DARK MATTER – THEORY

Cosmic Opportunities – 45th SLAC Summer Institute

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INTRODUCTION

We've learned a lot about the Universe

- Dark Matter: 23% ± 4%
- Dark Energy: 73% ± 4%
- Normal Matter: 4% ± 0.4%
- Neutrinos: 0.2% (Σm_ν/0.1 eV)

But there is still a lot missing. In particular dark matter implies

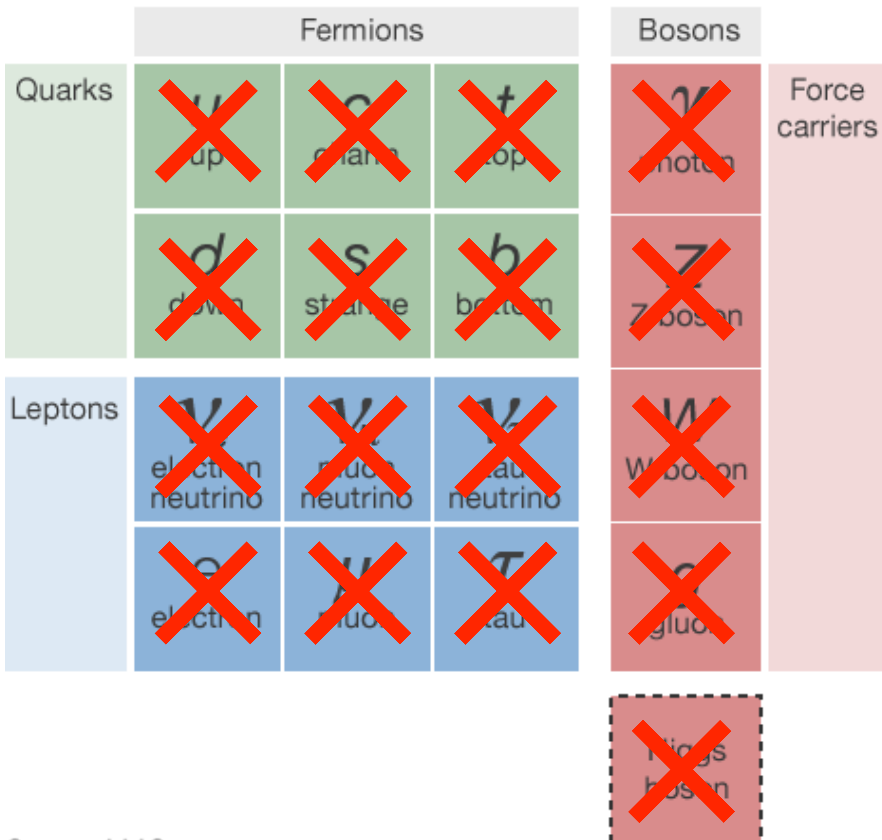
- There is a big problem with our standard theory of particle physics, or
- There is a big problem with our standard theory of gravity,
- Or both!

Here assume new particle physics is part of the answer

See McGaugh talk

DARK MATTER

See Frieman, Olive talks



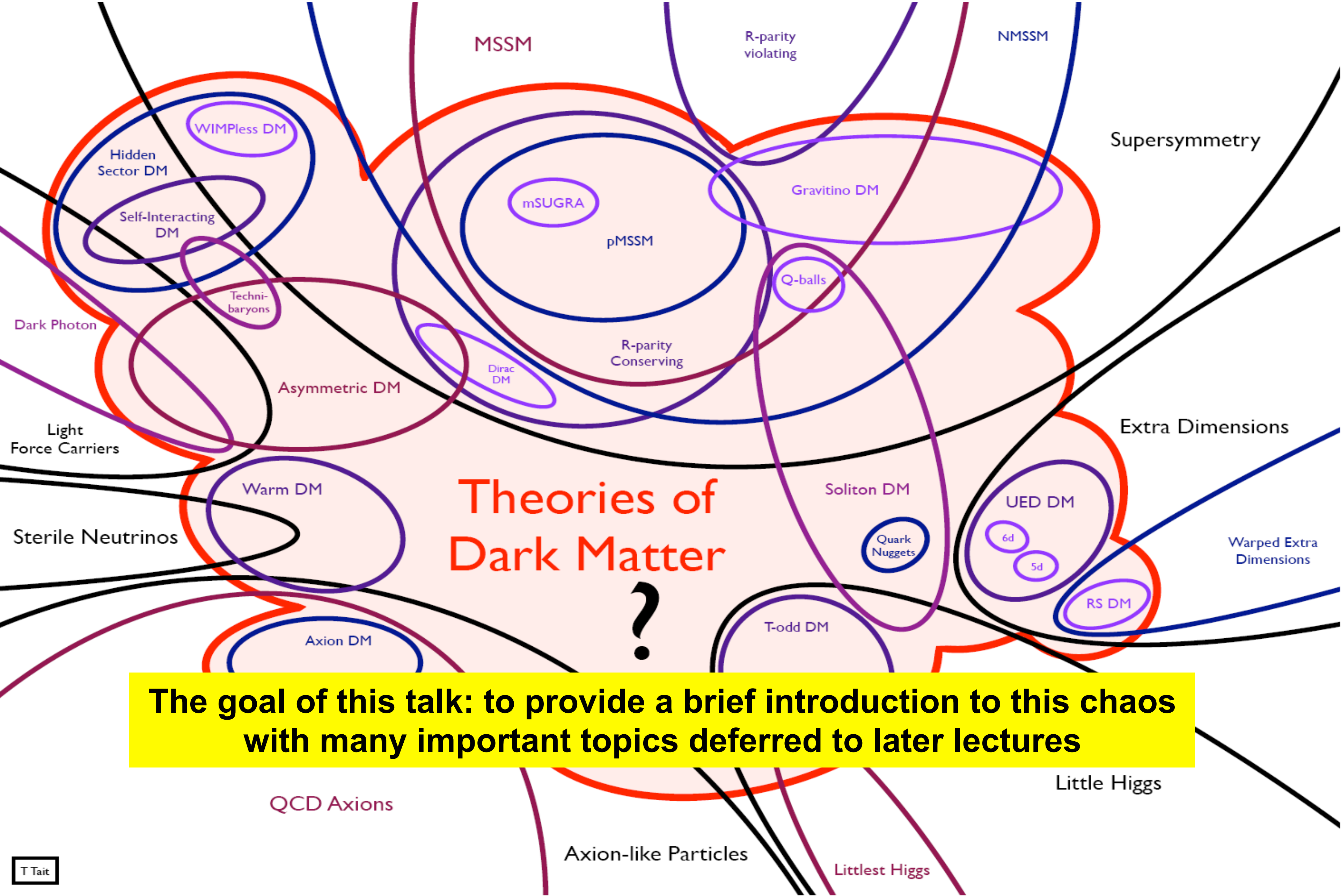
Source: AAAS

Known DM properties

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

None of the known particles can be cold DM

SO WHAT COULD DARK MATTER BE?



The goal of this talk: to provide a brief introduction to this chaos with many important topics deferred to later lectures

THE WEAK SCALE

Much of the attention has focused on WIMPs. Why?

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

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

- $G_F \sim 10^{-5}$ 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

FREEZE OUT: QUALITATIVE

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

$$XX \leftrightarrow qq$$

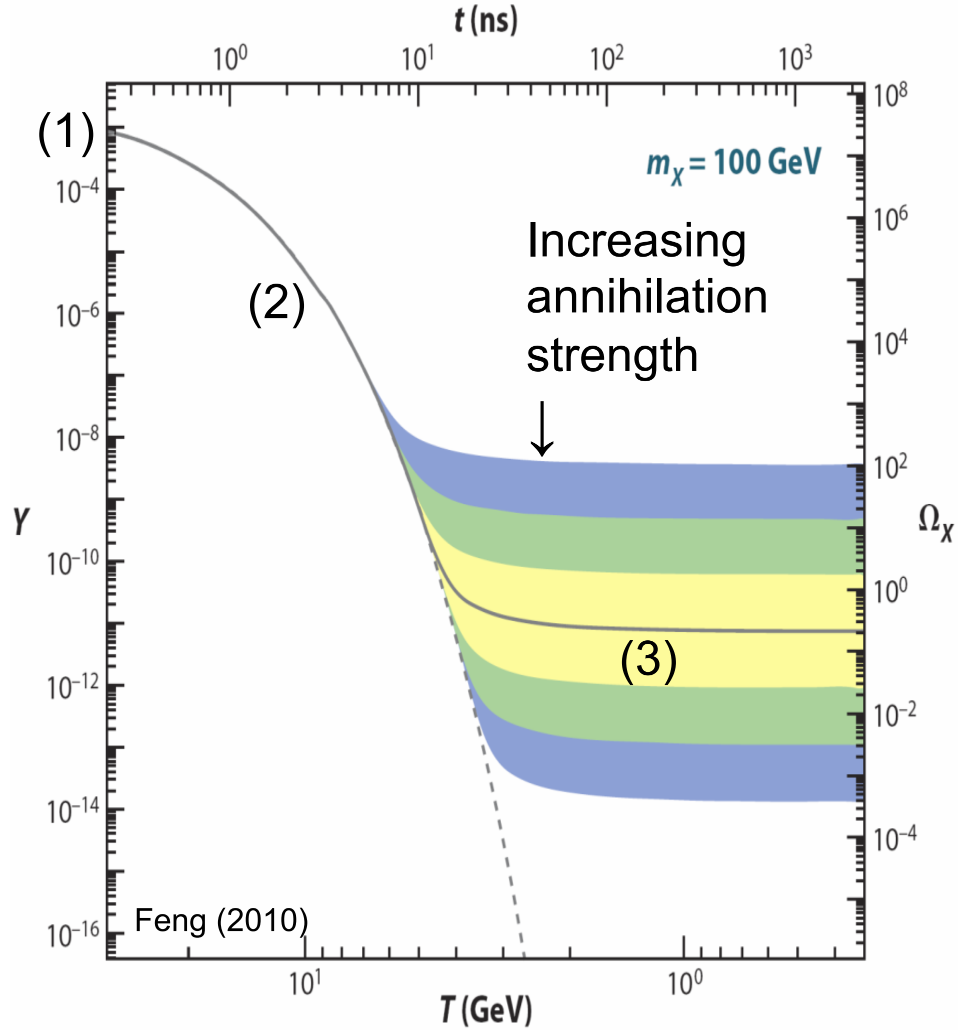
(2) Universe cools:

$$XX \underset{\not\leftarrow}{\rightarrow} qq$$

(3) Universe expands:

$$XX \underset{\not\leftarrow}{\not\rightarrow} qq$$

Zeldovich et al. (1960s)



