# WIMPS: AN OVERVIEW, CURRENT CONSTRAINTS, AND WIMP-LIKE EXTENSIONS

*Debates on the Nature of Dark Matter*

*The 8th Harvard-Smithsonian Conference on Theoretical Astrophysics*

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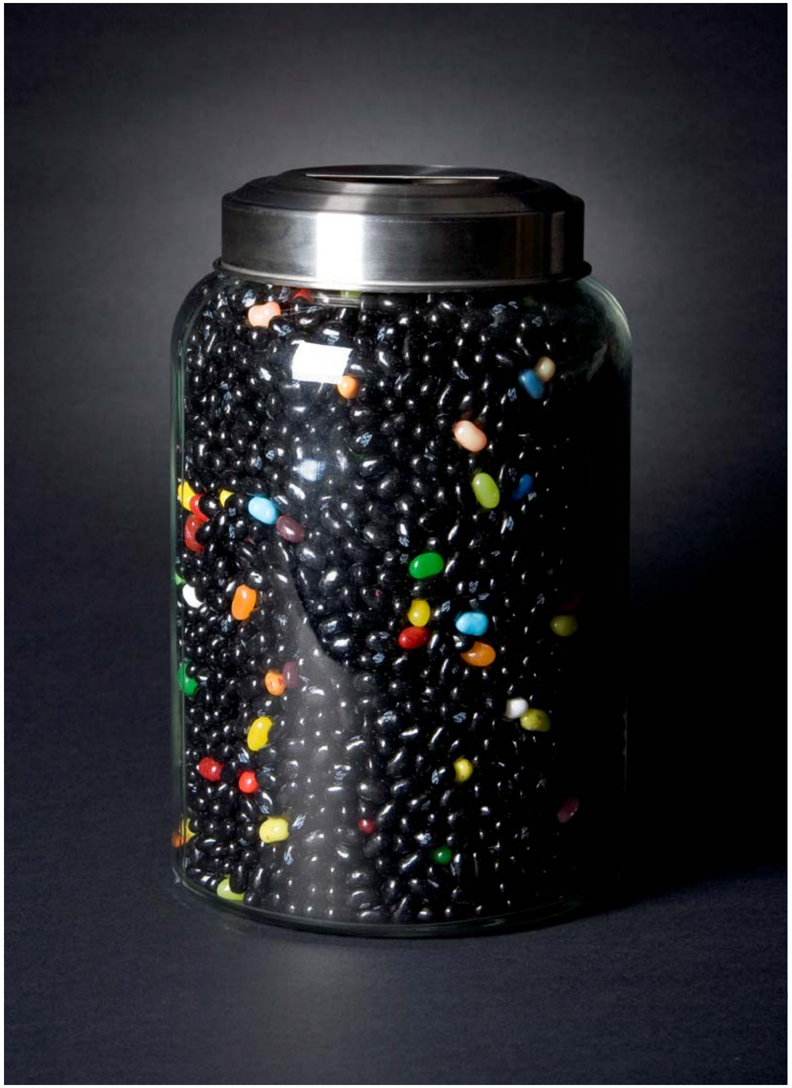
# OVERVIEW



We've learned a lot about the Universe in recent years, but there is still a lot missing

In particular, either

- There is a huge problem with our standard theory of particle physics, or
- There is a huge problem with our standard theory of gravity,
- Or both!

- Here assume it's particles:

  Dark Matter: 23% ± 4%

  Dark Energy: 73% ± 4%

  Normal Matter: 4% ± 0.4%

  Neutrinos: 0.2% ($\Sigma m_\nu$/0.1 eV)

# THE WEAK SCALE

Much of the attention has focused on WIMPs. Why?

- Fermi's constant $G_F$ introduced in 1930s to describe beta decay

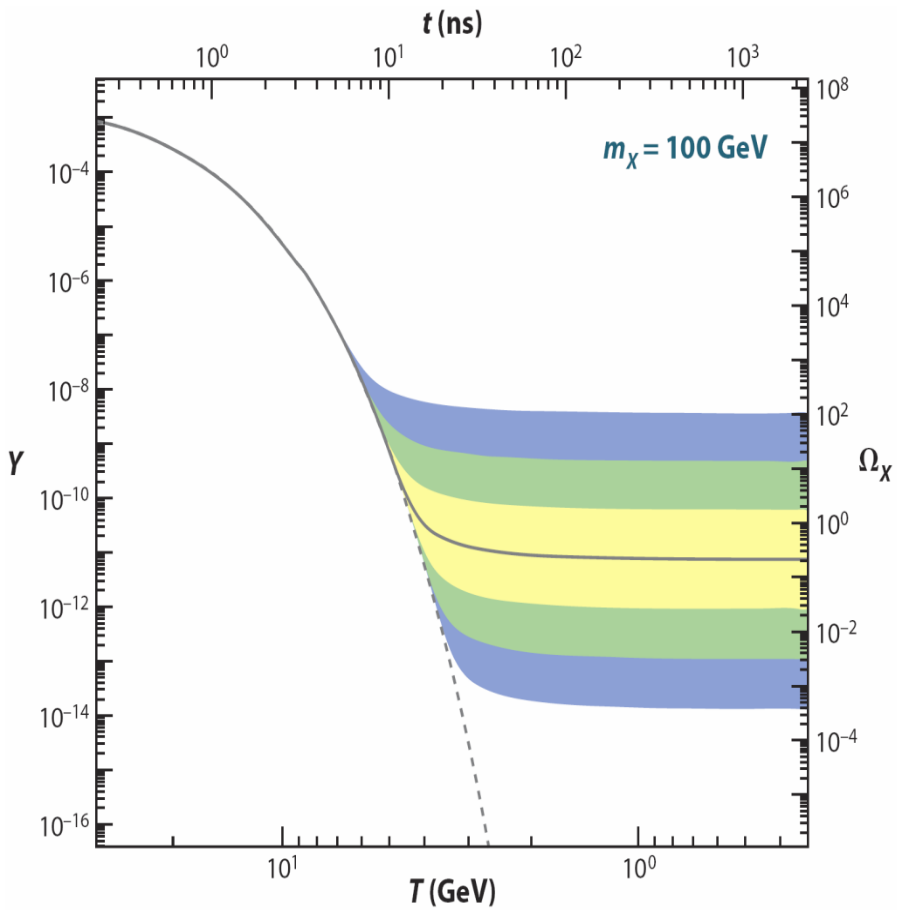
$$n \to p\, e^- \bar{\nu}$$

- $G_F \sim 10^{-5}$ GeV$^{-2}$ → a new mass scale in nature

$$m_{weak} \sim 100 \text{ GeV}$$

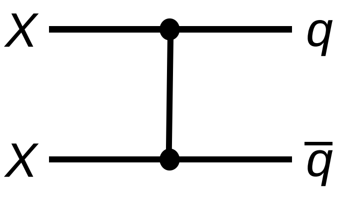
- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

# THE WIMP MIRACLE




- The relation between $\Omega_X$ and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$




- $m_X$ ~ 100 GeV, $g_X$ ~ 0.6 → $\Omega_X$ ~ 0.1

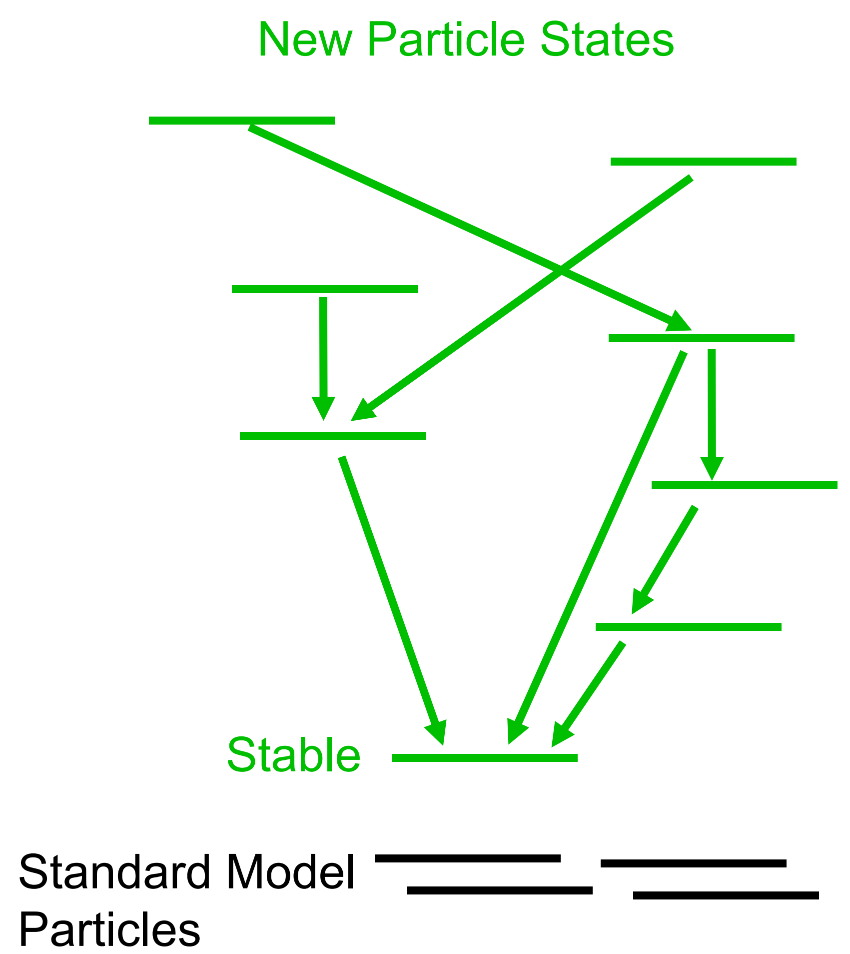
- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

