ASTRO AND PARTICLE CONNECTIONS

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University of Colorado, Boulder

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20-22 June 2011

TASI 2011: THE DARK SECRETS OF THE TERASCALE

- This TASI anticipates the coming revolution in terascale particle physics
- We are living through a period of scientific revolution in the closely allied field of cosmology
- These 3 lectures are devoted to explaining how the terascale and cosmology might be related

TASI 2011: The Dark Secrets of the Terascale

Week 1: **June 6-10** Tutorial: CalcHEP/CompHEP

	Monday	*Tuesday*	*Wednesday*	*Thursday*	*Friday*
9:00-10:15 AM		Ramond	Reina	Ramond	Ligeti
10:15-10:45 AM	coffee break	coffee break	coffee break	coffee break	coffee break
10:45-12:00 PM	Ramond	Reina	Ligeti	Ligeti	Ramond
2:00-3:15 PM	Reina	Kong	Ramond	Kong	Campbell
3:15-3:45 PM	coffee break	coffee break	coffee break	coffee break	coffee break
3:45-5:00 PM	Kong		Kong		
Evening 7:30 PM G1B30 Duane				Public lecture P. Ramond	

Week 2: **June 13-17** Tutorial: PYTHIA+PGS

9:00-10:15 AM	Martin	Campbell	Conway	Martin	Martin
10:15-10:45 AM	coffee break	coffee break	coffee break	coffee break	coffee break
10:45-12:00 PM	Campbell	Martin	Martin	Kong	Kong
2:00-3:15 PM	Kong	Kong	Conway	Conway (PGS)	
3:15-3:45 PM	coffee break	coffee break	coffee break	coffee break	
3:45-5:00 PM	Campbell				

Week 3: **June 20-24**

9:00-10:15 AM		Ponton	Wang	Everett	Wacker
10:15-10:45 AM	coffee break	coffee break	coffee break	coffee break	coffee break
10:45-12:00 PM	Ponton	Feng	Feng	Ponton	Everett
2:00-3:15 PM	Feng	Wang	Everett	Wacker	Ponton
3:15-3:45 PM	coffee break	coffee break	coffee break	coffee break	coffee break
3:45-5:00 PM	Wang		Wacker	Wang	
Evening 7:30 PM G1B30 Duane		Public lecture J. Feng			

Week 4: **June 27-July 1** Tutorial: MicrOMEGAs

9:00-10:15 AM	Chung	Lester	Chung	Lykken	Lester
10:15-10:45 AM	coffee break	coffee break	coffee break	coffee break	coffee break
10:45-12:00 PM	Lester	Chung	Lester	Lester	Lykken
2:00-3:15 PM	Murgia	Murgia	Saab	Saab	
3:15-3:45 PM	coffee break	coffee break	coffee break	coffee break	
3:45-5:00 PM	Pukhov	Pukhov	Pukhov	Pukhov	

OUTLINE

LECTURE 1

Essential Cosmology, Dark Energy, WIMP Miracle

LECTURE 2

WIMP Detection, WIMPs at Colliders

LECTURE 3

Other Terascale Dark Matter Possibilities

ESSENTIAL COSMOLOGY

- For the first time in history, we now have a complete *picture* of the Universe
- How did this come about?
- Here review the standard model of cosmology and some of the key observational evidence leading to it
- Little knowledge of cosmology assumed; focus on heuristic derivations, order-of-magnitude estimates, intuitive arguments

COSMOLOGY BASICS

- The evolution of the Universe is dominated by gravity, described by the Einstein equations $$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$
- The (flat, k=0) Friedmann-Lemaitre-Robertson-Walker metric is $$ds^2 = dt^2 - a^2(t) \left[dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 \right]$$
- The stress-energy tensor is $T^{\mu}{}_{\nu} = \mathrm{diag}\left[\rho(t), -p(t), -p(t), -p(t)\right]$
  We may parameterize various materials by w, where $p = w\rho$
- Stress-energy conservation $T^{\mu\nu}{}_{;\nu} = 0$ → $\rho \sim a^{-3(1+w)}$
- The Einstein equations imply the Friedmann equation $$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

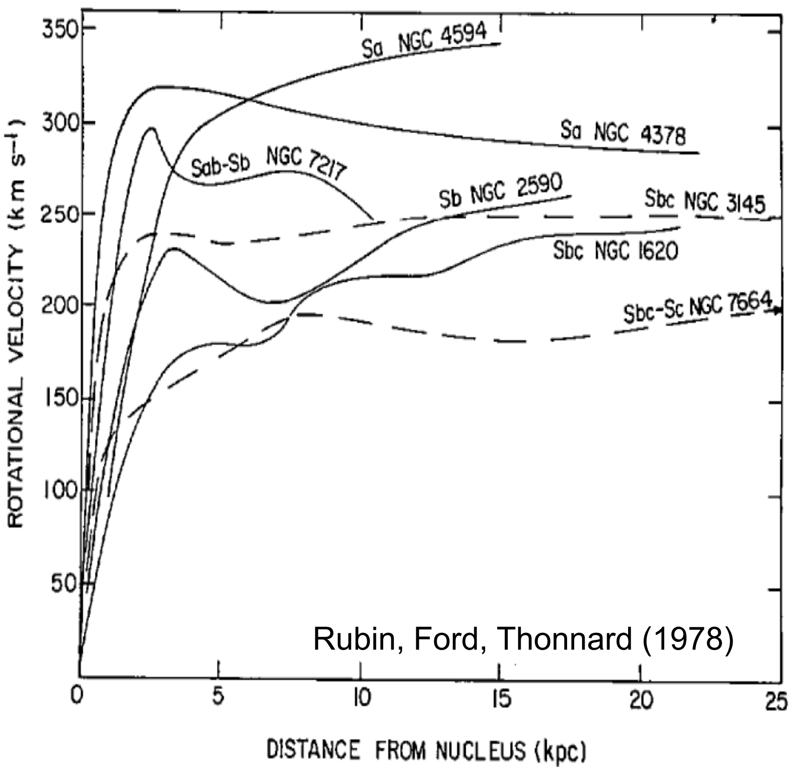
$$\mathrm{MD}: \ \rho \propto a^{-3} \Rightarrow \dot{a}^2 \propto \frac{1}{a} \Rightarrow a \propto t^{2/3}$$

$$\mathrm{RD}: \ \rho \propto a^{-4} \Rightarrow \dot{a}^2 \propto \frac{1}{a^2} \Rightarrow a \propto t^{1/2}$$

$$\mathrm{VD}: \ \rho \propto a^{0} \Rightarrow \dot{a}^2 \propto a^2 \Rightarrow a \propto e^{ct}$$

ROTATION CURVES OF GALAXIES

Rubin, Ford (1970); Bosma (1978)



Rubin, Ford, Thonnard (1978)

- Rotational velocity v_c as function of distance from center r
  - $v_c \sim O(300)$ km/s $\sim O(10^{-3})$ c
  - r ~ few kpc (pc = 3.26 ly)

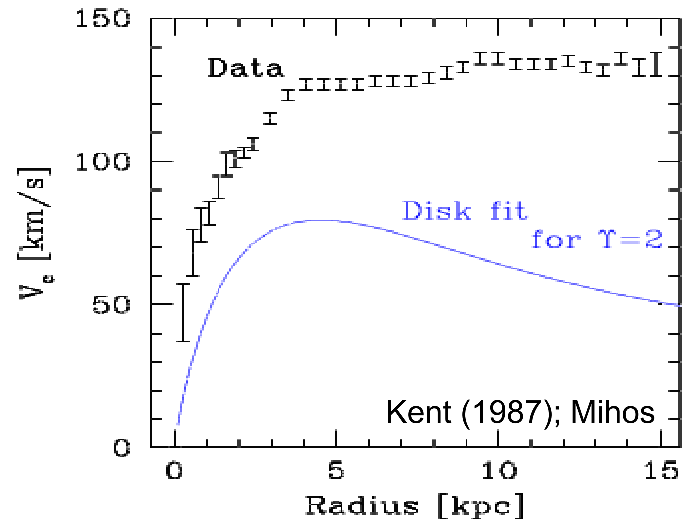
- Expect $v_c \sim r^{-1/2}$ beyond luminous region

$$\frac{mv_c^2}{r} = G_N \frac{mM}{r^2}$$

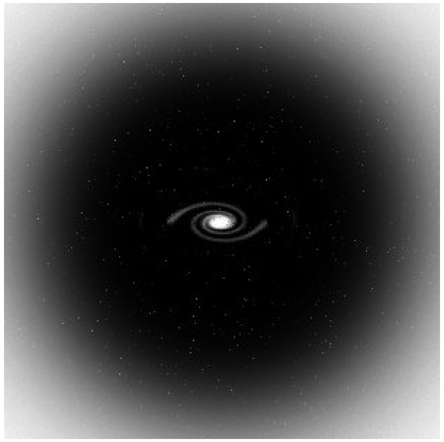
Instead find $v_c \sim$ constant

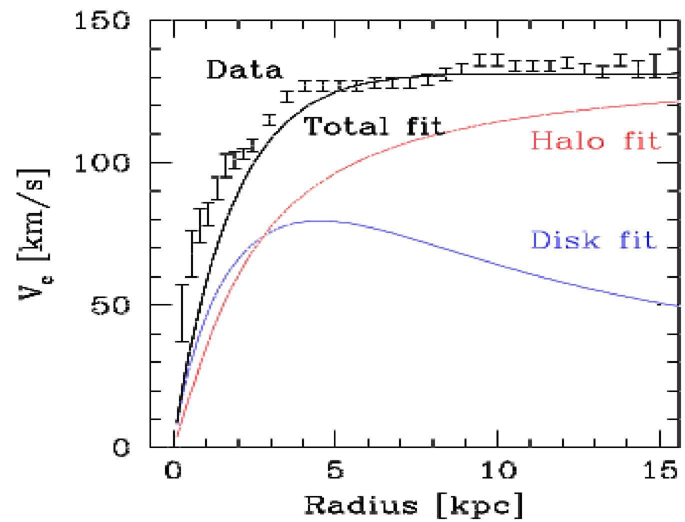
- The discrepancy may be resolved by missing mass and is classic (but not the first) evidence for dark matter

AN EXAMPLE: NGC 2403



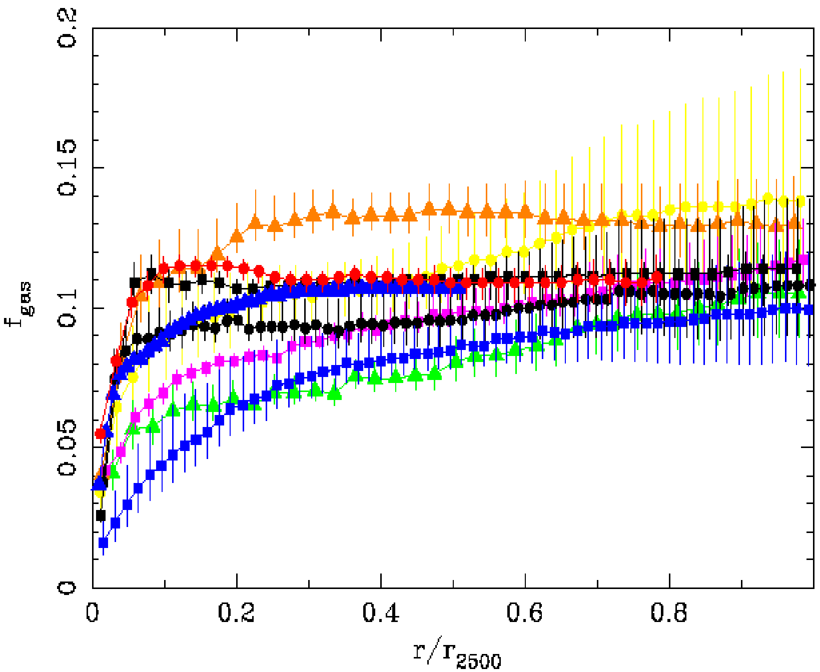
- v_c from HI line
- Fit mass-to-light ratio, dark halo model; this tells us about $\rho(r)$
- For Milky Way, get ρ~0.2-0.5 GeV/cm^3





MISSING MASS IN CLUSTERS OF GALAXIES

Zwicky (1933)



Allen, Schmidt, Fabian (2002)

- ~10-1000 galaxies, the largest gravitationally-bound structures;
- Intracluster gas mass, total mass constrained by X-rays from bremsstrahlung, lensing, etc.
- Gas mass fraction f_{gas} as function of distance from center
  - $f_{gas} = \rho_B / \rho_M$
  - $r_{2500} \sim$ Mpc

- Extrapolating from clusters to the whole Universe, this constrains $\Omega_M = \Omega_B \ \rho_M/\rho_B$, where $\Omega = \rho/\rho_c$ is energy density in units of the critical density and Ω_B is determined independently

RECESSIONAL VELOCITIES

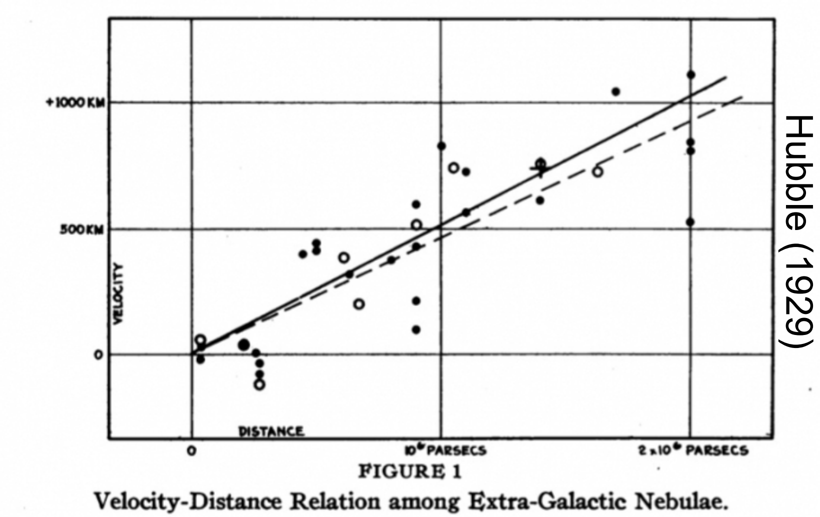
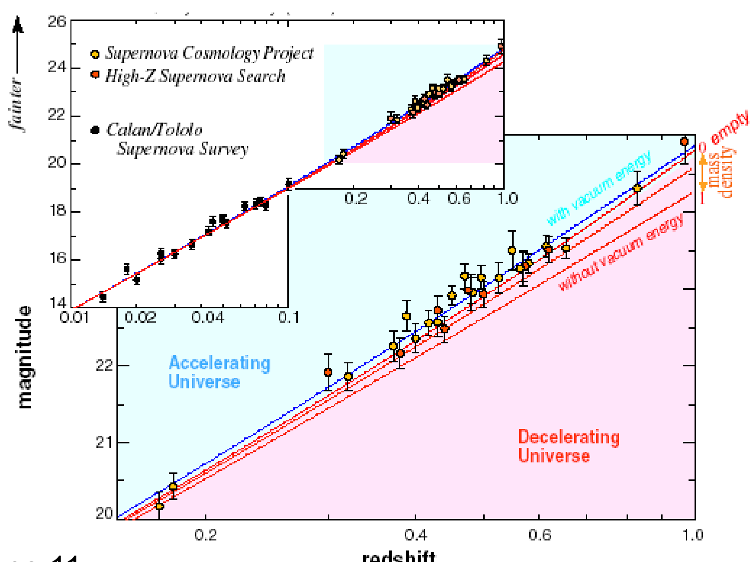


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble (1929)

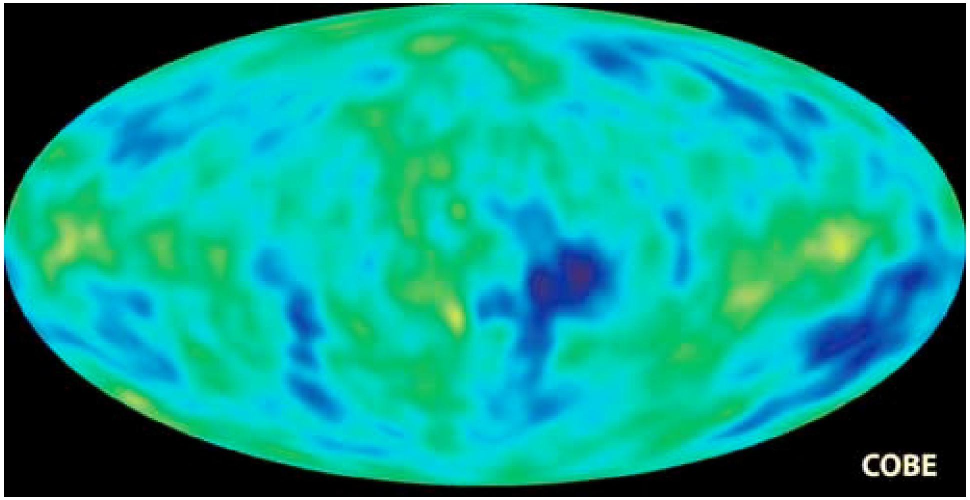


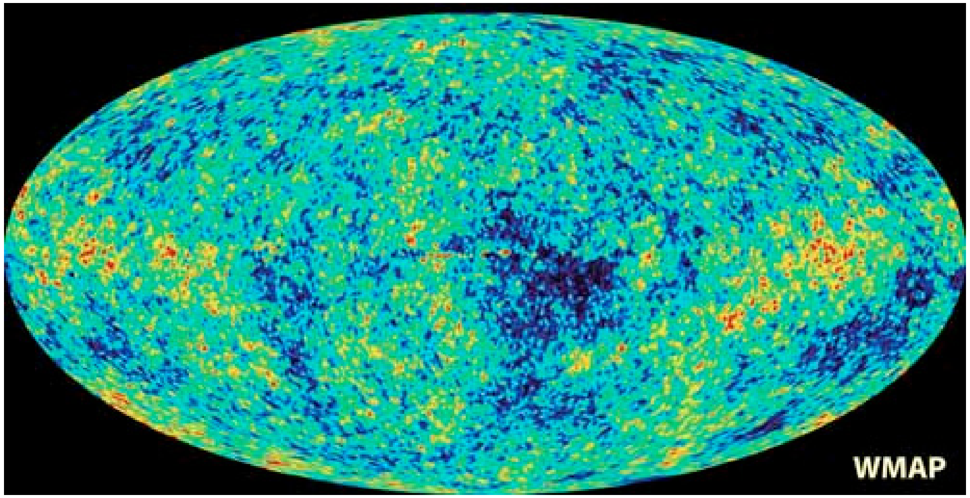
- The original evidence that the universe is expanding
- Now carried out to far larger distances with supernovae
- Constrains the acceleration of expansion:

$$\Omega_\Lambda - \Omega_M$$

"Attractive matter vs. repulsive dark energy"

COSMIC MICROWAVE BACKGROUND





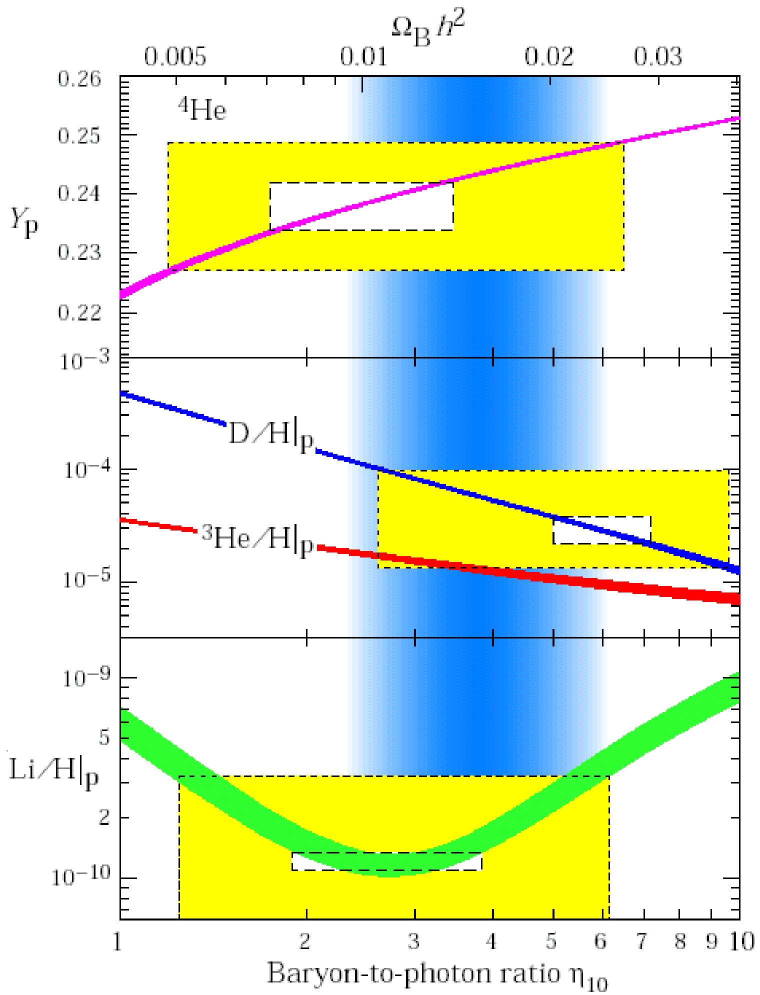
- $\delta T/T << 1$: The universe is isotropic and homogeneous on large scales

- Constrains the geometry of the universe:

  $$\Omega_\Lambda + \Omega_M$$

  "total energy density"

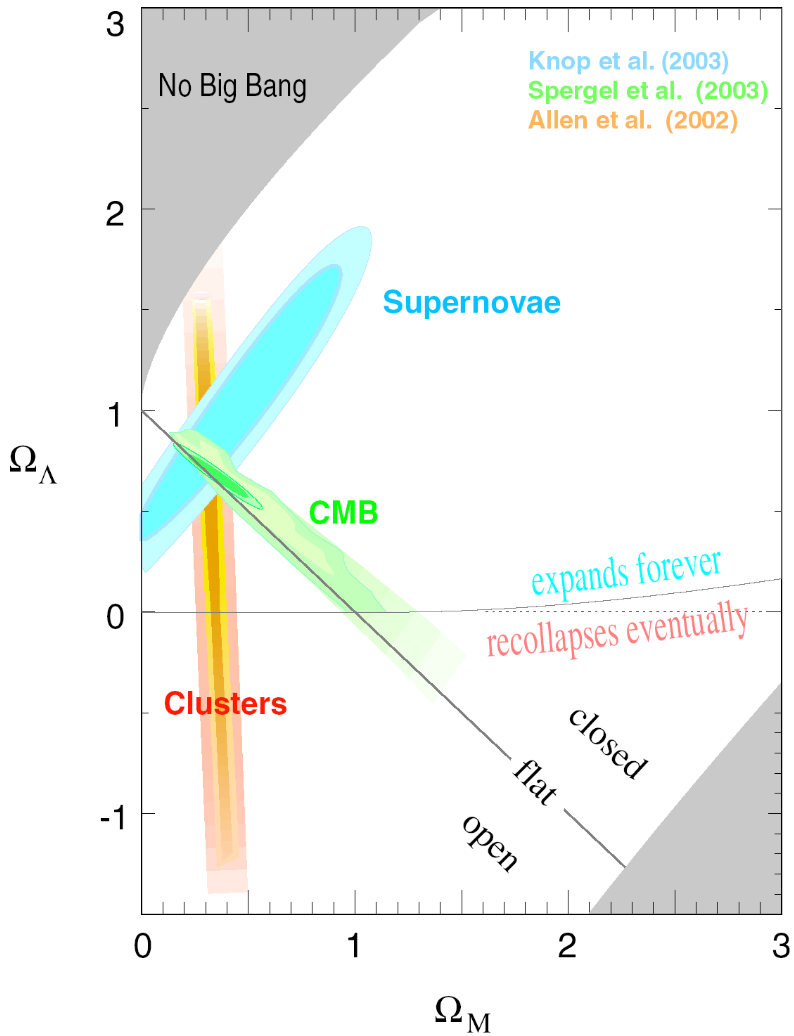
BIG BANG NUCLEOSYNTHESIS



Fields, Sarkar, PDG (2002)

- At T ~ 1 MeV, the universe cooled enough for light elements to start forming
- The abundance of each light species is fixed by η, the baryon-to-photon ratio
- These determinations are consistent* and constrain (with the CMB) the density in baryons: Ω_B

SYNTHESIS



- Remarkable agreement

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Baryons: 4% ± 0.4%
  [νs: 0.2% for Σm = 0.1 eV]

- Remarkable precision (~10%)

- Remarkable results

STANDARD COSMOLOGICAL HISTORY

- For many applications, temperature is a better clock than time. We would like to find the time-temperature correspondence.

- For radiation, $\rho \propto a^{-4}$

- But by dimensional analysis, $\rho \propto T^4 \Rightarrow T \propto \frac{1}{a}$

- The relations in the matter- and radiation-dominated eras are therefore

$$\text{MD} : T \propto t^{-2/3}$$

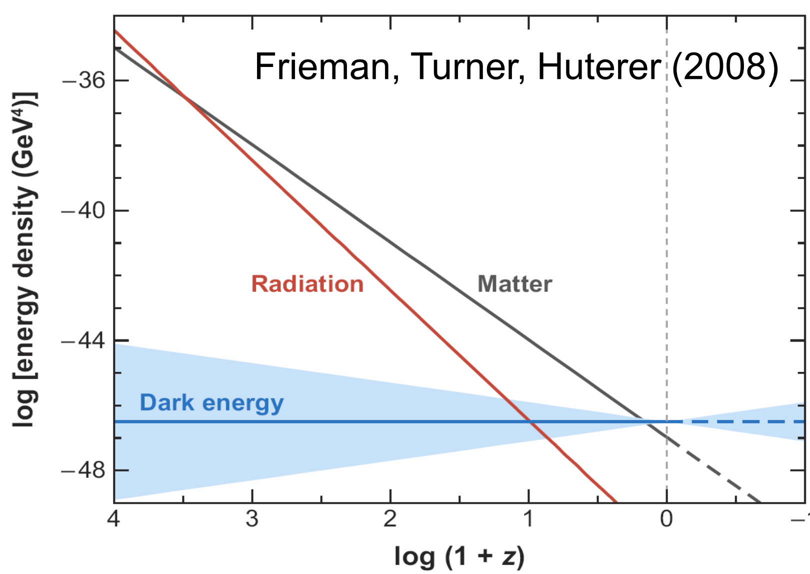
$$\text{RD} : T \propto t^{-1/2}$$

WHAT DOMINATES WHEN?

