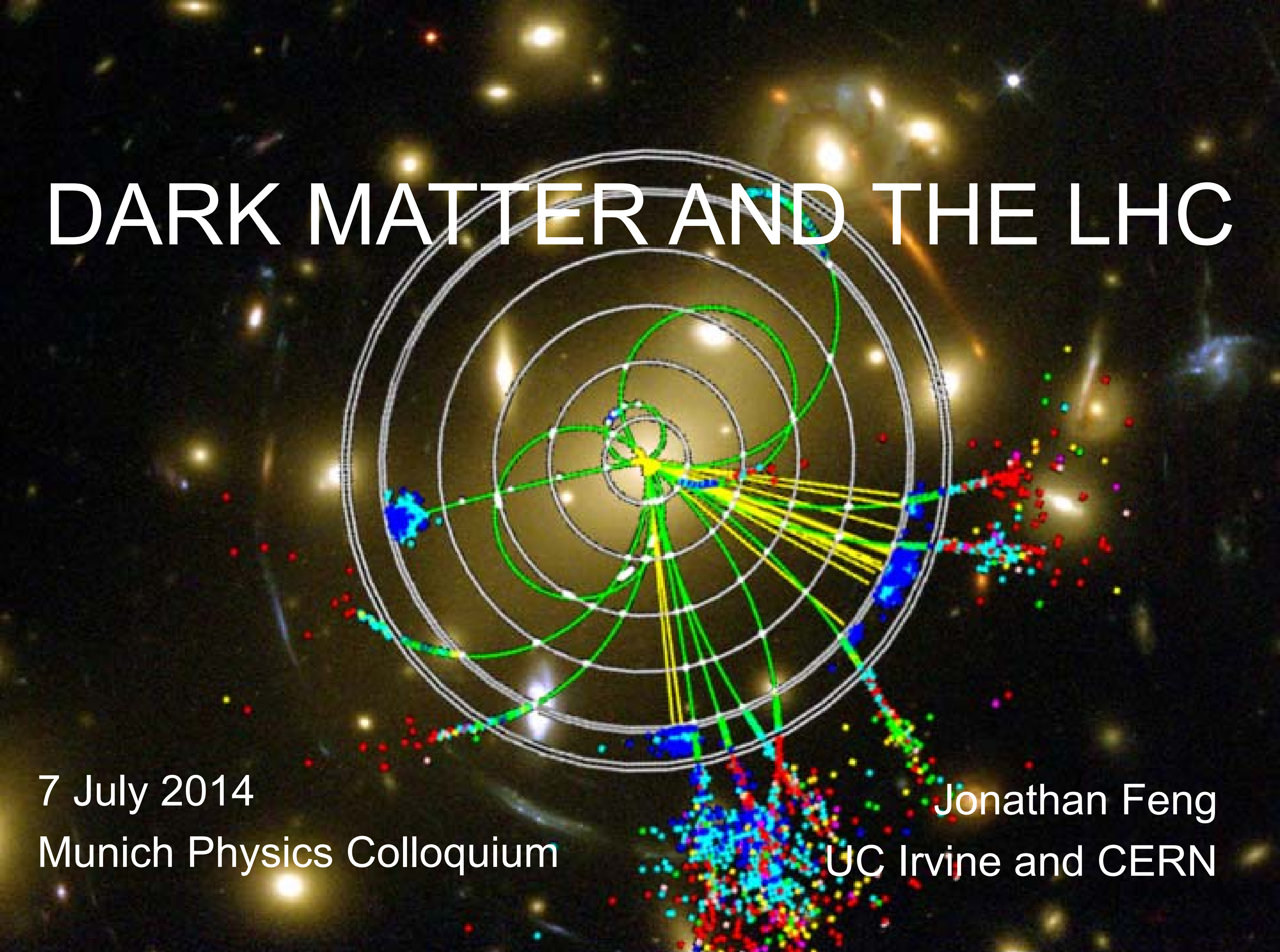


DARK MATTER AND THE LHC

7 July 2014
Munich Physics Colloquium

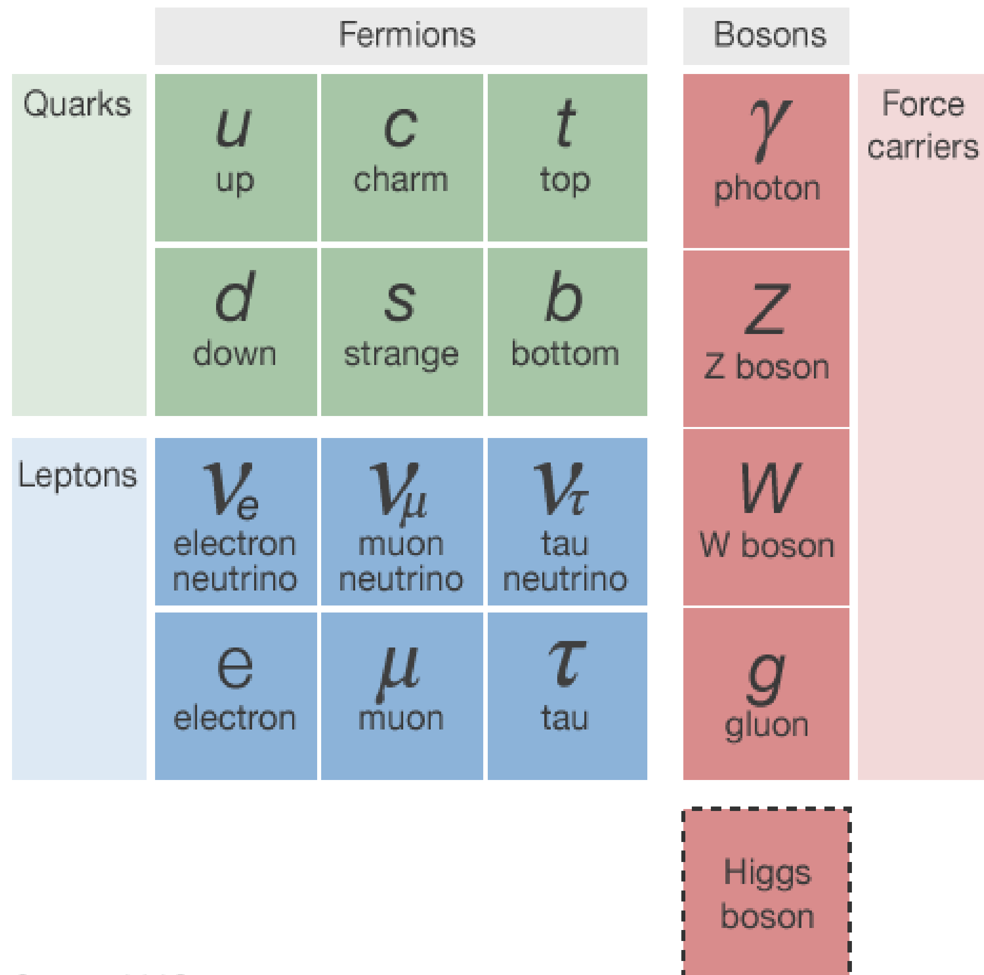
Jonathan Feng
UC Irvine and CERN

INTRODUCTION

- The Higgs discovery at the LHC capped a 50-year saga and completed the particle content of the Standard Model

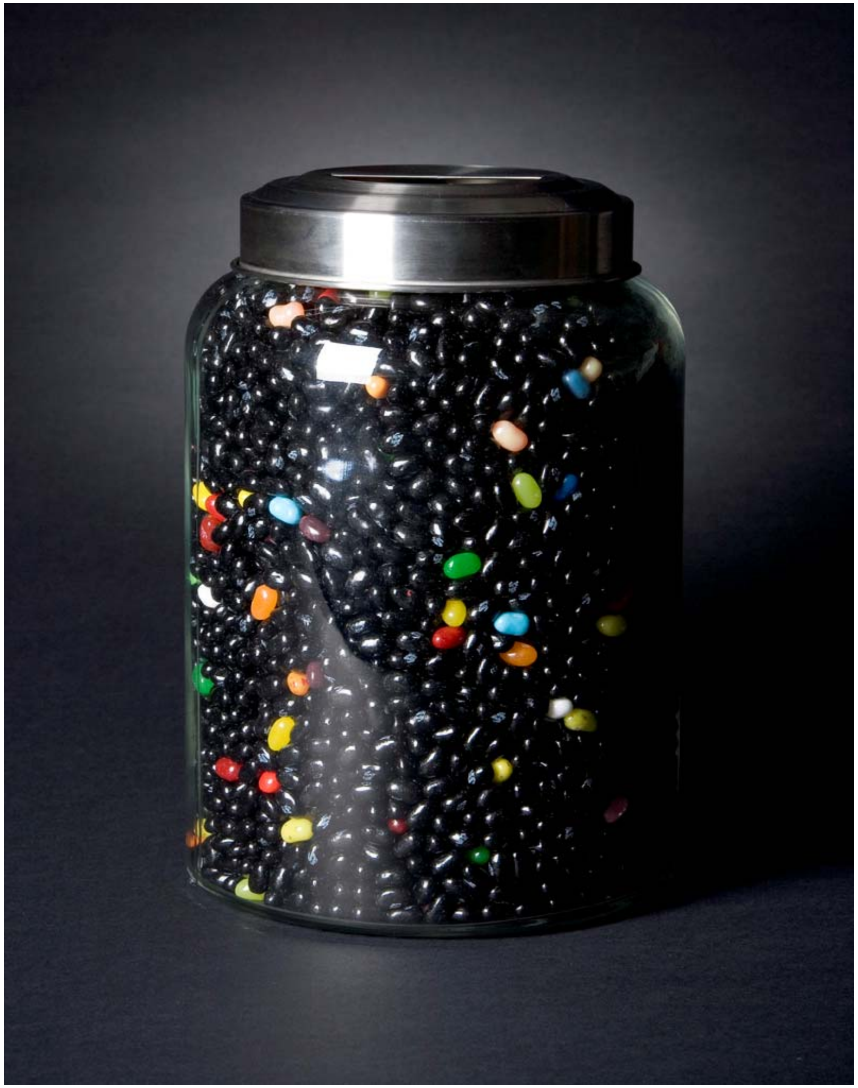
- No other new particles have been found

- But many expect more discoveries, and the Higgs may be just the LHC's opening act. 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

