DARK MATTER AND ITS PARTICLE PROPERTIES

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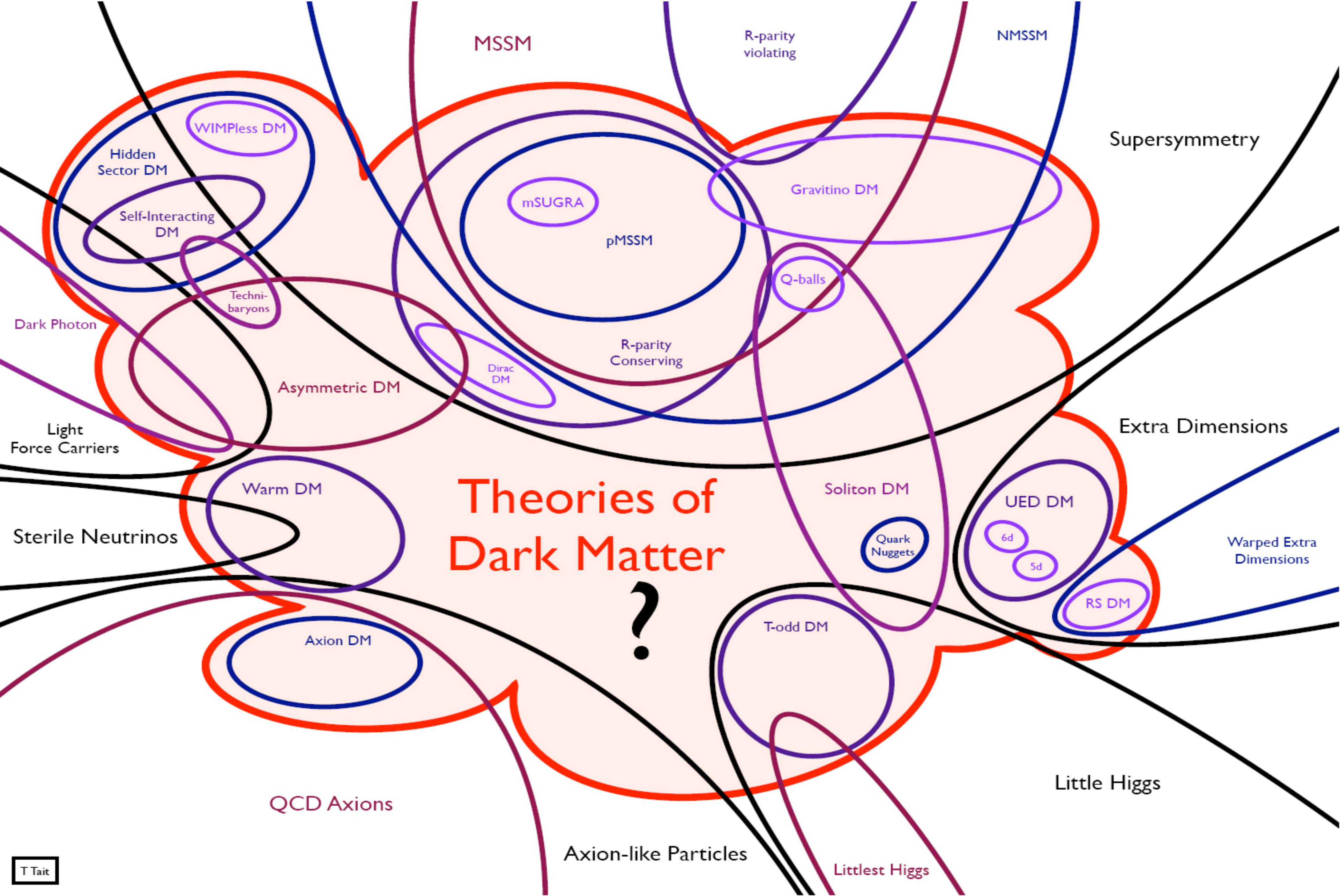
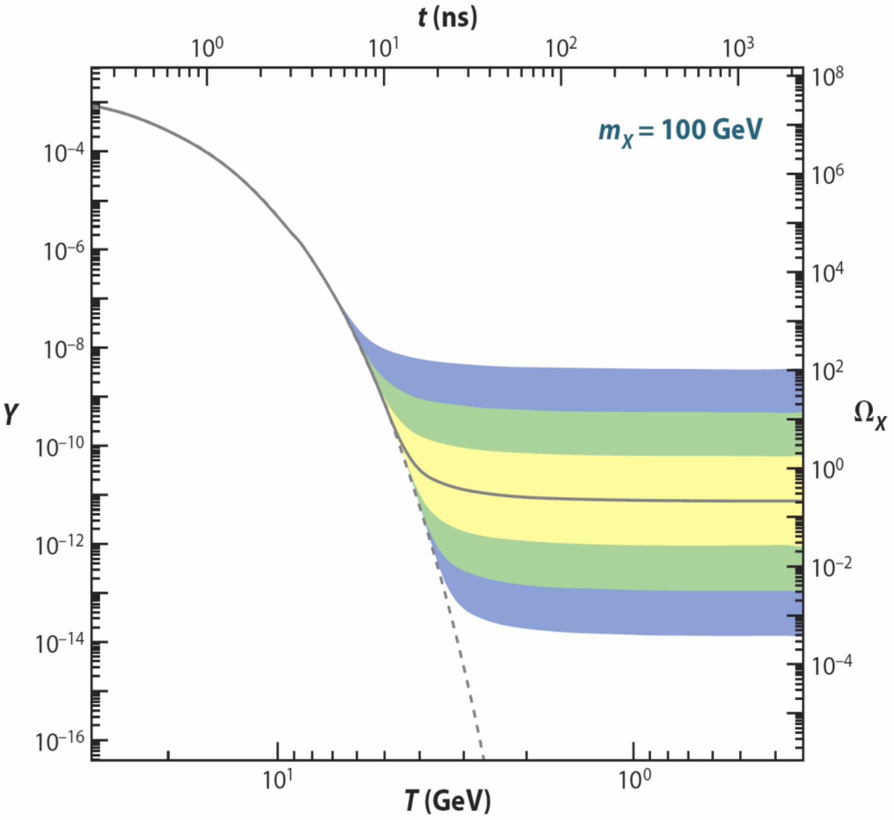
DARK MATTER CANDIDATES



OUTLINE

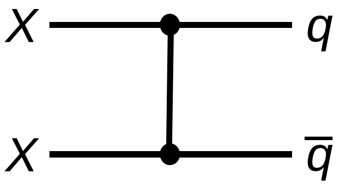
- WIMPs
  - Symmetric and Asymmetric
  - Direct Detection
  - Indirect Detection
  - Colliders
  - Complementarity
- Axions
- Warm Dark Matter
  - Sterile Neutrinos
  - SuperWIMPs
- Self-Interacting Dark Matter
  - Hidden Sector Dark Matter

