PARTICLE PHYSICS AND COSMOLOGY

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The 2014 European School
of High Energy Physics

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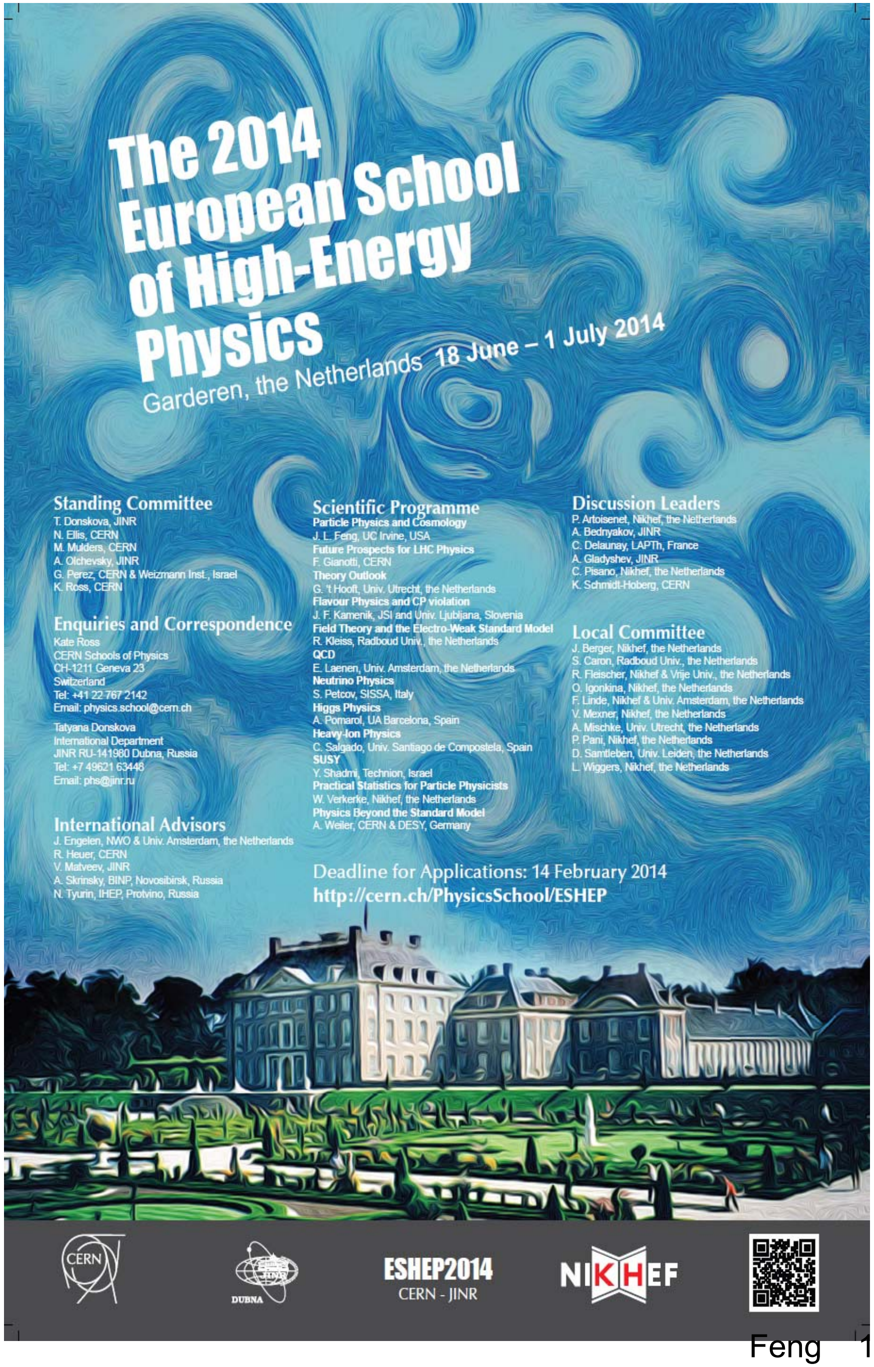

The 2014
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OUTLINE

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

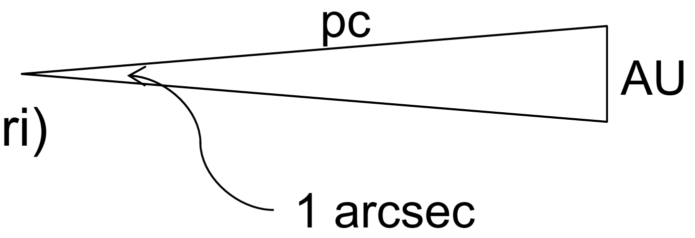
- Little previous knowledge of cosmology is assumed; focus on heuristic derivations, order-of-magnitude estimates, intuitive arguments, and some aspects that (at present) seem to be most linked to particle physics, and particularly high-energy physics. This is a huge topic, many important topics will be neglected.

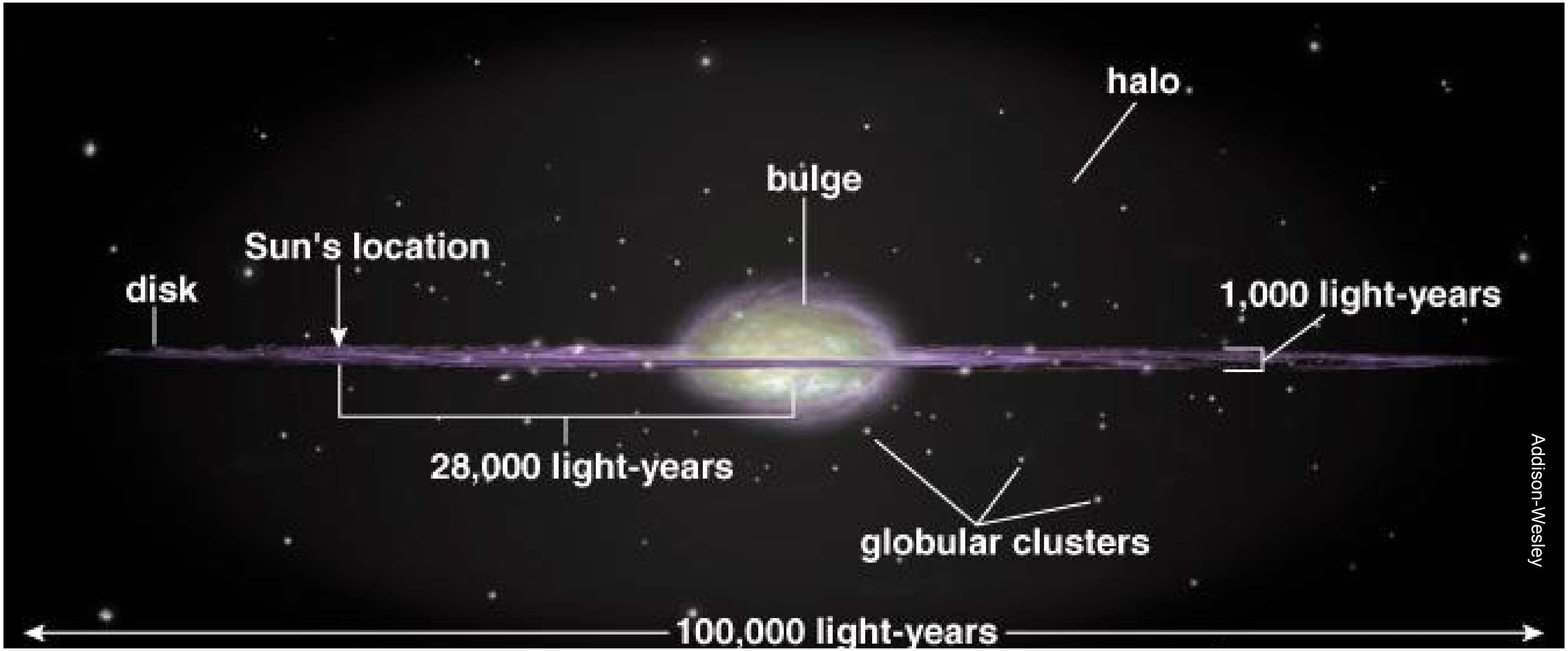
PARTICLE PHYSICS SCALES

- Natural units: $h = c = k_B = 1$
  - $h = c = 1$ is standard
  - $k_B = 1 \rightarrow 1$ 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

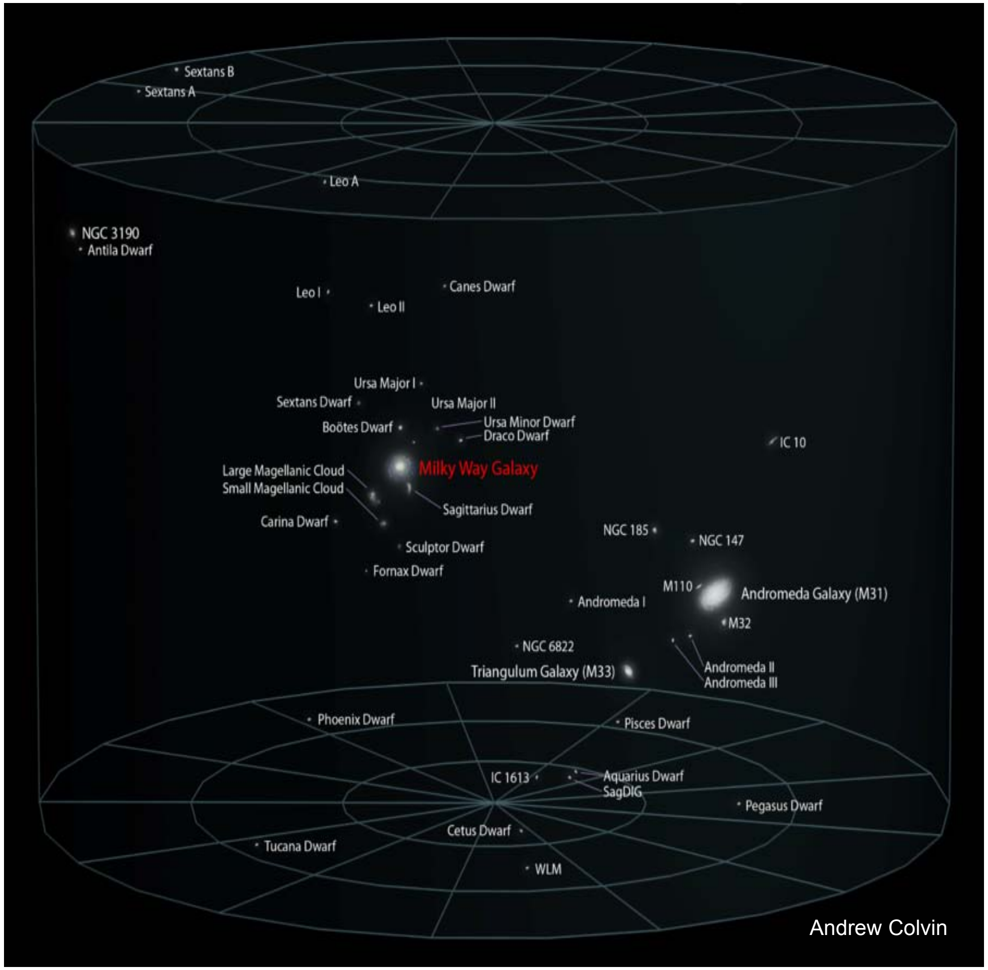




Addison-Wesley

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

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

  where $g = \det(g_{\mu\nu})$, $G = M_{\text{Pl}}^{-2}$, 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

