OUTLINE

LECTURE 1

Essential Cosmology: Contents and History of the Universe

LECTURE 2

WIMP Dark Matter: Candidates and Methods of Detection

LECTURE 3

Inflation, Gravitinos, and Hidden Sectors

WIMP EXAMPLES

- Weakly-interacting massive particles: many examples, broadly similar, but different in detail

- The prototypical WIMP: neutralinos in supersymmetry

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

- KK B^1 (“KK photons”) in universal extra dimensions

Servant, Tait (2002); Cheng, Feng, Matchev (2002)

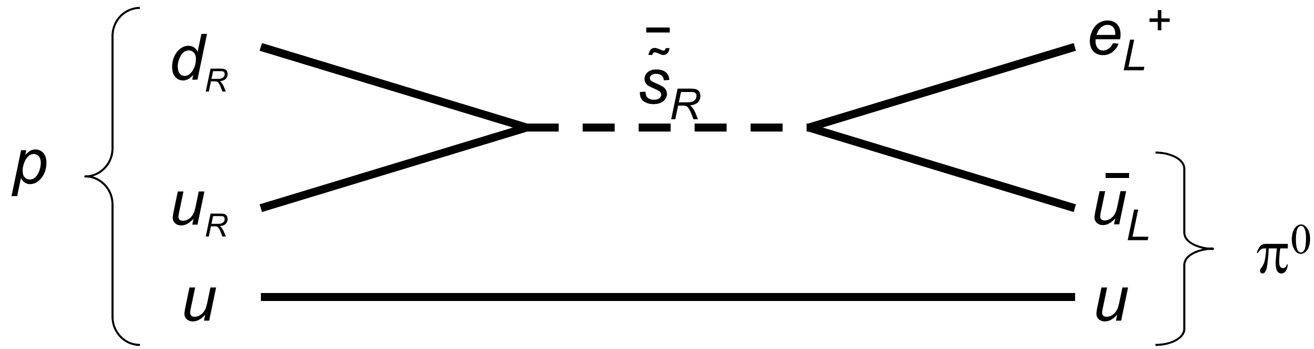
NEUTRAL SUSY PARTICLES

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2						$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$

R-PARITY AND STABLE LSPS

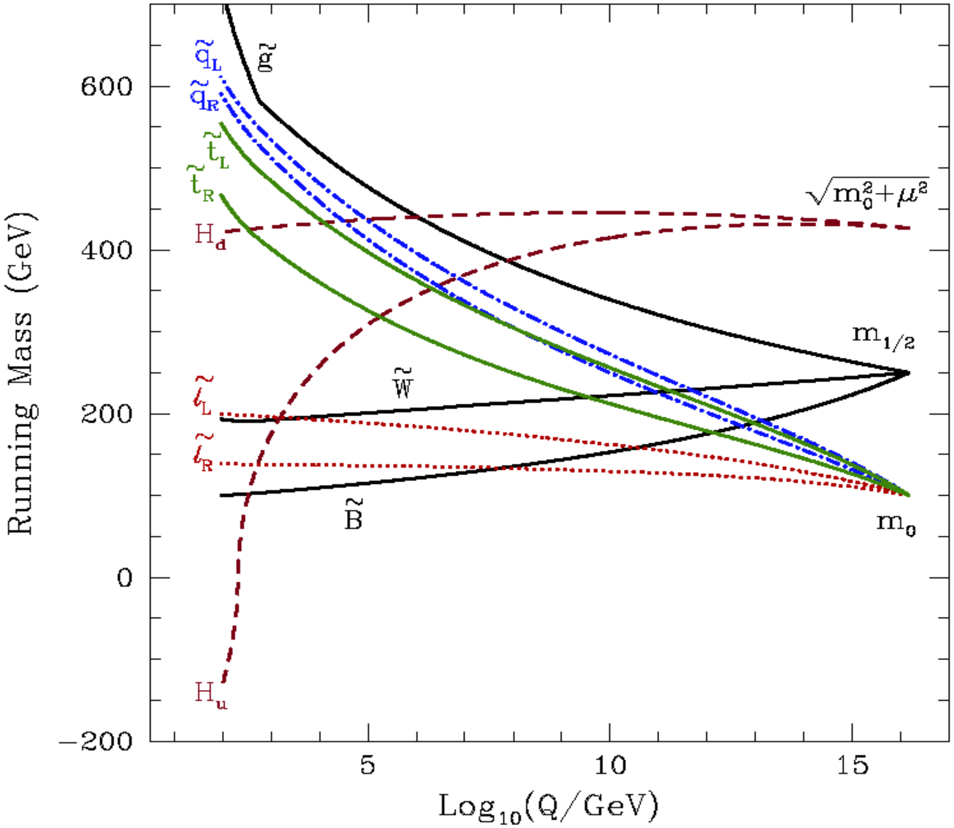
- One problem: proton decay



- Forbid this with R-parity conservation: $R_p = (-1)^{3(B-L)+2S}$
  - SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
  - Require $\Pi\ R_p = 1$ at all vertices
- Consequence: the lightest SUSY particle (LSP) is stable!

WHAT'S THE LSP?

- High-scale → weak scale through RGEs
- Gauge couplings increase masses;
  Yukawa couplings decrease masses
- "typical" LSPs: χ , $\tilde{\tau}_R$

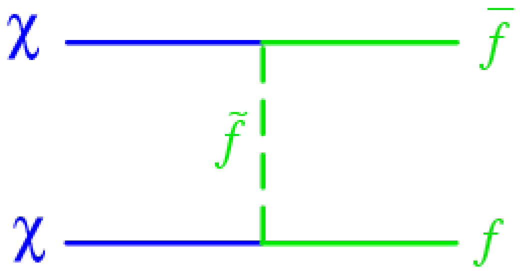


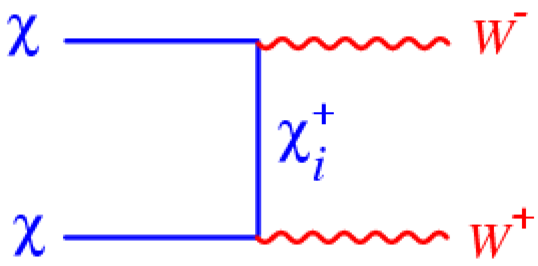
Olive (2003)

Particle physics alone → neutral, stable, cold dark matter

RELIC DENSITY

- Neutralinos annihilate through *many* processes. [→] But there are typically two dominant classes:

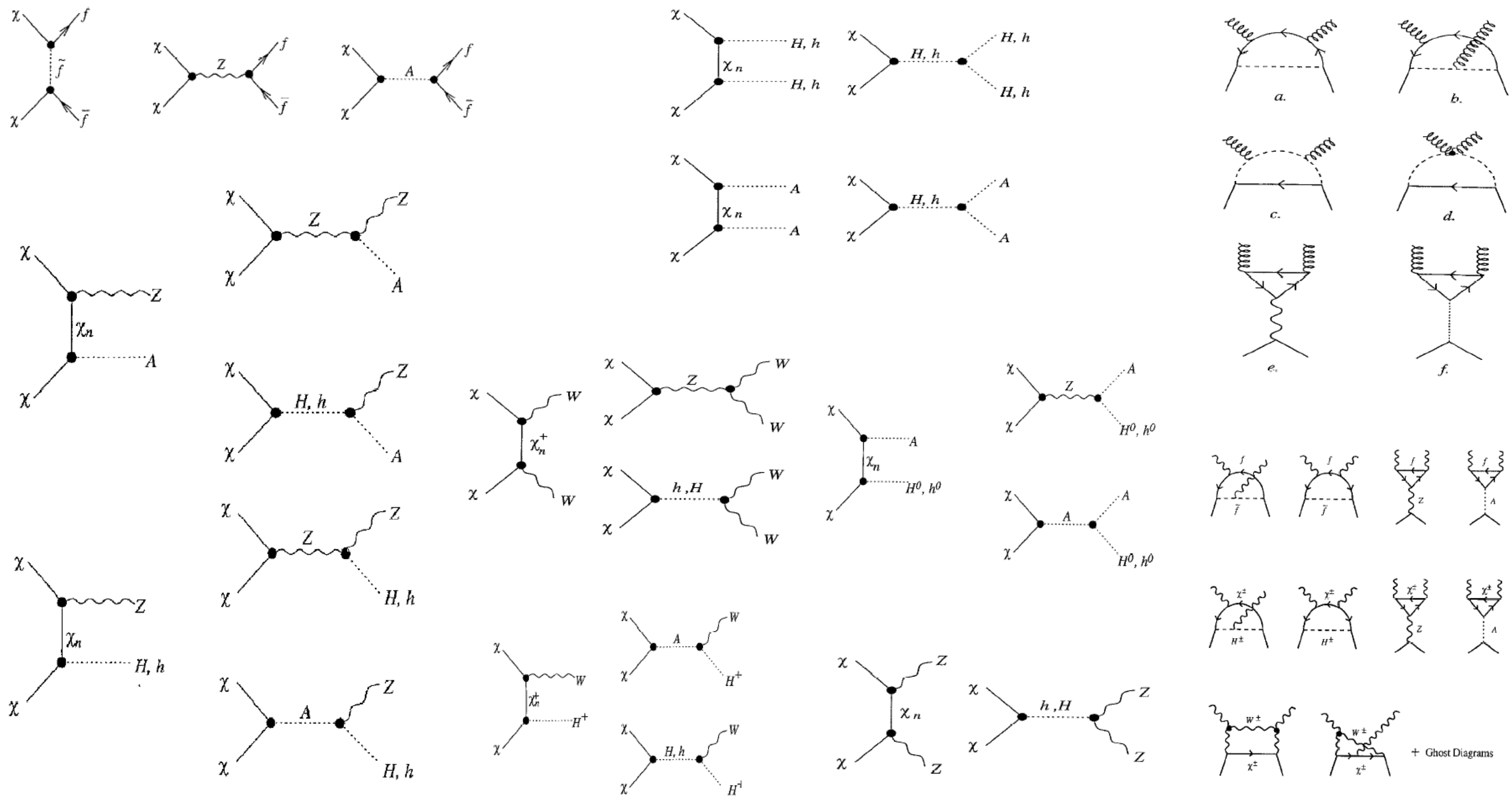




- χ are Majorana fermions, so Pauli exclusion → S_{in} = 0, L conservation →
  - P-wave suppression: $\sigma v \sim \sigma_0 + \sigma_1 v^2$, $mv^2/2 = 3T/2$ → $v^2 \sim 3T/m \sim 0.1$
  - m_f/m_W suppression
- Gauge boson diagrams suppressed for $\chi \approx$ Bino

Bottom line: annihilation is typically suppressed, $\Omega_{DM}h^2$ is typically high

NEUTRALINO ANNIHILATION



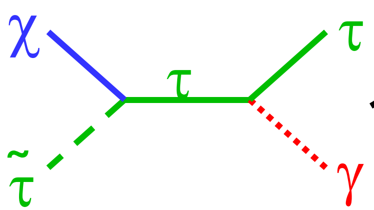
Jungman, Kamionkowski, Griest (1995)

COSMOLOGICALLY-PREFERRED SUSY

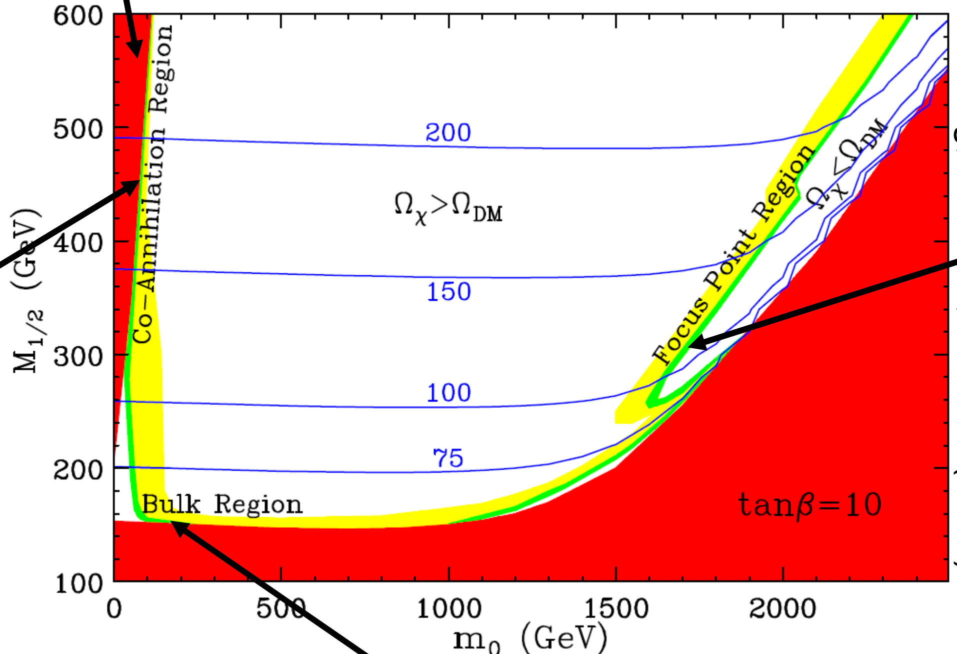
Typically get too much DM, but there are mechanisms for reducing it

Excluded:
Stau LSP

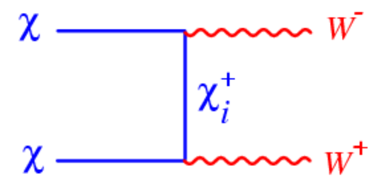
Yellow: pre-WMAP
Green: post-WMAP



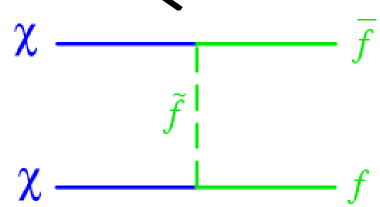
Stau and χ degenerate to within roughly T ~ m/25



Feng, Matchev, Wilczek (2003)



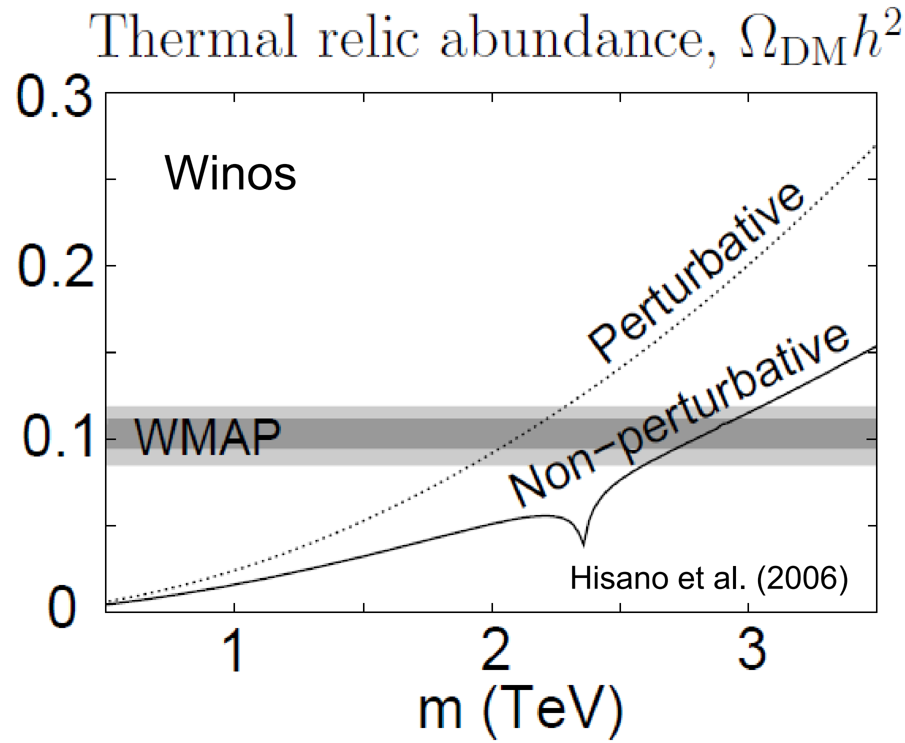
Higgsino-Bino Neutralinos



Light sfermions

COSMOLOGICALLY-PREFERRED SUSY

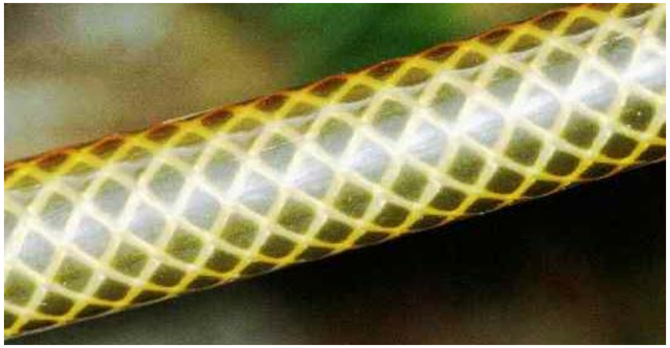
- After LHC8, there remain several neutralino candidates with the right relic density
  - Co-annihilating DM
    χ , $\tilde{\tau}_R$ degenerate, m < 600 GeV
  - Focus-point DM
    Bino-Higgsino mixture, m < 1 TeV
  - Wino-like DM
    m ~ 2.7-3 TeV
- Note: in this context, cosmology provides upper bounds!
- The Wino scenario is probably excluded by indirect detection, but the other two remain viable, provide interesting targets for LHC13 and future colliders



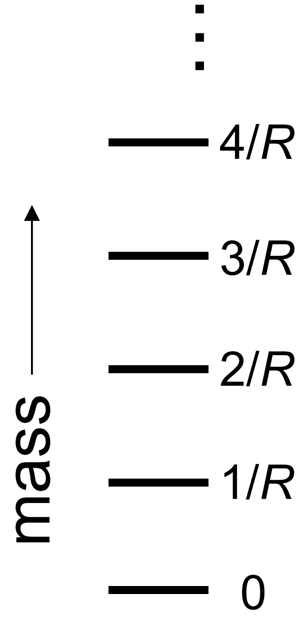
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

KK DARK MATTER

- Consider 1 extra spatial dimensions curled up in a small circle



- Particles moving in extra dimensions appear as a set of copies of normal particles.



