



SIMPLe Dark Matter and Non-Abelian Hidden Sectors

*Kimberly Boddy, University of Hawaii
U.S. Cosmic Visions: New Ideas in Dark Matter
24 March 2017*

WIMP(LESS) MIRACLE

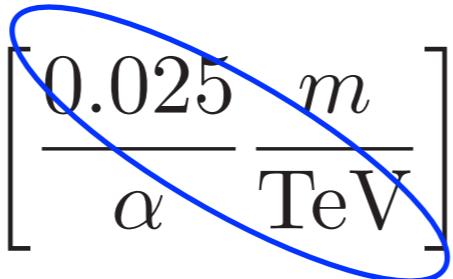
WIMP(LESS) MIRACLE

- Relic density from s-wave annihilation

$$\Omega_{\text{CDM}} \simeq 0.23 \frac{\xi_f}{k} \left[\frac{0.025}{\alpha} \frac{m}{\text{TeV}} \right]^2$$

WIMP(LESS) MIRACLE

- Relic density from s-wave annihilation

$$\Omega_{\text{CDM}} \simeq 0.23 \frac{\xi_f}{k} \left[\frac{0.025}{\alpha} \frac{m}{\text{TeV}} \right]^2 \quad \textit{WIMP miracle}$$


WIMP(LESS) MIRACLE

- Relic density from s-wave annihilation

$$\Omega_{\text{CDM}} \simeq 0.23 \frac{\xi_f}{k} \left[\frac{0.025}{\alpha} \frac{m}{\text{TeV}} \right]^2$$

WIMP miracle

WIMPless miracle

$$\Omega_{\text{CDM}} \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{\alpha^2}$$

Feng, Kumar (2008)

WIMP(LESS) MIRACLE

- Relic density from s-wave annihilation

$$\Omega_{\text{CDM}} \simeq 0.23 \frac{\xi_f}{k} \left[\frac{0.025}{\alpha} \frac{m}{\text{TeV}} \right]^2$$

WIMP miracle

WIMPless miracle

$$\Omega_{\text{CDM}} \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{\alpha^2}$$

Feng, Kumar (2008)

- Do not need to be restricted to weak-scale particles

WIMP(LESS) MIRACLE

- Relic density from s-wave annihilation

$$\Omega_{\text{CDM}} \simeq 0.23 \frac{\xi_f}{k} \left[\frac{0.025}{\alpha} \frac{m}{\text{TeV}} \right]^2$$

WIMP miracle

WIMPless miracle

$$\Omega_{\text{CDM}} \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{\alpha^2}$$

Feng, Kumar (2008)

- Do not need to be restricted to weak-scale particles
- Hidden sector may have dark forces and a different temperature $\xi = T^h/T$

WIMP(LESS) MIRACLE

- Relic density from s-wave annihilation

$$\Omega_{\text{CDM}} \simeq 0.23 \frac{\xi_f}{k} \left[\frac{0.025}{\alpha} \frac{m}{\text{TeV}} \right]^2$$

WIMP miracle

WIMPless miracle

$$\Omega_{\text{CDM}} \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{\alpha^2}$$

Feng, Kumar (2008)

- Do not need to be restricted to weak-scale particles
- Hidden sector may have dark forces and a different temperature $\xi = T^h/T$
- Visible and hidden sectors may have been connected at some high scale
 - Possibly useful for baryon asymmetry, reheating, SUSY, etc.
 - ξ must be sufficiently small to evade BBN/CMB bounds on N_{eff}

SU(N) GAUGE THEORY

- SU(N) hidden sector particles:
 - massless hidden gluon
 - fundamental fermions (i.e., hidden quarks)
 - adjoint fermions (i.e., hidden gluinos)
- 1-loop beta function coefficient
 - with SUSY: $b = -3N + N_f$
 - w/o SUSY: $b = -(11/3)*N + (2/3)*N_f$
- Confinement: $\Lambda = \mu^* \exp(2\pi/b\alpha(\mu))$