THE WIMP MIRACLE



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

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

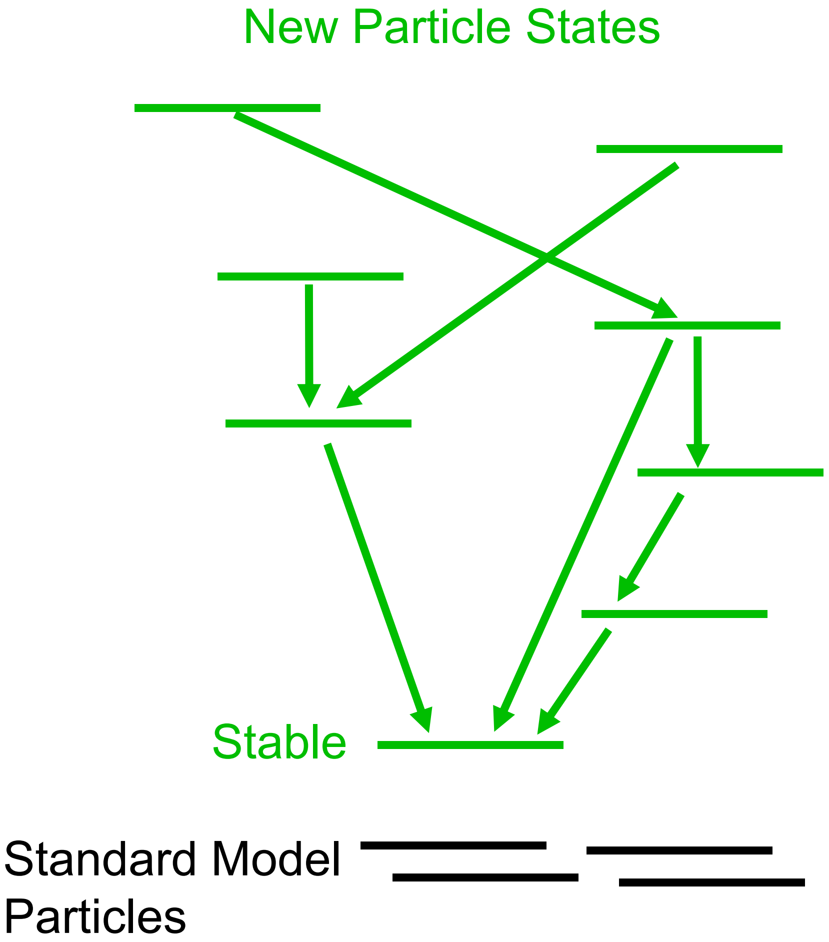


- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

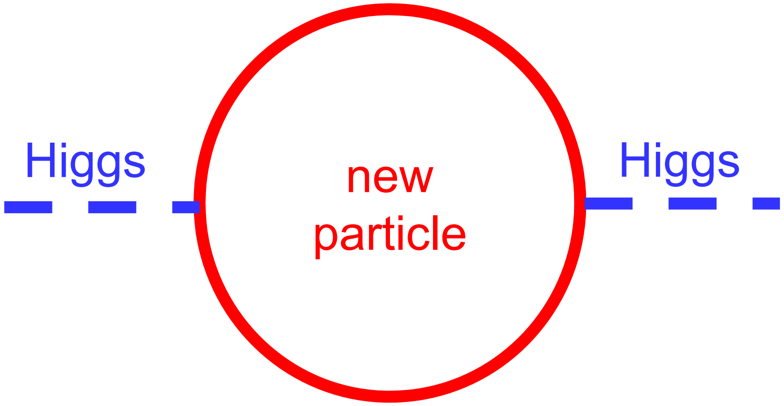
STABILITY

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

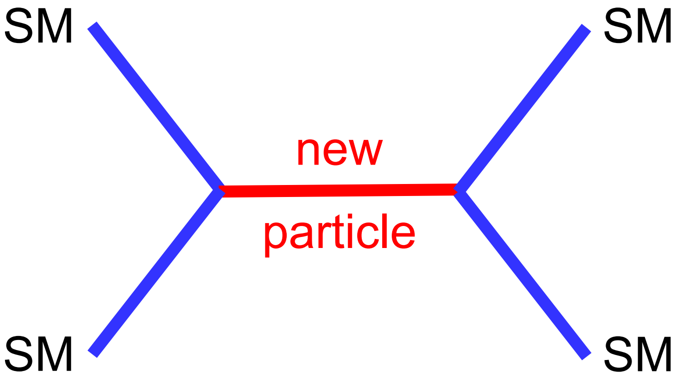


LEP'S COSMOLOGICAL LEGACY

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, motivates DM with $m_{DM} \sim 5$ GeV

ASYMMETRIC DARK MATTER

- The SM matter relic density was not generated by freeze-out, but by an asymmetry

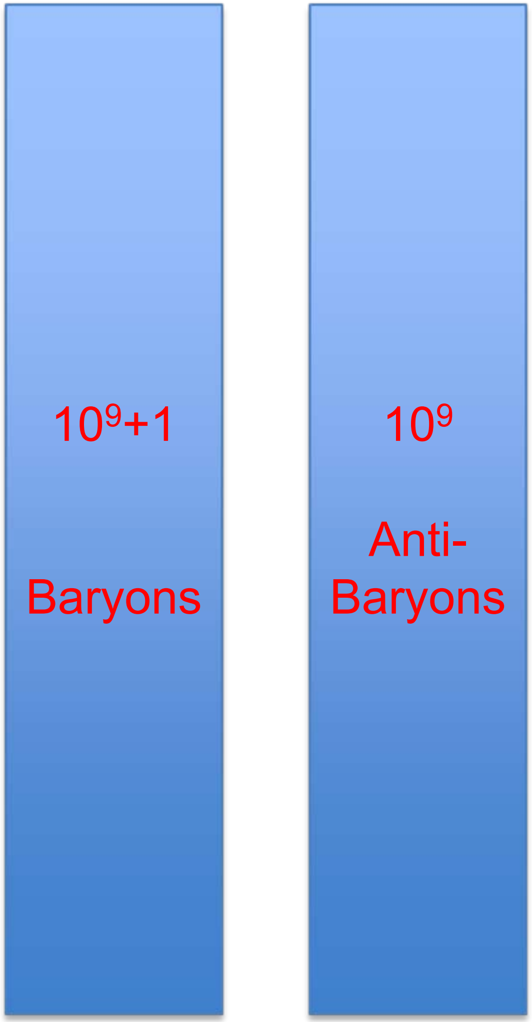
- If the dark matter relic density was generated in a similar way