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

  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

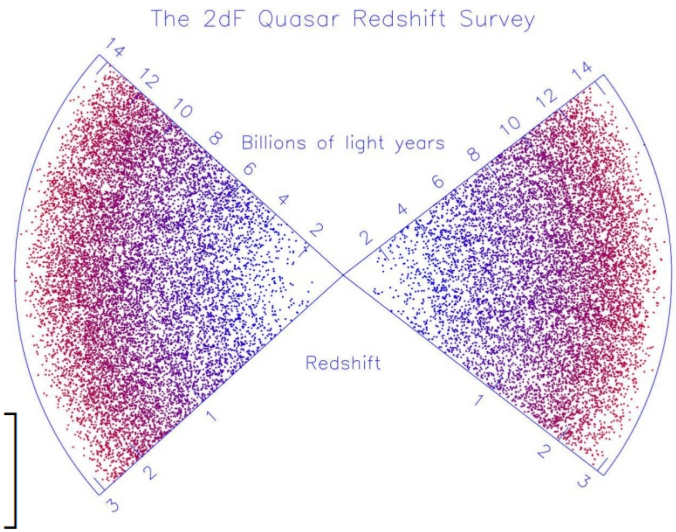
$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$

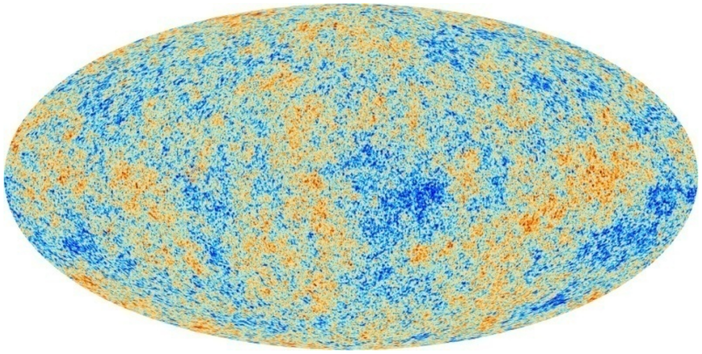
and stress-energy tensor

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

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 $T^{\mu\nu}{}_{;\nu} = 0 \rightarrow \rho \sim a^{-3(1+w)}$
- For example, we can consider 3 kinds of contributions to the energy density:

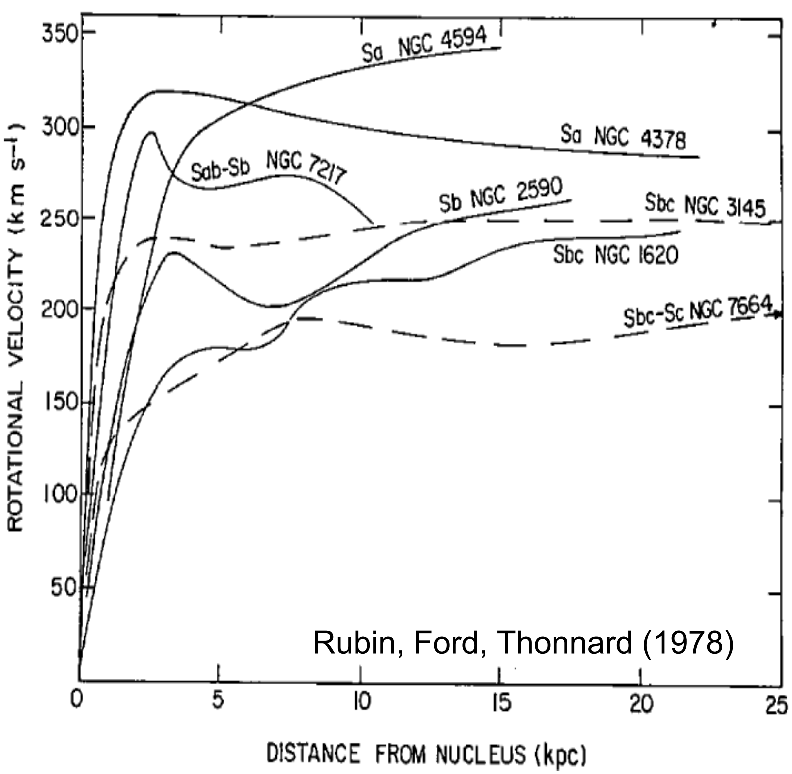
  Matter: ρ is diluted by expansion (w = 0) $\mathrm{MD}: \rho \propto a^{-3} \Rightarrow \dot{a}^2 \propto \frac{1}{a} \Rightarrow a \propto t^{2/3}$

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

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

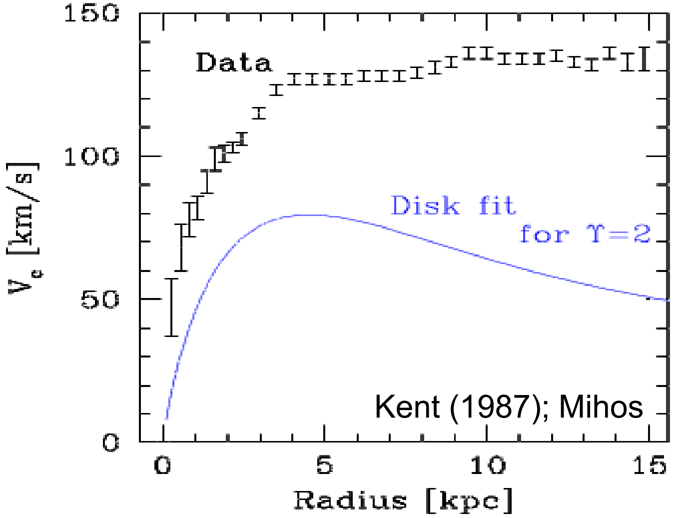
- Rotational velocity v_c as function of distance from center r
  - $v_c \sim O(300)$ km/s ~ $O(10^{-3})$ c
  - r ~ few kpc (pc = 3.26 ly)
- Expect $v_c \sim r^{-1/2}$ beyond luminous region

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

Instead find v_c ~ constant

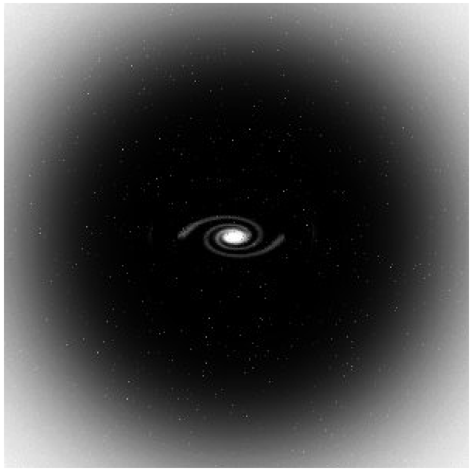
- The discrepancy may be resolved by missing mass and is classic (but not the first) evidence for dark matter

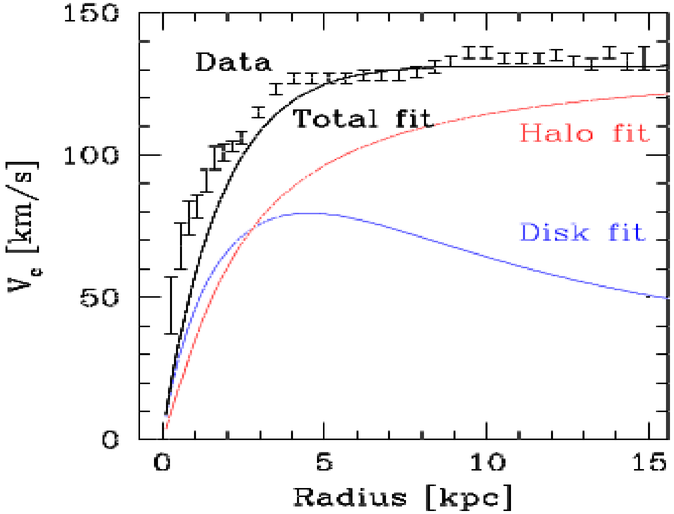
AN EXAMPLE: NGC 2403



Kent (1987); Mihos

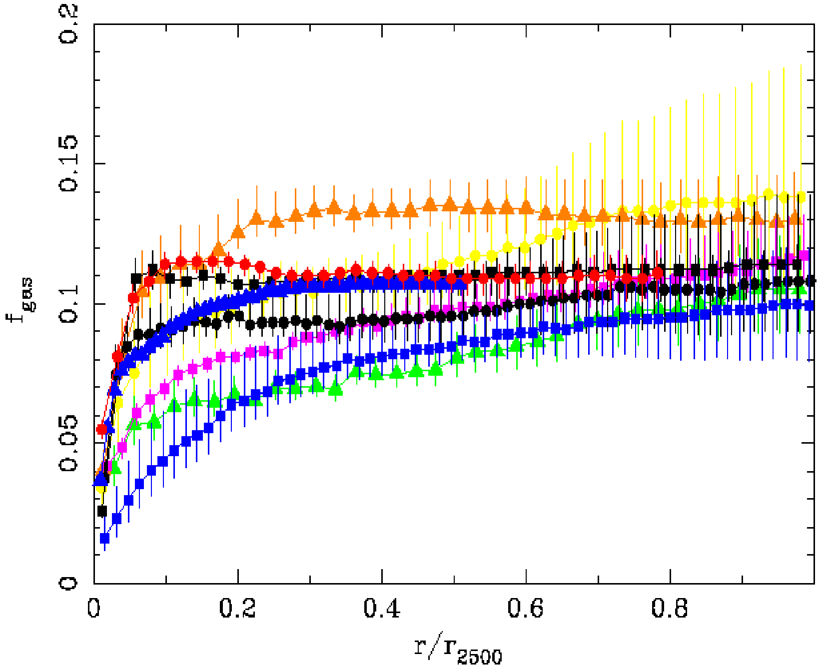
- v_c from HI line
- Fit mass-to-light ratio, halo model; this tells us about $\rho(r)$