FREEZE OUT: MORE QUANTITATIVE

- The Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2 \right]$$

Dilution from expansion

$\chi\chi \rightarrow f\bar{f}$

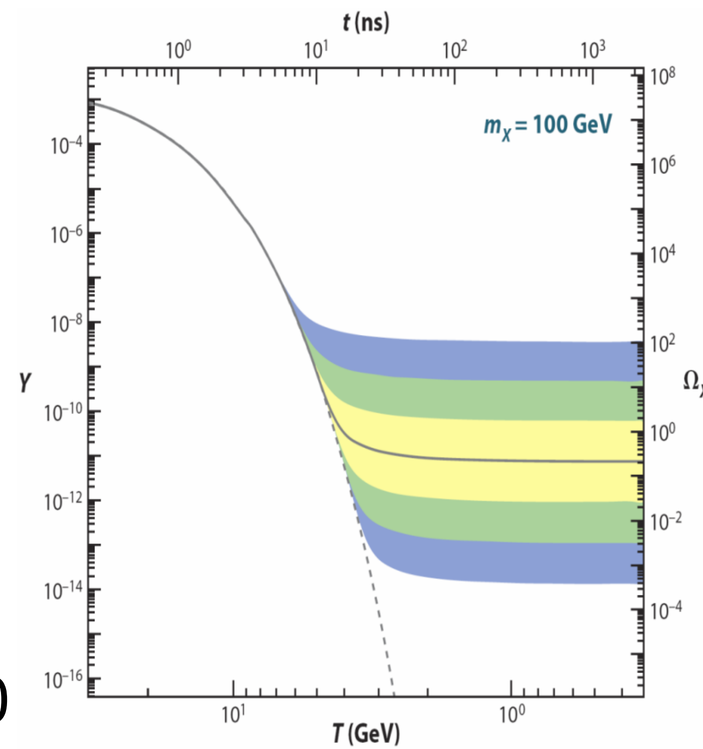
$f\bar{f} \rightarrow \chi\chi$

- n ≈ n_{eq} until interaction rate drops below expansion rate:

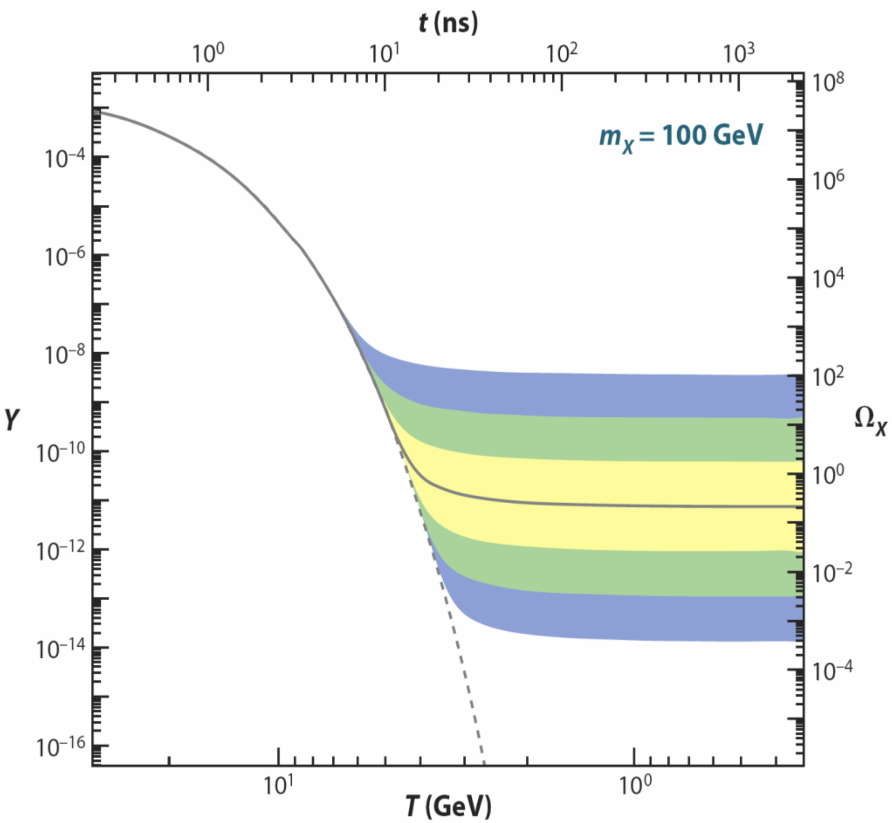
$$\underbrace{n_{\rm eq}}_{(mT)^{3/2}e^{-m/T}} \underbrace{\langle \sigma v \rangle}_{m^{-2}} \sim \underbrace{H}_{T^2/M_{\rm Pl}}$$

- Might expect freeze out at T ~ m, but the universe expands slowly! First guess: m/T ~ ln (M_{Pl}/m_W) ~ 40

(numerical results: ~25, v ~ 0.3c)

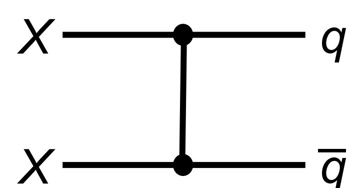


THE WIMP MIRACLE



- It turns out that the relation between Ω_X and annihilation strength is wonderfully simple:

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

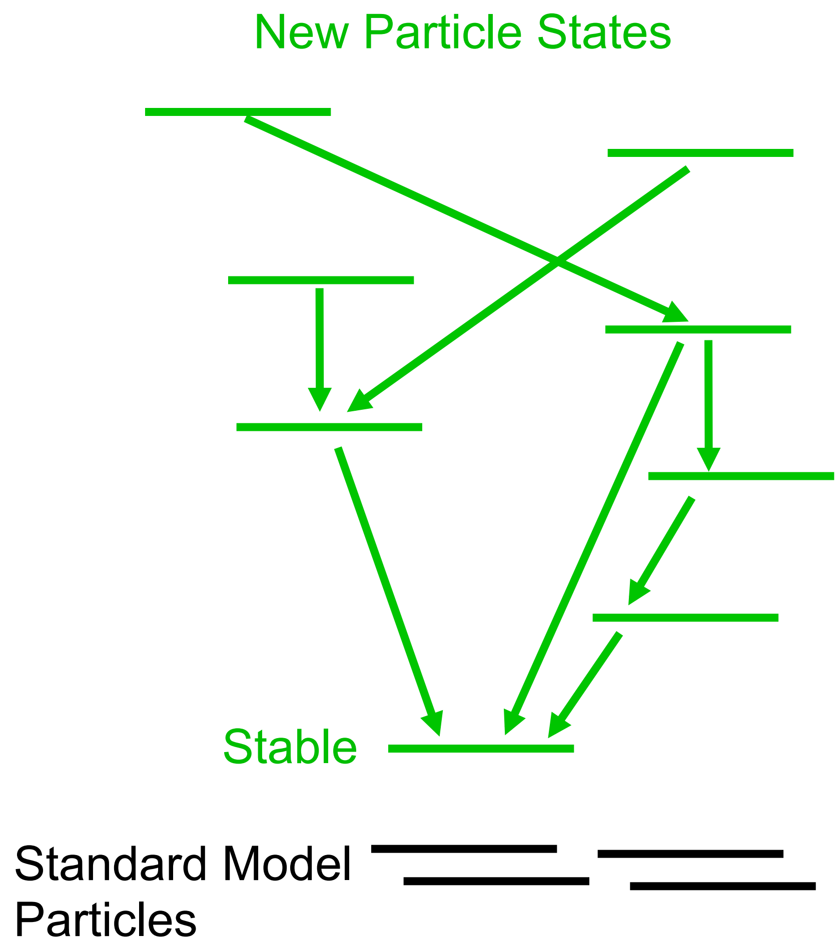


- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

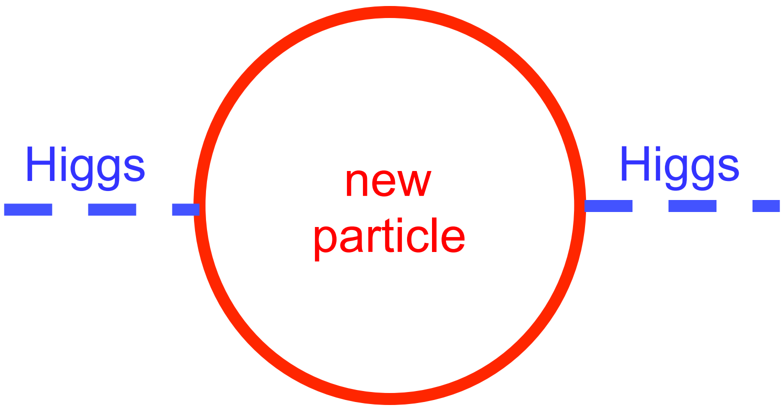
WIMP STABILITY

- The WIMP Miracle is well appreciated. But its success relies another less well-advertised "miracle"
- DM must be stable
- How natural is this? *A priori*, not very: the only stable particles we know about are very light

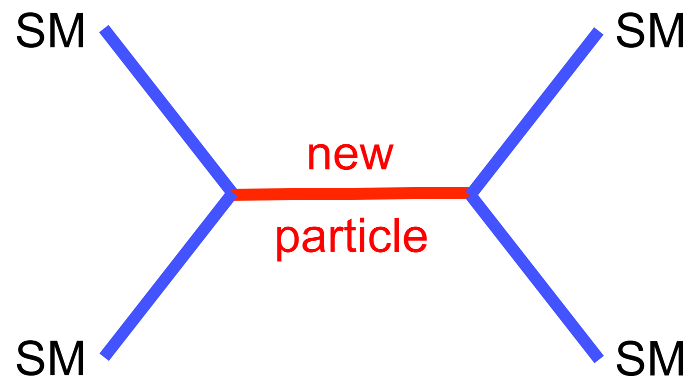


THE DISCRETE WIMP MIRACLE

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)

