Light Thermal Dark Matter & Hidden Sectors

Philip Schuster (SLAC)

FNAL Dark Matter Workshop
June 4, 2019

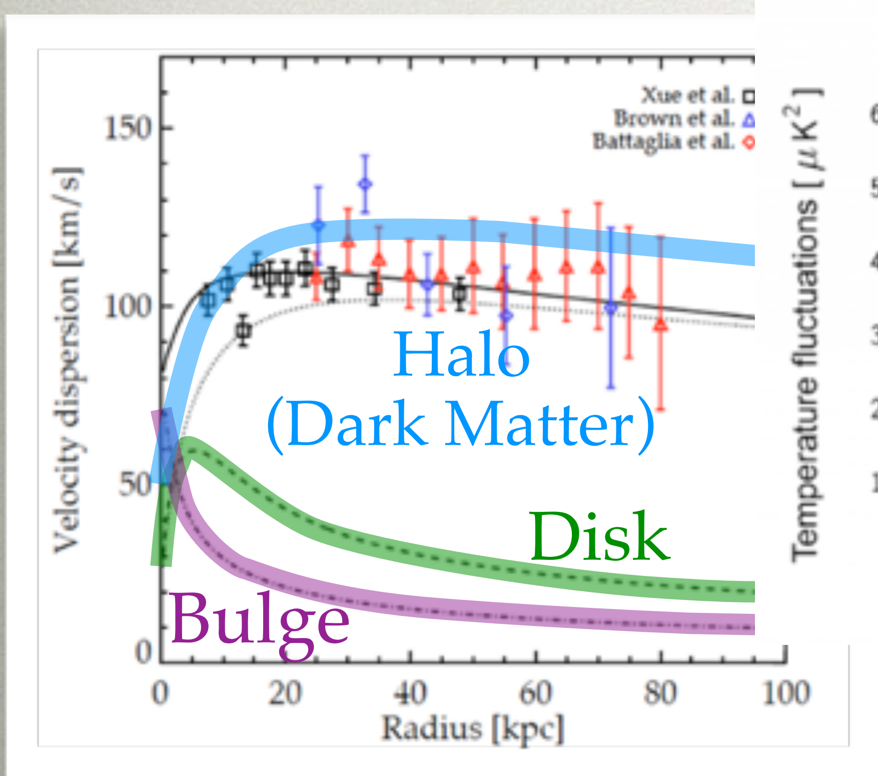
Outline

This is intended to be a non-technical introduction to sub-GeV thermal dark matter & hidden sectors

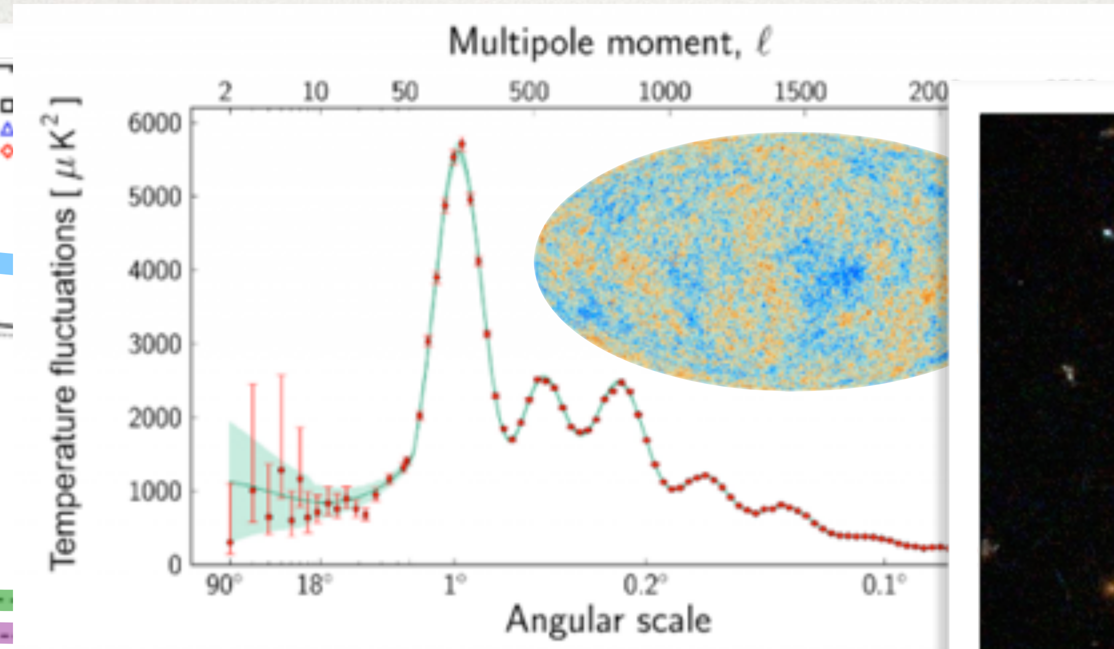
- The WIMP paradigm & thermal dark matter
- Beyond WIMPs
    - Thermal sub-GeV hidden sector dark matter
- Comments on thermal freeze-out/in parameter space w.r.t. direct detection experiments

See 2017 Cosmic Visions (1707.04591) report for many good references

Dark Matter



Rotation curves

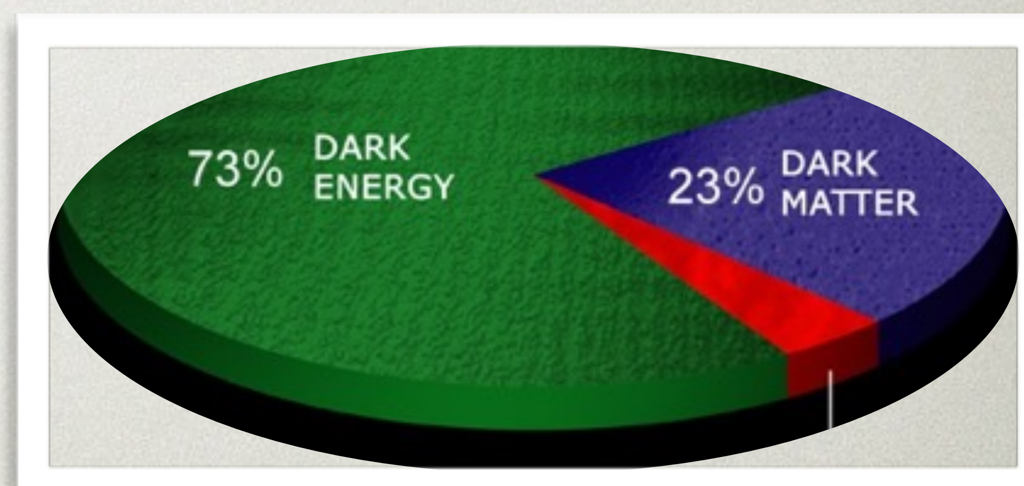


CMB Power Spectrum

Lensing

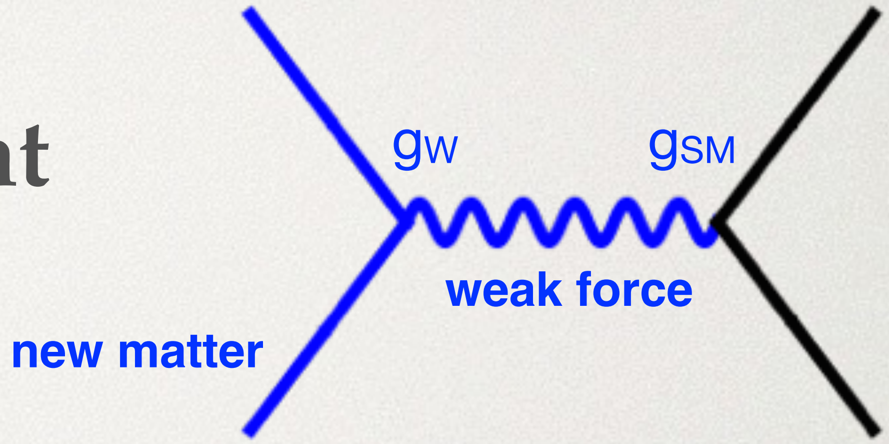
We know there is new physics in the form of dark matter!

