Super-Resonant Dark Matter (SRDM)

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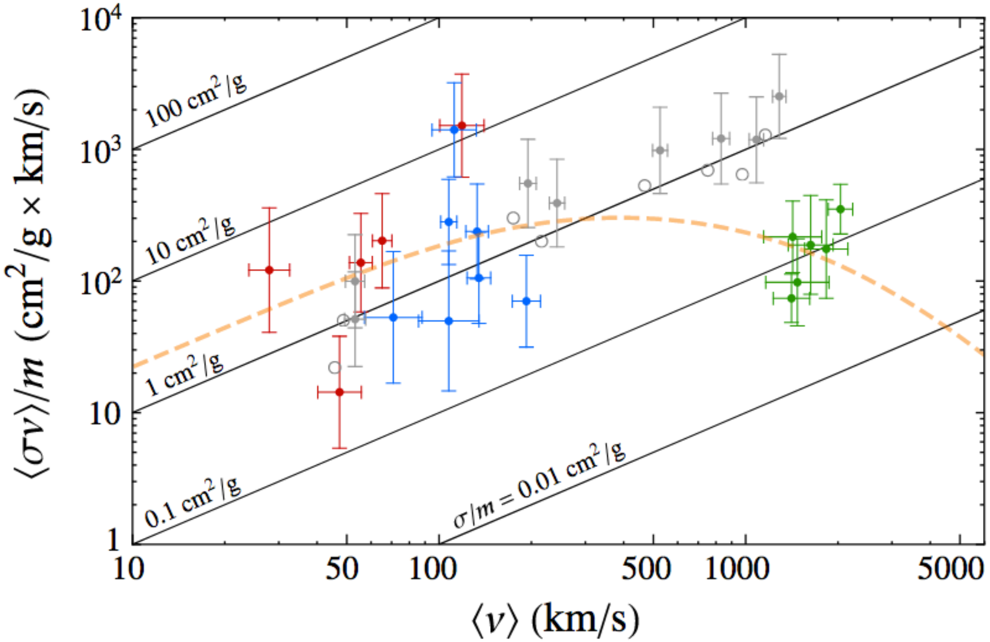
Observables to Consider

- DM relic abundance (~0.27)
- Small scale anomalies – in particular self-interaction at low velocities stronger than at high velocities
- Could be explained by an s-channel resonance
- Finally, any other relevant constraints – N_{eff}, direct detection bounds, etc.

- Dwarfs, LSB, halos (simulation), clusters, resp. Taken from Kaplinghat et al. 2016



The Model – Why SUSY?

- Will consider a dark sector of supersymmetric QCD with N_c colors and N_f flavors
- SUSY gives enormous control over dynamics (in particular gives exact non-perturbative superpotential)

$$W_{\text{ADS}} = (N_c - N_f)\left(\frac{\Lambda_{\text{H}}^{3N_c - N_f}}{\det \widetilde{M}}\right)^{\frac{1}{N_c - N_f}}$$

$$\widetilde{M}_{ij} = Q_i^a \bar{Q}_{a\,j}$$

- With flavor symmetry, tree level η' to π mass ratio is given by

$$r = \frac{N_c}{N_c - N_f}$$

- Thus we take N_c=2N_f (r = 2) – DM made of adjoints experience s-channel resonance

1-loop Mass Splitting

- At one loop singlet to adjoint mass ratio is corrected due to Kähler renormalization

$$m_S/m_M = 2(1-\delta) = 2\left(1 - \frac{m^2}{64\pi^2 v^2}\frac{104+41N_f^2}{N_f}\log\frac{v}{m}\right)$$

- With mass m and cutoff v
- Find that δ ~ velocity^2 at which the resonance “saturates”
- Given that the low-/high-velocity transition is around 500 km/s, dimensionless coupling y = m/v is quite small

Contact with (MS)SM

- Simplest way is by gauging U(1) baryon, called $U(1)_D$
- Adjoint mesons split into neutral and charged
- Introduce kinetic mixing with SM $U(1)_Y$

$$\epsilon \int d^2\theta W_{\mathrm{D}\alpha} W_{\mathrm{Y}}^{\alpha} + h.c. = \epsilon(-F_{\mathrm{D}\alpha\beta} F_{\mathrm{Y}}^{\alpha\beta} + 4i\bar{\lambda}_{\mathrm{D}} \partial\!\!\!/ \lambda_{\mathrm{Y}} + 2D_{\mathrm{D}} D_{\mathrm{Y}})$$