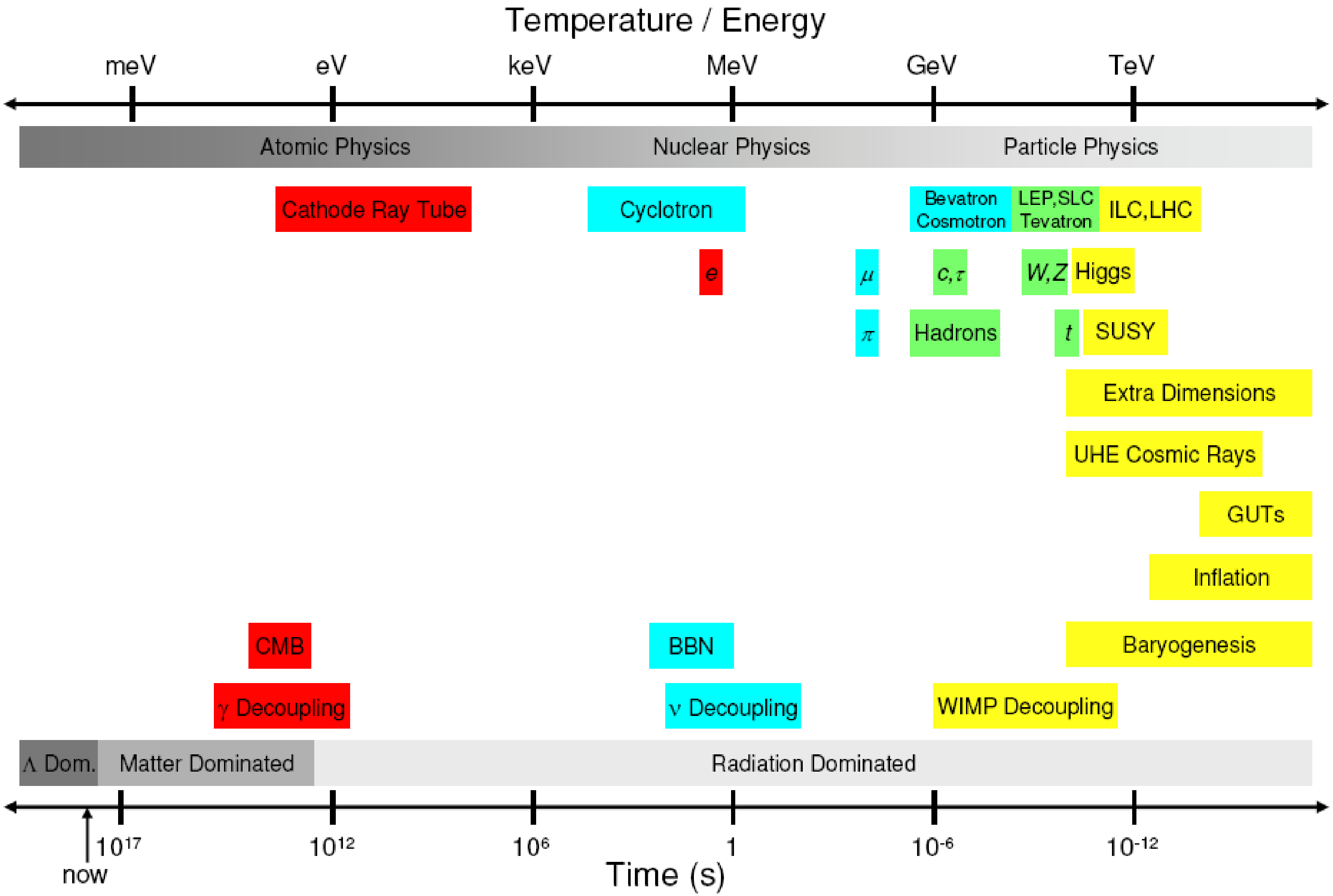
- We know $\Omega_\Lambda \approx 0.73$, $\Omega_M \approx 0.27$. We can also determine

$$\Omega_{\text{CMB}} \equiv \frac{\rho_{\text{CMB}}}{\rho_c} \sim \frac{T^4_{\text{CMB}}}{\frac{3H^2}{8\pi G}} \sim \frac{(2.7\ \text{K})^4(14\ \text{Gyr})^2}{(10^{19}\ \text{GeV})^2}$$
$$\sim \frac{(10^{-4}\ \text{eV})^4(14\pi \times 10^{16}\ \text{s})^2}{(10^{-16}\ \text{eV s})^2(10^{28}\ \text{eV})^2} \sim 10^{-4}$$

- Matter-radiation equality
  - $T \sim 10^4\ T_0 \sim \text{eV}$
  - $t \sim 10^{-6}\ t_0 \sim 10^{12}\ \text{s}$
- Vacuum-matter equality
  - yesterday (roughly)



THERMAL HISTORY OF THE UNIVERSE



DECOUPLING

- Decoupling of particle species is an essential concept for particle cosmology. It is described by the Boltzmann equation

$$\frac{dn}{dt} = \underbrace{-3Hn}_{\text{Dilution from expansion}} - \langle \sigma v \rangle \left[\underbrace{n^2}_{XX \to f\bar{f}} - \underbrace{n_{\rm eq}^2}_{f\bar{f} \to XX} \right]$$

- Particles decouple (or freeze out) when $n_{\rm eq} \langle \sigma v \rangle \sim H$

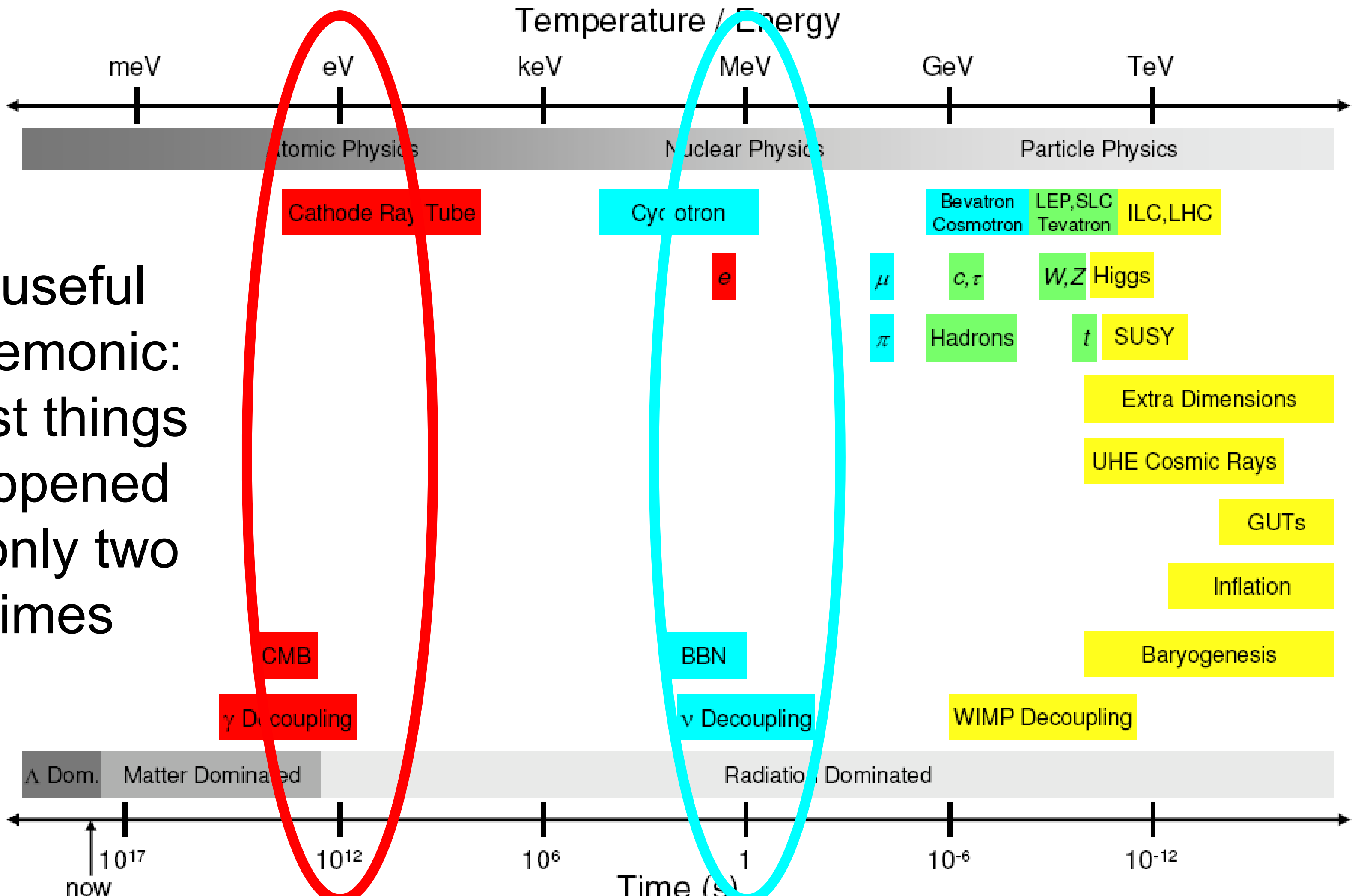
- An example: neutrino decoupling. By dimensional analysis,

$$n_{\rm eq} \sim T^3 \qquad \langle \sigma v \rangle \sim G_F^2 T^2 \qquad H \sim T^2 / M_{\rm Pl}$$

$$T^3 \sim M_W^4 / M_{\rm Pl} \Rightarrow T \sim \text{MeV}$$

THERMAL HISTORY OF THE UNIVERSE

A useful mnemonic: most things happened at only two times



PROBLEMS

The standard model of cosmology answers many questions, but also highlights many others:

- What is dark matter?
- What is the distribution of dark matter?
- How did structure form?
- What is dark energy?
- Why is the cosmological constant so small?
- Why matter and no anti-matter?
- Why are all energy densities roughly comparable now?
- How did the universe begin?
- …

Particle physics is required to answer these, not least because it is required to understand the hot early Universe

DARK ENERGY

- $\Omega_\Lambda \approx 0.73 \rightarrow \rho_\Lambda \sim (\text{meV})^4$: tiny, but all fields contribute
- Quantum mechanics:

$$\pm \tfrac{1}{2}\, \hbar\, \omega, \qquad \omega^2 = k^2 + m^2$$

- Quantum field theory:

$$\pm \tfrac{1}{2} \int^E d^3k\, \hbar\, \omega \sim \pm E^4,$$

where E is the energy scale where the theory breaks down

- We expect

$(M_{\text{Planck}})^4 \sim 10^{120}\, \rho_\Lambda$ $\qquad$ $(M_{\text{SUSY}})^4 \sim 10^{60}$ -$10^{90}\, \rho_\Lambda$

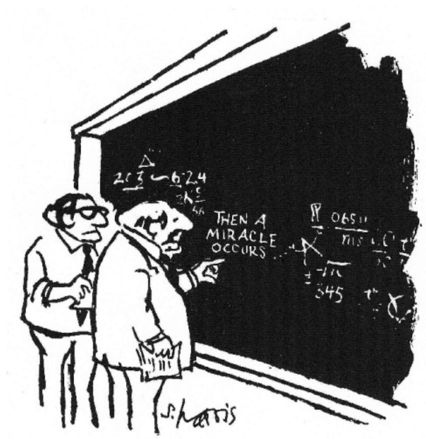
$(M_{\text{GUT}})^4 \sim 10^{108}\, \rho_\Lambda$ $\qquad$ $(M_{\text{weak}})^4 \sim 10^{60}\, \rho_\Lambda$

ONE APPROACH

- Small numbers ↔ broken symmetry

$$\rho_\Lambda \sim M_{Pl}^4$$

??



"I think you should be more explicit here in step two."

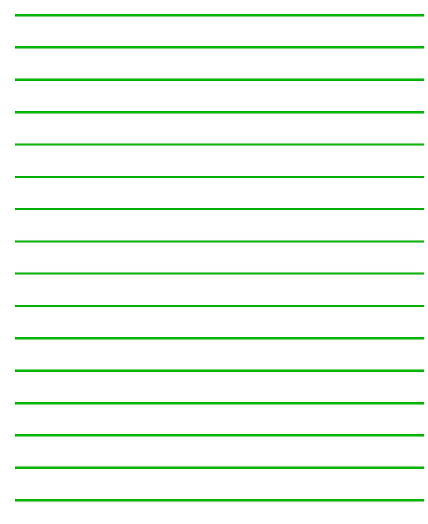
$$\rho_\Lambda = 0$$

$$\rho_\Lambda \sim m_\nu^4, \quad (M_W^2/M_{Pl})^4, \ldots$$

ANOTHER APPROACH

$\rho_\Lambda \sim M_{Pl}^4$

Many densely-spaced vacua (string landscape, eternal inflation, etc.)



Anthropic principle:
$-1 < \Omega_\Lambda < 100$

Weinberg (1989)

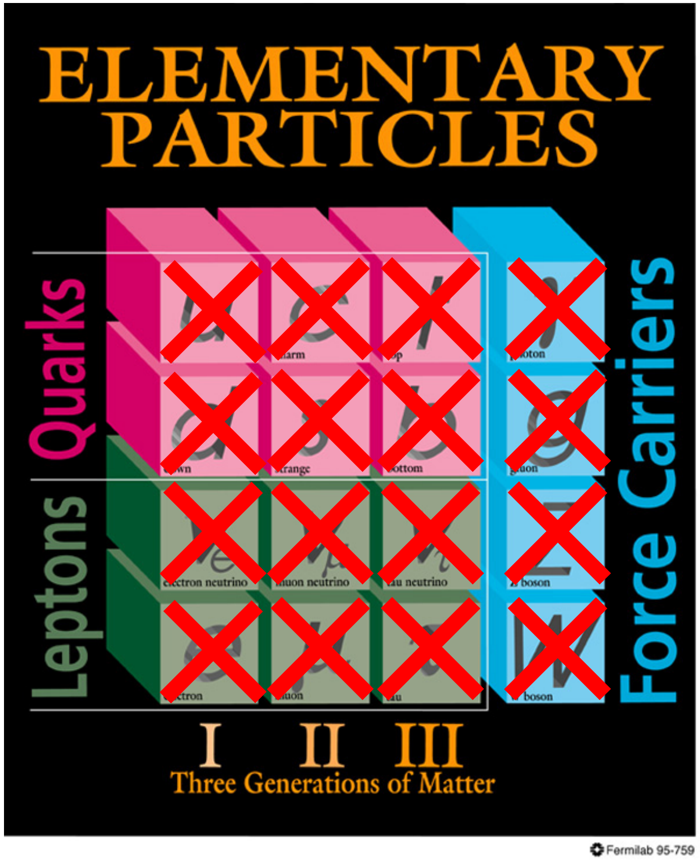
DARK ENERGY PROSPECTS

- These approaches are very different. Their only similarity is that the more you think about either one, the more you think the other one must be more promising.

- Terascale prospects:
  - Worst case imaginable: we discover only the minimal Higgs boson
  - Best case imaginable: we discover the minimal Higgs boson. At least we'll know that fundamental scalars exist!

- Challenge: identify a concrete scenario in which the LHC will shed light on dark energy (crazy is ok)

DARK MATTER



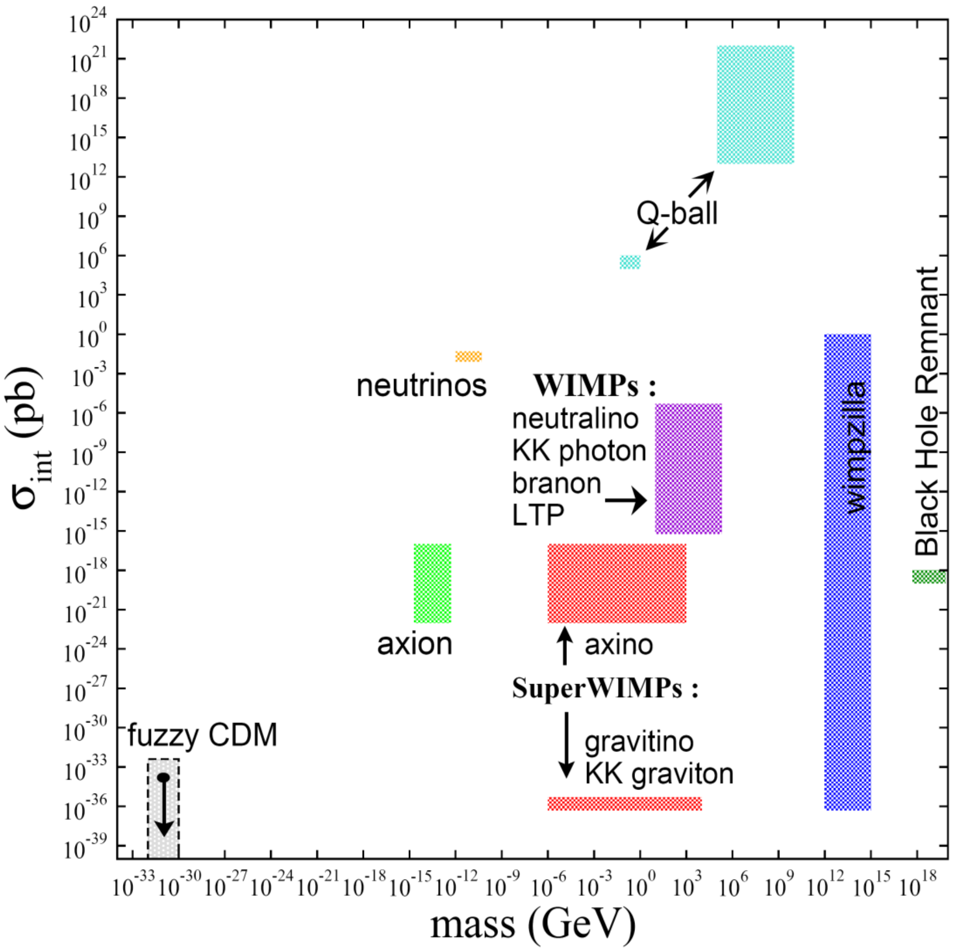
Known DM properties

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

Unambiguous evidence for new particles

DARK MATTER CANDIDATES

- There are many
- Masses and interaction strengths span many, many orders of magnitude, but the gauge hierarchy problem especially motivates Terascale masses



HEPAP/AAAC DMSAG Subpanel (2007)

FREEZE OUT: QUALITATIVE

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

$$XX \leftrightarrow \bar{q}q$$

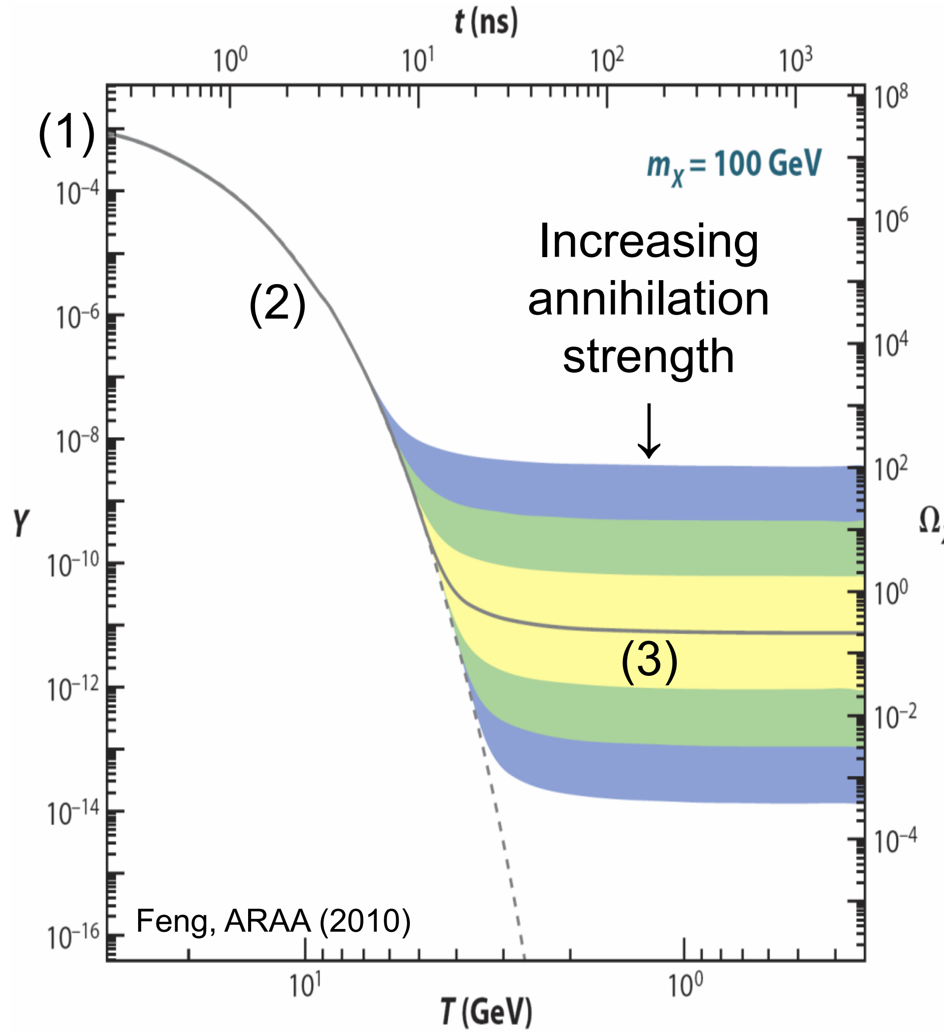
(2) Universe cools:

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

(3) Universe expands:

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

Zeldovich et al. (1960s)



FREEZE OUT: MORE QUANTITATIVE

- The Boltzmann equation:

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

Dilution from expansion

$\chi\chi \to f\bar{f}$

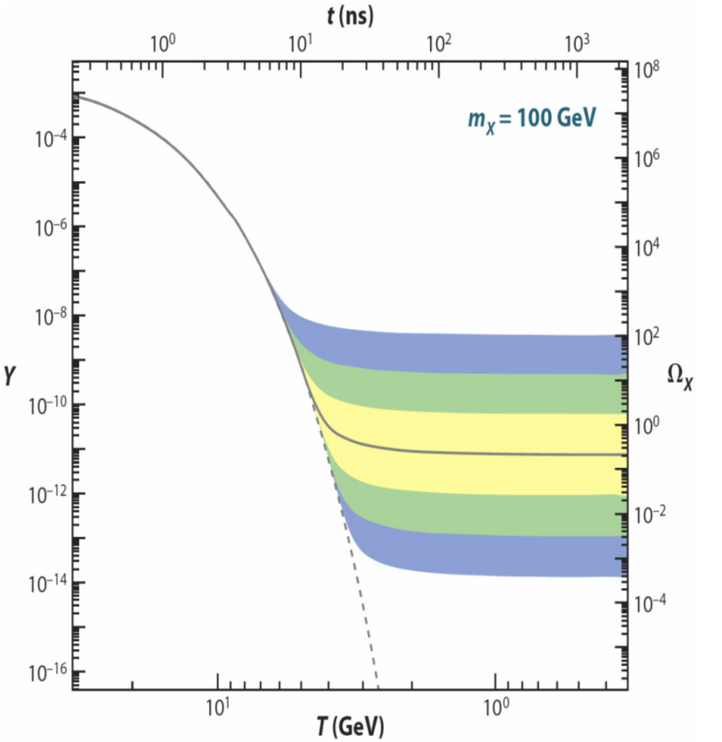
$f\bar{f} \to \chi\chi$

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

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

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

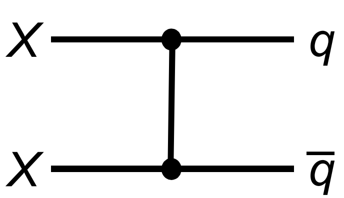
- Might expect freeze out at T ~ m, but the universe expands *slowly*! First guess: $m/T \sim \ln(M_{Pl}/m_W) \sim 40$



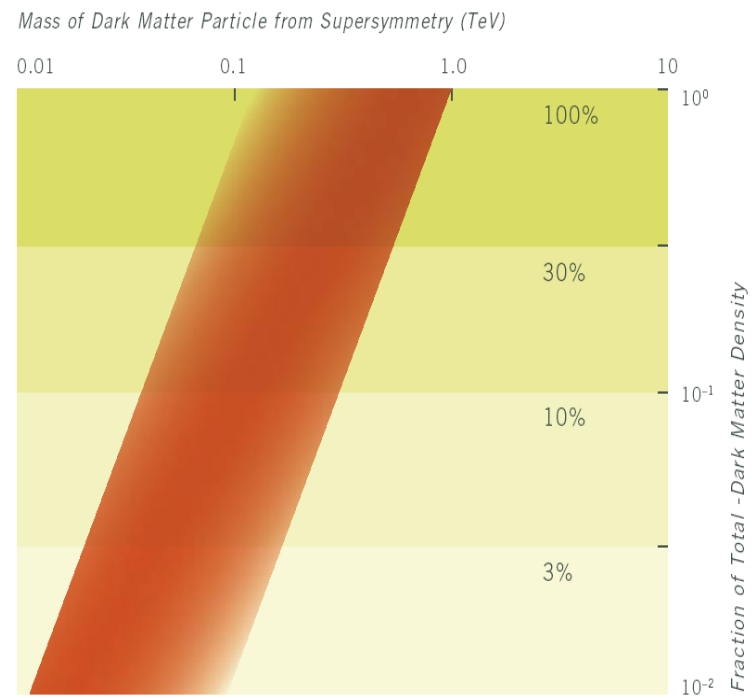
THE WIMP MIRACLE

- 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 ~ 100 GeV, g_X ~ 0.6 → Ω_X ~ 0.1

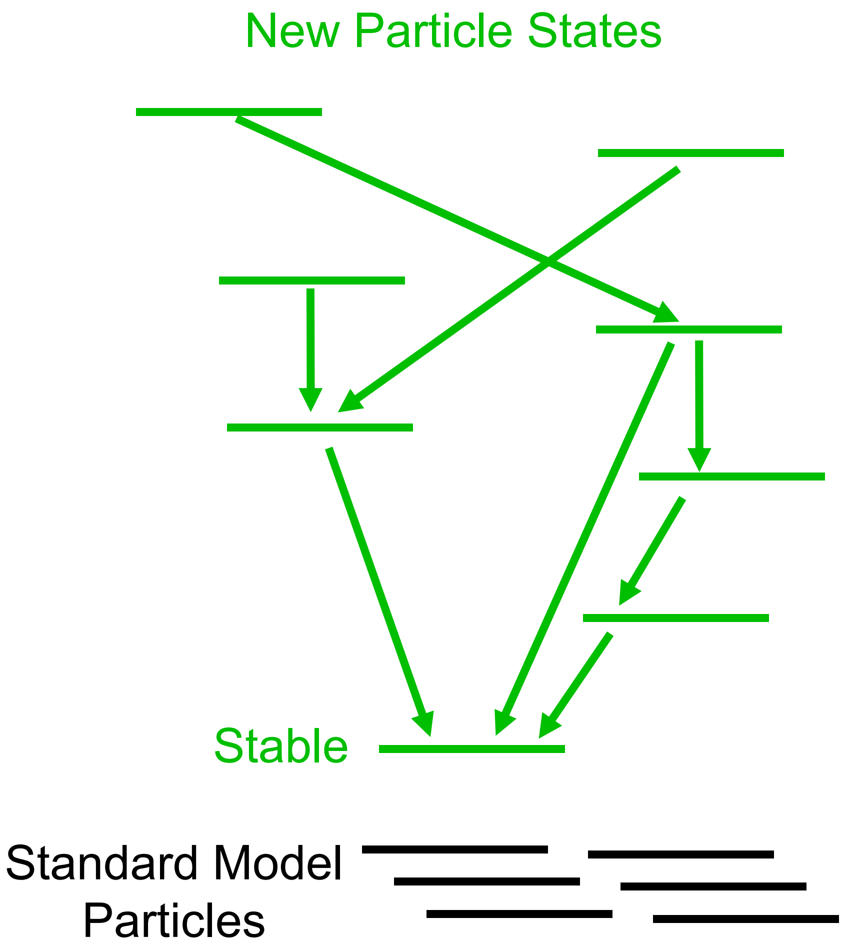


LHC/ILC HEPAP, Matchev et al. (2005)

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

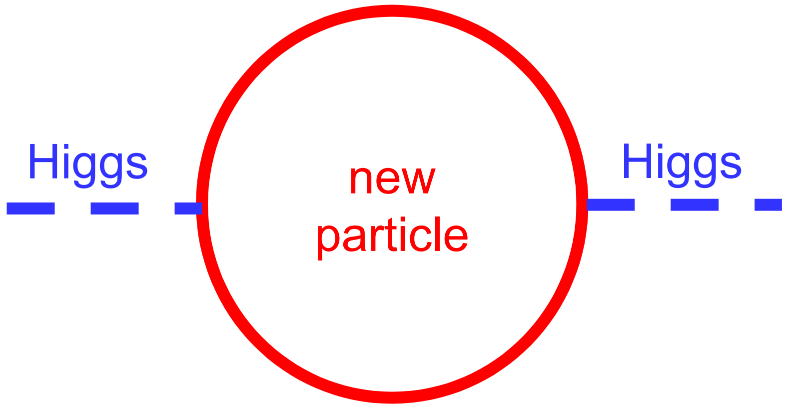
STABILITY

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

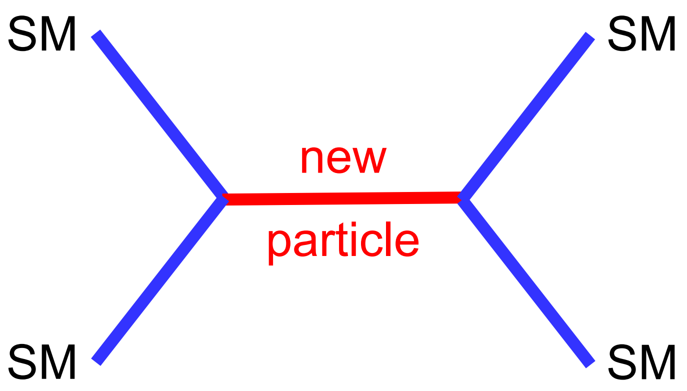


LEP'S COSMOLOGICAL LEGACY

Gauge Hierarchy requires



Precision EW excludes



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

  LEP constraints ↔ Discrete Symmetry ↔ Stability

Cheng, Low (2003); Wudka (2003)

- The result: dark matter is easier to explain than no dark matter, and the WIMP paradigm is more natural than ever before, leading to a proliferation of candidates