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} ~ 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

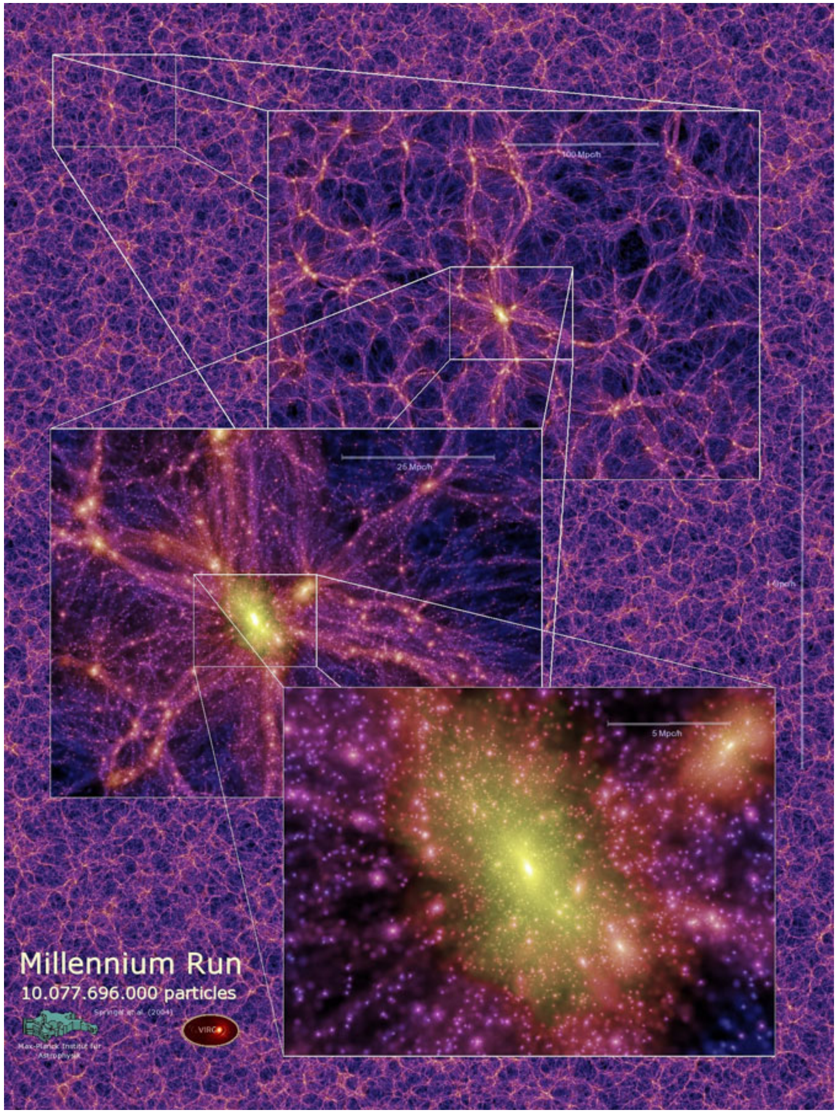
DARK MATTER DISTRIBUTION

- Many other observations lead to the same conclusions: weak lensing, strong lensing, Bullet Cluster, …
- Simulations and observations lead to a consistent picture on large scales
- DM clumps, leads to structure formation, every galaxy is surrounded by a dark matter halo
- Local DM properties

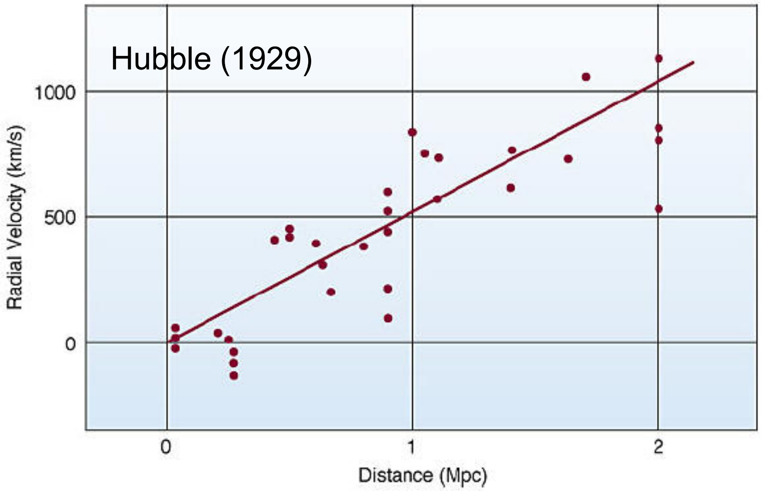
  $\rho \sim 0.2 – 0.5$ GeV/cm^3,

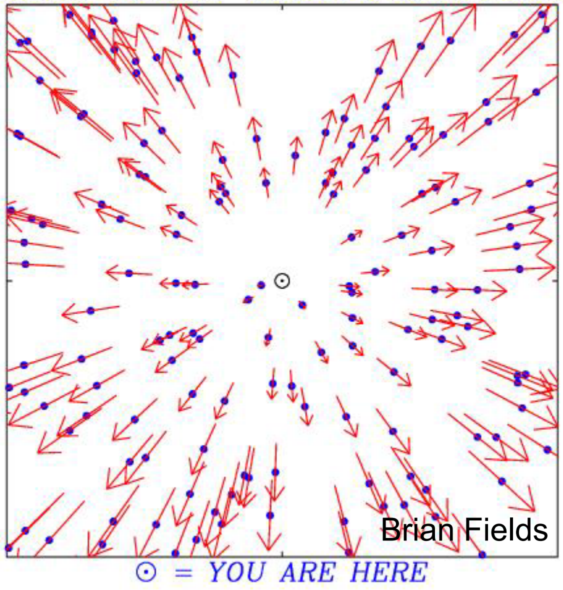
  overdense by factor of ~ 10^5

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



EXPANSION OF THE UNIVERSE


Hubble (1929)


Brian Fields

- 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

$$v = H d$$

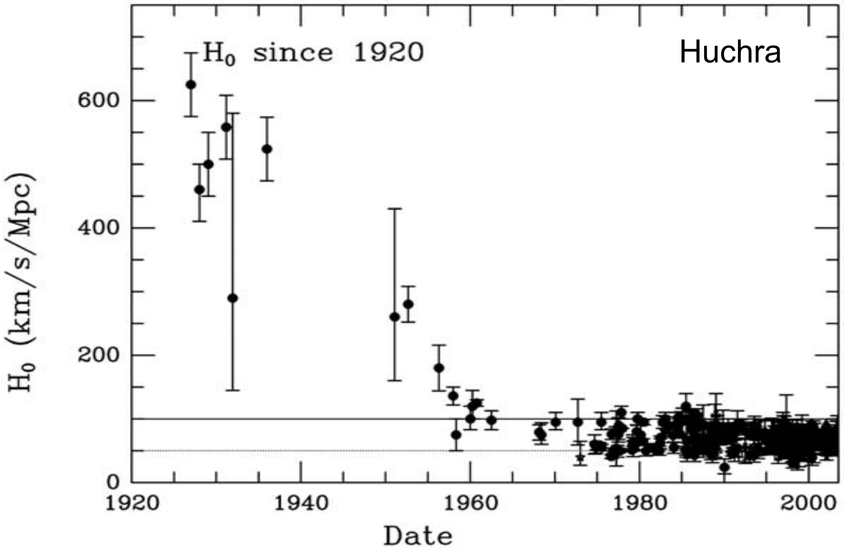
- The current value of the Hubble parameter is

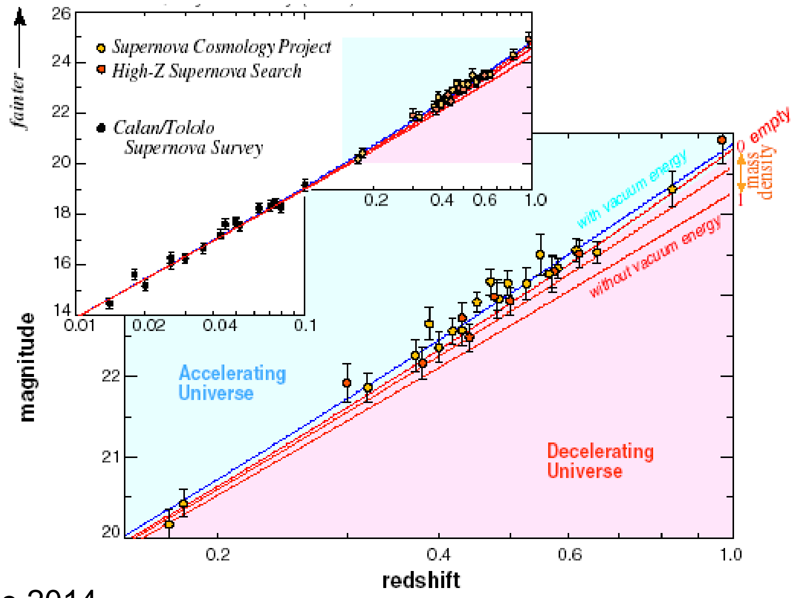
$$H_0 = h\ 100\ \text{km/s/Mpc}$$
$$h = 0.705 \pm 0.015 \quad (h^2 \approx ½)$$

- 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!