<u>But what is it?</u>



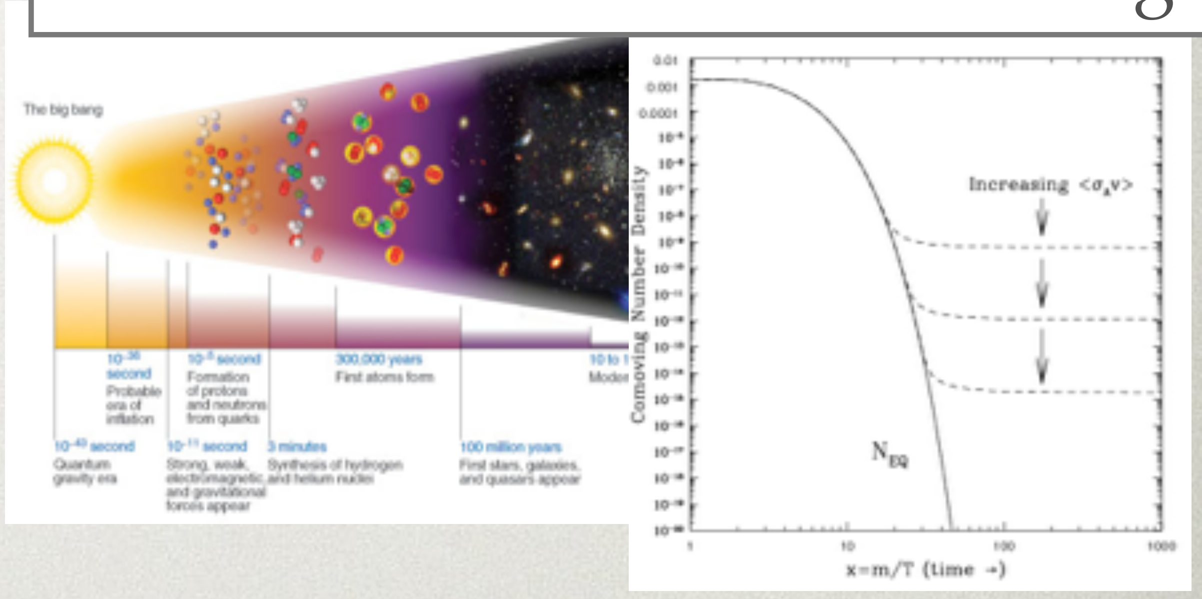
A Strong Candidate: WIMP DM

Simple, familiar particle content

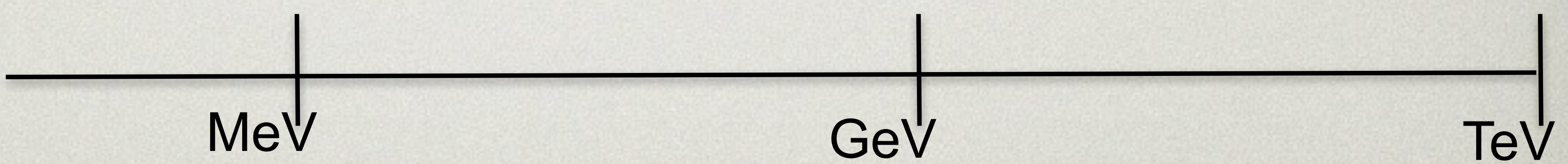


Simple, predictive cosmology

DM with thermal freeze-out origin

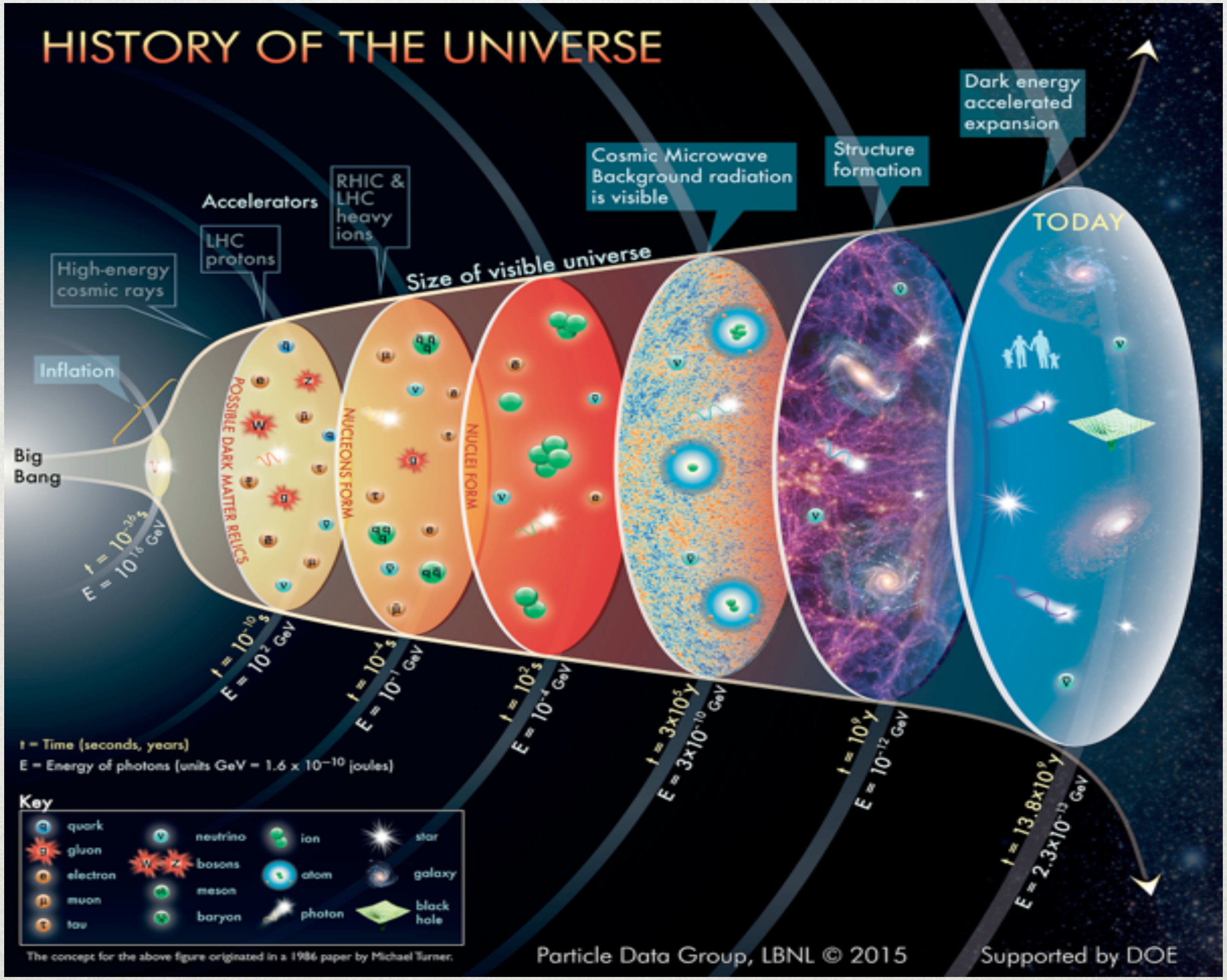


Motivated mass range



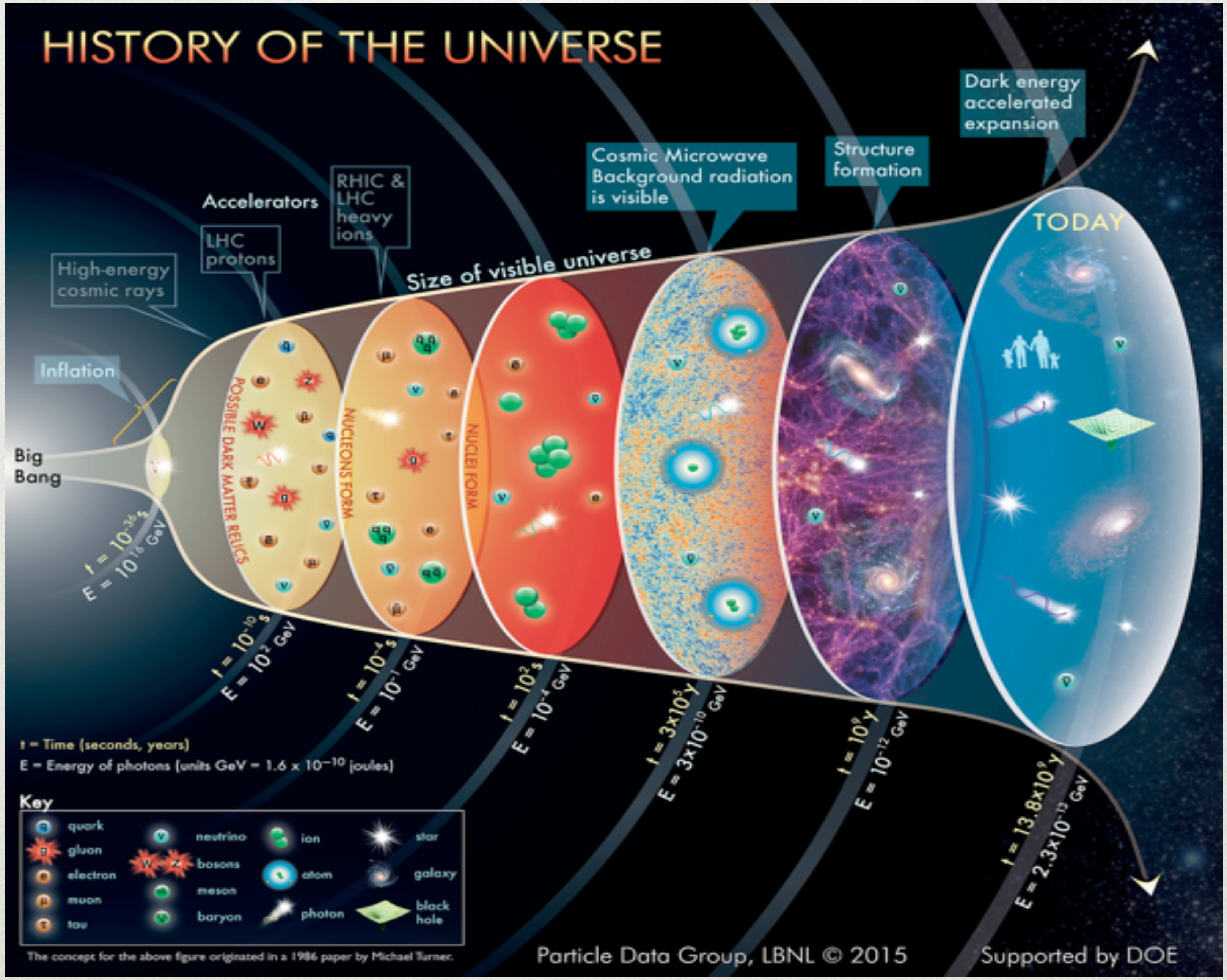
WIMP

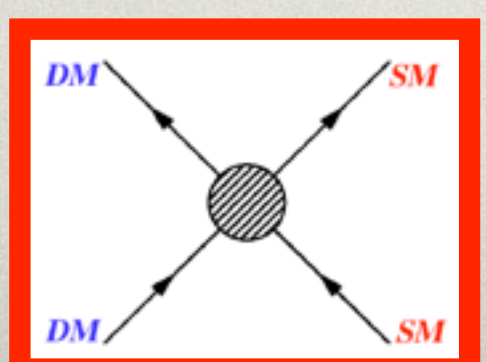
A Thermal Origin



A big lesson of 20th century cosmology — The Universe evolved from an era of hot thermodynamic equilibrium in an expanding space-time!

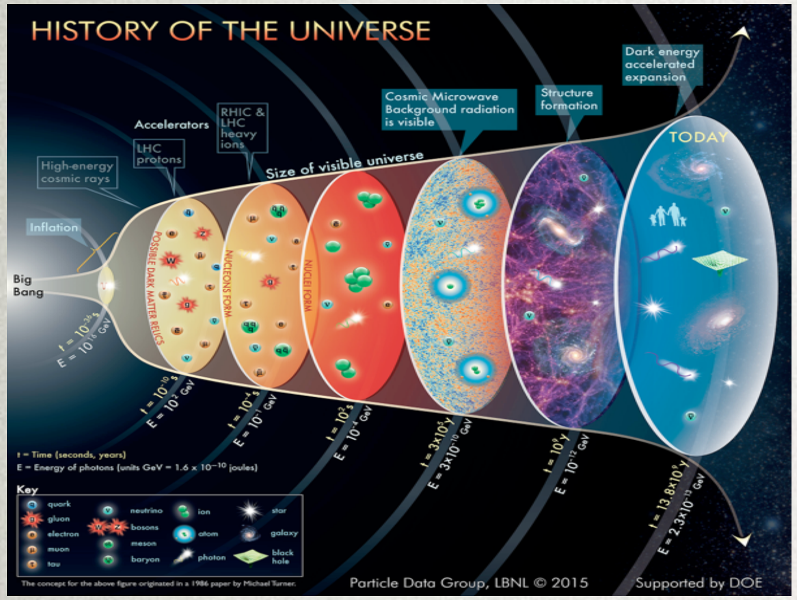
A Thermal Origin





Dark Matter interaction with familiar matter would (very) likely bring DM into thermodynamic equilibrium

A Thermal Origin



Simple and predictive Boltzmann equation governs evolution of number density "n"

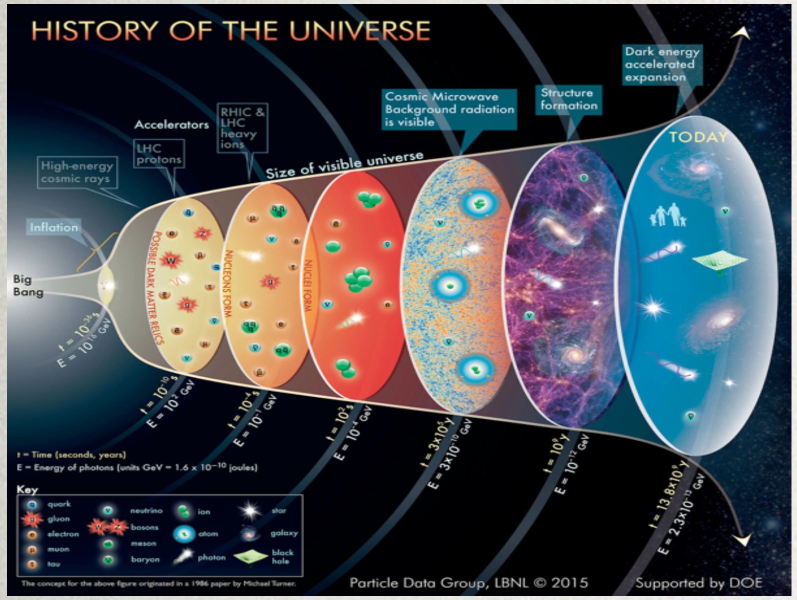
$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle \left(n^2 - n_{\text{eq}}^2\right)$$

(equilibrium number density)

Dilution from expanding Universe

Particle interactions provide thermal contact

A Thermal Origin



Simple and predictive Boltzmann equation governs evolution of number density "n"

$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle \left(n^2 - n_{\text{eq}}^2 \right)$$