KK-PARITY

Appelquist, Cheng, Dobrescu (2001)

- Problem: many extra 4D fields; some with mass *n*/*R*, but some are massless! E.g., 5D gauge field:

$$V_\mu(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V_\mu^n(x^\mu)\cos(ny/R) + \sum_m V_\mu^m(x^\mu)\sin(my/R)$$

$$V_5(x^\mu, y) = \underbrace{V_5(x^\mu)}_{\text{bad}} + \sum_n V_5^n(x^\mu)\cos(ny/R) + \sum_m V_5^m(x^\mu)\sin(my/R)$$

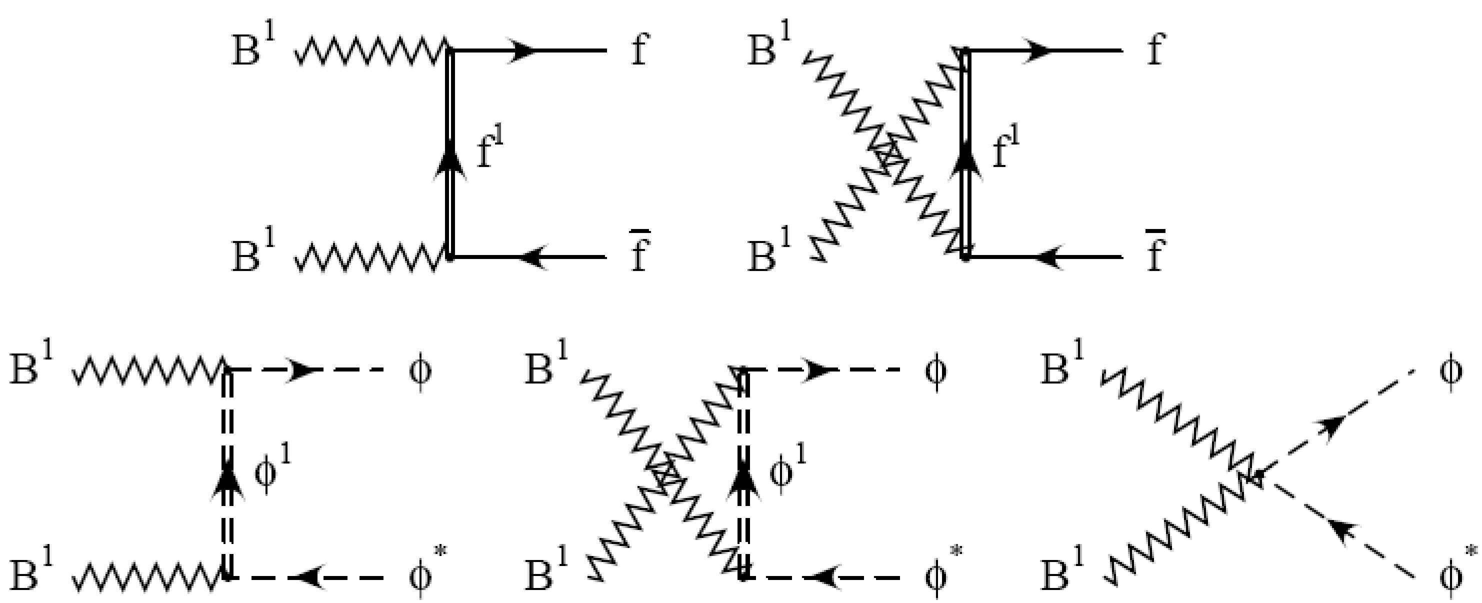
- Solution: compactify on S^1/Z_2 orbifold

$$y \to -y \ : \quad V_\mu \to V_\mu \quad V_5 \to -V_5$$

- Consequence: KK-parity $(-1)^{KK}$ conserved: interactions require an even number of odd KK modes
- 1st KK modes must be pair-produced at colliders
- LKP (lightest KK particle) is stable – dark matter!

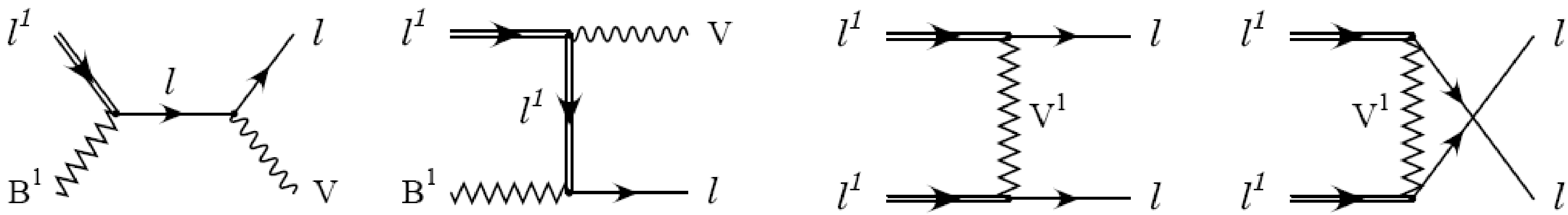
B^1 ANNIHILATION

- The level-1 KK hypercharge gauge boson B^1 is often the LKP, is neutral, and so is a natural DM candidate
- It’s a massive gauge boson, annihilates through S-wave processes, so preferred masses are larger than for Binos

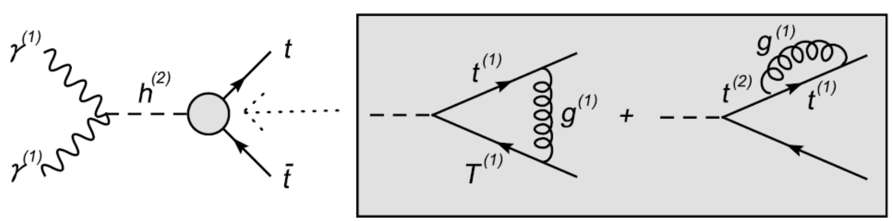


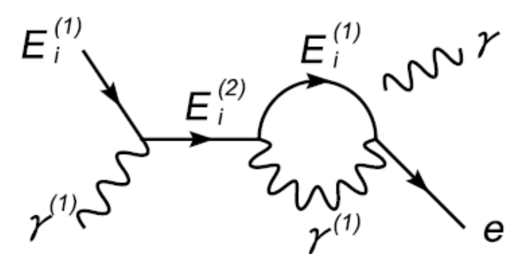
MORE B^1 ANNIHILATION

- Minimal UED has a compressed spectrum, so co-annihilation is natural. In contrast to SUSY, these typically add to the relic density



- Level-2 KK resonances

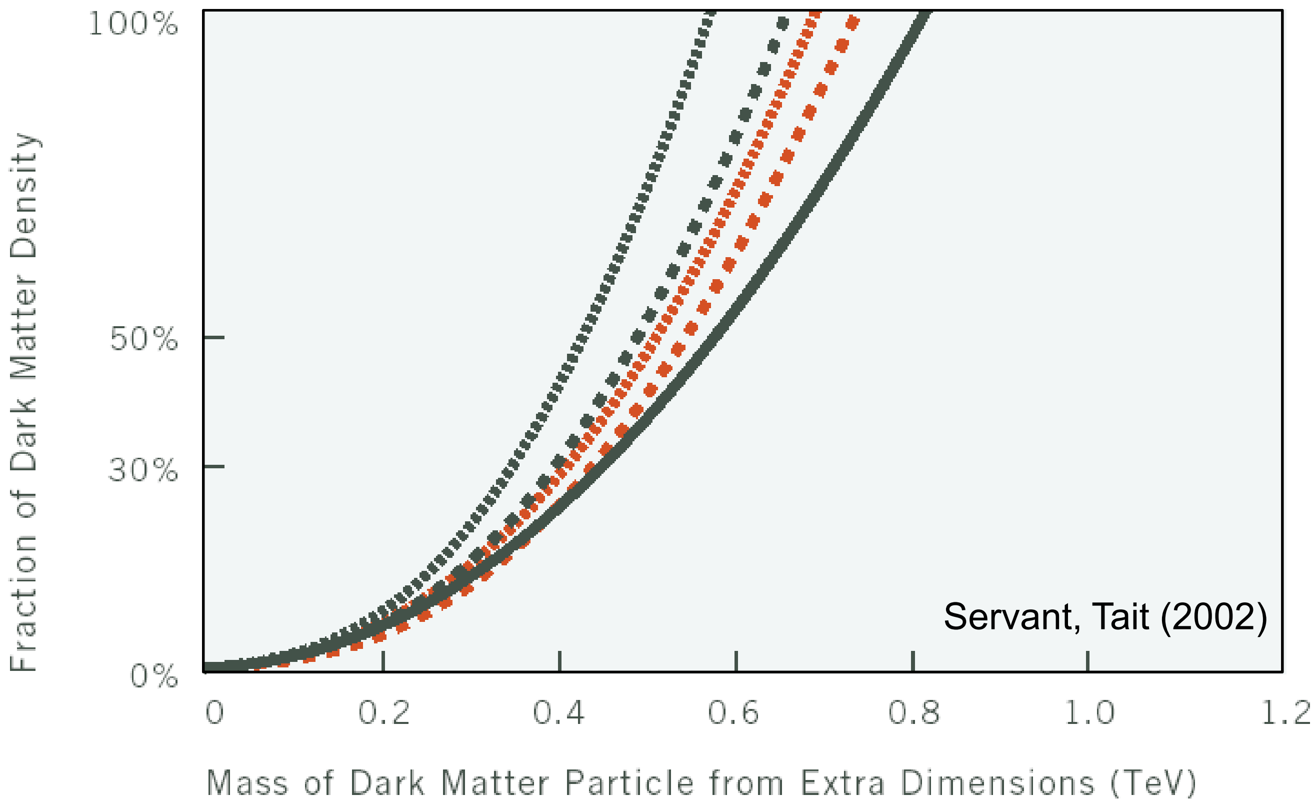




Servant, Tait (2002); Burnell, Kribs (2005)

Kong, Matchev (2005); Kakizaki, Matsumoto, Sato, Senami (2005)

