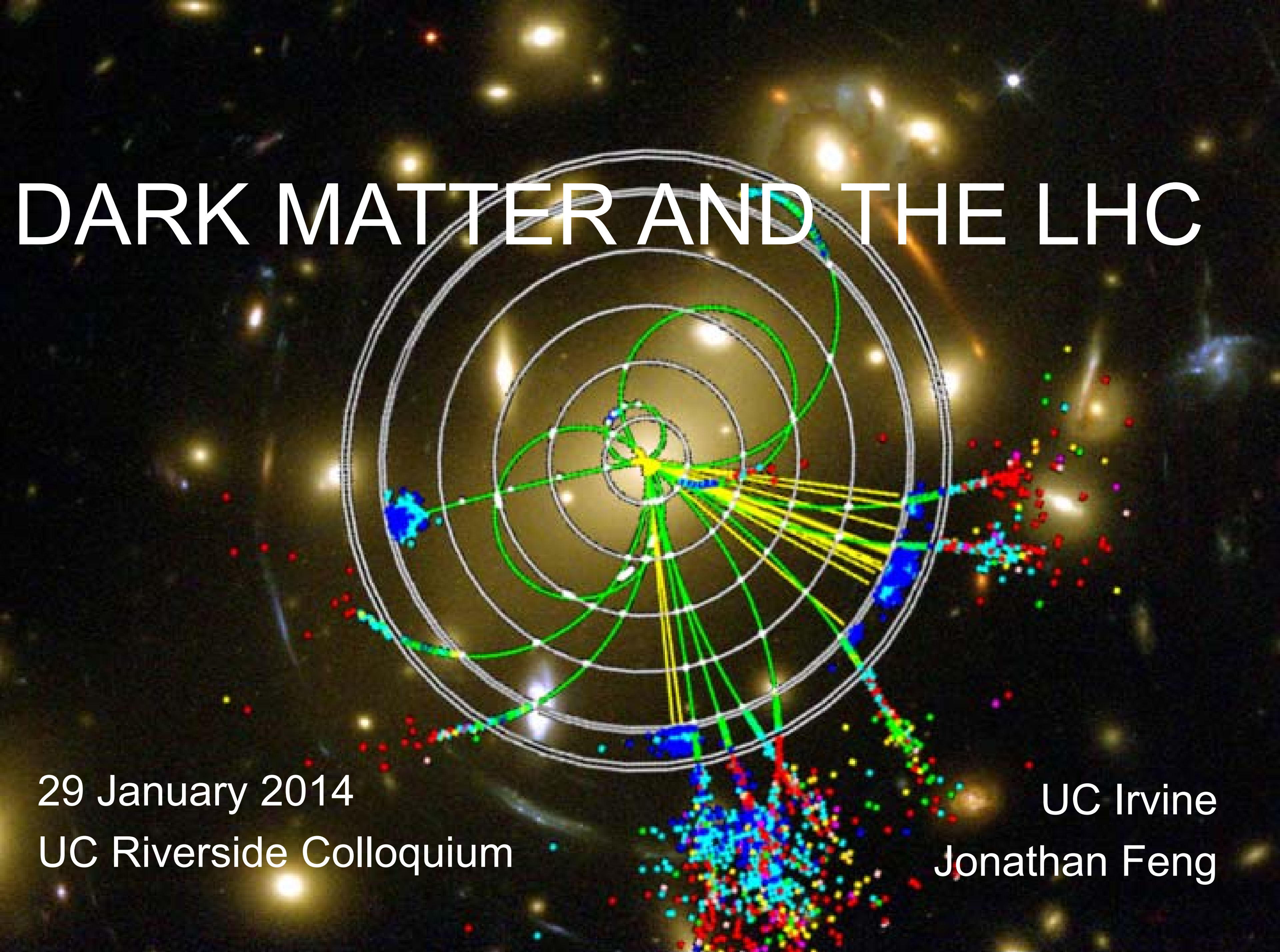


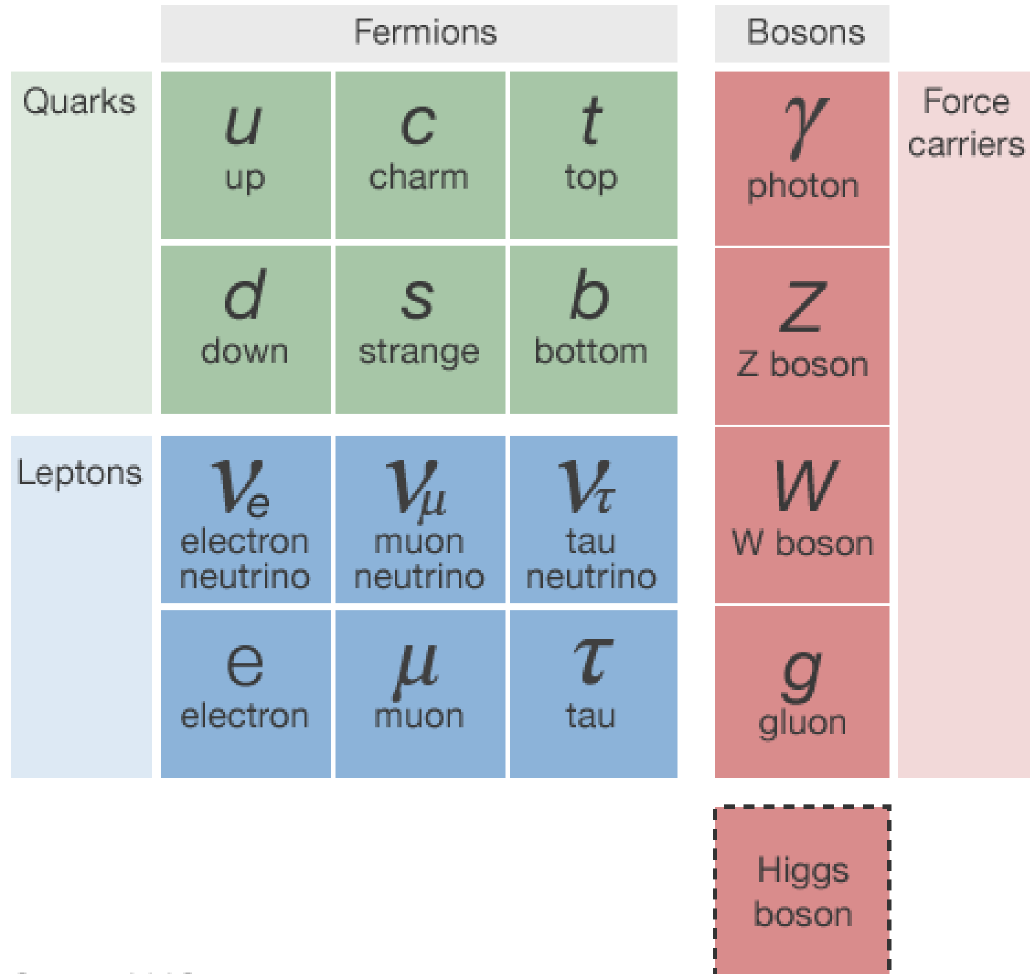
DARK MATTER AND THE LHC

29 January 2014
UC Riverside Colloquium

UC Irvine
Jonathan Feng

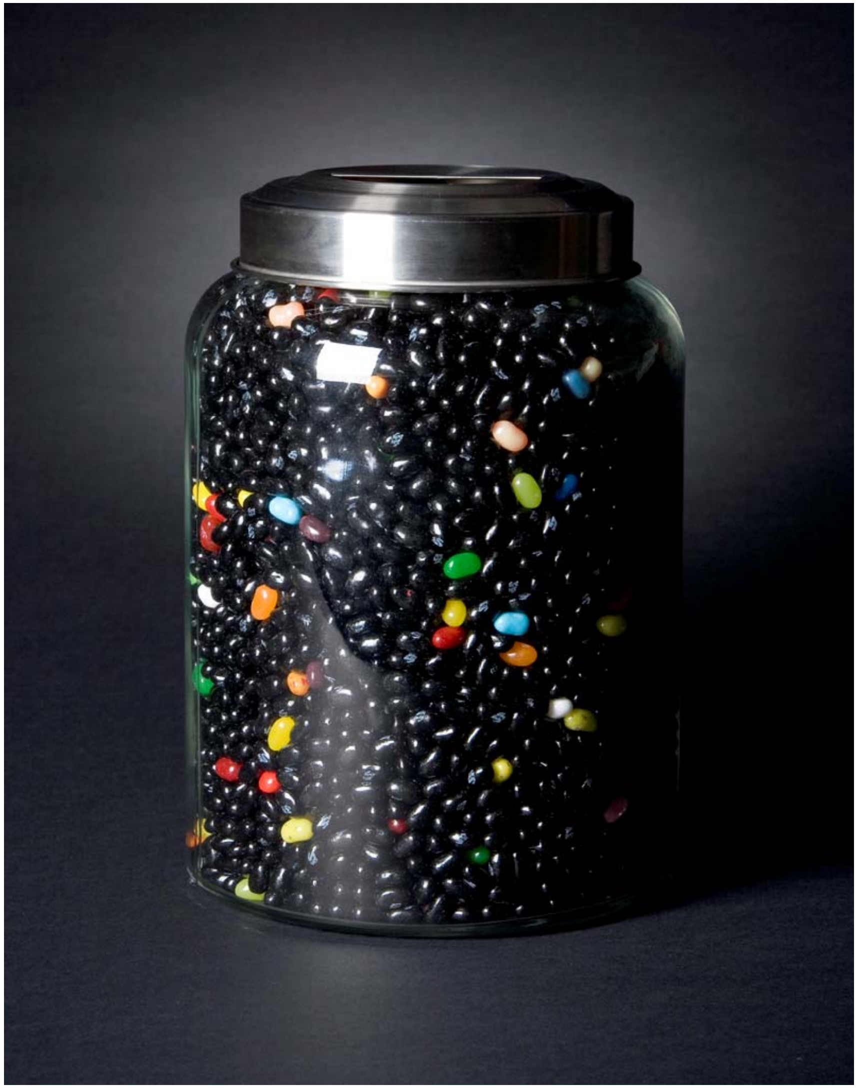
INTRODUCTION

- The Higgs discovery at the LHC was a landmark achievement
- It capped a 50-year saga and completed the particle content of the Standard Model
- But we expect there are more particles to discover, and the Higgs may be just the opening act for the LHC. Why?



Source: AAAS

EVIDENCE FOR DARK MATTER



- We have also learned a lot about the Universe in recent years
- There is now overwhelming evidence that normal (atomic) matter is not all the matter in the Universe:

  Dark Matter: 23% ± 4%

  Dark Energy: 73% ± 4%

  Normal Matter: 4% ± 0.4%

  Neutrinos: 0.2% (Σm_ν/0.1eV)

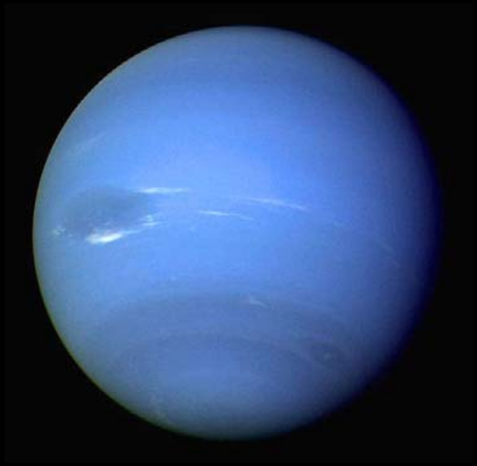
- To date, all evidence is from dark matter's gravitational effects; to identify it, we need to see it in other ways

A PRECEDENT

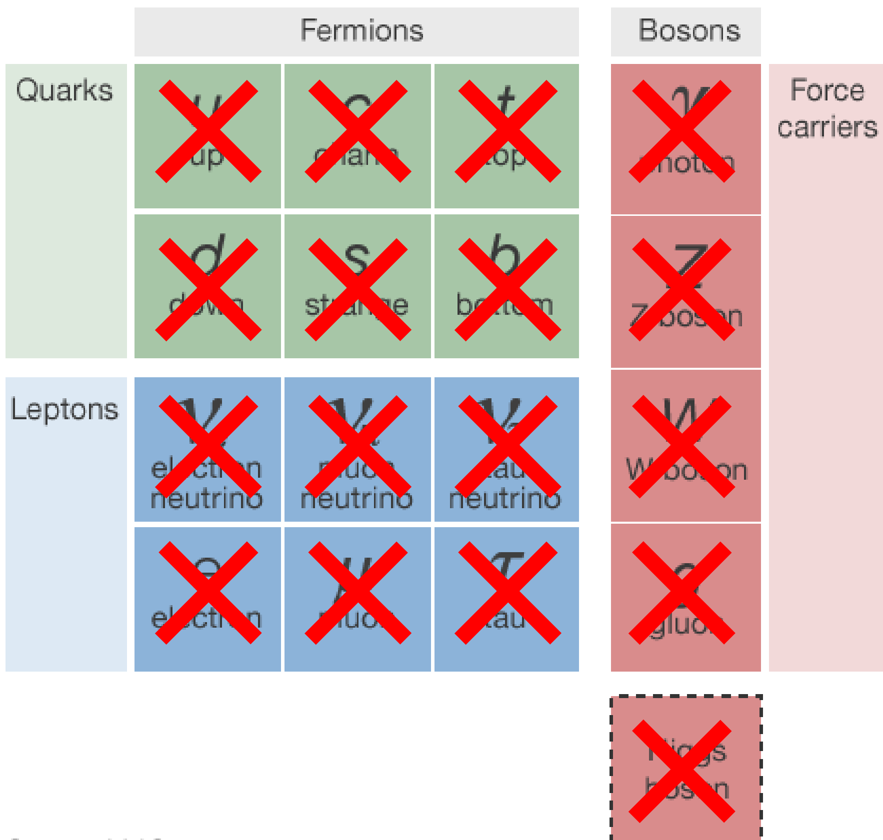
- In 1821 Alexis Bouvard found anomalies in the observed path of Uranus and suggested they could be caused by dark matter

- In 1845-46 Urbain Le Verrier determined the expected properties of the dark matter and how to find it. With this guidance, Johann Gottfried Galle discovered dark matter in 1846.

