PARTICLE PHYSICS AND COSMOLOGY

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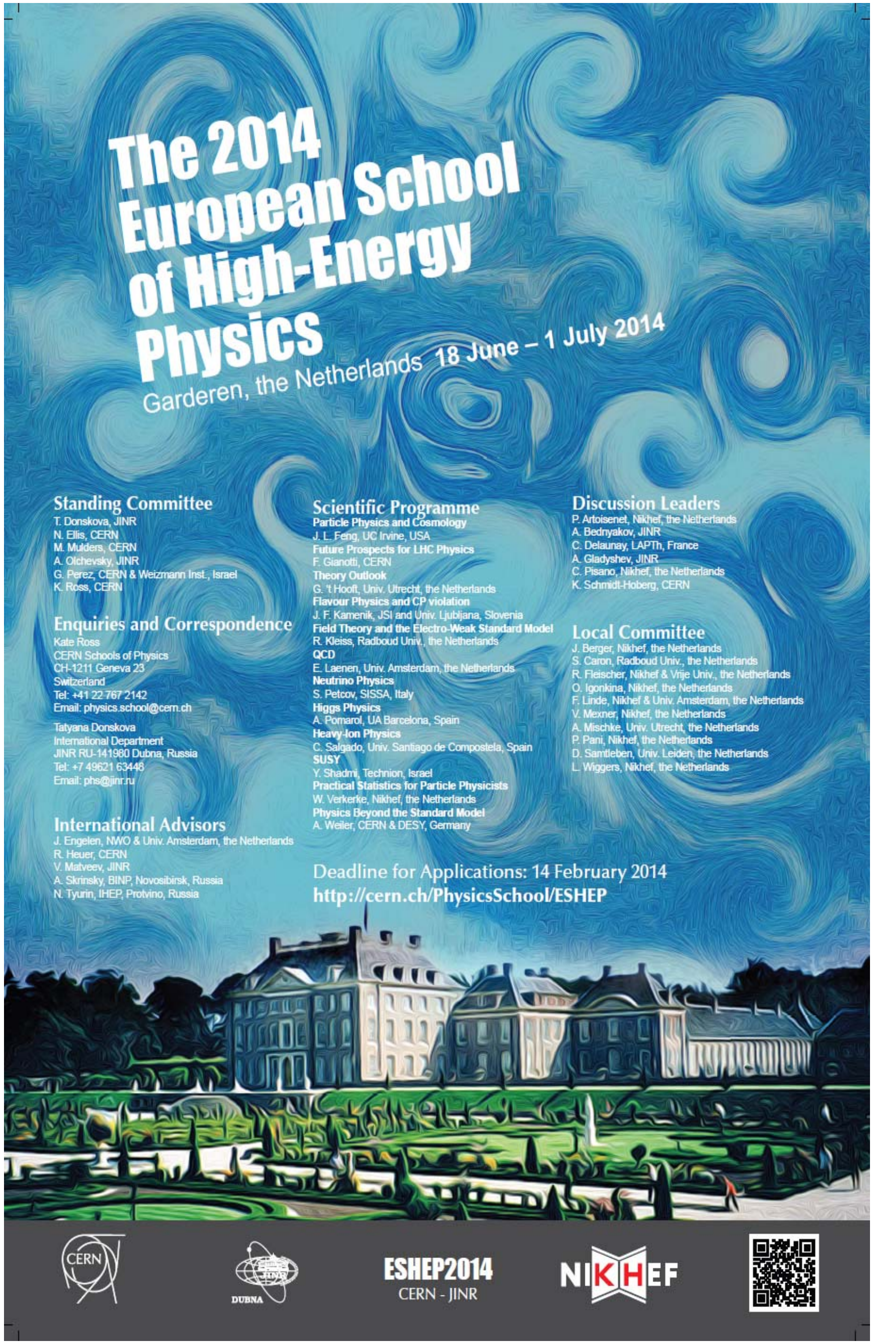
The 2014 European School of High Energy Physics

Garderen, the Netherlands

19-21 June 2014



The 2014 European School of High-Energy Physics

Garderen, the Netherlands 18 June – 1 July 2014

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Deadline for Applications: 14 February 2014
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OUTLINE

LECTURE 1

Essential Cosmology: Contents and History of the Universe

LECTURE 2

WIMP Dark Matter: Candidates and Methods of Detection

LECTURE 3

Inflation, Gravitinos, and Hidden Sectors

INTRODUCTION

- Why should HEP physicists care about cosmology?
  - We want to answer age-old questions about our Universe and our place in it
  - We are in a golden age of cosmology, and cosmology and particle physics have become inextricably intertwined
  - Many of the leading motivations for new particle physics come from cosmology: dark matter, dark energy, inflation, baryon asymmetry
  - Cosmology sets new interesting mass scales and can provide upper bounds on masses
  - Cosmology reaches the hard corners of parameter space (high masses, weak interactions)
  - HEP physicists and cosmologists have a lot to learn from each other
  - These topics capture the imagination of the public

ESSENTIAL COSMOLOGY

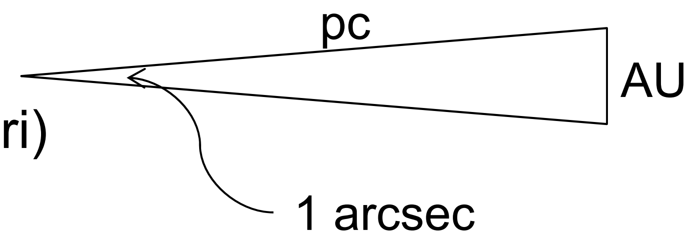
- For the first time in history, we now have a complete *picture* of the Universe
- How did this come about?
- We will first review the standard model of cosmology and some of the key observational evidence leading to it
- Little previous knowledge of cosmology is assumed; focus on heuristic derivations, order-of-magnitude estimates, intuitive arguments, and some aspects that (at present) seem to be most linked to particle physics, and particularly high-energy physics. This is a huge topic, many important topics will be neglected.

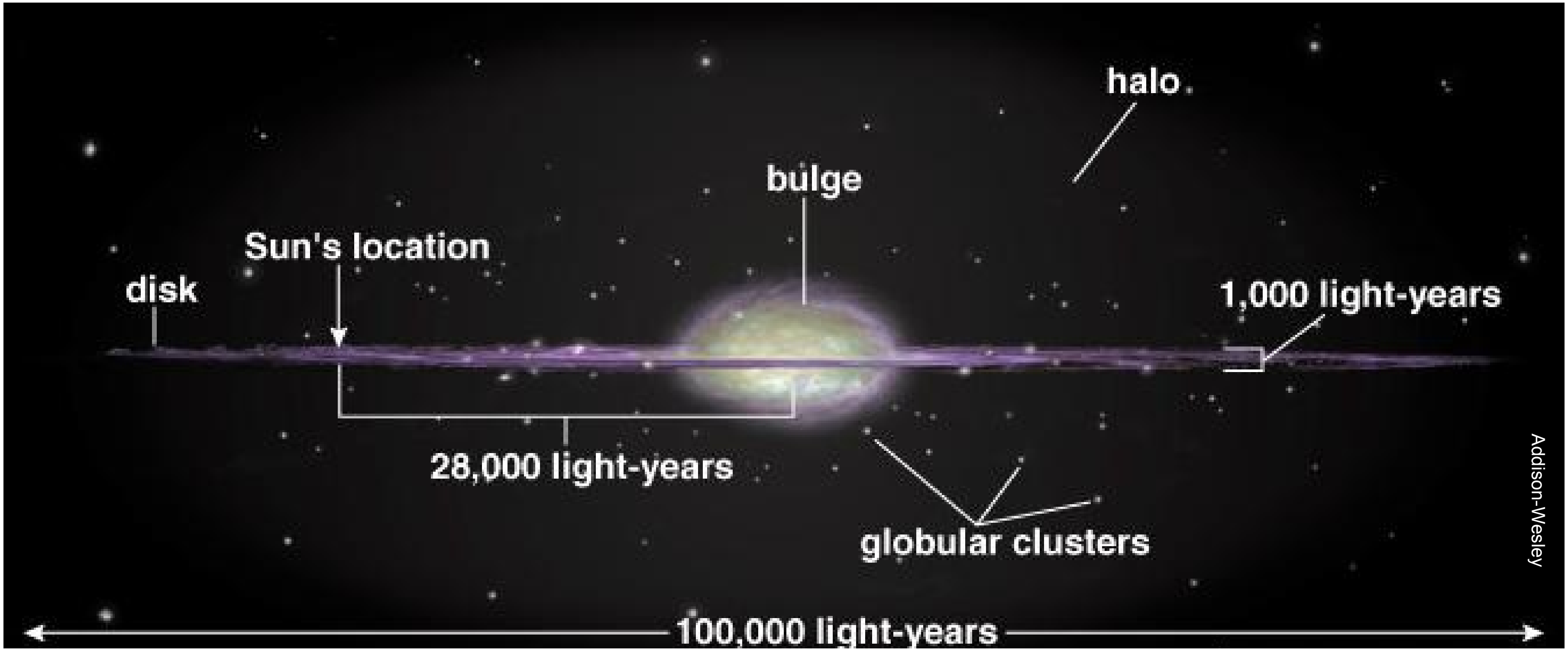
PARTICLE PHYSICS SCALES

- Natural units: $h = c = k_B = 1$
  - $h = c = 1$ is standard
  - $k_B = 1$ → 1 K = 0.08 meV
- Some useful energy scales
  - 10^{19} GeV: Planck scale
  - 10^{16} GeV: GUT scale
  - TeV: weak scale
  - GeV: binding energy of quarks (Λ_{QCD})
  - MeV: binding energy of nuclei
  - eV: binding energy of atoms
  - 0.1 meV: CMB temperature now

ASTROPHYSICS SCALES

- 1 pc = 3.3 ly. Some useful length scales
  - 10^{-5} pc: distance to Sun (AU)
  - pc: distance to the next star (Alpha Centauri)
  - 10 kpc: distance to Milky Way center

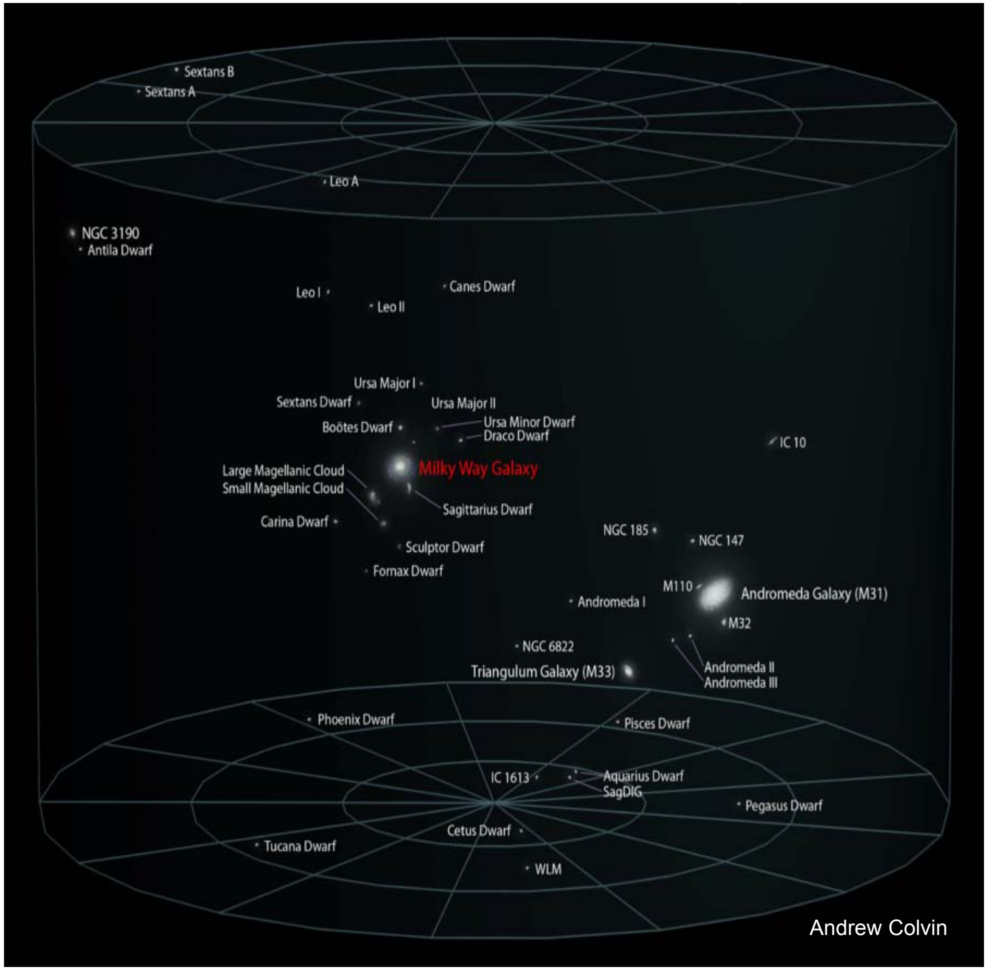




Addison-Wesley

ASTROPHYSICS SCALES

- Some useful length scales
  - 10^{-5} pc: distance to Sun
  - pc: distance to next-nearest star (Alpha Centauri)
  - 10 kpc: distance to Milky Way center
  - 10-100 kpc: distance to nearest dwarf galaxies
  - Mpc: distance to nearest big galaxy (Andromeda)
  - 10 Mpc: size of clusters of galaxies
  - 10 Gpc: size of the observable Universe



Andrew Colvin

COSMOLOGY BASICS

- The evolution of the Universe is dominated by gravity. We must therefore begin with some basic general relativity.

- Let the spacetime metric $g_{\mu\nu}$ be a dynamical field. This specifies lengths through

$$ds^2 = g_{\mu\nu}(x) dx^\mu dx^\nu$$

- With a dynamical metric, our theory is specified by the Einstein-Hilbert action

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G} + \mathcal{L}_{\mathrm{SM}} \right)$$

  where $g = \det(g_{\mu\nu})$, $G = M_{\mathrm{Pl}}^{-2}$, and $R = R(g_{\mu\nu}, \partial g_{\mu\nu}, \partial^2 g_{\mu\nu})$ is the scalar curvature.

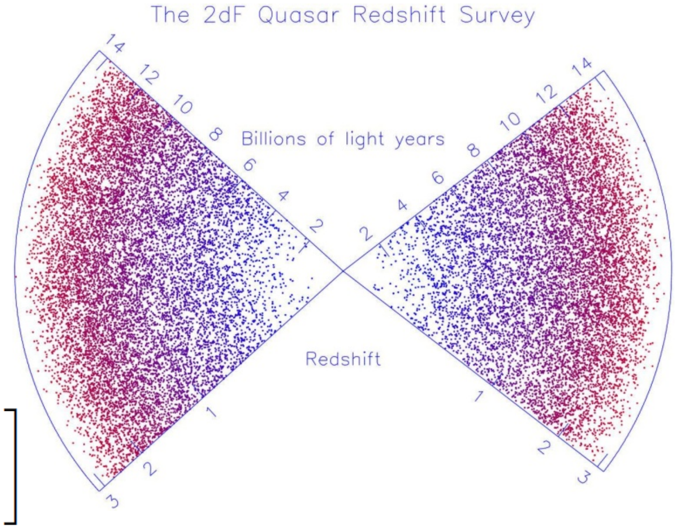
- Extremizing this action, we find the equations of motion

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} \qquad T_{\mu\nu} \equiv -2 \frac{\delta \mathcal{L}_{\mathrm{SM}}}{\delta g^{\mu\nu}} + g_{\mu\nu} \mathcal{L}_{\mathrm{SM}}$$

  These are the Einstein equations, where $R_{\mu\nu}$ is the Ricci curvature tensor, again a function of the metric, and $T_{\mu\nu}$ is the stress-energy tensor and contains all the particle physics.

COSMOLOGY BASICS

- The Einstein equations are complicated to solve, so we make some approximations, based on observations.



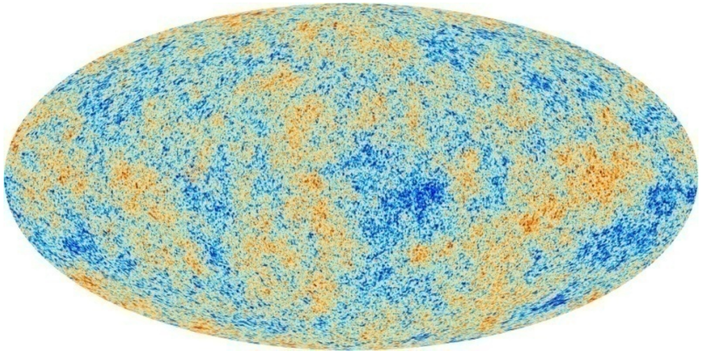
- The Universe appears to be homogeneous and isotropic on scales larger than ~10 Mpc.

- So we assume a Friedmann-Lemaitre-Robertson-Walker metric

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$

and stress-energy tensor

$$T^{\mu}{}_{\nu} = \mathrm{diag}\left[\rho(t), -p(t), -p(t), -p(t)\right]$$



Here *a(t)* is the scale factor and *k* is a constant that specifies the curvature (*k* = 0 implies a flat Universe);

ρ is energy density and *p* is pressure.

COSMOLOGY BASICS

- With these simplifications, the Einstein equations become quite manageable.
- The Einstein equations imply the Friedmann equation $\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$.

  We define the Hubble parameter $H \equiv \frac{\dot{a}}{a}$ and the critical density $\rho_c \equiv \frac{3H^2}{8\pi G}$.

- We may parameterize various materials by w, where $p = w\rho$. If w is constant, stress-energy conservation $T^{\mu\nu}{}_{;\nu} = 0$ → $\rho \sim a^{-3(1+w)}$
- For example, we can consider 3 kinds of contributions to the energy density:

  Matter: ρ is diluted by expansion (w = 0) $\text{MD}: \rho \propto a^{-3} \Rightarrow \dot{a}^2 \propto \frac{1}{a} \Rightarrow a \propto t^{2/3}$

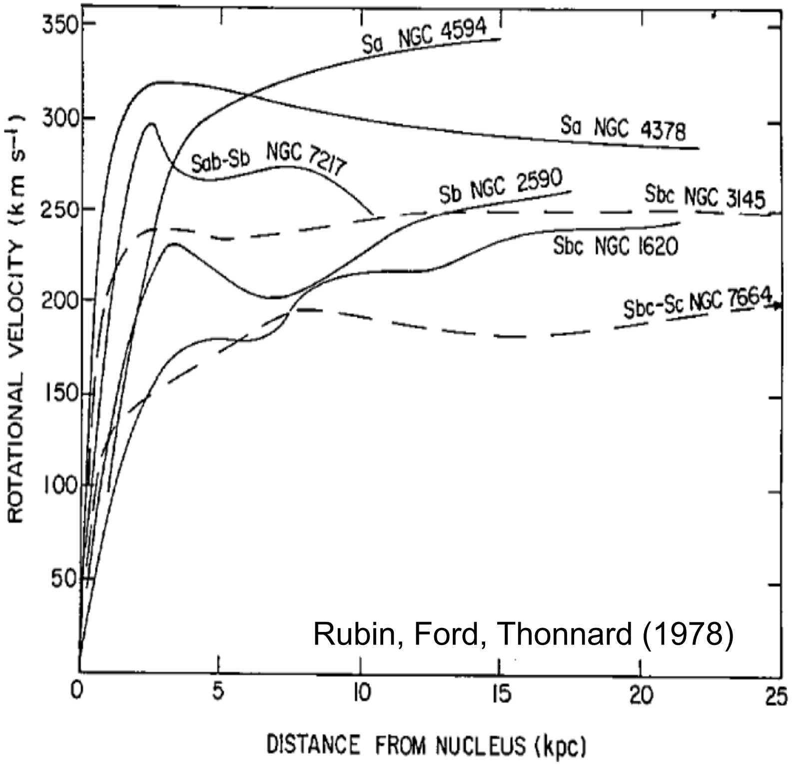
  Radiation: ρ is diluted by expansion and redshifting (w = 1/3) $\text{RD}: \rho \propto a^{-4} \Rightarrow \dot{a}^2 \propto \frac{1}{a^2} \Rightarrow a \propto t^{1/2}$

  Vacuum energy: ρ is not diluted (w = –1) $\text{VD}: \rho \propto a^0 \Rightarrow \dot{a}^2 \propto a^2 \Rightarrow a \propto e^{ct}$

- What do observations tell us about the contents of the Universe now?

ROTATION CURVES OF GALAXIES

Rubin, Ford (1970); Bosma (1978)



Rubin, Ford, Thonnard (1978)

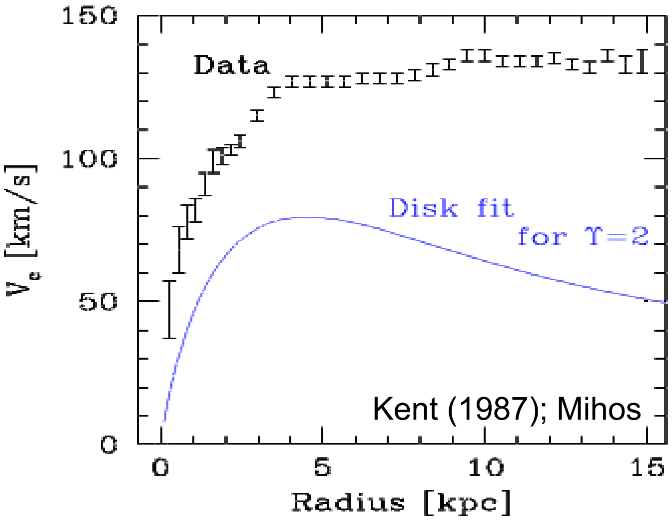
- Rotational velocity v_c as function of distance from center r
  - $v_c \sim O(300)$ km/s $\sim O(10^{-3})$ c
  - r ~ few kpc
- Expect $v_c \sim r^{-1/2}$ beyond luminous region

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

Instead find $v_c \sim$ constant

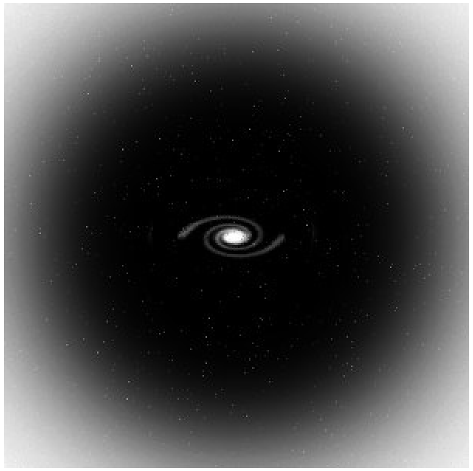
- The discrepancy may be resolved by missing mass and is classic (but not the first) evidence for dark matter

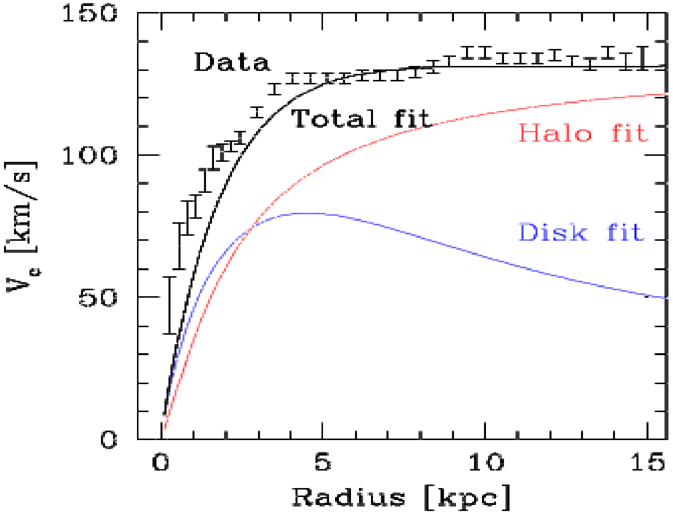
AN EXAMPLE: NGC 2403



Kent (1987); Mihos

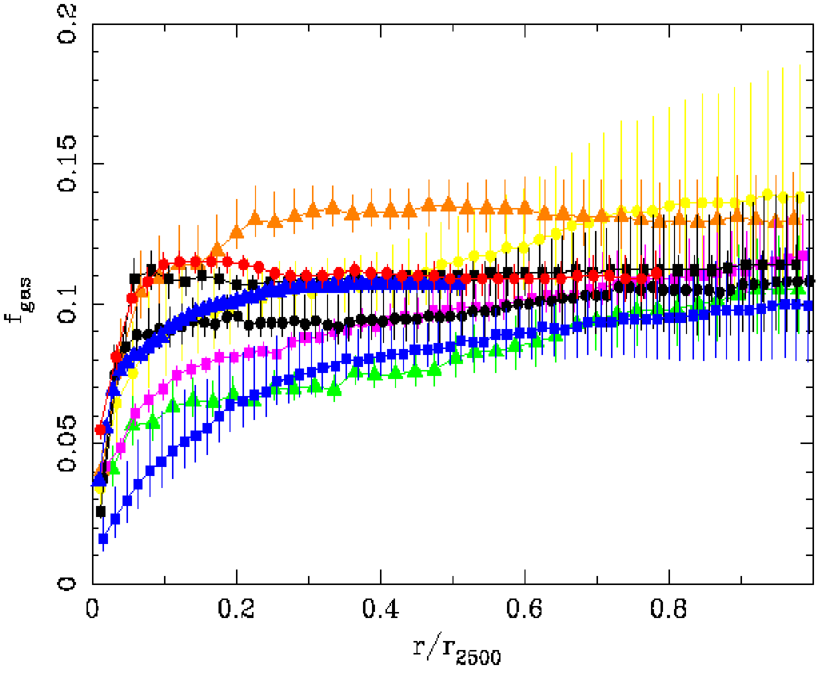
- v_c from HI line
- Fit mass-to-light ratio, halo model; this tells us about ρ(r)





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

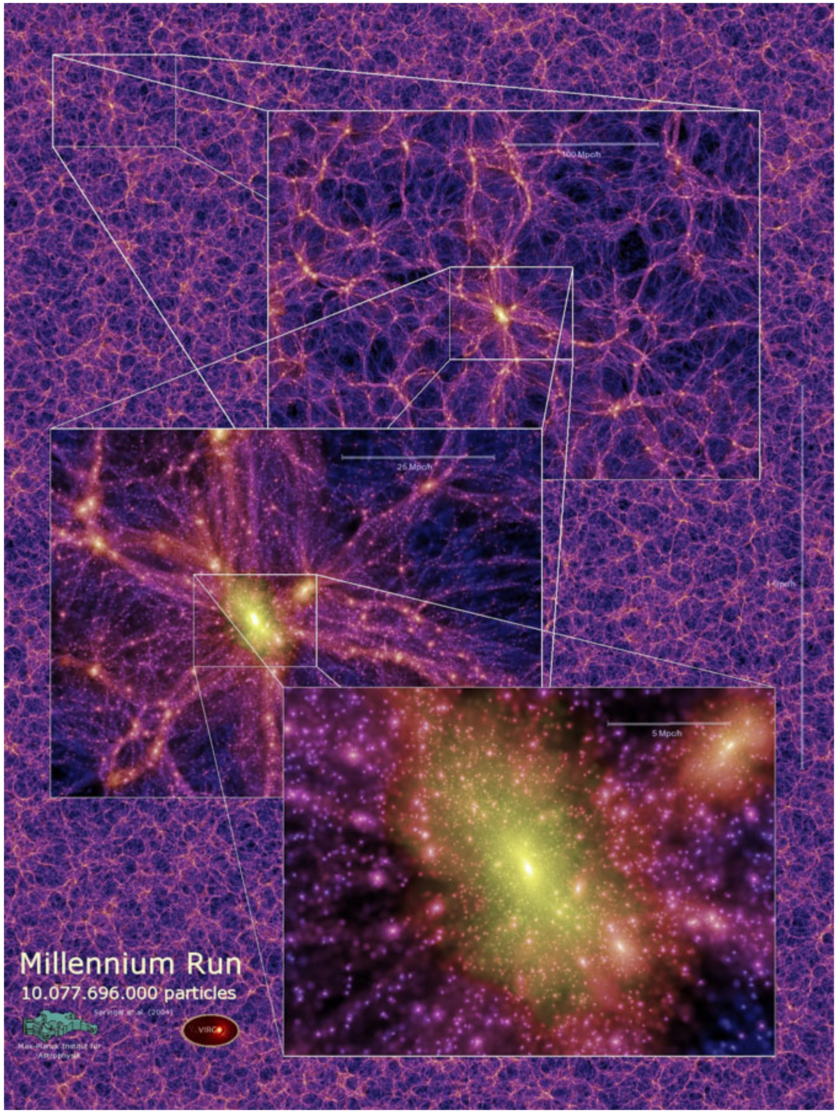
DARK MATTER DISTRIBUTION

- Evidence of dark matter from many other observations: weak lensing, strong lensing, Bullet Cluster, …
- Simulations and observations lead to a consistent picture on large scales
- DM is cold, it clumps and leads to structure formation; every galaxy is surrounded by a dark matter halo
- Local DM properties

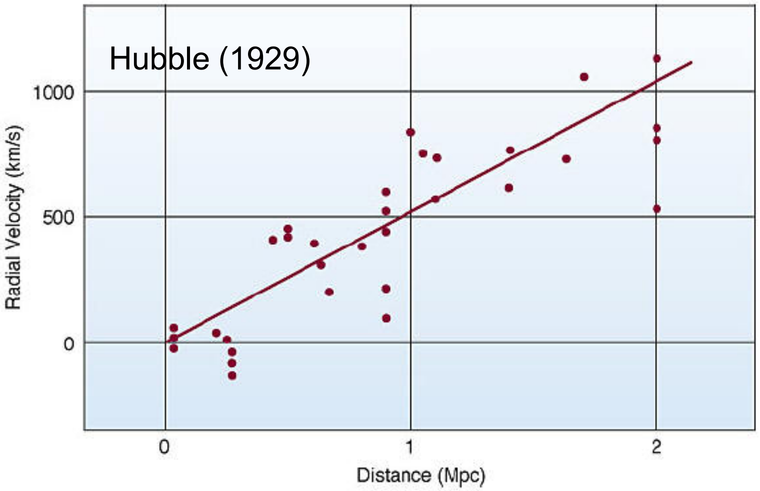
  $\rho \sim 0.2 - 0.5$ GeV/cm^3,

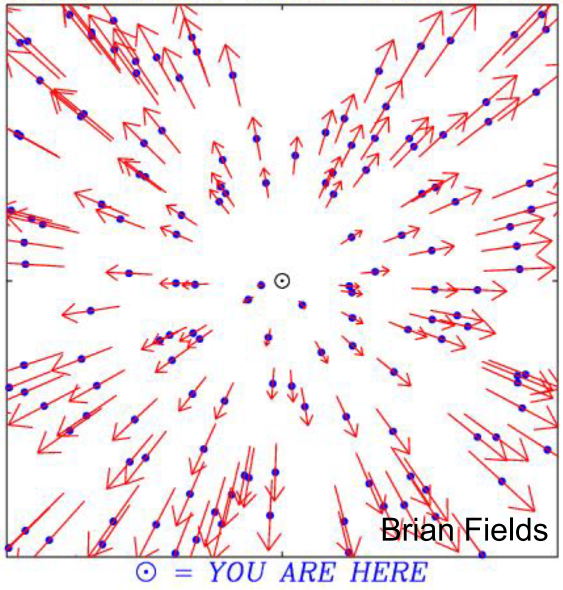
  overdense by factor of $\sim 10^5$

  $v \sim 10^{-3}\,c$ for many DM candidates, independent of mass (virial theorem)



EXPANSION OF THE UNIVERSE





- Galaxies that are far from us are receding from us, and the recessional velocity is roughly proportional to the distance
- This is Hubble's Law, and the constant of proportionality is Hubble's constant

$$v = H\,d$$

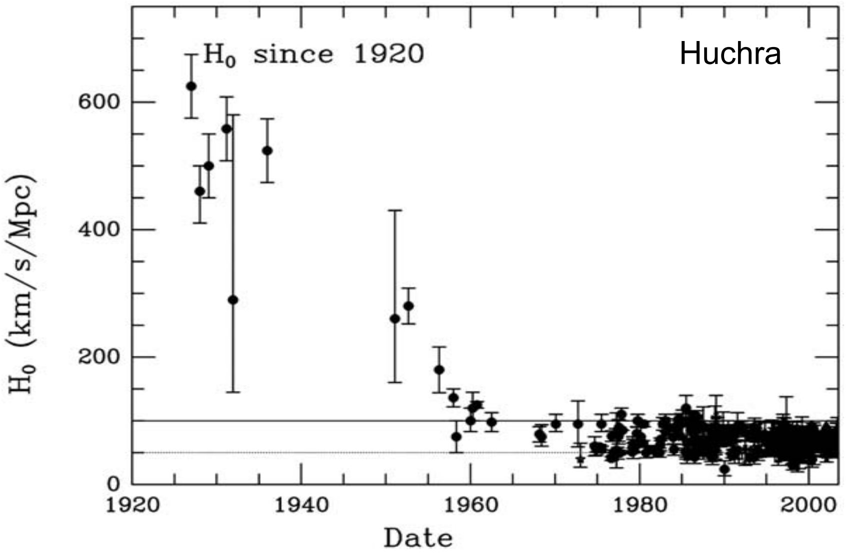
- The current value of the Hubble parameter is

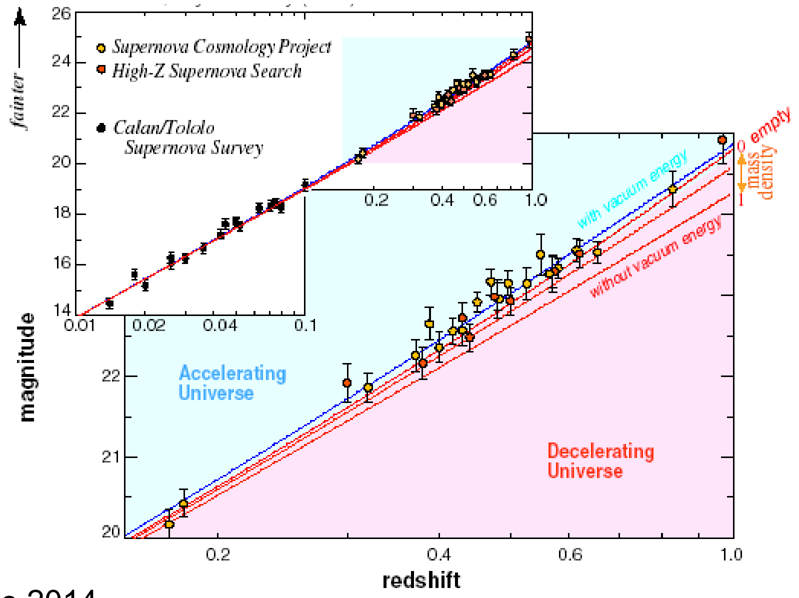
$$H_0 = h\ 100\ \text{km/s/Mpc}$$
$$h = 0.705 \pm 0.015 \quad (h^2 \approx ½)$$

- This means that light from distant galaxies is redshifted

$$\lambda_{\text{obs}} / \lambda_{\text{emit}} = 1 + z$$

EXPANSION OF THE UNIVERSE





- The original evidence for the expanding universe has now been extended to far larger distances with Type Ia supernovae

- Note the evolution of the measurement of H_0 -- a lesson in underestimated systematics

- The universe’s expansion is currently accelerating!

