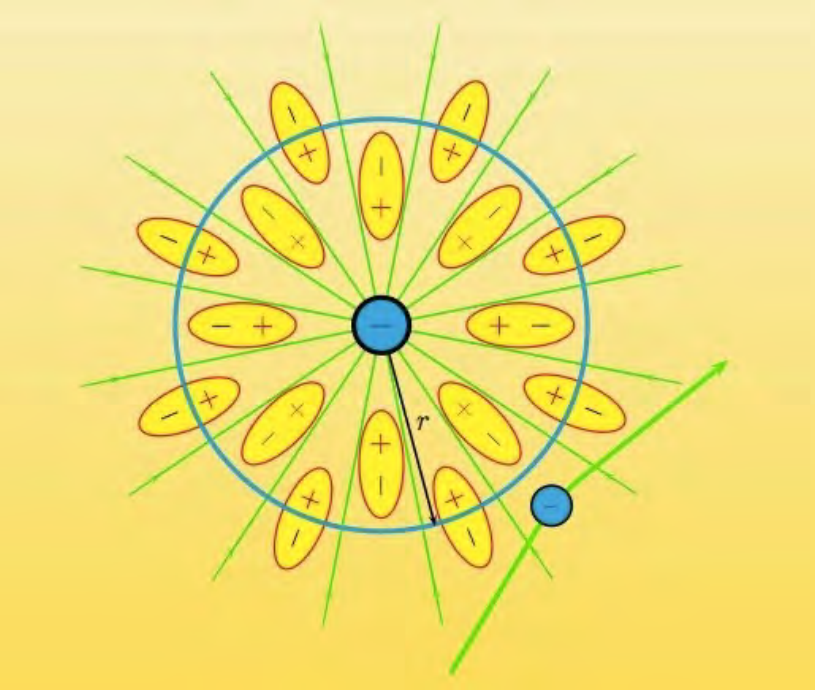
NEUTRAL SUSY PARTICLES

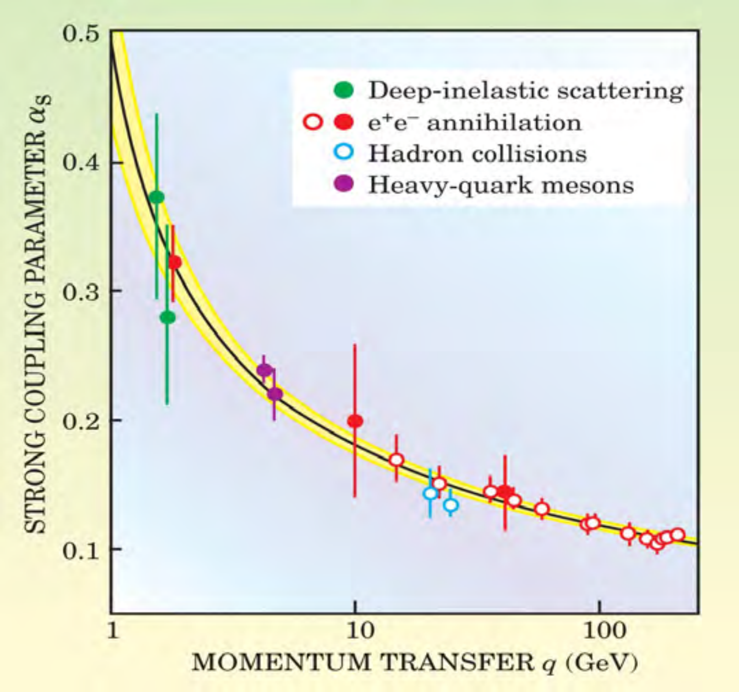
Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2						$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

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

RENORMALIZATION GROUP EQUATIONS

- RGEs play a crucial role in all of physics.
- For gauge couplings, it can be thought of as the effect of putting a charge in a dielectric, where in QFT, the vacuum is the dielectric.
- The most famous example may be the asymptotic freedom of the QCD coupling.

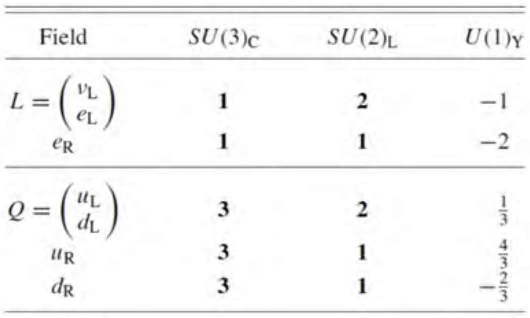




COUPLING CONSTANT UNIFICATION

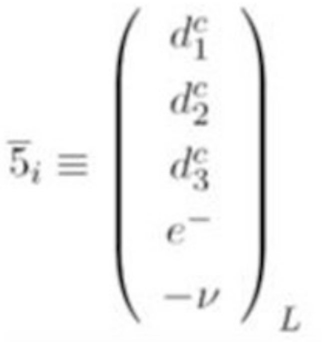
- In supersymmetry, RGEs play an especially important role.
- It is well known that the seemingly arbitrary quantum numbers of matter in the SM can be explained by grand unification.

SU(3) x SU(2) x U(1)

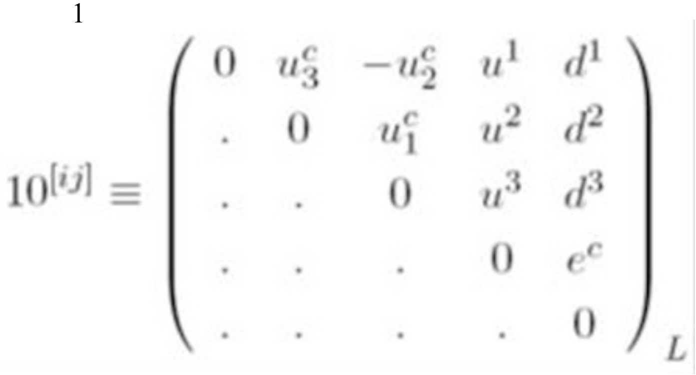


Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	**1**	**2**	-1
e_R	**1**	**1**	-2
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	**3**	**2**	$\frac{1}{3}$
u_R	**3**	**1**	$\frac{4}{3}$
d_R	**3**	**1**	$-\frac{2}{3}$
[N]	1	1	1

SU(5)



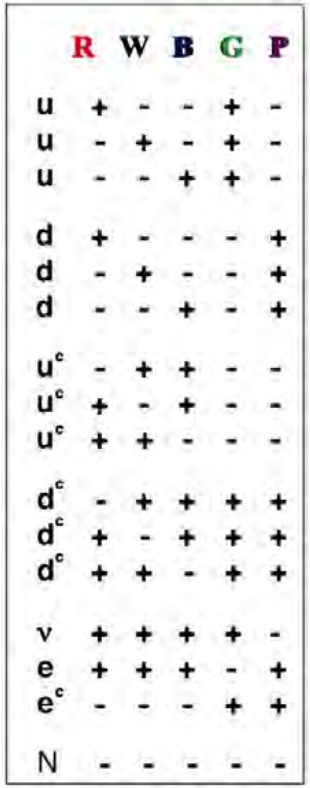
$$\bar{5}_i \equiv \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e^- \\ -\nu \end{pmatrix}_L$$



$$10^{[ij]} \equiv \begin{pmatrix} 0 & u_3^c & -u_2^c & u^1 & d^1 \\ . & 0 & u_1^c & u^2 & d^2 \\ . & . & 0 & u^3 & d^3 \\ . & . & . & 0 & e^c \\ . & . & . & . & 0 \end{pmatrix}_L$$

[1 ≡ N]

SO(10)

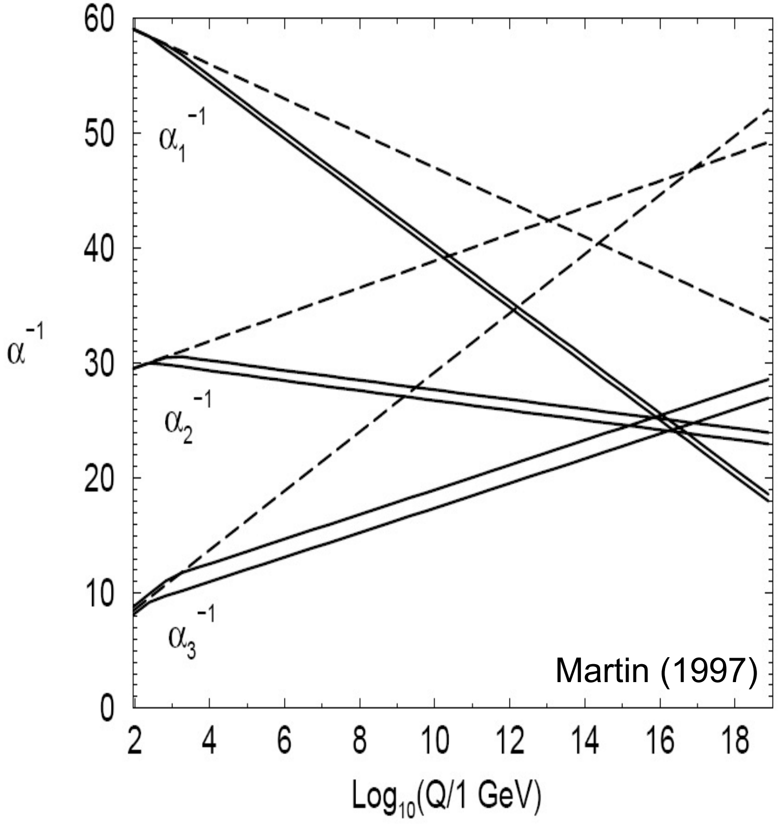


	R	W	B	G	P
u	+	-	-	+	-
u	-	+	-	+	-
u	-	-	+	+	-
d	+	-	-	-	+
d	-	+	-	-	+
d	-	-	+	-	+
u^c	-	+	+	-	-
u^c	+	-	+	-	-
u^c	+	+	-	-	-
d^c	-	+	+	+	+
d^c	+	-	+	+	+
d^c	+	+	-	+	+
ν	+	+	+	+	-
e	+	+	+	-	+
e^c	-	-	-	+	+
N	-	-	-	-	-

COUPLING CONSTANT UNIFICATION

- A requirement of grand unification is that the SU(3), SU(2), and U(1) gauge couplings unify at some scale.
- With the SM particle content, they don't.
- But with the addition of SUSY particles at the ~TeV scale, they do at Q ~ 10^{16} GeV.
  - Unifies at a coupling in the perturbative regime.
  - Unifies below the Planck scale.
  - But not too far below the Planck scale to induce too-fast proton decay.

Dimopoulos, Raby, Wilczek (1981)

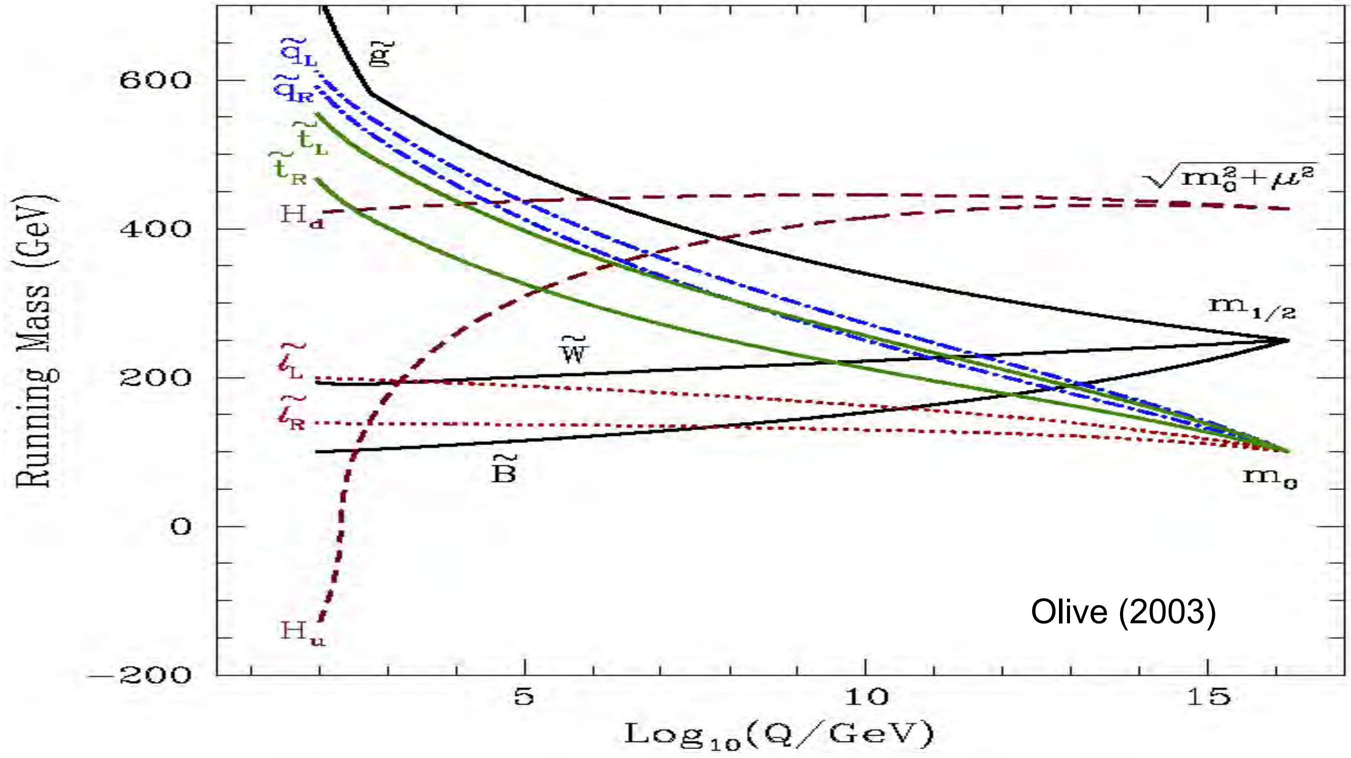


Martin (1997)

- Coupling constant unification is beautifully consistent with the fact that SM particles fit neatly into GUT multiplets, and it explains why $g_3 > g_2 > g_1$.

