Dark Matter and Friends

A colorful tale in the early Universe

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Theoretical Particle Physics

Nikhef

Nikhef Jamboree

December 12, 2017

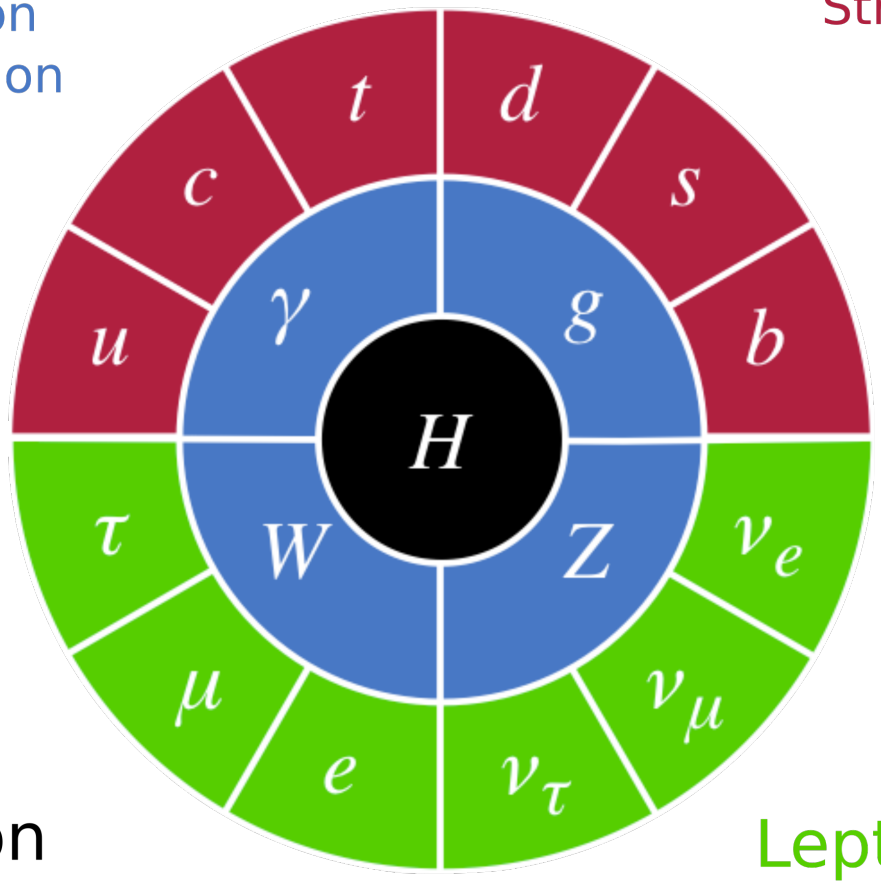
The Standard Model

Vector bosons

Electromagnetic interaction
Weak Interaction
Strong interaction

Quarks

Strong interaction



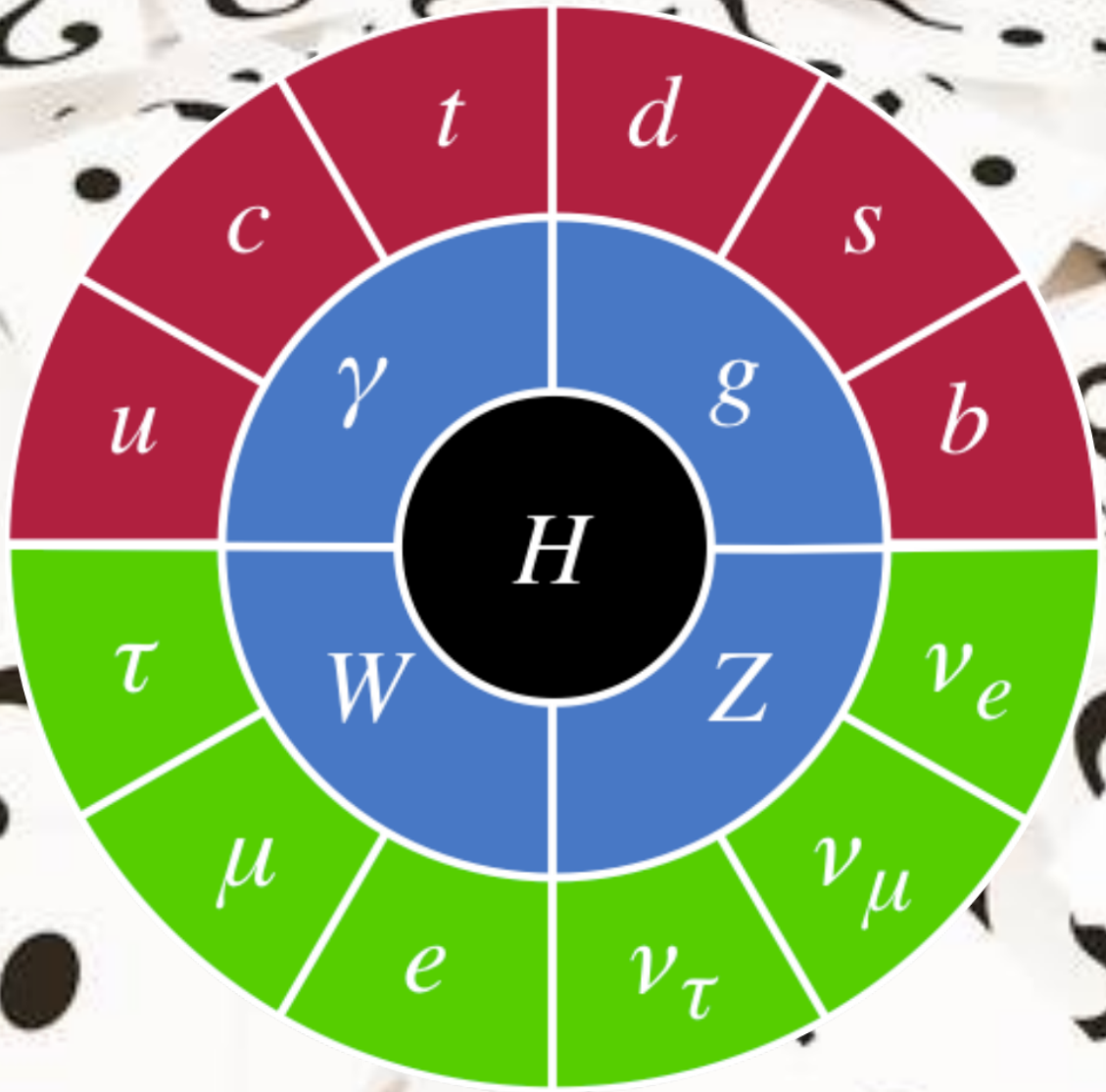
Higgs boson

Masses of (most of) the particles

Leptons

electron, muon, tau
neutrinos

The Standard Model



Unsolved Puzzles

Missing pieces

- Neutrino masses
- Matter-Antimatter asymmetry
- Dark Matter
- ...