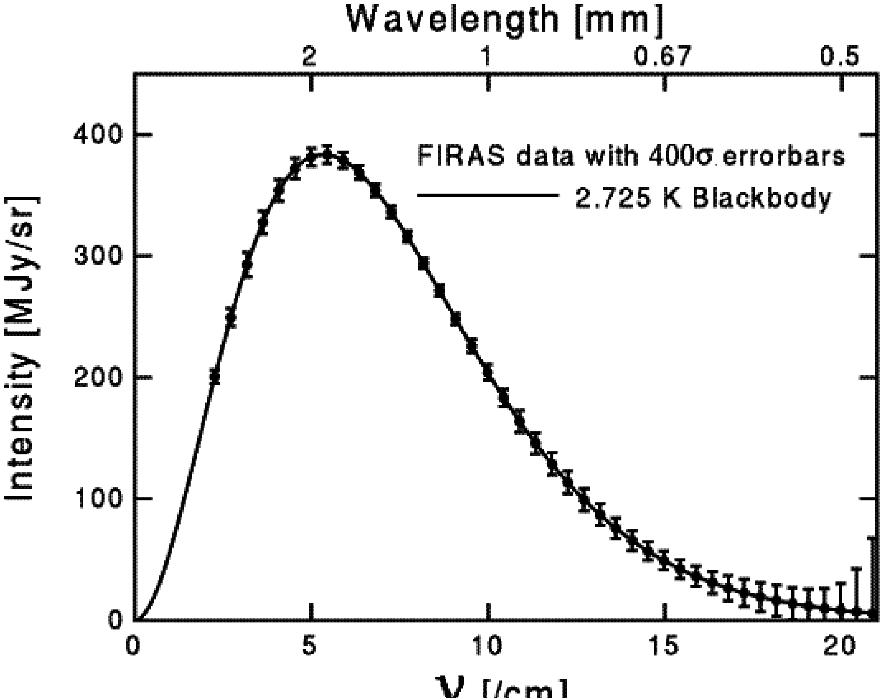
- Measurement of this expansion history constrains the acceleration of expansion:

$$\Omega_\Lambda - \Omega_M$$

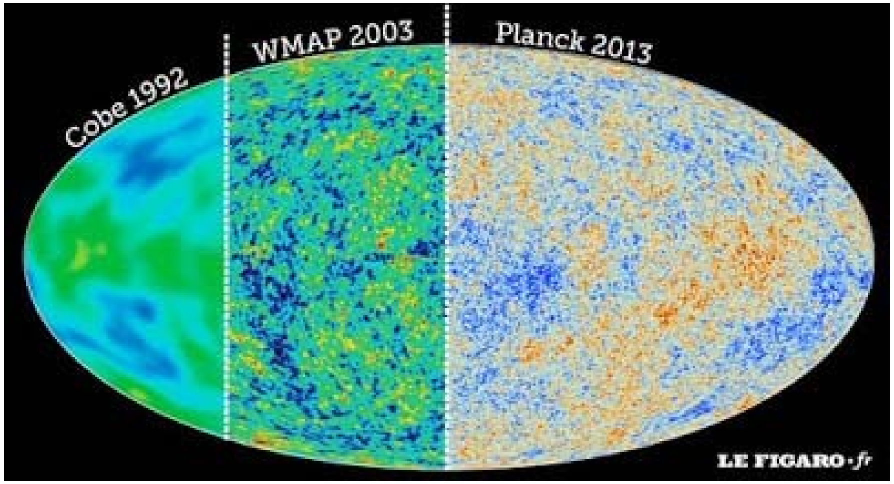
“Attractive matter vs. repulsive dark energy”

COSMIC MICROWAVE BACKGROUND

- The Universe is filled with an essentially perfect black body spectrum
- The temperature is 2.725 K in all directions, implying the Universe is highly isotropic on large scales



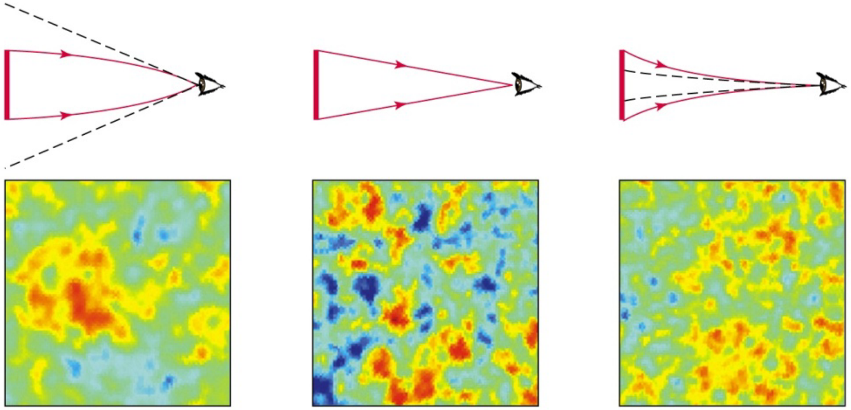
COSMIC MICROWAVE BACKGROUND

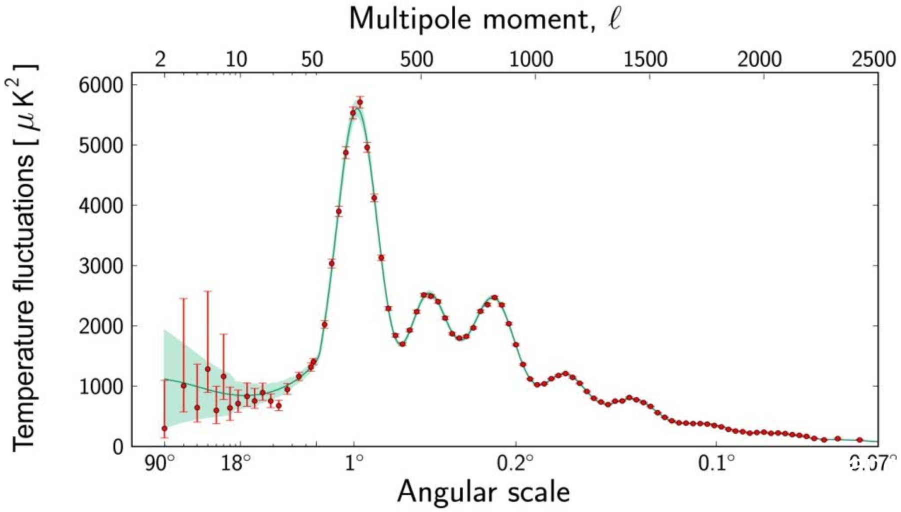


- There is, however, a tiny anisotropy of $\delta T/T \sim 10^{-5}$
- Dramatic improvements from COBE to WMAP to Planck
- Angular size of the hot and cold spots constrains the geometry:

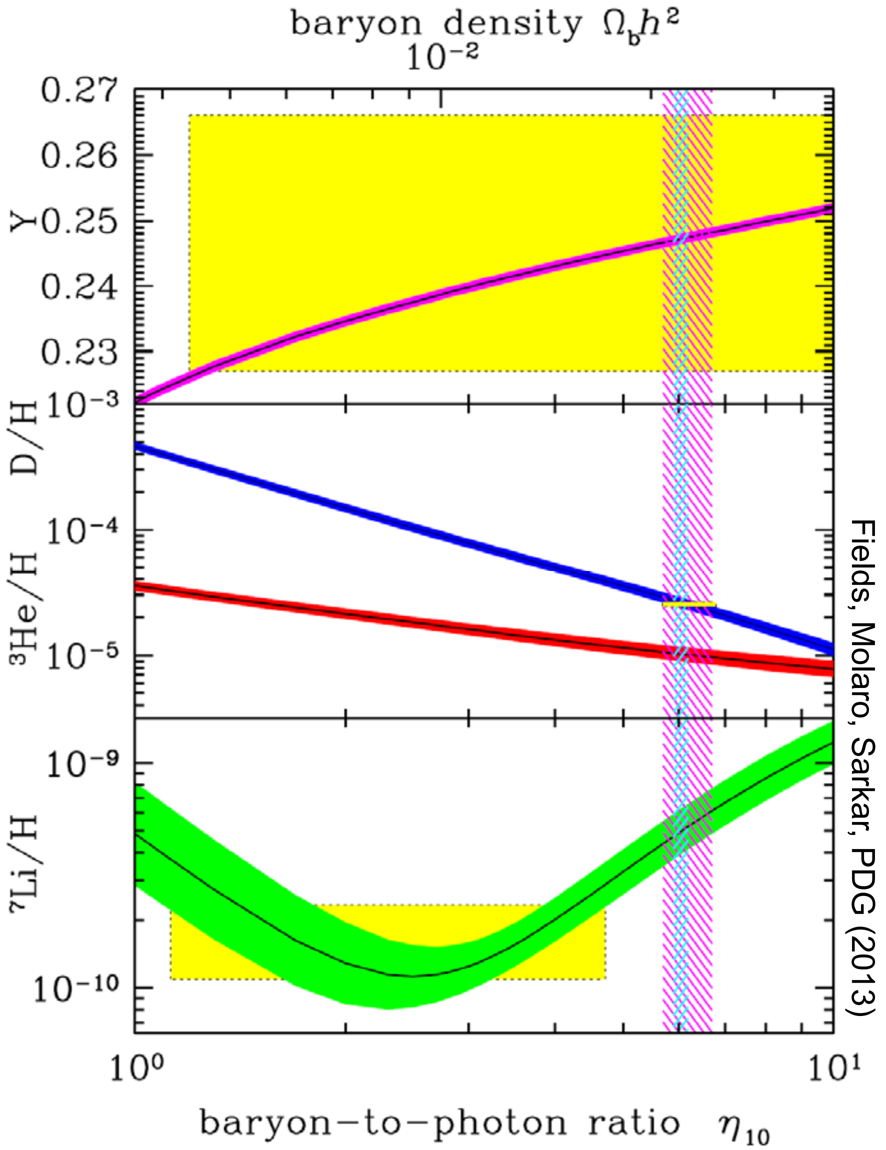
  $$\Omega_\Lambda + \Omega_M$$

  “total energy density”





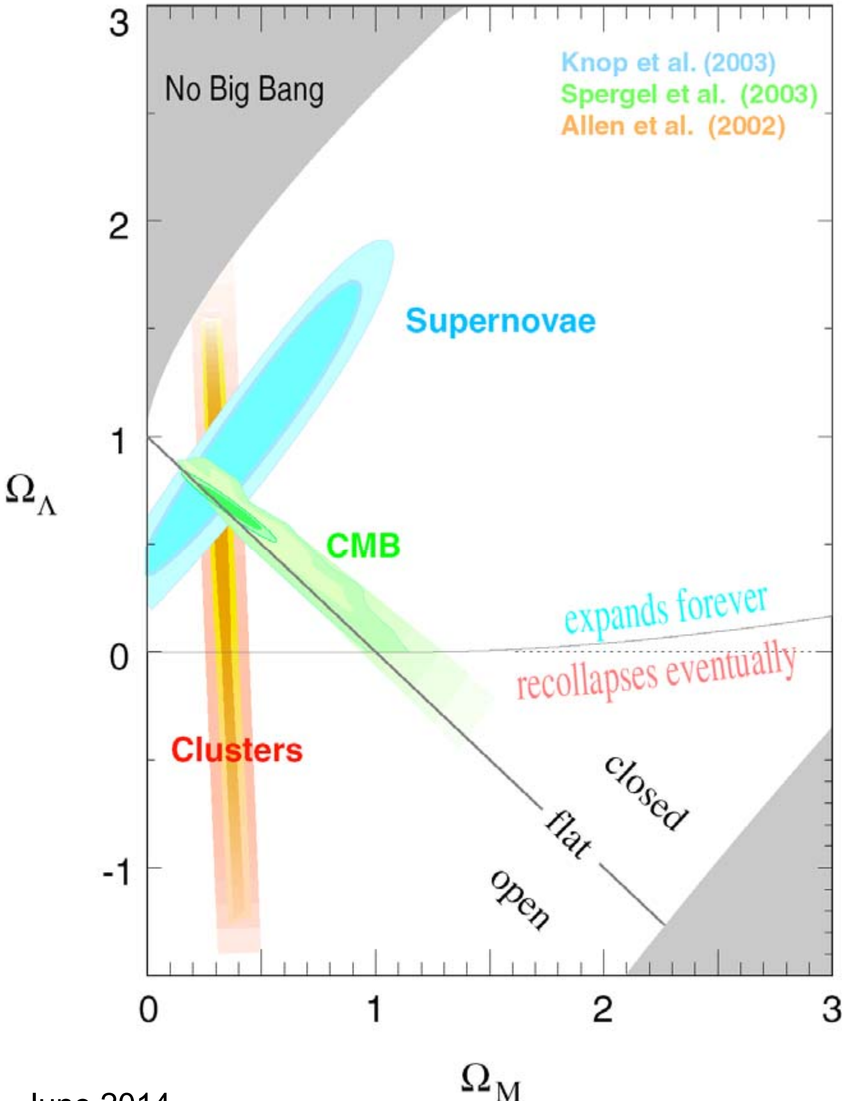
BIG BANG NUCLEOSYNTHESIS



Fields, Molaro, Sarkar, PDG (2013)

- At T ~ 1 MeV, around the binding energy of nuclei, the universe cooled enough for light elements to start forming
- The abundance of each light species is a function of a single parameter, η, the baryon-to-photon ratio
- BBN and CMB determinations are consistent (except possibly for Li) for a single choice of η and constrain 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 $\Sigma m = 0.1$ eV]

- Remarkable precision

- 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

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

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

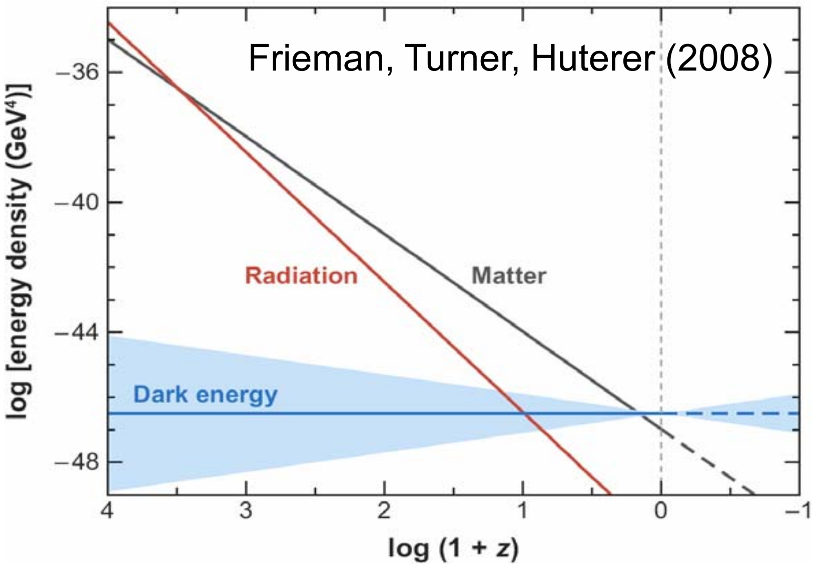
WHAT DOMINATES WHEN?

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

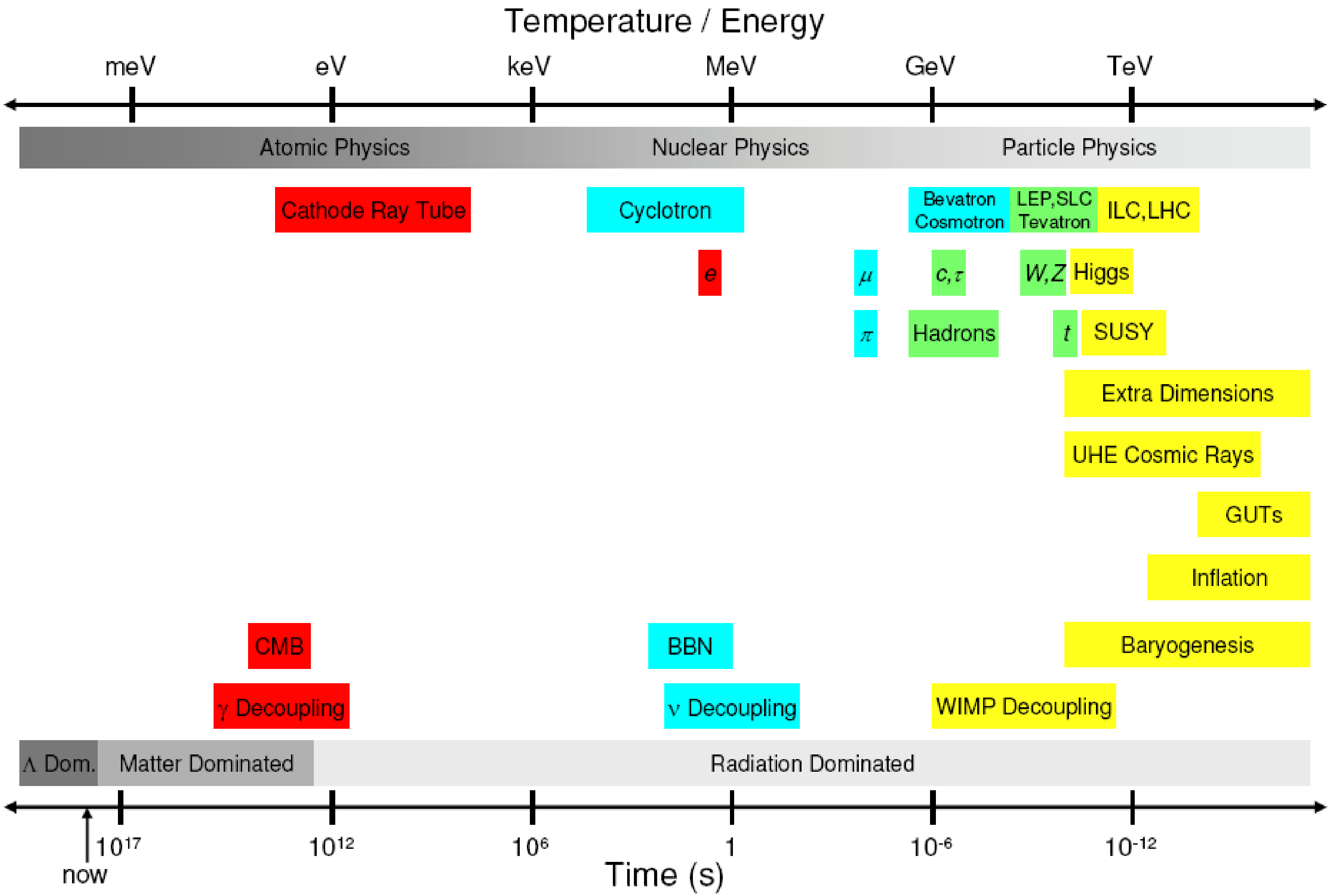
$$\Omega_{\mathrm{CMB}} \equiv \frac{\rho_{\mathrm{CMB}}}{\rho_c} \sim \frac{T^4_{\mathrm{CMB}}}{\frac{3H^2}{8\pi G}} \sim \frac{(2.7\ \mathrm{K})^4(14\ \mathrm{Gyr})^2}{(10^{19}\ \mathrm{GeV})^2}$$

$$\sim \frac{(10^{-4}\ \mathrm{eV})^4(14\pi \times 10^{16}\ \mathrm{s})^2}{(10^{-16}\ \mathrm{eV\ s})^2(10^{28}\ \mathrm{eV})^2} \sim 10^{-4}$$

- Matter-radiation equality
  - $T \sim 10^4\ T_0 \sim \mathrm{eV}$
  - $t \sim 10^{-6}\ t_0 \sim 10^{12}$ s
- Vacuum-matter equality
  - very recent past


Frieman, Turner, Huterer (2008)

THERMAL HISTORY OF THE UNIVERSE



DECOUPLING

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

$$\frac{dn}{dt} = -3\underset{\substack{\uparrow \\ \text{Dilution from} \\ \text{expansion}}}{H}n - \langle \sigma v \rangle \left[\underset{\substack{\uparrow \\ XX \to f\bar{f}}}{n^2} - \underset{\substack{\nwarrow \\ f\bar{f} \to XX}}{n_{\mathrm{eq}}^2} \right]$$

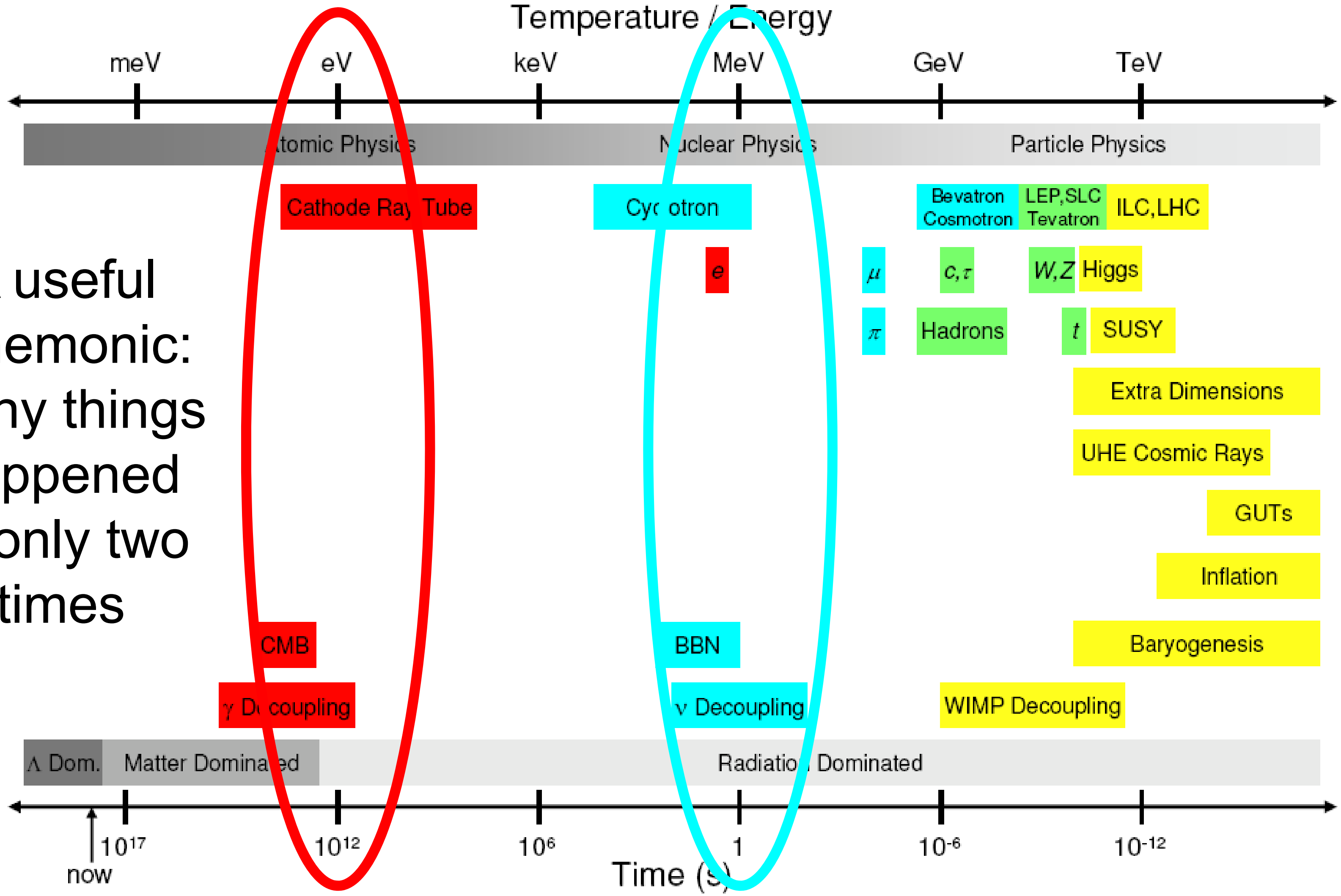
- Particles decouple (or freeze out) when $n_{\mathrm{eq}} \langle \sigma v \rangle \sim H$

- An example: neutrino decoupling. By dimensional analysis,

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

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

THERMAL HISTORY OF THE UNIVERSE



A useful mnemonic: many 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 (small-scale) 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?
- …

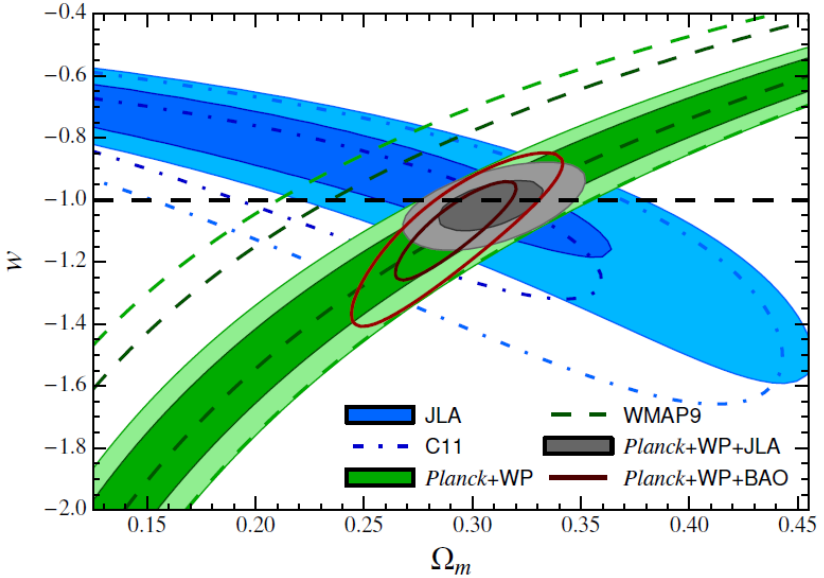
Particle physics is required to answer all of these, not least because it is required to understand the hot early Universe

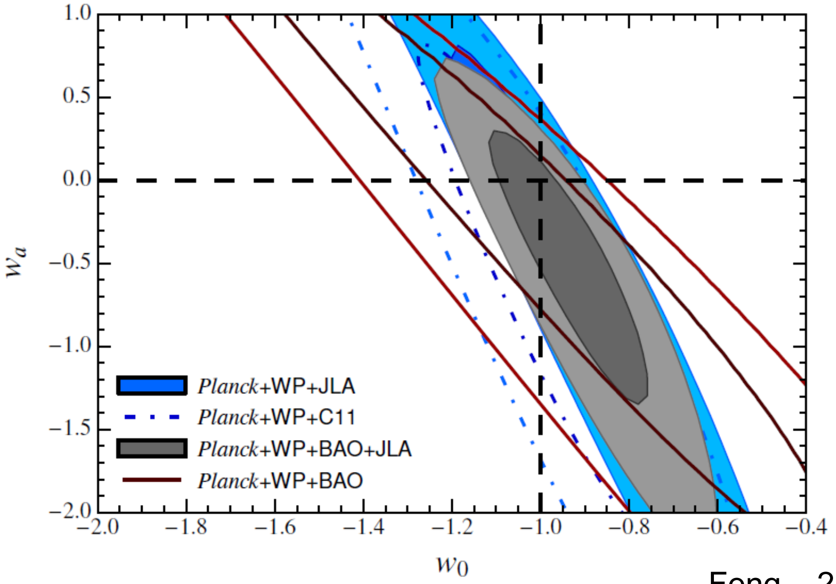
DARK ENERGY

- The properties of dark energy are now investigated by many methods
  - Supernovae
  - CMB
  - Weak lensing
  - Baryon acoustic oscillations
  - Galaxy cluster abundance

- The results are consistent with a cosmological constant, vacuum energy with w = -1 constant throughout the Universe's history

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

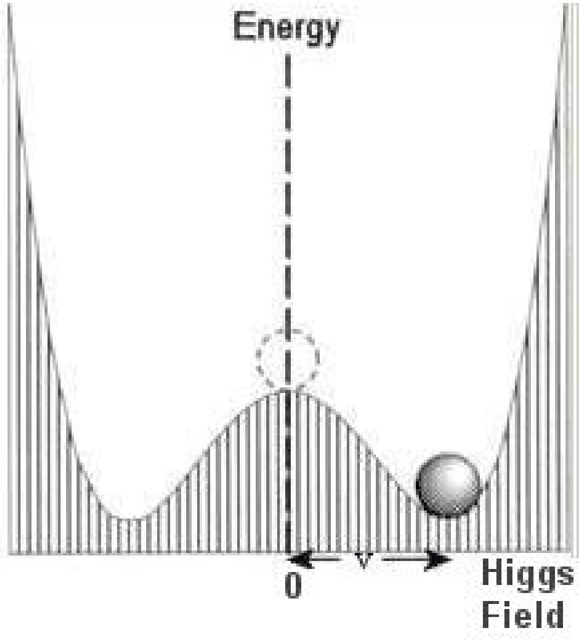




DARK ENERGY

- $\Omega_\Lambda \approx 0.73 \rightarrow \rho_\Lambda \sim (\text{meV})^4$: tiny, but all fields contribute
- Quantum mechanics:
  $\pm \frac{1}{2} \hbar \omega, \quad \omega^2 = k^2 + m^2$
- Quantum field theory:
  $\pm \frac{1}{2} \int^E d^3k\, \hbar\omega \sim \pm E^4,$

  where E is the energy scale where the theory breaks down

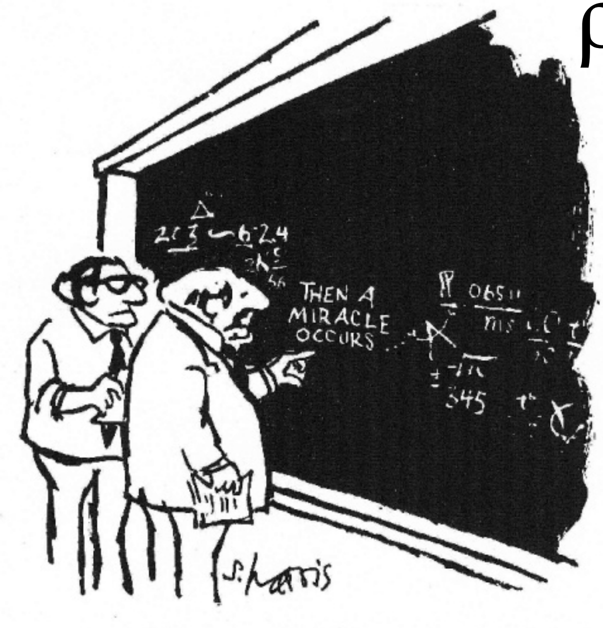


- We expect

  $(M_{\text{Planck}})^4 \sim 10^{120}\, \rho_\Lambda$ $\quad$ $(M_{\text{SUSY}})^4 \sim 10^{60}$ $-10^{90}\, \rho_\Lambda$
  $(M_{\text{GUT}})^4 \sim 10^{108}\, \rho_\Lambda$ $\quad$ $(M_{\text{weak}})^4 \sim 10^{60}\, \rho_\Lambda$

ONE APPROACH

- Small numbers ↔ broken symmetry



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

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

↓ ??

