Nonperturbative Dynamics in Dark Matter Freezeout

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SUSY Conference, University of Melbourne

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The Niels Bohr International Academy

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

The Scale of New Physics

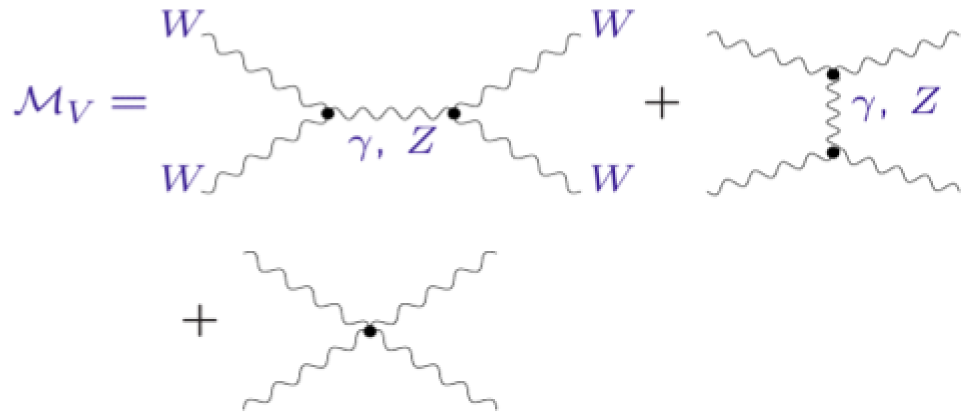
- Historically in HEP, we've often known where we were going
  - Fermi theory of weak decays needed new bosons
  - Precision measurements pointed to the top quark
  - Heavy bosons needed symmetry breaking
- After the Higgs discovery, we have no map
  - The Standard Model is stubbornly good
- Where are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

The LHC No-Lose Theorem

- The Higgs (or something else doing its job) had to be there
  - Symmetry has to break to make gauge bosons massive
- Why did it have to be within the LHC's reach?



This amplitude (missing a Higgs contribution) grows with energy, and predicts scattering probabilities greater than 1 beyond energies of about 800 GeV

Basics of Unitarity

- We start with a scattering matrix

$$S = 1 + iT$$

- Unitarity gives the optical theorem

$$S^\dagger S = I \Rightarrow \frac{1}{2}(T - T^\dagger) = |T_{ii}^2|$$

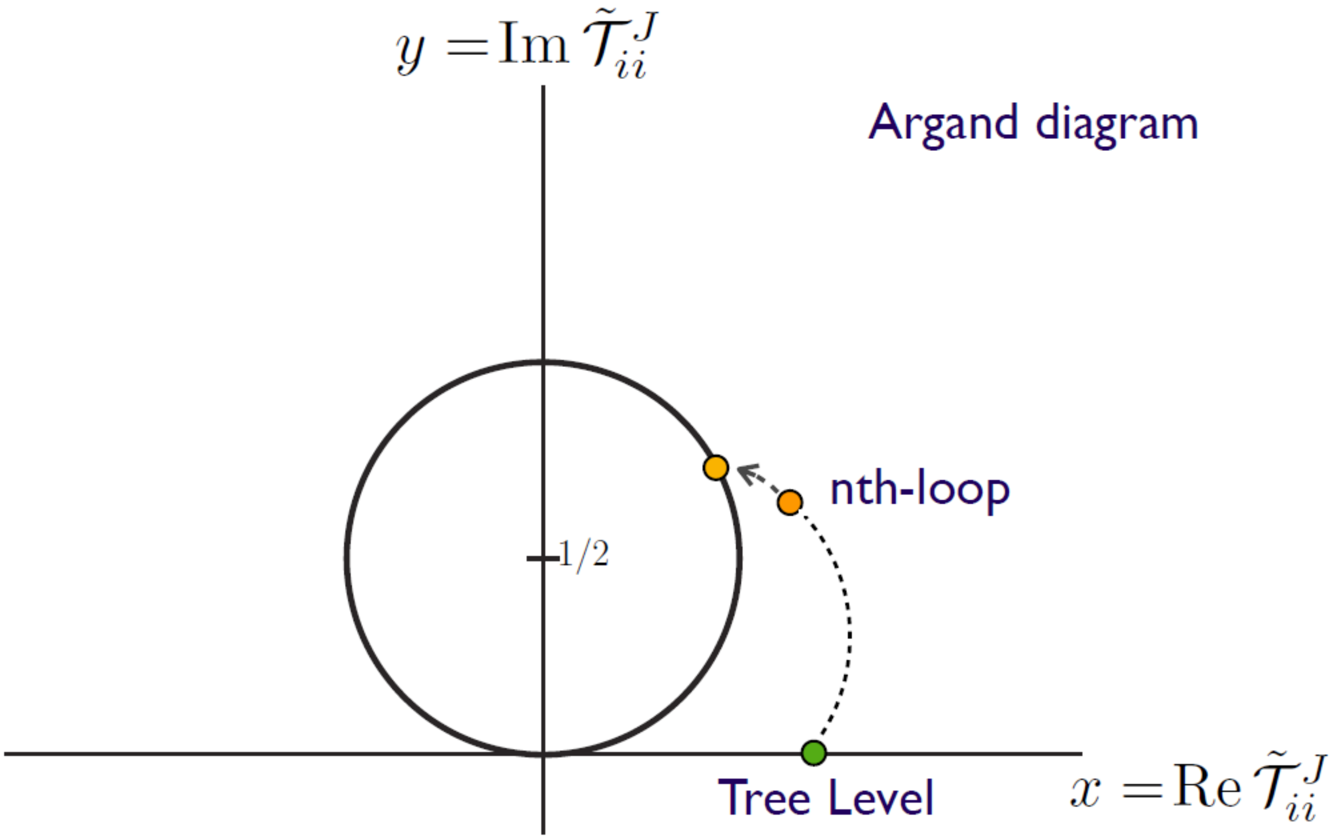
- Expanding in partial waves

$$\tilde{T}_{ij}^J = \frac{\lambda_i^{1/4}\lambda_f^{1/4}}{32\pi s}\int_{-1}^{1} T_{ij} P_J(\cos\theta) d\cos\theta$$

