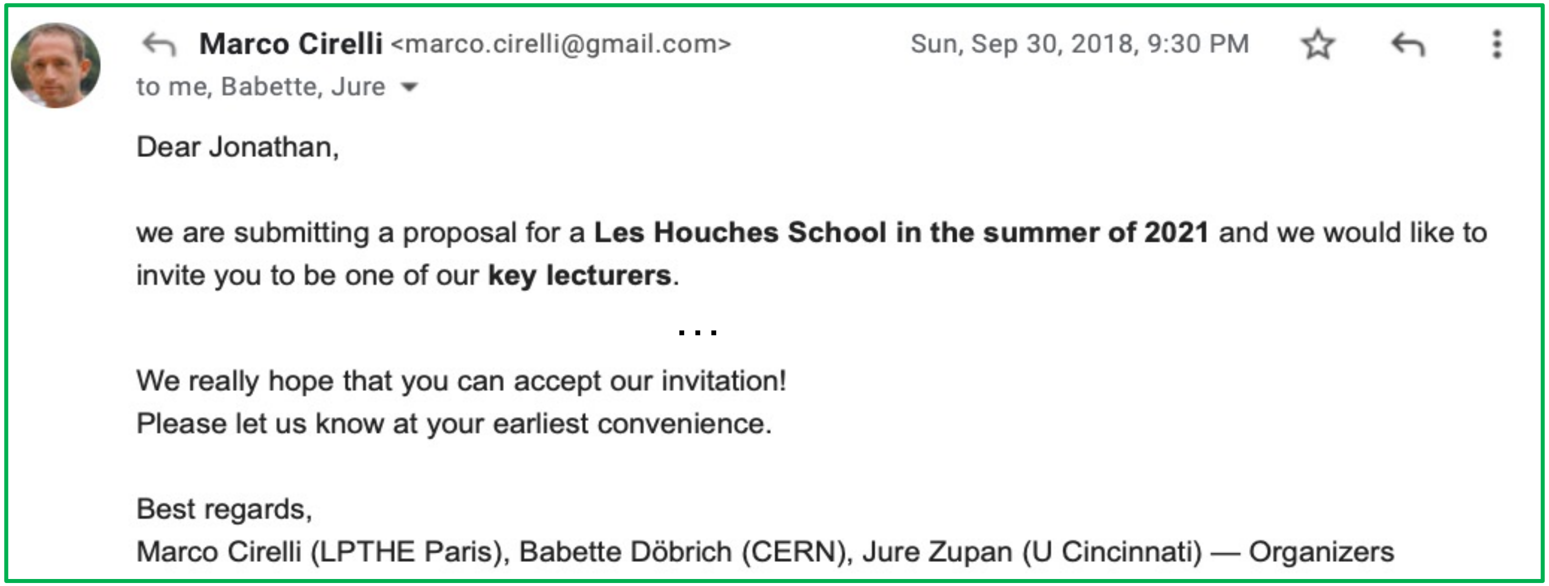
STANDARD WIMPS

Dark Matter

Les Houches Summer School

Jonathan Feng, UC Irvine, 27-29 July 2021

CONGRATULATIONS TO THE ORGANIZERS



Marco Cirelli <marco.cirelli@gmail.com> Sun, Sep 30, 2018, 9:30 PM

to me, Babette, Jure

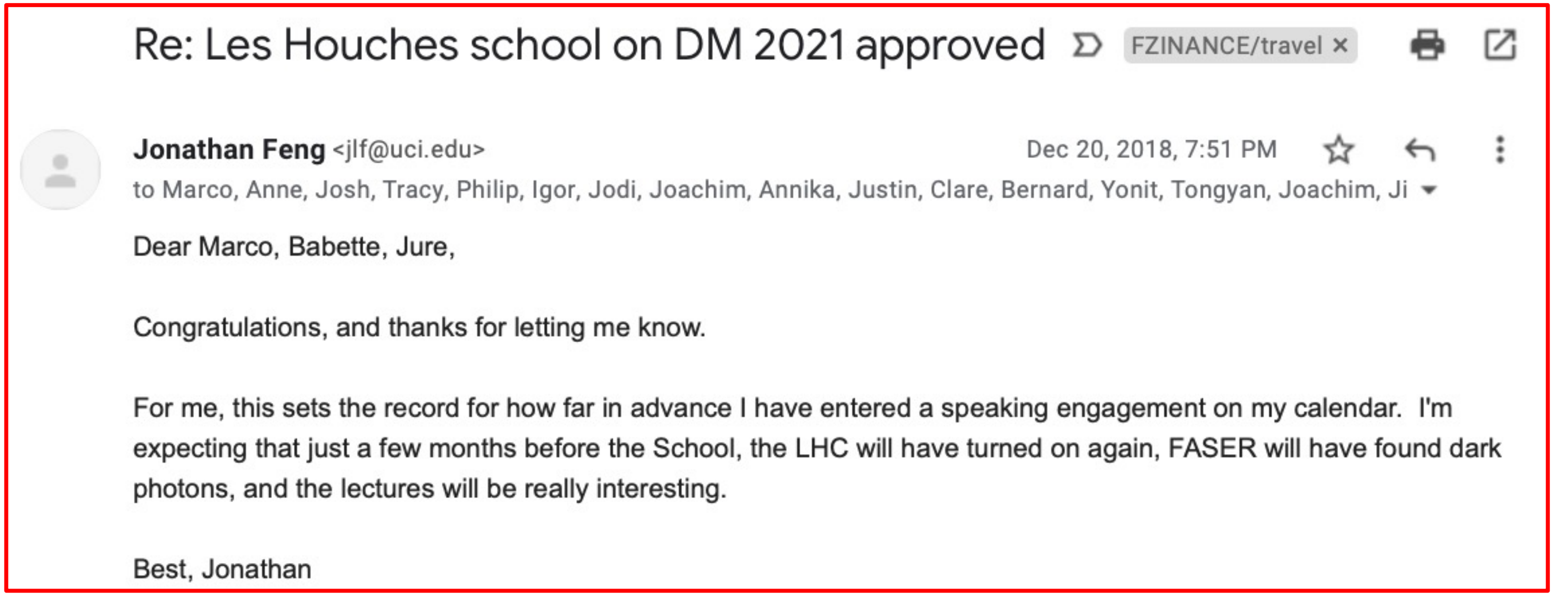
Dear Jonathan,

we are submitting a proposal for a **Les Houches School in the summer of 2021** and we would like to invite you to be one of our **key lecturers**.

…

We really hope that you can accept our invitation!
Please let us know at your earliest convenience.

Best regards,
Marco Cirelli (LPTHE Paris), Babette Döbrich (CERN), Jure Zupan (U Cincinnati) — Organizers



Re: Les Houches school on DM 2021 approved

Jonathan Feng <jlf@uci.edu> Dec 20, 2018, 7:51 PM

to Marco, Anne, Josh, Tracy, Philip, Igor, Jodi, Joachim, Annika, Justin, Clare, Bernard, Yonit, Tongyan, Joachim, Ji

Dear Marco, Babette, Jure,

Congratulations, and thanks for letting me know.

For me, this sets the record for how far in advance I have entered a speaking engagement on my calendar. I'm expecting that just a few months before the School, the LHC will have turned on again, FASER will have found dark photons, and the lectures will be really interesting.

Best, Jonathan

STEVEN WEINBERG (1933-2021)

- His 1987 Loeb Lectures, including the anthropic prediction of the cosmological constant, were the first physics talks I ever attended.
- Four Golden Lessons

Weinberg (2003)

  - No one knows everything, and you don't have to.
  - Head for the messes.
  - Forgive yourself for wasting time [working on the wrong questions].
  - Learn some of the history of your field.

OUTLINE

I. Why WIMPs?

- The Weak Scale
- The WIMP Miracle
- The Discrete WIMP Miracle

II. WIMPs in Supersymmetry

- Supersymmetry
- Stability and LSPs
- Neutralino Freezeout
- Cosmologically-Preferred Supersymmetry

III. WIMP Detection

- Direct Detection
- Indirect Detection
- Collider Searches

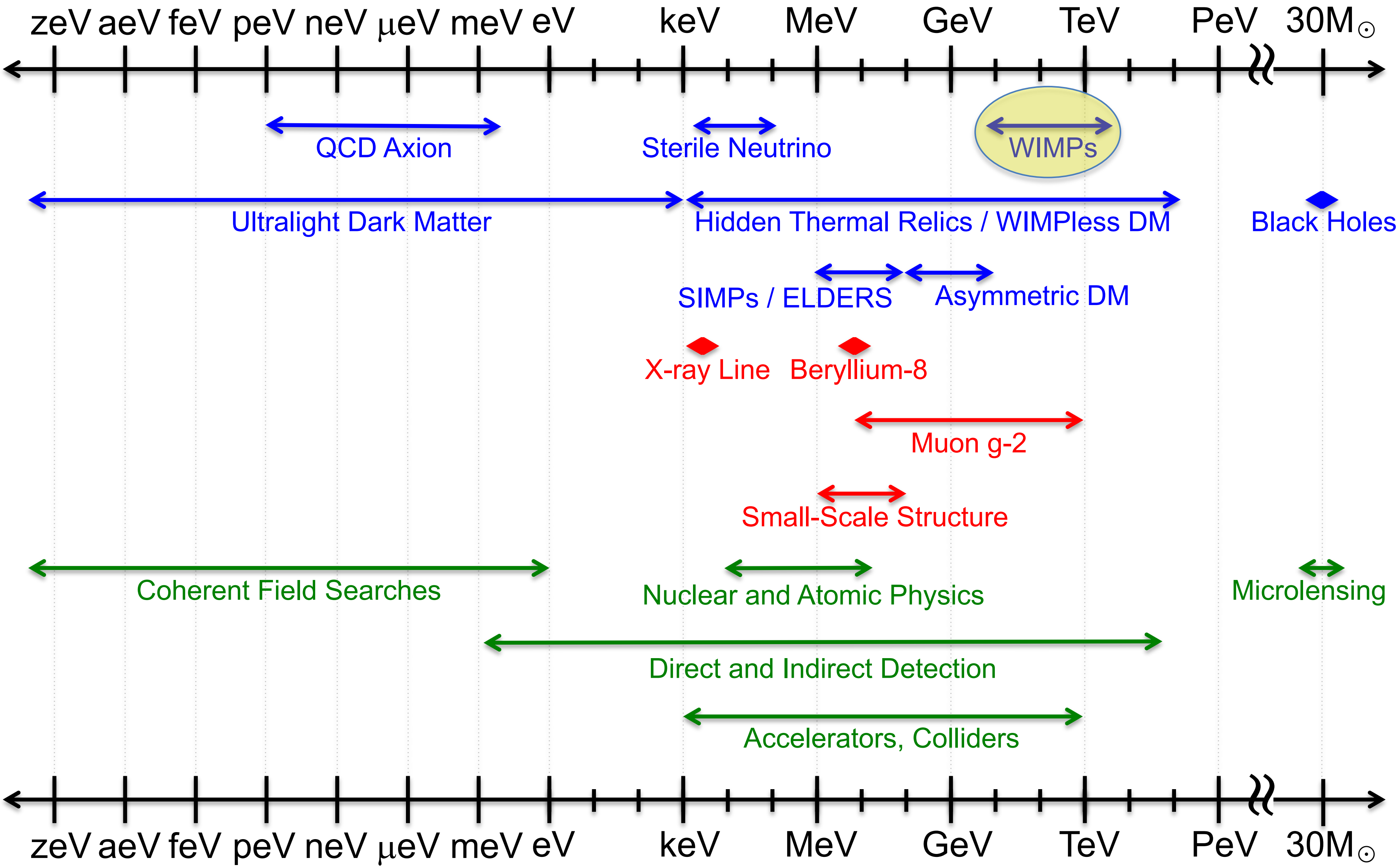
IV. WIMP Variations

- Inelastic WIMPs
- Isospin-Violating WIMPs
- SuperWIMPs
- WIMPless Dark Matter

3 90-minute lectures; questions welcome!

I. WHY WIMPS?

WHY WIMPS?



Modified from the Cosmic Visions Report (2017)

GOALS

- WIMPs have dominated the particle dark matter landscape for decades.

- It would be inconceivable to lecture about
  - DM production (Ruderman) without talking about WIMP freeze out.
  - DM direct detection (Cooley) without talking about WIMP direct detection.
  - DM indirect detection (Slatyer) without talking about WIMP indirect detection.
  - DM at accelerators (Harris) without talking about WIMPs at colliders.

- So there will be a lot of overlap with other lectures. The goal here is to
  - explain why WIMPs have been a dominant paradigm for so long,
  - gather together some of their basic features,
  - highlight the example of WIMPs in supersymmetry,
  - and present some of the variations on the WIMP theme that have by now suffused the literature and illustrate the richness of this circle of ideas.

- These lectures are targeted to graduate students starting DM research, but I hope there will be something of interest to others as well.

THE WEAK SCALE

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

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

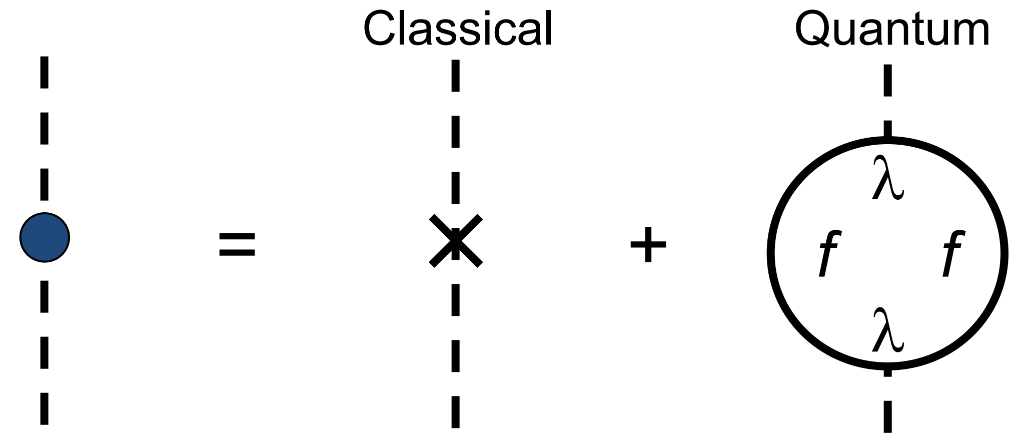
- The measured value, $G_F \sim 10^{-5}\ \mathrm{GeV}^{-2}$, introduces a new mass scale in nature, the weak scale:

$$m_{\mathrm{weak}} \sim 100\ \mathrm{GeV}\ .$$

- We still don't understand the origin of this mass scale, but every reasonable attempt so far introduces new particles at the weak scale.

NATURALNESS

- We have now discovered a particle that looks like a fundamental scalar with a mass $m_h \simeq 125$ GeV: the Higgs boson. Scalars are different:

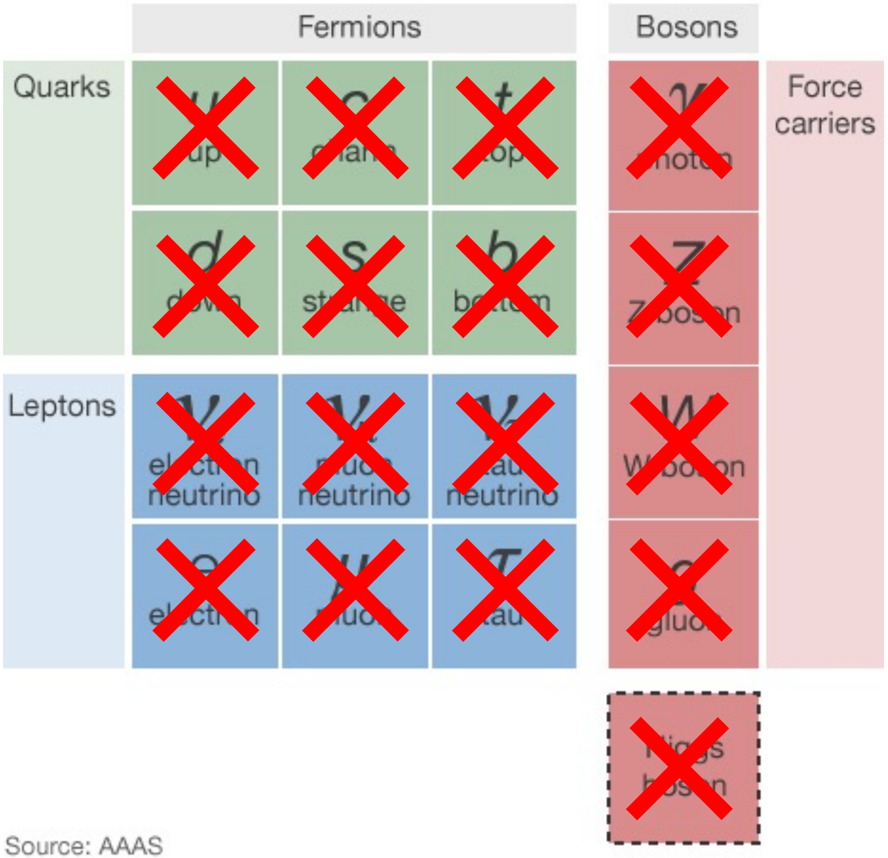


$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

- For $\Lambda \sim m_{\text{Planck}} \sim 10^{19}$ GeV, and f = top ($\lambda \sim 1$), the classical and quantum contributions must cancel to 1 part in 10^{32} to yield the physical Higgs mass.

- This is the naturalness, fine-tuning, or gauge hierarchy problem of the Standard Model. Its resolution likely requires new particles at the weak scale that introduce new quantum contributions to cancel the existing ones.

DARK MATTER



Source: AAAS

Known DM properties

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

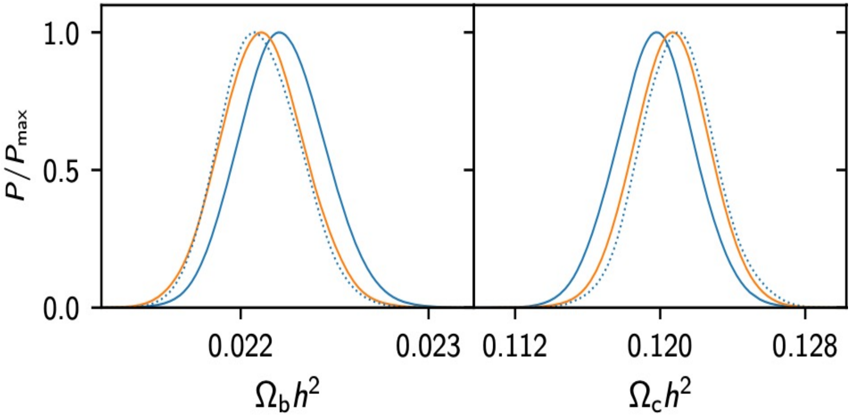
None of the known particles can be cold DM.

RELIC DENSITY

- We know little about dark matter. We know more about what it isn't than what it is.

- The one thing we do know *precisely* is the dark matter's relic density: $\Omega_{\mathrm{DM}}h^2 = 0.1200 \pm 0.0012.$

Planck Collaboration (2018)



- What can we learn from this about dark matter's particle properties?
  - Generically: nothing.
  - But if the dark matter now is a surviving relic of the hot Big Bang through thermal freeze out: a lot.