DARK MATTER

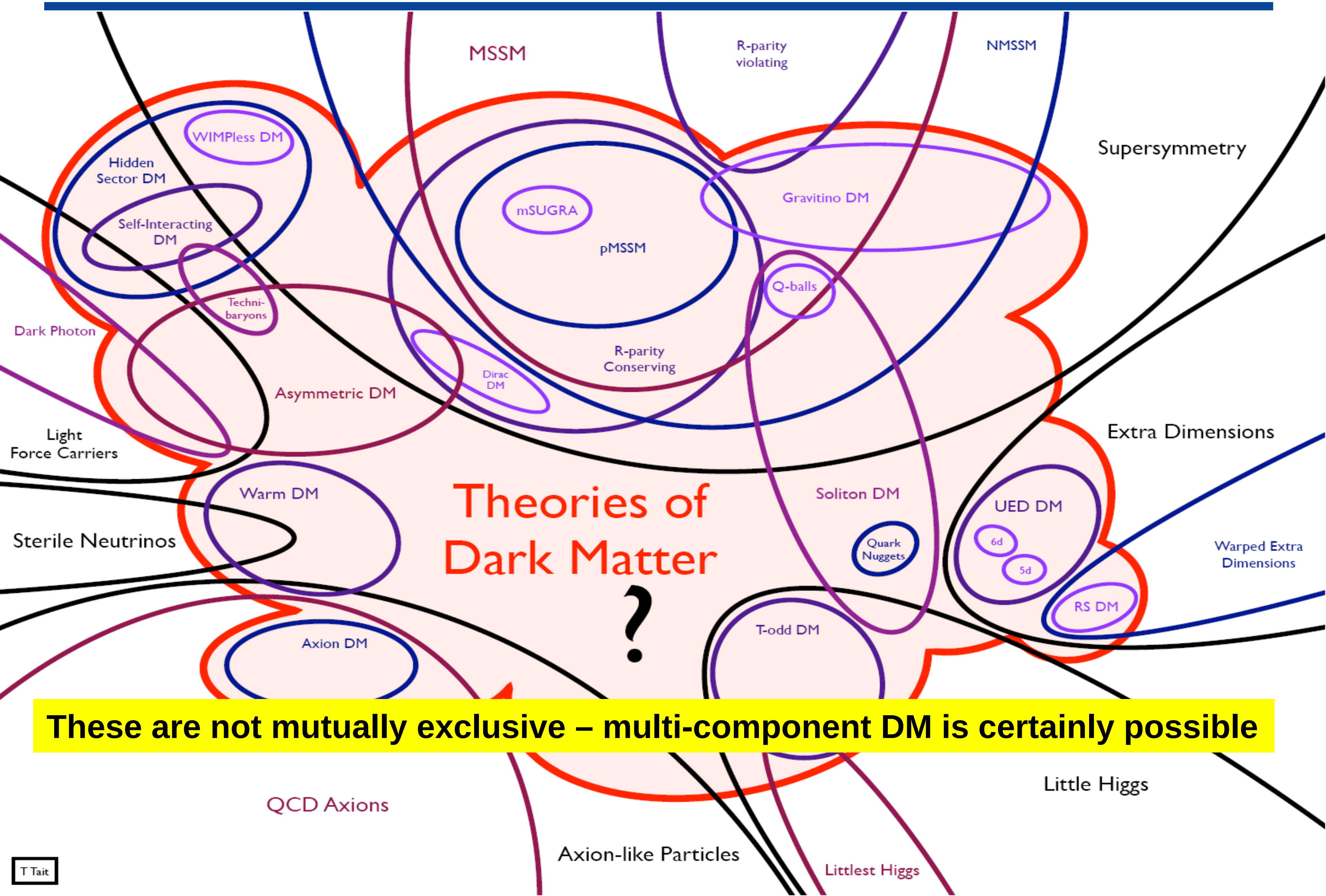
Source: AAAS

Known DM properties

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

Unambiguous evidence for new physics

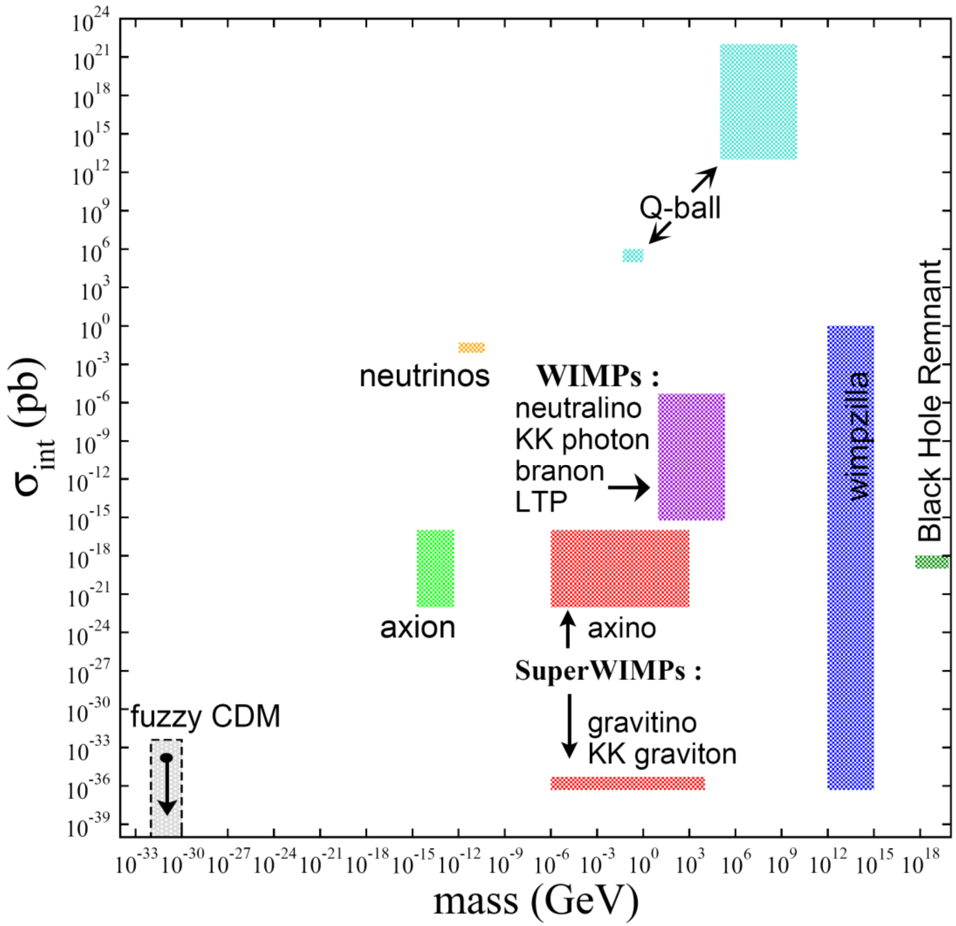
WHAT COULD DARK MATTER BE?



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
- Axions, sterile neutrinos, etc. are well-motivated, but focus here on ideas most relevant for particle colliders



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:

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

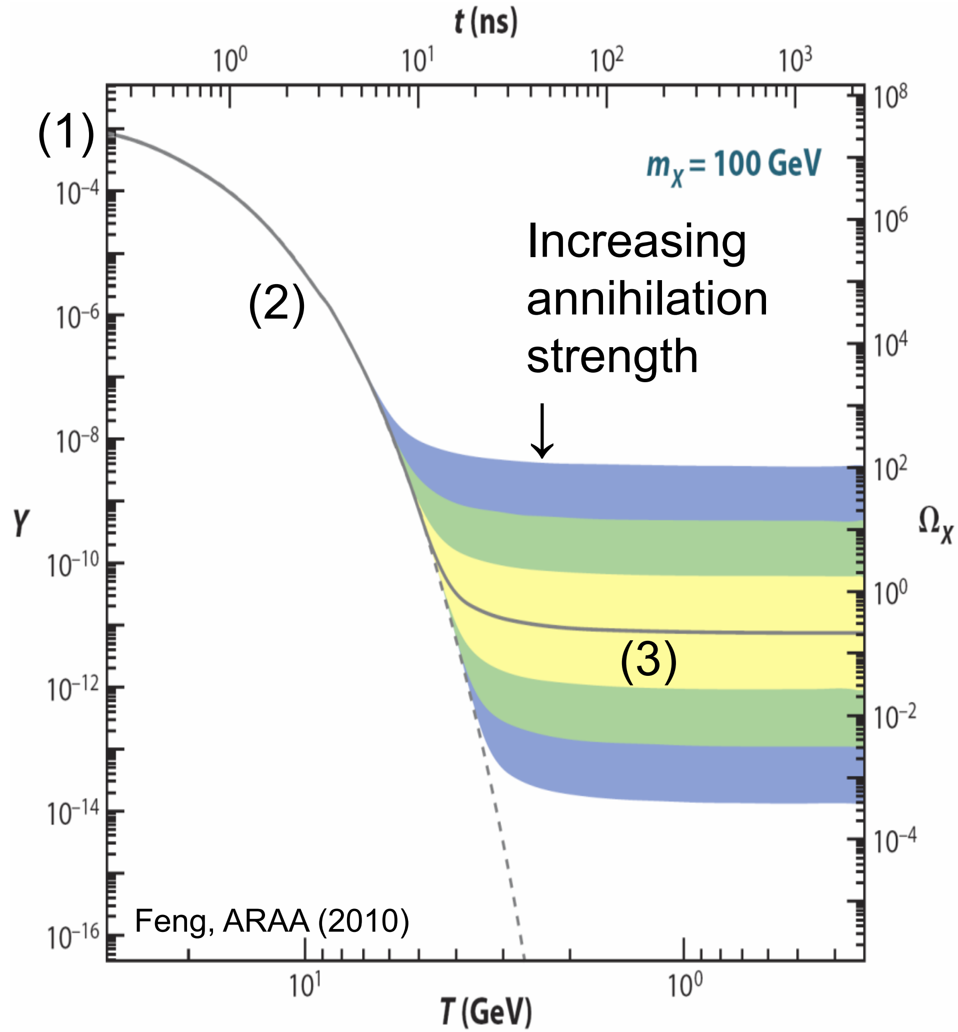
(2) Universe cools:

$$XX \underset{\not\leftarrow}{\rightarrow} \bar{q}q$$

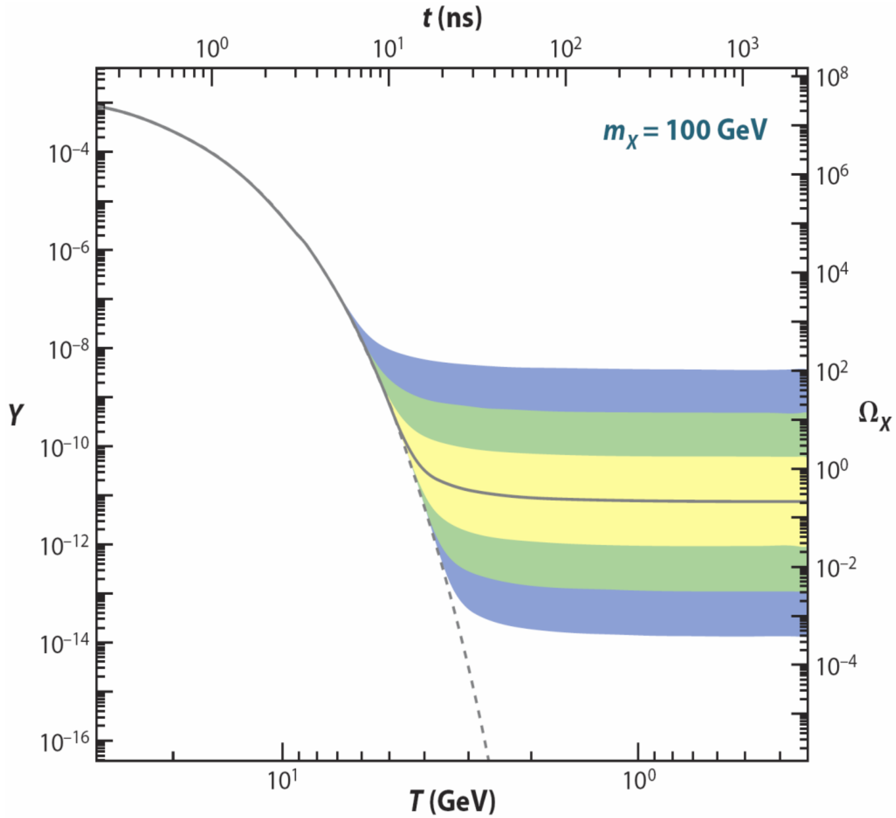
(3) Universe expands:

$$XX \underset{\not\leftarrow}{\not\rightarrow} \bar{q}q$$

Zeldovich et al. (1960s)

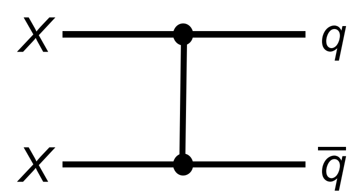


THE WIMP MIRACLE



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

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



- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

- 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)