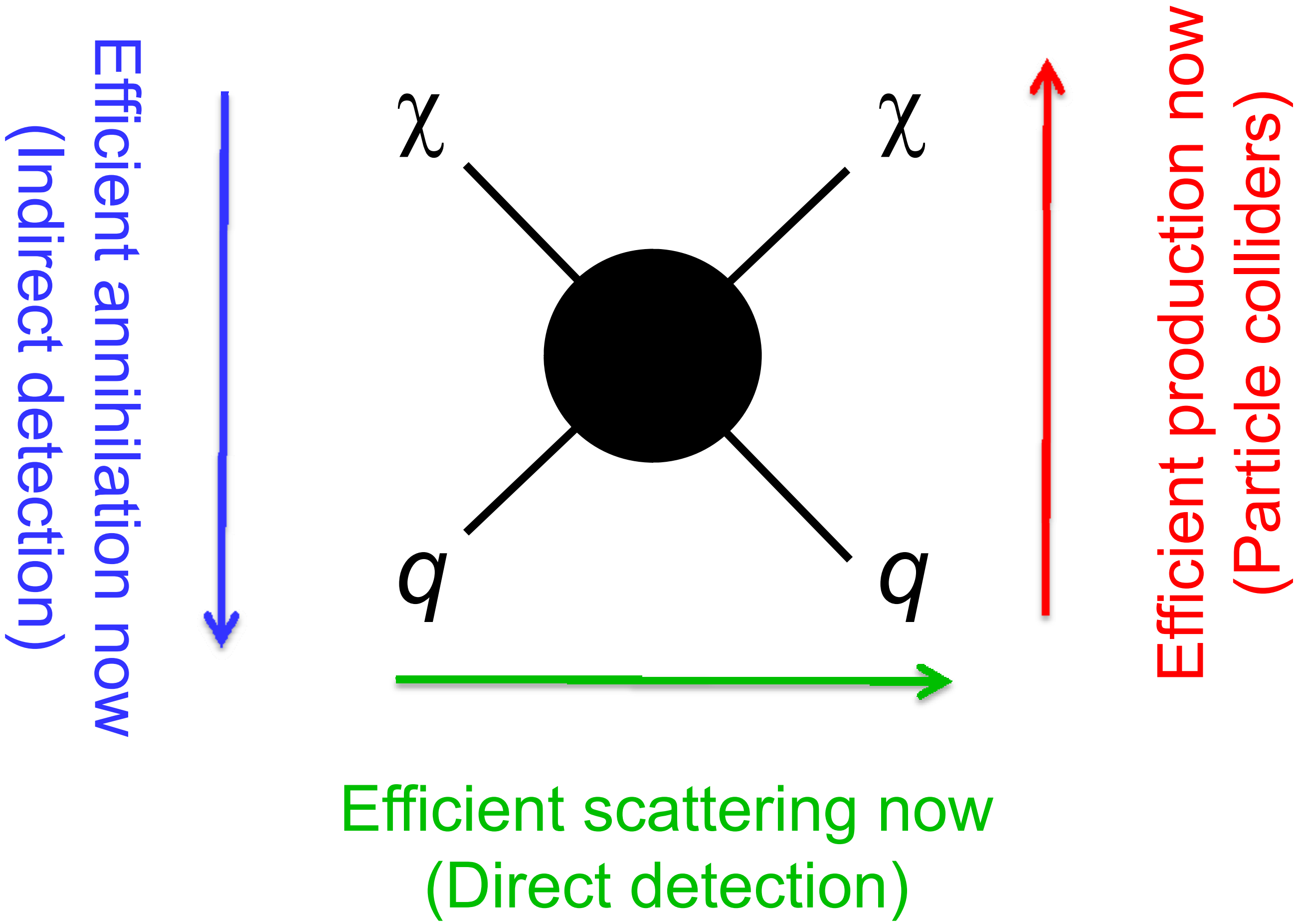
KK DARK MATTER RELIC DENSITY



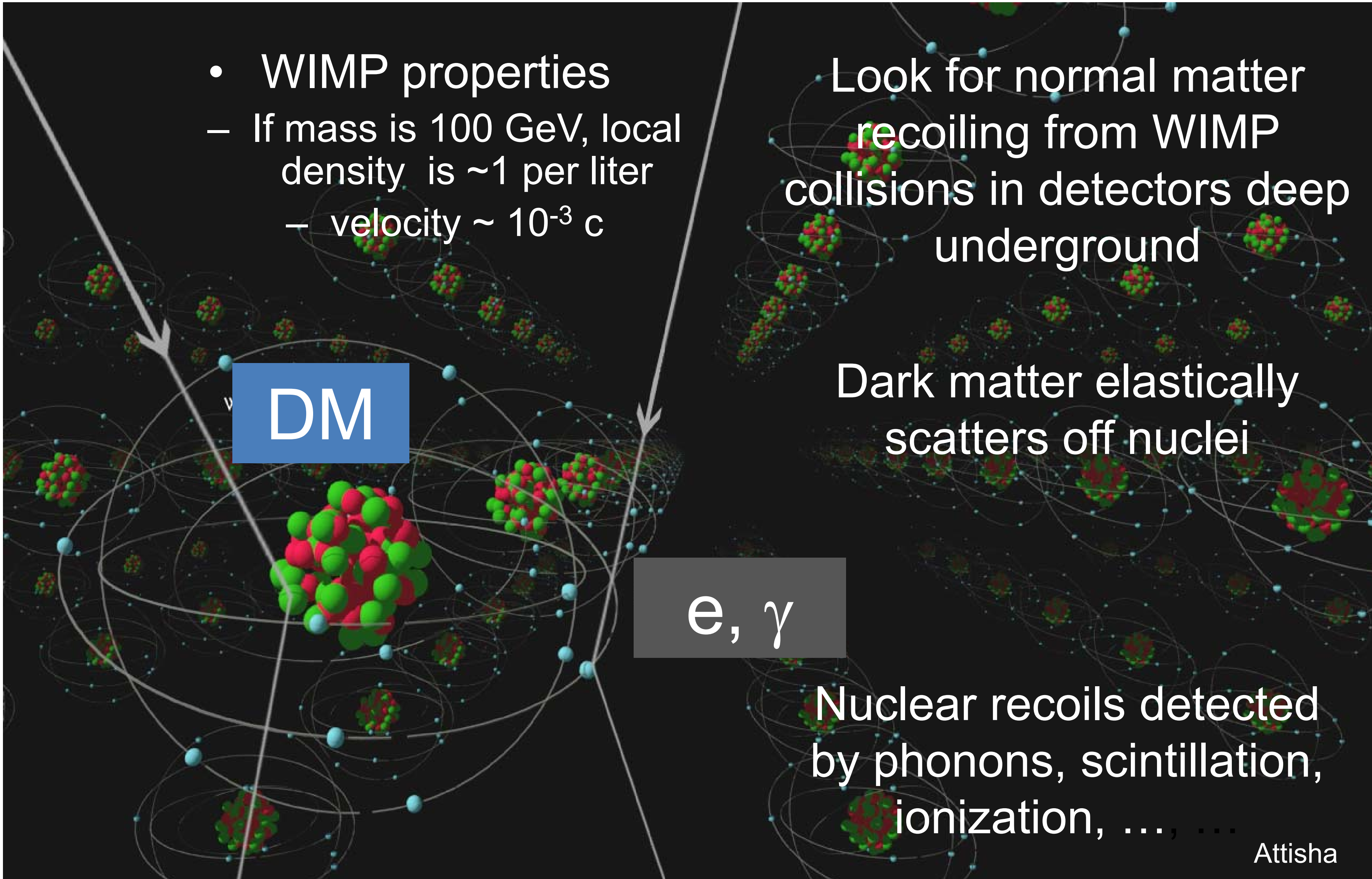
Prediction for $\Omega_{B^{(1)}} h^2$ The solid line is the case for $B^{(1)}$ alone, and the dashed and dotted lines correspond to the case in which there are one (three) flavors of nearly degenerate $e_R^{(1)}$. For each case, the black curves (upper of each pair) denote the case $\Delta = 0.01$ and the red curves (lower of each pair) $\Delta = 0.05$.

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

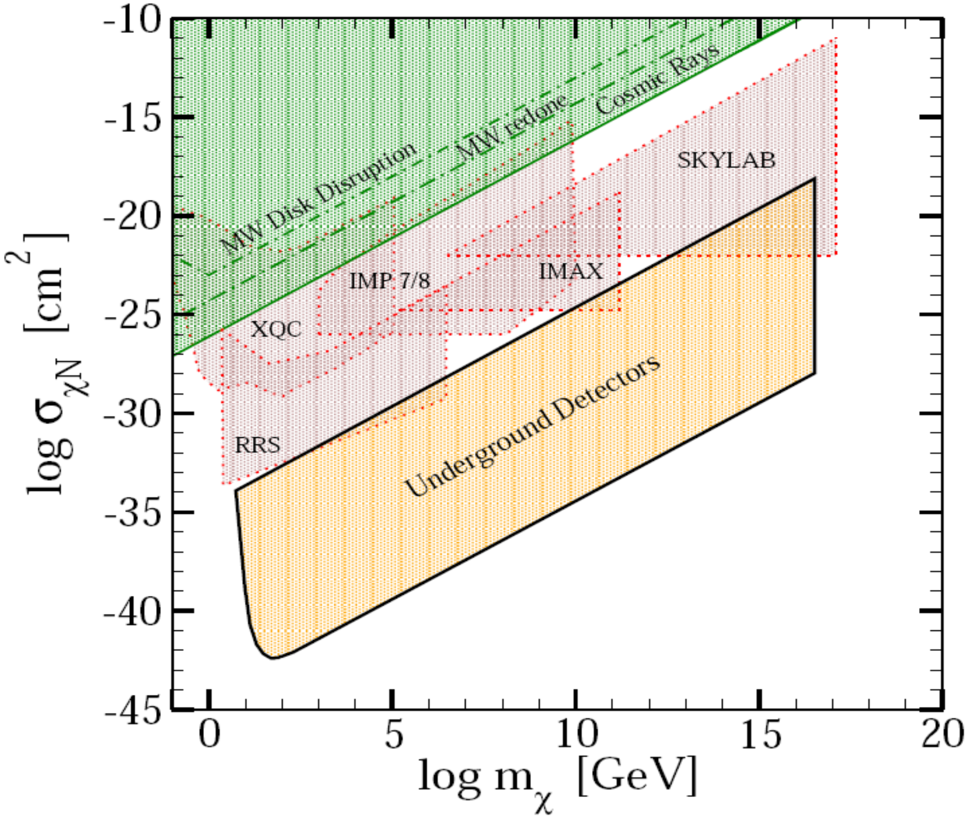
Look for normal matter recoiling from WIMP collisions in detectors deep underground

Dark matter elastically scatters off nuclei

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

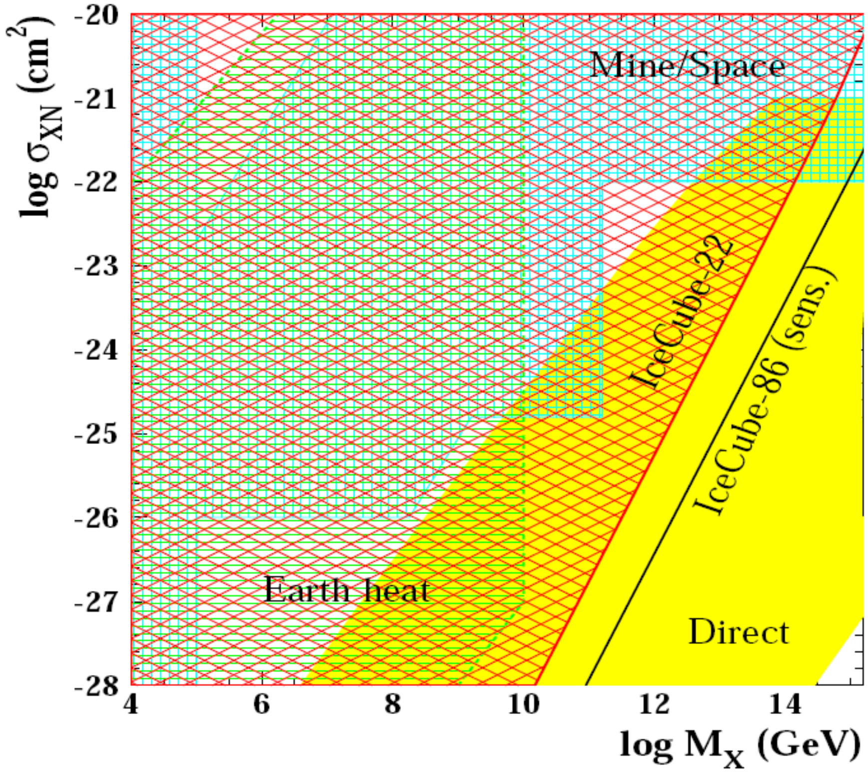
THE BIG PICTURE: UPPER BOUND

- What is the upper bound?



Mack, Beacom, Bertone (2007)

- Strongly-interacting window is now closed

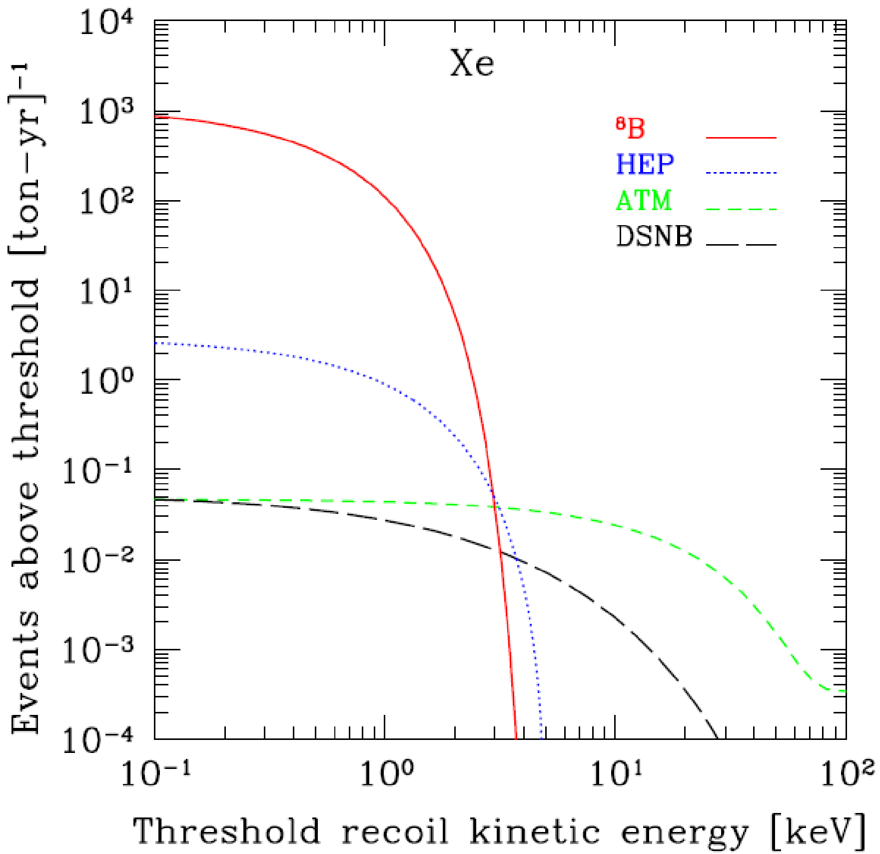


Albuquerque, de los Heros (2010)

THE BIG PICTURE: LOWER BOUND

- Is there (effectively) a lower bound?
- Solar, atmospheric, and diffuse supernova background neutrinos provide a difficult background
- The limits of background-free, non-directional direct detection searches (and also the metric prefix system!) will be reached by ~10 ton experiments probing

σ ~ 1 yb (10^{-3} zb, 10^{-12} pb, 10^{-48} cm^2)



Strigari (2009); Gutlein et al. (2010)

SPIN-INDEPENDENT VS. SPIN-DEPENDENT SCATTERING

- Consider neutralinos with quark interactions

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

- DM particles now have v ~ 10^{-3} c. In the non-relativistic limit, the first terms reduce to a spin-spin interactions, and so are called spin-dependent interactions

- The second terms are spin-independent interactions; focus on these here

SPIN-INDEPENDENT THEORY

- Theories give DM-quark interactions, but experiments measure DM-nucleus cross sections

$$\sigma_{\rm SI} = \frac{4}{\pi}\mu_N^2 \sum_q \alpha_q^{\rm SI\,2}\left[Z\frac{m_p}{m_q}f_{T_q}^p + (A-Z)\frac{m_n}{m_q}f_{T_q}^n\right]^2 ,$$

where $\mu_N = \dfrac{m_\chi m_N}{m_\chi + m_N}$ is the reduced mass, and $f_{T_q}^{p,n} = \dfrac{\langle p,n|m_q\bar{q}q|p,n\rangle}{m_{p,n}}$

is the fraction of the nucleon's mass carried by quark *q*, with

$$f_{T_u}^p = 0.020 \pm 0.004 \qquad f_{T_u}^n = 0.014 \pm 0.003 \qquad f_{T_s}^p = 0.118 \pm 0.062 \qquad f_{T_s}^n = 0.118 \pm 0.062$$

$$f_{T_d}^p = 0.026 \pm 0.005 \qquad f_{T_d}^n = 0.036 \pm 0.008 \qquad f_{T_{c,b,t}}^{p,n} = \frac{2}{27}f_{T_G}^{p,n} = \frac{2}{27}(1 - f_{T_u}^{p,n} - f_{T_d}^{p,n} - f_{T_s}^{p,n})$$

The last one accounts for gluon couplings through heavy quark loops.

- This may be parameterized by $\sigma_A = \dfrac{\mu_A^2}{M_*^4}\left[f_p Z + f_n(A-Z)\right]^2$,

where $f_{p,n}$ are the nucleon level couplings. Note that f_p and f_n are not necessarily equal.

