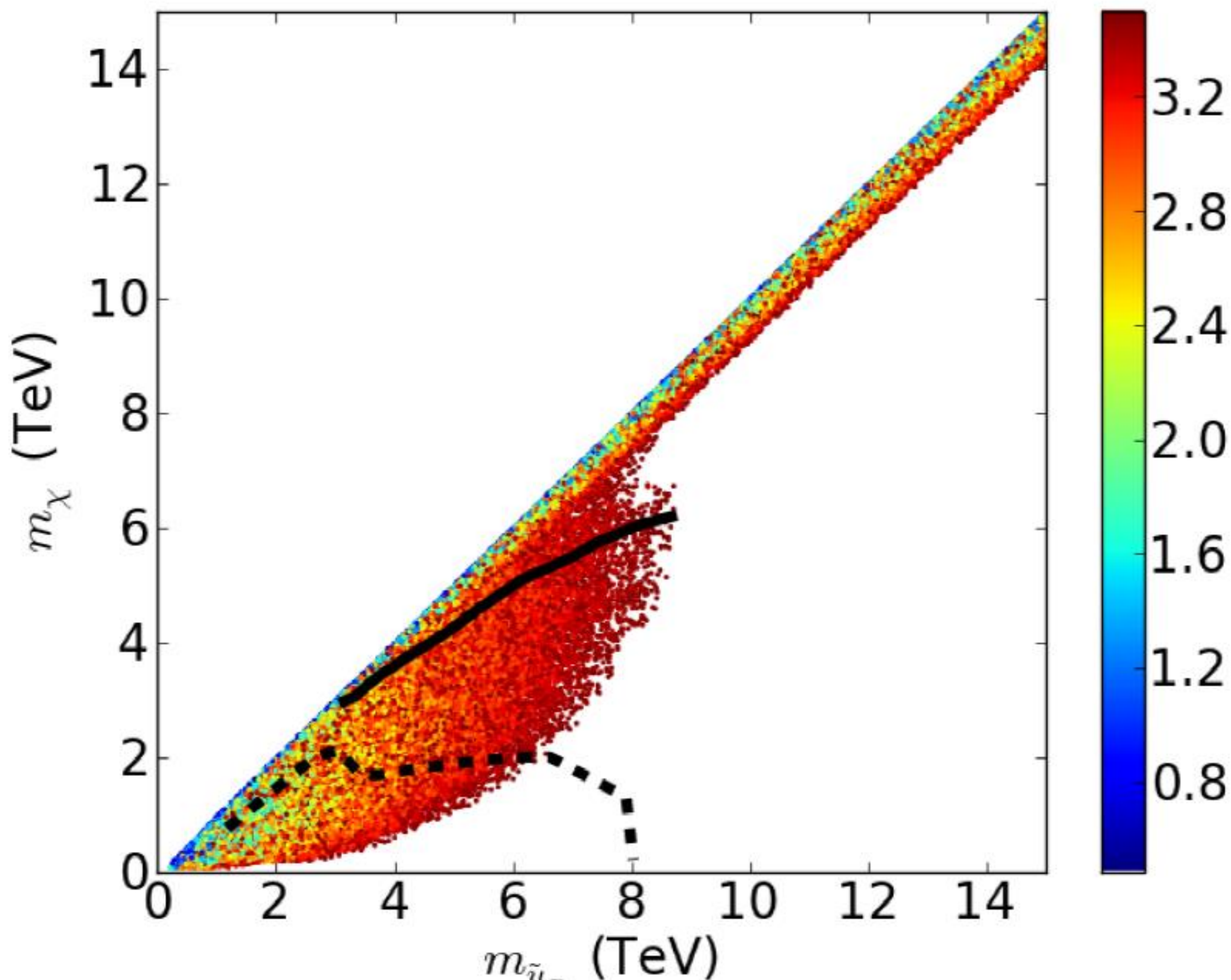
Dirac Dark Matter



Direct Detection

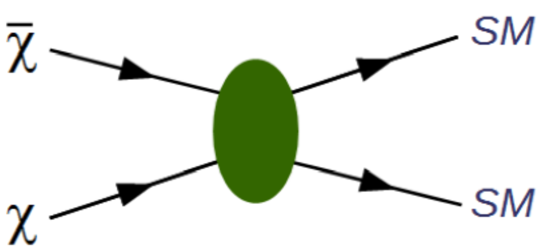


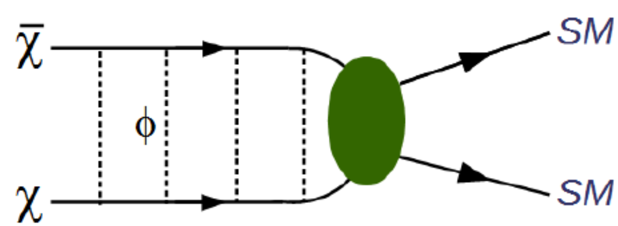
Majorana DM and FCC



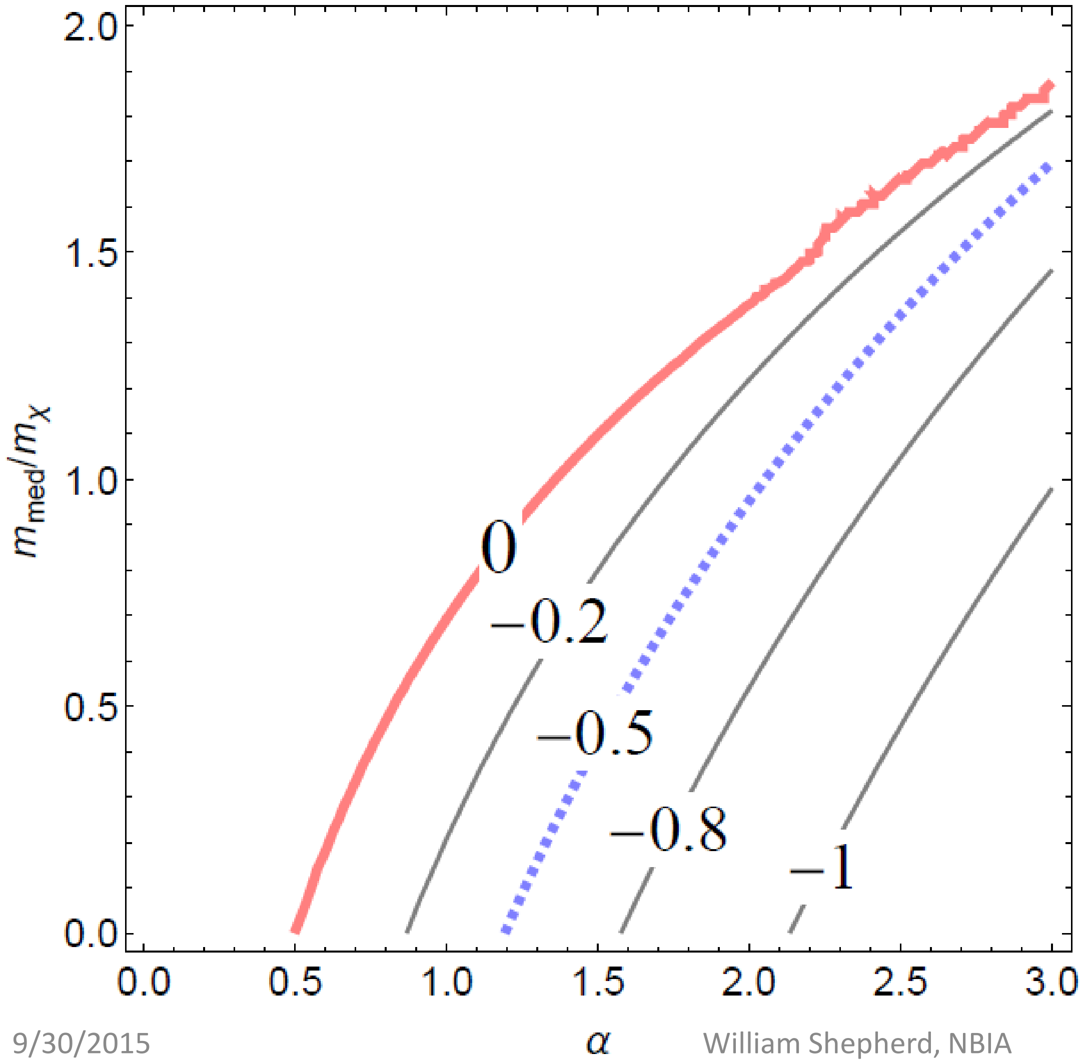
Strong Couplings and Bound States

- All of this analysis has focused on the case of very strong couplings to get high allowed mass
- These large couplings can also lead to other effects that may be important
  - Sommerfeld enhancements
  - Dark matter bound states