$$n_{DM} \sim n_B$$

$$\downarrow$$

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

Asymmetric DM motivates “light WIMPs” with $m_{DM} \sim 5$ GeV



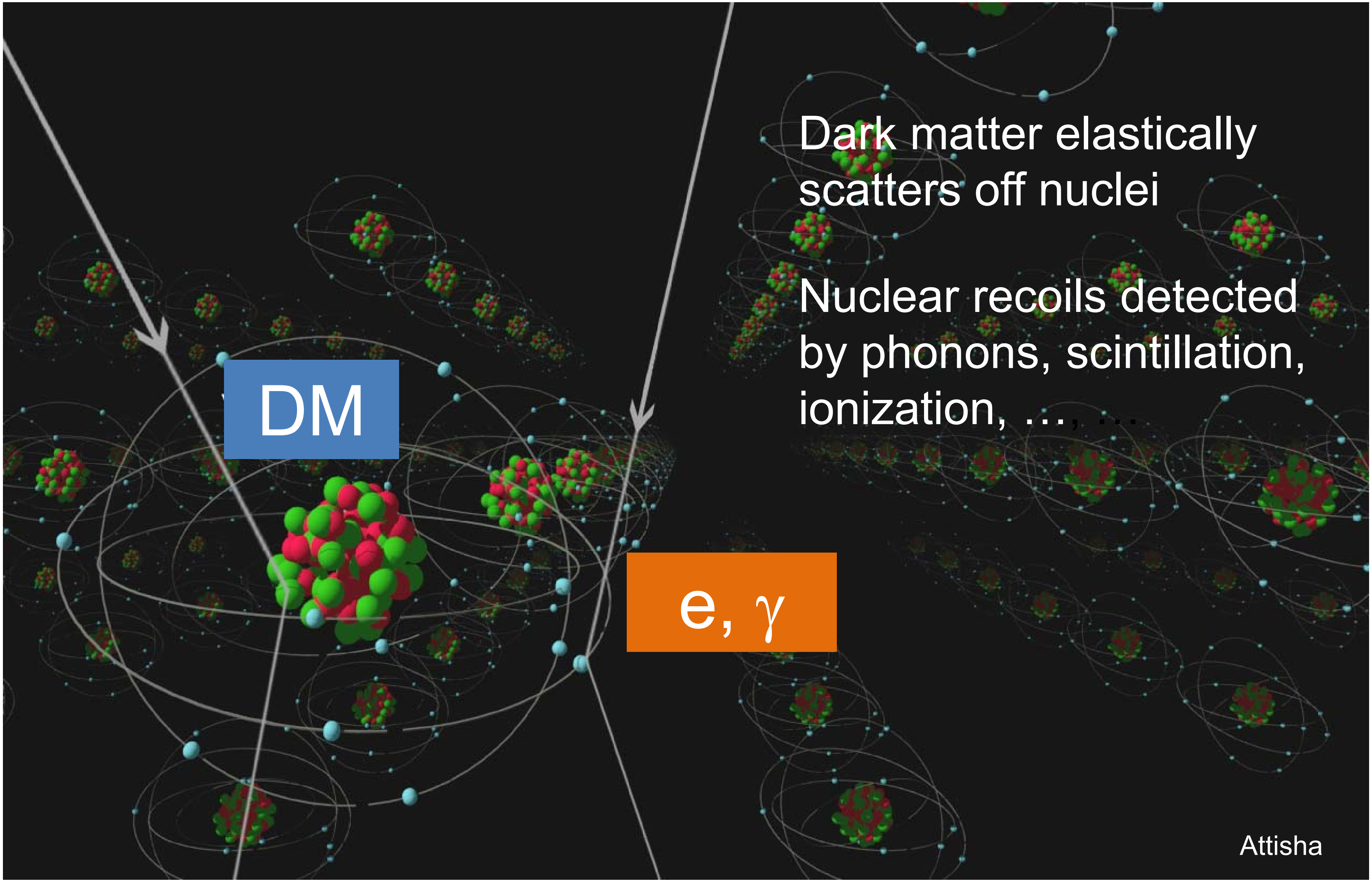
10^9+1

Baryons

10^9

Anti-Baryons

DIRECT DETECTION

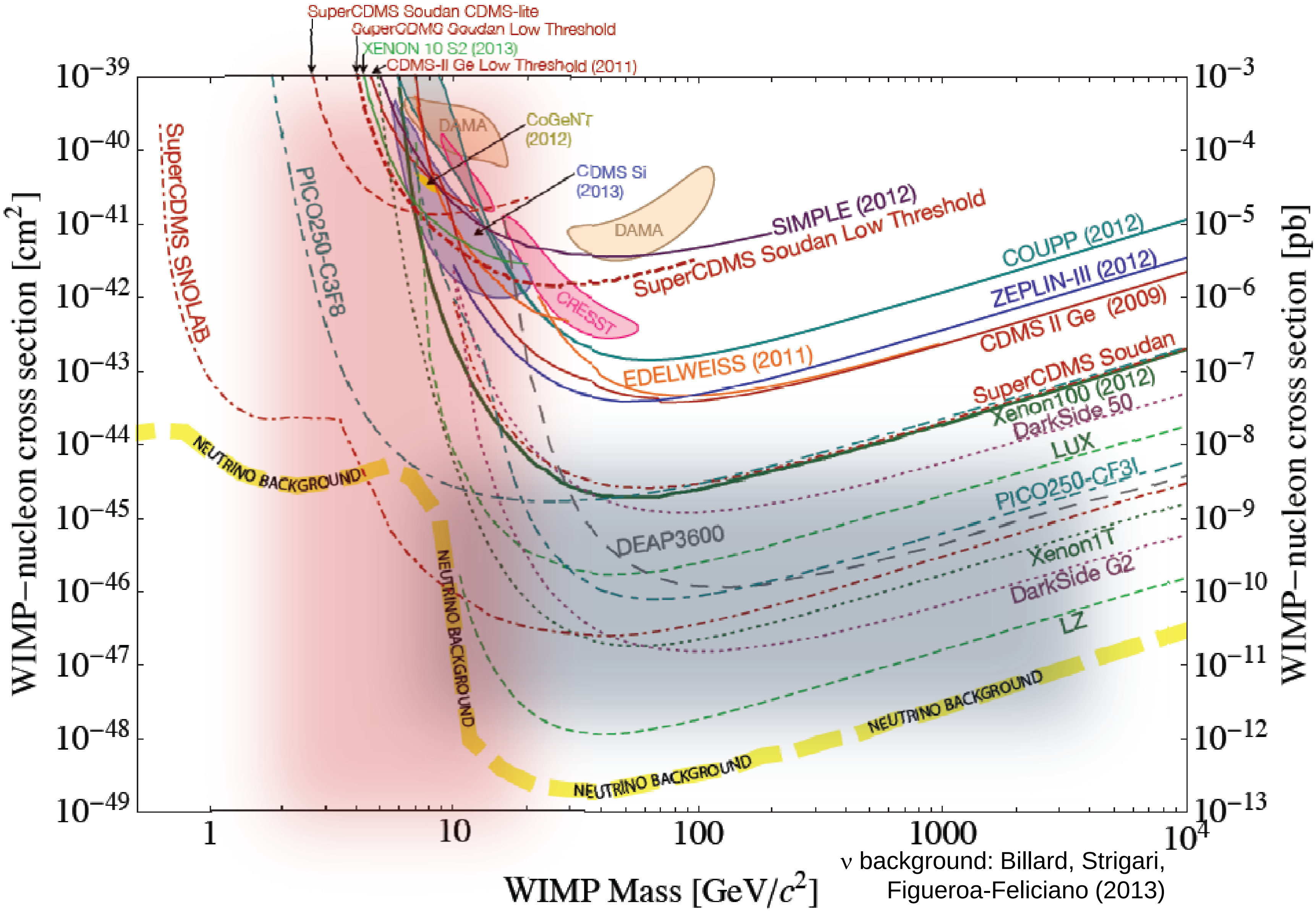


Dark matter elastically scatters off nuclei

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

Attisha

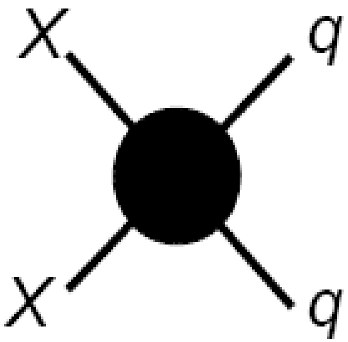
CURRENT STATUS AND FUTURE PROSPECTS



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

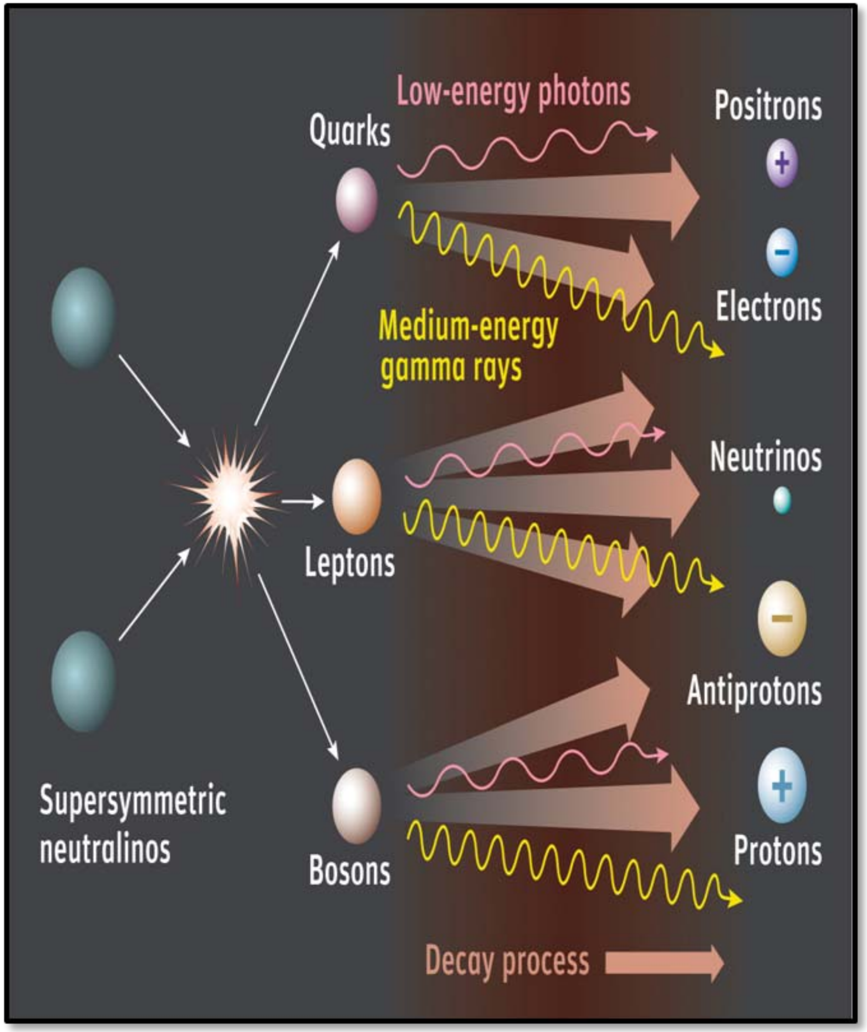
INDIRECT DETECTION

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



- The relic density provides a target annihilation cross section

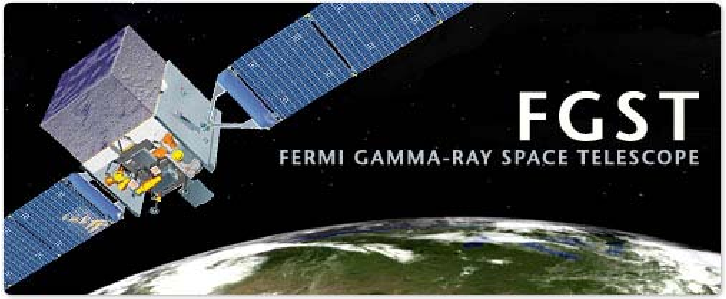
$$\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