WIMP EXAMPLES

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

- The prototypical WIMP: neutralinos in supersymmetry

Goldberg (1983)

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

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

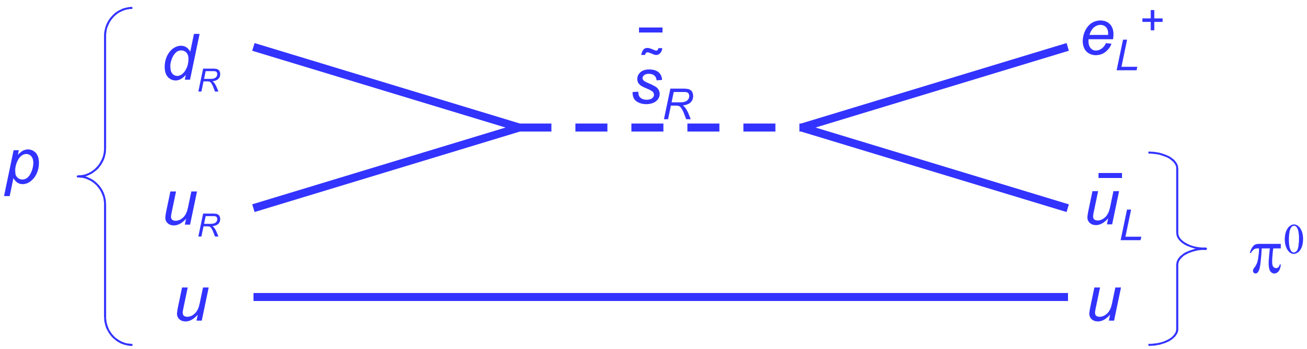
NEUTRAL SUSY PARTICLES

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

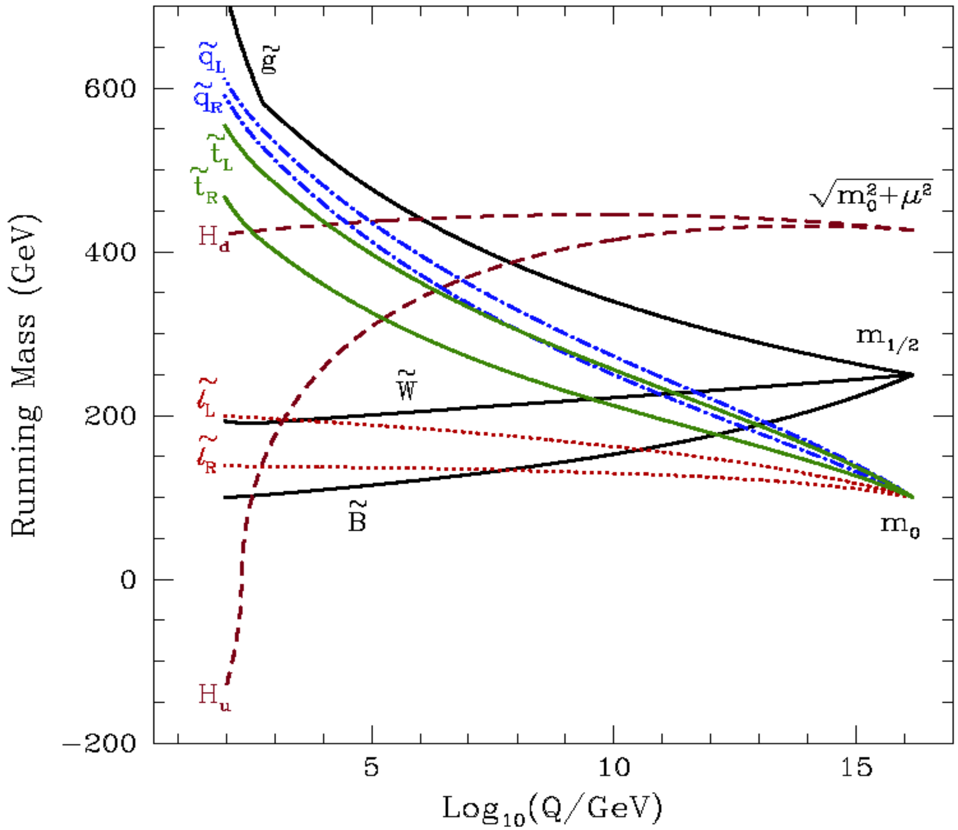
- One problem: proton decay



- 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 , $\tilde{\tau}_R$

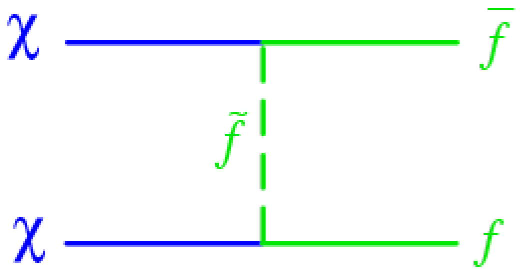


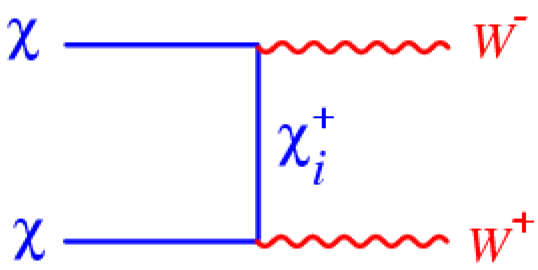
Olive (2003)

Particle physics alone → neutral, stable, cold dark matter

RELIC DENSITY

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



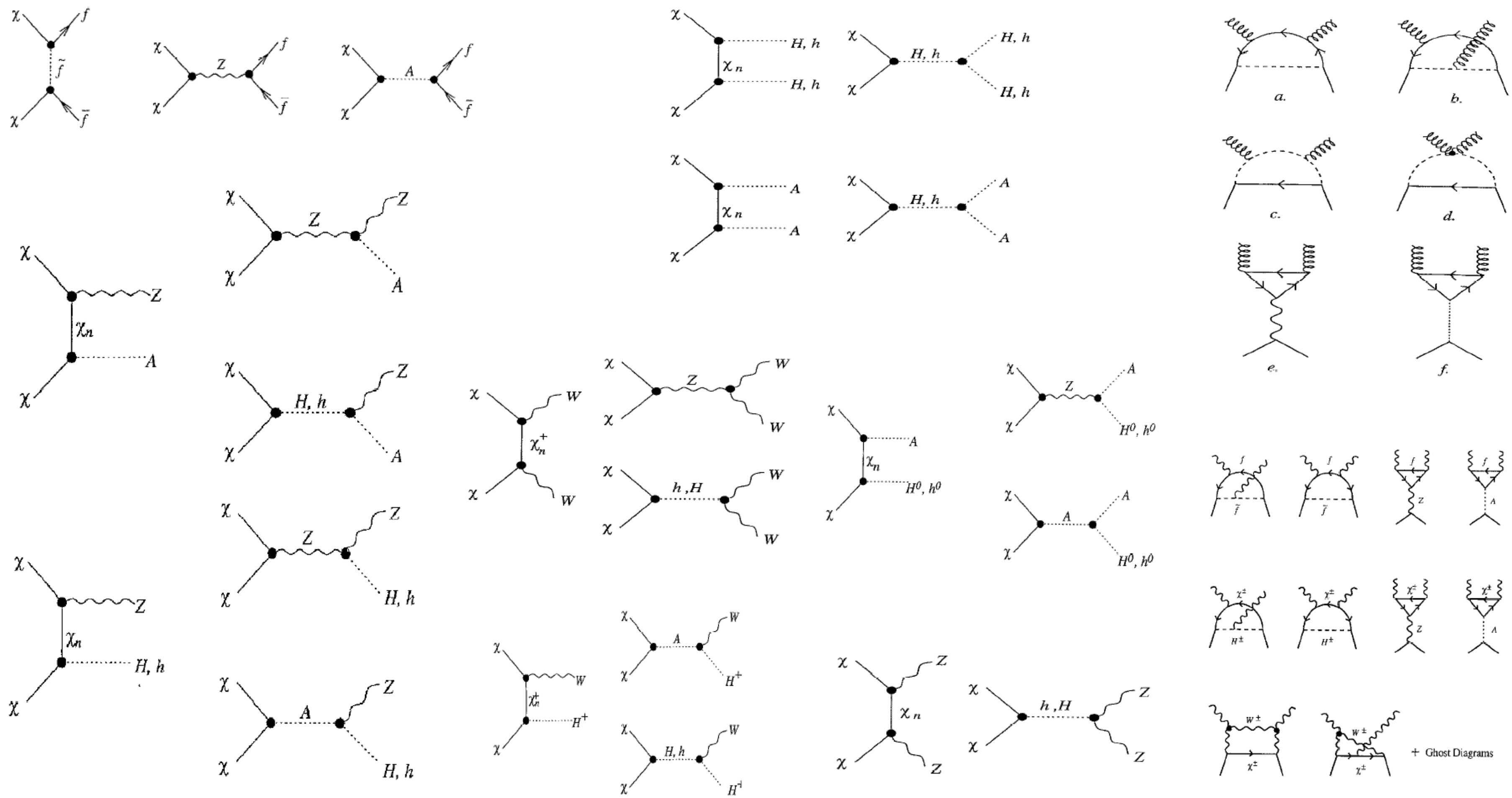


- χ are Majorana fermions, so Pauli exclusion → S_{in} = 0, L conservation →
  - P-wave suppression: $\sigma v \sim \sigma_0 + \sigma_1 v^2$, $mv^2/2 = 3T/2$ → $v^2 \sim 3T/m \sim 0.1$
  - m_f/m_W suppression

- Gauge boson diagrams suppressed for $\chi \approx$ Bino

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

NEUTRALINO ANNIHILATION



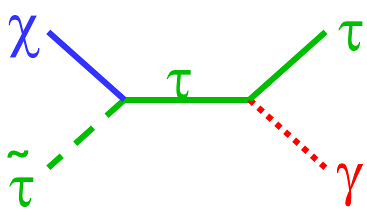
Jungman, Kamionkowski, Griest (1995)

COSMOLOGICALLY PREFERRED SUPERSYMMETRY

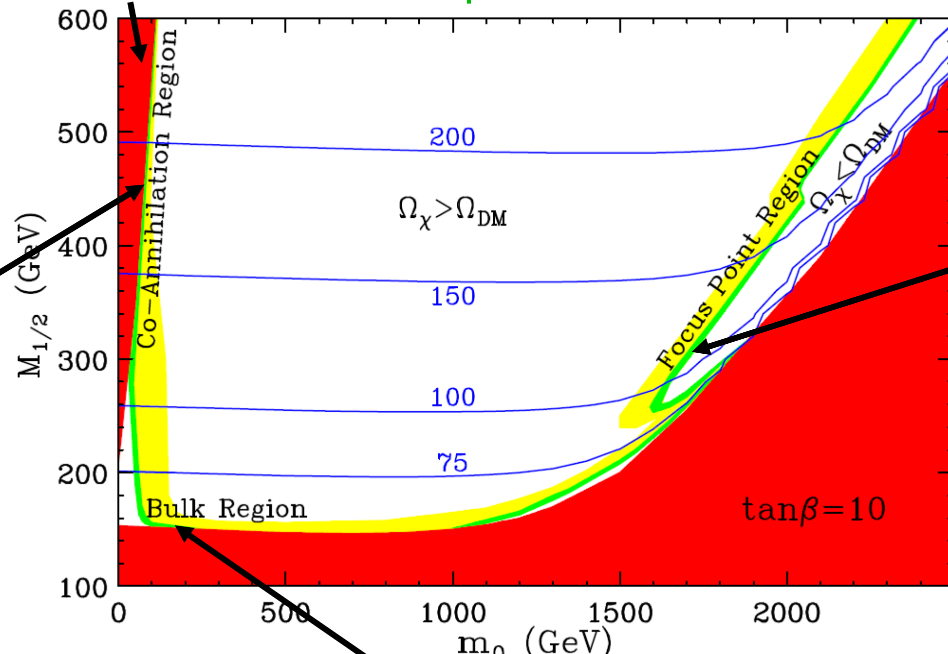
Typically get too much DM, but there are mechanisms for reducing it

Excluded:
Stau LSP

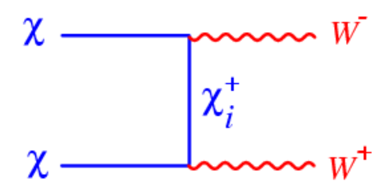
Yellow: pre-WMAP
Green: post-WMAP



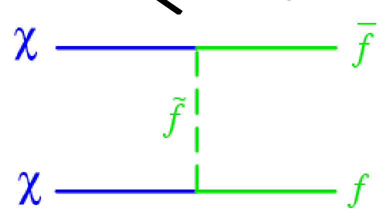
Stau and χ degenerate to within roughly T ~ m/25



Feng, Matchev, Wilczek (2003)



Mixed Neutralinos

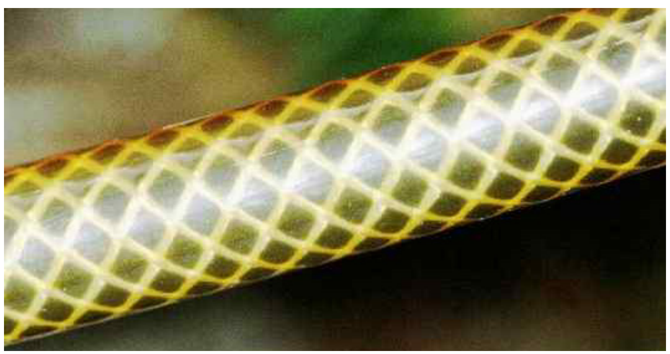


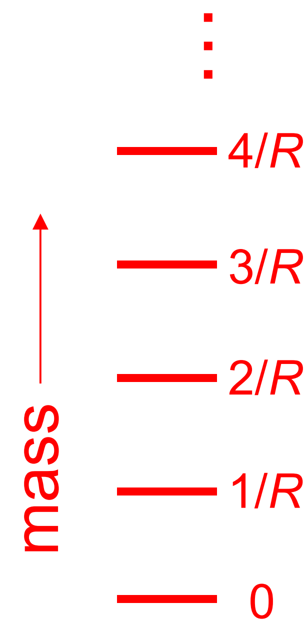
Light sfermions

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.





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

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

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

- A solution…

- Compactify on S^1/Z_2 instead (orbifold); require

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

- Unwanted scalar is projected out:

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

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

- Similar projection on fermions → chiral 4D theory, …

Appelquist, Cheng, Dobrescu (2001)

KK-PARITY

- A consequence: KK-parity $(-1)^{KK}$ conserved: interactions require an even number of odd KK modes

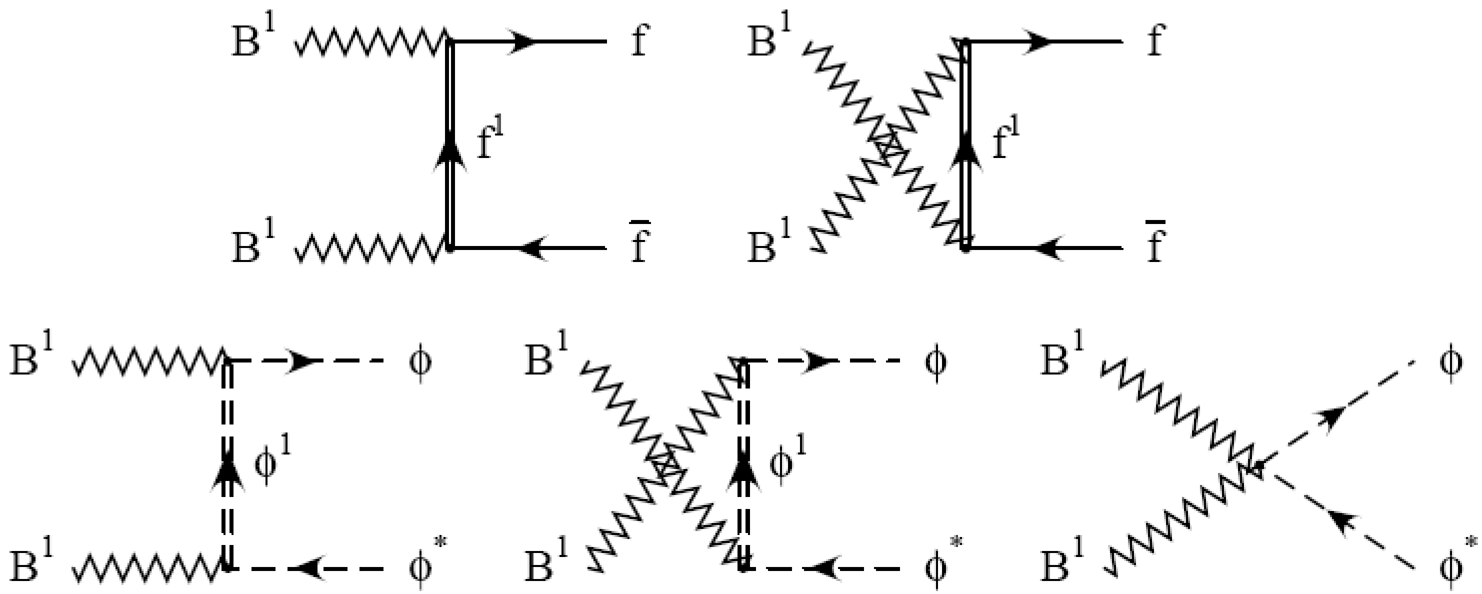
- 1st KK modes must be pair-produced at colliders

Appelquist, Cheng, Dobrescu (2001)
Macesanu, McMullen, Nandi (2002)

- LKP (lightest KK particle) is stable – dark matter!

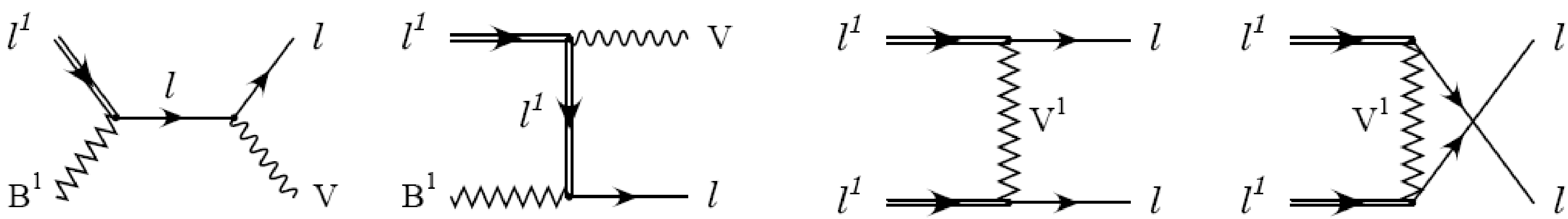
B^1 ANNIHILATION

- 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 in SUSY

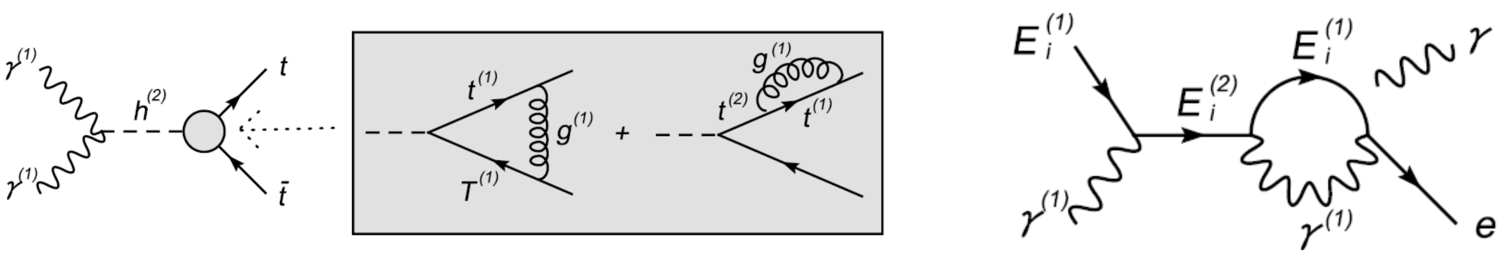


MORE B^1 ANNIHILATION

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



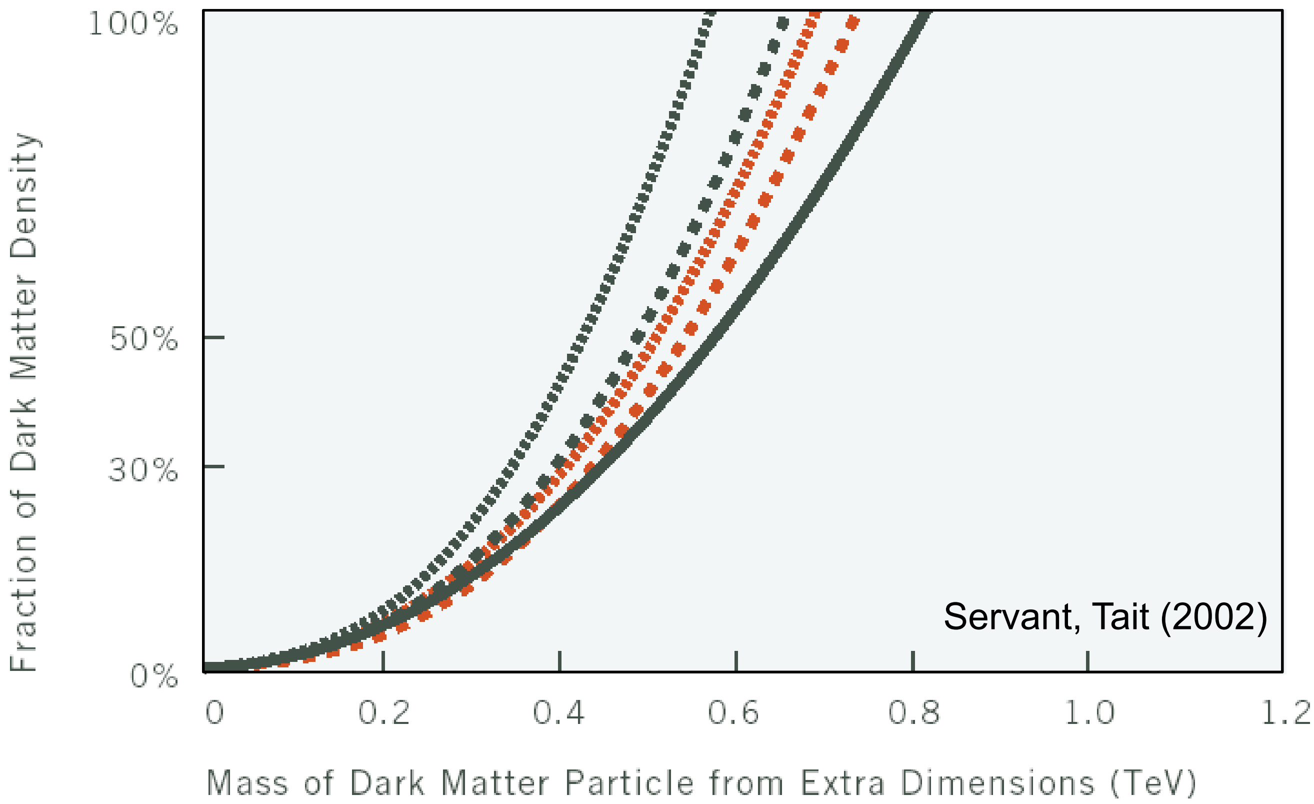
- Level-2 KK resonances



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) $\Delta = 0.05$.

LECTURE 1 SUMMARY

- The revolution in cosmology has produced remarkable progress and highlights remarkable problems

- Cosmology and particle physics both point to the Terascale for new particles, with viable WIMP candidates from SUSY, UED, etc.

- Next time: what are the implications for dark matter searches?