As Universe cools below DM mass, density decreases as $e^{-m/T}$

Eventually dark matter particles can't find each other to annihilate

$$\longrightarrow \quad n \langle \sigma_A v \rangle = H$$

freeze-out occurs

A Thermal Origin

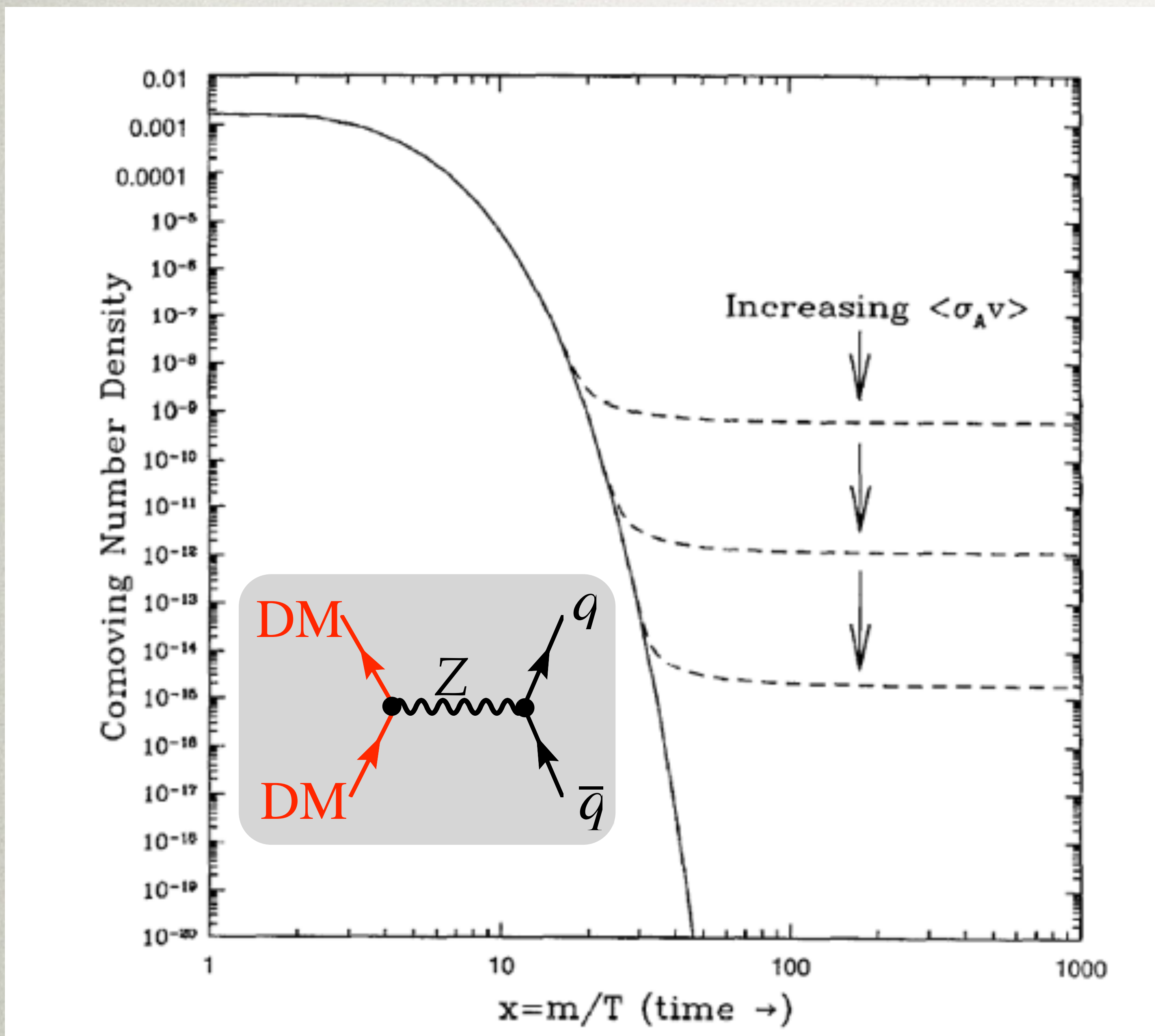
Near freeze-out:

$$n_f \sim (m_X T_f)^{3/2} e^{-m_X/T_f} \sim \frac{T_f^2}{M_{\rm Pl}\langle\sigma_A v\rangle}$$

$$\Omega_X = \frac{m_X n_0}{\rho_c} = \frac{m_X T_0^3}{\rho_c}\frac{n_0}{T_0^3} \sim \frac{m_X T_0^3}{\rho_c}\frac{n_f}{T_f^3} \sim \frac{x_f T_0^3}{\rho_c M_{\rm Pl}}\langle\sigma_A v\rangle^{-1}$$

A DM abundance (determined by interaction!) is left over to the present day

WIMPs and a Thermal Origin



Larger cross-section
⇒ later freeze-out
⇒ lower density

Correct DM density for:

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$$\simeq \frac{1}{(20\ \mathrm{TeV})^2}$$

Thermal origin suggests Dark Sector interactions and mass in the vicinity of the weak-scale

Compelled to Move Beyond WIMPs

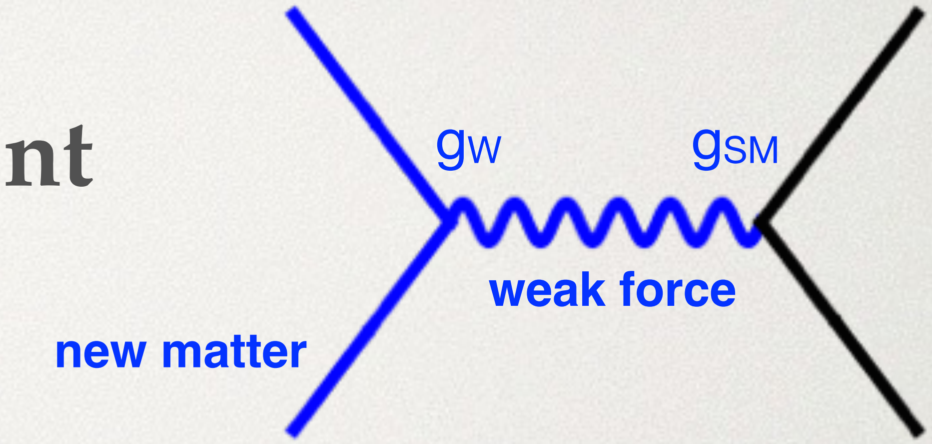
Basic weak-scale DM scenarios have been significantly constrained by the LHC, direct & indirect detection

Existing experimental program will corner remaining WIMP models over the next few years

What are we missing?

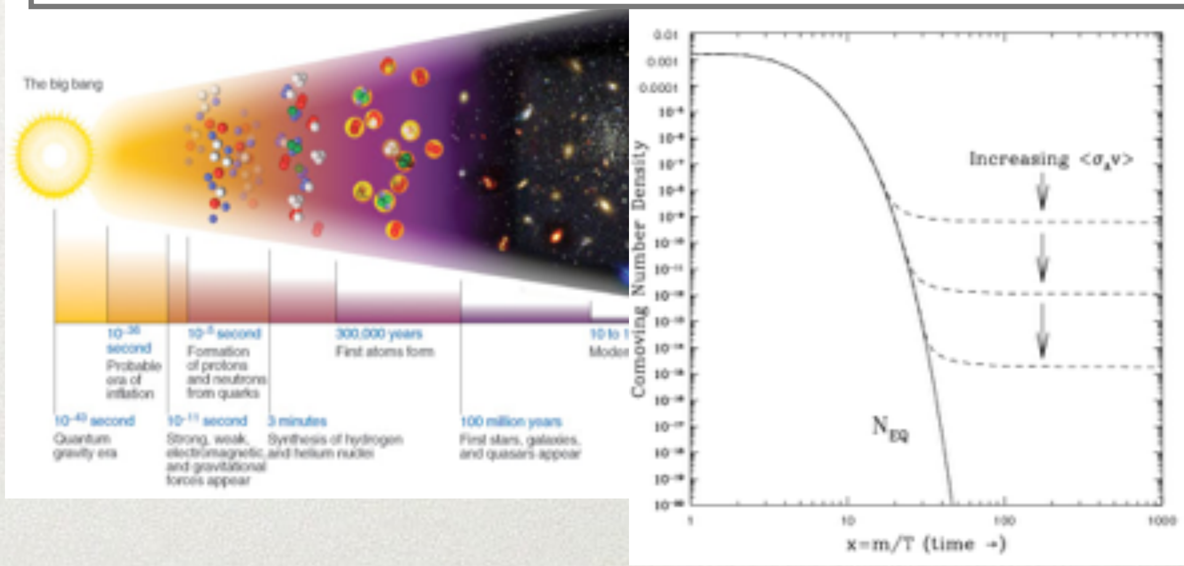
Logical Next Step Beyond WIMPs?

Simple, familiar particle content

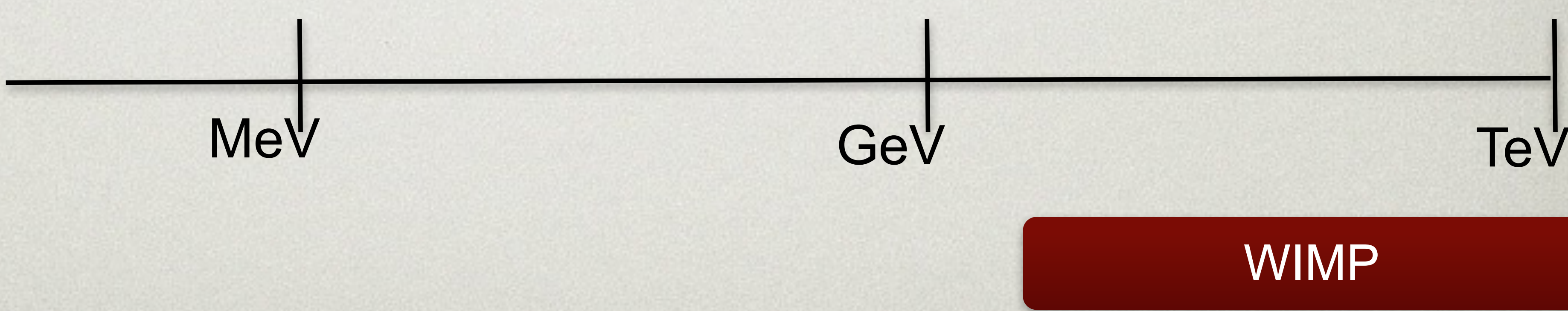


DM with thermal freeze-out origin

Simple, predictive cosmology



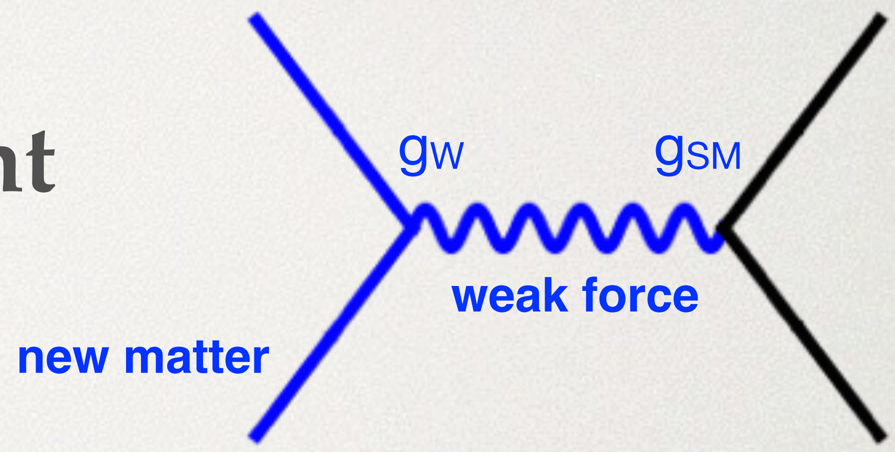
Motivated mass range



What attractive features can remain?

Lessons From Data

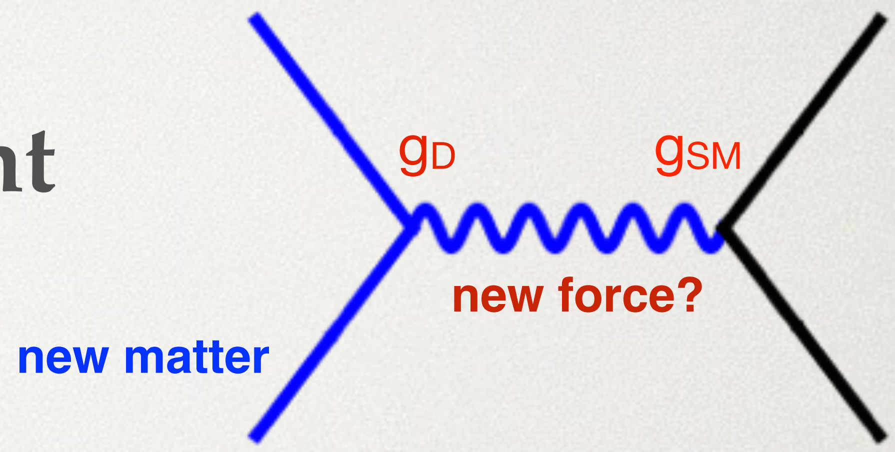
Simple, familiar particle content



The ingredient most at odds with data underlying WIMPs is that interactions are mediated by W/Z bosons.