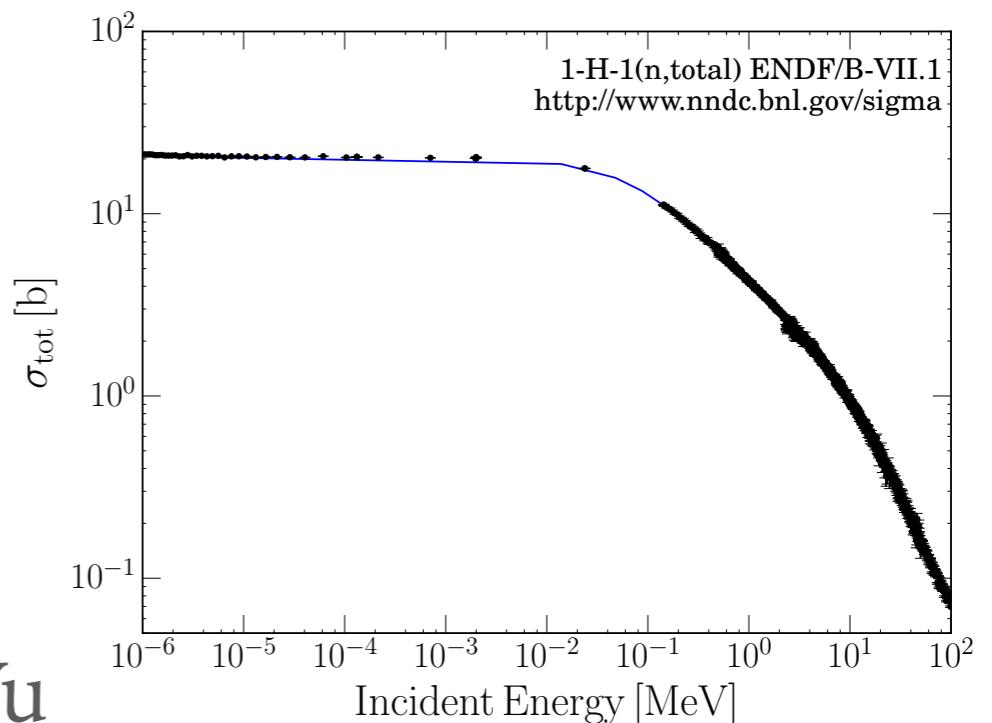
WHY CONSIDER CONFINING MODELS?

WHY CONSIDER CONFINING MODELS?

- Spectrum of composite states allow for inelastic processes
- Attempt to explain DAMA/LIBRA, INTEGRAL 511 keV line, Perseus 3.5 keV line

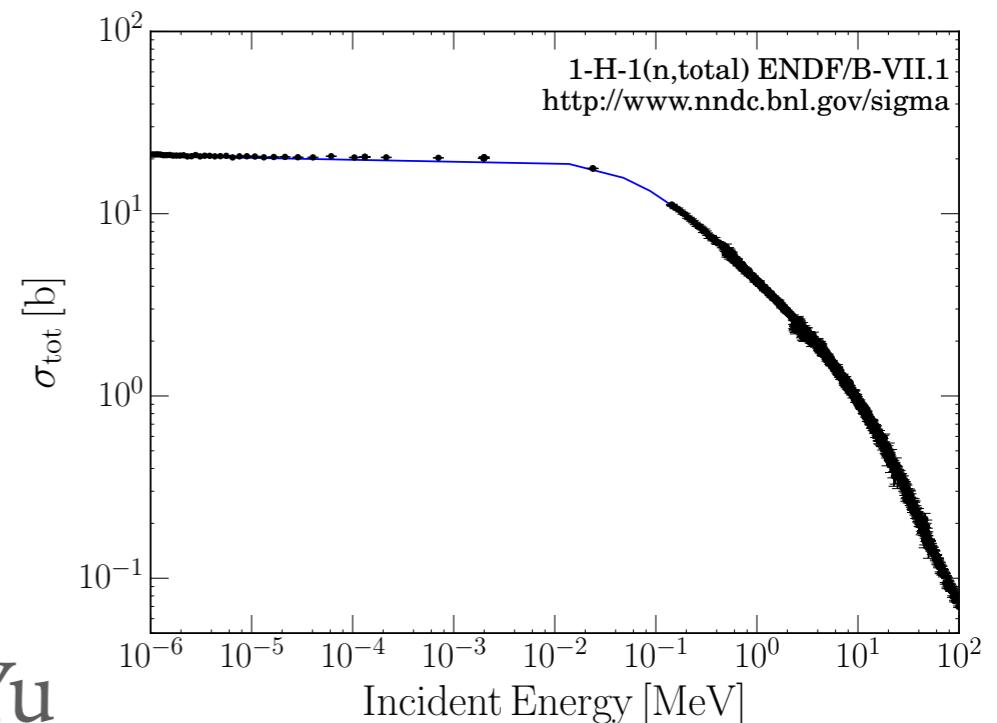
WHY CONSIDER CONFINING MODELS?