RGES AND BINO DARK MATTER

- All other couplings and masses also RG evolve in SUSY. Essential fact: gauge couplings increase masses, Yukawa couplings decrease masses.
- Depending on the initial conditions at the GUT scale, the lightest superpartners are typically the stau and the Bino.
- The Bino therefore emerges as a neutral, stable, cold DM candidate!



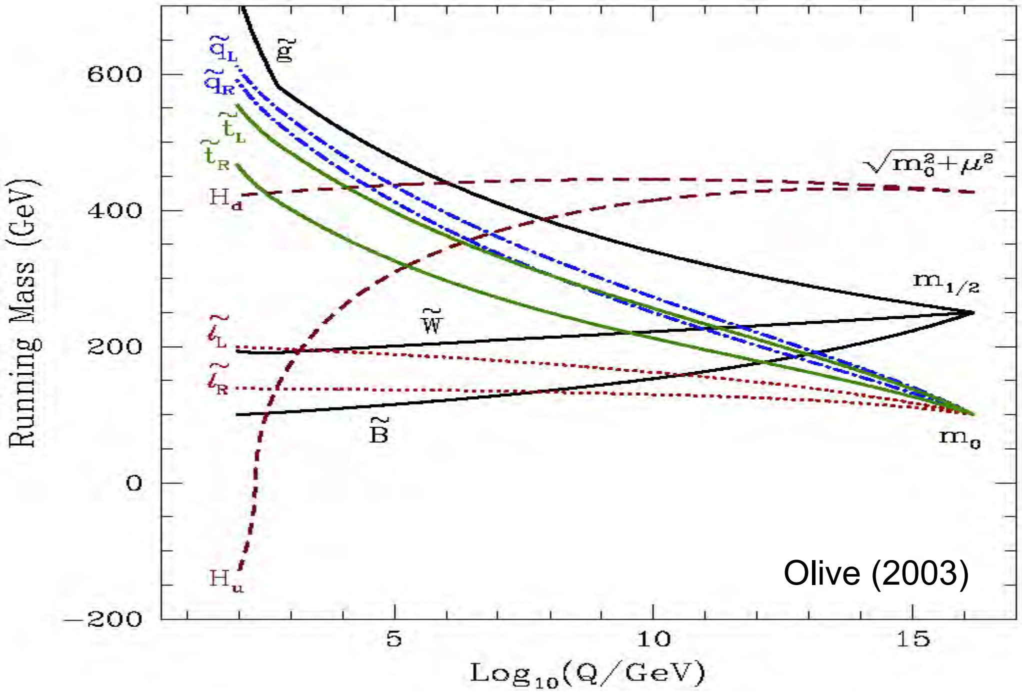
Olive (2003)

OTHER INTERESTING RGE IMPLICATIONS

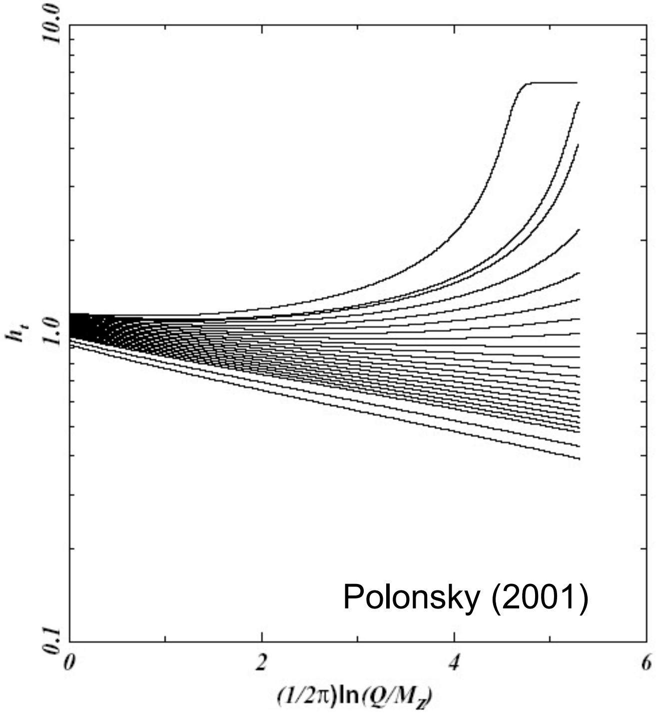
- Colored superpartners are typically heavier than uncolored superpartners. Squarks are expected to be heavier than sleptons.

- The Higgs mass^2 parameter evolves to negatlve values, explains why SU(2) is broken, and not SU(3) or U(1), and why $m_W << M_{Pl}$.

- The top quark Yukawa coupling generically runs to $\lambda \approx 1$, explains why $m_t \simeq 173$ GeV.



Olive (2003)



Polonsky (2001)

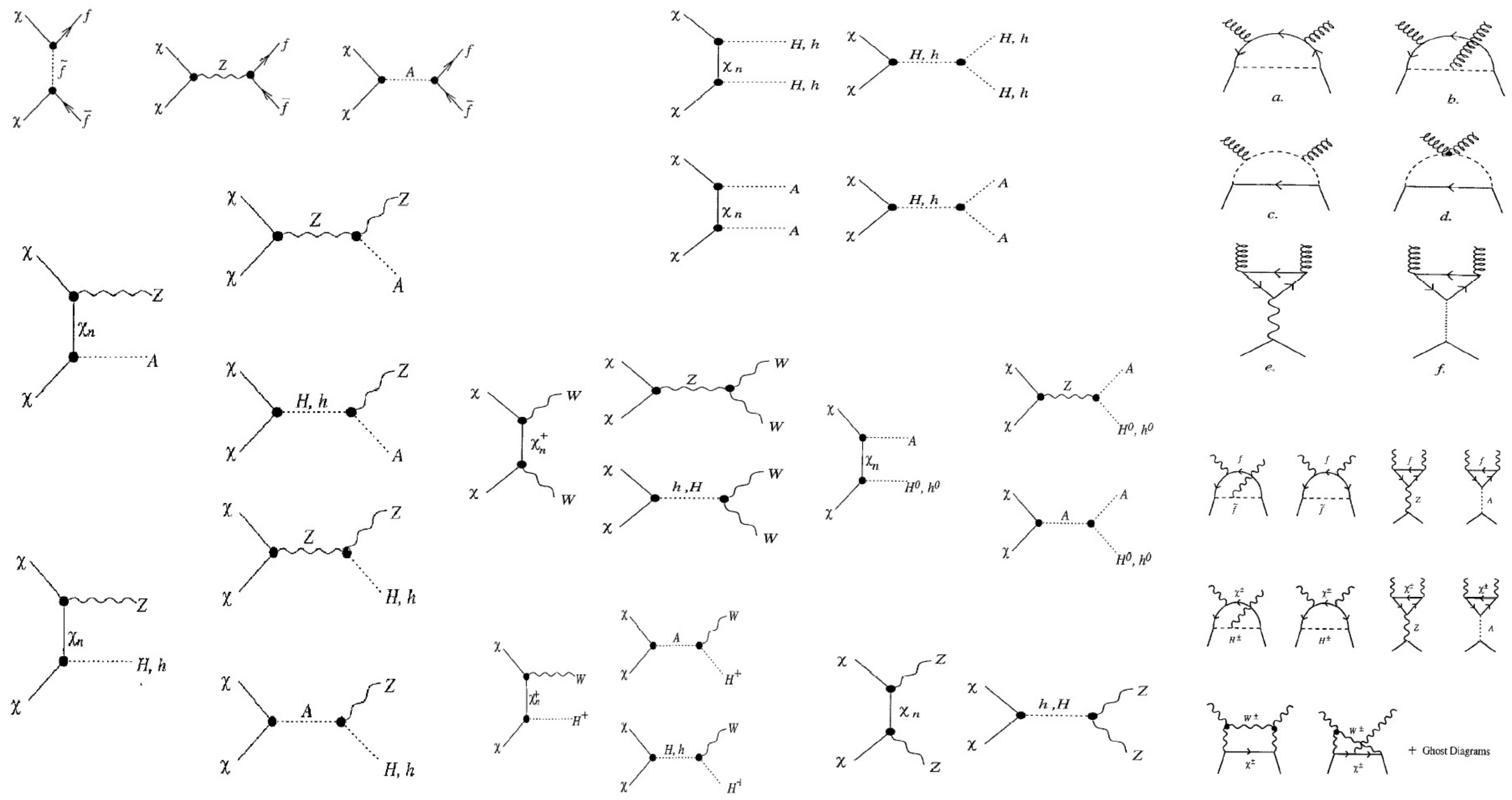
NEUTRALINO RELIC DENSITY

- If the Bino is WIMP dark matter, we can determine its thermal relic density in a well-defined supersymmetry model.

- The resulting research program is, then, clear:
  - The regions of parameter space that give too much dark matter are excluded.
  - The regions that give too little are allowed, but Binos aren't all the dark matter.
  - The regions that give just the right amount are cosmologically preferred and deserve special attention in search experiments, colliders, etc.

- We just need to determine how the Bino annihilates, calculate its annihilation rate in the early universe, evolve its number density to the present day, and calculate its thermal relic density.

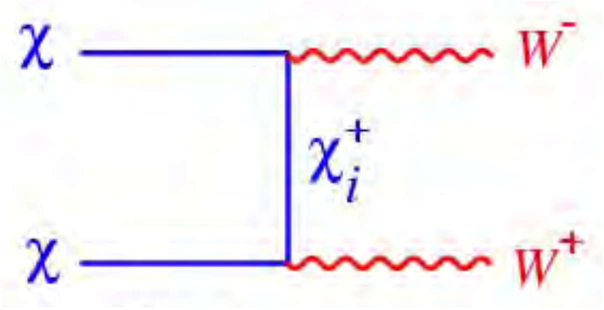
NEUTRALINO ANNIHILATION



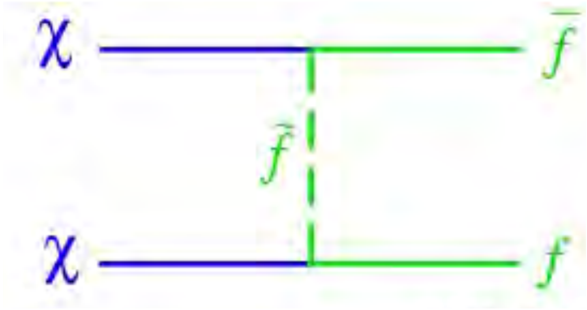
Jungman, Kamionkowski, Griest (1995)

RELIC DENSITY

- This is a mess! But we can bring order to chaos in the following way. Typically there are two dominant classes of annihilation processes:



- Gauge boson diagrams. These are absent for $\chi \approx$ Bino, because U(1) gauge bosons do not have 3- and 4-point self-interactions.