THERMAL FREEZE OUT

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

$$XX \leftrightarrow f\bar{f}$$

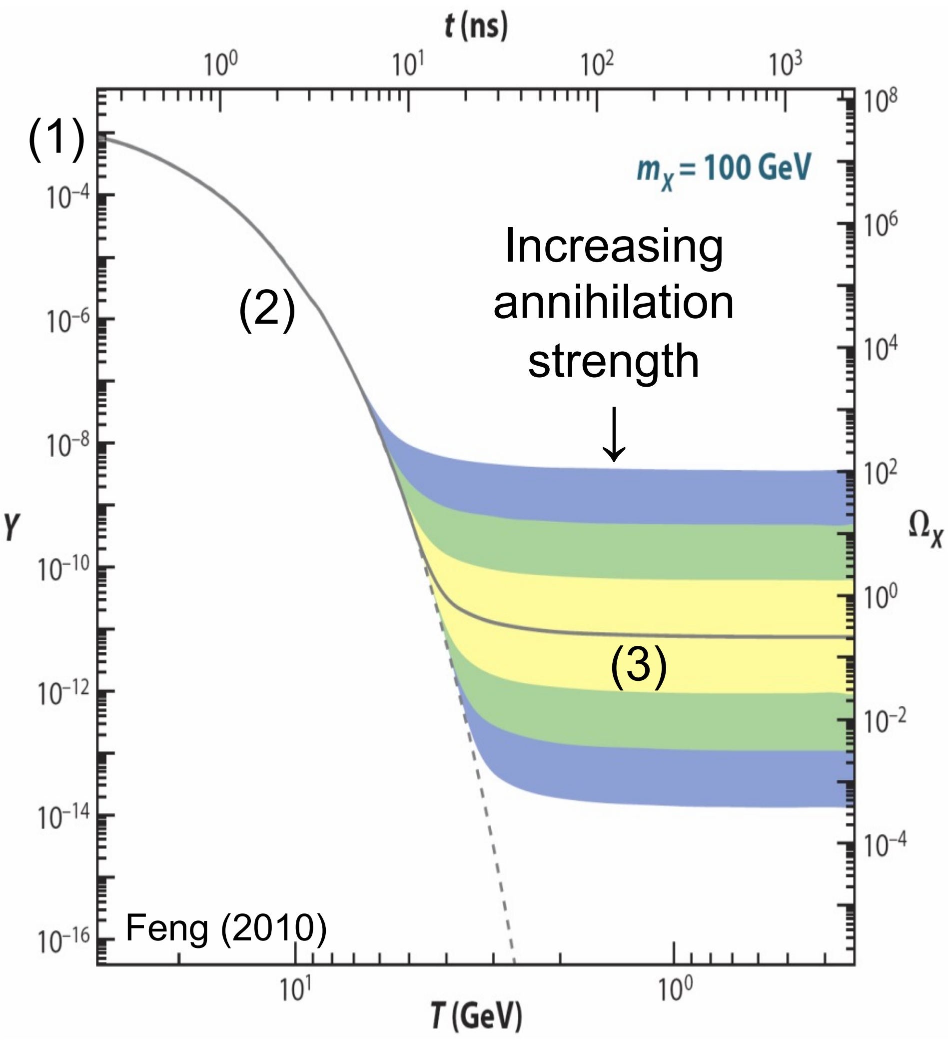
(2) Universe cools:

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

(3) Universe expands:

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

Zeldovich et al. (1960s)



Increasing annihilation strength ↓

Feng (2010)

THERMAL FREEZE OUT

- The Boltzmann equation:

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

Dilution from expansion

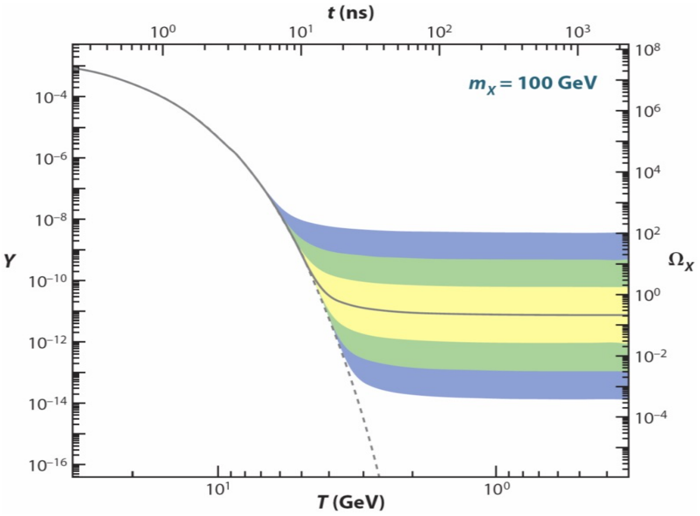
$\chi\chi \rightarrow f\bar{f}$

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

- $n \approx n_{eq}$ until interaction rate drops below expansion rate:

$$n_{\rm eq} \langle \sigma_A v \rangle \sim H$$

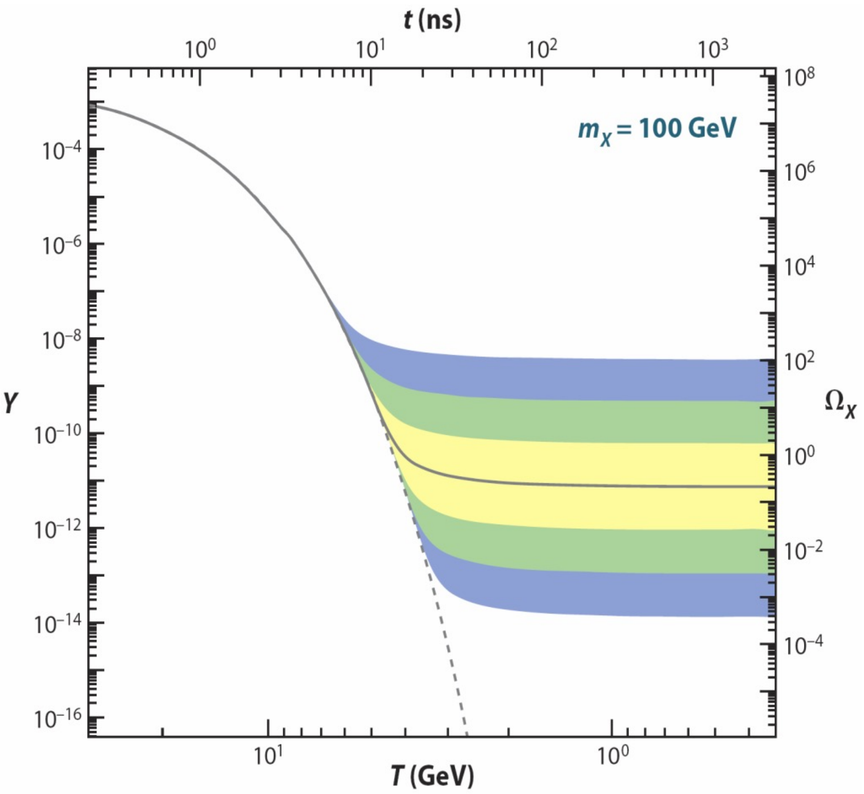
$$(mT)^{3/2} e^{-m/T} \qquad \frac{\alpha^2}{m^2} \qquad \frac{T^2}{M_{\rm Pl}}$$



- Might expect freeze out shortly after T drops below m, when n_{eq} becomes exponentially (Boltzmann) suppressed. But M_{Pl} is large, and the universe expands *slowly*! First guess is pretty good:

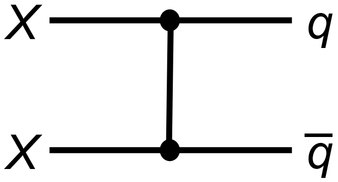
$$\frac{m}{T} \sim \ln \left(\frac{\alpha^2 M_{\rm Pl}}{\sqrt{mT}} \right) \quad \xRightarrow{m \sim m_{\rm weak}} \quad \frac{m}{T} \sim 25$$

THE WIMP MIRACLE



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

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



where we've assumed that the annihilation is characterized by a single mass scale.

- Keeping track of the constants, we find $m_X \sim 100 \text{ GeV}, g_X \sim 0.6$ → $\Omega_X \sim 0.1$.

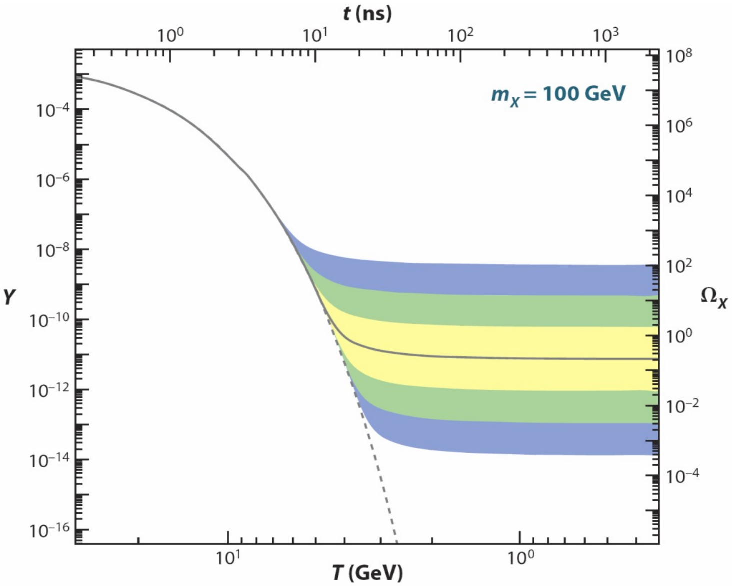
- A remarkable coincidence: particles with the right thermal relic density are now at the energy frontier! The LHC is a big DM search experiment.

THE WIMP MIRACLE

- In more detail, at freeze out, $\frac{m}{T} \sim 20$, so

  K.E. = $\frac{3}{2}kT \rightarrow T \sim \frac{1}{3}mv^2 \sim \frac{1}{20}\ m \rightarrow v \sim \frac{1}{3}$.

- At freezeout, dark matter was neither ultra-relativistic, nor non-relativistic. But it was far more relativistic then than it is now in our neighborhood, where $v \sim 10^{-3}$. This is a key difference to keep in mind!



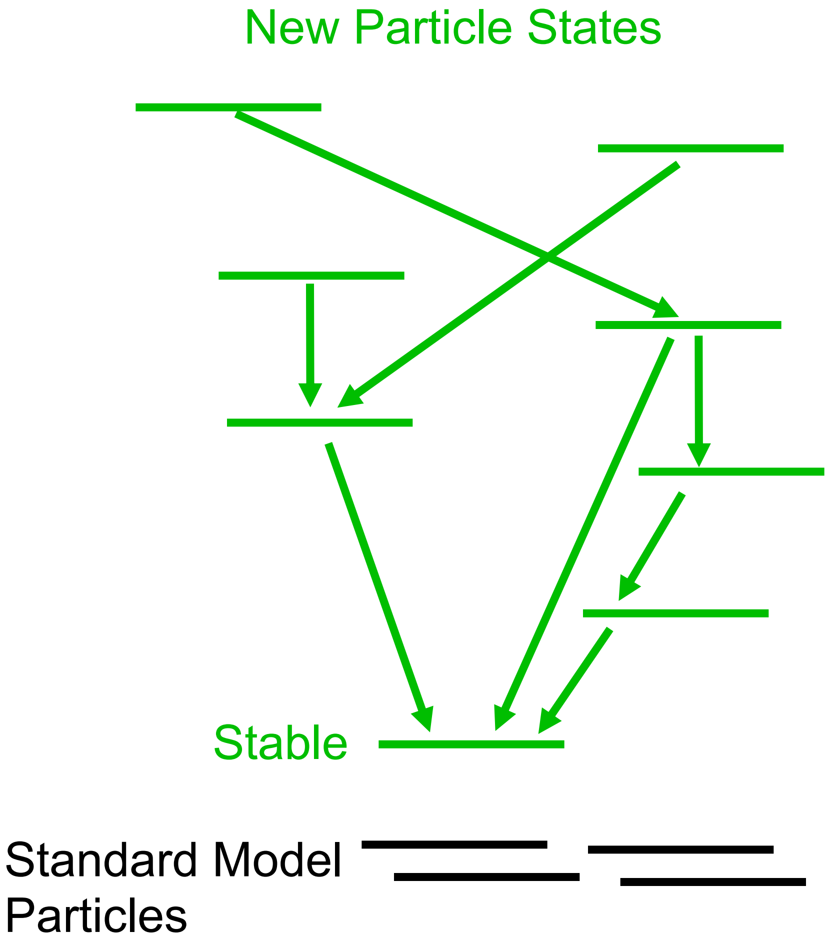
- Freeze out is at T ~ 5 GeV and t ~ ns, not at T ~ 100 GeV and t ~ ps.

- This is also called chemical freeze out (no number changing), which is distinct from kinetic freeze out (no energy exchange through $fX \rightarrow fX$).

- The WIMP miracle is not a precise coincidence. But it is tantalizing, and it is our strongest quantitative hint that our attempts to understand the universe on the largest and smallest scales may be related.

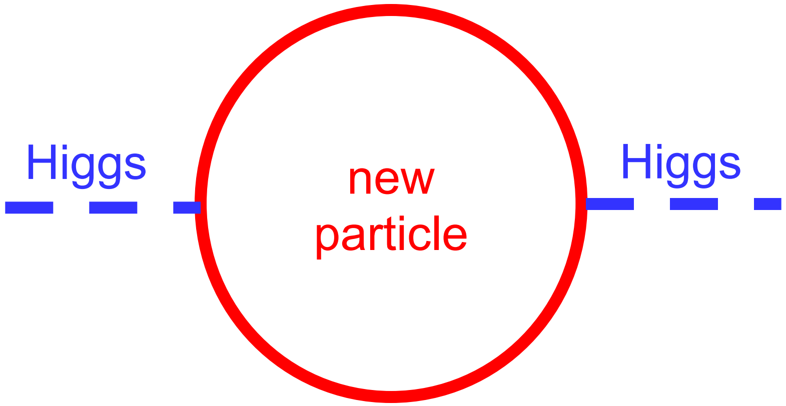
WIMP STABILITY

- The WIMP miracle is well appreciated. But its success relies on 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.
- But there are reasons, based on experimental data, to think that at least one weak scale particle might be stable.

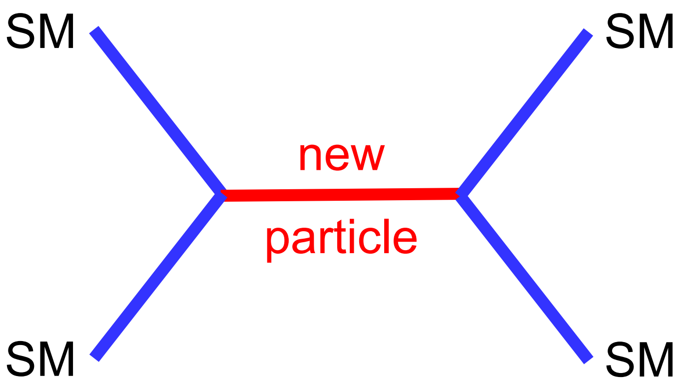


THE DISCRETE WIMP MIRACLE

Gauge Hierarchy requires



Precision EW constrains



- The 4-point SM interactions are highly constrained by many experiments, notably those at LEP through precision electroweak data.

- 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.

II. WIMPS IN SUPERSYMMETRY

WIMPS IN BSM MODELS

- For the reasons mentioned above, WIMPs appear generically in many BSM theories
  - Propose some new weak scale particles.
  - They help some things, but strain electroweak fits.
  - Impose a discrete symmetry to improve fits.
  - An ideal DM candidate emerges!

- Many examples
  - Neutralinos in supersymmetry

    Goldberg (1983); Elllis et al. (1983)
  - KK B1 (“KK photons”) in universal extra dimensions

    Servant, Tait (2004); Cheng, Feng, Matchev (2004)
  - Lightest T-odd particle in little Higgs theories

    Cheng, Low (2004)

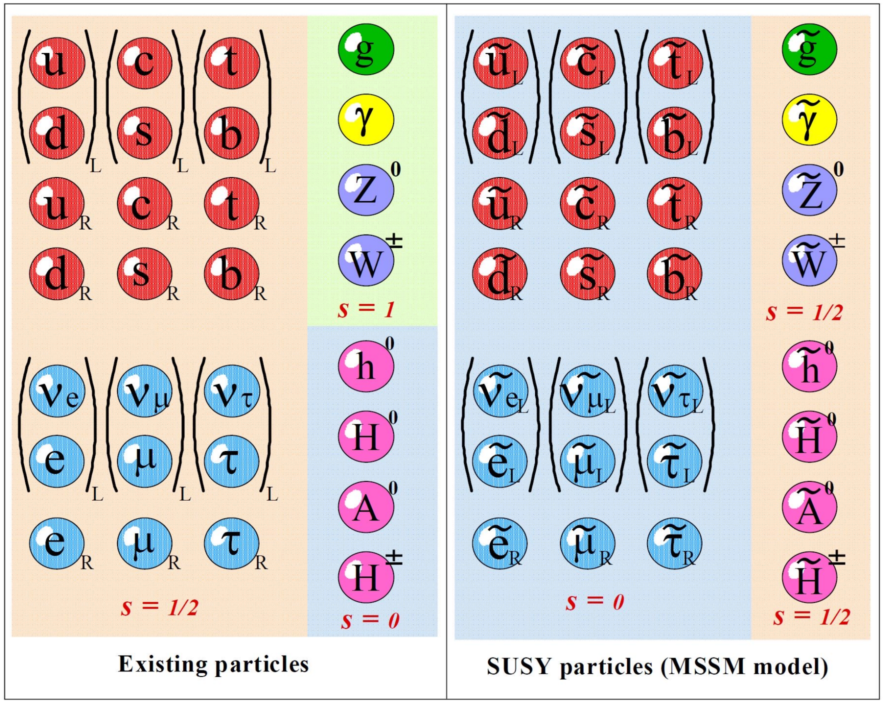
- Here focus on supersymmetry as an interesting example.

SUPERSYMMETRY

- Supersymmetry predicts a partner particle for every known particle: Spin 0 ↔ Spin $\frac{1}{2}$, Spin $\frac{1}{2}$ ↔ Spin 1.

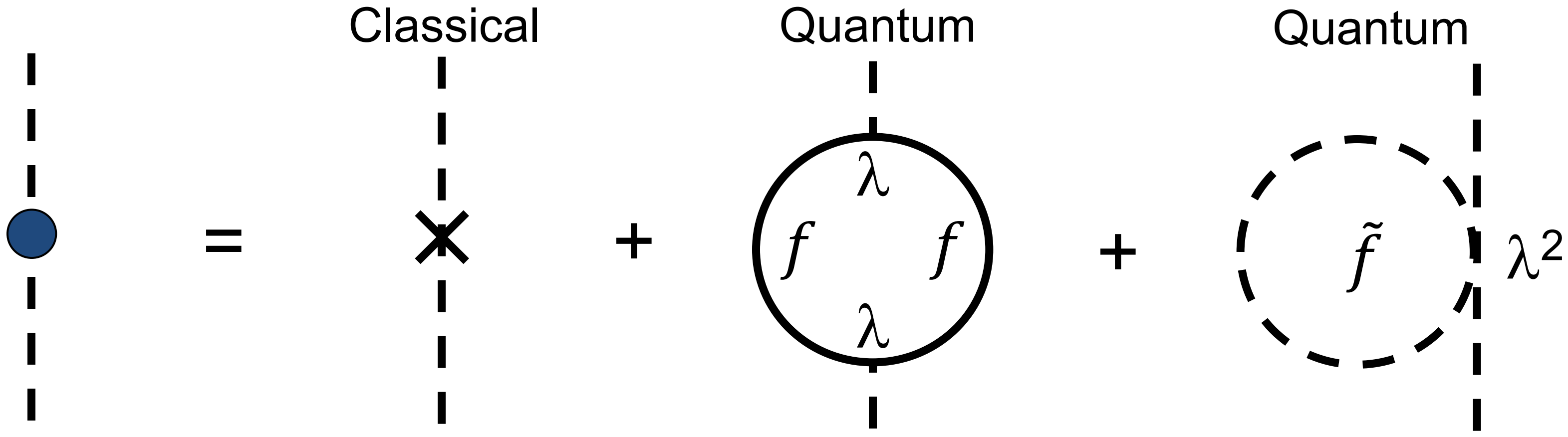
- New particles
  - Spin 0 squarks
  - Spin 0 sleptons
  - Spin $\frac{1}{2}$ gauginos:

    Bino, Winos, gluinos
  - Spin $\frac{1}{2}$ Higgsinos



- The Higgsino partner of the SM Higgs boson is a new fermion that introduces anomalies. In the Minimal Supersymmetric Standard Model (MSSM), we must add an additional Higgs boson and Higgsino to cancel these anomalies, but no more.

NATURALNESS IN SUPERSYMMETRY



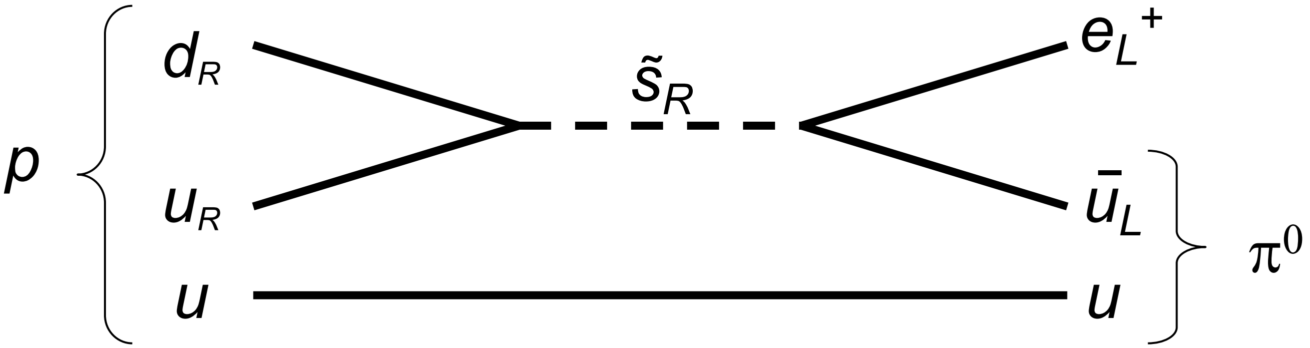
$$m_h^2 = (m_h^2)_0 \underbrace{- \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2}_{+\ \frac{1}{16\pi^2}\lambda^2(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_h)}$$

- For $\Lambda \sim m_{Pl}$ (m_W), and f = top, 1% fine-tuning → $m_{\tilde{t}} < 1$ (3) TeV
- Also, bounds on other sfermions are much weaker: $m_{\tilde{f}} < 10$ (30) TeV

Drees (1986); Dimopoulos, Giudice (1995); Pomoral, Tomasini (1996)

R-PARITY AND STABLE LSPS

- One immediate problem: supersymmetric particles mediate proton decay $p \to \pi^0 e^+$ and similar decay modes.



