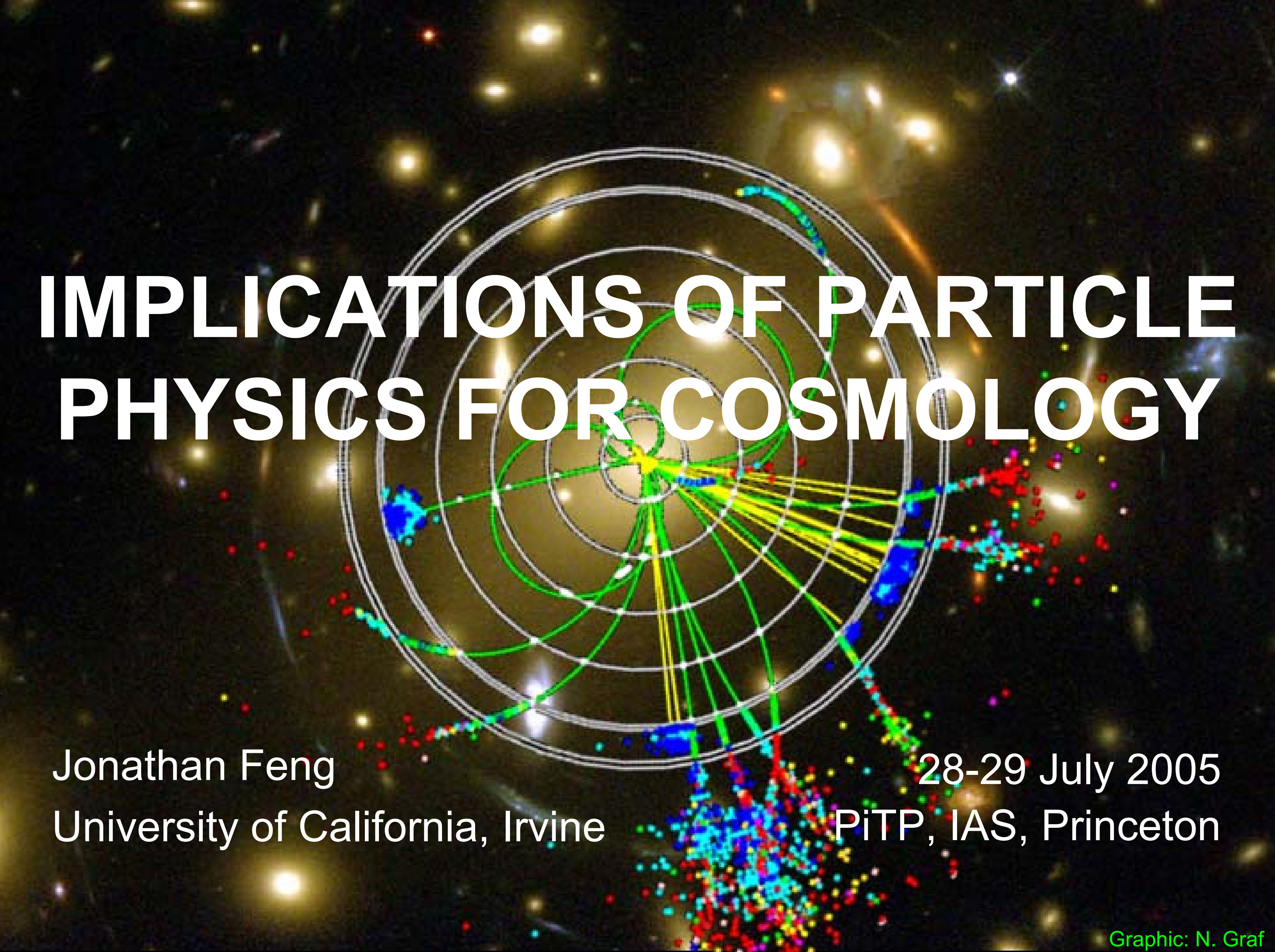

IMPLICATIONS OF PARTICLE PHYSICS FOR COSMOLOGY

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University of California, Irvine

28-29 July 2005
PiTP, IAS, Princeton

Graphic: N. Graf

OVERVIEW

- This Program anticipates the coming revolution in particle physics: LHC in 2007
- We are living through a period of scientific revolution in a closely allied field: cosmology
- These 3 lectures are devoted to explaining how these two might be related

REFERENCES AND DETAILS

Little cosmology background assumed. There are many reviews. See, for example:

- Jungman, Kamionkowski, Griest, hep-ph/9506380
- Bergstrom, hep-ph/0002126
- Bertone, Hooper, Silk, hep-ph/0404175
- Feng, hep-ph/0405215