- We find that

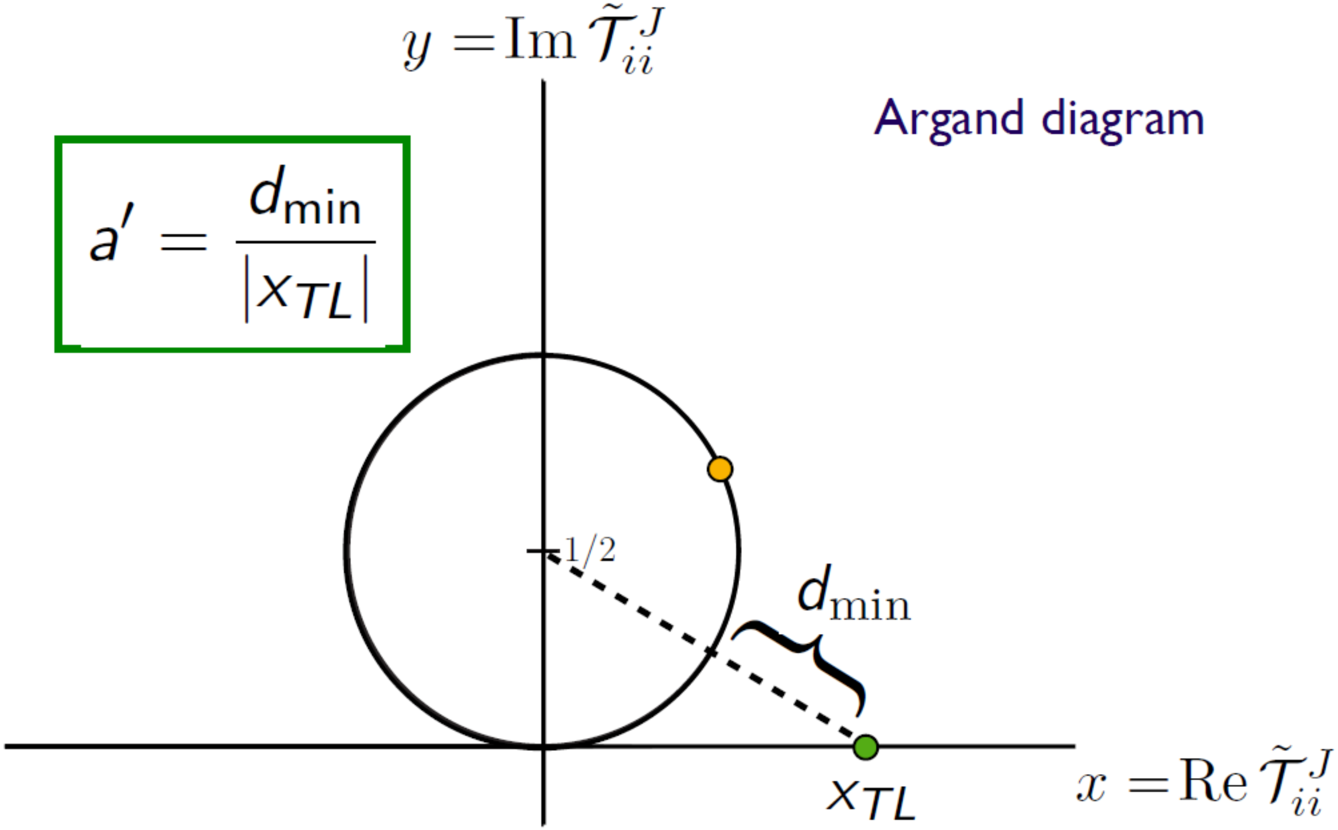
$$\mathrm{Im}\,\tilde{T}_{ii} = |\tilde{T}_{ii}|^2 \Rightarrow |\mathrm{Re}\,\tilde{T}_{ii}| < \frac{1}{2}$$