OUTLINE

LECTURE 1

Essential Cosmology, Dark Energy, WIMP Miracle

LECTURE 2

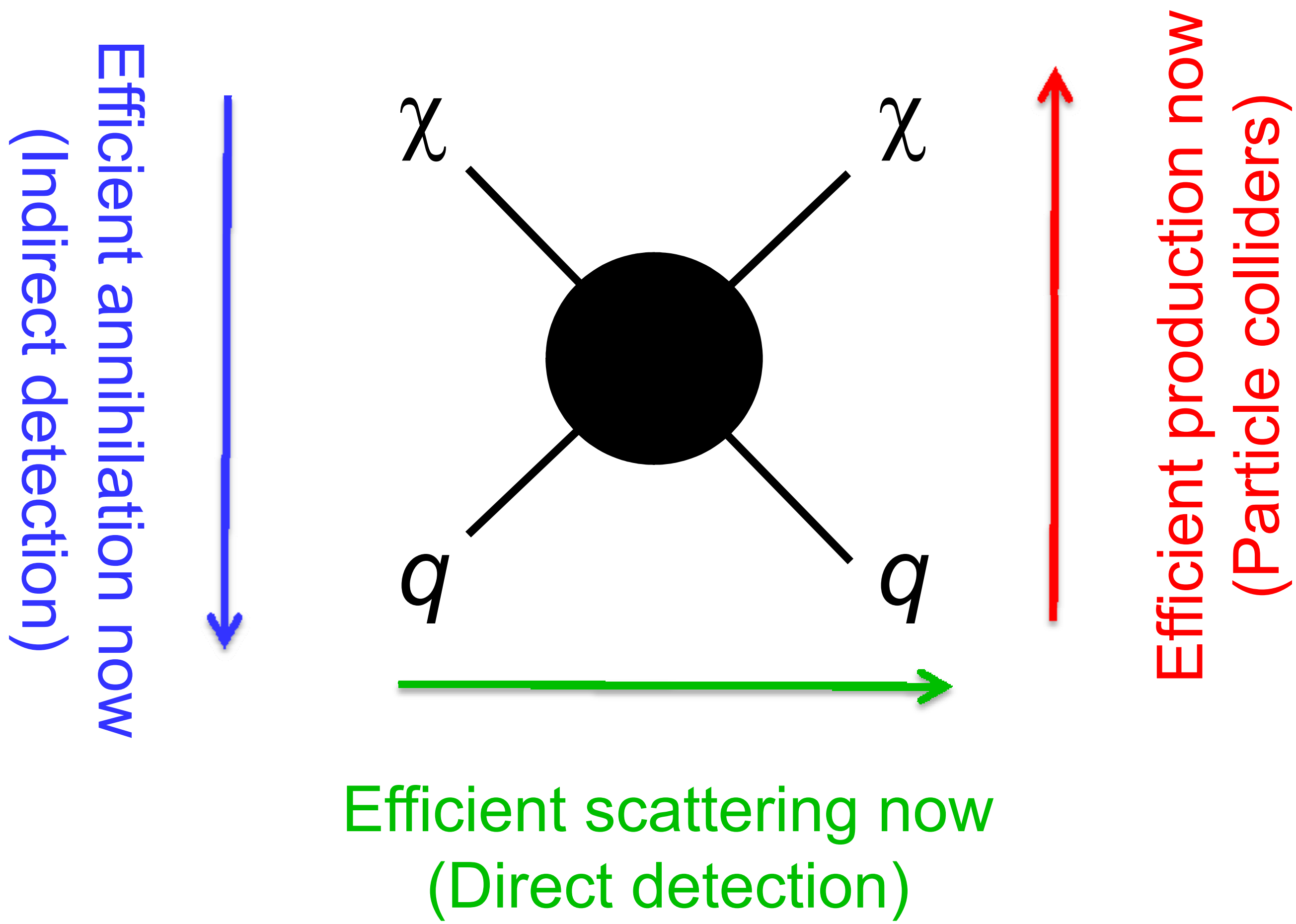
WIMP Detection, WIMPs at Colliders

LECTURE 3

Other Terascale Dark Matter Possibilities

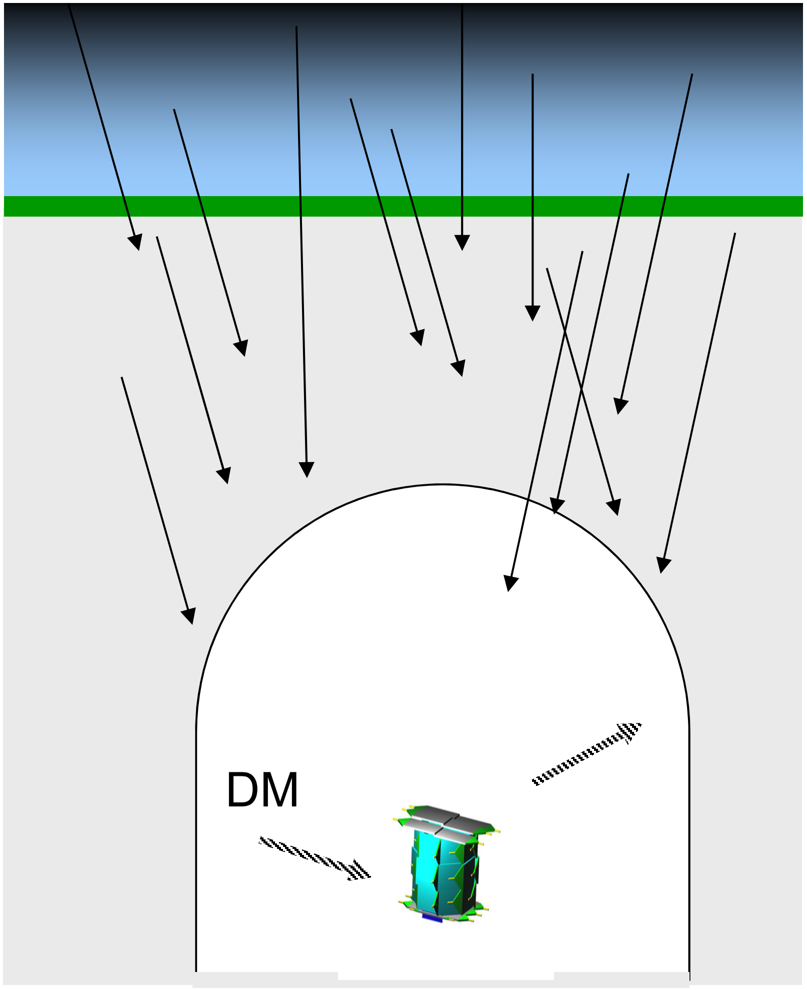
WIMP DETECTION

Correct relic density → Efficient annihilation then



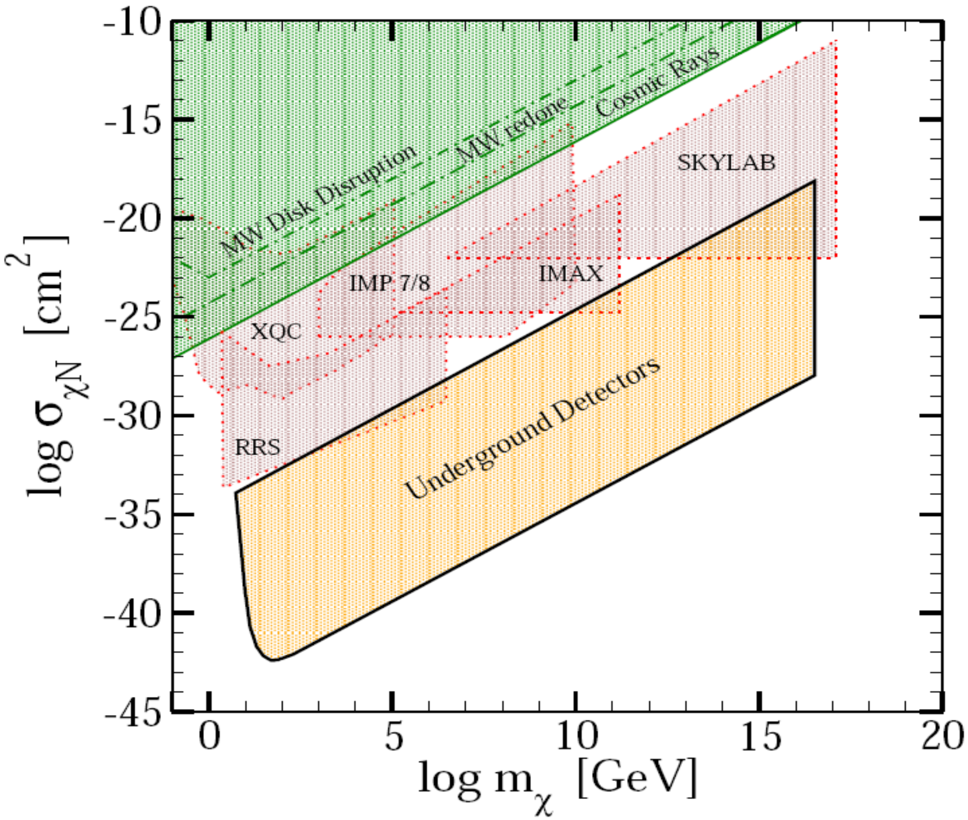
DIRECT DETECTION

- Look for normal matter recoiling from DM collisions
- WIMP properties
  - m ~ 100 GeV
  - velocity ~ 10^{-3} c
  - Recoil energy ~ 1-100 keV
- Typically focus on ultra-sensitive detectors placed deep underground
- But first, what range of interaction strengths are to be probed?



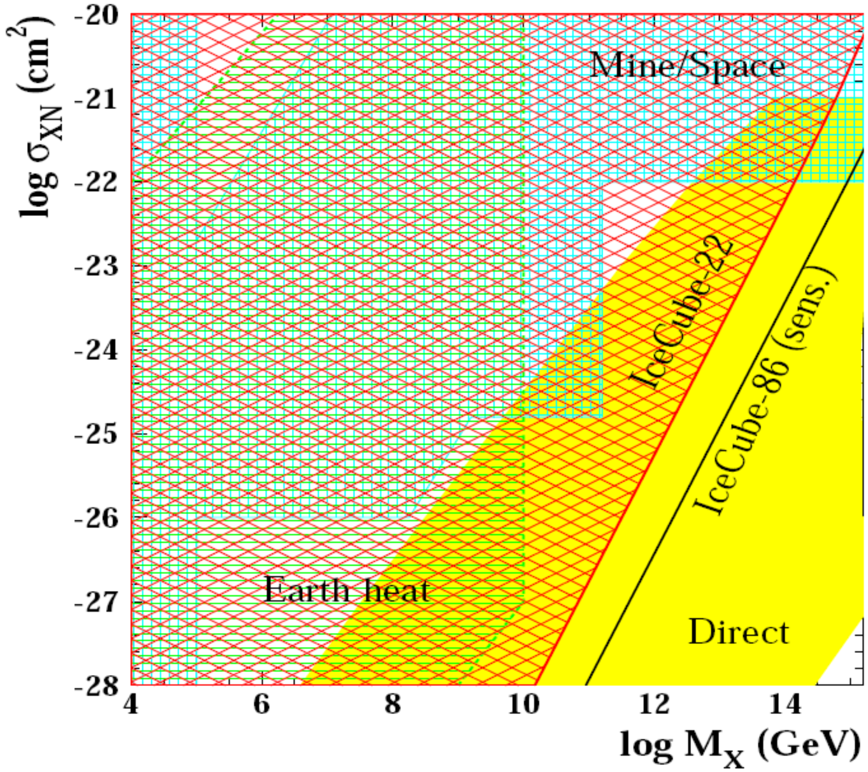
THE BIG PICTURE: UPPER BOUND

- What is the upper bound?



Mack, Beacom, Bertone (2007)

- Strongly-interacting window is now closed

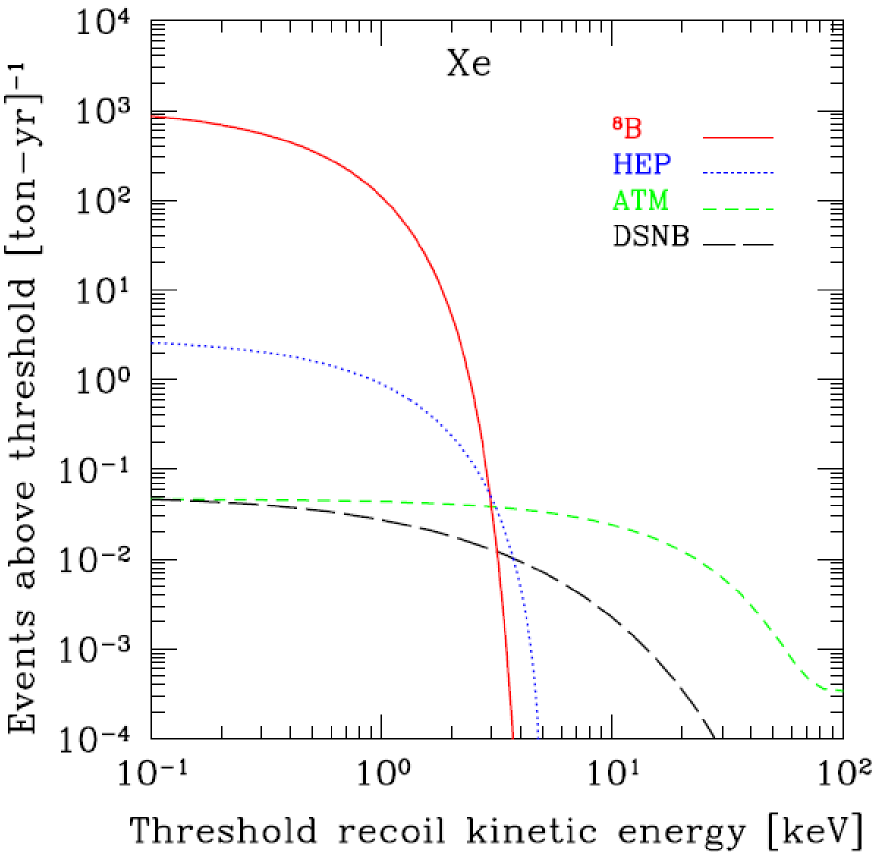


Albuquerque, de los Heros (2010)

THE BIG PICTURE: LOWER BOUND

- Is there (effectively) a lower bound?
- Solar, atmospheric, and diffuse supernova background neutrinos provide an "irreducible 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

$\sigma \sim 1$ 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

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

- DM particles now have v ~ 10^{-3} c. 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

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

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

$$f_{T_u}^p = 0.020 \pm 0.004 \quad f_{T_u}^n = 0.014 \pm 0.003 \quad f_{T_s}^p = 0.118 \pm 0.062 \quad f_{T_s}^n = 0.118 \pm 0.062$$
$$f_{T_d}^p = 0.026 \pm 0.005 \quad f_{T_d}^n = 0.036 \pm 0.008 \quad f_{T_{c,b,t}}^{p,n} = \frac{2}{27} f_{T_G}^{p,n} = \frac{2}{27}\left(1 - f_{T_u}^{p,n} - f_{T_d}^{p,n} - f_{T_s}^{p,n}\right)$$

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

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

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

Experiment: number of target nuclei

Astrophysics: local DM number density

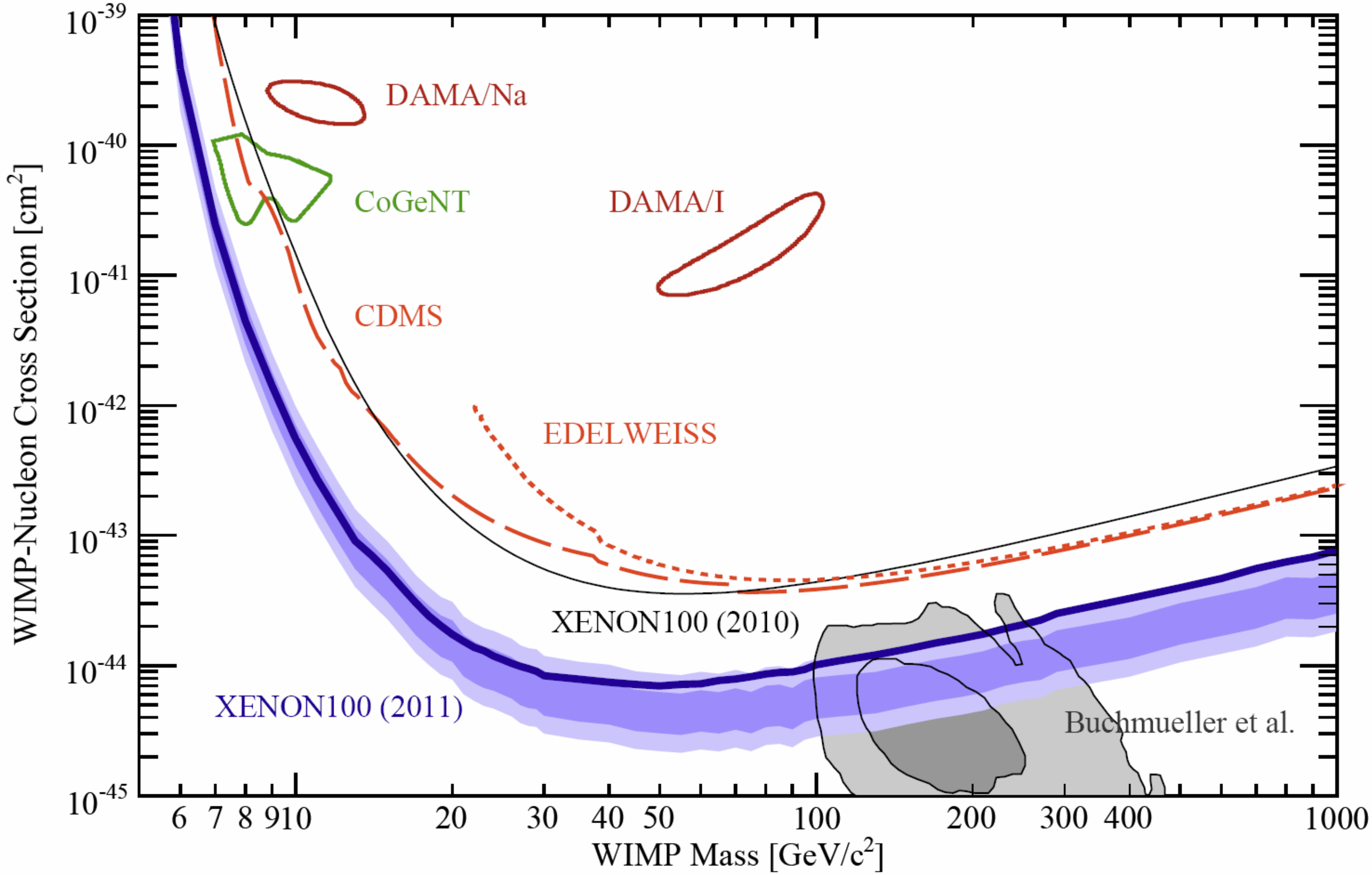
Experiment: recoil energy

Astrophysics: DM velocity distribution

Nuclear physics: form factor

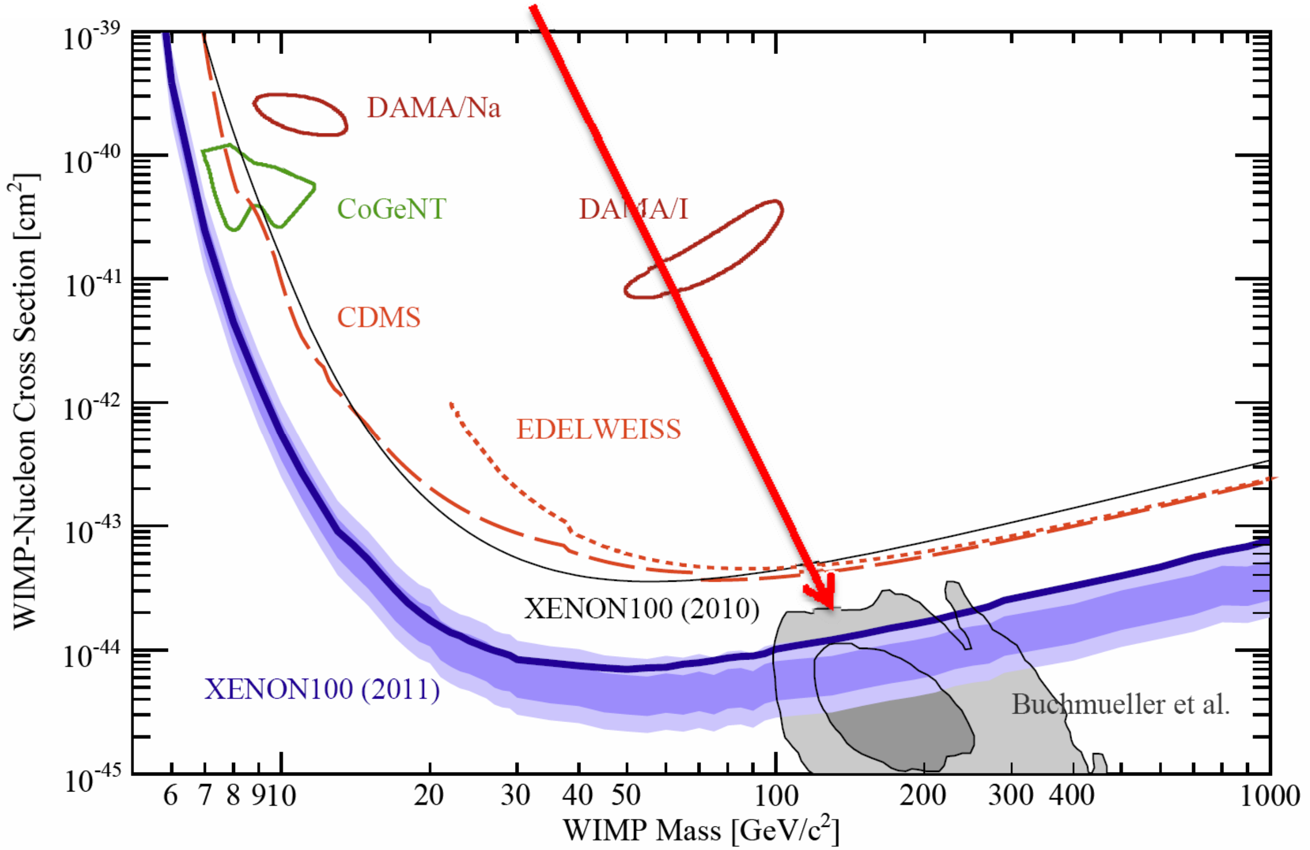
- Results are typically reported assuming $f_p = f_n$, so $\sigma_A \sim A^2$, and scaled to a single nucleon

SPIN-INDEPENDENT: CURRENT STATUS



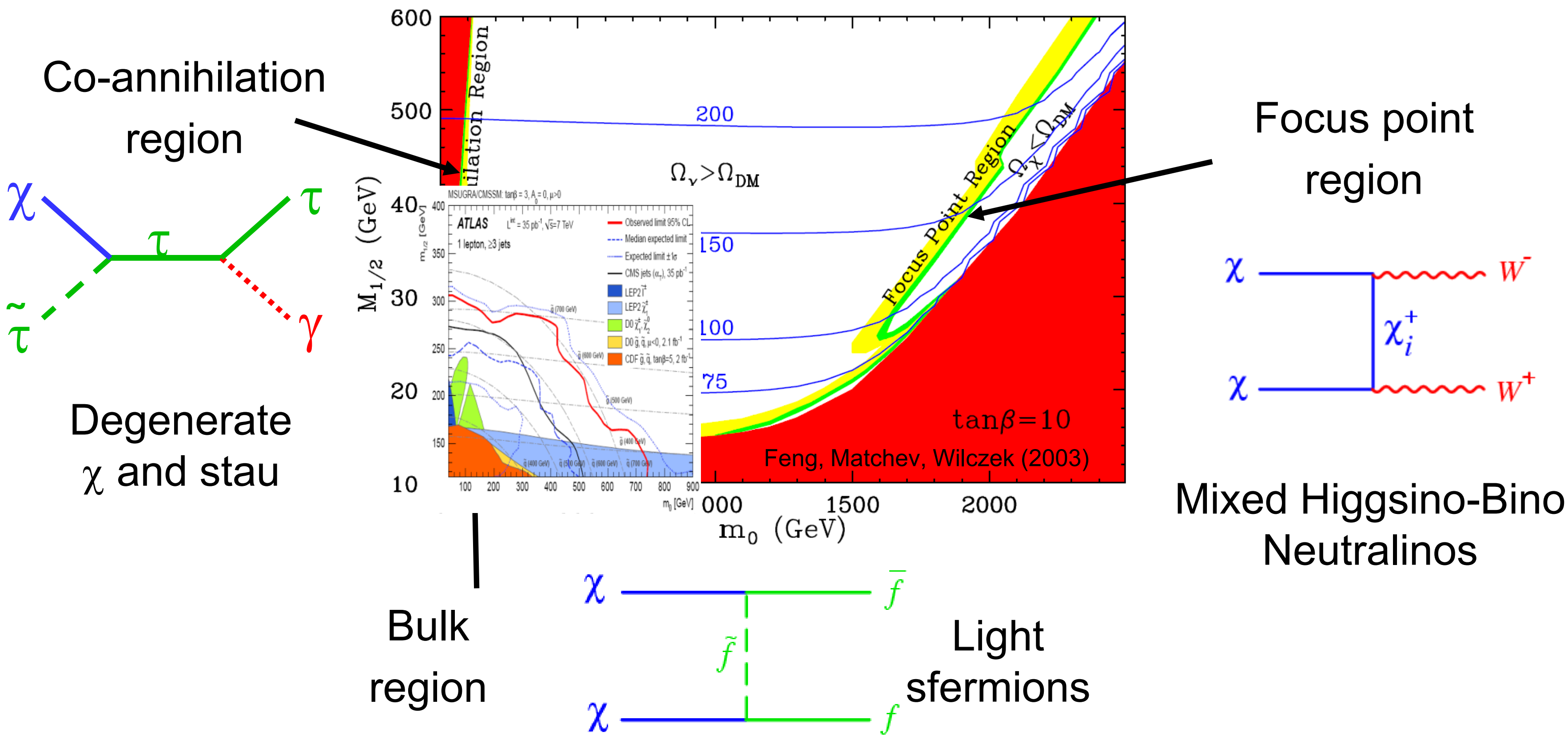
LOW CROSS SECTION FRONTIER

- The excitement stems from the confrontation of experiment with theory
- What are the shaded regions?



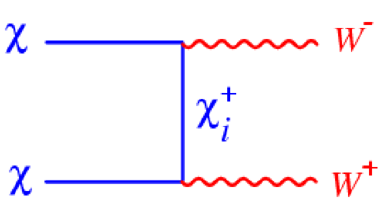
SUPERSYMMETRY

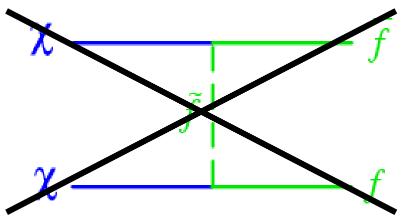
- Ad hoc theoretical assumptions → 4+1 parameters
- Assume Ω_x = 0.23 → require efficient annihilation channel
- Now constrained by LHC searches

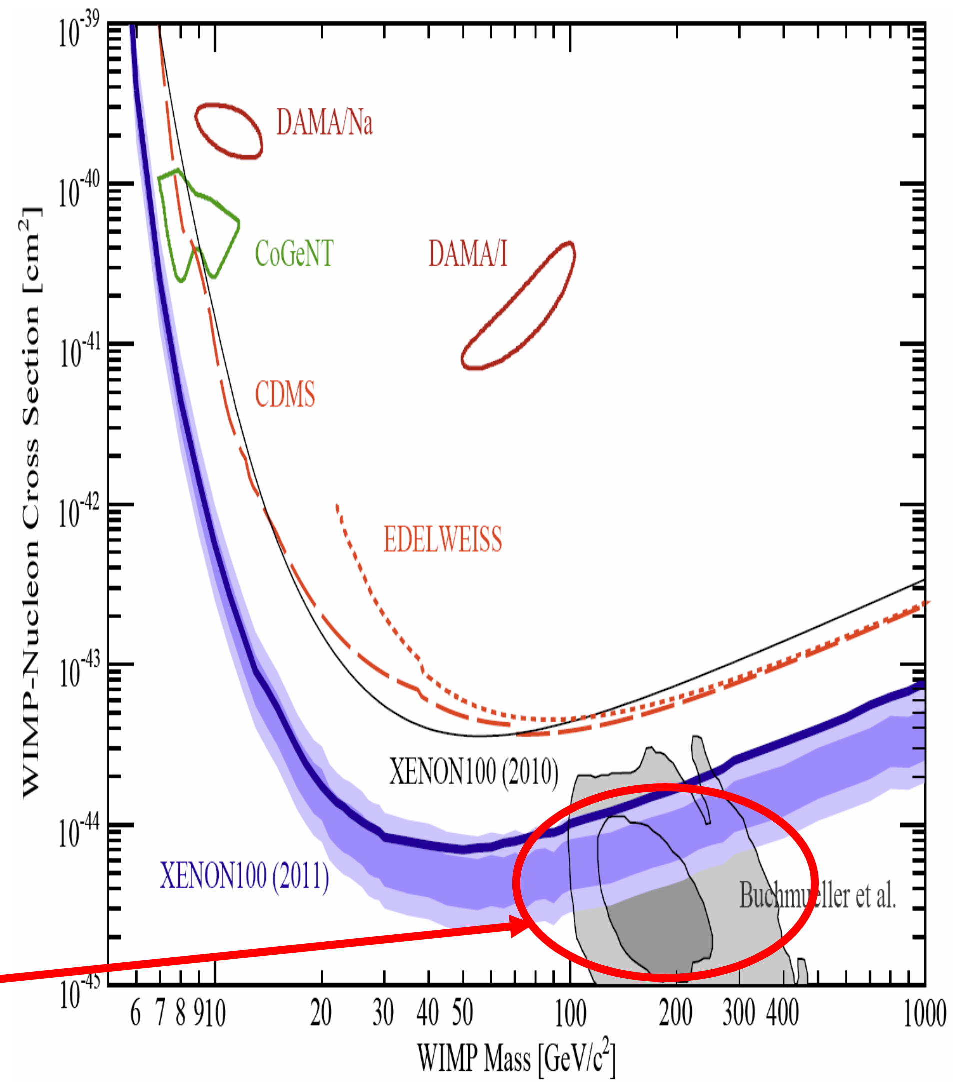


DIRECT DETECTION IMPLICATIONS

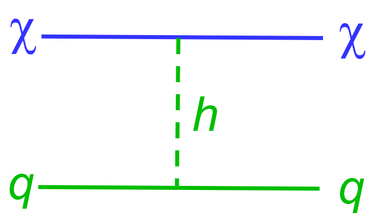
- The LHC is eliminating one option. If $M_2 > M_1$, no co-annihilation, resonances, Ω fixes the DM's coupling to Ws







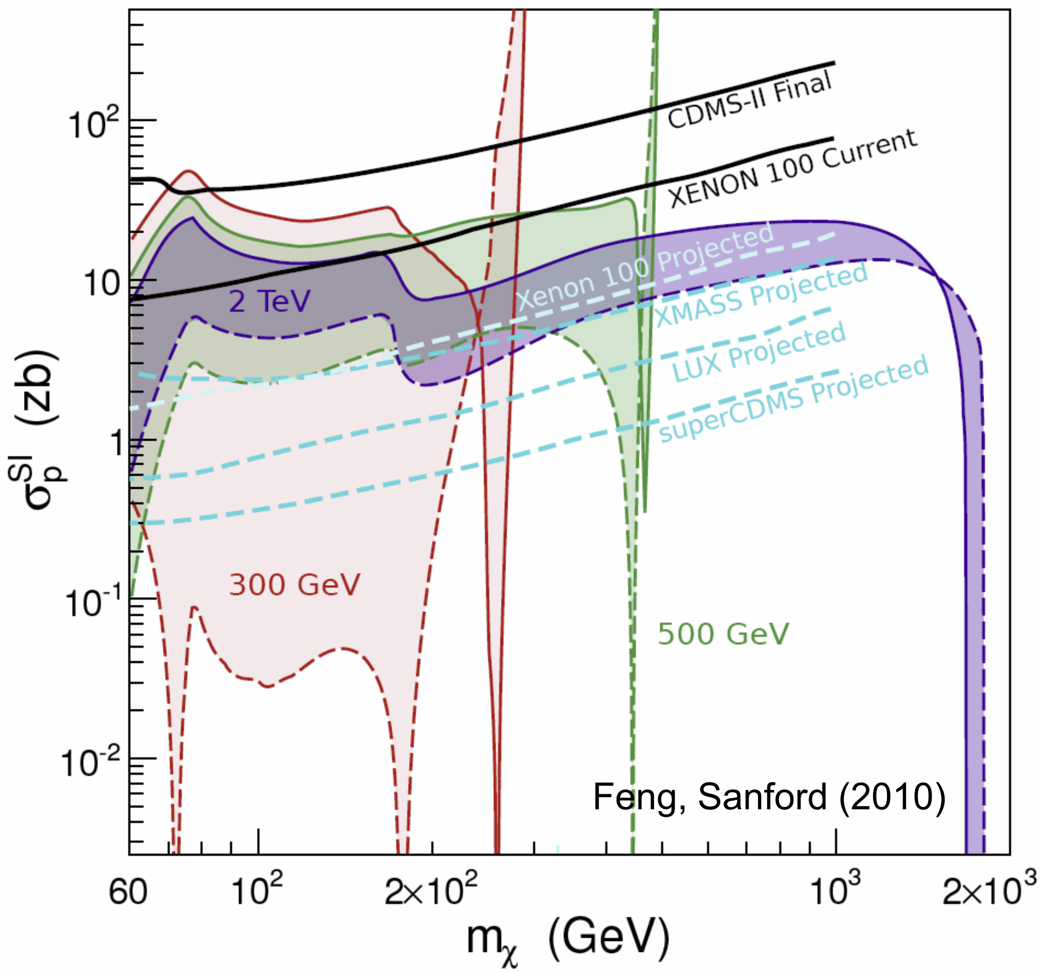
- But this also fixes the DM's coupling to the Higgs boson