OUTLINE

LECTURE 1

The Universe Observed, WIMP Cosmology

LECTURE 2

WIMP Detection, WIMPs at Colliders

LECTURE 3

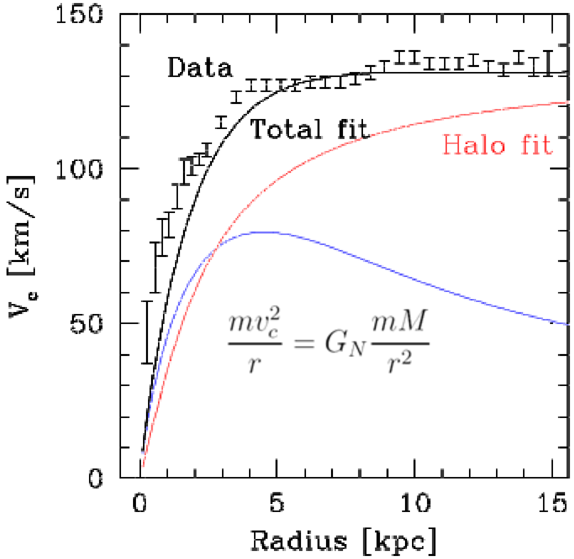
Gravitino Cosmology, SuperWIMPs at Colliders

THE UNIVERSE OBSERVED

- For the first time in history, we now have a complete picture of the Universe
- How did this come about?
- The evidence (in 5 slides or less):

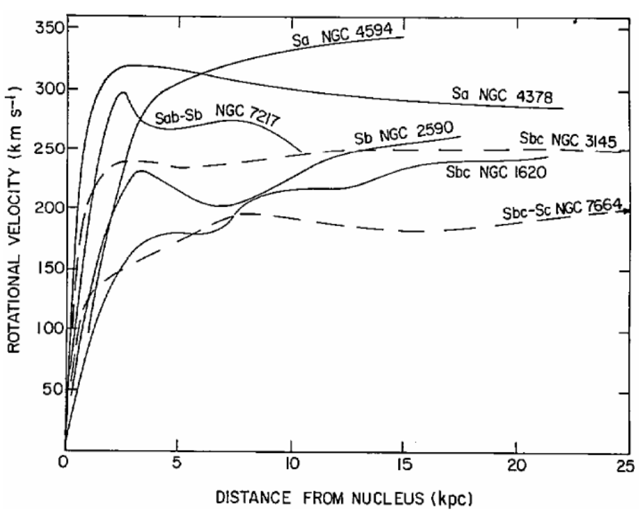
Rotation Curves

Galaxies and galactic clusters rotate



- Expect $v_c \sim r^{-1/2}$ beyond luminous region
- Instead find $v_c \sim$ constant
- Discrepancy resolved by postulating dark matter

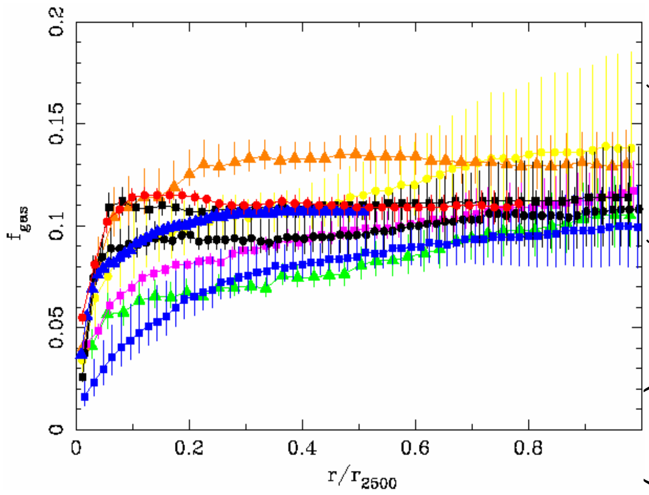
Then



Rubin, Ford, Thonnard (1978)

- In the universe, there's more than meets the eye

Now



Allen, Schmidt, Fabian (2002)

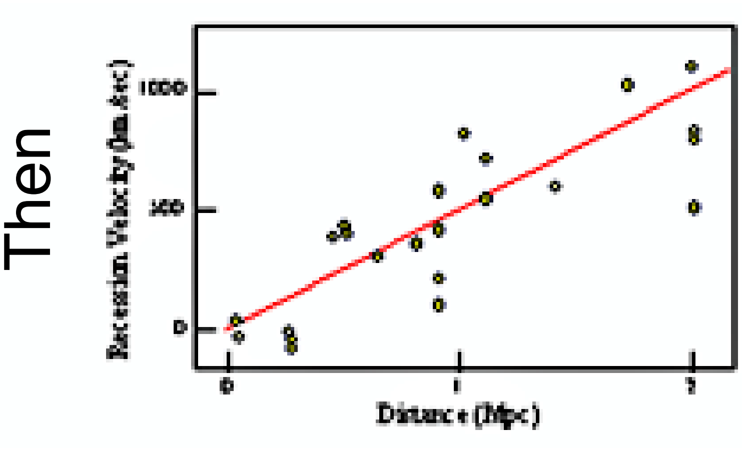
- Constrains the total amount of matter:

$$\Omega_M = \rho_M / \rho_c$$

ρ_c is the critical density

Recessional Velocities

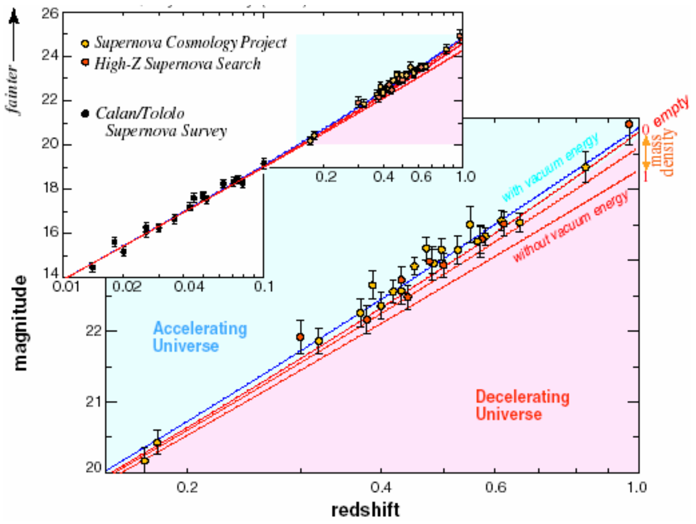
Then



Hubble (1929)

- The universe is expanding

Now



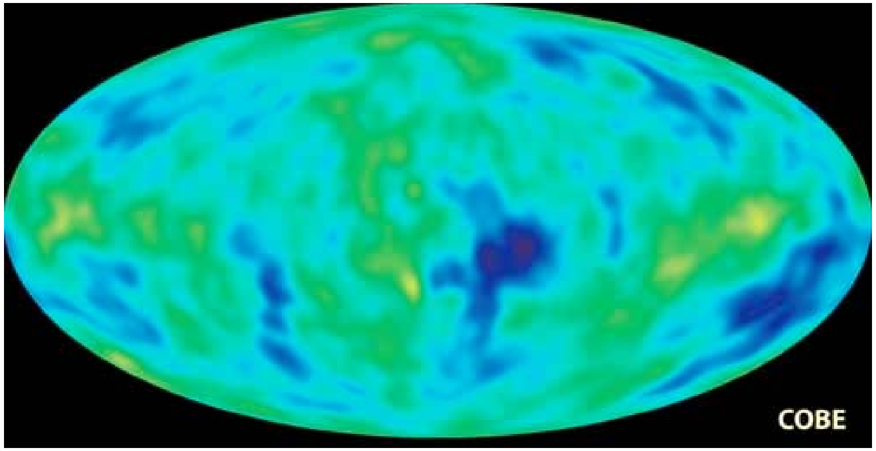
- Constrains the acceleration of expansion:

$$\Omega_\Lambda - \Omega_M$$

“Attractive matter vs. repulsive dark energy”