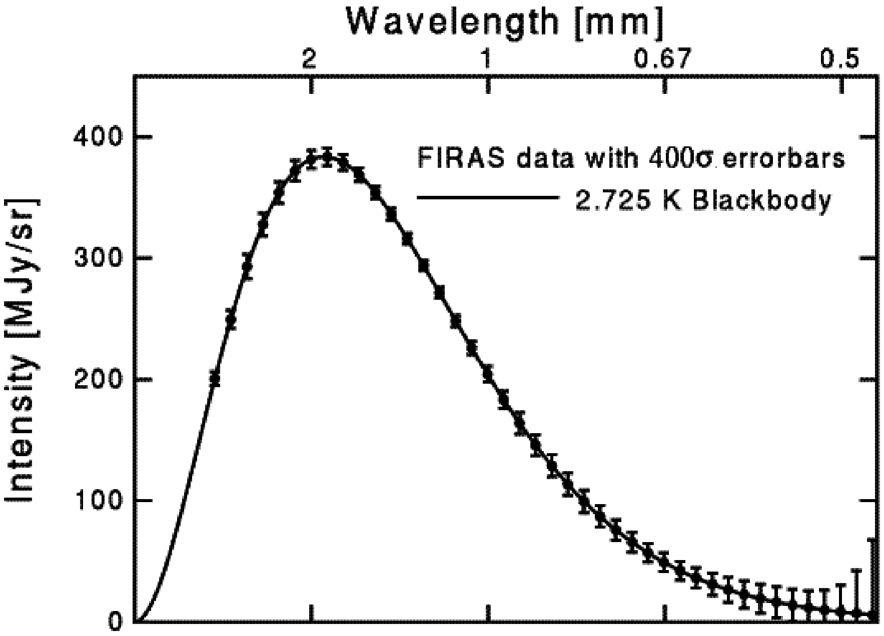
- Measurement of this expansion history constrains the acceleration of expansion:

$$\Omega_\Lambda - \Omega_M$$

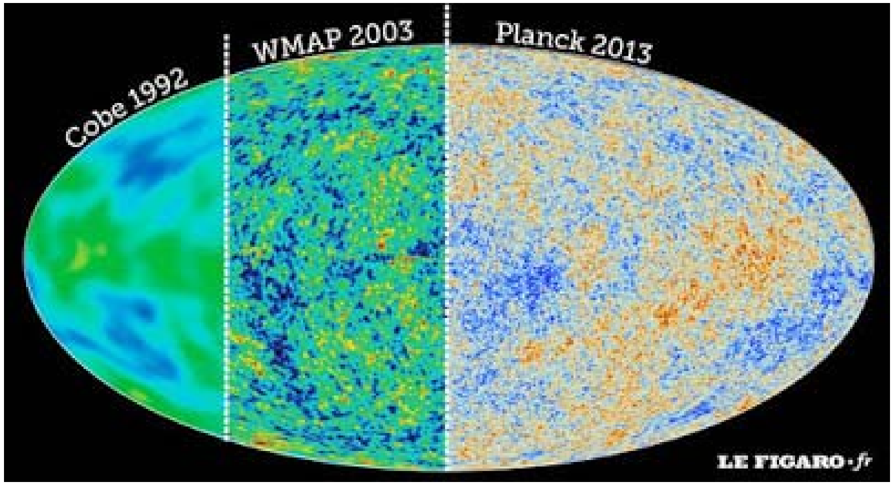
“Attractive matter vs. repulsive dark energy”

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



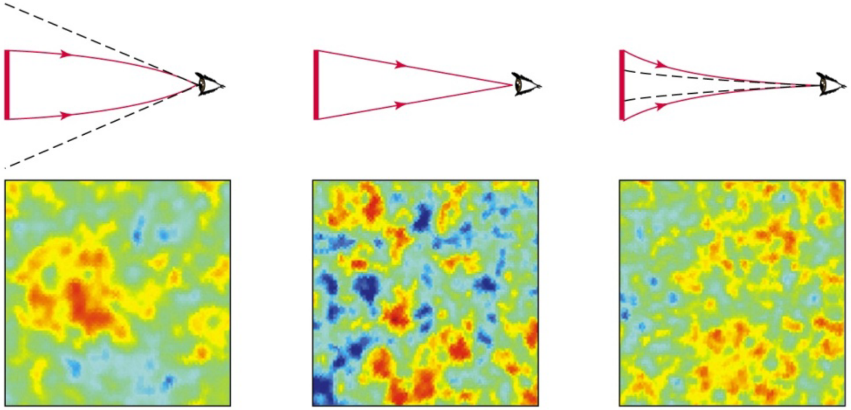
COSMIC MICROWAVE BACKGROUND

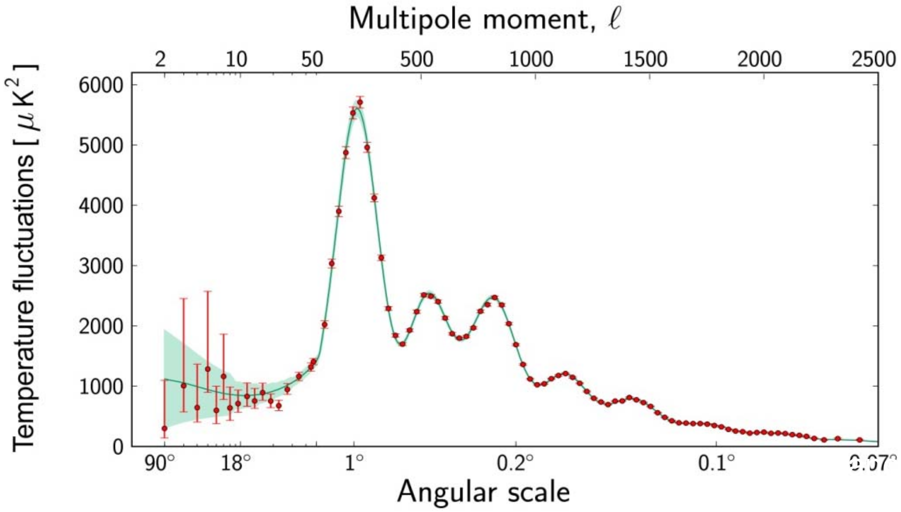


- There is, however, a tiny anisotropy of $\delta T/T \sim 10^{-5}$
- Dramatic improvements from COBE to WMAP to Planck
- Angular size of the hot and cold spots constrains the geometry:

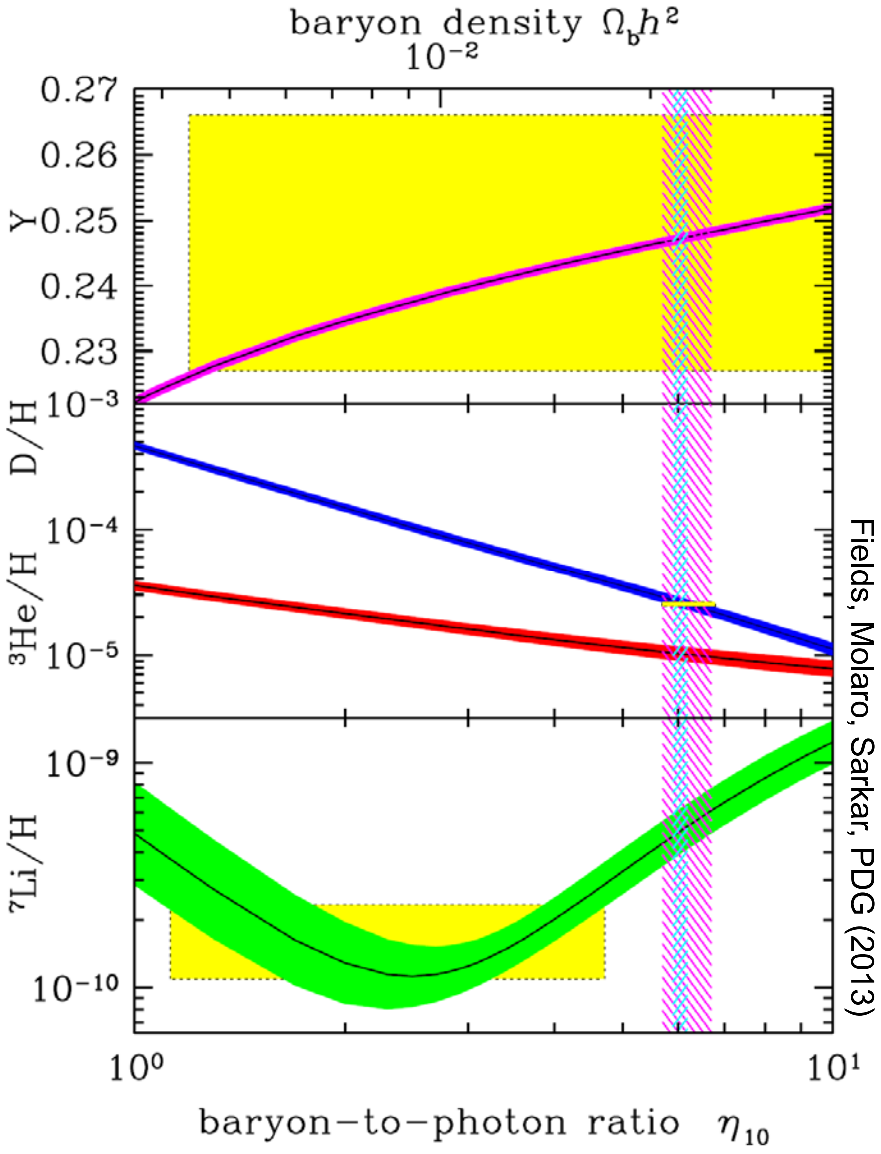
$$\Omega_\Lambda + \Omega_M$$

“total energy density”