$\rho_\Lambda = 0$

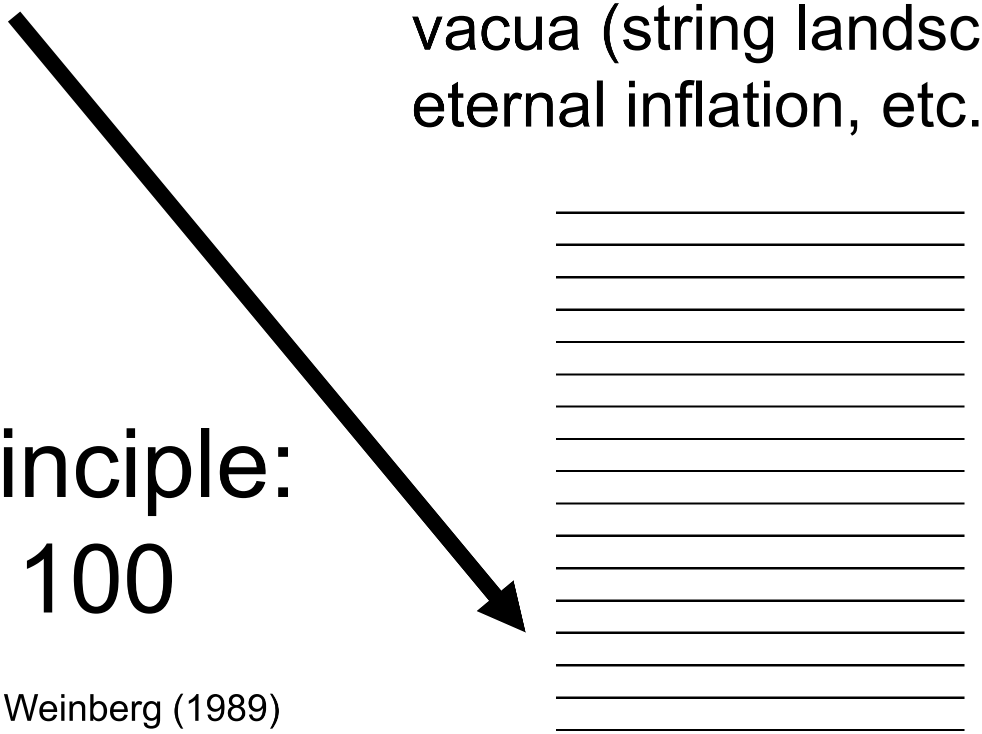
↗

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

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)

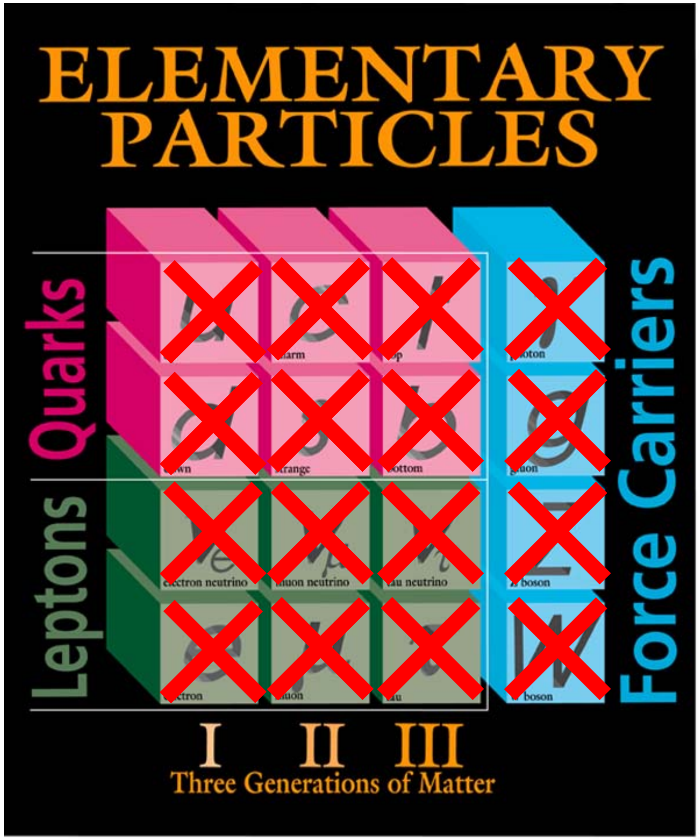
DARK ENERGY PROSPECTS

- 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

- The discrepancy between the expected and measured values of Ω_Λ is the greatest hierarchy problem in particle physics, not just because it is numerically large, but because we think we understand meV-scale physics

- Ways forward
  - Constrain DE properties, see if it deviates from a cosmological constant or indicates a deviation from GR
  - Make a breakthrough in understanding quantum gravity
  - Learn something unexpected about fundamental scalars

DARK MATTER



Fermilab 95-759

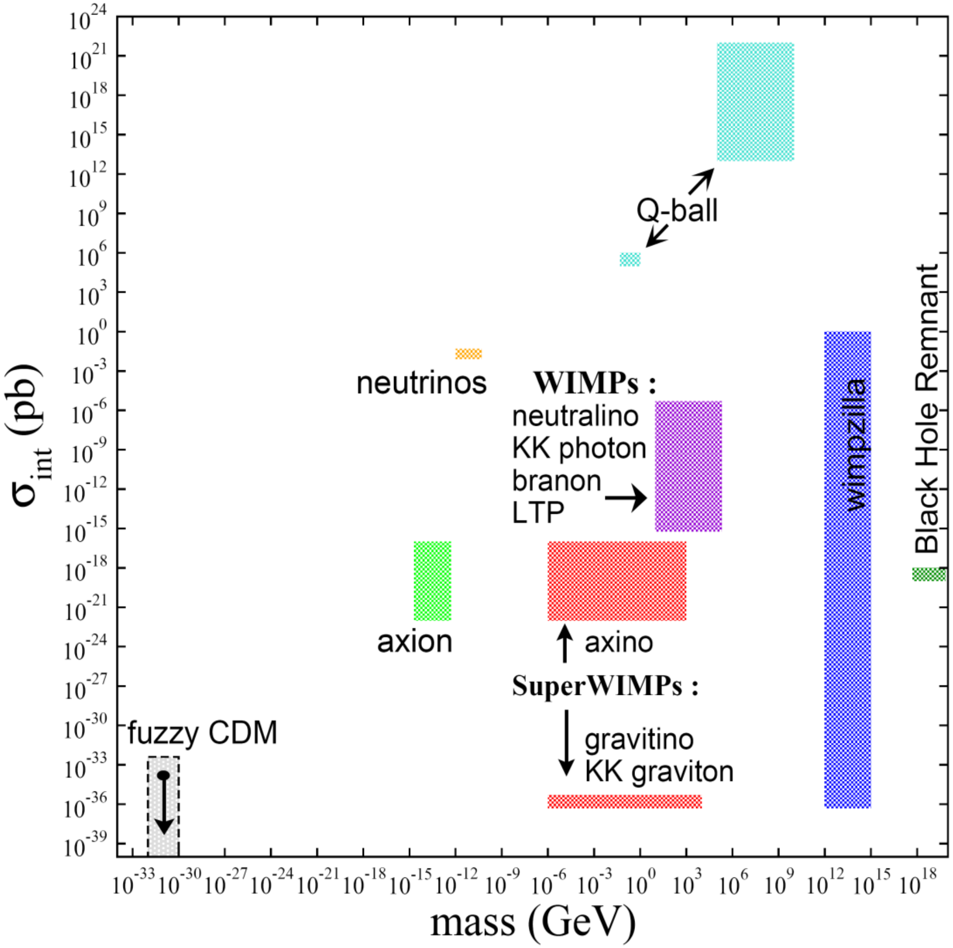
Known DM properties

- 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 particles with weak-scale masses



HEPAP/AAAC DMSAG Subpanel (2007)

FREEZE OUT: QUALITATIVE

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

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

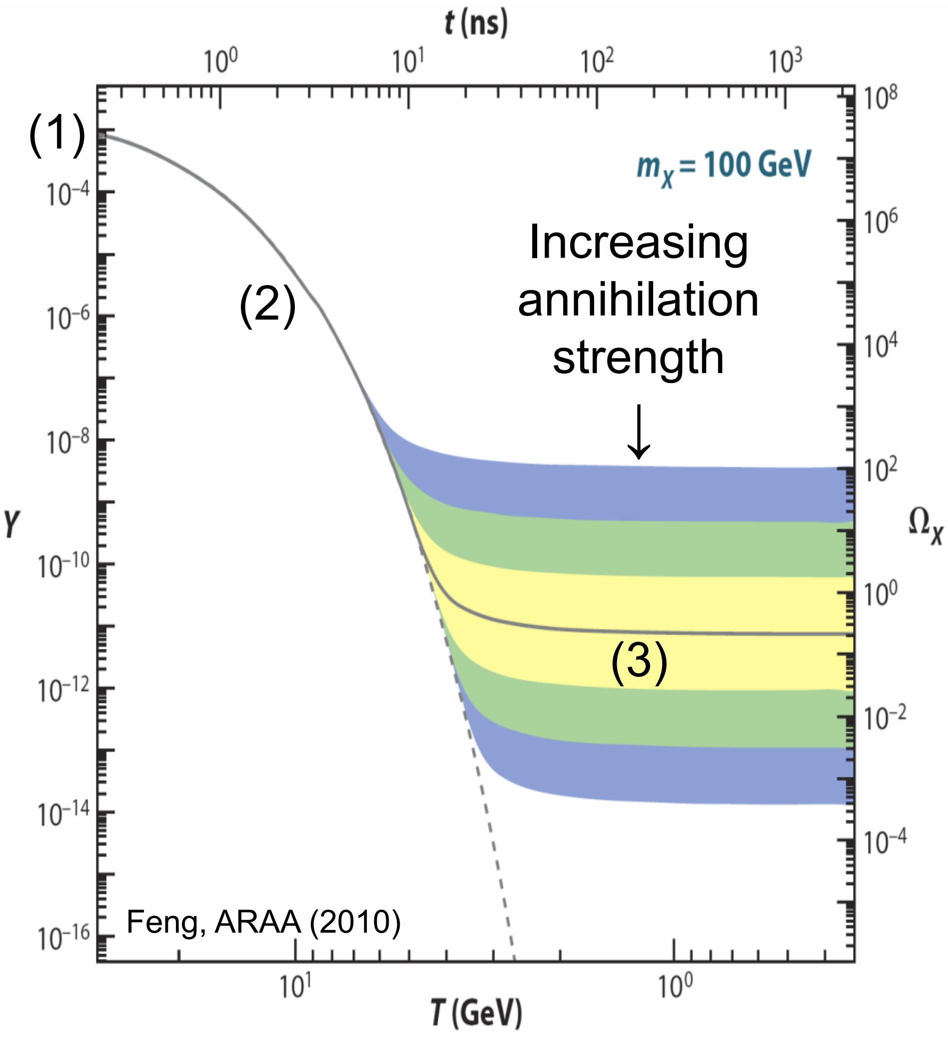
(2) Universe cools:

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

(3) Universe expands:

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

Zeldovich et al. (1960s)



Increasing annihilation strength ↓

Feng, ARAA (2010)

FREEZE OUT: MORE QUANTITATIVE

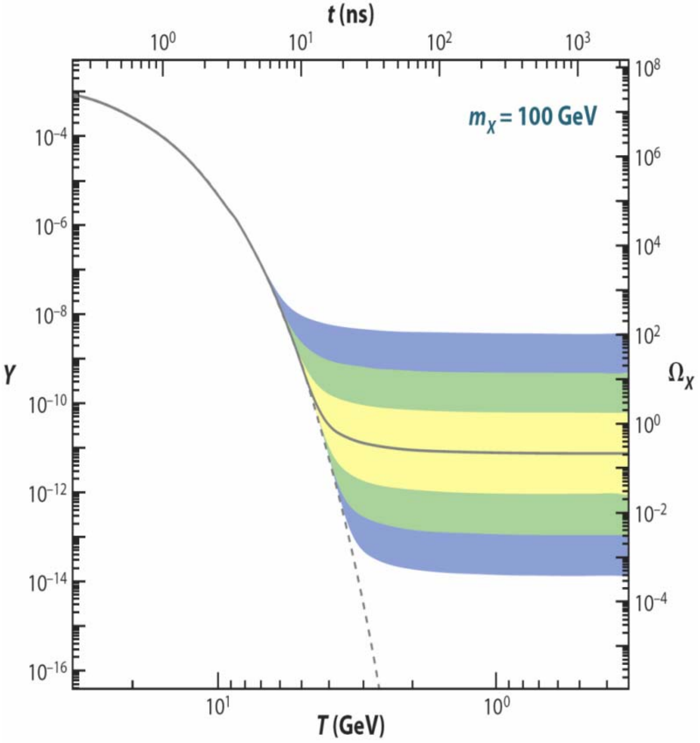
- The Boltzmann equation:

$$\frac{dn}{dt} = \underset{\substack{\uparrow \\ \text{Dilution from} \\ \text{expansion}}}{-3Hn} - \langle \sigma v \rangle \left[\underset{\substack{\uparrow \\ \chi\chi \to f\bar{f}}}{n^2} - \underset{\substack{\nwarrow \\ f\bar{f} \to \chi\chi}}{n_{\mathrm{eq}}^2} \right]$$

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

$$\underset{\substack{\uparrow \\ (mT)^{3/2}e^{-m/T}}}{n_{\mathrm{eq}}} \underset{\substack{\uparrow \\ m^{-2}}}{\langle \sigma v \rangle} \sim \underset{\substack{\uparrow \\ T^2/M_{\mathrm{Pl}}}}{H}$$

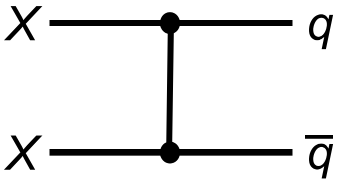
- Might expect freeze out at T ~ m, but the universe expands *slowly*! First guess: $m/T \sim \ln(M_{Pl}/m_W) \sim 40$



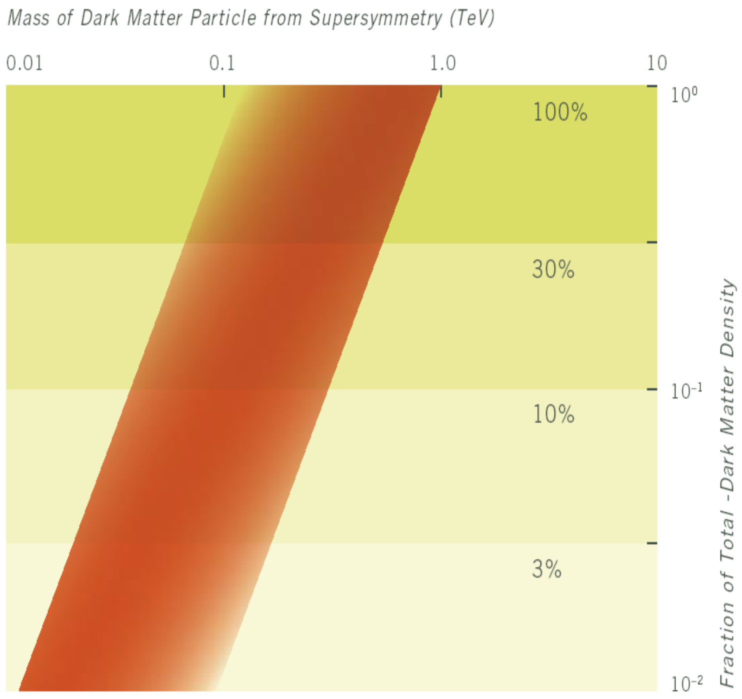
THE WIMP MIRACLE

- The relation between Ω_X and annihilation strength is wonderfully simple:

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



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



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

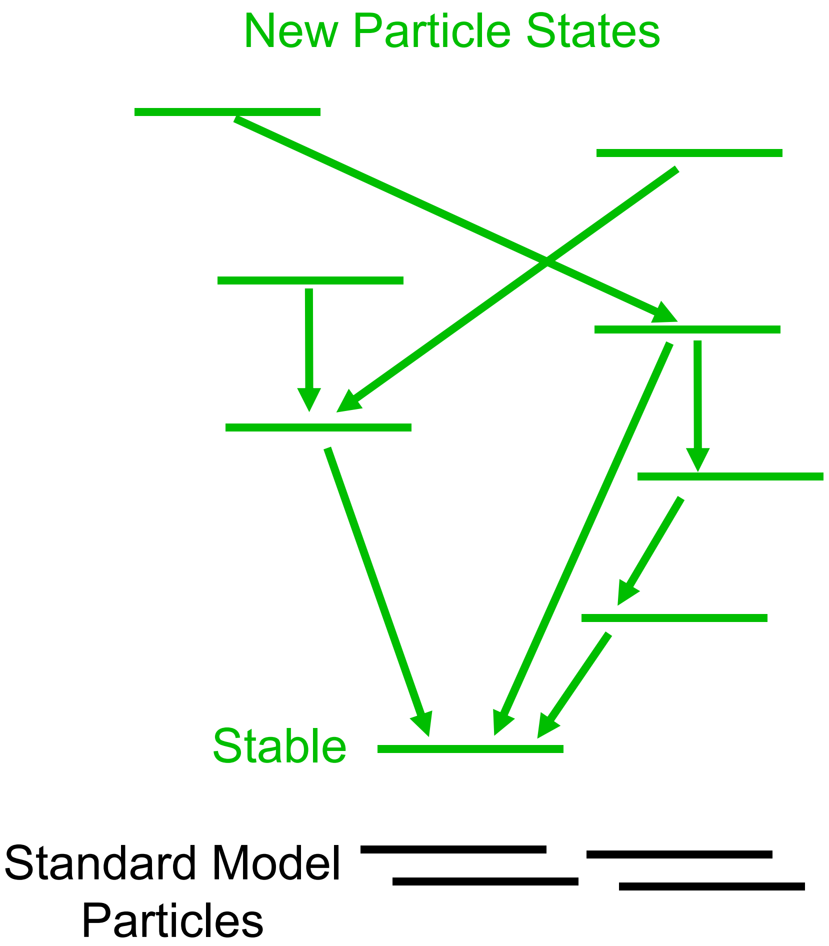
- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

WIMP STABILITY

- The WIMP Miracle is very well appreciated, and it is a quantitative feature. But its success relies on some less well-advertised qualitative features

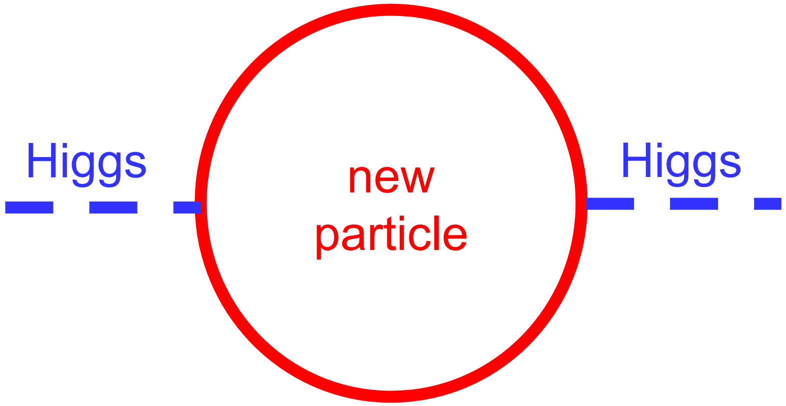
- First, the WIMP must be stable

- How natural is this? *A priori*, not very: the only stable particles we know about are very light

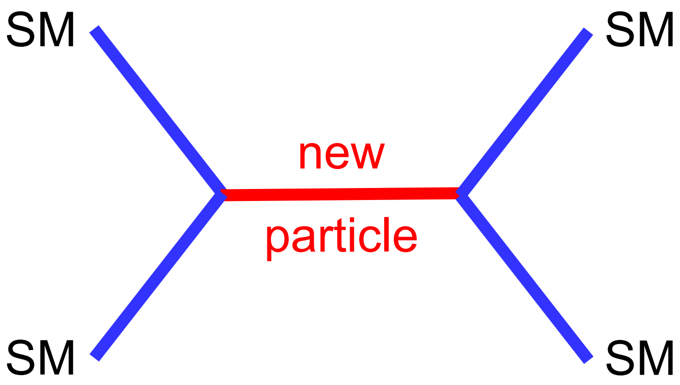


LEP'S COSMOLOGICAL LEGACY

Gauge Hierarchy requires



Precision EW excludes



In some cases, there are even stronger reasons to exclude these 4-particle interactions (e.g., proton decay in SUSY)

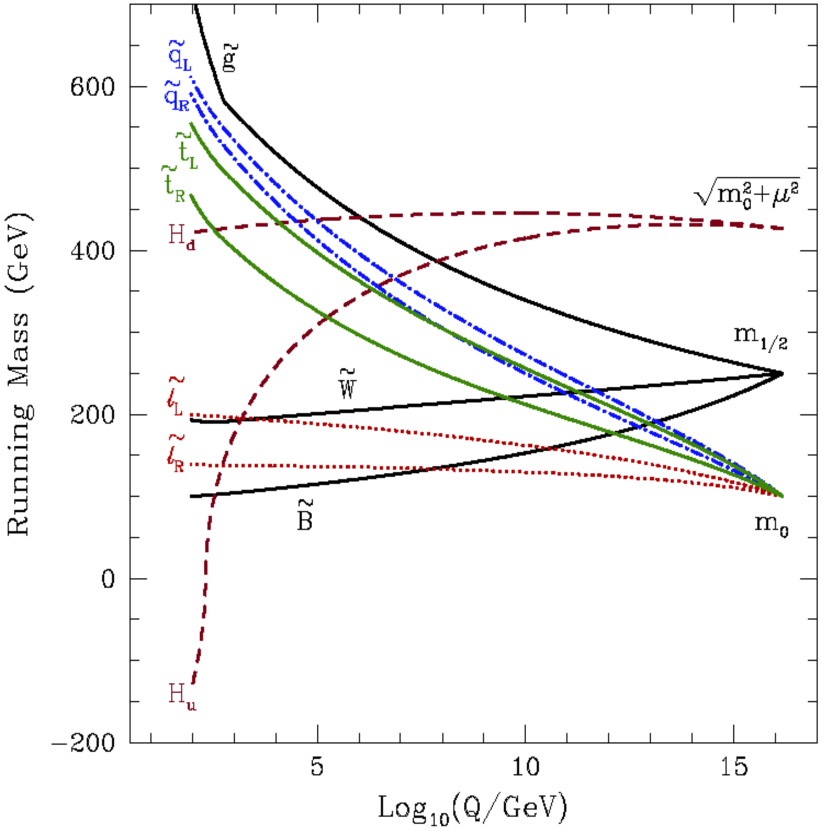
- Simple solution: impose a discrete parity, so all interactions require *pairs* of new particles. This also makes the lightest new particle stable:

LEP constraints ↔ Discrete Symmetry ↔ Stability

Cheng, Low (2003); Wudka (2003)

WIMP NEUTRALITY

- WIMPs must also be neutral
- How natural is this? Again, *a priori*, not very: what is the chance that the lightest new particle happens to be neutral?
- In fact, in many cases (SUSY, extra dims, …), masses are "proportional" to couplings, so neutral particles are the lightest



Bottom line: WIMPs, new particles that are *stable* and *neutral* with Ω ~ 0.1, appear in many models of new particle physics

LECTURE 1 SUMMARY

- The revolution in cosmology has produced remarkable progress
- This progress also highlights puzzles that require particle physics answers
- Cosmology and particle physics both point to the weak scale for new particles
- Next time: what are the opportunities for probing the weak scale with dark matter searches?

OUTLINE

LECTURE 1

Essential Cosmology: Contents and History of the Universe

LECTURE 2

WIMP Dark Matter: Candidates and Methods of Detection

LECTURE 3

Inflation, Gravitinos, and Hidden Sectors

WIMP EXAMPLES

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

- The prototypical WIMP: neutralinos in supersymmetry

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

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

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

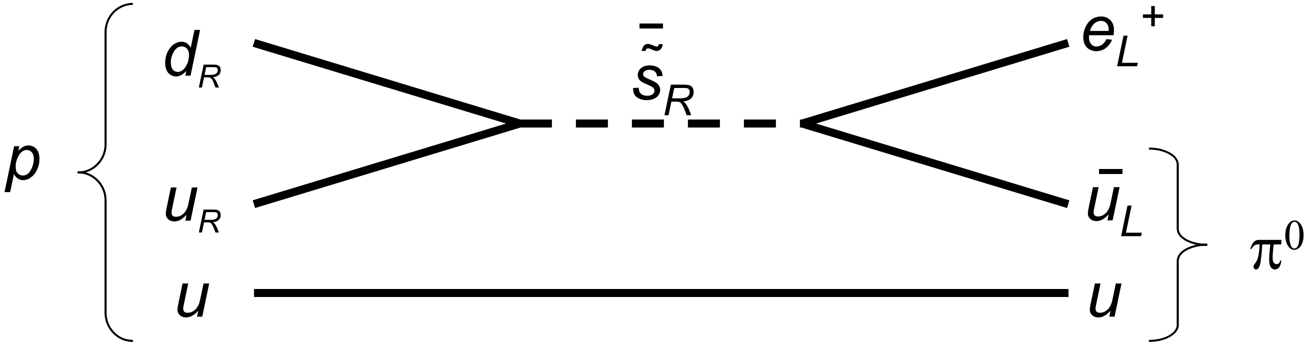
NEUTRAL SUSY PARTICLES

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

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

R-PARITY AND STABLE LSPS

- One problem: proton decay

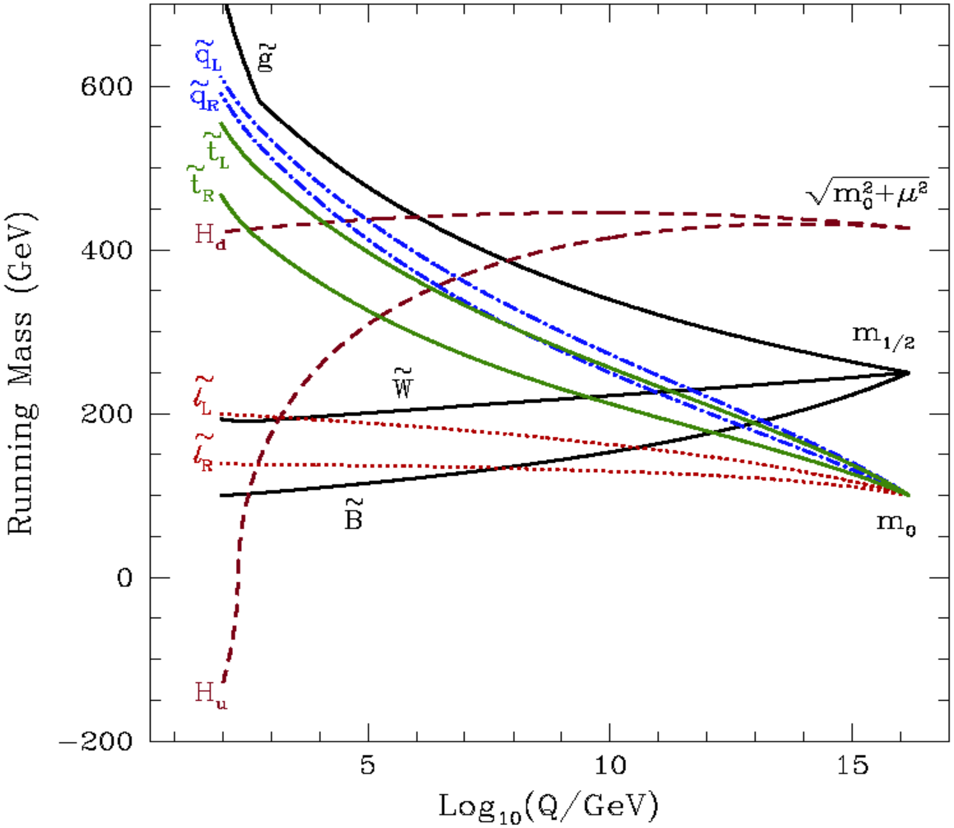


- Forbid this with R-parity conservation: $R_p = (-1)^{3(B-L)+2S}$
  - SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
  - Require $\Pi\ R_p = 1$ at all vertices
- Consequence: the lightest SUSY particle (LSP) is stable!

WHAT'S THE LSP?