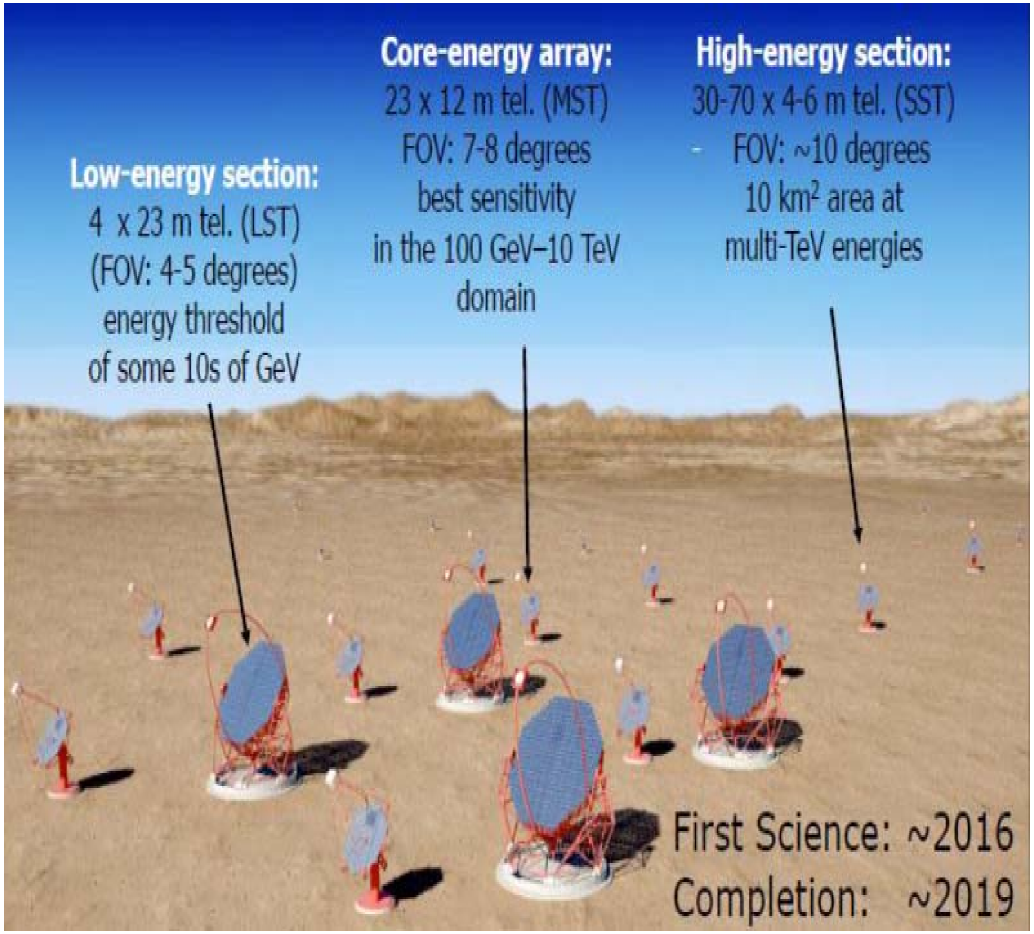


AN EXAMPLE: PHOTONS

Current: Veritas, Fermi-LAT, HAWC, Magic, HESS, …

Future: Cerenkov Telescope Array (CTA)





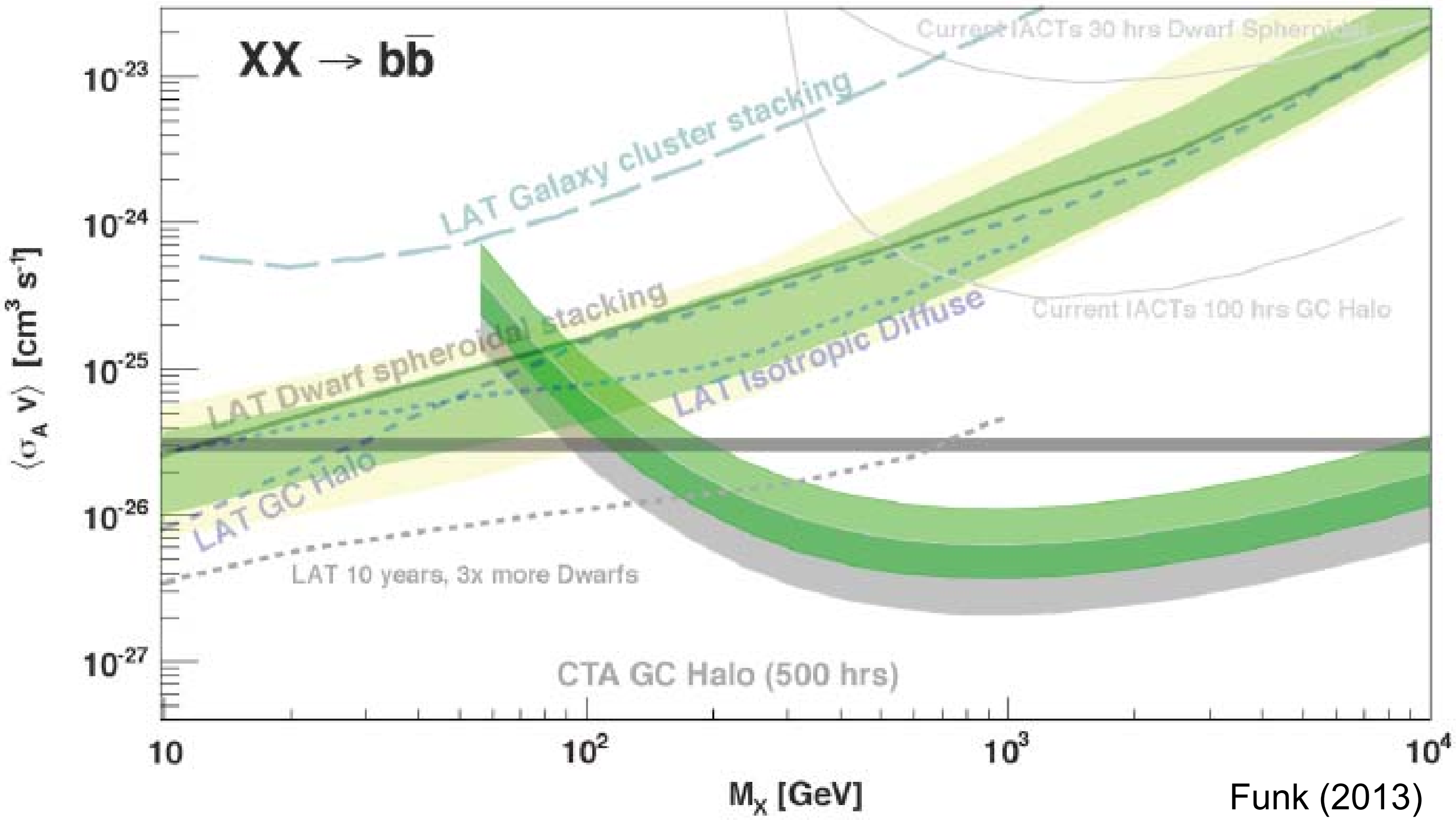
Low-energy section:
4 x 23 m tel. (LST)
(FOV: 4-5 degrees)
energy threshold
of some 10s of GeV

Core-energy array:
23 x 12 m tel. (MST)
FOV: 7-8 degrees
best sensitivity
in the 100 GeV–10 TeV
domain

High-energy section:
30-70 x 4-6 m tel. (SST)
- FOV: ~10 degrees
10 km^2 area at
multi-TeV energies