- Fermion diagrams. χ are Majorana fermions, so Pauli exclusion → the initial state has J=0. The final state therefore cannot be $f_L + \bar{f}_R$ in an *S*-wave. Need
  - *P* -wave: $\sigma v \sim \sigma_0 + \sigma_1 v^2$, $v^2 \sim 0.1$, or
  - Chiral flip: m_f / m_W.

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

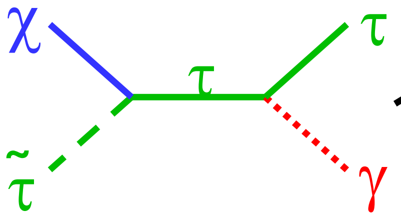
COSMOLOGICALLY-PREFERRED SUSY

There are a number of ways to enhance the annihilation. 3 instructive examples are shown here for the constrained MSSM model, also known as minimal supergravity.

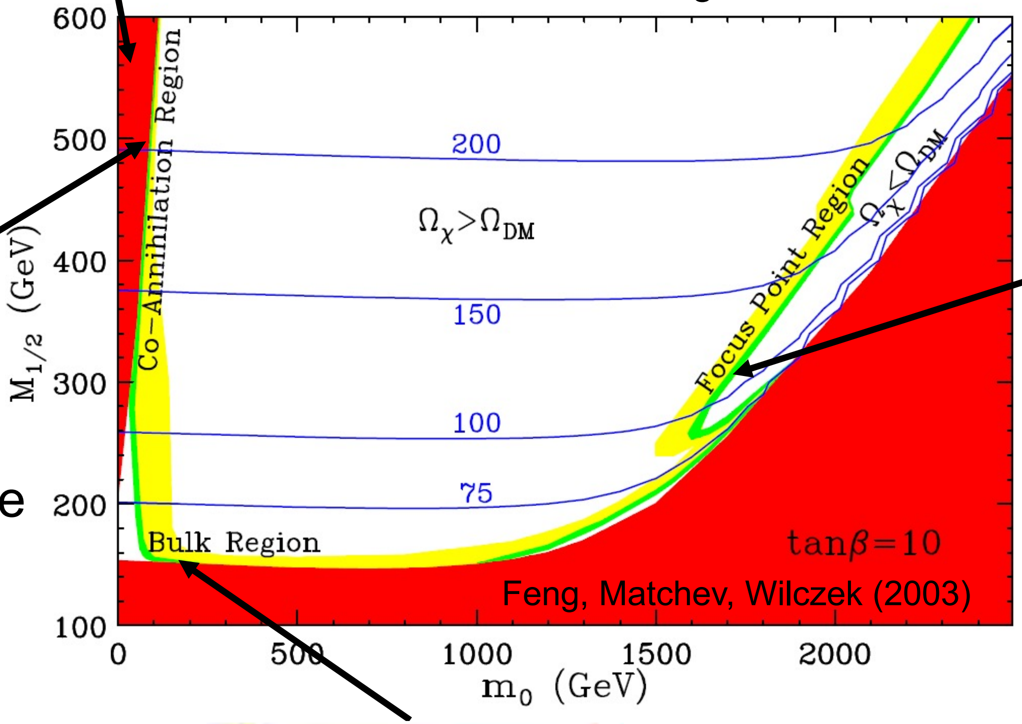
Excluded:

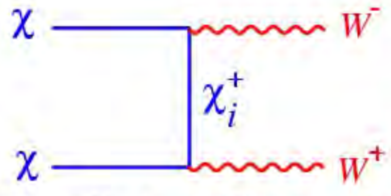
Stau LSP

Green: correct relic density
Yellow: almost correct relic density
Blue contours: fine tuning

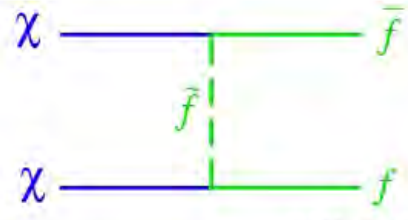


Co-annihilation: stau and Bino are 5% degenerate, so staus are present a freeze out T ~ m/20, help Binos annihilate.





Focus point SUSY:
Bino mixes with Higgsinos



Light SUSY: Bino and sfermion masses around 100 GeV

STATUS OF COSMOLOGICALLY-PREFERRED SUSY

- Light SUSY: Excluded by collider searches for 100 GeV sleptons.

- Focus-point DM: Stringently probed by direct detection.

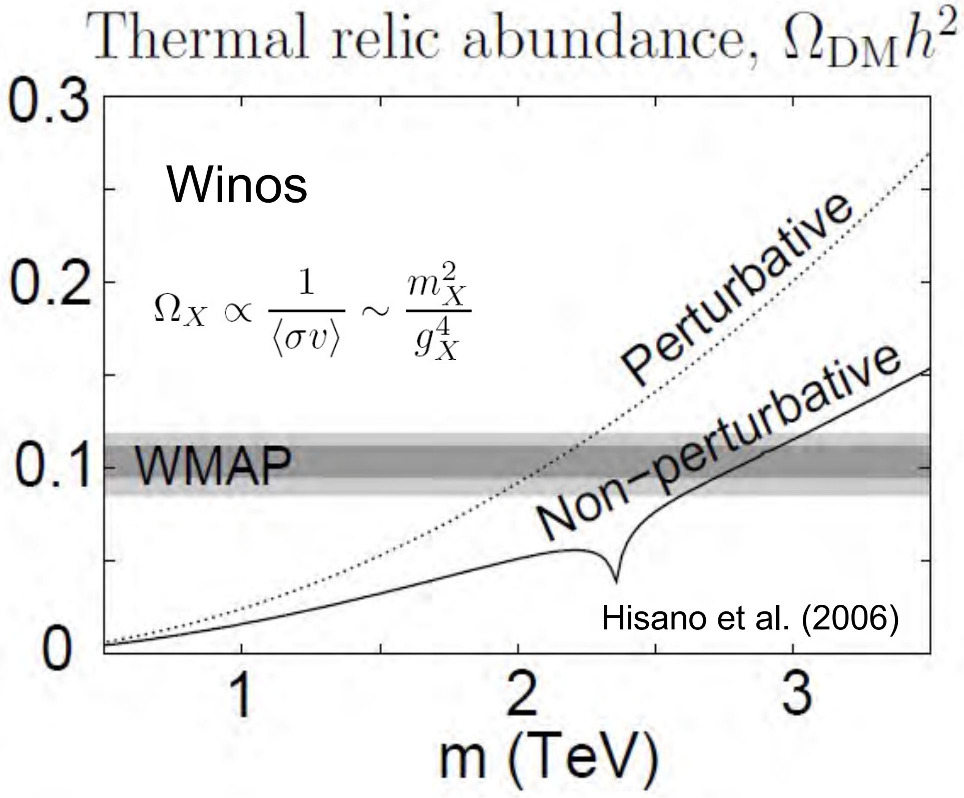
  Bino-Higgsino mixture, m < 1 TeV.

- Co-annihilating DM: still viable.

  χ , $\tilde{\tau}_R$ degenerate, m < 600 GeV.

  Can explain muon g-2.

- Outside of CMSSM: Wino-like DM with m ~ 2.7-3 TeV. Stringently probed by indirect detection.

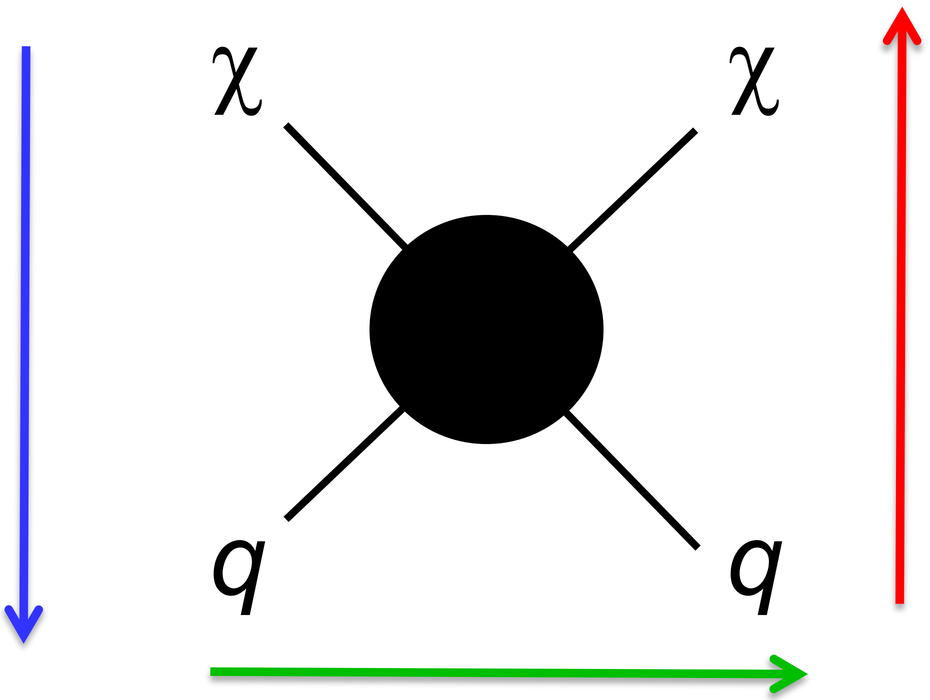


- Many other interesting scenarios outside of CMSSM. Note that SUSY can always be heavier, but in this context, cosmology provides upper bounds. This is an essential synergy between particle physics and cosmology – WIMPs cannot be decoupled away without sacrificing the WIMP miracle.

III. WIMP DETECTION

WIMP DETECTION

Correct relic density → Efficient annihilation then



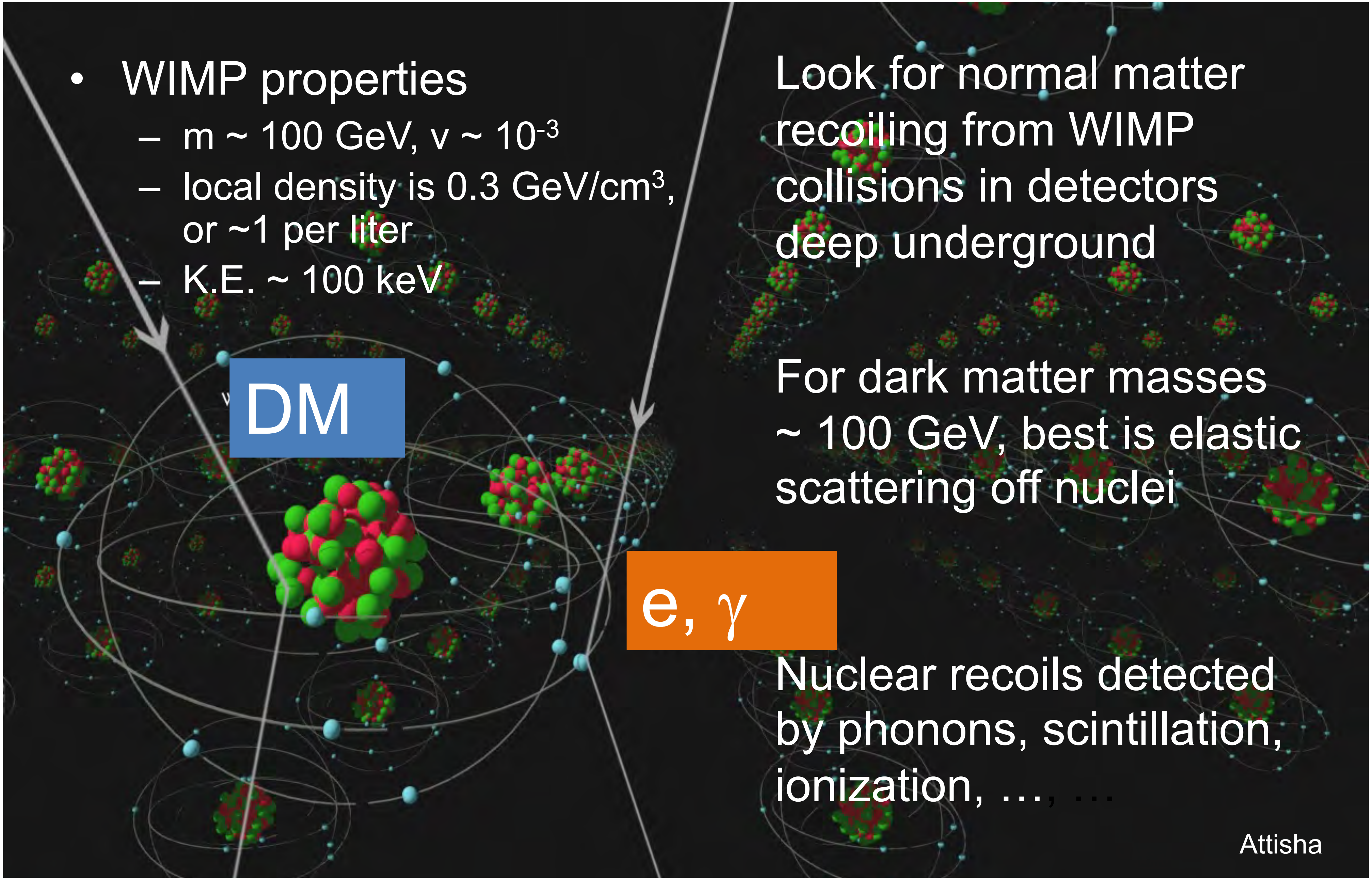
Efficient annihilation now
(Indirect detection)