Lessons From Data

Simple, familiar particle content



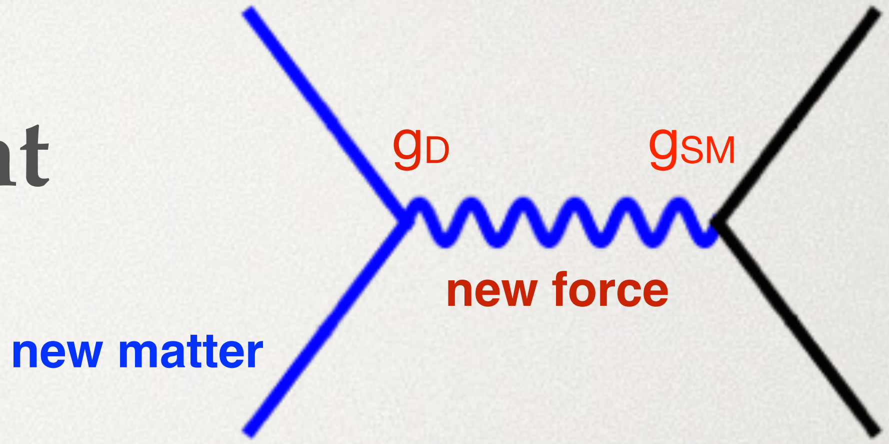
The ingredient most at odds with data underlying WIMPs is that interactions are mediated by W/Z bosons.

Dark matter could be charged under a new force!

(in keeping with the history of particle physics)

New Forces Interacting with The Standard Model

Simple, familiar particle content



Standard Model symmetries allow two types of (dim. 4) interactions with new force carriers at low-energy

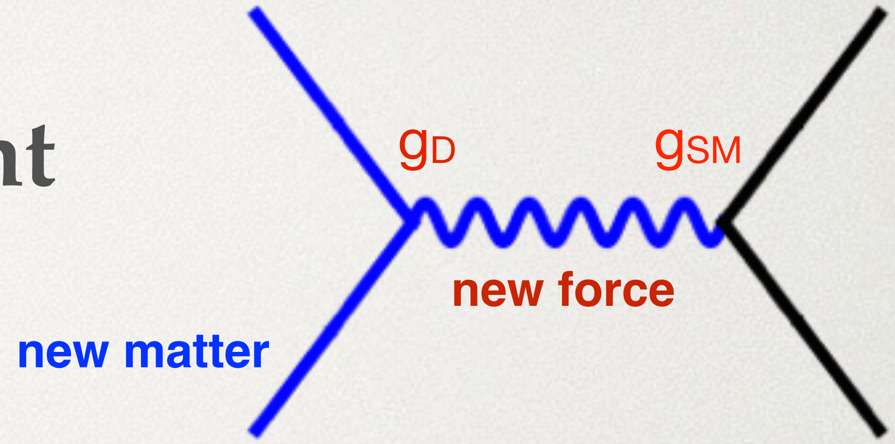
Vector Mixing $\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$

Higgs Mixing $\epsilon_h |h|^2 |\phi|^2$

+ a few other closely related possibilities…(see 1707.04591)

New Forces Interacting with The Standard Model

Simple, familiar particle content



Standard Model symmetries allow two interactions with new force carriers at low-energy

Vector Mixing $\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$

Higgs Mixing $\epsilon_h \, |h|^2 |\phi|^2$

Most compatible with cosmology & simple dark matter models, and illustrates much of the essential physics **will be focus of many talks**

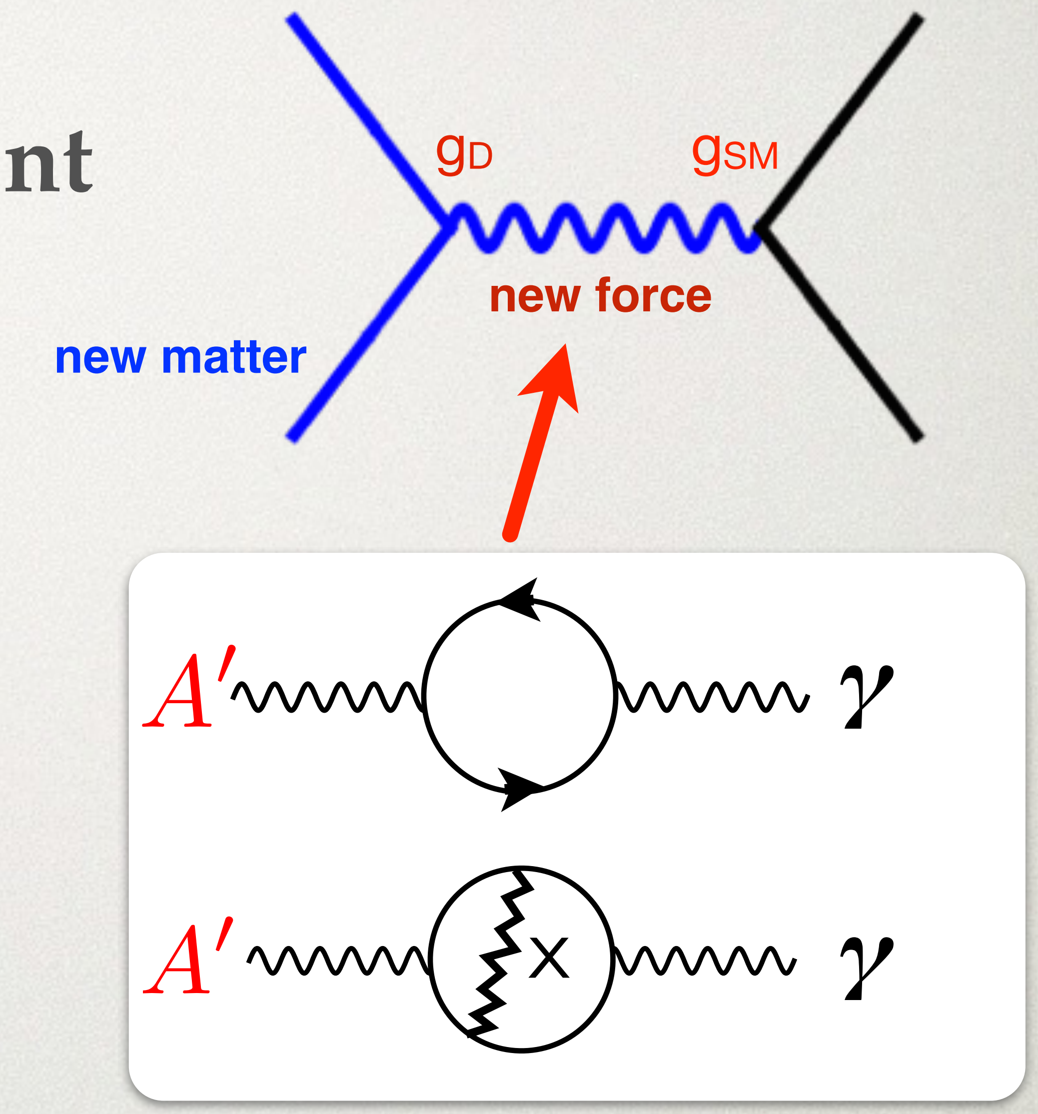
Increasingly constrained by LHC
(though other scalar couplings less constrained)

New Forces Interacting with The Standard Model

Simple, familiar particle content

Standard Model symmetries allow two interactions with new force carriers at low-energy

Vector Mixing $\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$

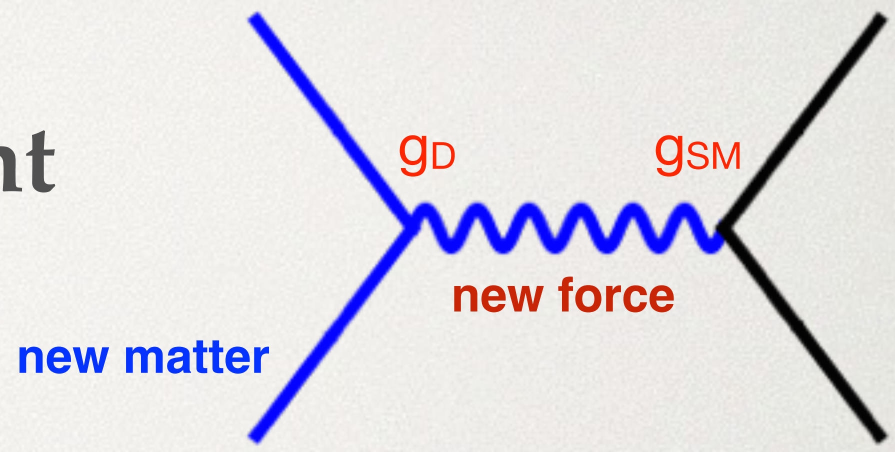


$g_{\rm SM} \sim (10^{-6} - 10^{-2})e$

Mediator particle with naturally small (loop-level) Standard Model couplings...would have missed such physics without dedicated search!

Hidden Sector Dark Matter

Simple, familiar particle content



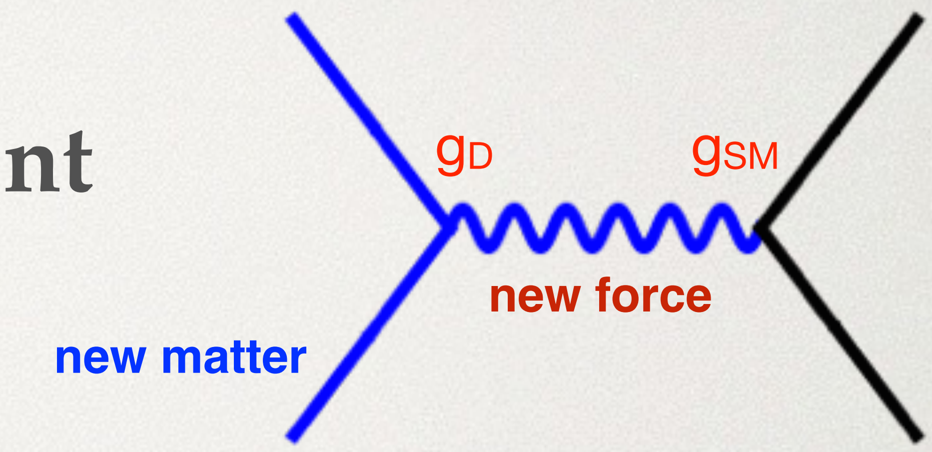
Dark Matter charged under a new force

Provides a familiar and simple explanation for dark matter stability (i.e. lightest charged particle is stable!)

Mediator mixing gives interaction with Standard Model

(Thermal) Hidden Sector DM

Simple, familiar particle content



Simple, predictive cosmology ??

Mass range ??

What About Thermal Abundance?

$$< \sigma v >= y/(m_{DM})^2 \sim 1/(20\text{TeV})^2$$

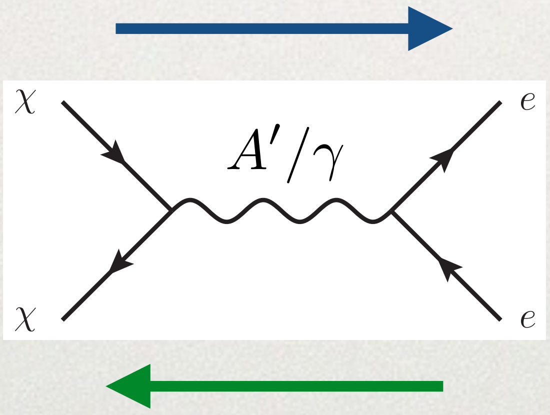
$$m_{DM} \sim \sqrt{y} \times 20 \text{ TeV} << \text{TeV}$$

Very weakly coupled thermal dark matter should have a mass below the TeV-scale to obtain measured relic density

(Direct) Thermal freeze-out works just fine down to ~MeV!

