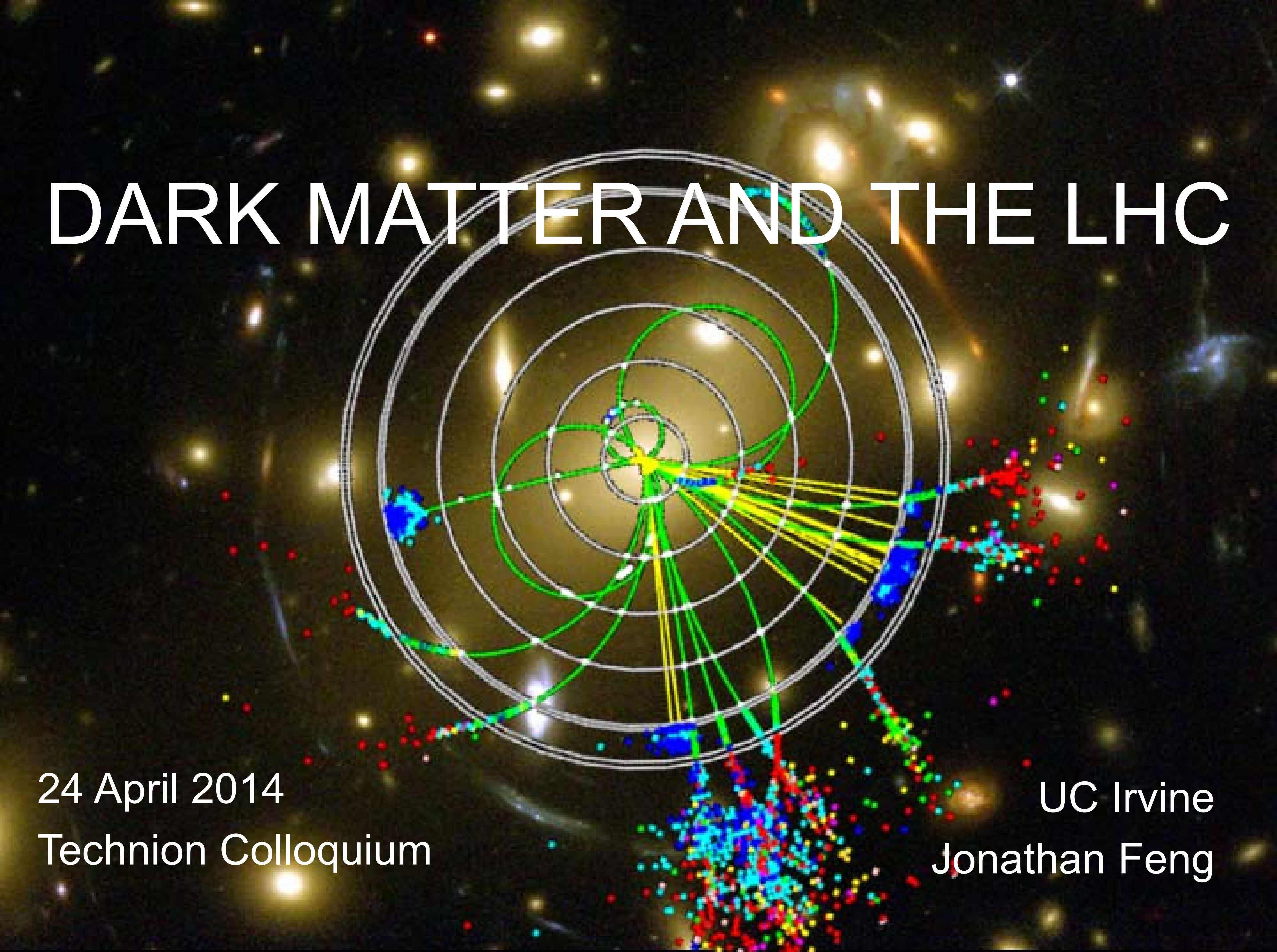


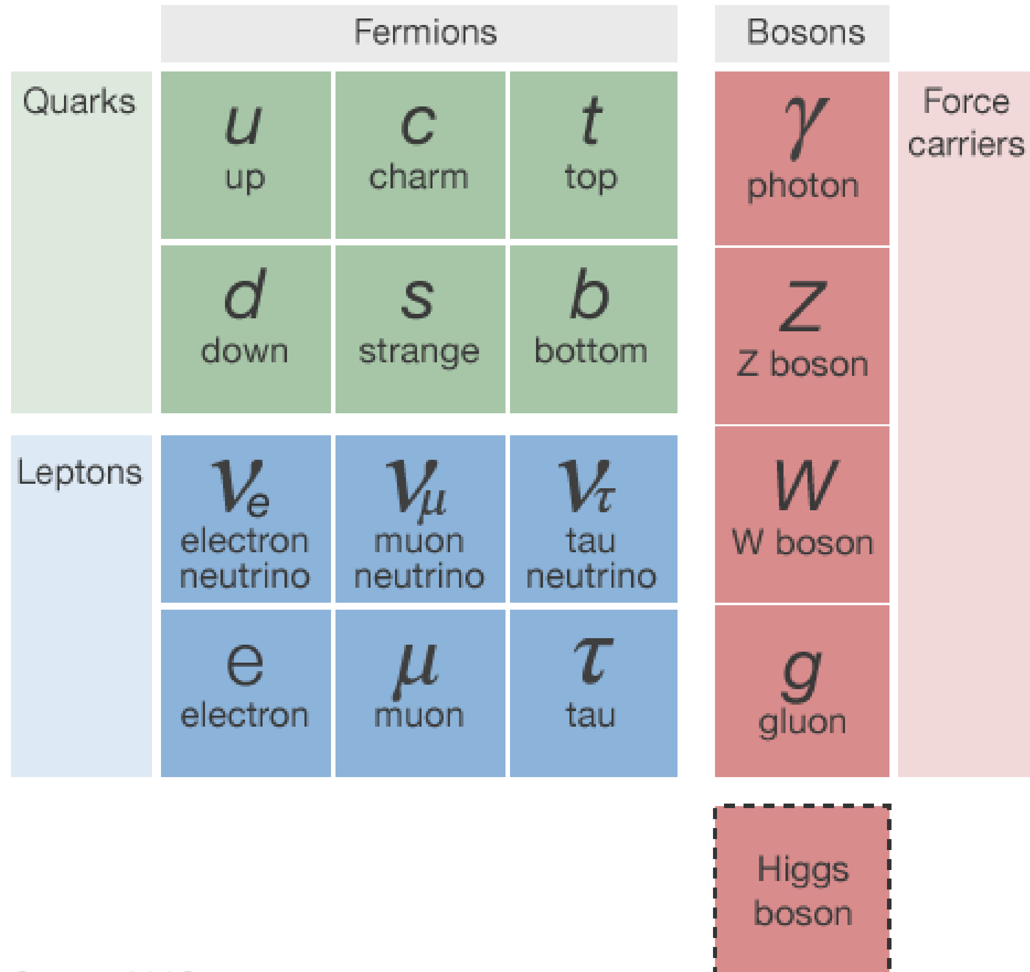
DARK MATTER AND THE LHC

24 April 2014
Technion Colloquium

UC Irvine
Jonathan Feng

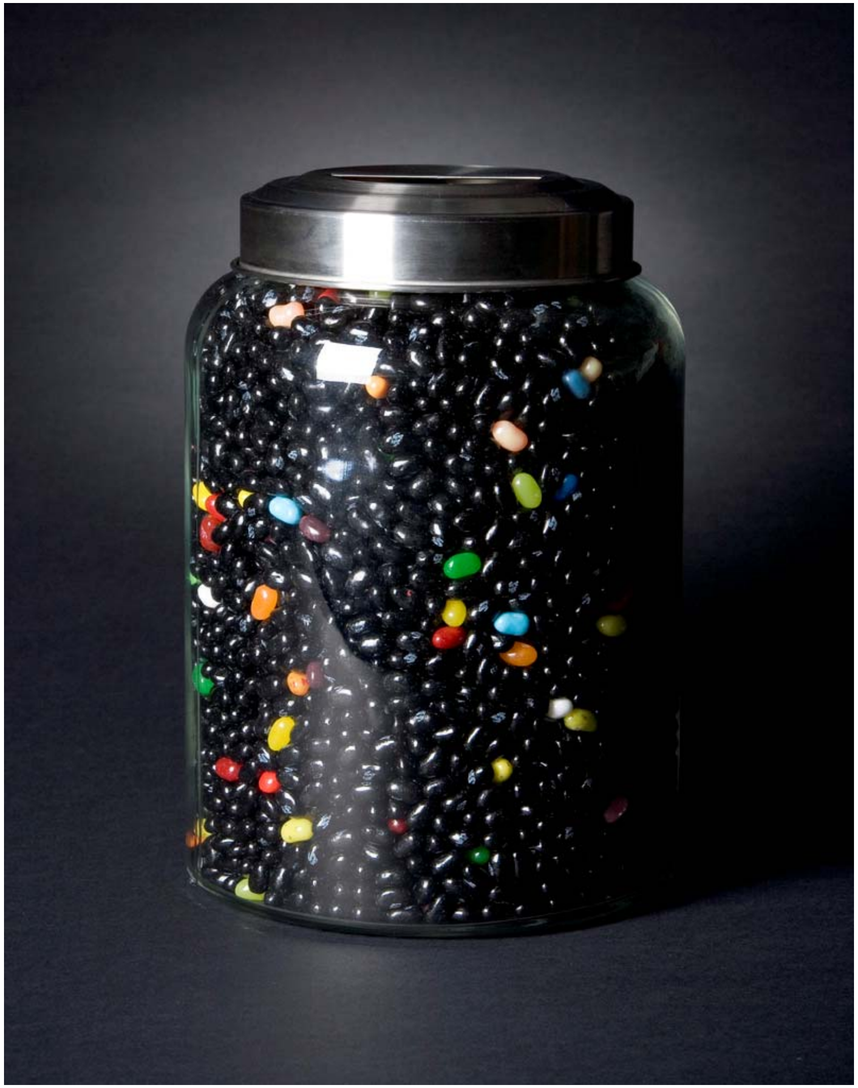
INTRODUCTION

- 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 many 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



- Our understanding of the Universe has been transformed in recent years
- There is now strong evidence that normal (atomic) matter is not all the matter in the Universe:

  Dark Matter: 23% ± 4%

  Dark Energy: 73% ± 4%

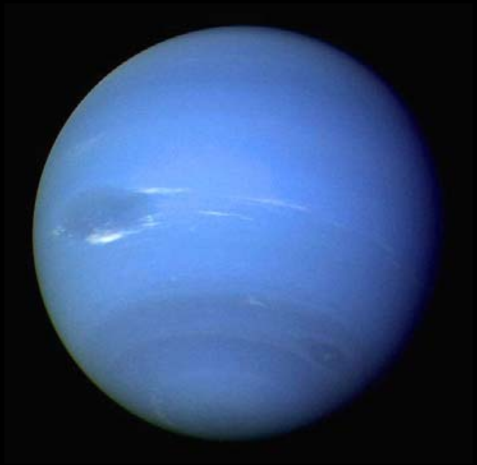
  Normal Matter: 4% ± 0.4%

  Neutrinos: 0.2% (Σm_ν/0.1eV)

- To date, all evidence for dark matter is from its 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

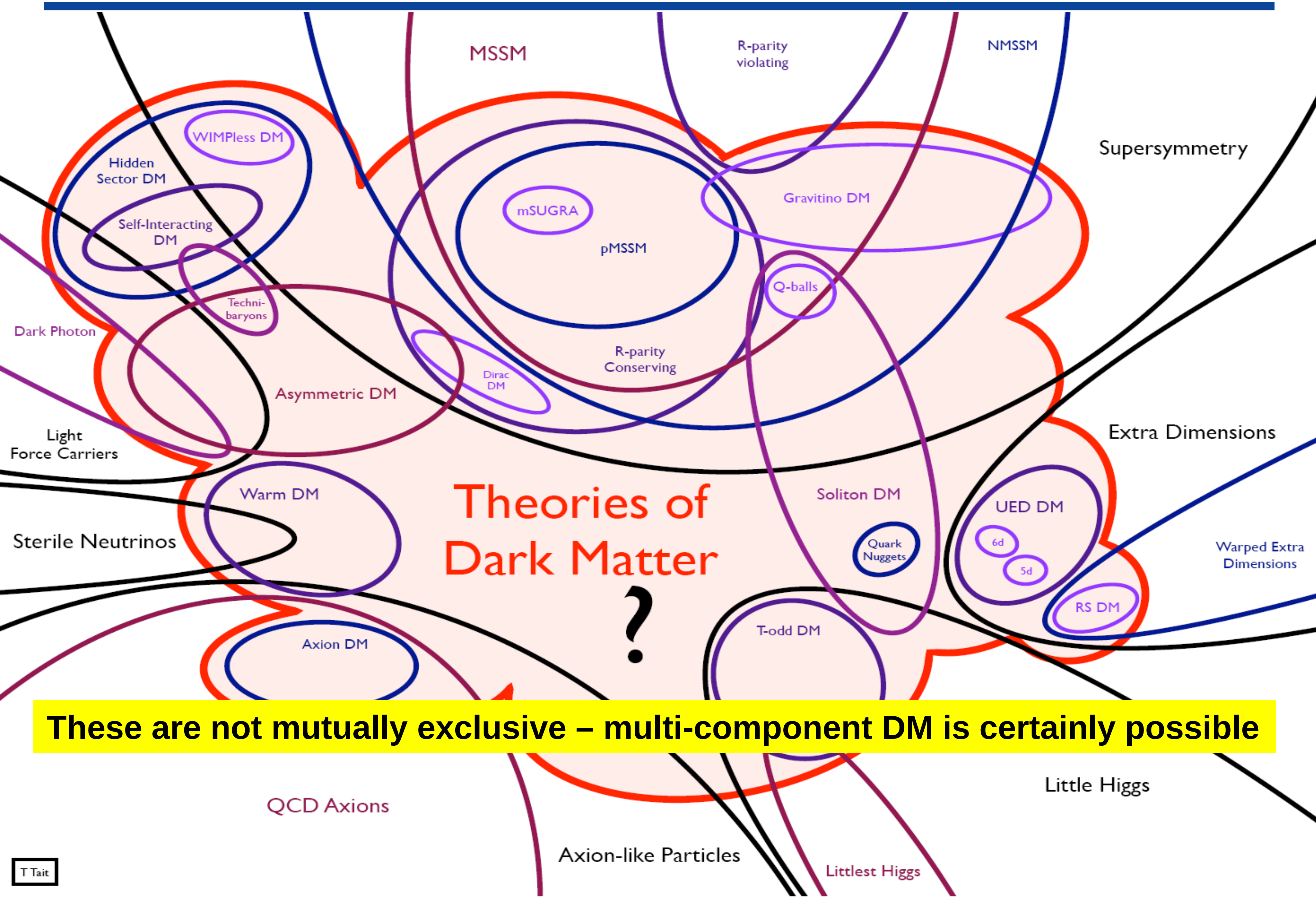
Source: AAAS

Known DM properties

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

Unambiguous evidence for new physics

WHAT COULD DARK MATTER BE?



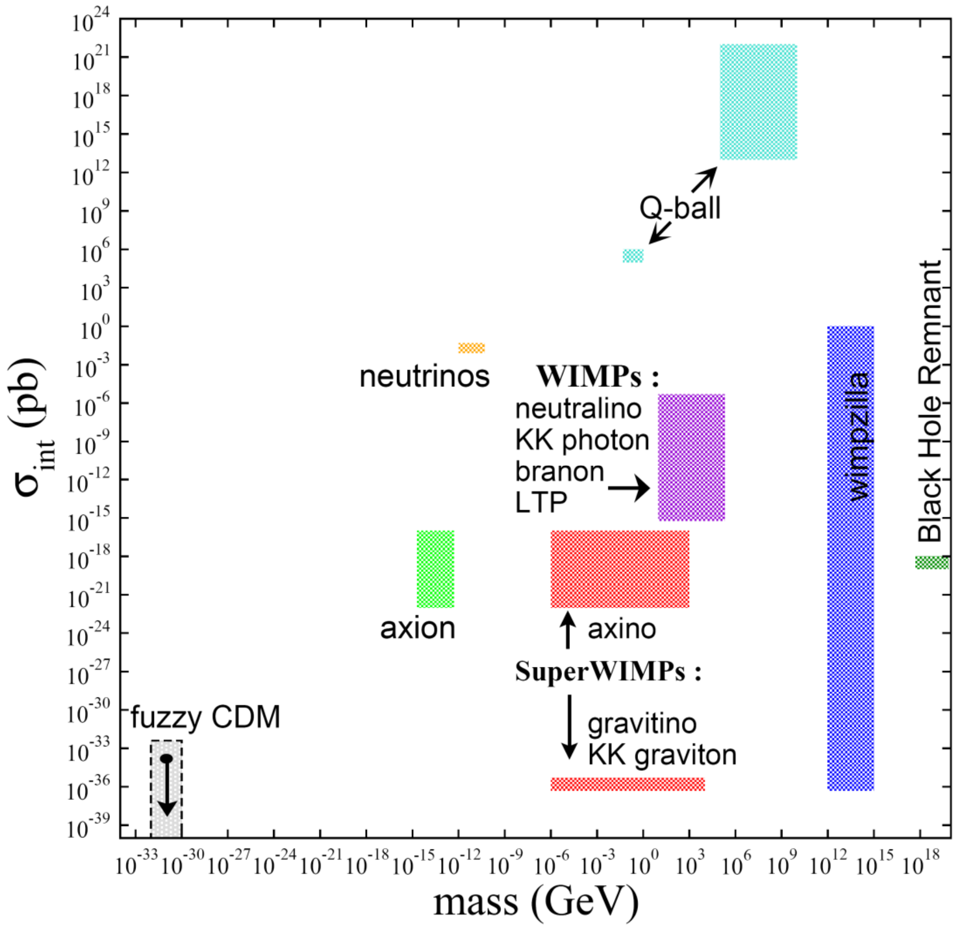
These are not mutually exclusive – multi-component DM is certainly possible

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

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

- $G_F \approx 1.1 \cdot 10^{-5}\ \mathrm{GeV}^{-2} \rightarrow$ 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:

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

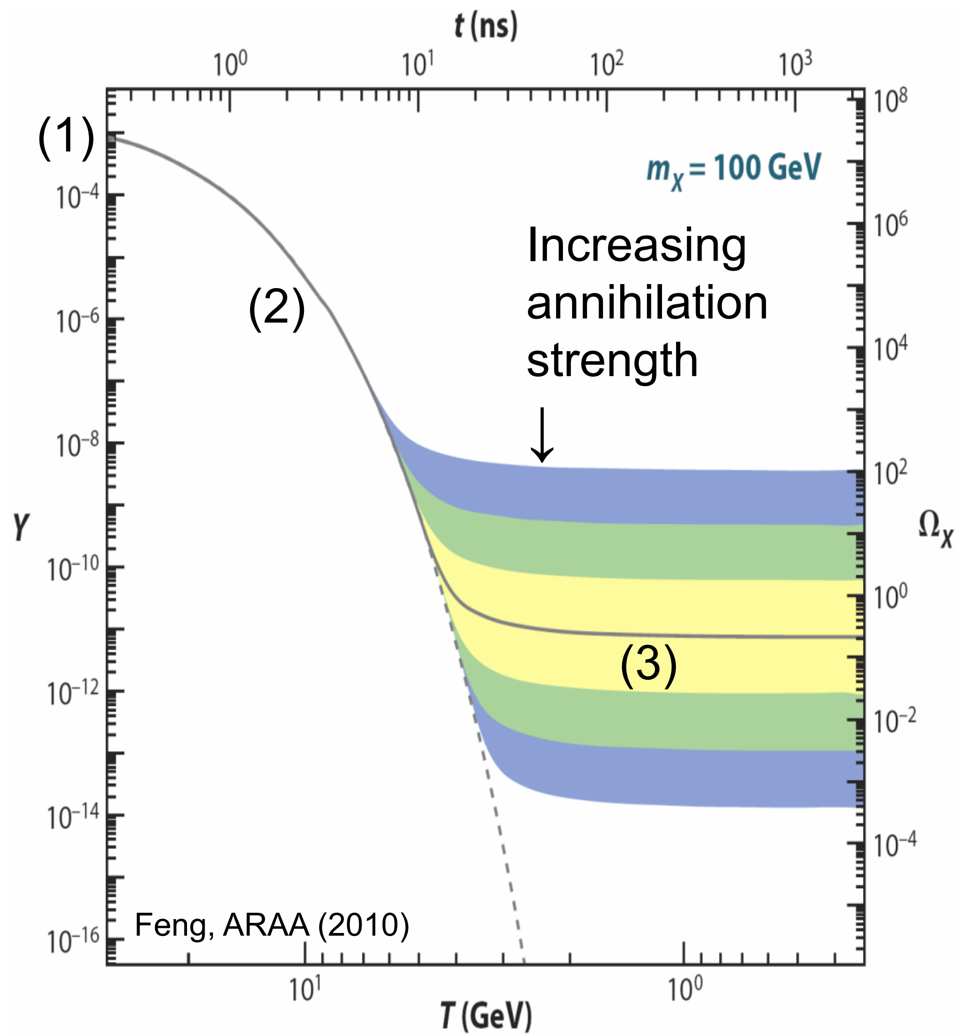
(2) Universe cools:

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

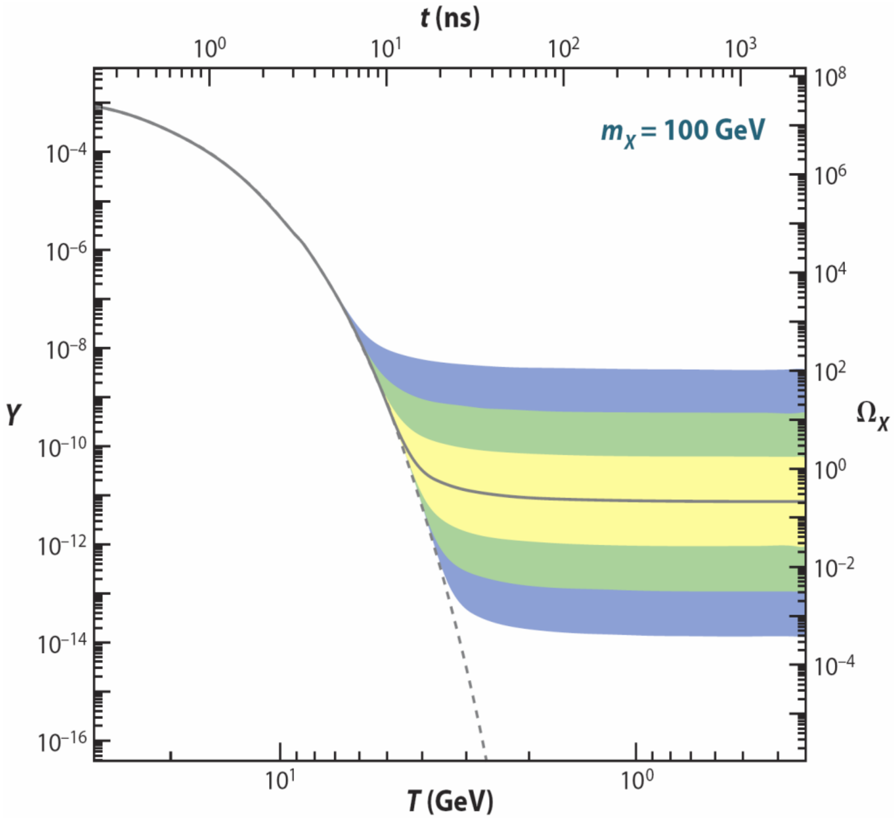
(3) Universe expands:

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

Zeldovich et al. (1960s)

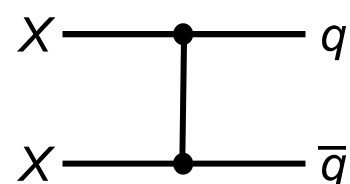


THE WIMP MIRACLE



- 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

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,

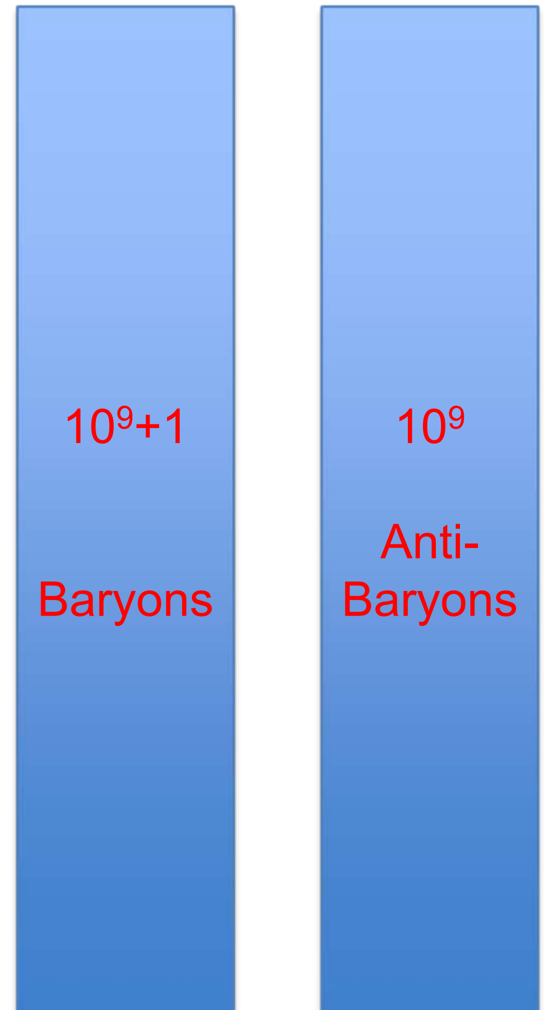
$$n_{DM} \sim n_B$$

$$\downarrow$$

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

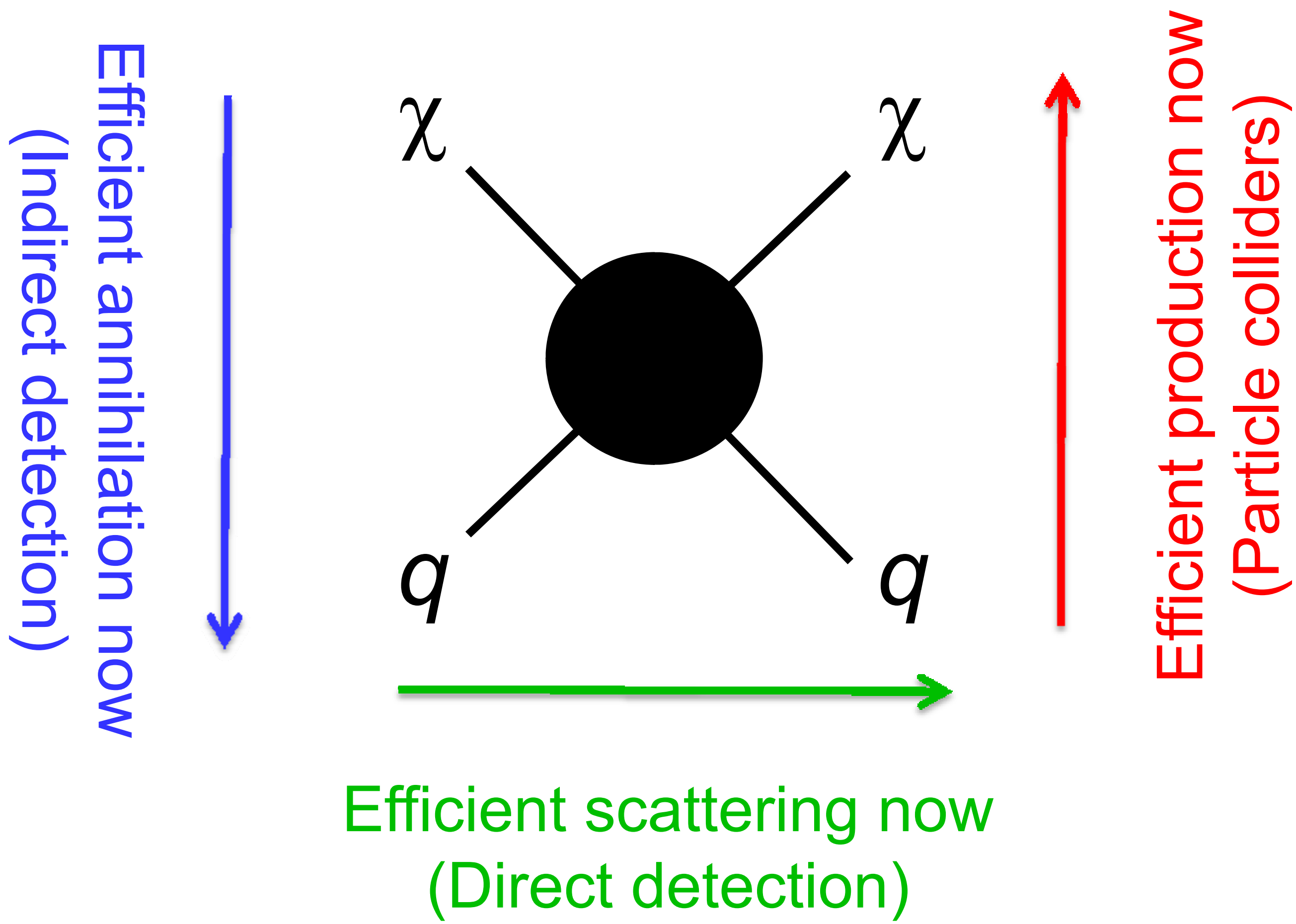
Asymmetric DM → $m_{DM} \sim 5$ GeV

"Light WIMPs"