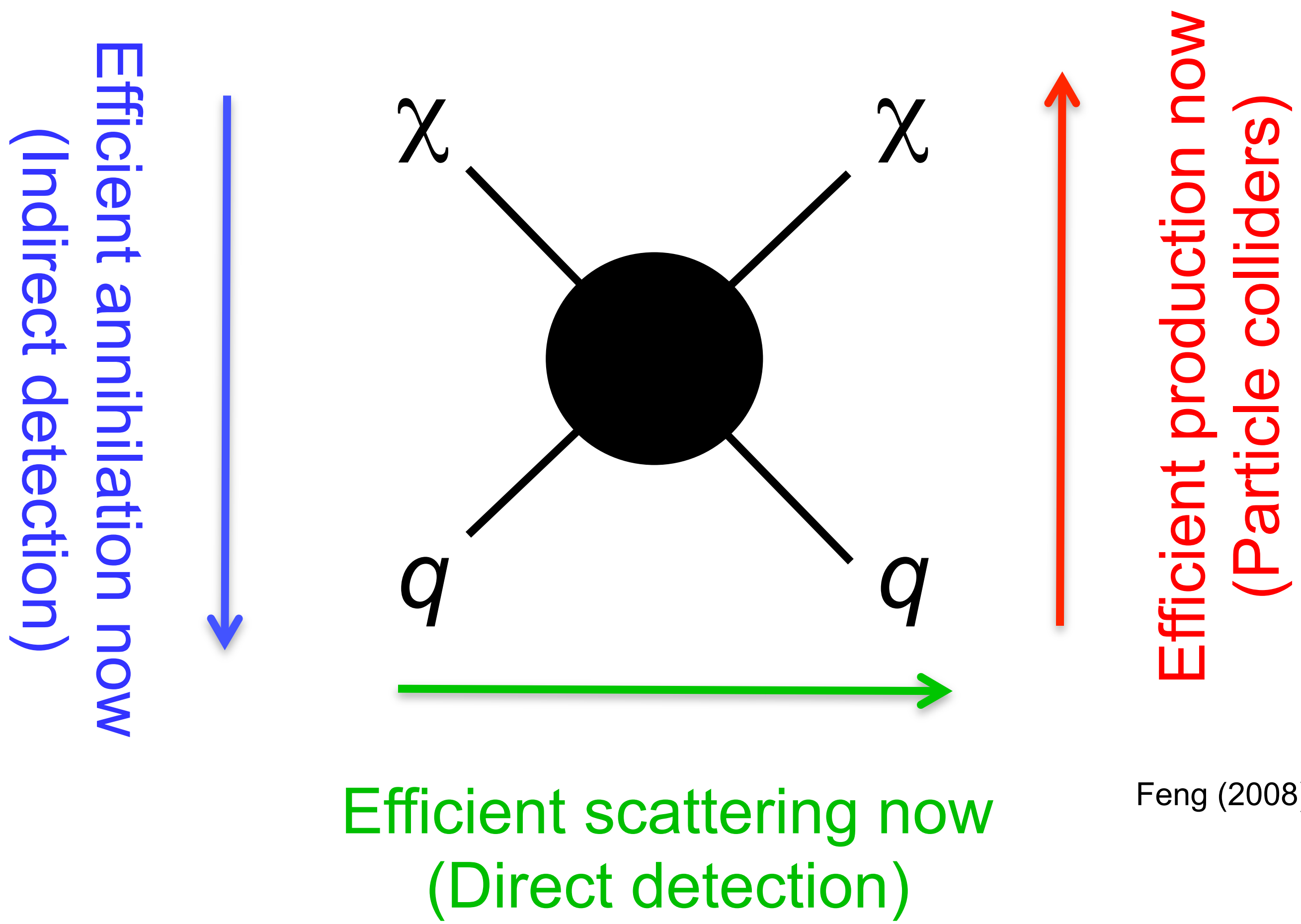
- Simple solution: impose a discrete parity, so all interactions require *pairs* of new particles. This also makes the lightest new particle stable: Discrete Symmetry ↔ Stability

Cheng, Low (2003); Wudka (2003)

- Remarkable coincidence: particle physics independently motivates particles that are stable enough to be dark matter

WIMP DETECTION

Correct relic density → Efficient annihilation then



Feng (2008)

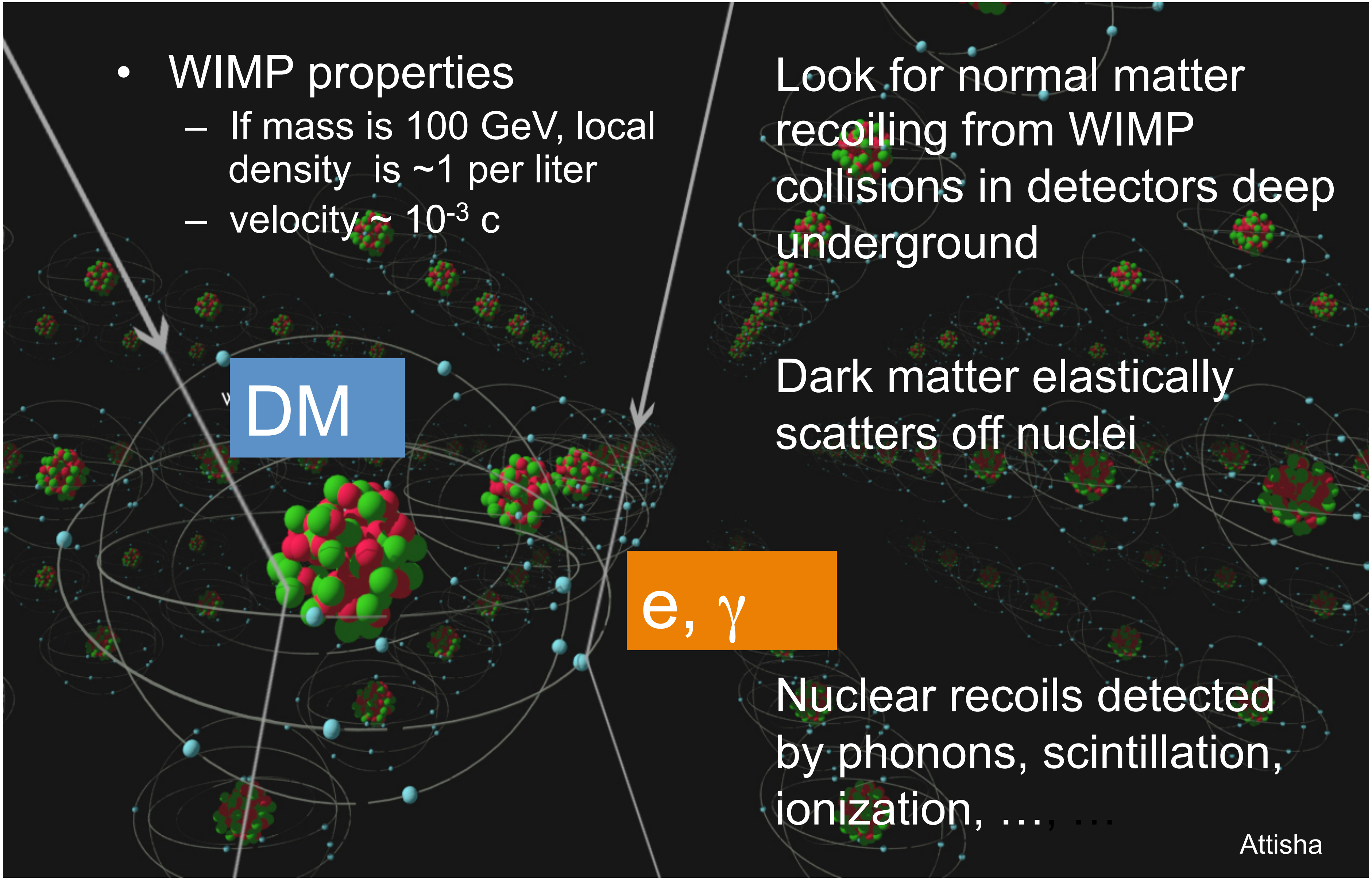
DIRECT DETECTION

- 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, …, …



SPIN-(IN)DEPENDENT SCATTERING

- Consider neutralinos with quark interactions

$$\mathcal{L} = \sum_{q=u,d,s,c,b,t} \left(\alpha_q^{\mathrm{SD}} \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q + \alpha_q^{\mathrm{SI}} \bar{\chi}\chi\bar{q}q \right)$$

- DM particles now have v ~ 10^{-3} c, so are highly non-relativistic
- In this limit, the first terms reduce to a spin-spin interactions, and so are called spin-dependent interactions; the second terms are spin-independent interactions
- Experiments probing both are important

See Tunnell, Dahl, Monzani, Pyle talks

SPIN-INDEPENDENT EXPERIMENT

- The rate observed in a detector is $R = \sigma_A I_A$, where

$$\sigma_A = \frac{\mu_A^2}{M_*^4}\left[f_p Z + f_n(A-Z)\right]^2$$

Particle theory: Coupling to p, n

$$I_A = N_T n_X \int dE_R \int_{v_{\rm min}}^{v_{\rm esc}} d^3v\, f(v) \frac{m_A}{2v\mu_A^2} F_A^2(E_R)$$