- 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.

Farrar, Fayet (1978)

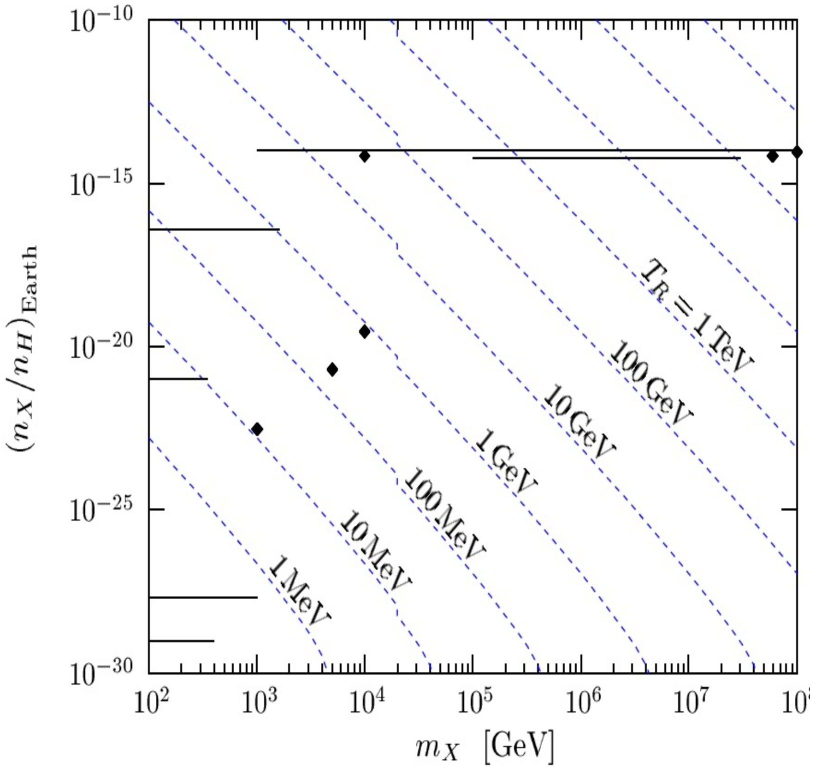
- Consequences
  - This eliminates proton decay and also many troubling 4-point interactions of SM particles.
  - The lightest SUSY particle (LSP) is stable and a potential DM candidate.

WHAT IS THE LSP?

- Should be neutral. Yes, but why? The story is more nuanced and interesting than is commonly appreciated.

- A colored LSP (say, a gluino) will bind with quarks to form a color-neutral state.
  - Yes, but there are severe bounds on exotic nuclei from sea water searches (solid lines and dots in figure), where the constraint is strengthened by testing deep sea water.

- But inflation can dilute this away.
  - Yes, but they are regenerated by reheating. Masses < TeV are excluded by T_{RH} > 1 MeV, but masses > TeV are allowed.



Kudo, Yamaguchi (2001)

- Bottom line: for m < TeV, the LSP should be color and electrically neutral.

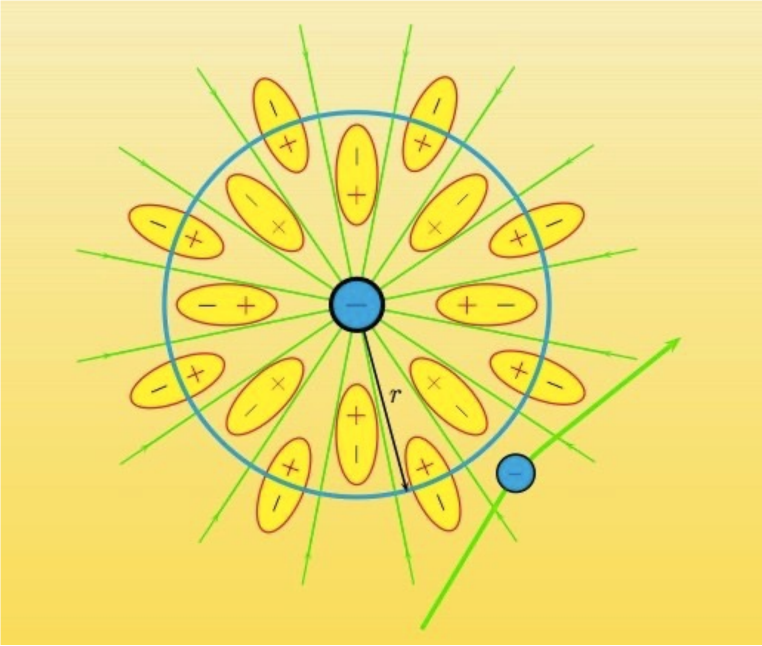
NEUTRAL SUSY PARTICLES

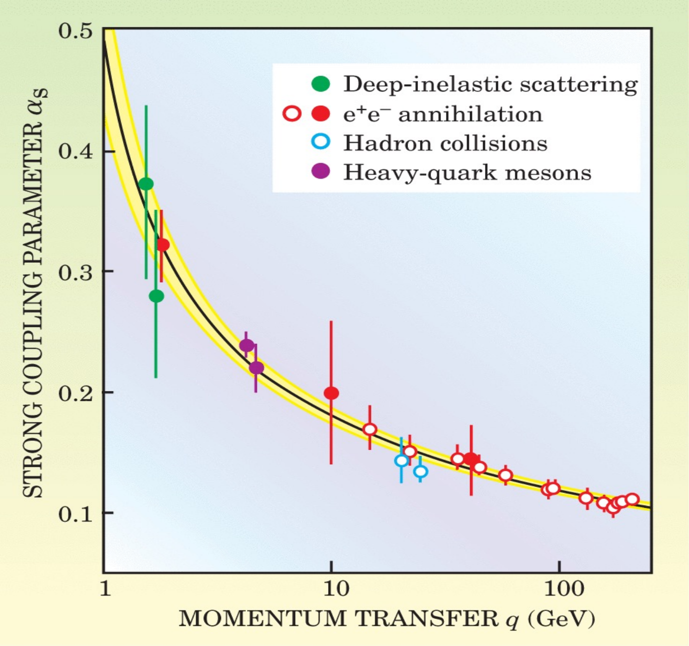
Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2						$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

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.



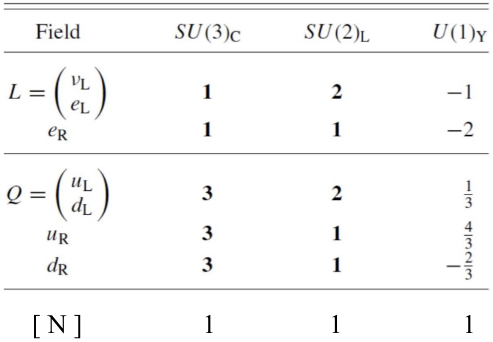


COUPLING CONSTANT UNIFICATION

- 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

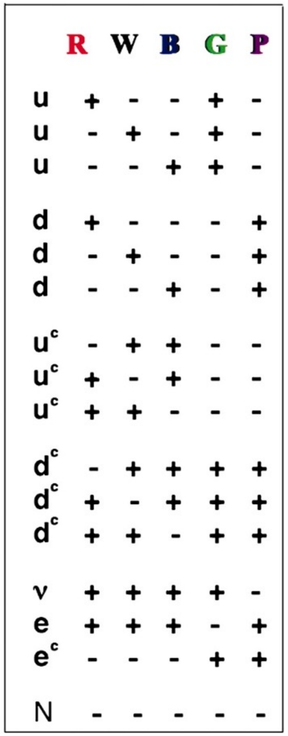
SU(5)

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

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

[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	-	-	-	-	-

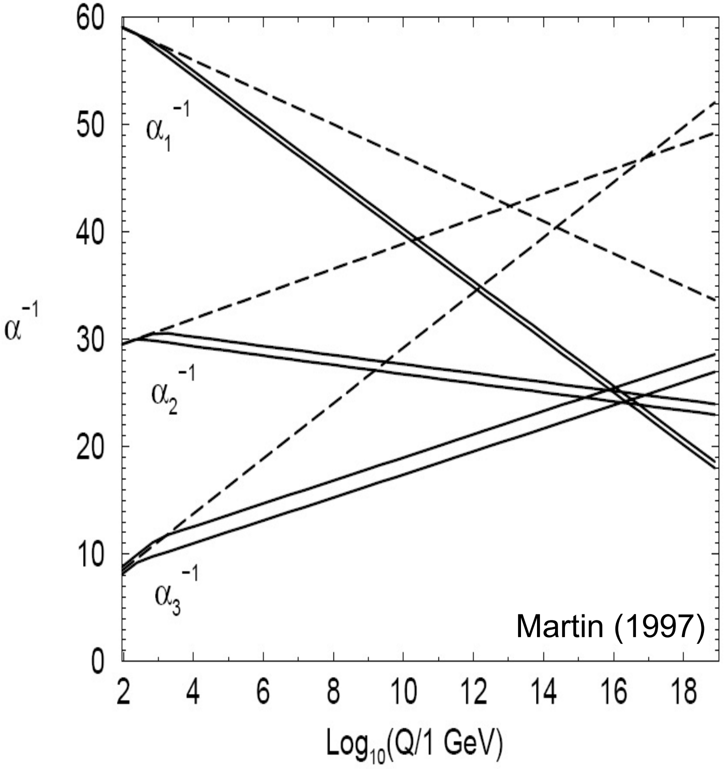
COUPLING CONSTANT UNIFICATION

- 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)

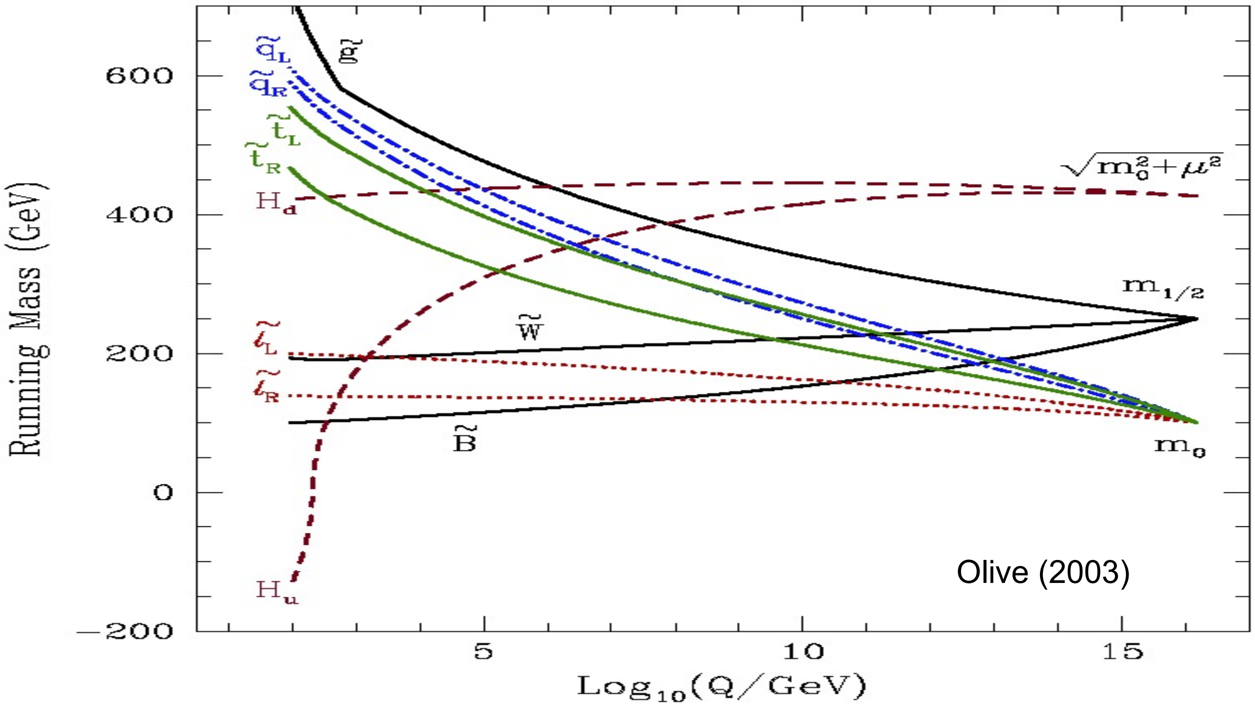
- Coupling constant unification is beautifully consistent with the fact that SM particles fit neatly into GUT multiplets, and it explains why $g_3 > g_2 > g_1$.

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!



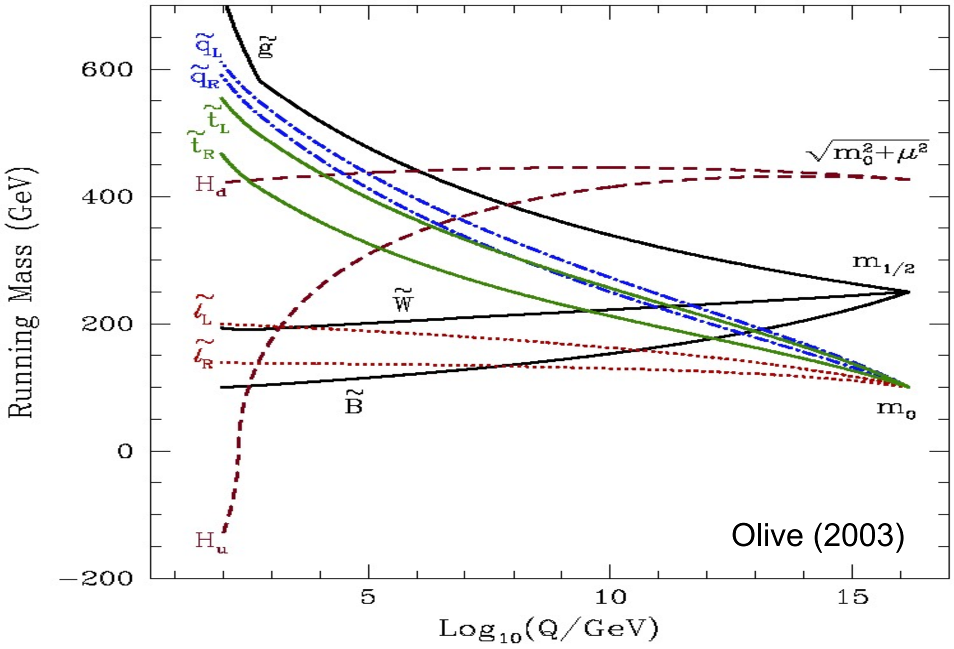
Olive (2003)

OTHER INTERESTING RGE IMPLICATIONS

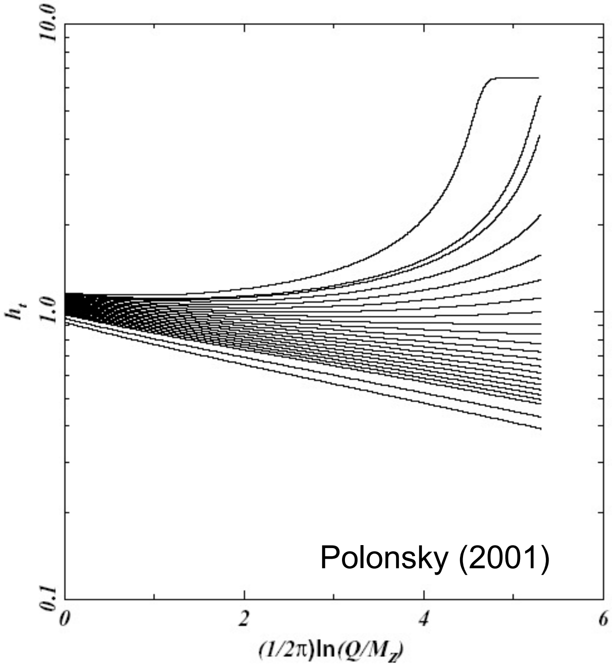
- Colored superpartners are typically heavier than uncolored superpartners. Squarks are expected to be heavier than sleptons.

- 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:

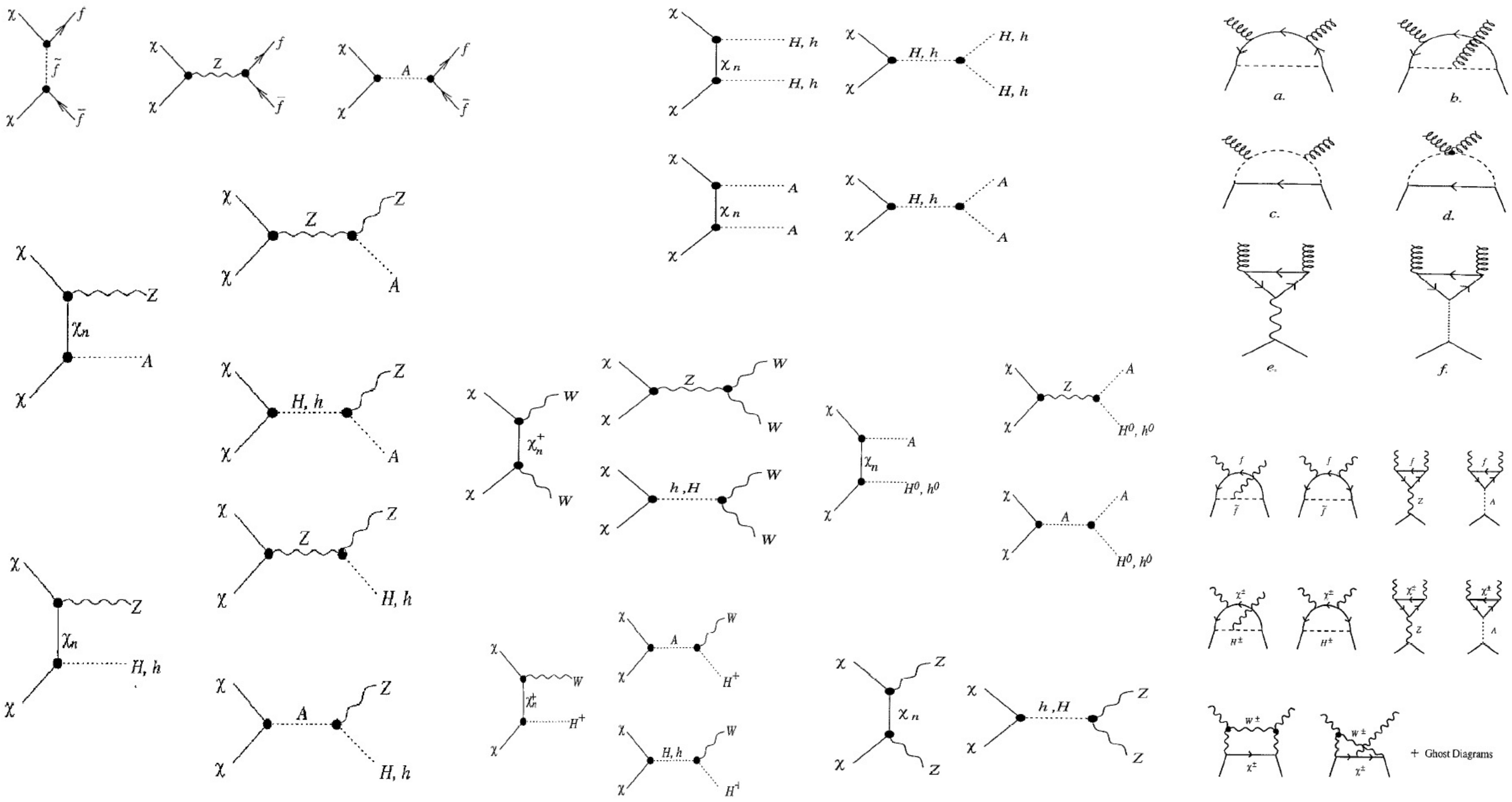
  - The regions of parameter space that give too much dark matter are excluded.

  - 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.

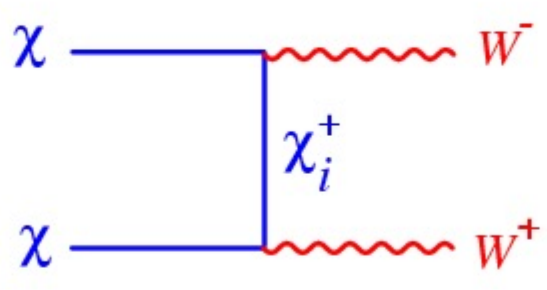
NEUTRALINO ANNIHILATION



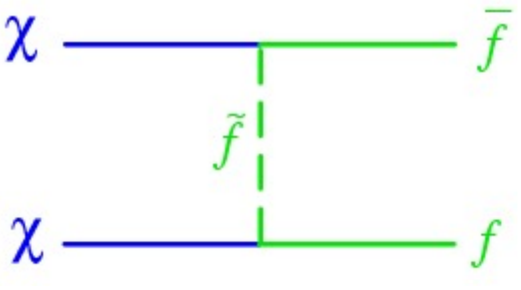
Jungman, Kamionkowski, Griest (1995)

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.

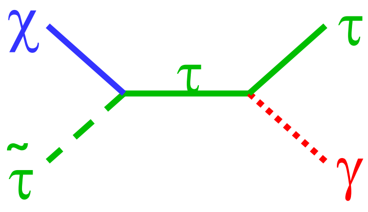
COSMOLOGICALLY-PREFERRED SUSY

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.