Striking coincidences

- Fine-tuning of the Higgs boson mass
- Unification of the forces

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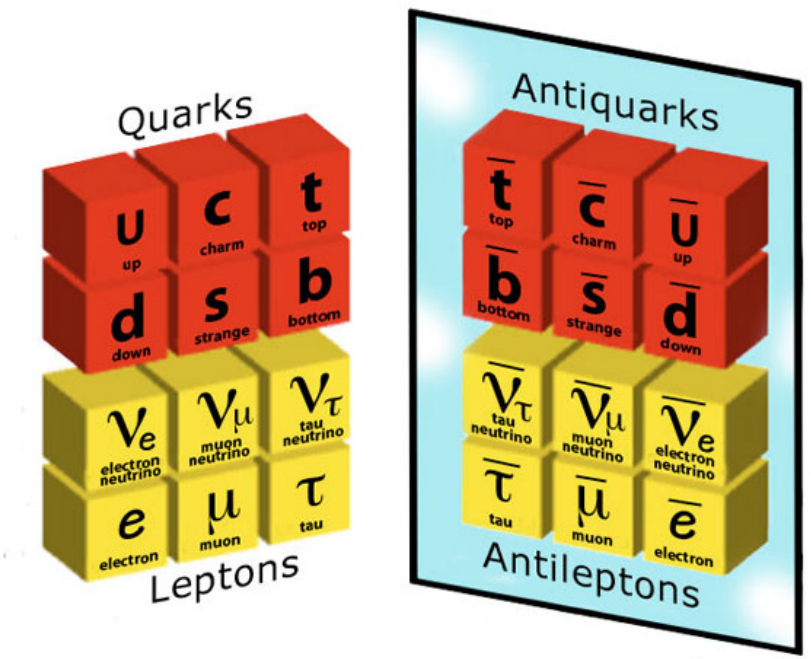

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Galaxy cluster CL0024+17
Hubble, 2004

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Galaxy cluster CL0024+17
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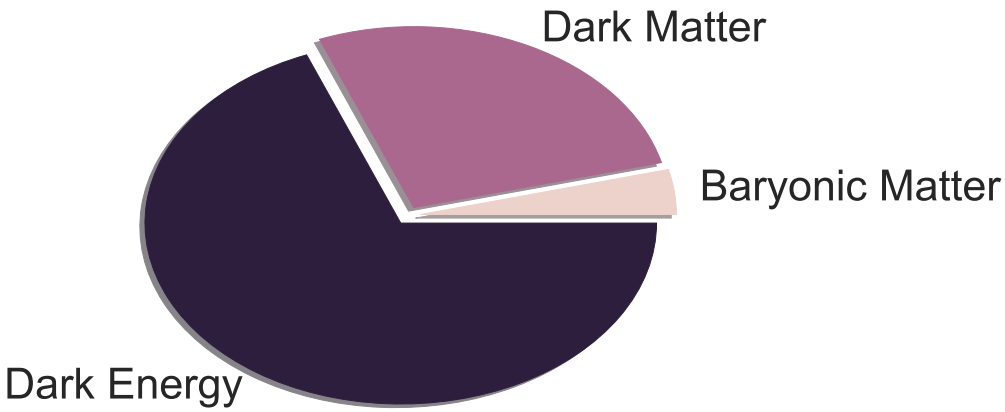
There must be new particles...but we do not know what they can be and what could be their masses!

Dark Matter



Galaxy cluster CL0024+17
(Hubble, 2004)

- *Dark Energy*: Acceleration of the expansion of the Universe
  Unknown source – Cosmological constant problem
- *Dark Matter*: Unknown source of mass $\Rightarrow$ New "dark" objects

What do we know about Dark Matter?

- Is it a new particle?

  Probably...

- How does it interact with us?

Gravity	**yes**
Strong nuclear force	**no**
Electromagnetism	**no**
Weak nuclear force	**maybe?**
New dark force	**maybe?**

- (How) does it interact with itself?

  If yes, not very much

- Then...what do we *actually* know?

  PLANCK (2013)