Experiment: number of target nuclei

Experiment: recoil energy

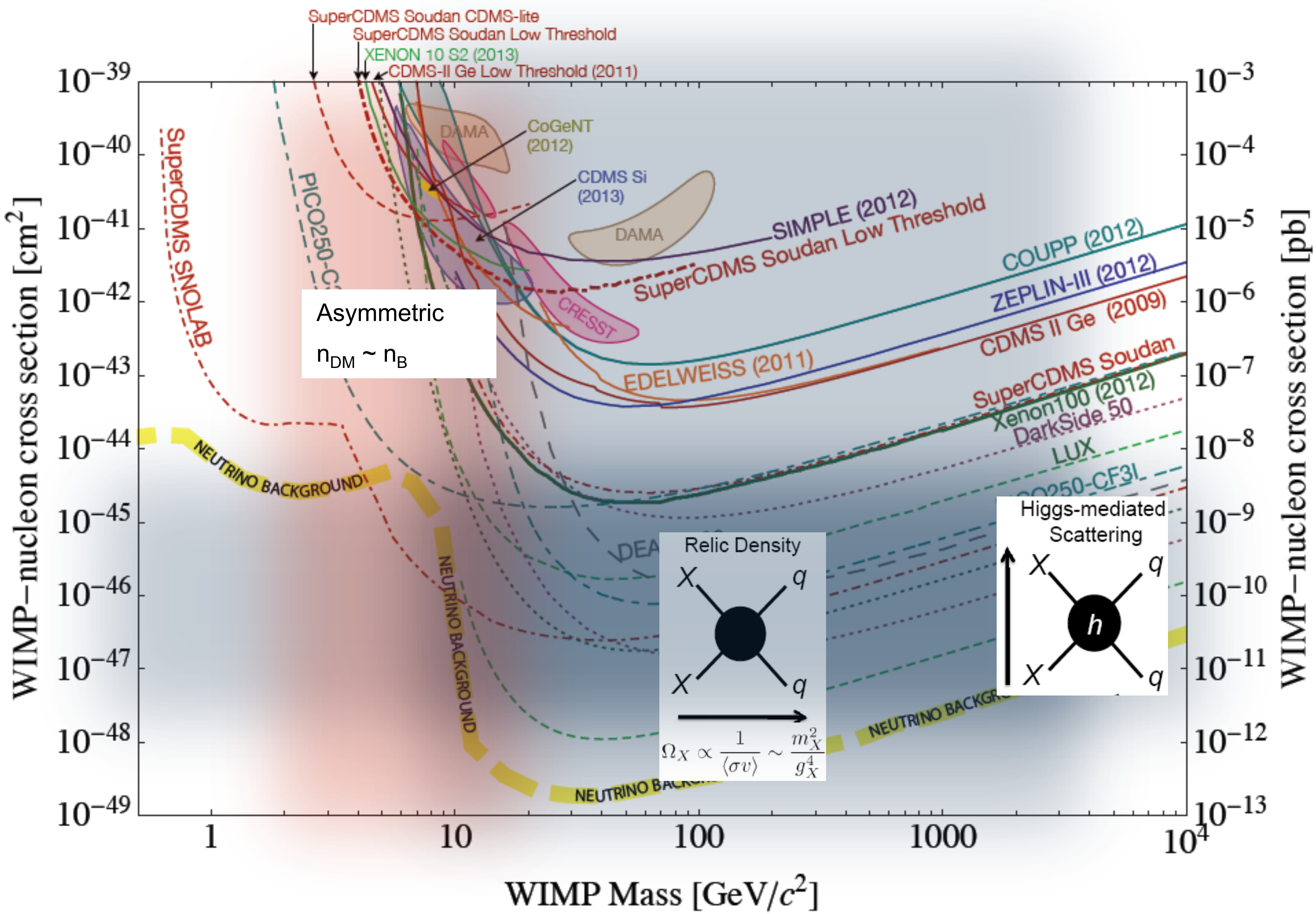
Astrophysics: DM velocity distribution

Nuclear physics: form factor

Astrophysics: local DM number density

- Results are typically reported assuming $f_p=f_n$, so $\sigma_A \sim A^2$, and scaled to a single nucleon

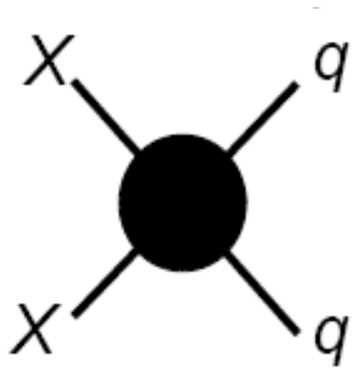
DIRECT DETECTION EXPERIMENTS

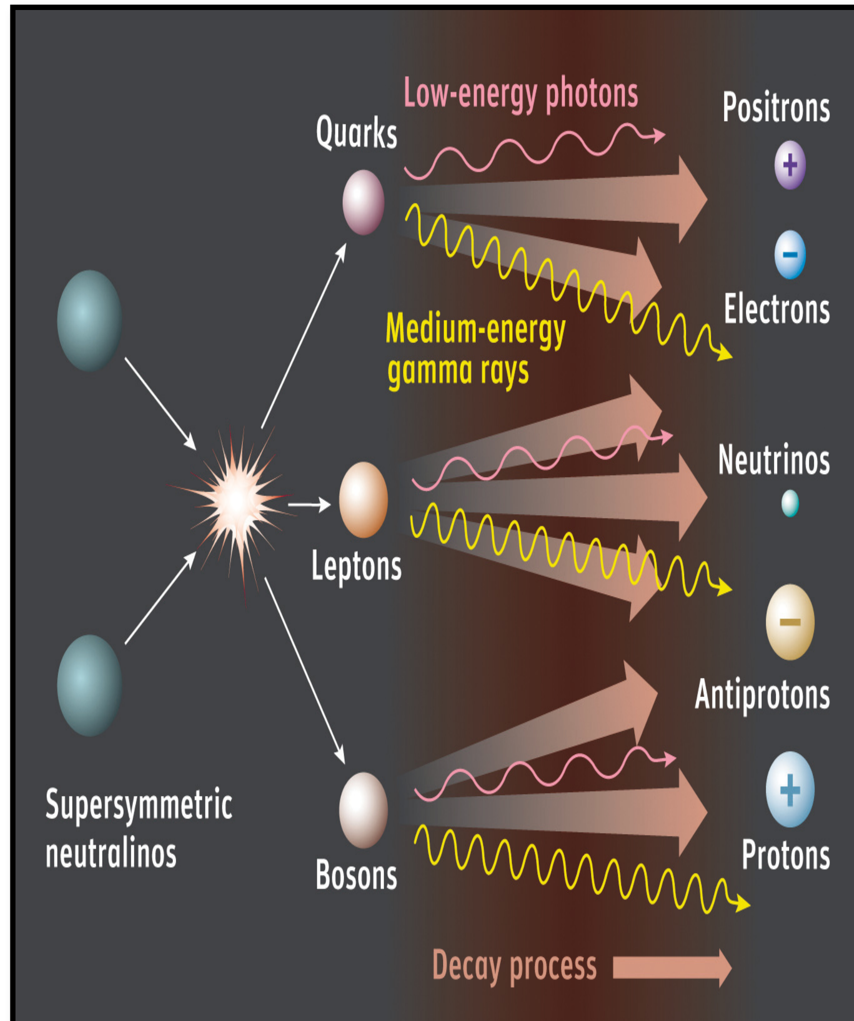


INDIRECT DETECTION

See Klein, Albert talks

- 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

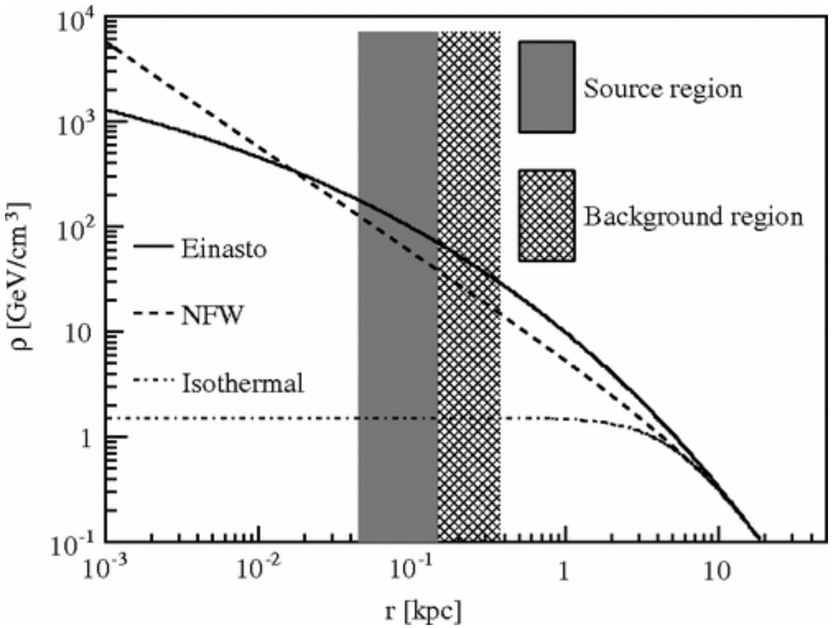
Two kinds of sources

- Galactic Center: close, large signal, but large backgrounds
- Dwarf Galaxies: farther and smaller, so smaller signal, but DM dominated, so smaller backgrounds

Two kinds of signal

- Continuum photons: XX → SM → γ
- Line photons: XX → $\gamma\gamma$, γZ through loop processes

In all cases, halo profiles are not well-determined at the center, introduces an uncertainty in flux of up to ~100