First Science: ~2016
Completion: ~2019

INDIRECT DETECTION: PHOTONS

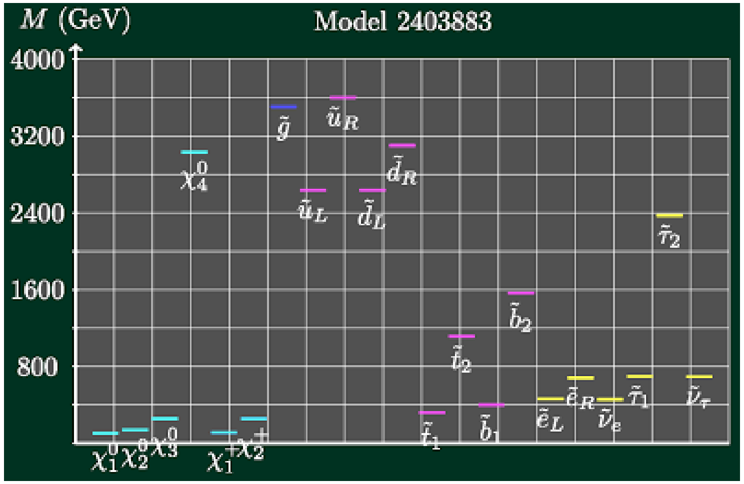


Funk (2013)

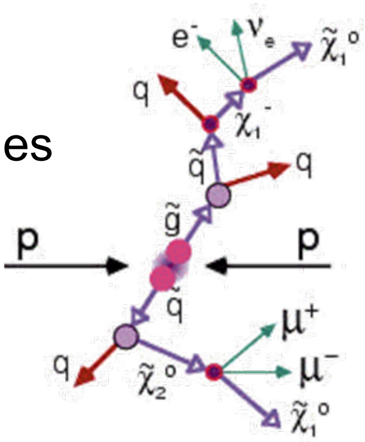
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV

DARK MATTER AT COLLIDERS

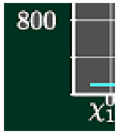
- Full Models (e.g., pMSSM Supersymmetry)



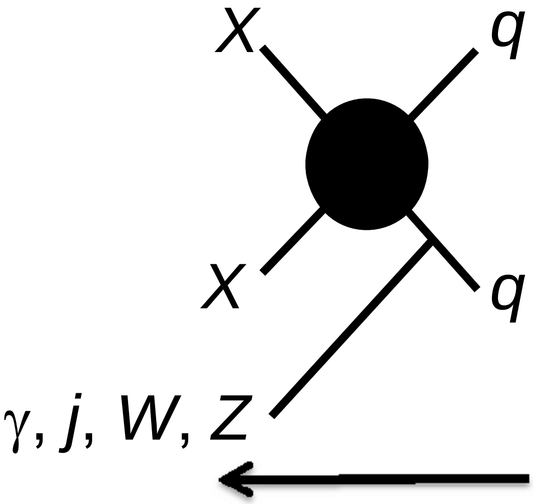
Cascades



- DM Effective Theories (Bare Bones Dark Matter)

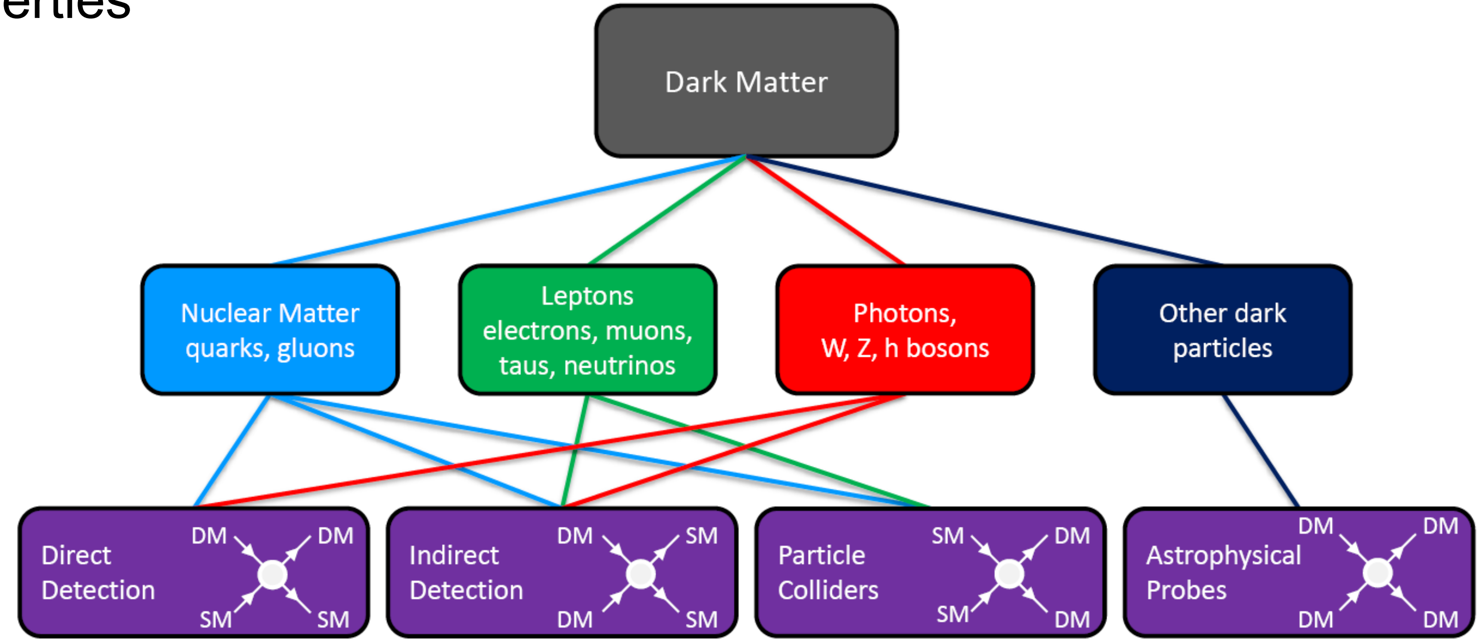


Mono-whatever



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



Dark Matter

Nuclear Matter
quarks, gluons

Leptons
electrons, muons,
taus, neutrinos

Photons,
W, Z, h bosons

Other dark
particles

Direct
Detection

Indirect
Detection

Particle
Colliders

Astrophysical
Probes

Mass measurement
for m > 500 GeV?

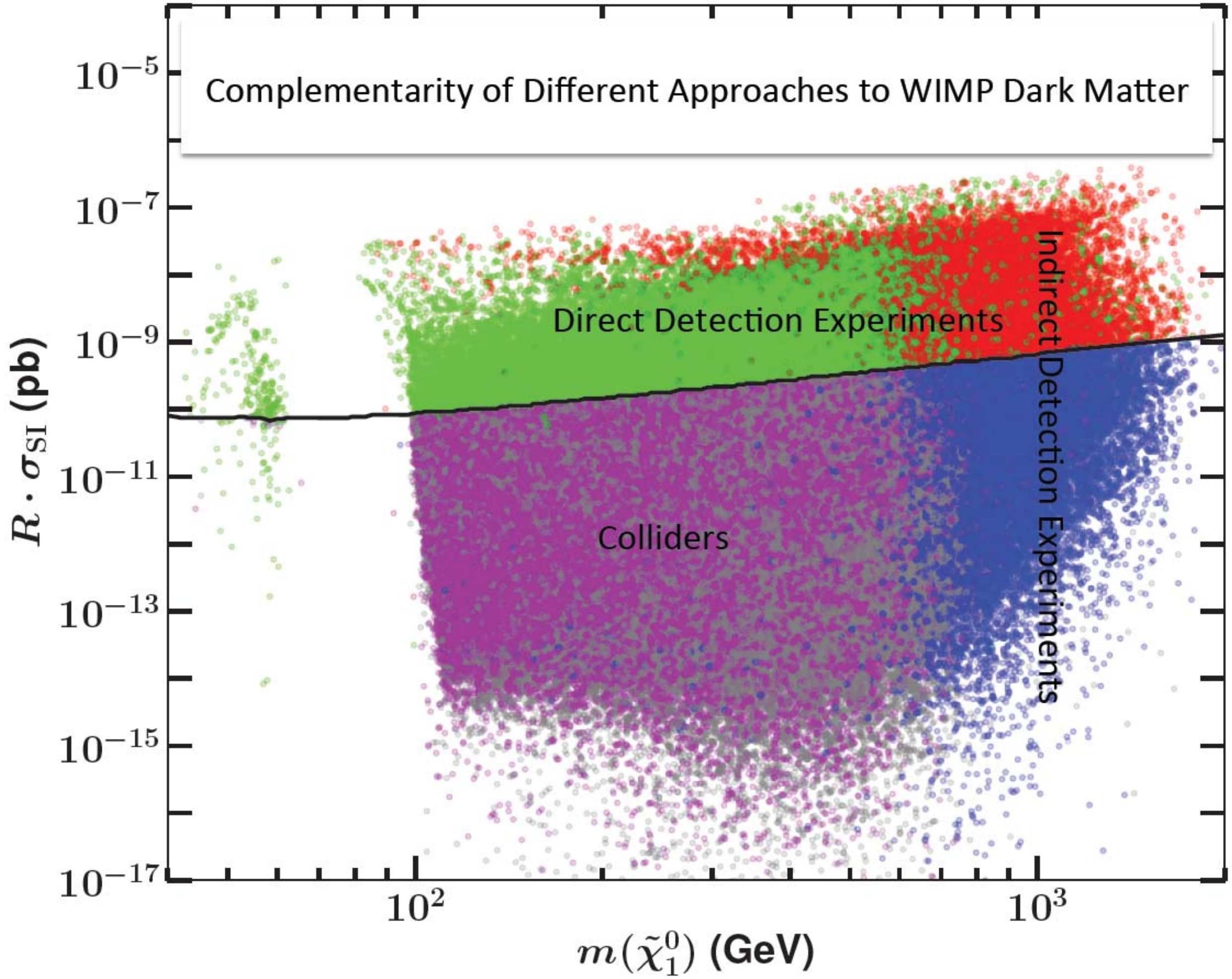
Asymmetric DM?