- Le Verrier wanted to call it "Le Verrier," but it is now known as Neptune, the farthest known planet (1846-1930, 1979-99, 2006-present)



DARK MATTER



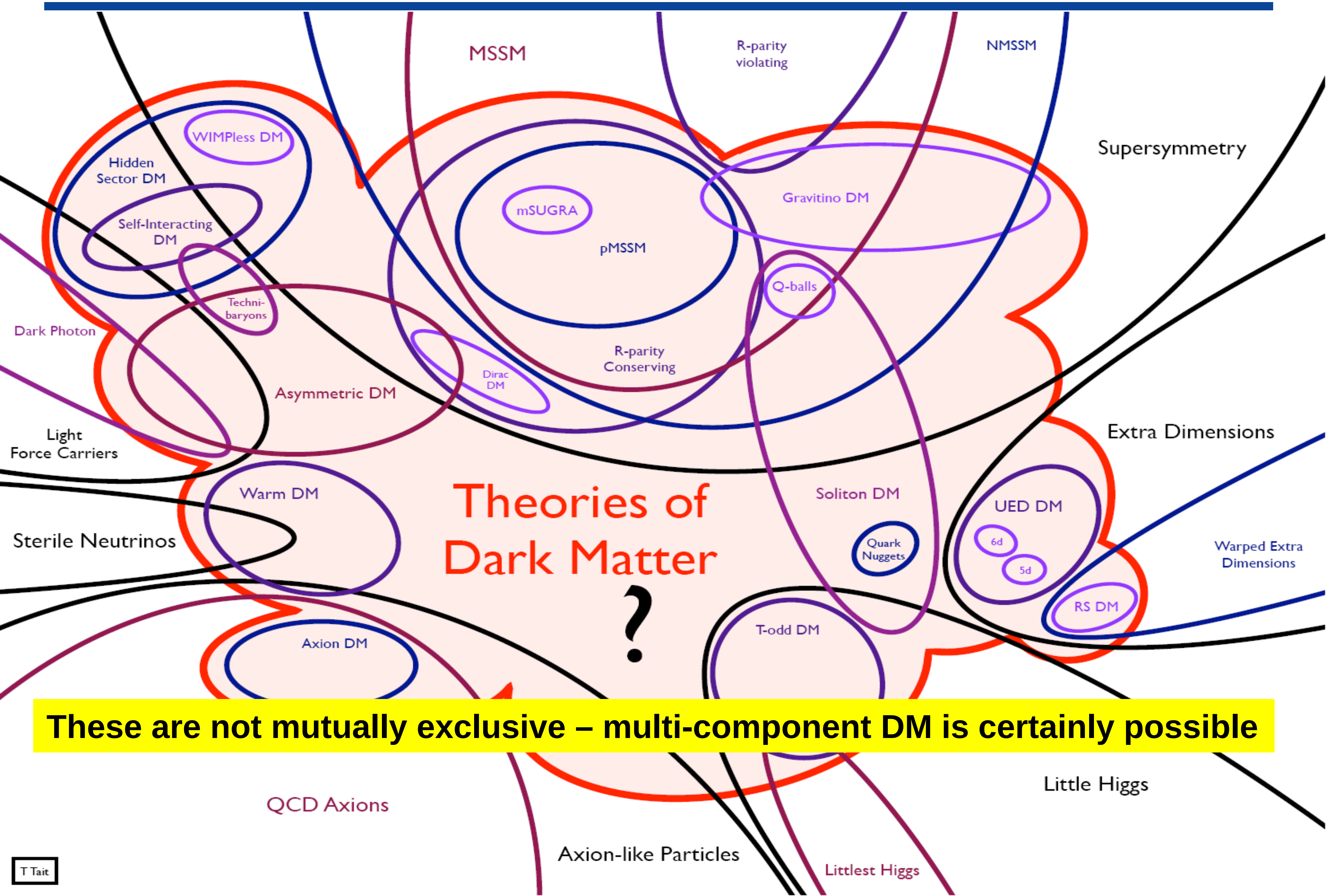
Source: AAAS

Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Unambiguous evidence for new particles

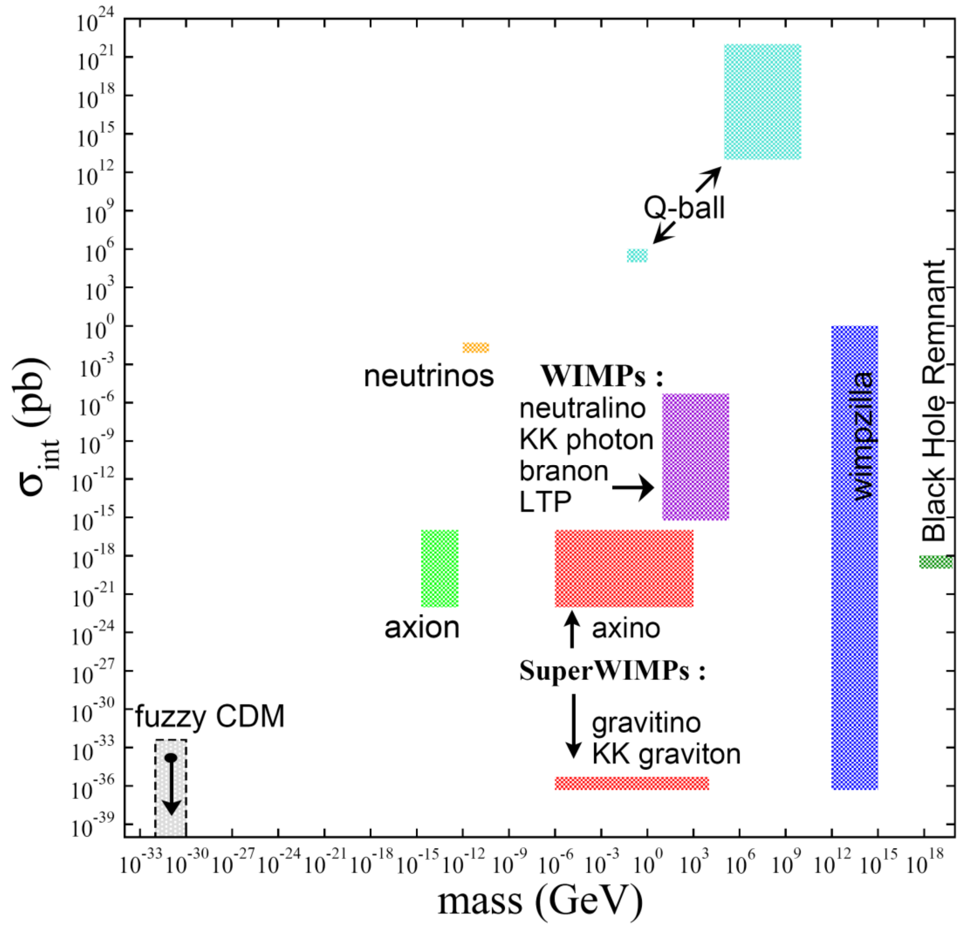
WHAT COULD DARK MATTER BE?



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

DARK MATTER CANDIDATES

- Clearly the observational constraints are no match for the creativity of theorists
- Masses and interaction strengths span many, many orders of magnitude
- But not all candidates are similarly motivated



HEPAP/AAAC DMSAG Subpanel (2007)

THE WEAK MASS SCALE

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

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

- $G_F \approx 1.1 \cdot 10^{-5}\ \mathrm{GeV}^{-2}$ → a new mass scale in nature

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

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

FREEZE OUT

(1) Assume a new heavy particle *X* is initially in thermal equilibrium:

$$XX \leftrightarrow \bar{q}q$$

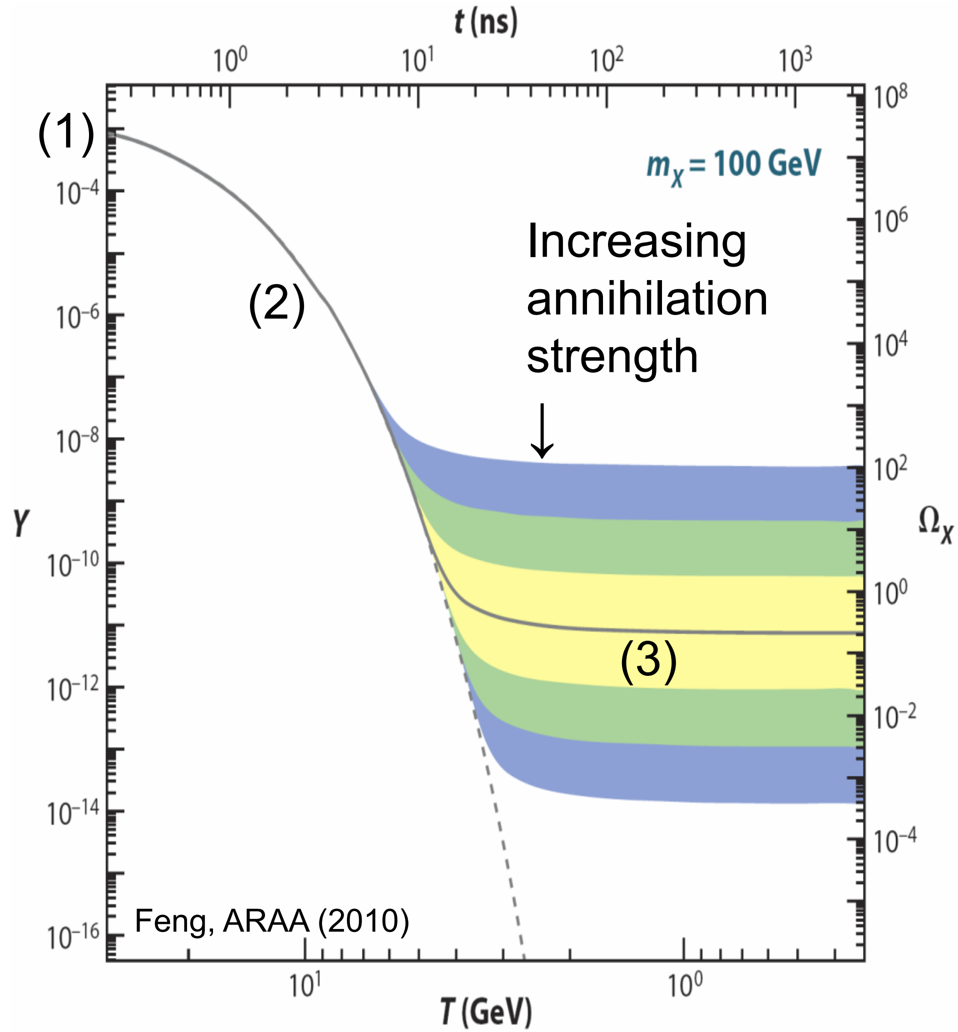
(2) Universe cools:

$$XX \;\substack{\rightarrow \\ \not\leftarrow}\; \bar{q}q$$

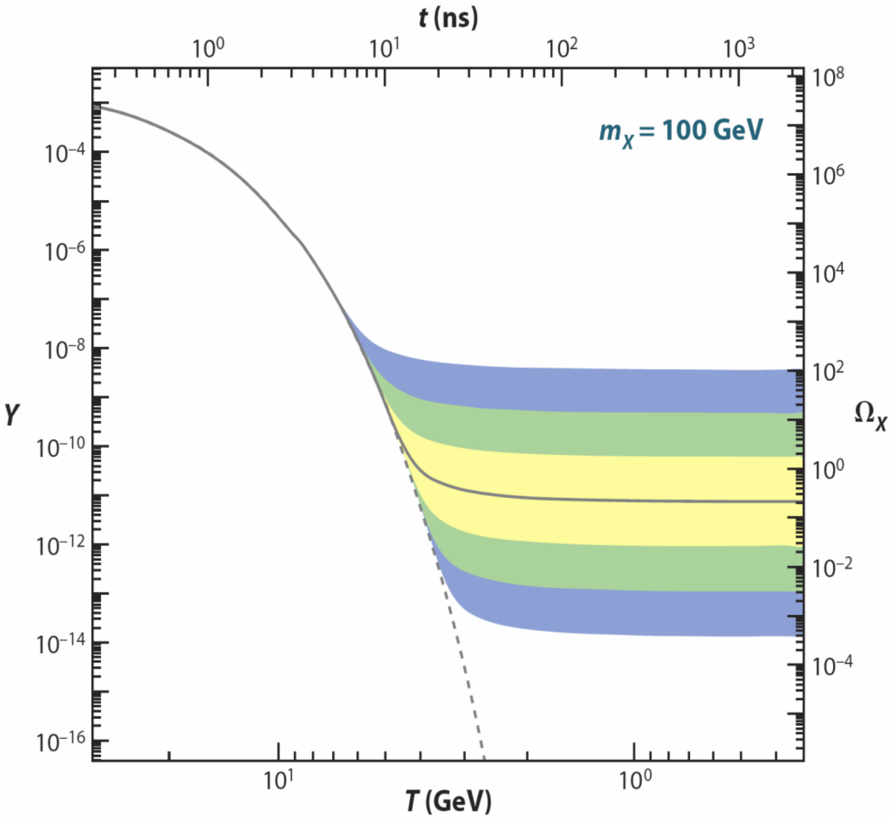
(3) Universe expands:

$$XX \;\substack{\not\rightarrow \\ \not\leftarrow}\; \bar{q}q$$

Zeldovich et al. (1960s)

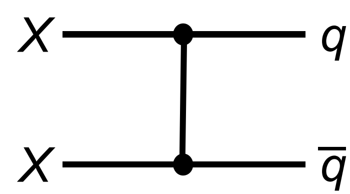


THE WIMP MIRACLE



- The relation between Ω_X and annihilation strength is wonderfully simple:

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

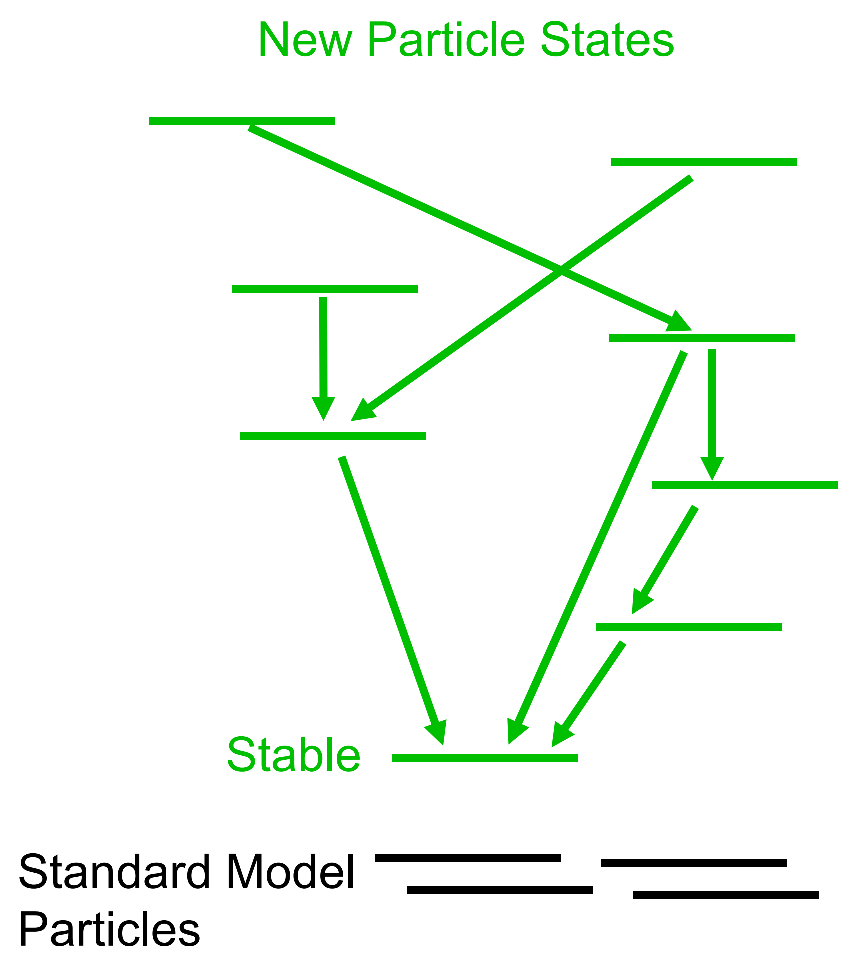


- m_X ~ 100 GeV, g_X ~ 0.6 → Ω_X ~ 0.1

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

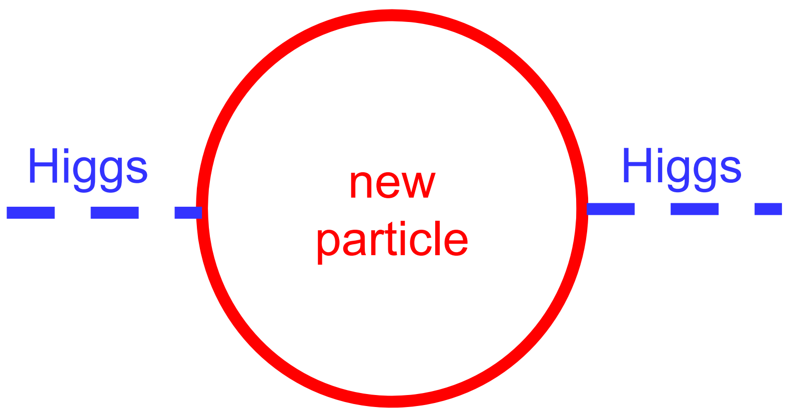
STABILITY

- This all assumes the WIMP is stable
- How natural is this?

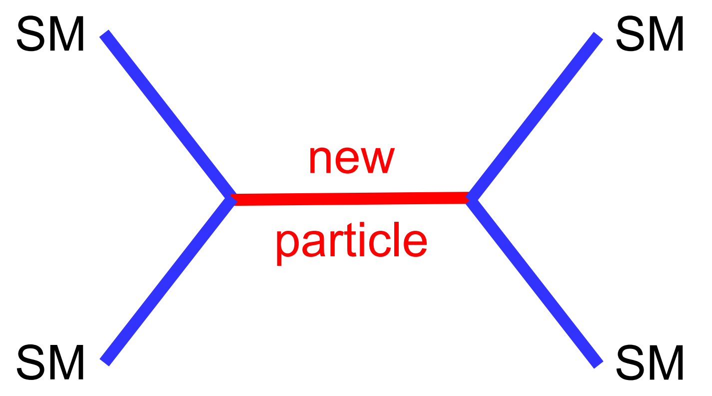


LEP'S COSMOLOGICAL LEGACY

Gauge Hierarchy requires



Precision EW excludes



- 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)

- The result: new, stable particles at the weak scale are predicted in many models and are ideal DM candidates

WIMPS FROM SUPERSYMMETRY

The classic WIMP: neutralinos predicted by supersymmetry

Goldberg (1983); Ellis et al. (1983)

Supersymmetry: extends rotations/boosts/translations, string theory, unification of forces,… For every known particle X, predicts a partner particle $\tilde{X}$

Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}u, \tilde{H}d)$

Particle physics alone → χ is lightest supersymmetric particle, stable, weakly-interacting, mass ~ 100 GeV. All the right properties for WIMP dark matter!

ASYMMETRIC DARK MATTER

- The SM matter relic density was not generated by freeze-out, but by an asymmetry
- If the dark matter relic density was generated in a similar way,

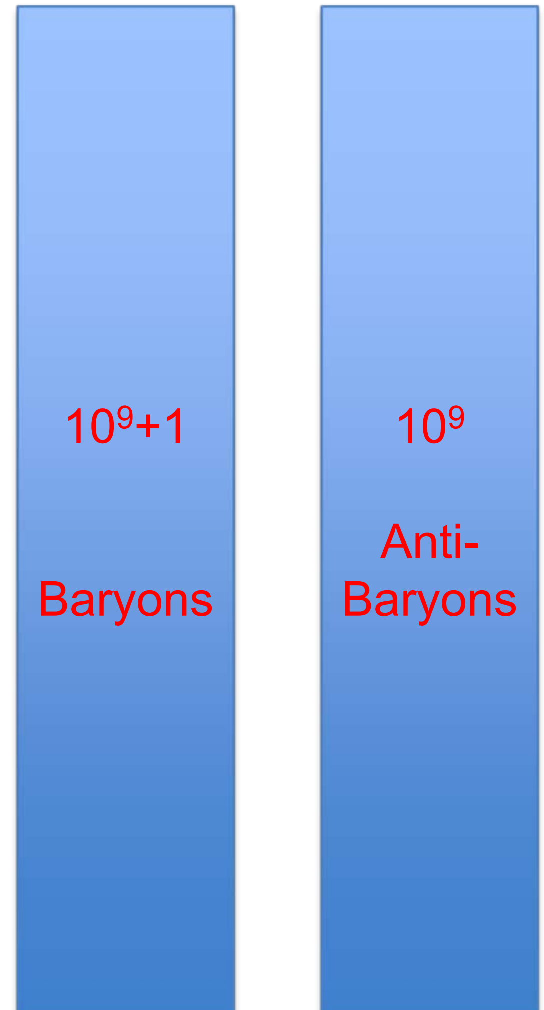
$$n_{DM} \sim n_B$$

$$\downarrow$$

$$m_{DM} / m_B \sim \Omega_{DM} / \Omega_B \sim 5$$

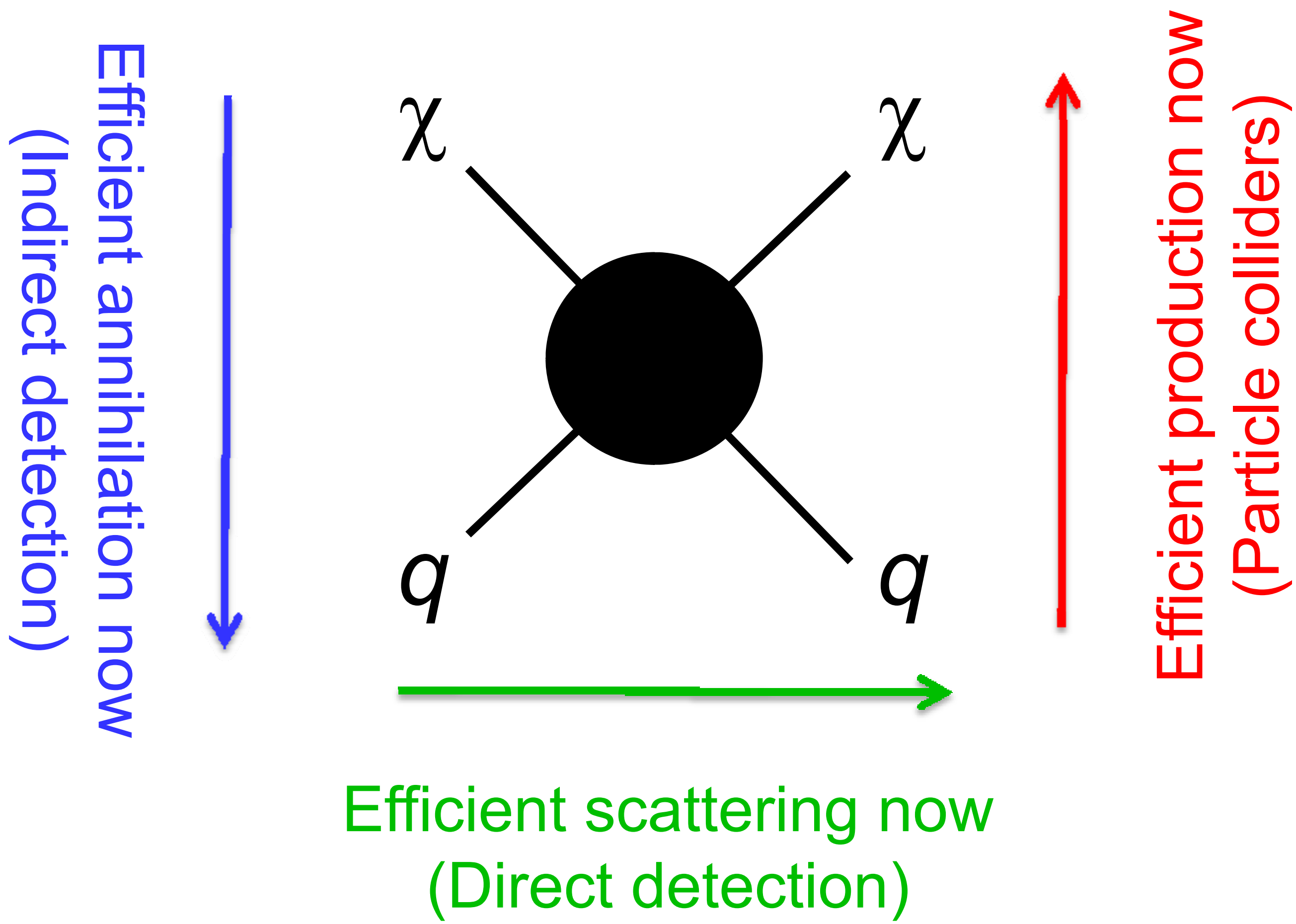
Asymmetric DM → $m_{DM} \sim 5$ GeV

"Light WIMPs"



WIMP DETECTION

Correct relic density → Efficient annihilation then



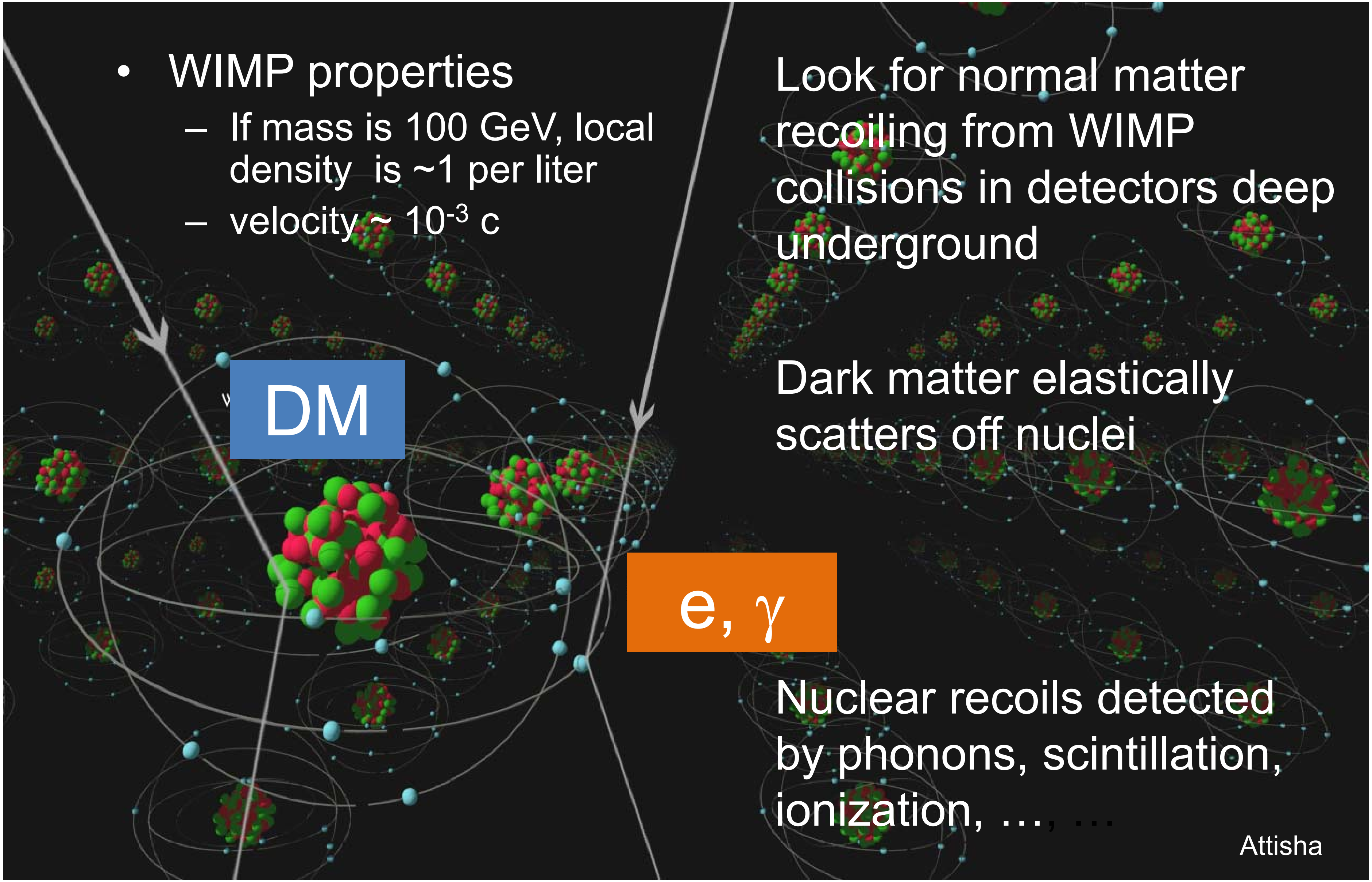
DIRECT DETECTION

- 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

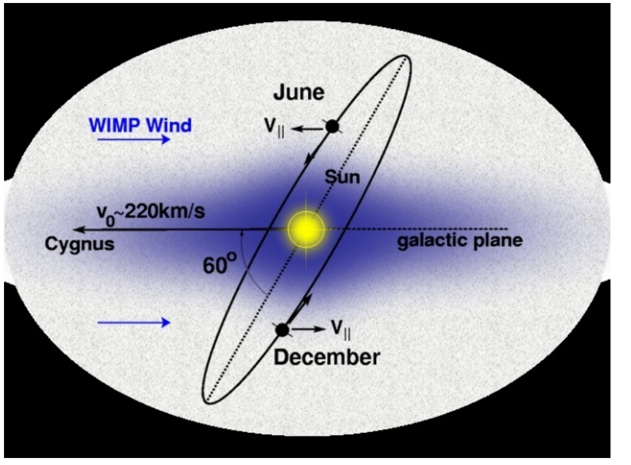
Nuclear recoils detected by phonons, scintillation, ionization, …, …