- High-scale → weak scale through RGEs
- Gauge couplings increase masses;

  Yukawa couplings decrease masses
- "typical" LSPs: χ , $\tilde{\tau}_R$

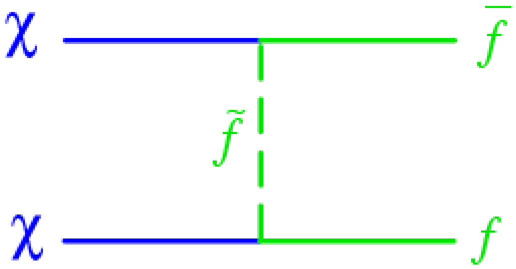


Olive (2003)

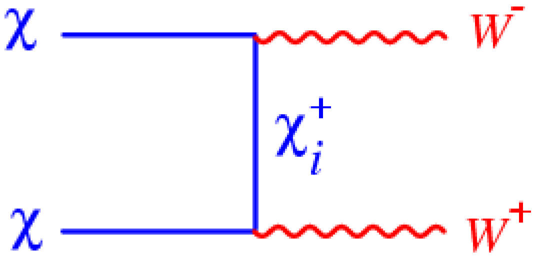
Particle physics alone → neutral, stable, cold dark matter

RELIC DENSITY

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



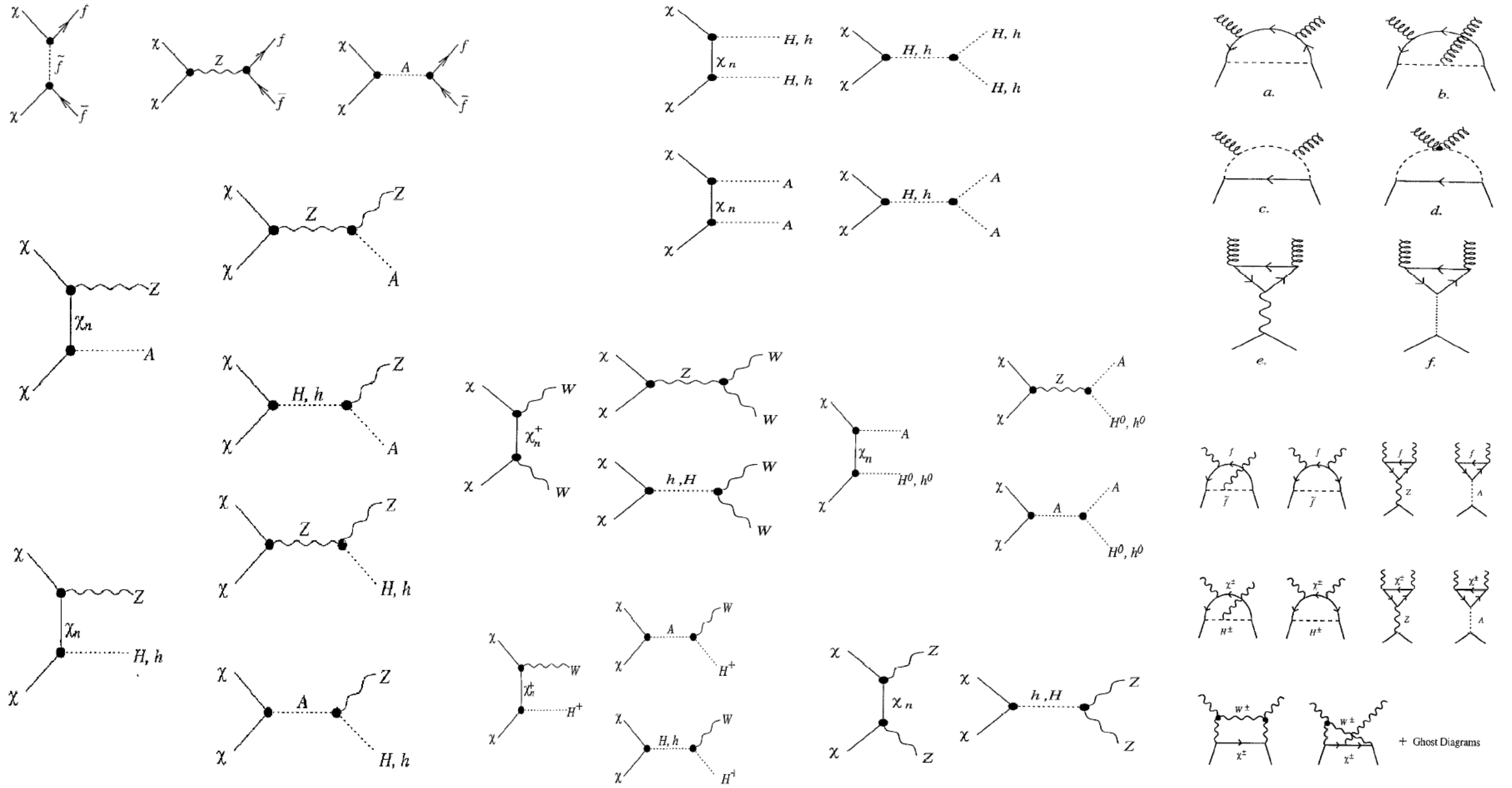
- χ are Majorana fermions, so Pauli exclusion → $S_{in} = 0$, L conservation →
  - P-wave suppression: $\sigma v \sim \sigma_0 + \sigma_1 v^2$,
    $mv^2/2 = 3T/2$ → $v^2 \sim 3T/m \sim 0.1$
  - m_f / m_W suppression



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

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

NEUTRALINO ANNIHILATION



Jungman, Kamionkowski, Griest (1995)

COSMOLOGICALLY-PREFERRED SUSY

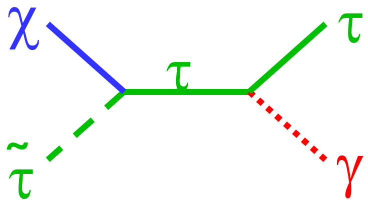
Typically get too much DM, but there are mechanisms for reducing it

Excluded:

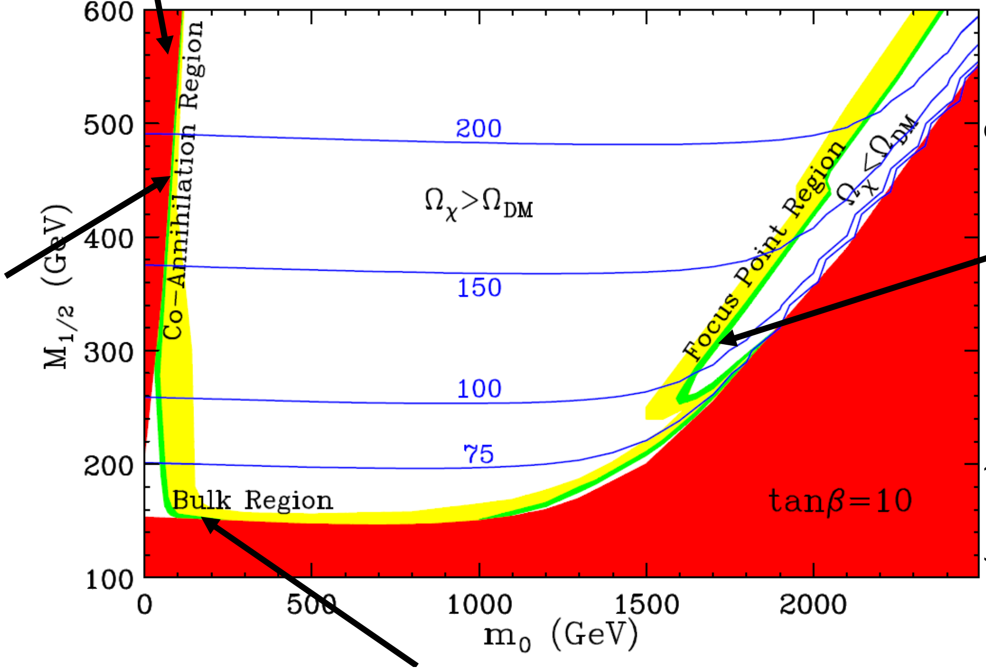
Stau LSP

Yellow: pre-WMAP

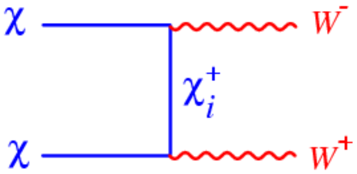
Green: post-WMAP



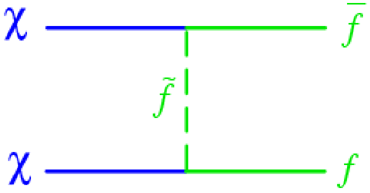
Stau and χ degenerate to within roughly T ~ m/25



Feng, Matchev, Wilczek (2003)



Higgsino-Bino Neutralinos



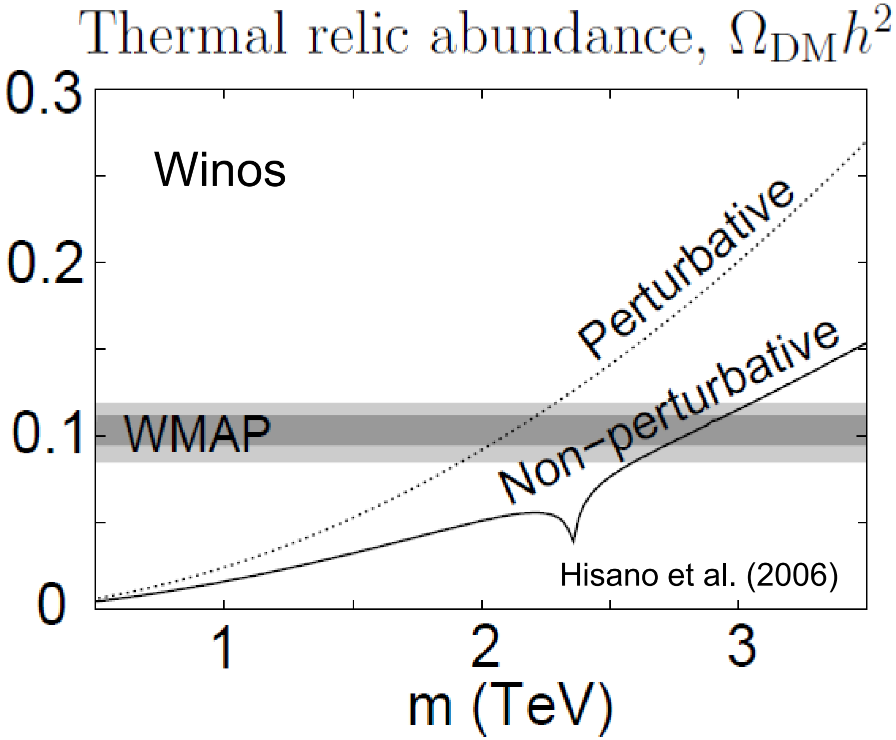
Light sfermions

COSMOLOGICALLY-PREFERRED SUSY

- After LHC8, there remain several neutralino candidates with the right relic density
  - Co-annihilating DM
    χ , $\tilde{\tau}_R$ degenerate, m < 600 GeV
  - Focus-point DM
    Bino-Higgsino mixture, m < 1 TeV
  - Wino-like DM
    m ~ 2.7-3 TeV

- Note: in this context, cosmology provides upper bounds!

- The Wino scenario is probably excluded by indirect detection, but the other two remain viable, provide interesting targets for LHC13 and future colliders

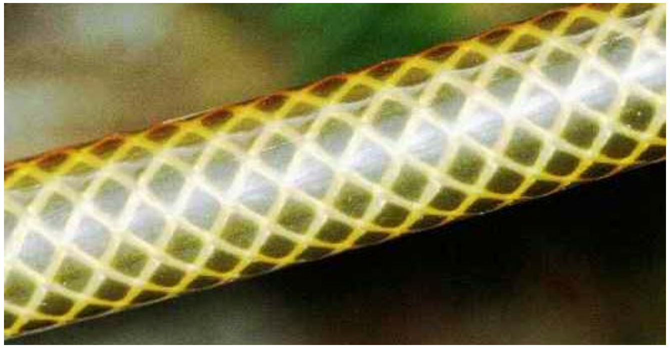


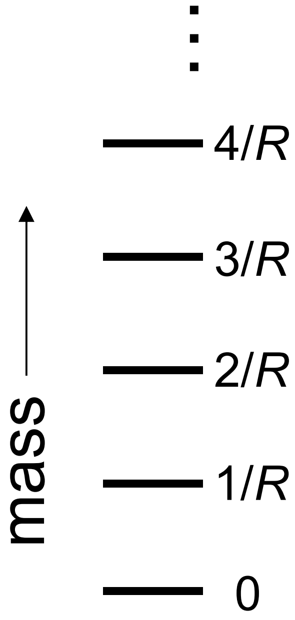
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

KK DARK MATTER

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

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





KK-PARITY

Appelquist, Cheng, Dobrescu (2001)

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

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

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

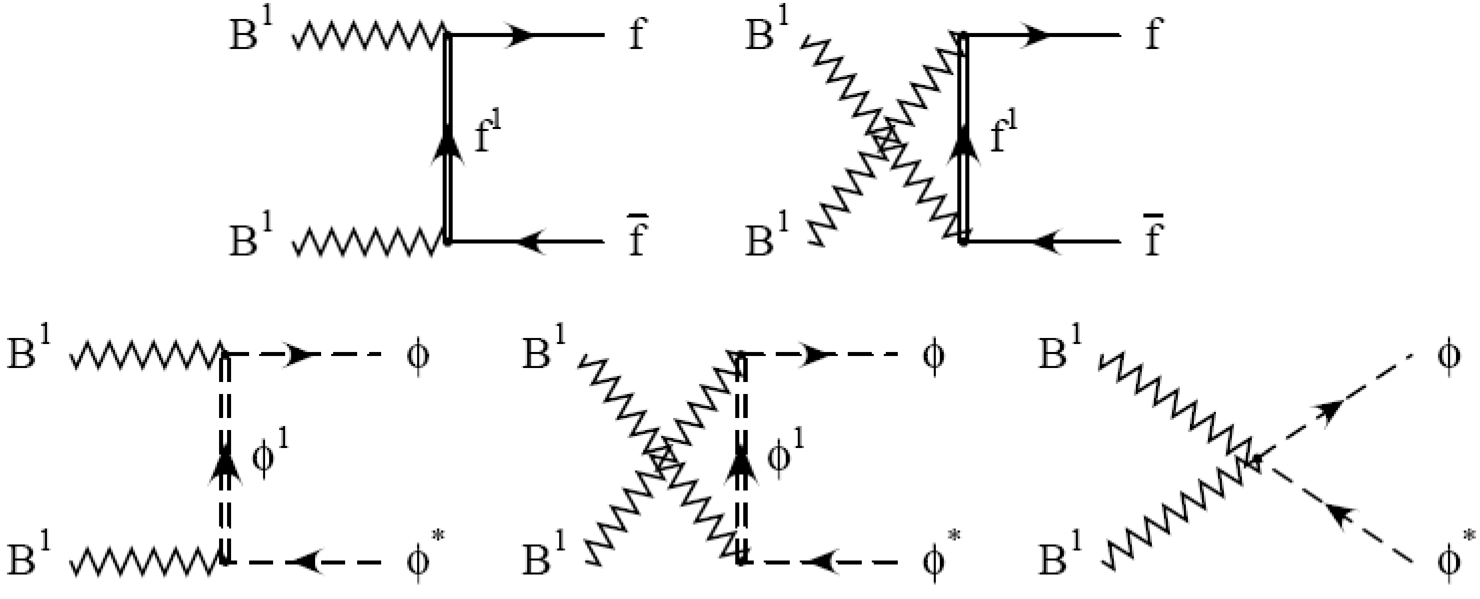
- Solution: compactify on S^1/Z_2 orbifold

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

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

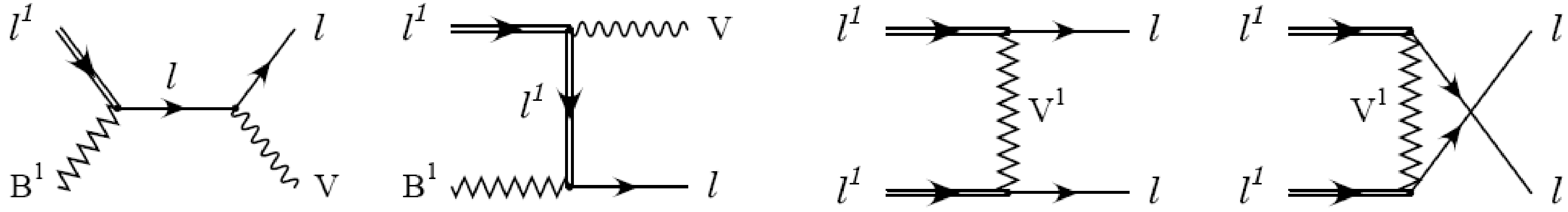
B^1 ANNIHILATION

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

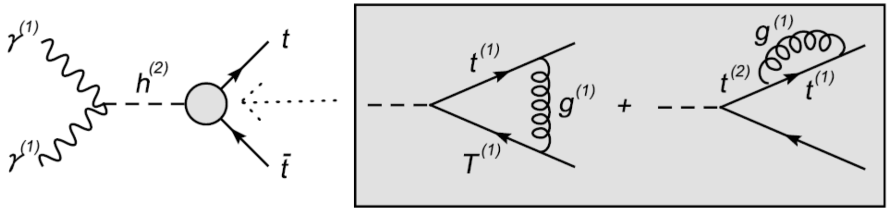


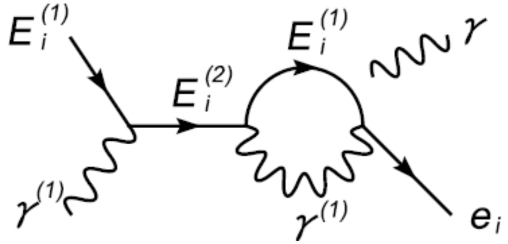
MORE B^1 ANNIHILATION

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



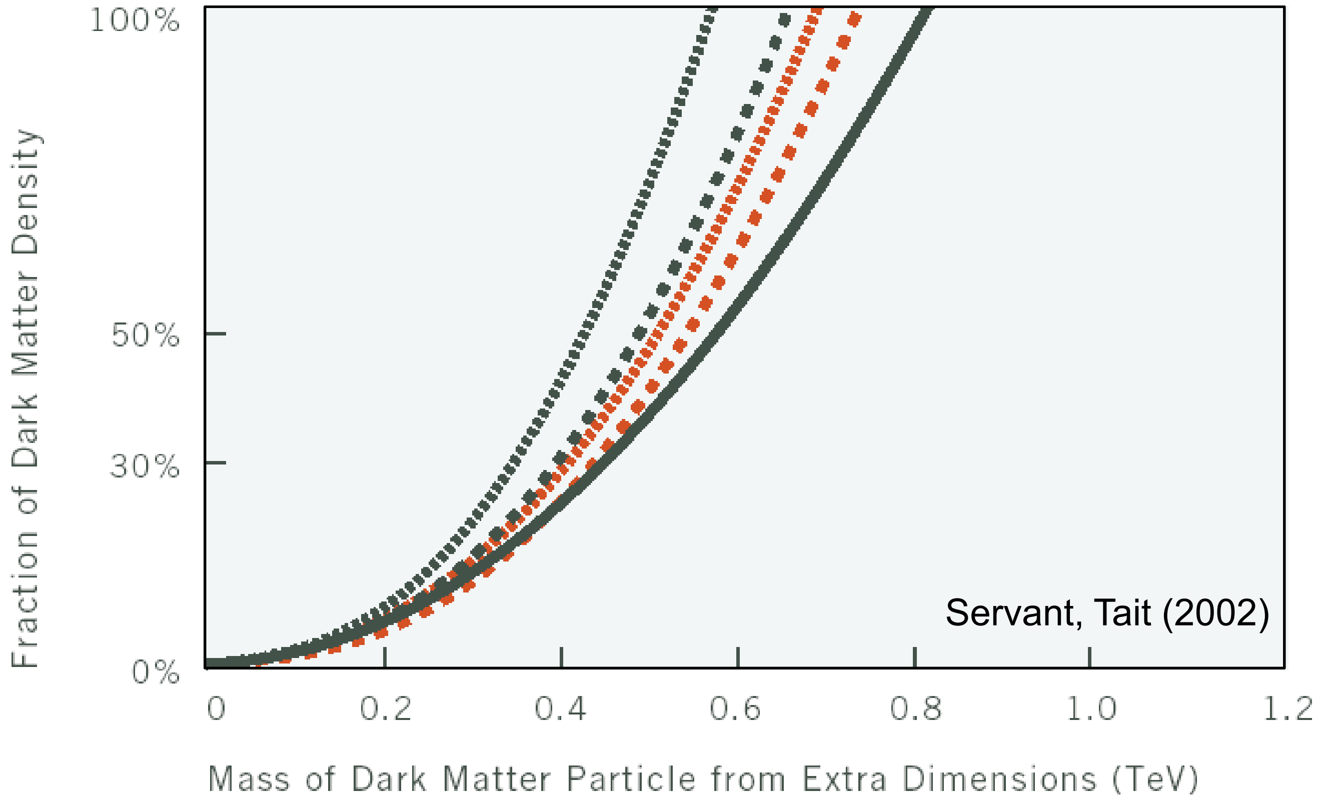
- Level-2 KK resonances





Servant, Tait (2002); Burnell, Kribs (2005)
Kong, Matchev (2005); Kakizaki, Matsumoto, Sato, Senami (2005)

KK DARK MATTER RELIC DENSITY

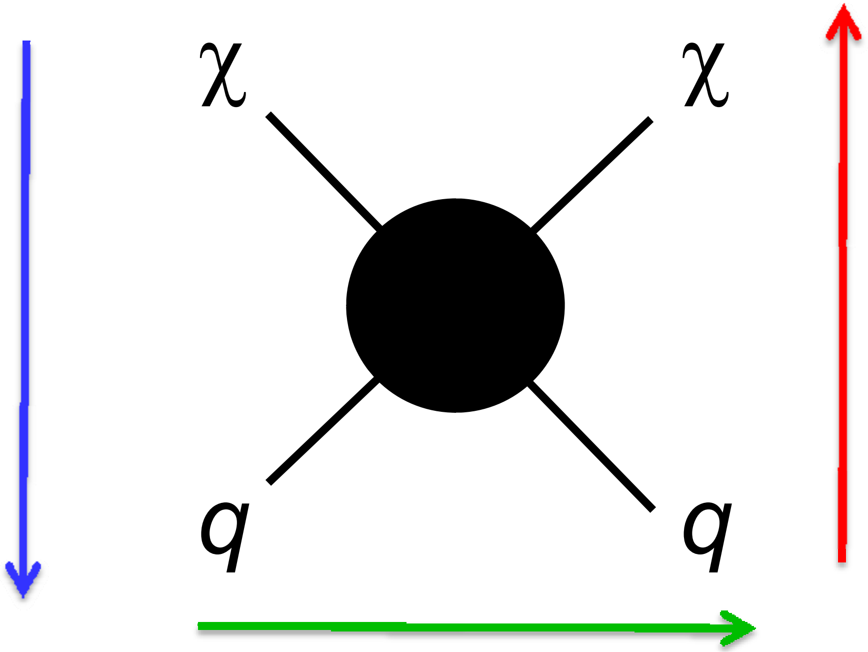


Servant, Tait (2002)

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

WIMP DETECTION

Correct relic density → Efficient annihilation then

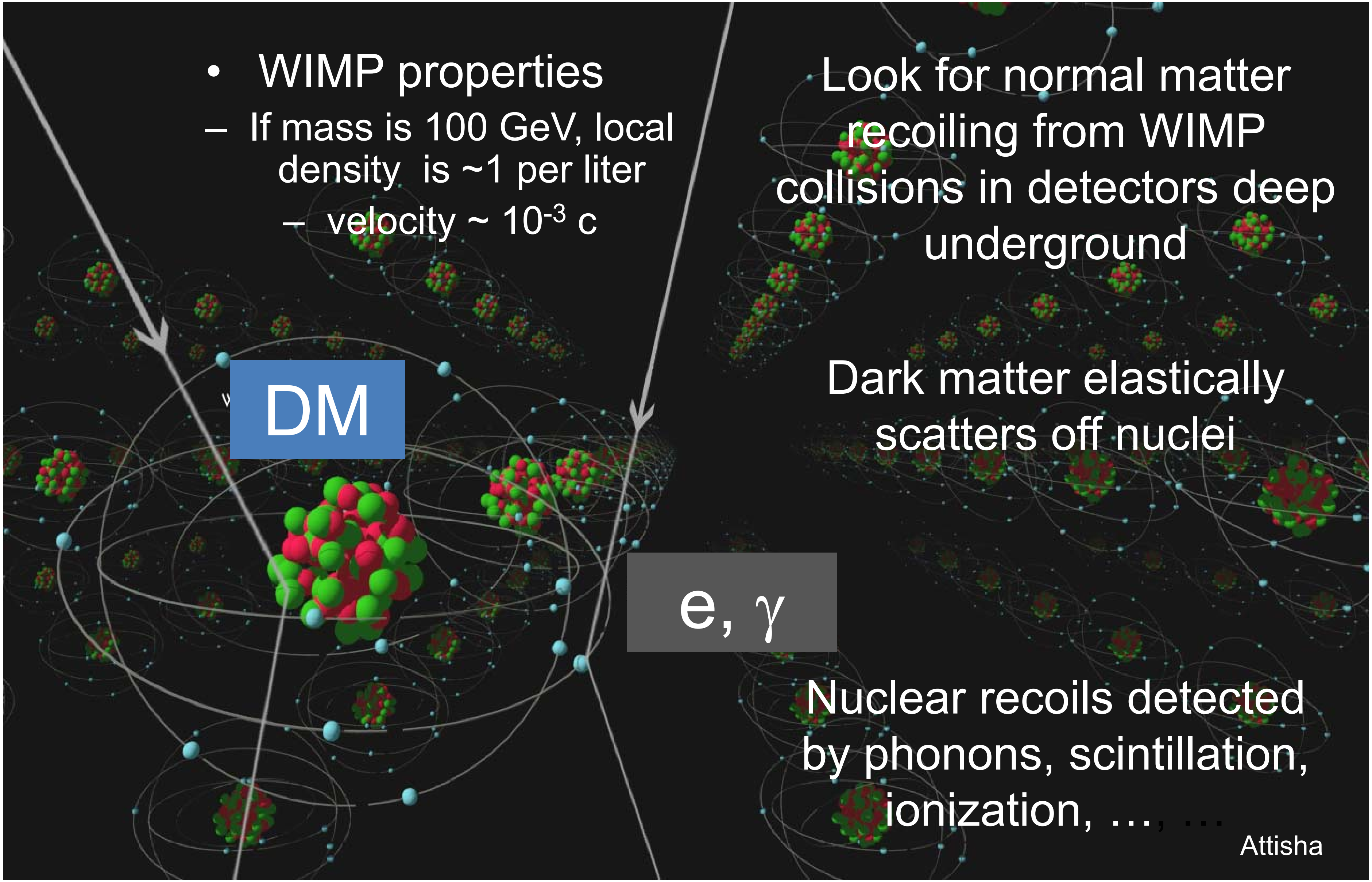


Efficient annihilation now
(Indirect detection)

Efficient production now
(Particle colliders)

Efficient scattering now
(Direct detection)

DIRECT DETECTION



- WIMP properties
  - If mass is 100 GeV, local density is ~1 per liter
  - velocity ~ 10^{-3} c

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

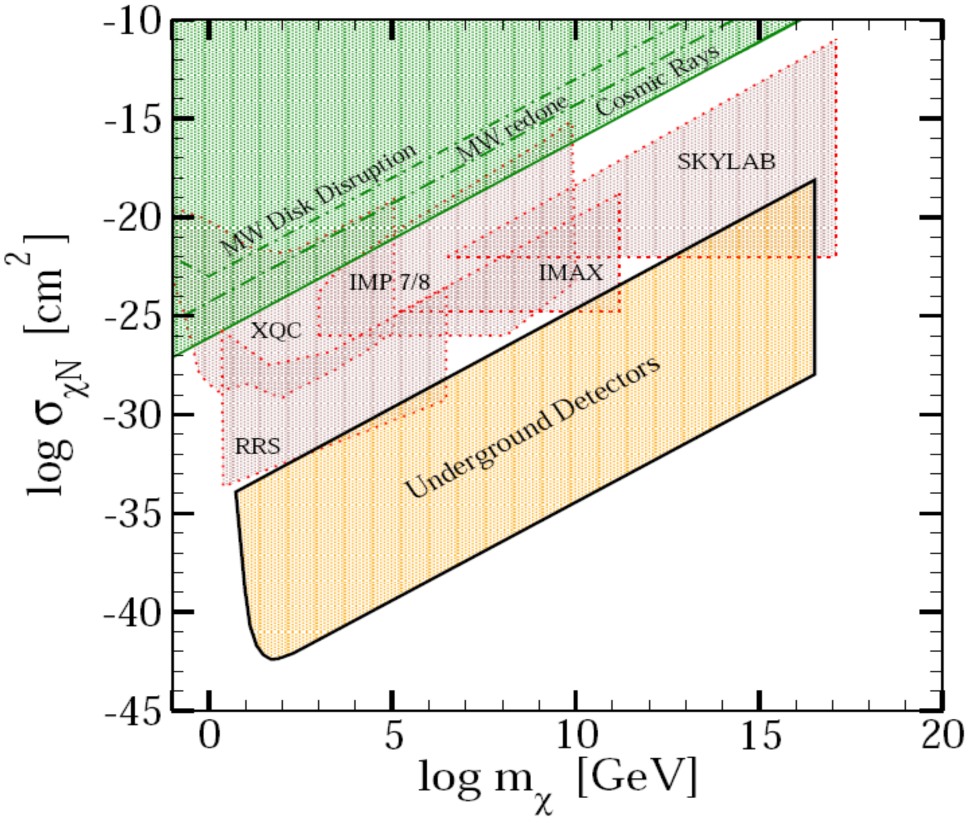
Dark matter elastically scatters off nuclei

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

Attisha

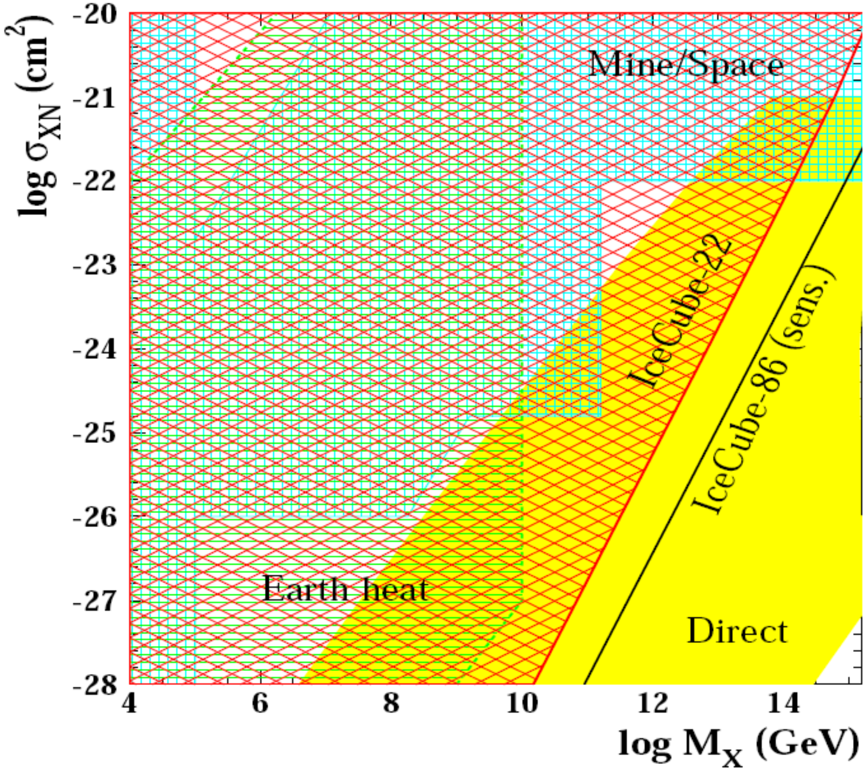
THE BIG PICTURE: UPPER BOUND

- What is the upper bound?



Mack, Beacom, Bertone (2007)

- Strongly-interacting window is now closed

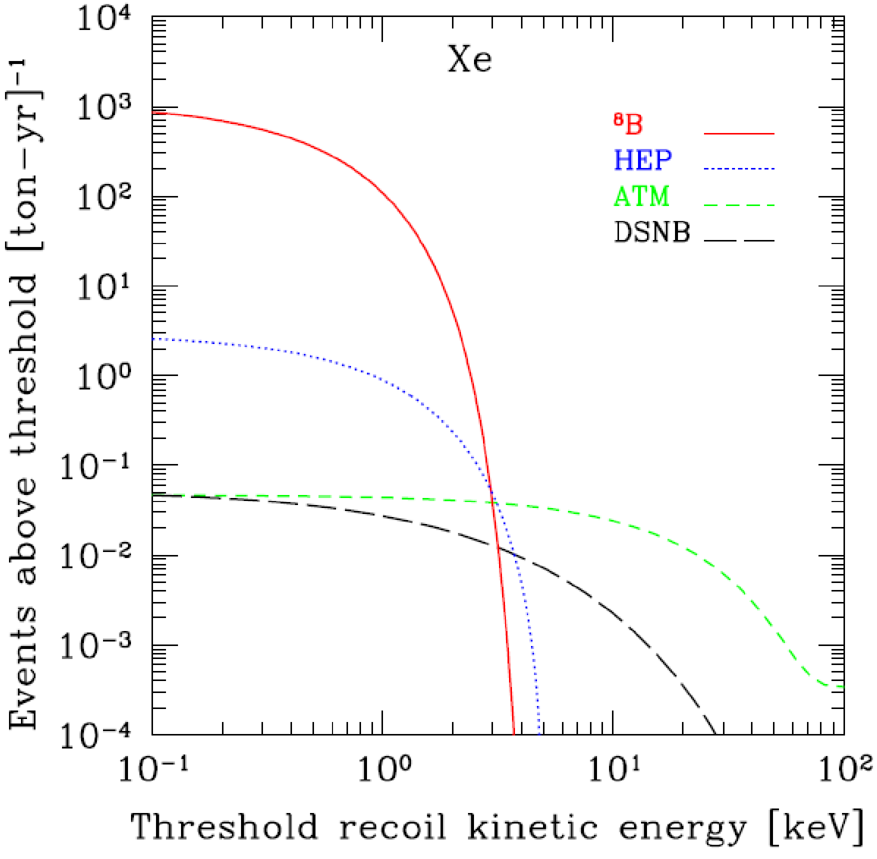


Albuquerque, de los Heros (2010)

THE BIG PICTURE: LOWER BOUND

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

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



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

SPIN-INDEPENDENT VS. SPIN-DEPENDENT SCATTERING

- Consider neutralinos with quark interactions

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

- 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

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

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

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

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

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

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

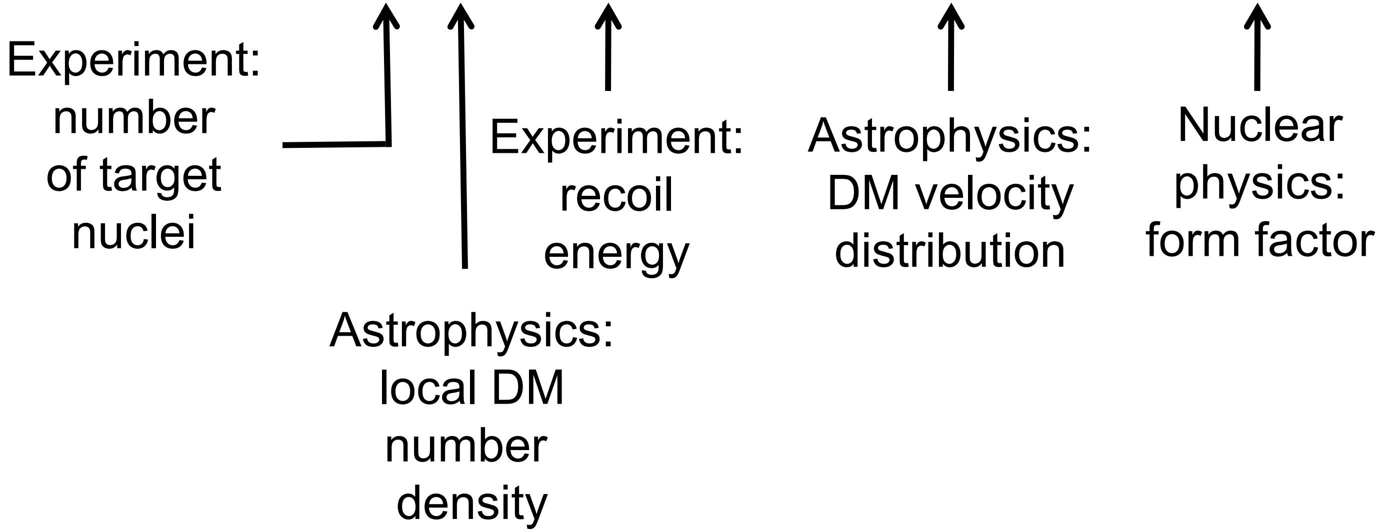
  where $f_{p,n}$ are the nucleon level couplings. Note that f_p and f_n are not necessarily equal.