A Picture of Unitarity



Schuessler and Zeppenfeld 0710.5175
Aydemir, Anber, Donoghue 1203.5153

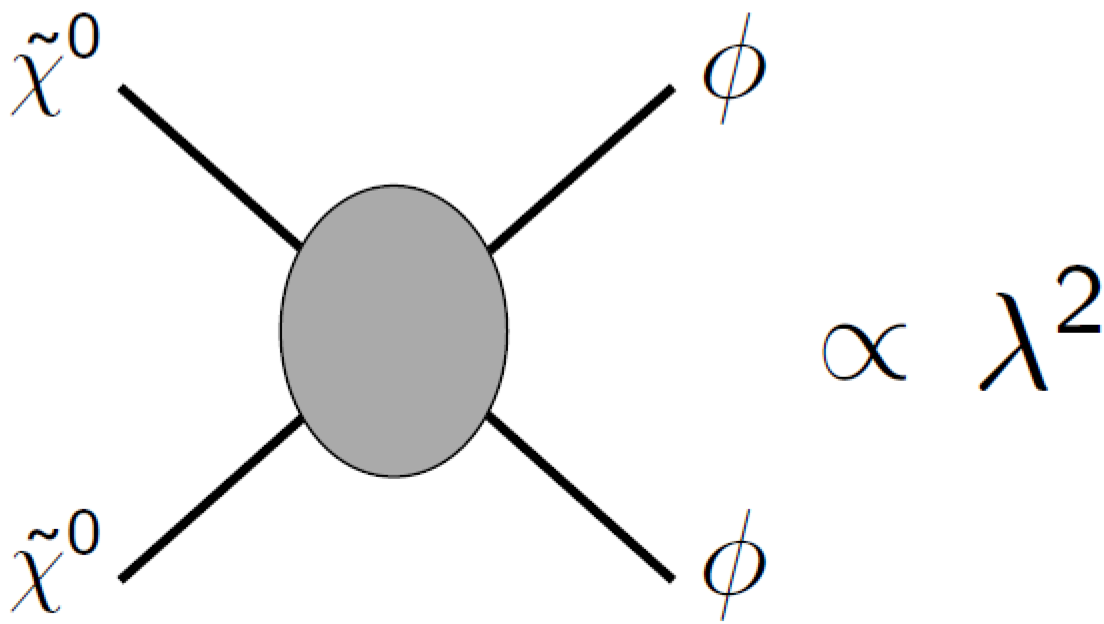
A Picture of Unitarity



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

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

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

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

- With breaking of the new symmetry by

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

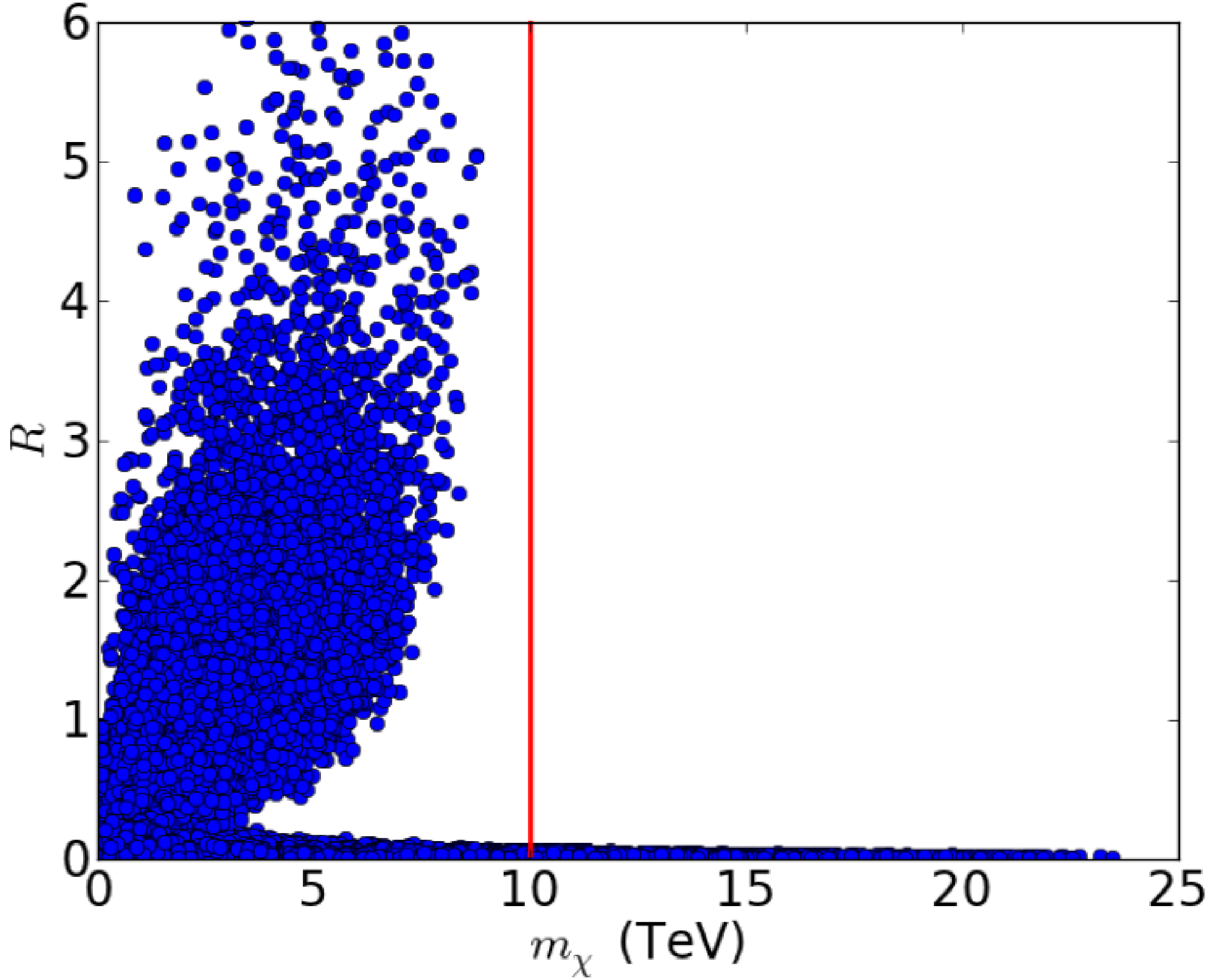
Babu, Kolda, March-Russell hep-ph/9710441

Gauge Portal Dark Matter

- This gives us 6 parameters and 1 new scale:

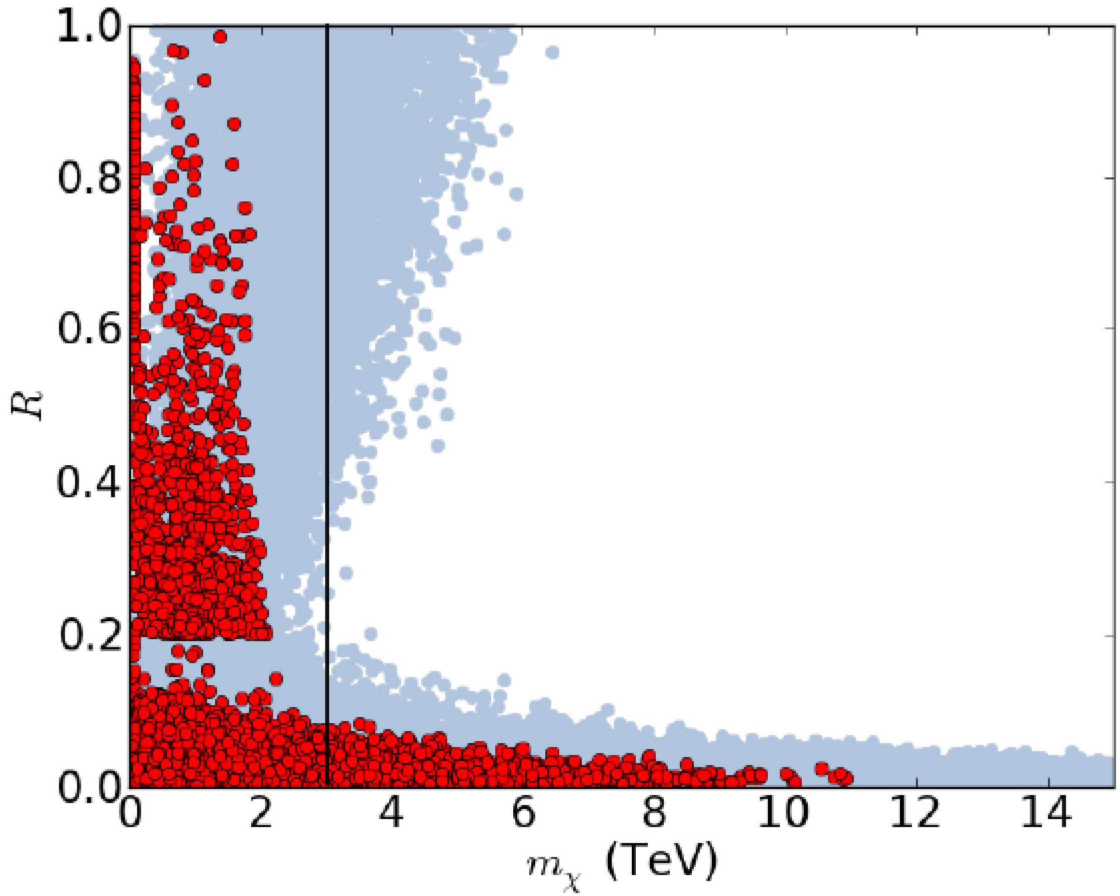
$$g', \lambda_\chi, \lambda_1, \lambda_2, \lambda_3, \sin\delta, \mathbf{u}$$