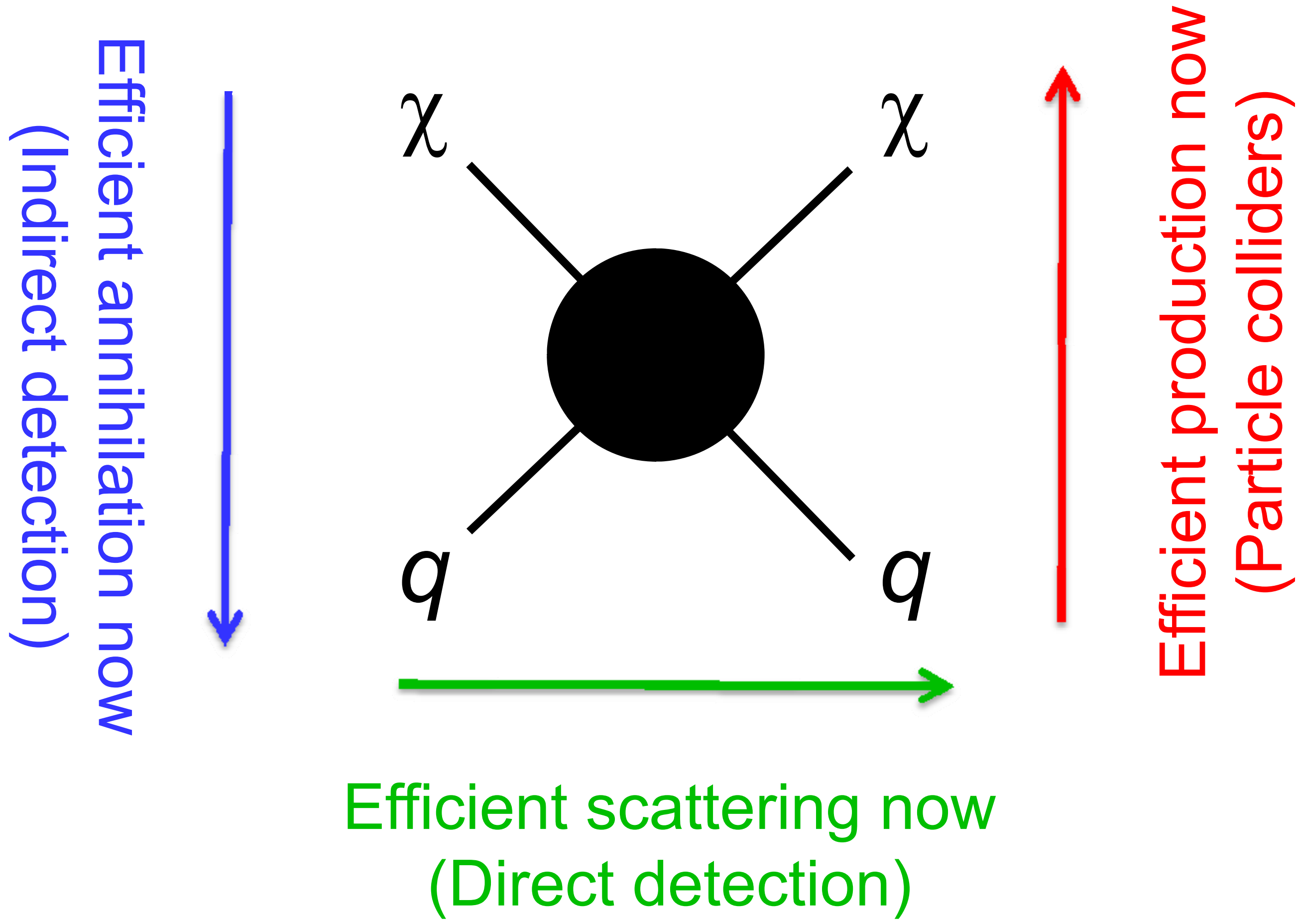
Supersymmetry: extends rotations/boosts/translations, string theory, unification of forces,… For every known particle X, predicts a partner particle $\tilde{X}$

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!

WIMP DETECTION

Correct relic density → Efficient annihilation then



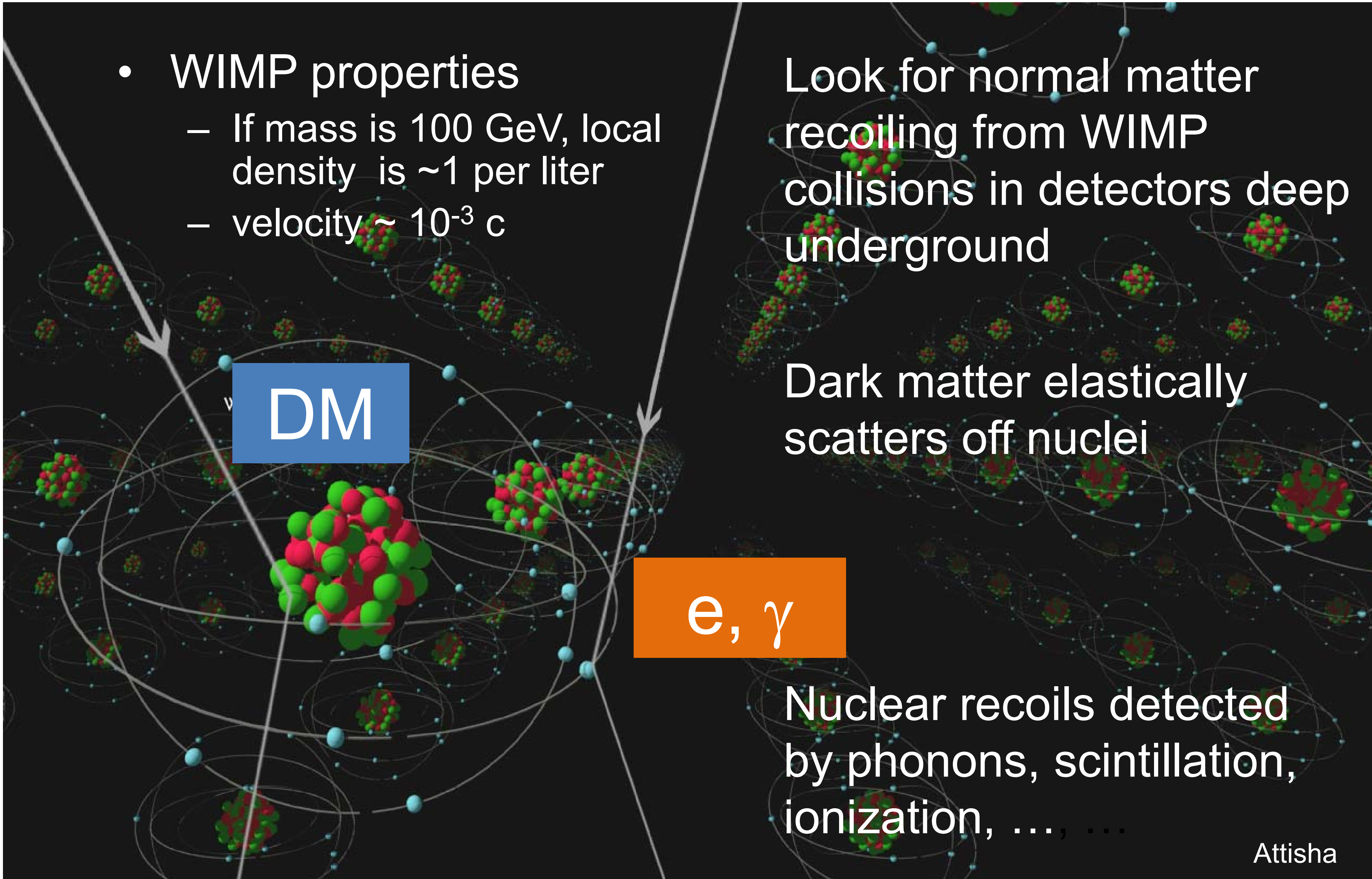
DIRECT DETECTION

- 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

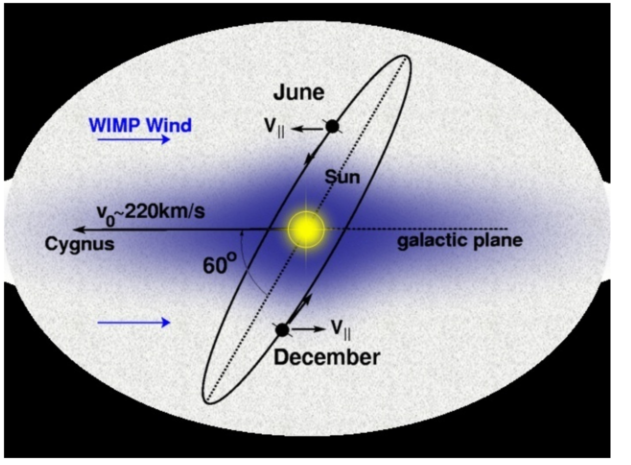
Dark matter elastically scatters off nuclei

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



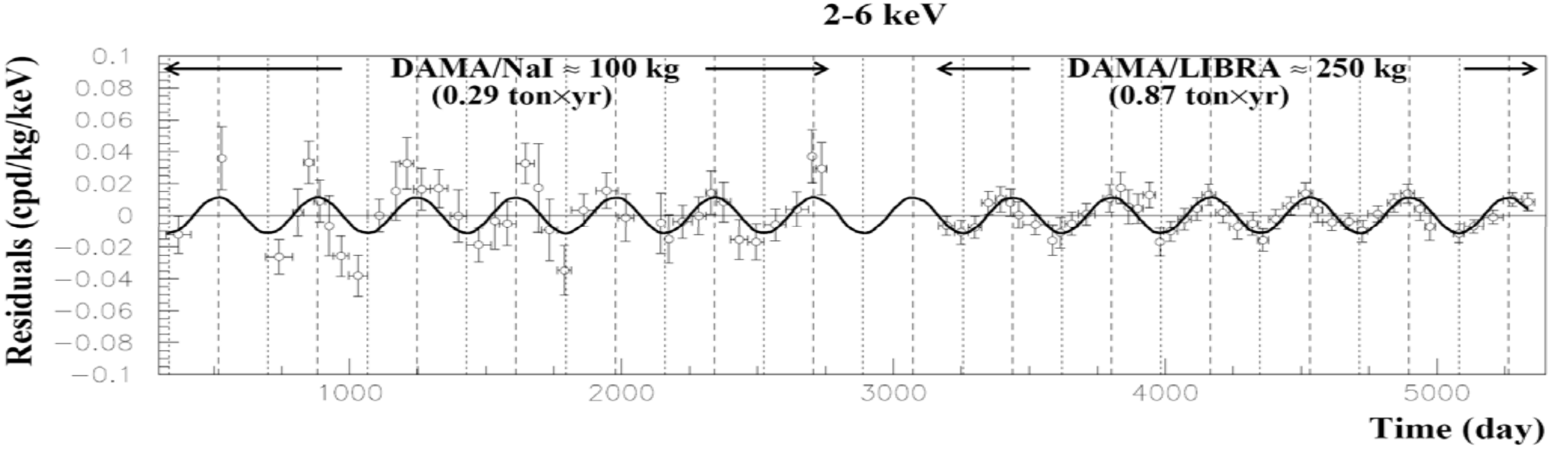
CURRENT STATUS

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



Drukier, Freese, Spergel (1986)