Efficient production now
(Particle colliders)

Efficient scattering now
(Direct detection)

Feng (2008)

DIRECT DETECTION



- WIMP properties
  - m ~ 100 GeV, v ~ 10^{-3}
  - local density is 0.3 GeV/cm^3, or ~1 per liter
  - K.E. ~ 100 keV

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

For dark matter masses ~ 100 GeV, best is elastic scattering off nuclei

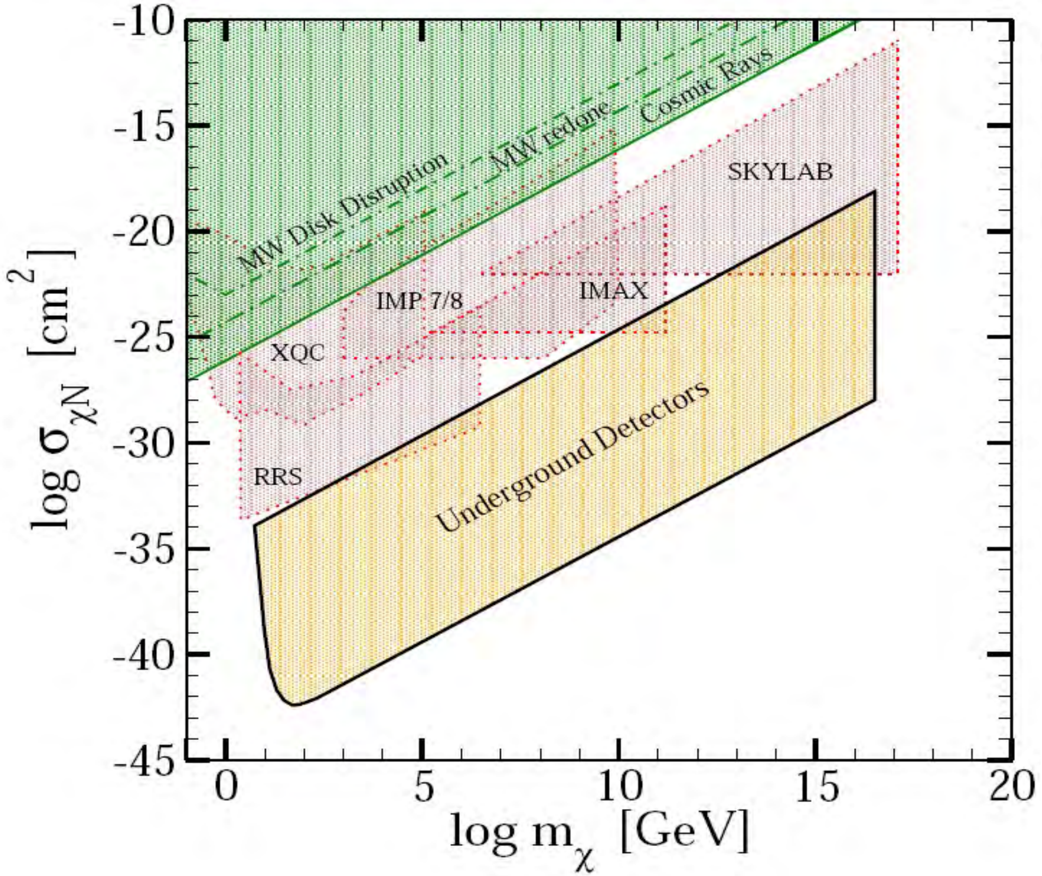
Nuclear recoils detected by phonons, scintillation, ionization, …, …

Attisha

THE BIG PICTURE: UPPER BOUND

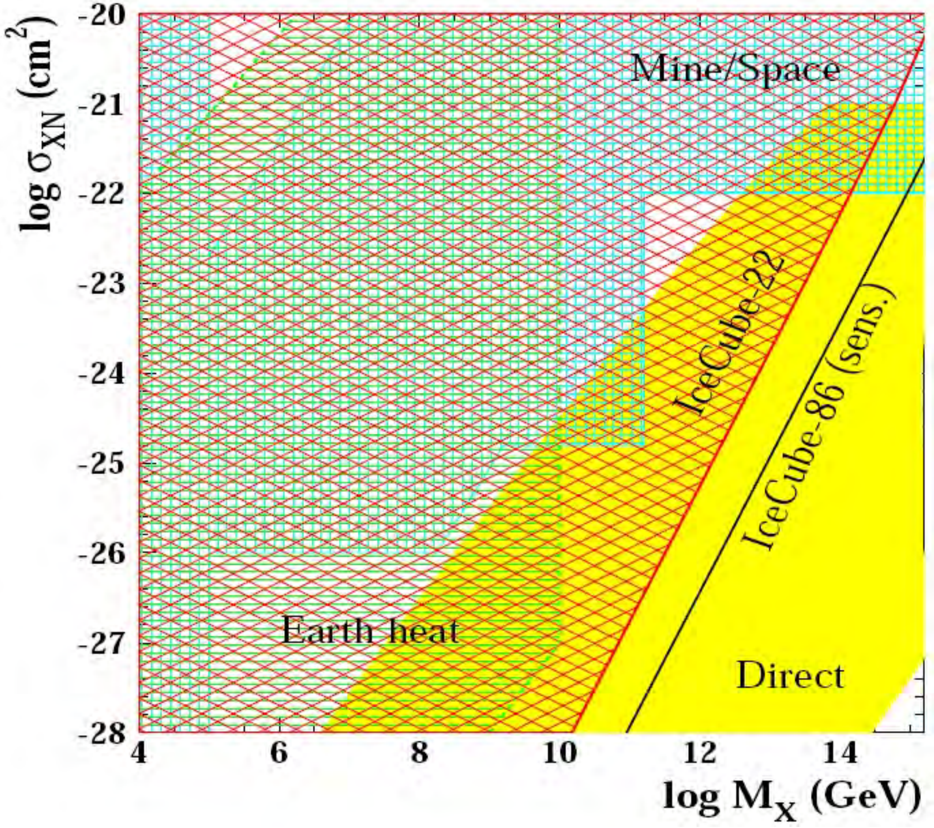
- The event rates depend on the interaction cross section. What is the upper bound? Another fascinating and underappreciated story.

- Strongly-interacting DM does not reach underground detectors.



Mack, Beacom, Bertone (2007)

- But the strongly-interacting window is now closed.



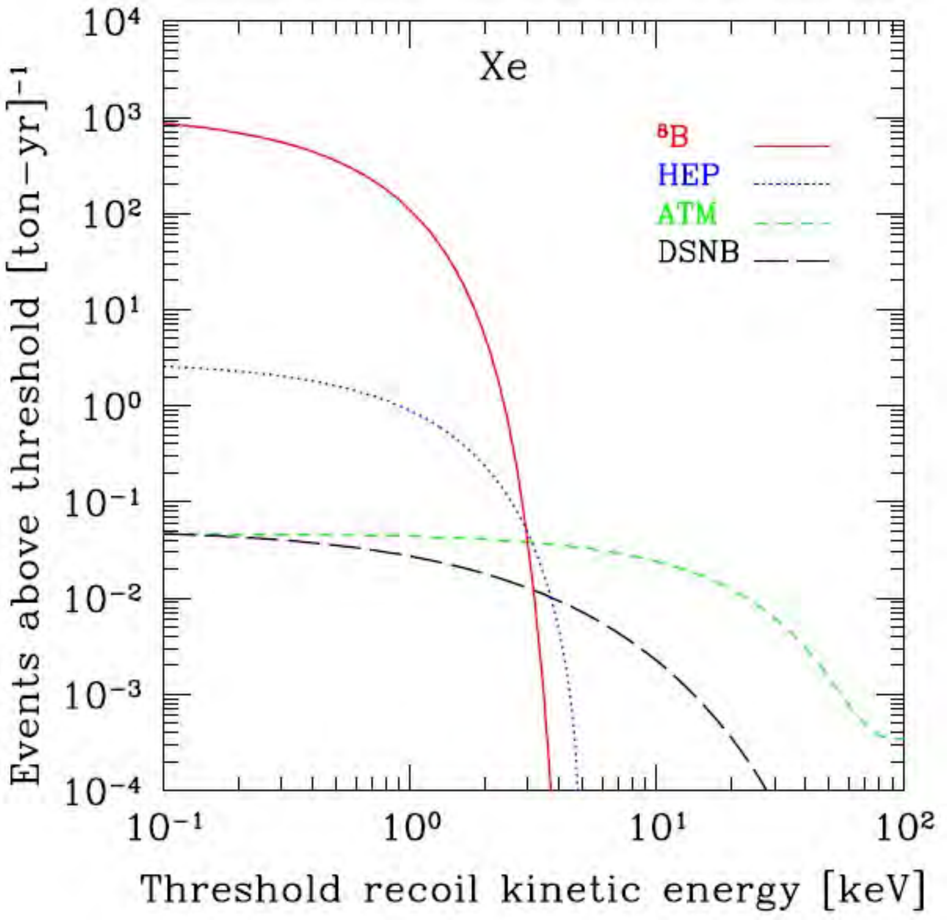
Albuquerque, de los Heros (2010)

THE BIG PICTURE: LOWER BOUND

- Is there (effectively) a lower bound?
- Solar, atmospheric, and diffuse supernova background neutrinos provide a difficult background: the “neutrino floor.”
- 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)

WIMP SCATTERING

- Consider WIMPs 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 $v \sim 10^{-3}$. In the non-relativistic limit, the first terms reduce to spin-spin interactions, and so are called spin-dependent (SD) interactions.

- The second terms are spin-independent (SI) 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.*

- This may be parameterized by

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

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

Experiment: recoil energy

Astrophysics: DM velocity distribution

Nuclear physics: form factor

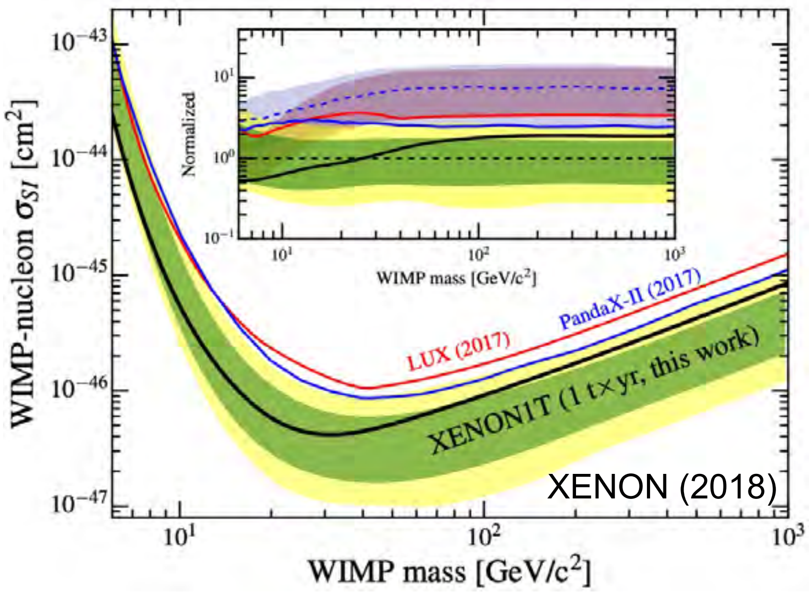
Astrophysics: local DM number density

- Results are typically reported assuming $f_p = f_n$, so $\sigma_A \sim A^2$, and scaled to a single nucleon. DM sees the whole nucleus, doesn’t resolve nucleons, and so in this approximation, bigger nuclei are better.