WIMP DETECTION

Correct relic density → Efficient annihilation then



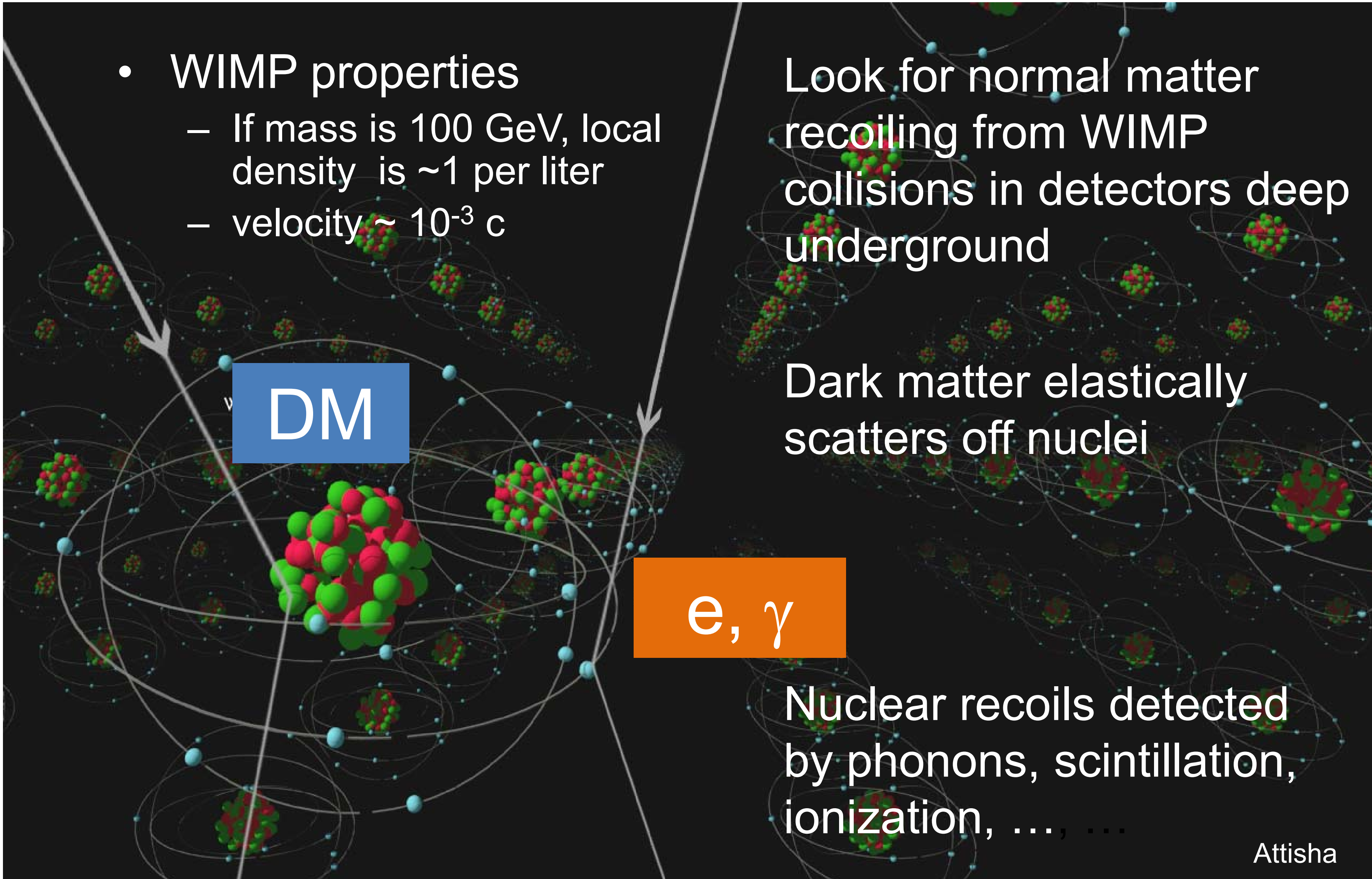
DIRECT DETECTION

- 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

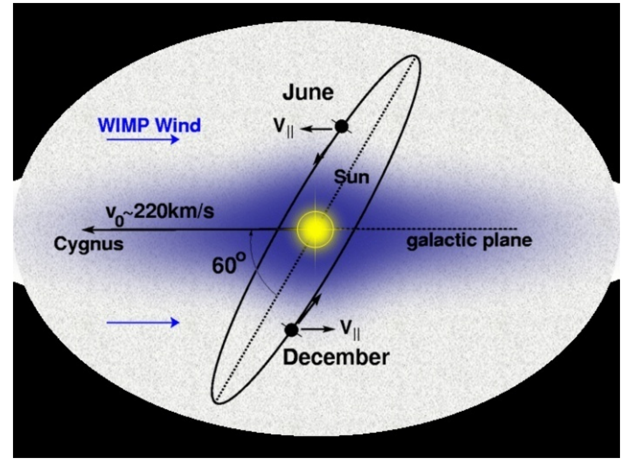
Nuclear recoils detected by phonons, scintillation, ionization, …, …



Attisha

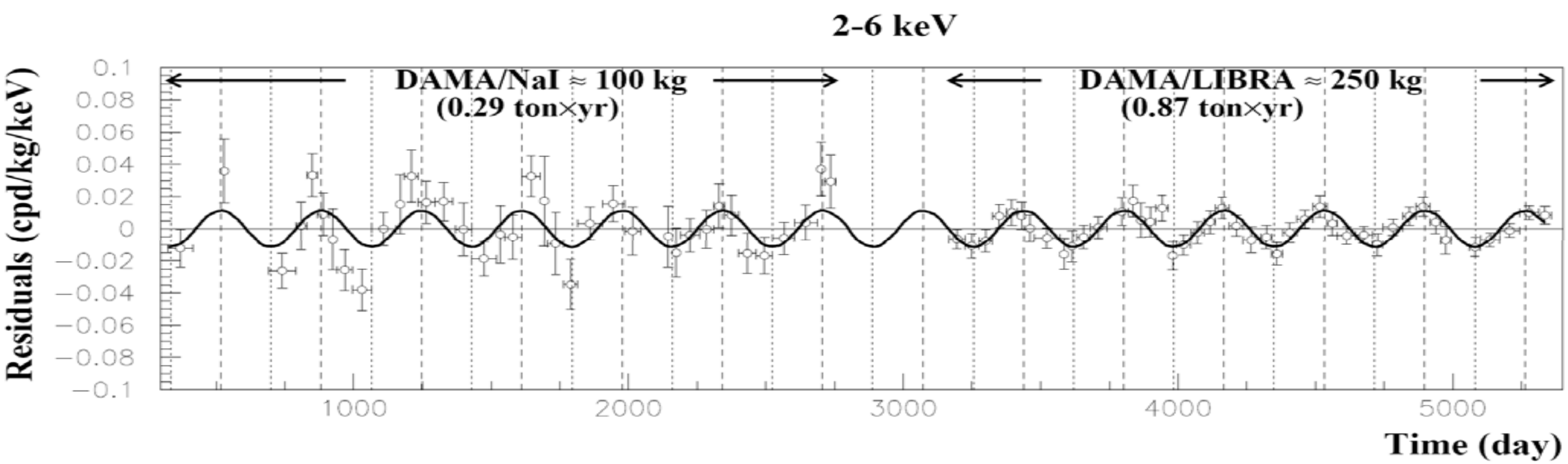
CURRENT STATUS

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



Drukier, Freese, Spergel (1986)

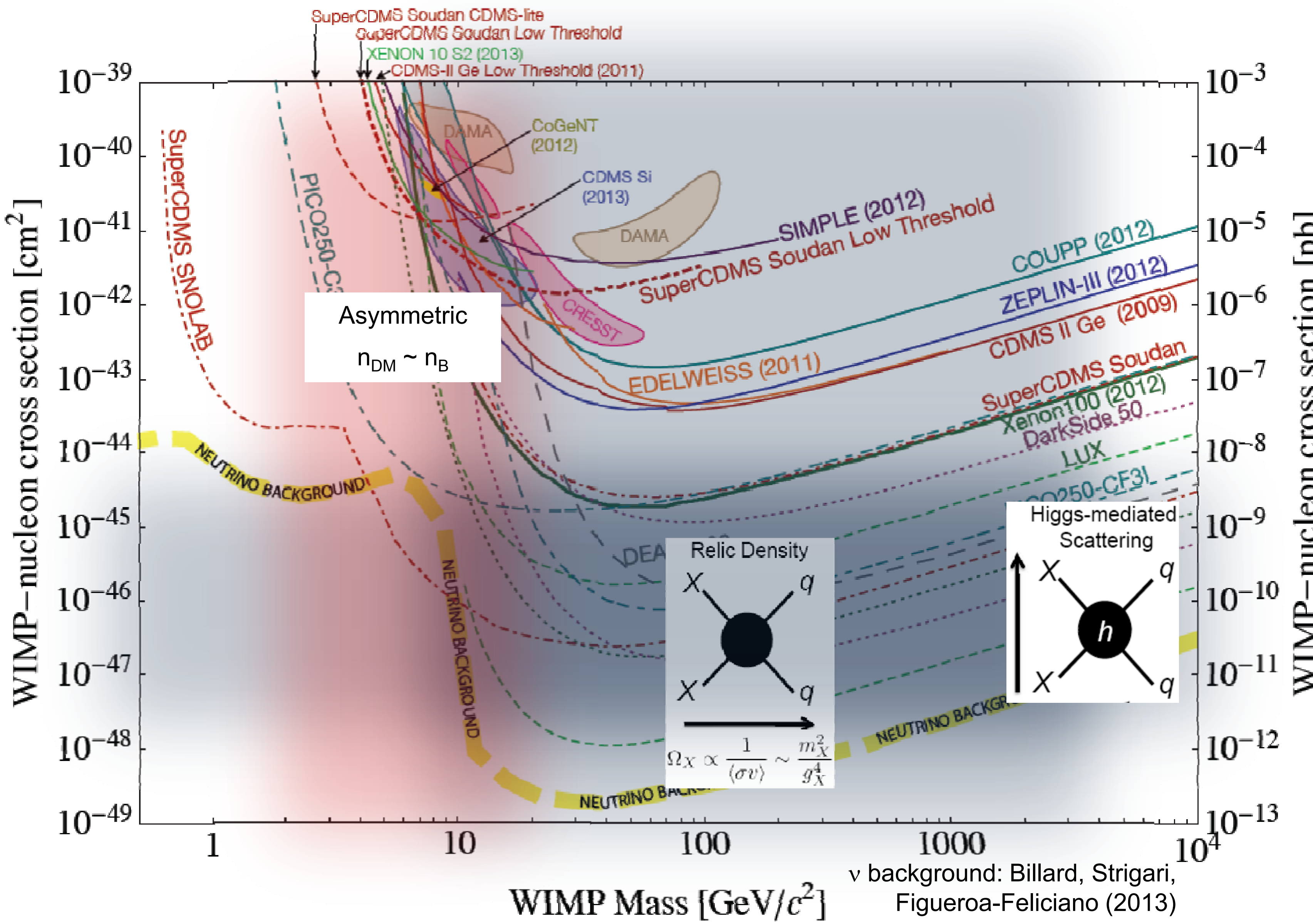
DAMA: 9σ signal with T ~ 1 year, max ~ June 2



DAMA (2013)