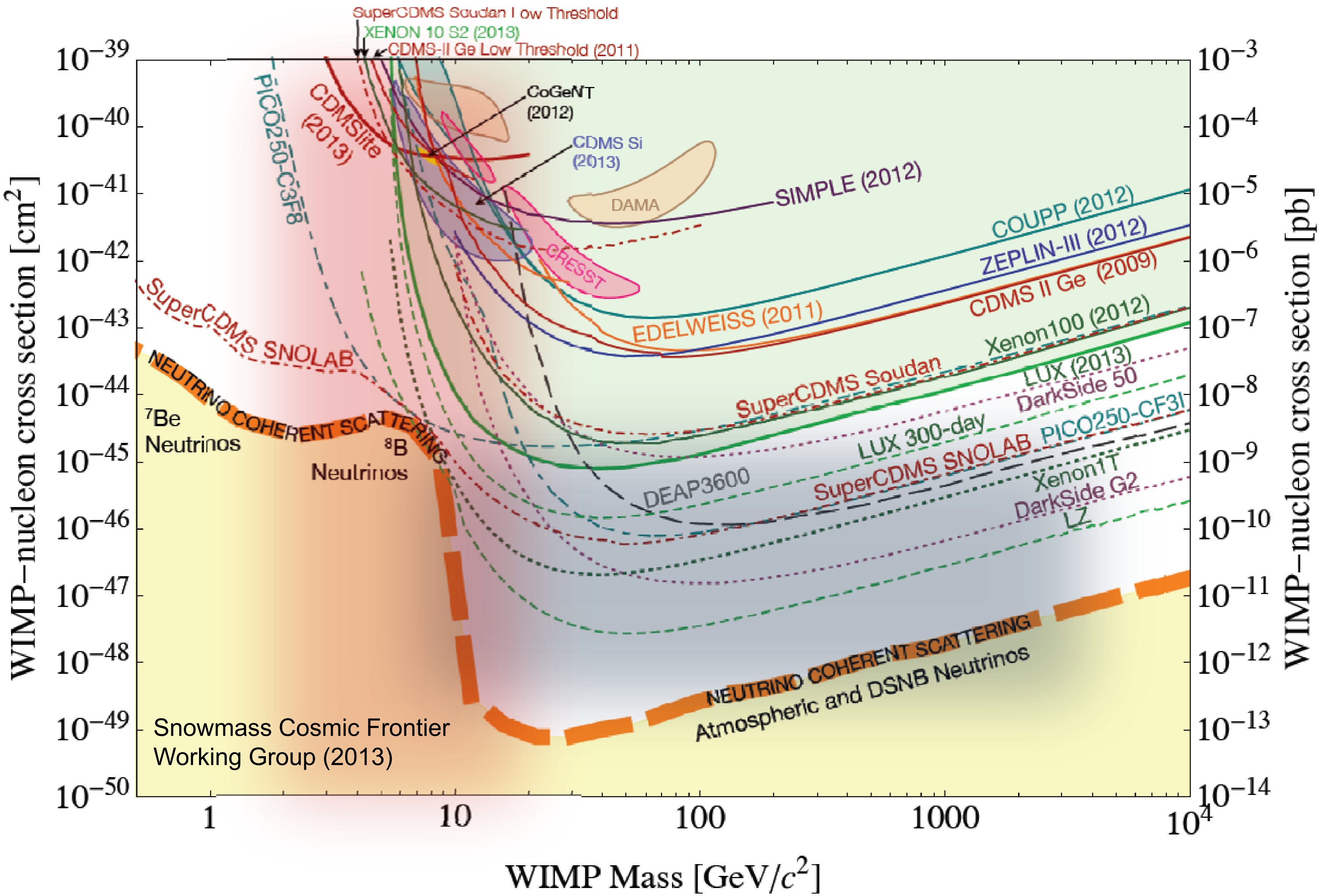
DAMA: 9σ signal with T ~ 1 year, max ~ June 2



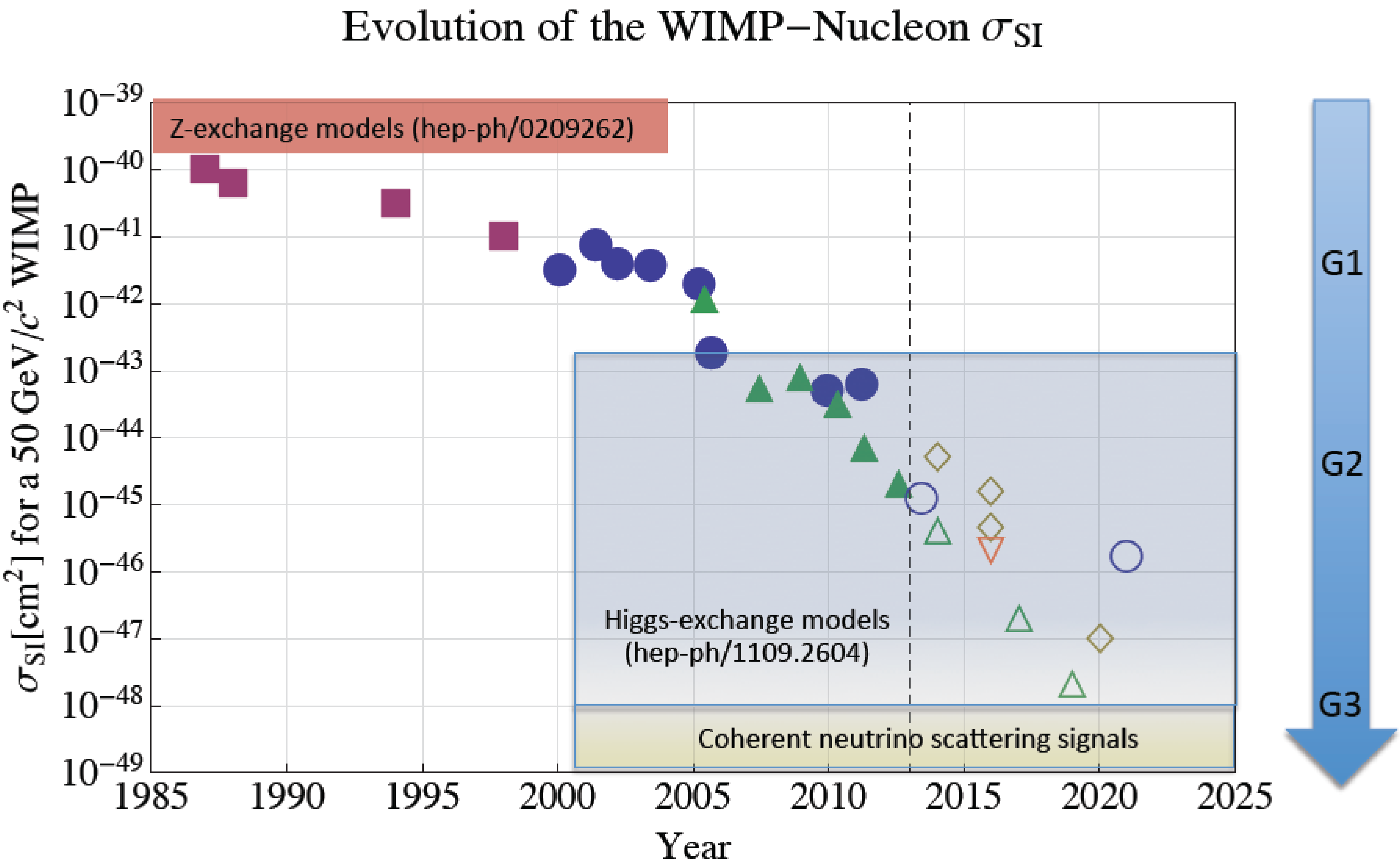
DAMA (2013)