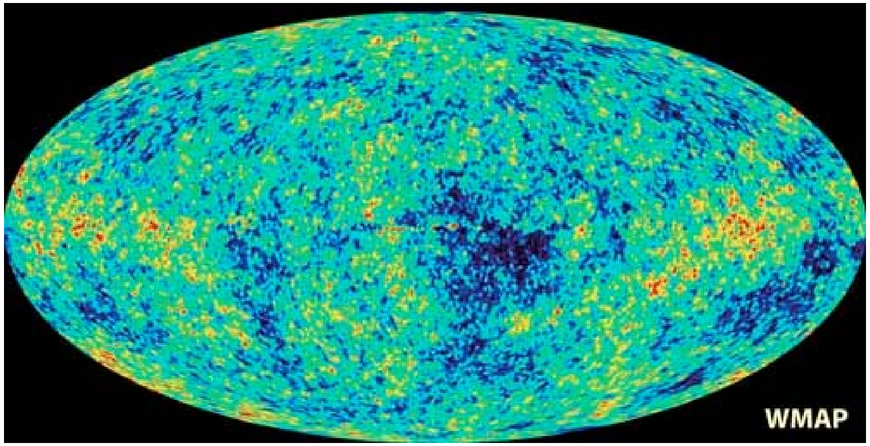
Cosmic Microwave Background

Then



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

Now

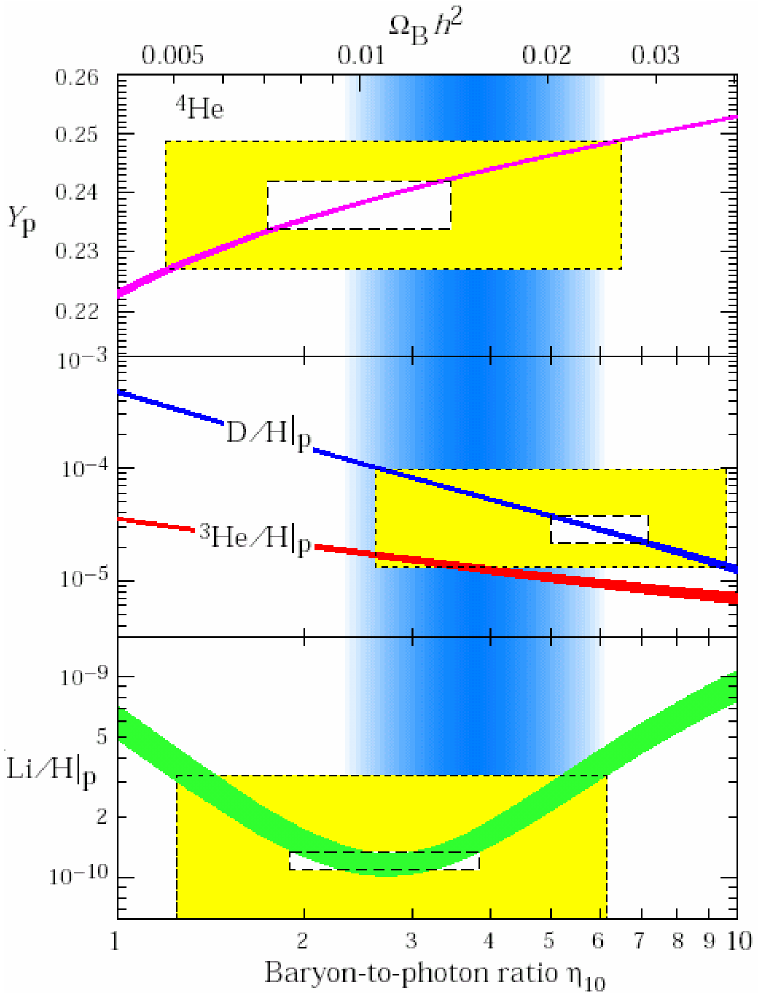


- Constrains the geometry of the universe:

$$\Omega_\Lambda + \Omega_M$$

“total energy density”

Big Bang Nucleosynthesis



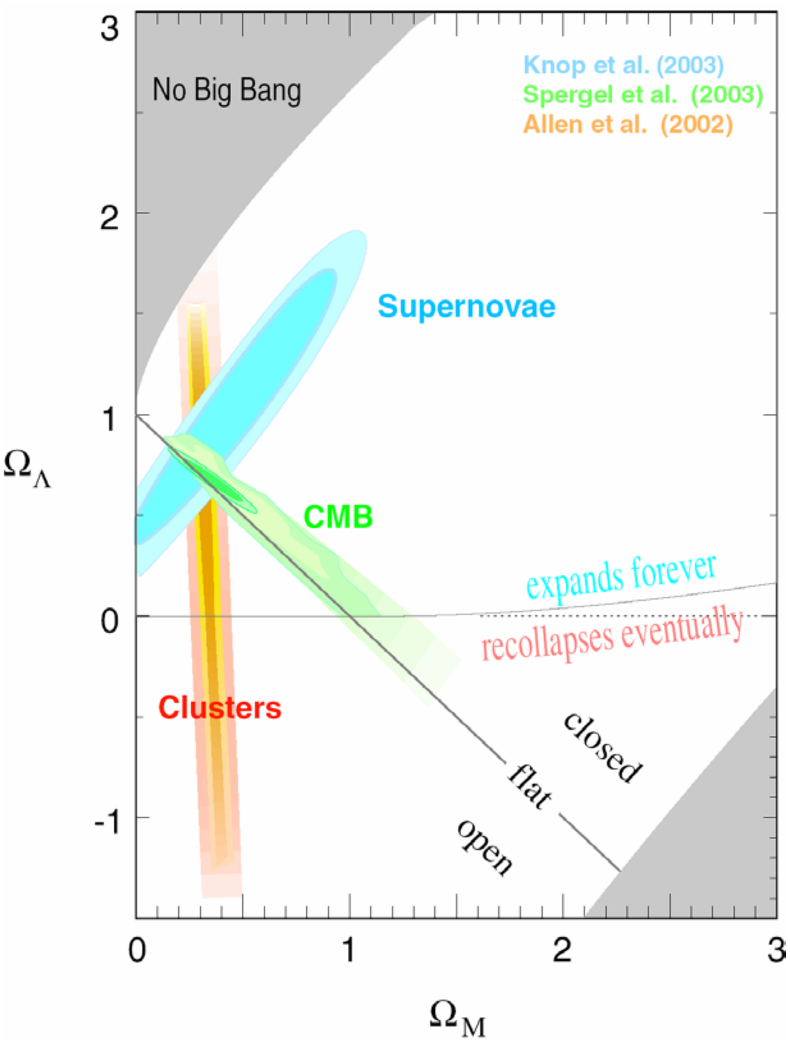
Fields, Sarkar, PDG (2002)