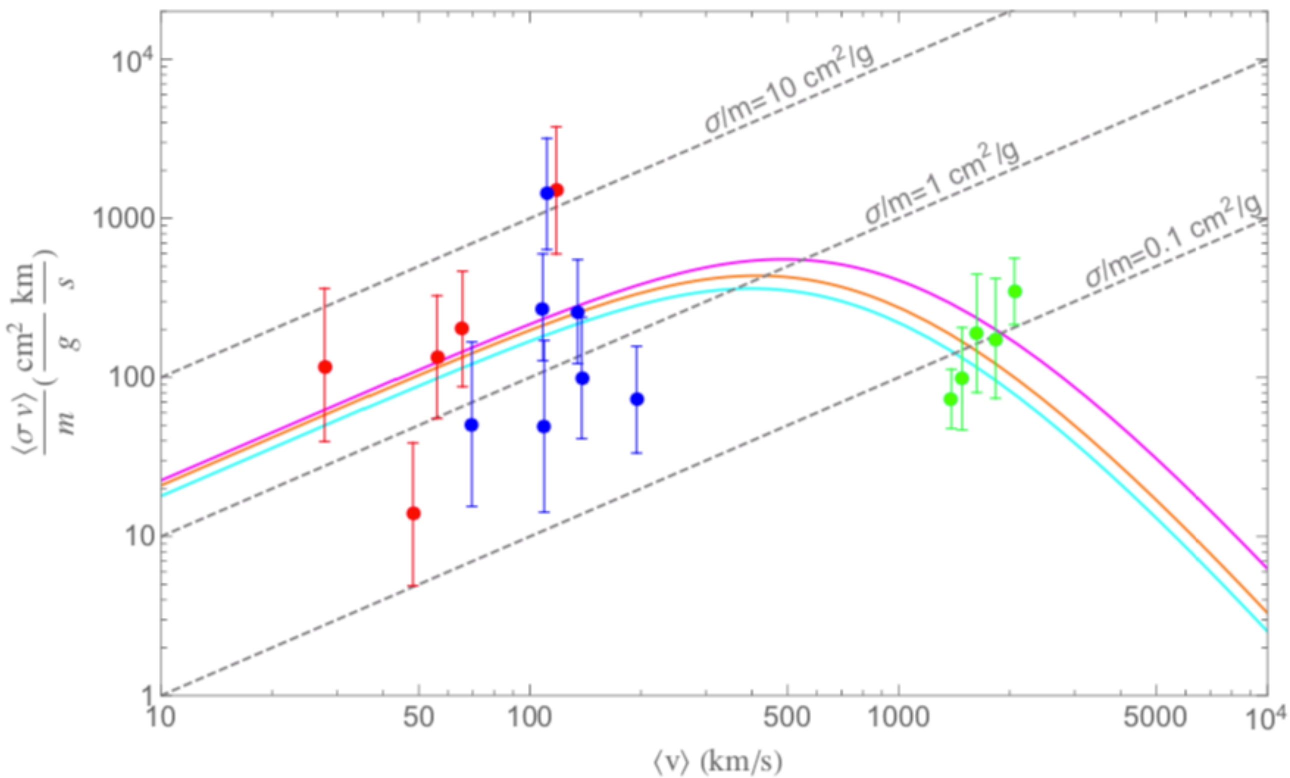
- All three terms (photon, photino, D-) have consequences
- D-term most important andcommunicates MSSM SUSY breaking to charged boson masses

$$m_{\pm,\mathrm{bos}}^2 = m_0^2 \left(1 + \frac{g_D^2}{4\pi^2} \log \frac{v}{m_D} \pm \epsilon \frac{g_{\mathrm{D}}}{e} \cos 2\beta \frac{(56\mathrm{GeV})^2}{m_0^2}\right)$$