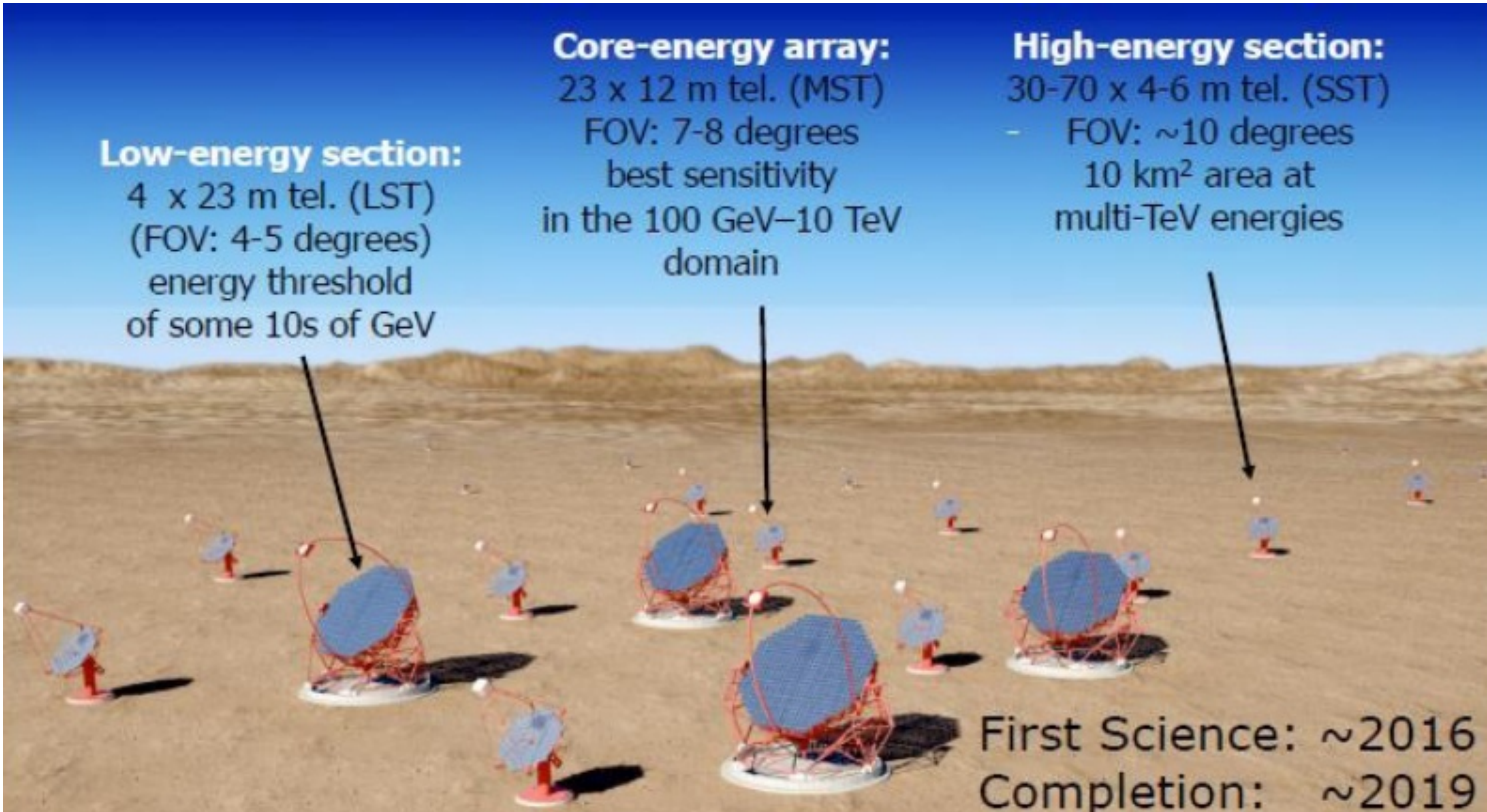


PHOTONS: CURRENT EXPERIMENTS

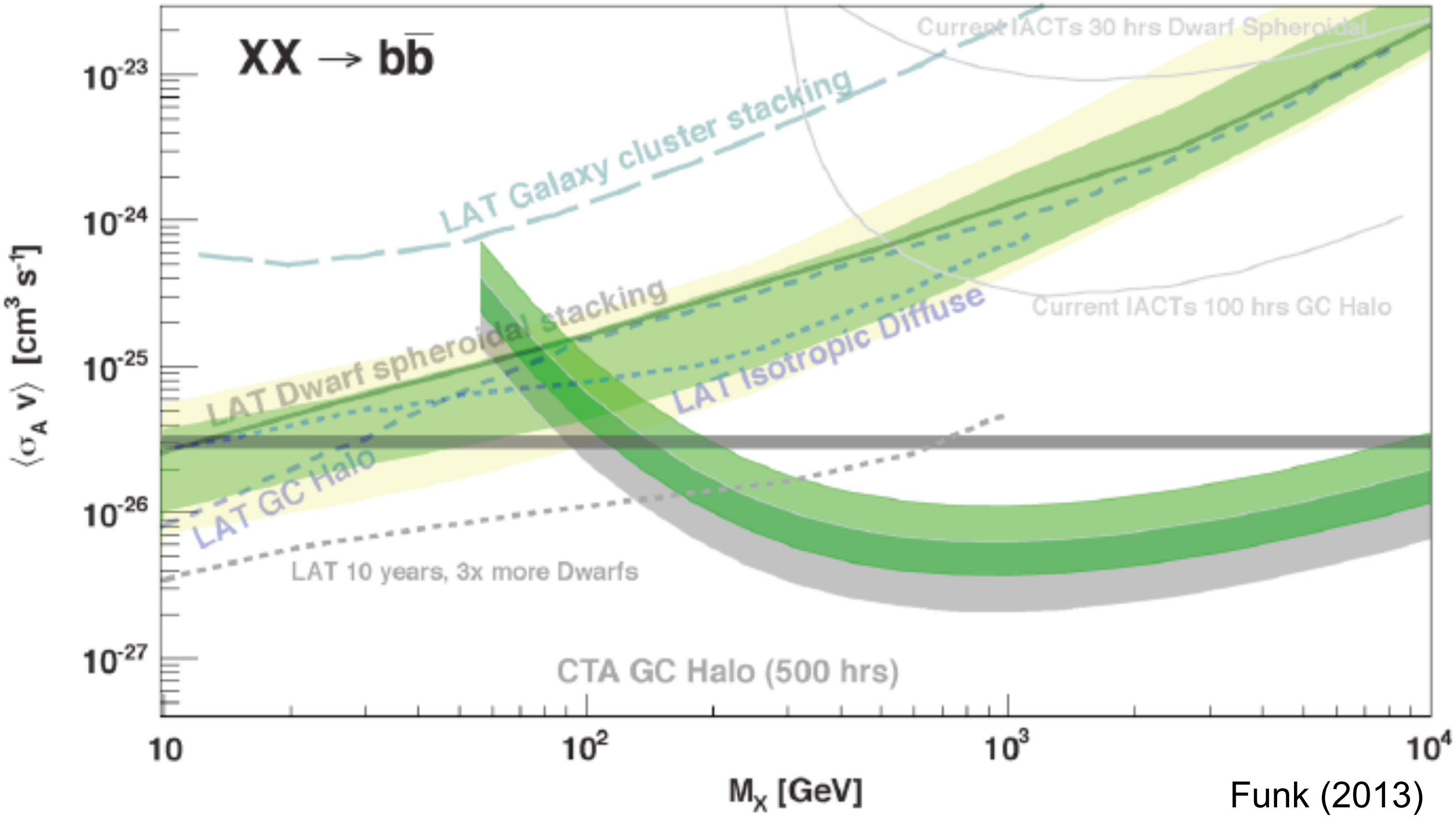
Veritas, Fermi-LAT, HAWC, and others

PHOTONS: FUTURE EXPERIMENTS

Cerenkov Telescope Array



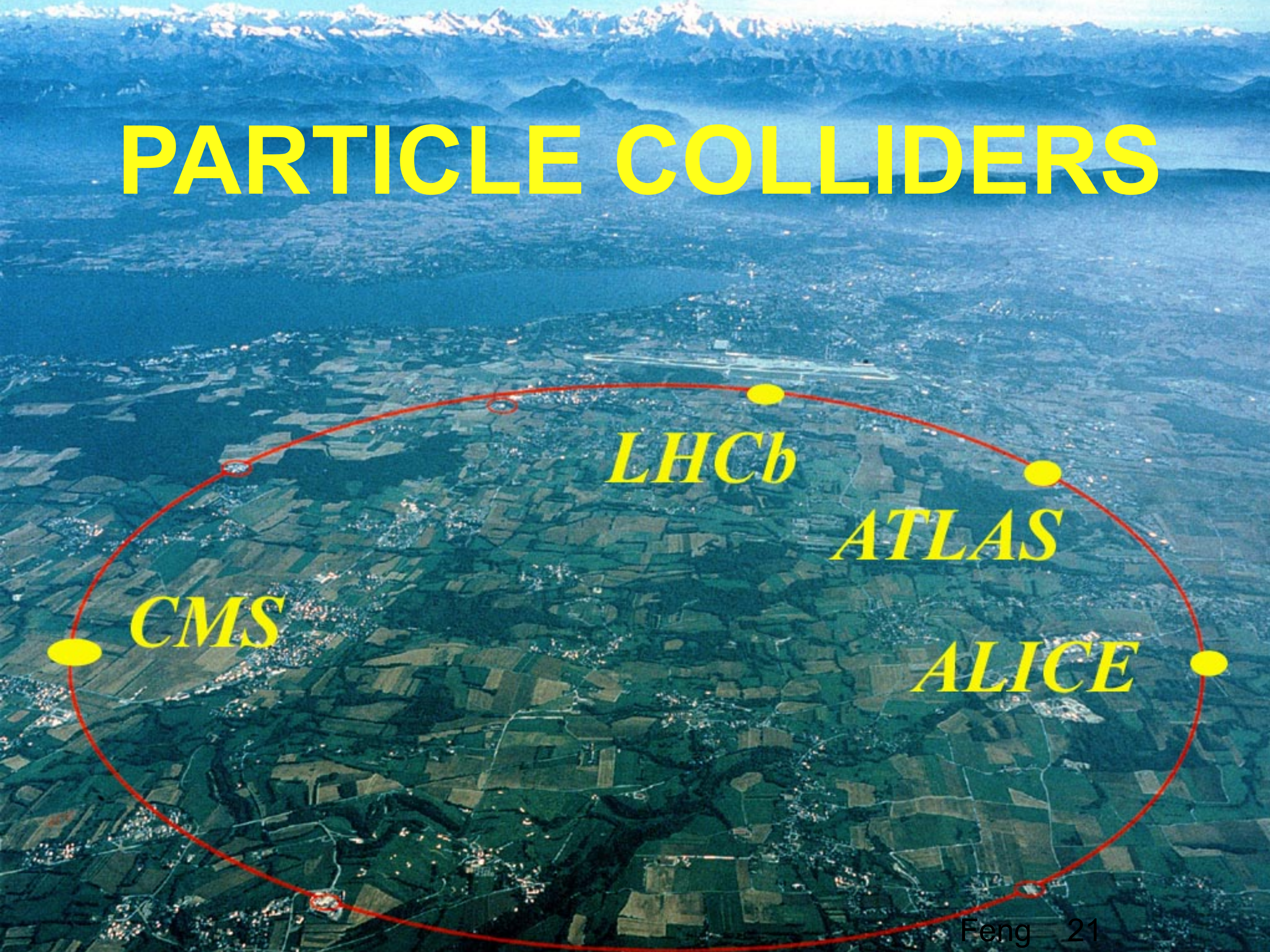
PHOTONS: STATUS AND PROSPECTS



Funk (2013)