- At t ~ 1 s, T ~ 1 MeV, universe cooled enough for nuclei to start forming
- The abundance of each light species is fixed by η, the baryon-to-photon ratio
- These determinations are consistent*, constrain

  Ω_B

  the amount of baryons

Synthesis



- Remarkable agreement

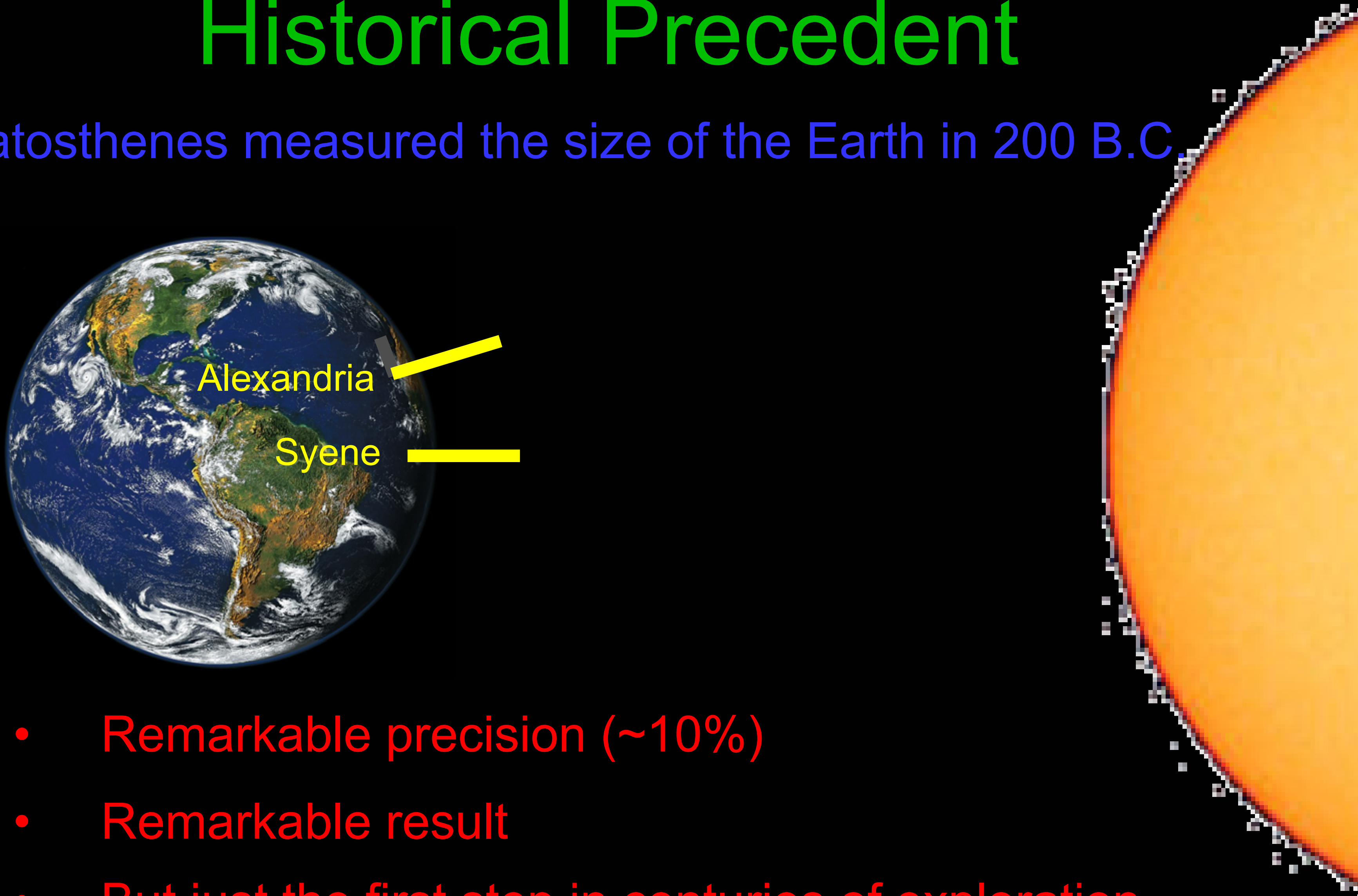
  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Baryons: 4% ± 0.4%
  [νs: 0.2% for $\Sigma m = 0.1$ eV]

- Remarkable precision (~10%)

- Remarkable results

Historical Precedent

Eratosthenes measured the size of the Earth in 200 B.C.