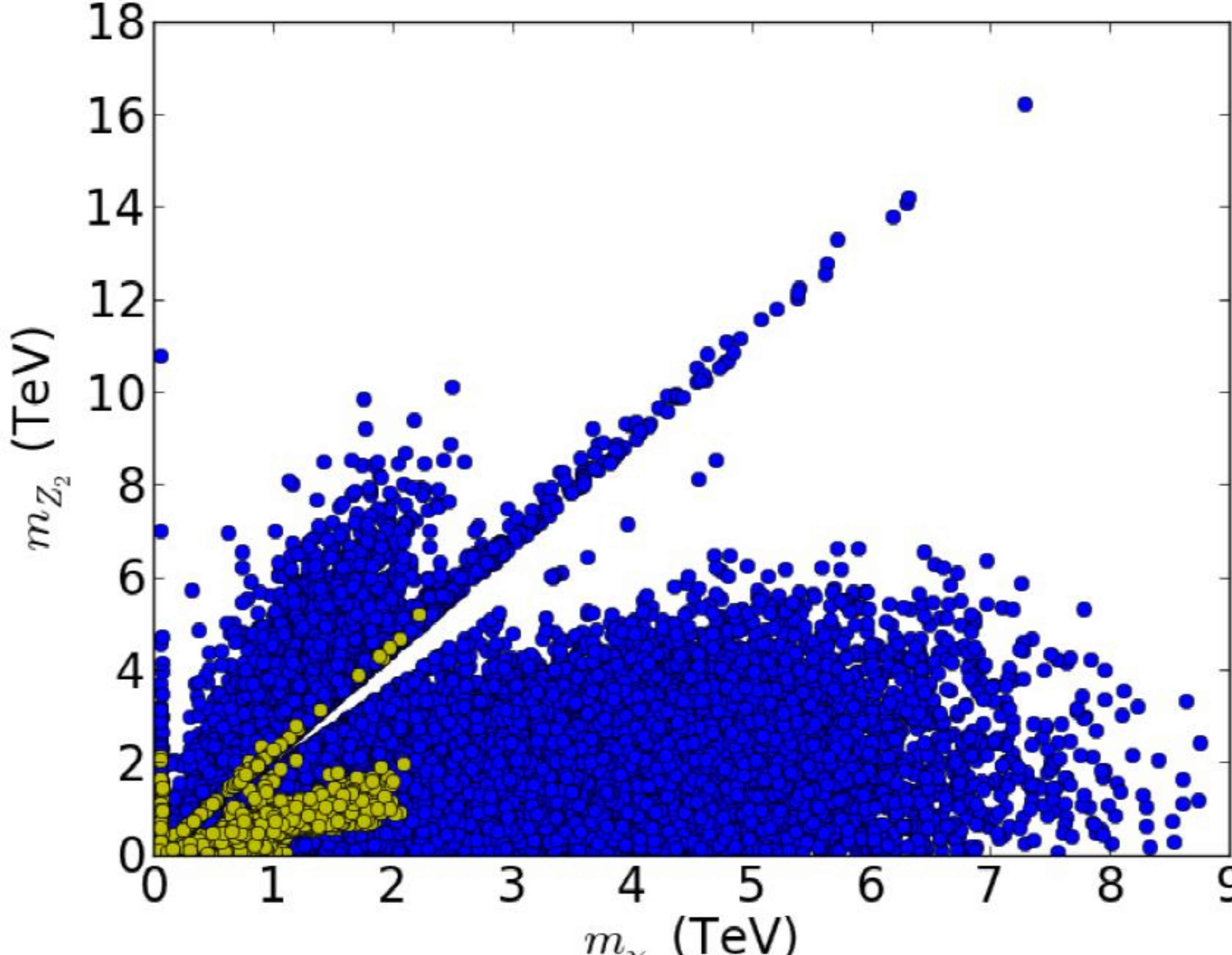
- The dimensionless couplings can be constrained directly from unitarity, but only ratios of scales can be constrained
- Here, the annihilation rate will set upper bounds on the scale of symmetry breaking



$$R = \min\left\{\frac{|2m_\chi - m_{Z'}|}{m_\chi}, \frac{|2m_\chi - m_{\phi^0}|}{m_\chi}\right\}$$

