Perturbative Unitarity and Dark Matter

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with

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arXiv:1407.0395
arXiv:1410.1534
arXiv:1412.5660
arXiv:1501.03153

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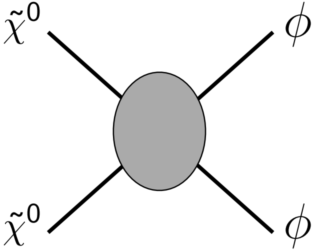
Unitarity and Thermal Dark Matter

- Heavy Dark Matter needs to annihilate efficiently
- Annihilation cross section bounded by unitarity
  Griest and Kamionkowski, 1990



$$\propto \lambda^2$$

- Generic Unitarity Bound : 120 TeV for λ non perturbative
- **Can we identify lower characteristic scales using unitarity?**

Perturbative Unitarity

Given a scattering matrix

$$S = 1 + iT$$

Optical theorem

$$S^\dagger S = I \Rightarrow -i(T - T^\dagger) = T^\dagger T$$

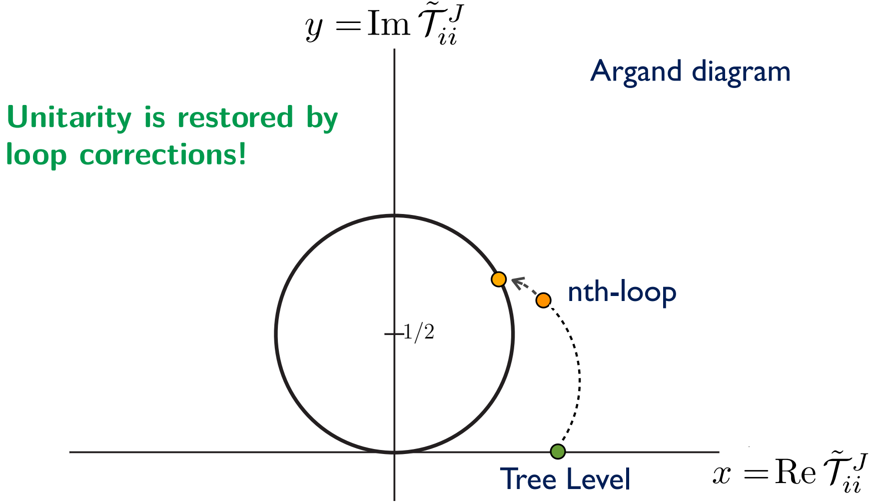
Use Partial Wave Decomposition

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

We find

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

Unitarity in the Complex Plane

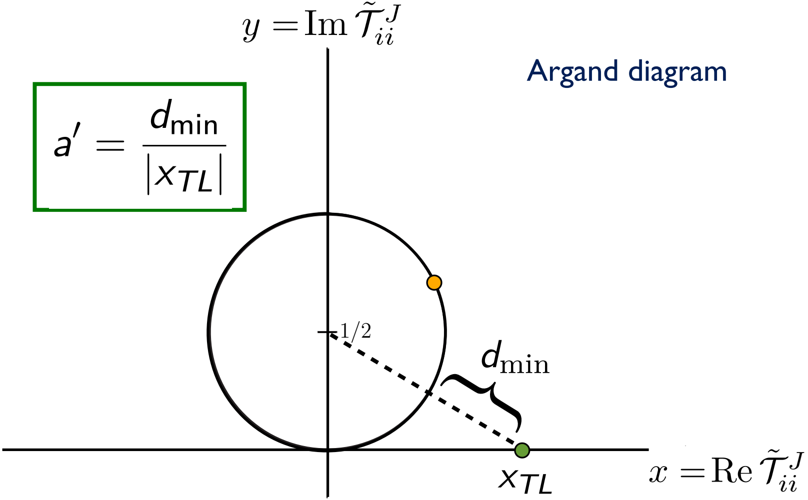


Schuessler and Zeppenfeld [arXiv:07105175, Schuessler's thesis (2005)]
Aydemir, Anber, Donoghue [arXiv:1203.5153]