SPIN-INDEPENDENT EXPERIMENT

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

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

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



Experiment: number of target nuclei

Astrophysics: local DM number density

Experiment: recoil energy

Astrophysics: DM velocity distribution

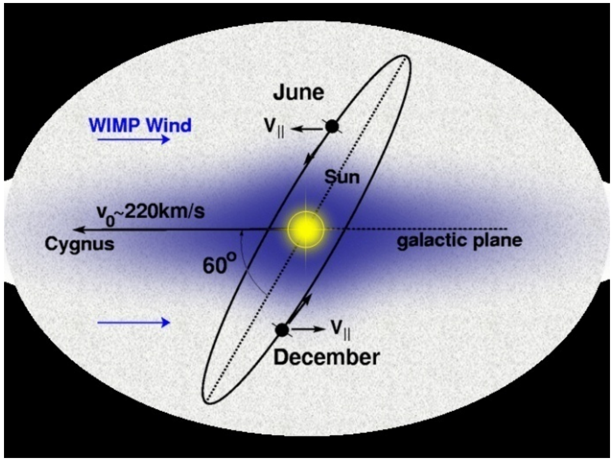
Nuclear physics: form factor

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

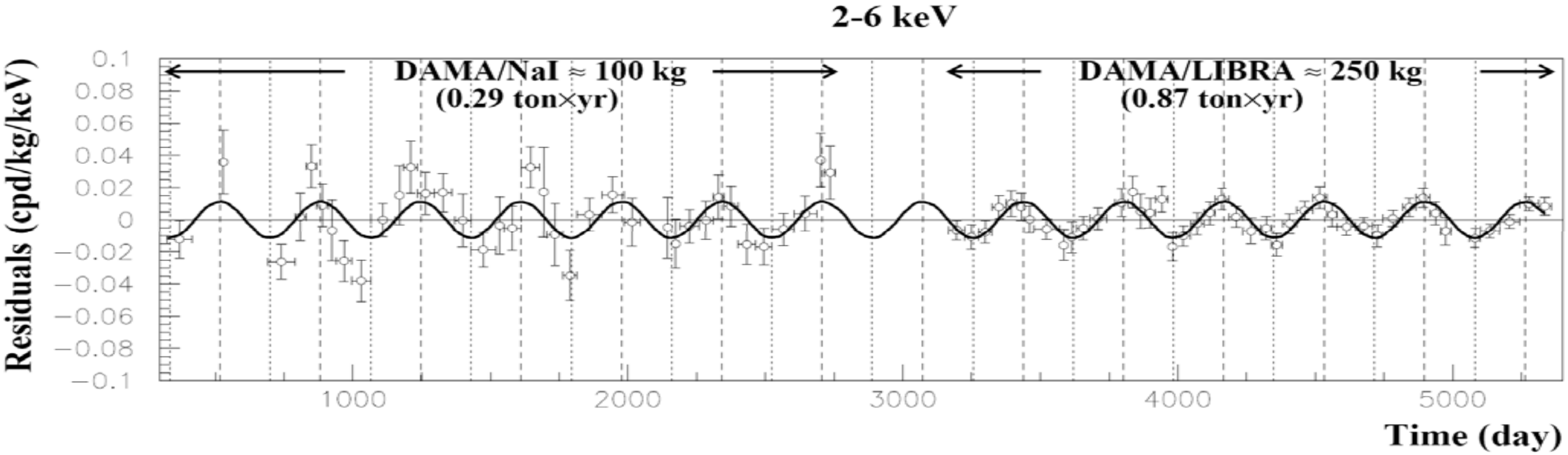
CURRENT STATUS

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

Drukier, Freese, Spergel (1986)



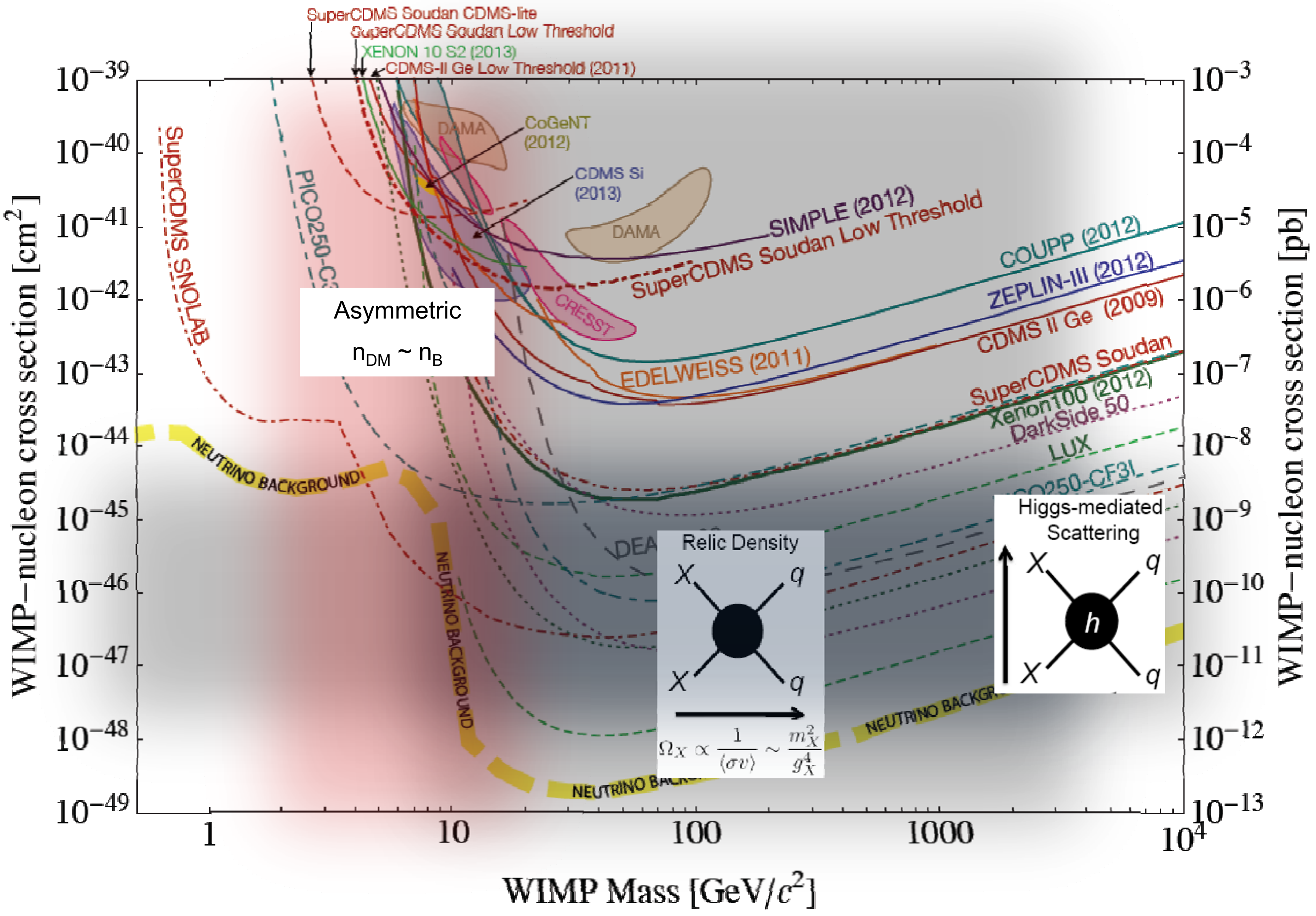
DAMA: 9σ signal with T ~ 1 year, max ~ June 2



DAMA (2013)

DAMA signal now supplemented by others

CURRENT STATUS AND FUTURE PROSPECTS



Asymmetric

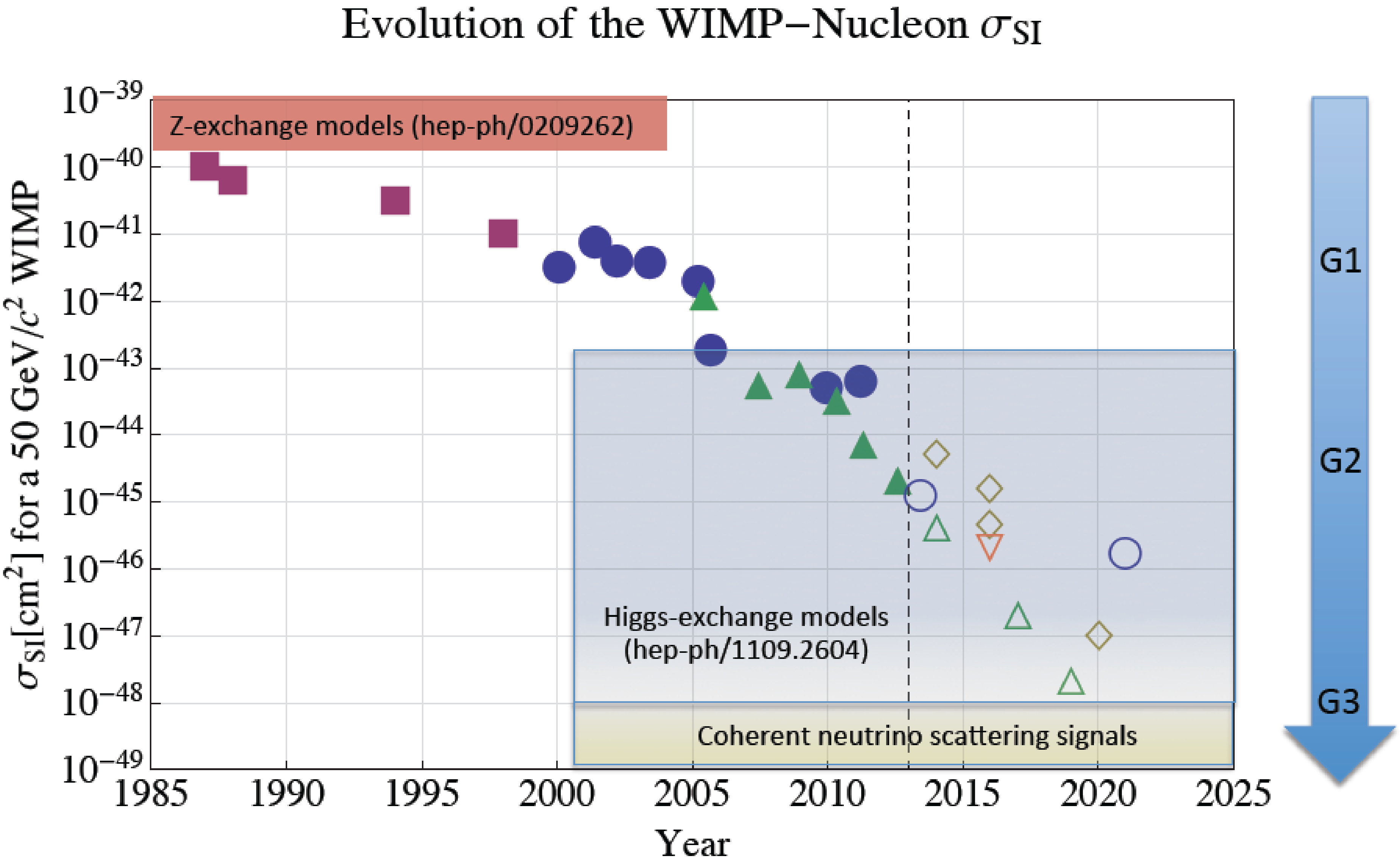
$n_{DM} \sim n_B$

Relic Density

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

Higgs-mediated Scattering

MOORE'S LAW FOR DARK MATTER



ISOSPIN-VIOLATING DARK MATTER

- The direct detection anomalies have motivated many DM ideas. As an example, consider a particularly simple model with HEP implications: IVDM

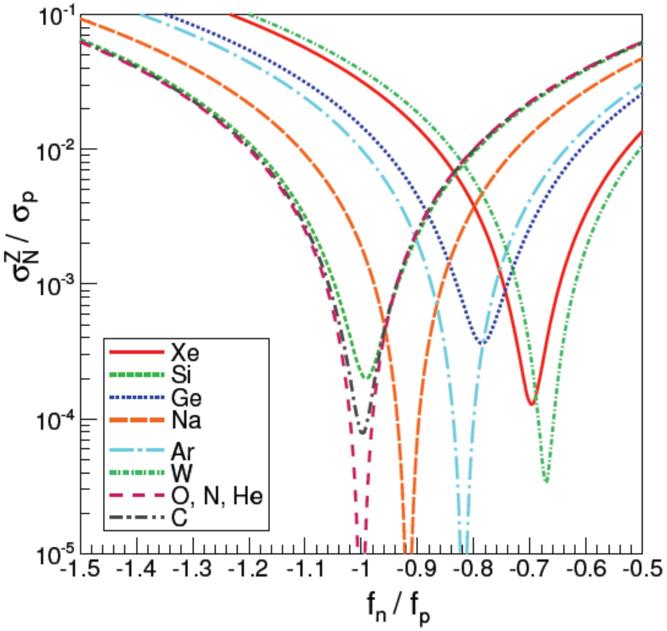
- Recall that DM scattering off nuclei is
  - $\sigma_A \sim [\, f_p Z + f_n (A-Z)\,]^2$

- Typically assume
  - $f_n = f_p$, $\sigma_A \sim A^2$

- IVDM relaxes this assumption, introduces 1 new parameter: f_n / f_p

- Can decouple any given isotope by a suitable choice of f_n / f_p .

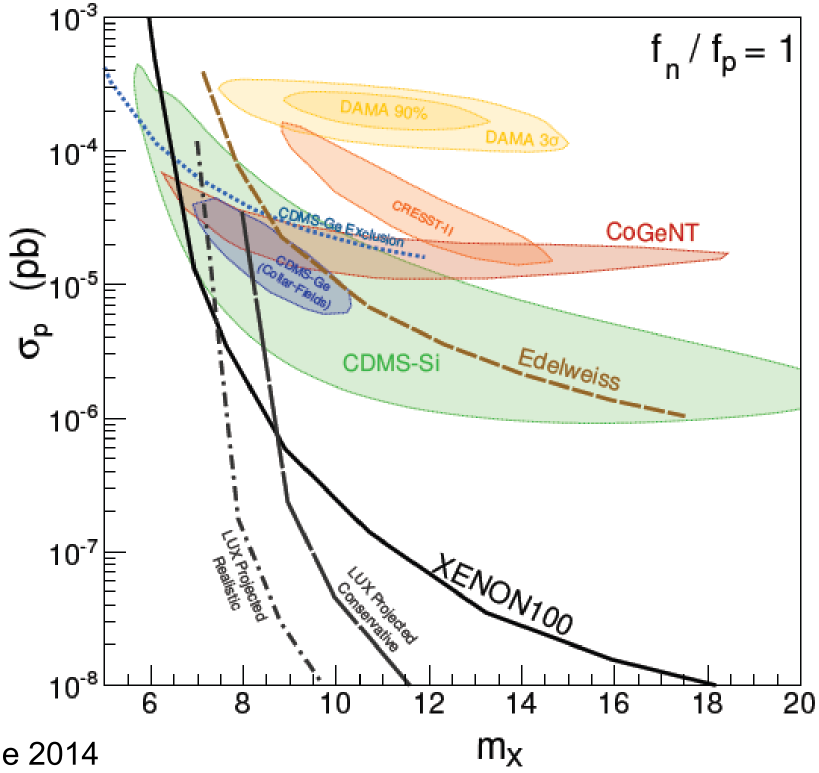
- Crucially important to account for isotope distributions

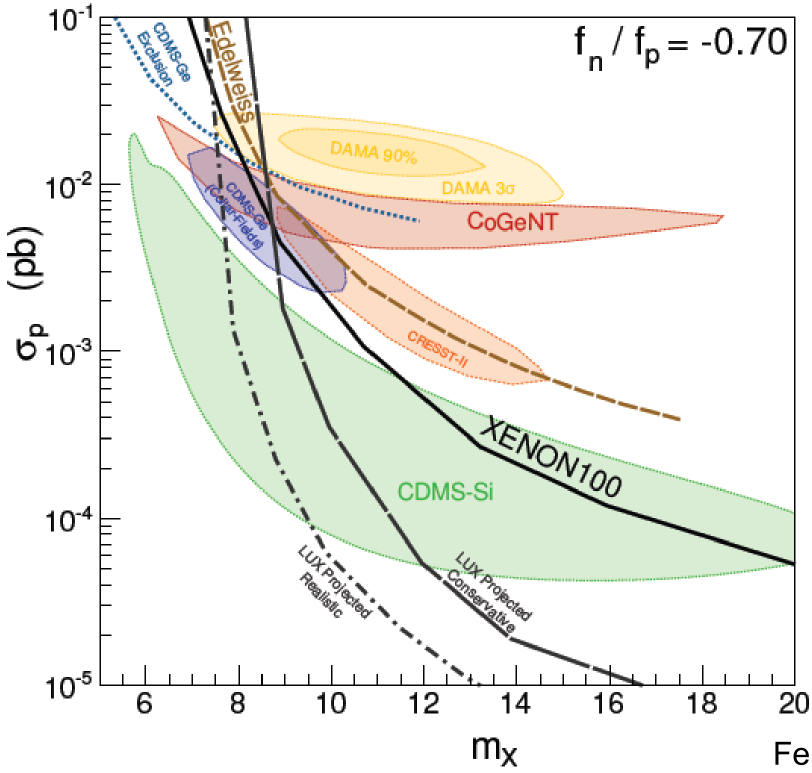


Feng, Kumar, Marfatia, Sanford (2013)

IVDM IMPLICATIONS

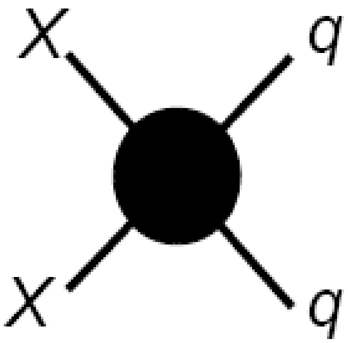
- LUX/XENON and DAMA are irreconcilable, but LUX/XENON and CDMS are consistent for $f_n/f_p = -0.7$ (roughly $f_u/f_d = -1$)
- Compared to the usual isospin-conserving case $f_n/f_p = 1$, larger DM couplings to up and down quarks are allowed, and are even required to explain anomalies; strong implications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





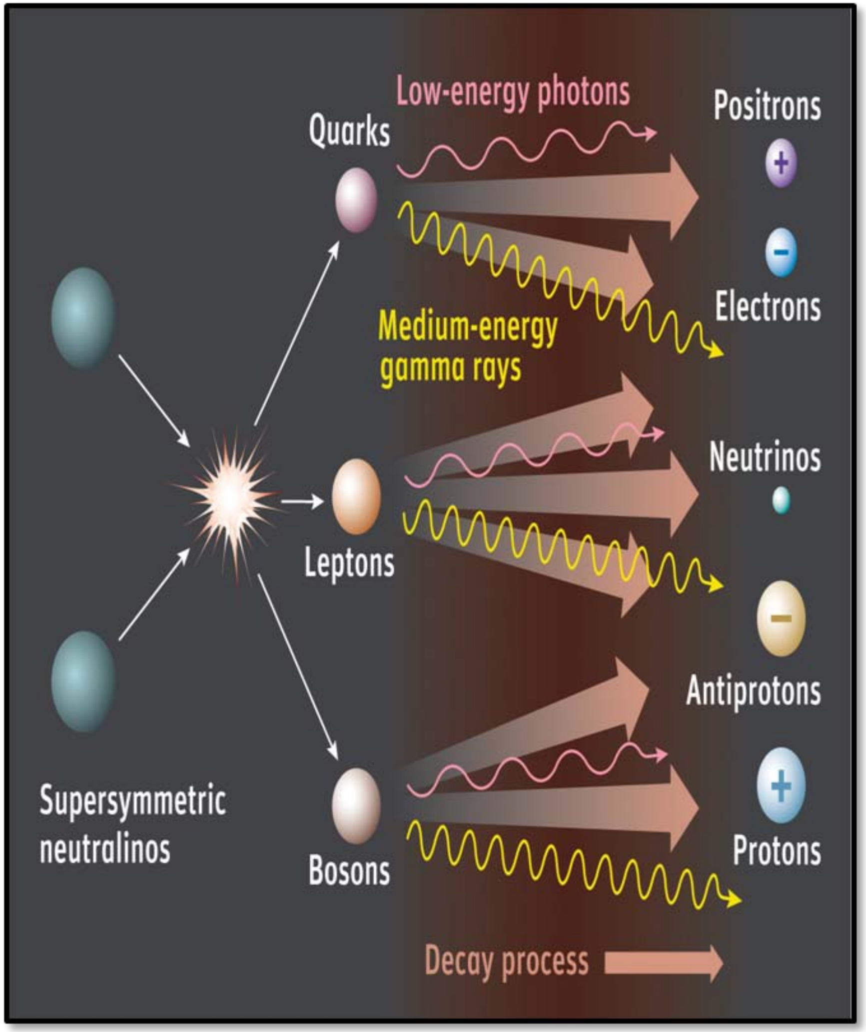
INDIRECT DETECTION

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



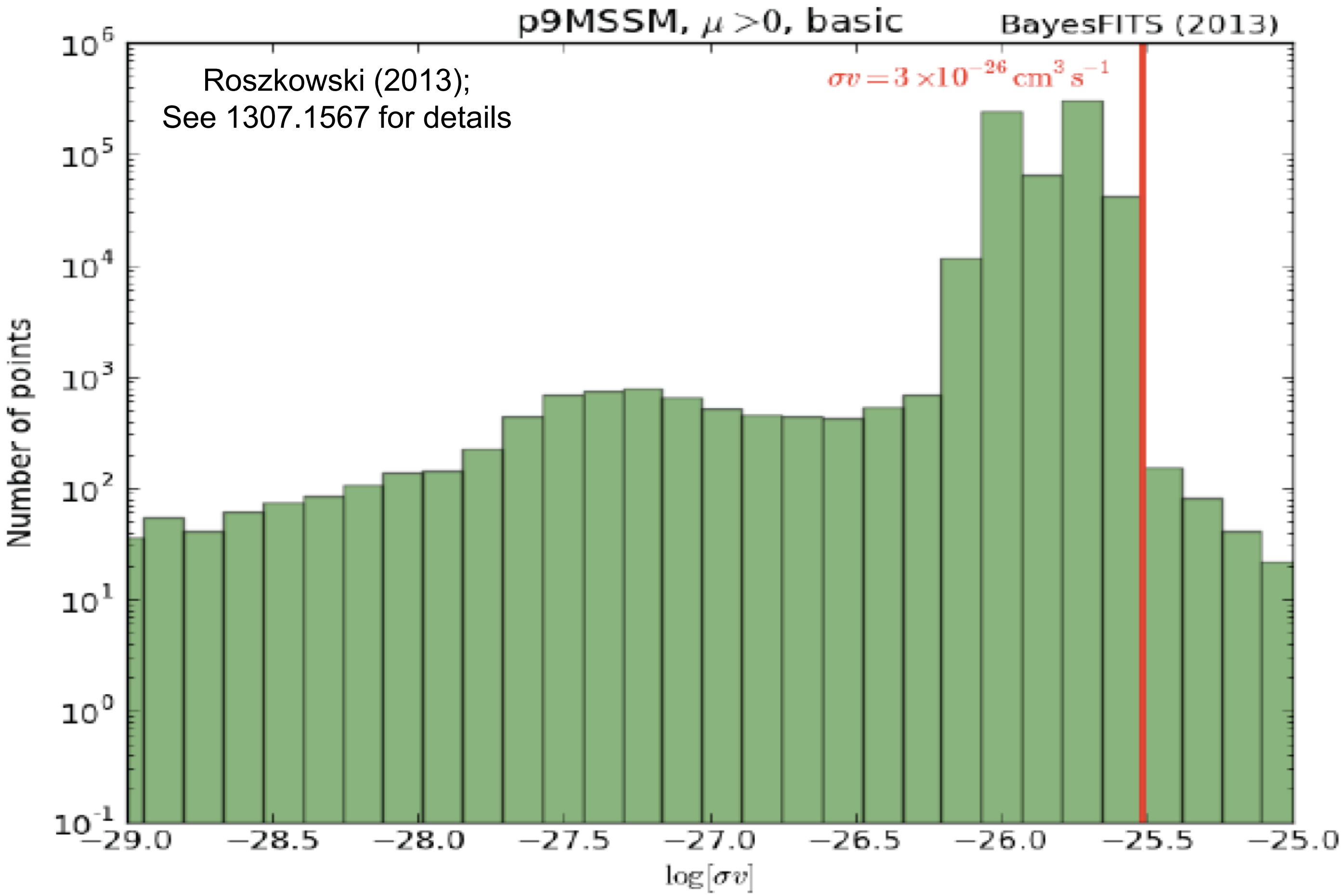
- The relic density provides a target annihilation cross section

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



ROBUSTNESS OF THE TARGET CROSS SECTION

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



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, VERITAS, … .
some particles an experiment

The flux factorizes:

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

Particle physics: two kinds of signals

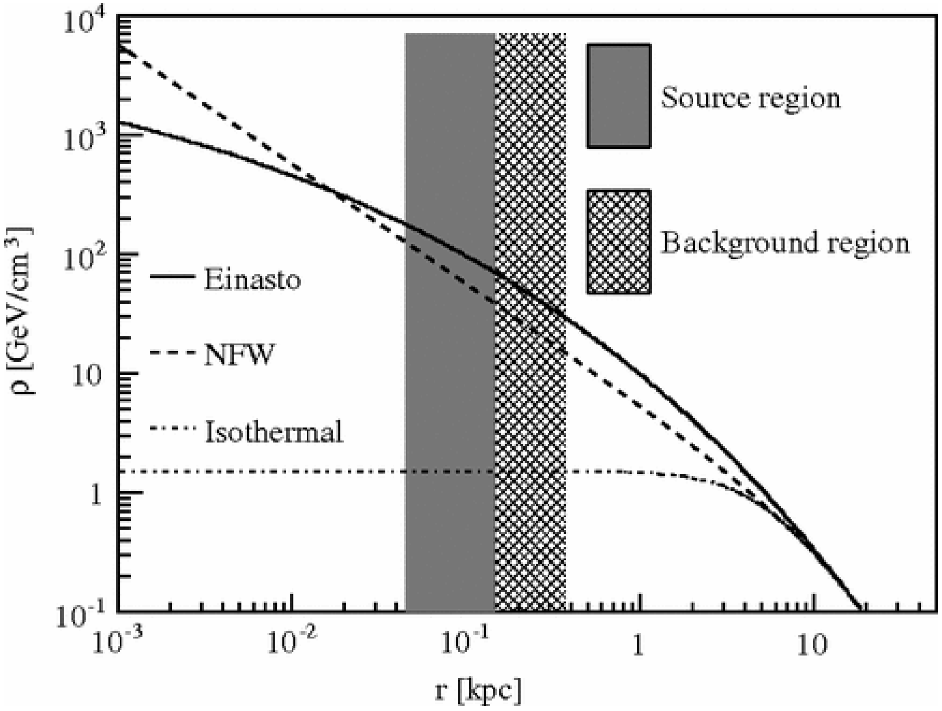
- Lines from XX → $\gamma\gamma$, γZ: loop-suppressed rates, but distinctive signal
- Continuum from XX → ff → γ: τree-level rates, but a broad signal

HALO PROFILES

Astrophysics: two kinds of sources

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

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

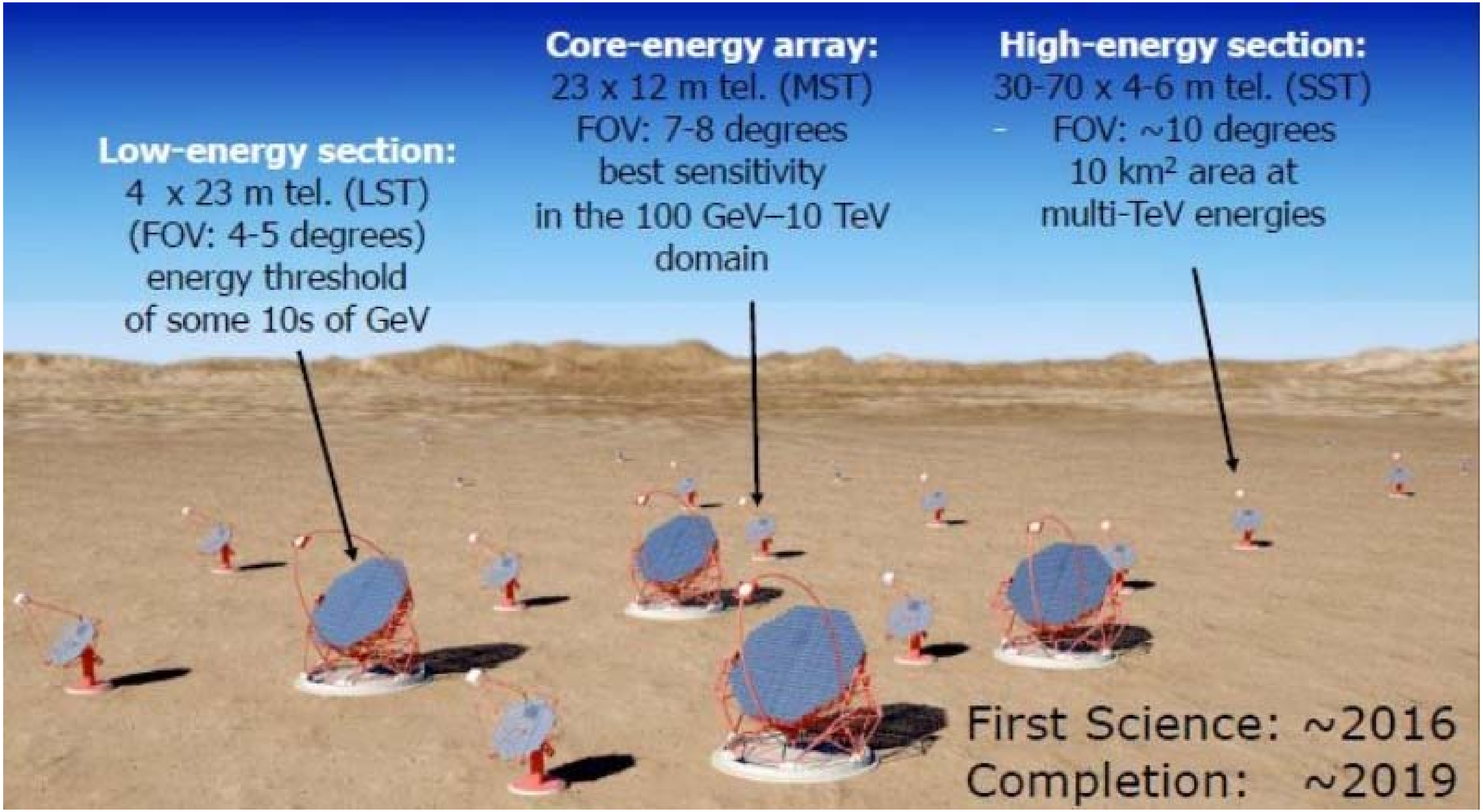


PHOTONS: CURRENT EXPERIMENTS

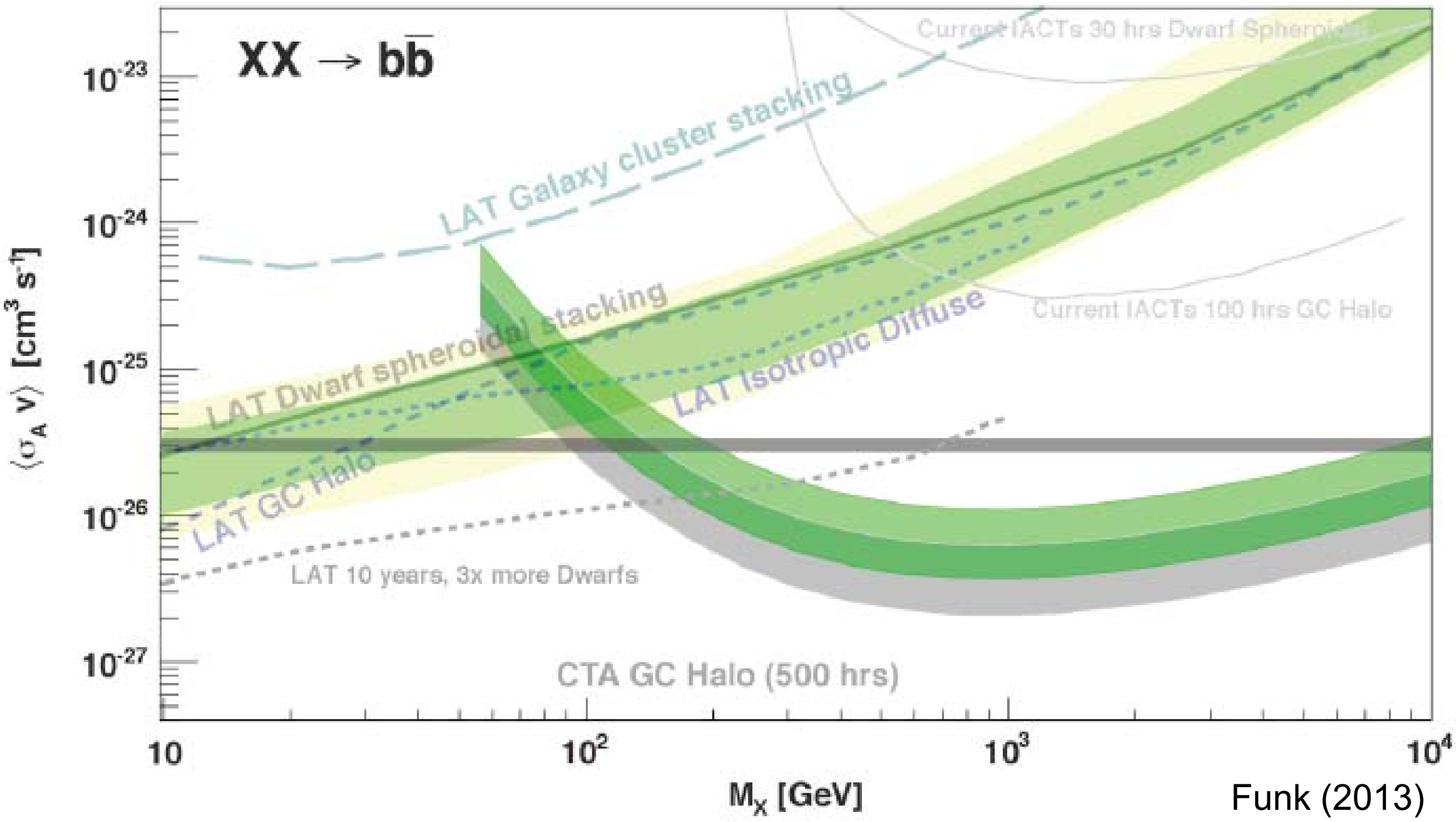
Veritas, Fermi-LAT, HAWC, and others

PHOTONS: FUTURE EXPERIMENTS

Cerenkov Telescope Array



PHOTONS: STATUS AND PROSPECTS



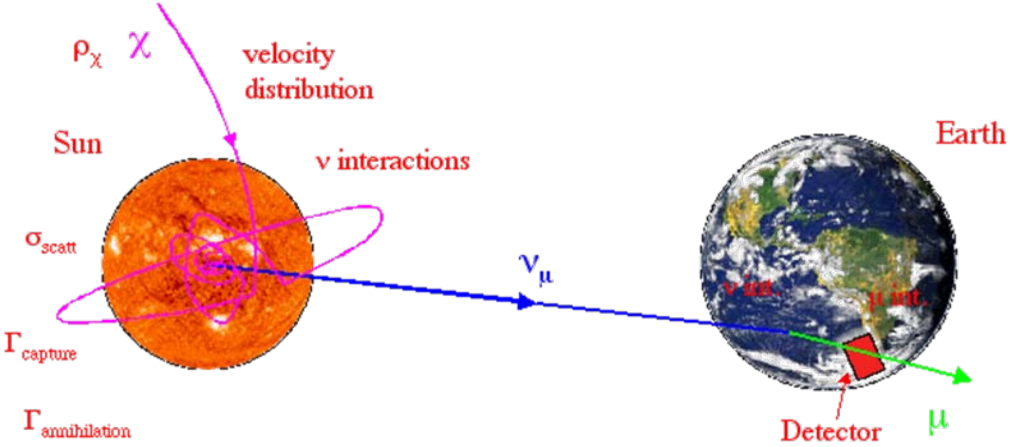
Funk (2013)