SPIN-INDEPENDENT EXPERIMENT

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

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

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

Experiment: number of target nuclei

Astrophysics: local DM number density

Experiment: recoil energy

Astrophysics: DM velocity distribution

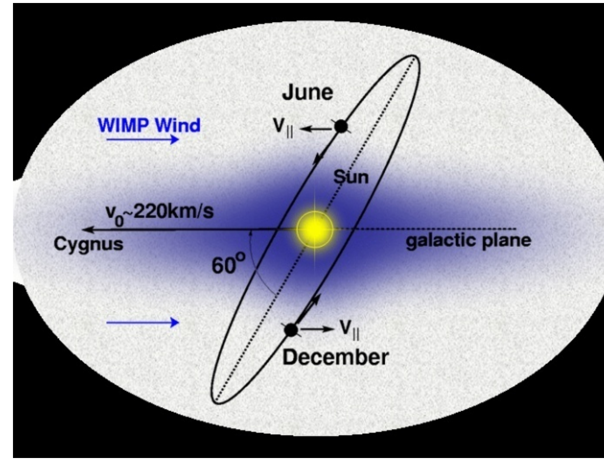
Nuclear physics: form factor

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

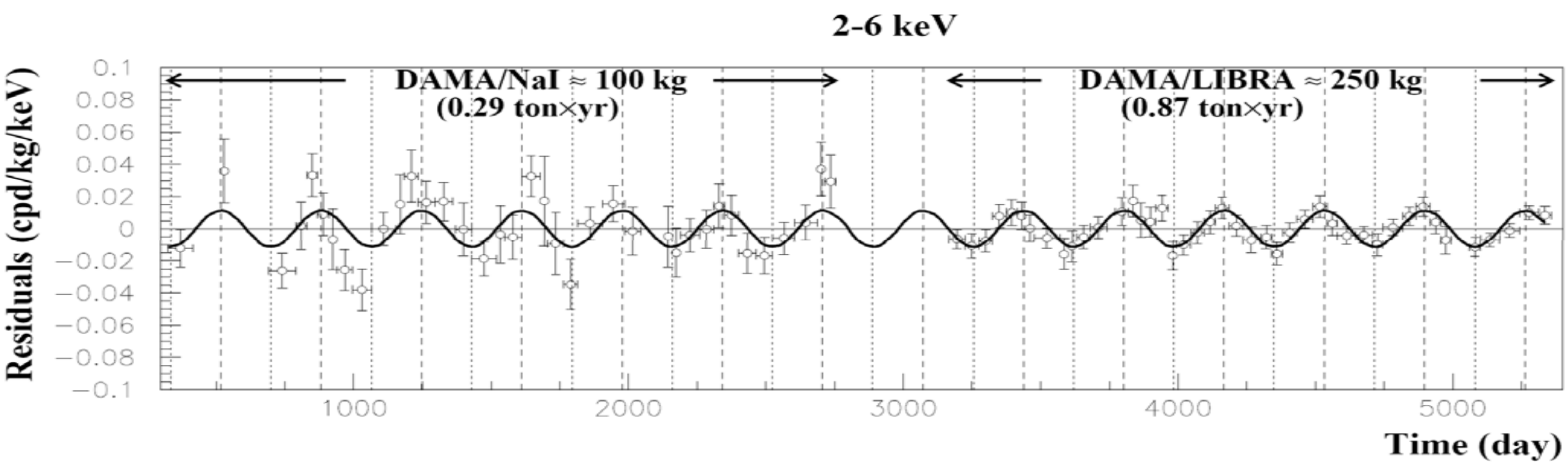
CURRENT STATUS

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

Drukier, Freese, Spergel (1986)



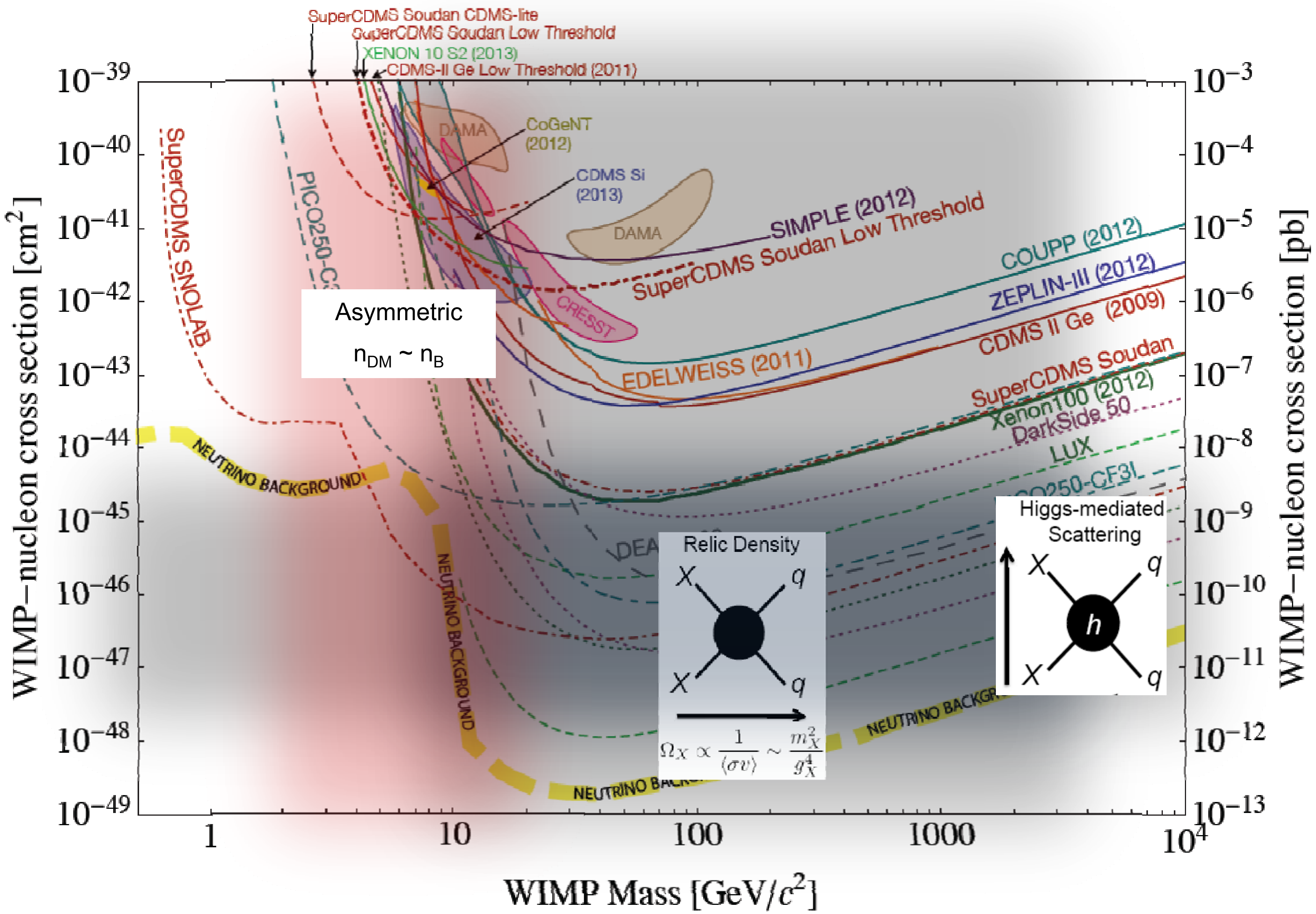
DAMA: 9σ signal with T ~ 1 year, max ~ June 2



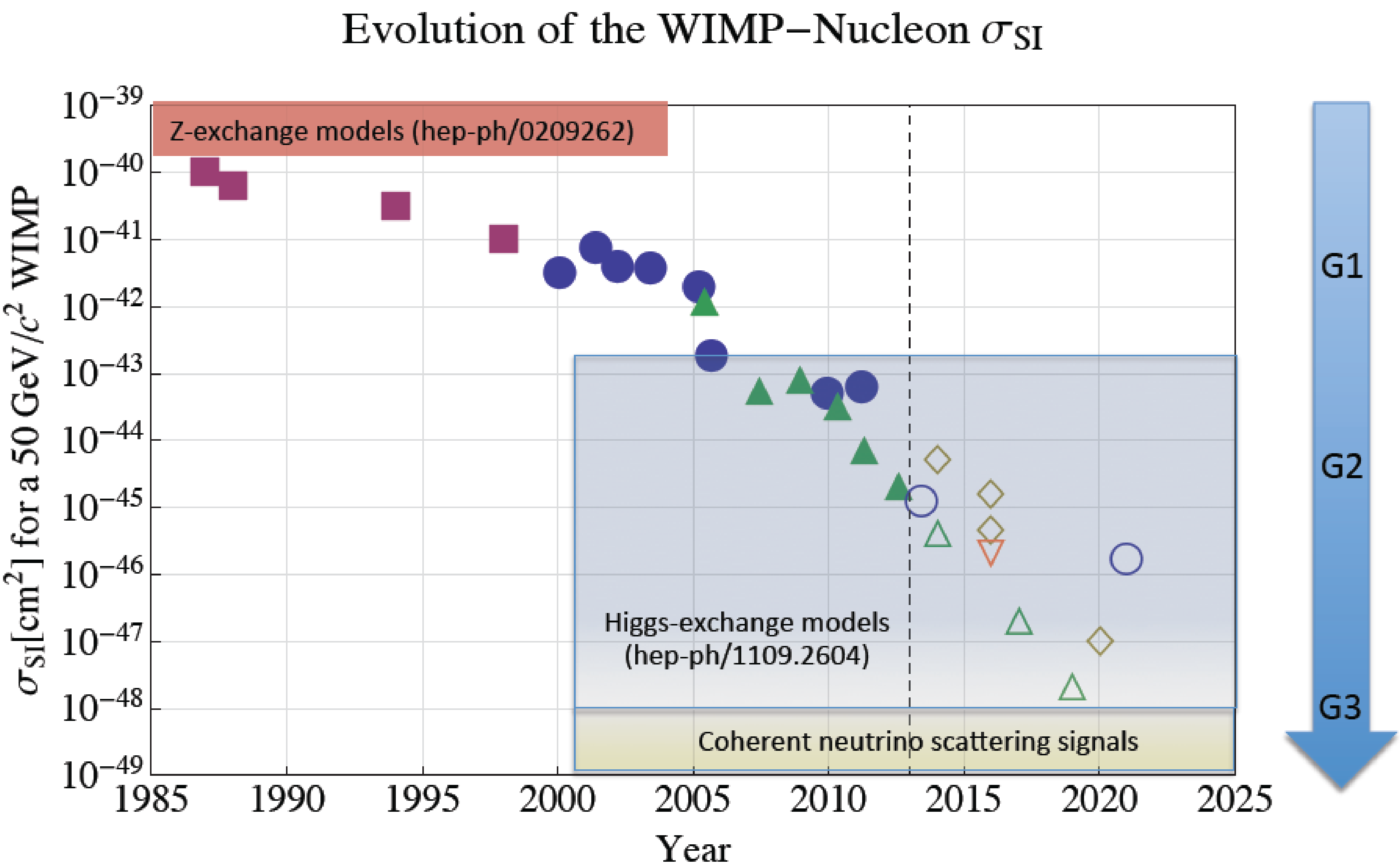
DAMA (2013)

DAMA signal now supplemented by others

CURRENT STATUS AND FUTURE PROSPECTS



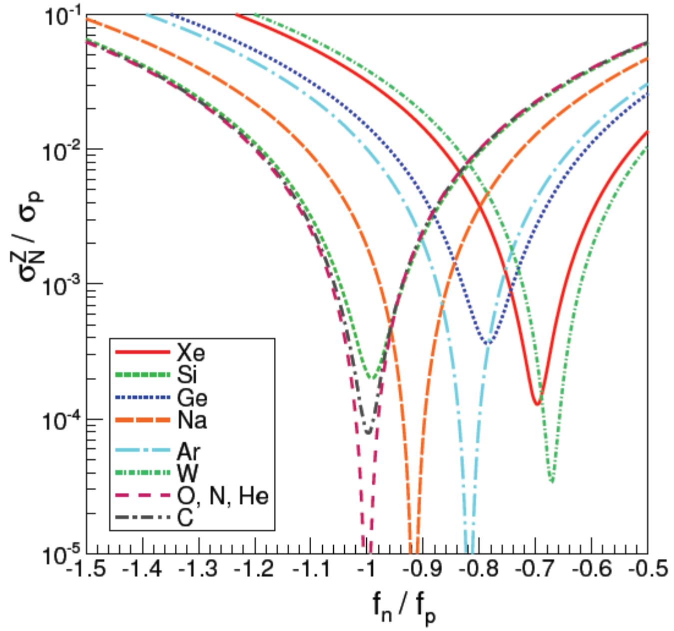
MOORE'S LAW FOR DARK MATTER



ISOSPIN-VIOLATING DARK MATTER

- The direct detection anomalies have motivated many DM ideas. As an example, consider a particularly simple model with HEP implications: IVDM
- Recall that DM scattering off nuclei is
  - $\sigma_A \sim [\ f_p Z + f_n (A-Z)\ ]^2$
- Typically assume
  - $f_n = f_p$, $\sigma_A \sim A^2$
- IVDM relaxes this assumption, introduces 1 new parameter: f_n / f_p

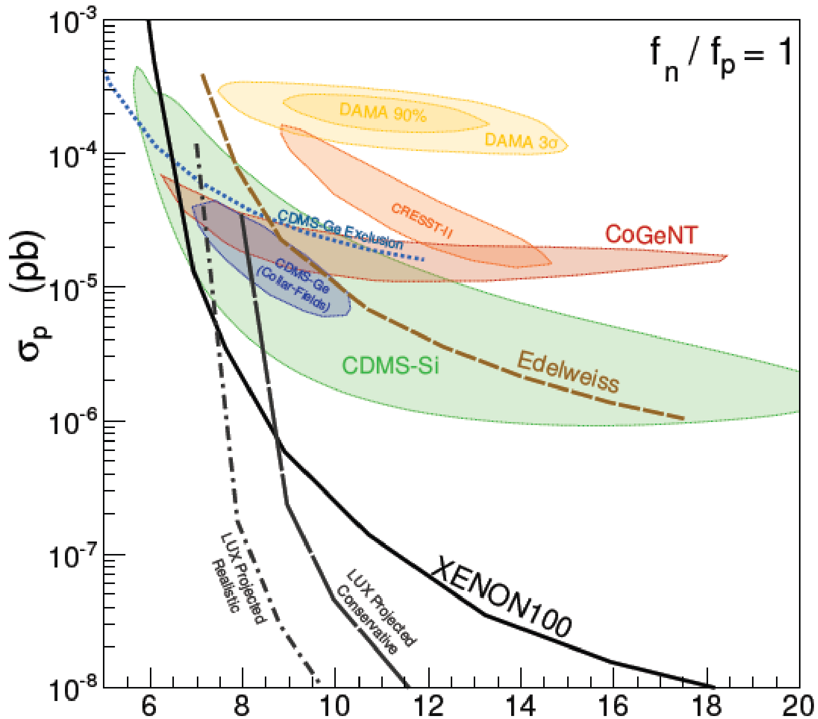
- Can decouple any given isotope by a suitable choice of f_n / f_p .
- Crucially important to account for isotope distributions

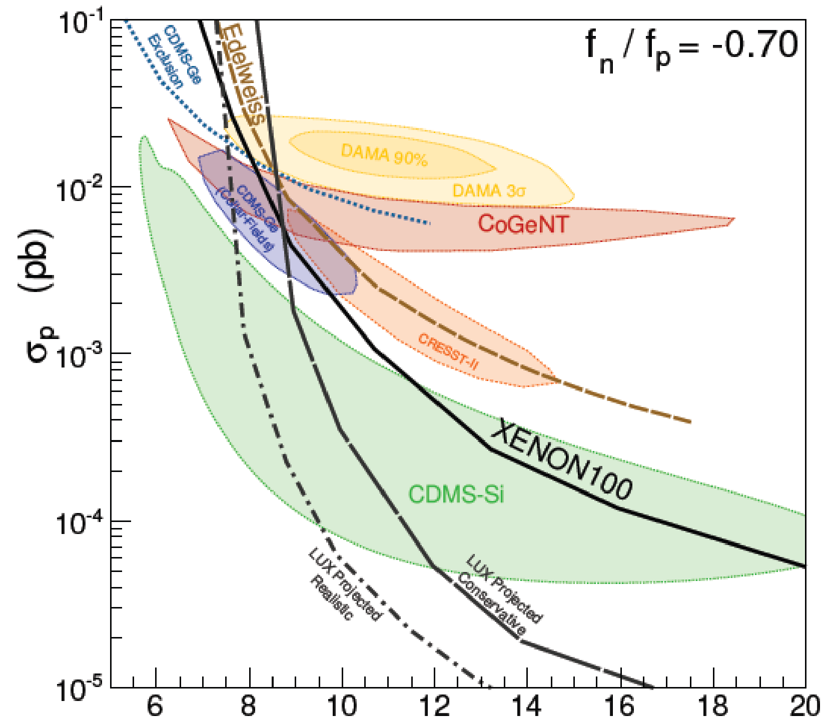


Feng, Kumar, Marfatia, Sanford (2013)