Attisha

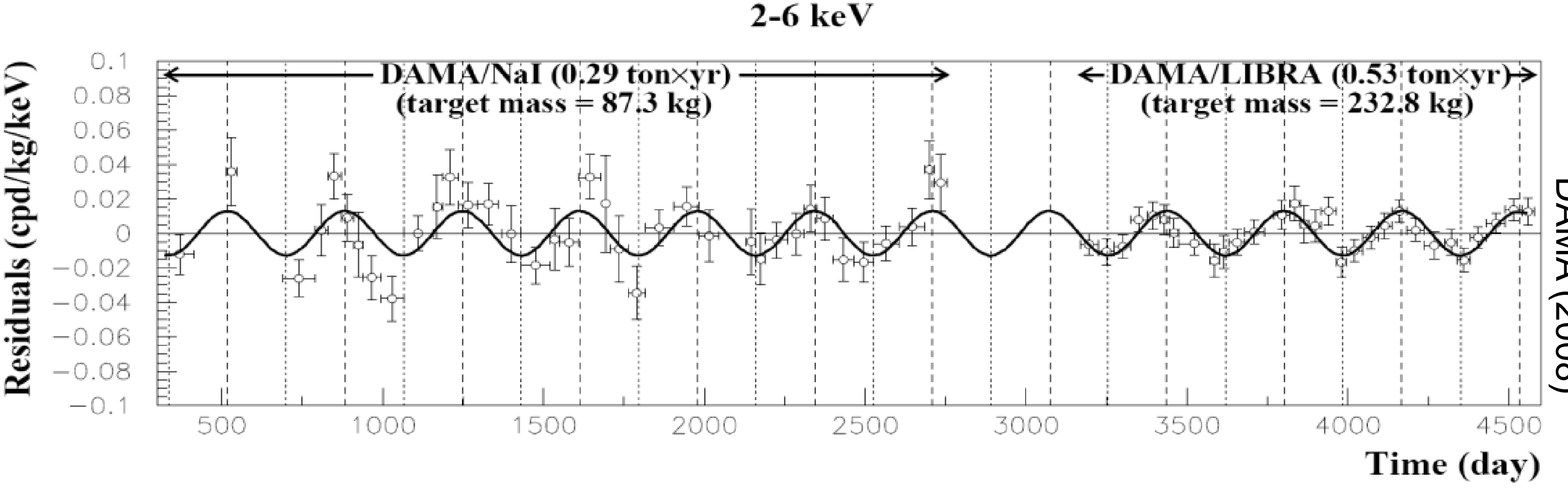
CURRENT STATUS

There are claimed signals: Collision rate should change as Earth's velocity adds with the Sun's → annual modulation



Drukier, Freese, Spergel (1986)

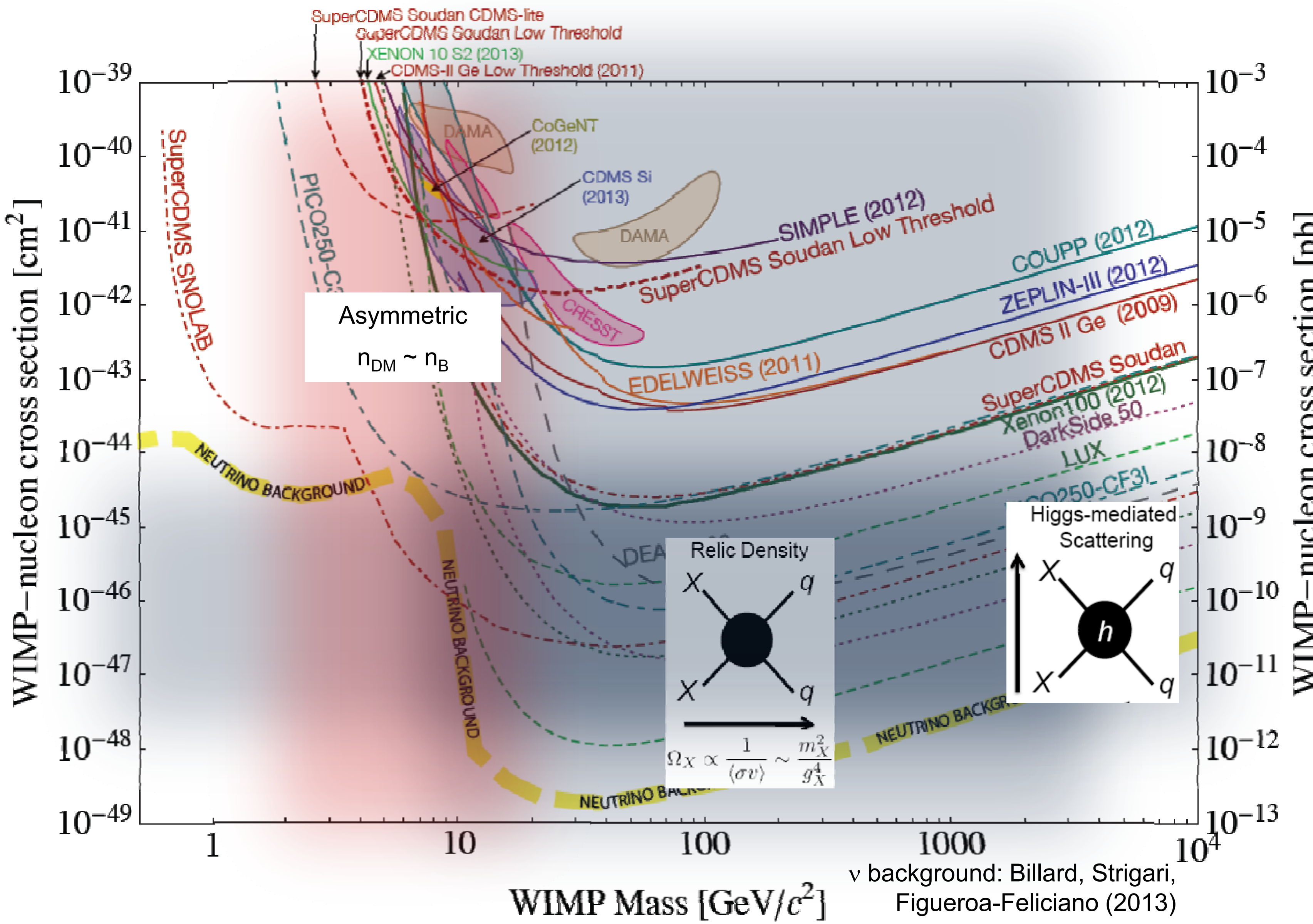
DAMA: 8σ signal with T ~ 1 year, max ~ June 2



DAMA (2008)

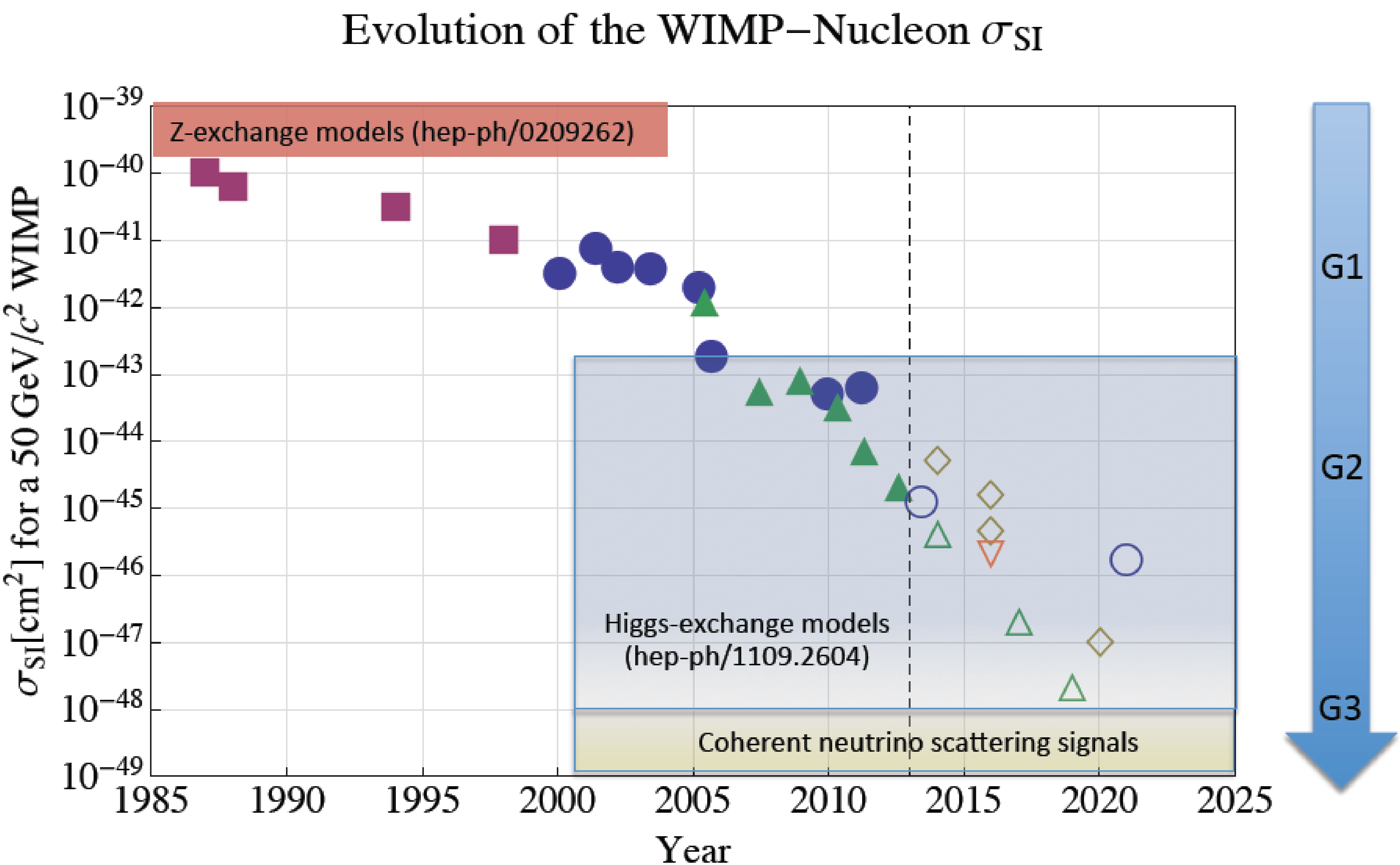
DAMA signal now supplemented by others

CURRENT STATUS AND FUTURE PROSPECTS



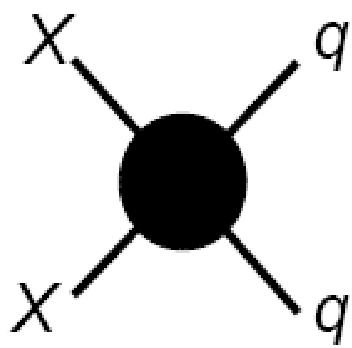
ν background: Billard, Strigari, Figueroa-Feliciano (2013)

MOORE'S LAW FOR DARK MATTER



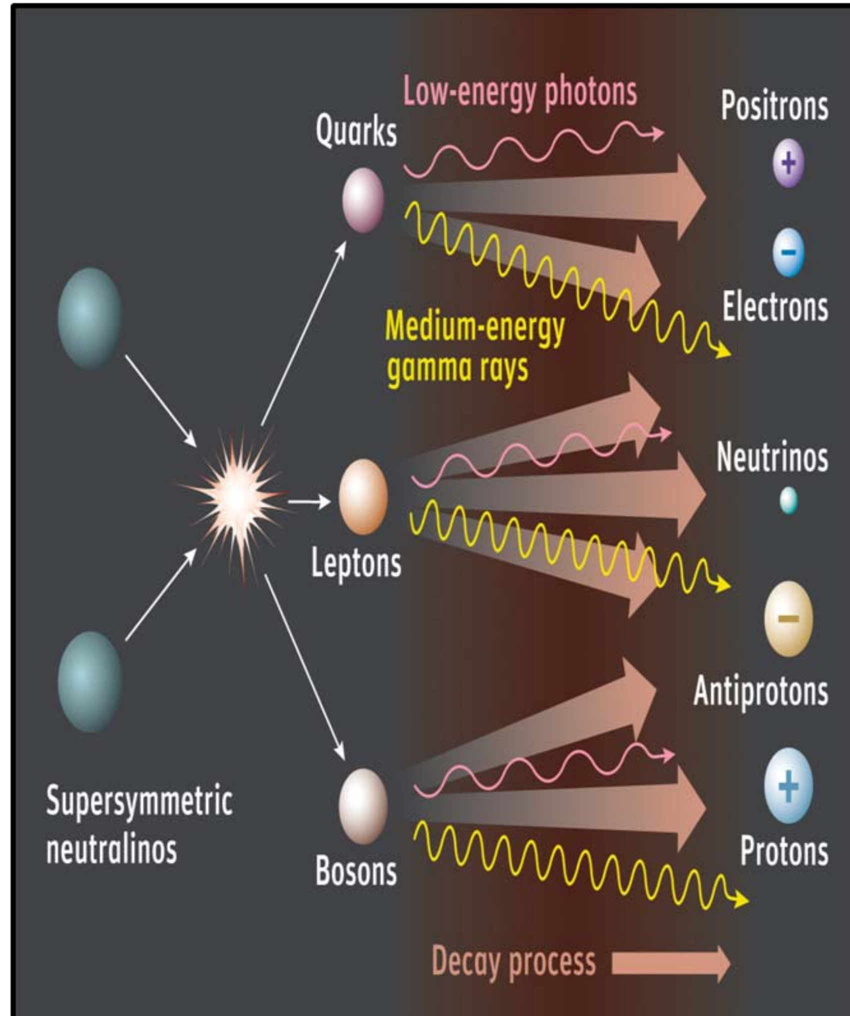
INDIRECT DETECTION

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



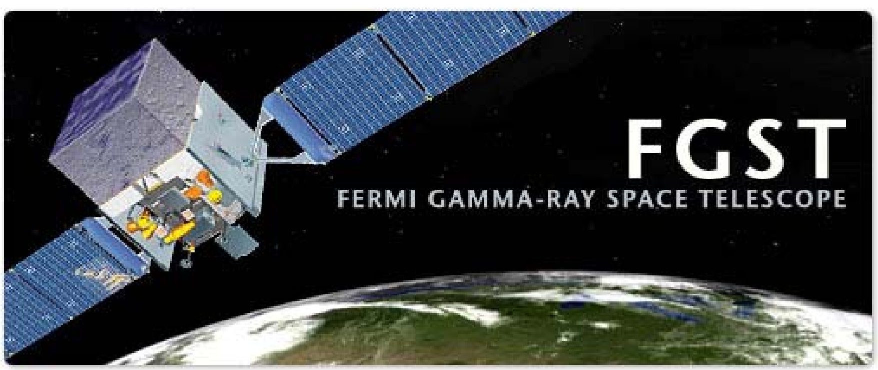
- The relic density provides a target annihilation cross section