- Spectrum of composite states allow for inelastic processes
 - Attempt to explain DAMA/LIBRA, INTEGRAL 511 keV line, Perseus 3.5 keV line
- Composite states have large self-interaction cross sections
 - Attempt to explain small-scale structure anomalies
 - $\sigma/m \sim 1 \text{ cm}^2/\text{g} \sim \text{barn}/\text{GeV}$
 - Velocity dependence
 - See talks by Peter and Kaplinghat/Yu



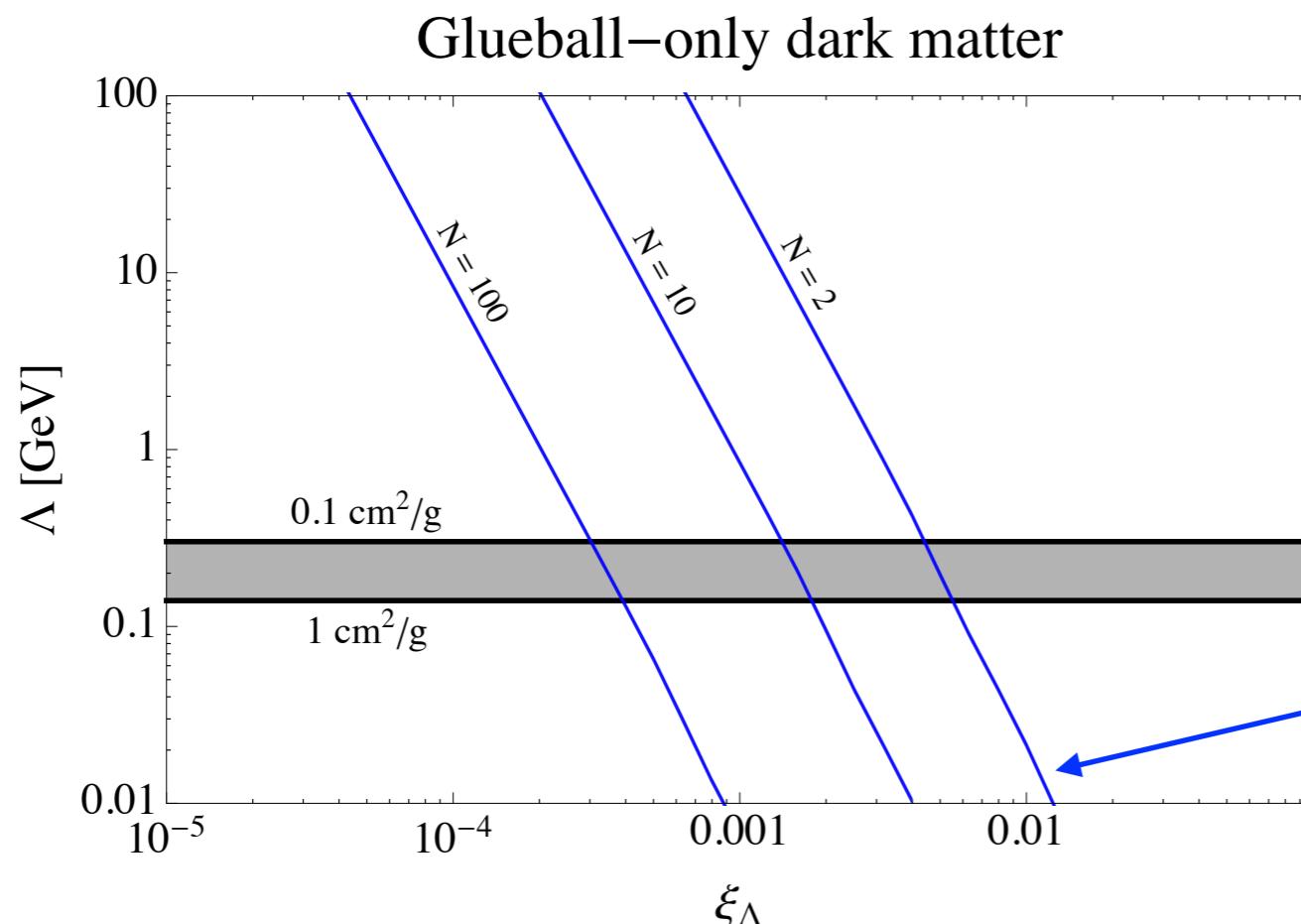
WHY CONSIDER CONFINING MODELS?