  $\Omega h^2 = 0.1199 \pm 0.0027$

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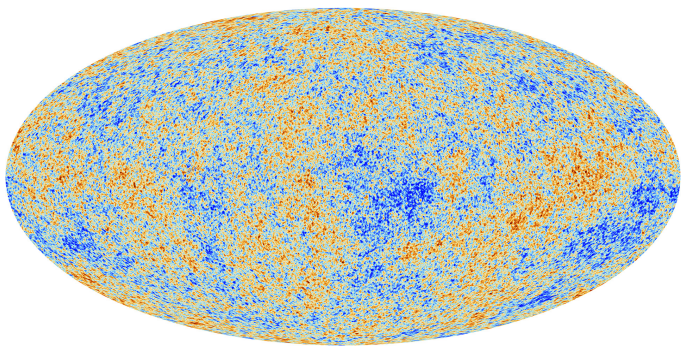
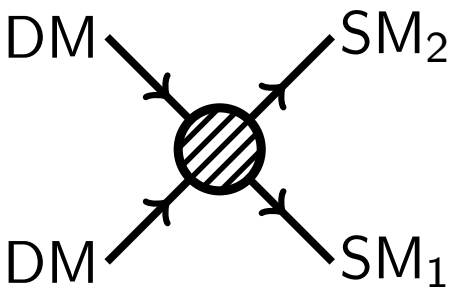
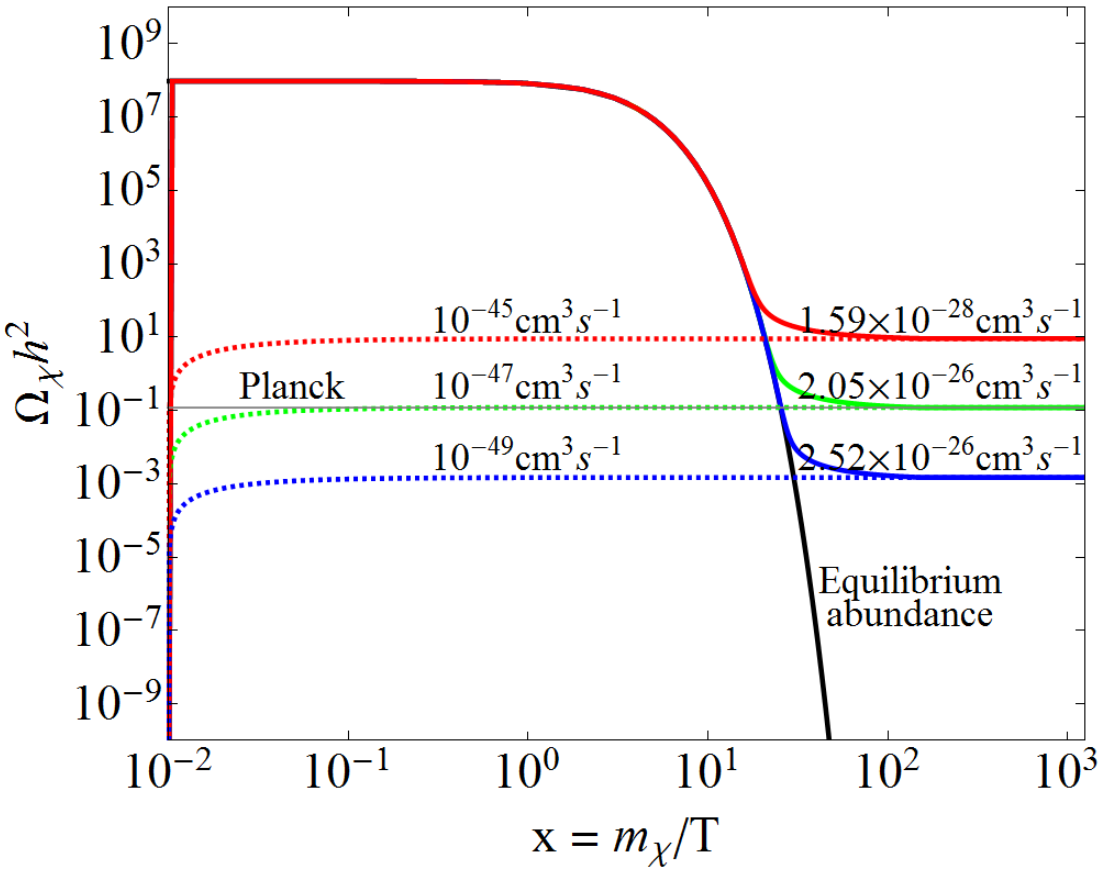


Thermal Dark Matter

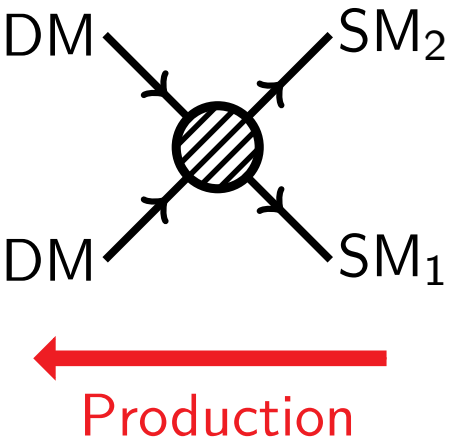
Assume thermal equilibrium between Dark Matter and the SM