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



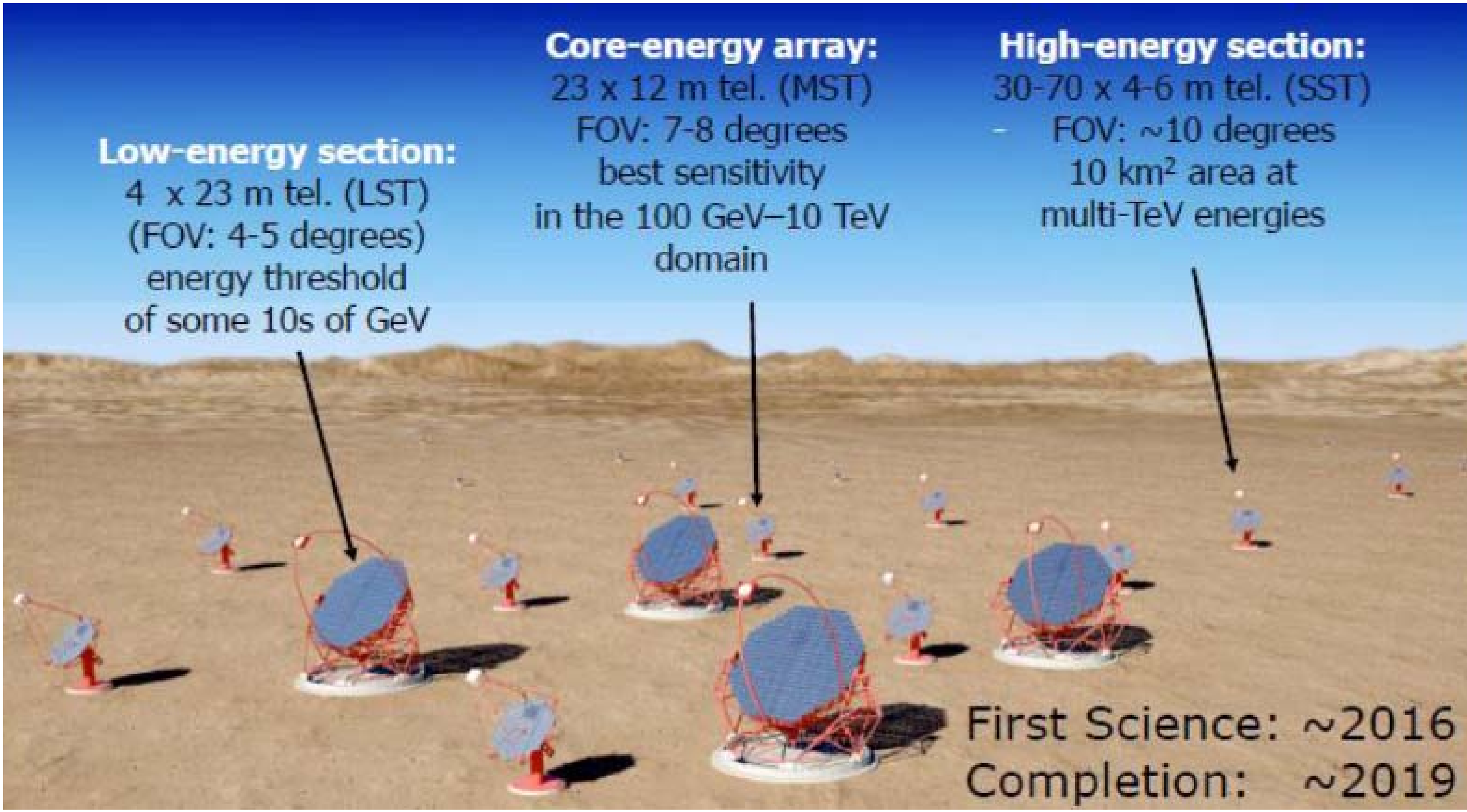
INDIRECT DETECTION: PHOTONS

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

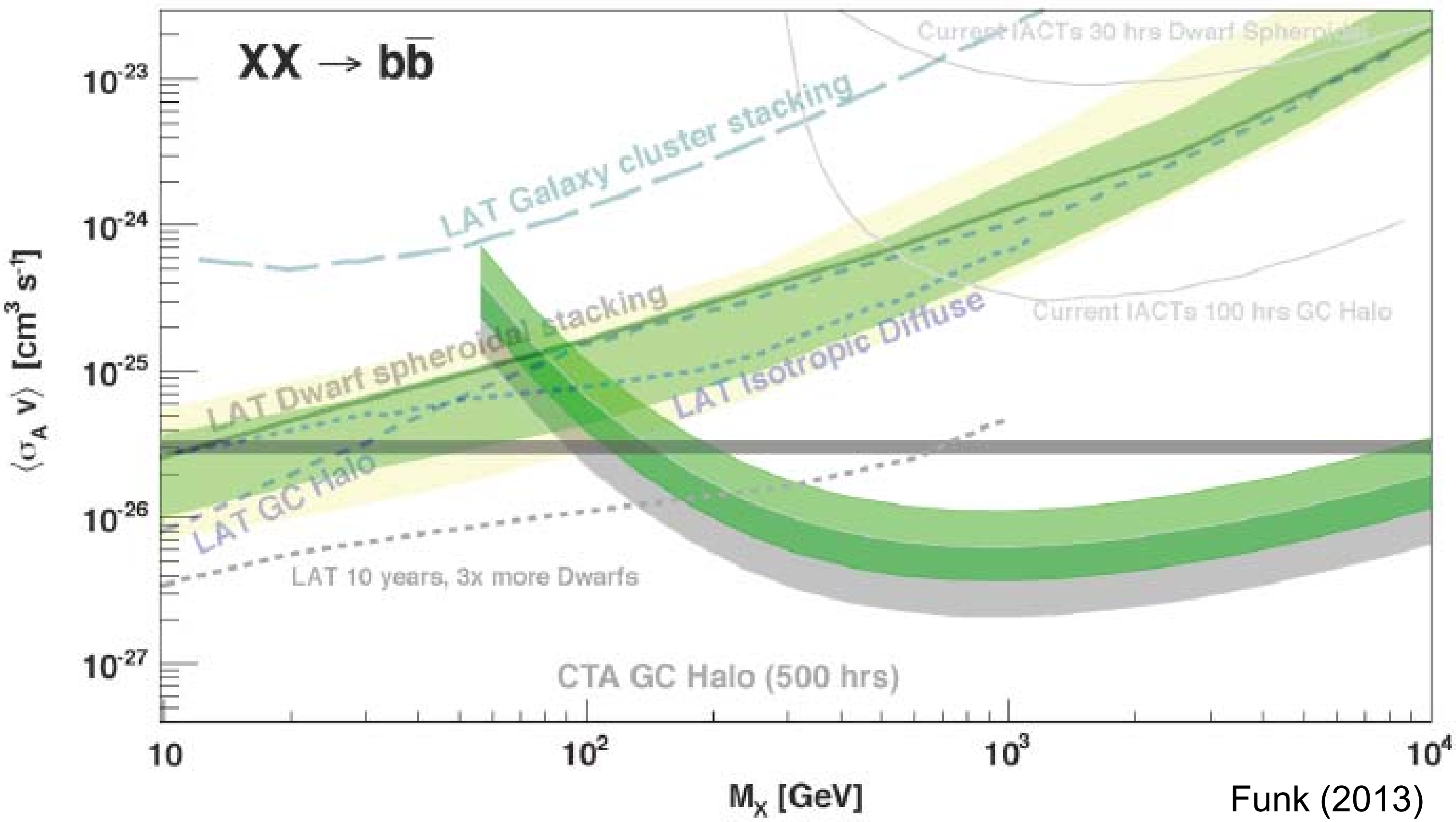


INDIRECT DETECTION: PHOTONS

Future: Cerenkov Telescope Array



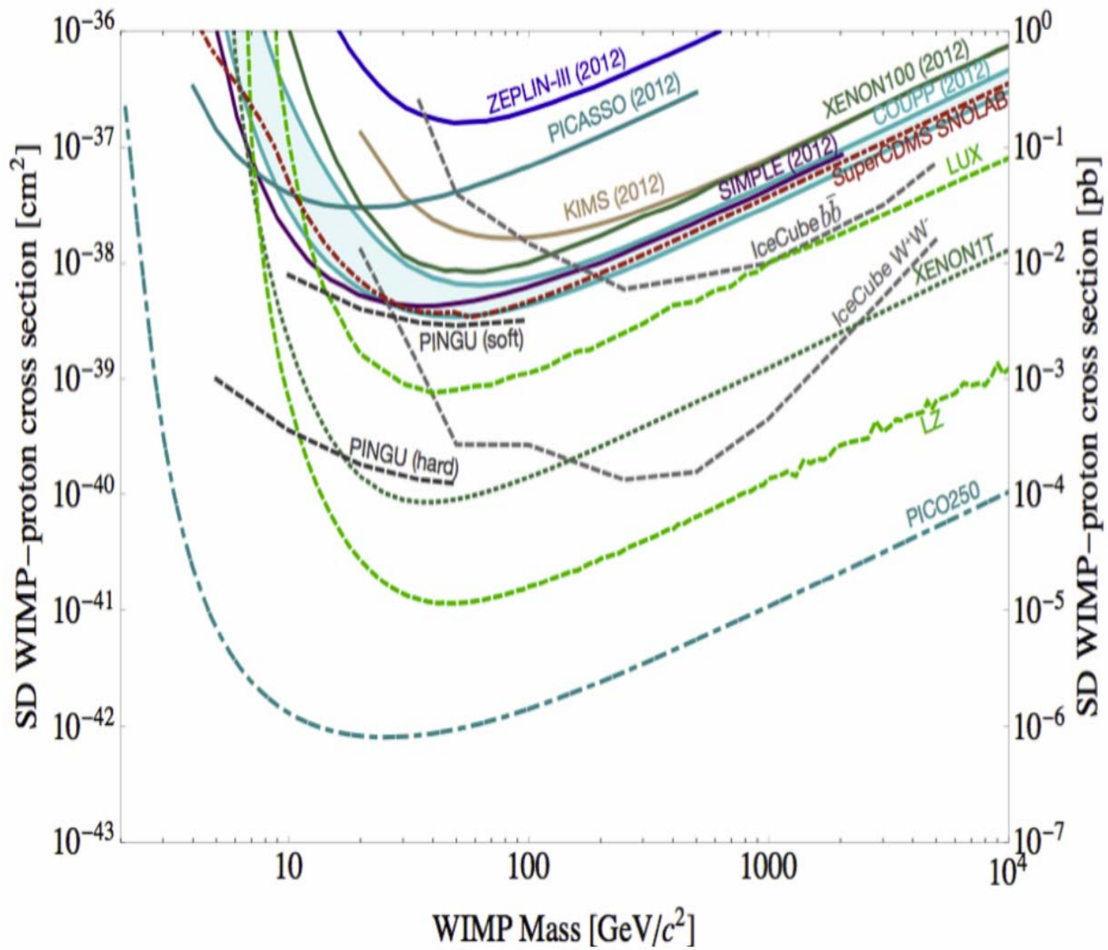
INDIRECT DETECTION: PHOTONS

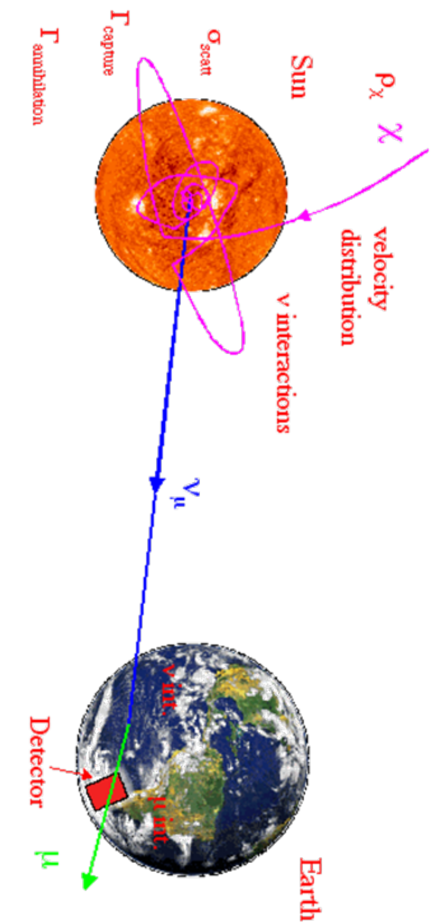


Funk (2013)