DETECTION STRATEGIES

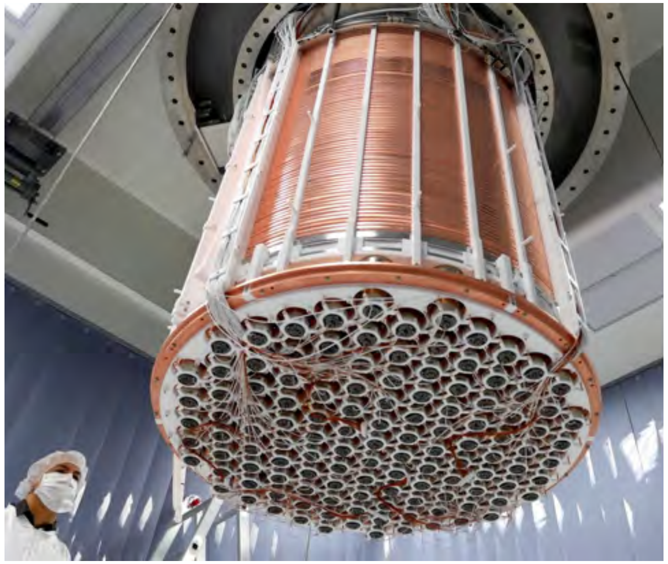
The state-of-the-art: large, underground, background-free experiments, looking for a few events each year.

Currently leading constraints at m_X ~ 100 GeV are from ~ 1 tonne experiments using liquid noble gases: XENON, LUX, and PandaX.



XENON (2018)

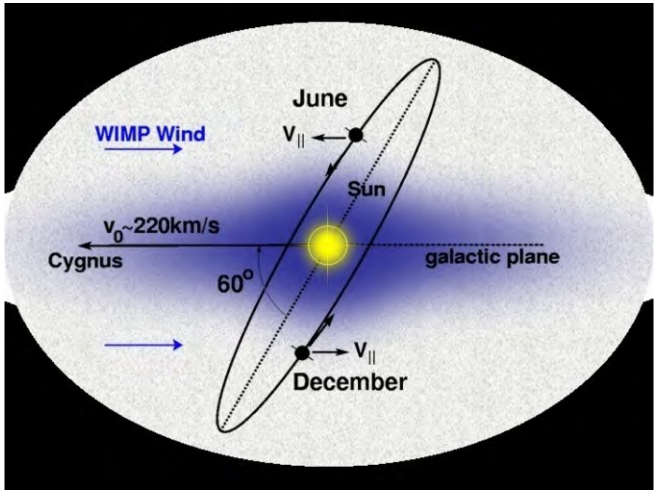




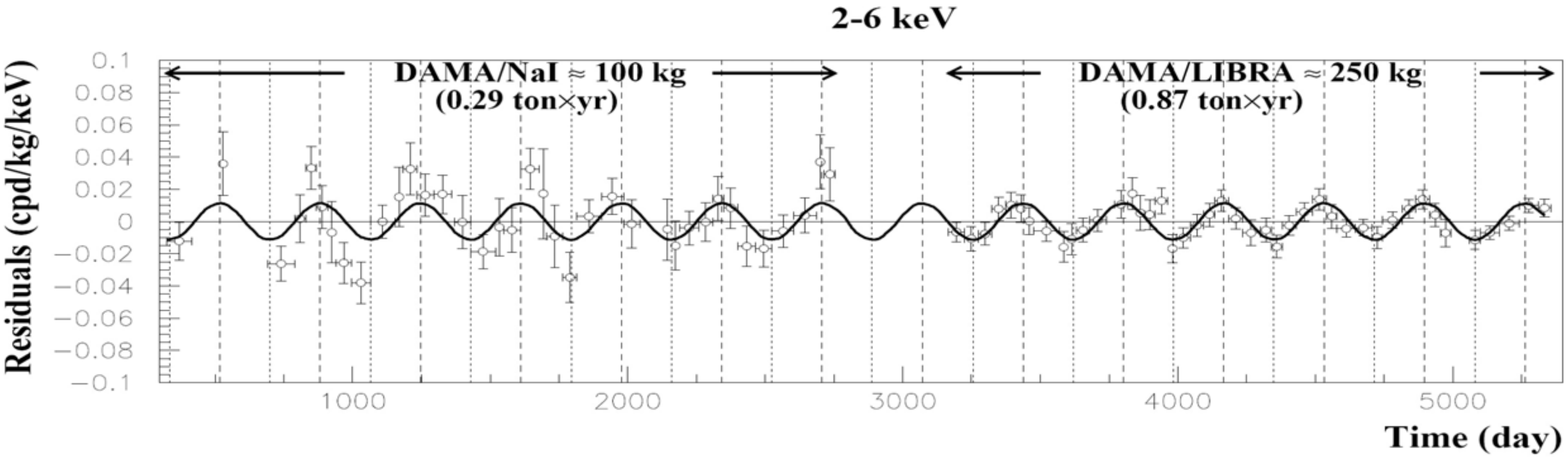
DETECTION STRATEGIES

An alternative strategy: look for annual modulation, where the collision rate changes as the Earth's velocity adds with the Sun's.

Drukier, Freese, Spergel (1986)



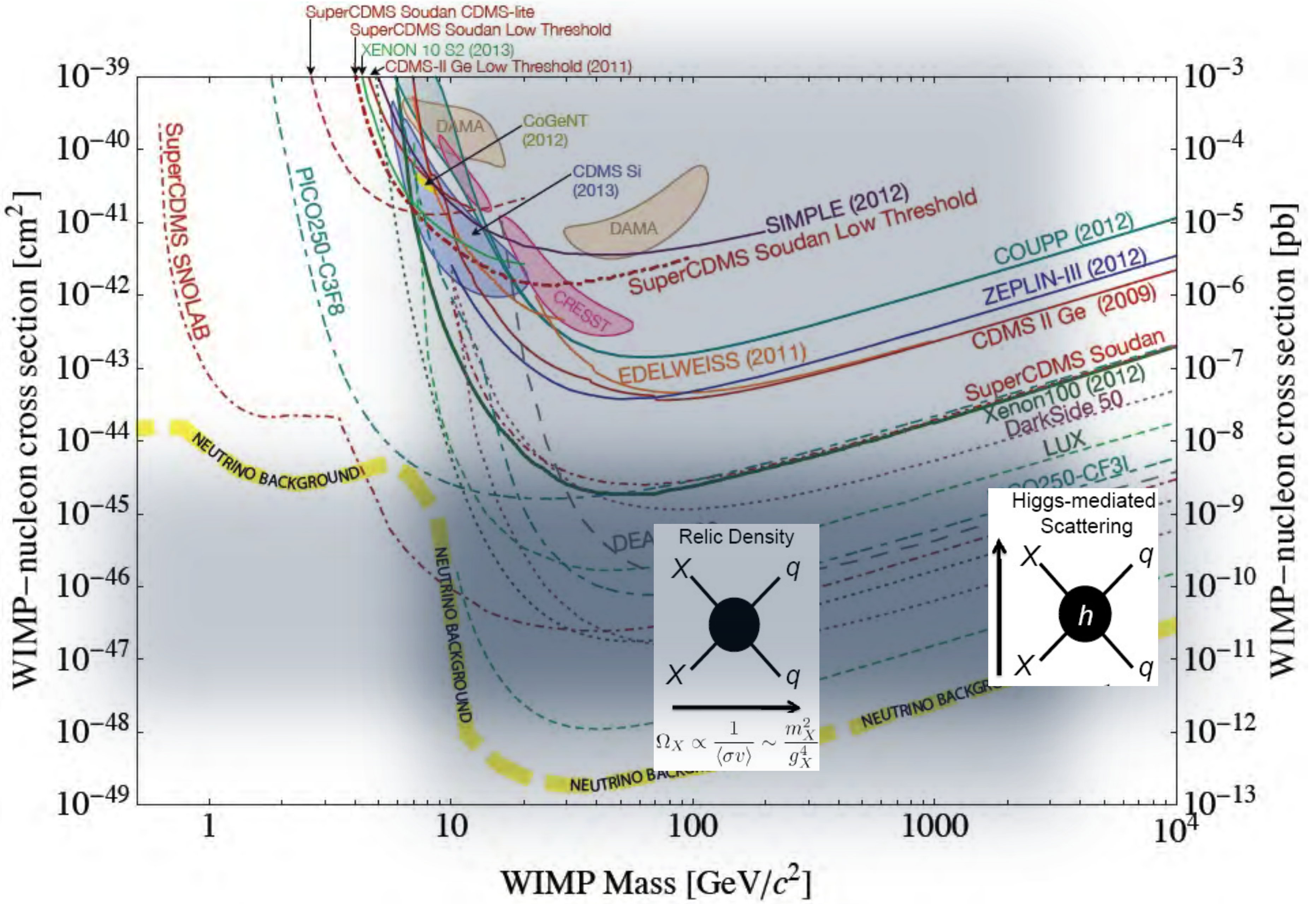
DAMA: many σ signal with period T ~ 1 year, and maximum ~ June 2



DAMA (2013)

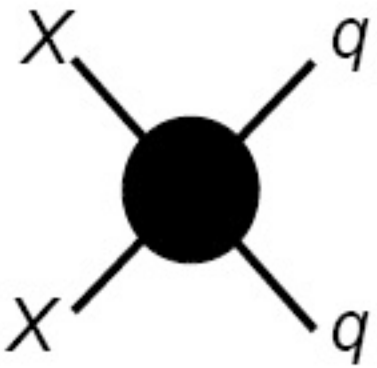
A few % modulation on top of a large constant background.