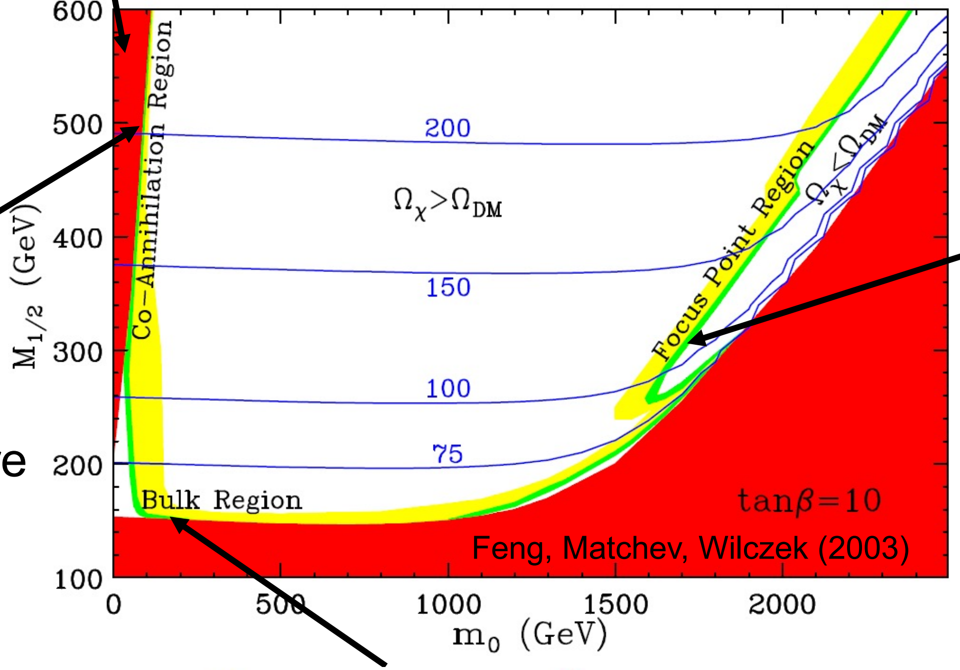
Excluded:

Stau LSP

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

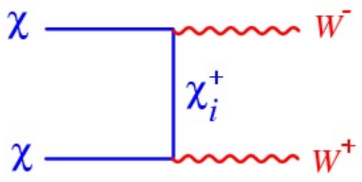


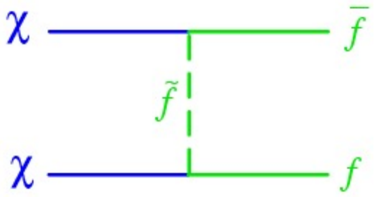
Co-annihilation: stau and Bino are 5% degenerate, so staus are present a freeze out T ~ m/20, help Binos annihilate.



Feng, Matchev, Wilczek (2003)

Focus point SUSY:
Bino mixes with Higgsinos





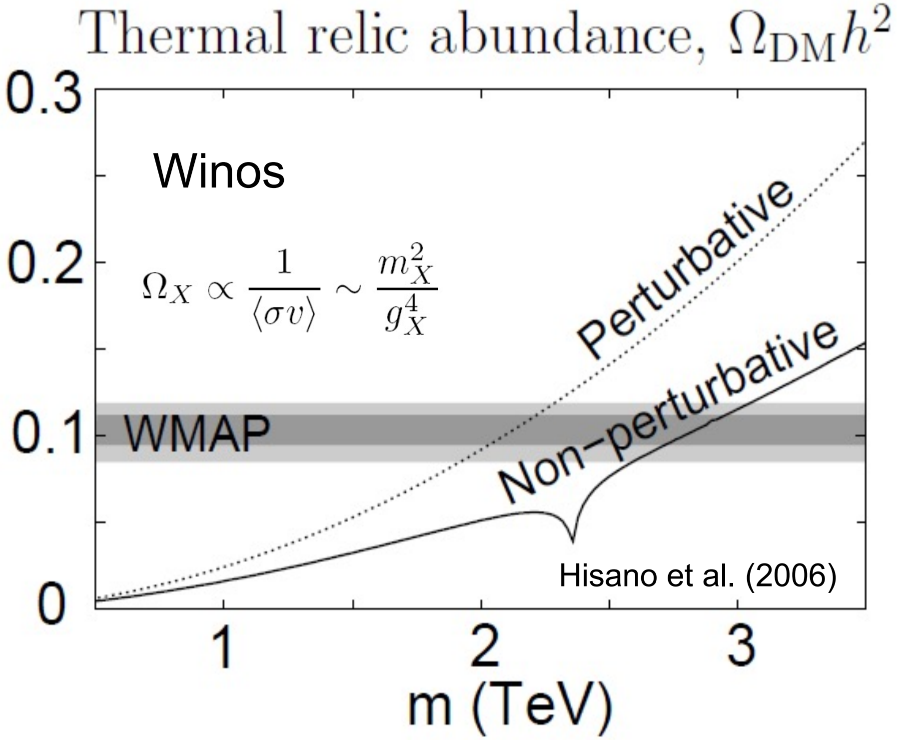
Light SUSY: Bino and sfermion masses around 100 GeV

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.

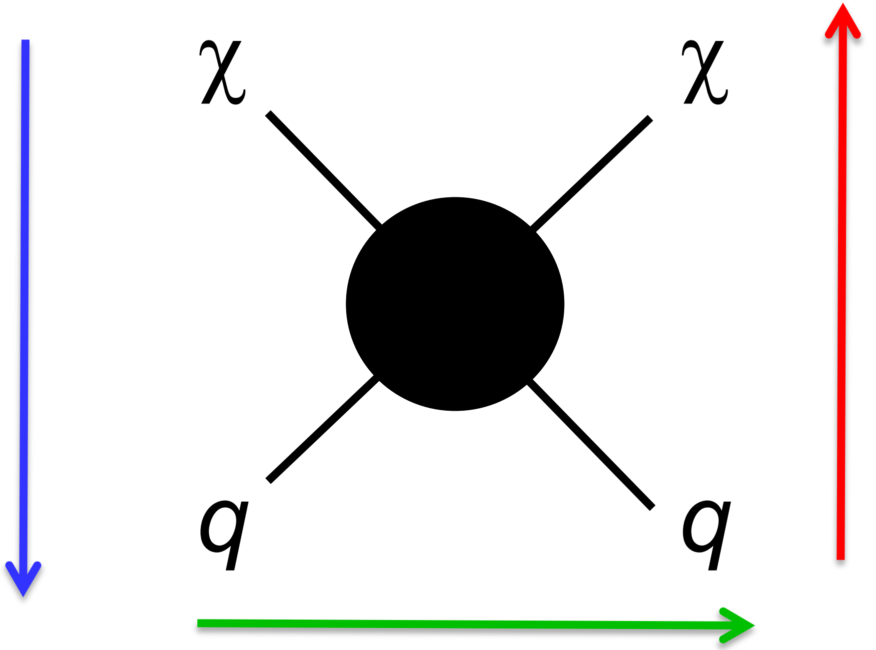


- Many other interesting scenarios outside of CMSSM. Note that SUSY can always be heavier, but in this context, cosmology provides upper bounds. This is an essential synergy between particle physics and cosmology – WIMPs cannot be decoupled away without sacrificing the WIMP miracle.

III. WIMP DETECTION

WIMP DETECTION

Correct relic density → Efficient annihilation then



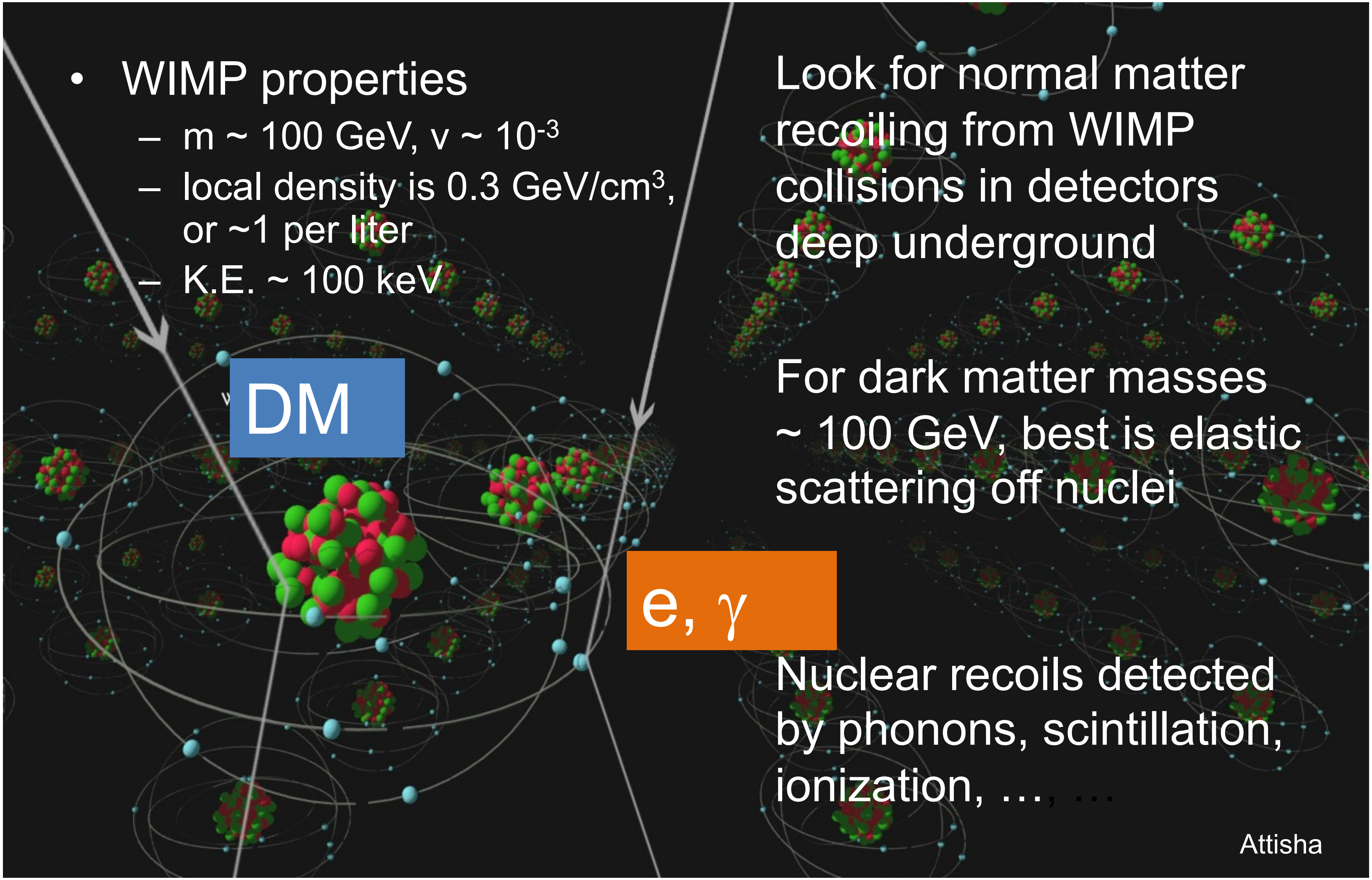
Efficient annihilation now
(Indirect detection)

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

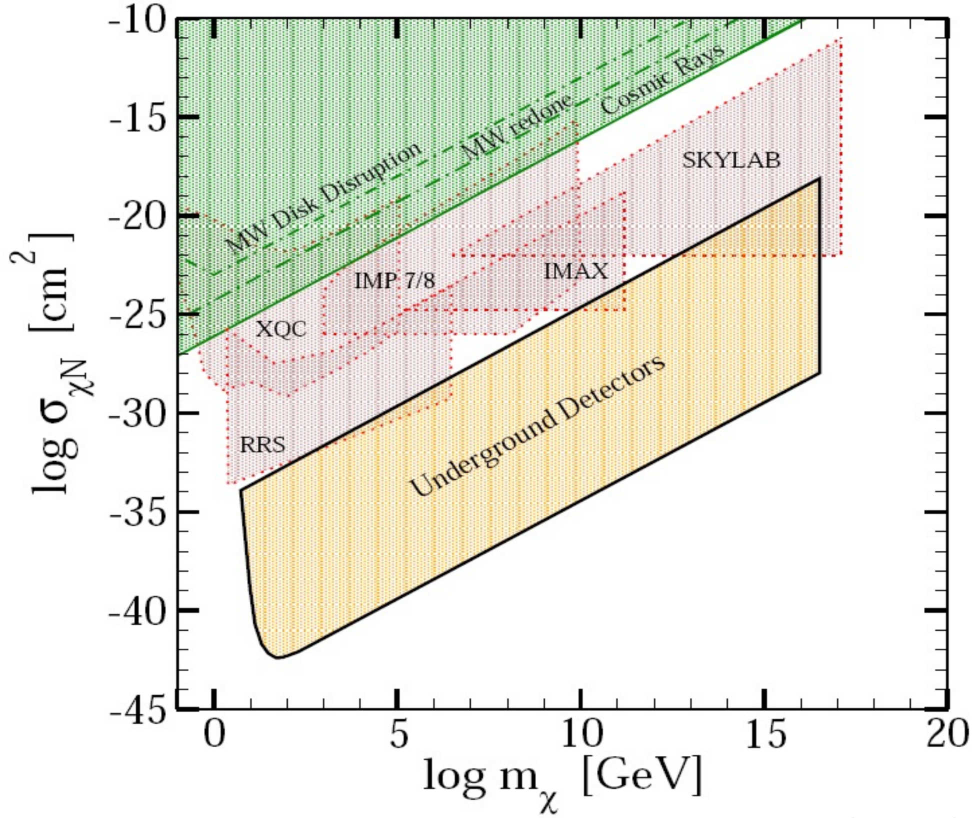
Nuclear recoils detected by phonons, scintillation, ionization, …, …

Attisha

THE BIG PICTURE: UPPER BOUND

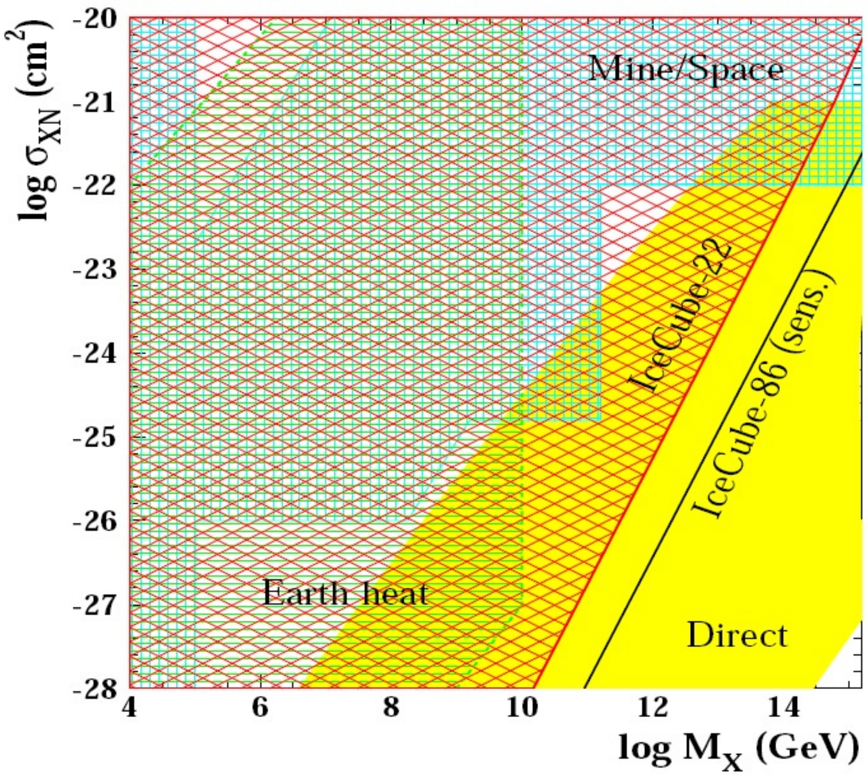
- The event rates depend on the interaction cross section. What is the upper bound? Another fascinating and underappreciated story.

- Strongly-interacting DM does not reach underground detectors.



Mack, Beacom, Bertone (2007)

- But the strongly-interacting window is now closed.



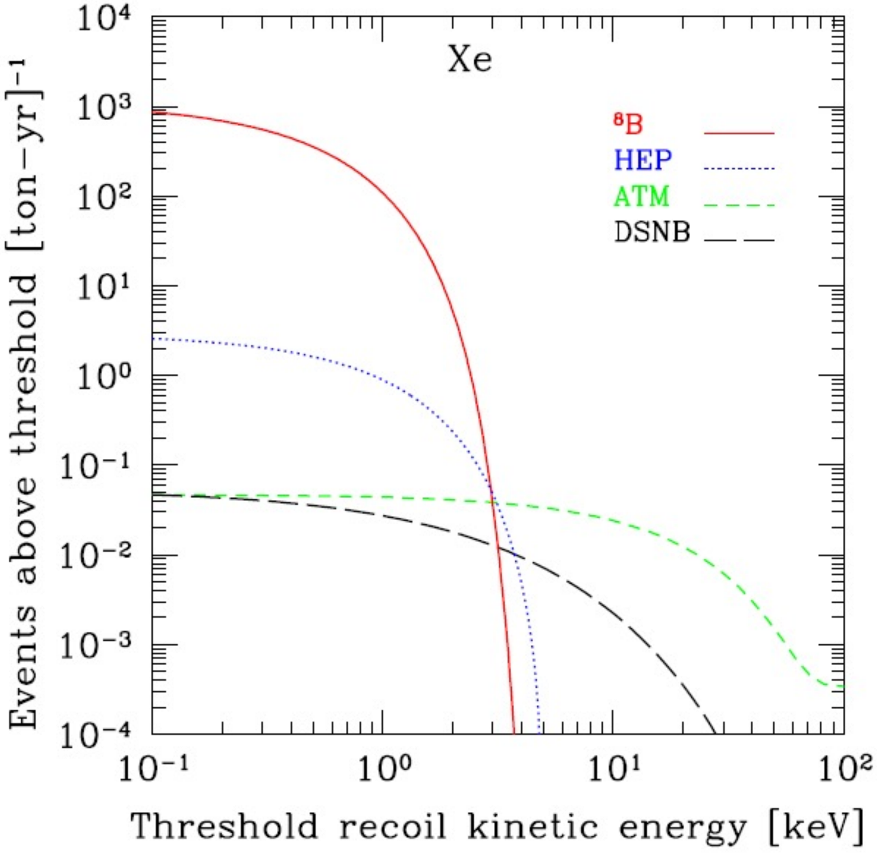
Albuquerque, de los Heros (2010)

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

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

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

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

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

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

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

Experiment: number of target nuclei

Experiment: recoil energy

Astrophysics: DM velocity distribution

Nuclear physics: form factor

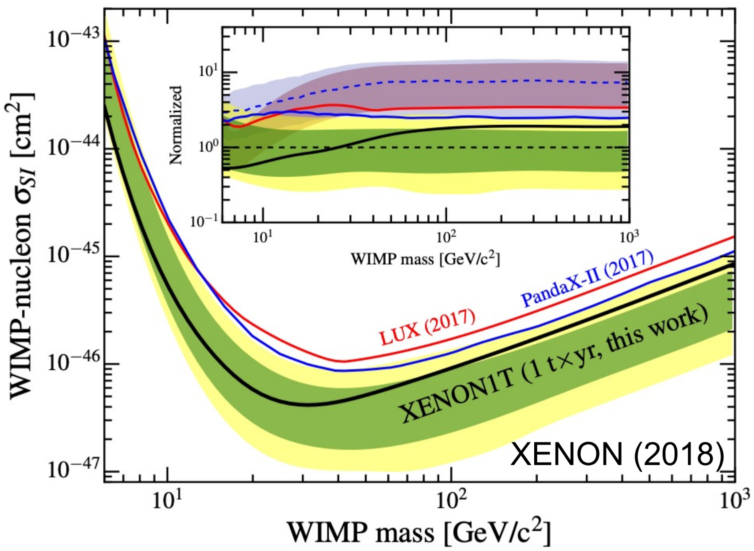
Astrophysics: local DM number density

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

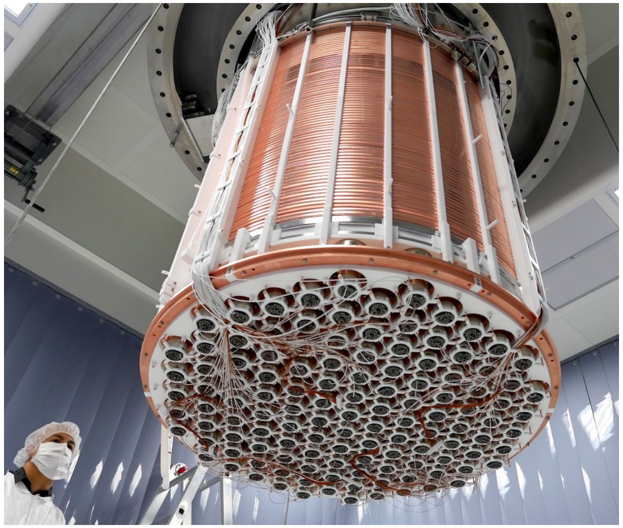
DETECTION STRATEGIES

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.