- Since the Higgs mass is almost fixed, predictions collapse to a small region with σ ~ 1-10 zb

MODEL INDEPENDENCE

- Can relax unification assumptions
- There are exceptions from accidental mass degeneracies, leading to co-annihilation and resonances, but the generic conclusions are surprisingly robust
- The bottom line: the LHC is starting to eliminate models with poor direct detection prospects, but those with bright prospects remain



STATUS OF NEUTRALINO DM

~10 zeptobarn

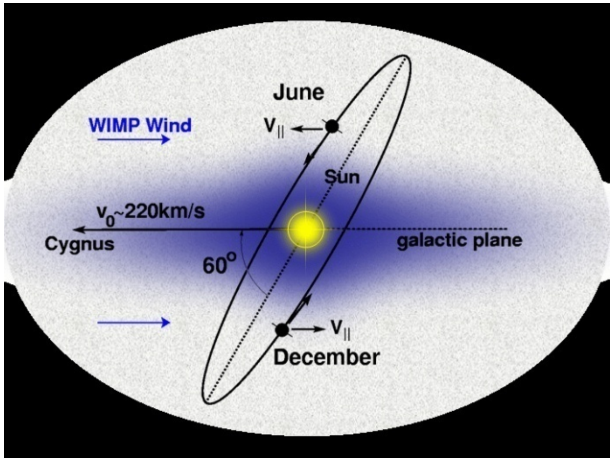
~zeptobarn

No signal

Signal

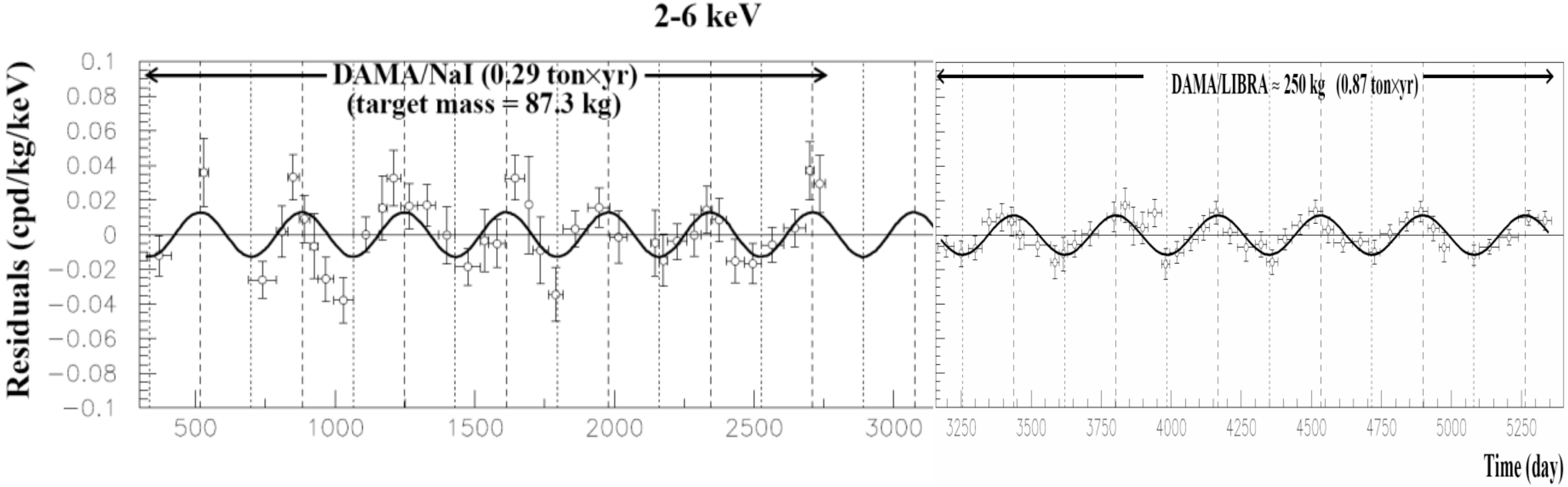
LOW MASS FRONTIER

Collision rate should change as Earth's velocity adds constructively/destructively with the Sun's → annual modulation



Drukier, Freese, Spergel (1986)

DAMA/LIBRA: 8.9σ signal with T ≈ 1 year, maximum ≈ June 2

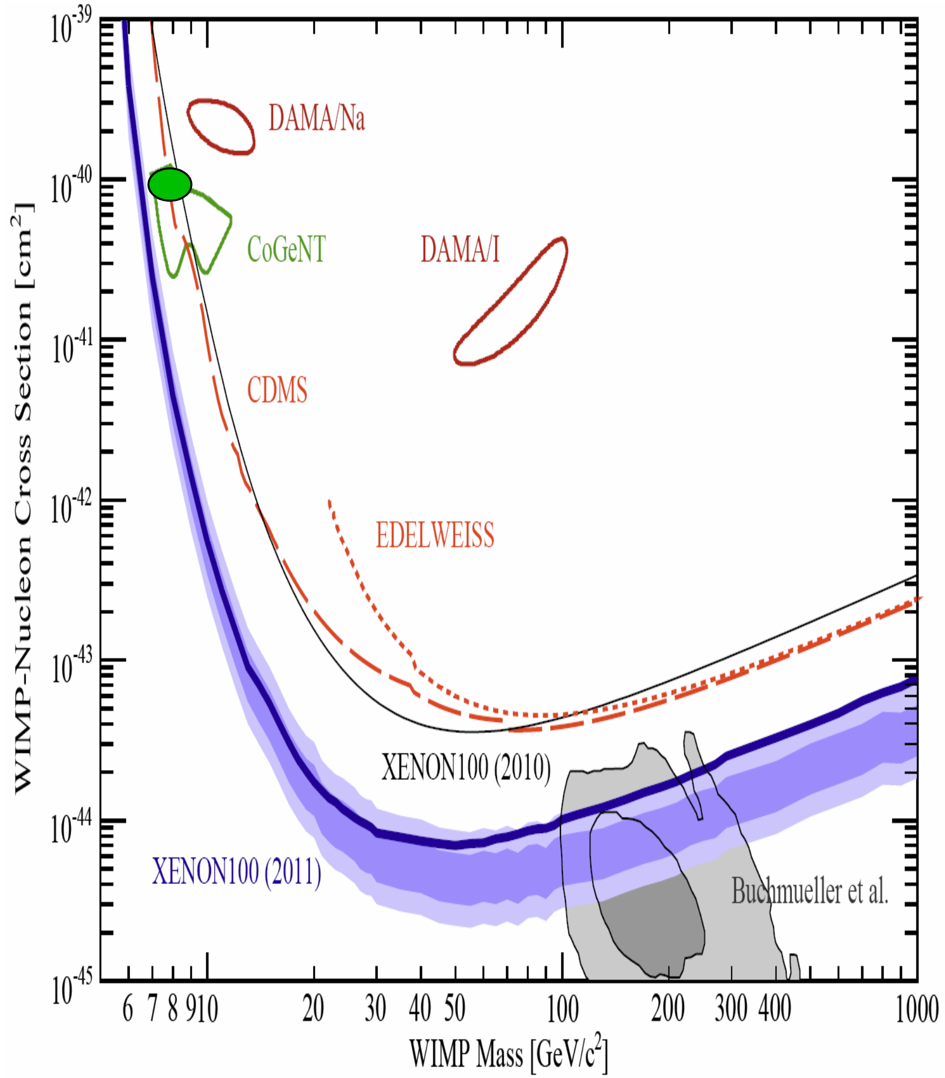


DAMA/LIBRA (2010)

CURRENT STATUS

- DAMA is now supplemented by CoGeNT
- Most recently, the CoGeNT favored region has been further constrained, preliminary 2.8σ annual modulation signal presented
- Theoretical puzzles
  - Low mass and high σ
  - DAMA ≠ CoGeNT
  - Excluded by XENON, CDMS
- Many proposed explanations

Hooper, Collar, Hall, McKinsey (2010)
Fitzgerald, Zurek (2010)
Fox, Liu, Weiner (2010)
…



ISOSPIN-VIOLATING DARK MATTER

- Recall that DM scattering off nuclei is
  - $\sigma_A \sim [\, f_p Z + f_n (A-Z) \,]^2$
- Typically assume
  - $f_n = f_p$
  - $\sigma_A \sim A^2$
- One simple possibility is to relax this assumption, introduce 1 extra parameter: f_n / f_p

Giuliani (2005)
Chang, Liu, Pierce, Weiner, Yavin (2010)
Feng, Kumar, Marfatia, Sanford (2011)

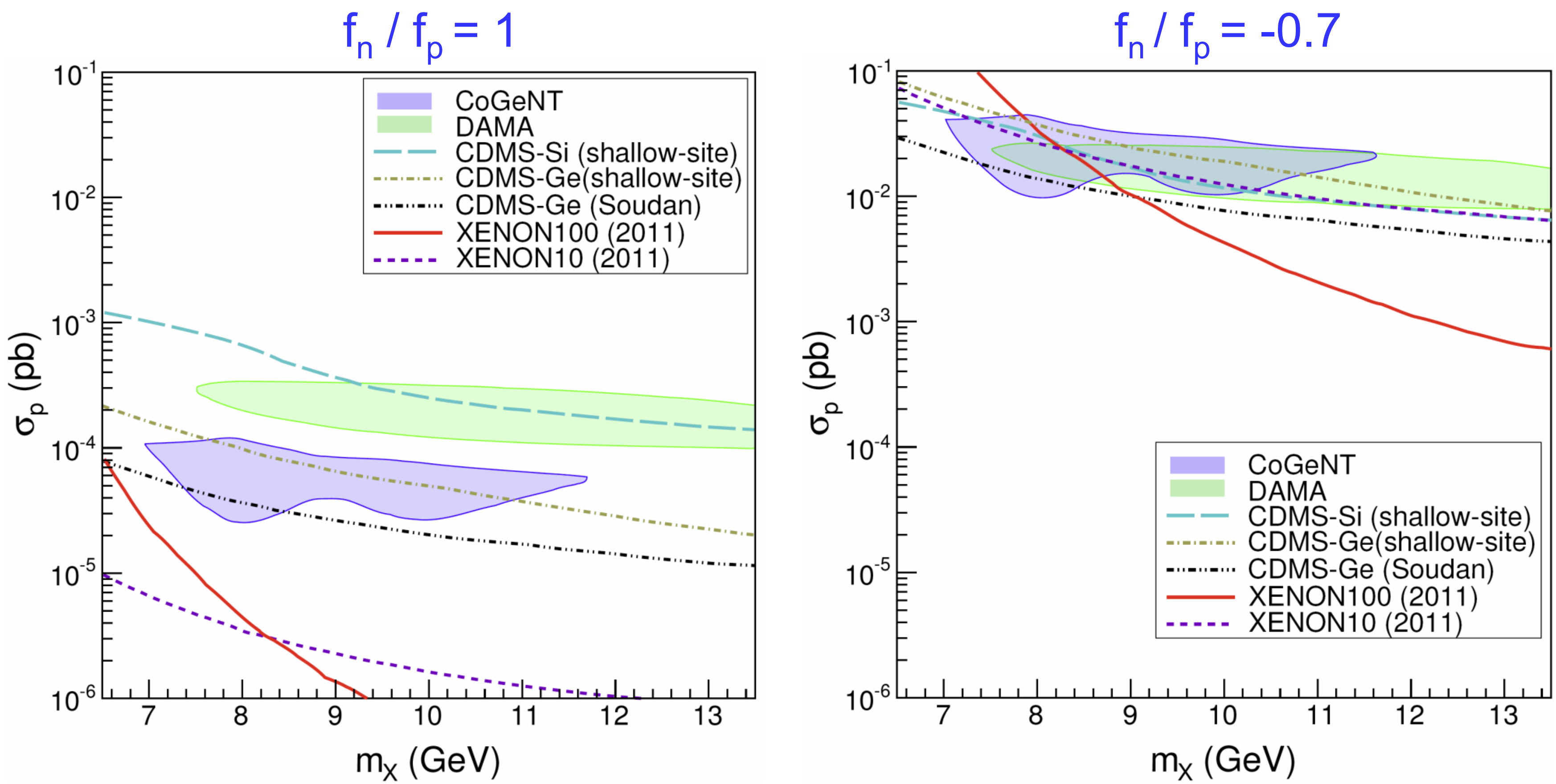
- Can decouple any given isotope by a suitable choice of f_n / f_p .
- Crucially important to account for isotope distributions

TABLE II. A_i for isotopes and their fractional number abundances η_i in percent for all isotopes with $\eta_i > 1\%$.

Xe	Ge	Si	Ca	W	Ne
128 (1.9)	70 (21.2)	28 (92.2)	40 (96.9)	182 (26.5)	20 (90.5)
129 (26.4)	72 (27.7)	29 (4.7)	44 (2.1)	183 (14.3)	22 (9.3)
130 (4.1)	73 (7.7)	30 (3.1)		184 (30.6)	
131 (21.2)	74 (35.9)			186 (28.4)	
132 (26.9)	76 (7.4)				
134 (10.4)					
136 (8.9)					

Feng, Kumar, Marfatia, Sanford (2011)

RECONCILING XENON/DAMA/COGENT



Feng, Kumar, Marfatia, Sanford (2011)

IMPLICATIONS OF THE IVDM RESOLUTION

- IVDM cannot resolve disagreements between identical targets; if correct, IVDM implies CDMS and CoGeNT are marginally consistent

- Predictions for all other elements are fixed. For example, as conventionally plotted (assuming $f_p = f_n$),

$$\sigma_p(\text{oxygen, carbon}) \approx 8.4\ \sigma_p(\text{germanium})$$
$$\sigma_p(\text{flourine}) \approx 4.2\ \sigma_p(\text{germanium})$$

- XENON will see a signal soon; CRESST may have already

- Reverses $\sigma \sim A^2$ conventional wisdom. Need more than one target material and more than one experiment per material

INDIRECT DETECTION

Dark Matter Madlibs!

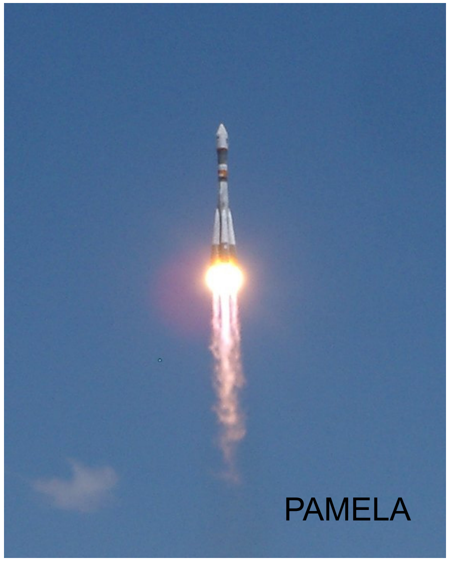
Dark matter annihilates in ____________________ to
a place

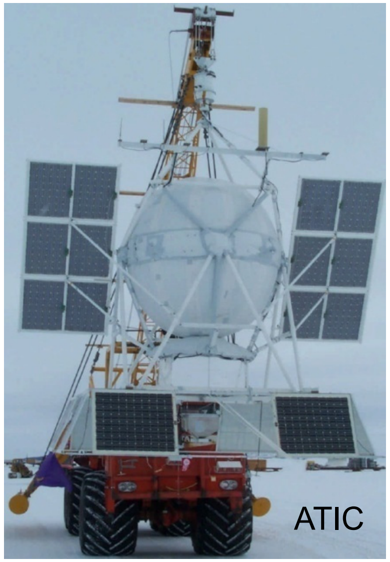
____________ , which are detected by ________________ .
particles an experiment

INDIRECT DETECTION

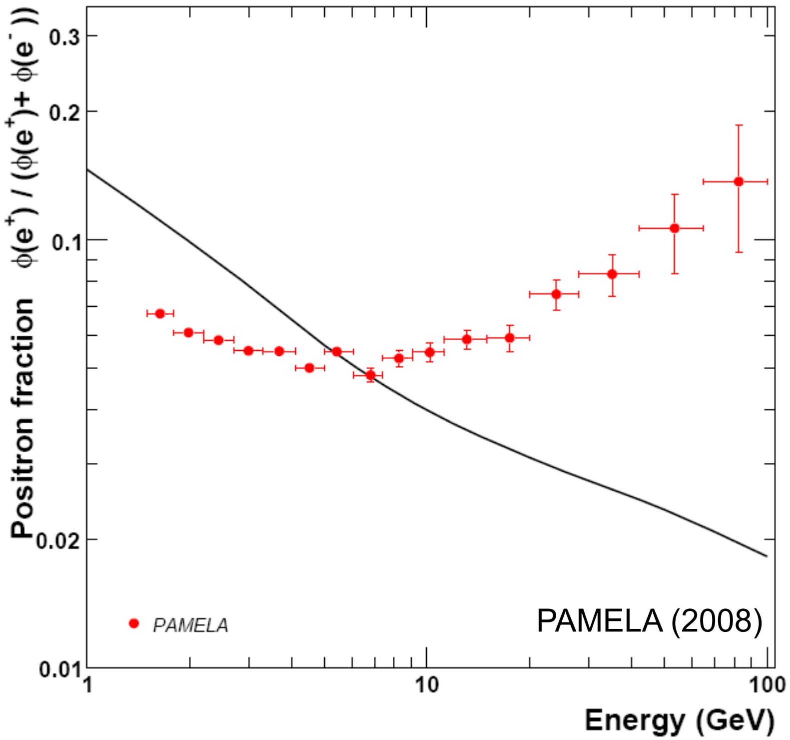
Dark Matter annihilates in ___the halo___ to
a place

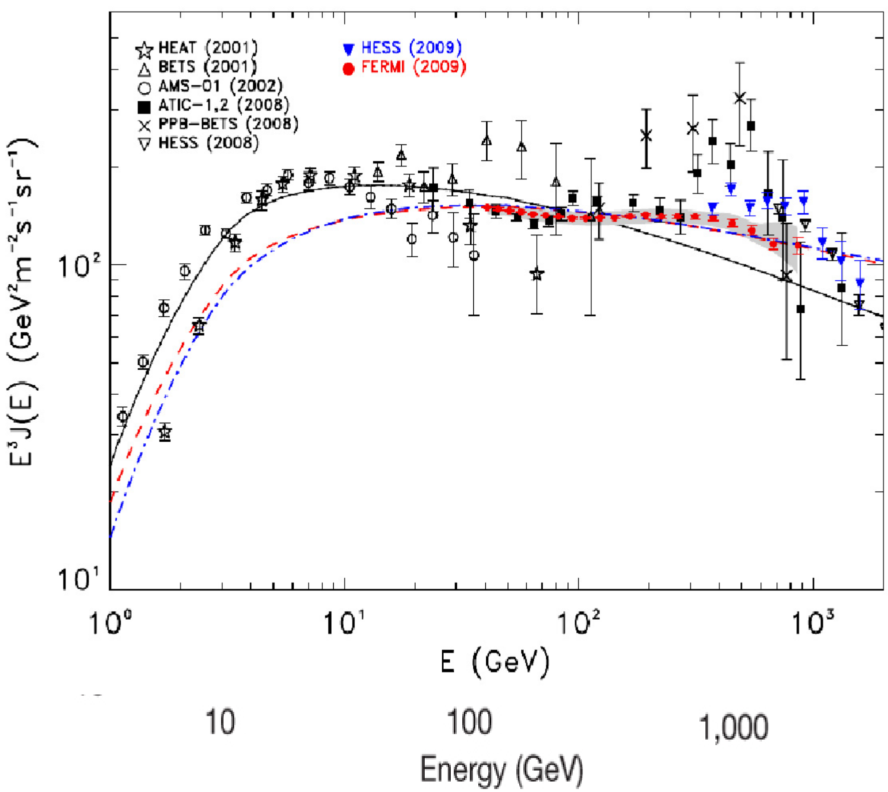
___positrons___ , which are detected by ___PAMELA/ATIC/Fermi…___.
some particles an experiment





CURRENT STATUS





Solid lines are the astrophysical bkgd from GALPROP (Moskalenko, Strong)

ARE THESE DARK MATTER?

- Energy spectrum shape consistent with WIMP dark matter candidates

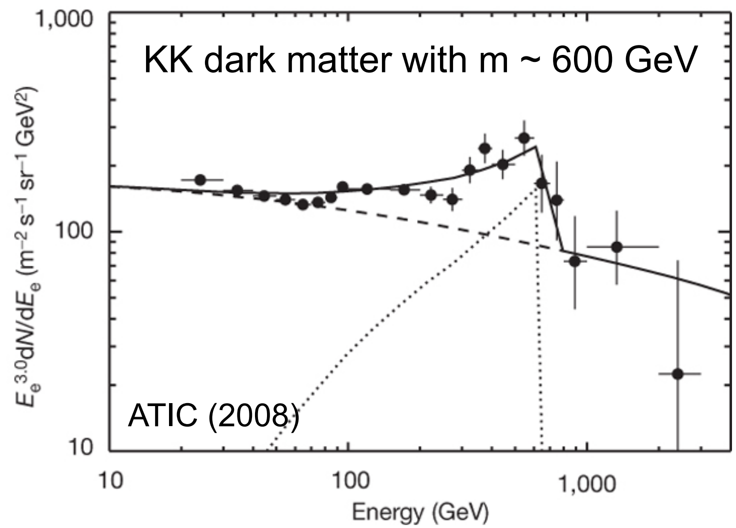
$$\frac{d\Phi_{e^+}}{d\Omega dE} = \frac{\rho_\chi^2}{m_\chi^2} \sum_i \sigma_i v B^i_{e^+} \int dE_0 \, f_i(E_0) \, G(E_0, E)$$

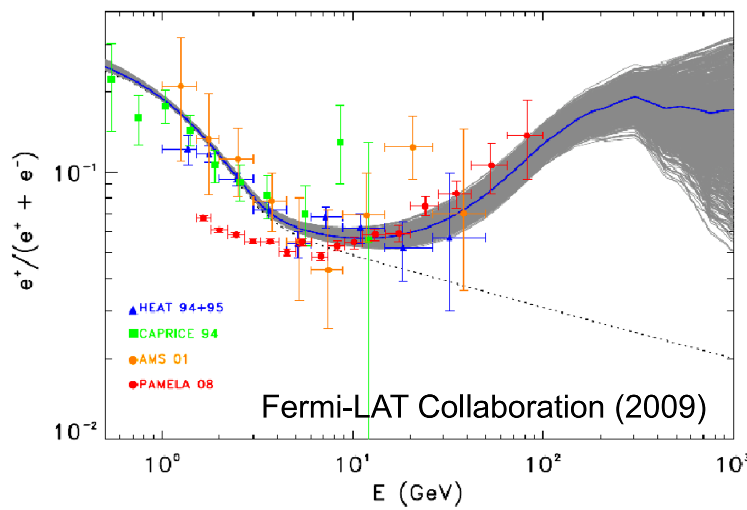
- Flux is a factor of 100-1000 too big for a thermal relic; requires
  - Enhancement from particle physics
  - Alternative production mechanism

Cirelli, Kadastik, Raidal, Strumia (2008)
Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)
Feldman, Liu, Nath (2008); Ibe, Murayama, Yanagida (2008)
Guo, Wu (2009); Arvanitaki et al. (2008)

- Pulsars can explain PAMELA

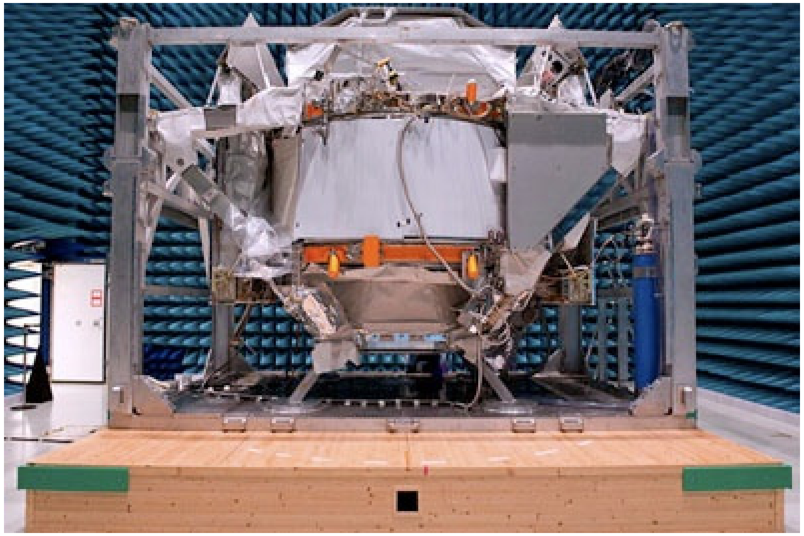
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
Yuksel, Kistler, Stanev (2008); Profumo (2008)
Fermi-LAT Collaboration (2009)

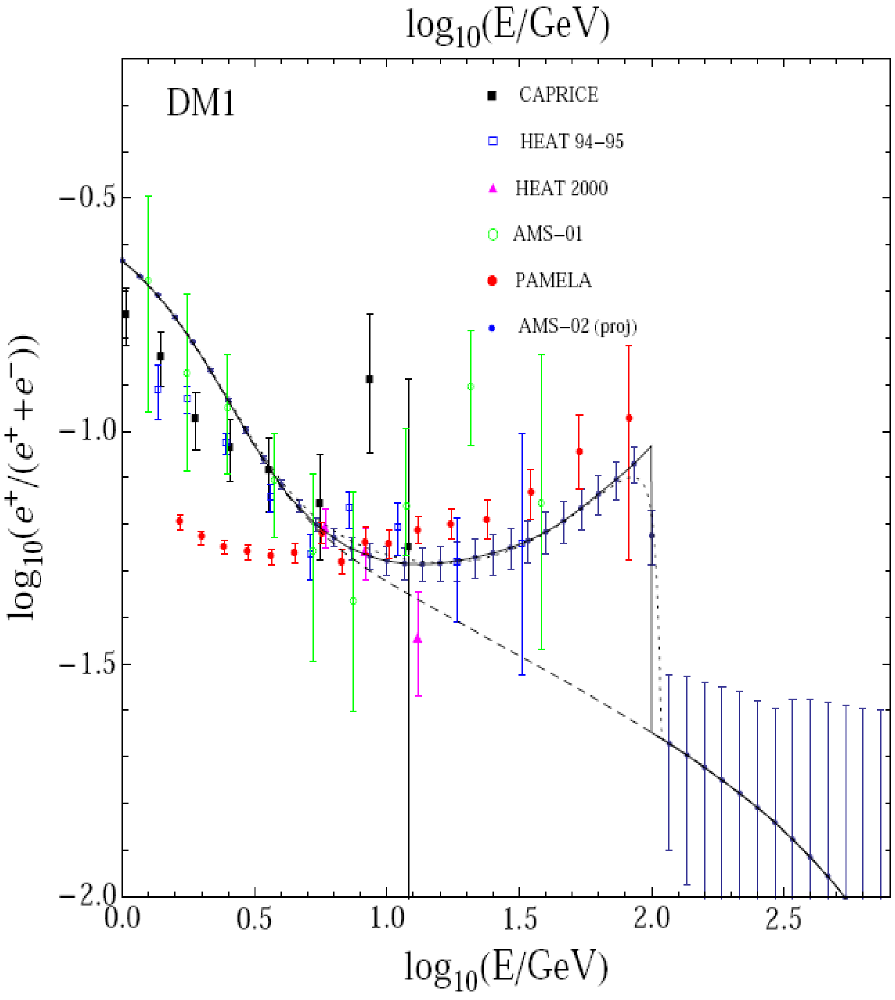




ALPHA MAGNETIC SPECTROMETER

- Carried by the Space Shuttle on 16 May 2011 to the International Space Station
- Can AMS-02 disentangle dark matter from pulsars?