- Spectrum of composite states allow for inelastic processes
 - Attempt to explain DAMA/LIBRA, INTEGRAL 511 keV line, Perseus 3.5 keV line
- Composite states have large self-interaction cross sections
 - Attempt to explain small-scale structure anomalies
 - $\sigma/m \sim 1 \text{ cm}^2/\text{g} \sim \text{barn}/\text{GeV}$
 - Velocity dependence
 - See talks by Peter and Kaplinghat/Yu
- Confinement separates physics of early and late universe



MINIMAL MODEL

- Gluons and composite glueballs with mass $\sim \Lambda$
- Massless gluon sets relic density; no Boltzmann suppression
- Geometric scattering cross section (velocity-independent)
- Need to account for cannibalization



target SIDM (at small N)

$$\sigma \sim \frac{4\pi}{\Lambda^2 N^2}$$
$$\Omega_{gb} \approx \frac{s_0}{\rho_{c0}} \frac{2(N^2 - 1)}{g_* S(T_f)} \xi_\Lambda^3 \Lambda$$

CANNIBALIZATION

- 3-to-2 scattering keeps glueballs in kinetic equilibrium until decoupling via Hubble expansion
- Visible and hidden sectors conserve entropy separately

$$s^h = \frac{2\pi^2}{45} g_{*S}^h (T^h)^3 \propto a^{-3}$$

- At confinement, conserve energy density between gluons and glueballs

$$\rho = s^h T^h \approx \Lambda n = \Lambda \left(\frac{\Lambda T^h}{2\pi} \right)^{3/2} e^{-\Lambda/T^h}$$