BIG BANG NUCLEOSYNTHESIS



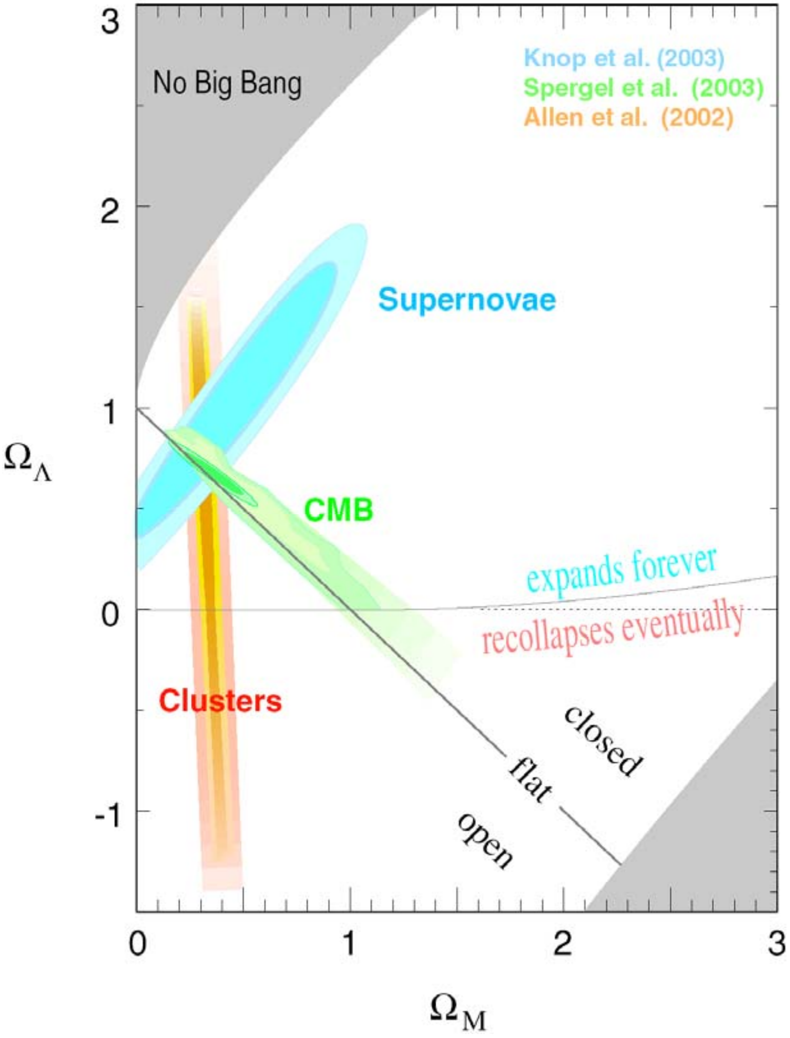
Fields, Molaro, Sarkar, PDG (2013)

- 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

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

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

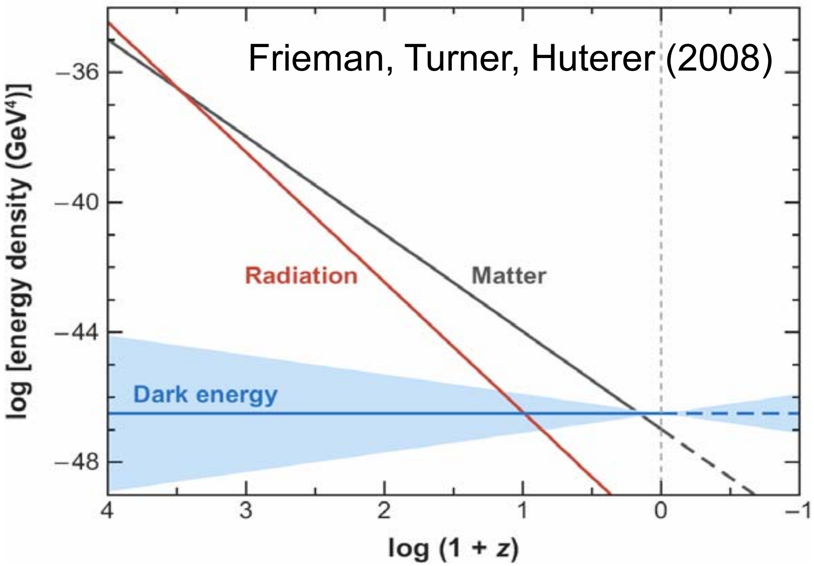
WHAT DOMINATES WHEN?

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

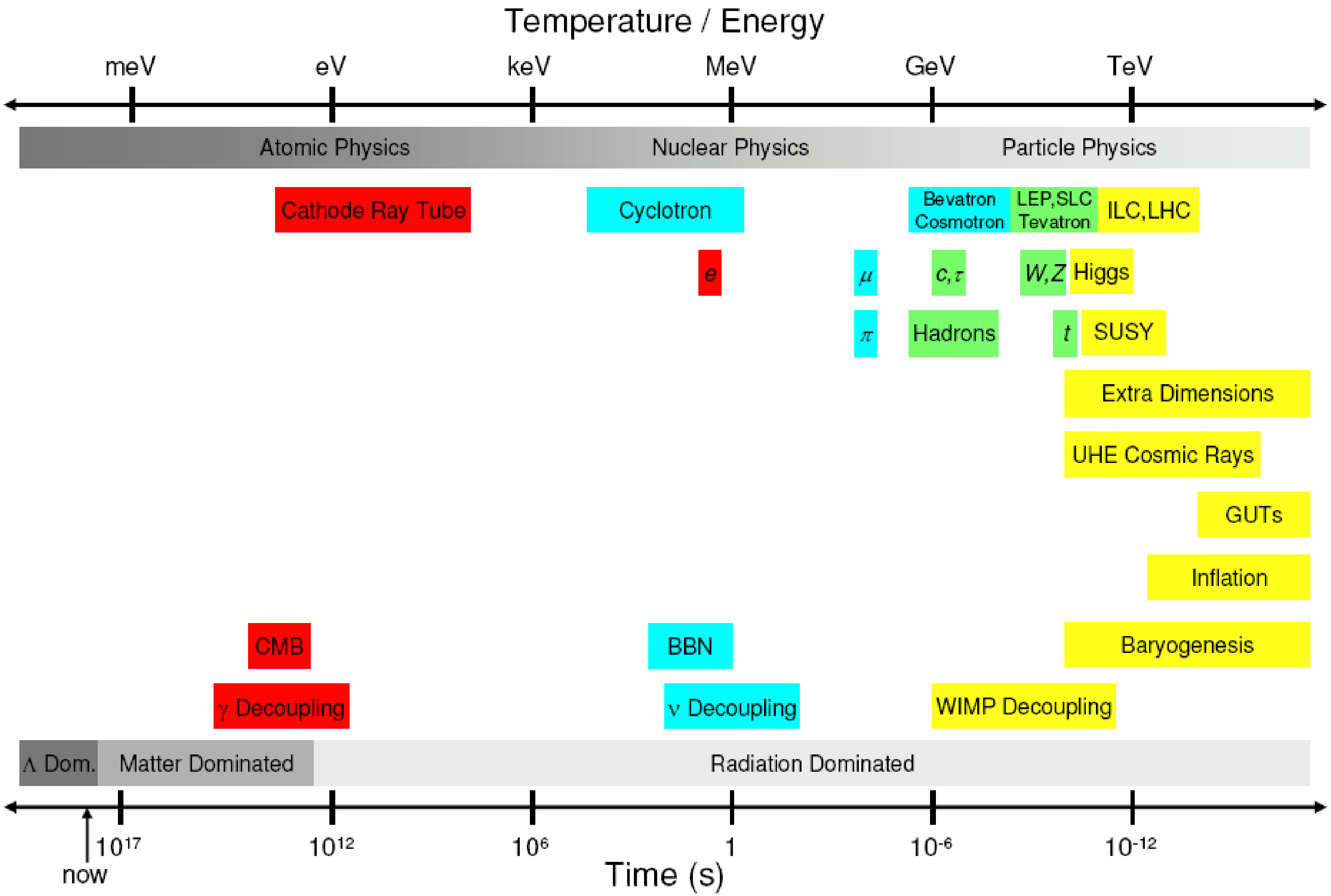
$$\Omega_{\text{CMB}} \equiv \frac{\rho_{\text{CMB}}}{\rho_c} \sim \frac{T^4_{\text{CMB}}}{\frac{3H^2}{8\pi G}} \sim \frac{(2.7\ \text{K})^4(14\ \text{Gyr})^2}{(10^{19}\ \text{GeV})^2}$$