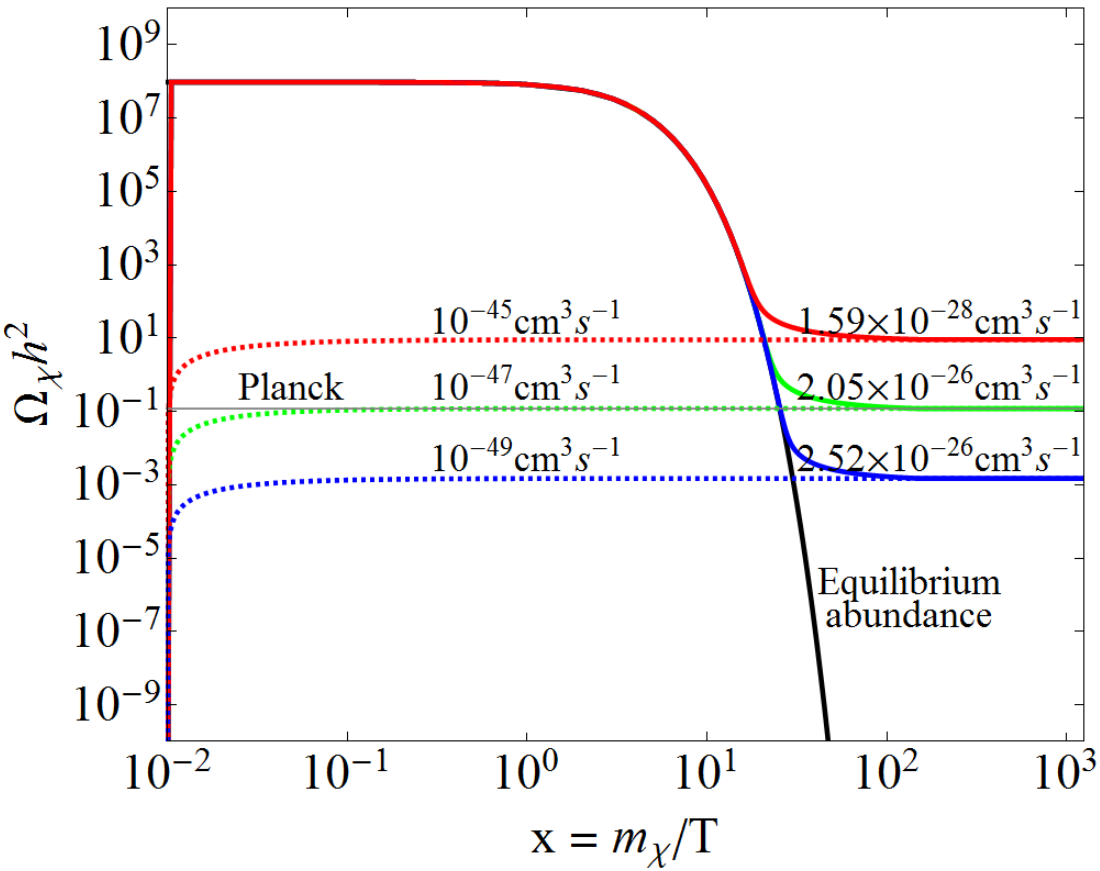




Thermal Dark Matter

Step 1: The whole Universe was in a hot dense state...

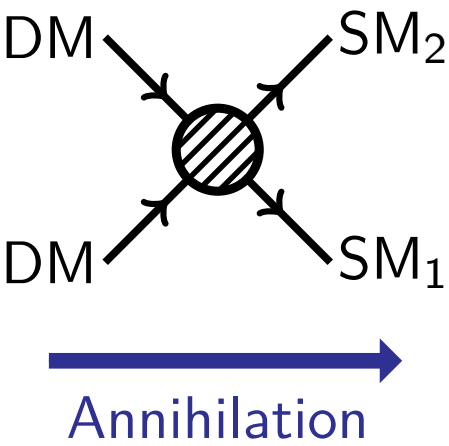


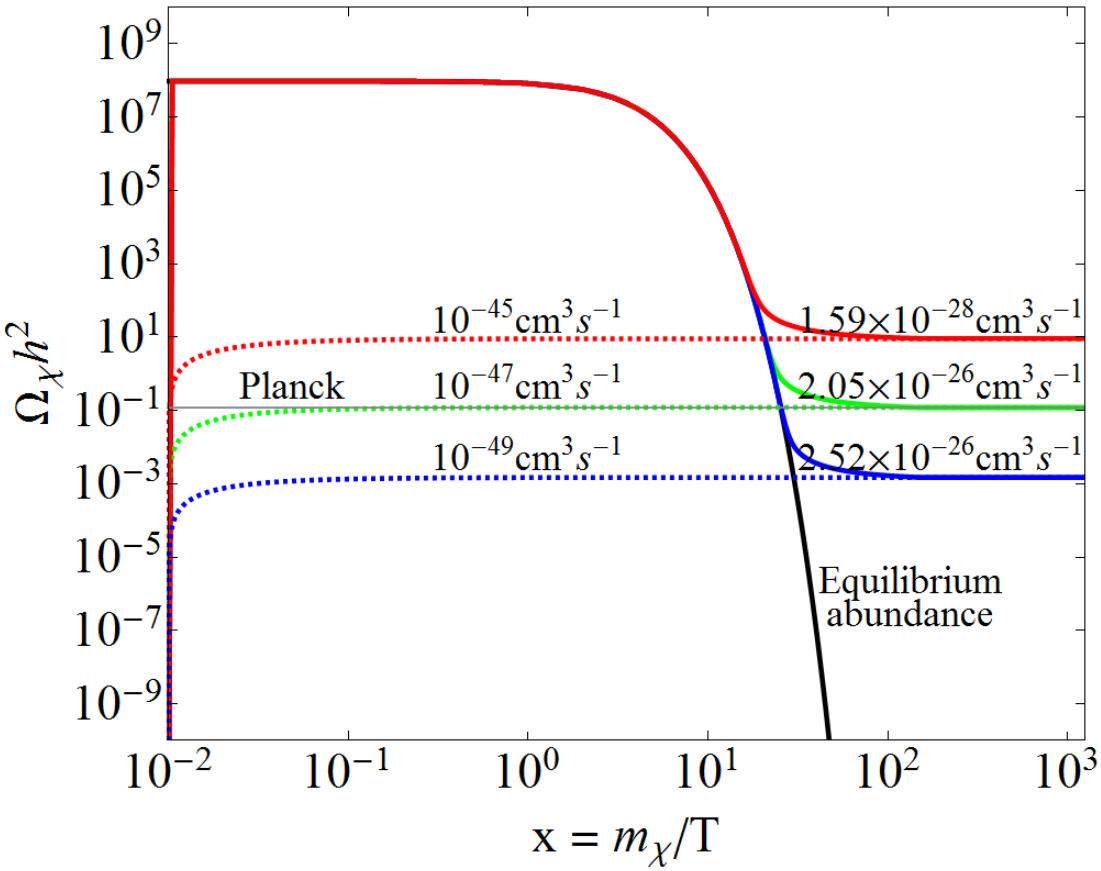


...and Dark Matter is produced from SM annihilation.

Thermal Dark Matter

Step 2: The Universe cools down...DM cannot be produced anymore...