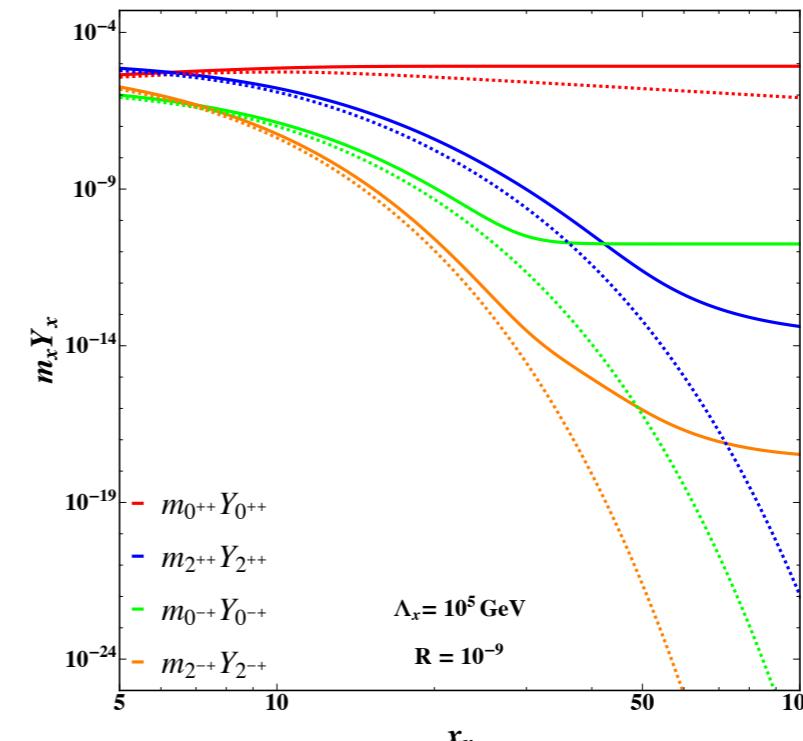
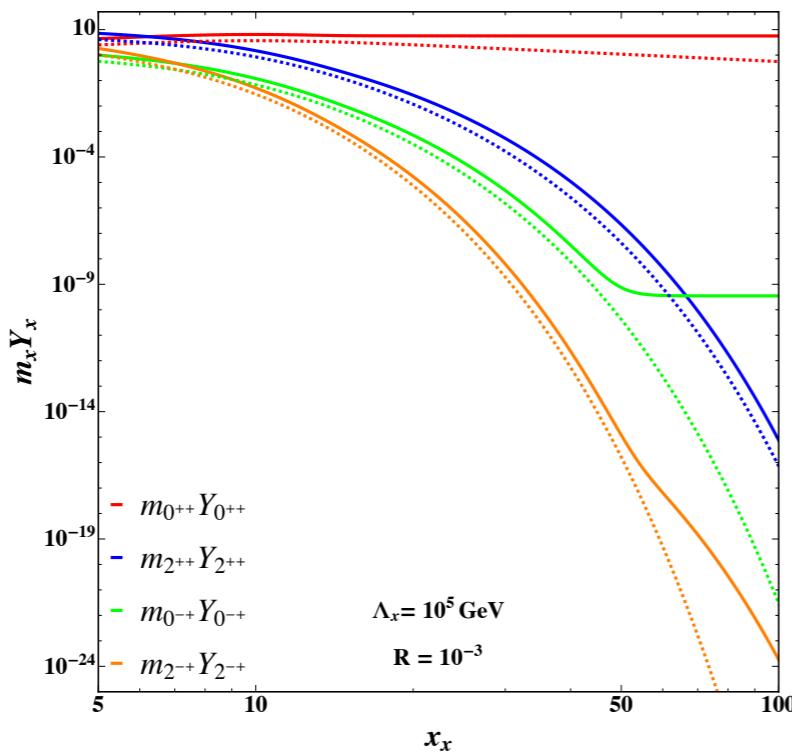
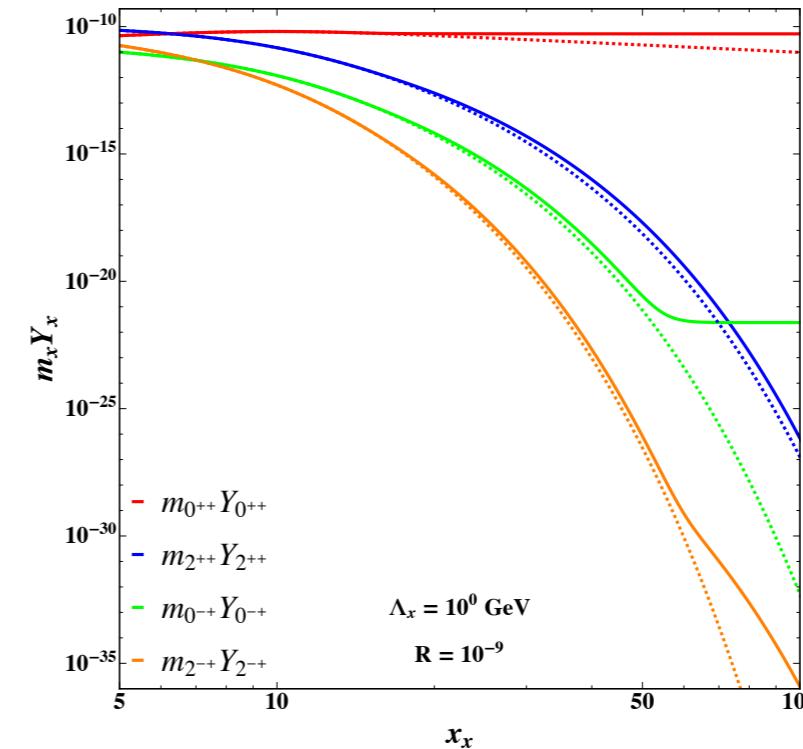