‘Pure Vector’ Interactions




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

Colored Scalars and Dark Matter

- In a SUSY-inspired model, we add

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

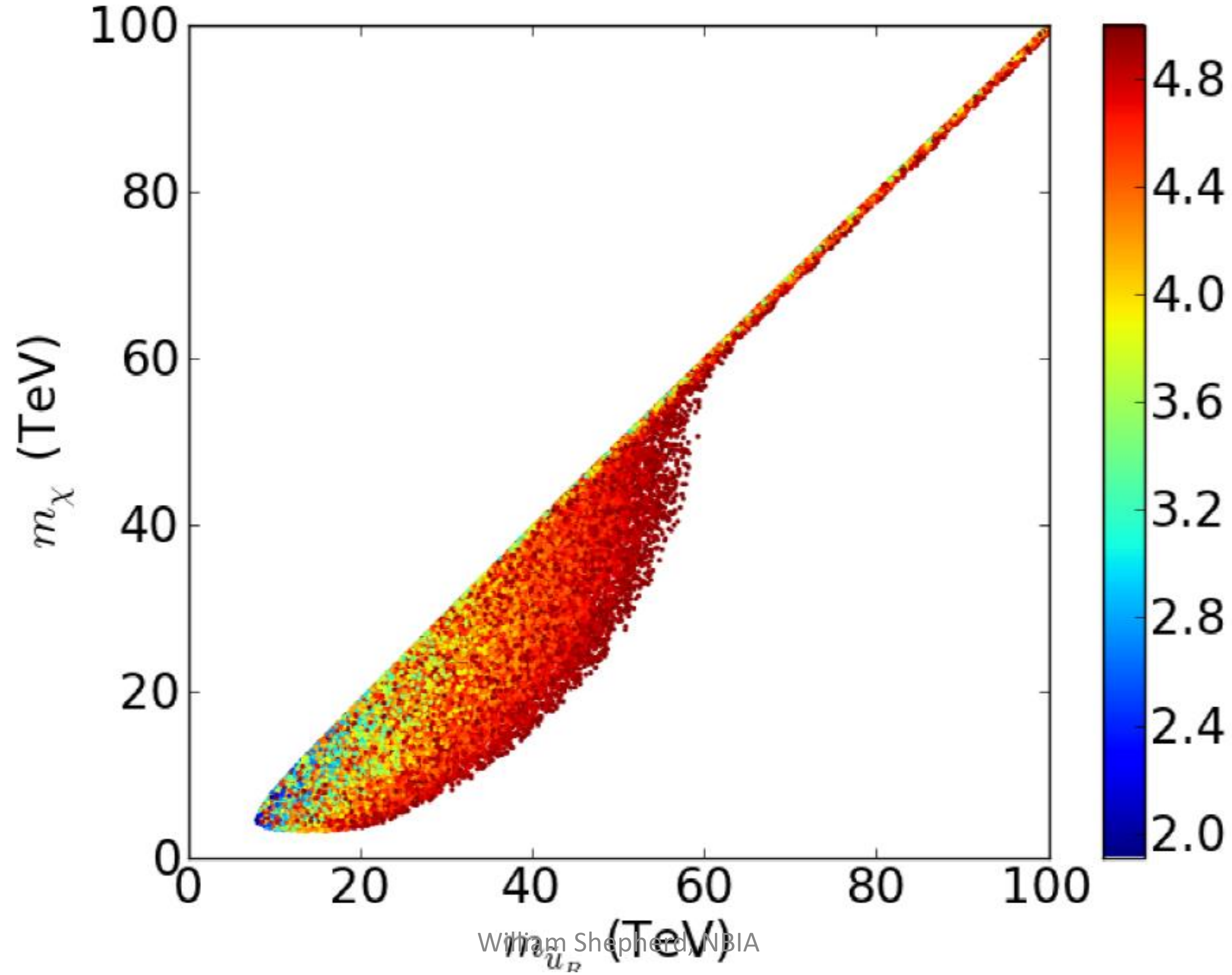
- And the Lagrangian terms

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

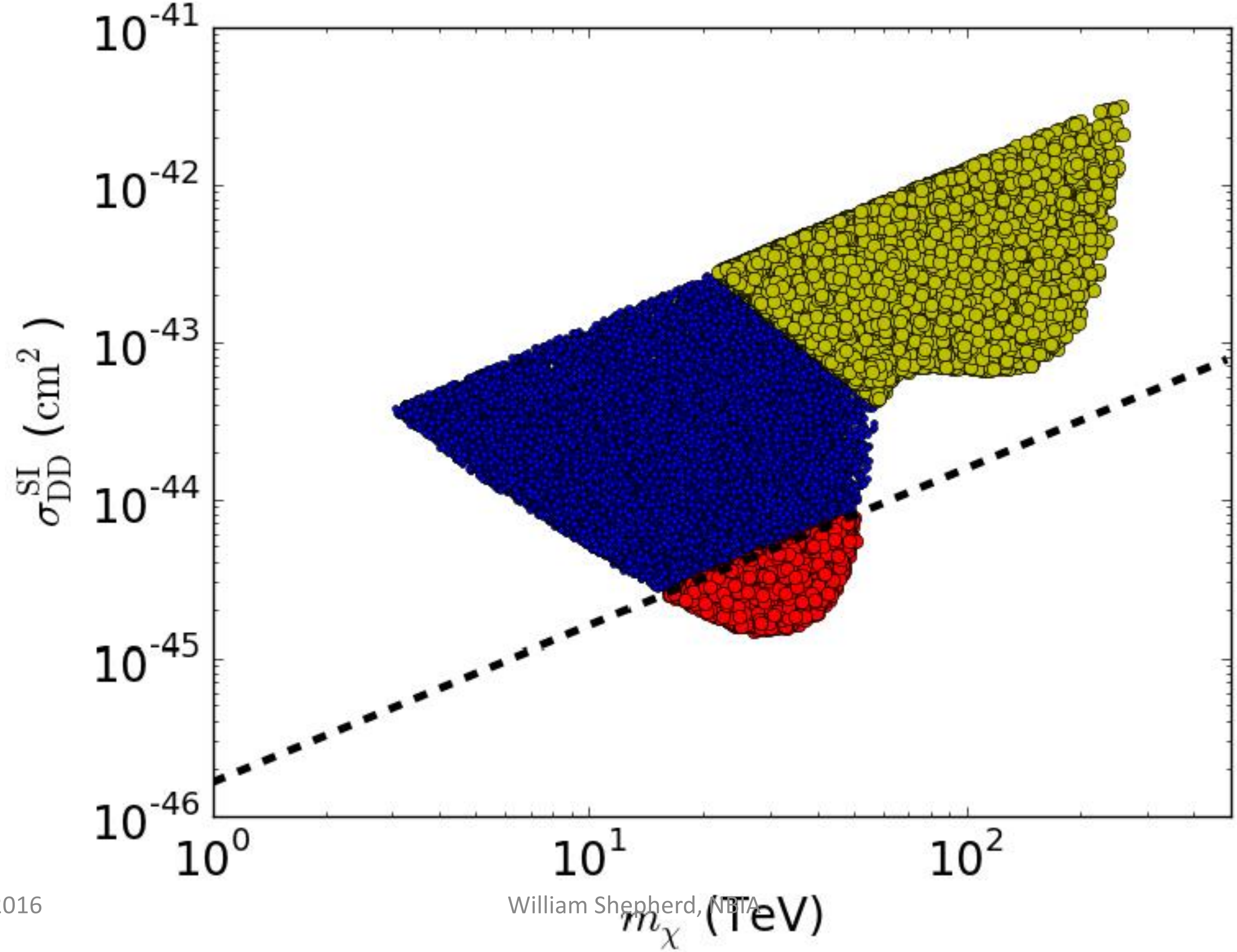
- This introduces the new parameter and scales