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

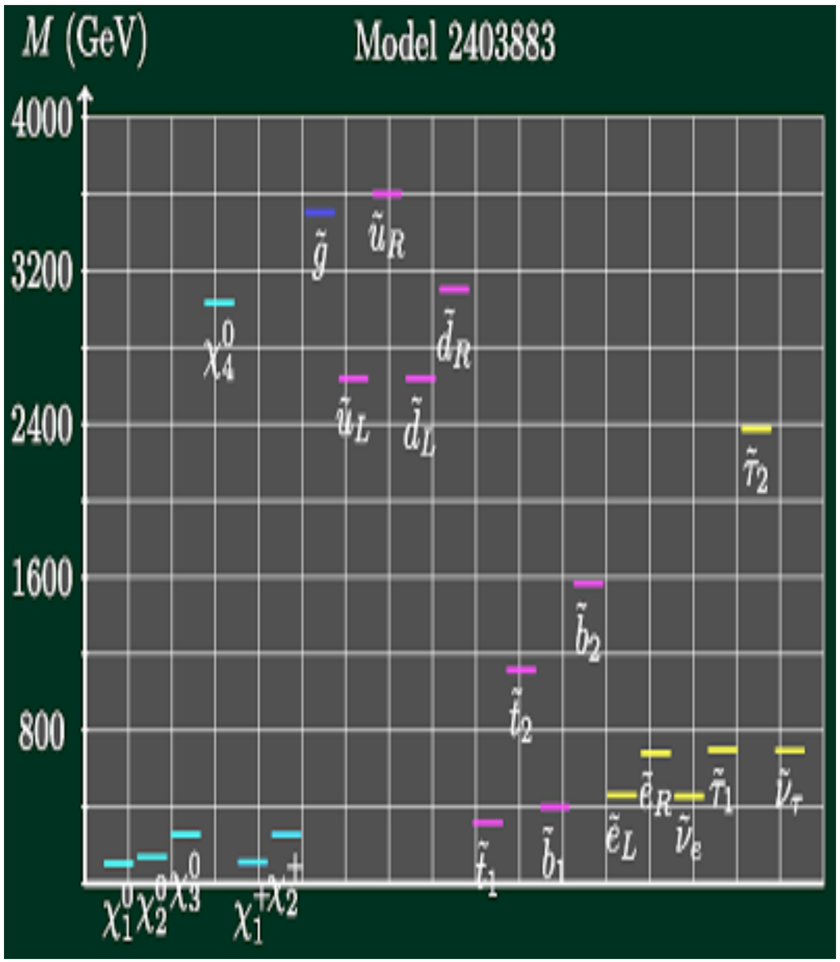
PARTICLE COLLIDERS



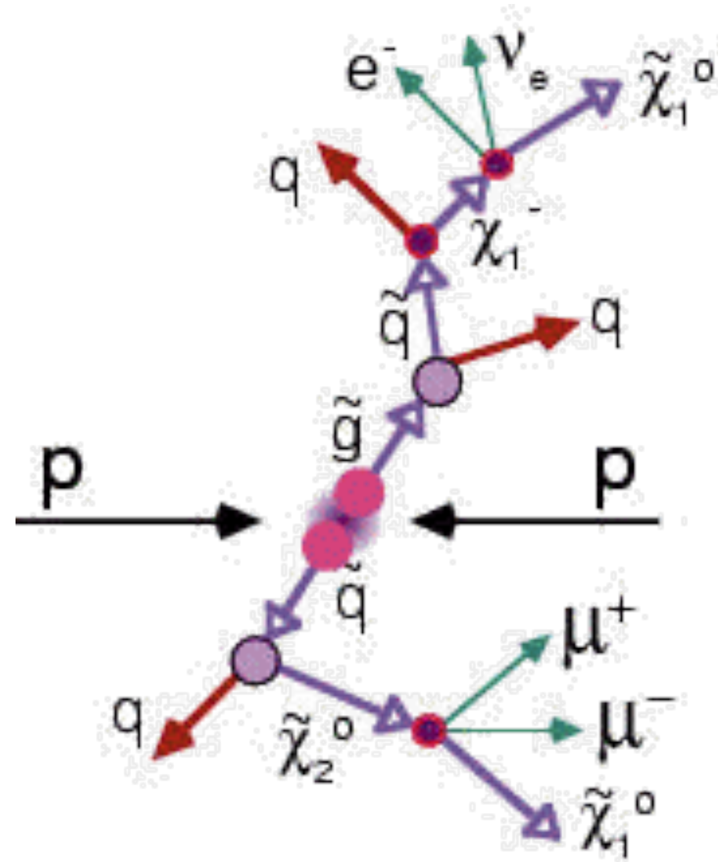
DARK MATTER AT COLLIDERS

See Eno, Toro talk

Full Models, Simplified Models

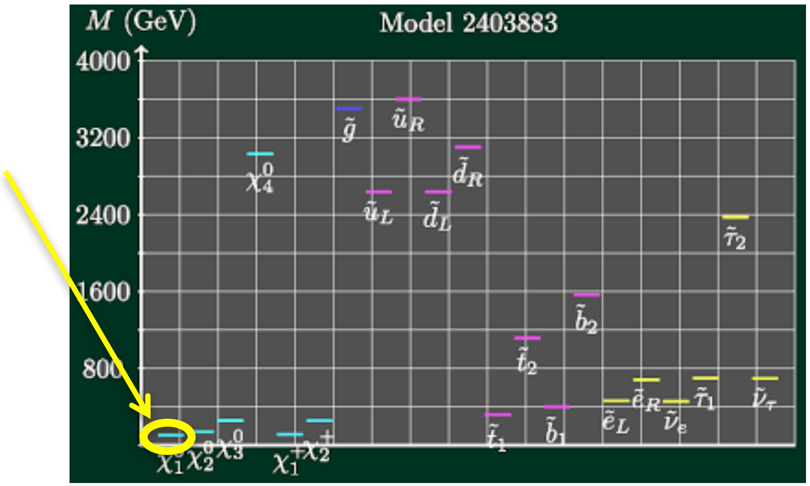


Produce other particles, which decay to DM



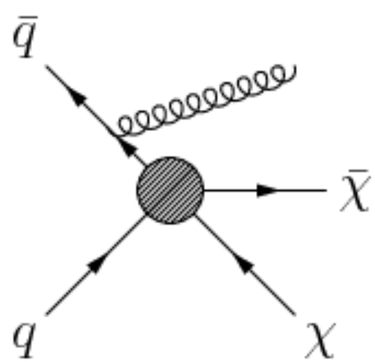
DARK MATTER AT COLLIDERS

DM Effective Theories
(Bare Bones Dark Matter)



Birkedal, Matchev, Perelstein (2004)

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



Now systematically classify all possible 4-pt 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)

AXIONS

Peccei, Quinn (1977)
Wilczek (1978)
Weinberg (1978)

- 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, a pseudoscalar

$$\mathcal{L}_a = -\frac{g_3^2}{32\pi^2}\,\frac{a}{f_a}\,\epsilon^{\mu\nu\rho\sigma}G^\alpha_{\mu\nu}G^\alpha_{\rho\sigma}$$

- The axion couples to gluons and quarks, and also to photons through

- The axion's properties are largely determined by f_a

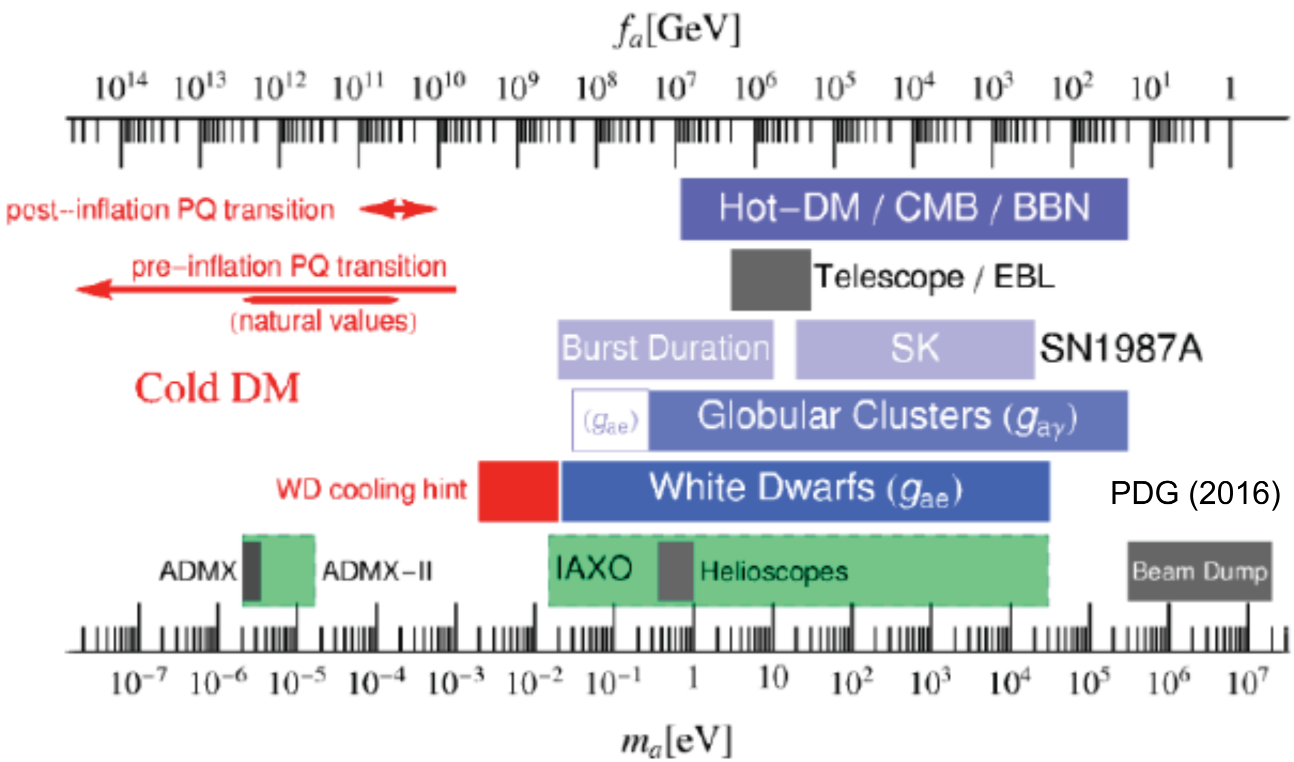
$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\, m_\pi f_\pi \frac{1}{f_a} \approx 6\ \mu\text{eV}\left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$$

AXION DARK MATTER

- The relic density is $\Omega_a \simeq 0.4\, \theta_i^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{1.18}$

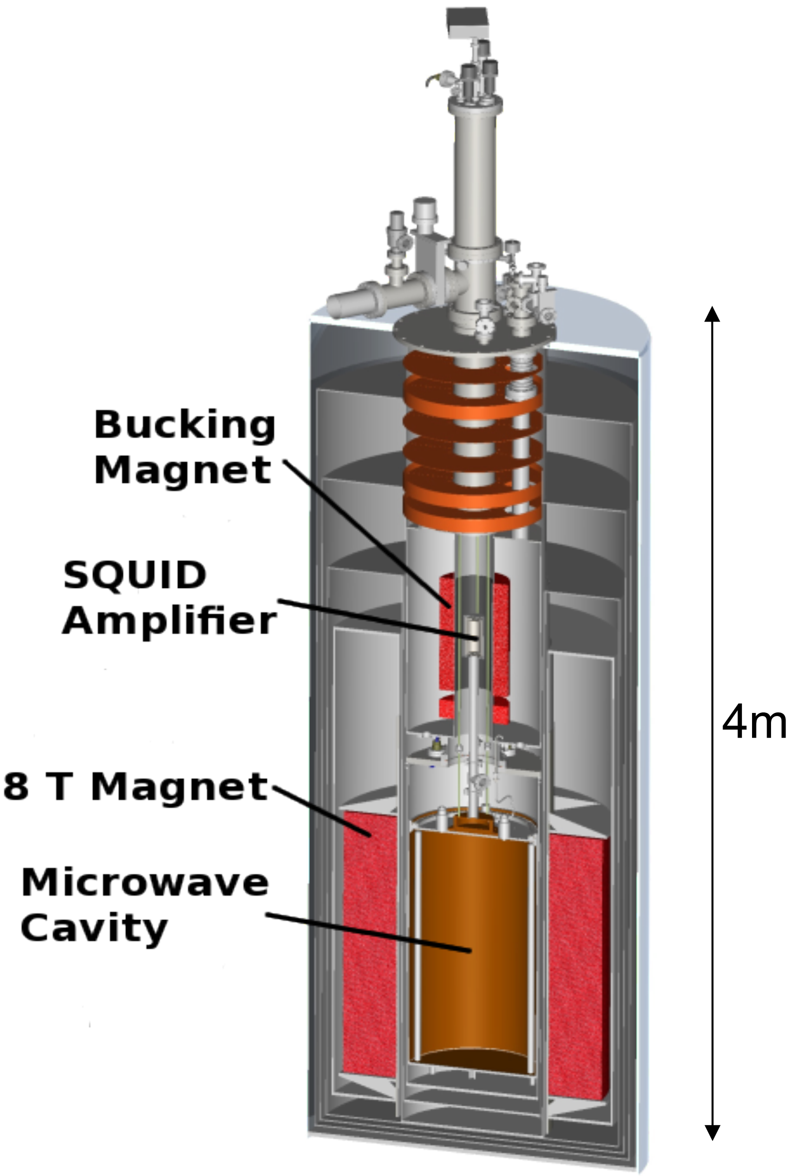
  If misalignment is θ_i ~1, then f_a ~ 10^{12} GeV, m_a ~ 1-100 μeV