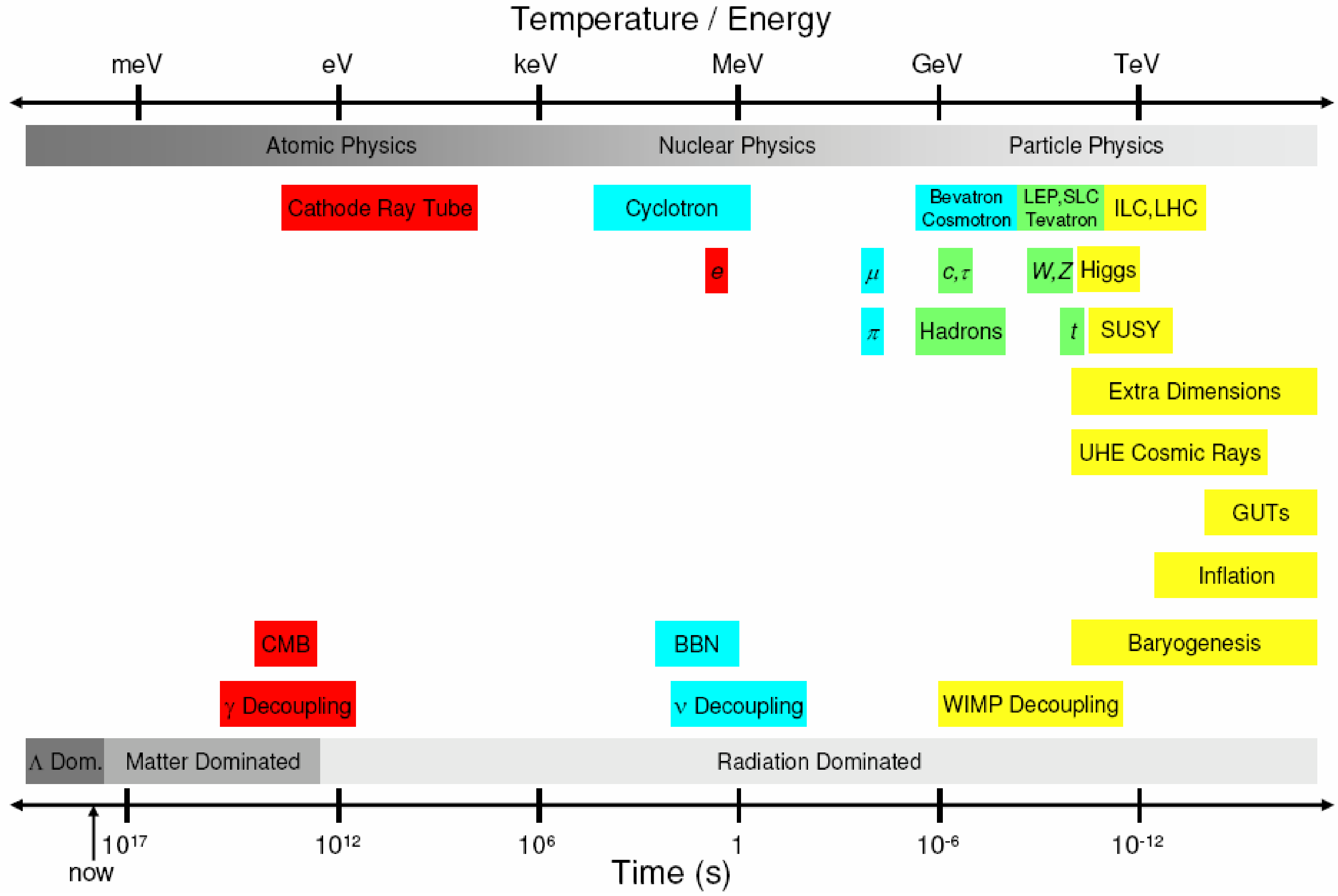
- Remarkable precision (~10%)
- Remarkable result
- But just the first step in centuries of exploration