# WIMP STABILITY

- The WIMP Miracle is very well appreciated, and it is a quantitative feature. But its success relies on some less well-advertised qualitative features

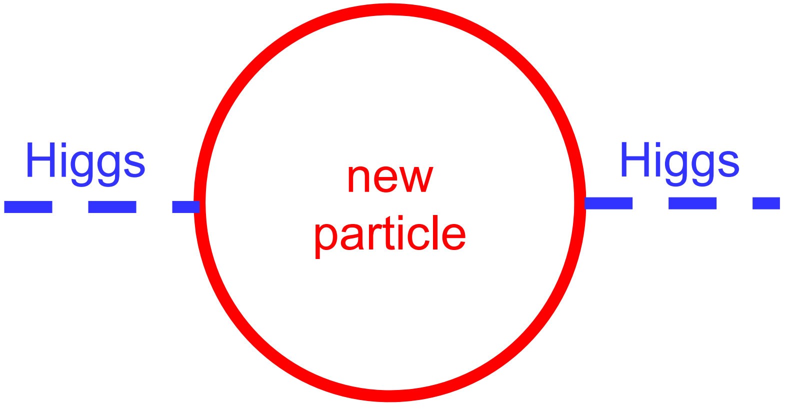
- First, the WIMP must be stable

- How natural is this? *A priori*, not very: the only stable particles we know about are very light

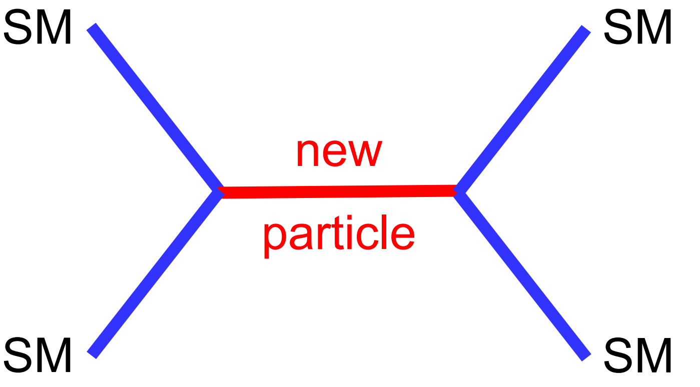


# LEP'S COSMOLOGICAL LEGACY

Gauge Hierarchy requires




Precision EW excludes




In some cases, there are even stronger reasons to exclude these 4-particle interactions (e.g., proton decay in SUSY)

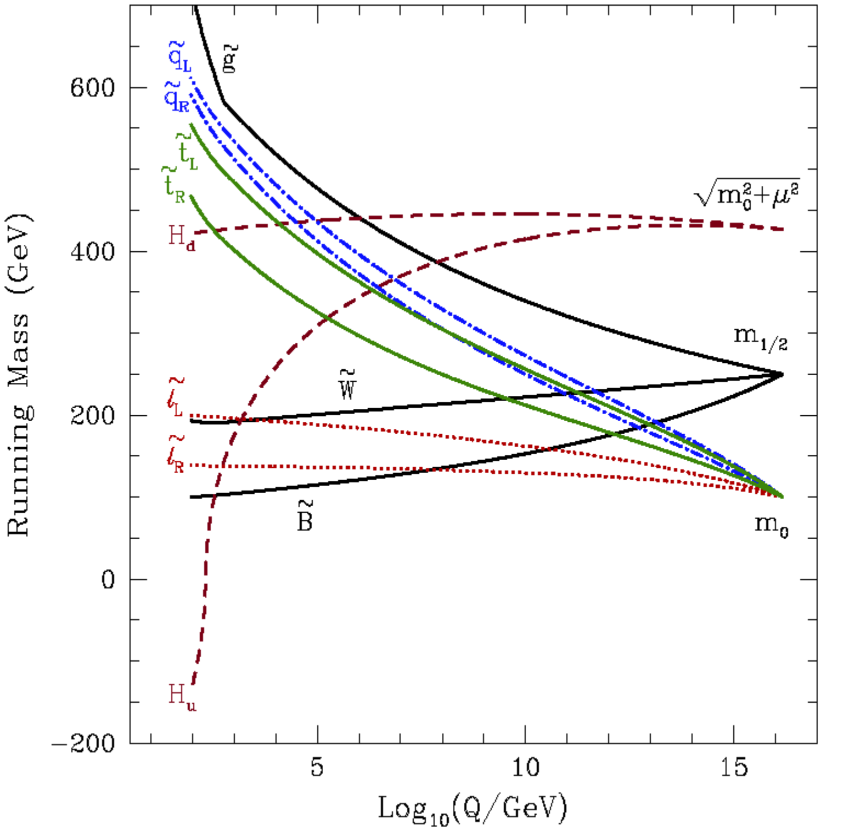
- Simple solution: impose a discrete parity, so all interactions require *pairs* of new particles. This also makes the lightest new particle stable:

LEP constraints ↔ Discrete Symmetry ↔ Stability

Cheng, Low (2003); Wudka (2003)

# WIMP NEUTRALITY

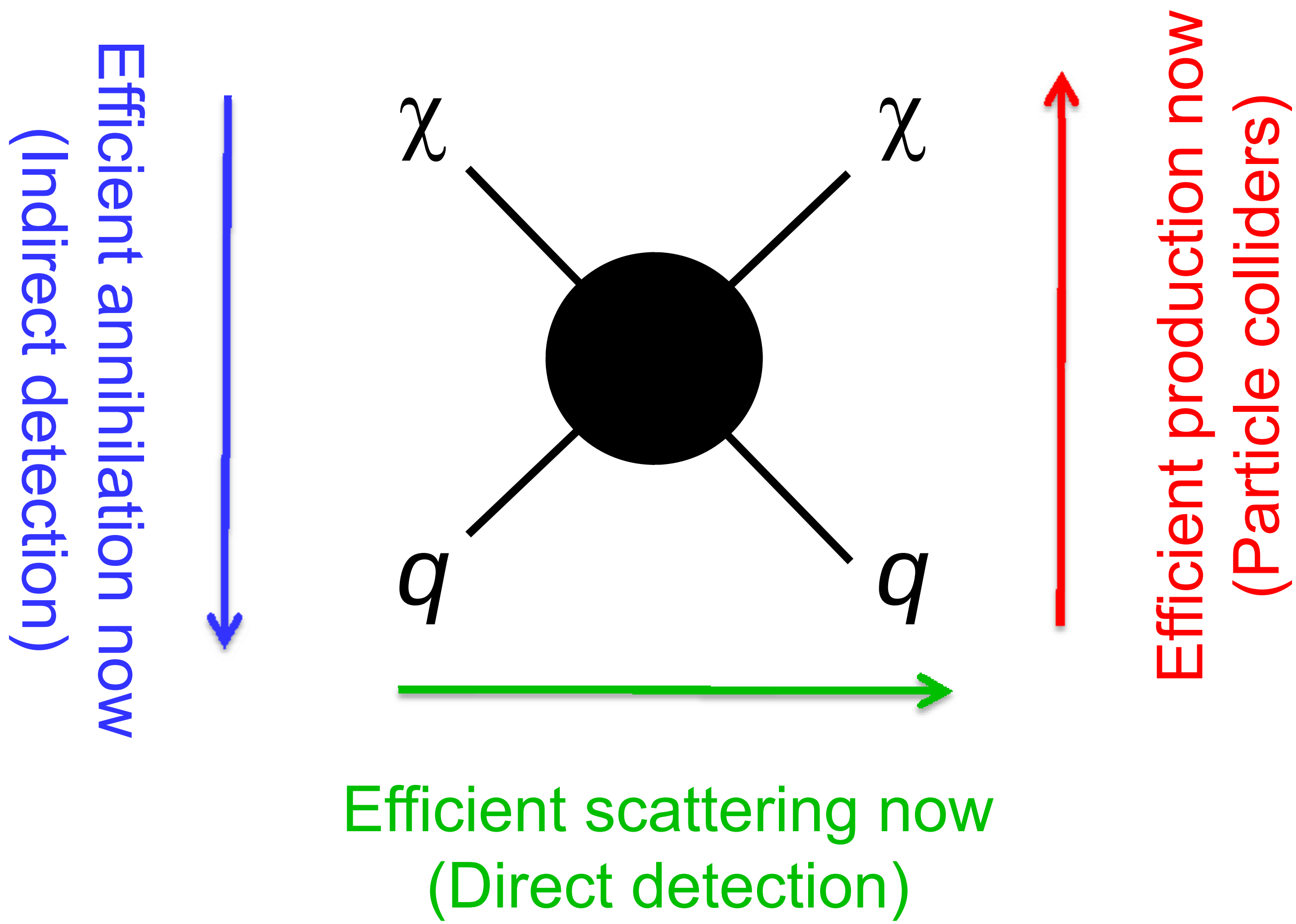
- WIMPs must also be neutral
- How natural is this? Again, *a priori*, not very: what is the chance that the lightest one happens to be neutral?
- In fact, in many cases (SUSY, extra dims, …), masses are "proportional" to couplings, so neutral particles are the lightest