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

INDIRECT DETECTION: NEUTRINOS

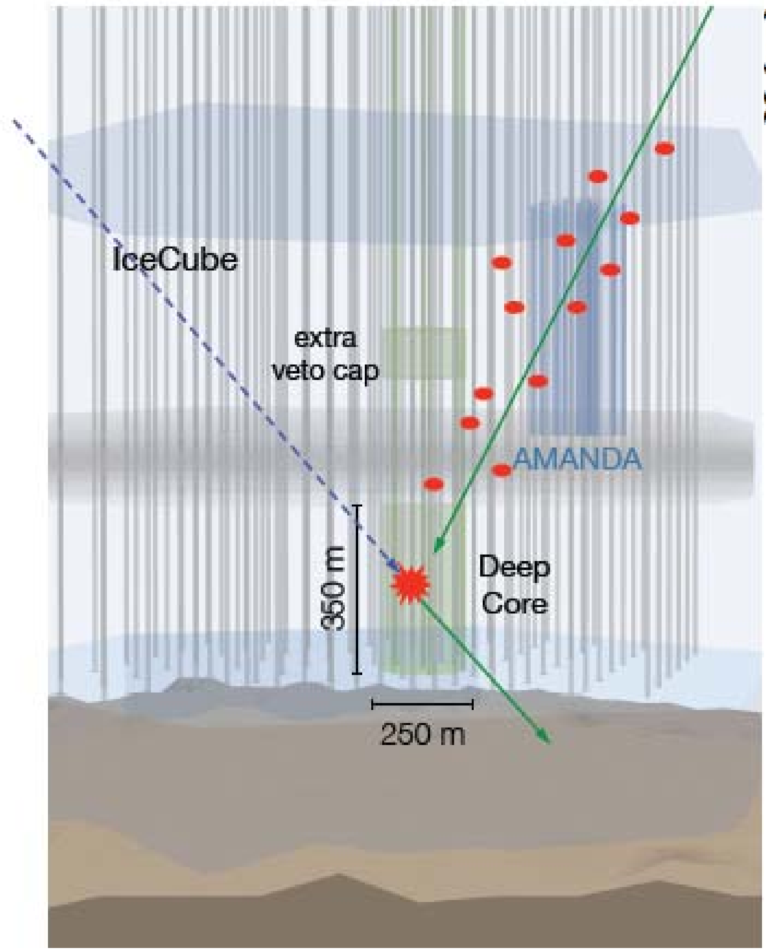




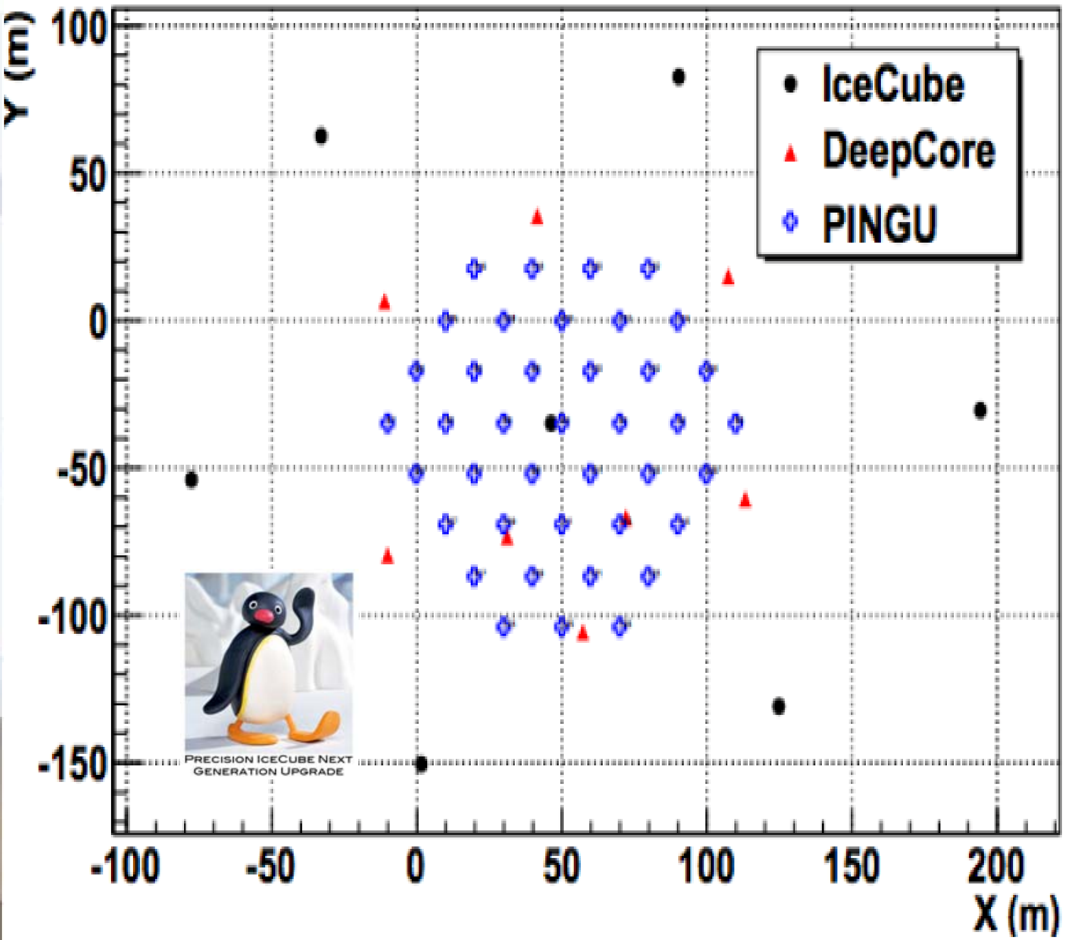
Dark matter may collect and then annihilate in the Sun, producing the smoking-gun signal of high energy neutrinos from the Sun, providing sentsitive probes of spin-*dependent* interactions

INDIRECT DETECTION: NEUTRINOS

Current: IceCube/DeepCore

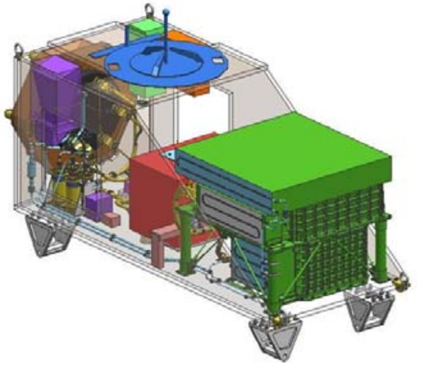


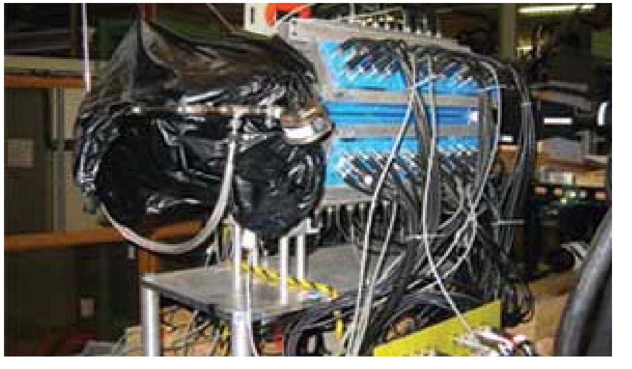
Future: PINGU



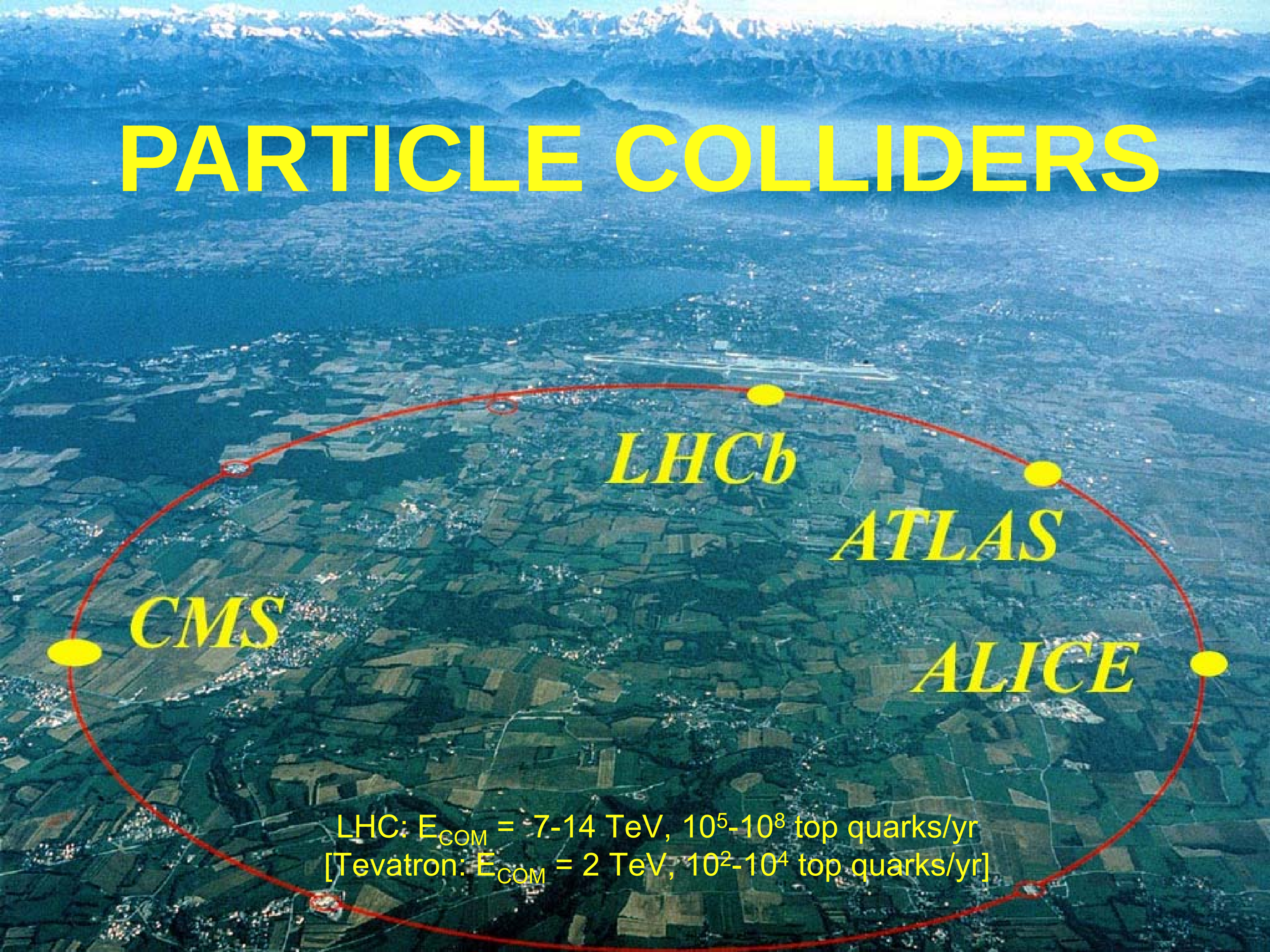
INDIRECT DETECTION: ANTI-MATTER

- Positrons (PAMELA, Fermi-LAT, AMS, CALET)
- Anti-Protons (PAMELA, AMS)
- Anti-Deuterons (GAPS)





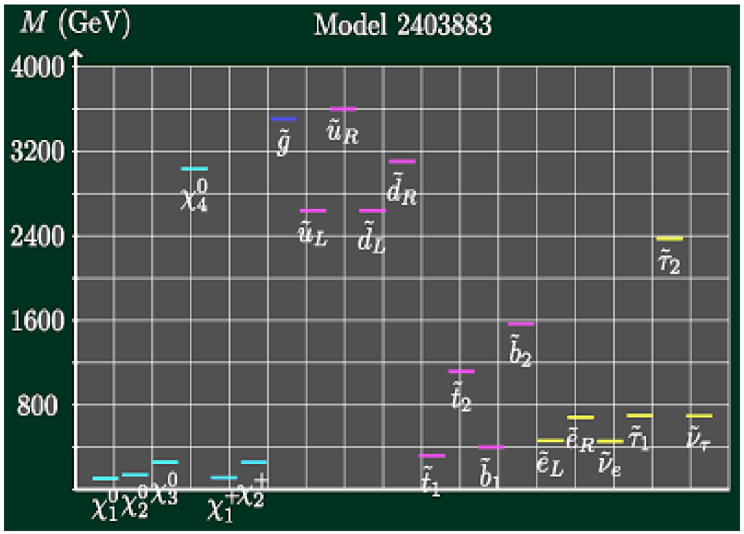
PARTICLE COLLIDERS



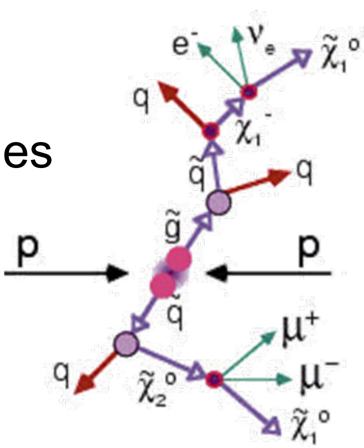
LHC: E_{COM} = 7-14 TeV, 10^5-10^8 top quarks/yr
[Tevatron: E_{COM} = 2 TeV, 10^2-10^4 top quarks/yr]

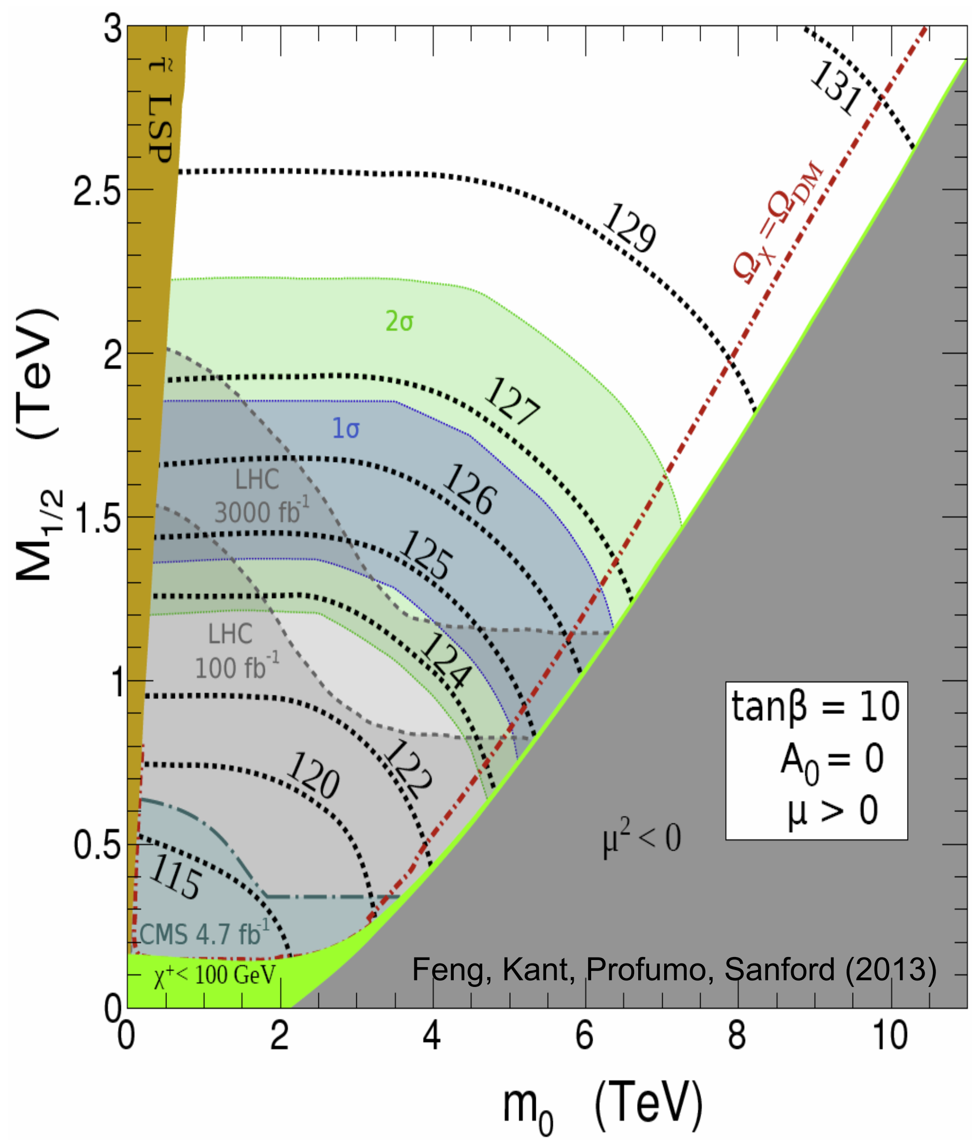
DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)