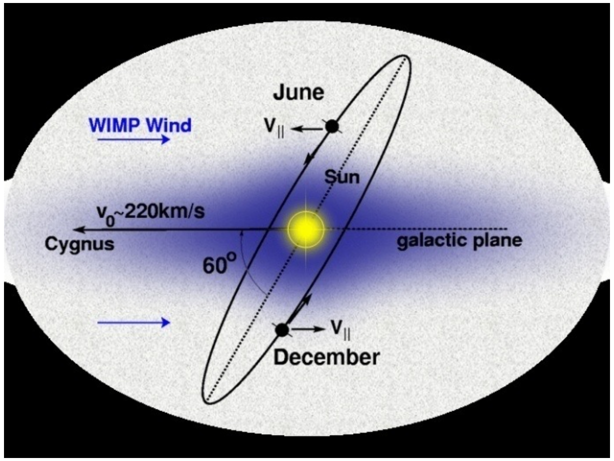
XENON (2018)



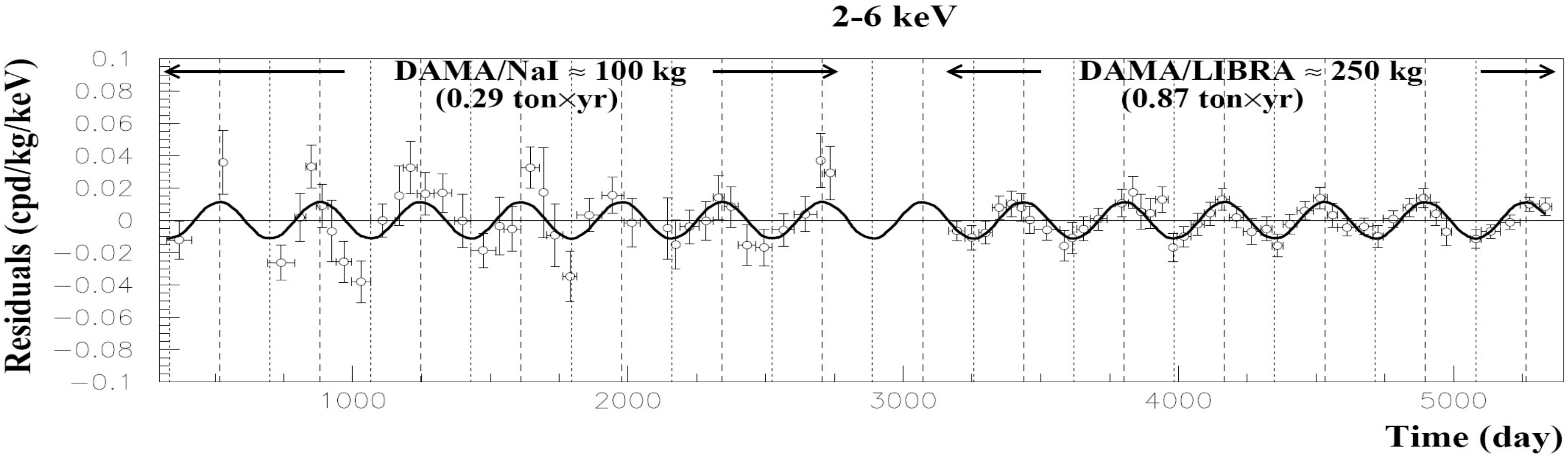
DETECTION STRATEGIES

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)



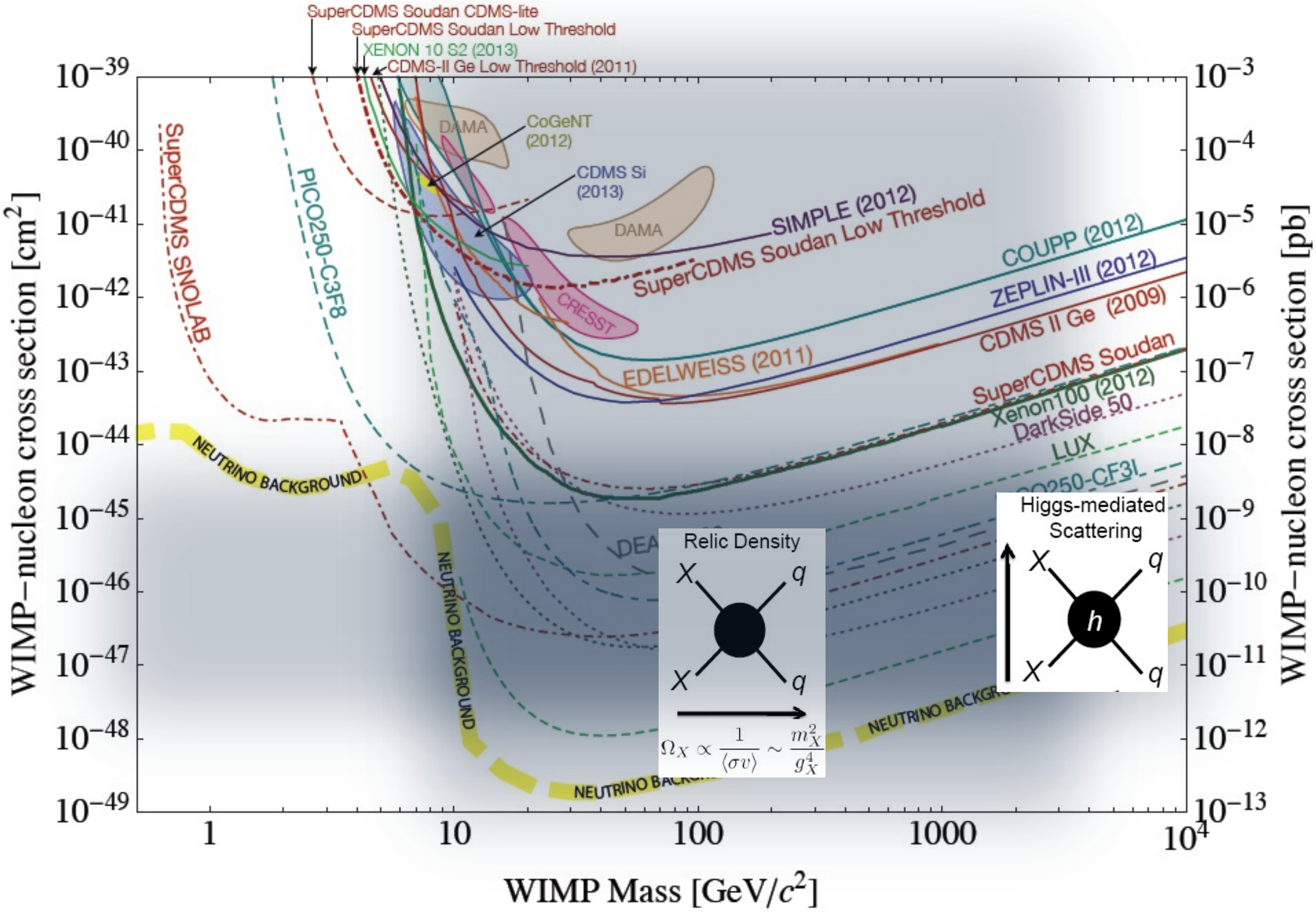
DAMA: many σ signal with period T ~ 1 year, and maximum ~ June 2



DAMA (2013)

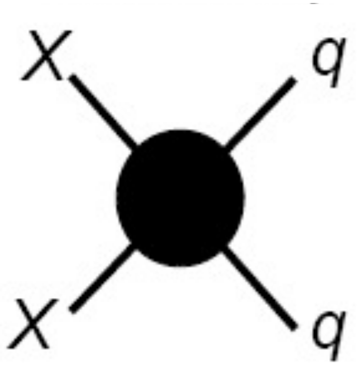
A few % modulation on top of a large constant background.

FUTURE PROSPECTS

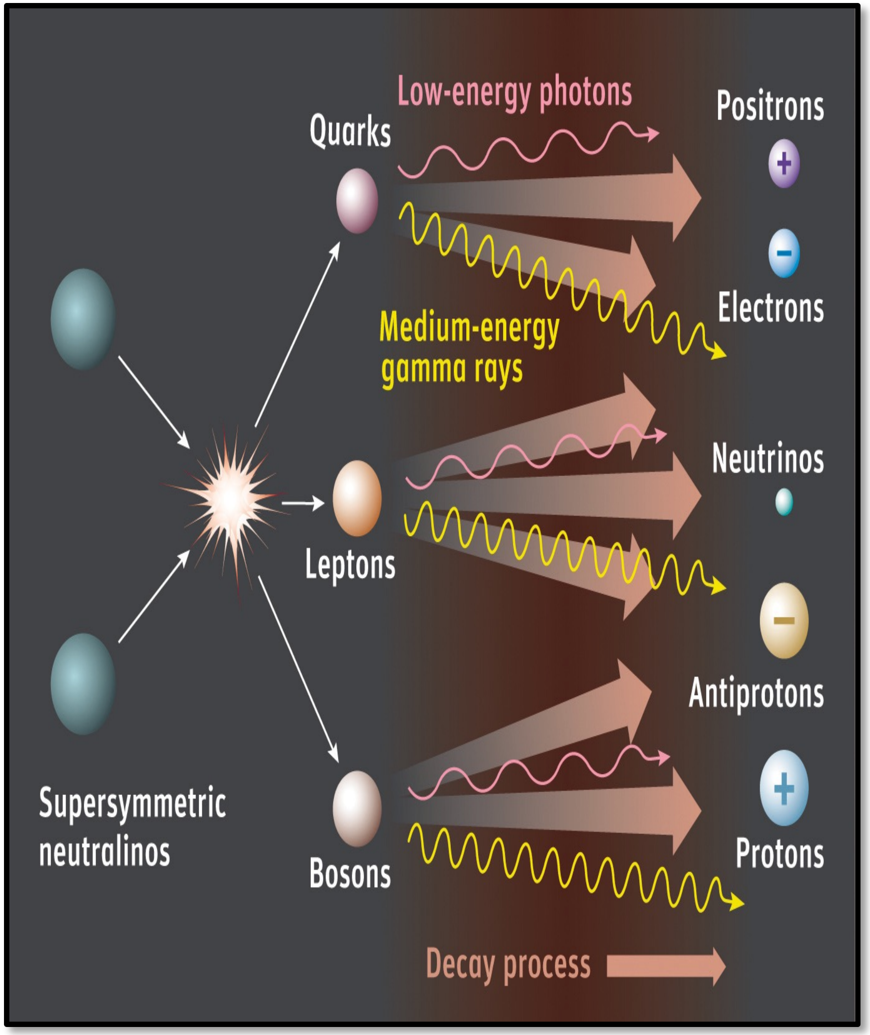


INDIRECT DETECTION

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

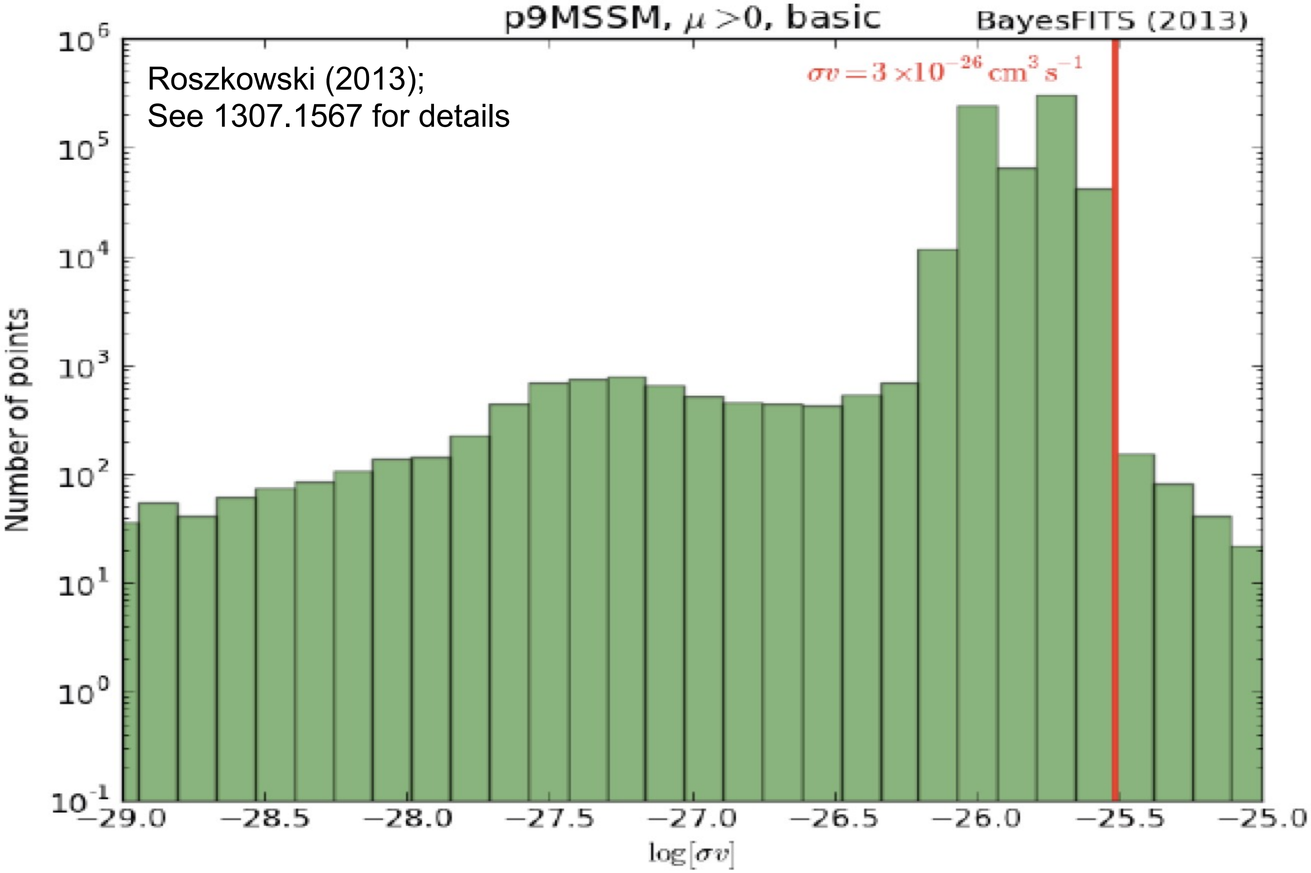


- The relic density provides a target annihilation cross section $\langle \sigma_A v \rangle \sim (2 \text{ to } 3) \times 10^{-26} \text{ cm}^3/\text{s}$



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 ~ 1/3 is not v ~ 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 _the GC / dwarf galaxies_ to

a place

photons , which are detected by _Fermi, CTA, …_ .

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

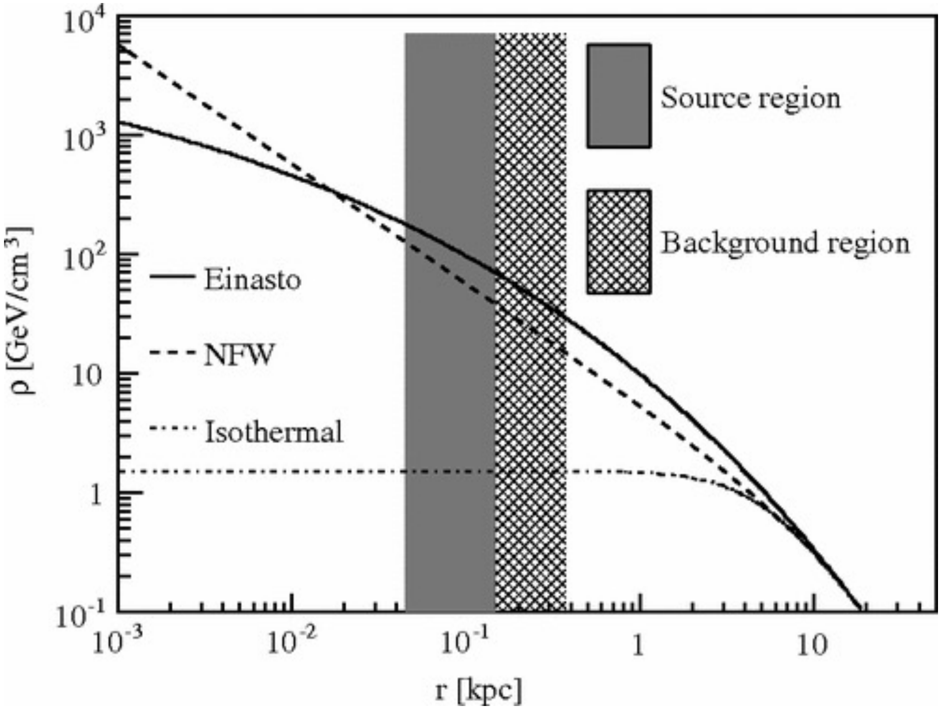
- Lines from XX → γγ, γZ: loop-suppressed rates, but distinctive signal.
- Continuum from XX → ff → γ: τree-level rates, but a broad signal.