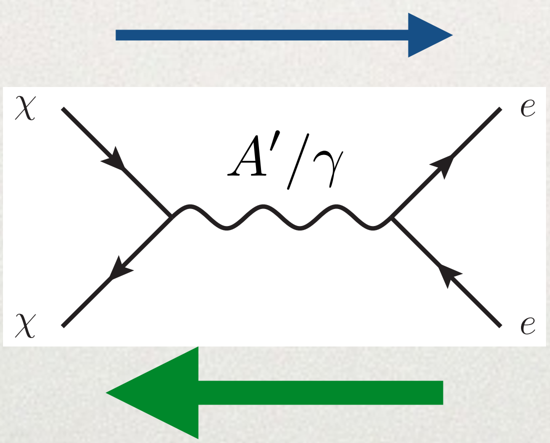
Ultra-Small Coupling & New Possibilities

If coupling is large enough for DM to thermalize, then detailed balance results



Ultra-Small Coupling & New Possibilities

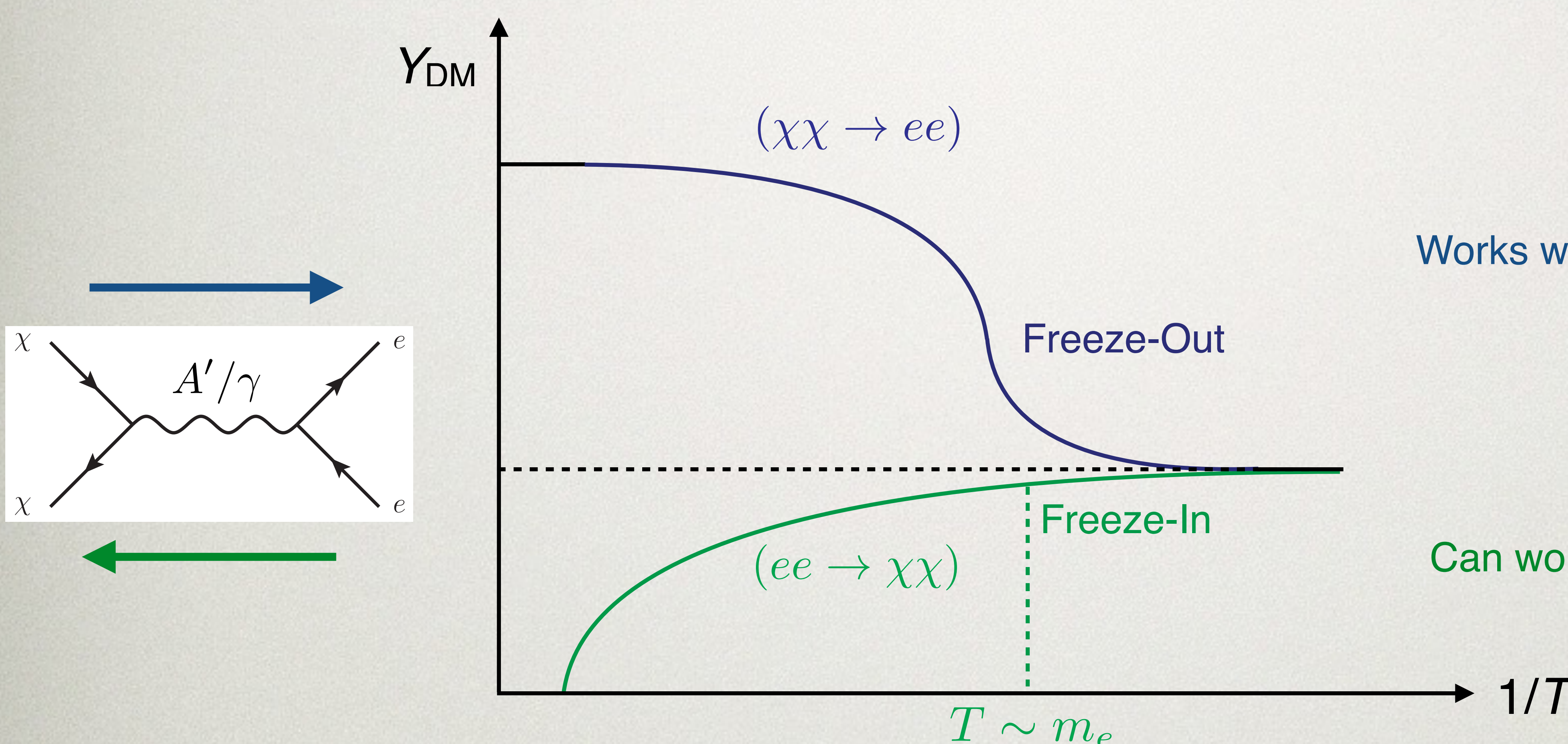
If coupling is large enough for DM to thermalize, then detailed balance results



But if coupling is too small for thermalization to occur, then DM is still produced through occasional SM reactions

Ultra-Small Coupling & New Possibilities

"Freeze-in" through a vector mediator



Works well above ~MeV

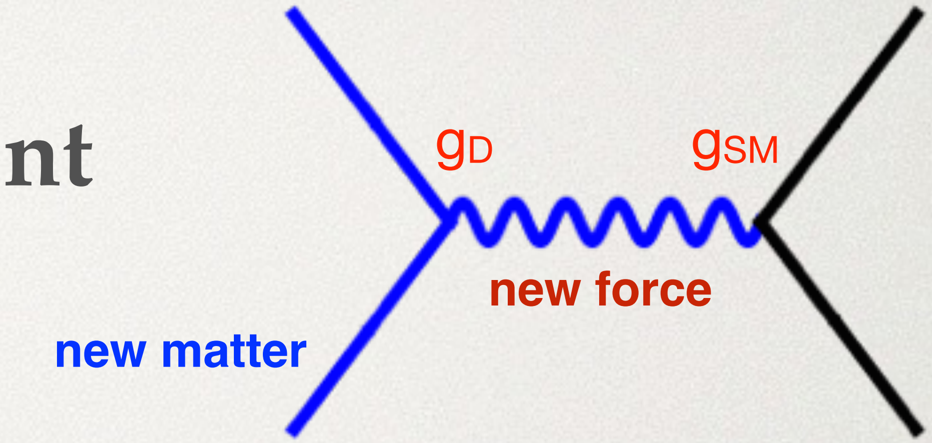
Can work below ~MeV

$$\Gamma(ee \to \chi\chi) \sim \alpha_{\rm em}^2\, q^2\, T\ ,\ \ n_\chi \sim n_e(\Gamma/H)\ ,\ \ \rho_{\rm DM} \sim T_{\rm eq}\, T^3$$

$$\Longrightarrow \boxed{q \sim \frac{1}{\alpha_{\rm em}} \left(\frac{m_e\, T_{\rm eq}}{m_\chi\, m_{\rm pl}}\right)^{1/2} \sim 10^{-11} \left(\frac{\rm MeV}{m_\chi}\right)^{1/2}}$$

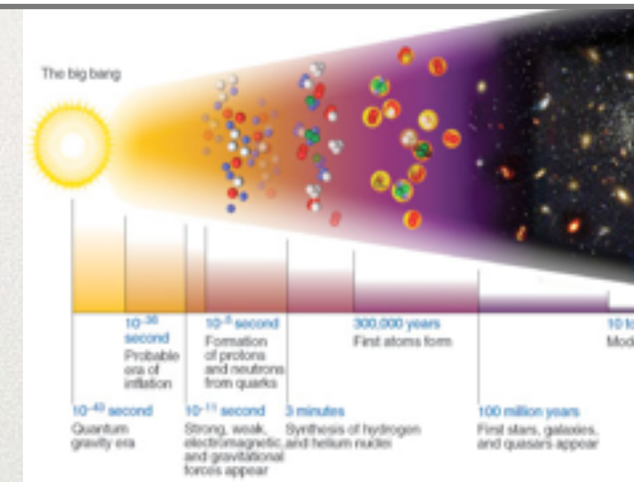
(Thermal) Hidden Sector DM

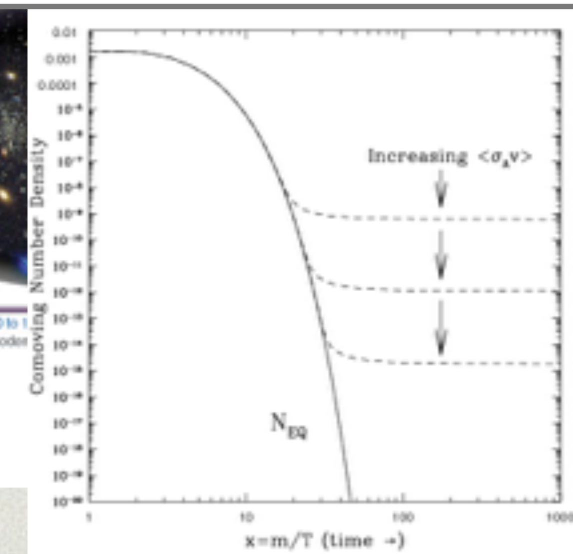
Simple, familiar particle content



Simple, predictive cosmology

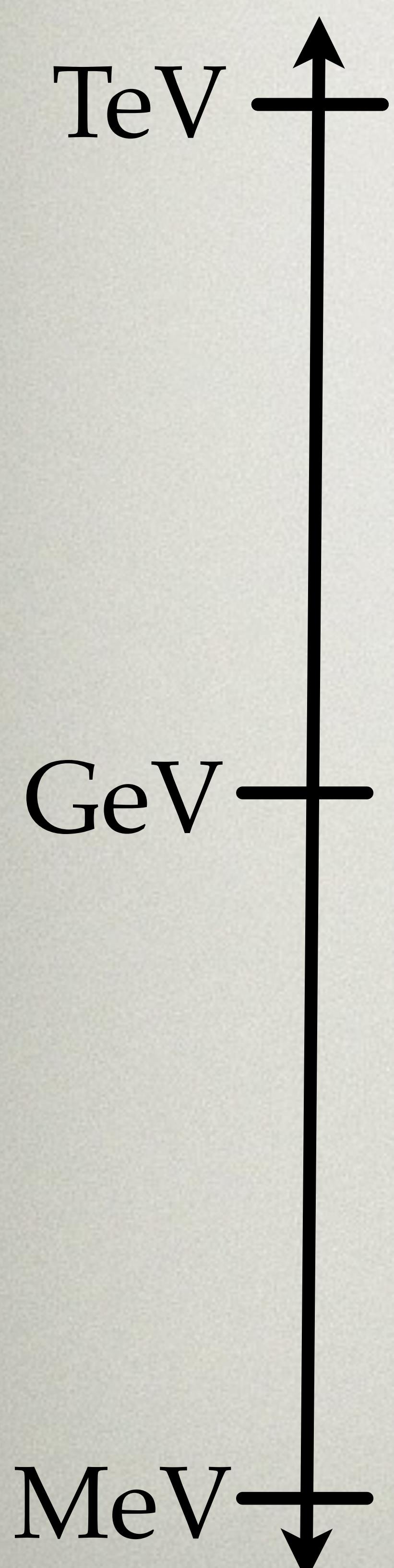
DM with thermal freeze-out/in origin





Mass range ??

the Vicinity of the Weak Scale



SM Matter

M_W

$M_{proton} \sim M_{large} e^{-\#}$

(accidentally close to weak scale)

$m_e \sim \text{small } \# \times M_W$

(derived from weak scale)

Dark Matter?

For decades: look here!

Generic mass scale for matter with O(1) coupling to origin of EWSB

...but where do we expect hidden sector matter – with only small couplings to SM matter (generated radiatively)?