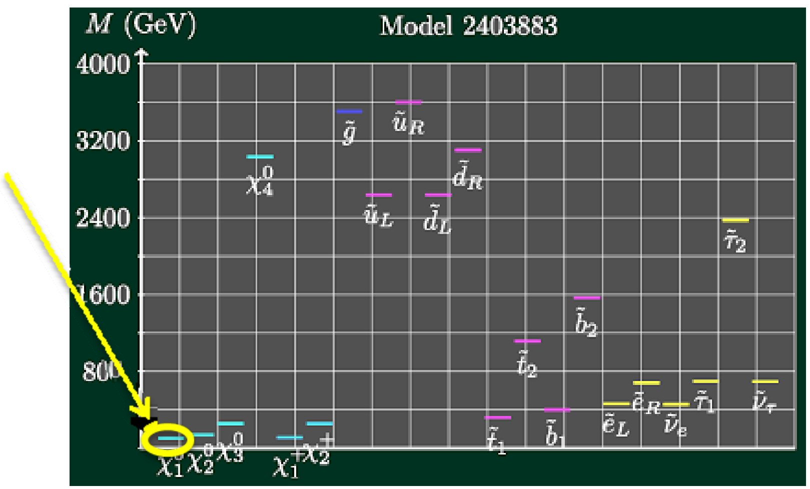
Cascades



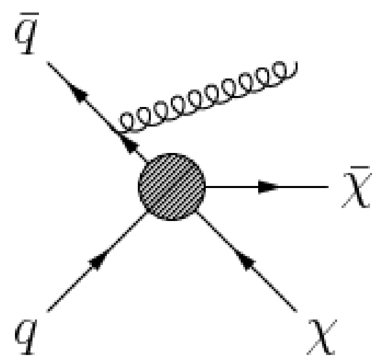


DARK MATTER AT COLLIDERS

DM Effective Theories
(Bare Bones Dark Matter)



Mono-γ, jet, W, Z, h



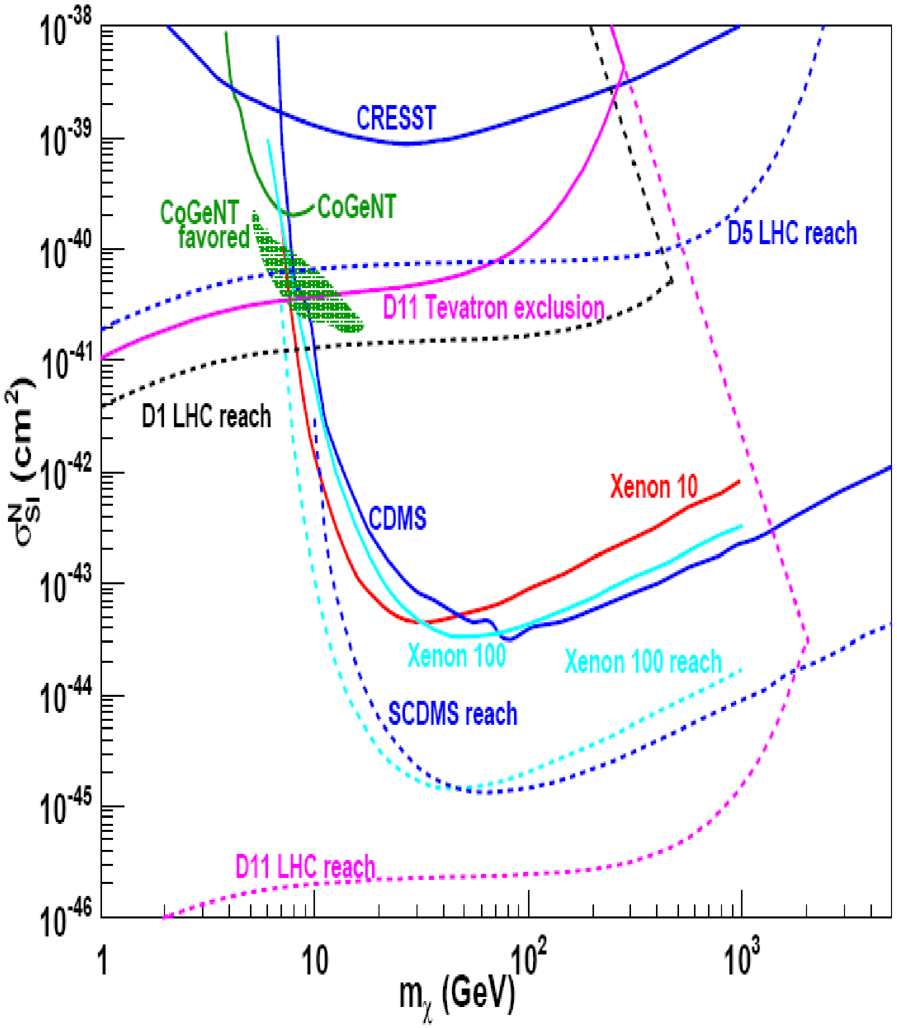
Birkedal, Matchev, Perelstein (2004)
Feng, Su, Takayama (2005)

Can systematically classify all possible $qq\chi\chi$ interactions

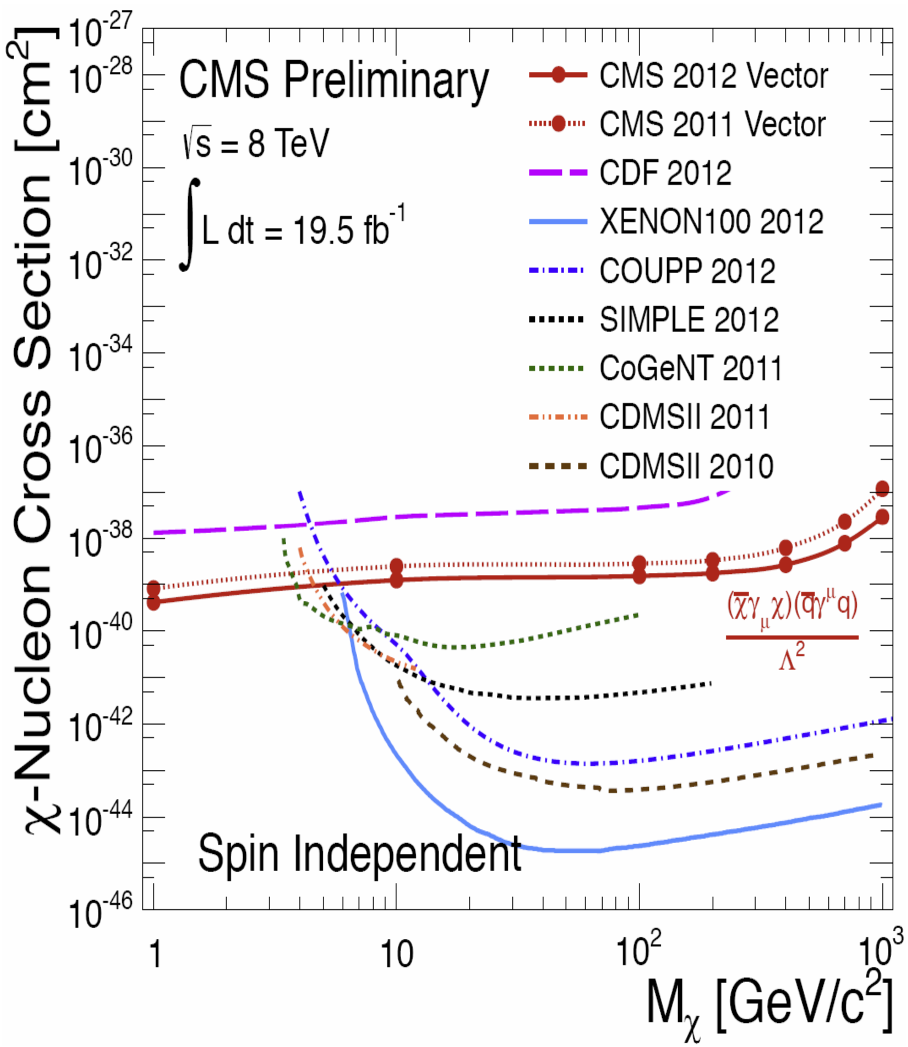
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)

DM EFFECTIVE THEORY



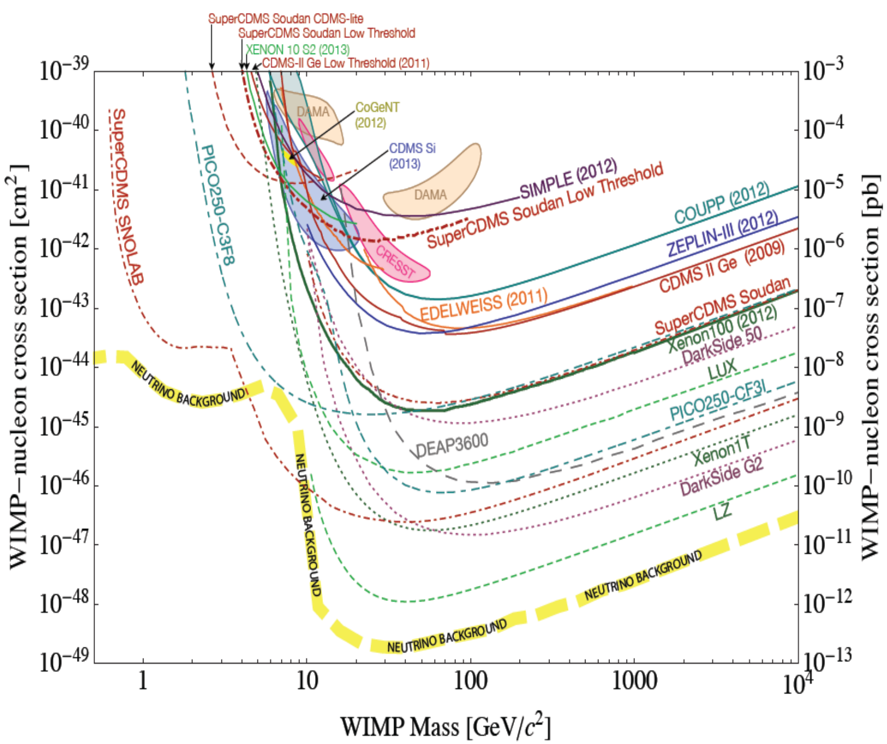
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)



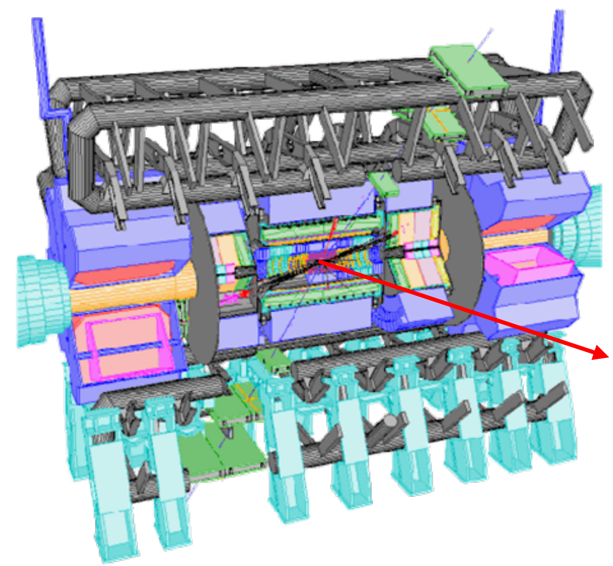
THE FUTURE

If there is a signal, what do we learn?

- Cosmology and dark matter searches can't prove it's SUSY



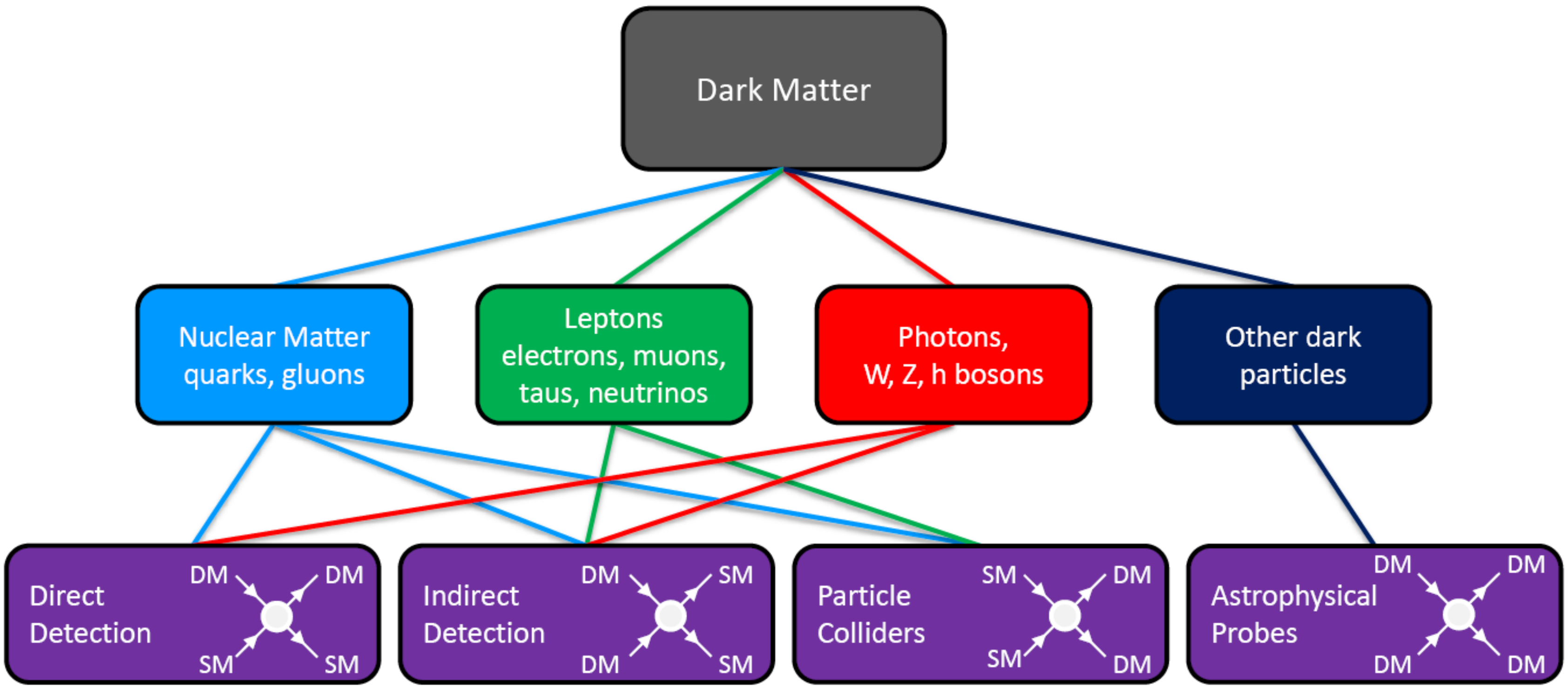
- Particle colliders can't prove it's DM



Lifetime > 10^{-7} s → 10^{17} s ?