Bottom line: WIMPs, new particles that are *stable* and *neutral* with $\Omega \sim 0.1$, appear in many models of new particle physics

# CURRENT CONSTRAINTS

Correct relic density → Efficient annihilation then



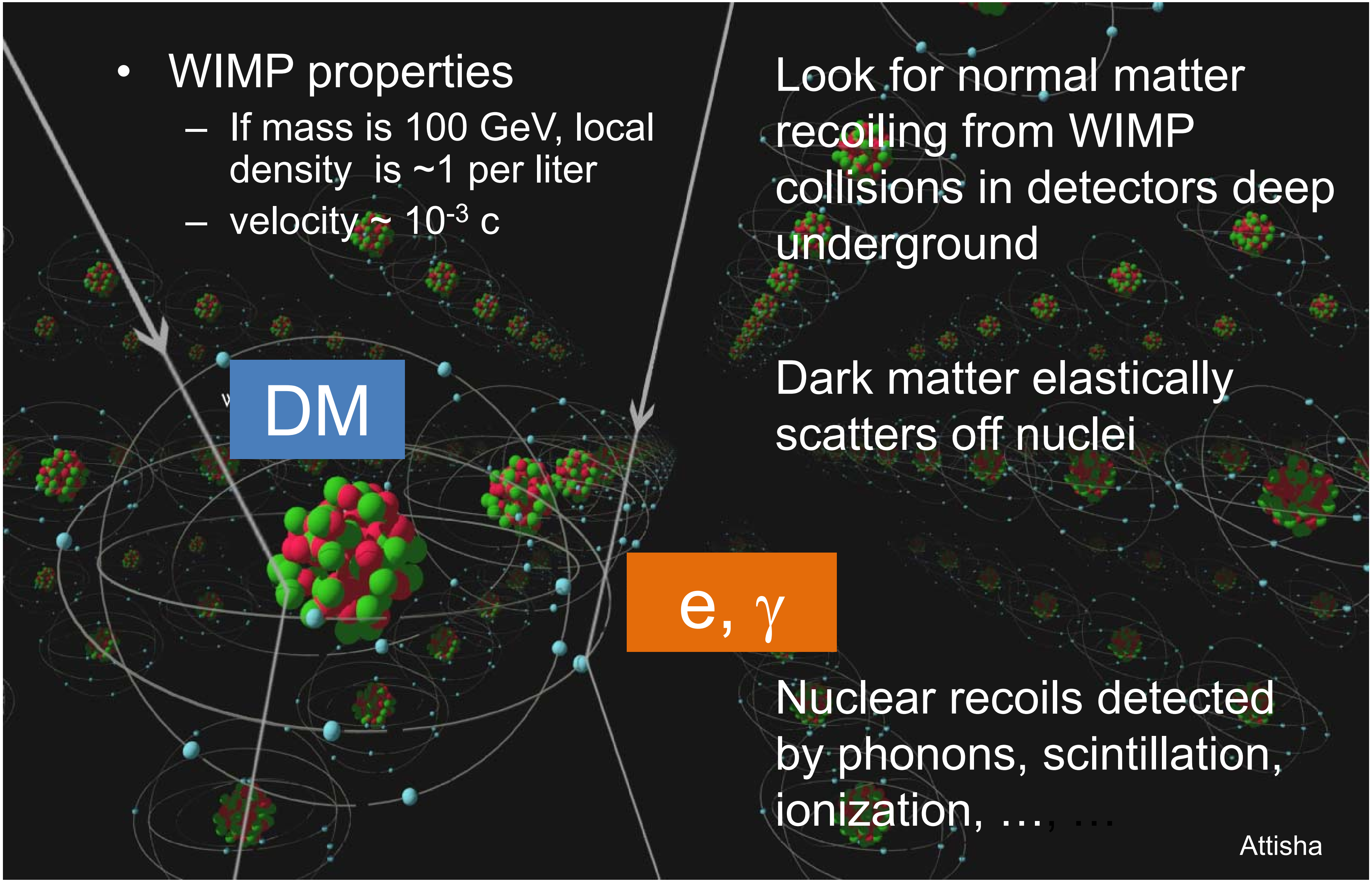
# DIRECT DETECTION

- WIMP properties
  - If mass is 100 GeV, local density is ~1 per liter
  - velocity ~ $10^{-3}$ c

Look for normal matter recoiling from WIMP collisions in detectors deep underground