IVDM IMPLICATIONS

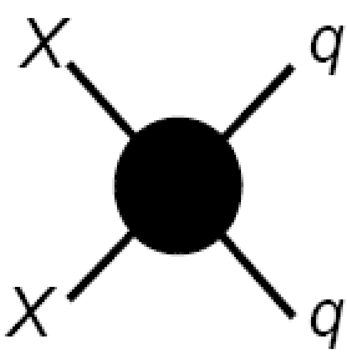
- LUX/XENON and DAMA are irreconcilable, but LUX/XENON and CDMS are consistent for $f_n/f_p = -0.7$ (roughly $f_u/f_d = -1$)
- Compared to the usual isospin-conserving case $f_n/f_p = 1$, larger DM couplings to up and down quarks are allowed, and are even required to explain anomalies; strong implications for LHC





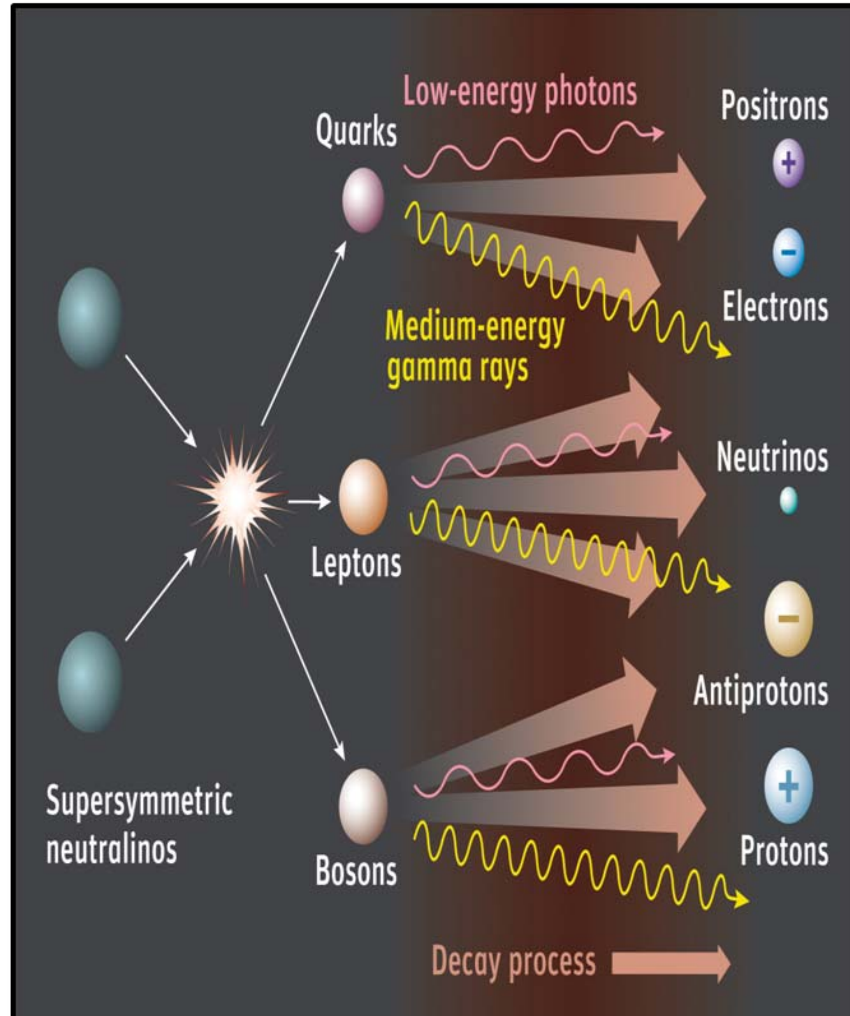
INDIRECT DETECTION

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



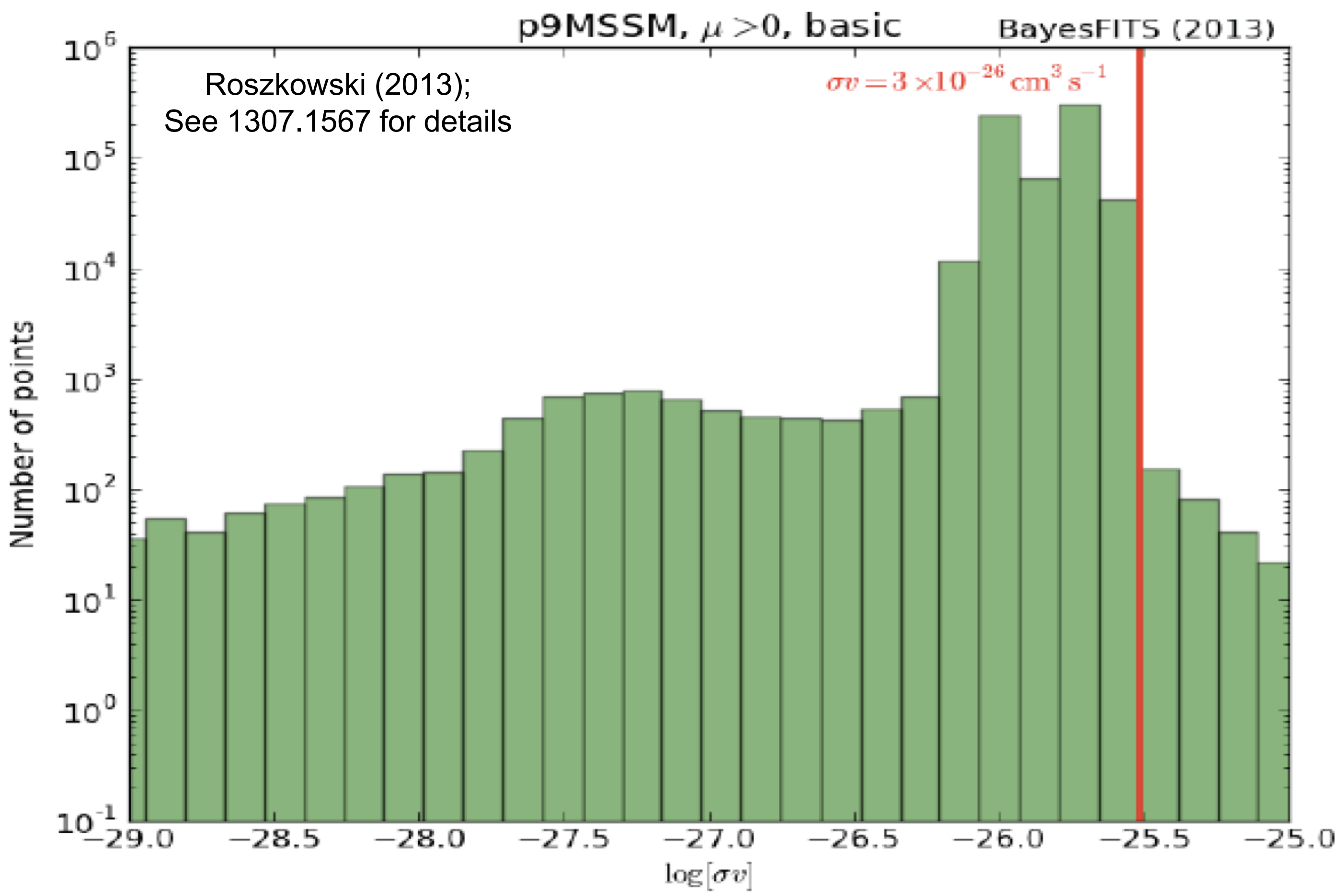
- The relic density provides a target annihilation cross section

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



ROBUSTNESS OF THE TARGET CROSS SECTION

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



INDIRECT DETECTION

FILL IN THE BLANKS:

Dark matter annihilates in ________________ to
a place

____________ , which are detected by ______________ .
particles an experiment

PHOTONS

Dark Matter annihilates in __the GC / dwarf galaxies__ to
(a place)

__photons__ , which are detected by __Fermi, VERITAS, …__ .
(some particles) (an experiment)

The flux factorizes: $$\frac{d\Phi_\gamma}{d\Omega dE} = \underbrace{\sum_i \frac{dN_\gamma^i}{dE} \sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

Particle physics: two kinds of signals

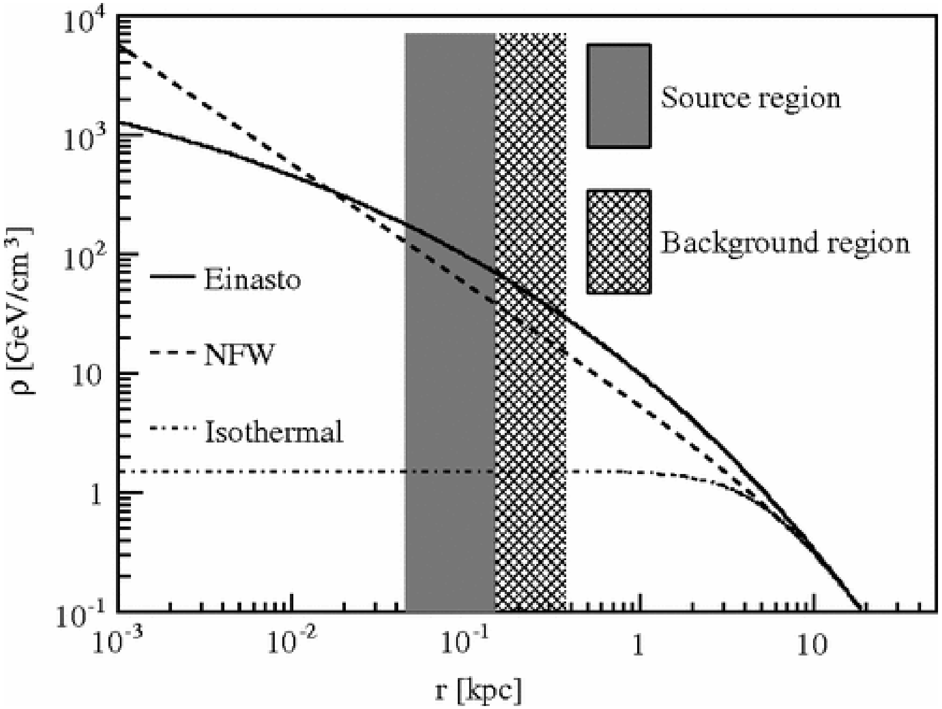
- Lines from XX → $\gamma\gamma$, γZ: loop-suppressed rates, but distinctive signal
- Continuum from XX → ff → γ: τree-level rates, but a broad signal