Unitarity and Loop Corrections

Argand diagram

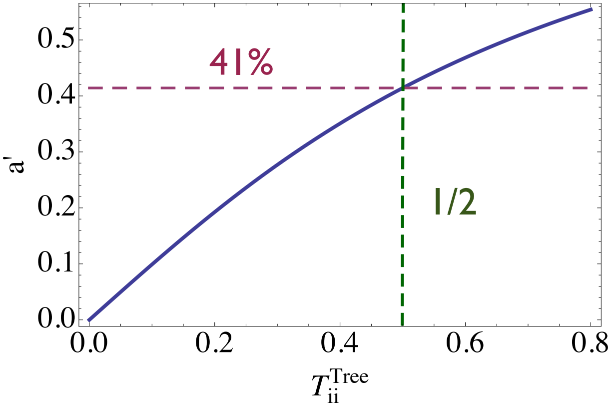
$$a' = \frac{d_{\min}}{|x_{TL}|}$$



Schuessler and Zeppenfeld [arXiv:07105175, Schuessler's thesis (2005)]

Perturbativity breakdown

- For large $\tilde{\mathcal{T}}_{ii}$ restoring unitarity violates perturbativity!



Schuessler and Zeppenfeld [arXiv:07105175, Schuessler thesis (2005)]

- **New perturbativity bounds on Dark Matter models**

Application: Squark-Dark Matter simplified model

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

- Example: Majorana fermionic Dark Matter
  DiFranzo, Nagao, Rajaraman, Tait [arXiv:1308.2679]
- MFV – Consider one degenerate flavor triplet

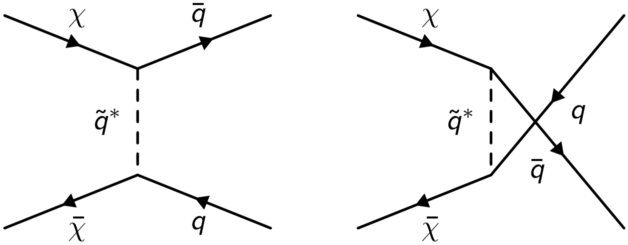
$$\tilde{u}_R = (\tilde{u}_R, \tilde{c}_R, \tilde{t}_R)$$

- Three parameters – Two mass scales

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

Squark-Dark Matter – Strategy

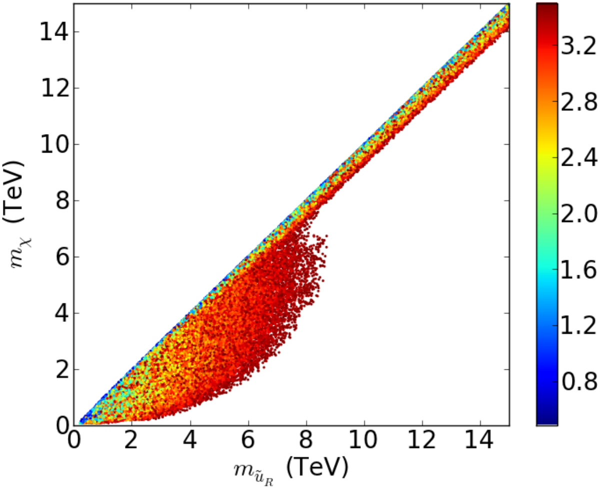
- Same diagrams for Unitarity, Direct Detection and Relic Density constraints



- Unitarity $\Rightarrow$ $\lambda_{\mathrm{dark}} \lesssim 3.5$
- Negative interference $\Rightarrow$ suppressed annihilation rate