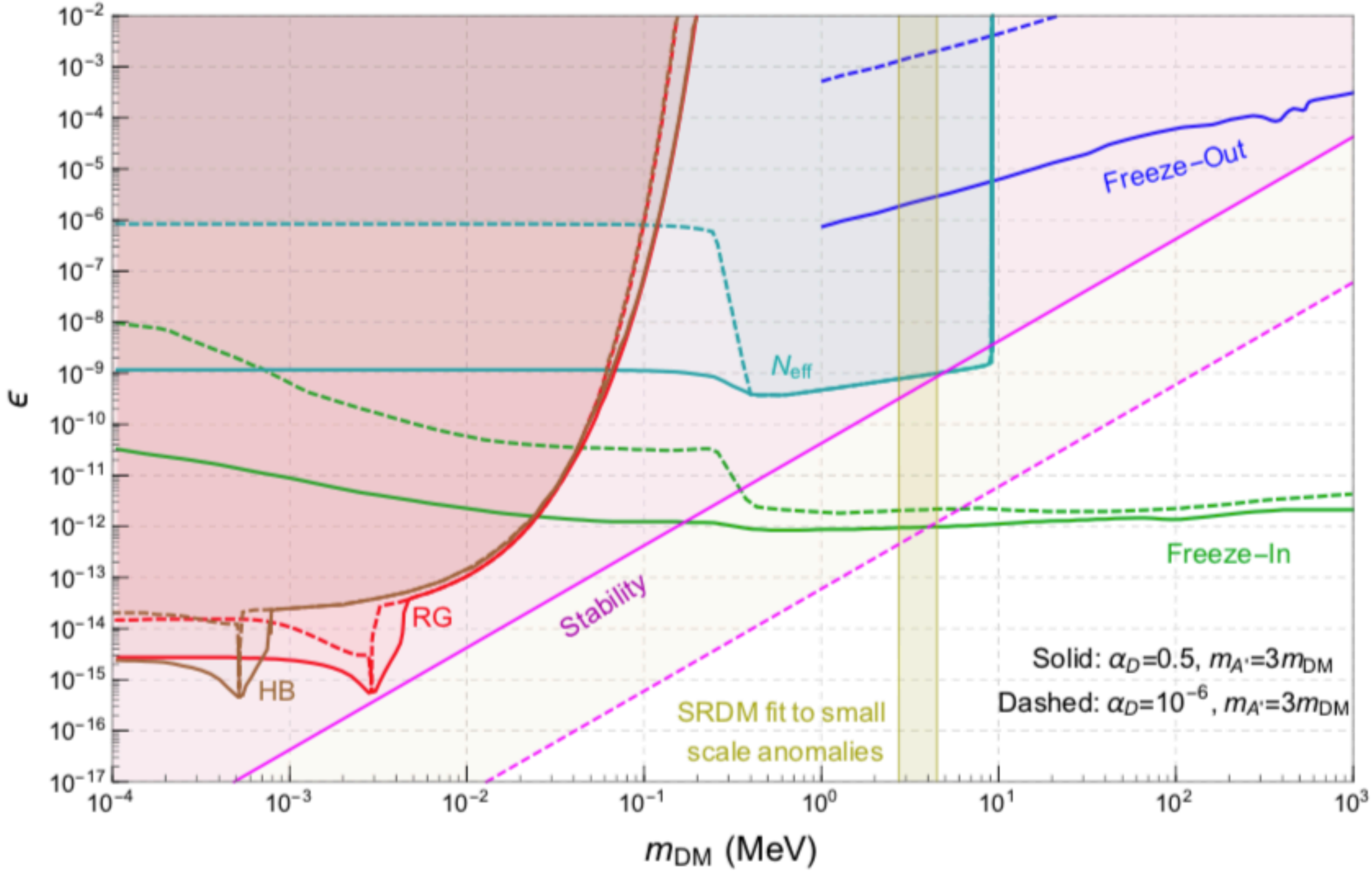
- Fermions only feel supersymmetric dark QED term
- Therefore, in general only neutral feel resonance

Self-Interactions

- Plotted for N_f = 2 (orange), 4 (cyan), 25 (magenta)
- For N_f = 2, find m = 3 MeV and y = 5×10^{-4}
- For larger N_f, coupling quite stable but mass decreases