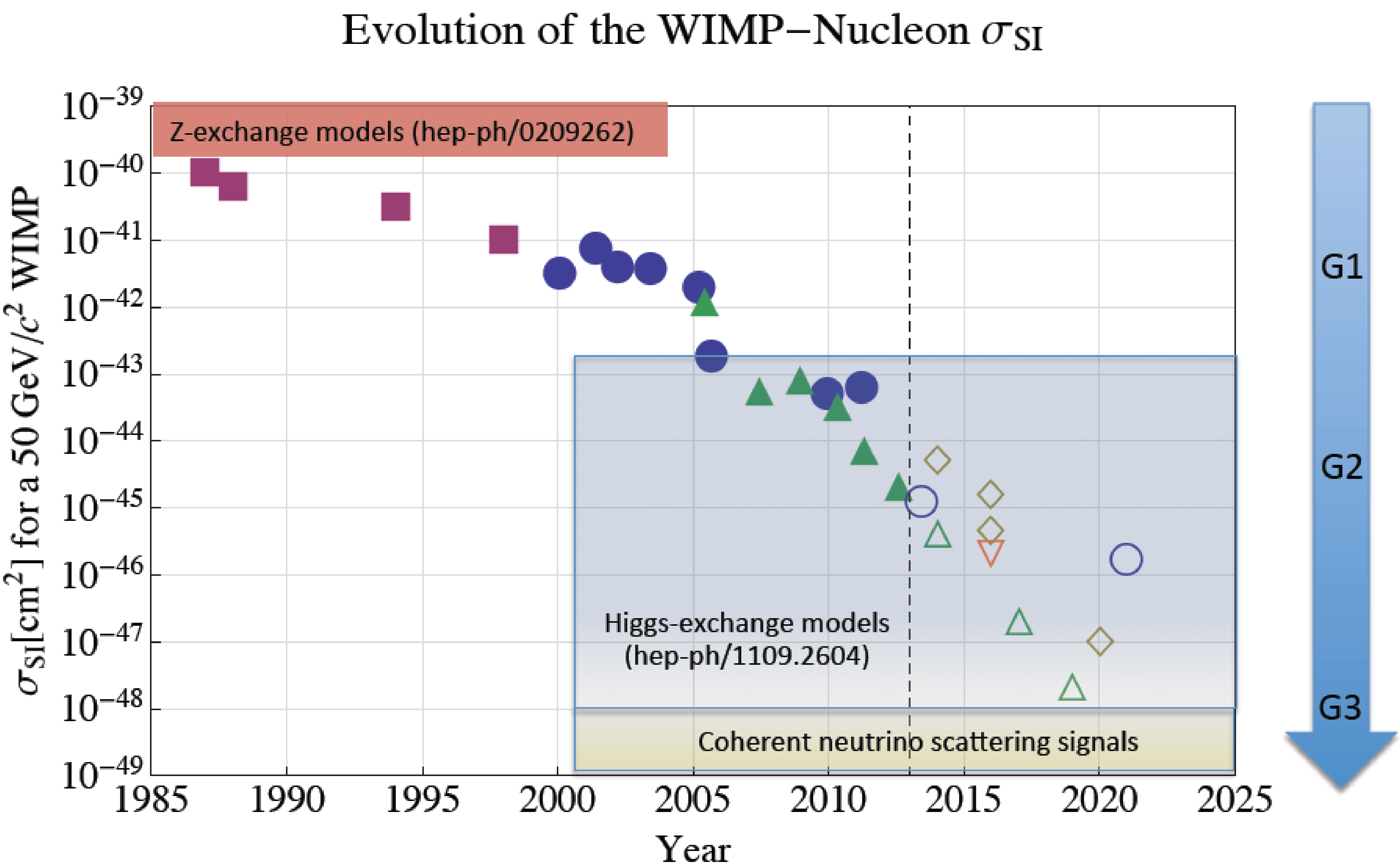
DAMA signal now supplemented by others

CURRENT STATUS AND FUTURE PROSPECTS



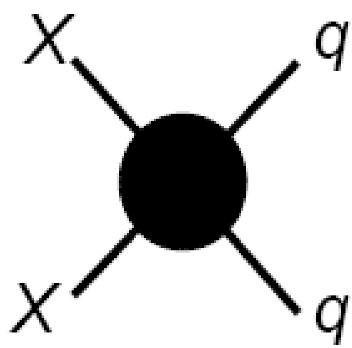
ν background: Billard, Strigari, Figueroa-Feliciano (2013)