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

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



THERMAL HISTORY OF THE UNIVERSE



DECOUPLING

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

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

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

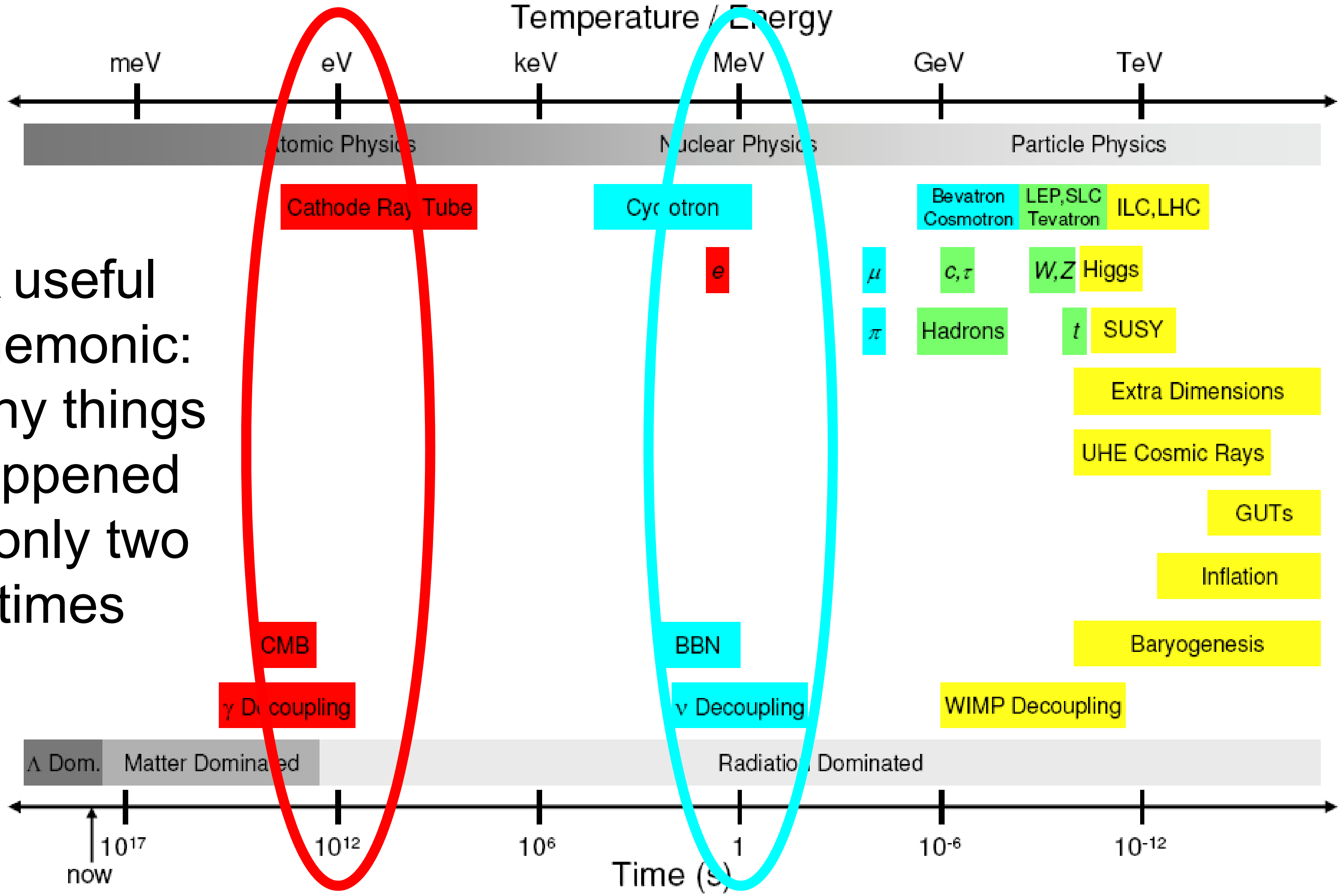
- An example: neutrino decoupling. By dimensional analysis,

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

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

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?
- …

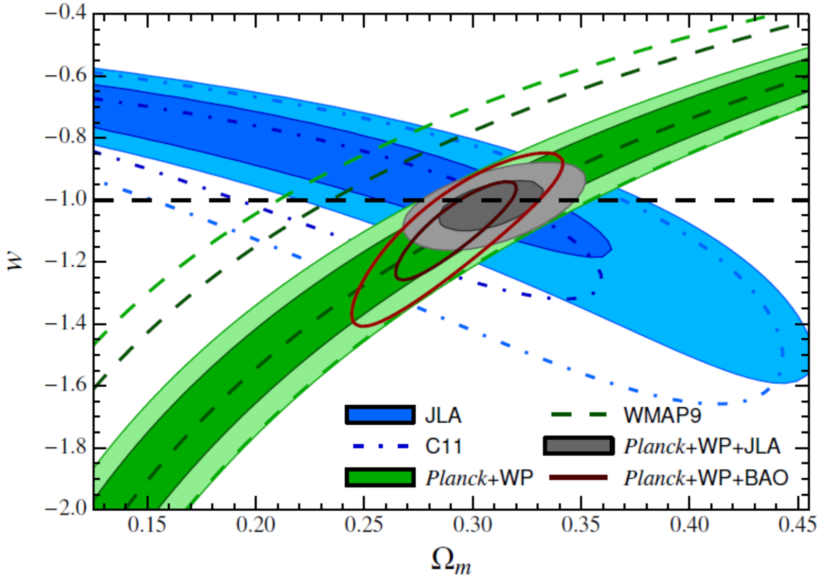
Particle physics is required to answer all of these, not least because it is required to understand the hot early Universe

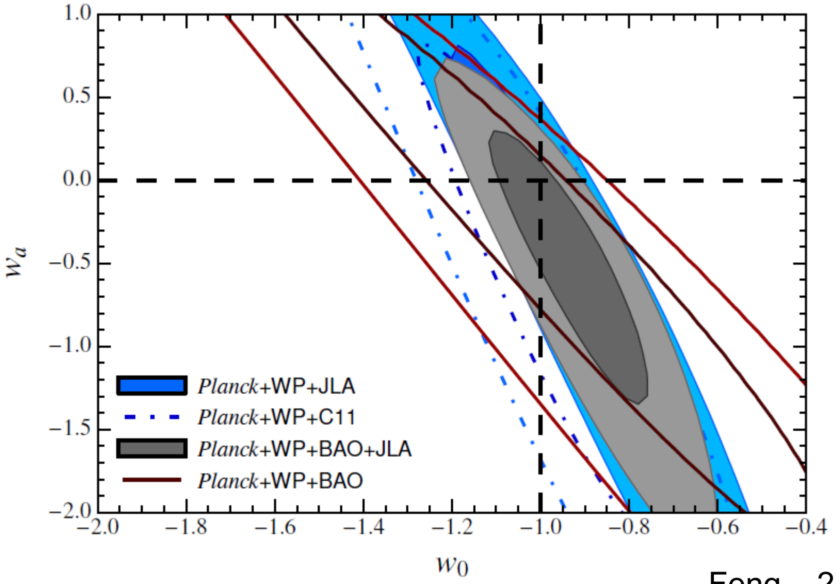
DARK ENERGY

- 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

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

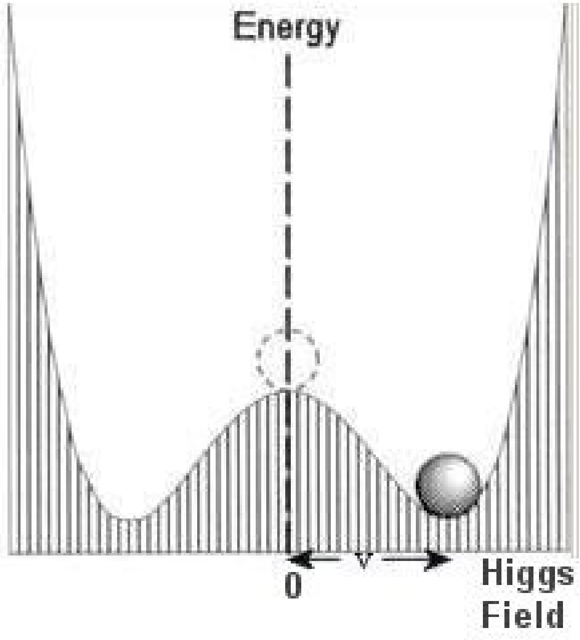




DARK ENERGY

- $\Omega_\Lambda \approx 0.73 \rightarrow \rho_\Lambda \sim (\mathrm{meV})^4$: 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

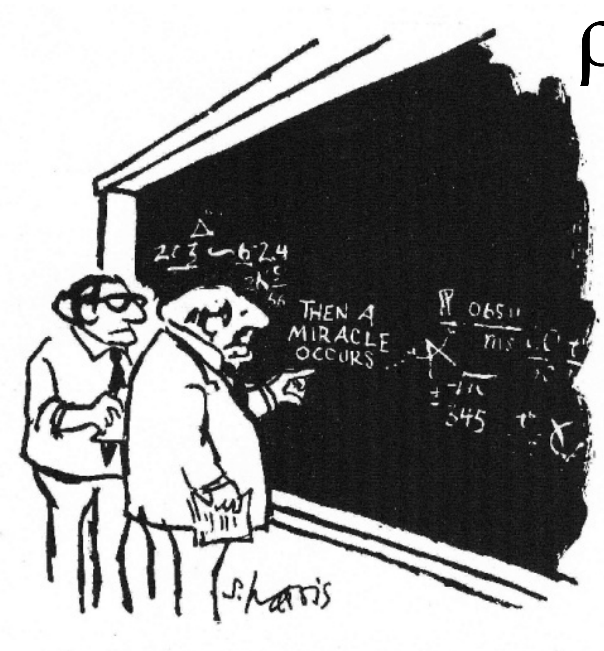


- We expect

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

ONE APPROACH

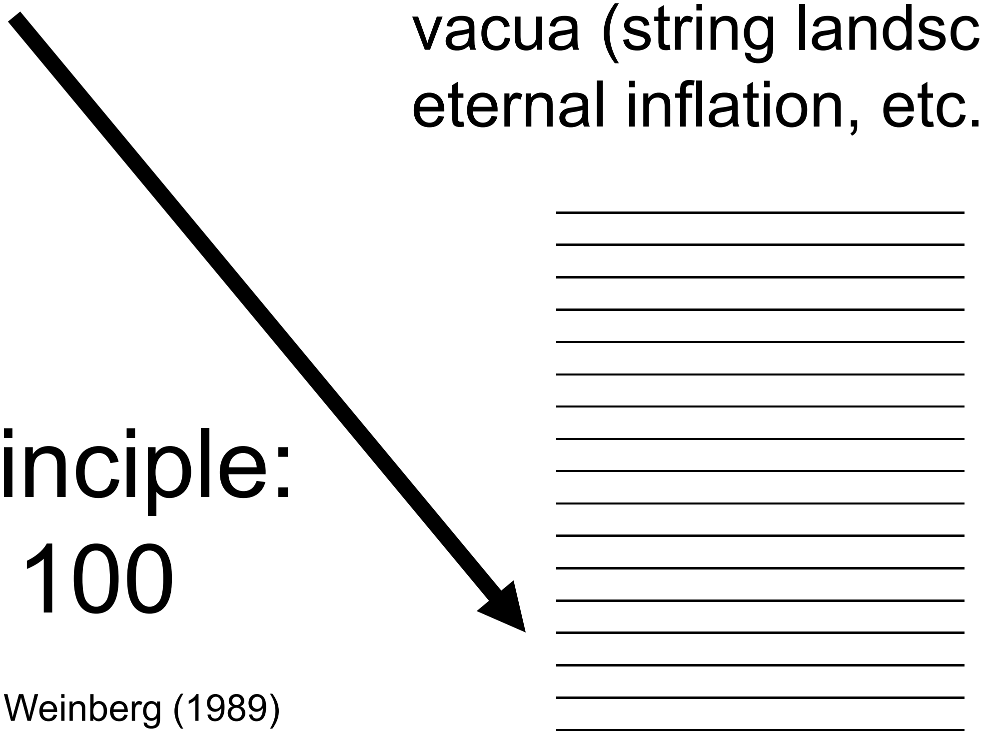
- Small numbers ↔ broken symmetry



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

$$\begin{tikzcd}
\rho_\Lambda \sim M_{Pl}^4 \arrow[d, "??"'] & \rho_\Lambda \sim m_\nu^4, \\
\rho_\Lambda = 0 \arrow[ur] & (M_W^2/M_{Pl})^4, \ldots
\end{tikzcd}$$