Lifetime:
10^{-7} s → 10^{17} s?

Detailed
particle properties?

COMPLEMENTARITY: FULL MODELS

pMSSM 19-parameter scan of SUSY parameter space



Cahill-Rowley et al. (2013)

Different SUSY models are probed by different experiments

AXIONS

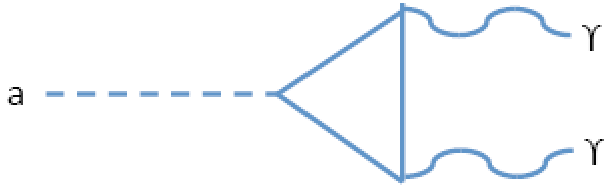
- Strongly motivated by the strong CP problem

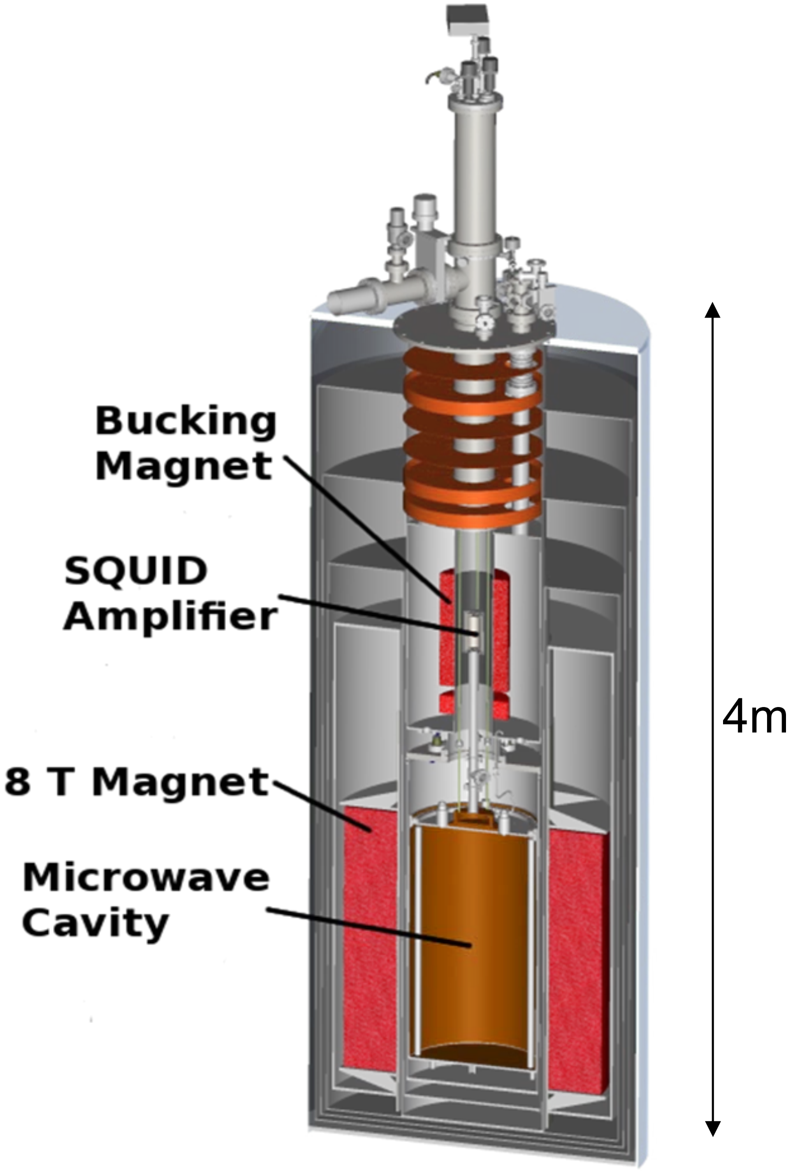
$$\theta_{\rm CP} \frac{g_3^2}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^\alpha_{\mu\nu} G^\alpha_{\rho\sigma}$$