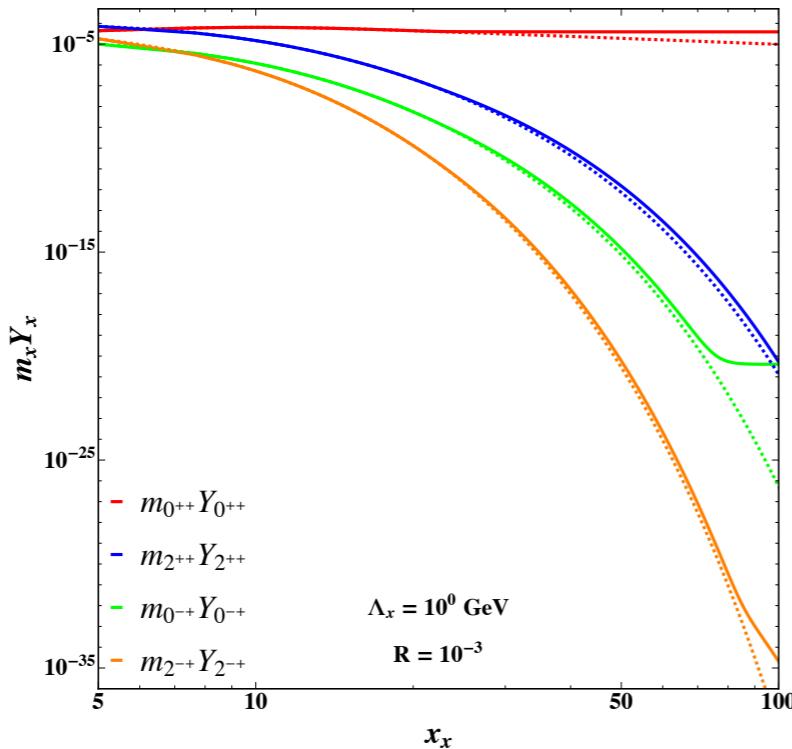
- Temperature decreases slower than for normal nonrelativistic matter