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)

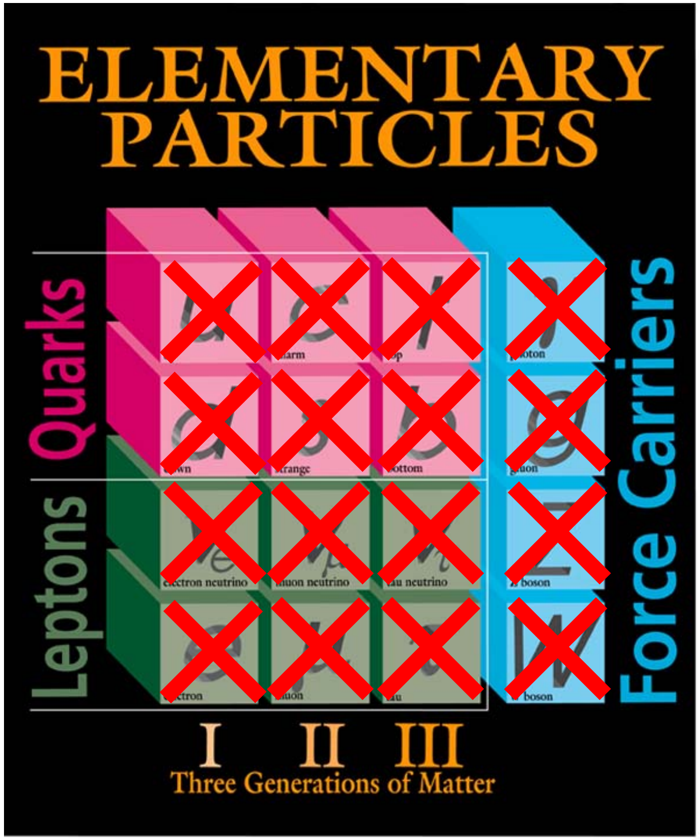
DARK ENERGY PROSPECTS

- 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

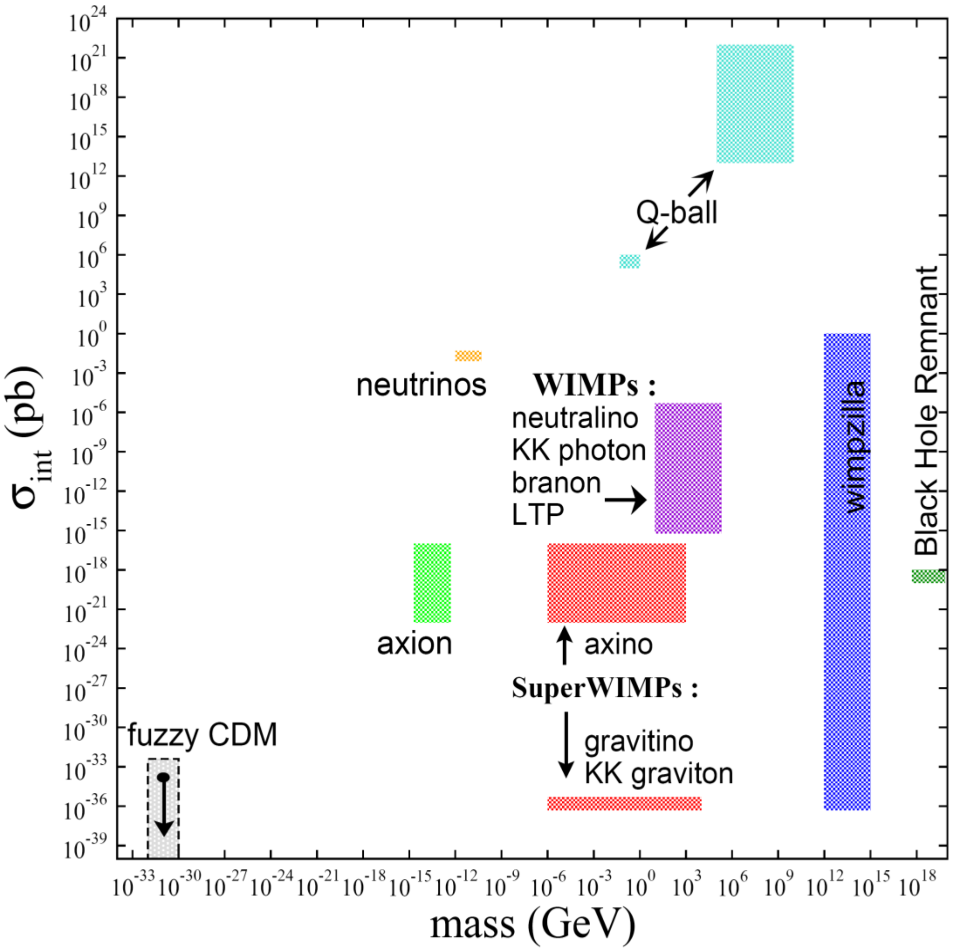
Known DM properties

- 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:

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

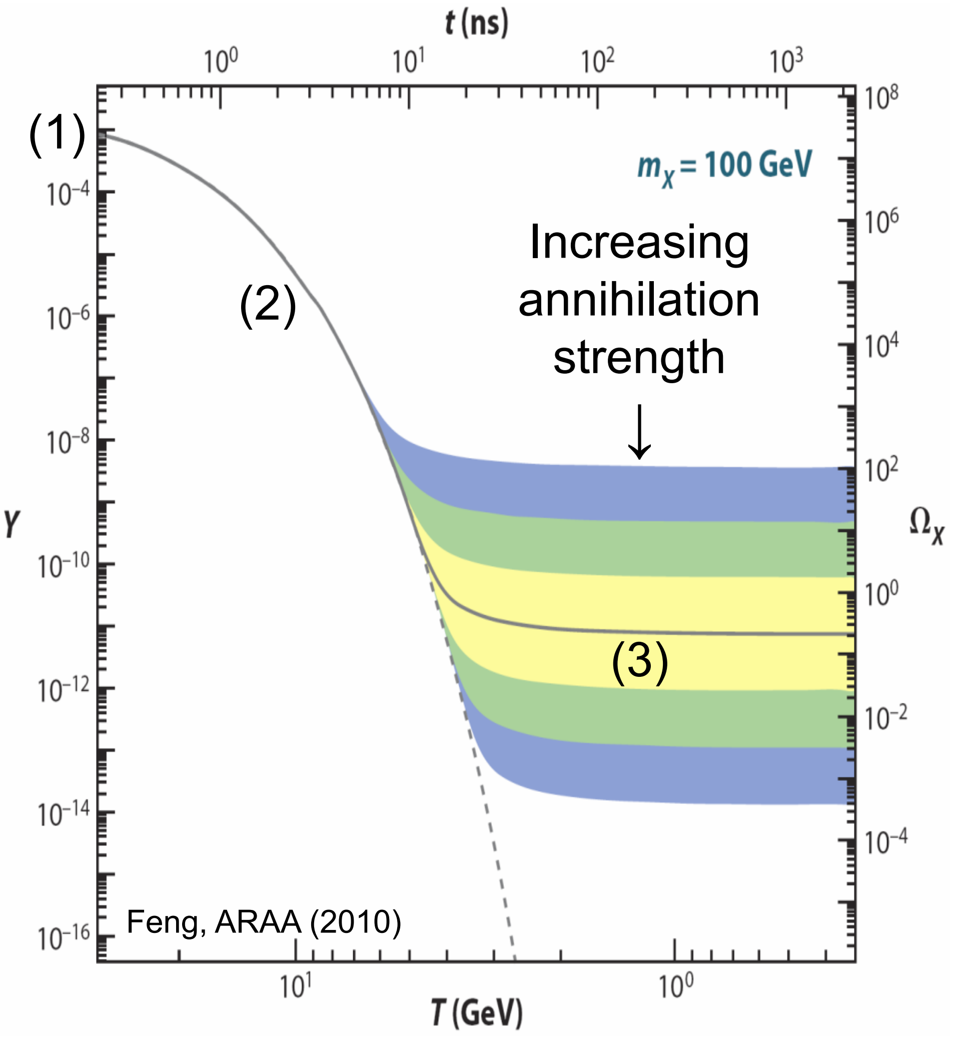
(2) Universe cools:

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

(3) Universe expands:

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

Zeldovich et al. (1960s)



Feng, ARAA (2010)