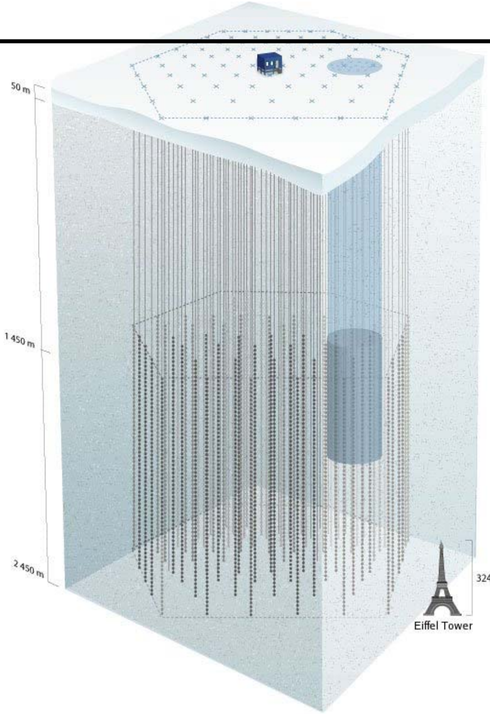
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV

INDIRECT DETECTION: NEUTRINOS

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

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

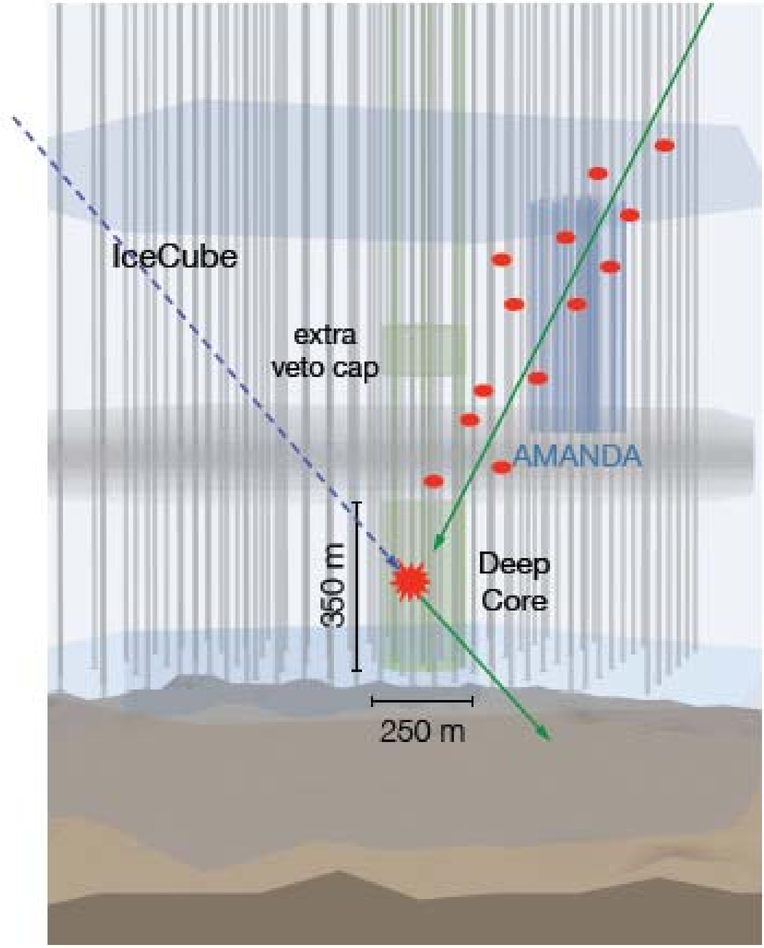


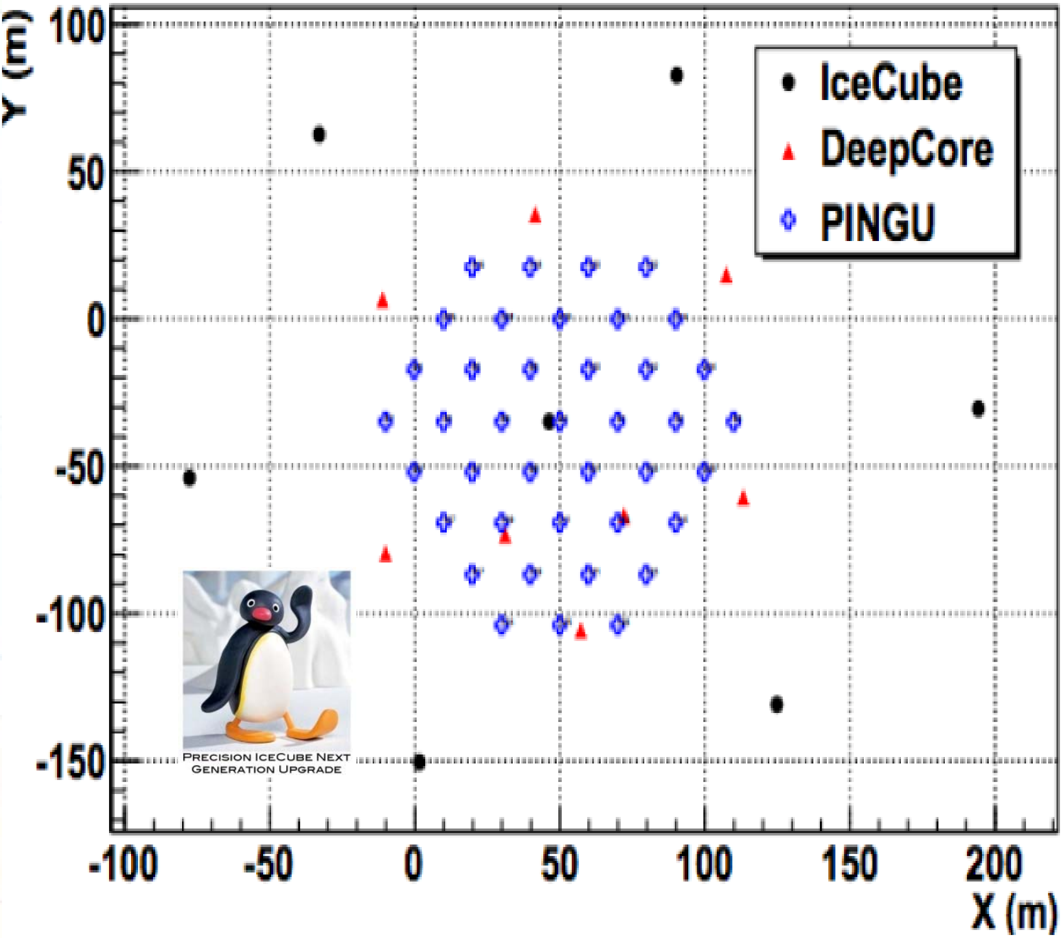


NEUTRINOS: EXPERIMENTS

Current: IceCube/DeepCore, ANTARES

Future: PINGU

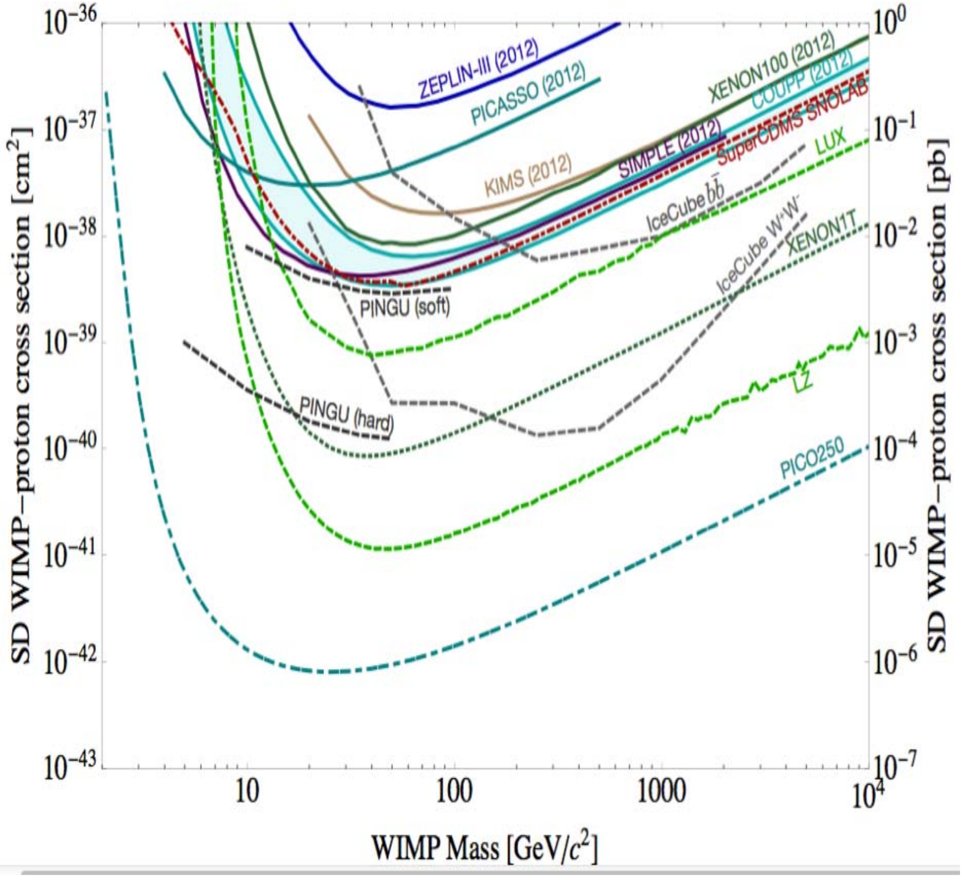




NEUTRINOS: STATUS AND PROSPECTS

The Sun is typically in equilibrium

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



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

INDIRECT DETECTION: ANTI-MATTER

Dark Matter annihilates in ___the halo___ to
a place

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

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

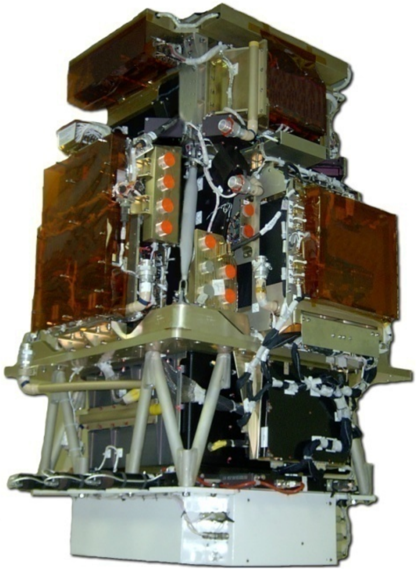
- bumps around the local halo before arriving in our detectors
- for example, positrons, created with energy E_0, detected with energy E

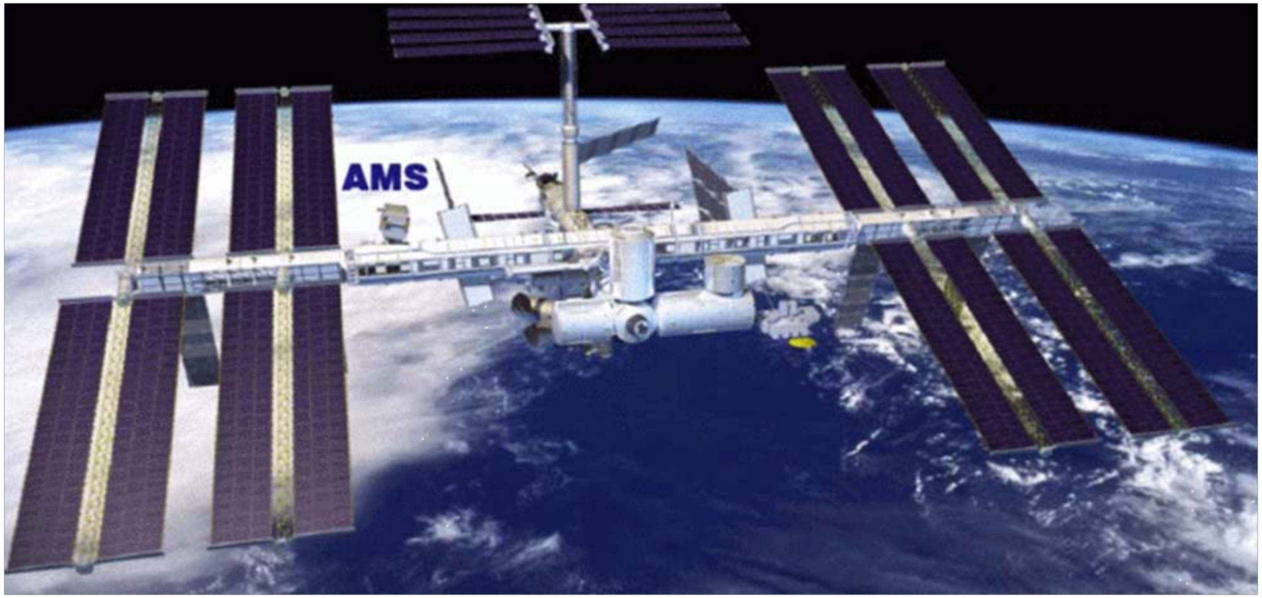
$$\frac{d\Phi_{e^+}}{d\Omega dE} = \frac{\rho_\chi^2}{m_\chi^2} \sum_i \sigma_i v B_{e^+}^i \int dE_0 \, f_i(E_0) \, G(E_0, E)$$

ANTI-MATTER: EXPERIMETS

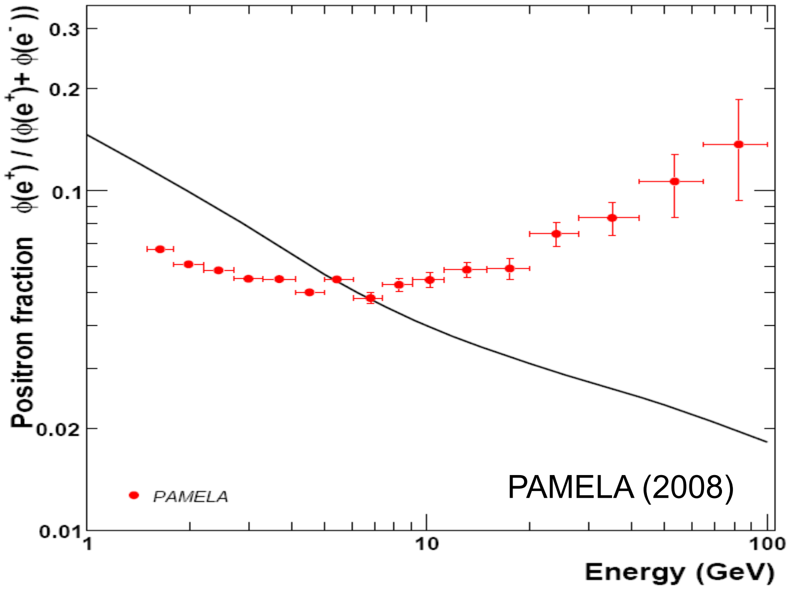
- Positrons (PAMELA, Fermi-LAT, AMS, CALET)

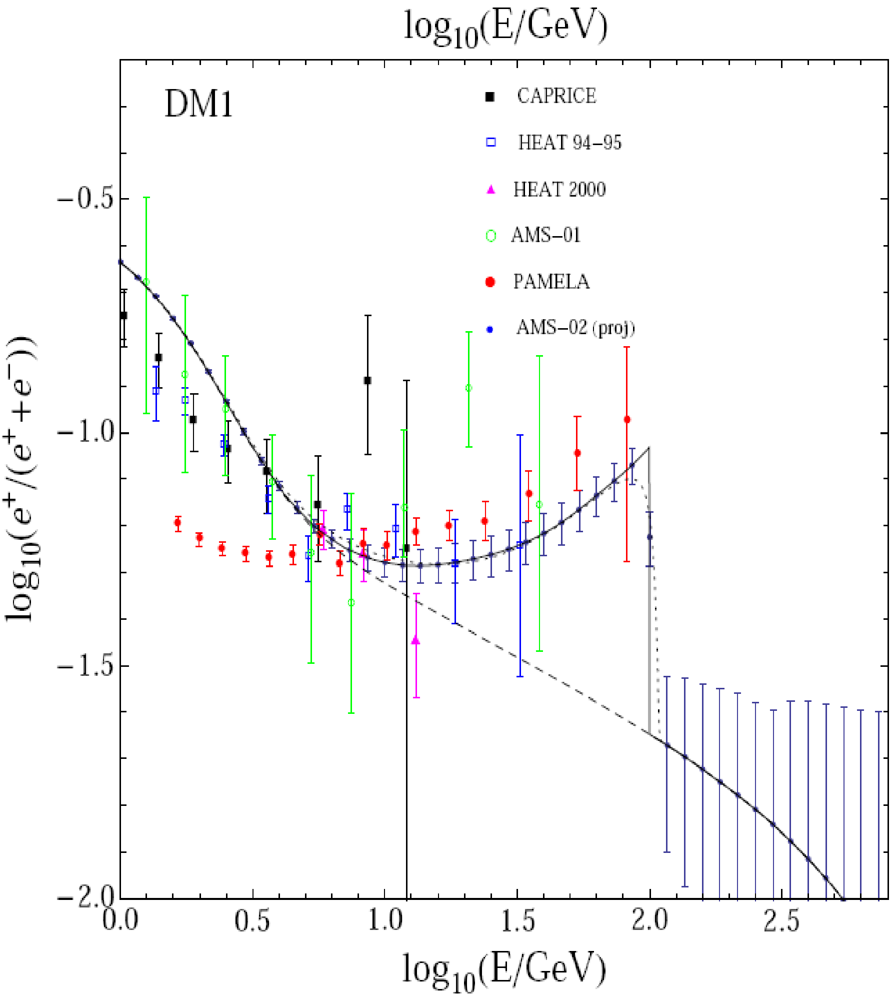
- Anti-Protons (PAMELA, AMS)
- Anti-Deuterons (GAPS)





POSITRONS: STATUS AND PROSPECTS

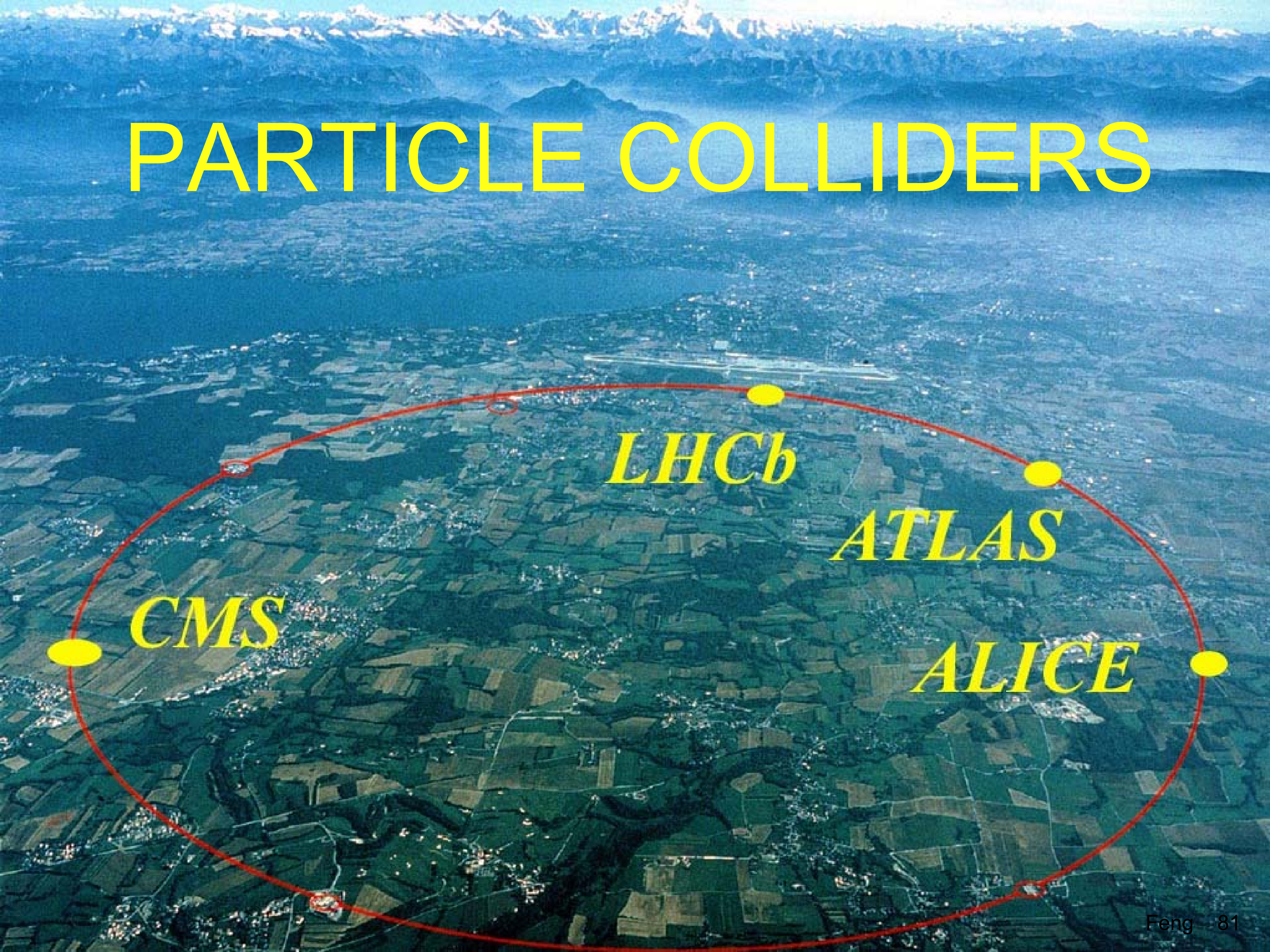




Pato, Lattanzi, Bertone (2010)

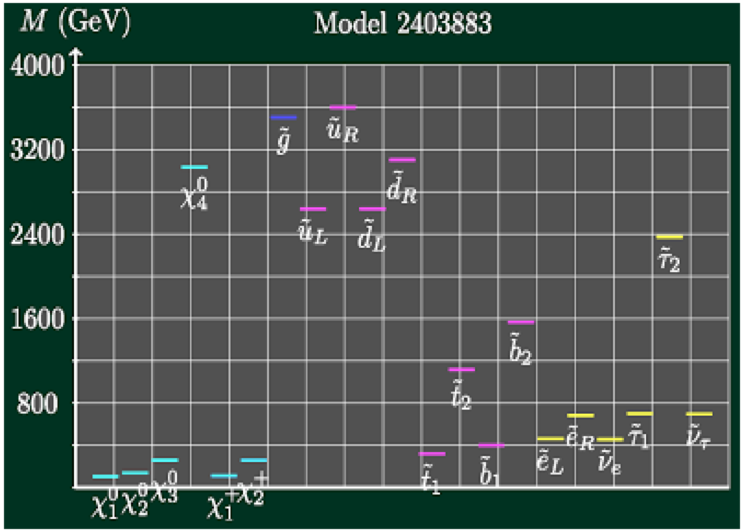
- Flux is a factor of 100-1000 too big for a thermal relic; requires
    - Enhancement from particle physics
    - Alternative production mechanism
- Difficult to distinguish from pulsars

PARTICLE COLLIDERS

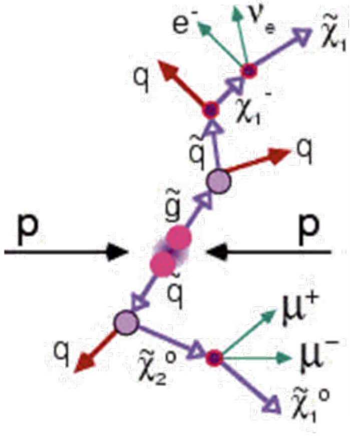


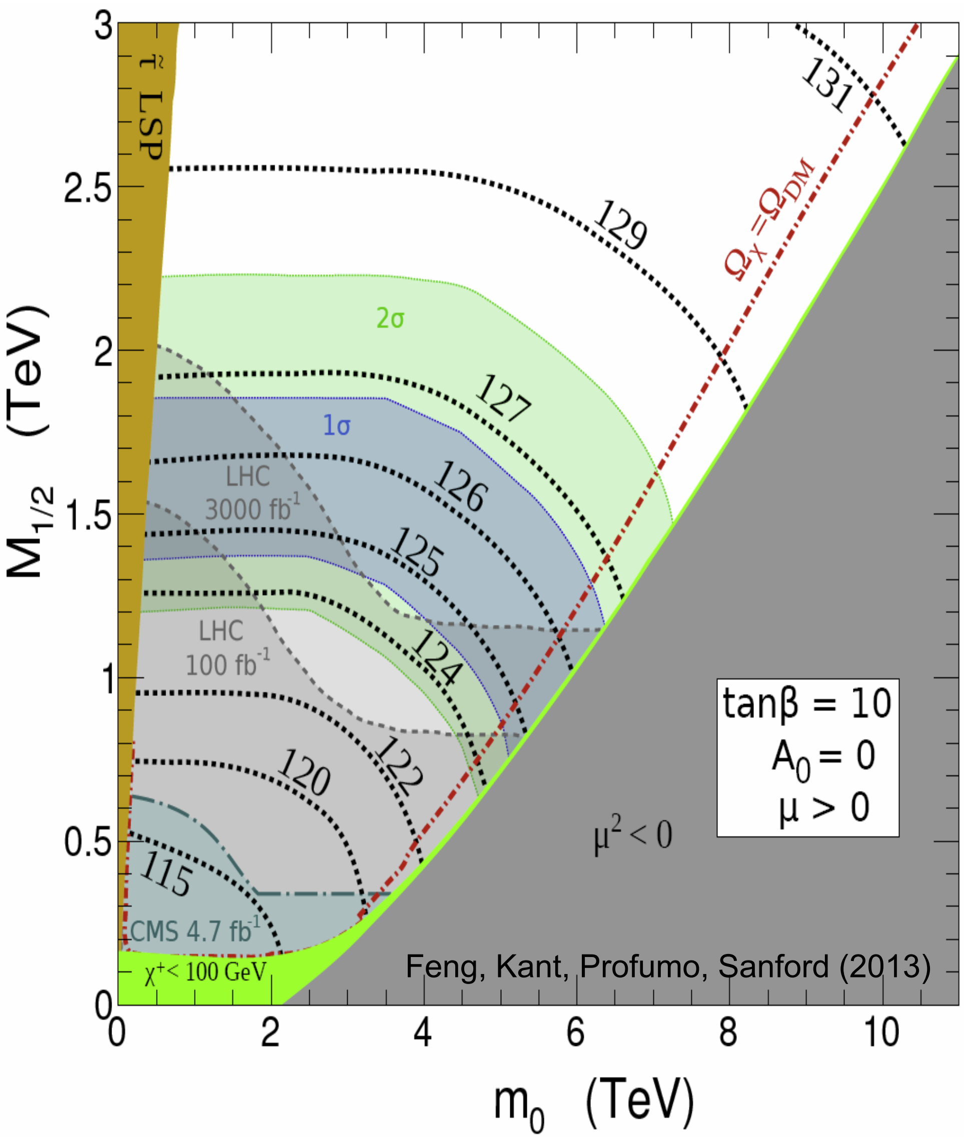
DARK MATTER AT COLLIDERS

Full Models (e.g., SUSY)



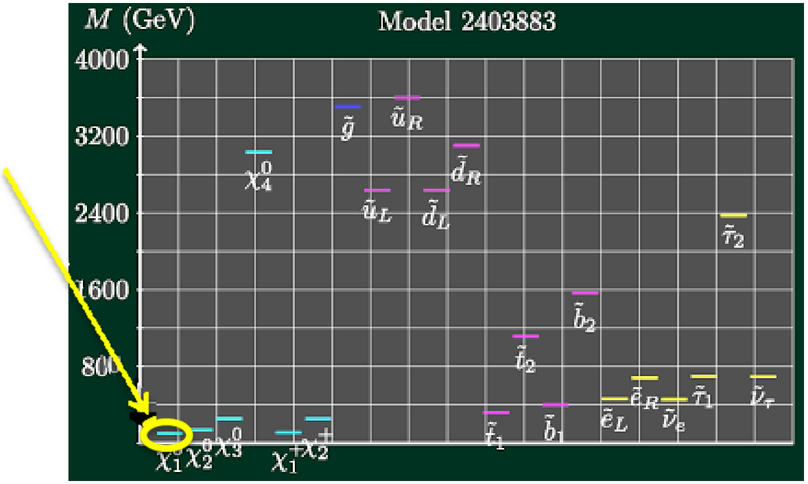
Cascades:
Produce other particles, which decay to DM



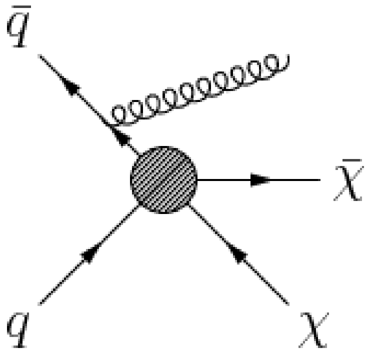


DARK MATTER AT COLLIDERS

DM Effective Theories (Bare Bones Dark Matter)

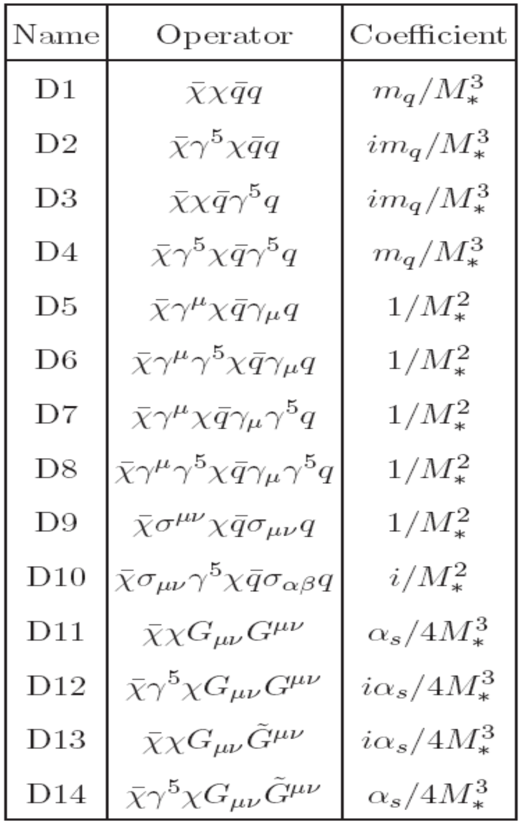


Produce DM directly, but in association with something else so it can be seen: Mono-γ, jet,W,Z,h,b,t