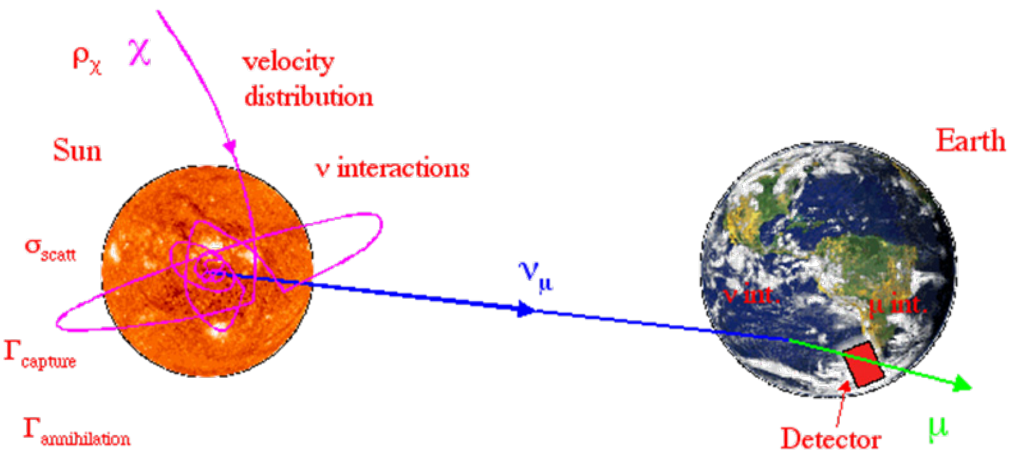


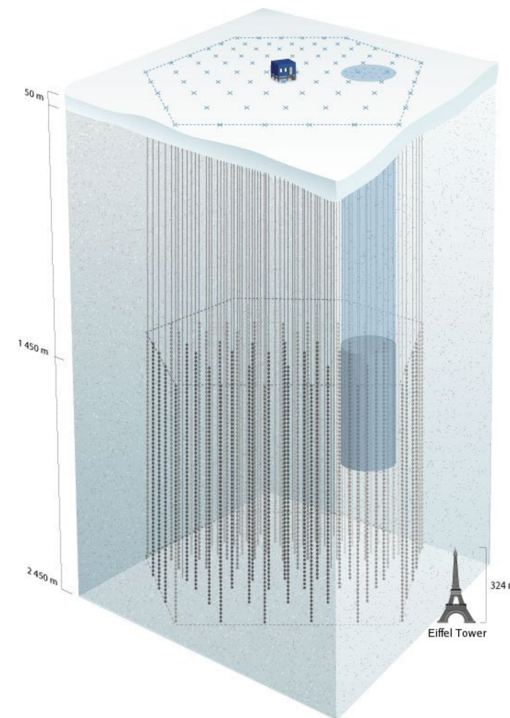


Pato, Lattanzi, Bertone (2010)

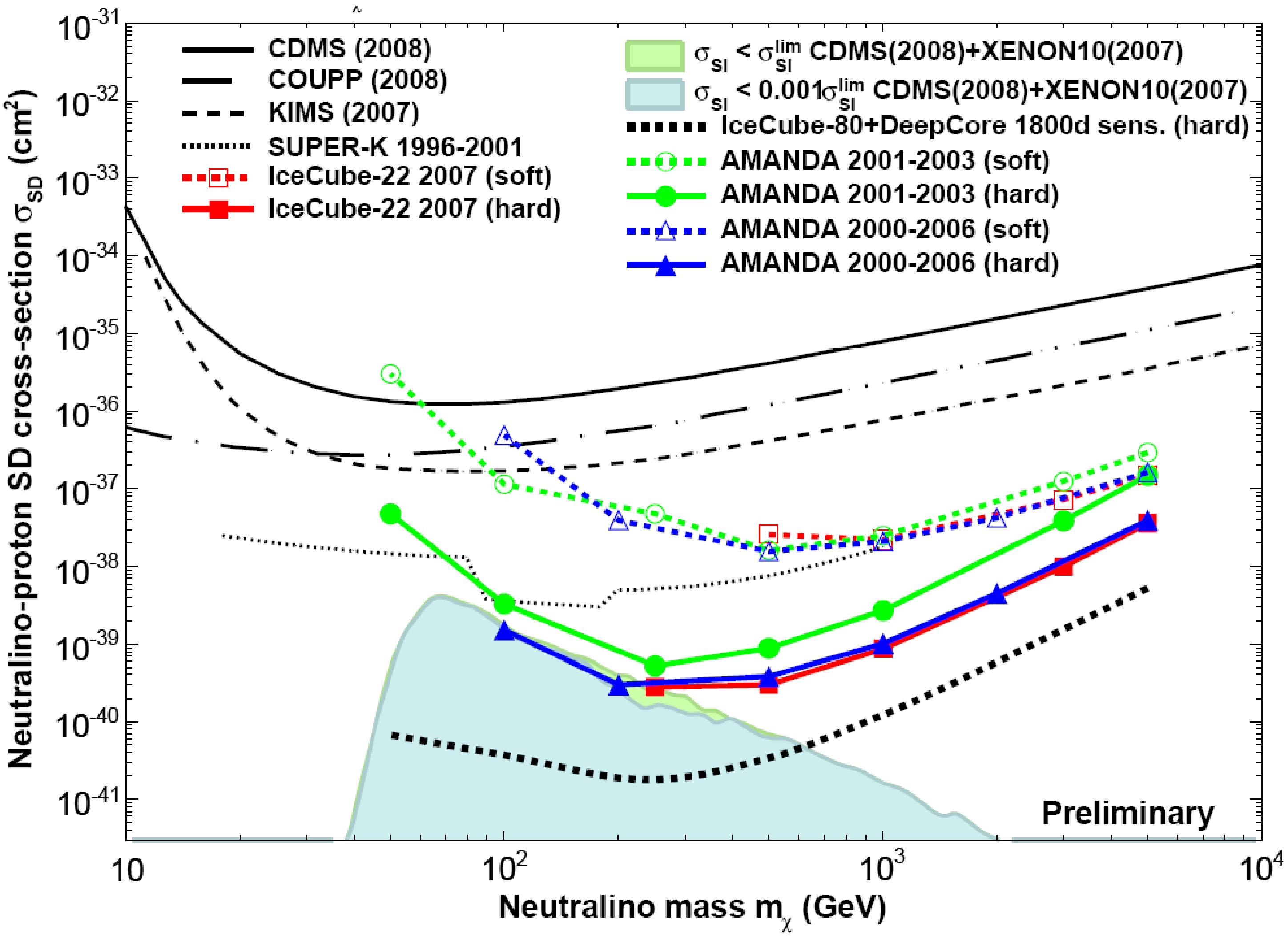
Dark Matter annihilates in __the center of the Sun__ to
a place

neutrinos , which are detected by _____IceCube_____ .
some particles an experiment





SPIN-DEPENDENT SCATTERING



Dark Matter annihilates in __the galactic center__ to
a place

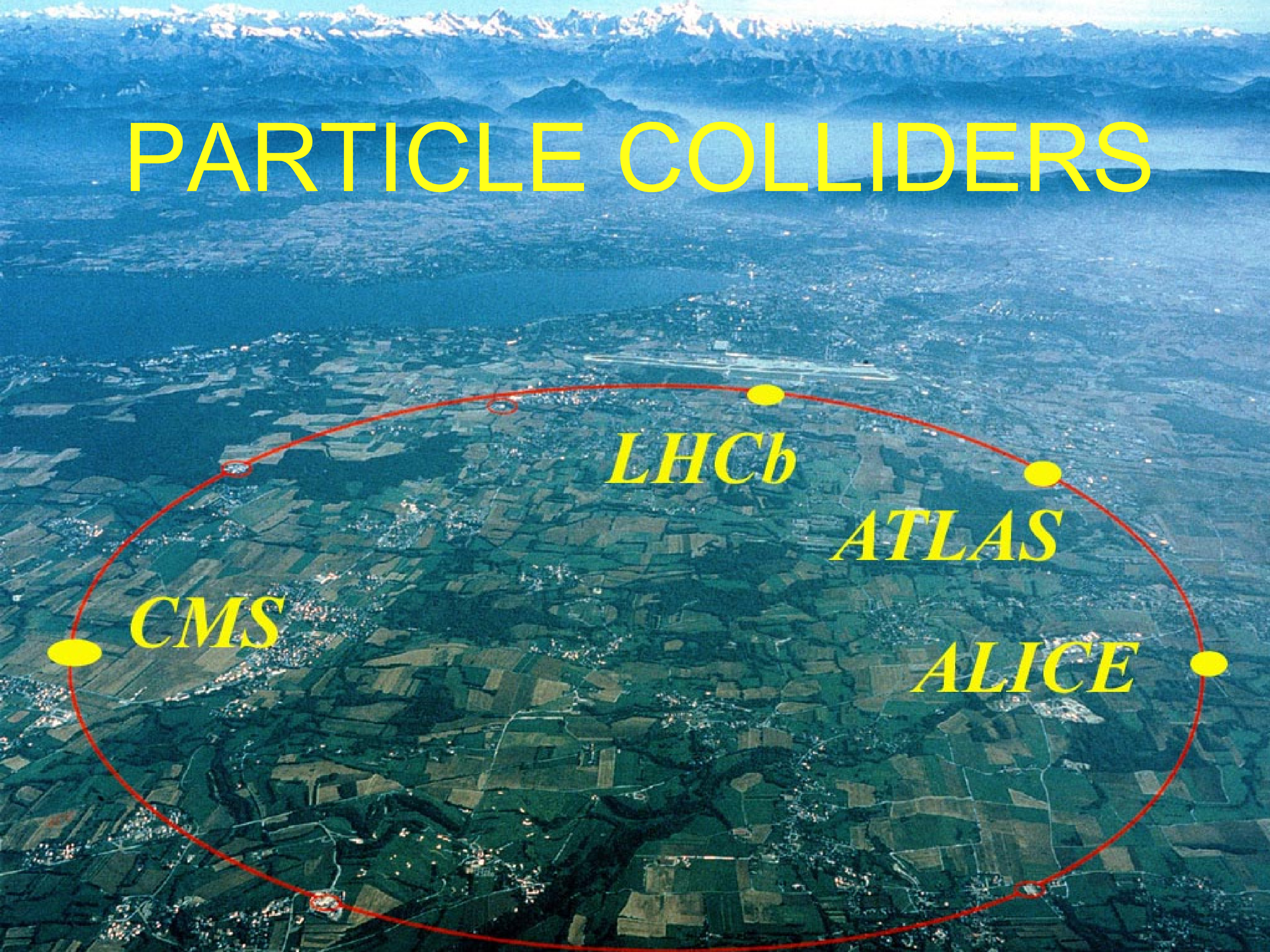
__photons__ , which are detected by __Fermi, VERITAS, …__ .
some particles an experiment

- Lines from XX → γγ, γZ
- Continuum from XX → ff → γ

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

Halo profiles are poorly understood near the galactic center

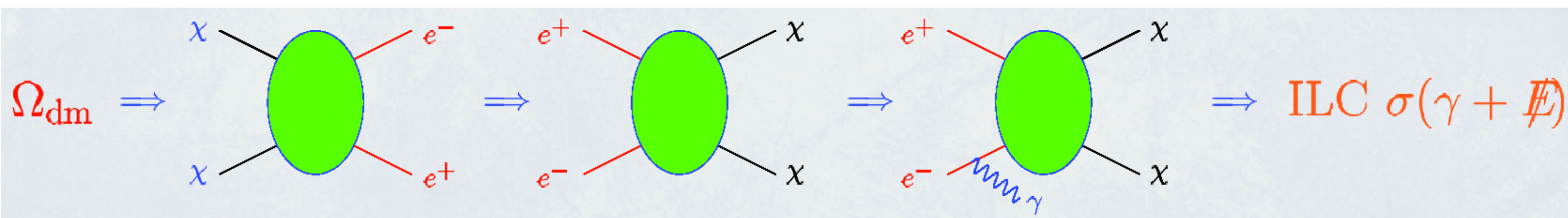
PARTICLE COLLIDERS



DIRECT PRODUCTION AT COLLIDERS

- Thermal relic WIMPs annihilate to SM particles, and so should be produced directly at colliders

- Pair production is invisible, so consider photon radiation



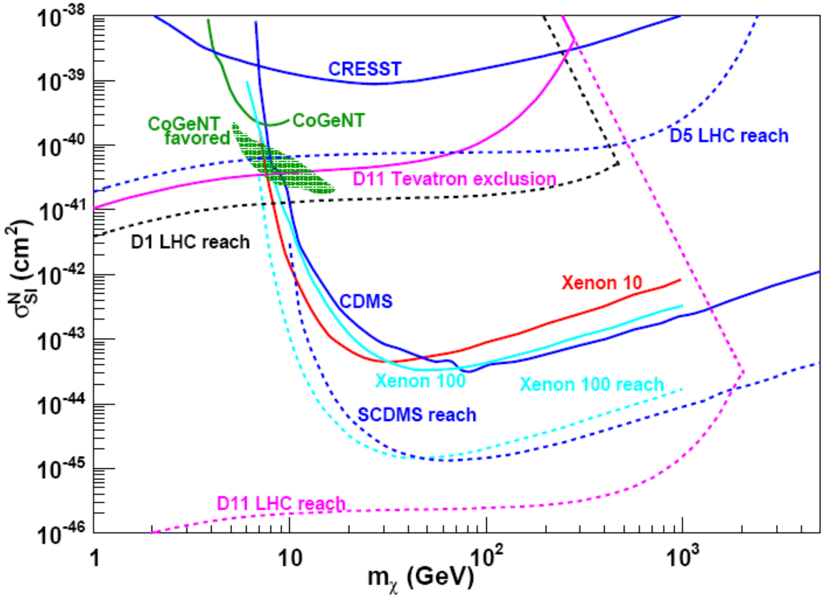
- Also mono-jets, mono-photons at Tevatron and LHC

Birkedal, Matchev, Perelstein (2004); Feng, Su, Takayama (2005)

Konar, Kong, Matchev, Perelstein (2009)

WIMP EFFECTIVE THEORY

- This idea has recently been extended and studied systematically
- Assume WIMPs are light, integrate out all other particles, yielding a list of effective operators (motivated by DAMA, CoGeNT, for example)



Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)

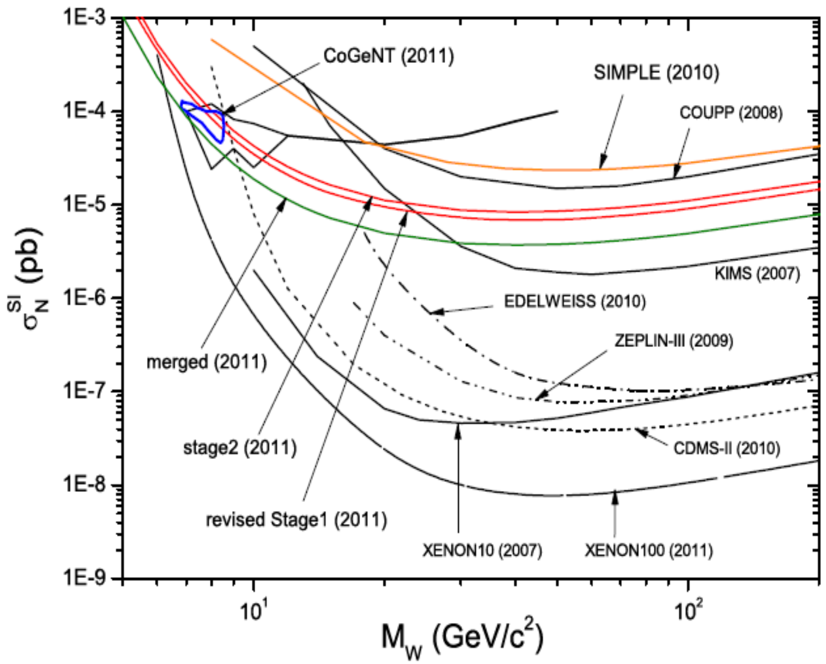
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

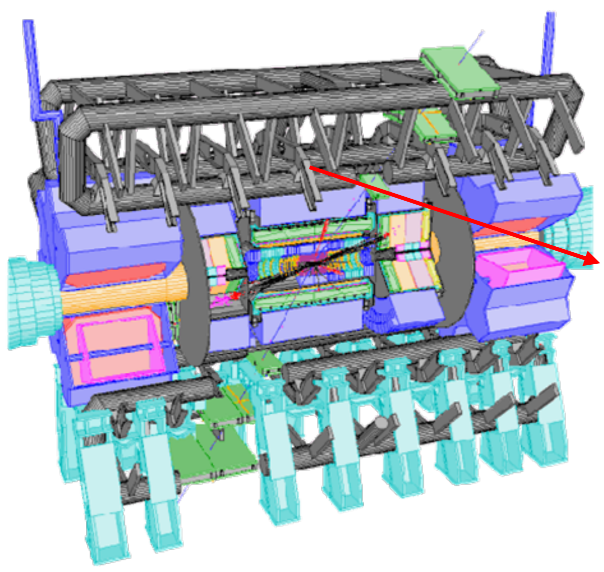
PRECISION DM AT COLLIDERS

If there is a signal, what do we learn?

- Cosmology can't discover SUSY

- Particle colliders can't discover DM

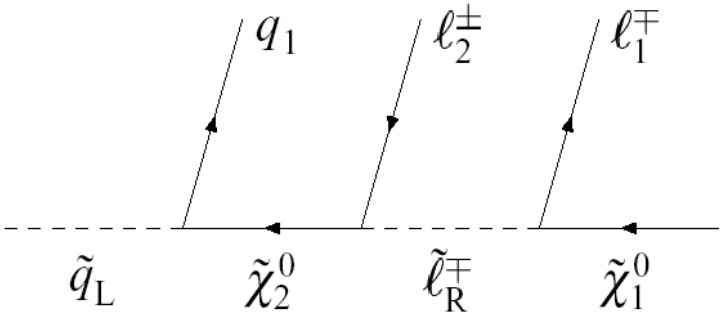


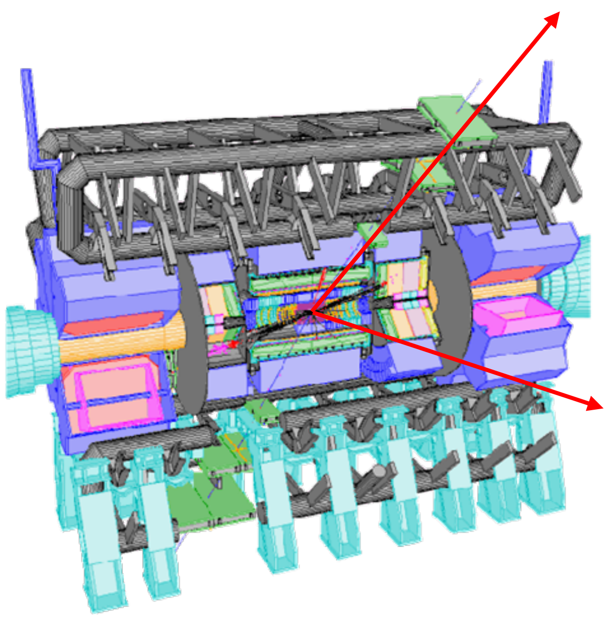


Lifetime > 10^{-7} s → 10^{17} s ?

DARK MATTER AT THE LHC

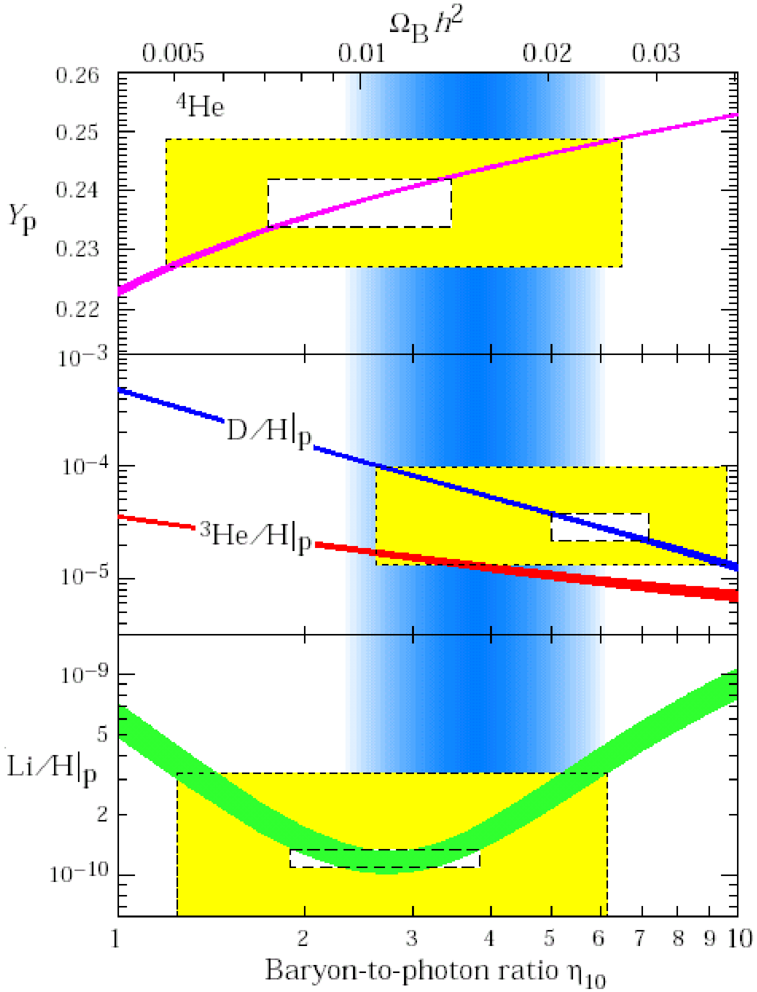
- What LHC actually sees:
  - E.g., $\tilde{q}\tilde{q}$ pair production
  - Each $\tilde{q}$ → neutralino χ
  - 2 χ's escape detector
  - missing momentum





- This is not the discovery of dark matter
  - Lifetime > 10^{-7} s → 10^{17} s?