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

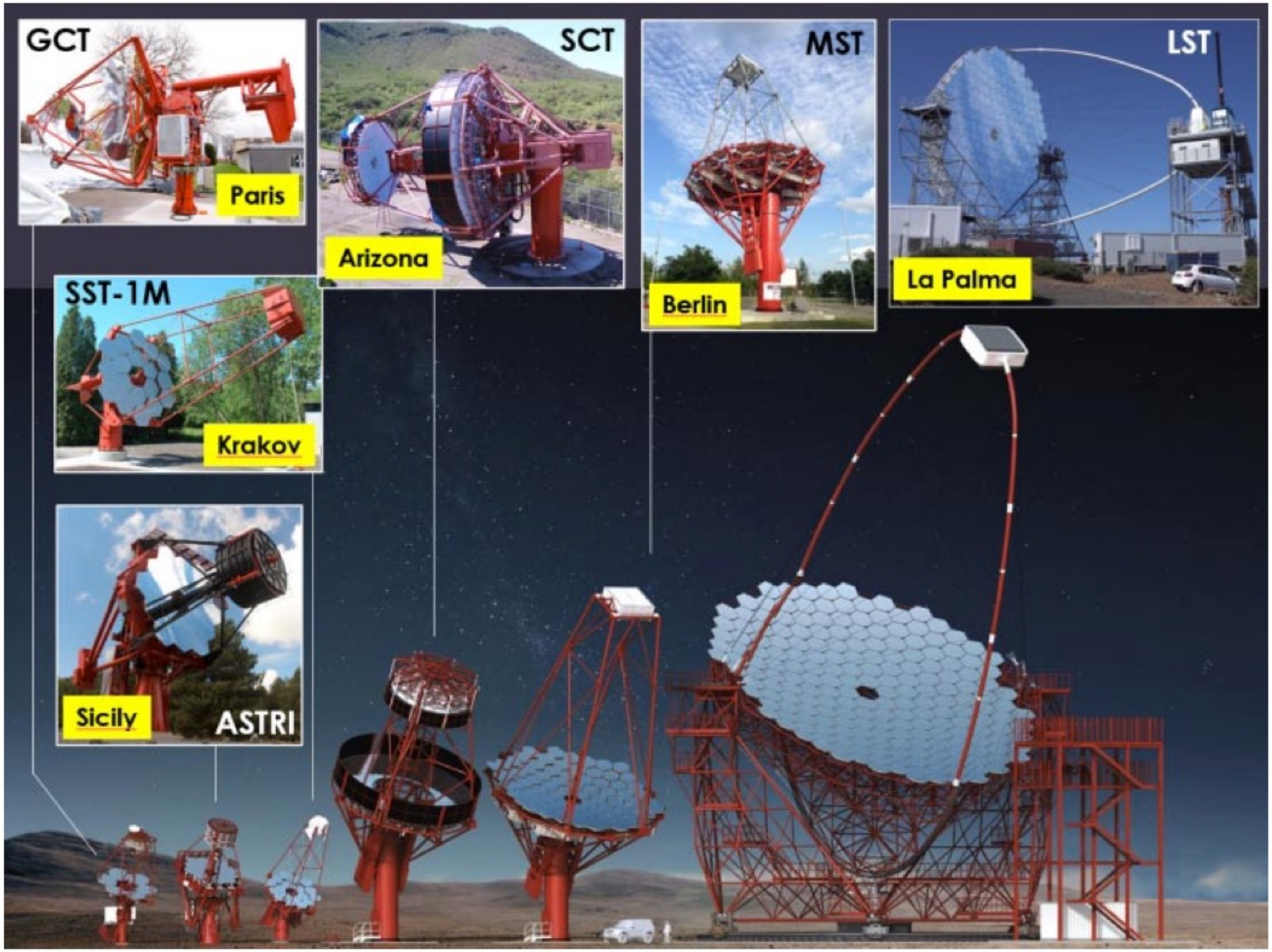


PHOTONS: EXPERIMENTS

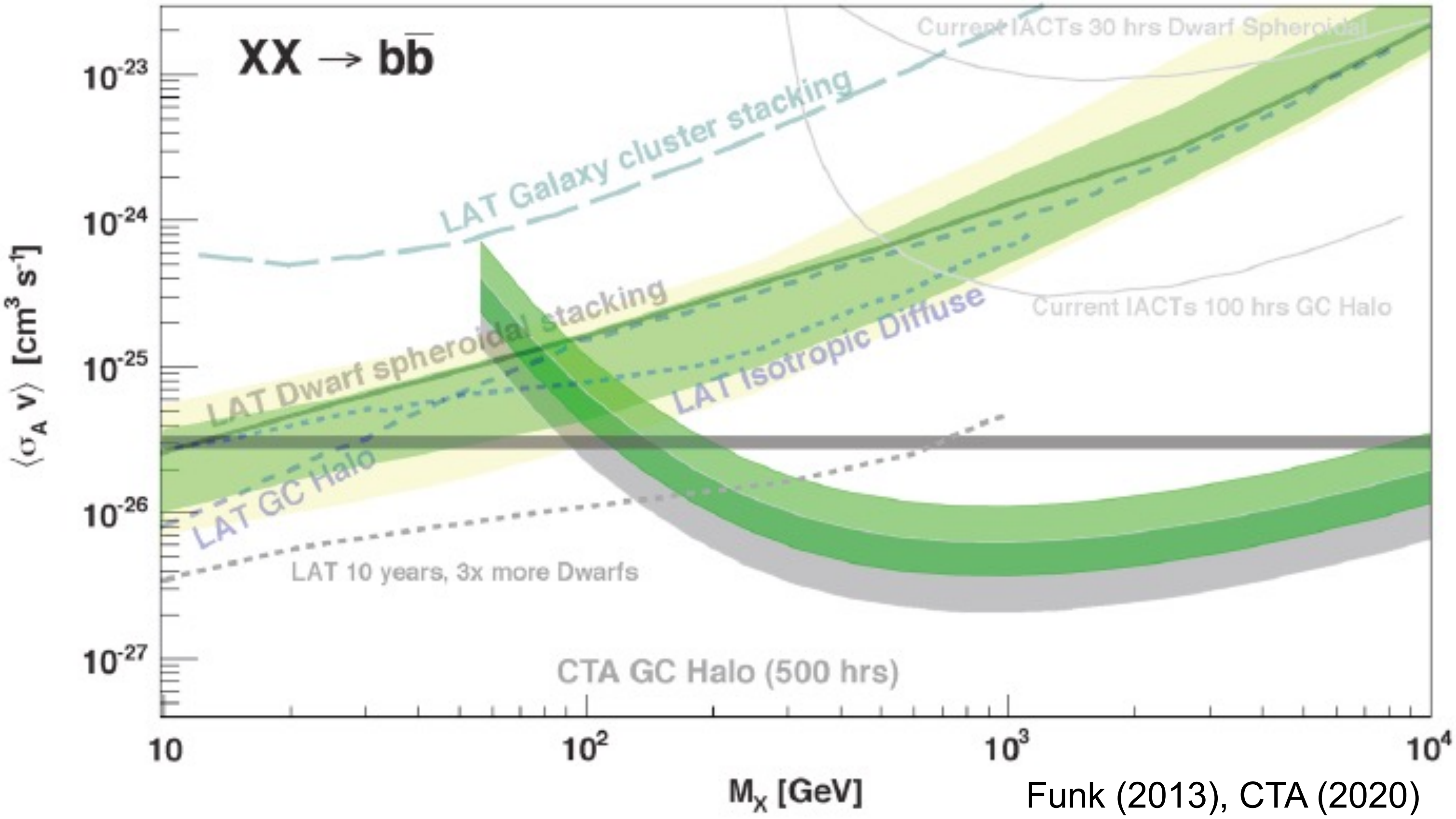
Veritas, Fermi-LAT, HAWC, and others

PHOTONS: EXPERIMENTS

Cerenkov Telescope Array



PHOTONS: STATUS AND PROSPECTS



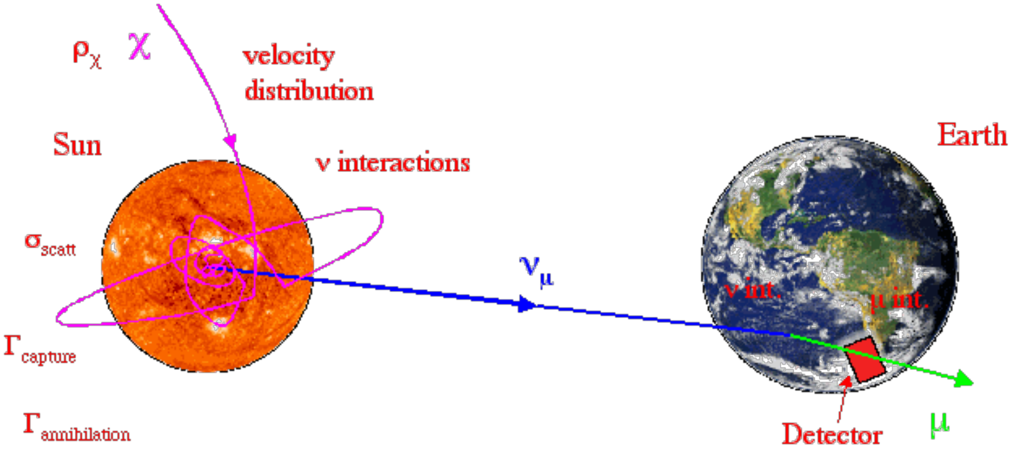
Funk (2013), CTA (2020)

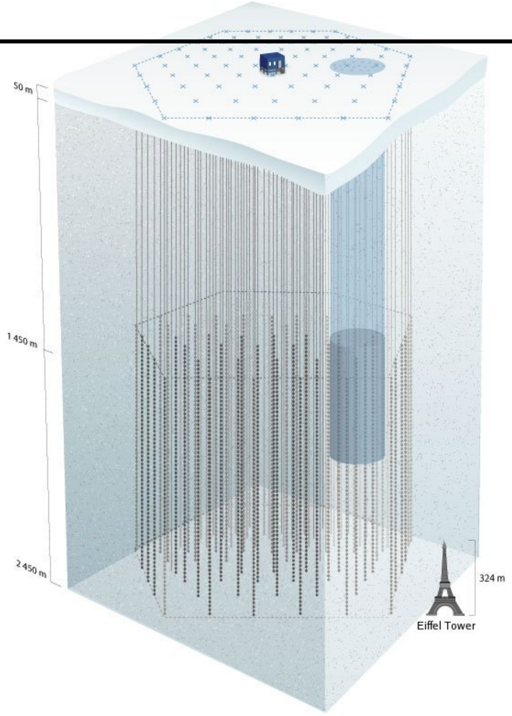
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses above 10 TeV

INDIRECT DETECTION: NEUTRINOS

Dark Matter annihilates in the center of the Sun to
a place

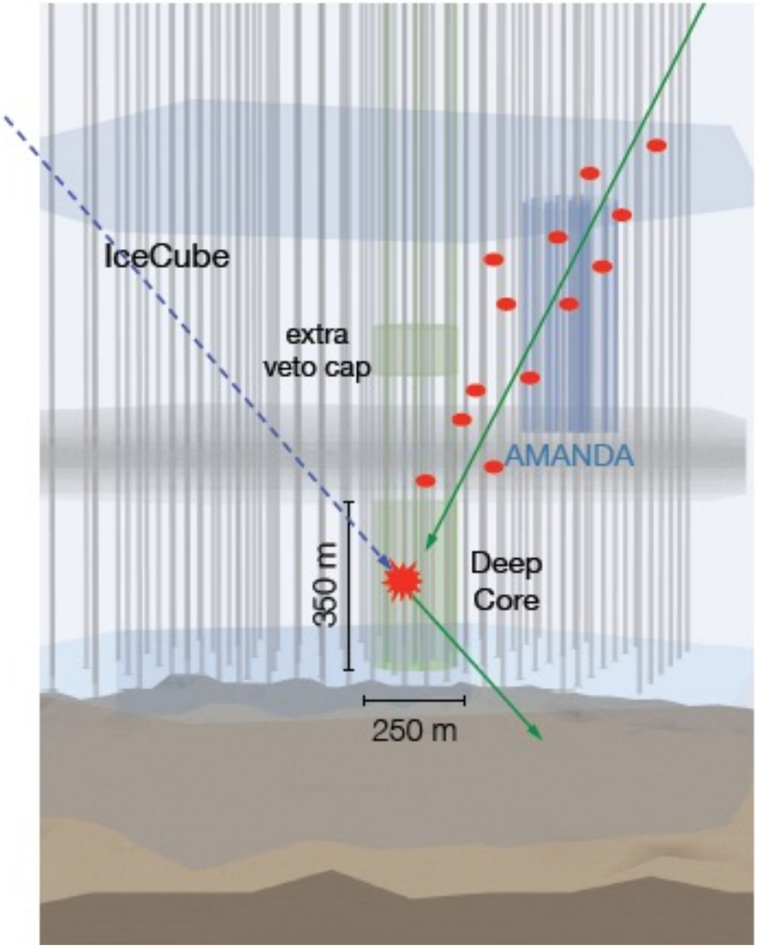
neutrinos, which are detected by Ice Cube / DeepCore.
some particles
an experiment





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

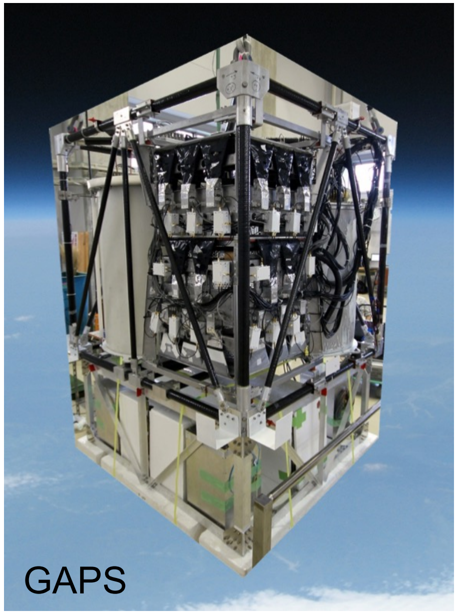
Dark Matter annihilates in the halo (a place) to positrons (some particles), which are detected by Fermi/AMS/… (an experiment).

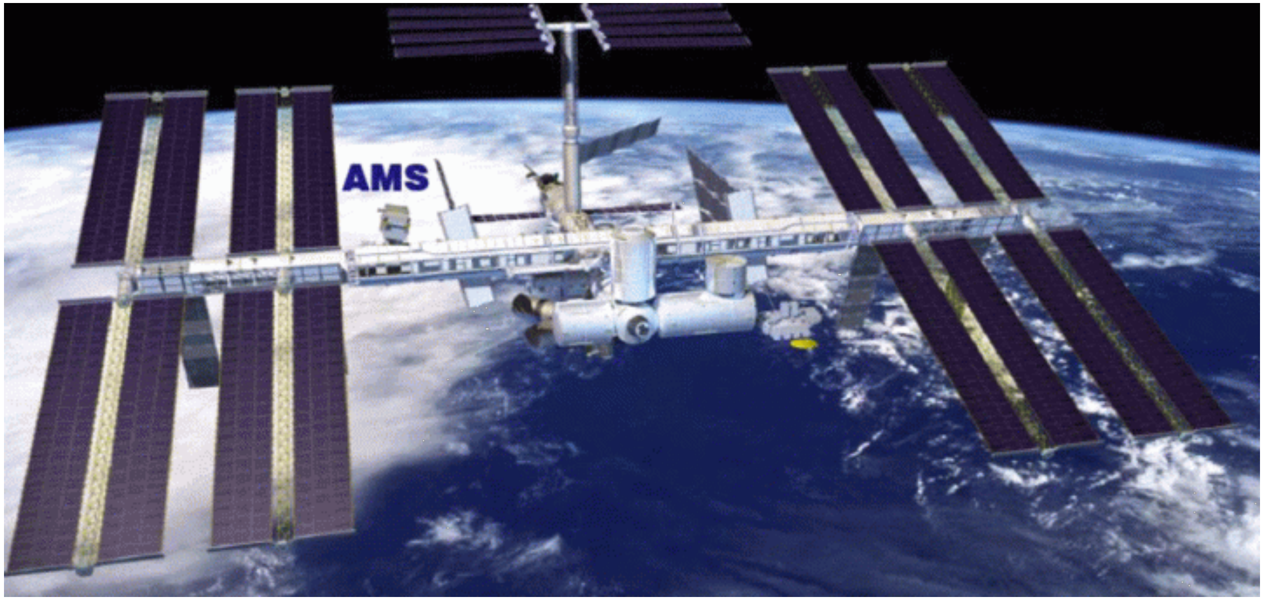
- In contrast to photons and neutrinos, anti-matter does not travel in straight lines, but rather bumps around the local halo before arriving in our detectors.
- For example, positrons, created with energy E_0, detected with energy E

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

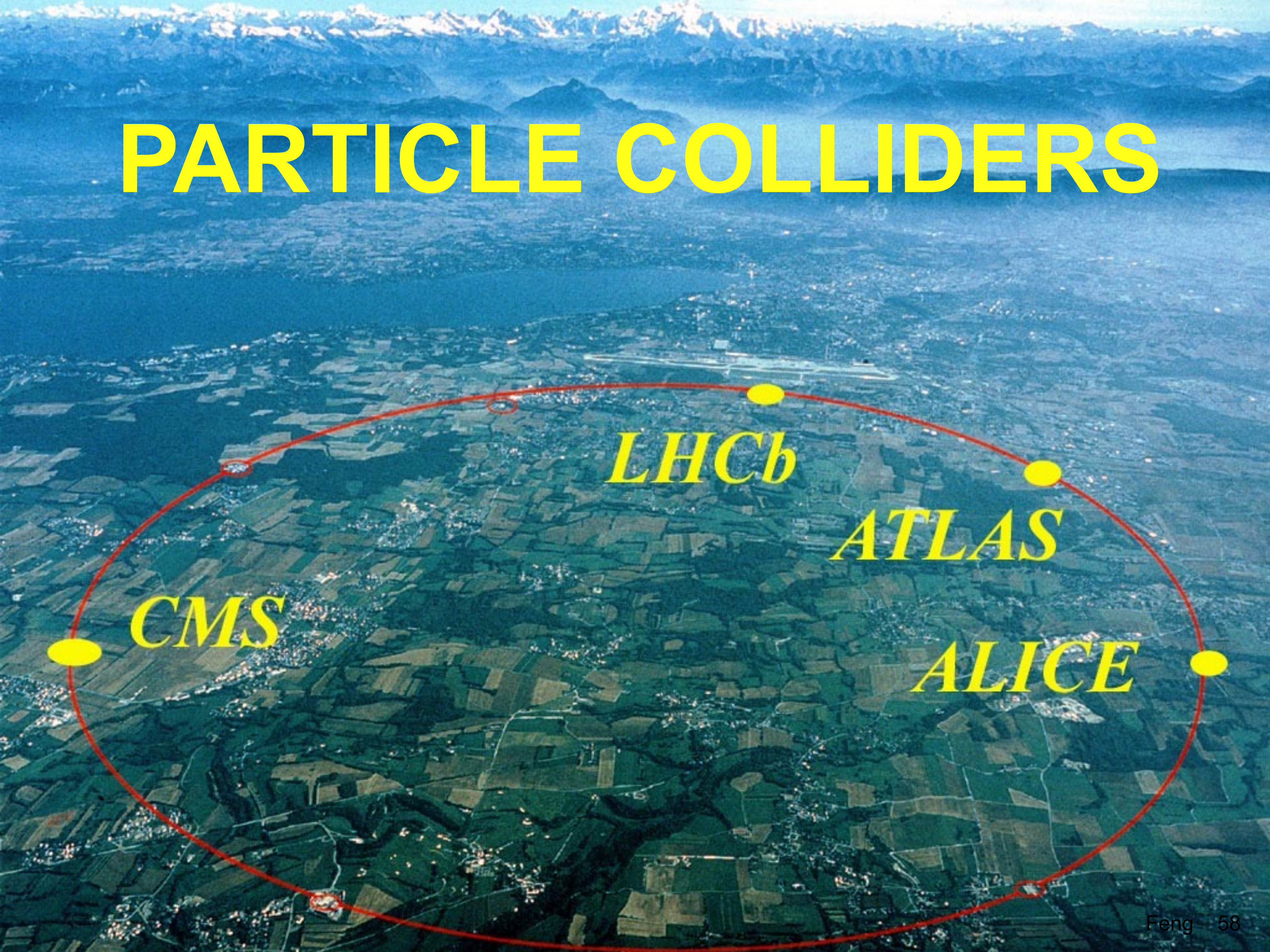
ANTI-MATTER: EXPERIMENTS

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



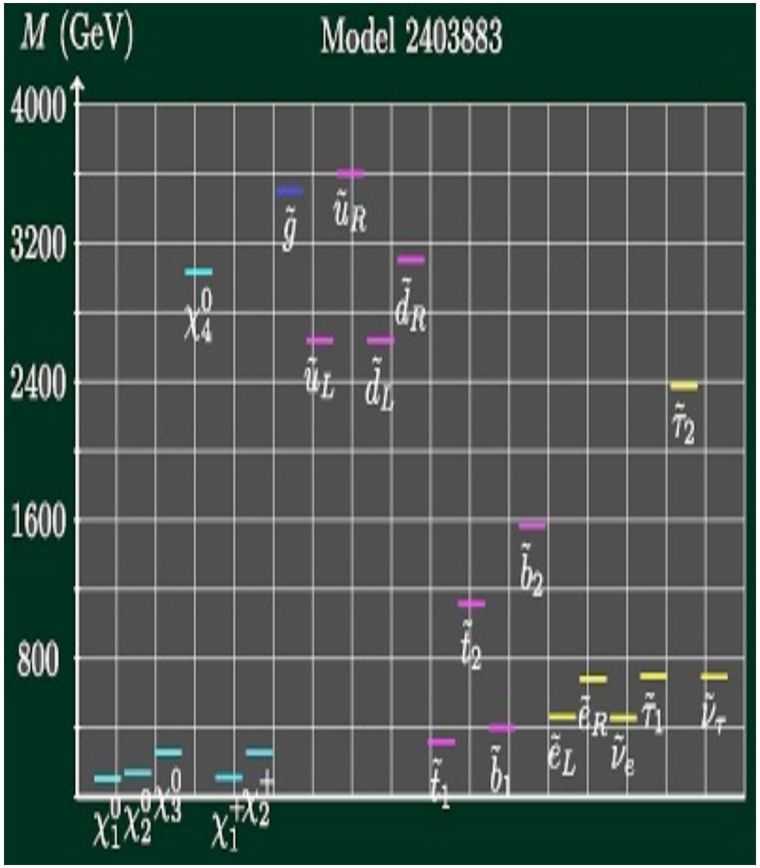


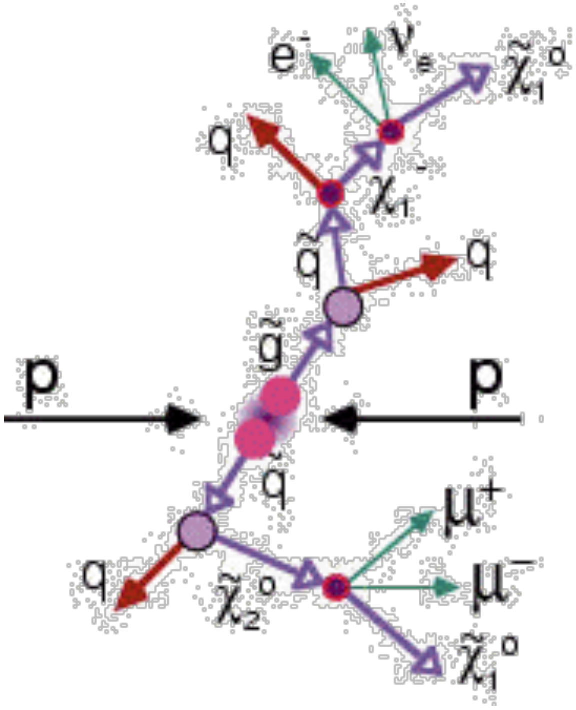
PARTICLE COLLIDERS



FULL MODELS AND SIMPLIFIED MODELS

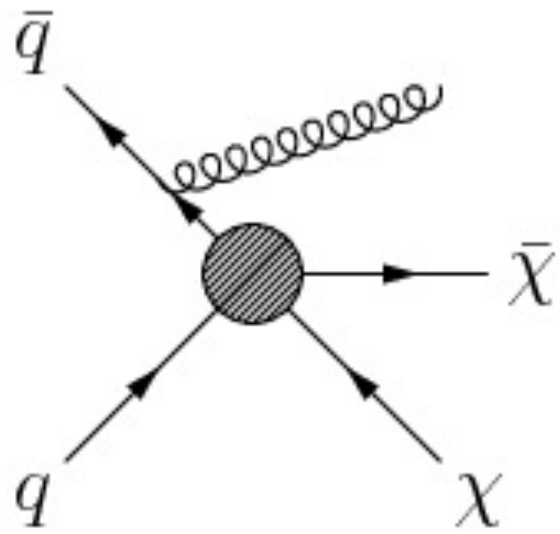
- Consider full models (e.g., SUSY), or simplified models (e.g., minimal DM model) that have just a few particles and parameters. Produce other particles that decay to DM, look for missing E_T signatures.