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

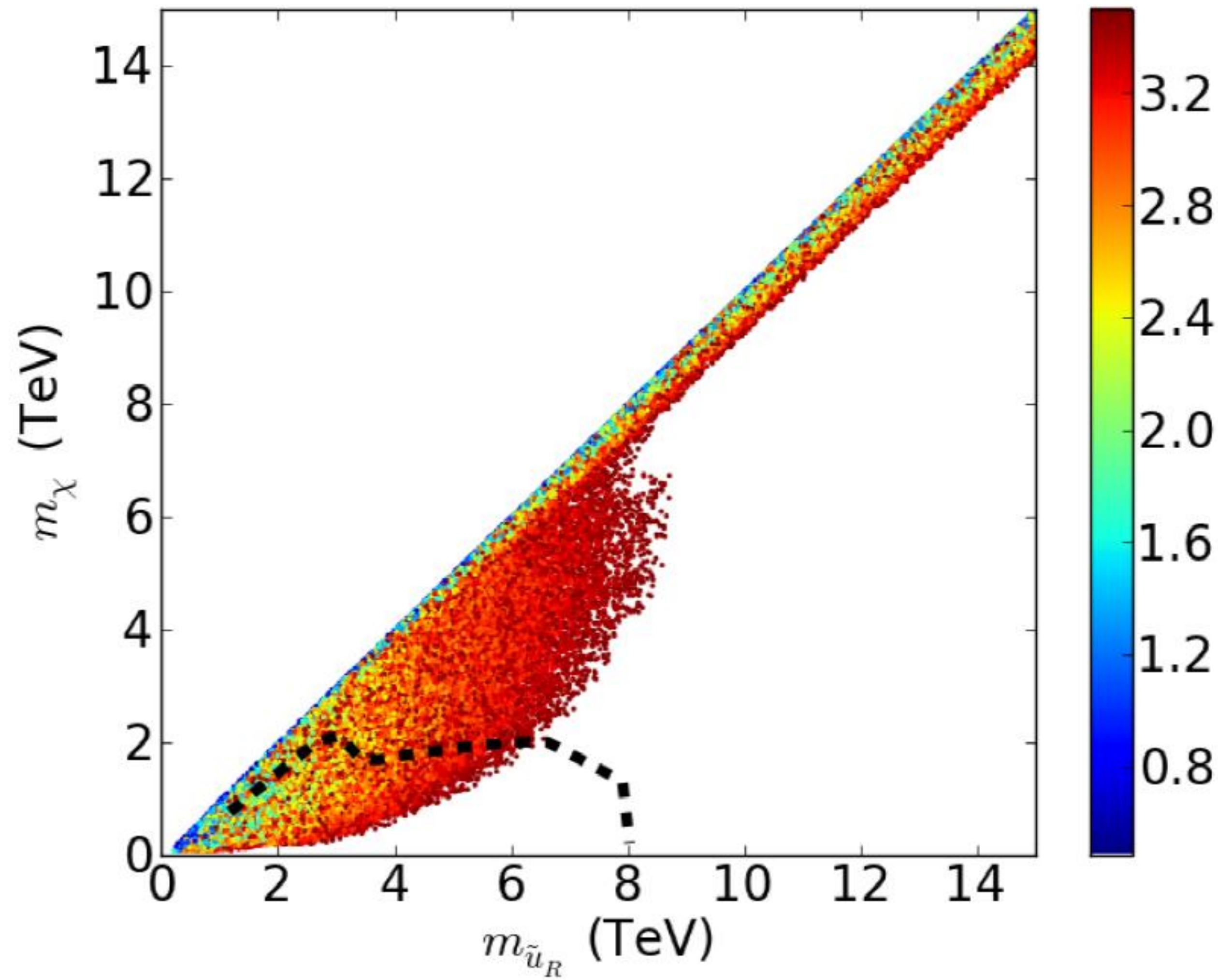
Dirac Dark Matter



Direct Detection

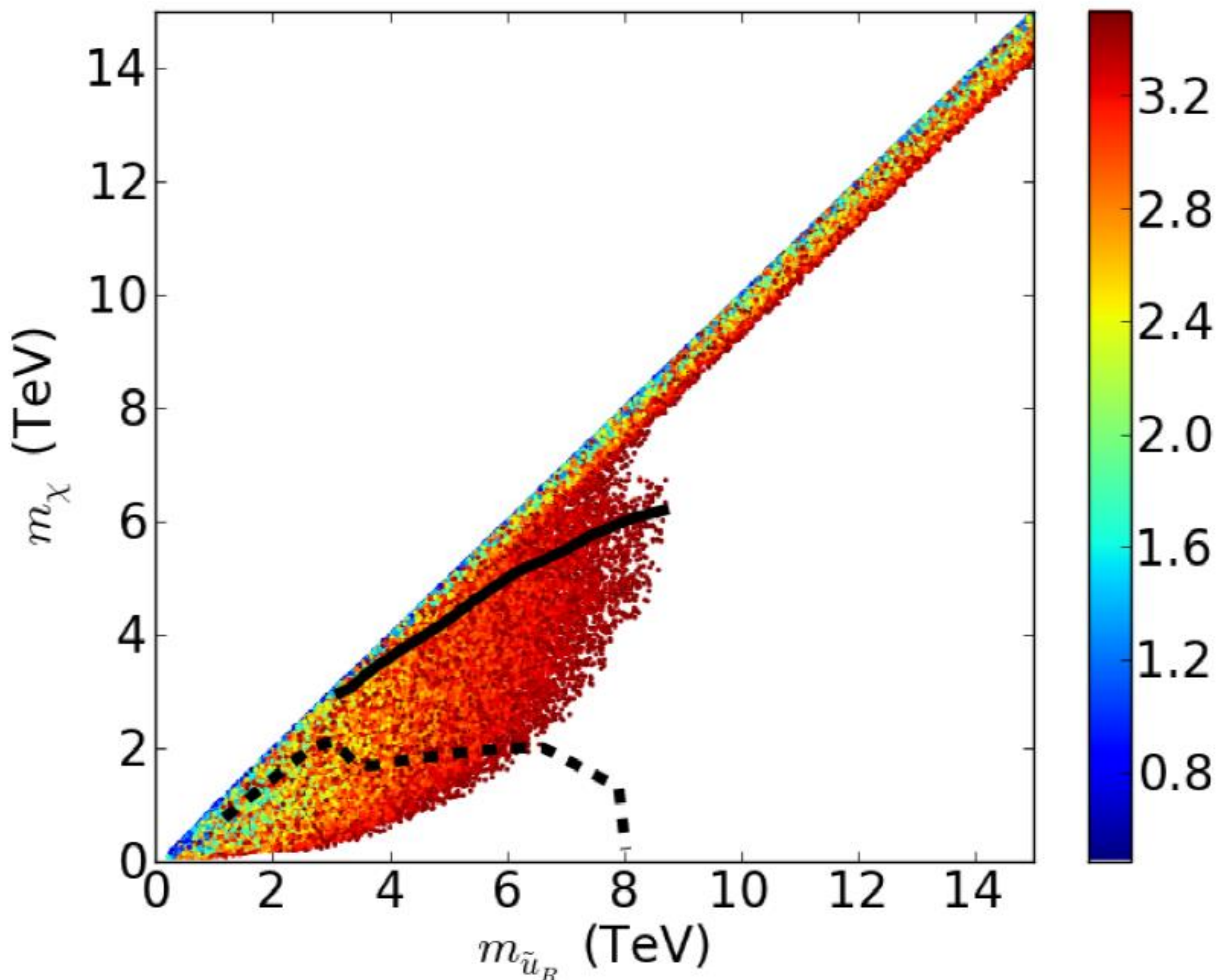


Majorana Dark Matter



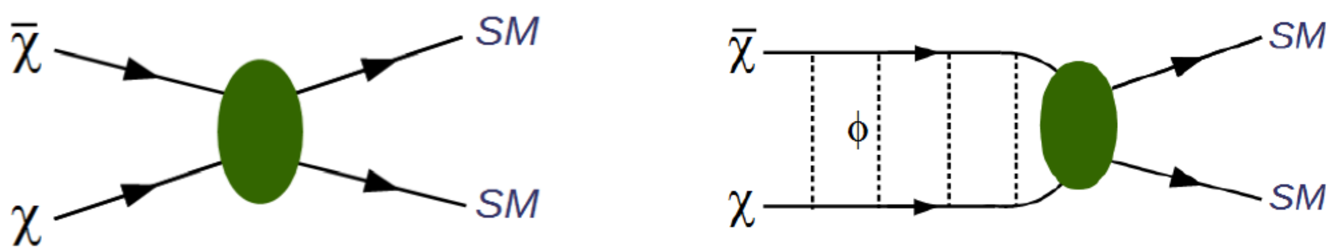
Cohen, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker [arXiv:1311.6480]