THE VICINITY OF THE WEAK SCALE

TeV

GeV

MeV

SM Matter

M_W

$$M_{proton} \sim M_{large} e^{-\#}$$

(accidentally close to weak scale)

$$m_e \sim \text{small } \# \times M_W$$

(derived from weak scale)

Dark Matter?

Generic mass scale for matter with O(1) coupling to origin of EWSB

Where do we expect hidden-sector matter?

$$\sim M_W \times e^{-\#}$$

(e.g. “hidden valley” scenario: ~conformal to weak scale, then confining)

(e.g. dark sector scalar mixing with SM higgs)

$$\text{small } \# \times M_W$$

THE VICINITY OF THE WEAK SCALE

SM Matter

Dark Matter?

TeV

GeV

MeV

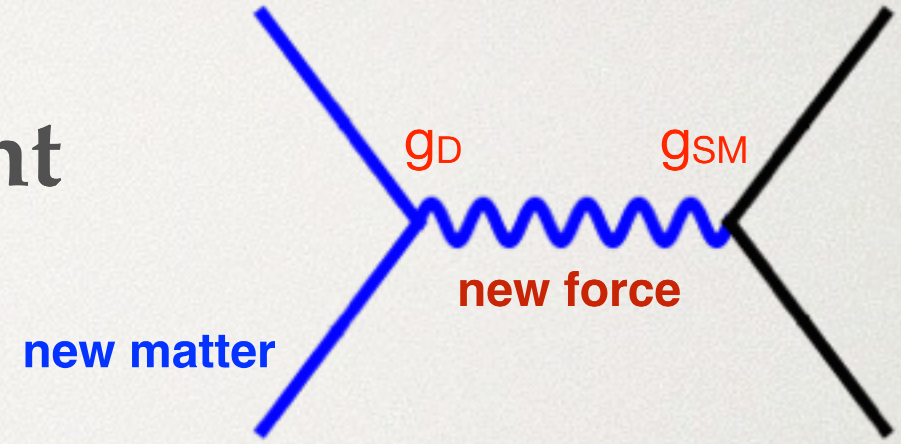
Moving beyond WIMPs, the <u>broad</u> vicinity of the weak scale is still an excellent place to focus on:

- **An important scale!**
- **Below the weak scale is natural for very weakly coupled new physics**
- **Thermal DM works well here!**

(derived from weak scale)

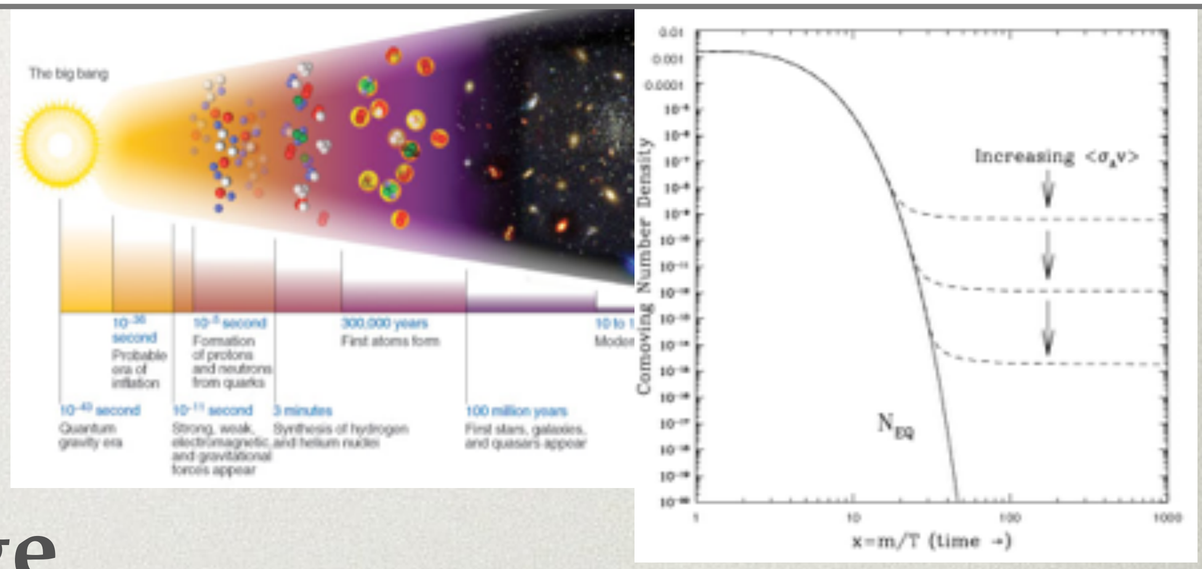
A Strong Candidate: (Thermal) Hidden Sector DM

Simple, familiar particle content

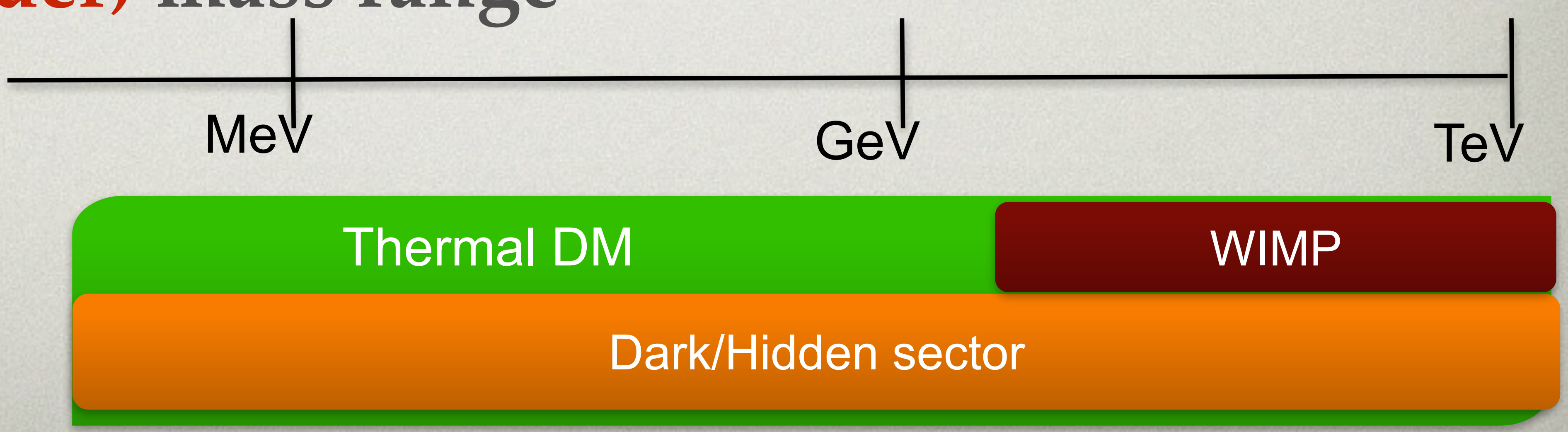


Simple, predictive cosmology

DM with thermal freeze-out/in origin

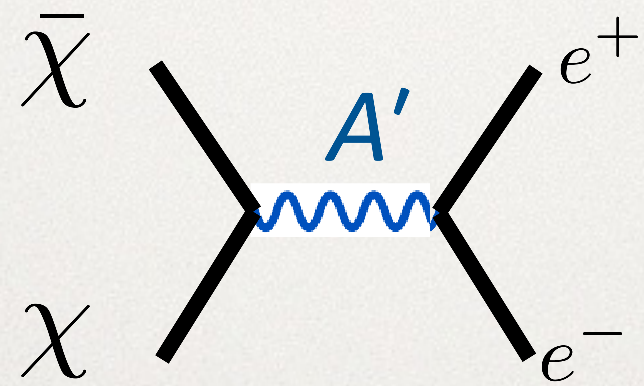


Motivated **(broader)** mass range



Predictions

Early universe thermal freeze-out cross-section bounded by DM abundance



$$\sigma v \sim \alpha_D \epsilon^2 \alpha \times \frac{m_\chi^2}{m_{A'}^4} \text{ x (velocity factors)}$$

Want to use annihilation cross-section to infer coupling strength, as a function of mass

But we can't do this without precisely choosing a dark matter current! This will fix the velocity (and spin) factors

We need to consider the spin & interaction structure (i.e. the form of the dark matter current) for thermal dark matter framework to become quantitatively predictive

Predictive Models

For a given choice of spin & parity, form of the current is determined by Lorentz invariance. Structure of mass terms also important.

Particle Type | Dark Matter Current | Different Low-Energy Phenomenology!

Model	Mass terms	J_D^μ	scattering $\mathcal{M} \propto$	scattering $\sigma \propto$	Annilhilation $\sigma v \propto$	CMB-viable?
Fermion DM – Direct Annihilation						
Majorana	$\not{U}(1)_D$	$\bar{\Psi}\gamma^\mu\gamma_5\Psi$	$\vec{\sigma}\cdot\vec{v}$	v^2	p-wave $\propto v^2$	Y
Dirac	$U(1)_D$-inv.	$\bar{\Psi}\gamma^\mu\Psi$	1	1	s-wave $\propto v^0$	N
Pseudo-Dirac	$U(1)_D$-inv. & $\not{U}(1)_D$	$\bar{\Psi}_L\gamma^\mu\Psi_H$	1 (inelastic)	kin. forbidden [a]	kin. forbidden	Y
Scalar DM – Direct Annihilation						
Complex	$U(1)_D$-inv.	$\phi^*\partial^\mu\phi - \phi\partial^\mu\phi^*$	1	1	p-wave $\propto v^2$	Y
Pseudo-complex	$U(1)_D$-inv. & $\not{U}(1)_D$	$\phi_L\partial^\mu\phi_H - \phi_H\partial^\mu\phi_L$	v^2 (inelastic)	kin. forbidden	kin. forbidden [b]	Y

Predictive Models

For a given choice of spin & parity, form of the current is determined by Lorentz invariance. Structure of mass terms also important.

Particle Type | **Dark Matter Current** | **Different Low-Energy Phenomenology!**