MOORE'S LAW FOR DARK MATTER



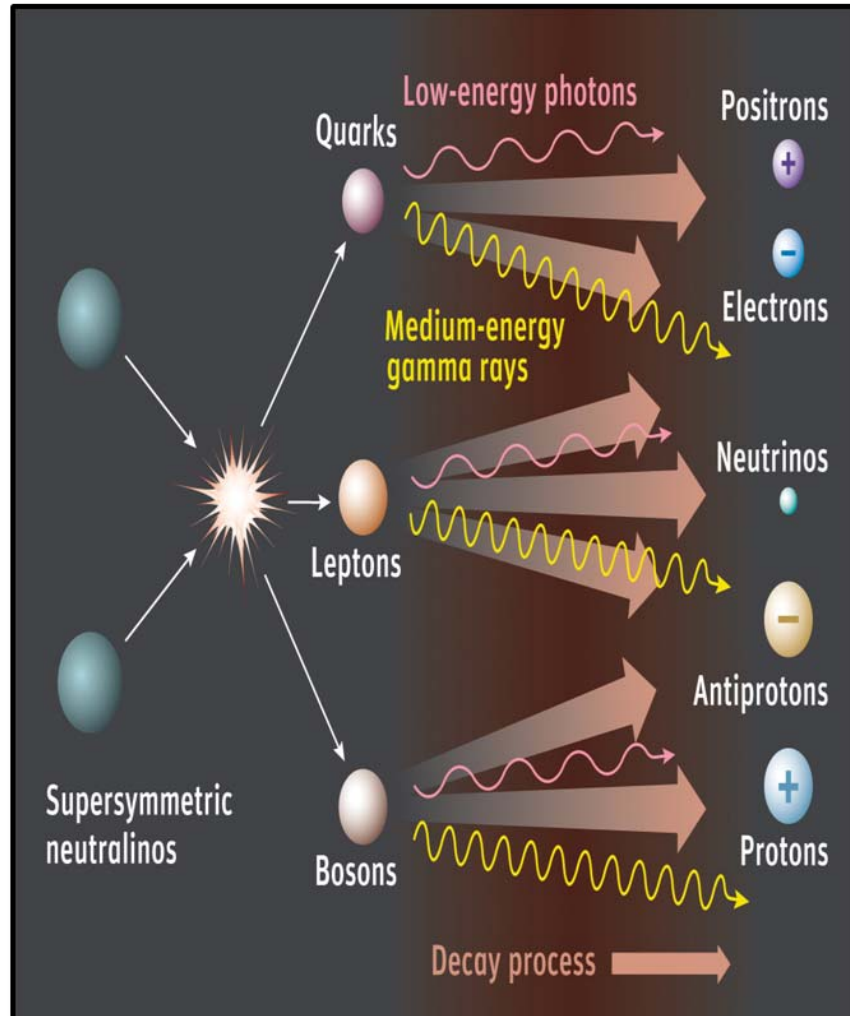
INDIRECT DETECTION

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



- The relic density provides a target annihilation cross section

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

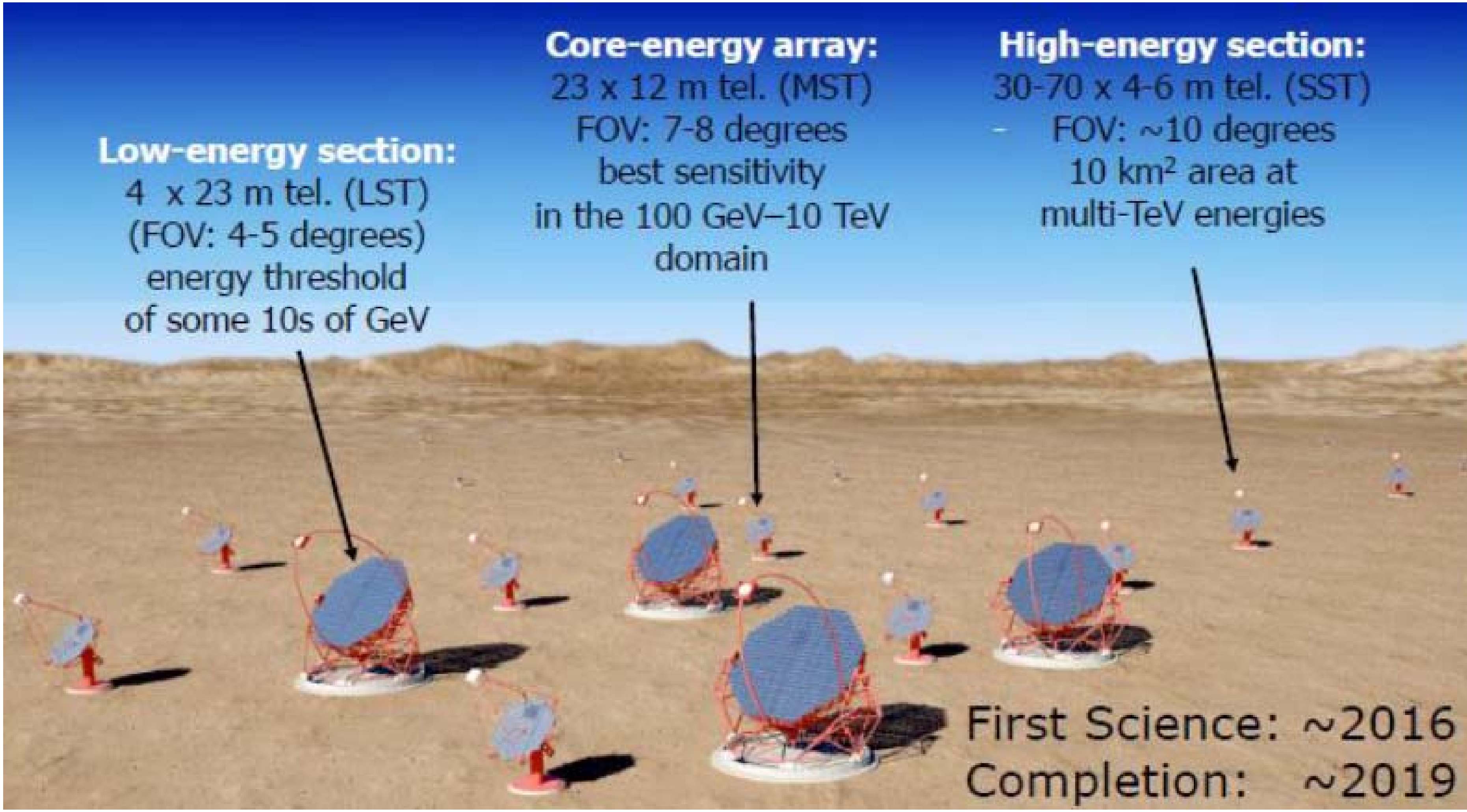


FOR EXAMPLE: INDIRECT DETECTION BY PHOTONS

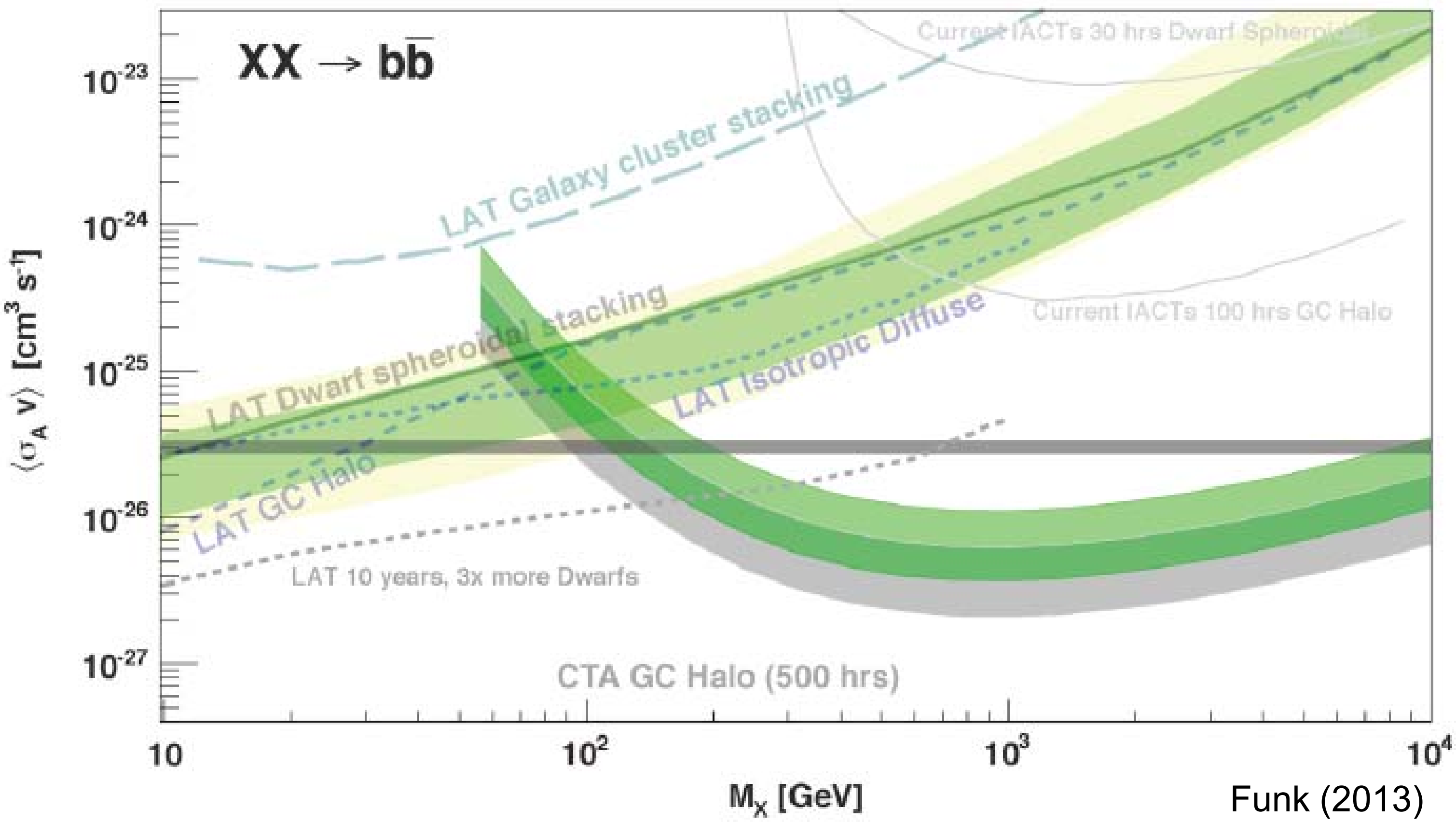
Current: Veritas, Fermi-LAT, HAWC, and others

INDIRECT DETECTION: PHOTONS

Future: Cerenkov Telescope Array



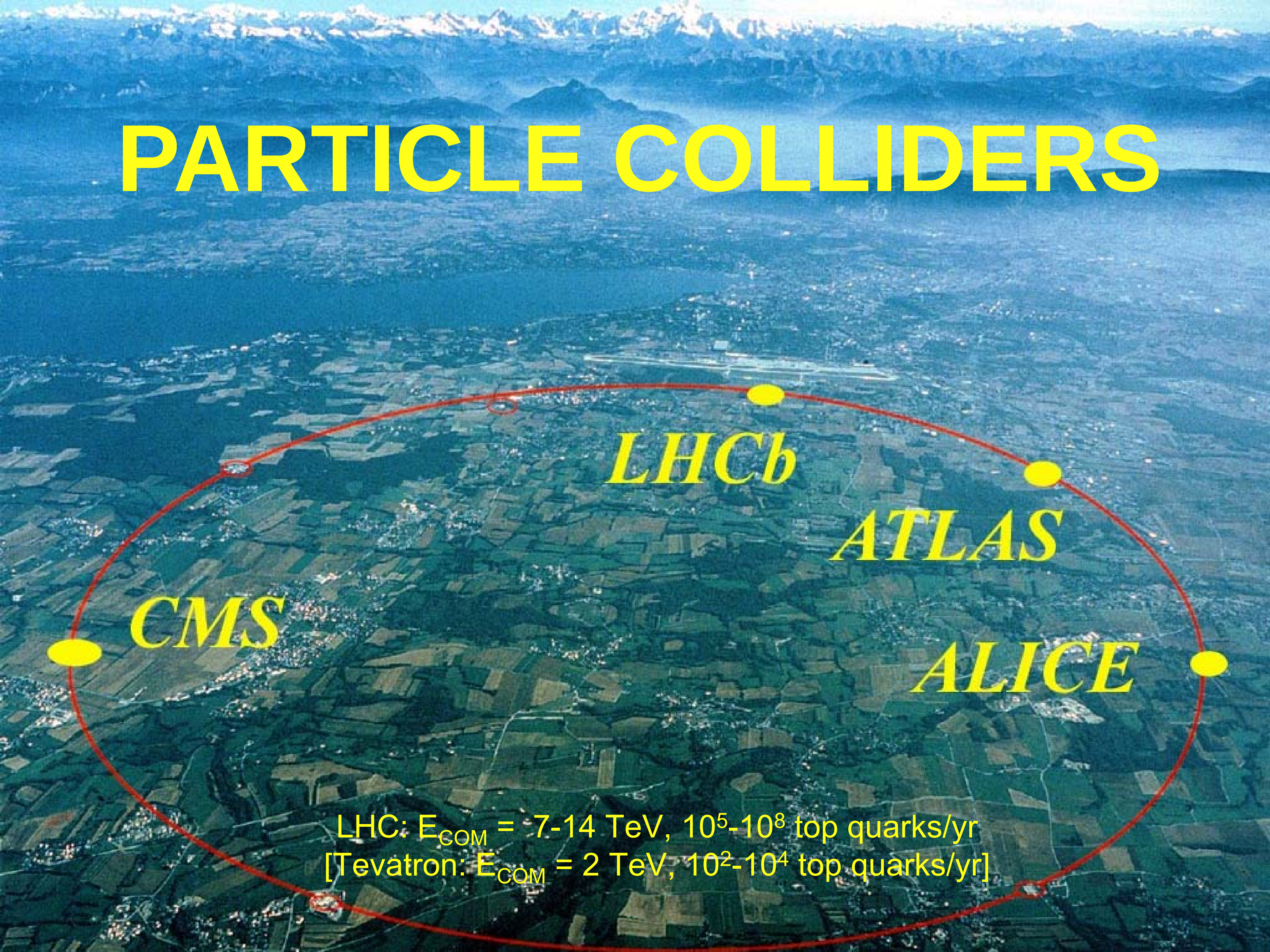
INDIRECT DETECTION: PHOTONS



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

PARTICLE COLLIDERS

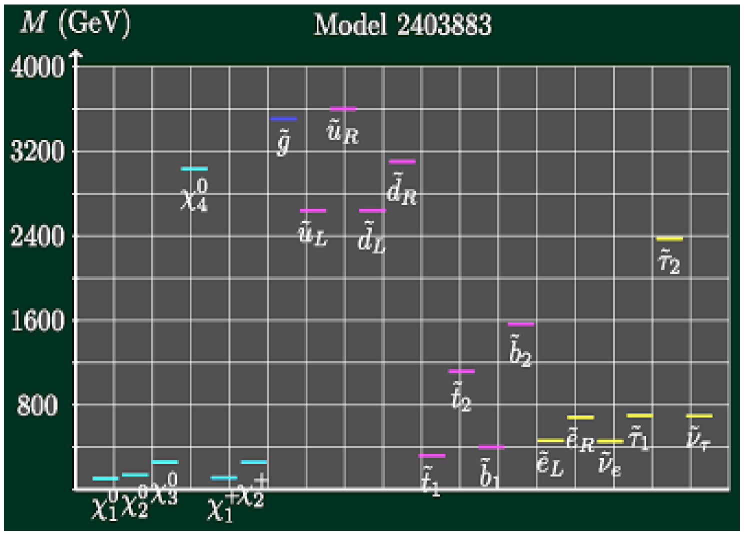


LHC: E_{COM} = 7-14 TeV, 10^5-10^8 top quarks/yr

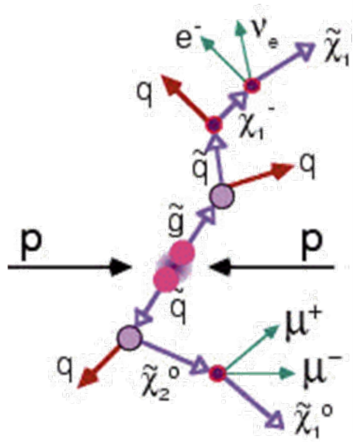
[Tevatron: E_{COM} = 2 TeV, 10^2-10^4 top quarks/yr]