DAMA signal now supplemented by others

CURRENT STATUS AND FUTURE PROSPECTS

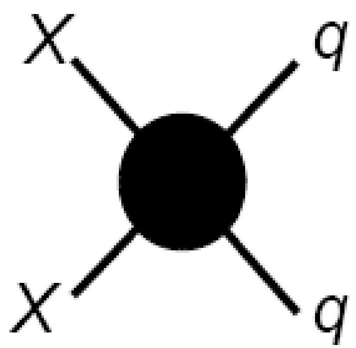


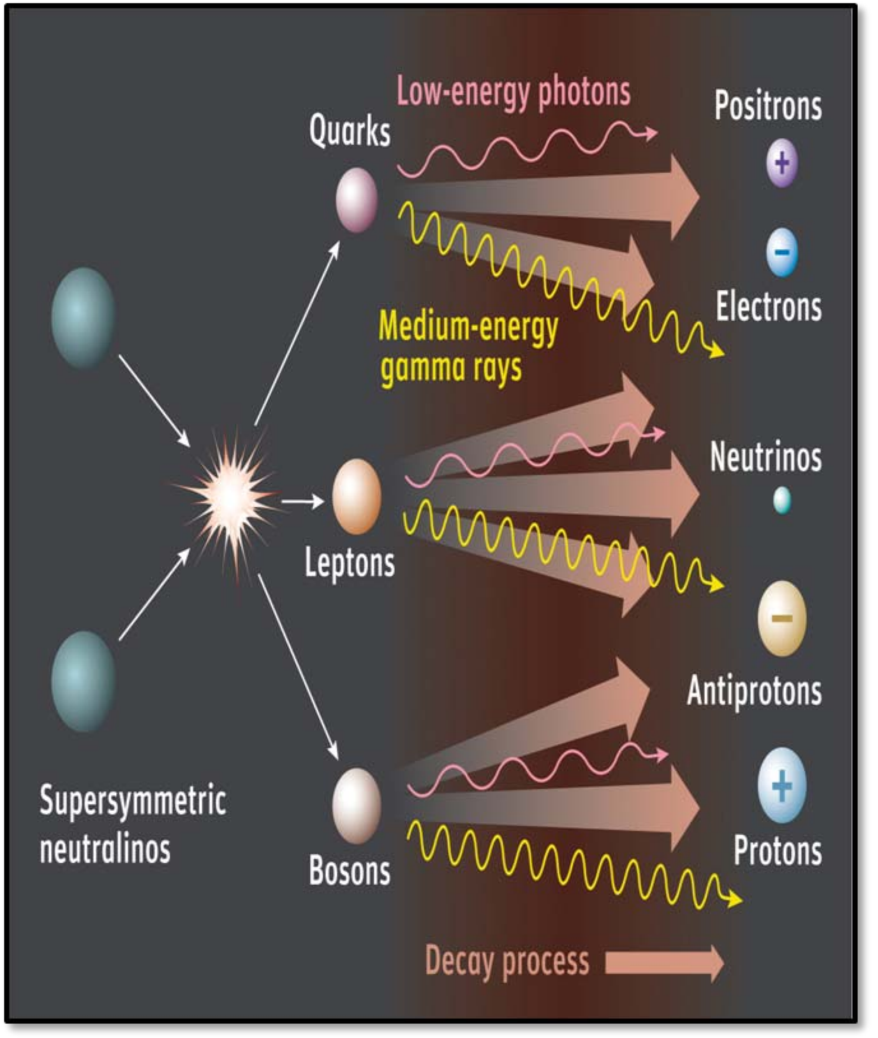
MOORE'S LAW FOR DARK MATTER



INDIRECT DETECTION

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



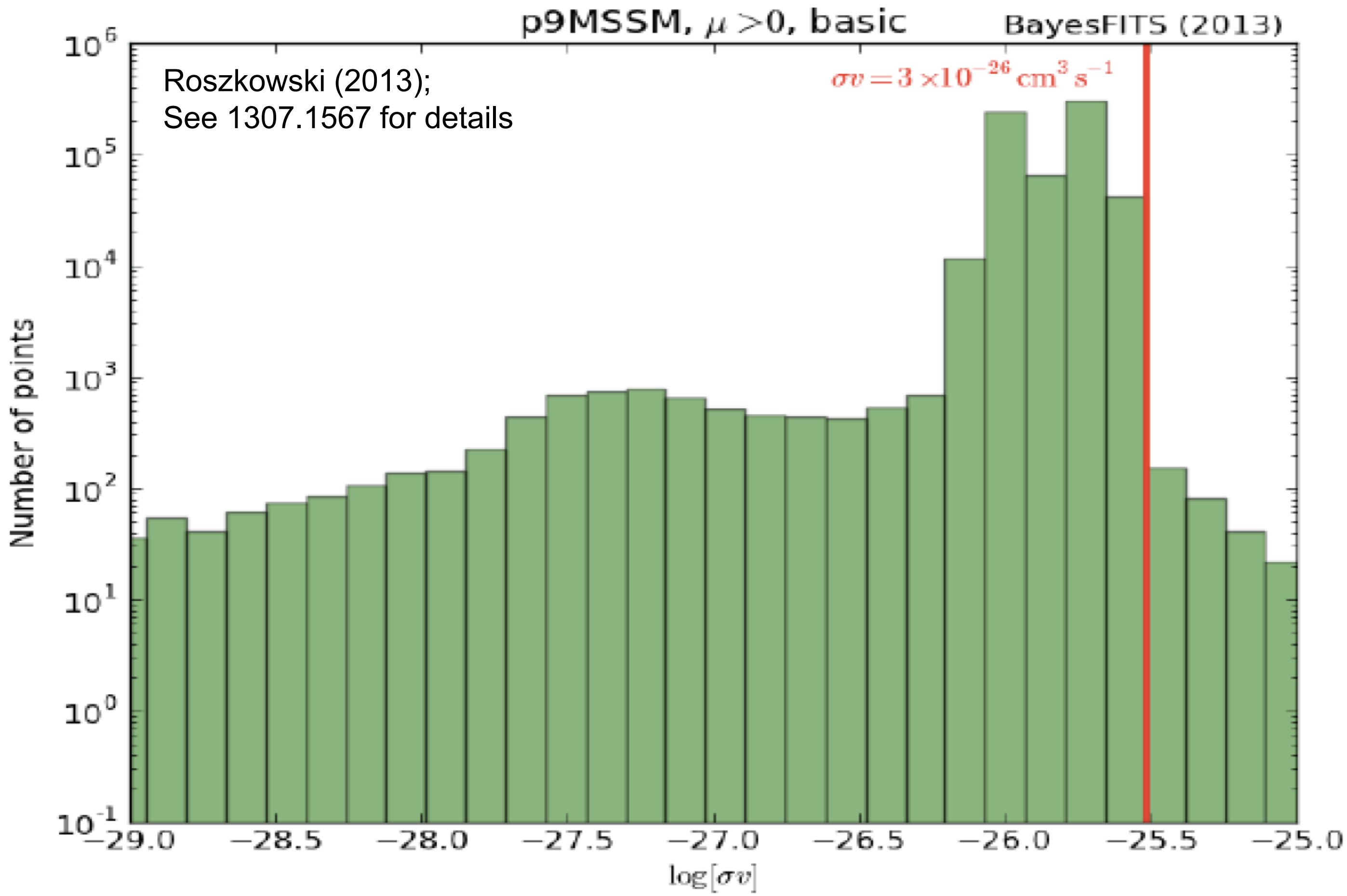


- The relic density provides a target annihilation cross section

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

ROBUSTNESS OF THE TARGET CROSS SECTION

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

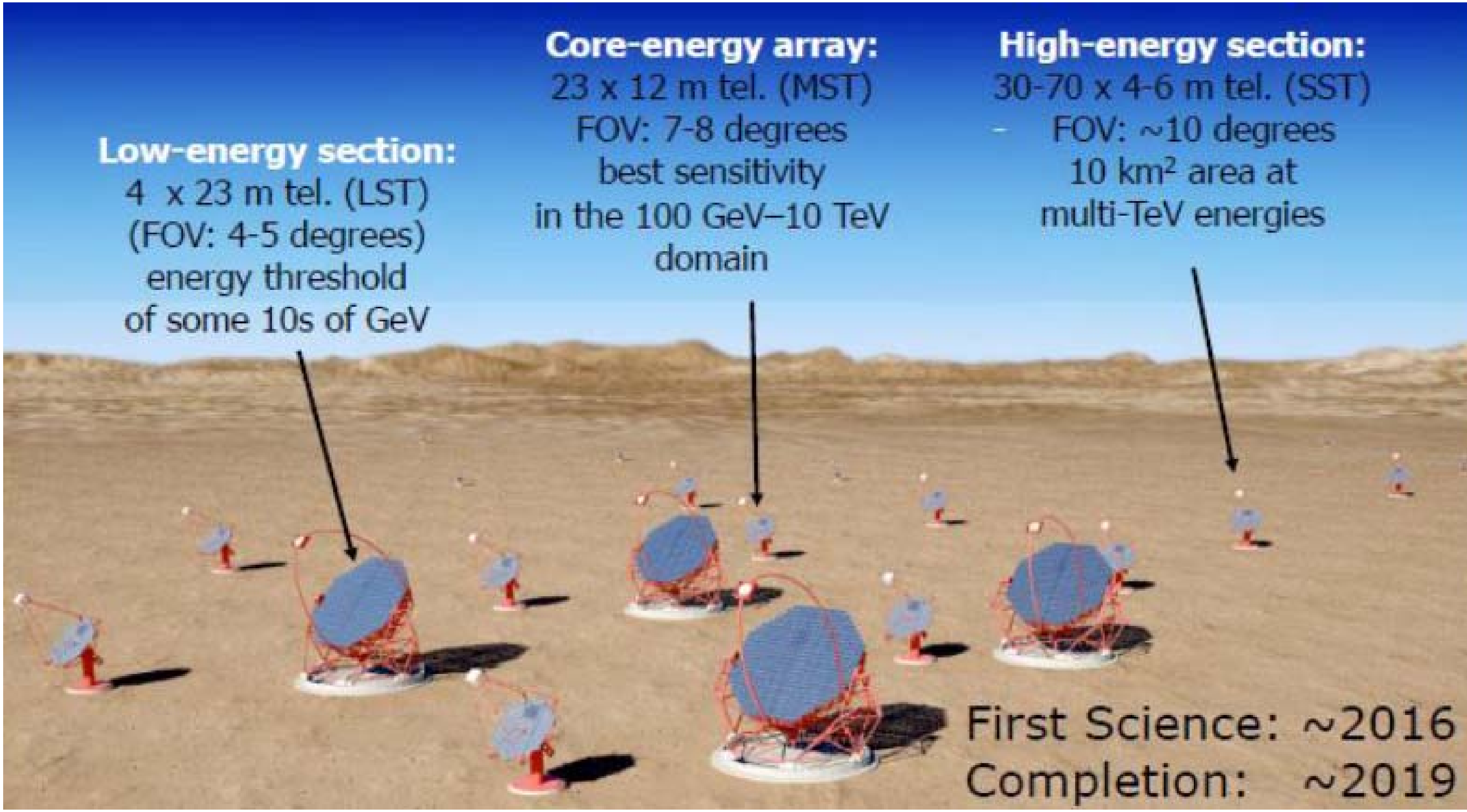


FOR EXAMPLE: INDIRECT DETECTION BY PHOTONS

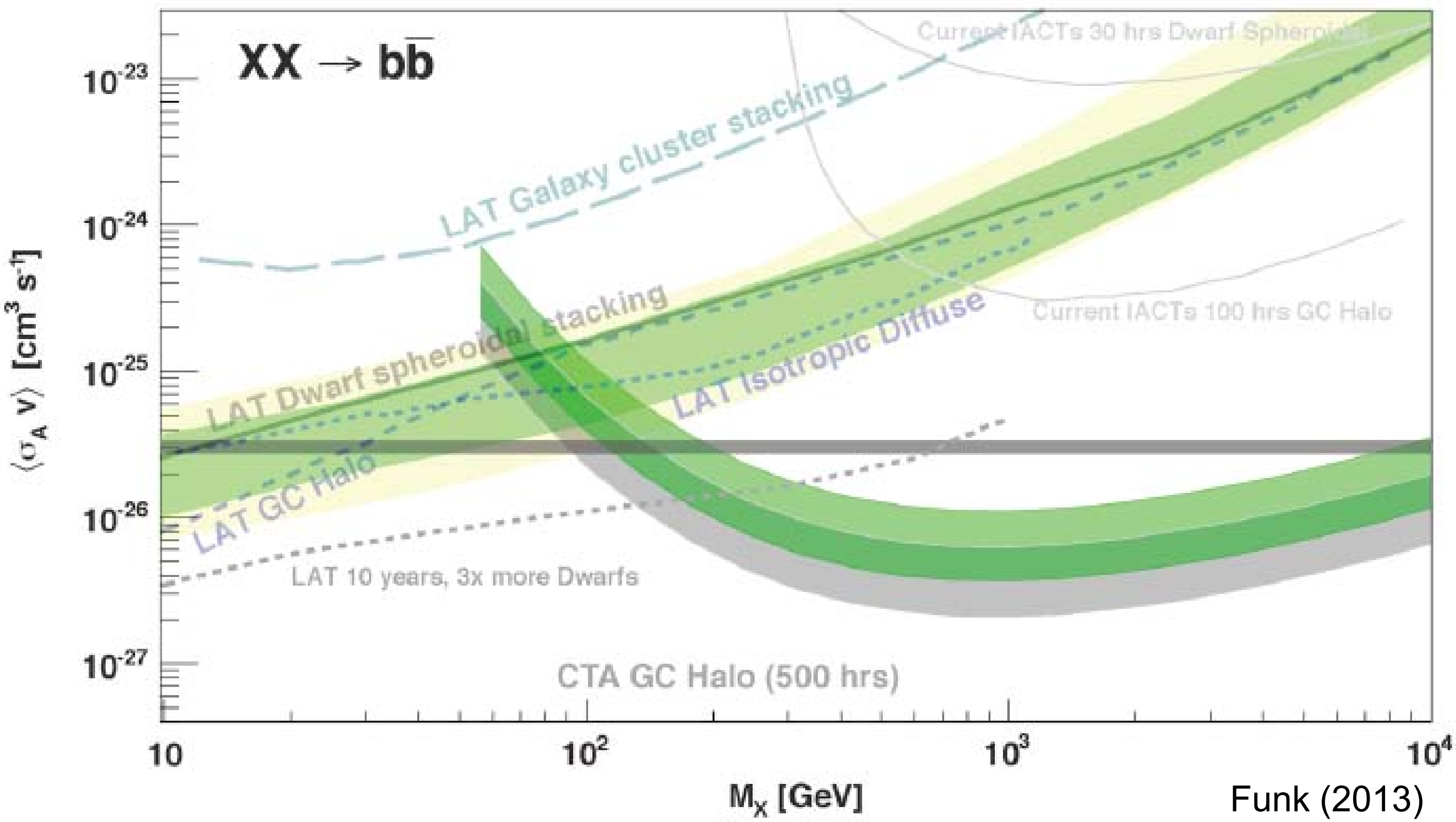
Current: Veritas, HESS, MAGIC, Fermi-LAT, HAWC, and others