FREEZE OUT: MORE QUANTITATIVE

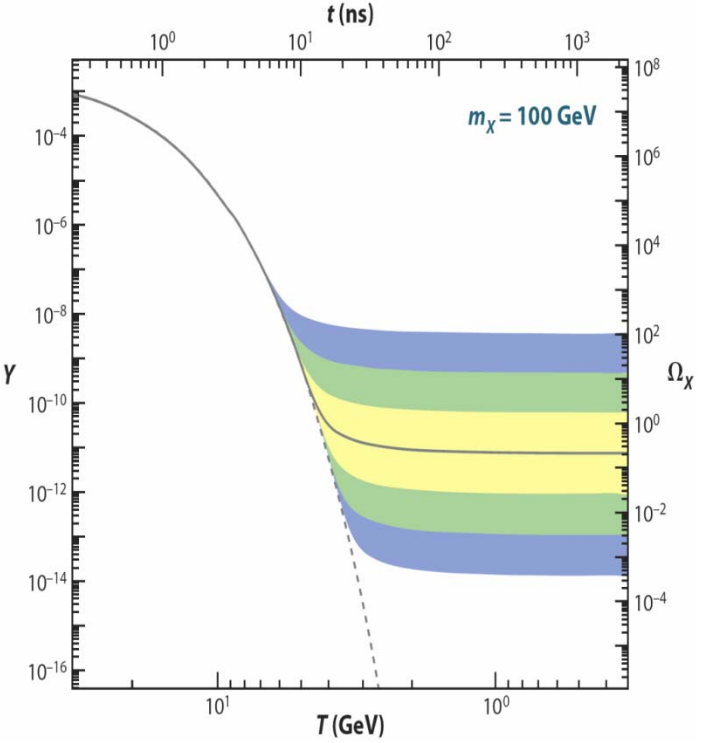
- The Boltzmann equation:

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

- n ≈ n_{eq} until interaction rate drops below expansion rate:

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

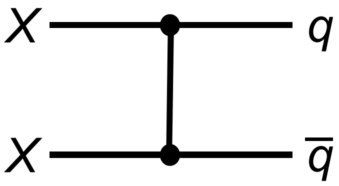
- Might expect freeze out at T ~ m, but the universe expands *slowly*! First guess: m/T ~ ln (M_{Pl}/m_W) ~ 40



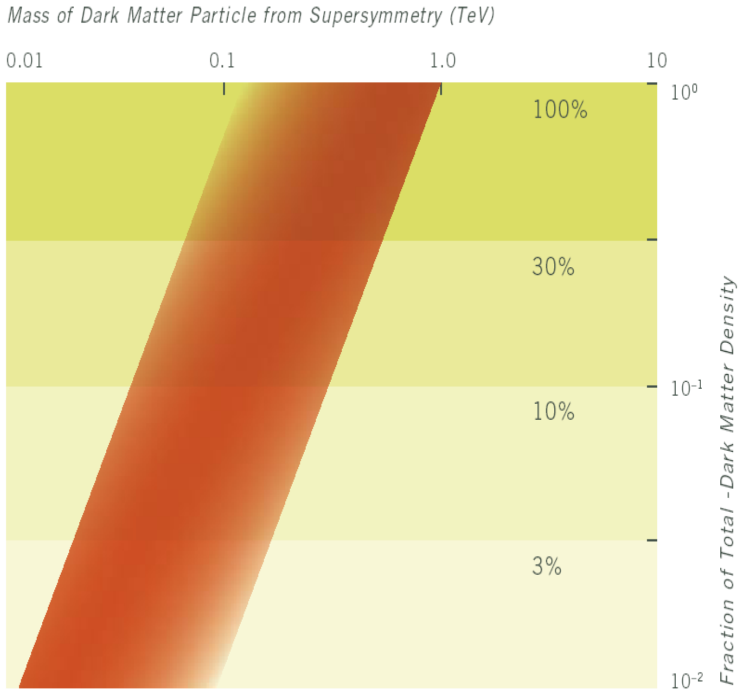
THE WIMP MIRACLE

- 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)

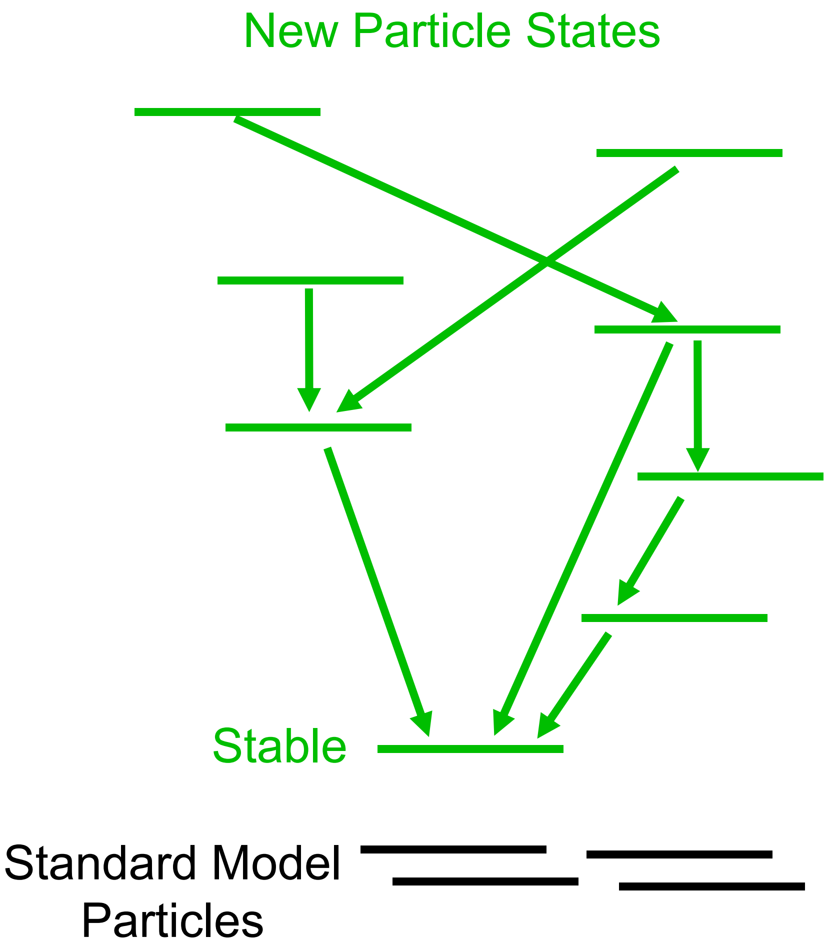
- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

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

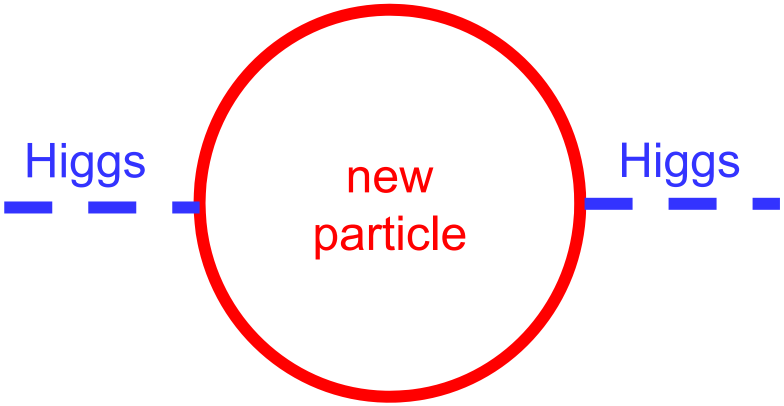
- First, the WIMP must be stable

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

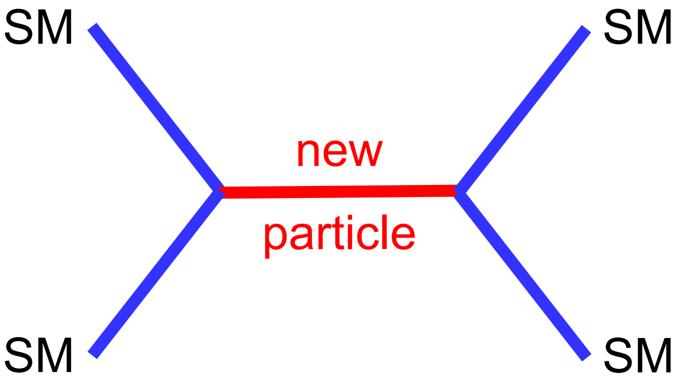


LEP'S COSMOLOGICAL LEGACY

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)

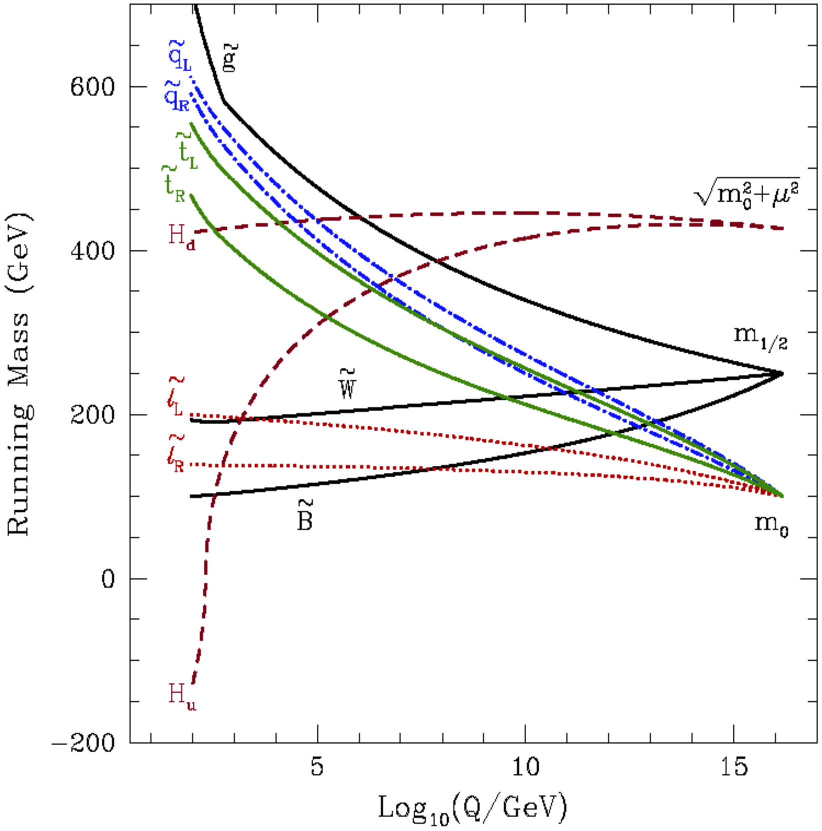
- Simple solution: impose a discrete parity, so all interactions require *pairs* of new particles. This also makes the lightest new particle stable:

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?