HALO PROFILES

Astrophysics: 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

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

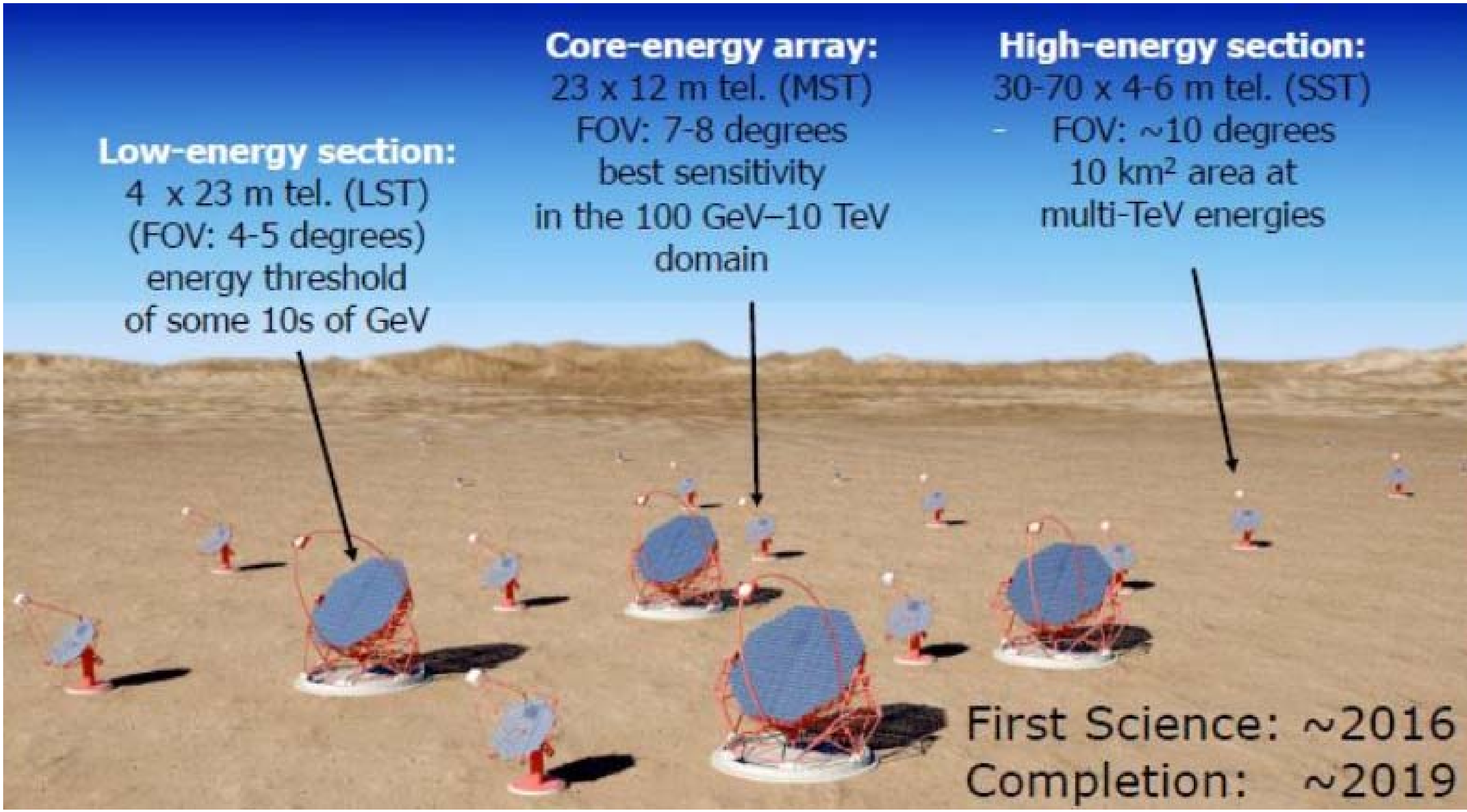


PHOTONS: CURRENT EXPERIMENTS

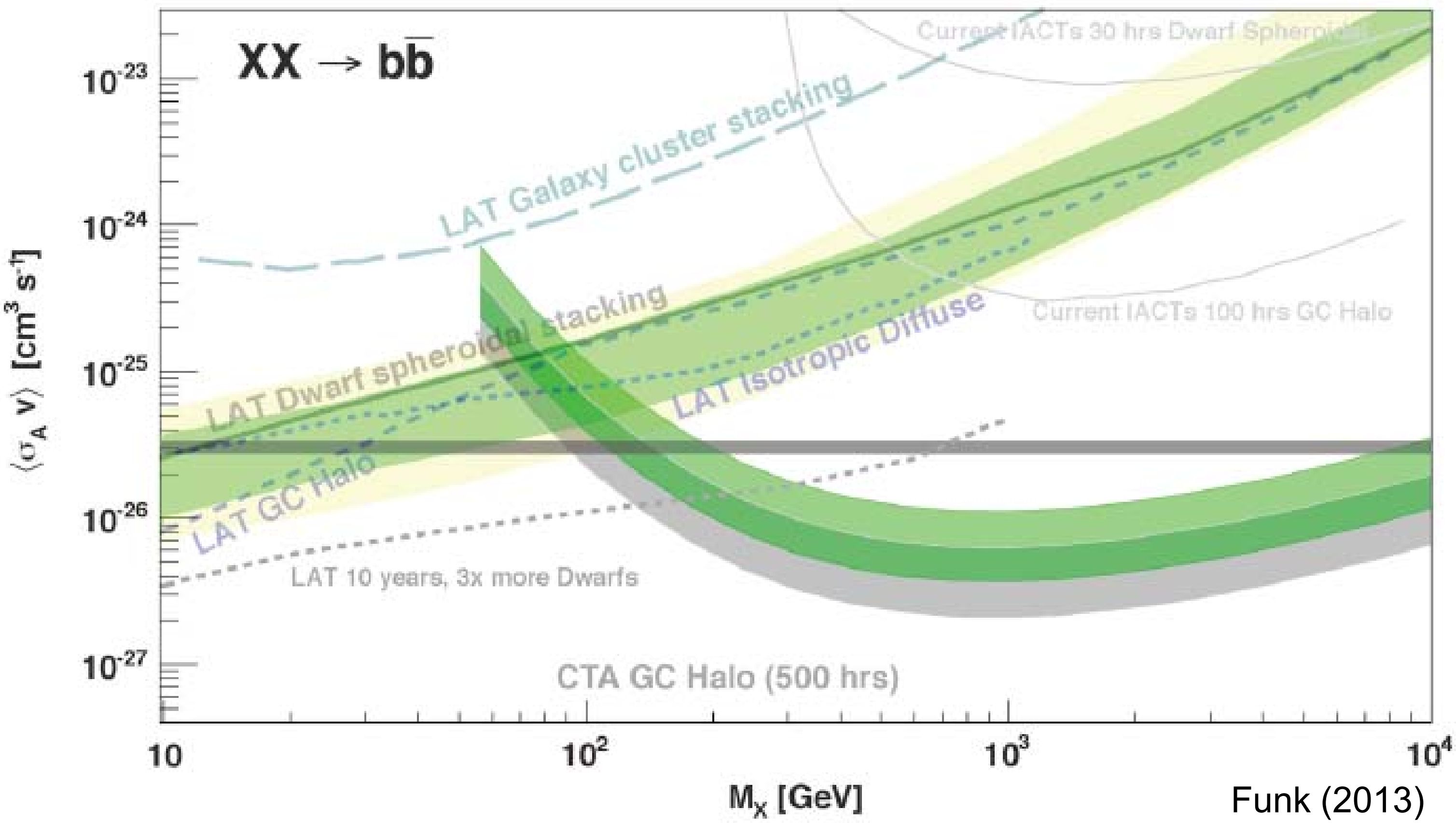
Veritas, Fermi-LAT, HAWC, and others

PHOTONS: FUTURE EXPERIMENTS

Cerenkov Telescope Array



PHOTONS: STATUS AND PROSPECTS



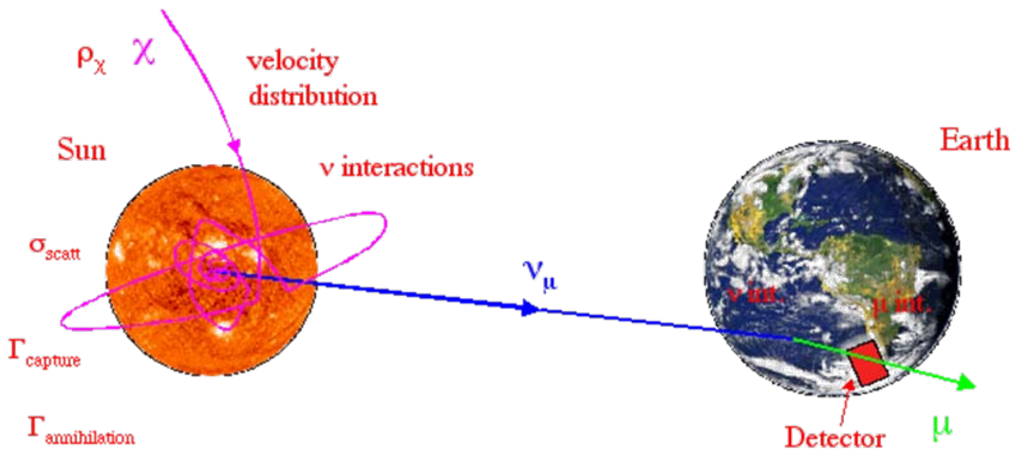
Funk (2013)

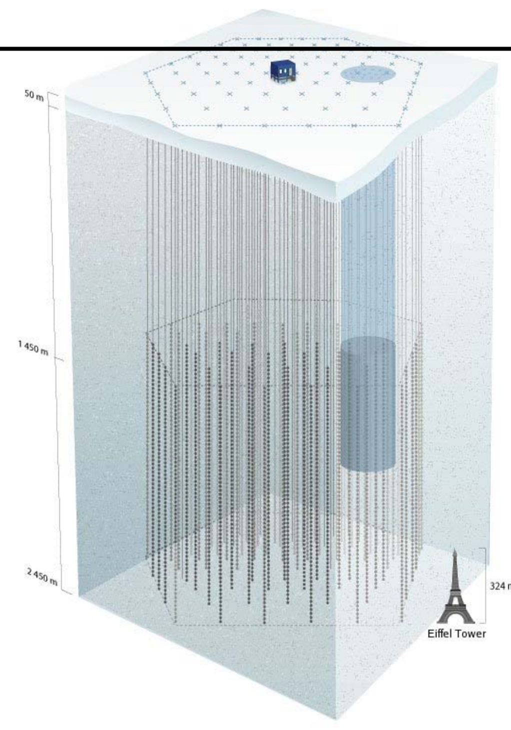
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV

INDIRECT DETECTION: NEUTRINOS

Dark Matter annihilates in __the center of the Sun__ to
a place

neutrinos , which are detected by __ANTARES / PINGU__ .
some particles | an experiment

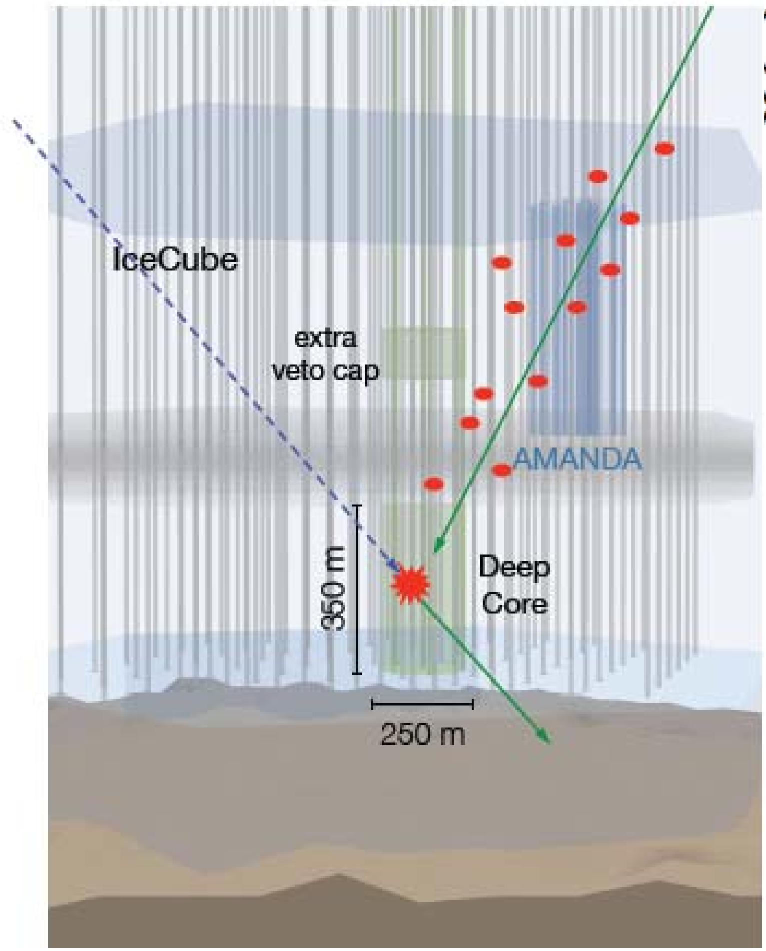


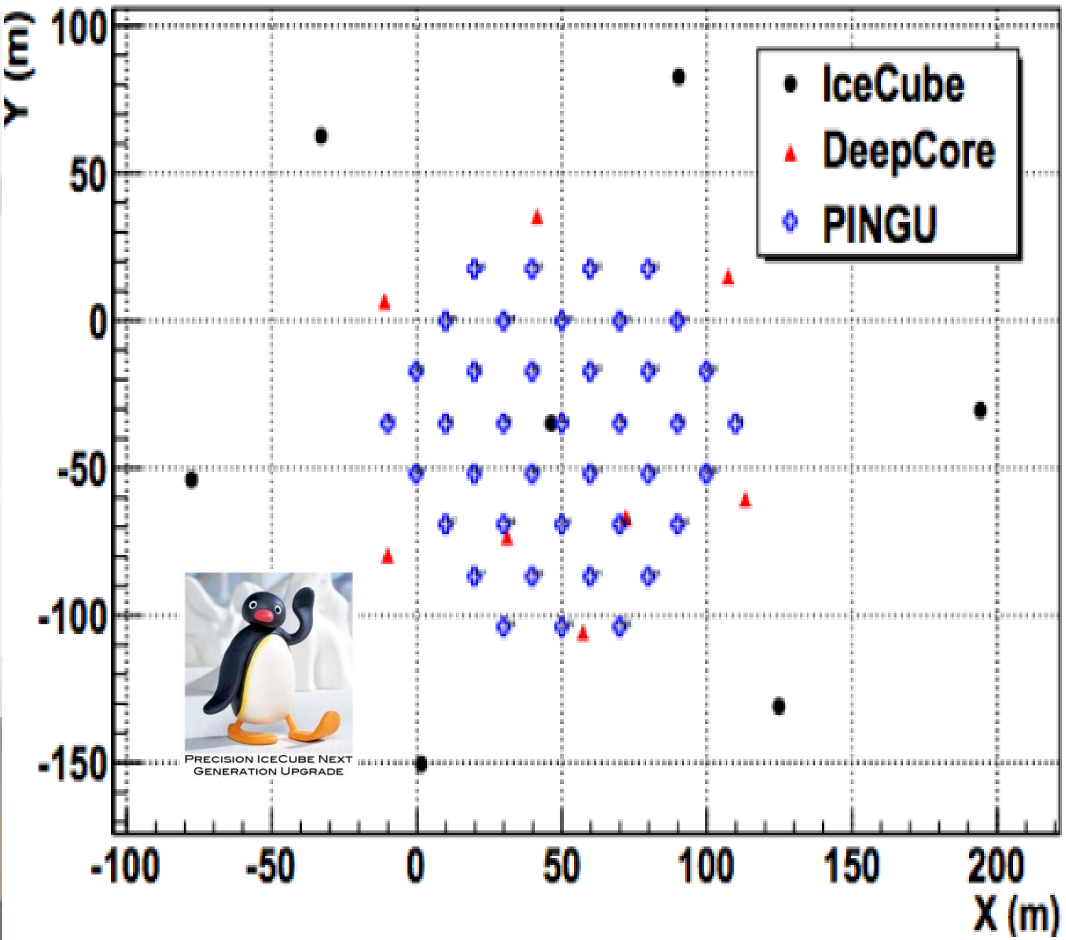


NEUTRINOS: EXPERIMENTS

Current: IceCube/DeepCore, ANTARES

Future: PINGU

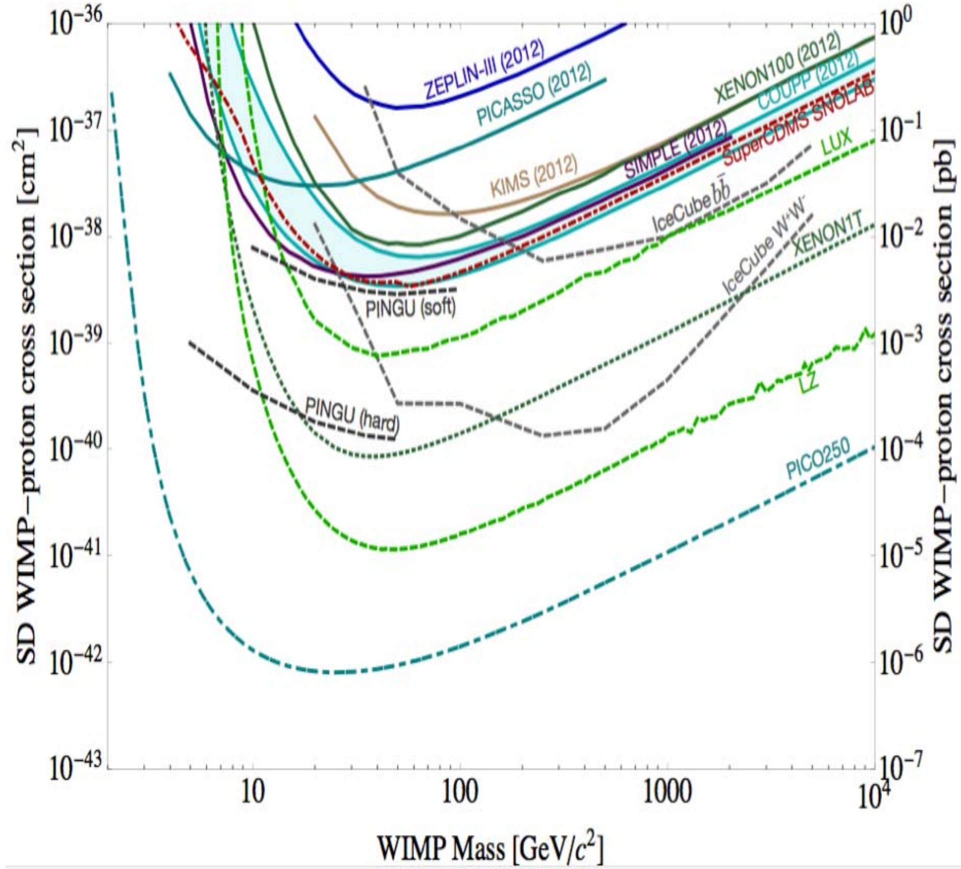




NEUTRINOS: STATUS AND PROSPECTS

The Sun is typically in equilibrium

- Spin-dependent scattering off hydrogen → capture rate → annihilation rate
- Neutrino indirect detection results are typically plotted in the (m_X, σ_{SD}) plane, compared with direct detection experiments



Future experiments like PINGU may discover the smoking-gun signal of HE neutrinos from the Sun, or set stringent σ_{SD} limits, extending the reach of IceCube/DeepCore

INDIRECT DETECTION: ANTI-MATTER

Dark Matter annihilates in ___the halo___ to
a place

___positrons___, which are detected by ___Fermi/AMS/…___.
some particles | an experiment

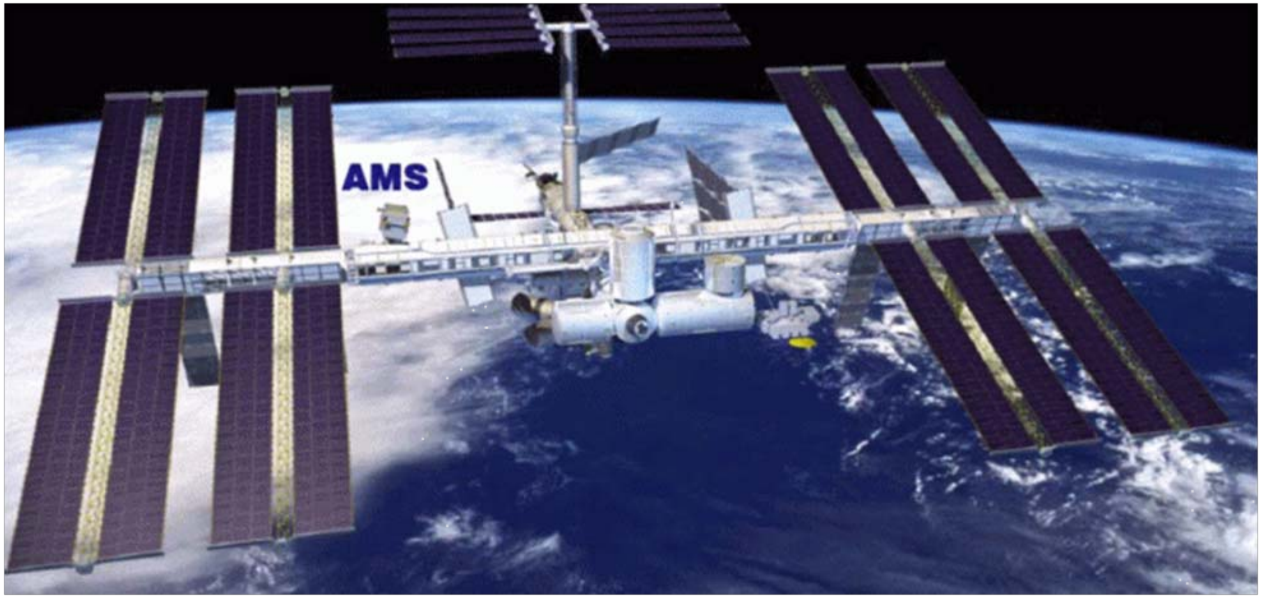
In contrast to photons and neutrinos, anti-matter does not travel in straight lines