- More generally, f_a < M_{planck} , and supernovae and red giant constraints require f_a > 10^9 GeV,, so m_a ~ peV to eV

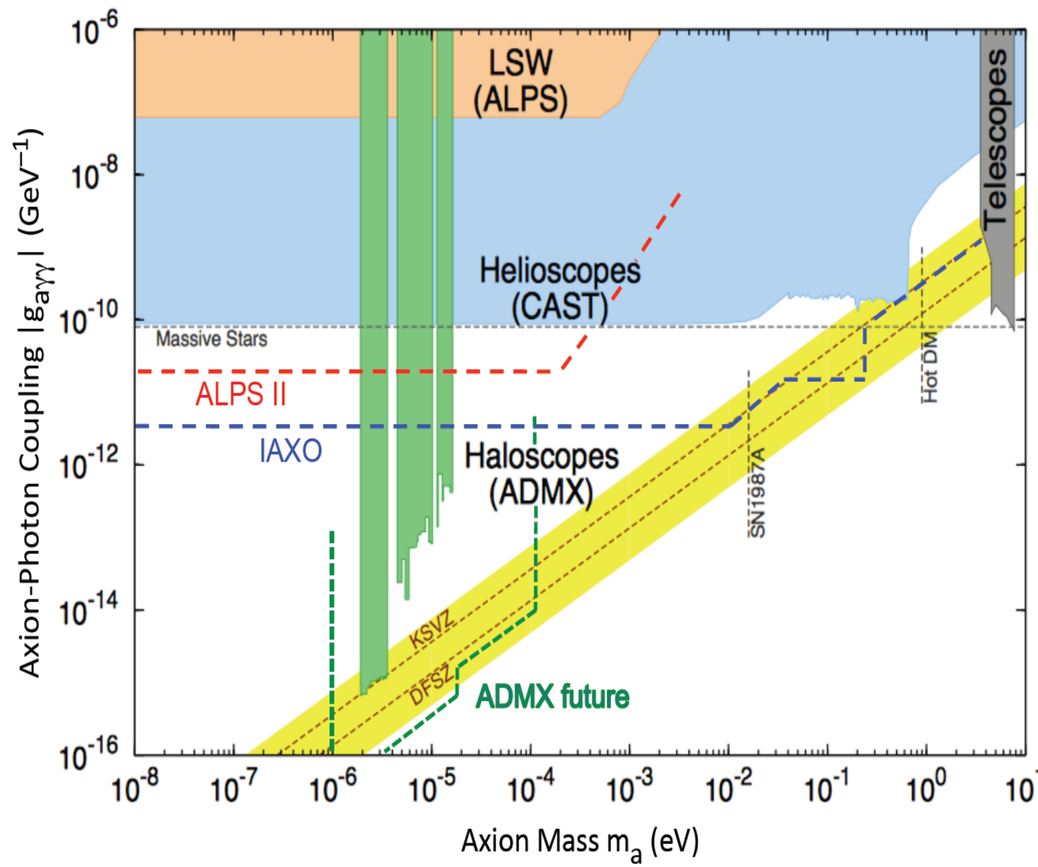


PDG (2016)

AXION SEARCHES



See van Bibber, Graham talks



Graham, Irastorza, Lamoreaux, Lindner, va Bibber (2016)

RECENT DEVELOPMENTS

- In the last few years, there has been a flurry of activity

- Classic candidates have been generalized to broad classes of dark matter

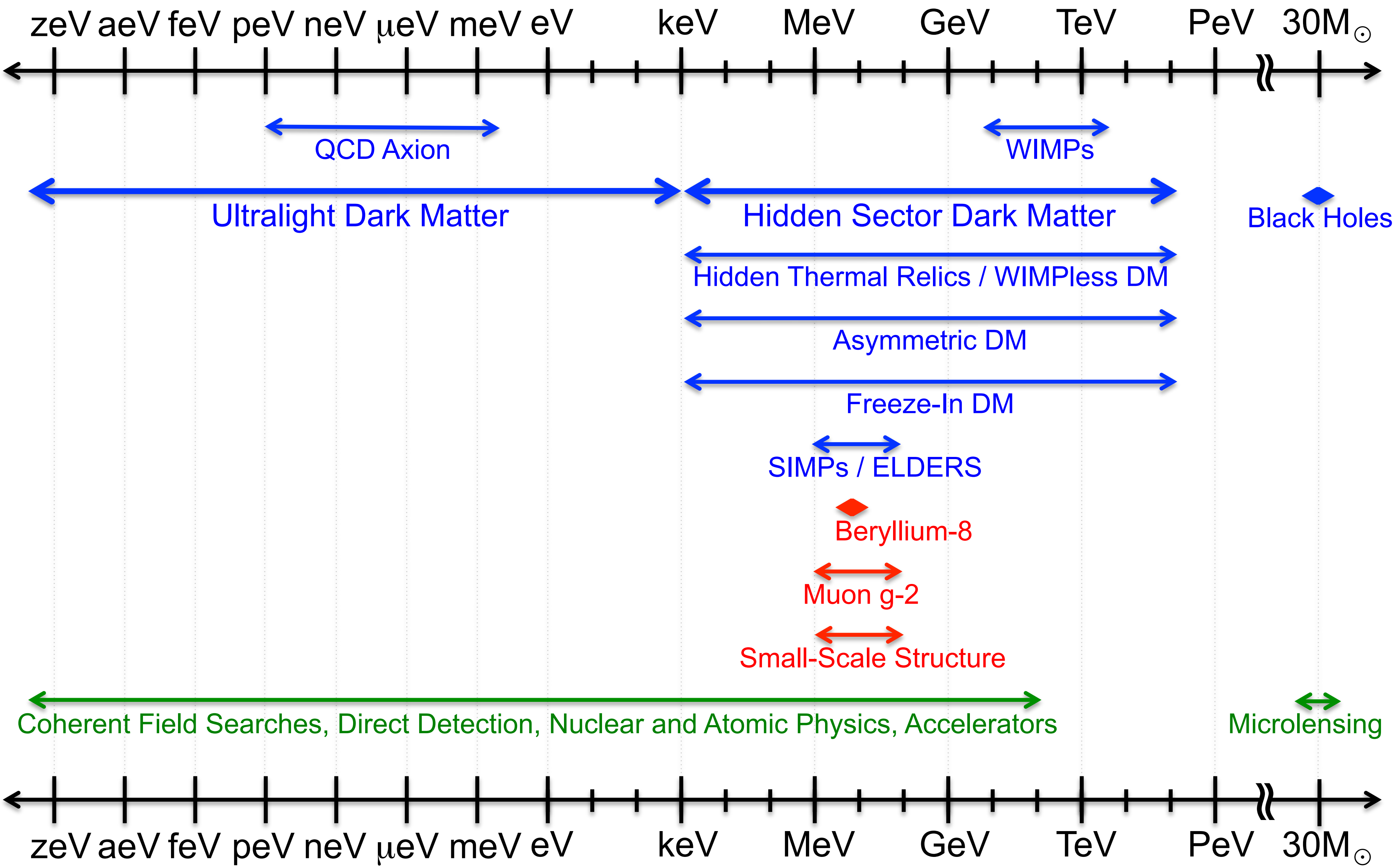
  Axions → Axion-like Particles (ALPs) → Ultralight DM

  WIMPs → WIMPless DM→ Hidden Sector DM

- New anomalies have been reported and new experimental search techniques have been proposed

See Schuster, Toro, Perez talks

DM CANDIDATES, ANOMALIES, SEARCH TECHNIQUES



Cosmic Visions White Paper (2017)

HIDDEN SECTOR DARK MATTER

- All evidence for dark matter is gravitational. Perhaps it's in a hidden sector, composed of particles with no SM gauge interactions (electromagnetic, weak, strong)

- This hidden sector may have a rich structure with matter and forces of its own

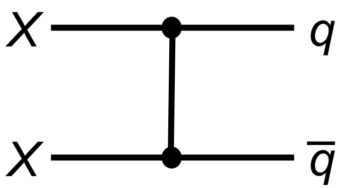
- It may also have non-gauge interactions with the SM

WIMPLESS DARK MATTER

Feng, Kumar (2008)

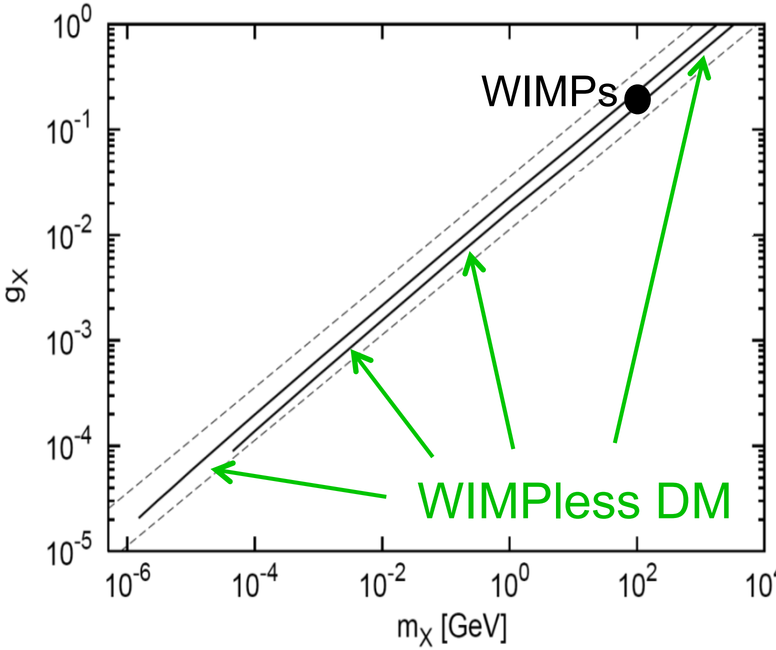
- Recall the WIMP miracle: the relation between Ω_X and annihilation strength is wonderfully simple:

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



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

- In a hidden sector, the coupling g_X doesn't have to be 0.6



- WIMPless dark matter: light, weakly-coupled DM can also have the correct relic density, sets "thermal targets," opens connections to low-energy particle, nuclear, AMO, CM physics