$$\frac{T^h}{\Lambda} \simeq \frac{1}{3 \log(a)}$$

EXCITED GLUEBALL STATES

.....

$$R = s^h/s$$



MINIMAL “SUSY” MODEL

- Hidden sector particle content:

- Gluon g
- Gluino \tilde{g} , with mass m_X (early universe hLSP)
- Fine-structure constant at m_X

$$\alpha_X = \frac{6\pi}{11N \ln(m_X/\Lambda)}$$

- Composite particles with “strong” interactions

- Glueballs $G=(gg)$, with mass $\sim \Lambda$
- Glueballinos $\tilde{G}=(g\tilde{g})$, with mass $\sim m_X$
- Glueballino elastic scattering via exchange of glueballs
 - Modeled with Yukawa potential $V(r) = -\frac{\alpha}{r} \exp(-\Lambda r)$
 - Classical regime gives desired velocity dependence in cross section, but must solve numerically

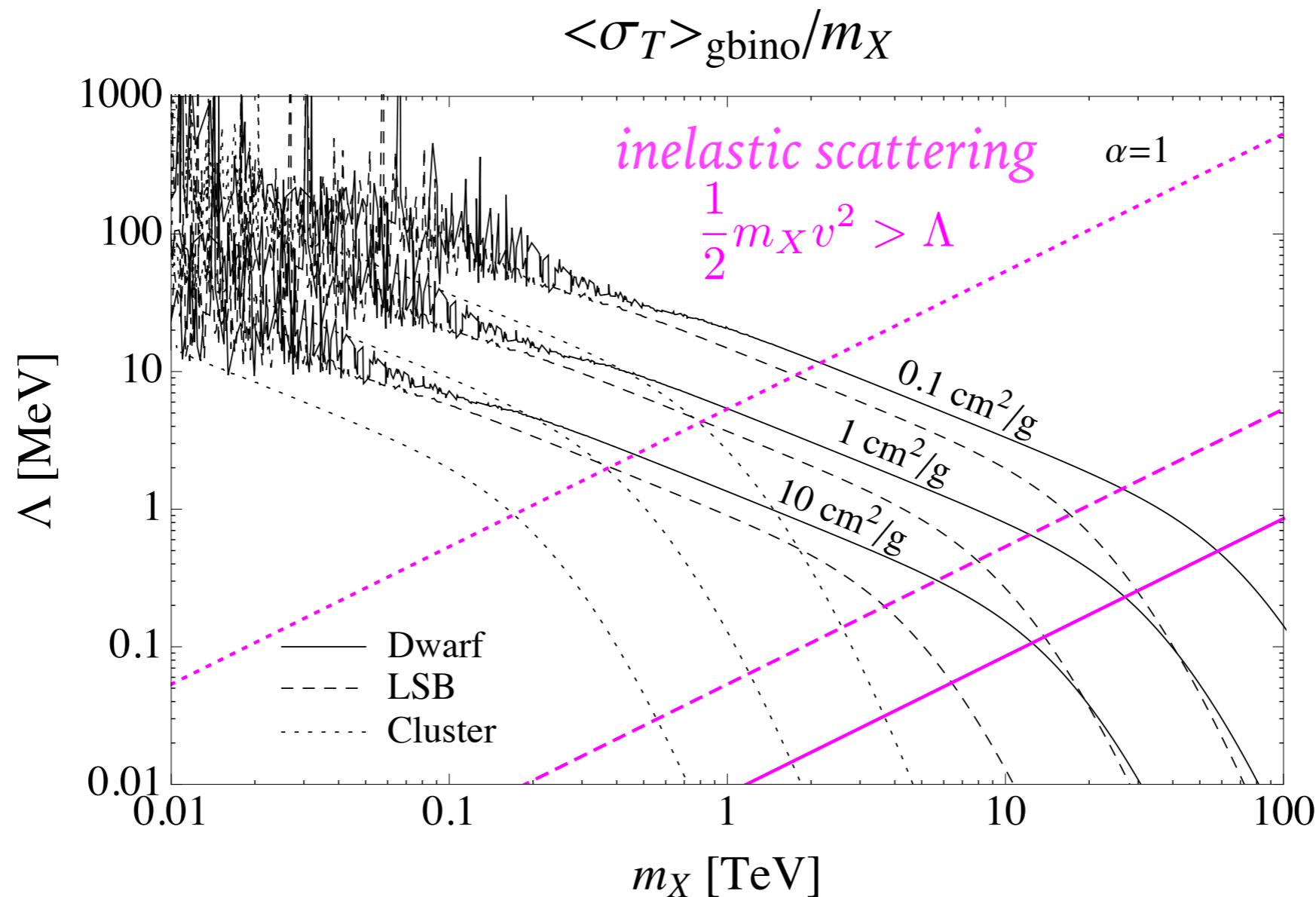
$$\langle\sigma v\rangle = \frac{3}{8} \frac{N^2}{N^2 - 1} \frac{\pi \alpha_X^2}{m_X^2}$$

$$\Omega_{\tilde{g}} \approx \frac{s_0}{\rho_{c0}} \frac{\sqrt{g_*^{\text{tot}}}}{g_{*S}(T_f)} \frac{3.79 x_f}{M_{\text{Pl}} \langle\sigma v\rangle}$$