- bumps around the local halo before arriving in our detectors
- for example, positrons, created with energy E_0, detected with energy E

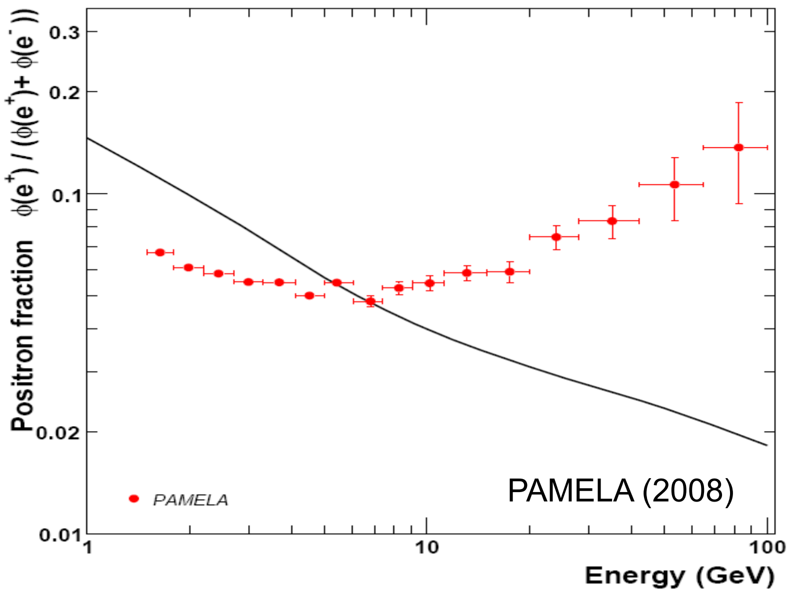
$$\frac{d\Phi_{e^+}}{d\Omega dE} = \frac{\rho_\chi^2}{m_\chi^2} \sum_i \sigma_i v B_{e^+}^i \int dE_0 \, f_i(E_0) \, G(E_0, E)$$

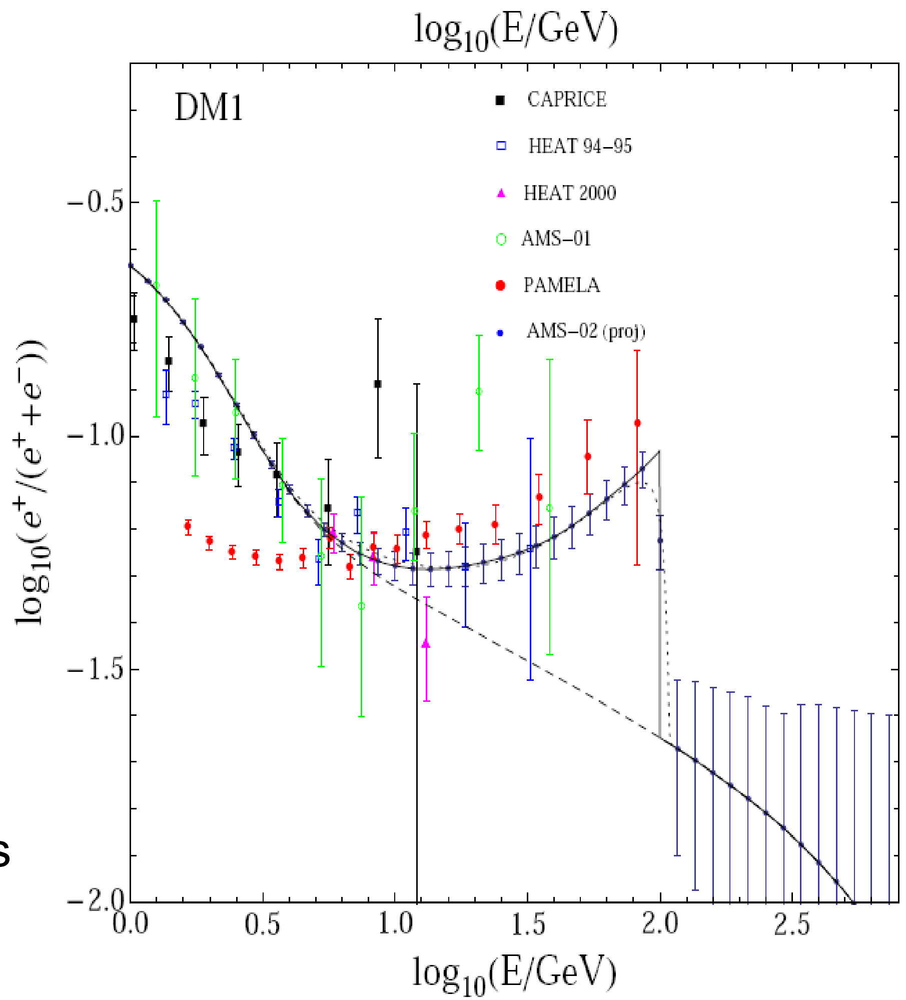
ANTI-MATTER: EXPERIMETS

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



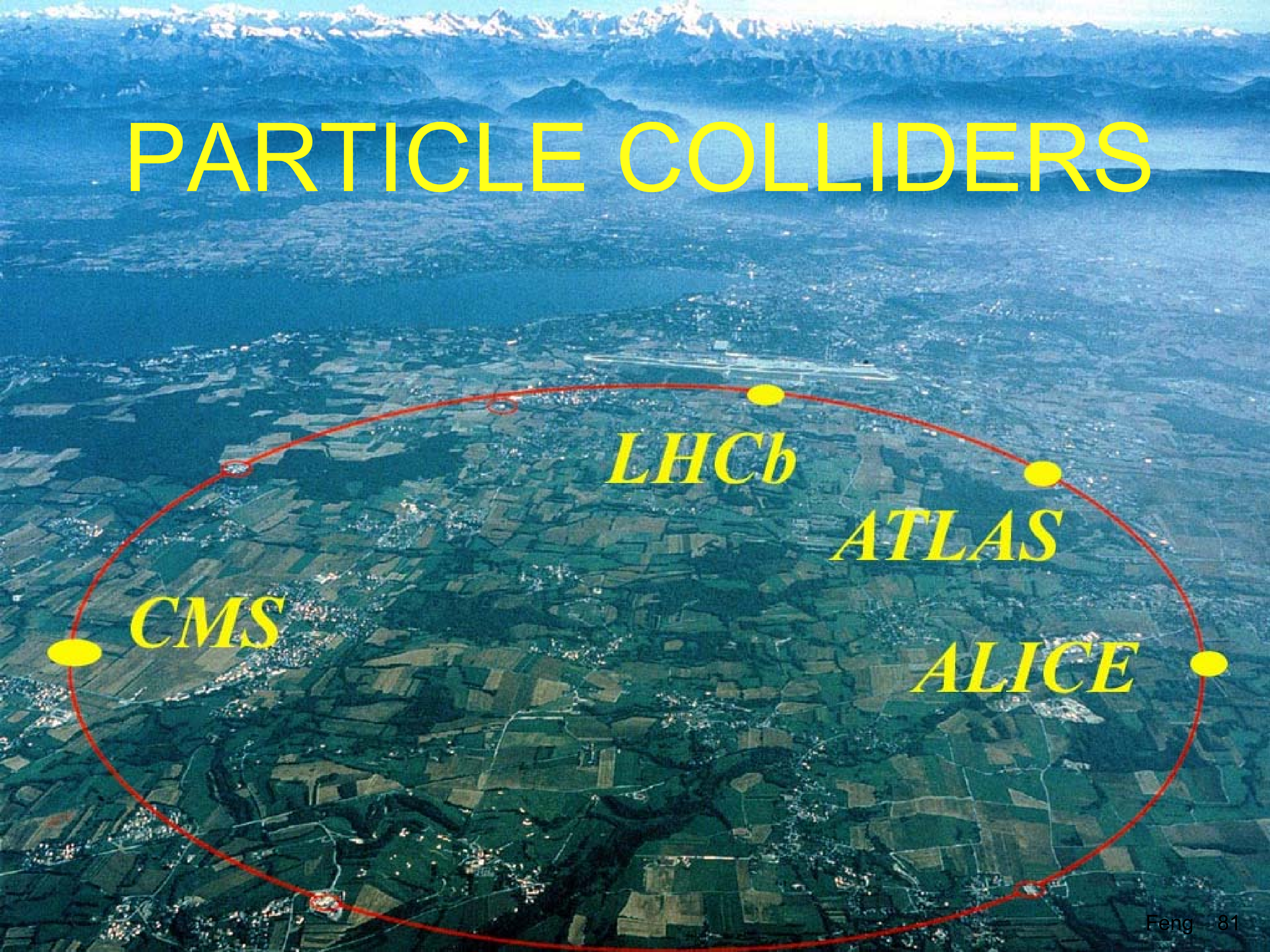
POSITRONS: STATUS AND PROSPECTS





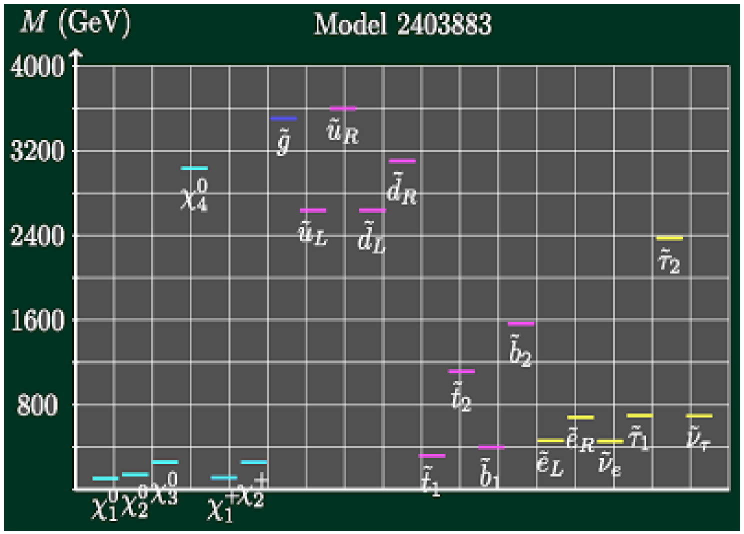
Pato, Lattanzi, Bertone (2010)

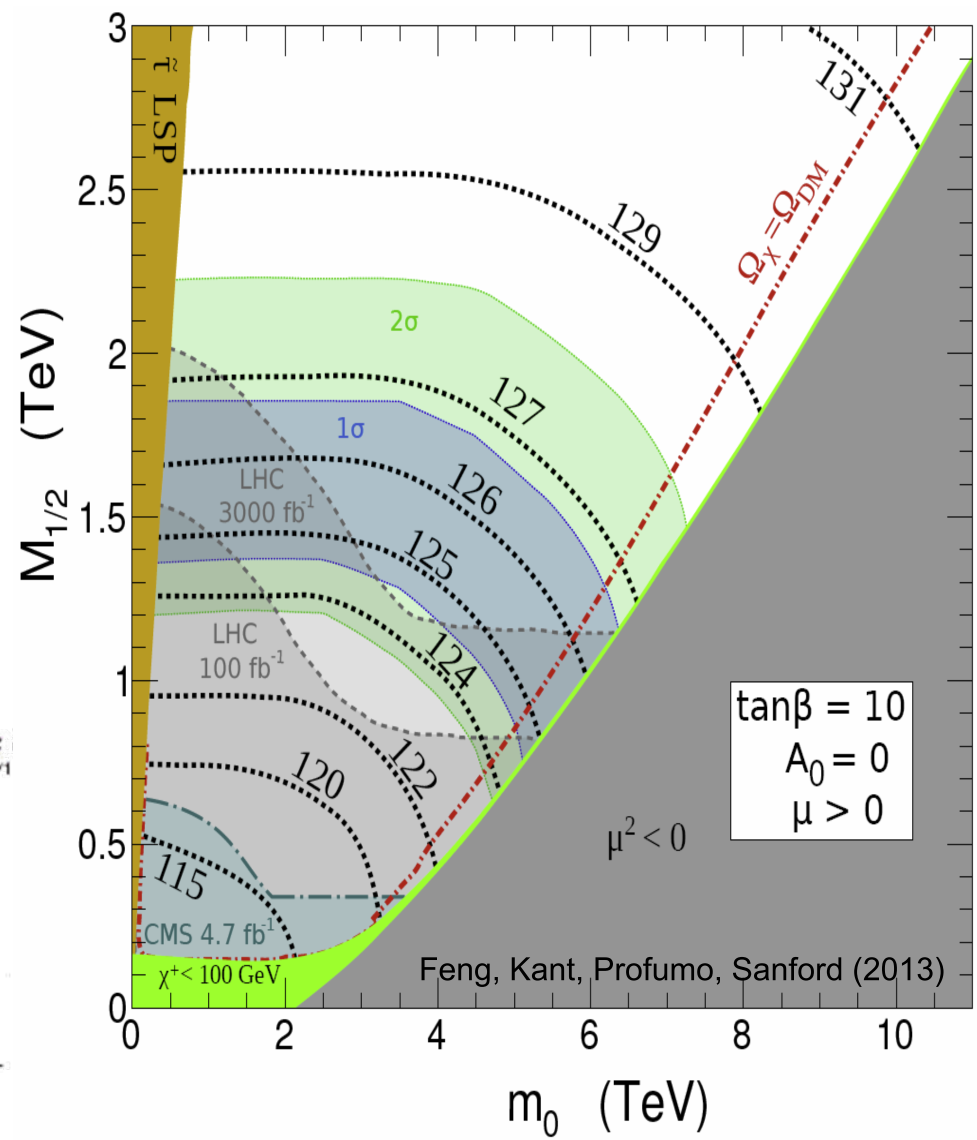
- Flux is a factor of 100-1000 too big for a thermal relic; requires
  - Enhancement from particle physics
  - Alternative production mechanism
- Difficult to distinguish from pulsars


PARTICLE COLLIDERS
LHCb
ATLAS
CMS
ALICE

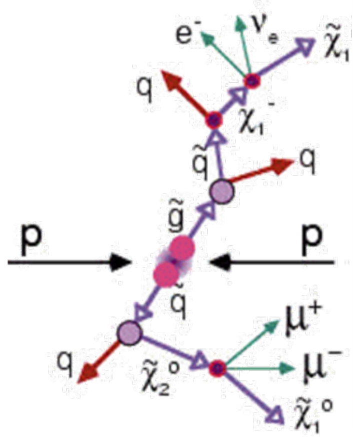
DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)