- Current bound from electric dipole moments is

$$\theta_{\rm CP} < 10^{-10}$$

- Motivates introduction of the axion field, which couples to two photons



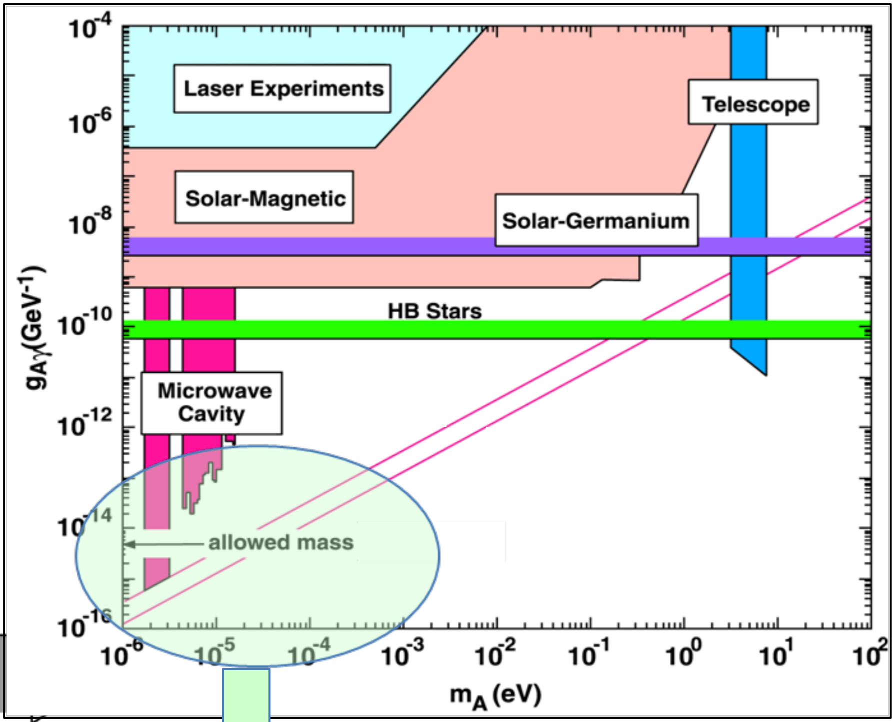


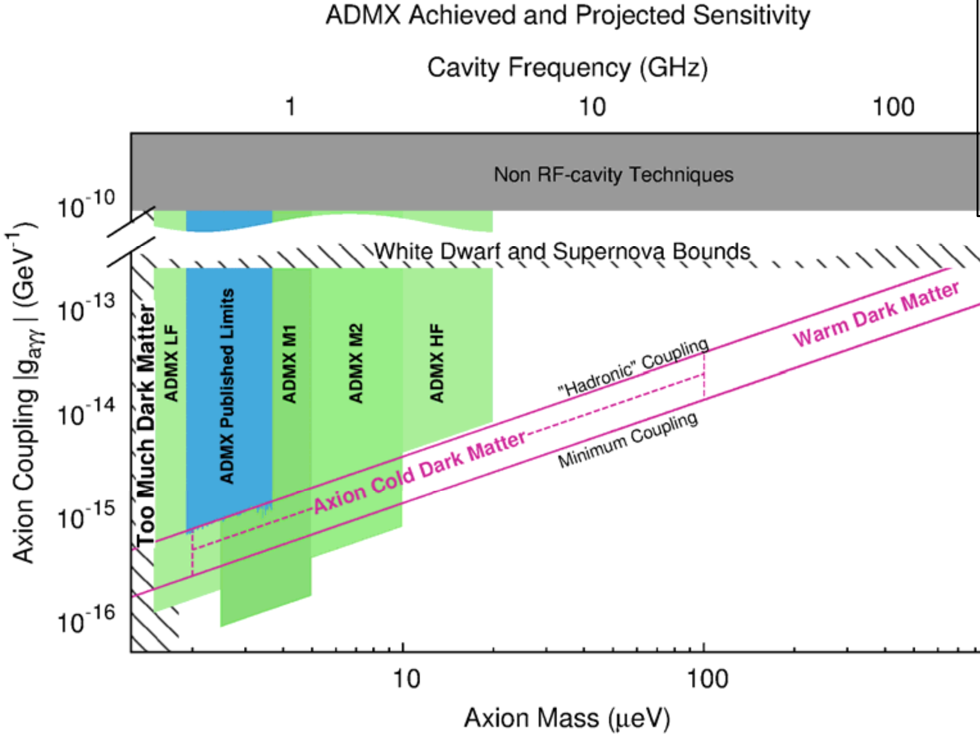
AXION PROPERTIES

Many production mechanisms, but all yield cold dark matter

Parameter space constrained by

- Supernova cooling, etc.
- Relic density
- Direct detection constraints




ADMX Achieved and Projected Sensitivity

- Favored mass: μeV to meV
- ADMX is projected to cover the first of these three decades in its first year of operations, and the second decade over the following two years

STERILE NEUTRINOS

- Strongly motivated by the fact that neutrinos have mass

$$\mathcal{L}_{\nu_R} = \bar{\nu}^\alpha i \not{D} \nu^\alpha - \left(\lambda^\nu_{i\beta} \bar{L}^i \nu^\beta \tilde{\phi} + \text{h.c.} \right) - \frac{1}{2} M_{\alpha\beta} \bar{\nu}^\alpha \nu^\beta$$

- No SM gauge interactions, but they mix with the active neutrinos

$$m_\nu = \begin{pmatrix} 0 & \lambda_{i\beta}\langle\phi\rangle \\ \lambda^*_{\alpha j}\langle\phi\rangle & M_{\alpha\beta} \end{pmatrix} \qquad \nu_s = \cos\theta\, \nu_R + \sin\theta\, \nu_L$$

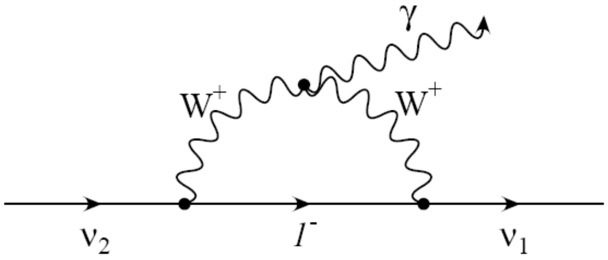
- Correct relic density for ~keV masses

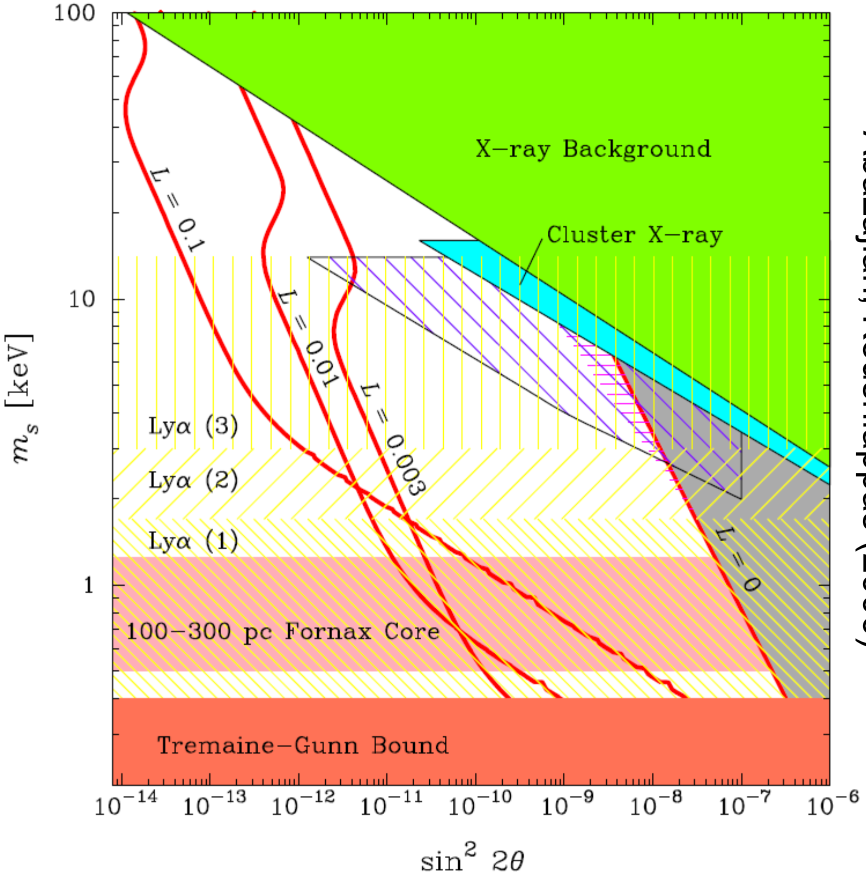
$$\Omega_{\nu_s} \approx 0.2 \frac{\sin^2 2\theta}{10^{-8}} \left[\frac{m_s}{3 \text{ keV}} \right]^{1.8}$$

STERILE NEUTRINO PROPERTIES

- Decays may be detected as X-ray lines

$$\Gamma(\nu_s \to \gamma\nu_a) = \frac{9\alpha}{2048\pi^4} G_F^2 \sin^2 2\theta\, m_s^5 \simeq \frac{1}{1.5\times 10^{32}\ \mathrm{s}} \frac{\sin^2 2\theta}{10^{-10}} \left[\frac{m_s}{\mathrm{keV}}\right]^5$$





Abazajian, Koushiappas (2006)

- May be warm dark matter, depending on mass and production mechanism

$$\lambda_{\mathrm{FS}} \approx R\,\frac{\mathrm{keV}}{m_s}$$

$$R = 0.9,\ 0.6,\ \text{and}\ 0.2\ \mathrm{Mpc}$$

Kusenko (2009)

HIDDEN SECTOR DARK MATTER

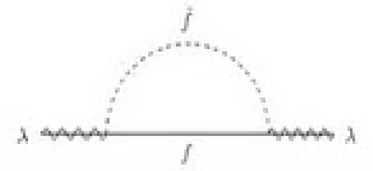
- Dark matter could be in a hidden “dark sector,” with no SM couplings; this is viable and perhaps even natural, since all solid evidence for DM is gravitational

- However, a priori, it’s a bit unsatisfying
  - Missing the particle physics motivations of many popular DM candidates
  - Too much model-building freedom, lack of predictivity
  - Makes no use of the WIMP miracle

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

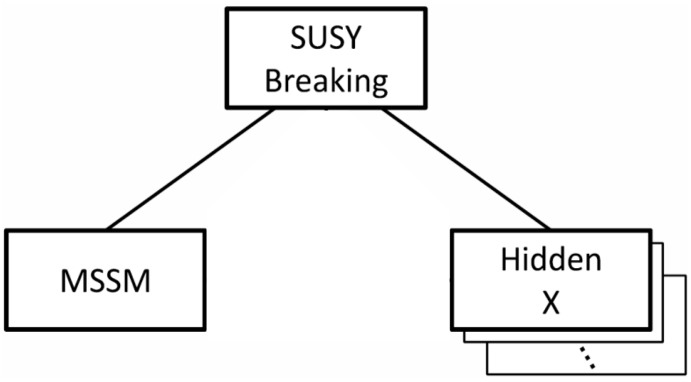
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