The Perturbative Sector

- Suppressed annihilation cross section

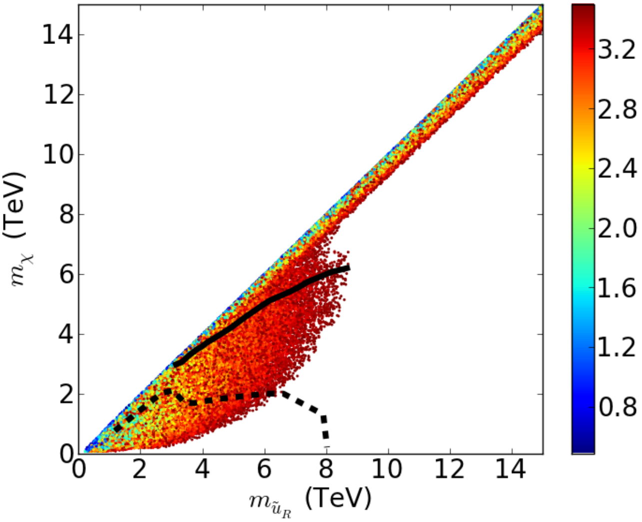


- 10 TeV bound on Squark and Dark Matter masses!

Squark Portal at 100 TeV – Exclusion reach

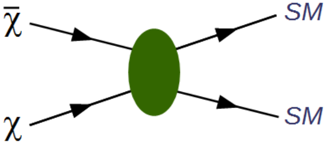
Snowmass 100 TeV search recasted for large λ_{dark}

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

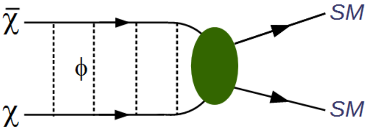


Consequences of breaking perturbativity

The Dark Matter candidate forms bound states



Elementary DM annihilation



Bound state decay

Completely different physics in the dark sector!

- Different depletion mechanism
- Different collider/indirect/DD phenomenology

Find new energy scales by considering bound states?

Massive Mediators – Gauge boson exchange

Exchange of a **massive** Z' – Vector and axial-vector interaction

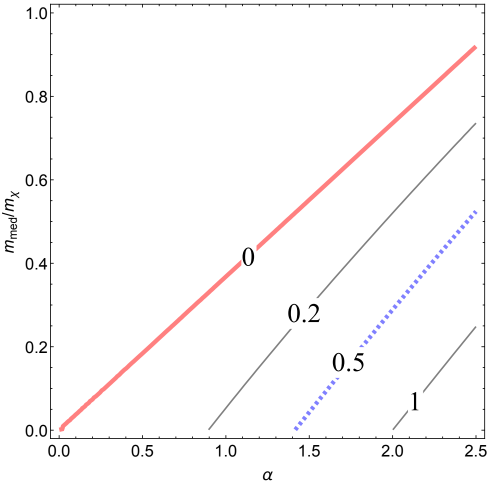
$$\mathcal{L} \supset g' \bar{\chi} \gamma_\mu \left(\lambda_0 + i\lambda_5\gamma_5\right) \chi \, Z^\mu$$

- Yukawa Potential – Spin-spin interaction

$$V(r) = \frac{e^{-m_{Z'} r}}{4\pi r} \left(\lambda_0^2 - \lambda_5^2 \vec{\sigma}_1 . \vec{\sigma}_2\right)$$

- Short range interaction
- Binding energy depends on the mediator mass
- Set a new upper bound on the Dark Matter mass using the binding energy

Finding Characteristic Energy Scales – Yukawa potential



Δ/m_χ contours

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

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

- For $|\Delta| \gg T_{freeze}$ (blue), Dark Matter dynamics is dominated by bound states formation!

Summary and Outlook

- Perturbative Unitarity coupled with relic density sets powerful constraints on the scales of thermal Dark Matter models
- Combining unitarity constraints with current and future experimental results will allow to "corner" weakly interacting Dark Matter for large classes of models
- The unitarity bound corresponds to a fundamental change in the Dark Matter dynamics due to the formation of bound states
- For portals, the bound state dynamics can be fully derived
  $\Rightarrow$ Compute a physically motivated bound!
- New refined bounds can be computed for our models. Calculation of the potentials for the Higgs and squark portals in progress.