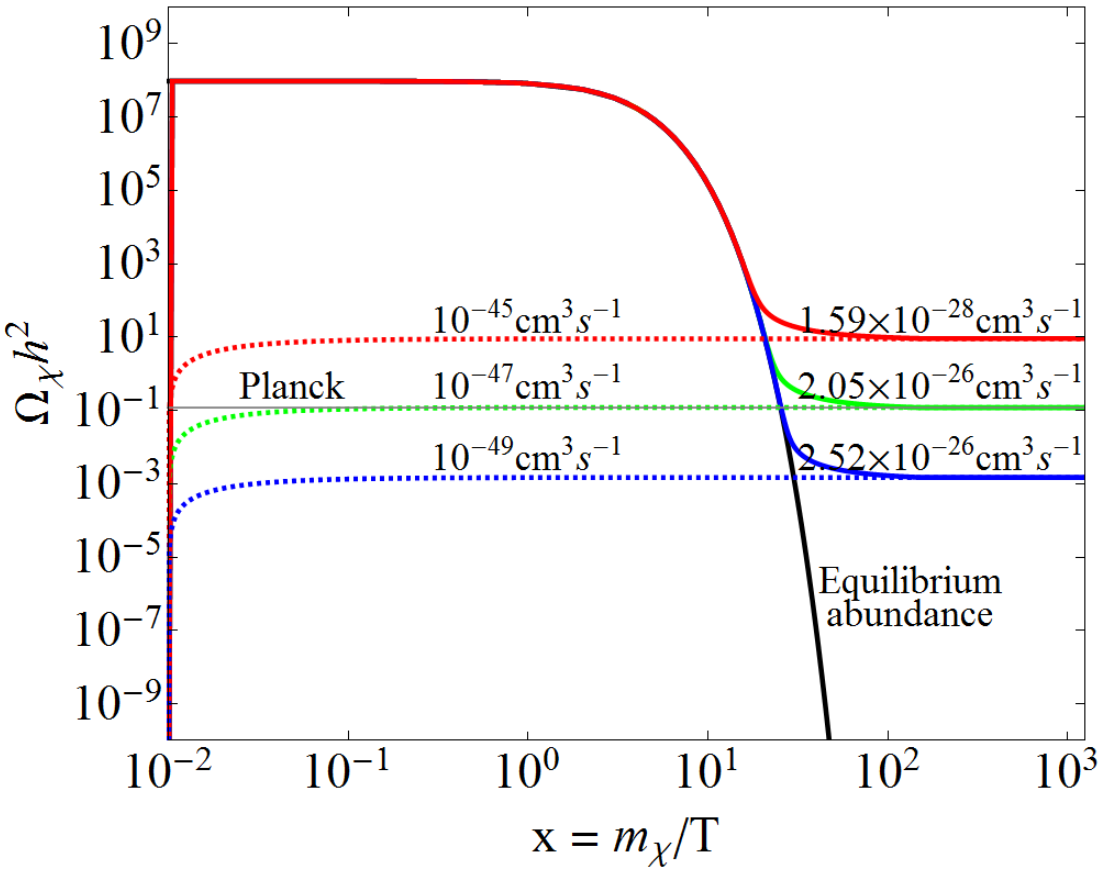




...and annihilates back to the SM...back to square one?

Thermal Dark Matter

Step 3: The Universe expands way to fast...



Thermal Dark Matter

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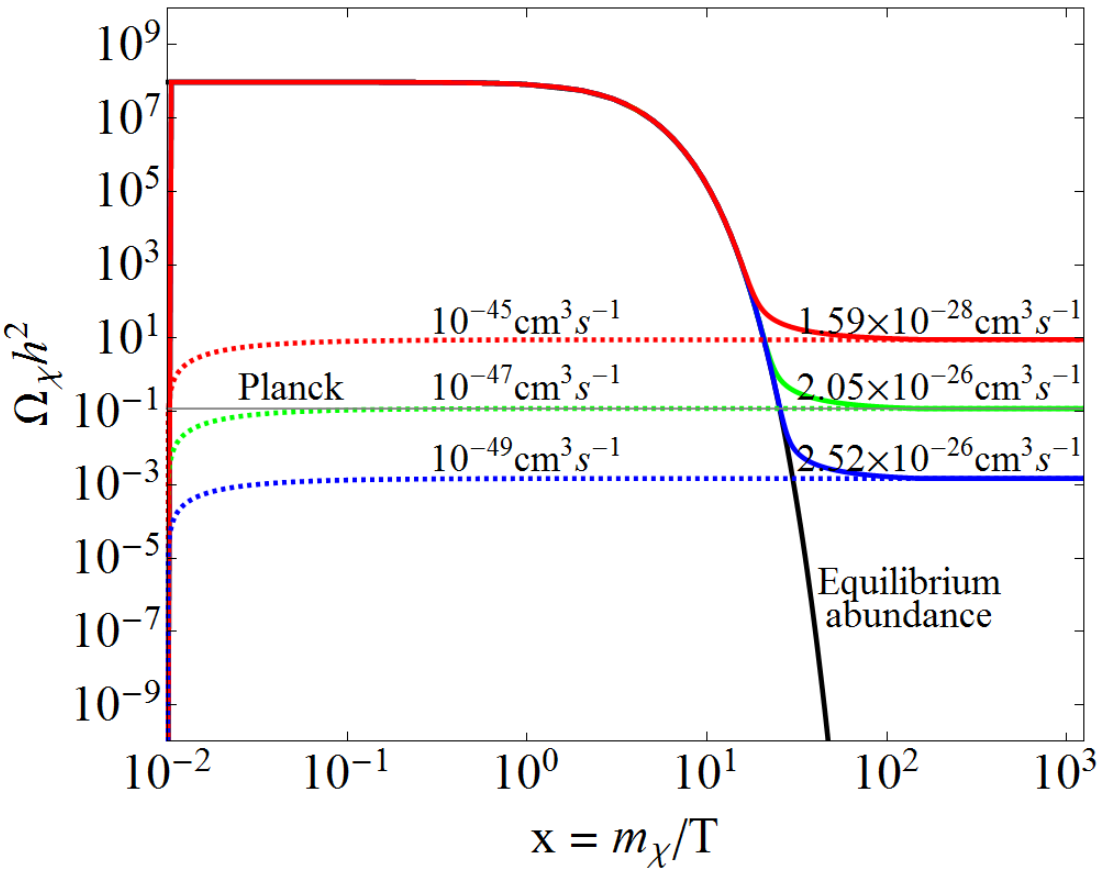
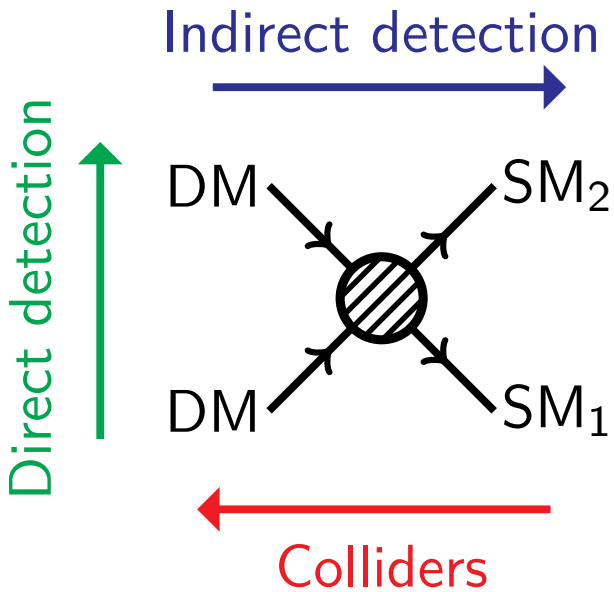