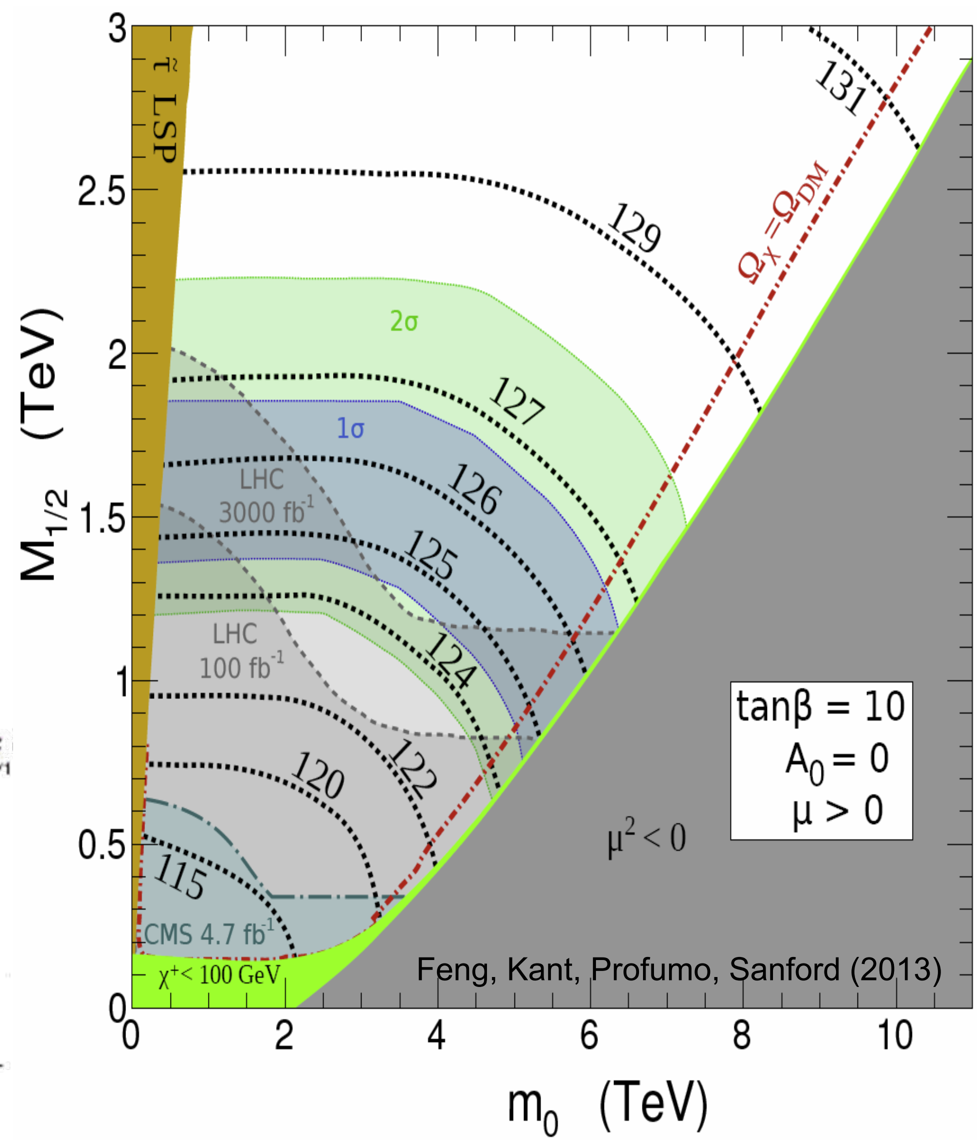
DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)



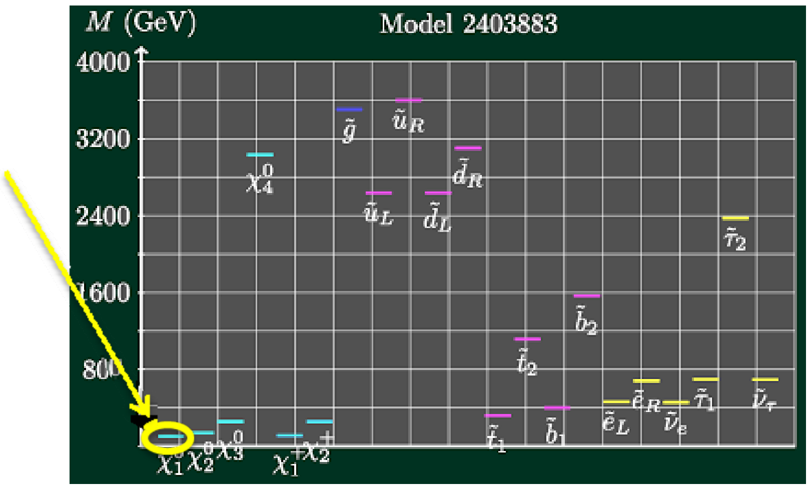
Cascades: Produce other particles, which decay to DM



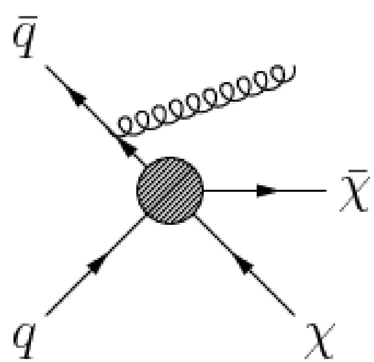


DARK MATTER AT COLLIDERS

DM Effective Theories
(Bare Bones Dark Matter)



Produce DM directly, but in association with something else so it can be seen: Mono-γ, jet,W,Z,h,b,t



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

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

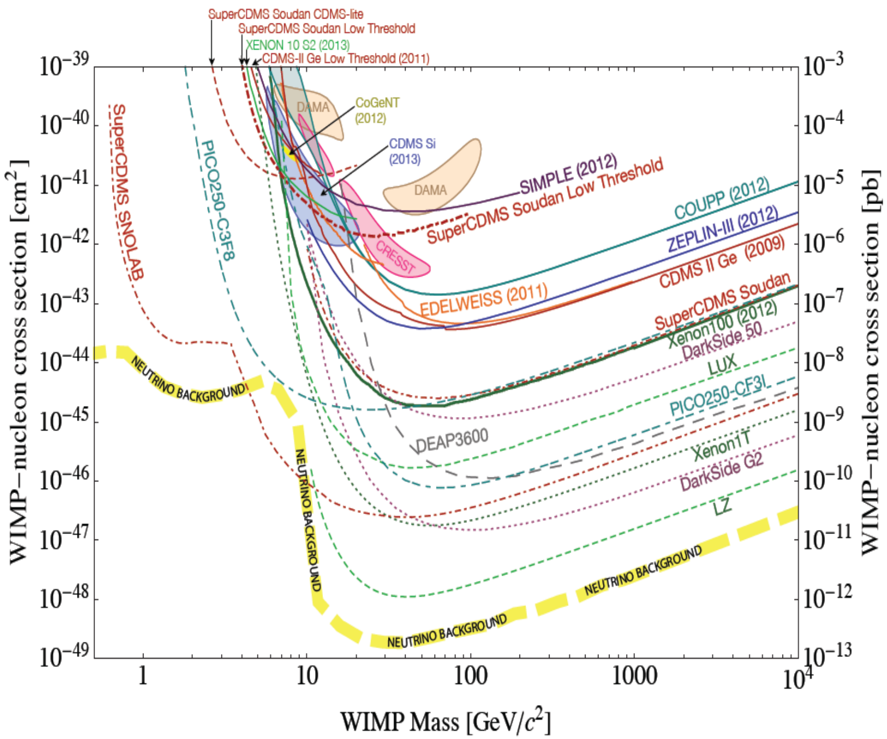
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
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)

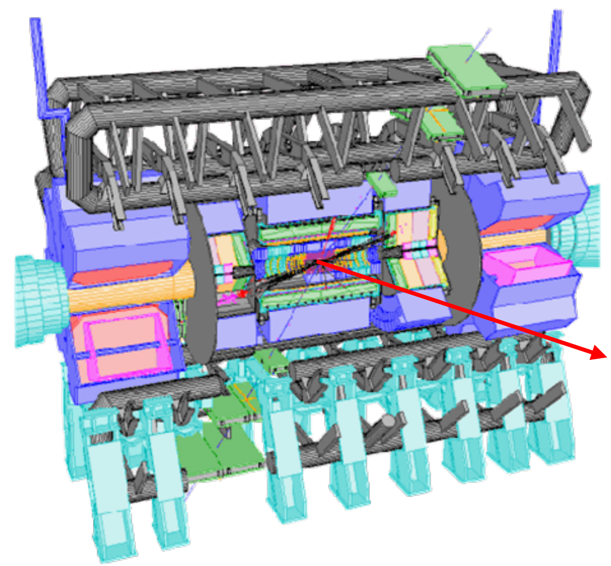
THE FUTURE

If there is a signal, what do we learn?

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



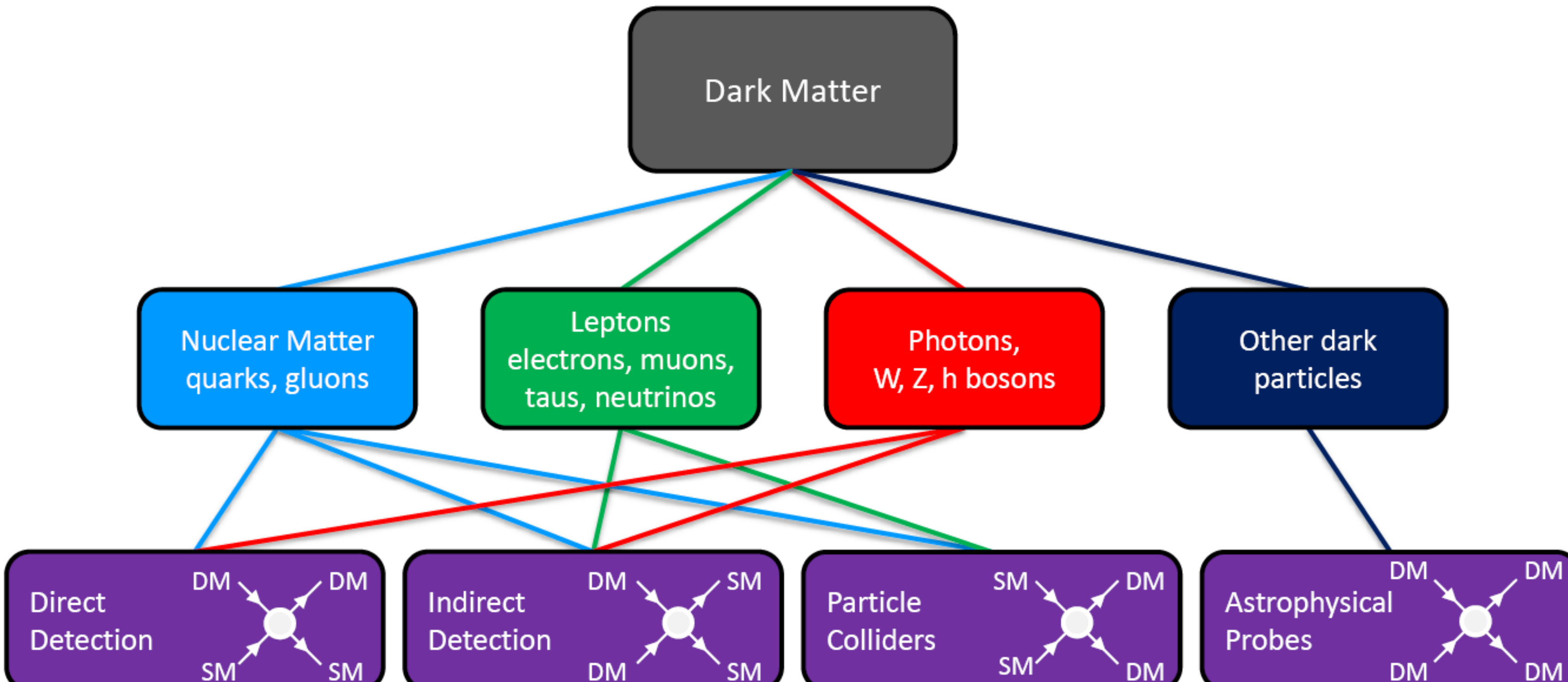
- Particle colliders can't prove it's DM



Lifetime > 10^{-7} s → 10^{17} s ?