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

Now systematically classify all possible 4-pt interactions



Name	Operator	Coefficient
D1	$\bar\chi\chi\bar q q$	m_q/M_*^3
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	$\bar\chi\chi\bar q\gamma^5 q$	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$

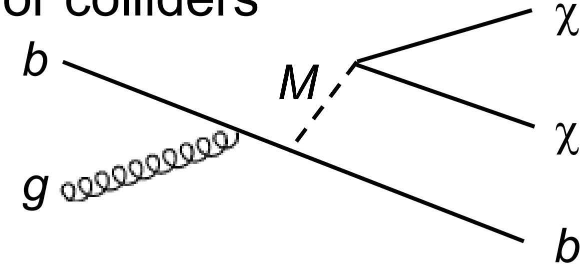
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu (2010)
Bai, Fox, Harnik (2010)

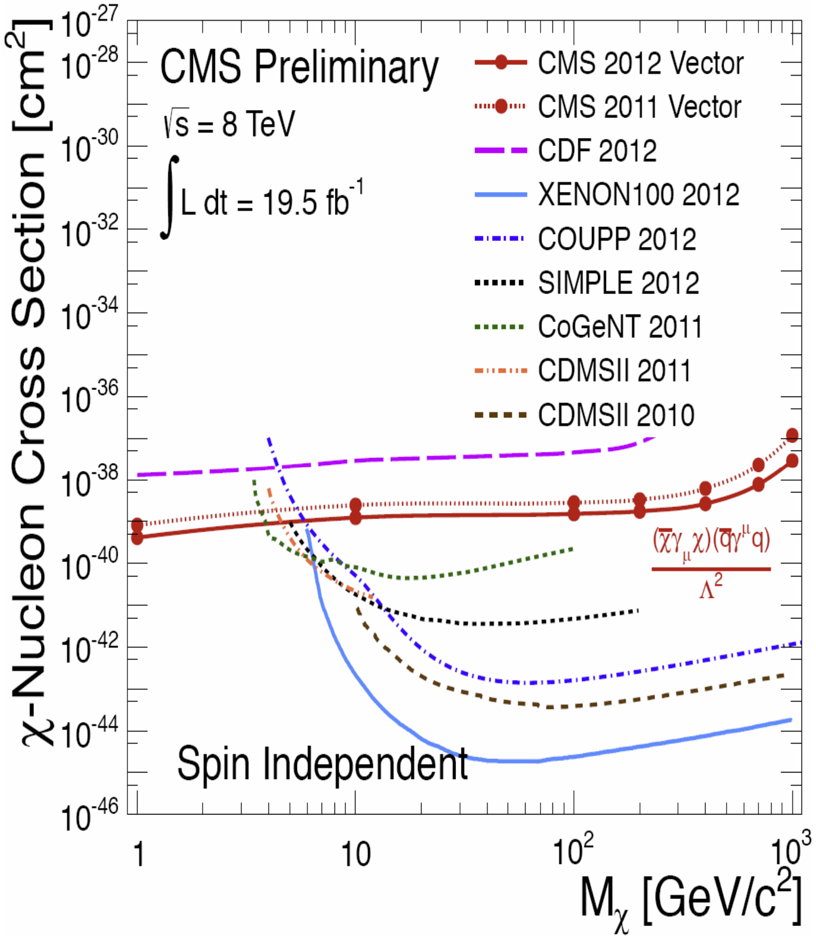
WIMP EFFECTIVE THEORY

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

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

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

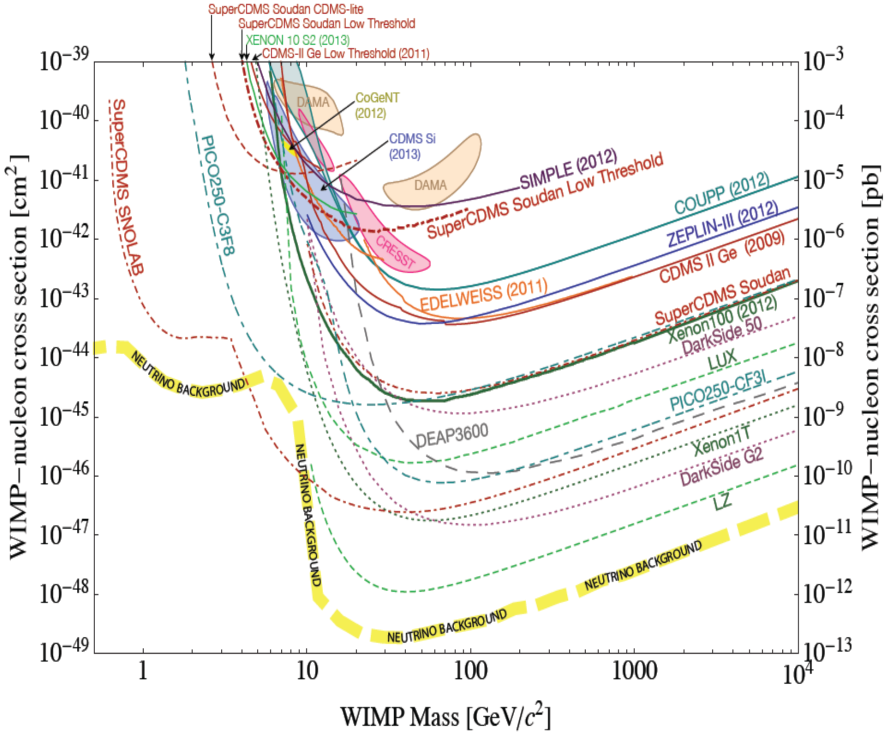




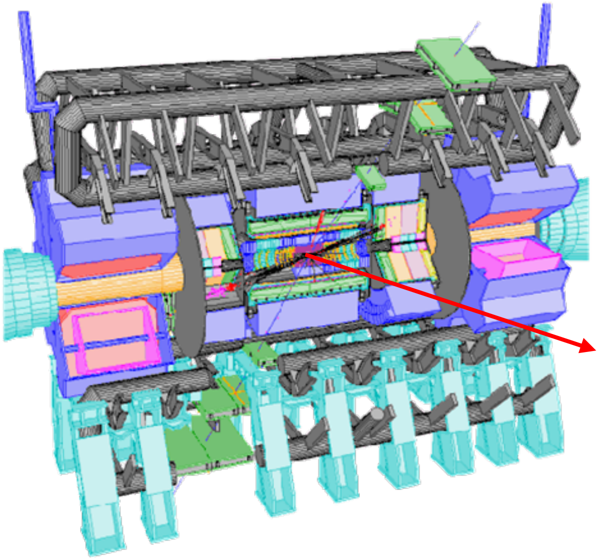
THE FUTURE

If there is a signal, what do we learn?

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



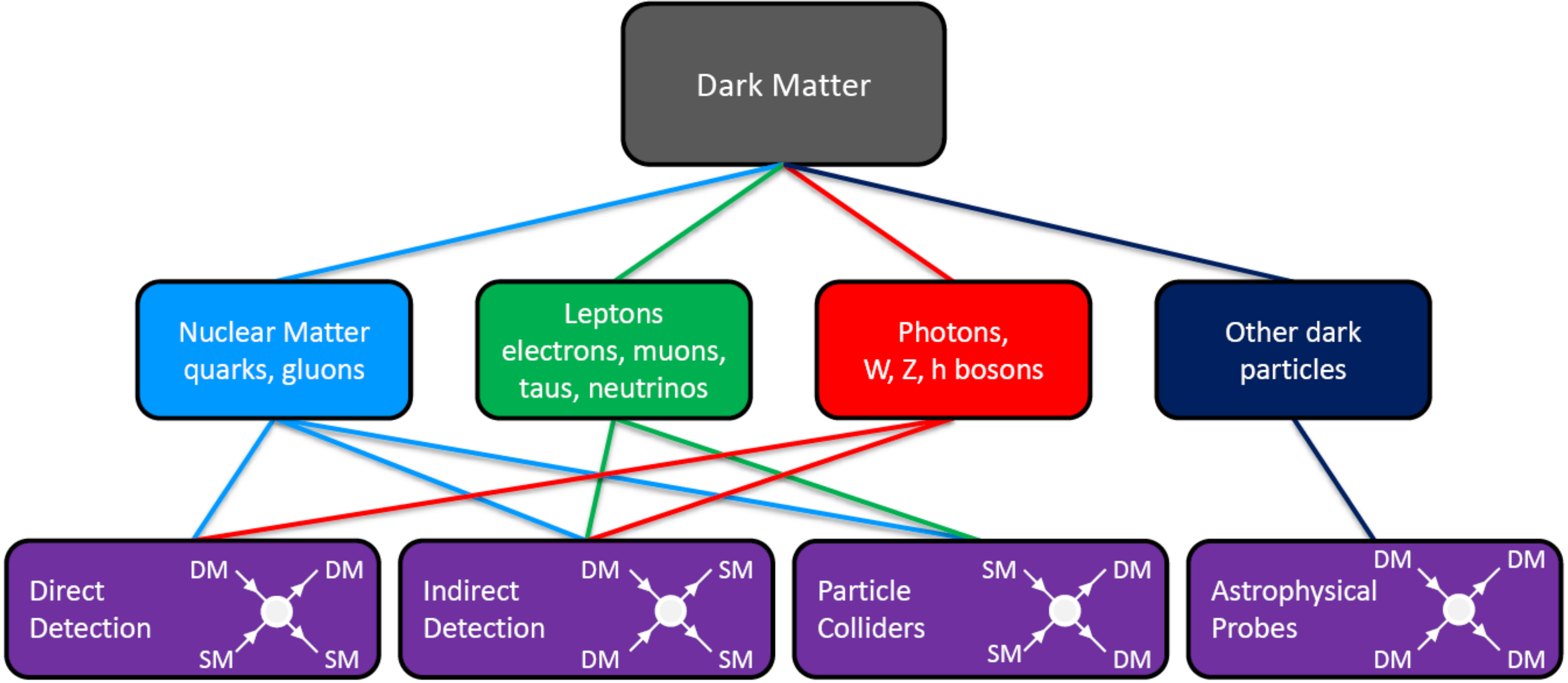
- Particle colliders can't prove it's dark matter



Lifetime > 10^{-7} s → 10^{17} s ?

DARK MATTER COMPLEMENTARITY

- Before a signal: Different experimental approaches are sensitive to different dark matter candidates with different characteristics, and provide us with different types of information – complementarity!
- After a signal: we are trying to identify a quarter of the Universe: need high standards to claim discovery and follow-up studies to measure properties



Dark Matter

Nuclear Matter
quarks, gluons

Leptons
electrons, muons,
taus, neutrinos

Photons,
W, Z, h bosons

Other dark
particles

Direct
Detection

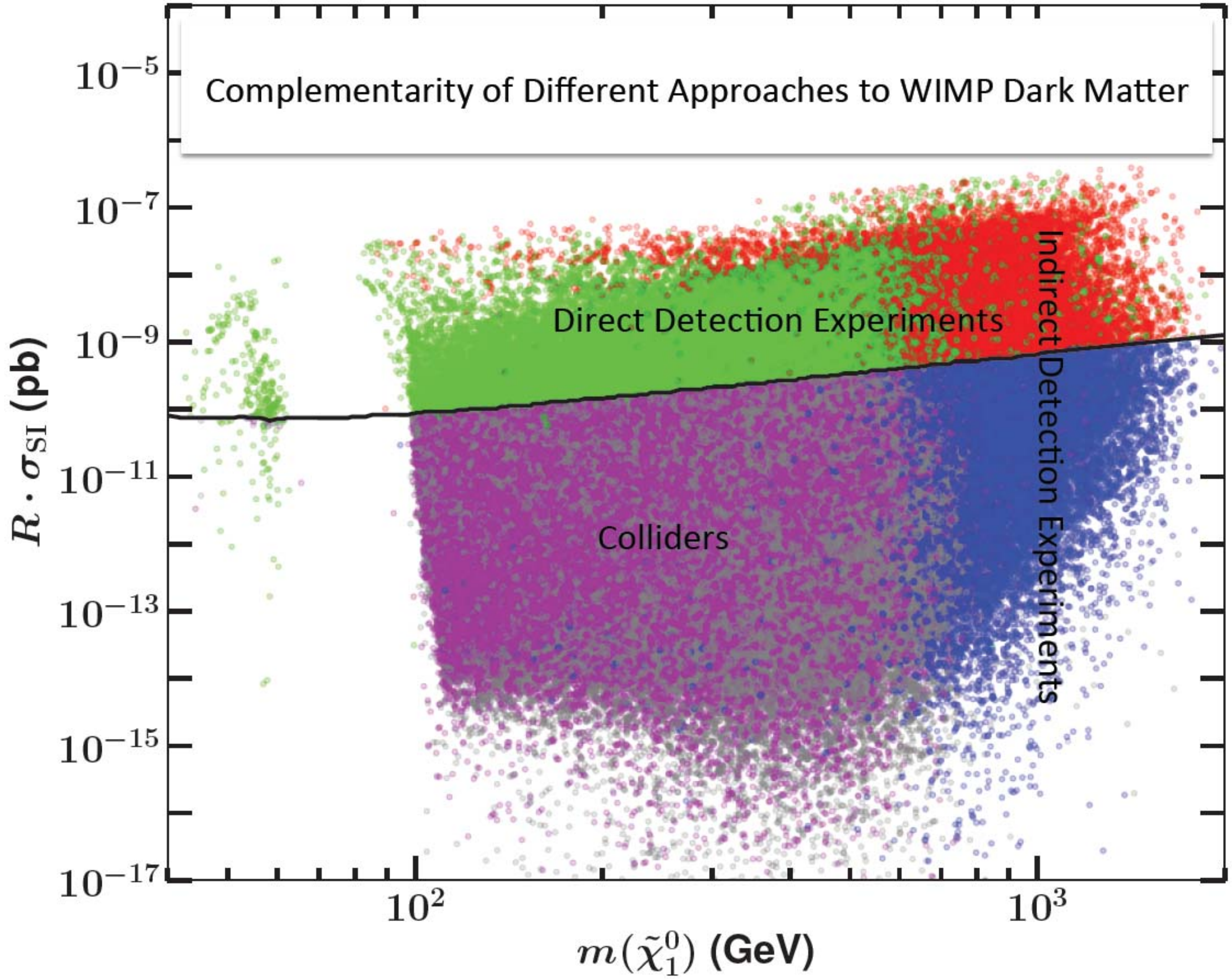
Indirect
Detection

Particle
Colliders

Astrophysical
Probes

COMPLEMENTARITY: FULL MODELS

pMSSM 19-parameter scan of SUSY parameter space



Cahill-Rowley et al. (2013)

Different expts probe different models, provide cross-checks

LECTURE 2 SUMMARY

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

OUTLINE

LECTURE 1

Essential Cosmology: Contents and History of the Universe

LECTURE 2

WIMP Dark Matter: Candidates and Methods of Detection

LECTURE 3

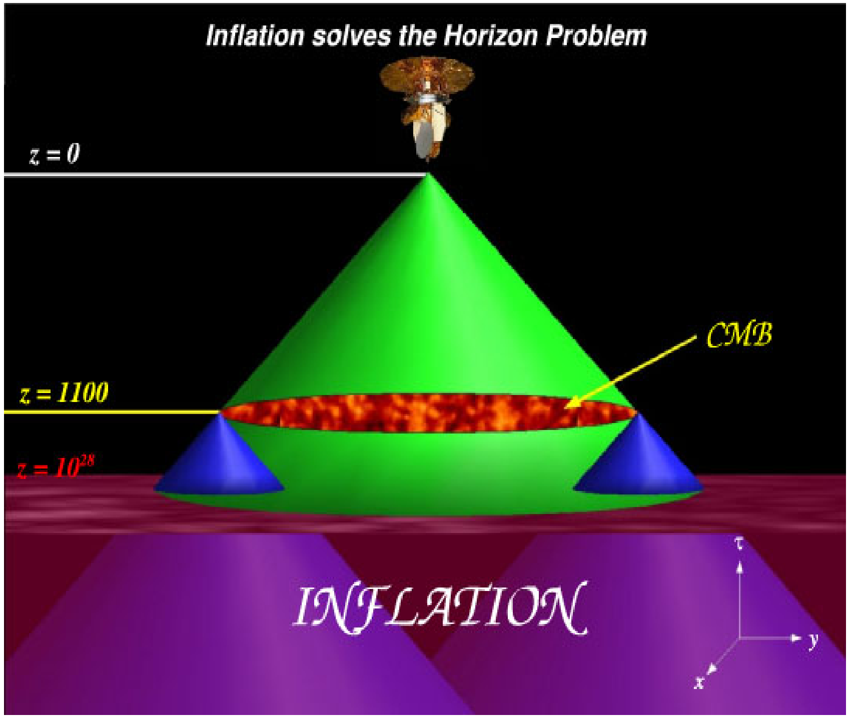
Inflation, Gravitinos, and Hidden Sectors

INFLATION

- The standard model of cosmology includes not just the hot Big Bang we have described, but also an earlier period of inflation with vacuum-dominated expansion:

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

- Inflation has many motivations. One is the horizon problem: Why do causally-disconnected parts of the CMB have the same temperature?
- With inflation, these regions of the Universe had the same origin, are causally connected



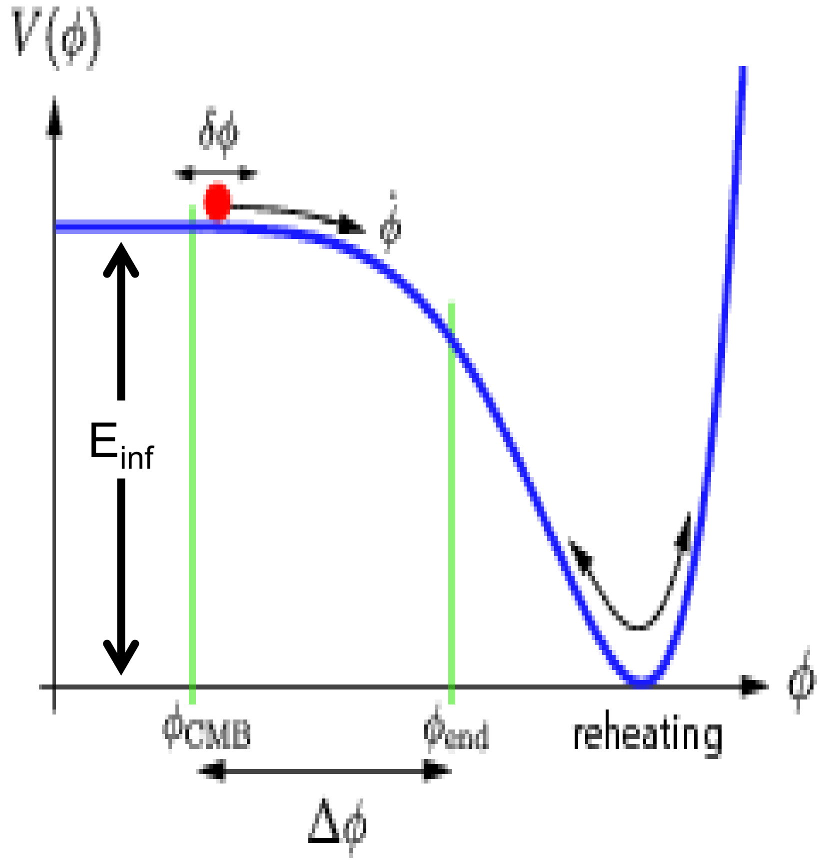
INFLATION

- There are many models of inflation, but the basic picture is simple:

- Initially, the inflaton stays at high potential energy E_{inf} and the Universe expands exponentially

- Eventually the scalar field rolls down, its potential energy is transferred to the SM particles

- The hot Big Bang begins with *reheat temperature* $T_{RH} < E_{inf}$



GRAVITINO DARK MATTER

- WIMPs are not the only DM candidates; they are not even the only ones predicted by SUSY: gravitinos provide a nice case study of *very* weakly interacting dark matter

- SUSY: graviton G → gravitino $\tilde{G}$, spin 3/2

- Mass $m_{\tilde{G}} \sim F/M_{\mathrm{Pl}}$, where $F^{1/2}$ is the scale of SUSY breaking
  - Ultra-light (GMSB): $F \sim (100\ \mathrm{TeV})^2$, $m_{\tilde{G}} \sim$ eV
  - Light (GMSB): $F \sim (10^7\ \mathrm{GeV})^2$, $m_{\tilde{G}} \sim$ keV
  - Heavy (SUGRA): $F \sim (10^{11}\ \mathrm{GeV})^2$, $m_{\tilde{G}} \sim$ TeV
  - Obese (AMSB): $F \sim (10^{12}\ \mathrm{GeV})^2$, $m_{\tilde{G}} \sim$ 100 TeV

- The gravitino interaction strength $\sim 1/F$

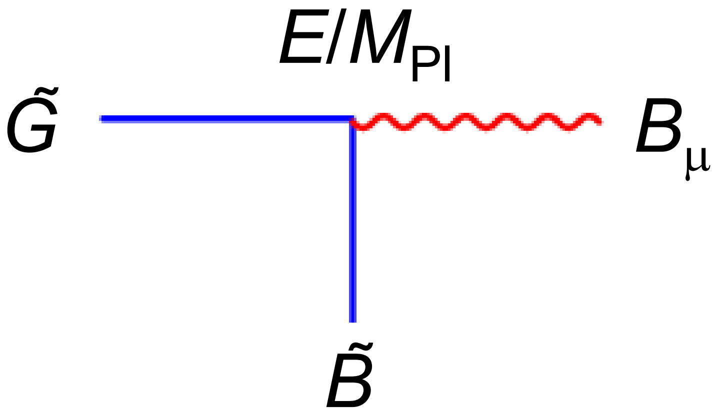
- A huge range of implications for cosmology and HEP

HEAVY GRAVITINOS

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

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

Couplings grow with energy, but are typically extremely weak



OPTION 1: GRAVITINOS FROM REHEATING

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

- What happens? A question of rates:

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

  SM interaction rate >> expansion rate >> $\tilde{G}$ 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:

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

- Change variables:
  Entropy density s ~ T^3

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

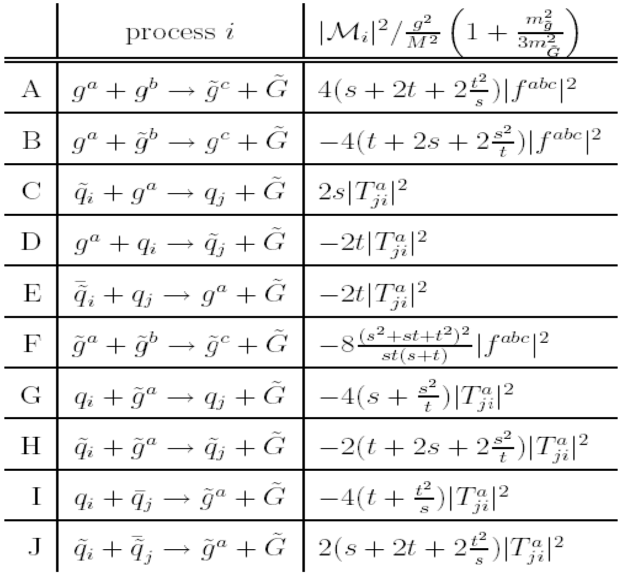
- New Boltzmann equation:

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

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

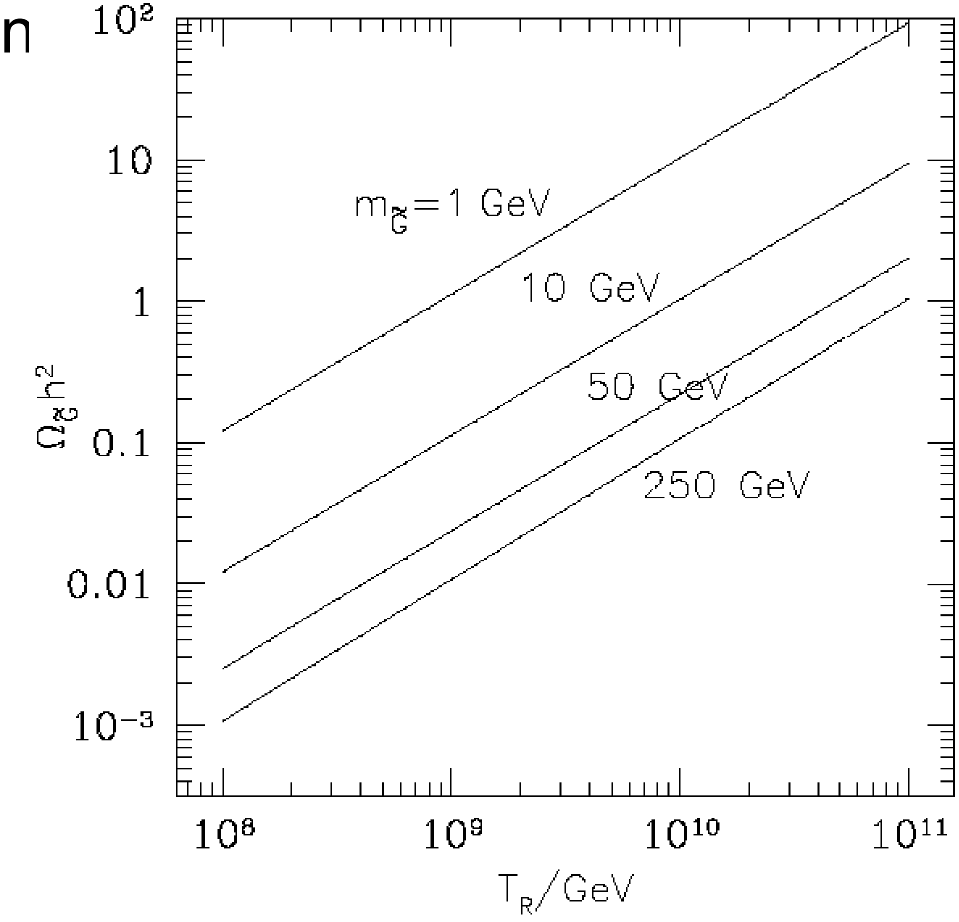
BOUNDS ON T_{RH}

- $<\sigma v>$ 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	$g^a + g^b \longrightarrow \tilde{g}^c + \tilde{G}$	$4(s+2t+2\frac{t^2}{s})\lvert f^{abc}\rvert^2$
B	$g^a + \tilde{g}^b \longrightarrow g^c + \tilde{G}$	$-4(t+2s+2\frac{s^2}{t})\lvert f^{abc}\rvert^2$
C	$\tilde{q}_i + g^a \longrightarrow q_j + \tilde{G}$	$2s\lvert T_{ji}^a\rvert^2$
D	$g^a + q_i \longrightarrow \tilde{q}_j + \tilde{G}$	$-2t\lvert T_{ji}^a\rvert^2$
E	$\bar{\tilde{q}}_i + q_j \longrightarrow g^a + \tilde{G}$	$-2t\lvert T_{ji}^a\rvert^2$
F	$\tilde{g}^a + \tilde{g}^b \longrightarrow \tilde{g}^c + \tilde{G}$	$-8\frac{(s^2+st+t^2)^2}{st(s+t)}\lvert f^{abc}\rvert^2$
G	$q_i + \tilde{g}^a \longrightarrow q_j + \tilde{G}$	$-4(s+\frac{s^2}{t})\lvert T_{ji}^a\rvert^2$
H	$\tilde{q}_i + \tilde{g}^a \longrightarrow \tilde{q}_j + \tilde{G}$	$-2(t+2s+2\frac{s^2}{t})\lvert T_{ji}^a\rvert^2$
I	$q_i + \bar{q}_j \longrightarrow \tilde{g}^a + \tilde{G}$	$-4(t+\frac{t^2}{s})\lvert T_{ji}^a\rvert^2$
J	$\tilde{q}_i + \bar{\tilde{q}}_j \longrightarrow \tilde{g}^a + \tilde{G}$	$2(s+2t+2\frac{t^2}{s})\lvert T_{ji}^a\rvert^2$

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

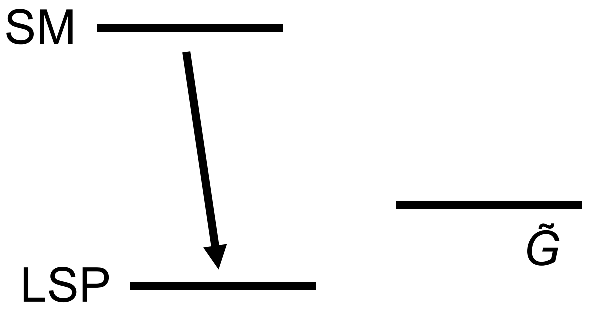


Bolz, Brandenburg, Buchmuller (2001)

OPTION 2: GRAVITINOS FROM LATE DECAYS

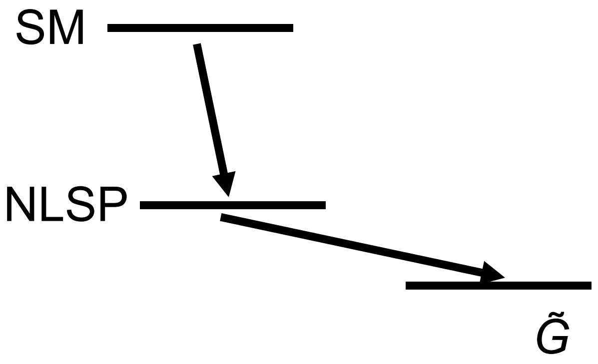
- What if gravitinos are diluted by inflation, and the universe reheats to low temperature? No “primordial” relic density

- $\tilde{G}$ not LSP



- No impact – implicit assumption of most of the literature

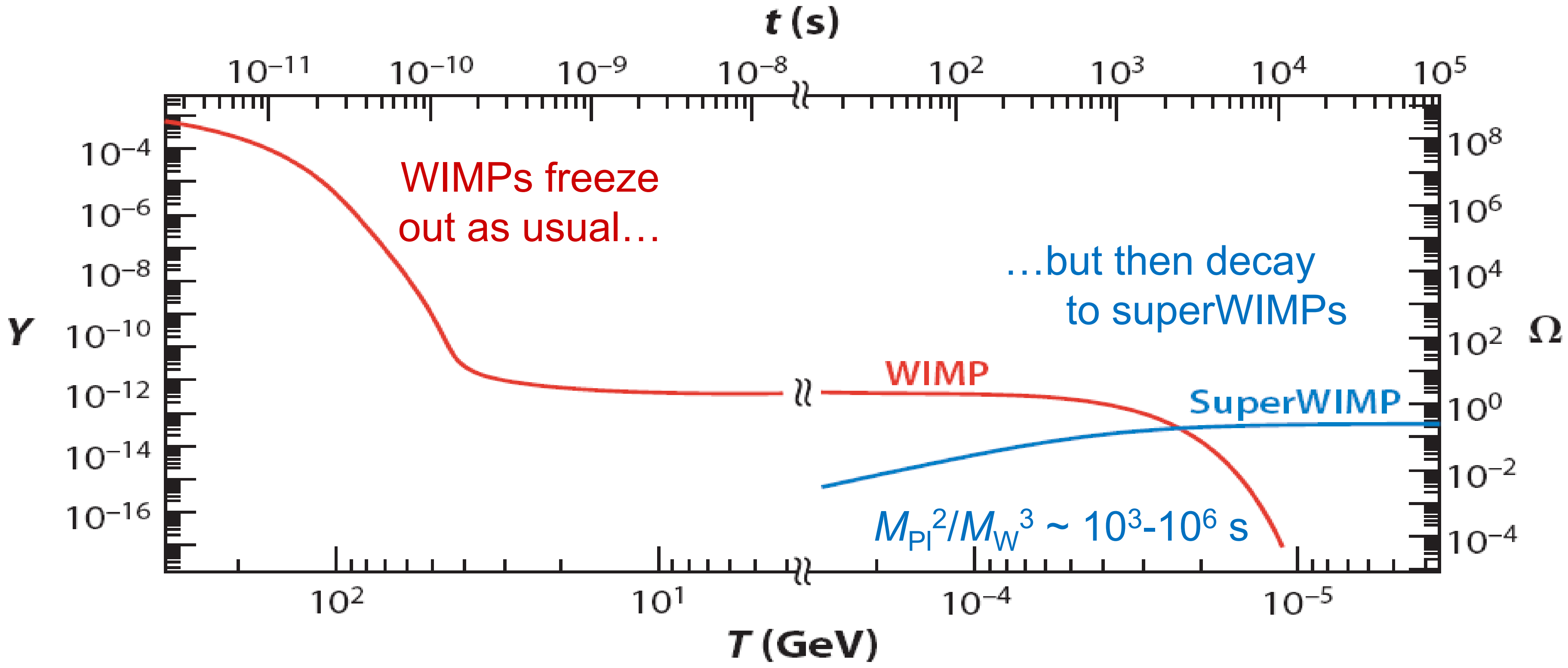
- $\tilde{G}$ LSP



- Completely different particle physics and cosmology

FREEZE OUT WITH SUPERWIMPS

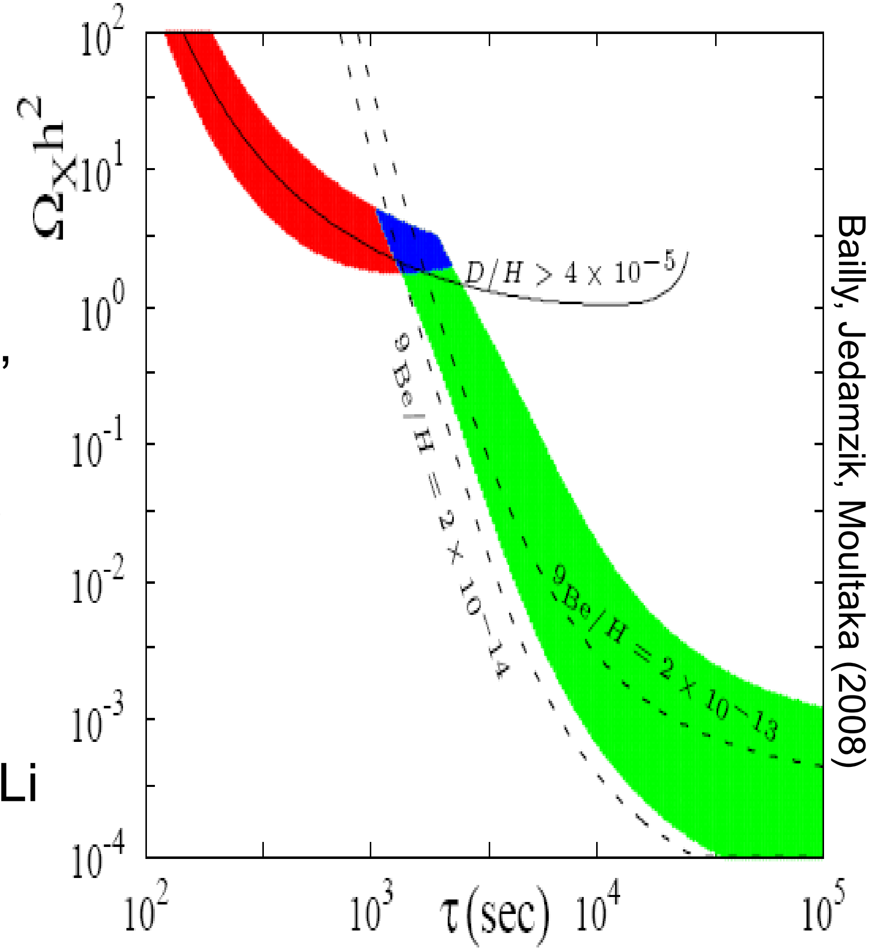
Feng, Rajaraman, Takayama (2003)