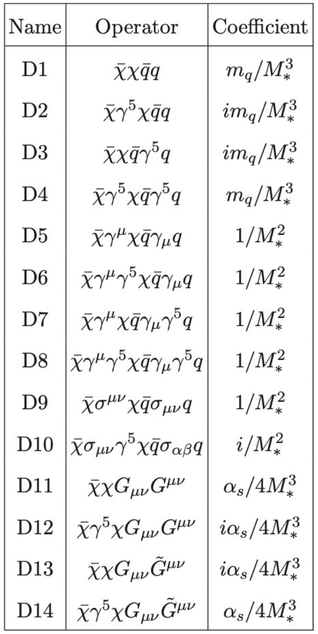




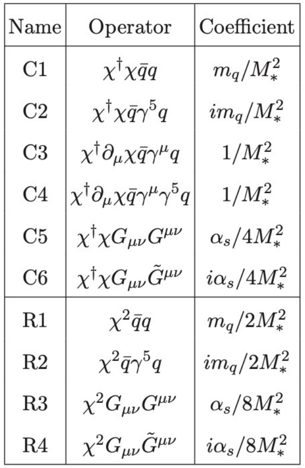
WIMP EFFECTIVE THEORY

- 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, ….





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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Birkedal, Matchev, Perelstein (2004)

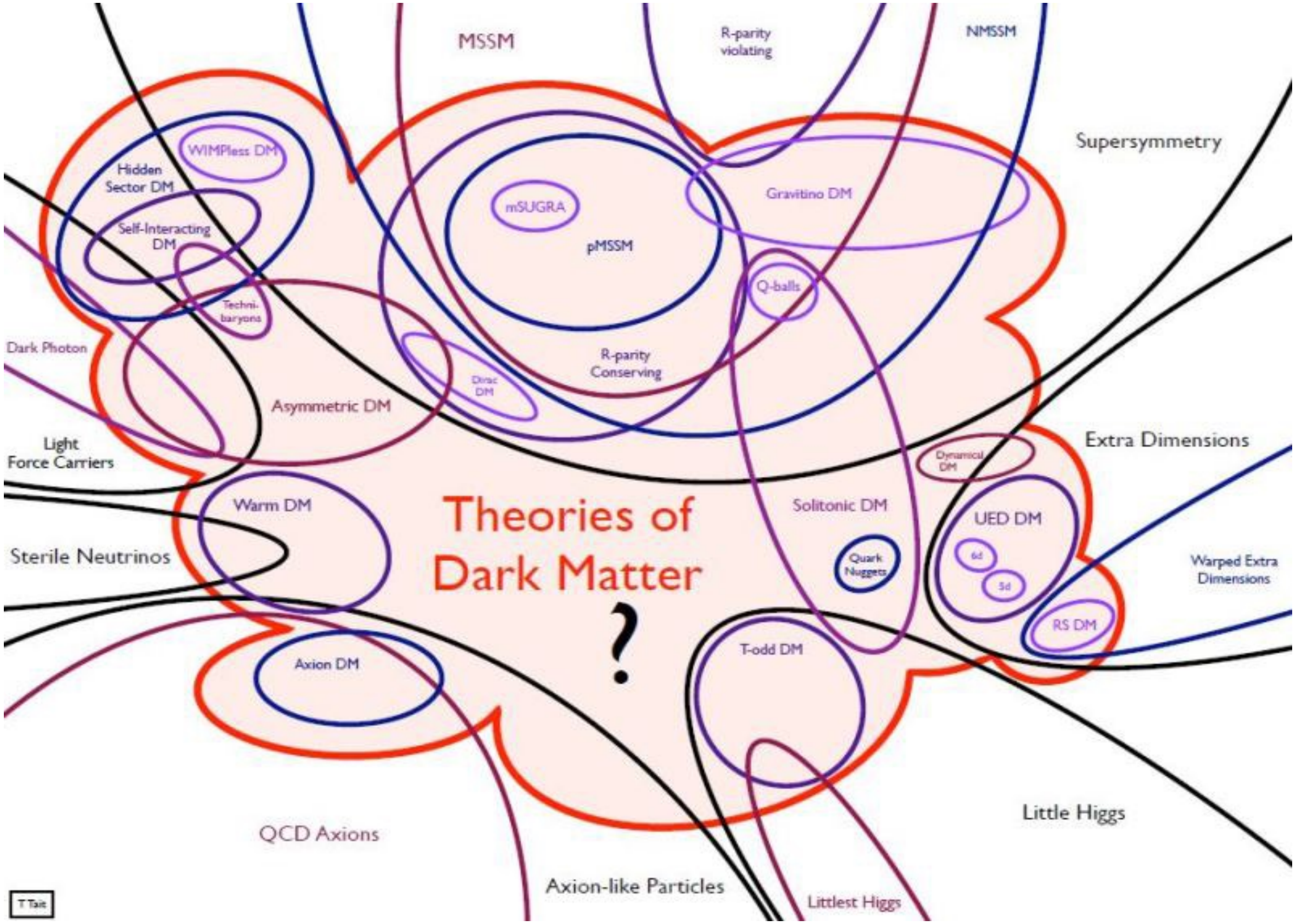
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)

- 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.

IV. WIMP VARIATIONS

WIMP VARIATIONS

- The WIMP paradigm has spawned many spin-offs that preserve the WIMP miracle to various extents, but have vastly different implications for particle physics and astrophysics.



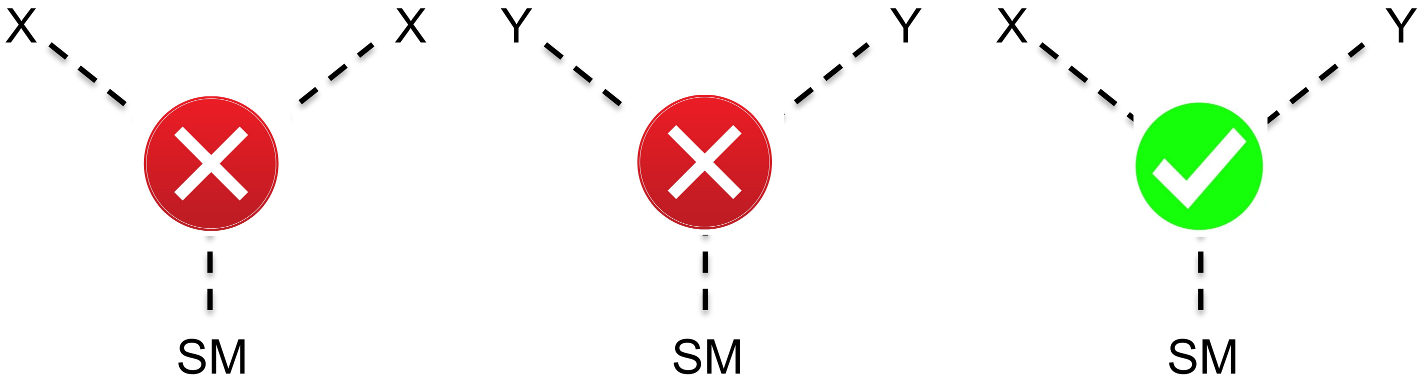
INELASTIC DARK MATTER

- The DAMA signal, whatever its ultimate fate, has been a fantastic driver for new ideas in dark matter.

- A prominent example: inelastic dark matter. Grew out of considerations of another SUSY WIMP candidate, the (messenger) sneutrino, a complex scalar, which could be split into two real scalars.

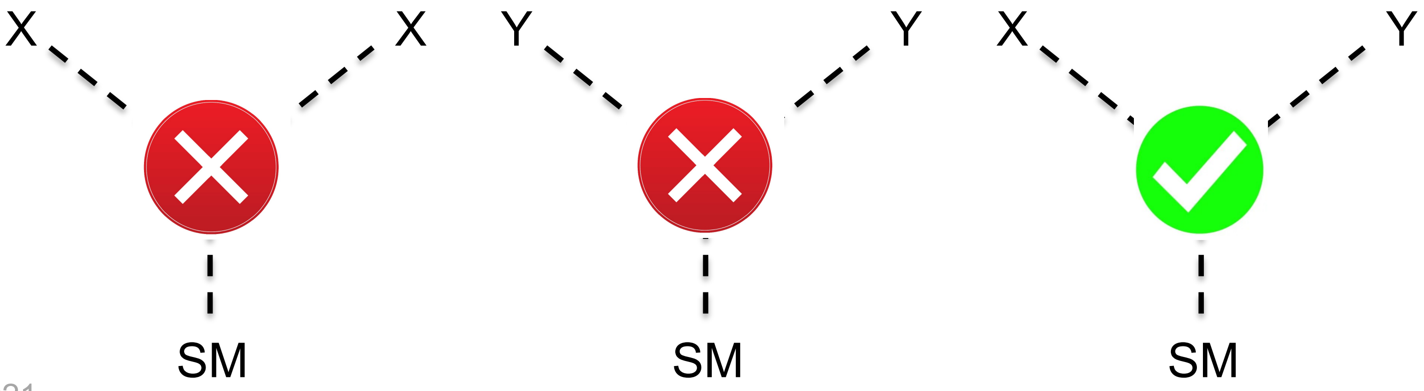
Han, Hempfling (1997); Hall, Moroi, Murayama (1998); Tucker-Smith, Weiner (2001)

- Consider two highly-degenerate WIMPy particles X and Y, and assume there are only off-diagonal couplings:



INELASTIC DARK MATTER

- Suppose m_X, m_Y ~ 100 GeV, but $\Delta = m_Y - m_X$ ~ MeV.
- In the early universe, and particularly at freeze out, $\Delta << T$, so X and Y freeze out as usual. Eventually all Y's decay to X's, X is the DM.
- But now, since v ~ 10^{-3}, K.E. ~ 100 keV, there is not enough energy for X's to up-scatter to Y's, and so X dark matter escapes all direct and indirect searches, opening up new parameter for other searches.
- For Δ ~ 100 keV, can suppress scattering off of Ge (CDMS), preserve scattering off of I (DAMA), reconcile DAMA with other null results.

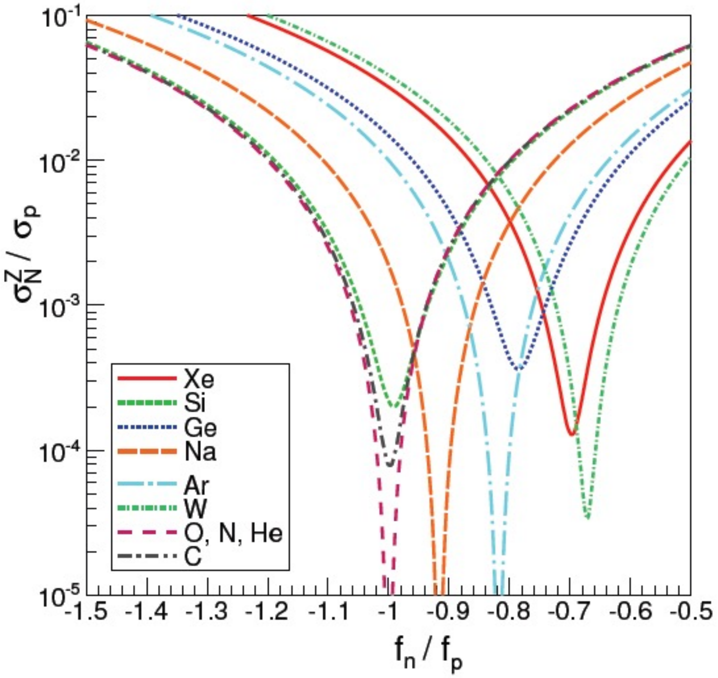


ISOSPIN-VIOLATING DARK MATTER

- Recall that DM scattering off nuclei is

$$\sigma_A \sim [\, f_p Z + f_n (A-Z) \,]^2$$

- Typically assume $f_n = f_p$, $\sigma_A \sim A^2$.
- But there is no model-independent reason that f_n and f_p are equal, or even that they have the same sign.
- IVDM relaxes this assumption, introduces 1 new parameter: f_n / f_p .



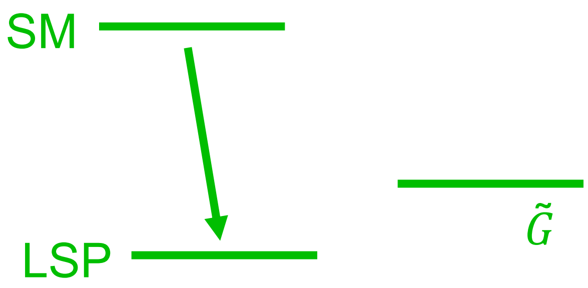
Feng, Kumar, Marfatia, Sanford (2013)

- Can decouple any given isotope by a suitable choice of f_n / f_p , and isotope distributions in each target become important. At one time could reconcile DAMA with all null results with IVDM, but not now.
- Lasting lesson: one should take all comparisons across different target materials and different techniques with a grain of salt.

GRAVITINO DM AND LONG-LIVED PARTICLES

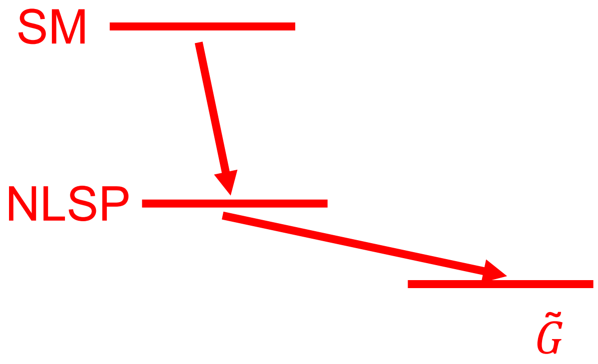
- In all supersymmetric models, there is yet another new neutral particle: the gravitino $\tilde{G}$. Its mass can be anything from eV to PeV, but its couplings are typically superweak (weaker than weak), as expected for the graviton's partner.

- $\tilde{G}$ not LSP



- Assumption of most of literature

- $\tilde{G}$ LSP



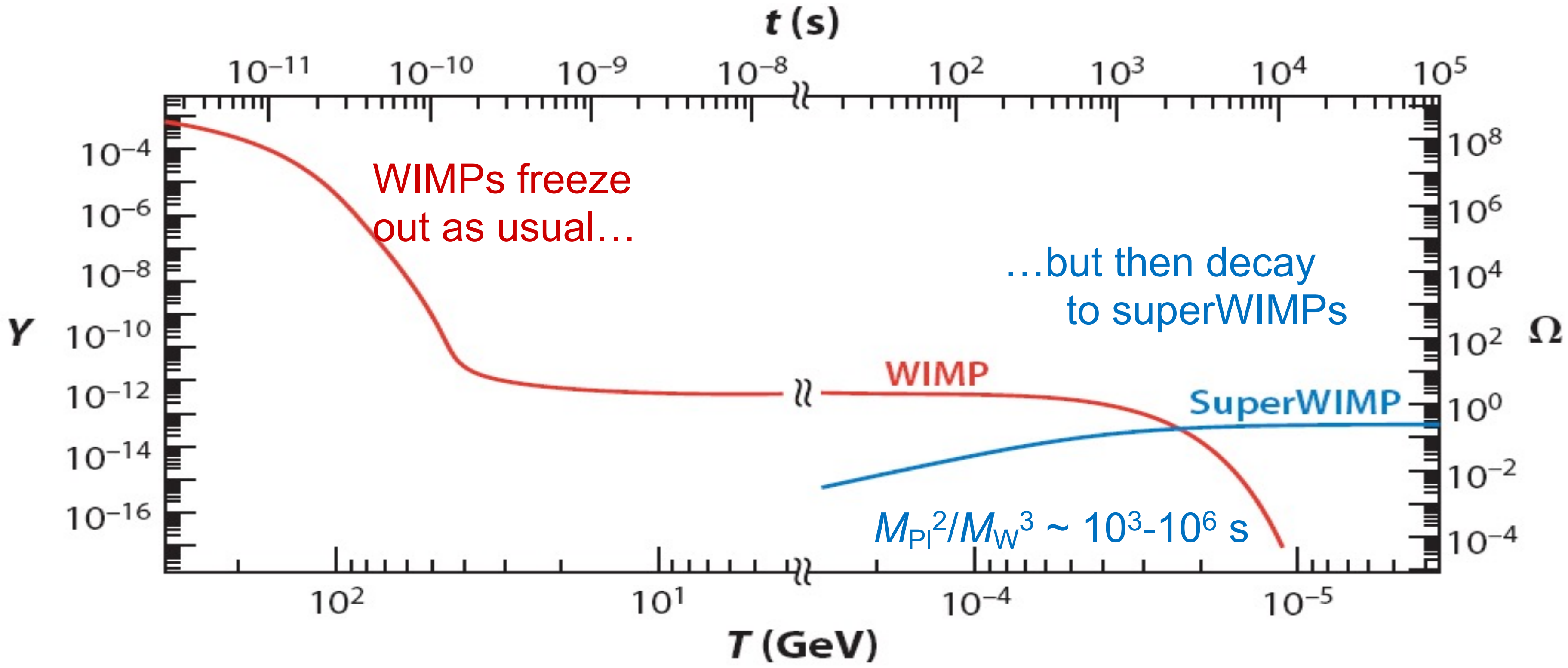
- Completely different cosmology and particle physics

Dine, Nelson, Nir, Shirman (1994, 1995); Dimopoulos, Dine, Raby, Thomas (1996)

FREEZE OUT WITH SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

If the WIMP and superWIMP masses are similar, the superWIMPs naturally inherit the right density through the WIMP miracle, share all the motivations of WIMPs, but DM becomes superweakly interacting.



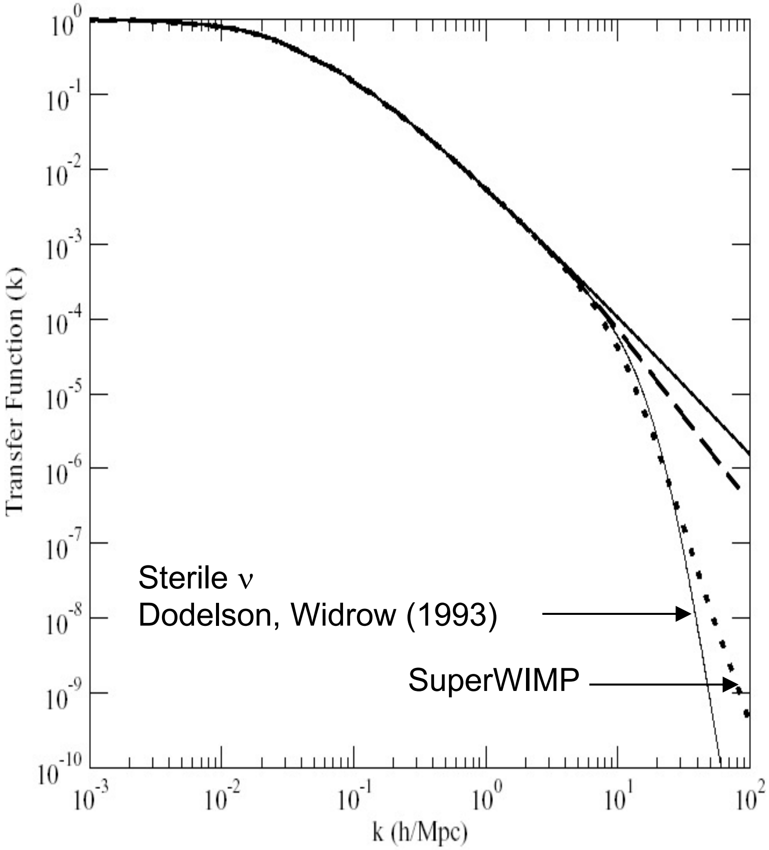
WIMPs freeze out as usual…

…but then decay to superWIMPs

$M_{Pl}^2/M_W^3 \sim 10^3$-10^6 s

WARM DARK MATTER

- SuperWIMPs are produced in late decays with large velocity (0.1c – c).
- This motion prevents them from forming potential wells, suppresses small scale structure.
- Hot DM, like active neutrinos, is excluded, but superWIMPs could be warm DM with cold DM pedigree.
- Also implications for BBN, CMB.