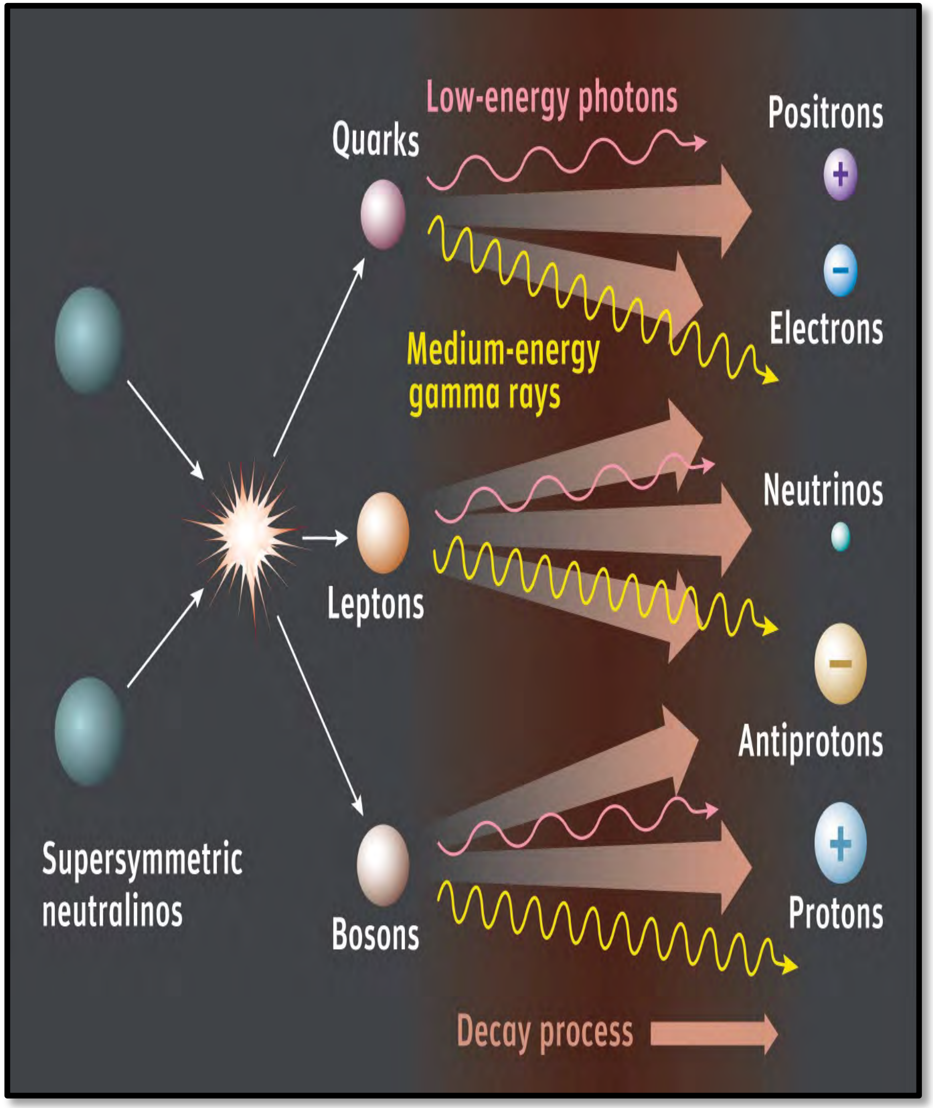
FUTURE PROSPECTS



INDIRECT DETECTION

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

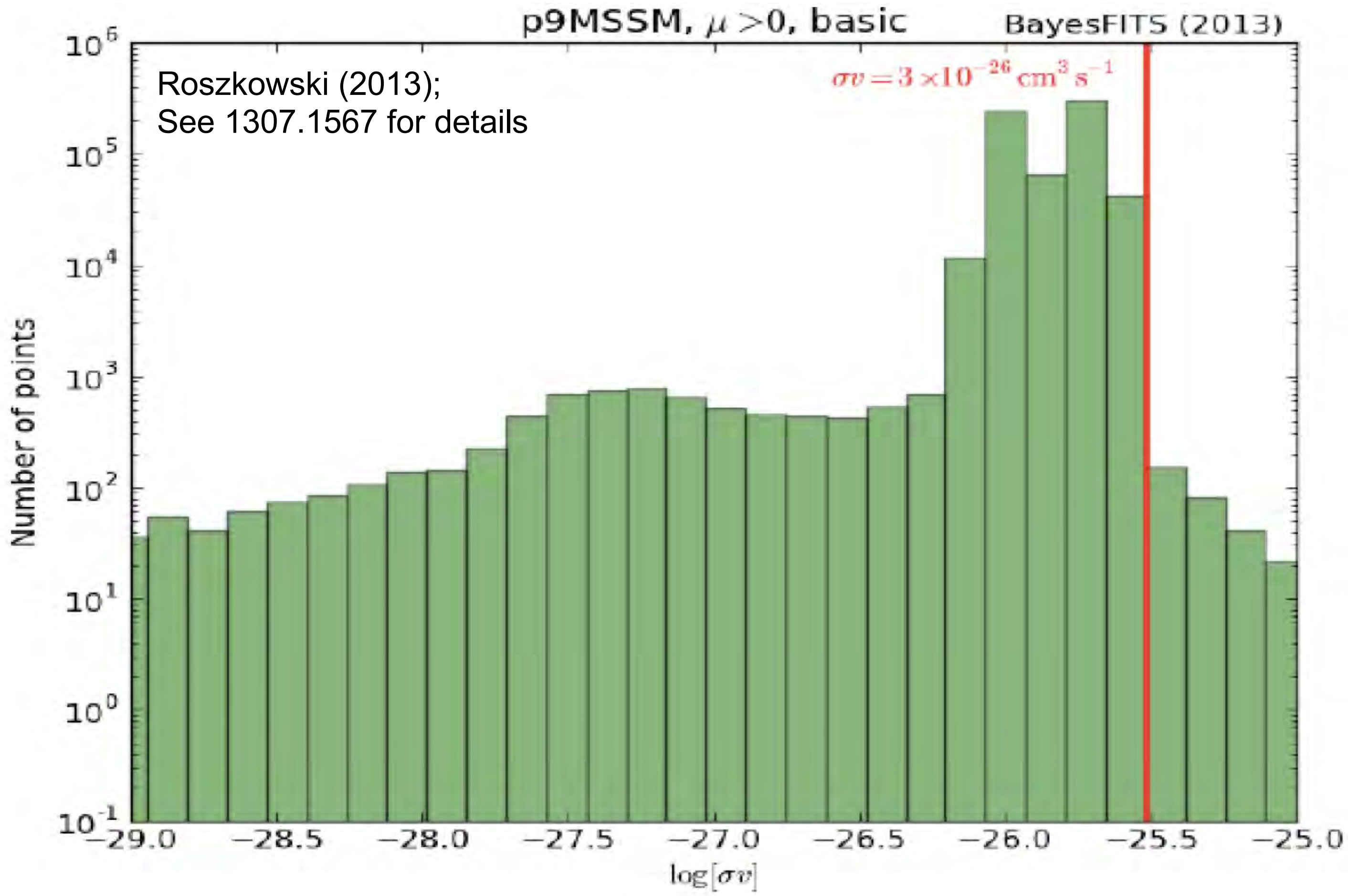




- The relic density provides a target annihilation cross section $\langle \sigma_A v \rangle \sim$ (2 to 3) x 10^{-26} cm^3/s

ROBUSTNESS OF THE TARGET CROSS SECTION

- Relative to direct detection, indirect rates typically have smaller particle physics uncertainties (but larger astrophysical uncertainties), since annihilation determines both the relic density and the rate. The correspondence is not perfect, though, because $v \sim 1/3$ is not $v \sim 10^{-3}$.



Roszkowski (2013);
See 1307.1567 for details

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 <u> the GC / dwarf galaxies </u> to
a place

<u> photons </u> , which are detected by <u> Fermi, CTA, … </u> .
some particles an experiment

The flux factorizes:

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

Particle physics: two kinds of signals

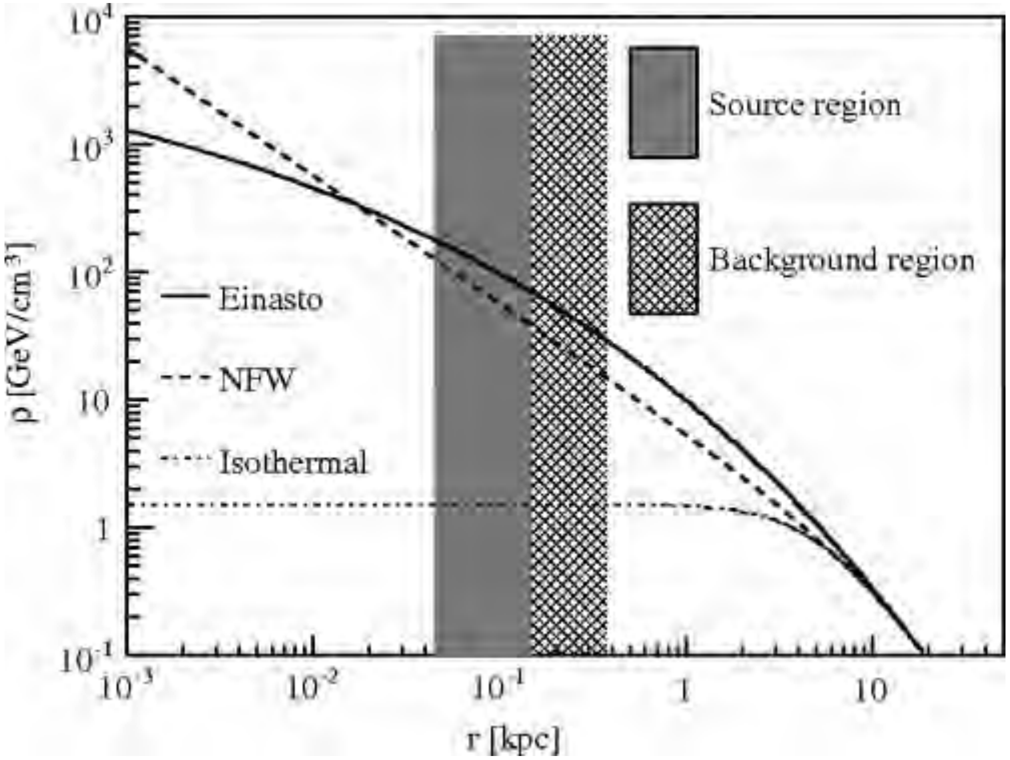
- Lines from XX → $\gamma\gamma$, γZ: loop-suppressed rates, but distinctive signal.
- Continuum from XX → ff → γ: τree-level rates, but a broad signal.