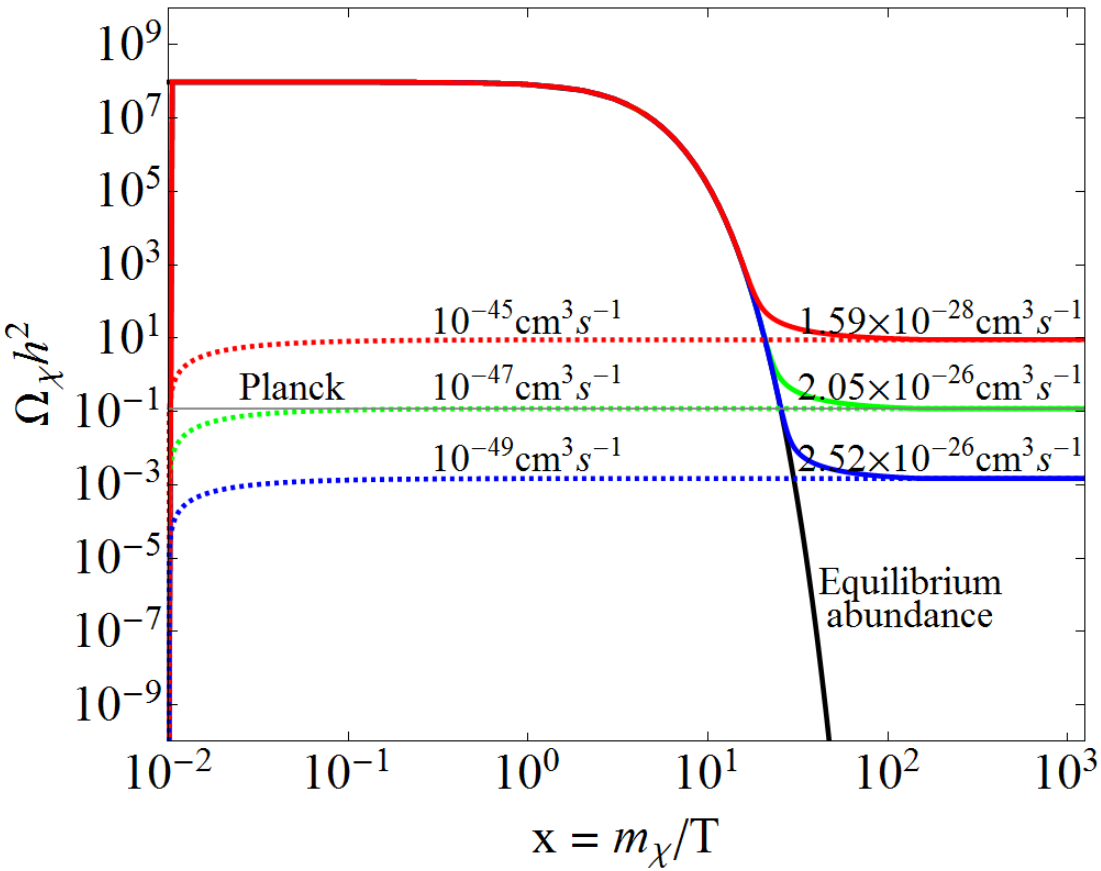
...and Dark Matter cannot keep up. This is **freeze-out**.

Thermal Dark Matter

Advantages: Multiple detection channels...



- The DM density is *fully calculable* and proportional to $\frac{m_{\rm DM}^2}{\lambda^2}$