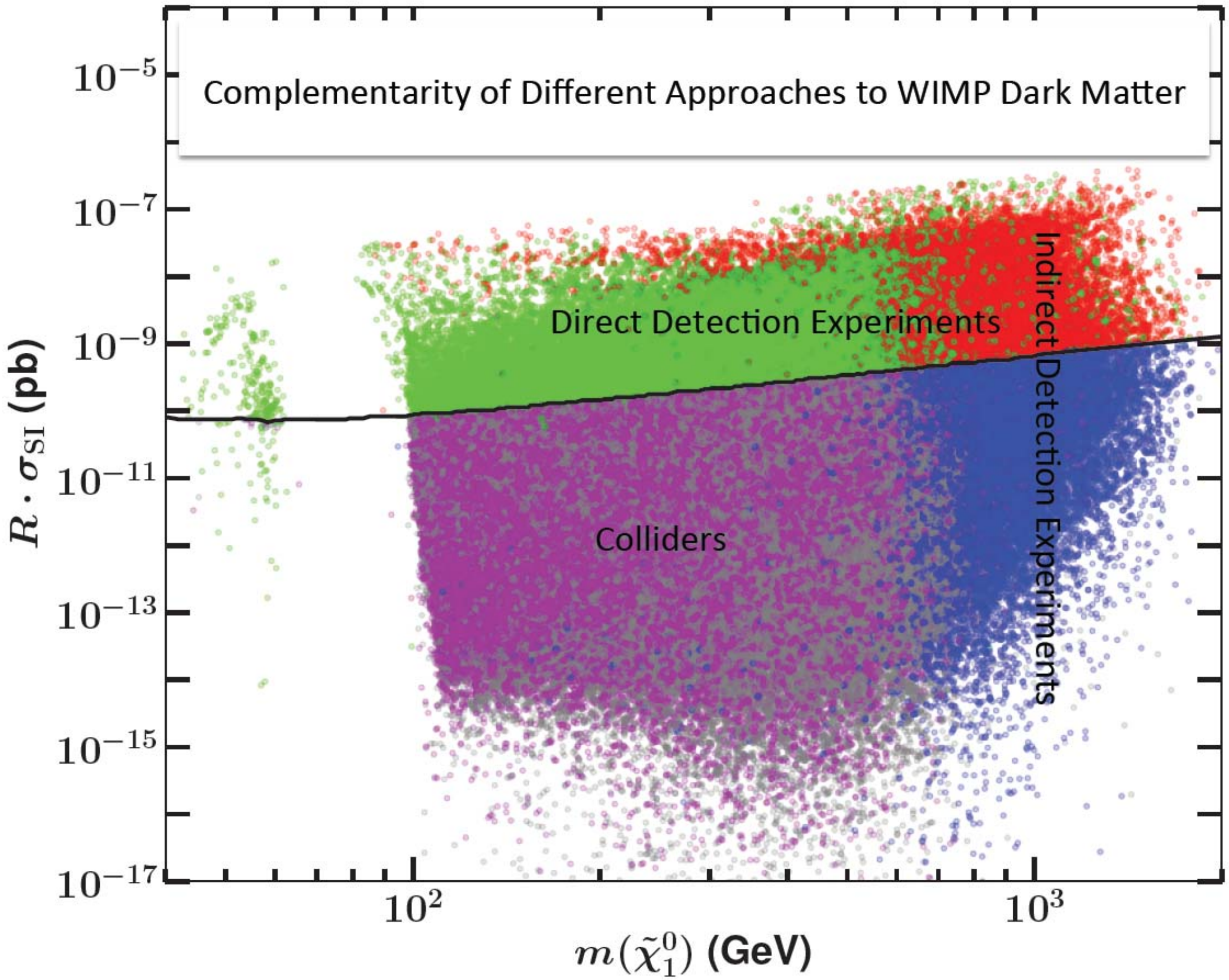
DARK MATTER COMPLEMENTARITY

- 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

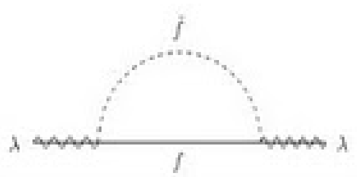
- *A priori* there are both pros and cons
  - Lots of freedom: interesting astrophysics, etc.
  - Too much freedom: no connections to known problems
  - No WIMP miracle

Spergel, Steinhardt (1999); Foot (2001)

HIDDEN DM: SOME RECENT DEVELOPMENTS

- WIMPless Miracle: In many supersymmetric hidden sectors, $m_X \sim g_X^2$, which leaves the relic density invariant

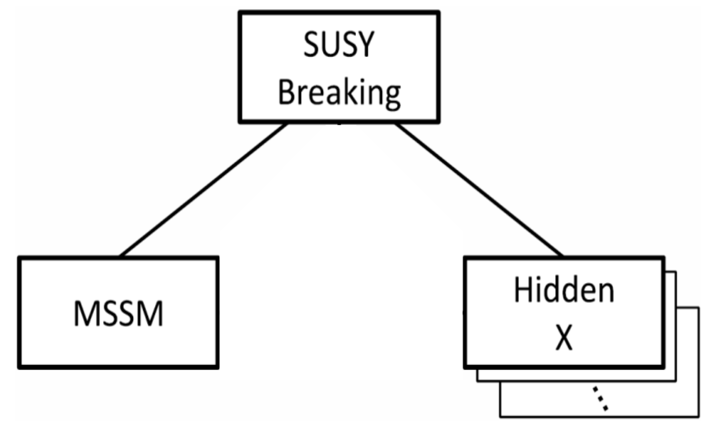
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



Restores

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

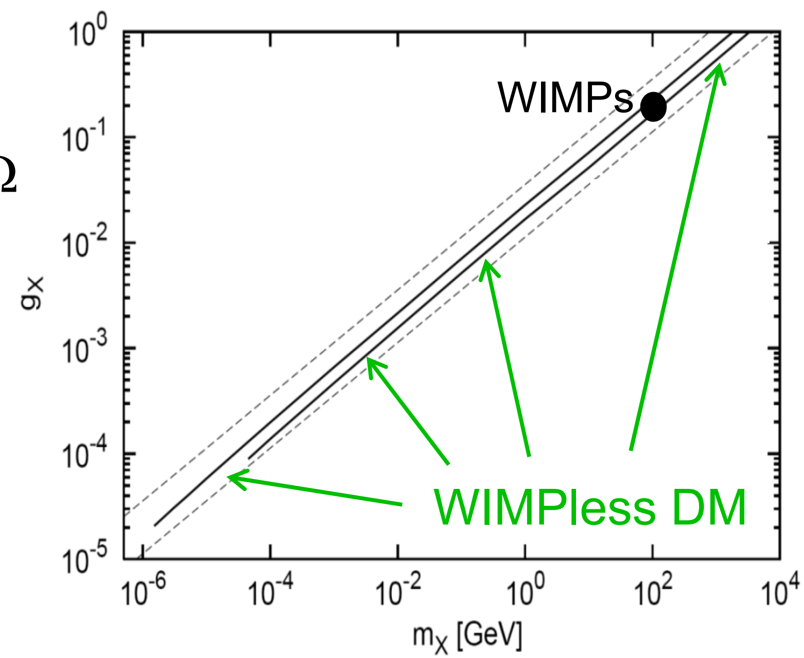
Feng, Kumar (2008)



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

$$\sigma_T/m \sim 0.1\ \text{cm}^2/\text{g} \sim 0.1\ \text{barn/GeV}$$

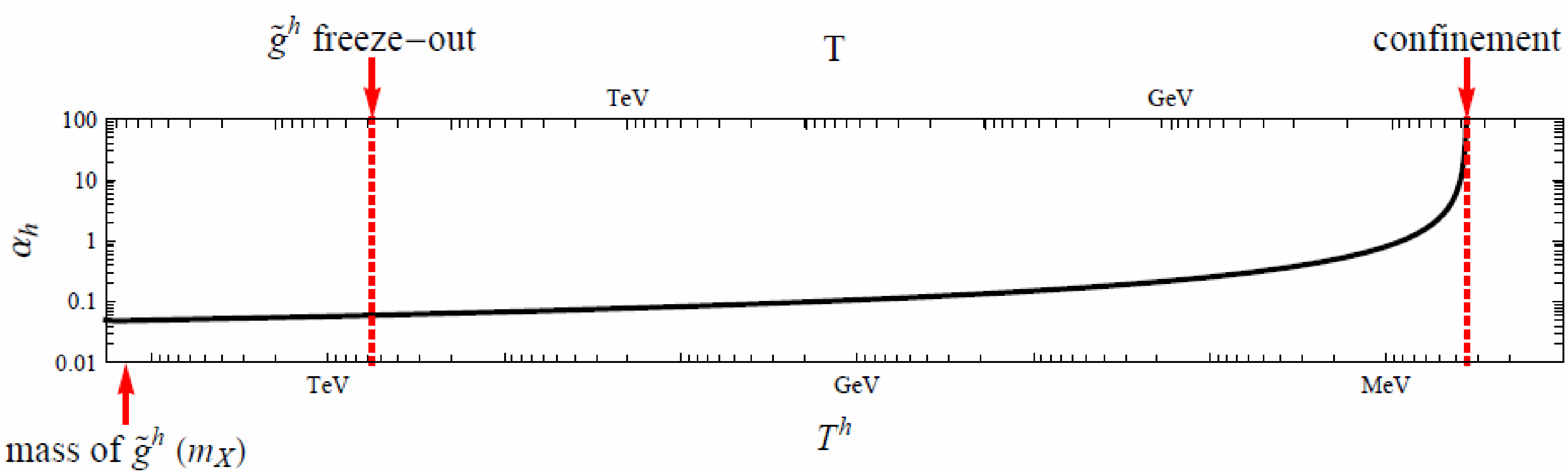
Rocha et al. (2012), Peter et al. (2012); Vogelsberger et al. (2012); Zavala et al. (2012)



DM FROM QCD-LIKE HIDDEN SECTOR

Feng, Shadmi (2011), Boddy, Feng, Kaplinghat, Tait (2013)

- WIMPless miracle → weak interactions
  Self-interactions → strong interactions
- A natural possibility: QCD-like hidden sectors
- For example, SUSY with hidden gluons g and gluinos $\tilde{g}$
  - At early times, interaction is weak, ~10 TeV gluinos freezeout with the correct relic density
  - At late times, interaction is strong, Λ ~ 1 MeV, glueball (gg) and glueballino ($g\tilde{g}$) bound states form strongly self-interacting dark matter



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