INDIRECT DETECTION: PHOTONS

Future: Cerenkov Telescope Array



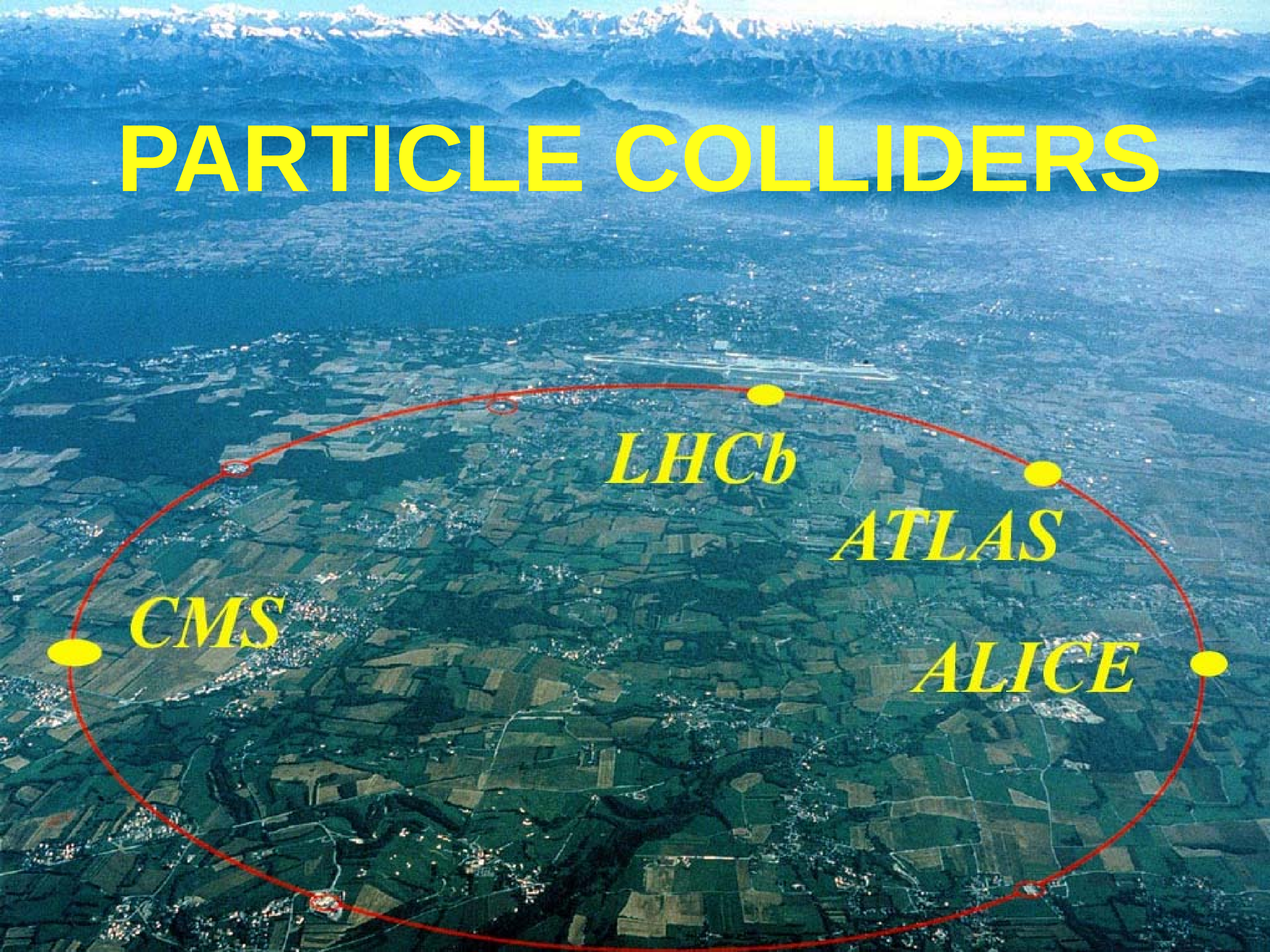
INDIRECT DETECTION: PHOTONS



Funk (2013)

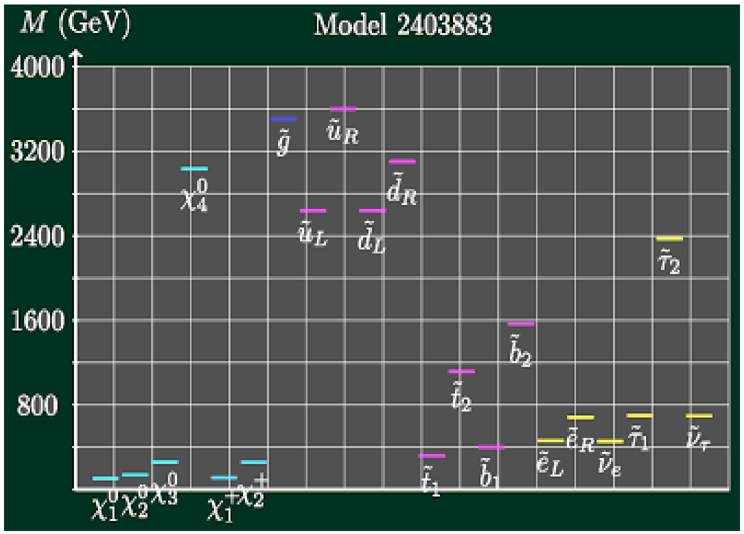
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV

PARTICLE COLLIDERS

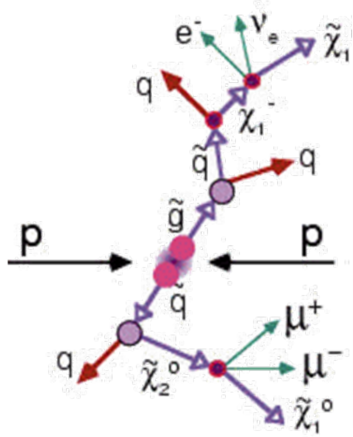


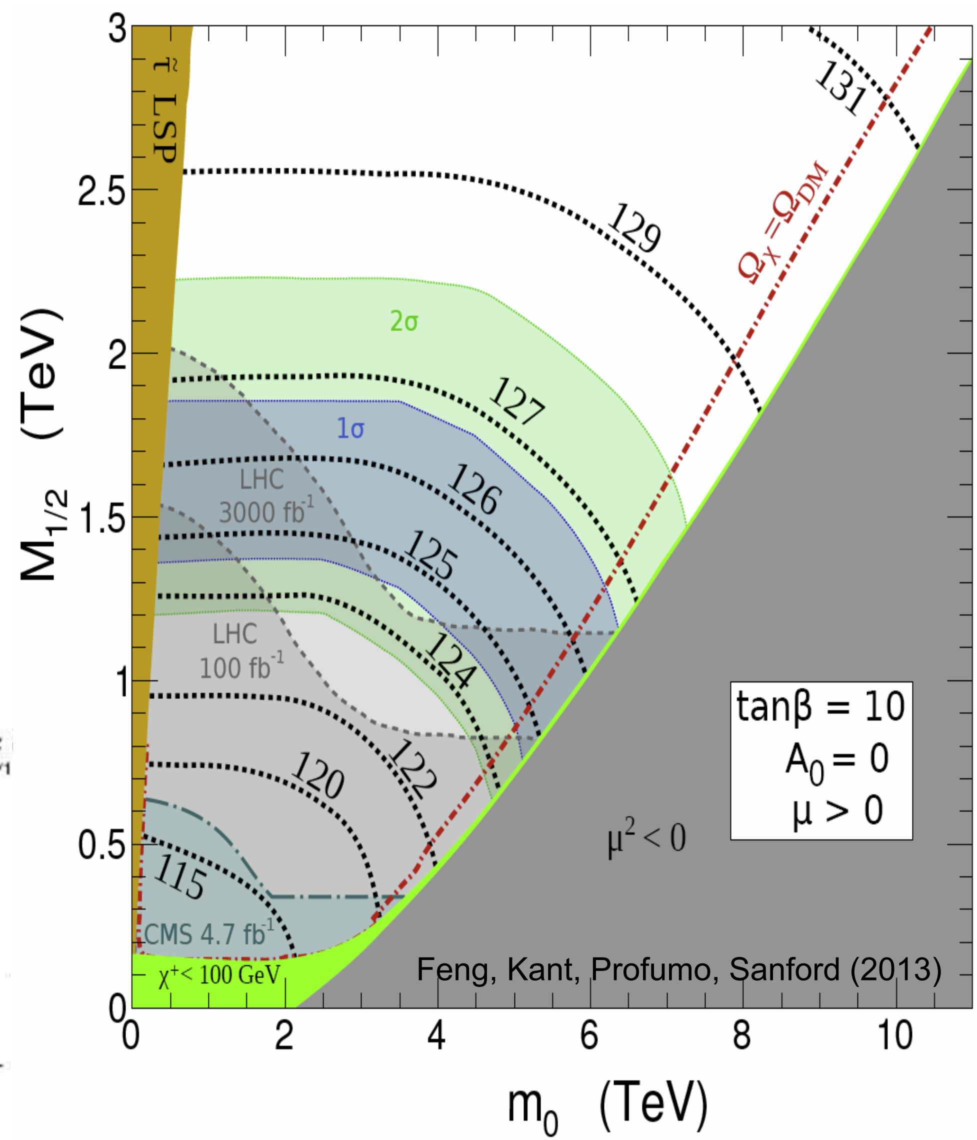
DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)



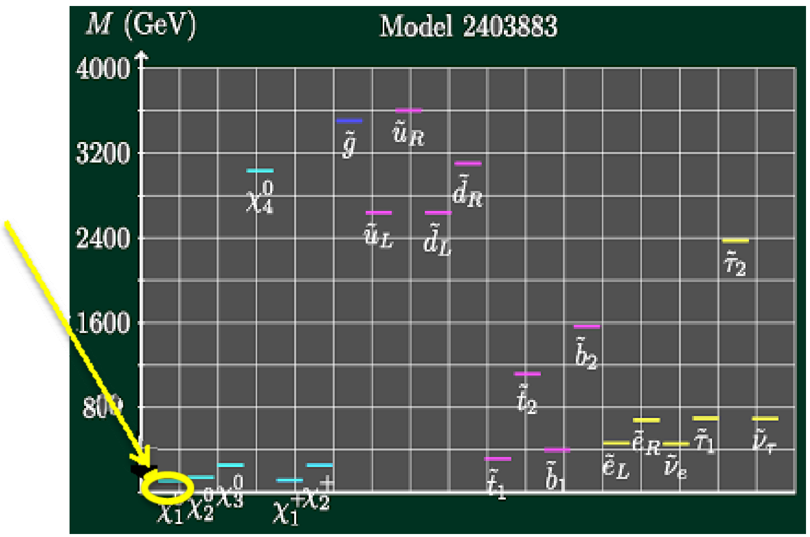
Cascades:
Produce other particles, which decay to DM

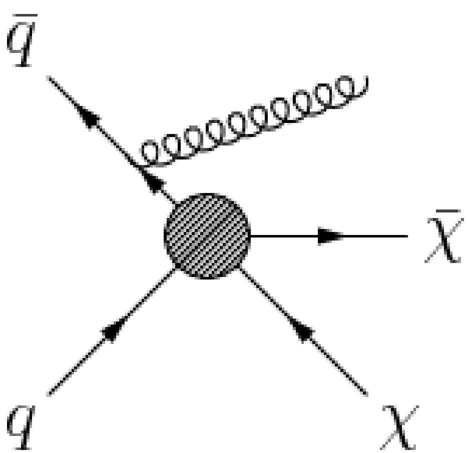




DARK MATTER AT COLLIDERS

DM Effective Theories





Alternatively, save energy by just producing DM directly

DM pair production is invisible, so must radiate something to "tag" the event

The DM relic density is tied to rates for

Mono-photons at e^+e^- colliders

Birkedal, Matchev, Perelstein (2004)

Mono-jets at the LHC

Feng, Su, Takayama (2005)