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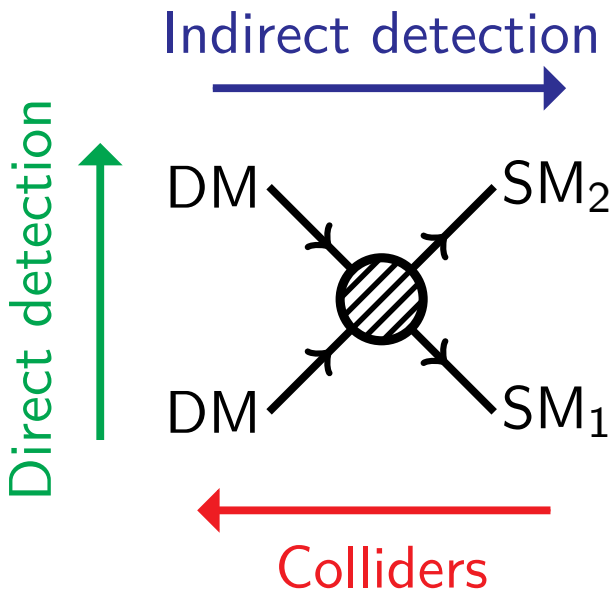
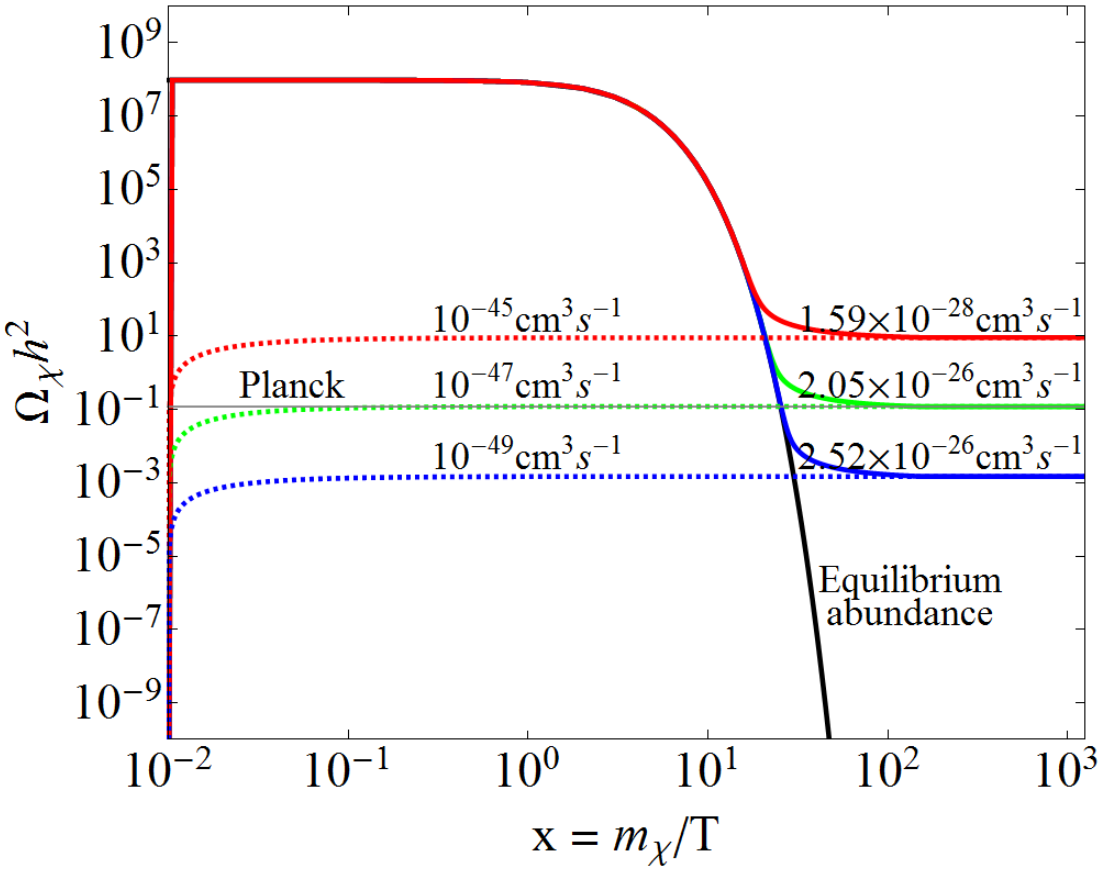




Thermal Dark Matter models have a maximum energy scale!

Theories have Layers (of Complexity)

Studying Thermal Dark Matter: Two Approaches

Complete Models (SUSY)

Sasha Caron's talk

"Dark Matter – Synergies"

Start small and add layers

Studying Thermal Dark Matter: Two Approaches

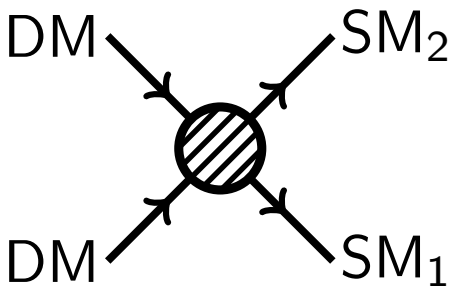
Complete Models (SUSY)

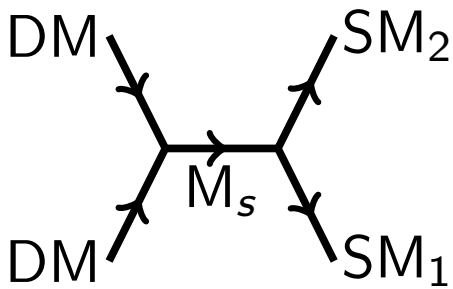
Start small and add layers

- What elements in a model drive the Dark Matter annihilation?

Modeling Dark Matter Annihilation: Minimal Models

- "Just what is needed": SM + DM (+ Mediator)
  Cirelli, Fornengo, Strumia [2005], Abdallah et al. [2015], ...





- Easy to understand, useful tool for experiments
- Limited number of experimental signatures
- **TeV scale** constraints on the Dark Matter mass from relic density...maybe too tight?

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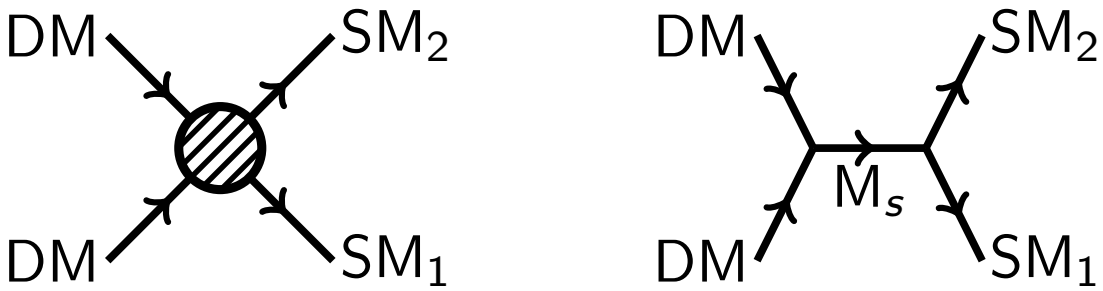

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Are we missing something?

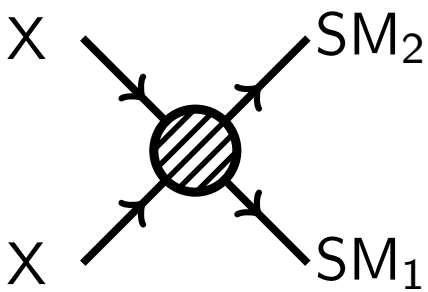
Adding a new layer: Coannihilation

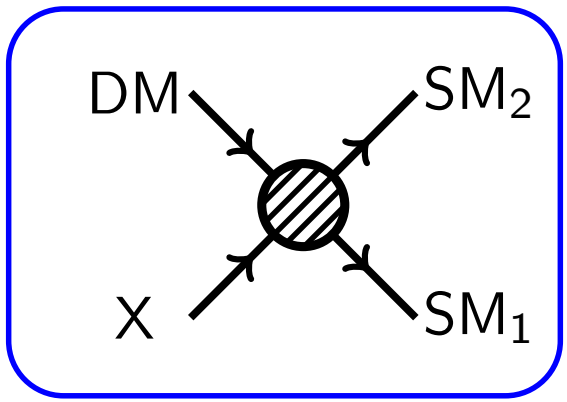
In many models...