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

LATE DECAYS AND BBN

- Late decays deposit energy into the Universe, potentially destroy the light elements
- Simple way around this is to make decays before T ~ MeV, t ~ 1s
- More ambitious: as we saw previously, ^{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)

COSMIC MICROWAVE BACKGROUND

- Late decays may also distort the black body CMB spectrum

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

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

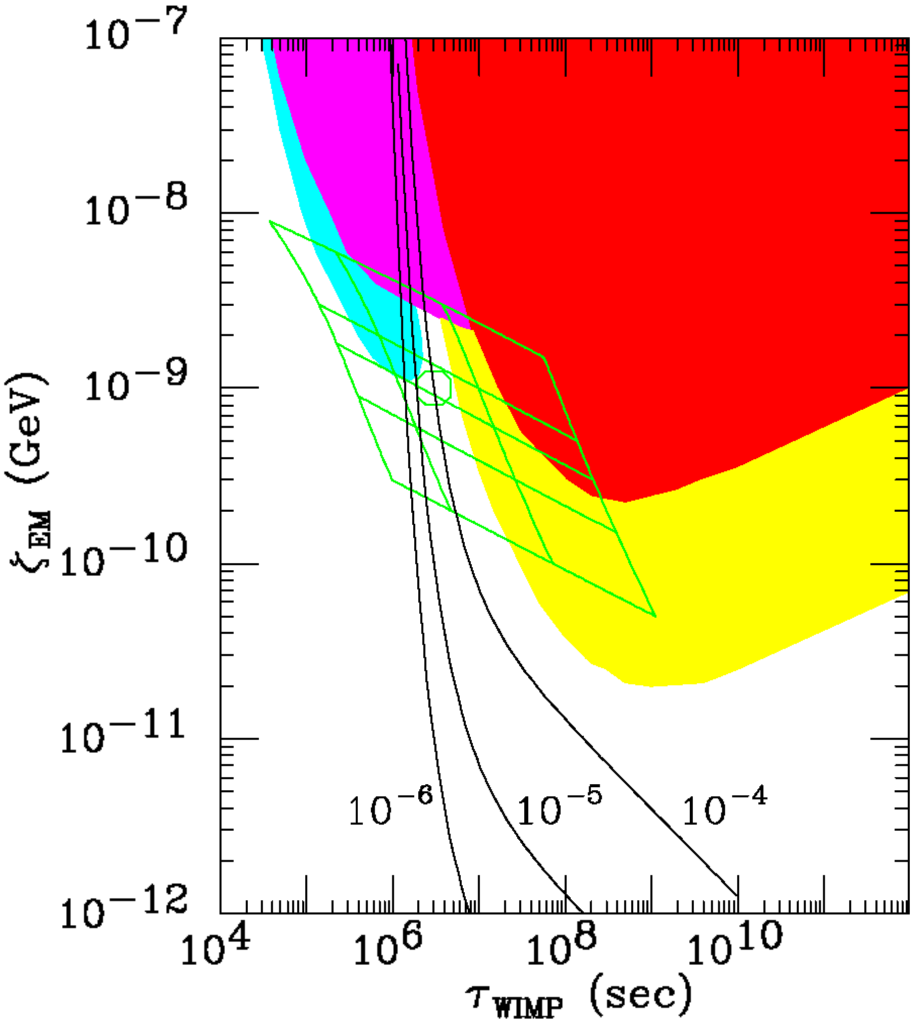
μ=0: Planckian spectrum

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

Hu, Silk (199

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

Future: possibly $|\mu| \sim 5 \times 10^{-8}$



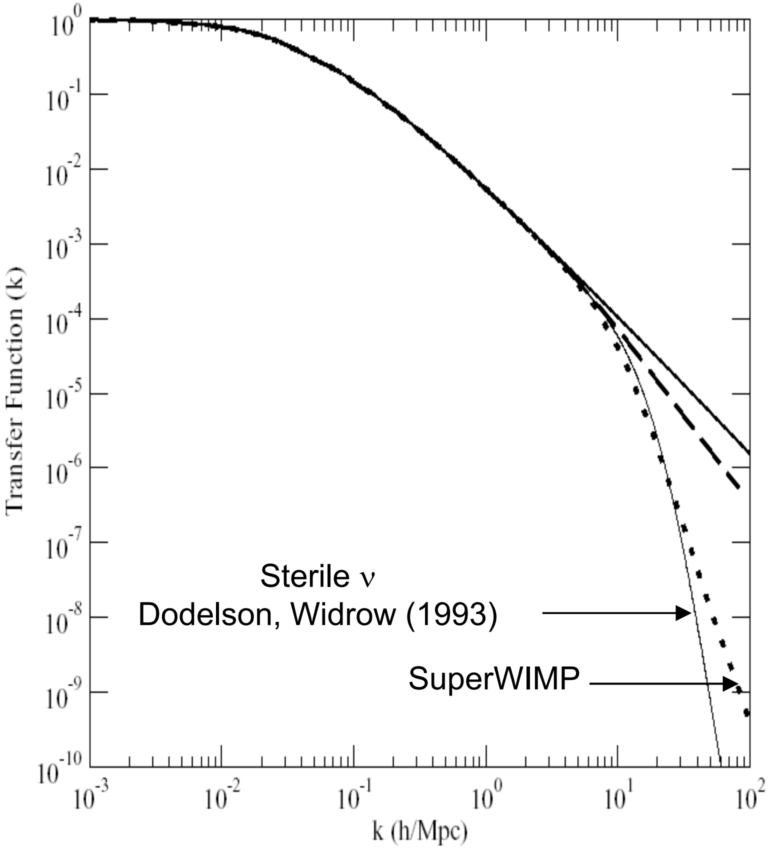
Feng, Rajaraman, Takayama (2003)

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. This is quantified 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



Kaplinghat (2005)

IMPLICATIONS FOR THE LHC

- SuperWIMP DM → metastable particles, may be charged

- Signature of new physics is “stable”, charged, massive particles, not misssing E_T

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

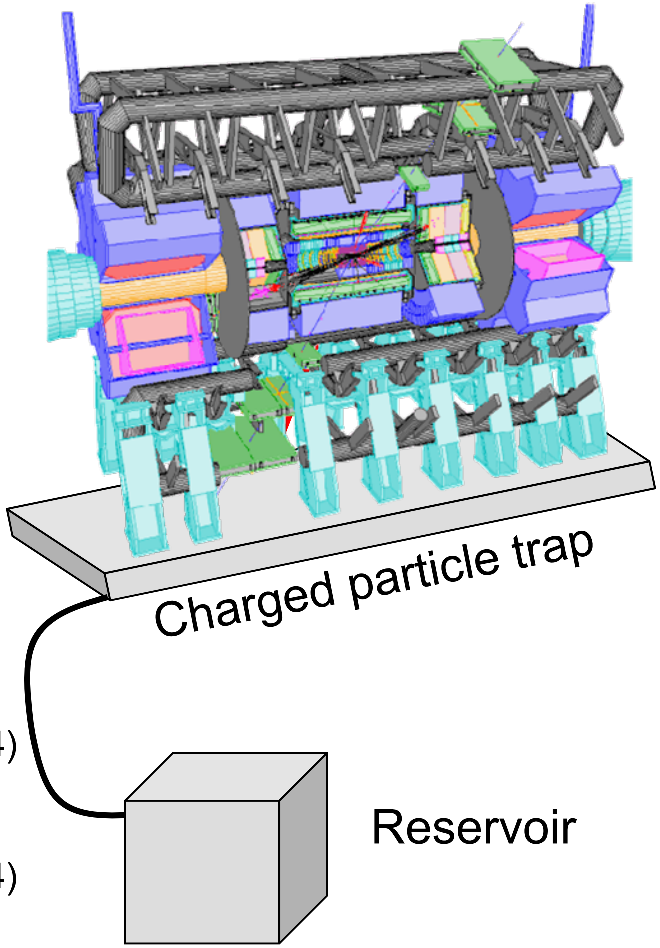
Feng, Smith (2004)

  - Catch sleptons in LHC detectors

Hamaguchi, Kuno, Nakawa, Nojiri (2004)

  - Dig sleptons out of detector hall walls

De Roeck 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

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 → $m_{\tilde{G}} >$ 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, e.g., by low reheating temperature
  - ΛWCDM: $m_{\tilde{G}} < 16$ eV. Gravitinos are only part of the DM, mixed warm-cold scenario

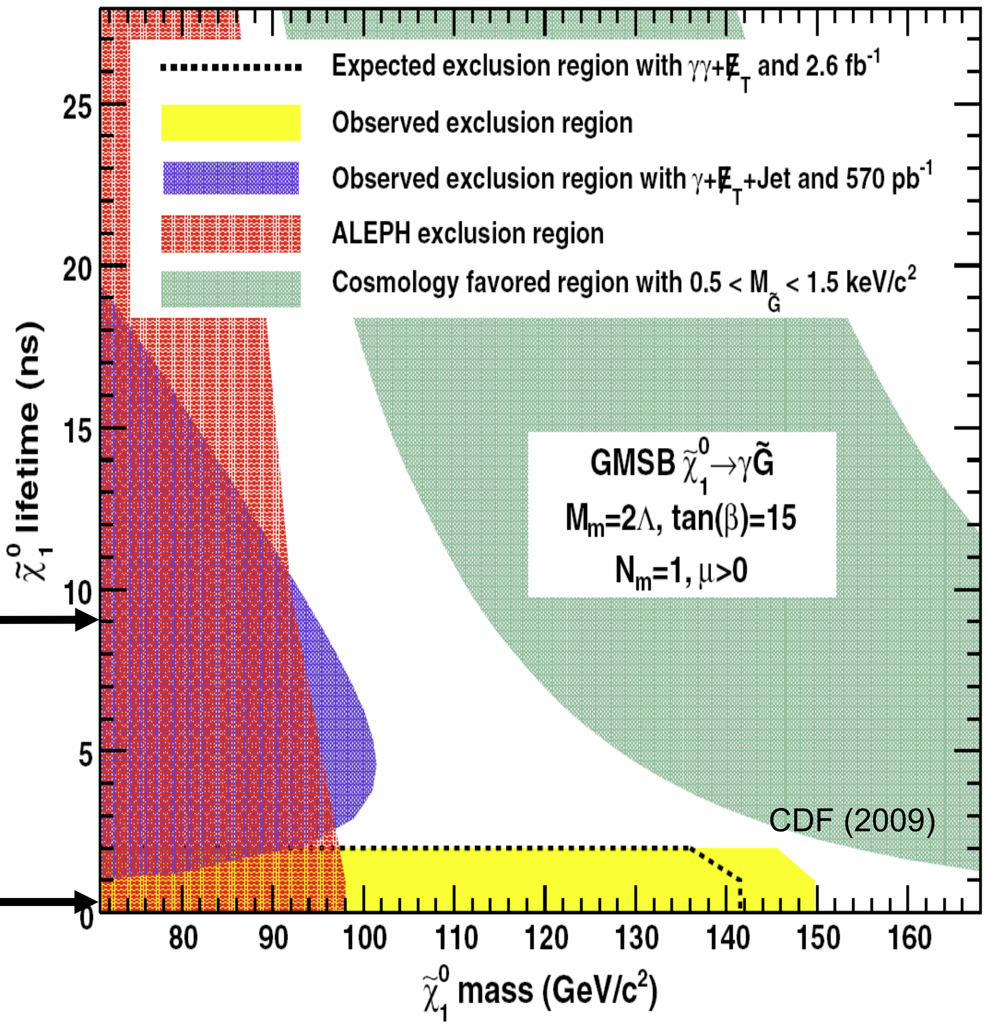
CURRENT BOUNDS

- 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



CDF (2009)

HIDDEN SECTORS

- All current evidence for DM is gravitational. Perhaps DM is in a hidden sector, composed of particles with no SM strong, weak, or electromagnetic interactions

SM

Hidden
X

- *A priori* there are both pros and cons
  - Lots of freedom: can have interesting new phenomena
  - Too much freedom: no connections to the problems of particle physics we would like to solve, WIMP miracle, ...

HIDDEN SECTOR INTERACTIONS

- There are many ways the hidden particles could couple to us. How should we think about this?

- Use effective operators as an organizing principle:

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

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

- *M* is a (presumably) large "mediator mass," so we expect high-dimension operators to be suppressed. There are not too many possibilities at dimension 4.

HIGGS PORTAL

Patt, Wilczek (2006)

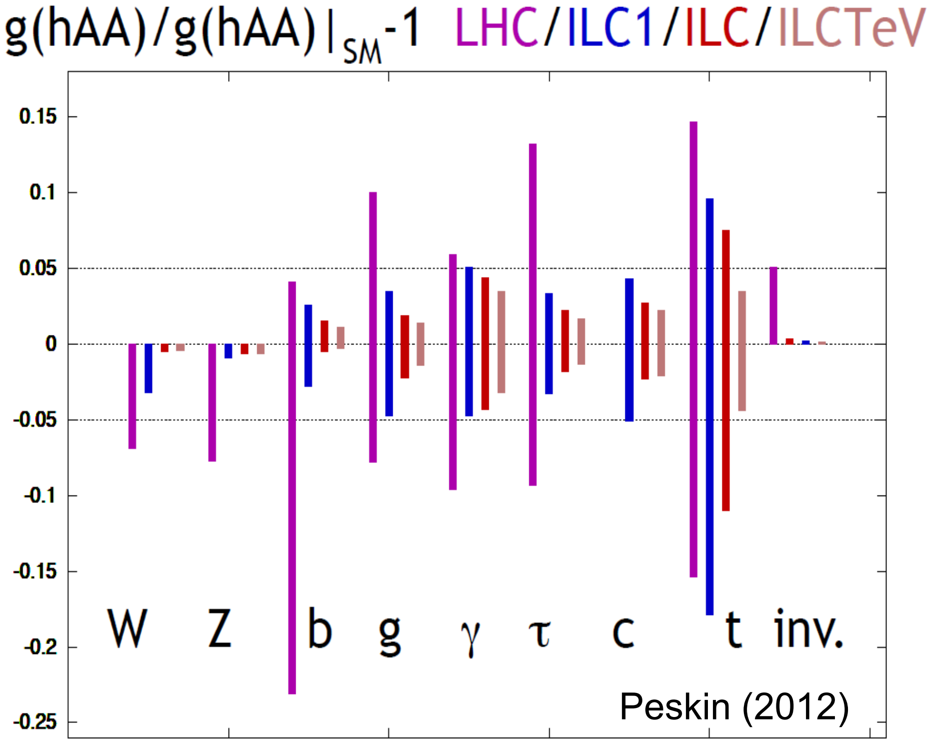
- One possibility is

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

where the *h* subscript denotes "hidden"

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

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



Peskin (2012)

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

HIDDEN PHOTONS

Holdom (1986)

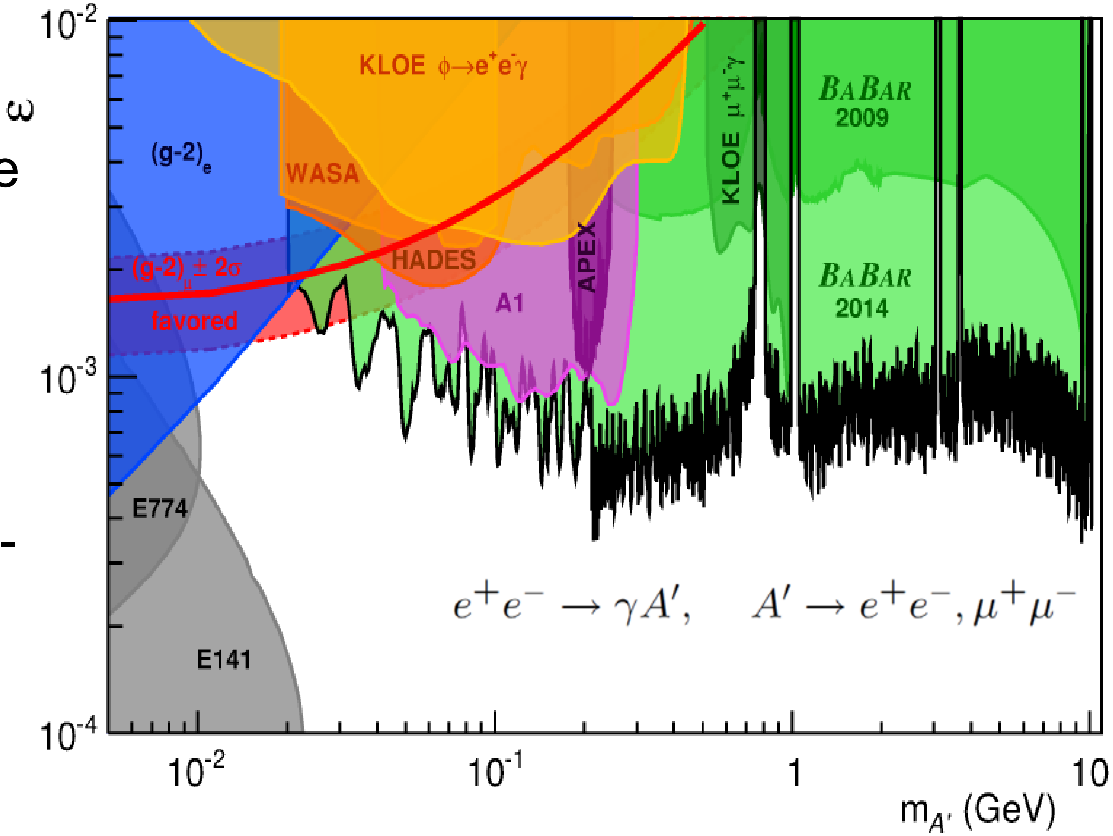
- Another possibility is $$\epsilon F_{\mu\nu} F_h^{\mu\nu}$$

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

- The hidden photon cannot be the DM, but may be a portal to the dark sector

- Diagonalizing the mass matrix, one finds that the SM particles have a hidden "milli-charge" proportional to ε

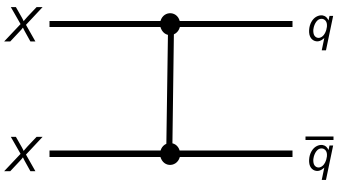
- Motivates searches at the "intensity frontier"



HIDDEN SECTOR FREEZEOUT

- The thermal relic density

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

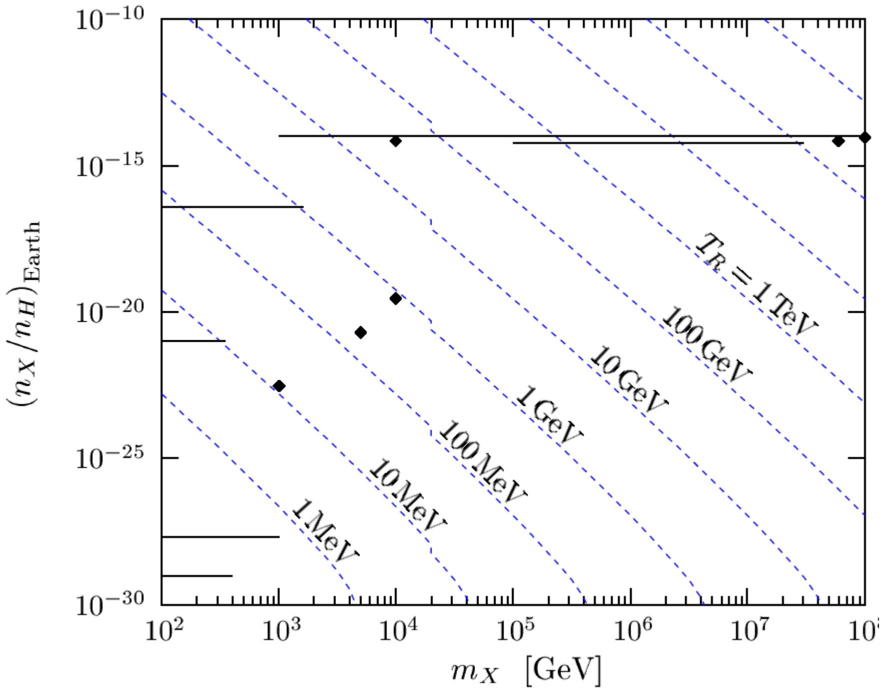


constrains only one combination of mass and coupling

- 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

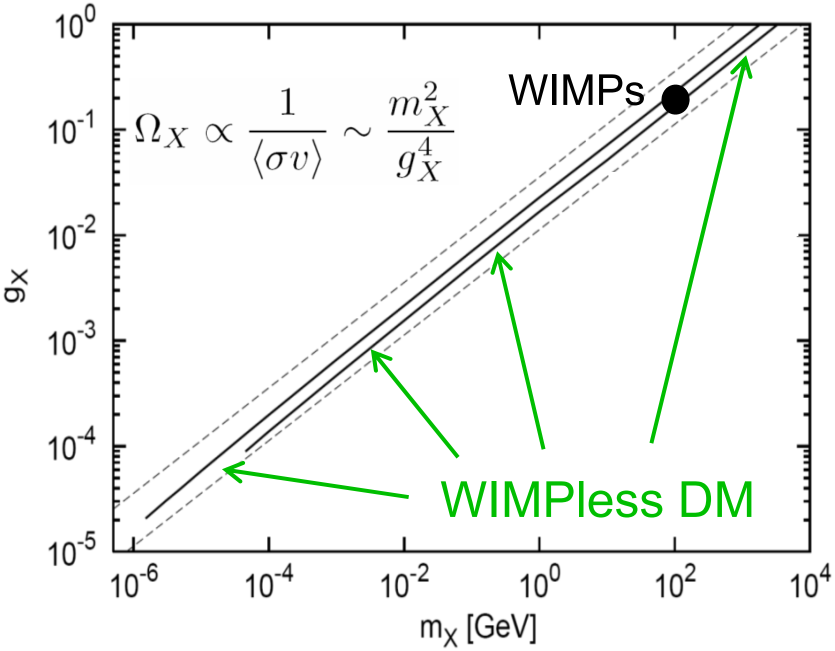
THE WIMPLESS MIRACLE

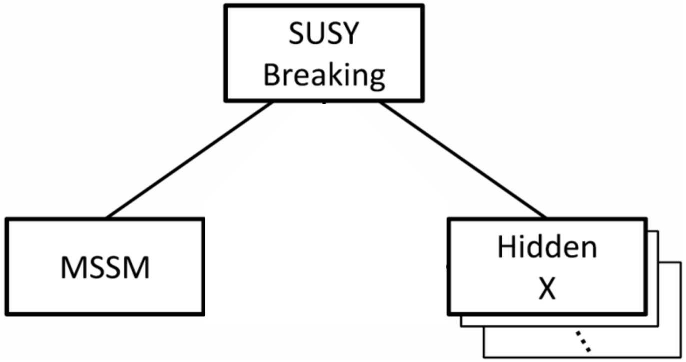
Feng, Kumar (2008); Feng, Tu, Yu (2009); Feng, Shadmi (2011)

- In a hidden sector, we can have other couplings
- In fact, in many SUSY models, to avoid unseen flavor effects, superpartner masses satisfy

$$m_X \sim g_X^2$$

- If this holds in a hidden sector, we have a “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?





SUSY Breaking

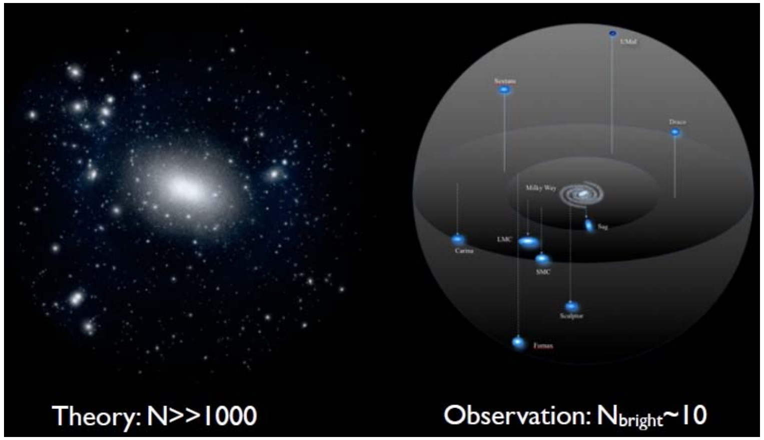
MSSM

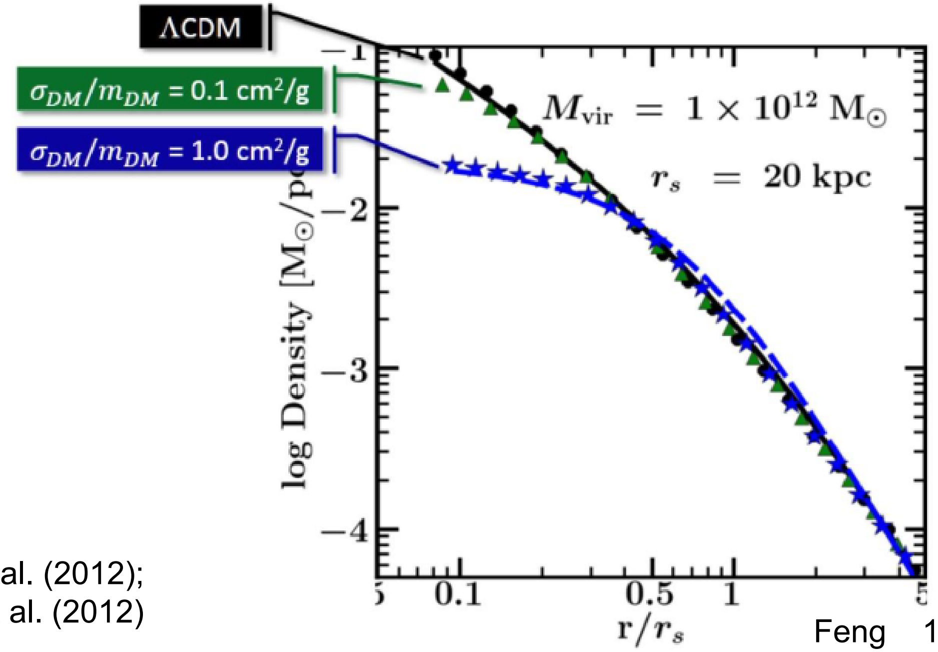
Hidden X

SELF-INTERACTING DARK MATTER

- If dark matter is completely hidden, can we learn anything about it?
- The Bullet Cluster provided evidence for dark matter. But the fact that dark matter passed through unperturbed →

  $\sigma_T/m < 1$ cm^2/g (or barn/GeV)
- But there are indications that the self-interactions may be near this limit
  - Cusps vs. cores
  - Number of visible dwarf galaxies





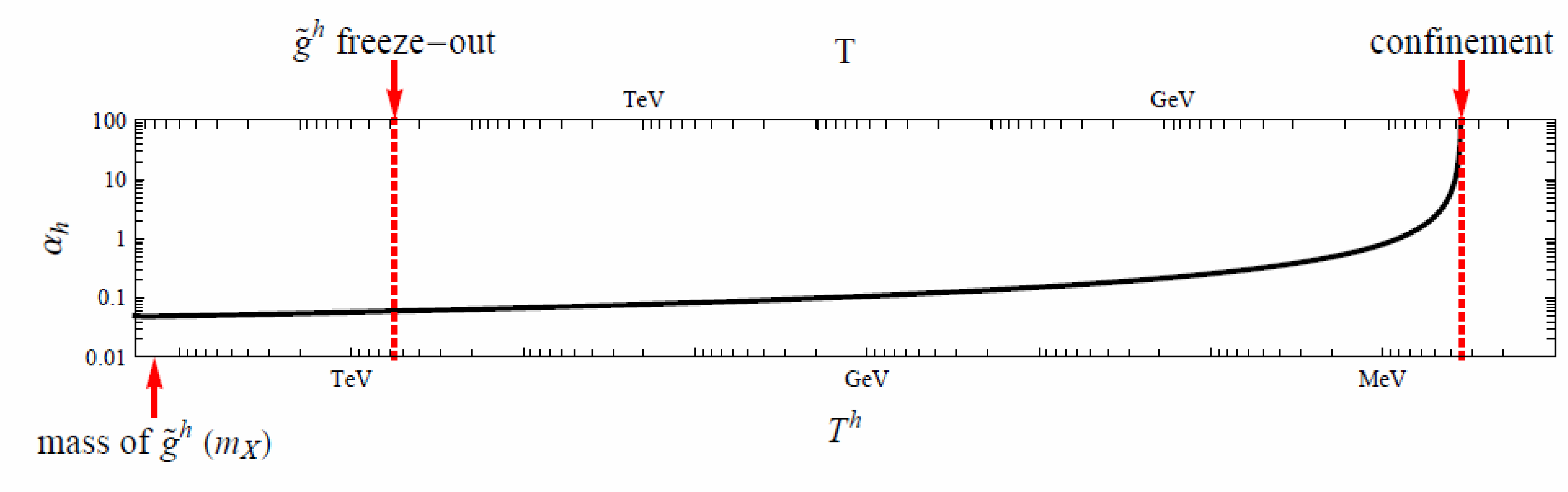
Rocha et al. (2012), Peter et al. (2012); Vogelsberger et al. (2012); Zavala et al. (2012)

DARK MATTER FROM HIDDEN QCD

Feng, Shadmi (2011), Boddy, Feng, Kaplinghat, Tait (2014)

- A simple example: pure SU(N) with hidden gluons g and gluinos $\tilde{g}$
- At early times, interaction is weak, ~10 TeV $\tilde{g}$ freezeout with correct Ω

  At late times, interaction is strong, glueballs (gg) and glueballinos ($g\tilde{g}$) form and self-interact with σ_T/m ~ 1 cm^2/g ~ 1 barn/GeV



- WIMP-like: TeV-masses with correct thermal relic density
- But completely different: self-interacting, multi-component dark matter

LECTURE 3 SUMMARY

- In addition to WIMPs, there are many other attractive DM candidates with similar motivations, but completely different implications for cosmology and HEP
- Examples: long-lived charged particles, prompt photons, invisible Higgs decays, hidden photons, …
- Is any of this right? LHC will be running soon, direct and indirect detection, astrophysical probes are improving rapidly – we will see soon