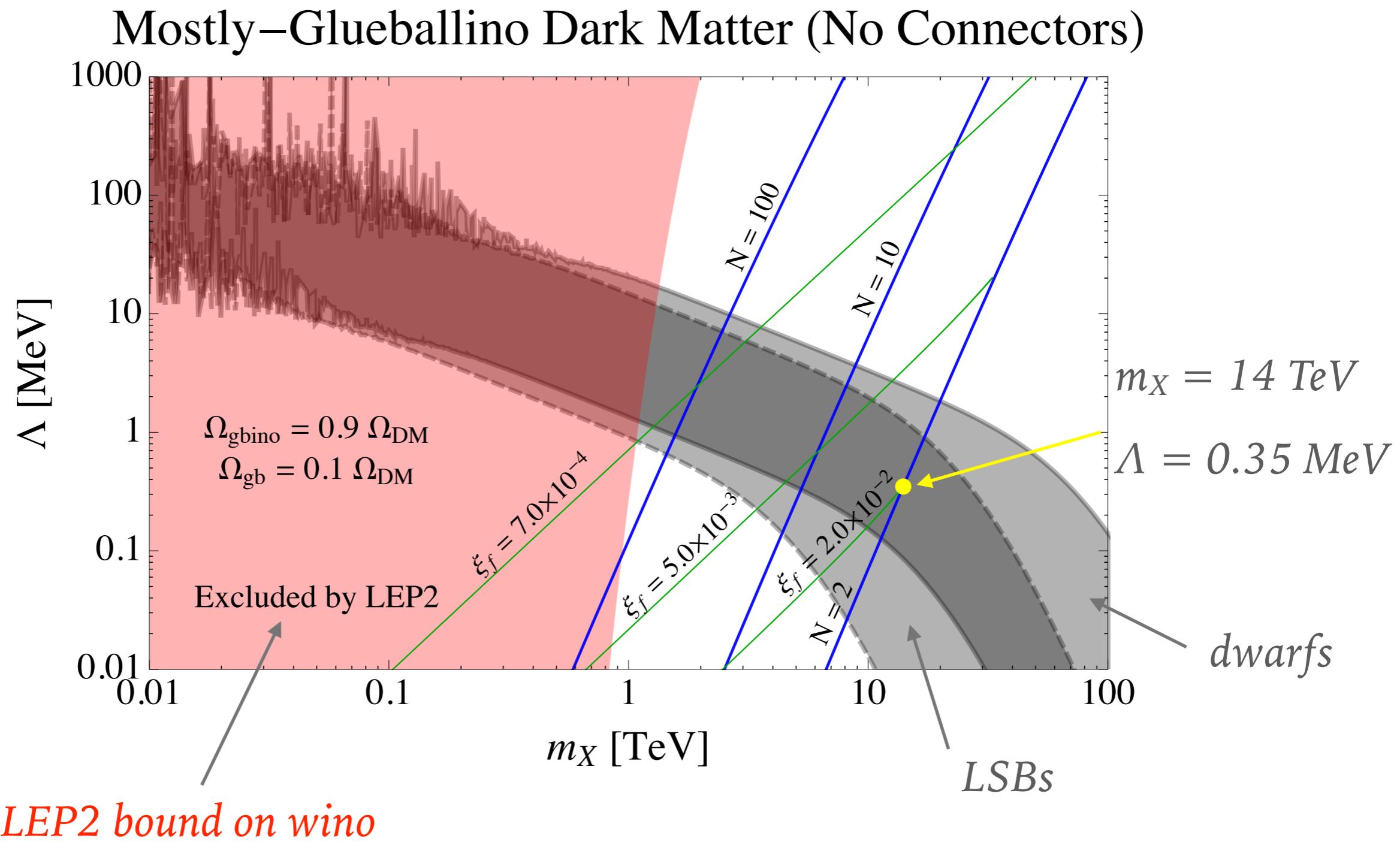
DARK MATTER SCATTERING

$$\langle \sigma_T \rangle = \int_0^{2\sqrt{2}v_0} \frac{d^3 v}{(2\pi v_0^2)^{3/2}} e^{-v^2/2v_0^2} \sigma_T(v)$$

$v_0(\text{dwarf}) \sim 40 \text{ km/s}$
 $v_0(\text{LSB}) \sim 100 \text{ km/s}$
 $v_0(\text{cluster}) \sim 1000 \text{ km/s}$



RELIC ABUNDANCE



SUMMARY

- Non-abelian SU(N) models are motivated cosmologically and astrophysically
 - Help from lattice QCD for precise calculations?
 - Help from N-body simulations for multi-component dark matter?
- Rich phenomenology \longleftrightarrow More complexity, more problems
- Particle models must provide consistent description of gravitational properties of dark matter
- With precision cosmology and more sensitive astrophysical probes, we should take care to understand limits/constraints