EFFECTIVE INTERACTIONS

- There are many ways the hidden particles could couple to us. Use effective operators as an organizing principle:

$$\mathcal{L} = \mathcal{O}_4 + \frac{1}{M}\mathcal{O}_5 + \frac{1}{M^2}\mathcal{O}_6 + \ldots$$

where the operators are grouped by their mass dimension, with [scalar] = 1, [fermion] = 3/2, [$F_{\mu\nu}$] = 2

- *M* is a (presumably) large "mediator mass," so start with dimension 4 operators. There are not too many:

Neutrino portal	Higgs portal	Photon portal
hLN	$h^\dagger h \phi_h^\dagger \phi_h$	$F_{\mu\nu} F_h^{\mu\nu}$

NEUTRINO PORTAL

See Grossman, Kaufman, Friedland, Tanaka, Blucher talks

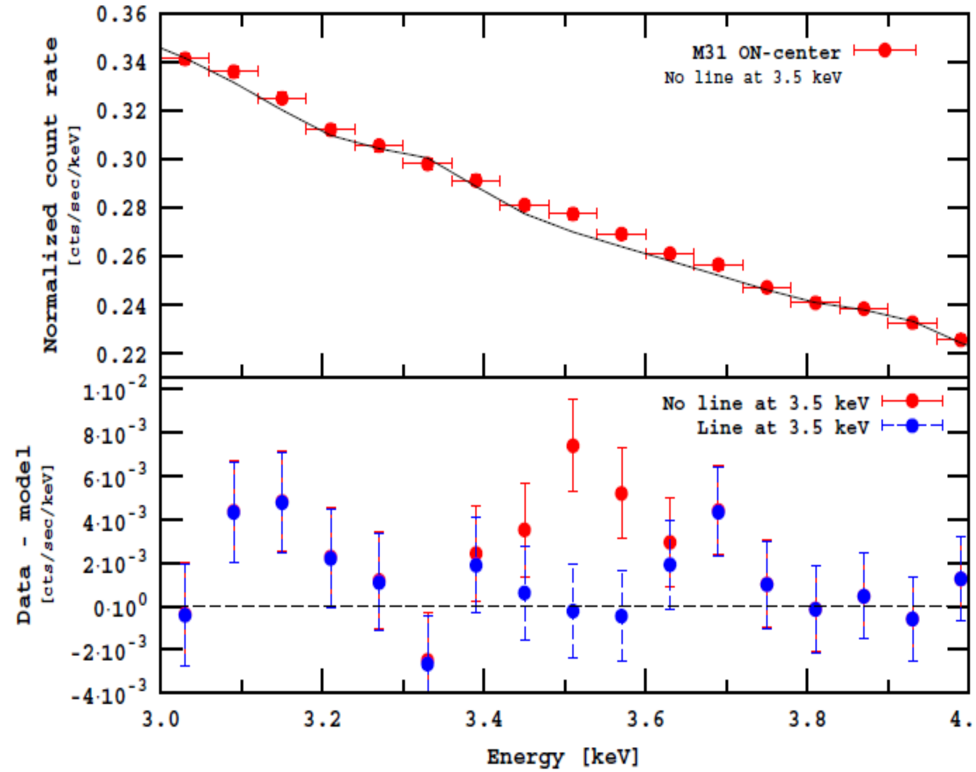
- One possibility is

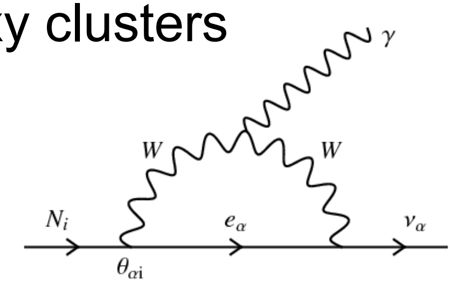
$$hLN$$

N is a total gauge singlet, the right-handed, or sterile, neutrino, and may be dark matter

- If N is dark matter, its favored mass range is ~keV

- This has received renewed attention from the 3.5 keV X-ray line seen from galaxies and galaxy clusters





Abazajian, Fuller, Tucker (2001)

Boyarsky, Ruchayskiy, Iakubovskyi, Franse (2014)
Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall (2014)

HIGGS PORTAL

- Another possibility is

$$h^\dagger h \phi_h^\dagger \phi_h$$

where the *h* subscript denotes "hidden"

- When EW symmetry is broken, h → v + h, this leads to invisible Higgs decays

- A leading motivation for precision Higgs studies and future colliders, such as ILC, CLIC, FCC

See Gray talk

Patt, Wilczek (2006)

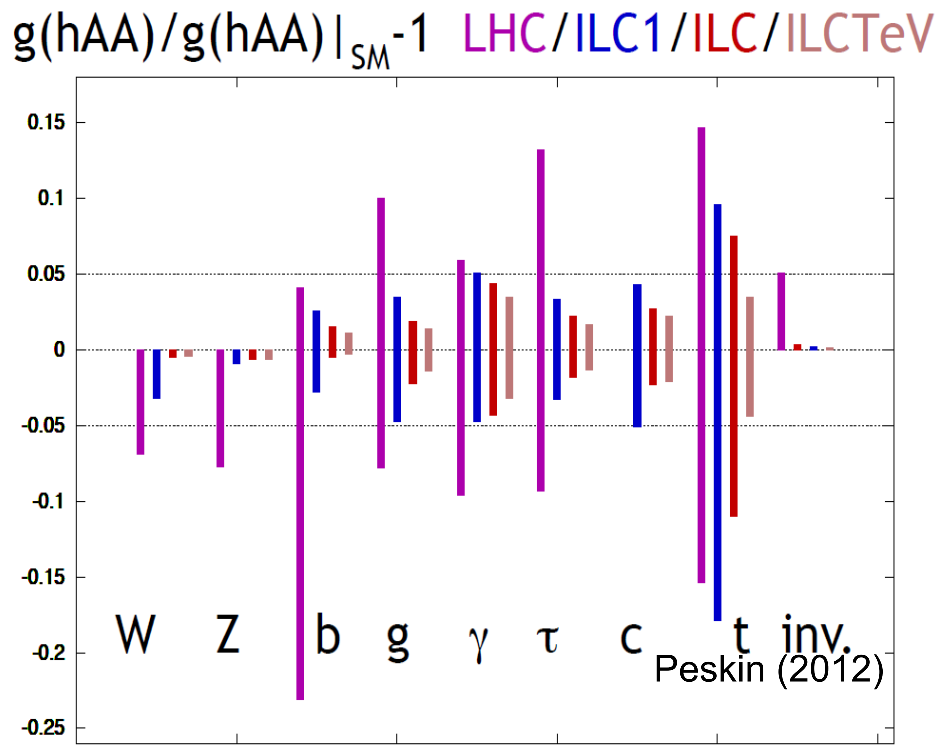


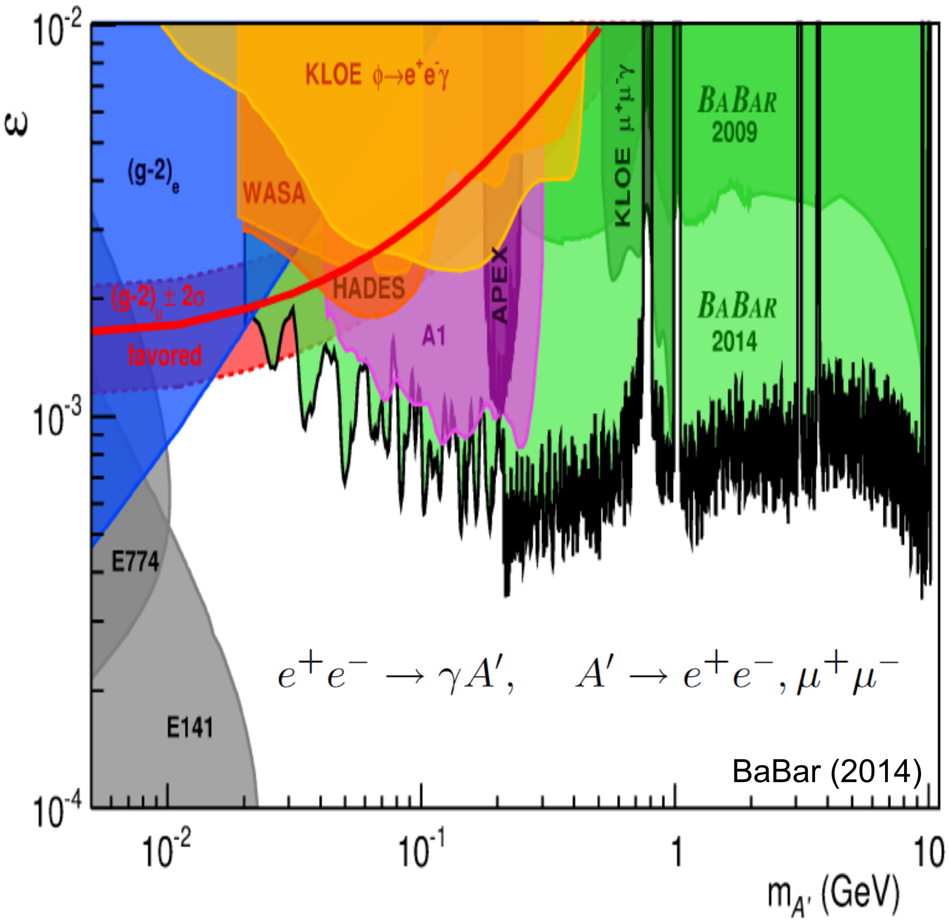
Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). More details of the presentation are given in the caption of Fig. 1. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

PHOTON PORTAL

Okun (1982)
Galison, Manohar (1984)
Holdom (1986)

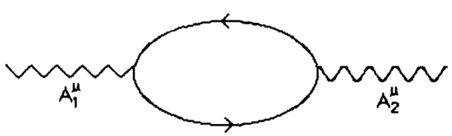
- Another possibility is $\epsilon F_{\mu\nu} F_h^{\mu\nu}$

  which leads to kinetic mixing between the SM photon and a hidden photon A’, which must have a mass



- Diagonalizing, one finds that SM particles have hidden charge proportional to ε

- ε ~ 10^{-3} from 1-loop effects, even for arbitrarily heavy particles in the loop (non-decoupling)



- A’ cannot be DM, but may be a portal to the dark sector, motivates searches at the “intensity frontier”

CONCLUSIONS

- Dark matter is one of the great scientific puzzles of our time and is now leading evidence for new particles and forces. Much of BSM physics is now also DM physics
- Classic candidates (sterile neutrinos, axions, WIMPs) remain viable, many powerful searches ongoing
- Many new candidates are emerging, motivating new search techniques and connections to other subfields of physics