DM EFFECTIVE THEORY

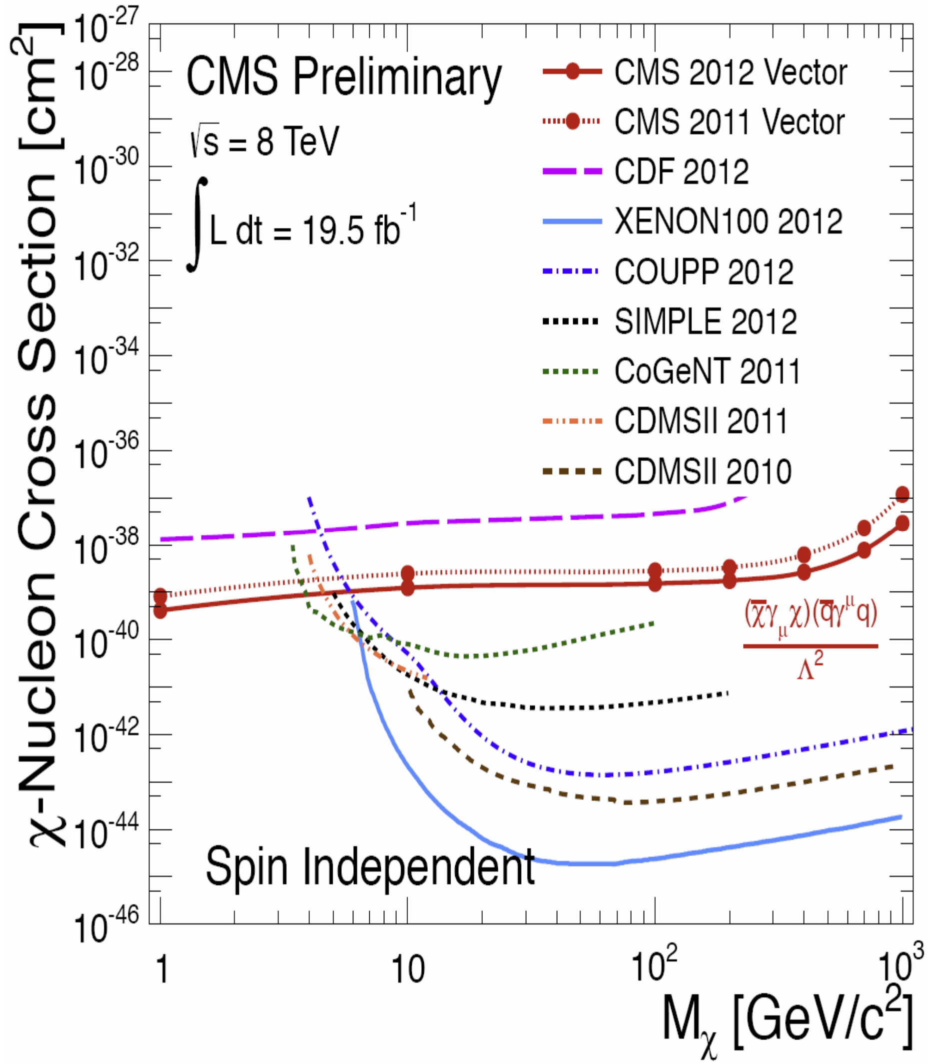
- This approach received a huge boost when hints of light DM motivated a hierarchy between the DM and mediator masses

Beltran, Hooper, Kolb, Krusberg, Tait (2006)
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)

- There is now a mono-γ,j,b,t,W,Z,h industry, probing dark matter at the LHC one operator at a time

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	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$

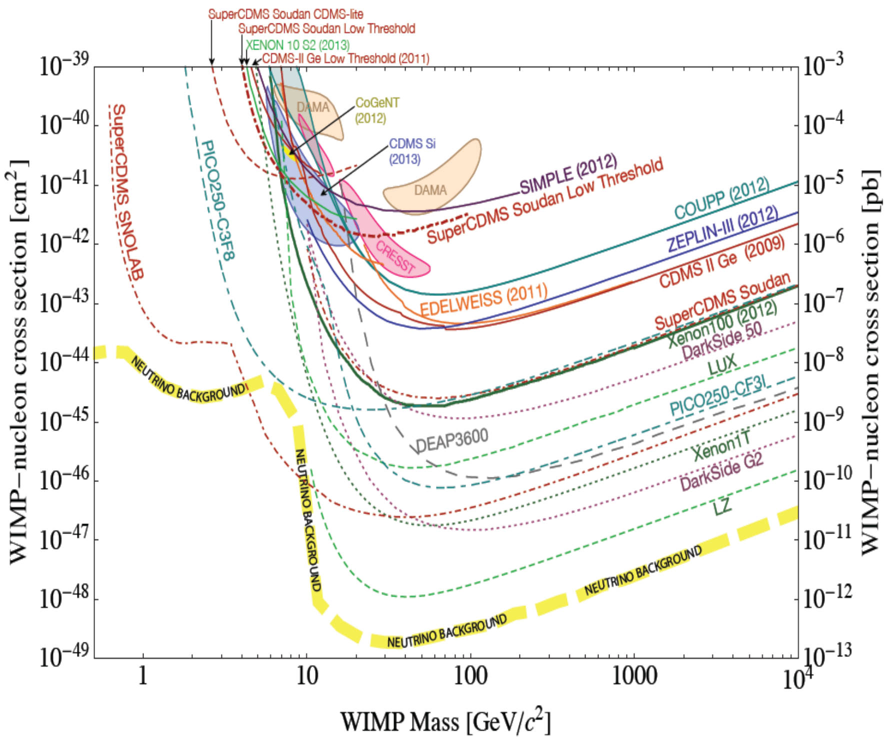
⋮



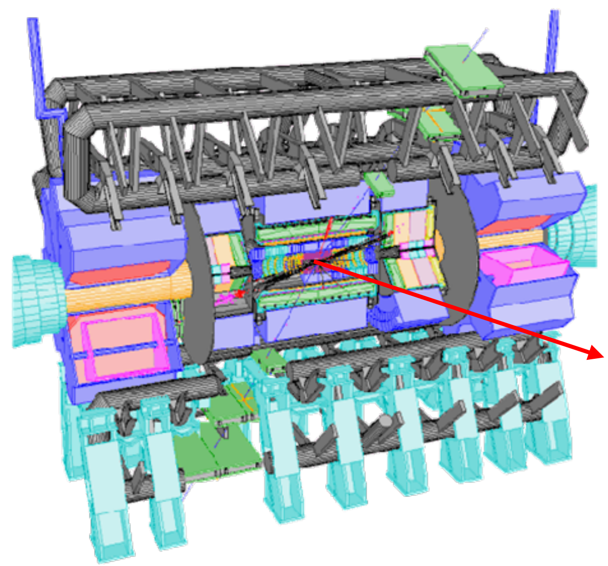
THE FUTURE

If there is a signal, what do we learn?

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



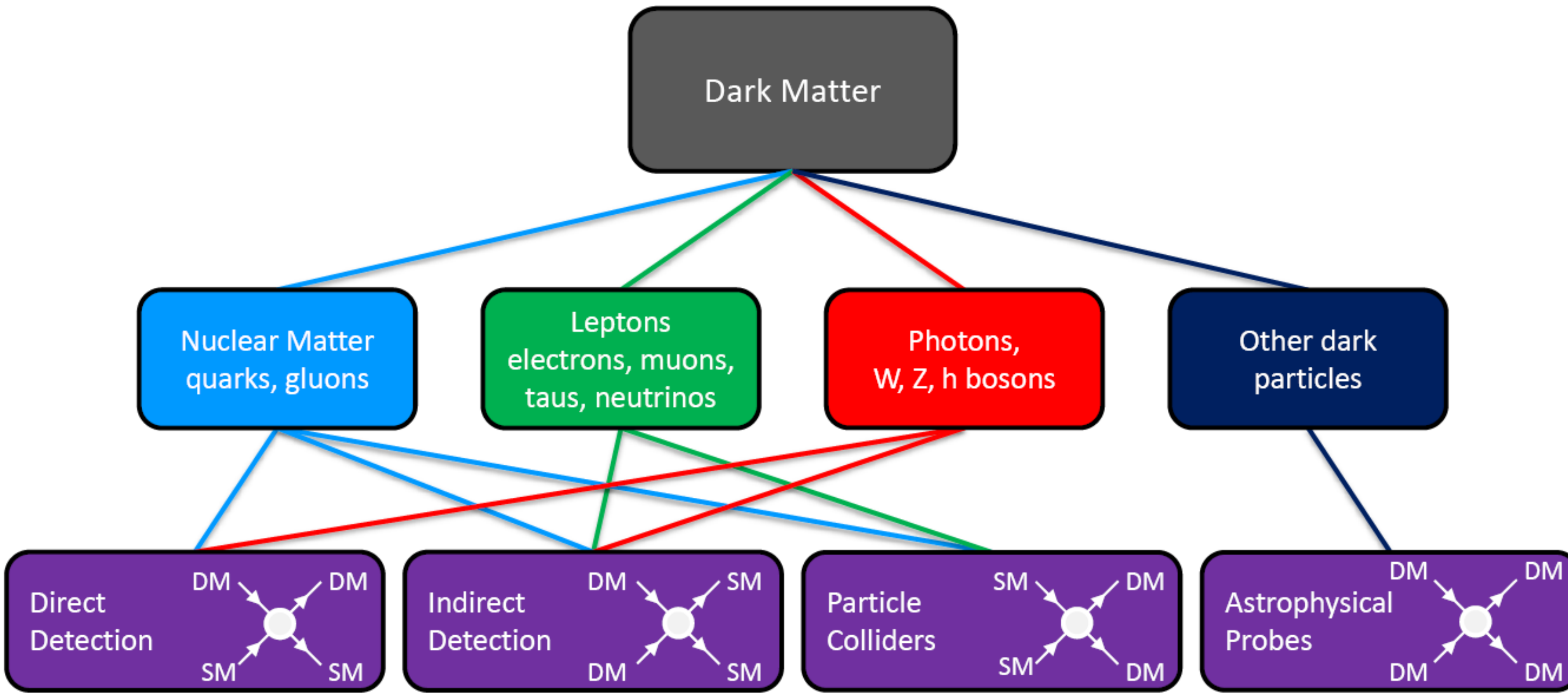
- Particle colliders can't prove it's DM



Lifetime > 10^{-7} s → 10^{17} s ?