Kaplinghat (2005)

LATE DECAYS AND BBN

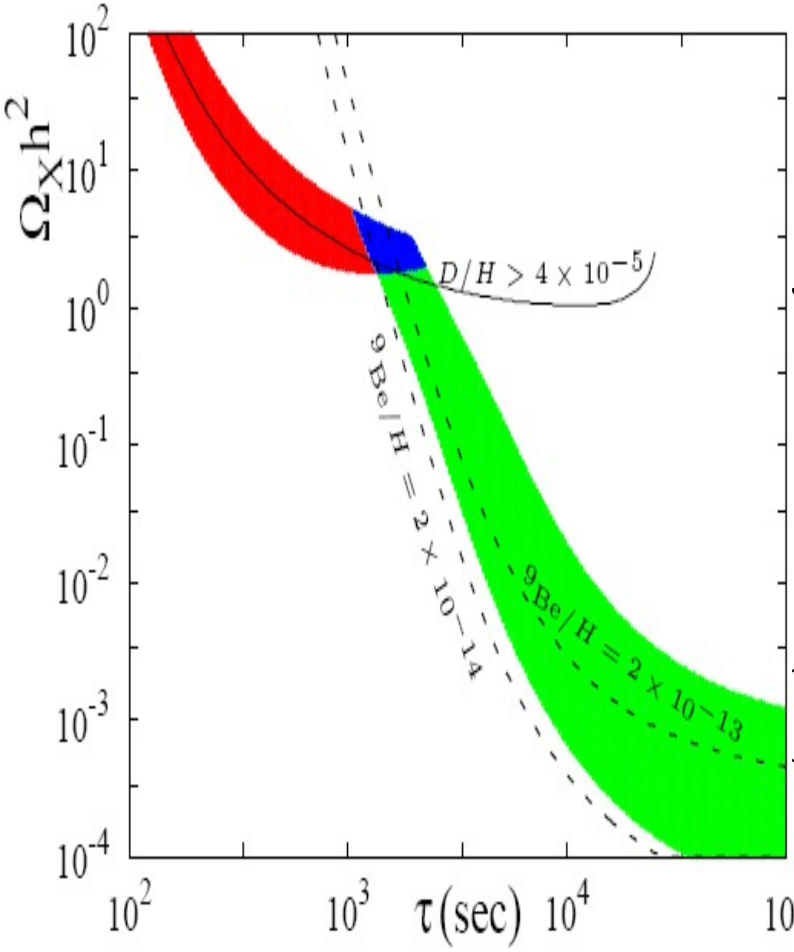
- Late decays deposit energy into the Universe, potentially destroy light elements

- Simple way around this is to make decays before T ~ MeV, t ~ 1s

- More ambitious: ^{7}Li does not agree with standard BBN prediction
  - Too low by factor of 3, ~5σ at face value
  - May be solved by convection in stars, but then why so uniform?

- Also the standard BBN prediction for ^{6}Li may be too low

- Decays after 1 s can possibly fix both



Bailly, Jedamzik, Moultaka (2008)

LATE DECAYS AND CMB

- Late decays may also distort the black body CMB spectrum

- For 10^5 s < τ < 10^7 s, get "μ distortions":

$$\frac{1}{e^{E/(kT)+\mu} - 1}$$

μ=0: Planckian spectrum

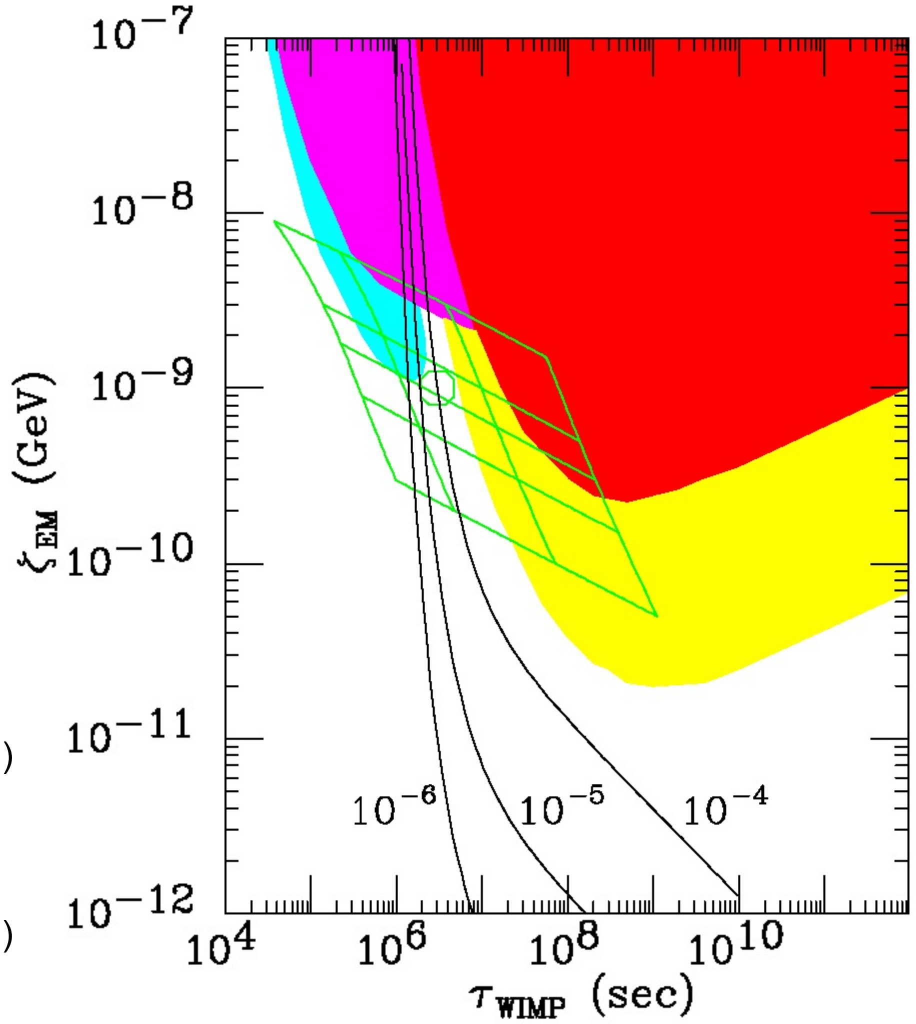
$\mu \neq$0: Bose-Einstein spectrum

Hu, Silk (1993)

- Current bound: $|\mu| < 9 \times 10^{-5}$

COBE-FIRAS (1996)

Future: possibly $|\mu| \sim 10^{-8}$



Feng, Rajaraman, Takayama (2003)

IMPLICATIONS FOR THE LHC

- If DM is a superWIMP, the parent particle is metastable, and can also be charged.

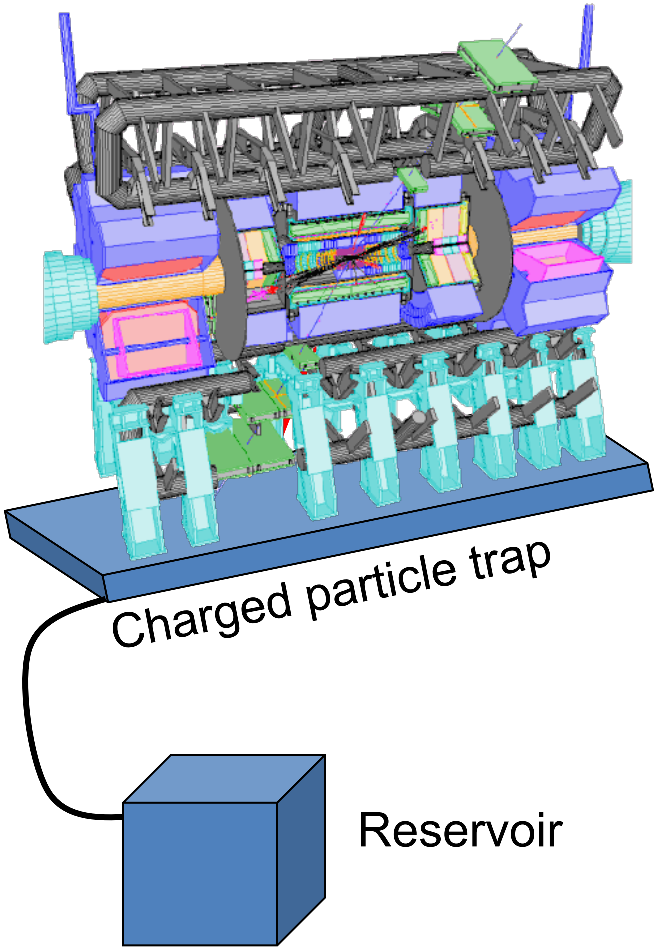
- Signature of new physics is "stable," charged, massive particles, not missing E_T.

- If stable on timescales of seconds to months, can collect these particles and study their decays. Several ideas:
  - Catch sleptons in a 1m thick water tank

    Feng, Smith (2004)
  - Catch sleptons in LHC detectors

    Hamaguchi, Kuno, Nakawa, Nojiri (2004)
  - Dig sleptons out of detector hall walls

    De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape (2005)

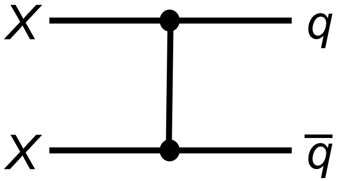


WIMPLESS DARK MATTER

Feng, Kumar (2008)

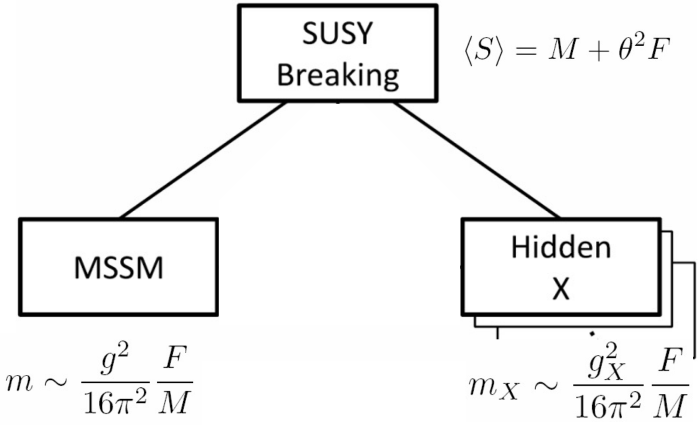
- Recall the WIMP miracle: the relation between Ω_X and annihilation strength is wonderfully simple:

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



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

- Consider SUSY with a hidden sector. In models that suppress flavor violation (GMSB, AMSB…), $m_X \sim g_X^2$



SUSY Breaking

$\langle S \rangle = M + \theta^2 F$

MSSM

Hidden X

$$m \sim \frac{g^2}{16\pi^2} \frac{F}{M}$$

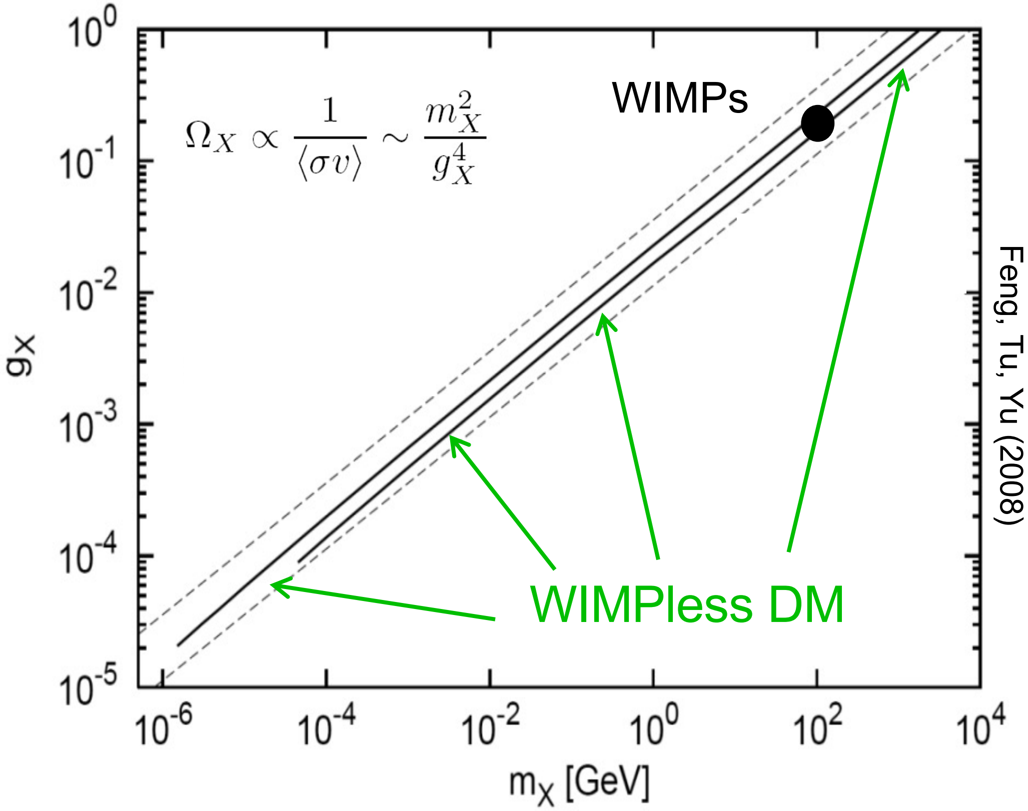
$$m_X \sim \frac{g_X^2}{16\pi^2} \frac{F}{M}$$

- The hidden sector superpartner masses and gauge couplings can be vastly different from the MSSM, but the thermal relic density is the same.

WIMPLESS DARK MATTER

Feng, Kumar (2008)

- WIMPless miracle: with a hidden sectors, the gauge coupling may not be ~ 1. But light, weakly-coupled DM can also have the correct thermal relic density, opening up a whole new set of dark sector signals in particle physics and cosmology, all with the same WIMP miracle pedigree.



Feng, Tu, Yu (2008)

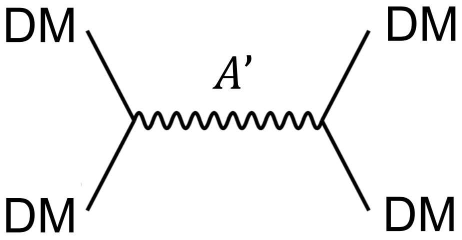
SELF-INTERACTING DARK MATTER

- WIMPless DM (and related scenarios) open up sub-GeV DM, self-interacting DM, strongly-interacting DM with a host of new implications.

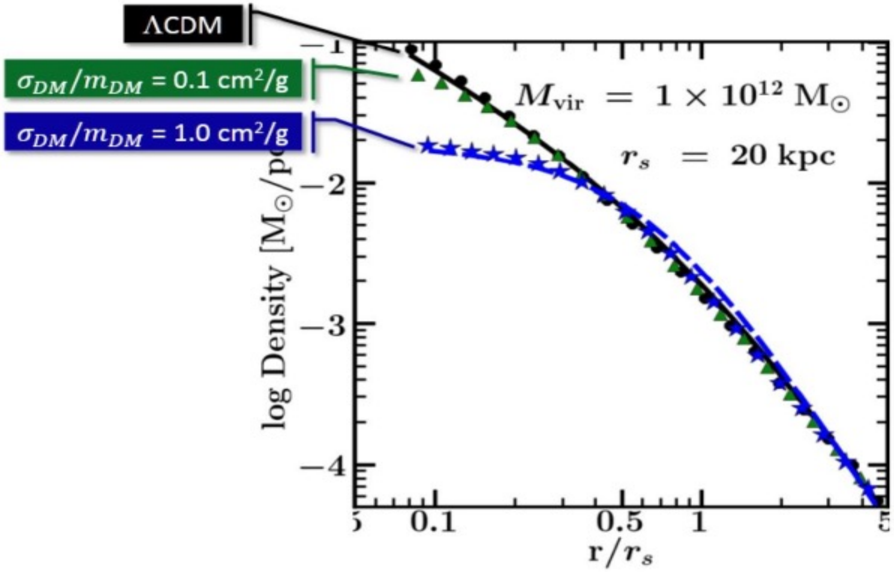
- For example: there are indications from small-scale structure that dark matter may be strongly self-interacting (cuspy halo profiles, etc.)

- To make a difference, the required self-interaction cross section is

$$\frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \sim (100\ \text{MeV})^{-3}$$

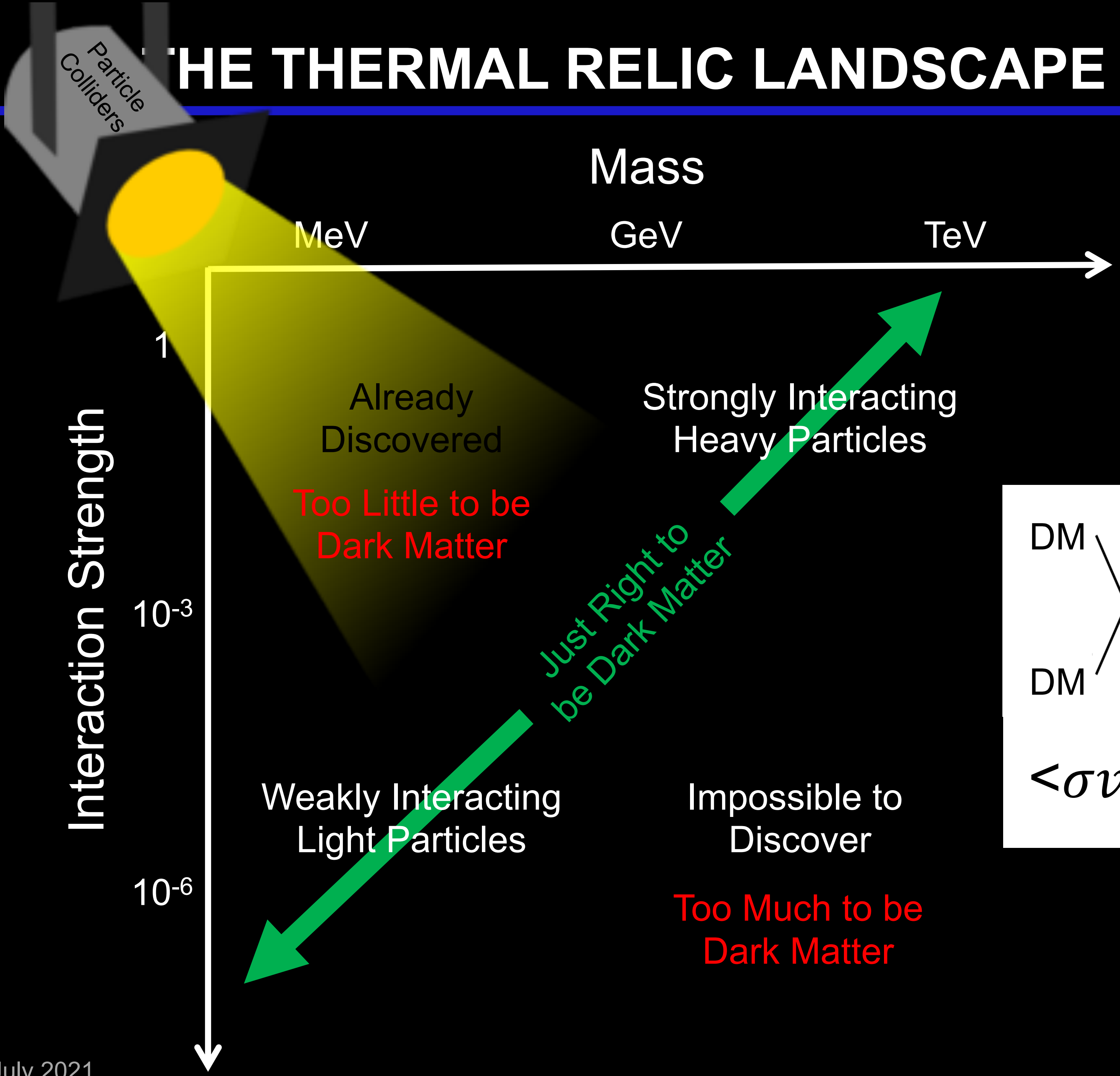


- This can be explained by a characteristic dark sector mass scale of ~ 10-100 MeV.



Tulin, Yu (2017)
Rocha et al. (2012), Peter et al. (2012);
Vogelsberger et al. (2012); Zavala et al. (2012)

THE THERMAL RELIC LANDSCAPE



Already Discovered

Too Little to be Dark Matter

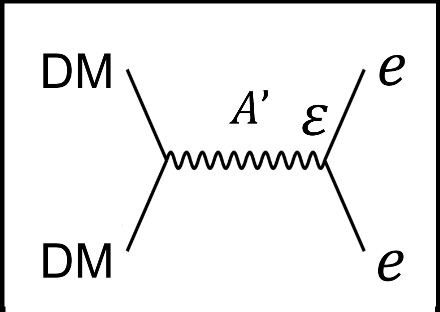
Strongly Interacting Heavy Particles

Just Right to be Dark Matter

Weakly Interacting Light Particles

Impossible to Discover

Too Much to be Dark Matter



$$<\sigma v> \sim \frac{\varepsilon^2}{m_{A'}^2}$$

SUMMARY

I. Why WIMPs?

The WIMP miracle, and discrete WIMP miracle imply that WIMPs emerge naturally as stable, cold, collisionless DM candidates with the correct thermal relic density from connections to central problems in particle physics.

II. WIMPs in Supersymmetry

The neutralino is the leading supersymmetric WIMP candidate, with the WIMP miracle realized in a variety of regions of parameter space.

III. WIMP Detection

The WIMP miracle suggests promising signal rates in many direct, indirect, and collider search experiments.

IV. WIMP Variations

Variations on the WIMP theme have new and extremely interesting implications:

- Inelastic DM (motivates collider searches)
- Isospin-violating DM (motivates diversity of direct detection targets)
- SuperWIMPs (warm DM, BBN, CMB)
- WIMPless DM (light DM, self-interacting DM, strongly-interacting DM)