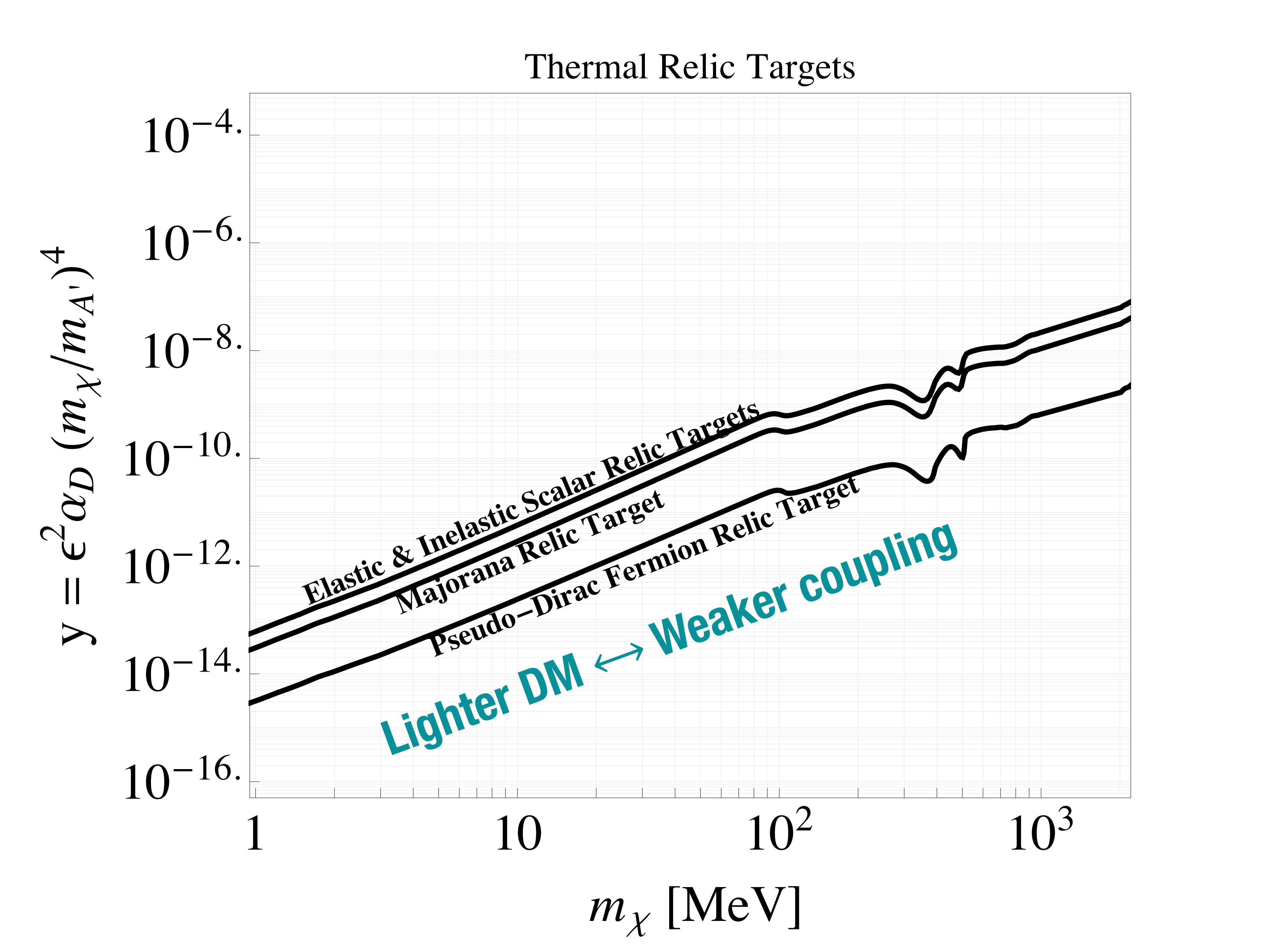
Model	Mass terms	J_D^μ	scattering $\mathcal{M} \propto$	scattering $\sigma \propto$	Annilhilation $\sigma v \propto$	CMB-viable?
Fermion DM – Direct Annihilation						
Majorana	$\not{U}(1)_D$	$\bar{\Psi}\gamma^\mu\gamma_5\Psi$	$\vec{\sigma}\cdot\vec{v}$	v^2	p-wave $\propto v^2$	Y
Dirac	$U(1)_D$-inv.	$\bar{\Psi}\gamma^\mu\Psi$	1	1	s-wave $\propto v^0$	N
Pseudo-Dirac	$U(1)_D$-inv. & $\not{U}(1)_D$	$\bar{\Psi}_L\gamma^\mu\Psi_H$	1 (inelastic)	kin. forbidden [a]	kin. forbidden	Y
Scalar DM – Direct Annihilation						
Complex	$U(1)_D$-inv.	$\phi^*\partial^\mu\phi - \phi\partial^\mu\phi^*$	1	1	p-wave $\propto v^2$	Y
Pseudo-complex	$U(1)_D$-inv. & $\not{U}(1)_D$	$\phi_L\partial^\mu\phi_H - \phi_H\partial^\mu\phi_L$	v^2 (inelastic)	kin. forbidden	kin. forbidden [b]	Y

Just like neutralino WIMP candidates

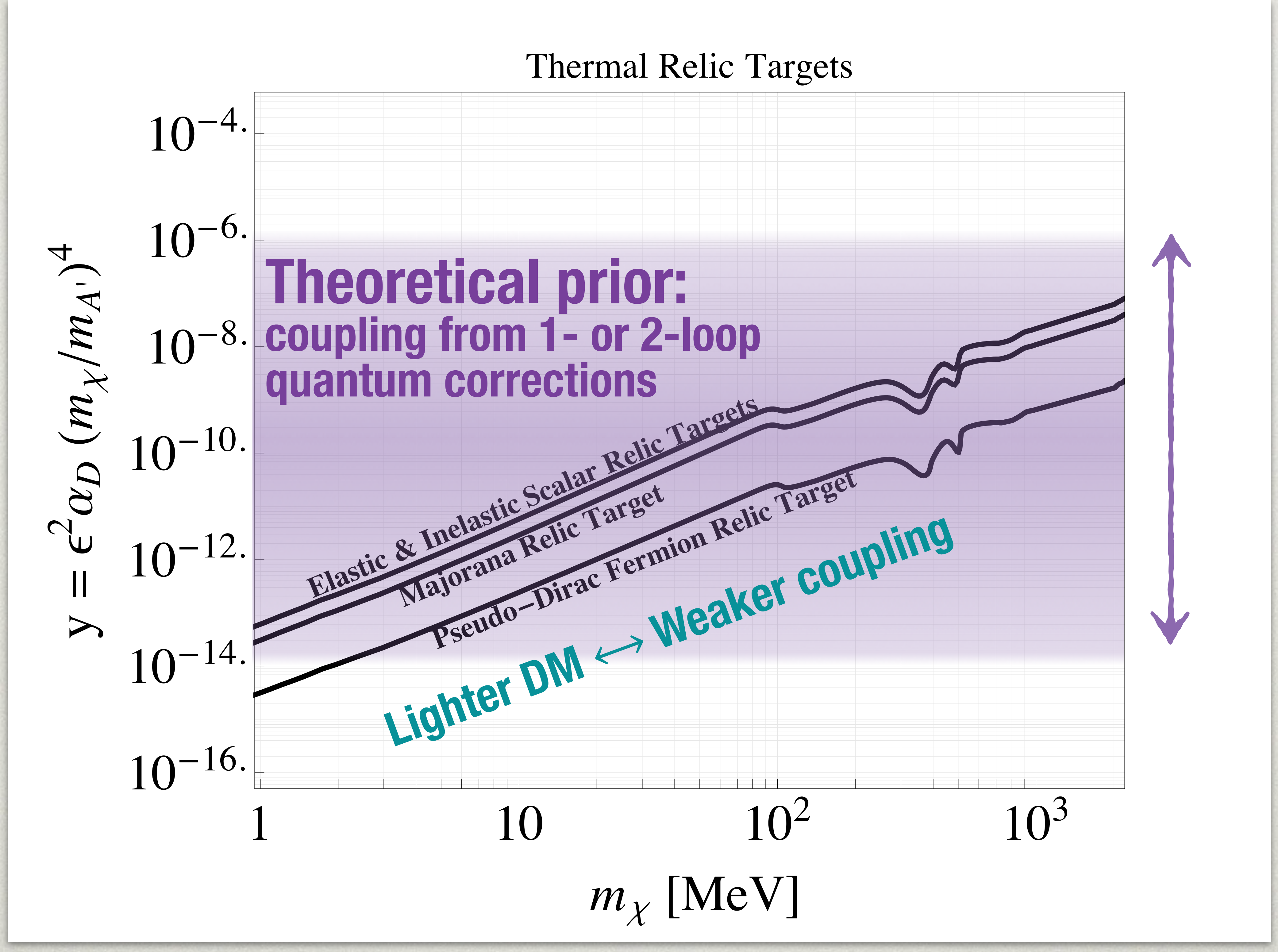
Just like sneutrino or Dirac neutrino WIMP candidate

Obvious similarity to WIMP phenomenology!

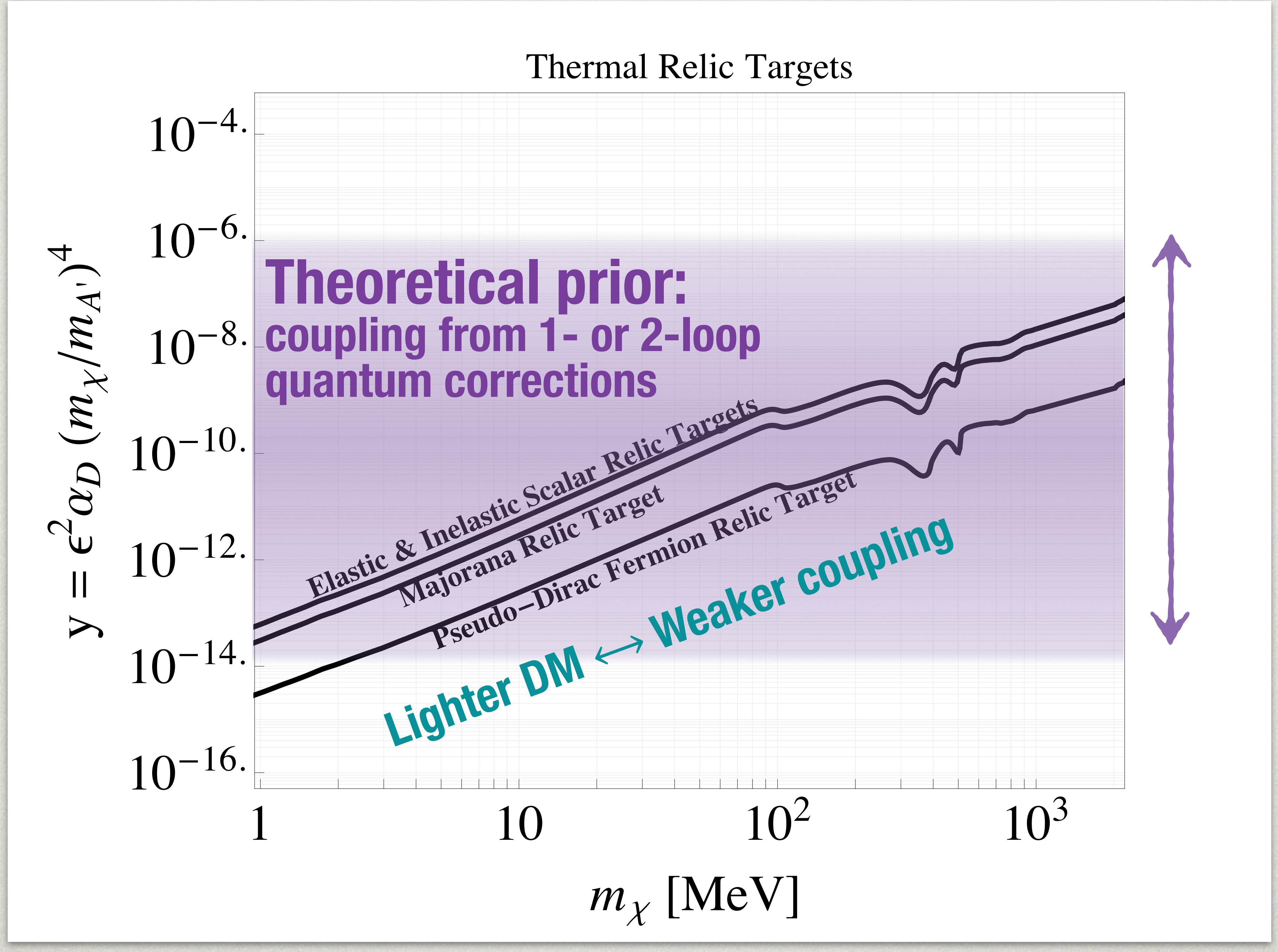
Coupling "Predictions"



Coupling "Predictions"