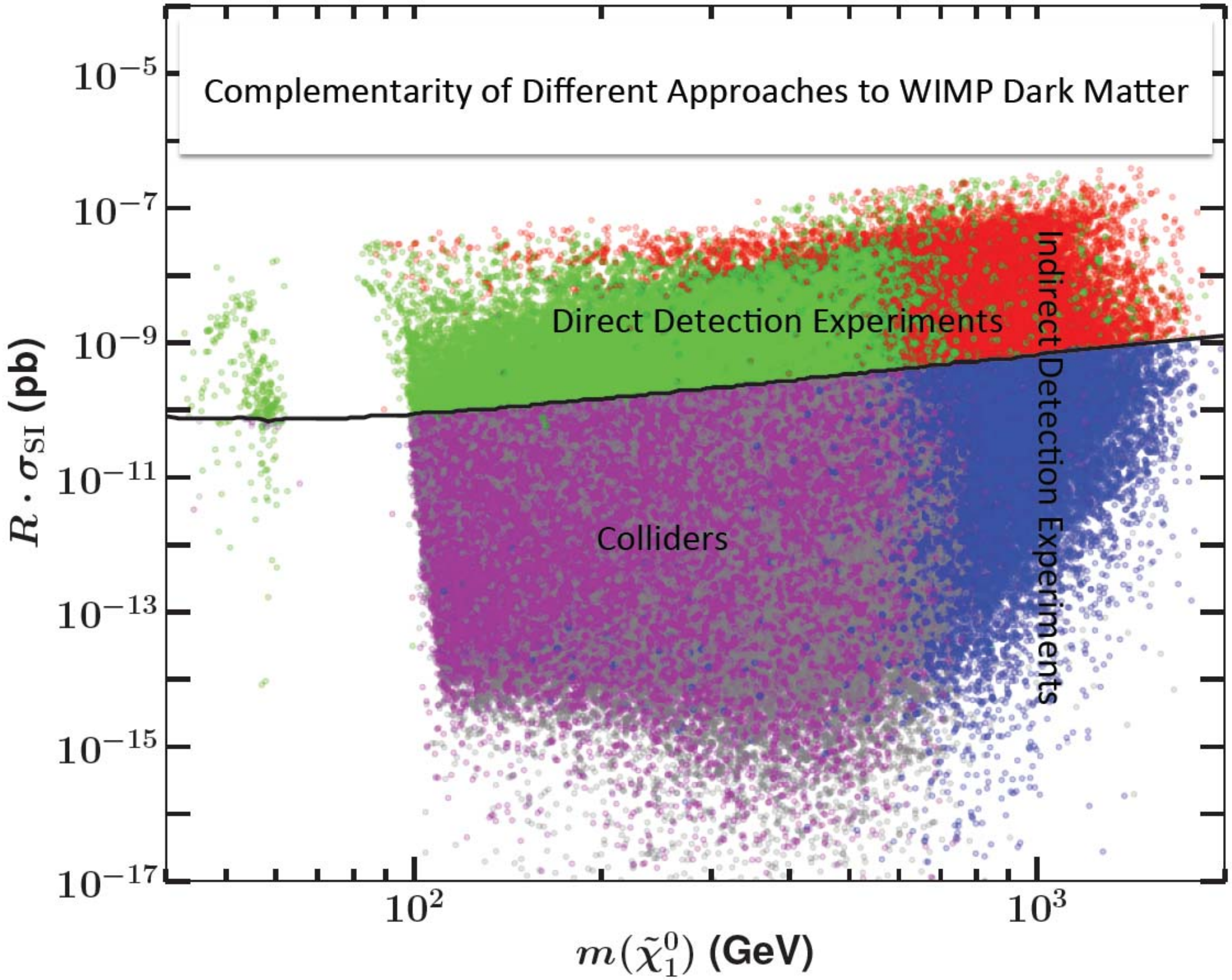
DARK MATTER COMPLEMENTARITY

- 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, …
  - Too much freedom: no connections to known problems, no WIMP miracle to guide experiments, …

THE WIMPLESS MIRACLE

Feng, Kumar (2008); Feng, Tu, Yu (2009); Feng, Shadmi (2011)

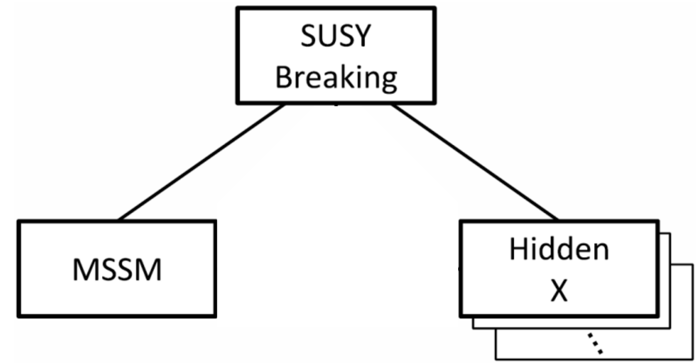
- Can we recover the WIMP miracle in a hidden sector?

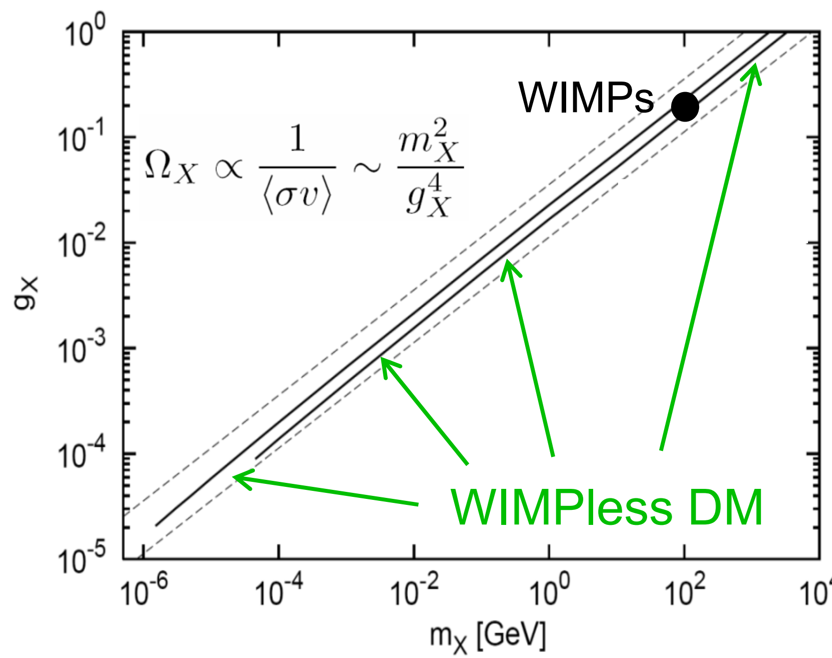
- Consider SUSY: in fact,in many SUSY models, to avoid unseen flavor effects, superpartner masses satisfy

$$m_X \sim g_X^2$$

- If this holds in a hidden sector, we have a "WIMPless Miracle": hidden sectors of these theories automatically have DM with the right Ω (but they aren't WIMPs)

- Is this what the new physics flavor problem is telling us?





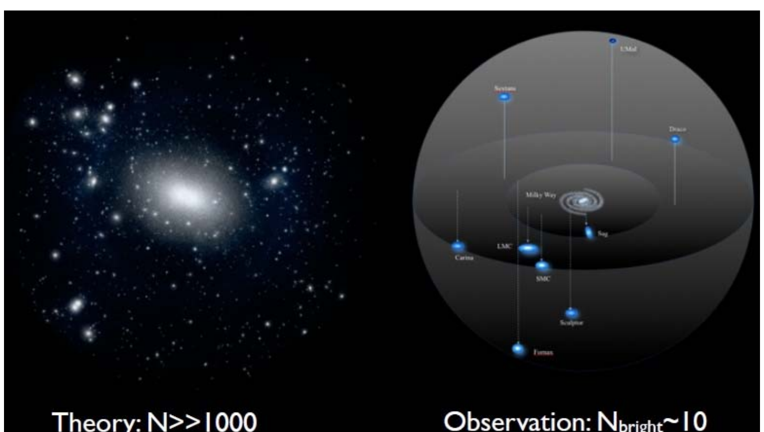
SELF-INTERACTING DARK MATTER

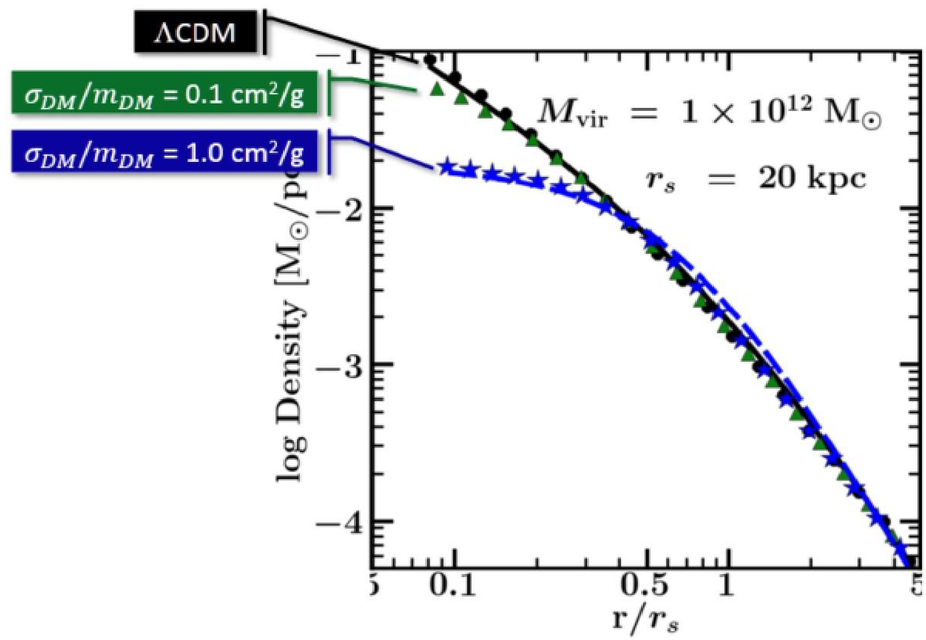
- If dark matter is completely hidden, can we learn anything about it?

- The Bullet Cluster provided evidence for dark matter. But the fact that dark matter passed through unperturbed →

  $\sigma_T/m < 1\ cm^2/g$ (~ 1 barn/GeV)

- But there are indications that the self-interactions may be near this limit
  - Cusps vs. cores
  - Number of visible dwarf galaxies



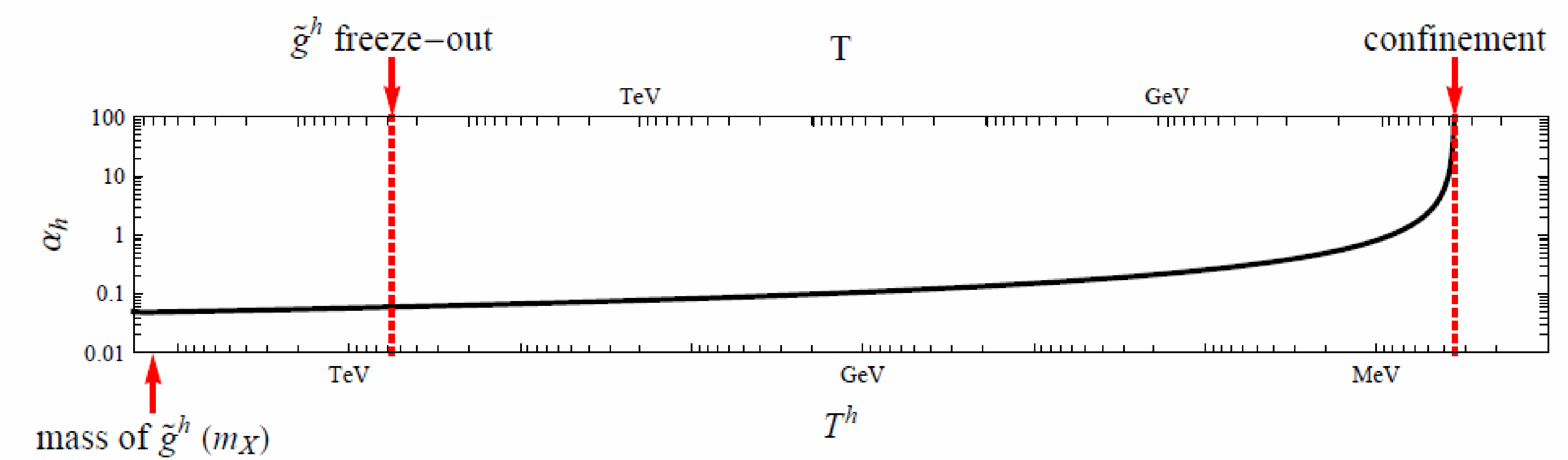


A SIMPle THEORY OF DARK MATTER

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, ~10 TeV $\tilde{g}$ freezeout with correct Ω

  At late times, interaction is strong, glueballs (gg) and glueballinos ($g\tilde{g}$) form and self-interact with σ_T/m ~ 1 cm^2/g ~ 1 barn/GeV



- Realizes WIMPless miracle: TeV-masses with correct thermal relic density
- But self-interacting (and predicts a keV line, which may have been seen)

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