THE EXAMPLE OF BBN

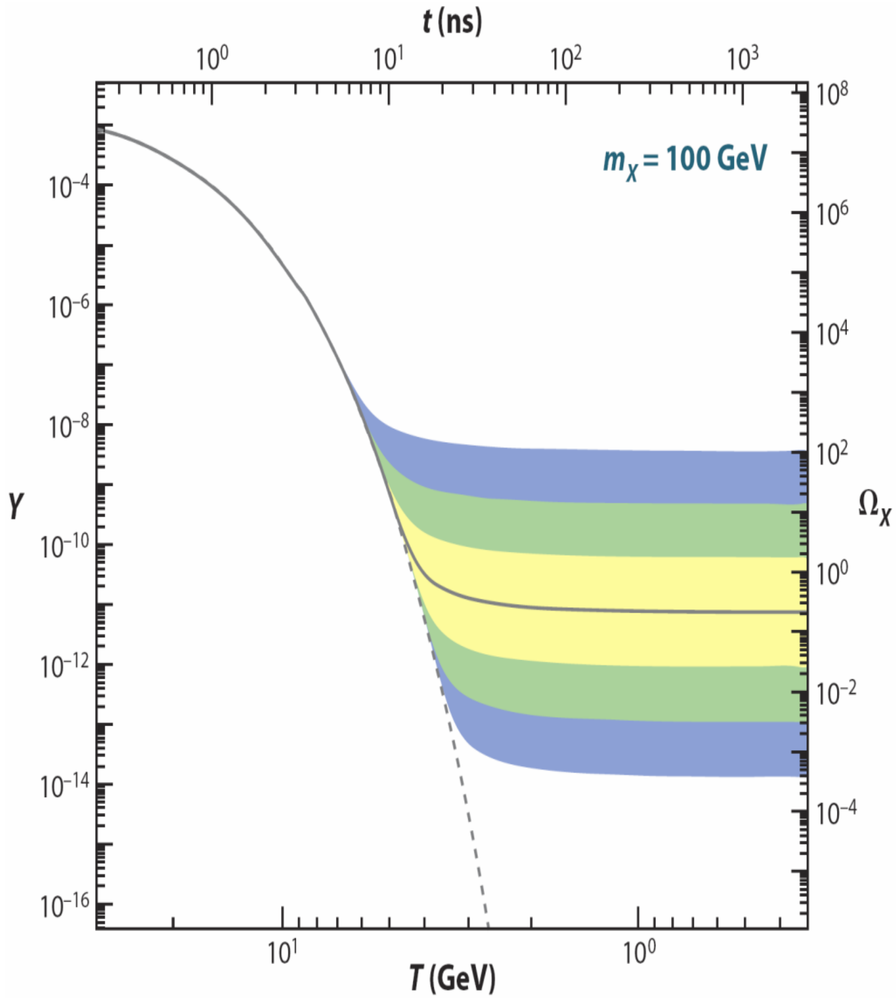


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

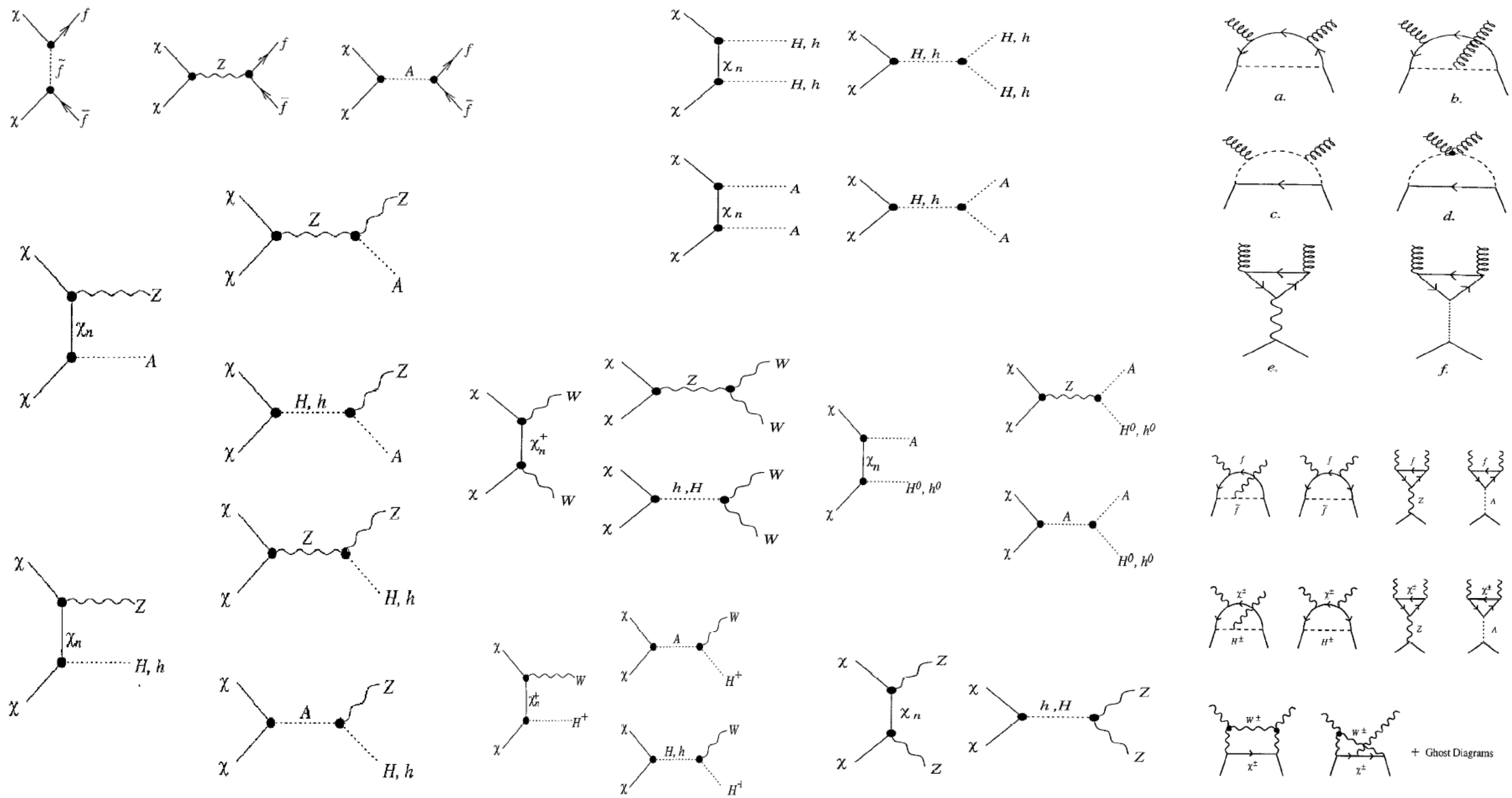
  t ~ 1 sec

DARK MATTER ANALOGUE



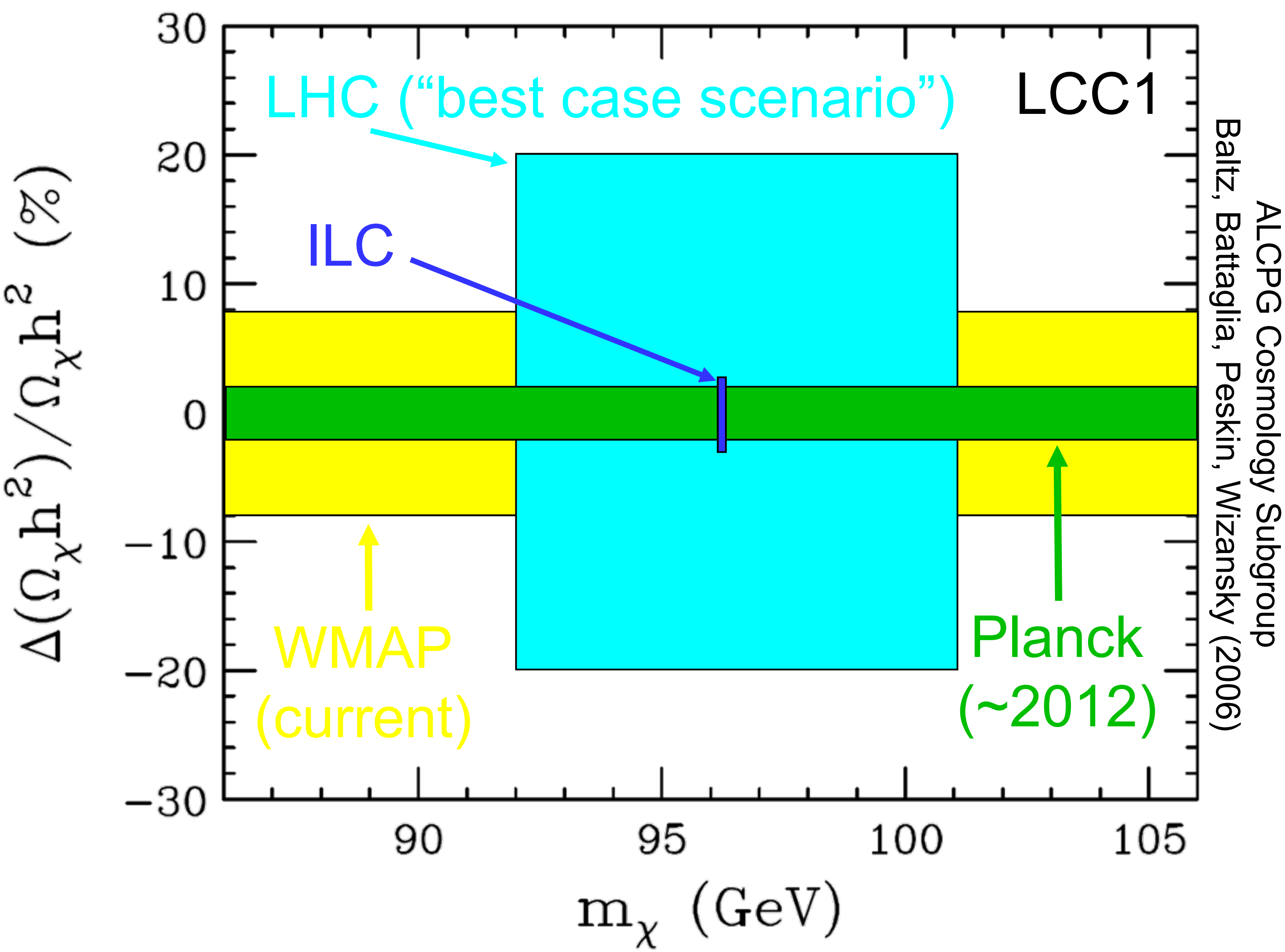
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

WIMP ANNIHILATION PROCESSES



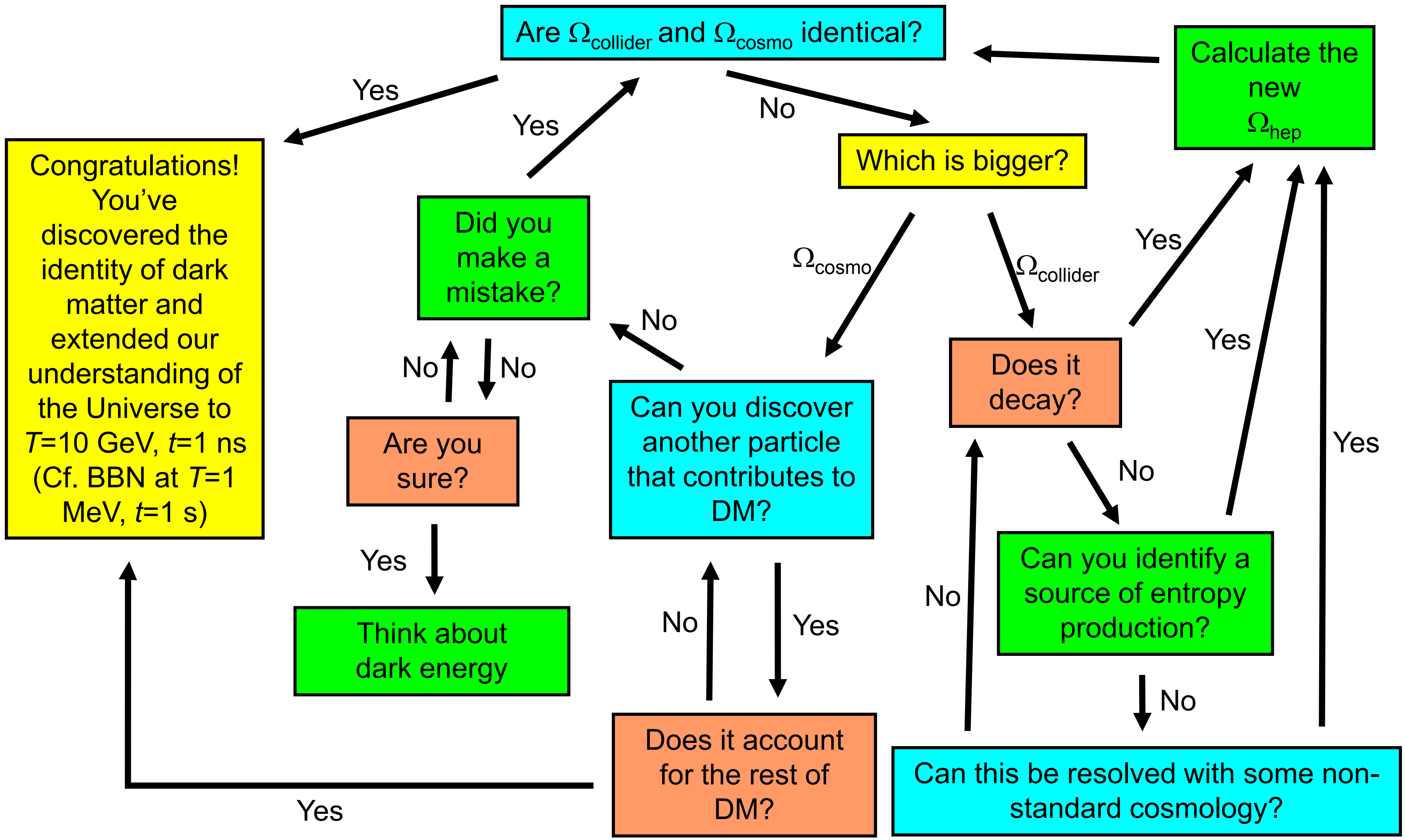
Jungman, Kamionkowski, Griest (1995)

RELIC DENSITY DETERMINATIONS



% level comparison of predicted $\Omega_{collider}$ with observed Ω_{cosmo}

IDENTIFYING DARK MATTER



LECTURE 2 SUMMARY

- Thermal relic WIMPs can be detected directly, indirectly, and at colliders, and the thermal relic density implies significant rates
- There are currently tantalizing anomalies
- Definitive dark matter detection and understanding will require signals in several types of experiments

OUTLINE

LECTURE 1

Essential Cosmology, Dark Energy, WIMP Miracle

LECTURE 2

WIMP Detection, WIMPs at Colliders

LECTURE 3

Other Terascale Dark Matter Possibilities

NEW DISSERTATION AWARD IN THEORETICAL PARTICLE PHYSICS

- Established in 2011 by the APS's Division of Particles and Fields
- The Award recognizes exceptional young scientists who have performed original doctoral thesis work of outstanding scientific quality and achievement in the area of theoretical particle physics. The annual Award consists of $1,500, a certificate citing the accomplishments of the recipient, and an allowance of up to $1,000 for travel to attend a meeting of the Division of Particles and Fields (DPF) or APS, where the Award will be presented.
- Nominations of 2011 PhDs due 1 October 2011. Questions? See http://www.aps.org/programs/honors/dissertation/particle.cfm or contact Vernon Barger, Michael Dine, Jonathan Feng, Ben Grinstein (chair), JoAnne Hewett (2011 Selection Committee)

MANY INTERESTING QUESTIONS AND TOPICS

- What about late decaying dark matter?
- What is warm dark matter?
- What about gravitinos, axinos, etc.?
- The thermal relic density only constrains one combination of coupling and mass. Why focus on WIMPs only?
- What are the most stringent bounds on dark matter self-interactions?
- What are the constraints on charged stable particles from sea water?
- What is your favorite dark matter candidate?
- Shouldn't we be working on LHC physics?
- …

GRAVITINO DARK MATTER

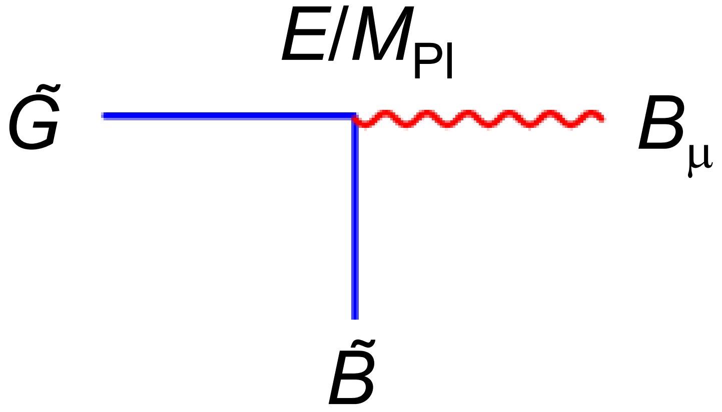
- SUSY: graviton G → gravitino $\tilde{G}$, spin 3/2
- Mass $m_{\tilde{G}} \sim F/M_{Pl}$
  - Ultra-light (GMSB): $F \sim (100\ \text{TeV})^2$, $m_{\tilde{G}} \sim$ eV
  - Light (GMSB): $F \sim (10^7\ \text{GeV})^2$, $m_{\tilde{G}} \sim$ keV
  - Heavy (SUGRA): $F \sim (10^{11}\ \text{GeV})^2$, $m_{\tilde{G}} \sim$ TeV
  - Obese (AMSB): $F \sim (10^{12}\ \text{GeV})^2$, $m_{\tilde{G}} \sim$ 100 TeV
- The gravitino interaction strength ~ 1/F
- A huge range of scenarios, phenomena

HEAVY GRAVITINOS

- $m_{\tilde{G}}$ ~ F/M_{Pl} ~ TeV, same scale as the other superpartners

- $\tilde{G}$ interactions: $$-\frac{i}{8M_{\rm Pl}}\bar{\tilde{G}}_\mu\left[\gamma^\nu,\gamma^\rho\right]\gamma^\mu\tilde{B}F_{\nu\rho}$$

Couplings grow with energy, but are typically extremely weak



OPTION 1: GRAVITINOS FROM REHEATING

- Inflation dilutes relic densities. But at the end of inflation, the Universe reheats and can regenerate particles. Assume the reheat temperature is between the Planck and TeV scales.

- Gravitinos are produced in reheating. What happens?

$$\sigma_{\rm SM} n \sim T \gg H \sim \frac{T^2}{M_{\rm Pl}} \gg \sigma_{\tilde{G}} n \sim \frac{T^3}{M_{\rm Pl}^2}$$

SM interaction rate >> expansion rate >> *G* interaction rate

- Thermal bath of MSSM particles X: occasionally they interact to produce a gravitino: X X → X $\tilde{G}$

GRAVITINO RELIC DENSITY

- The Boltzmann equation:

$$\frac{dn}{dt} = \underbrace{-3Hn}_{\text{Dilution from expansion}} - \langle \sigma v \rangle \left[\underbrace{\cancelto{0}{n^2}}_{f\tilde{G} \to f\bar{f}} - \underbrace{n_{\text{eq}}^2}_{f\bar{f} \to f\tilde{G}} \right]$$

- Change variables: Entropy density s ~ T^3

$$t \to T \qquad n \to Y \equiv \frac{n}{s}$$

- New Boltzmann equation:

$$\frac{dY}{dT} = -\frac{\langle \sigma_{\tilde{G}} v \rangle}{HTs} n^2 \sim \langle \sigma_{\tilde{G}} v \rangle \frac{T^3 T^3}{T^2 T T^3}$$

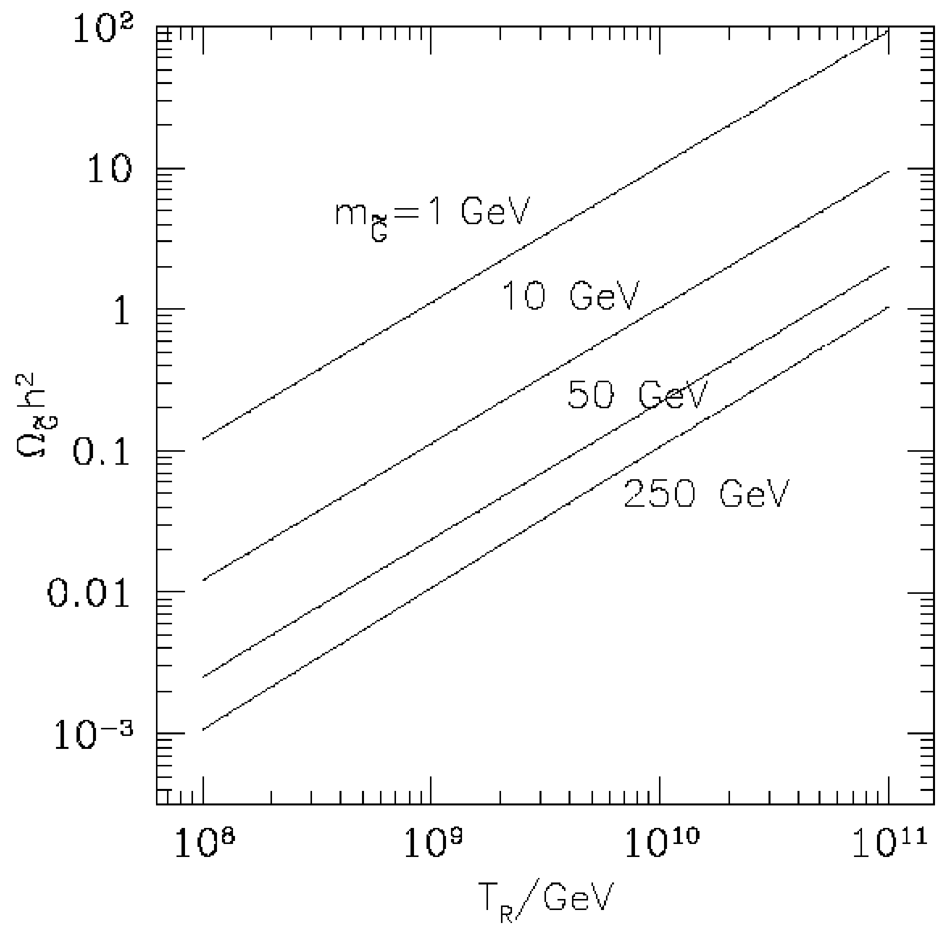
- Simple: *Y* ~ reheat temperature T_{RH}

BOUNDS ON T_{RH}

- $<\sigma v>$ for important production processes:

	process i	$\lvert\mathcal{M}_i\rvert^2/\frac{g^2}{M^2}\left(1+\frac{m_{\tilde g}^2}{3m_{\tilde G}^2}\right)$
A	$g^a + g^b \to \tilde g^c + \tilde G$	$4(s+2t+2\frac{t^2}{s})\lvert f^{abc}\rvert^2$
B	$g^a + \tilde g^b \to g^c + \tilde G$	$-4(t+2s+2\frac{s^2}{t})\lvert f^{abc}\rvert^2$
C	$\tilde q_i + g^a \to q_j + \tilde G$	$2s\lvert T^a_{ji}\rvert^2$
D	$g^a + q_i \to \tilde q_j + \tilde G$	$-2t\lvert T^a_{ji}\rvert^2$
E	$\bar{\tilde q}_i + q_j \to g^a + \tilde G$	$-2t\lvert T^a_{ji}\rvert^2$
F	$\tilde g^a + \tilde g^b \to \tilde g^c + \tilde G$	$-8\frac{(s^2+st+t^2)^2}{st(s+t)}\lvert f^{abc}\rvert^2$
G	$q_i + \tilde g^a \to q_j + \tilde G$	$-4(s+\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
H	$\tilde q_i + \tilde g^a \to \tilde q_j + \tilde G$	$-2(t+2s+2\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
I	$q_i + \bar q_j \to \tilde g^a + \tilde G$	$-4(t+\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$
J	$\tilde q_i + \bar{\tilde q}_j \to \tilde g^a + \tilde G$	$2(s+2t+2\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$

- $T_{RH} < 10^8 - 10^{10}$ GeV; constrains inflation
- $\tilde G$ may be all of DM if bound saturated

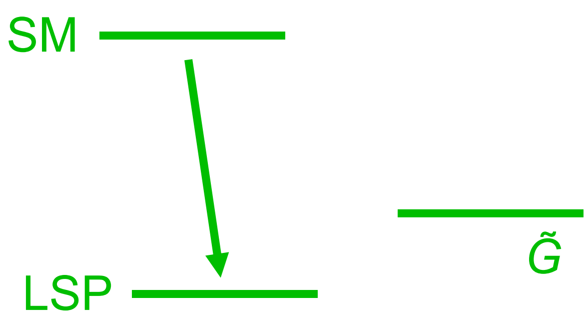


Bolz, Brandenburg, Buchmuller (2001)

OPTION 2: GRAVITINOS FROM LATE DECAYS

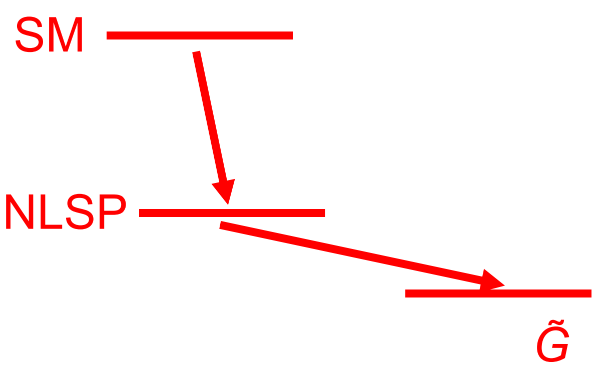
- What if gravitinos are diluted by inflation, and the universe reheats to low temperature? No "primordial" relic density

- $\tilde{G}$ not LSP



- No impact – implicit assumption of most of the literature

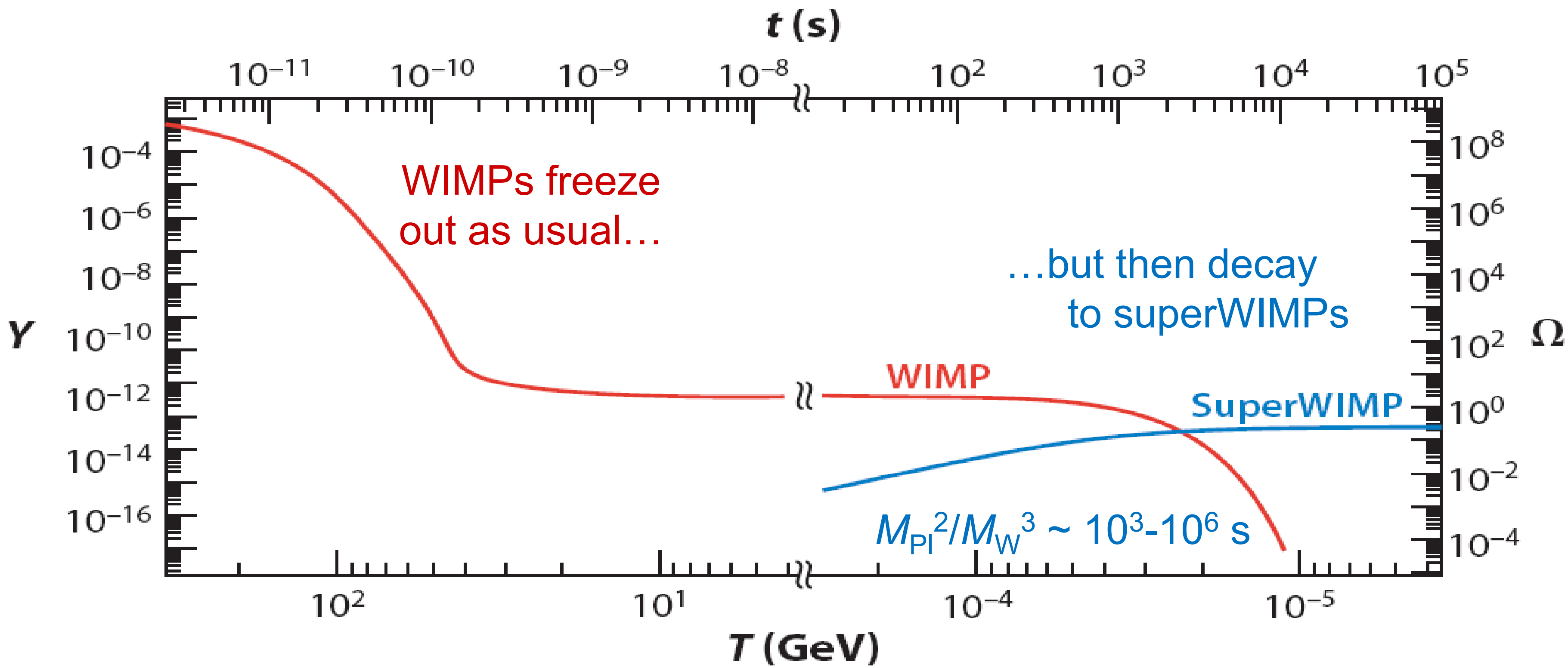
- $\tilde{G}$ LSP



- Completely different particle physics and cosmology

FREEZE OUT WITH SUPERWIMPS

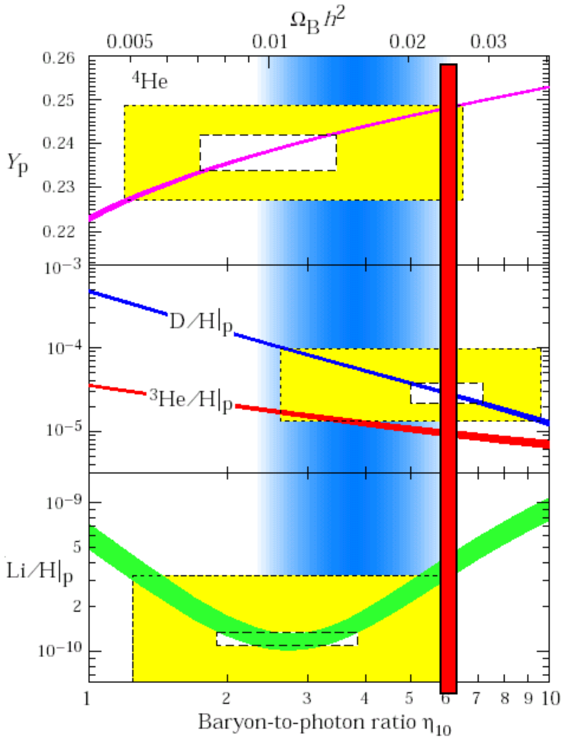
Feng, Rajaraman, Takayama (2003)



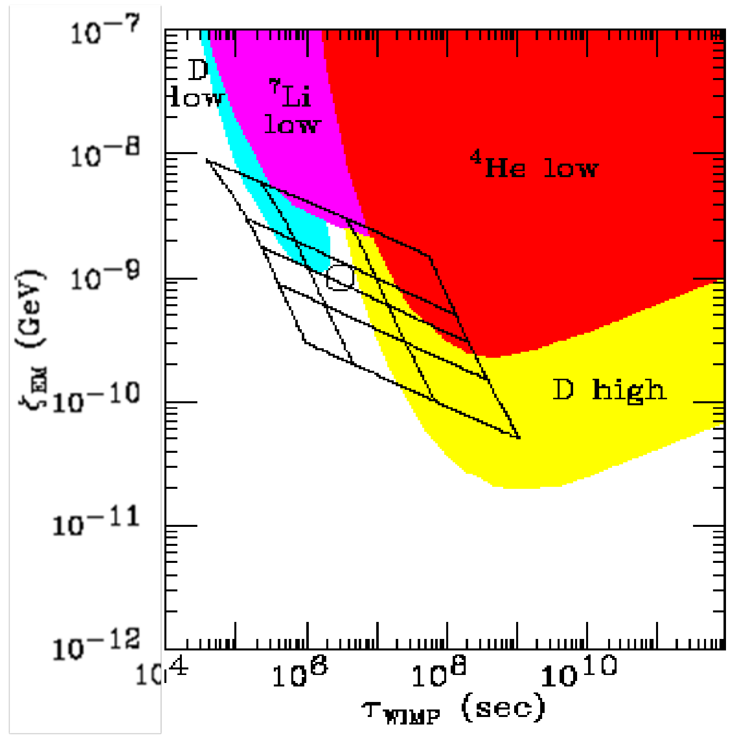
SuperWIMPs naturally inherit the right density (WIMP miracle), share all the motivations of WIMPs, but are superweakly interacting

COSMOLOGY OF LATE DECAYS

Late decays impact light element abundances



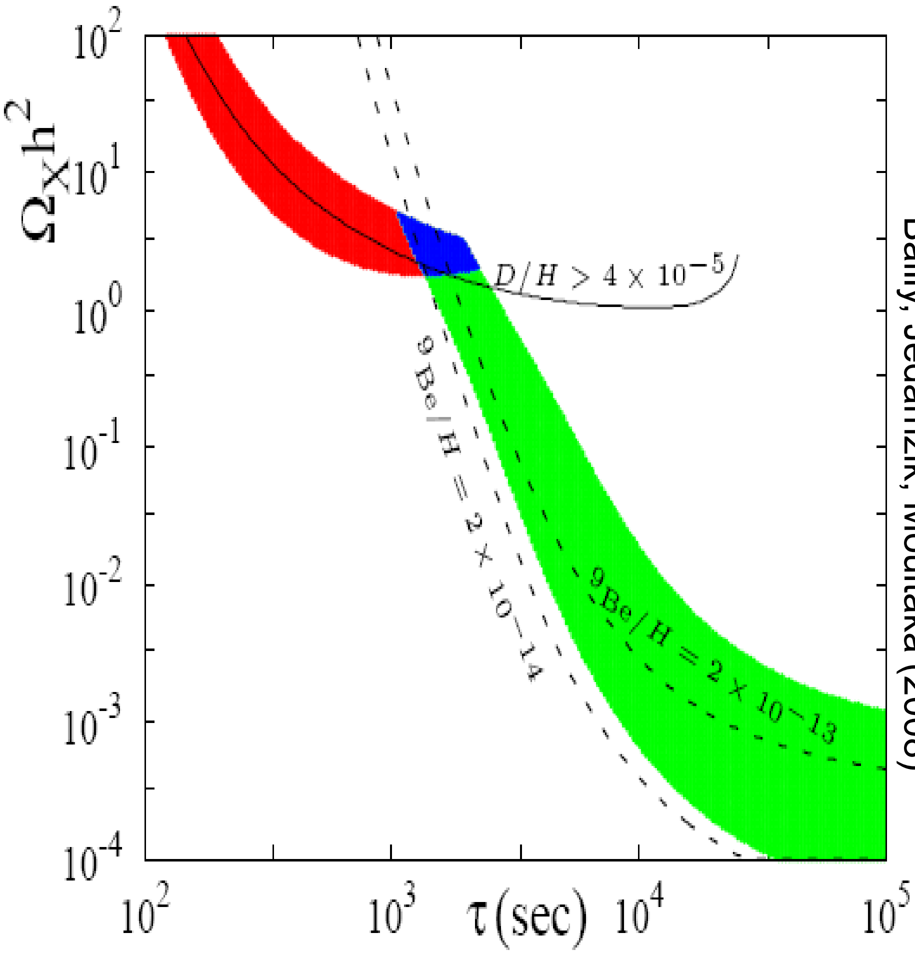
Fields, Sarkar, PDG (2002)