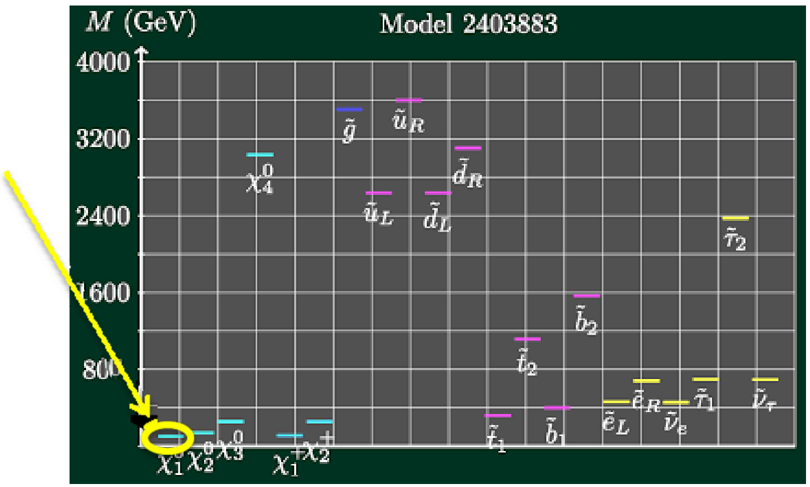


Cascades: Produce other particles, which decay to DM

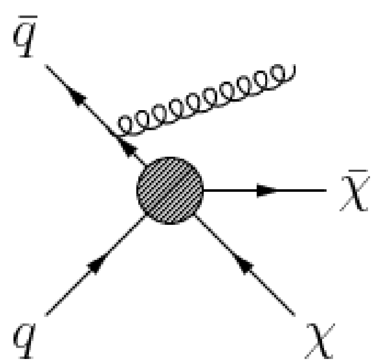


DARK MATTER AT COLLIDERS

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)

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

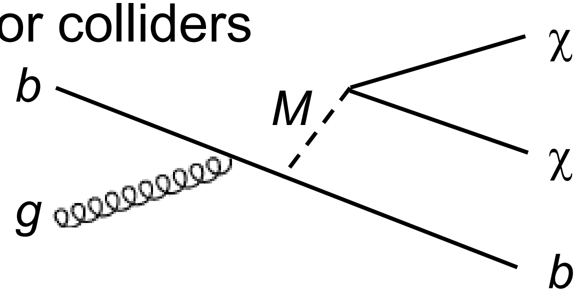
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)

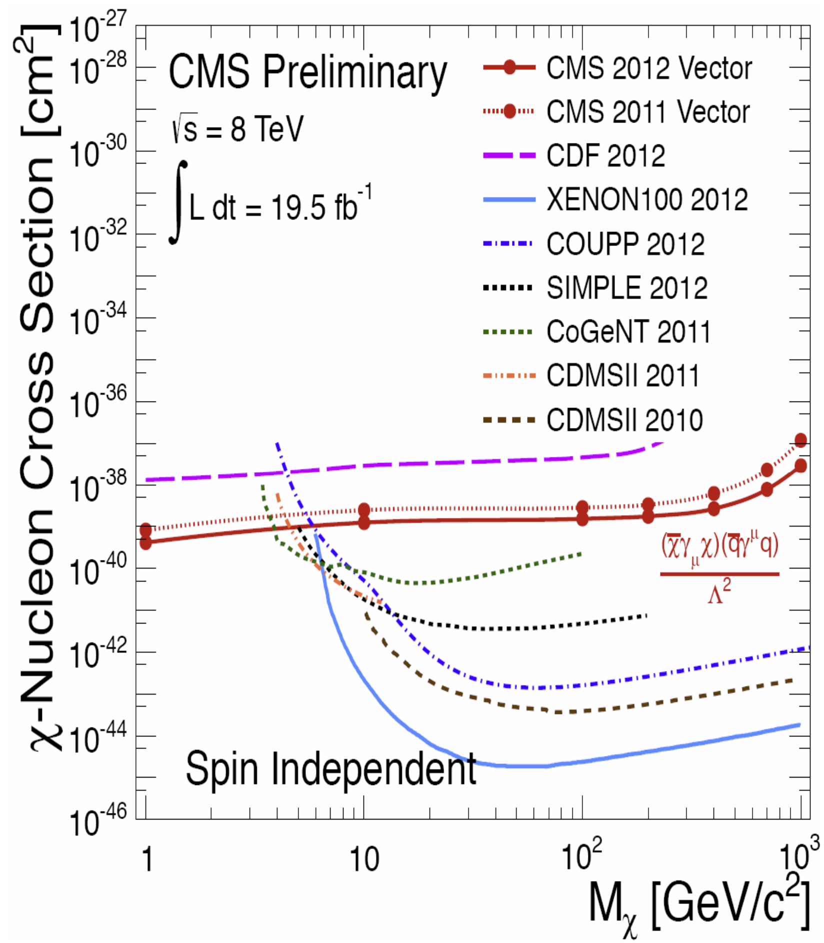
WIMP EFFECTIVE THEORY

- One operator can correspond to many channels. E.g., $bb\chi\chi$ leads to
  - *bb* → $\chi\chi$+ X: monophoton, monojet channel
  - *bg* → $b\chi\chi$: mono-*b* channel
  - *gg* → $bb\chi\chi$: sbottom pair channel

- WIMP effective theory allows comparison to indirect, direct search results; colliders do very well for some operators, low masses

- This assumes the mediators are heavy compared to the WIMPs and the energies involved, which is not always true for colliders

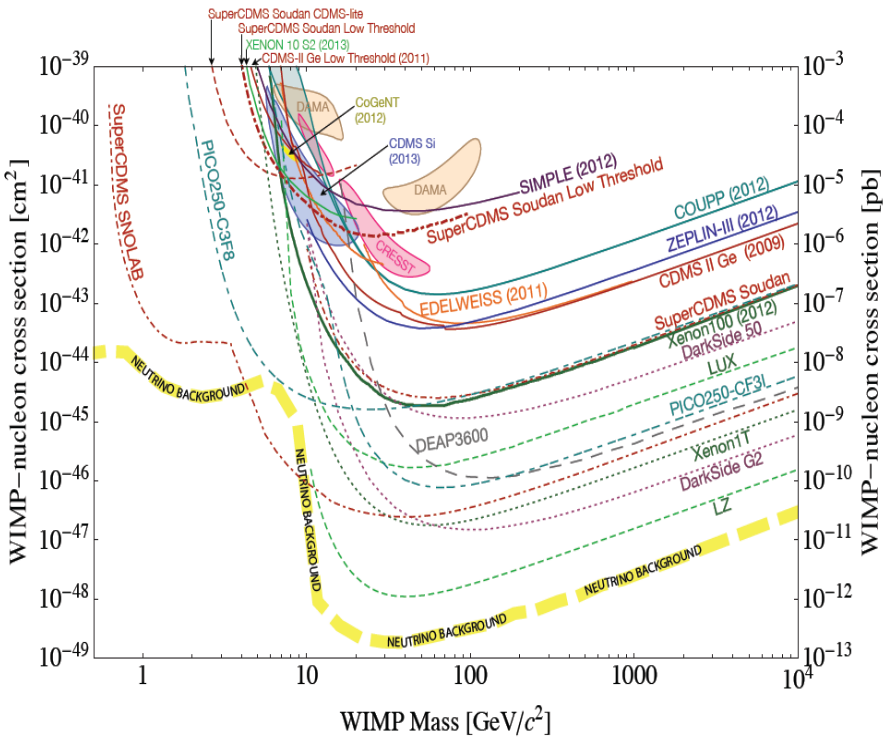




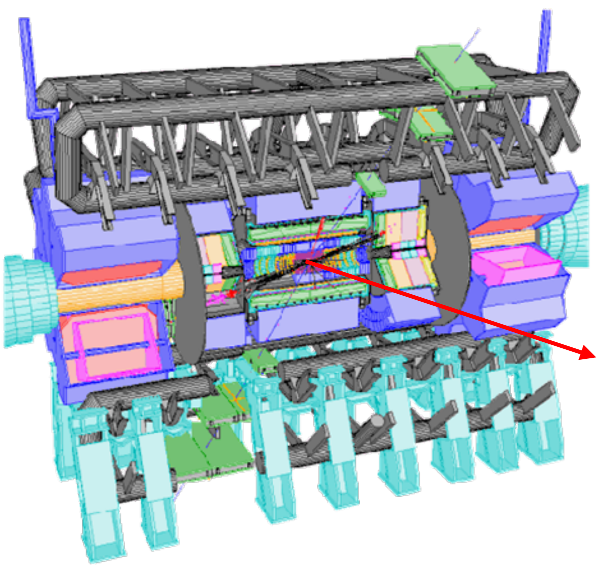
THE FUTURE

If there is a signal, what do we learn?

- Cosmology and dark matter searches can't identify the particle nature



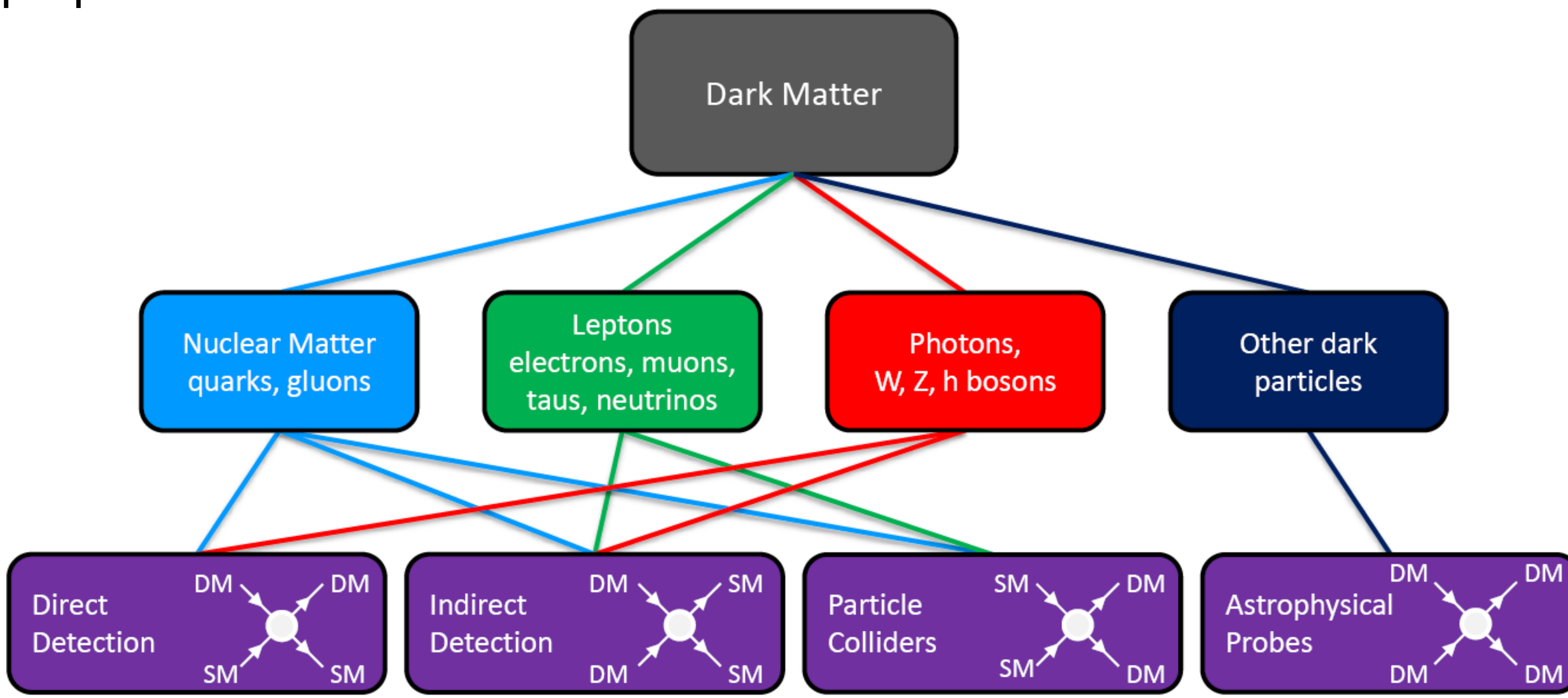
- Particle colliders can't prove it's dark matter



Lifetime > 10^{-7} s → 10^{17} s ?

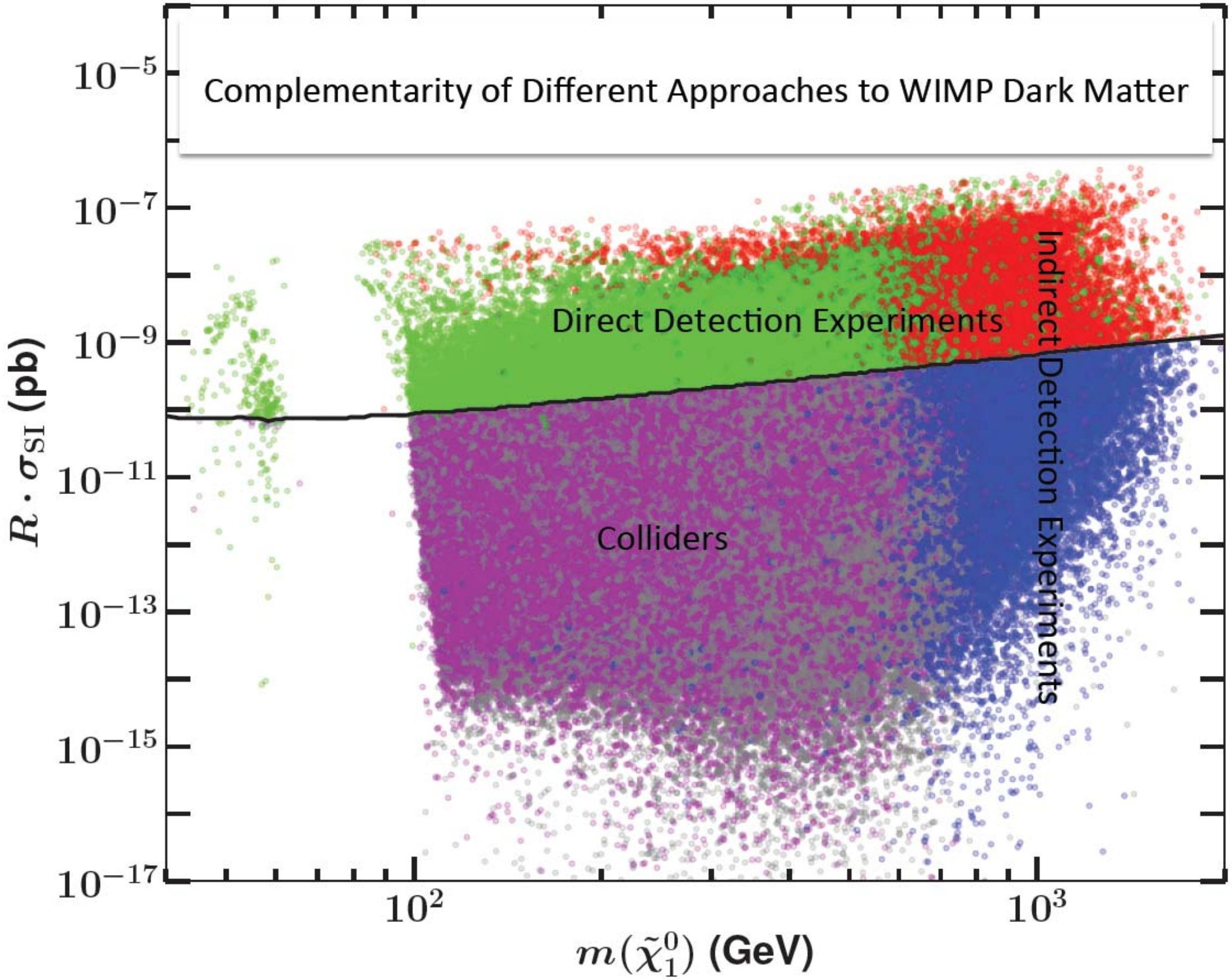
DARK MATTER COMPLEMENTARITY

- 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

LECTURE 2 SUMMARY

- WIMPs are natural dark matter candidates in many models of BSM physics
- The relic density implies significant rates for direct detection, indirect detection, and colliders
- A time of rapid experimental advances on all fronts
- Definitive dark matter detection and understanding will require signals in several types of experiments