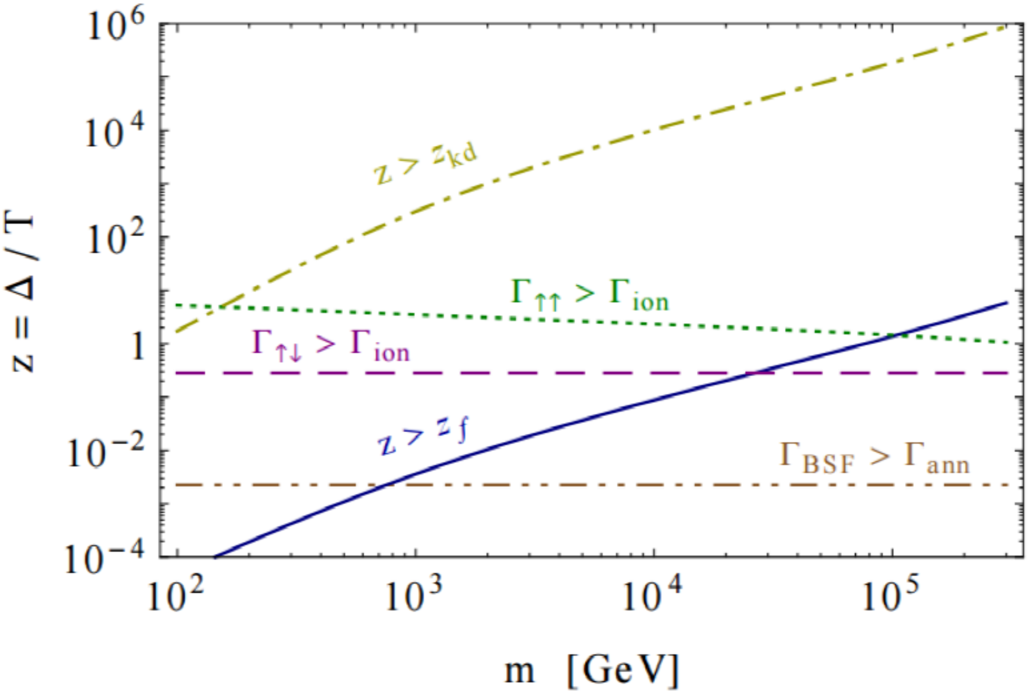
Yukawa Potential Bound States



$$V(r) = \alpha \frac{e^{-m_{\rm med} r}}{r}$$

$$T_{freeze} \sim \frac{m_\chi}{20}$$

Cosmological Rates



$$\Delta = \frac{m\alpha^2}{4}$$

↑↓ and ↑↑ bound states

von Harling and Petraki, 1407.7874

Beyond Yukawa Potentials

- Constraining to consider just a pure pseudoscalar, the leading potential is

$$V(r) = V_S(r)\sigma_1.\sigma_2 + V_T(r)S_{12}(\hat{r})$$

$$V_S = \frac{\alpha_A}{12}\left(\frac{m_\phi}{m_\chi}\right)^2 \frac{e^{-m_\phi r}}{r}$$

$$V_T = \frac{\alpha_A}{12}\left(\frac{m_\phi}{m_\chi}\right)^2 \left(1 + \frac{3}{m_\phi r} + \frac{3}{(m_\phi r)^2}\right) \frac{e^{-m_\phi r}}{r}$$

- This gives very different states from the Yukawa or Coulomb ansätze
  - Rates will also be affected by mediator mass

Outlook

- Perturbativity arguments can be made fully rigorous through unitarity considerations
- These unitarity bounds provide strong constraints on dark matter dynamics
- Combined with collider searches we will be able to place strong limits on WIMPs
- Models with strong coupling like these may already be affected by new phenomena due to bound state formation
    - Investigations of cosmological impact of bound state dynamics are in progress