True FCC Reach

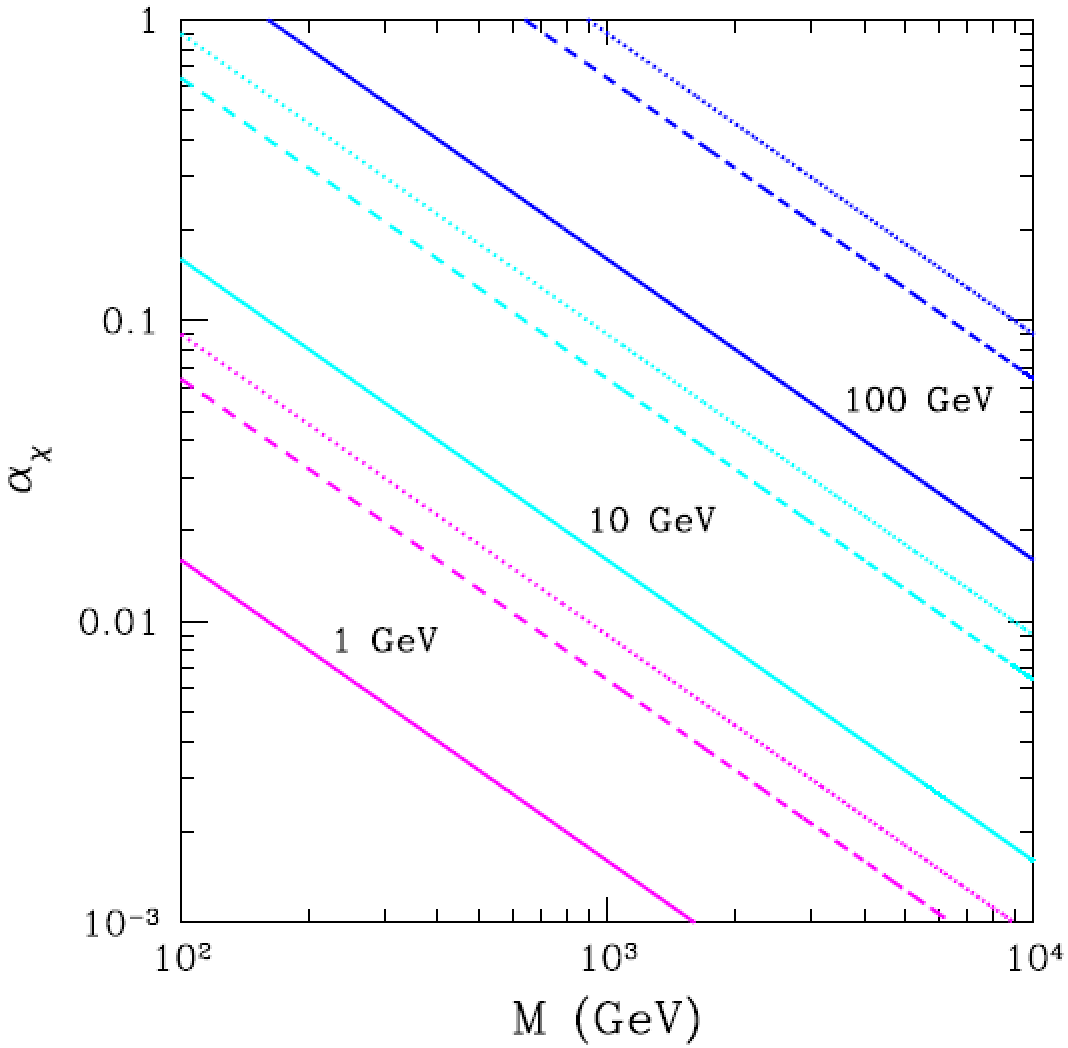


Strong Couplings and Bound States

- 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



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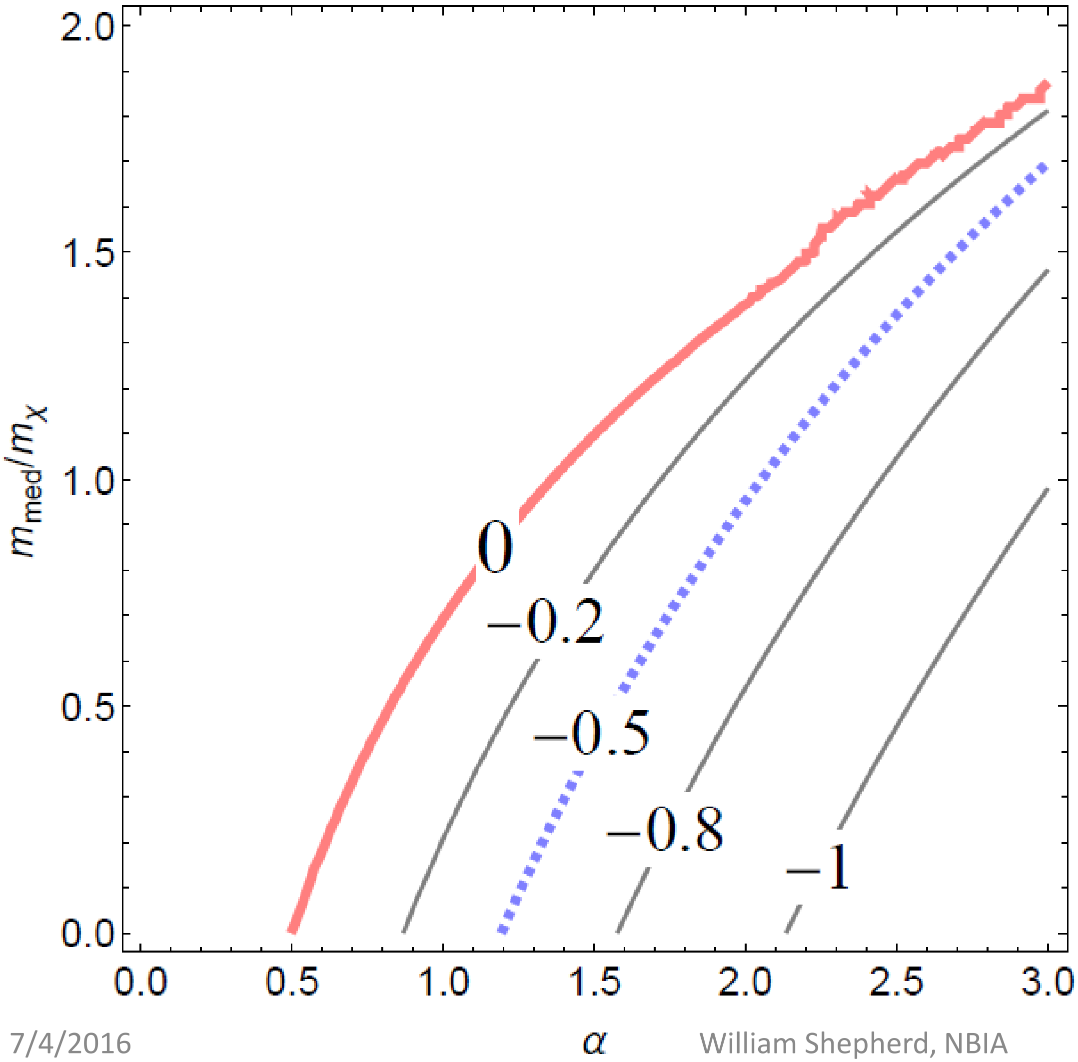
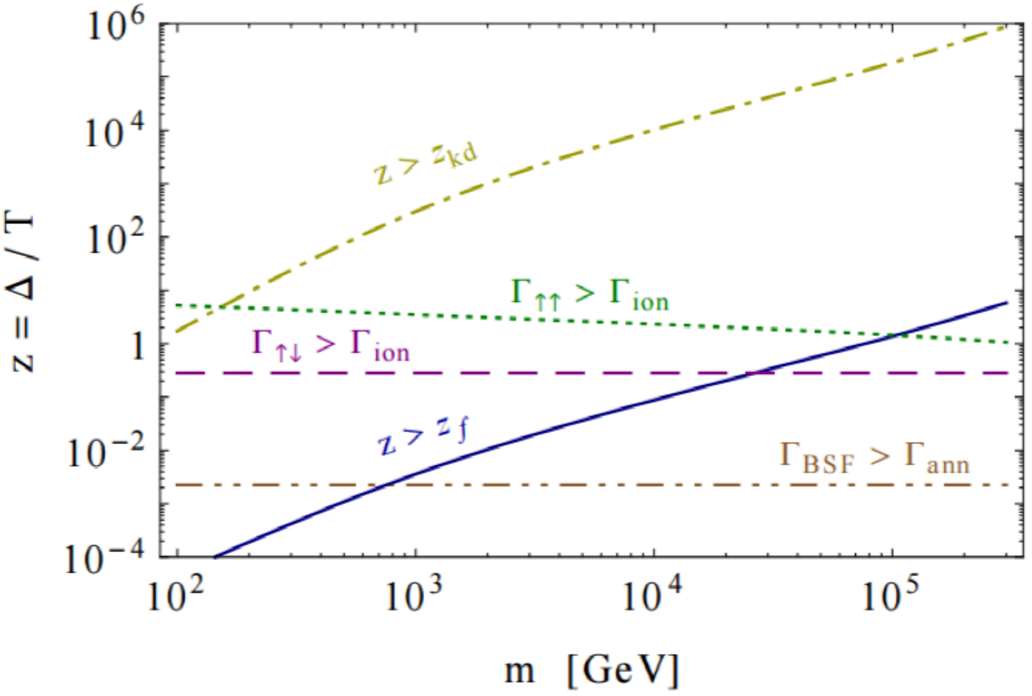