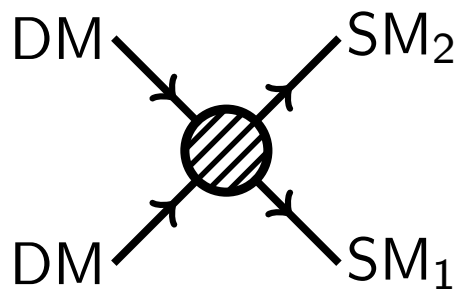
AND

$\mathrm{DM} \longleftrightarrow \mathrm{X}$

The annihilation processes help each other!



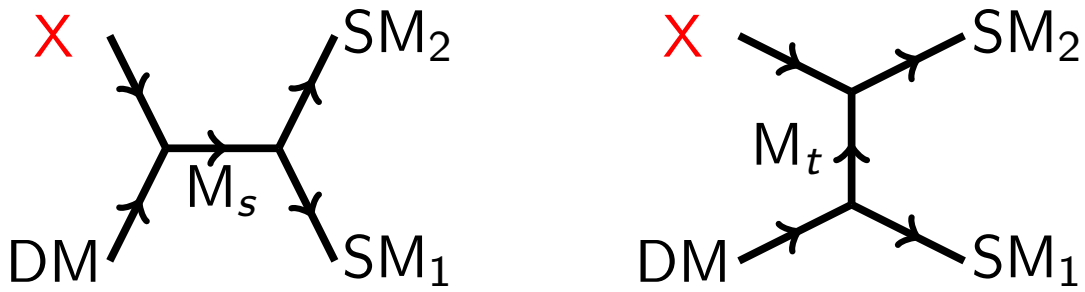




- **How heavier can Dark Matter be with coannihilation?**

Modeling (Co)-annihilation?

- "Almost Just what is needed": SM + DM (+ Mediator) + X

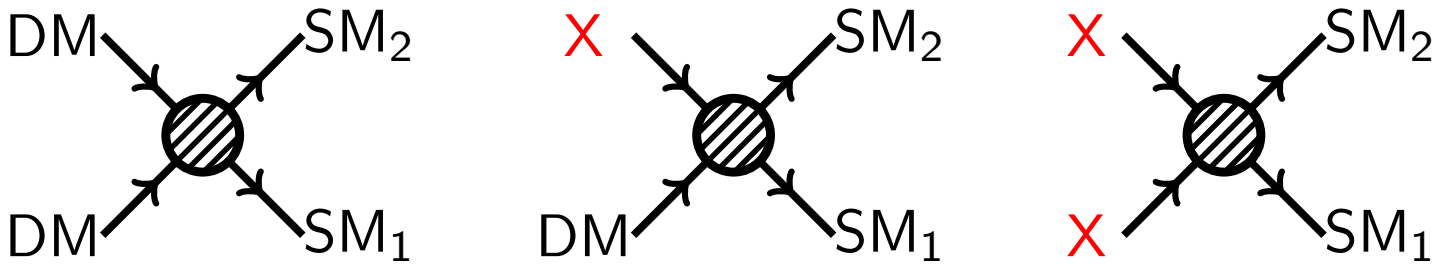


- X is not submitted to the same restrictions as Dark Matter

  $\Rightarrow$ *Many more experimental signatures!*
- Much larger number of models....is it still tractable?
  M. Baker et al. (JGU Mainz) [arXiv:1510.03434, 1605.08056]
- Are there simple models that should **considerably** loosen the bounds on the Dark Matter mass?

One (tiny) Step Further: Colored Dark Sectors

We already know that X helps the Dark Matter to annihilate



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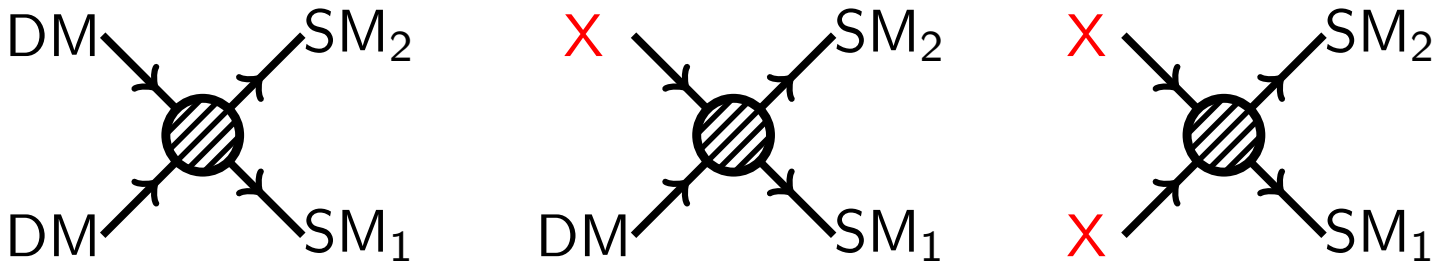

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Now, the Dark Matter can reach masses of 10-20 TeV!

Conclusion and perspectives

- Dark Matter is one of the most striking evidence for new physics so far but we do not know what its mass could be.
- The thermal Dark Matter hypothesis provides an elegant mechanism explaining its current relic density and requires interactions with the Standard Model
- Accounting for coannihilation allows for an excellent coverage of the annihilation mechanisms existing in "complete" theories and allows for much heavier Dark Matter
- Color Dark Sector models are simple and economical ways to see how heavy the Dark Matter can be, providing further motivation to look for $\mathcal{O}(10)$ TeV particles.
- This result makes a strong case for the next generation of particle colliders, that could go up to 100 TeV