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

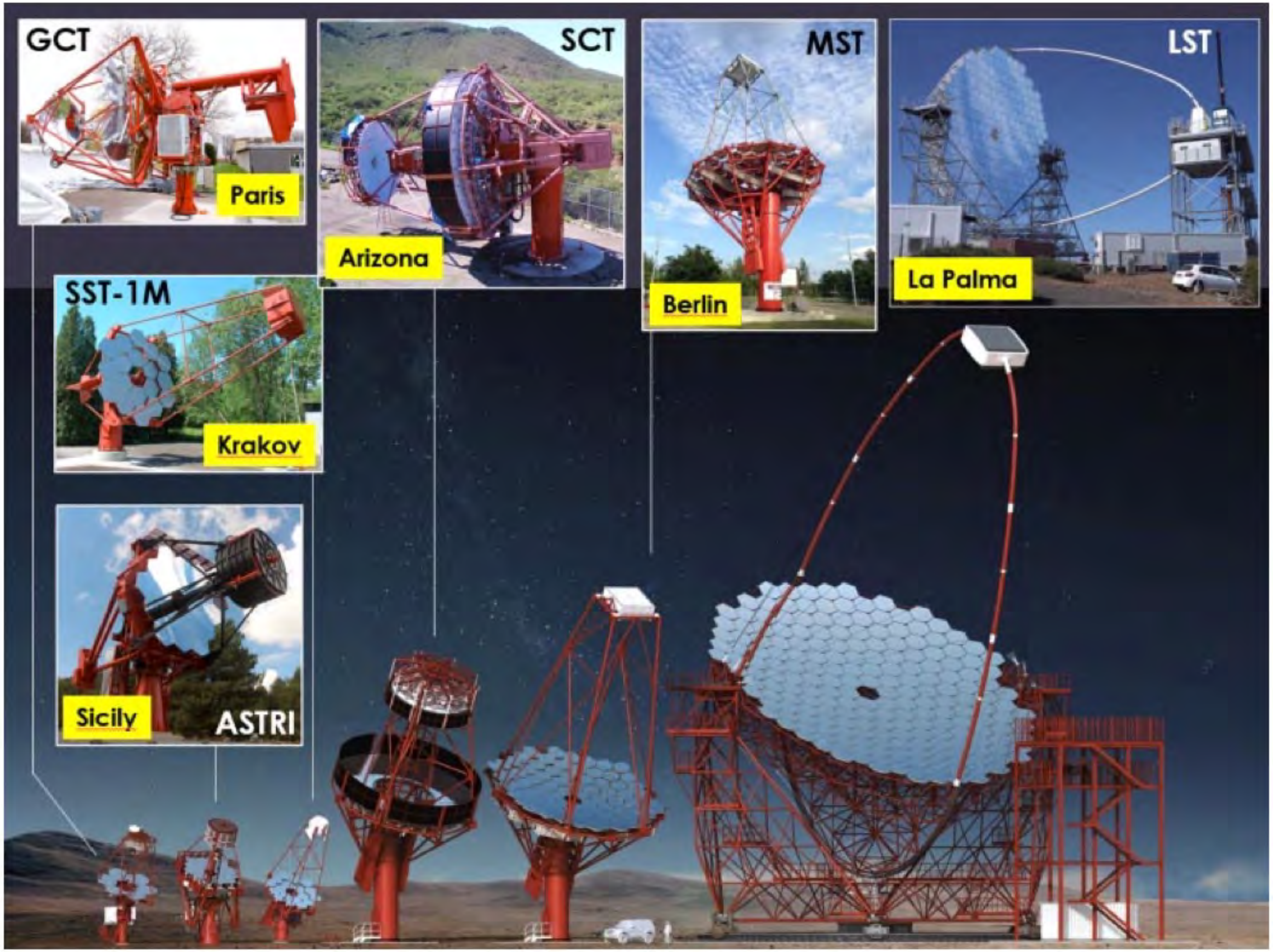


PHOTONS: EXPERIMENTS

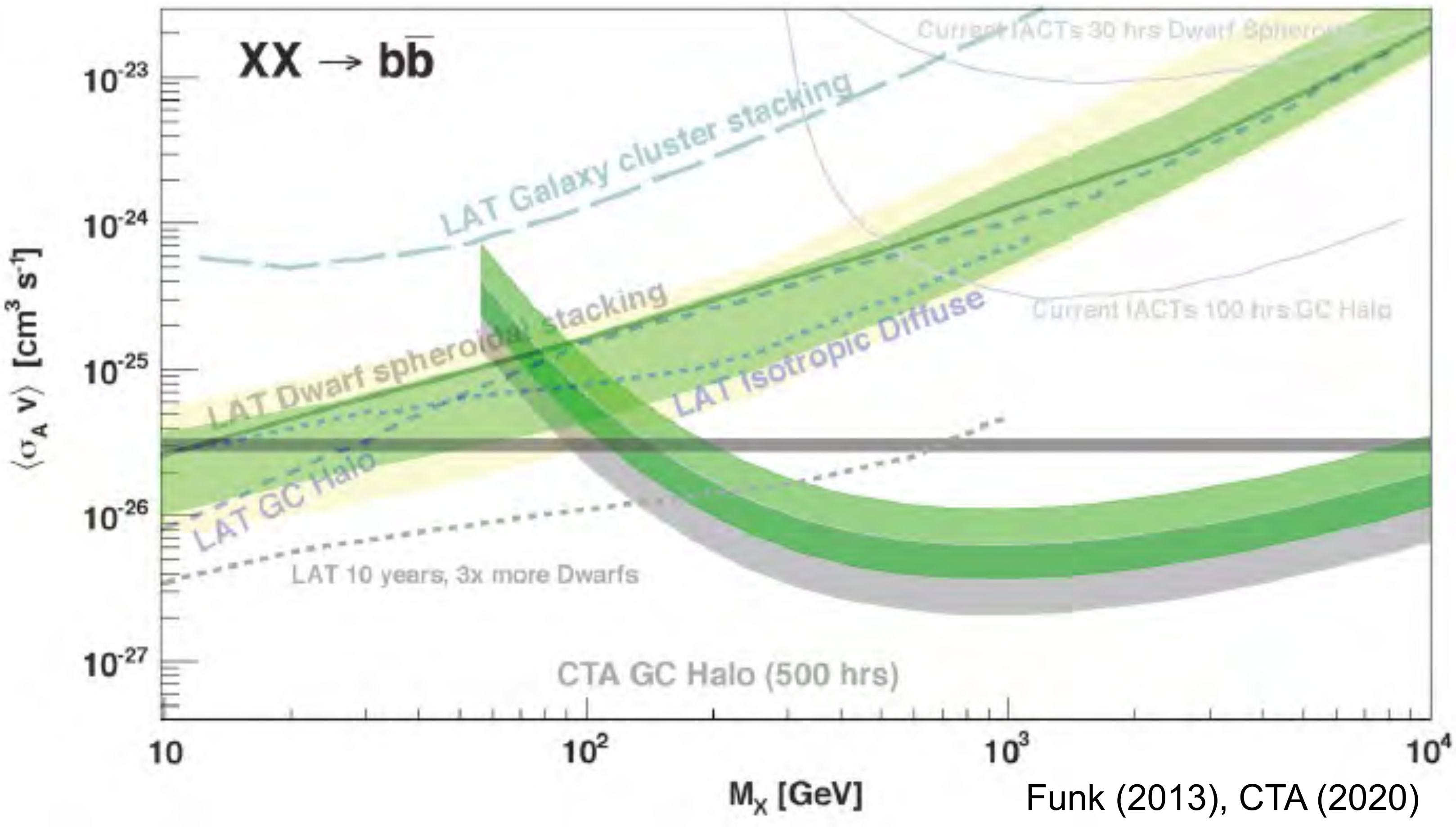
Veritas, Fermi-LAT, HAWC, and others

PHOTONS: EXPERIMENTS

Cerenkov Telescope Array



PHOTONS: STATUS AND PROSPECTS



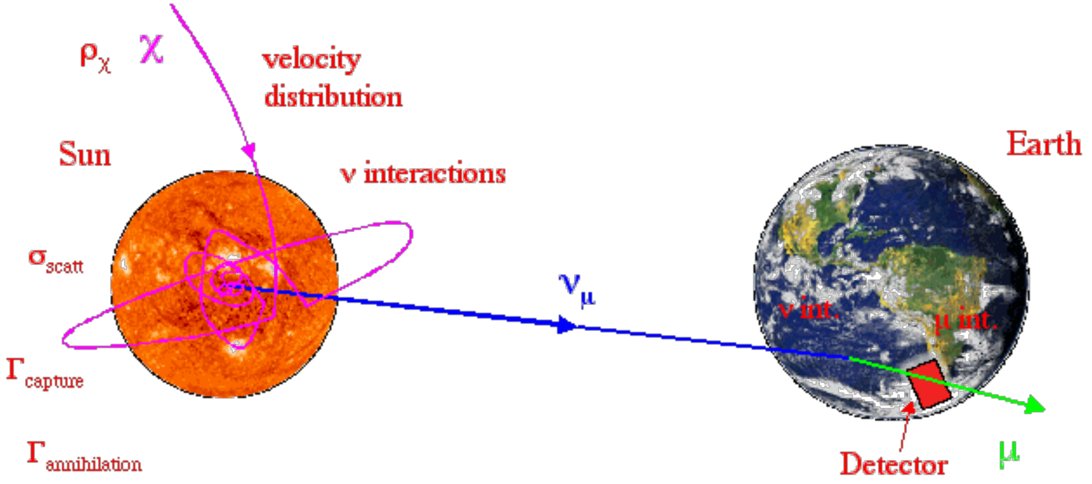
Funk (2013), CTA (2020)

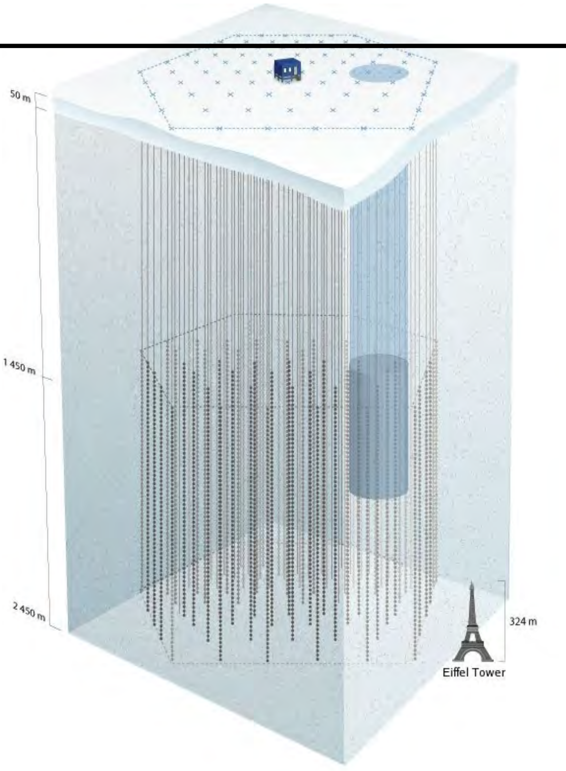
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses above 10 TeV

INDIRECT DETECTION: NEUTRINOS

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

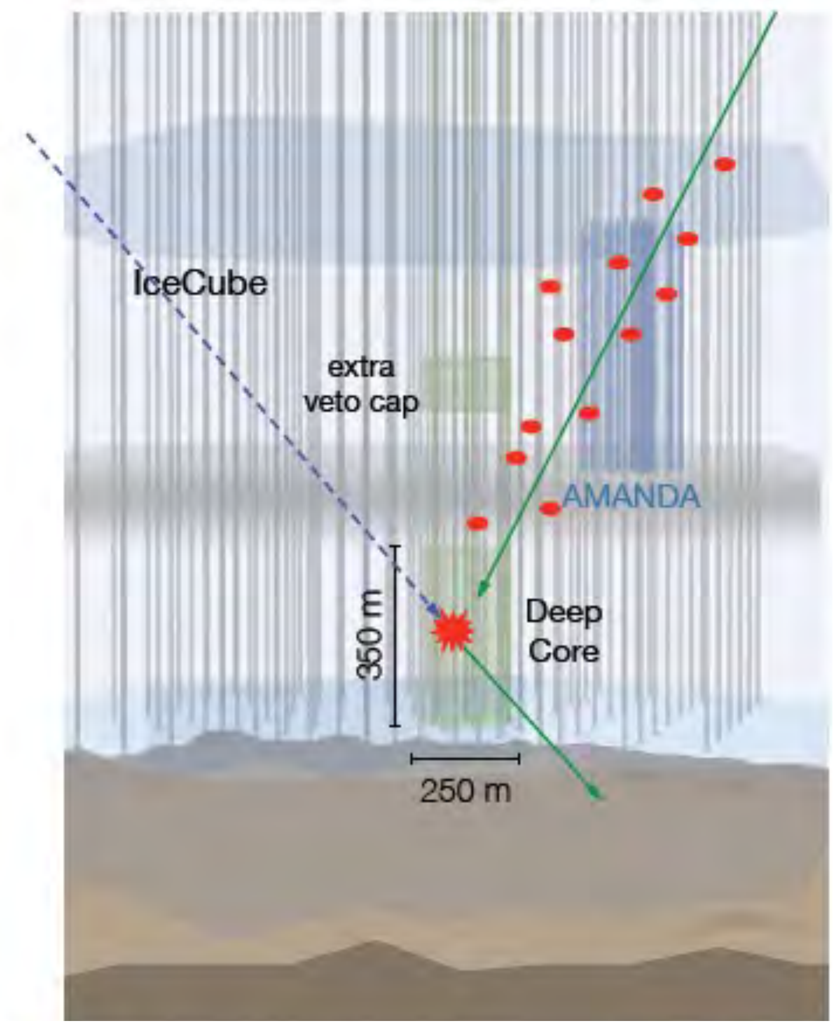
neutrinos , which are detected by _Ice Cube / DeepCore_ .
some particles an experiment





NEUTRINOS: EXPERIMENTS

Current: IceCube/DeepCore, ANTARES



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 may discover the smoking-gun signal of HE neutrinos from the Sun, or set stringent σ_{SD} limits.

INDIRECT DETECTION: ANTI-MATTER

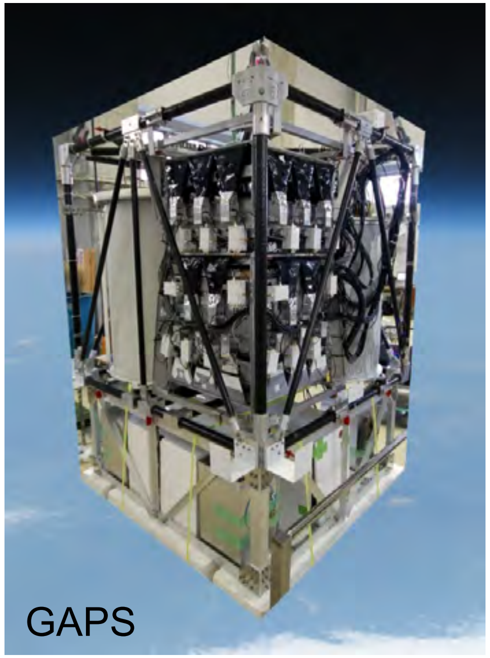
Dark Matter annihilates in ____the halo____ to
a place
____positrons____ , which are detected by ____Fermi/AMS/…____.
some particles an experiment