Fitting to Relic Abundance



Modified plot from Chang et al. 2021

Comments on last slide

- Freeze-out is ruled out in our mass range by N_{eff}
- Stability is condition that neutral DM is lighter than charged DM (otherwise would down-scatter and lose resonance)
- Freeze-in is allowed for a wide range of α_D
- Dark photon must be heavier than DM
- Otherwise, wide range of dark photon masses allowed as freeze-in line moves up like $m_A^{1/2}$

Conclusions

- SUSY provides a natural mechanism for resonant behavior
- DM self-coupling and mass (~MeV) are fixed by small scale anomalies
- Couples to SM via dark photon portal
- Freeze-out excluded but freeze-in sees wide parameter space
- Relic DM is a combination of neutral and charged, giving possibility of direct or indirect detection

EXTRA SLIDES

Affleck-Dine-Seiberg Superpotential

- Chiral symmetry breaking, but no confinement
- Bosonic components of quarks (squarks) get VEVs, partially Higgsing the gauge group before it gets strongly coupled (in their sector)
- Can parameterize the vacuum manifold (moduli space) with color singlet meson fields
- Instead, superpotential generated through instantons (only $N_f = N_c - 1$) or gluino condensate

$$W_{\mathrm{ADS}} = (N_c - N_f)\left(\frac{\Lambda_{\mathrm{H}}^{3N_c - N_f}}{\det \widetilde{M}}\right)^{\frac{1}{N_c - N_f}}$$

$$\widetilde{M}_{ij} = Q_i^a \bar{Q}_{a\,j}$$

- Quantities here are holomorphic, not canonical

ADS Continued

- Quark mass protects from run-away potential

$$W = (N_c - N_f)\left(\frac{\Lambda^{3N_c - N_f}}{\det \widetilde{M}}\right)^{\frac{1}{N_c - N_f}} + \sqrt{N_f}\mu S \qquad \widetilde{M} = \frac{1}{\sqrt{N_f}} S \cdot \mathbf{1} + M$$

- As the quark mass approaches the cutoff, the VEV lowers to the cutoff, and the UV gauge theory breaks at stronger coupling
- Reflected in IR by meson masses approaching cutoff
- The ground state of the theory the singlet S has a VEV
- Will expand the denominator around this VEV

Chiral Anomaly and Decaying Mesons

- Where does this process come from? $\pi^0 \to \gamma\gamma$
- Take QCD with chiral fermion content (like SM)
- Generates anomalous non-gauged symmetries
- Where the massless IR fermions to match this?
- None. Instead get a WZW term in chiral Lagrangian proportional to

$$\pi^0 F\widetilde{F} \qquad\qquad \pi^0 \to \pi^0 + \alpha$$

- In our case, there are fermions in the IR (remember meson superfields), but anomaly unmatched
- Our dark neutral mesons can decay too

Chiral Anomaly Continued

- Our WZW term is proportional to

$$((1-N_f)\,\mathrm{Tr}\left(\widetilde{M}Q^2\right)+2\,\mathrm{Tr}\left(\widetilde{M}Q\right)\mathrm{Tr}\,Q-\mathrm{Tr}\,\widetilde{M}\,\mathrm{Tr}\,Q^2)(W_\alpha W^\alpha|_{\theta^2})$$

- Where Q is the diagonal quark charge matrix
- But dark photon mixing with SM photon means neutral mesons can decay to two photons
- Prevent this by enforcing

$$Q^2 \propto \mathbf{1} \text{ and } \mathrm{Tr}\,Q = 0$$

- First already required to maintain quark mass degeneracy
- Second not possible if N_f is odd