Dark matter elastically scatters off nuclei

Nuclear recoils detected by phonons, scintillation, ionization, …, …

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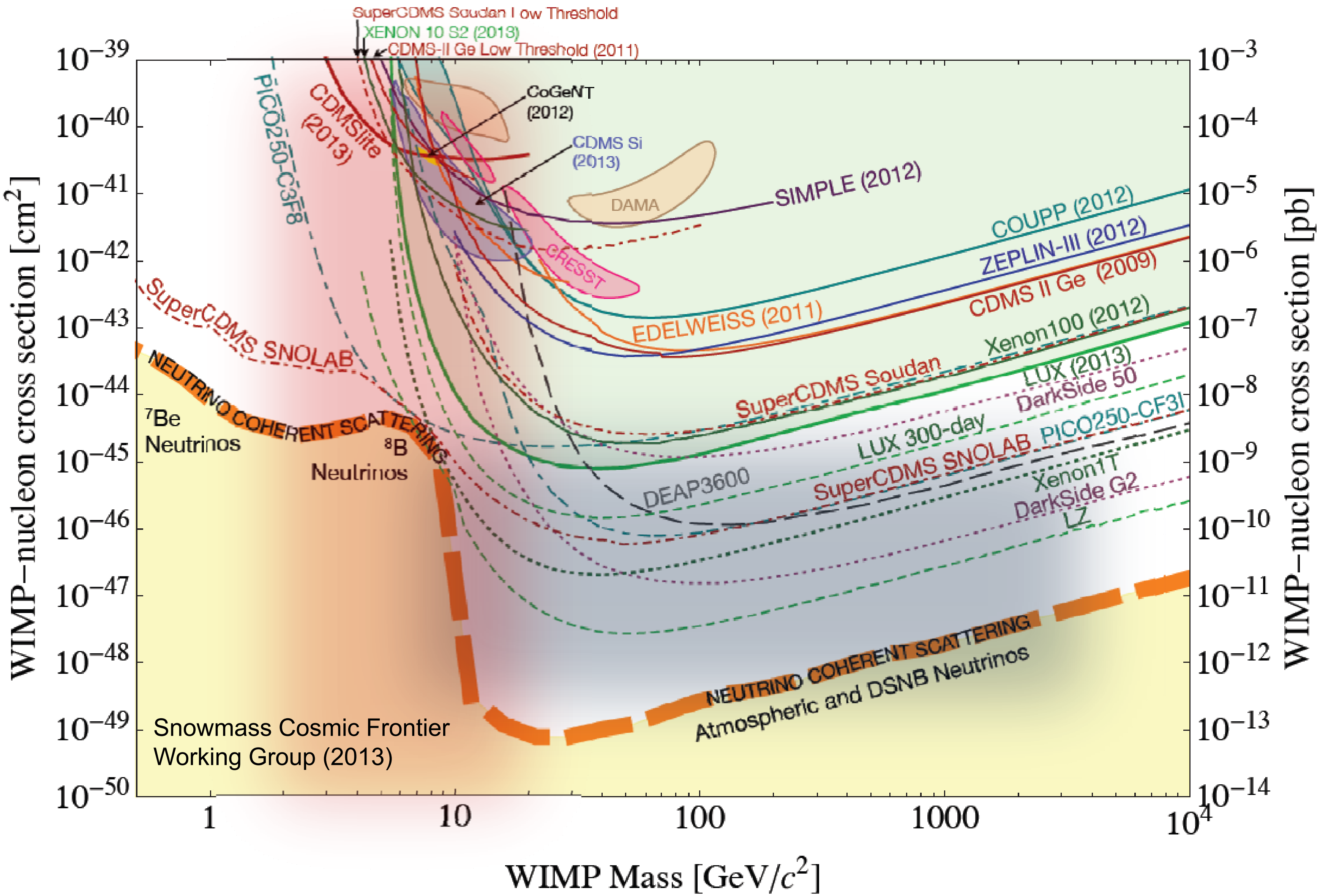
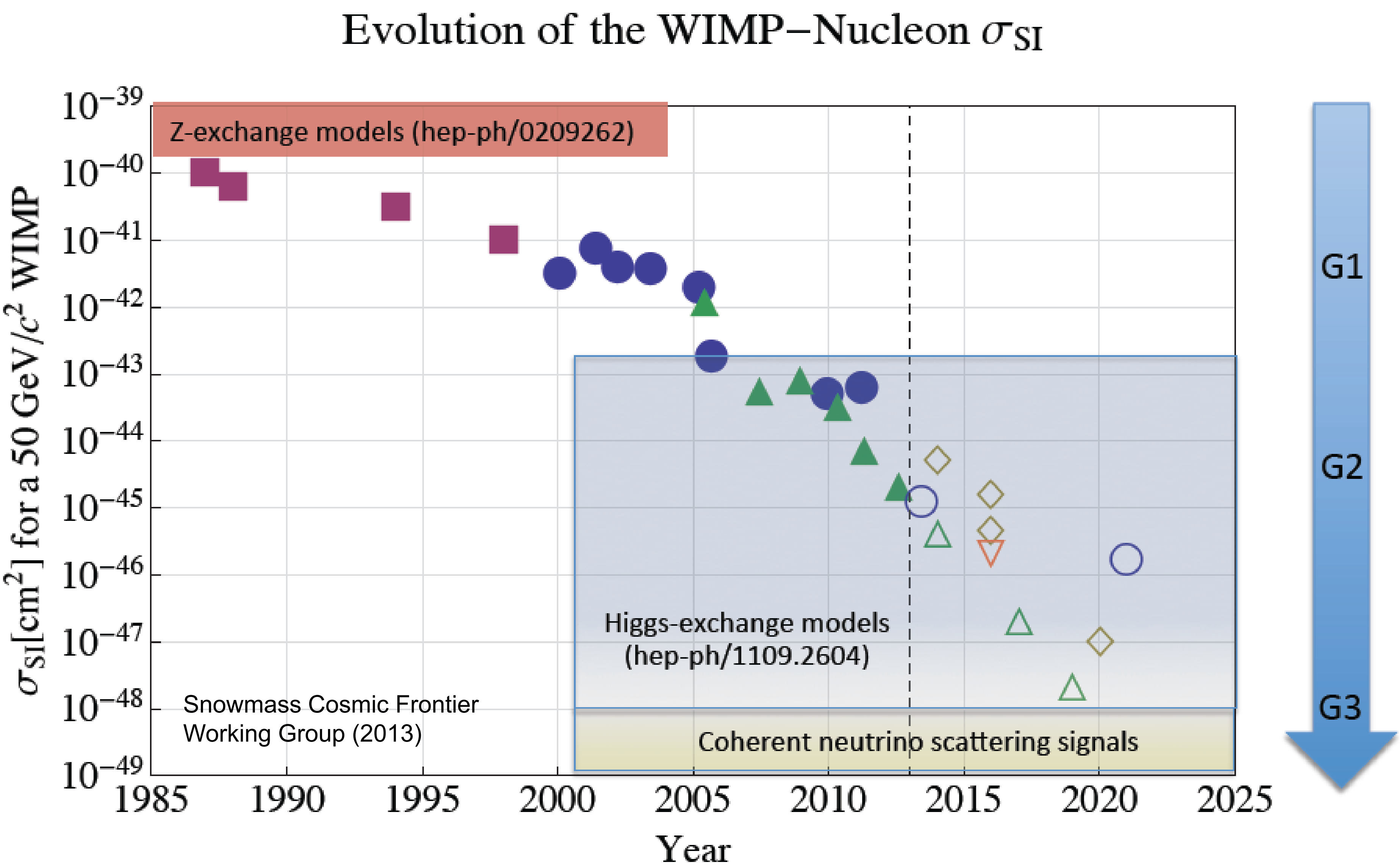
# CURRENT STATUS AND FUTURE PROSPECTS

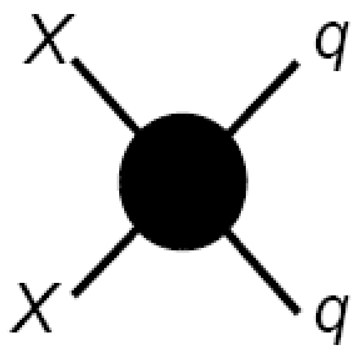


# MOORE'S LAW FOR DARK MATTER



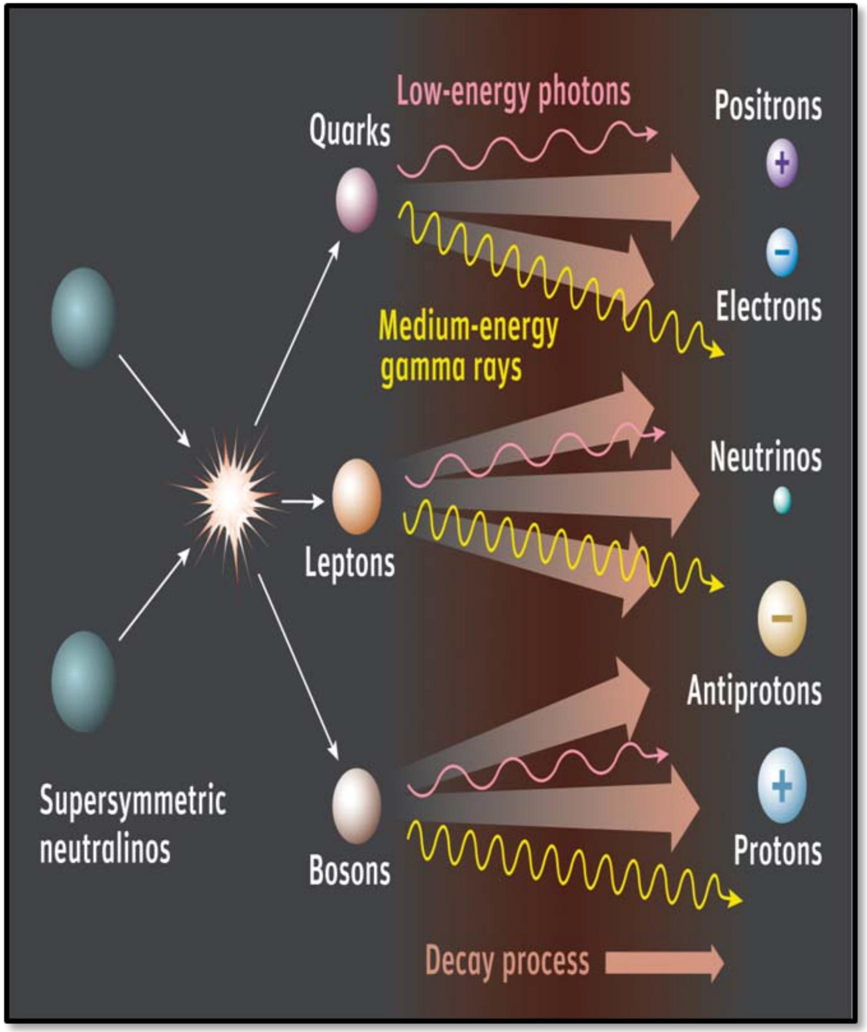
# INDIRECT DETECTION

- Dark matter may pair annihilate in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons



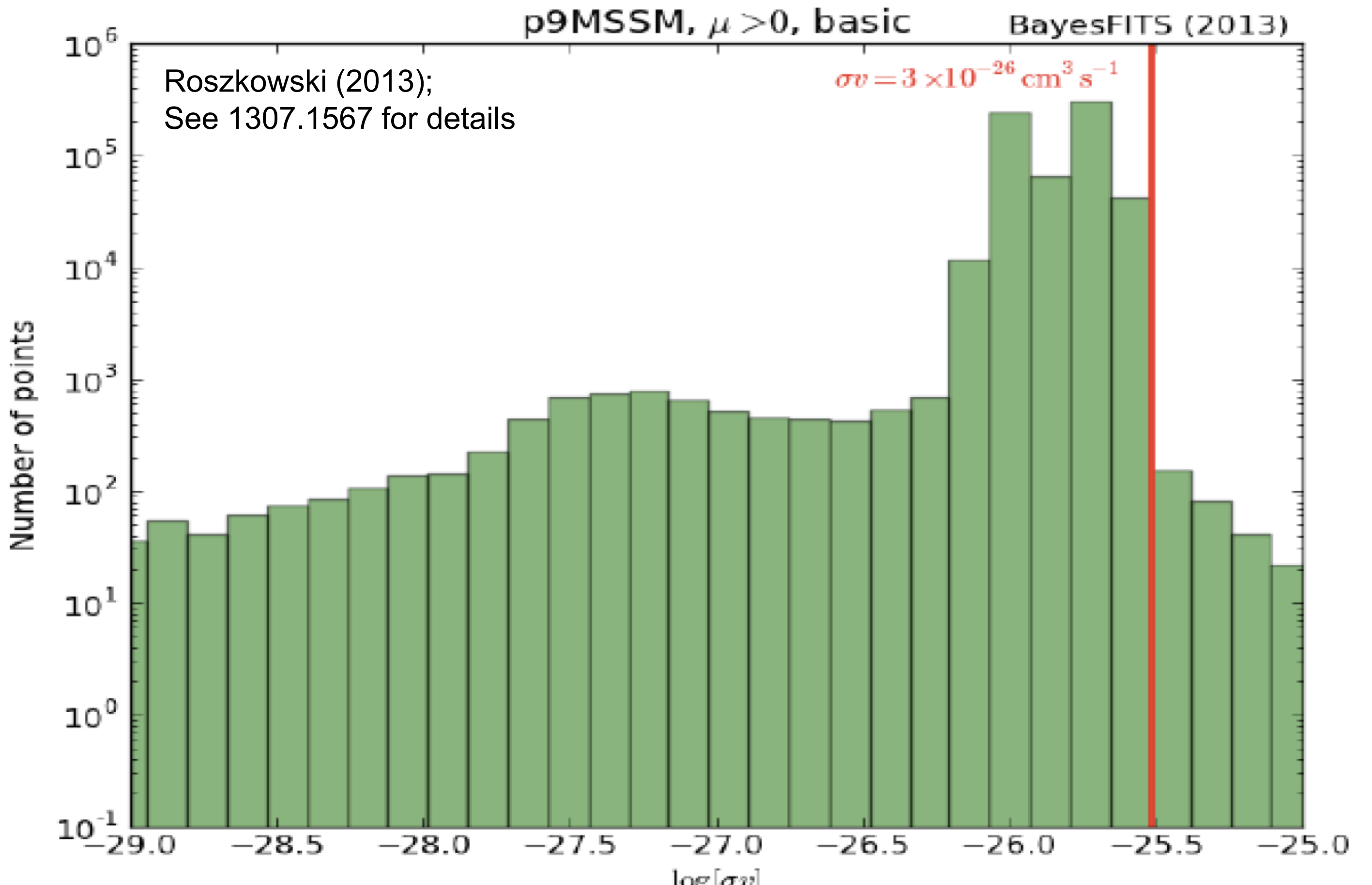

- The relic density provides a target annihilation cross section

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



# ROBUSTNESS OF THE TARGET CROSS SECTION

Relative to direct, indirect rates have larger astrophysical uncertainties, but smaller particle physics uncertainties