$$V(r) = \alpha \frac{e^{-m_{\rm med} r}}{r}$$

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

Cosmological Rates



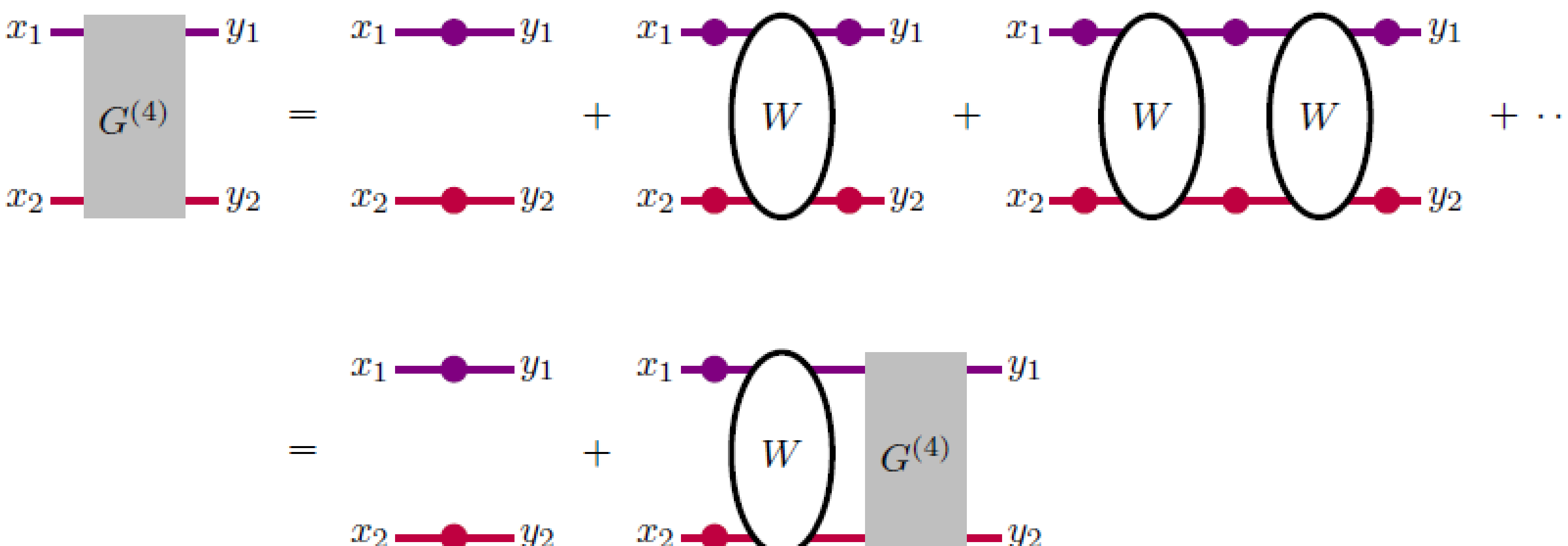
$$\Delta = \frac{m\alpha^2}{4}$$

↑↓ and ↑↑ bound states

von Harling and Petraki, 1407.7874

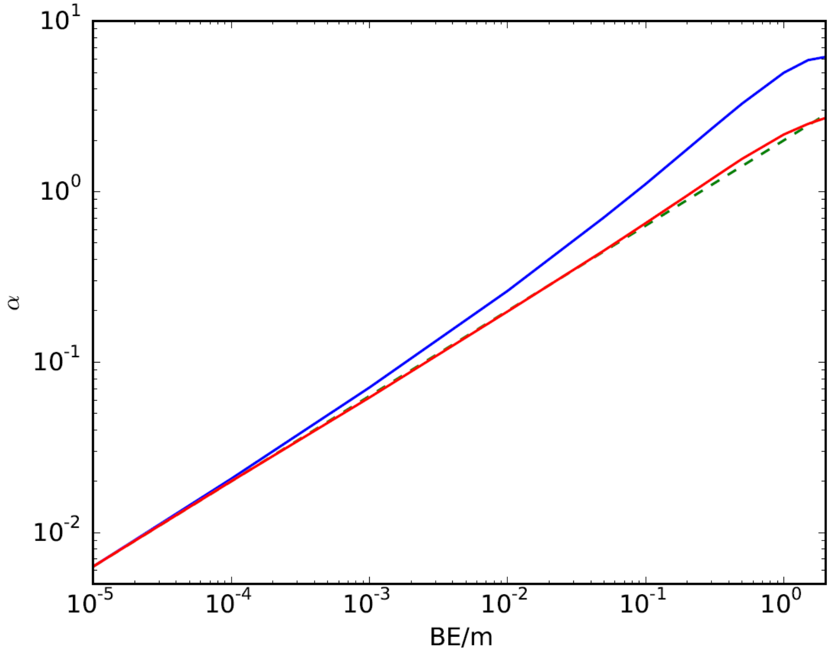
Bethe-Salpeter Equation

- States that are strongly bound enough to matter will have momenta high enough to require relativistic treatment
- If ladder diagrams are the dominant contribution to the binding the Bethe-Salpeter equation describes the physics



Relativistic Corrections

- States with binding energies of M/10 or larger require relativistic corrections to the coupling of a factor of 2 or more
- This will be an important shift in the cosmological implications of strong coupling



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