The D-term

- The last slide was pretty constraining, remember D-term

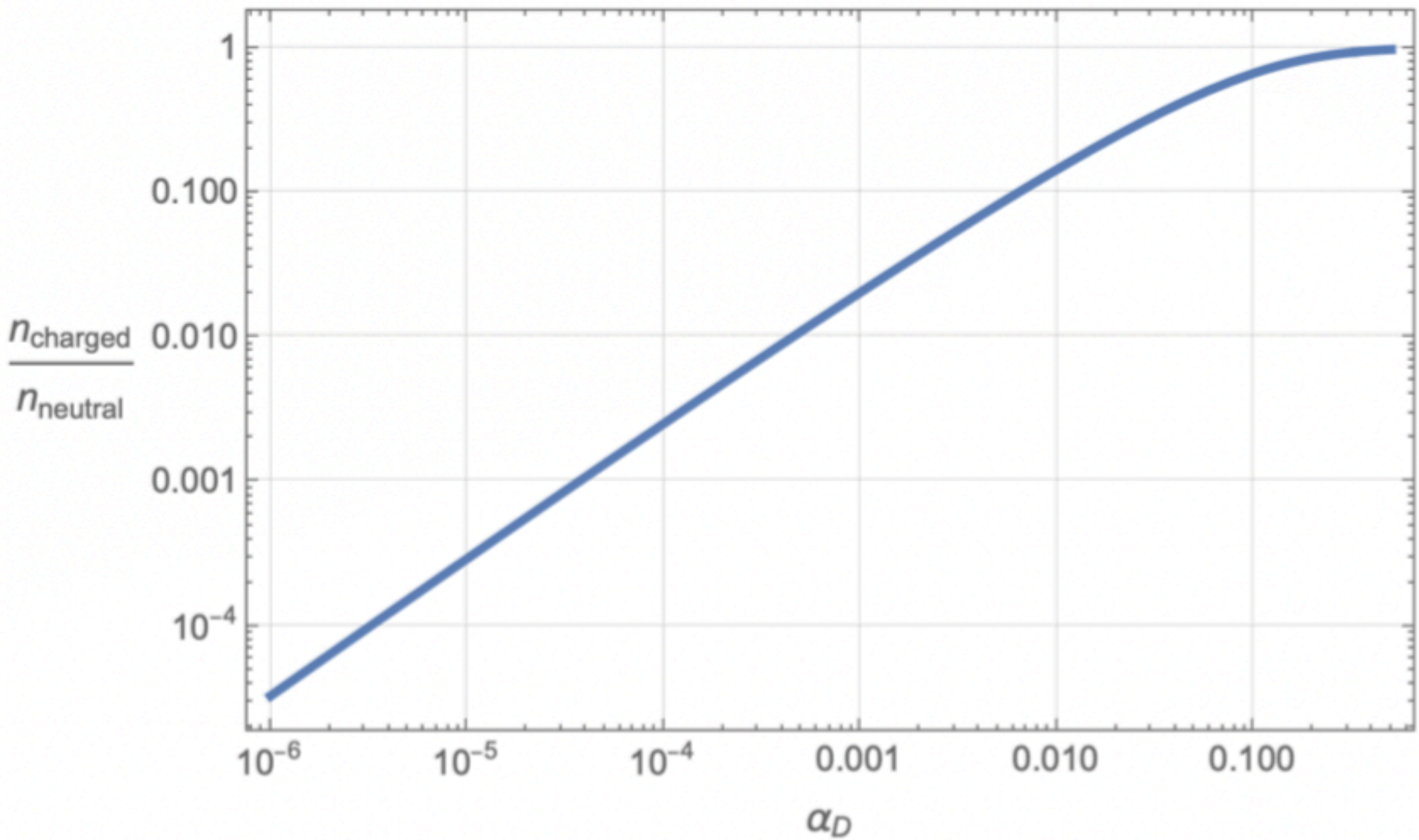
$$\mathcal{L} \supset \frac{1}{2}D_{\mathrm{D}}^2 + D_{\mathrm{D}}J_{\mathrm{D}} + \frac{1}{2}D_{\mathrm{Y}}^2 + D_{\mathrm{Y}}J_{\mathrm{Y}} + 2\epsilon D_{\mathrm{D}}D_{\mathrm{Y}}$$

- Where the Js are scalar-quadratic currents
- Solving for D EOM gives scalar-quartic terms
- But the MSSM current has a VEV (Higgs)

$$2\epsilon\frac{g_{\mathrm{Y}}}{2}(|H_u|^2 - |H_d|^2)g_{\mathrm{D}}\sum_i q_i\phi_i^*\phi_i$$

- A mass splitting for charged bosonic mesons
- The lightest particles of the theory are protected from decay by dark charge conservation

Relic DM



1
0.100
0.010
0.001
10^{-4}
$\frac{n_{\text{charged}}}{n_{\text{neutral}}}$
10^{-6}
10^{-5}
10^{-4}
0.001
0.010
0.100
α_D