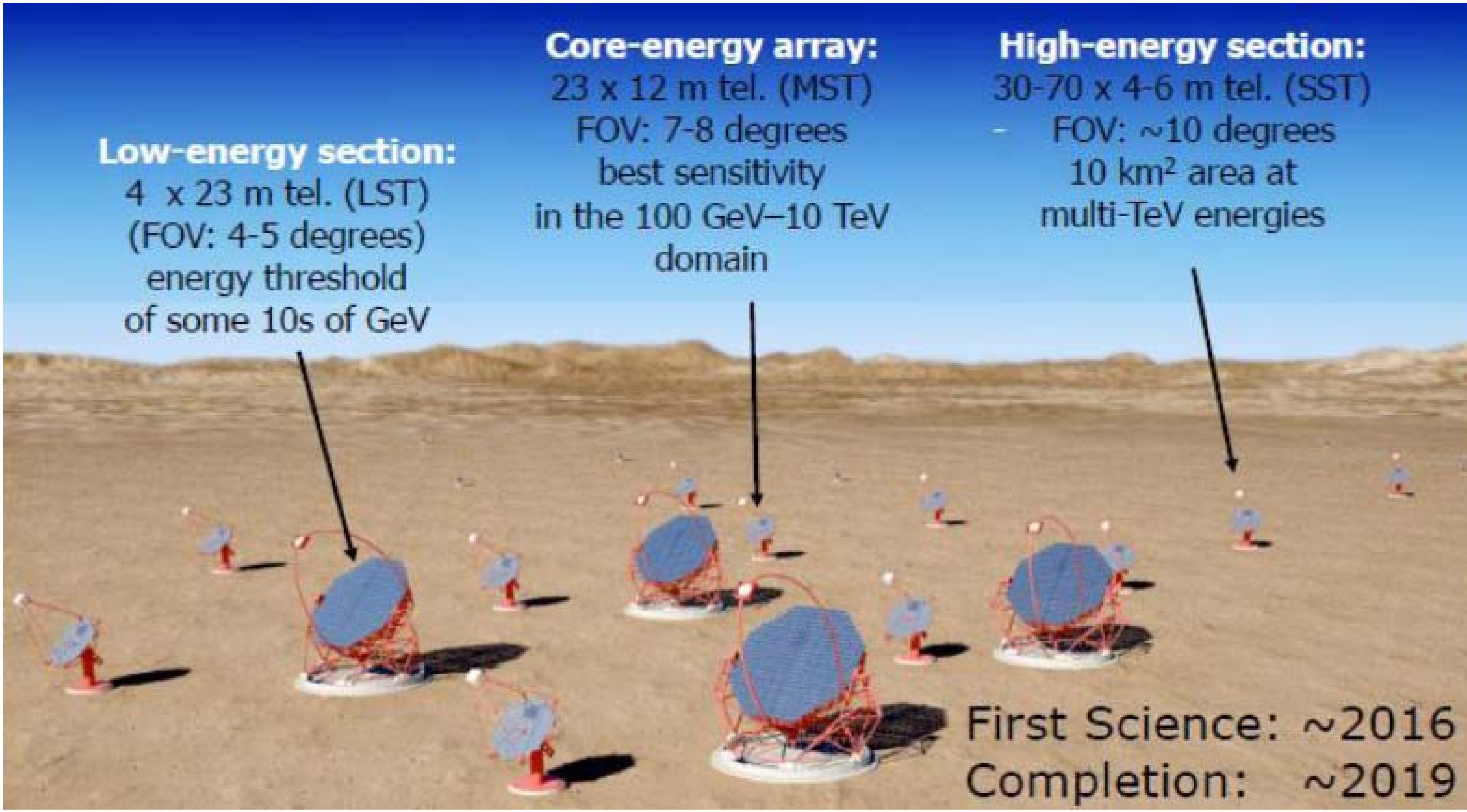


# INDIRECT DETECTION: PHOTONS

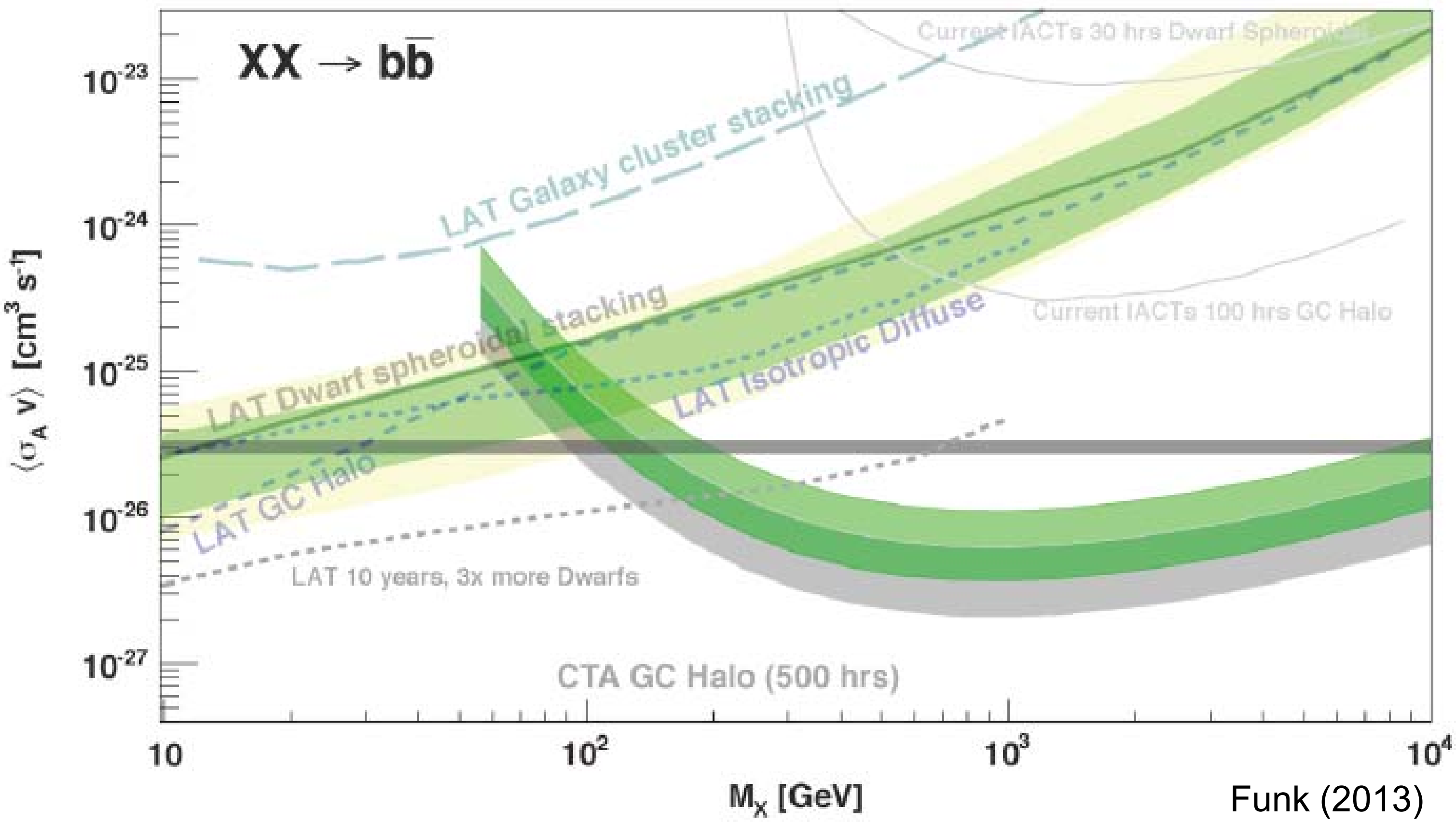
Current: Veritas, Fermi-LAT, HAWC, and others


# INDIRECT DETECTION: PHOTONS

## Future: Cerenkov Telescope Array



# INDIRECT DETECTION: PHOTONS

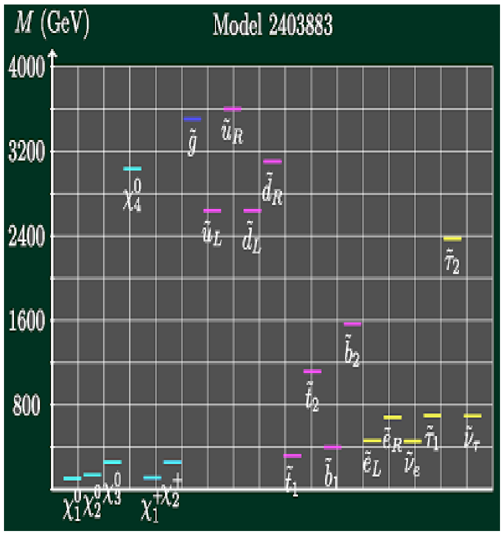


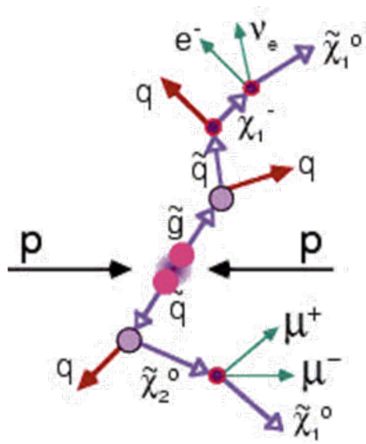

Funk (2013)

- Fermi-LAT sensitive to light WIMPs with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV

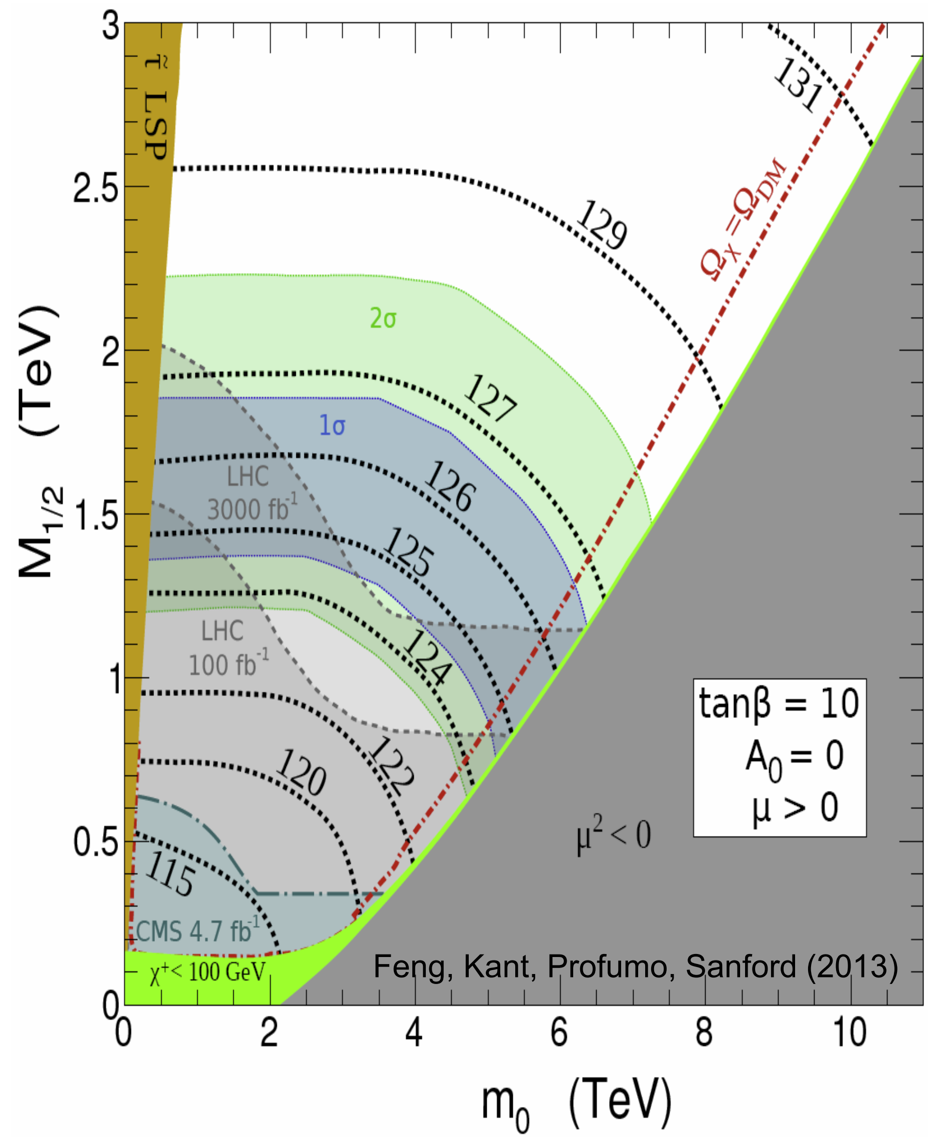
# DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)