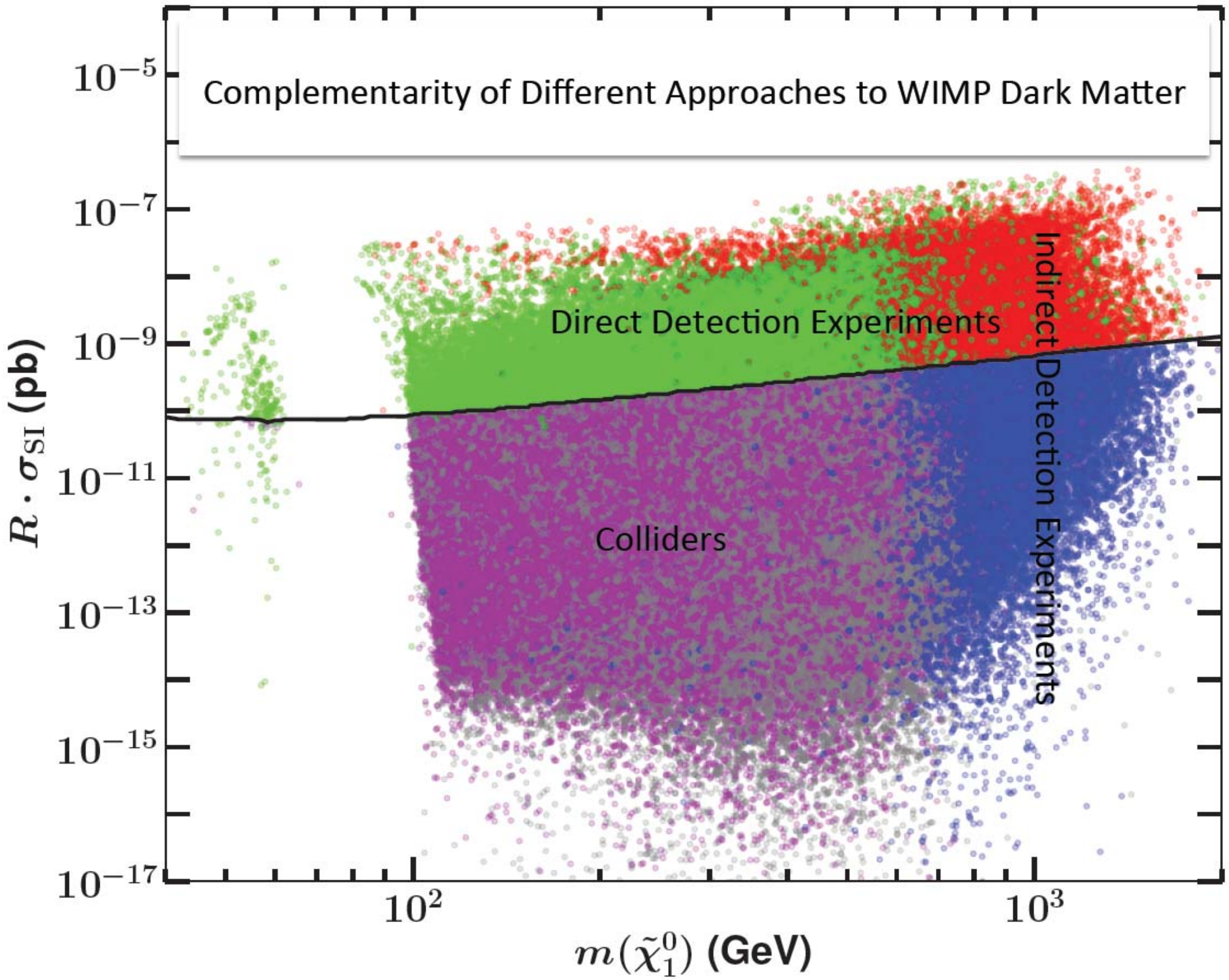
DARK MATTER COMPLEMENTARITY

- Before a signal: Different experimental approaches are sensitive to different dark matter candidates with different characteristics, and provide us with different types of information – complementarity!
- After a signal: we are trying to identify a quarter of the Universe: need high standards to claim discovery and follow-up studies to measure properties



COMPLEMENTARITY: FULL MODELS

pMSSM 19-parameter scan of SUSY parameter space



Cahill-Rowley et al. (2013)

Different expts probe different models, provide cross-checks

BEYOND WIMPS

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

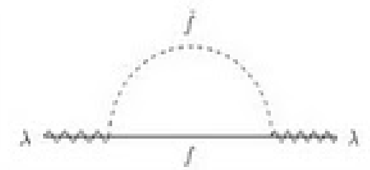
- *A priori* there are both pros and cons
  - Interesting self-interactions, astrophysics
  - Less obvious connections to particle physics
  - No WIMP miracle

Spergel, Steinhardt (1999); Foot (2001)

NEW MOTIVATIONS FOR HIDDEN DARK MATTER

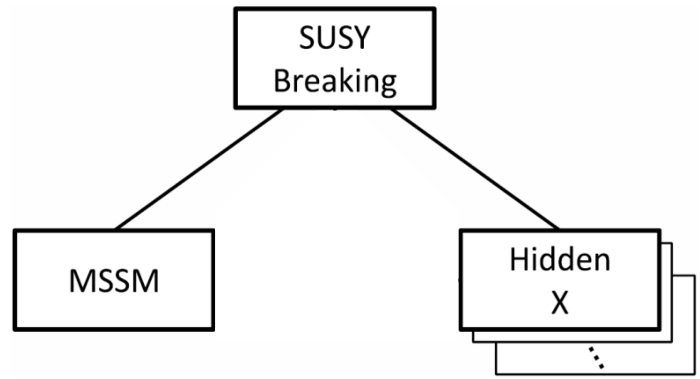
- WIMPless Miracle: Consider hidden sectors in SUSY models. In many models, $m_X \sim g_X^2$, which leaves the relic density invariant

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



Restores
  – Particle physics motivations
  – Structure, predictivity
  – The miracle: SUSY hidden sectors automatically have DM with the right Ω

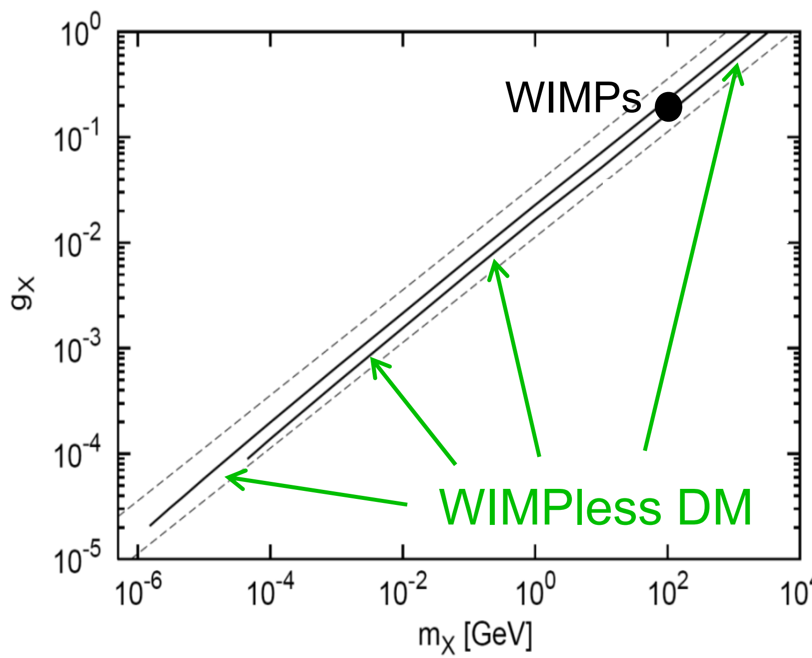
Feng, Kumar (2008)



- Self-interactions: Observations vs. simulations motivate self-interacting DM with

$$\sigma_T/m \sim 0.1\text{–}1 \text{ cm}^2/\text{g (or barn/GeV)}$$

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



SELF-INTERACTING DM FROM SU(N) HIDDEN SECTOR

Boddy, Feng, Kaplinghat, Tait (2013)

- WIMPless miracle requires weak interactions, self-interactions require strong interactions

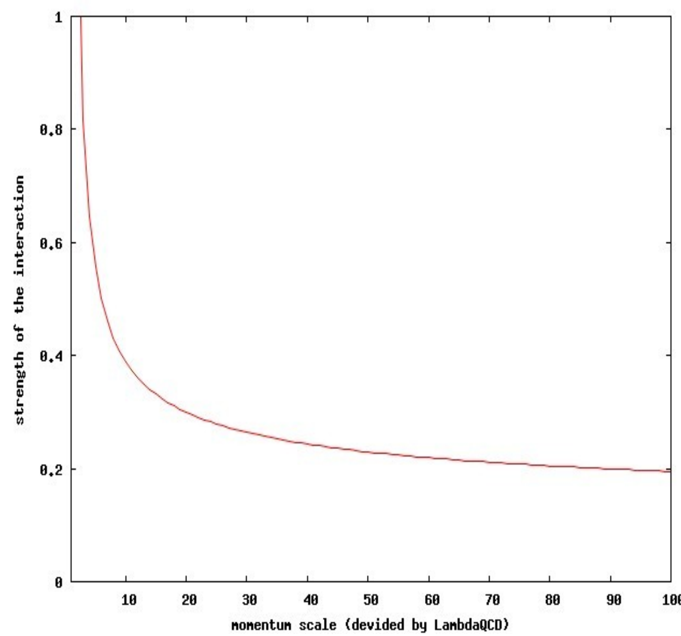
- A natural possibility to consider is a non-Abelian hidden sector with weak coupling at high scales and early times, and strong coupling at low scales now (cf. QCD)

Feng, Shadmi (2011)

$$V(r) = -\frac{\alpha}{r}\exp(-\Lambda r)$$

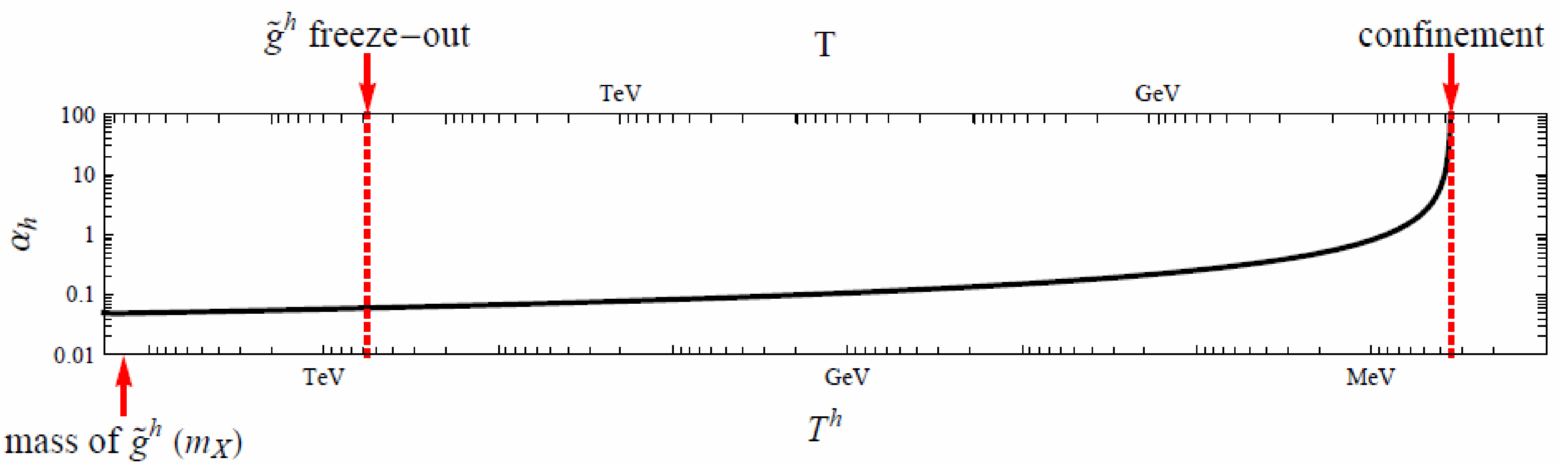
$$\sigma_T = \int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

Feng, Kaplinghat, Yu (2010); Tulin, Yu, Zurek (2013)



SELF-INTERACTING DM FROM SU(N) HIDDEN SECTOR

- WIMPless miracle requires weak interactions, self-interactions require strong interactions
- A simple possibility: a non-Abelian hidden sector with weak coupling at early times, and strong coupling now (cf. QCD)
- For example, SUSY with hidden gluons g and gluinos $\tilde{g}$
  - ~10 TeV gluinos freezeout with the correct relic density
  - At Λ ~ 1 MeV, glueball (gg) and glueballino ($g\tilde{g}$) bound states form strongly self-interacting dark matter



Feng, Kaplinghat, Yu (2010); Feng, Shadmi (2011), Tulin, Yu, Zurek (2013); Boddy, Feng, Kaplinghat, Tait (2014)

CONCLUSIONS

- Particle Dark Matter
  - Central topic at the interface of cosmology and particles
  - Both cosmology and particle physics → new particles at the weak scale ~ 100 GeV

- Candidates
  - WIMPs: Many well-motivated candidates
  - Hidden dark matter: Similar motivations, but qualitatively new properties
  - Many others

- LHC is coming back on line in 2015, direct and indirect detection, astrophysical probes are improving rapidly – this field will be transformed in the next few years