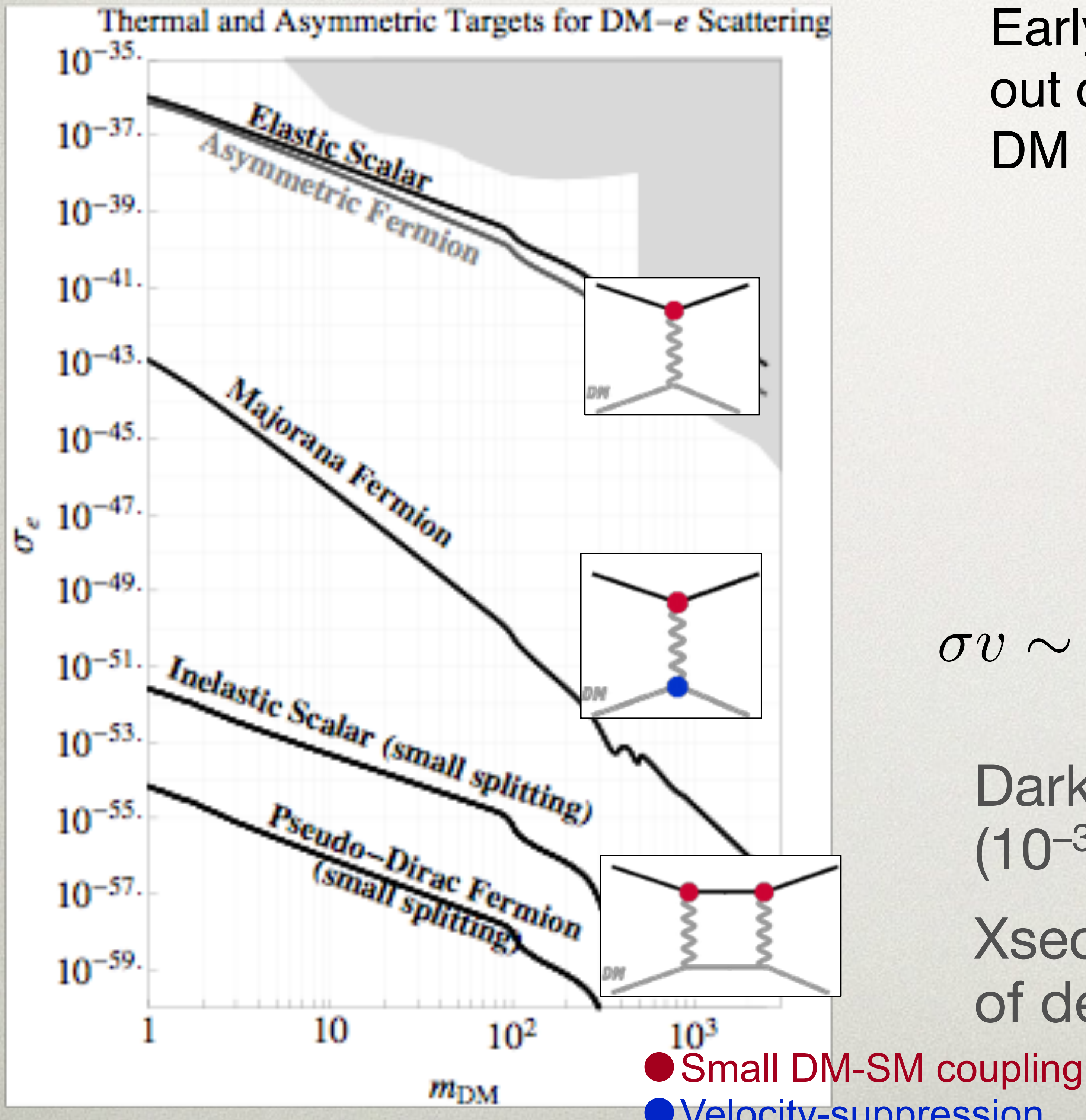


Coupling "Predictions"

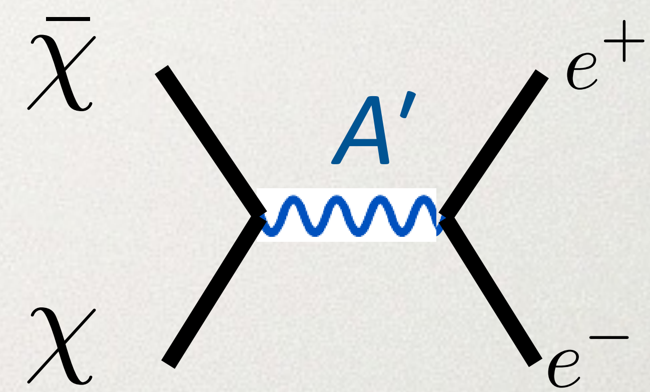


Similarly, predictions from freeze-in can be obtained (see talks by J. Shelton and N. Blinov)

Direct Detection Rate "Predictions"



Early universe thermal freeze-out cross-section bounded by DM abundance

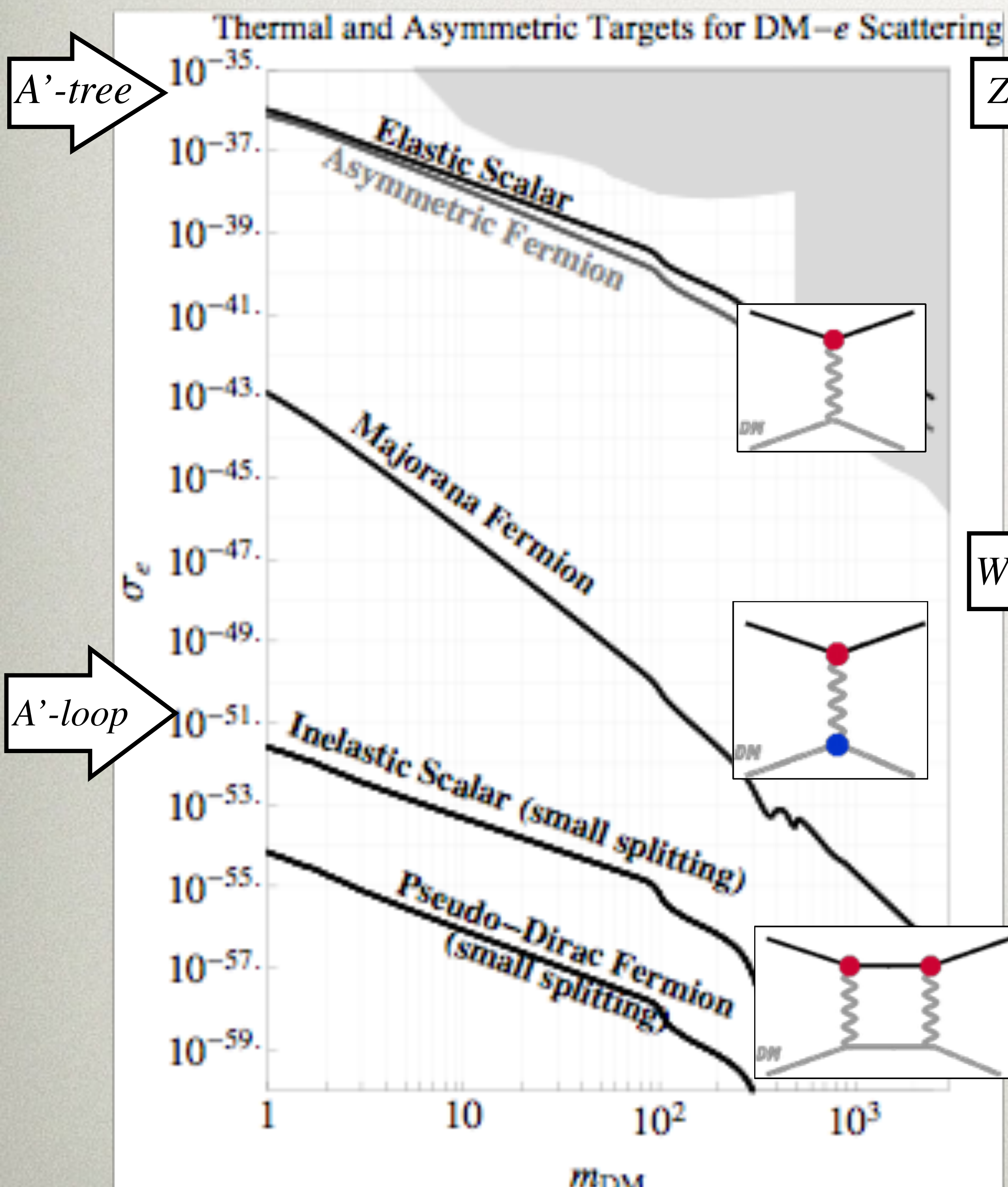


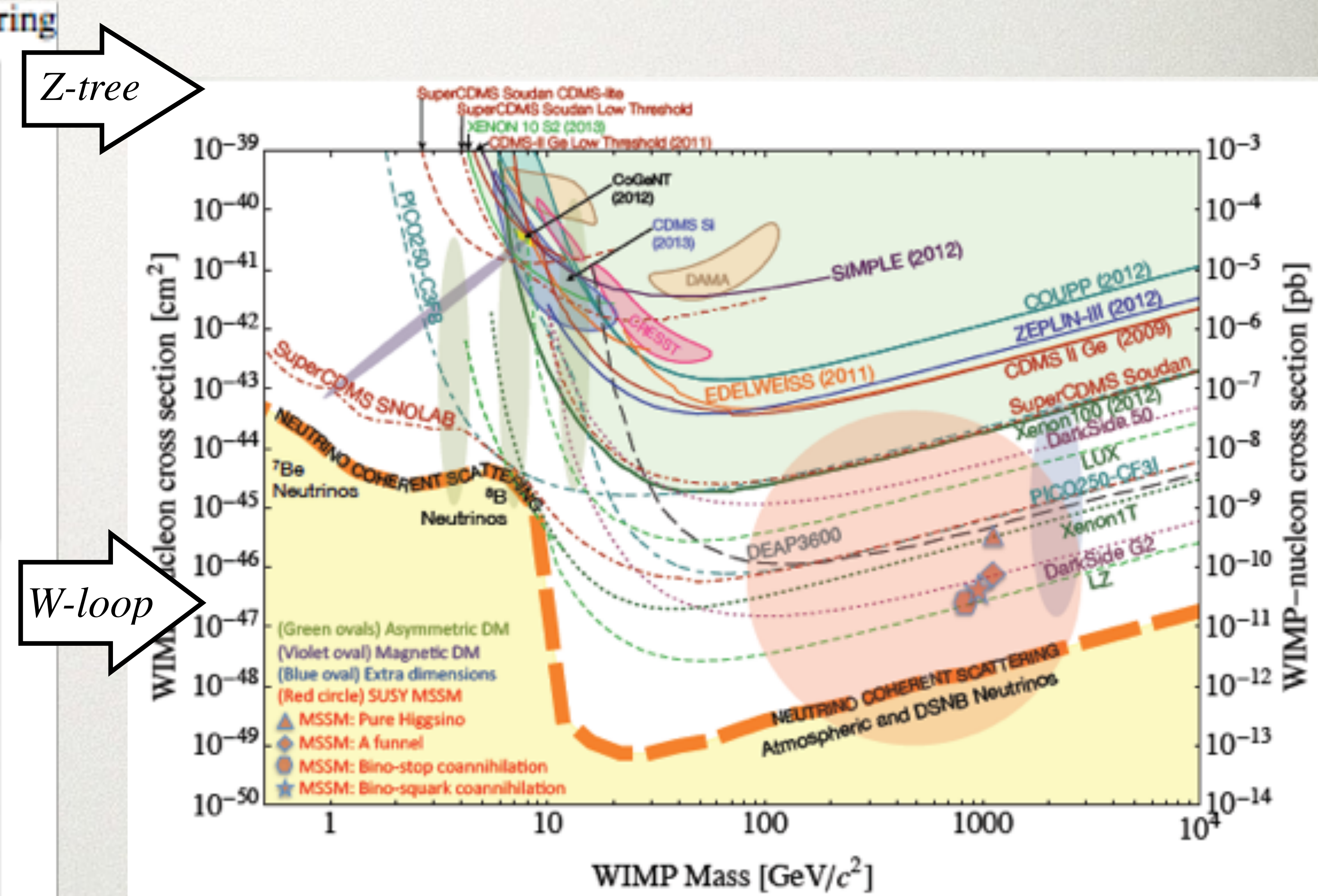
$$\sigma v \sim \alpha_D \epsilon^2 \alpha \times \frac{m_\chi^2}{m_{A'}^4}$$ x (velocity factors)

Dark matter halo is non-relativistic! (10^{-3} *c*) ⇒

Xsec predictions spread over tens of decades (much like for WIMPs!)

Direct Detection Rate "Predictions"





Similar to WIMPs: thermal LDM motivates large range of direct detection cross-section

Conclusions

- Thermal dark matter is simple & predictive.
  We should explore this idea to the best of our abilities!
- Hidden sector thermal dark matter is a natural generalization of WIMPs — offers good motivations to explore sub-GeV mass scales
- Simple models of freeze-out/in can offer guidance in the rate vs mass parameter space — **direct detection rates down to the neutrino floor are motivated by thermal DM.**