Feng, Rajaraman, Takayama (2003)

- Complicated nucleocosmochemistry
- BBN typically excludes large lifetimes
- BBN excludes $\chi \rightarrow Z\,\tilde{G}$ (hadrons dangerous) but $\tilde{l} \rightarrow l\,\tilde{G}$ ok

LATE DECAYS AND THE LITHIUM PROBLEM(S)



Bailly, Jedamzik, Moultaka (2008)

- ^{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?
- ^{6}Li may also not agree
  - Too high
- Late decays can fix both

COSMIC MICROWAVE BACKGROUND

- Late decays may also distort the CMB spectrum

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

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

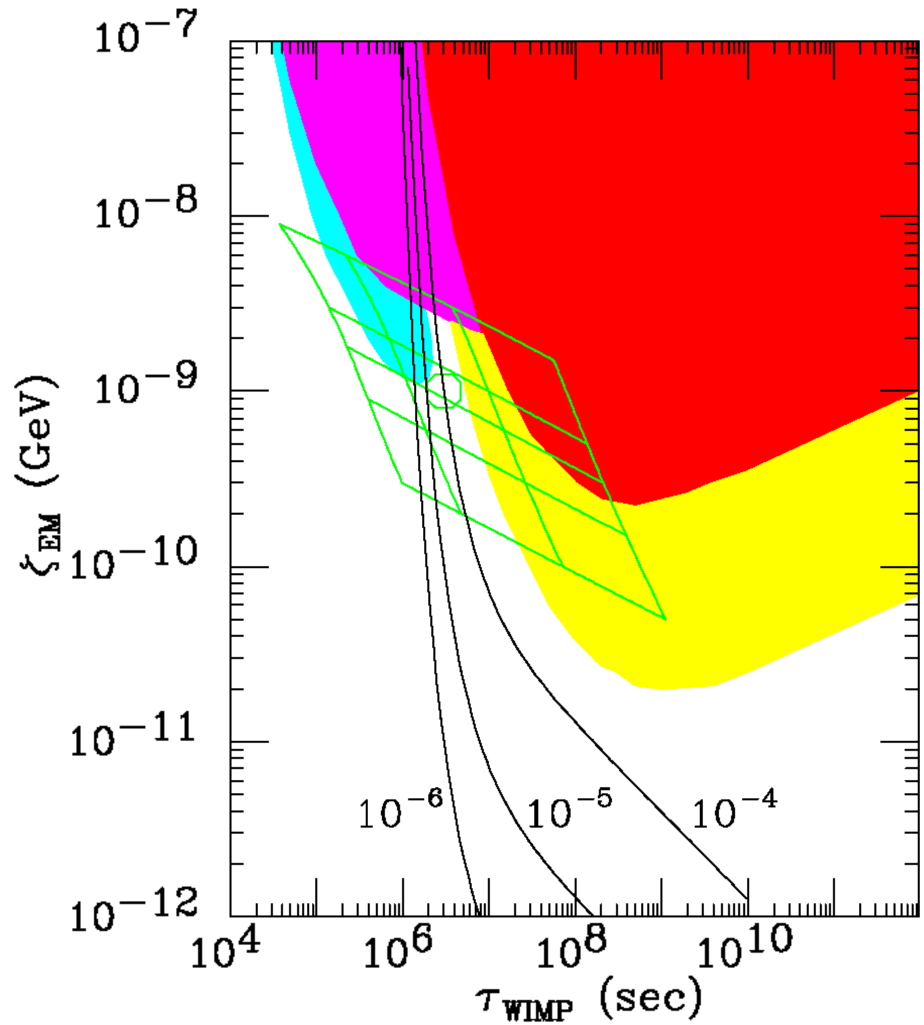
μ=0: Planckian spectrum

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

Hu, Silk (1993)

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

Future: possibly $|\mu|$ ~ 5 x 10^{-8}



Feng, Rajaraman, Takayama (2003)

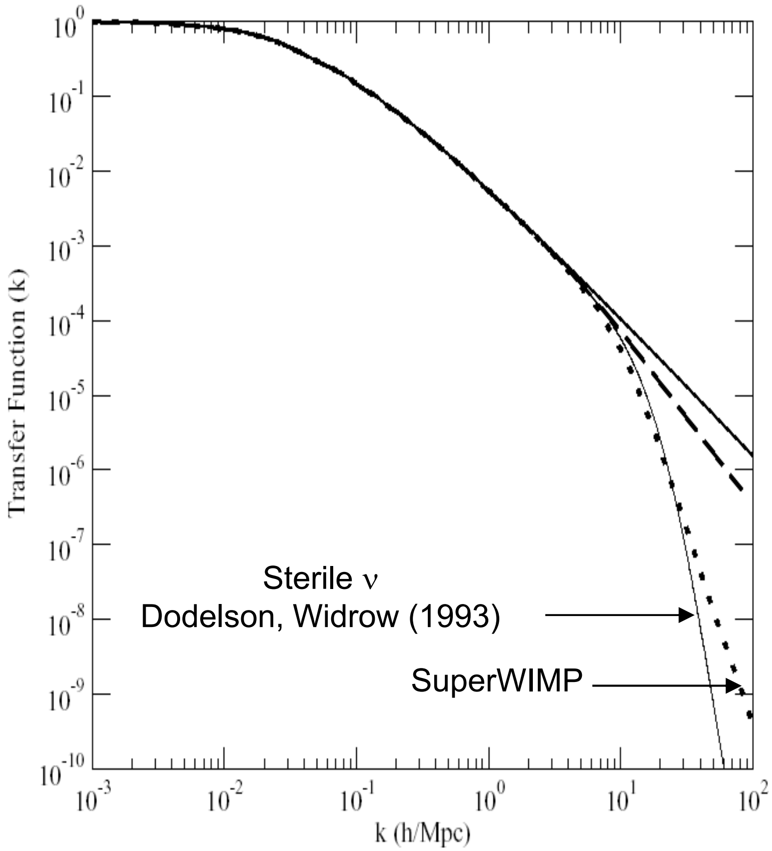
WARM DARK MATTER

- SuperWIMPs are produced in late decays with large velocity (0.1c – c)
- Suppresses small scale structure, as determined by the free-streaming scale

$$\lambda_{\rm FS} = \int_{\tau_X}^{t_{\rm EQ}} \frac{v(t)dt}{a(t)}$$

- Warm DM with cold DM pedigree

Dalcanton, Hogan (2000)
Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Feng, Rajaraman, Takayama (2005)
Strigari, Kaplinghat, Bullock (2006)
Bringmann, Borzumati, Ullio (2006)



Kaplinghat (2005)

THE COMPLETE MSUGRA

- If LSP = gravitino, then no reason to exclude stau (N)LSP region

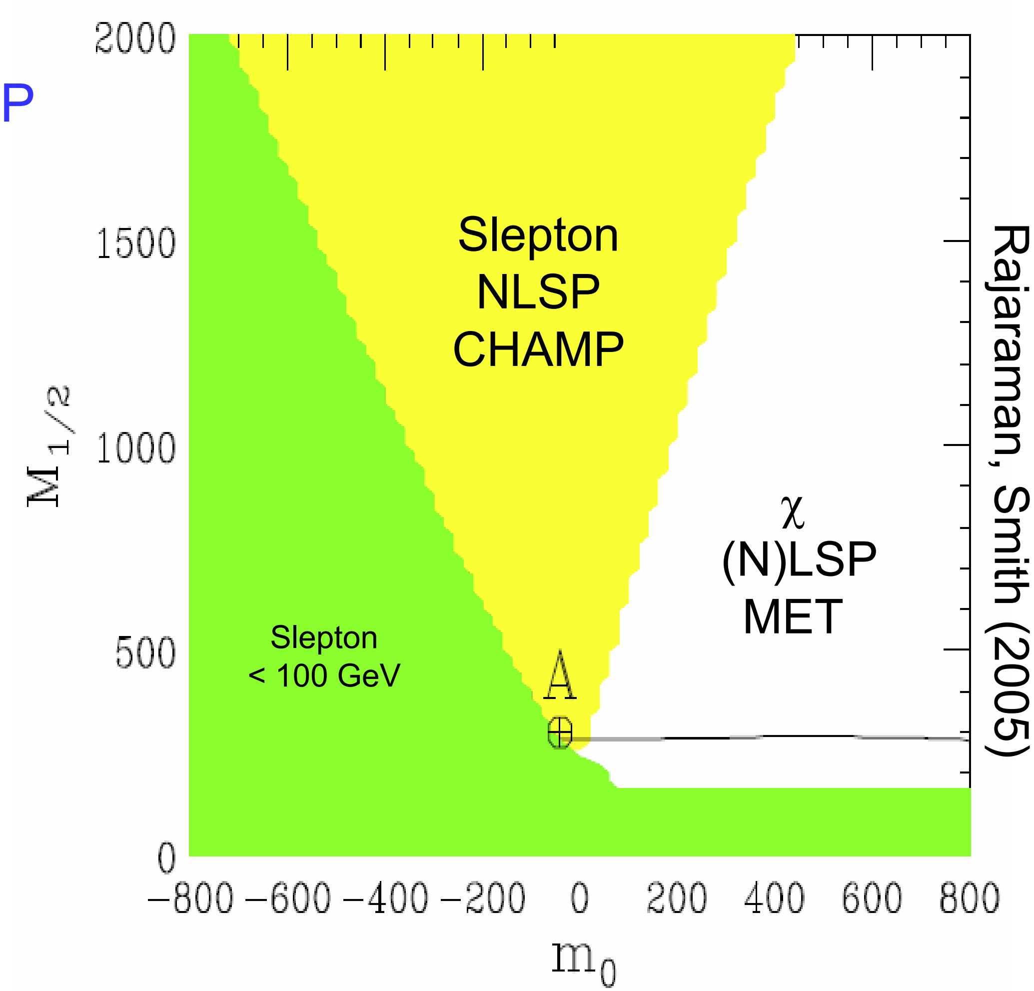
- Extend the mSUGRA parameters to

$$m_0^2, M_{1/2}, A_0, \tan\beta,\ \text{sign}(\mu),\ \text{and}\ m_{3/2}$$

and include negative

$$m_0 \equiv \text{sign}(m_0^2)\sqrt{|m_0^2|}$$

- Much of the new parameter space is viable with a slepton NLSP and a gravitino LSP



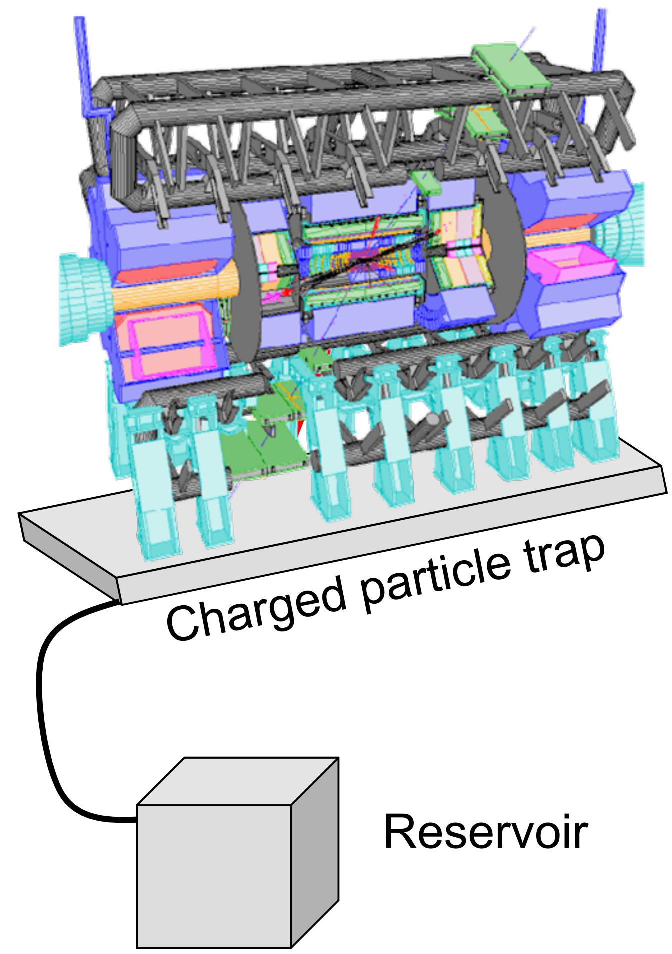
CHARGED PARTICLE TRAPPING

- SuperWIMP DM → metastable particles, may be charged, far more spectacular than misssing E_T
- 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 et al. (2005)



WHAT WE COULD LEARN FROM CHARGED PARTICLE DECAYS

$$\tau(\tilde{l} \to l\tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^5} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^{-4}$$

- Measurement of τ, $m_{\tilde{l}}$ and E_l → $m_{\tilde{G}}$ and G_N
  - Probes gravity in a particle physics experiment
  - Measurement of G_N on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines $\Omega_{\tilde{G}}$: SuperWIMP contribution to dark matter
  - Determines F : supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

Hamaguchi et al. (2004); Takayama et al. (2004)

LIGHT GRAVITINO DM

- The original SUSY DM scenario
  - Universe cools from high temperature
  - Gravitinos decouple while relativistic, $\Omega_{\tilde{G}} h^2 \approx m_{\tilde{G}} / 800$ eV
  - Favored mass range: keV gravitinos

Pagels, Primack (1982)

- This minimal scenario is now excluded
  - $\Omega_{\tilde{G}} h^2 < 0.1 \rightarrow m_{\tilde{G}} < 80$ eV
  - Gravitinos not too hot $\rightarrow m_{\tilde{G}} >$ few keV
  - keV gravitinos are now the most disfavored

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto (2005)
Seljak, Makarov, McDonald, Trac (2006)

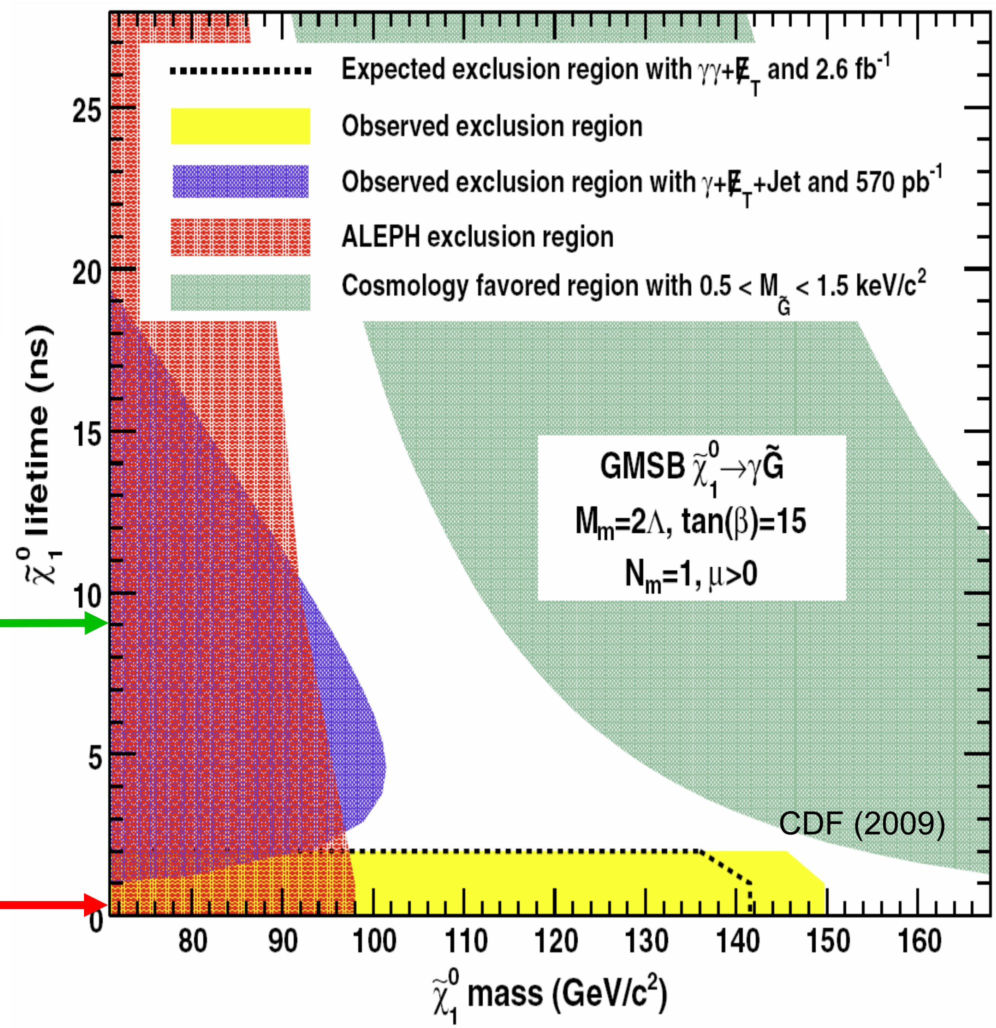
- Two ways out
  - ΛWDM: $m_{\tilde{G}} >$ few keV. Gravitinos are all the DM, but thermal density is diluted by low reheating temperature, late entropy production, …
  - ΛWCDM: $m_{\tilde{G}} < 16$ eV. Gravitinos are only part of the DM, mixed warm-cold scenario

CURRENT BOUNDS

- Remarkably, this lifetime difference is observable at colliders!

$$c\tau_{\rm NLSP} \approx 50\ {\rm cm} \left(\frac{200\ {\rm GeV}}{m_{\rm NLSP}}\right)^5 \left(\frac{m_{\tilde{G}}}{\rm keV}\right)^2$$

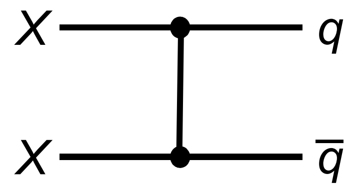
- $m_{\tilde{G}}$ > few keV: Delayed photon signatures
- $m_{\tilde{G}}$ < 16 eV: Prompt photon signatures



WIMP MIRACLE REVISITED

- The thermal relic density

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

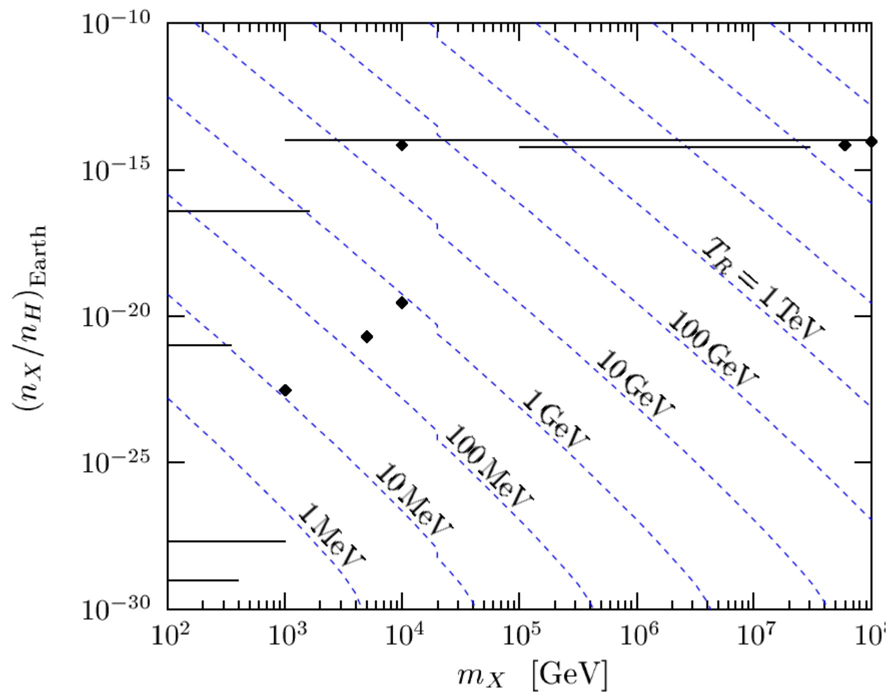


constrains only one combination of mass and coupling

- In the SM, however, we only have a few choices
  - Weak coupling: $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$
  - EM and strong: highly constrained

CHARGED STABLE RELICS

- Charged stable relics create anomalously heavy isotopes
- Severe bounds from sea water searches
- Inflation can dilute this away, but there is an upper bound on the reheating temperature



Kudo, Yamaguchi (2001)

Masses < TeV are excluded by T_{RH} > 1 MeV, but masses > TeV are allowed

HIDDEN DARK MATTER

- We can introduce hidden sectors composed of particles without SM interactions, but with their own interactions

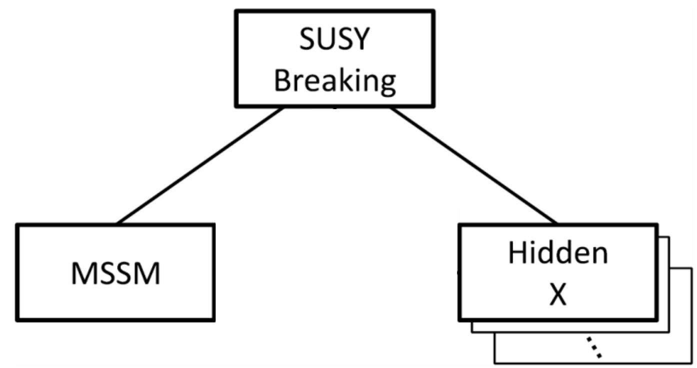
- Dark matter may be in such a sector
  - Interesting self-interactions, astrophysics
  - Less obvious connections to particle physics
  - No WIMP miracle

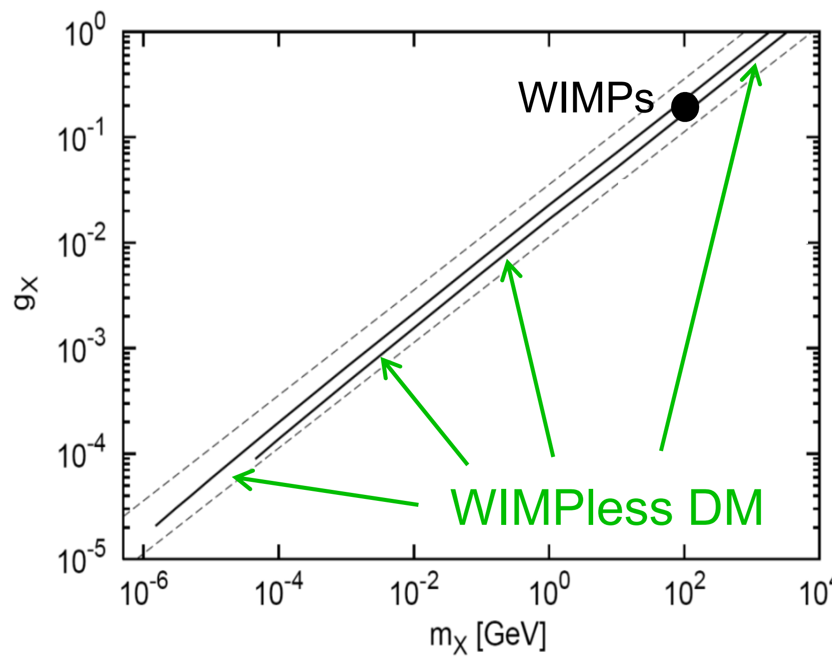
Spergel, Steinhardt (1999); Foot (2001)

THE WIMPLESS MIRACLE

Feng, Kumar (2008); Feng, Tu, Yu (2009); Feng, Shadmi (2011)

- In SUSY, however, there may be additional structure. E.g., in GMSB, AMSB, the masses satisfy $m_X \sim g_X^2$
- This leaves the relic density invariant $$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$
- "WIMPless Miracle": hidden sectors of these theories automatically have DM with the right Ω (but they aren't WIMPs)
- Is this what the new physics flavor problem is telling us?!

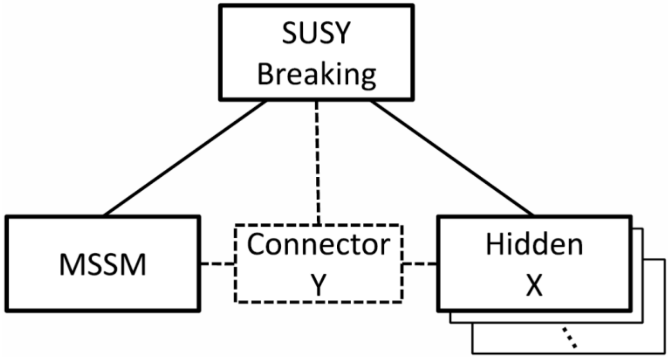




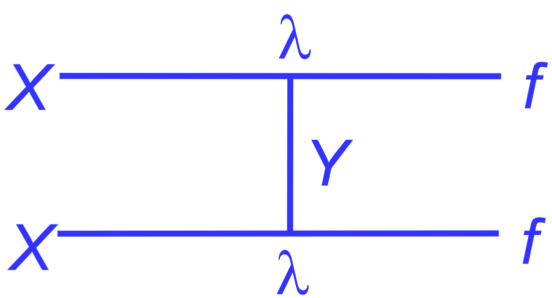
WIMPLESS DM SIGNALS

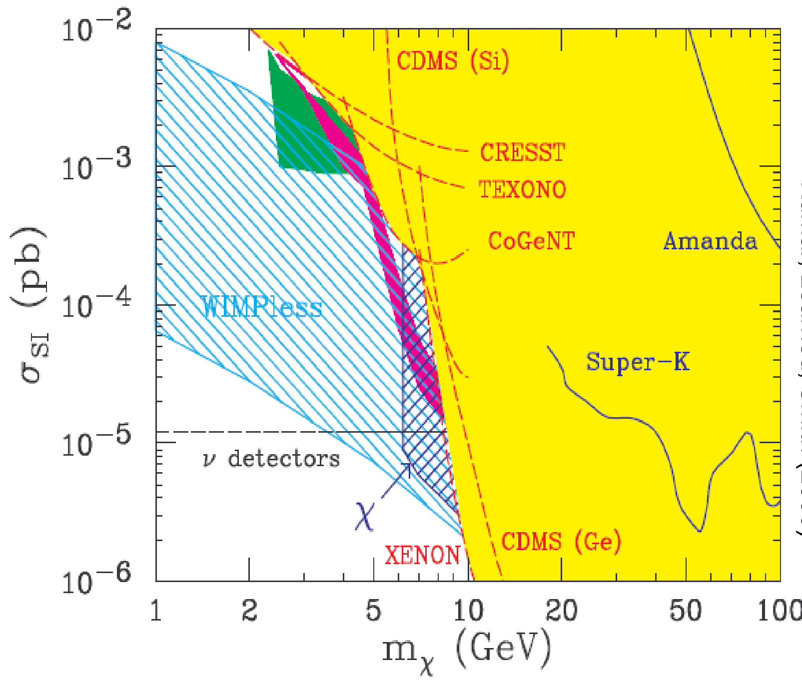
- Hidden DM may have only gravitational effects, but still interesting: e.g., it may interact through "dark photons", self-interact through Rutherford scattering

Ackerman, Buckley, Carroll, Kamionkowski (2008)
Feng, Kaplinghat, Tu, Yu (2009)



- Alternatively, hidden DM may interact with normal matter through connector particles, can explain DAMA and CoGeNT signals





Kumar, Learned, Smith (2009)

LECTURE 3 SUMMARY

- WIMPs are not the only class of DM that naturally have the right relic density, nor are they the only DM candidate predicted by SUSY, extra dimensions, …

- These other candidates may have completely different implications for cosmology, colliders

- Is any of this right? LHC is running, direct and indirect detection, astrophysical probes are improving rapidly – this field will be transformed soon