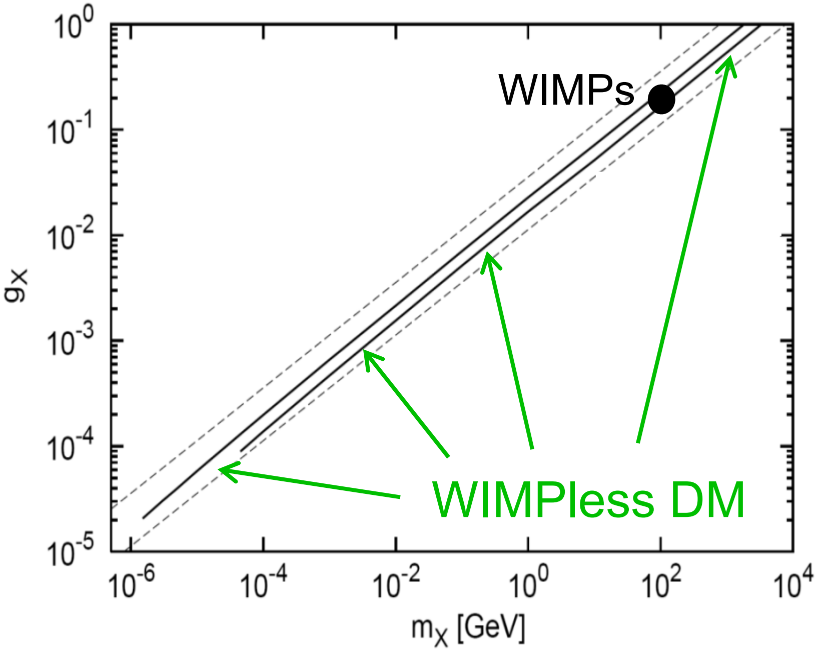


Restores

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

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





- 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

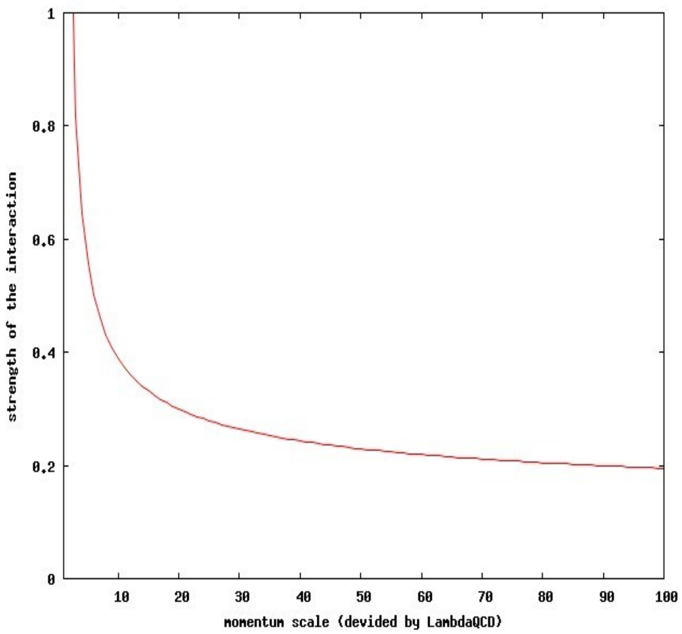
- A natural possibility to consider is a non-Abelian hidden sector with weak coupling at high scales and early times, and strong coupling at low scales now (cf. QCD)

Feng, Shadmi (2011)

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

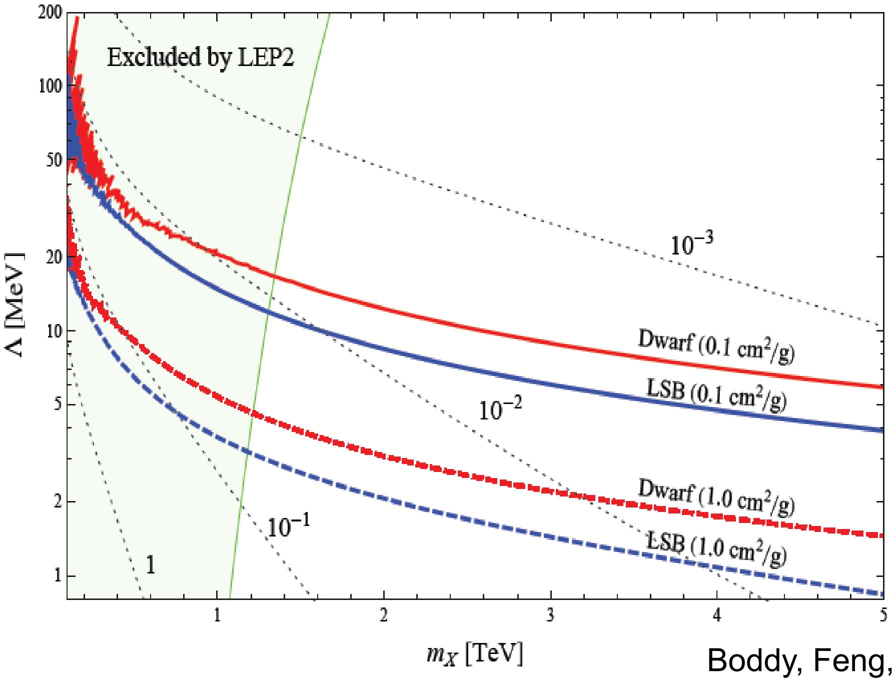
$$\sigma_T = \int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

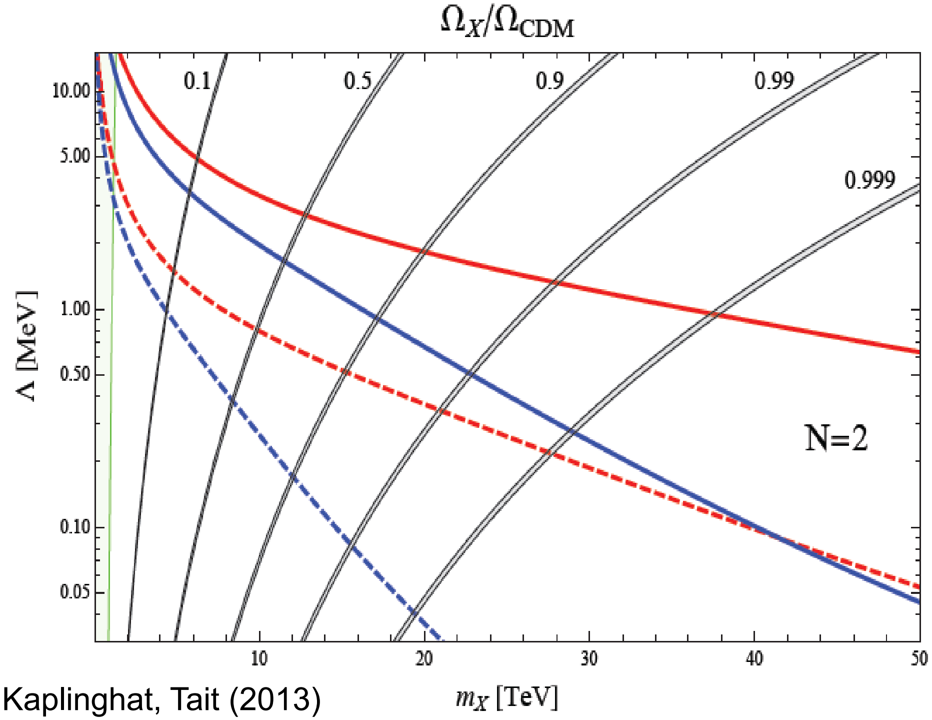
Feng, Kaplinghat, Yu (2010); Tulin, Yu, Zurek (2013)



SELF-INTERACTING DM FROM SU(N) HIDDEN SECTOR

- An extremely simple possibility: AMSB with a pure SU(N) hidden sector (just hidden gluons and gluinos)
  - ~1-10 TeV gluinos freezeout with the correct relic density
  - At Λ ~ 10 MeV, $(g\tilde{g})$ and (gg) bound states form
  - $(g\tilde{g})$ dark matter strongly self-interacts through (gg) exchange





Boddy, Feng, Kaplinghat, Tait (2013)

SUMMARY

- Many interesting dark matter candidates
- Vanilla WIMPs are still very well motivated, as are other cold dark matter candidates, such as axions
- But there are also well-motivated warm dark matter candidates and self-interacting dark matter candidates
- Astrophysics may motivate specific candidates and provides unique probes of particle properties