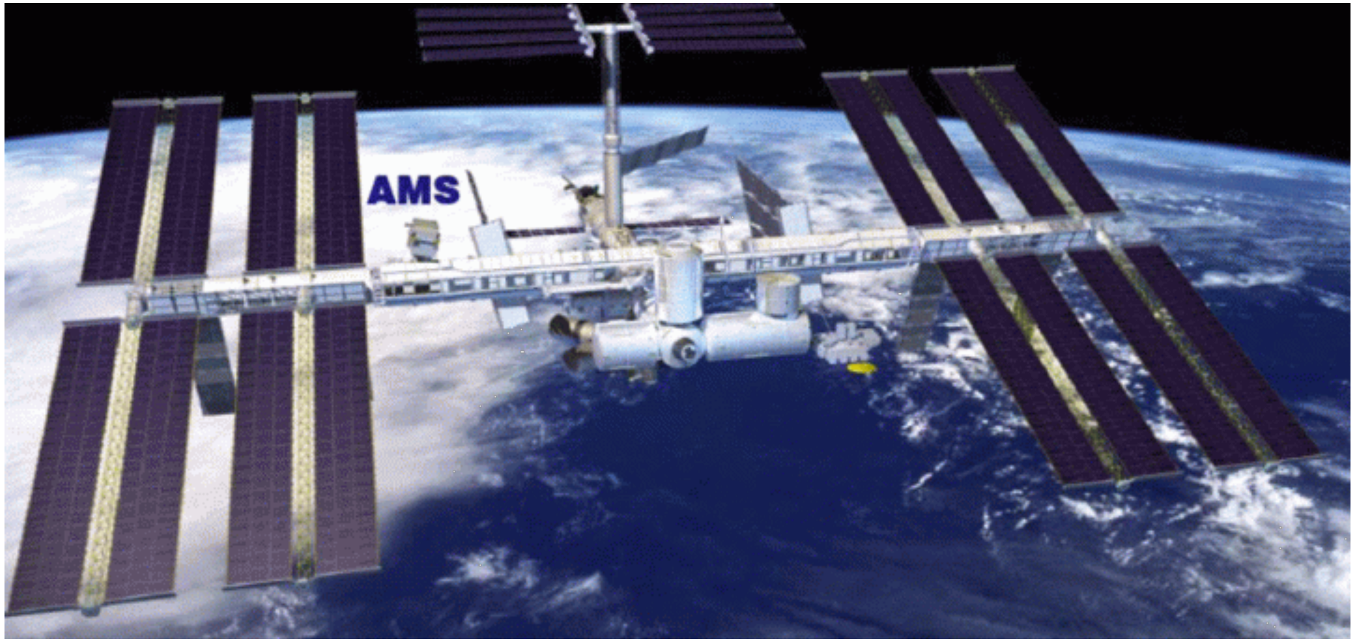
- In contrast to photons and neutrinos, anti-matter does not travel in straight lines, but rather bumps around the local halo before arriving in our detectors.
- For example, positrons, created with energy E_0, detected with energy E

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

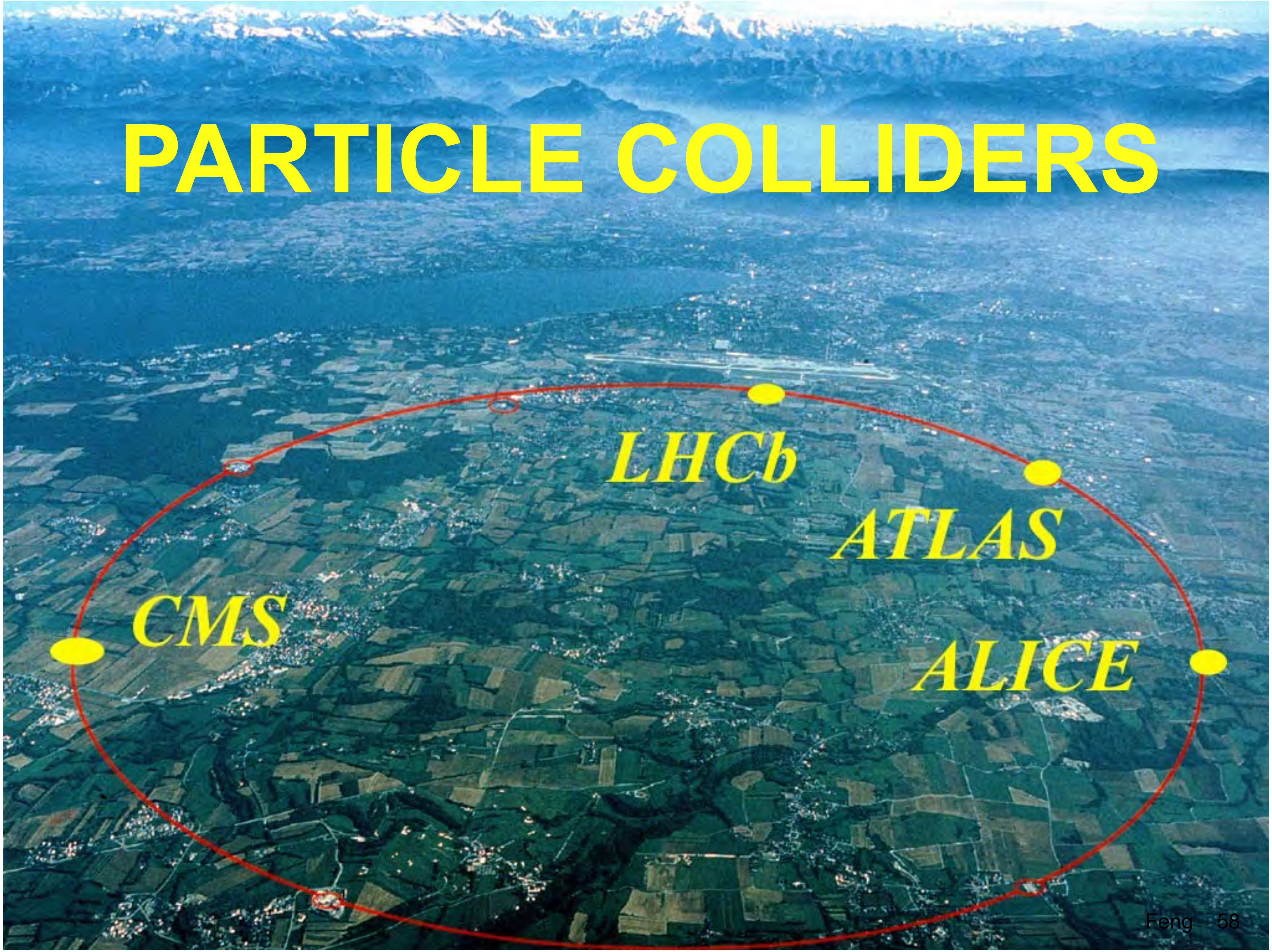
ANTI-MATTER: EXPERIMENTS

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



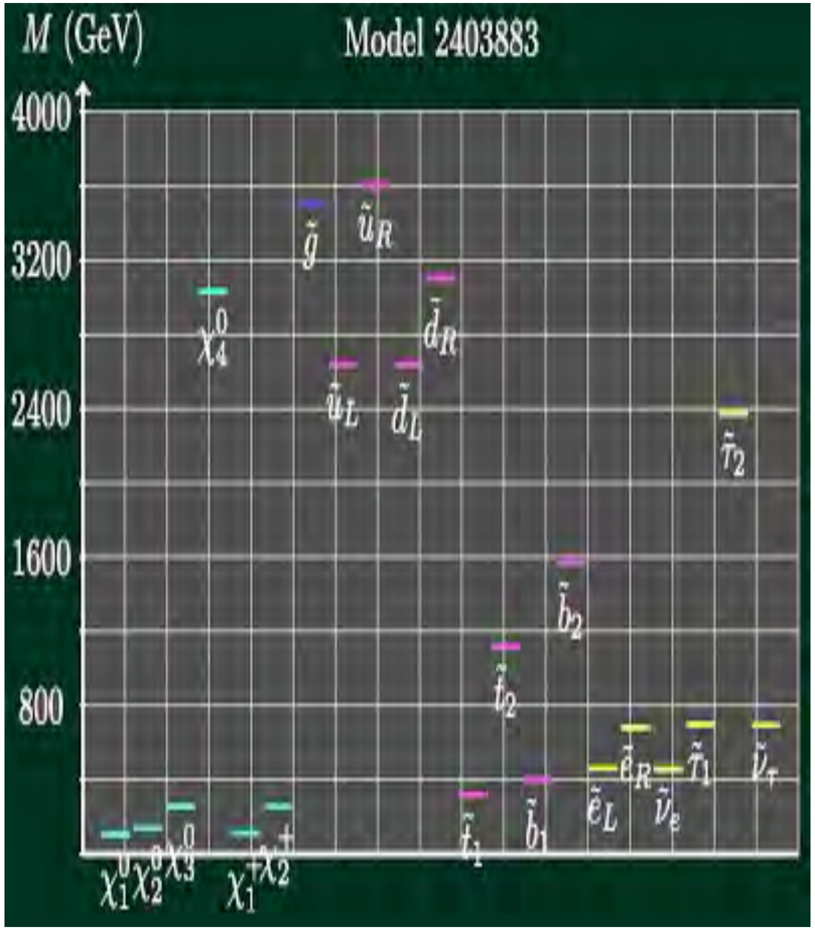


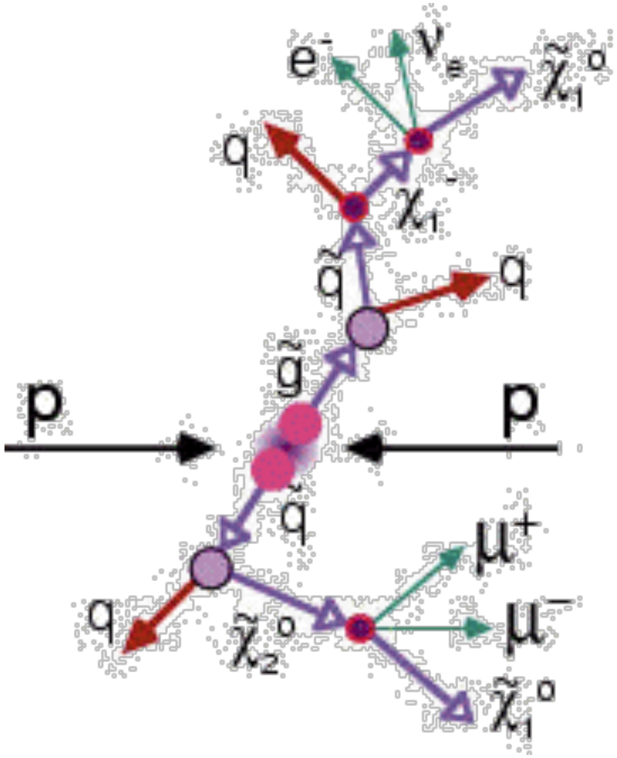
PARTICLE COLLIDERS



FULL MODELS AND SIMPLIFIED MODELS

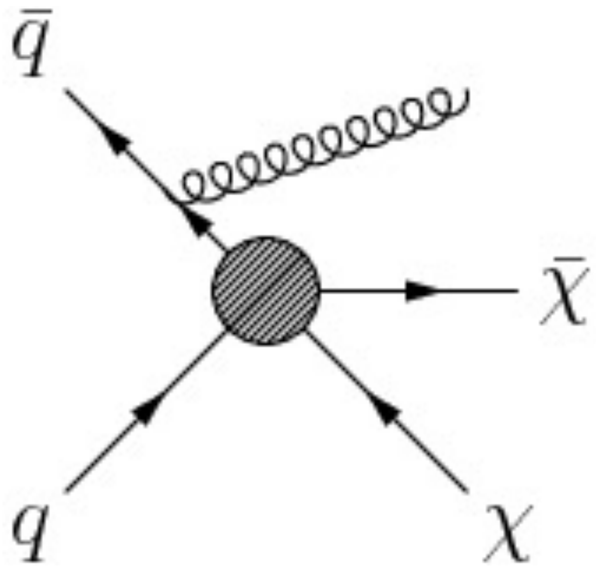
- Consider full models (e.g., SUSY), or simplified models (e.g., minimal DM model) that have just a few particles and parameters. Produce other particles that decay to DM, look for missing E_T signatures.



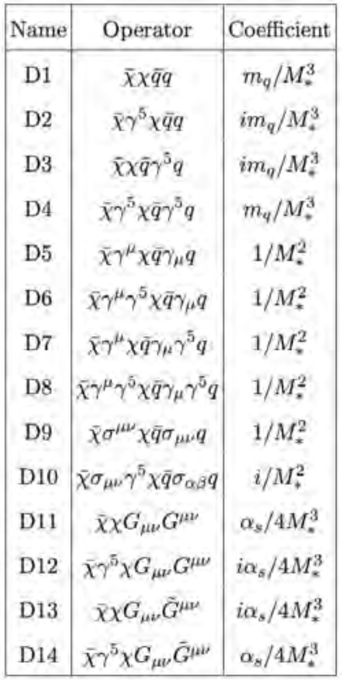


WIMP EFFECTIVE THEORY

- Alternatively, produce the DM directly, but in association with something else that can be seen. Model the blob as an effective operator, look for mono-X, where $X =$ photon, jet, W, Z, h, b, t, ….



Birkedal, Matchev, Perelstein (2004)



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

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

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

- Allows comparison of direct detection, indirect detection, and collider searches with various signatures, but requires that the EFT is valid (mediator is heavy), which is not always true for colliders.