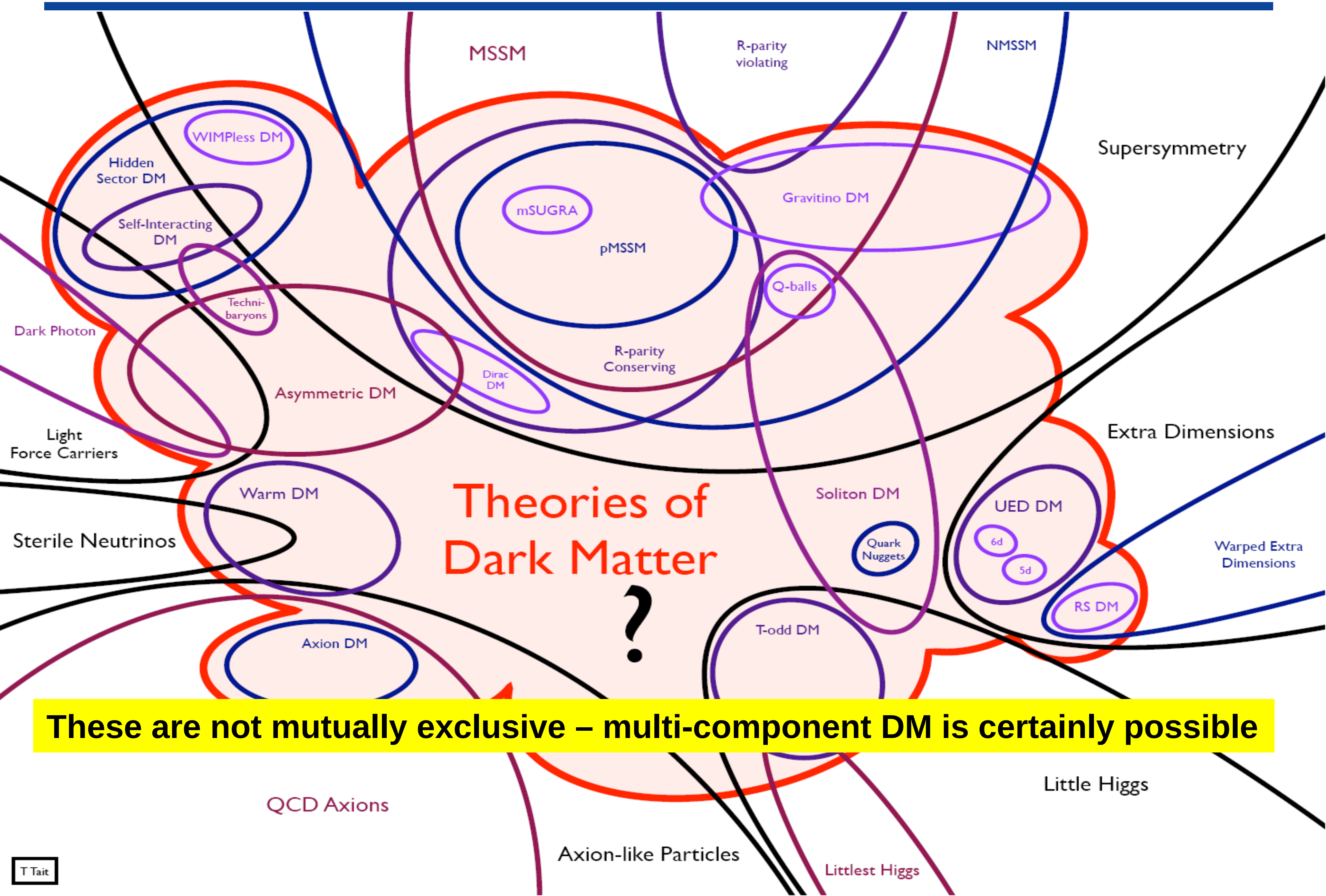



The LHC has not seen WIMPs, but has not yet probed the parameter space indicated by EDMs, Higgs,... : wait for LHC14 and HL-LHC



# WIMP-LIKE EXTENSIONS



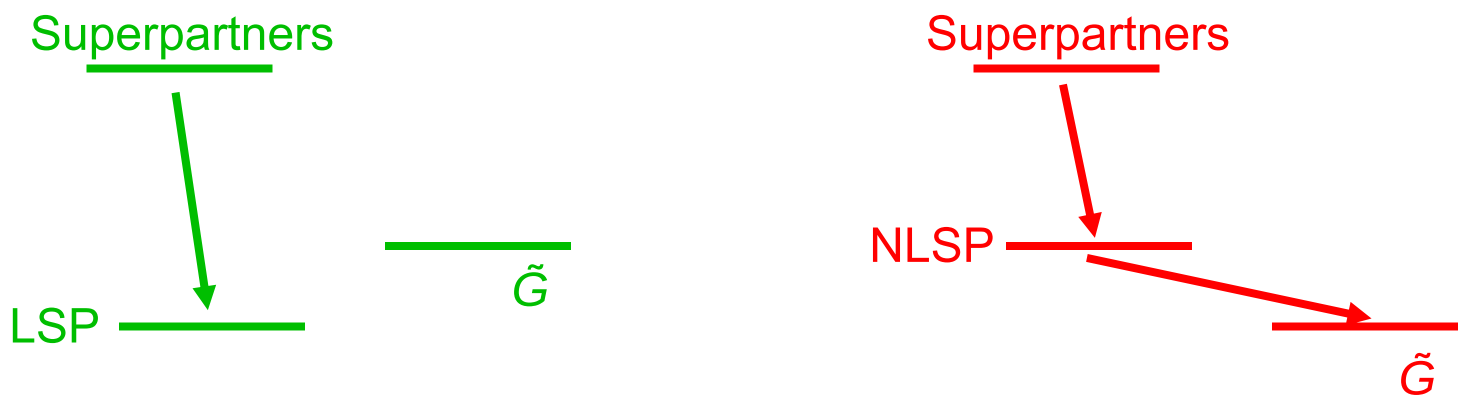

**These are not mutually exclusive – multi-component DM is certainly possible**

# SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

- An example: Gravitinos in supersymmetry with $m_{\tilde{G}} \sim m_{SUSY}$

- $\tilde{G}$ not LSP: WIMPs
- $\tilde{G}$ LSP: SuperWIMPs




- WIMP-like: TeV masses, same particle models, superWIMP inherits the right relic density

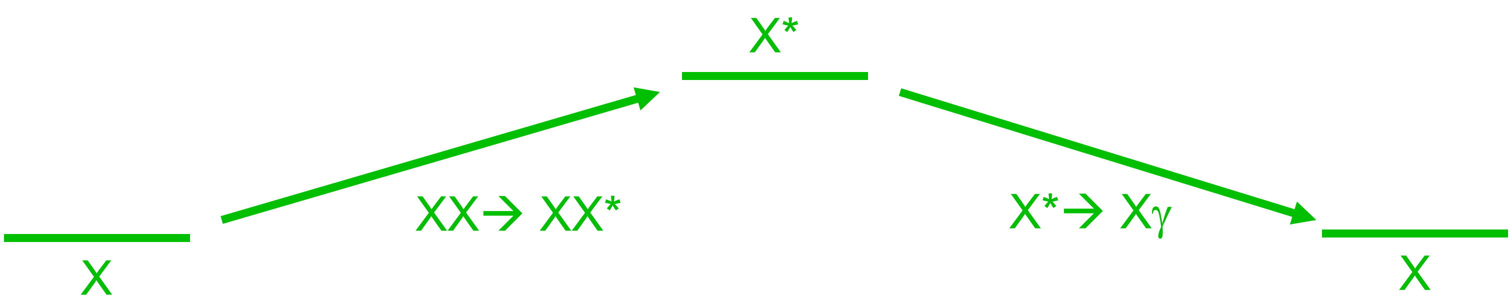
  But completely different: superweakly-interacting, warm DM, BBN, long-lived charged particles at LHC, …

# EXCITING DARK MATTER

Finkbeiner, Weiner (2007)

- WIMP dark matter X with a nearly degenerate state X*

- X* created in collisions with $m_X v^2 > \Delta m \sim$ keV to MeV




- WIMP-like: TeV masses, correct thermal relic density

  But completely different: dark photons to mediate up-scatter, de-excitation → INTEGRAL, 3.5 keV line, …

# HIDDEN DARK MATTER

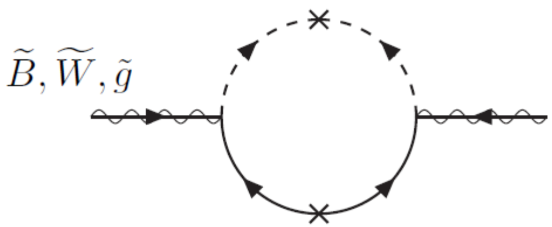
- All evidence for dark matter is gravitational. Perhaps it's in a hidden sector, composed of particles without EM, weak, strong interactions


- *A priori* there are both pros and cons
  - Lots of freedom: interesting astrophysics, etc.
  - Too much freedom: no connections to known problems
  - No relation to WIMPs and the WIMP miracle

Spergel, Steinhardt (1999); Foot (2001)

# WIMPLESS DARK MATTER

- The flavor problem → SUSY models with $m_X \sim g_X^2$

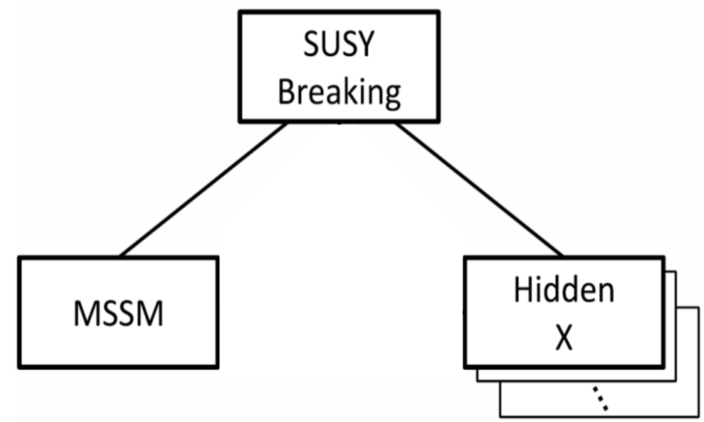


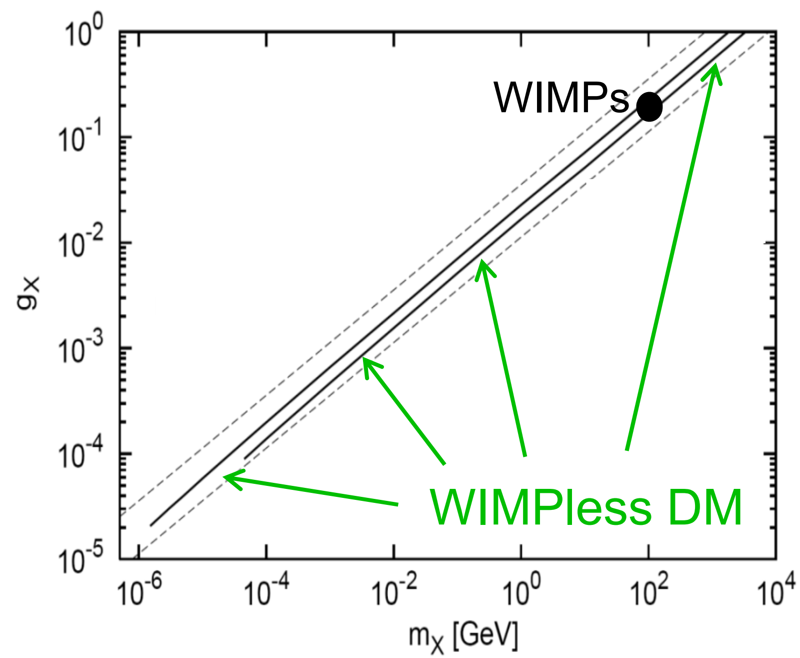

- If this applies also in hidden sectors, these will have DM with the correct relic density

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- Restores
  - Particle physics motivations
  - Structure, predictivity
  - WIMP miracle without WIMPs

Feng, Kumar (2008)



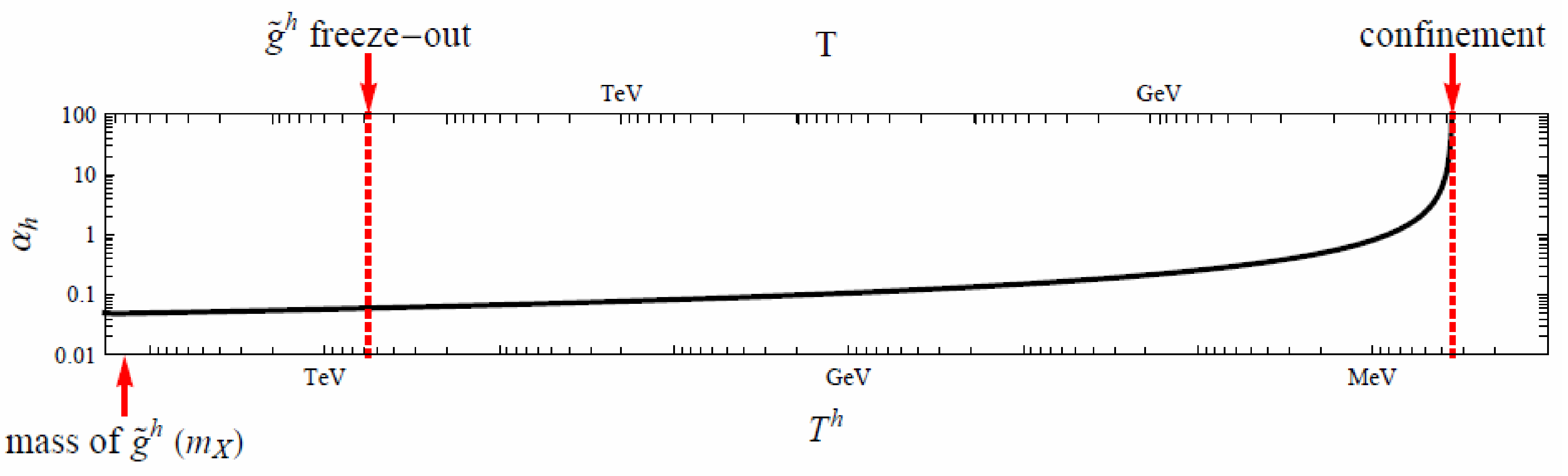



# WIMPLESS SELF-INTERACTING DARK MATTER

Feng, Shadmi (2011), Boddy, Feng, Kaplinghat, Tait (2014)

- A simple example: pure SU(N) with hidden gluons g and gluinos $\tilde{g}$
- At early times, interaction is weak, ~1-10 TeV $\tilde{g}$ freezeout with correct $\Omega$
  At late times, interaction is strong, glueballs (gg) and glueballinos ($g\tilde{g}$) form and self-interact with $\sigma_T/m \sim 0.1\ cm^2/g \sim 0.1$ barn/GeV

Rocha et al. (2012), Peter et al. (2012); Vogelsberger et al. (2012); Zavala et al. (2012)




- WIMP-like: TeV-masses with correct thermal relic density
- But completely different: self-interacting, multi-component dark matter

# CONCLUSIONS

- Overview
  - WIMPs, new, stable, neutral particles with the right thermal relic density, are motivated by particle physics alone
  - The fact that they might be dark matter is hard to ignore
- Current Constraints
  - Direct Detection: approaching the neutrino background
  - Indirect Detection: approaching the target annihilation cross section
  - Colliders: LHC probes deeper into the weak scale
- WIMP-like Extensions
  - SuperWIMPs, excited dark matter, WIMPless dark matter, and many others
  - WIMP-like, but predict a rich variety of observable phenomena