Big Problems

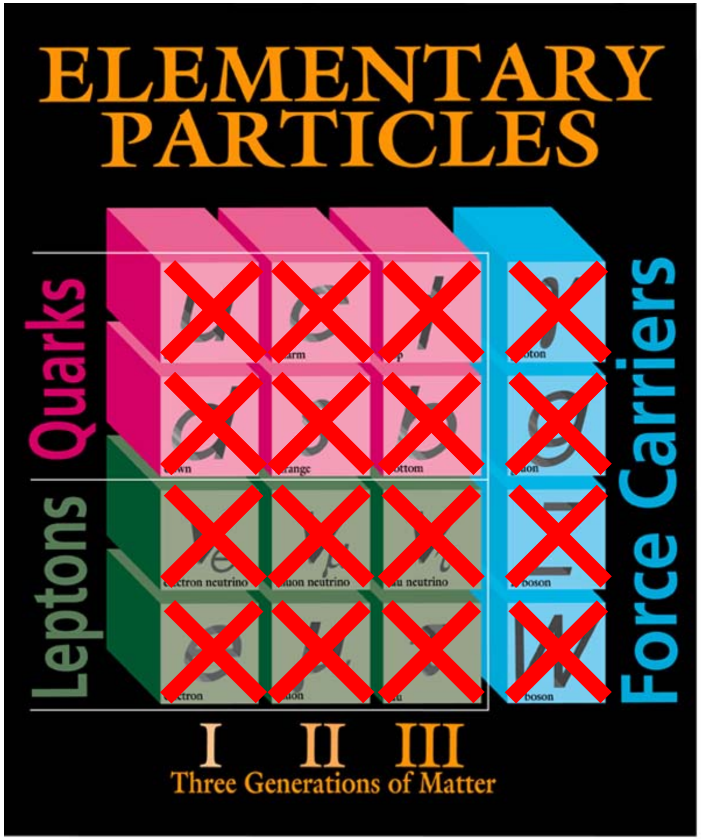
- What is dark matter?
- What is the distribution of dark matter?
- How did structure form?
- What is dark energy?
- Why is the cosmological constant so small?
- How did the universe begin?
- Why are there 3 large spatial dimensions?
- Why matter and no anti-matter?
- Why are all energy densities roughly comparable now?
- What is the source of the highest energy cosmic rays?
- …

These are difficult to answer with cosmology and astrophysics alone.

PARTICLE PHYSICS AT THE ENERGY FRONTIER



DARK MATTER



Fermilab 95-759

Known DM properties

- Stable
- Non-baryonic
- Cold*

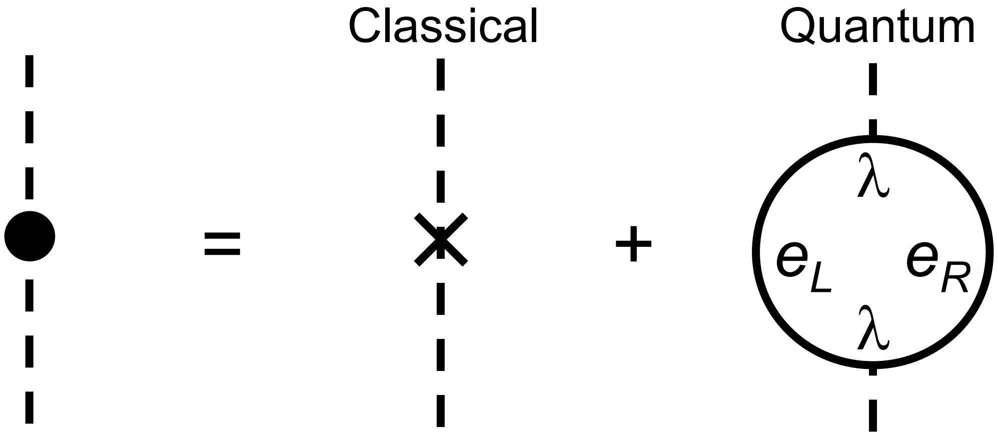
DM: precise, unambiguous evidence for new particles

Dark Matter Candidates

- The Wild, Wild West of particle physics: primodial black holes, axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,…
- Masses and interaction strengths span many, many orders of magnitude
- But independent of cosmology, we expect new particles:

  electroweak symmetry breaking

Electroweak Symmetry Breaking



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

$m_h \sim 100$ GeV, $\Lambda \sim 10^{19}$ GeV → cancellation of 1 part in 10^{34}

At $M_{\text{weak}} \sim 100$ GeV we expect new physics:
supersymmetry, extra dimensions, something!

Thermal Relic DM Particles

(1) Initially, DM is in thermal equilibrium:

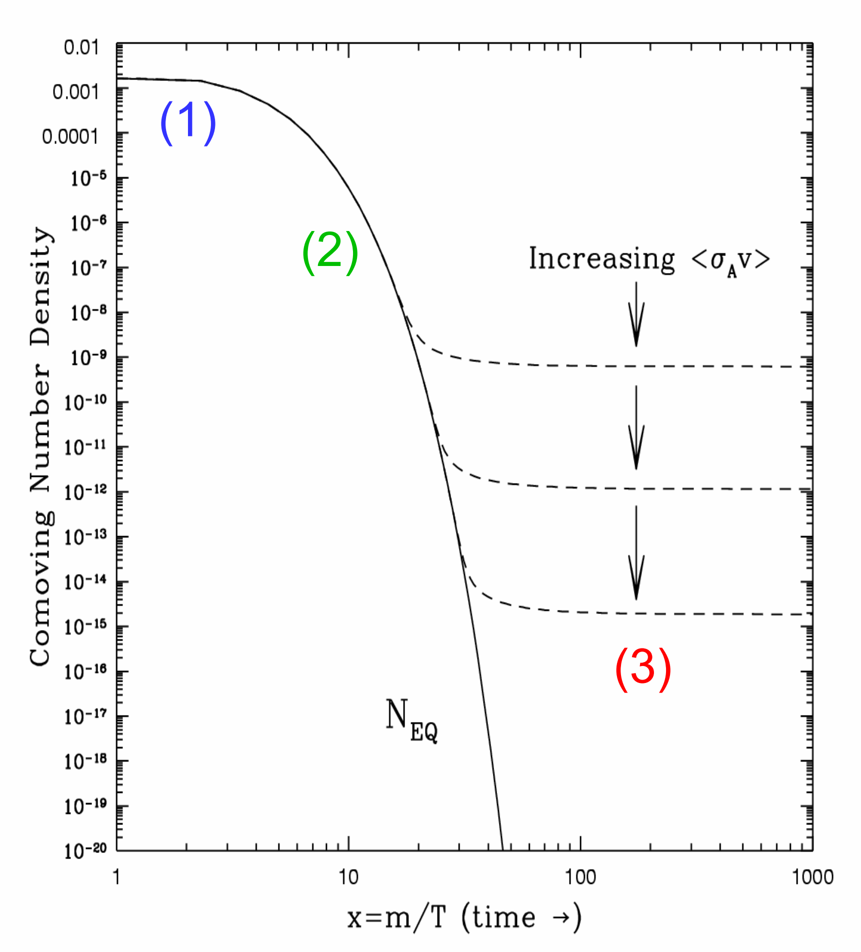
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$N = N_{EQ} \sim e^{-m/T}$$

(3) χs “freeze out”:

$$N \sim \text{const}$$



Thermal Relic Abundance

- The Boltzmann equation:

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

Dilution from expansion

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

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

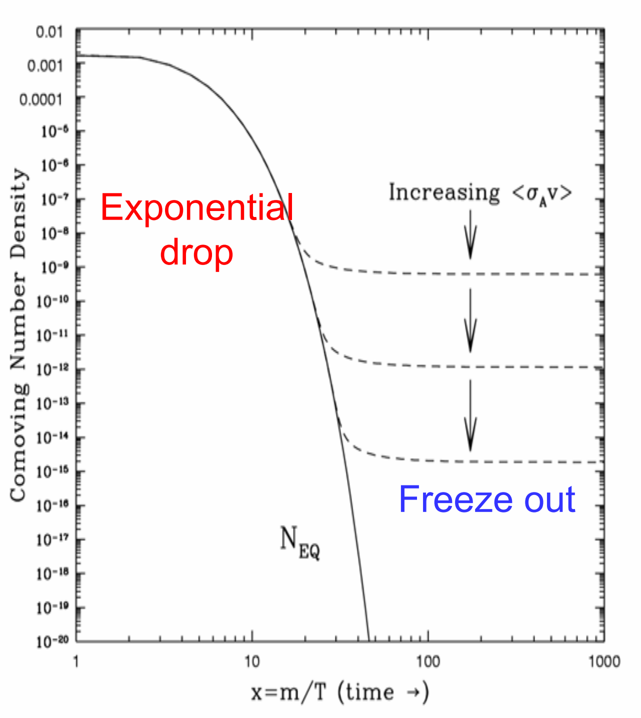
- $n \approx n_{eq}$ until interaction rate drops below expansion rate:

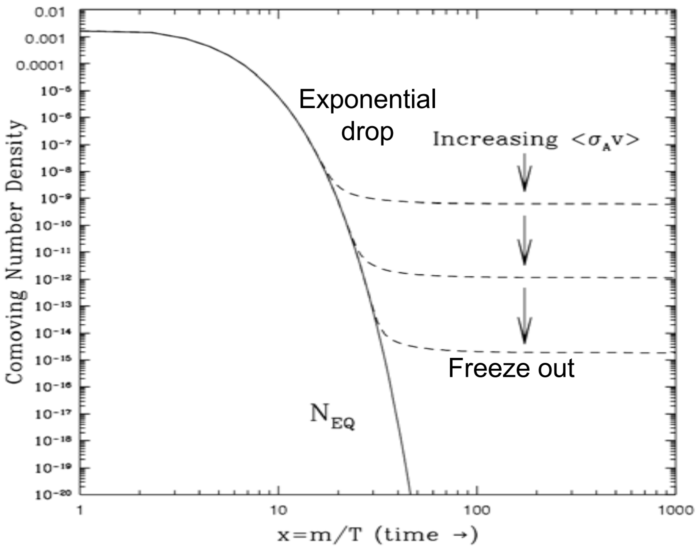
$$n_{\rm eq}\langle\sigma v\rangle \sim H$$

$(mT)^{3/2}e^{-m/T}$

$T^2/M_{\rm Pl}$

- The universe expands *slowly*! Mass *m* particles freeze out at *T ~ m/25*

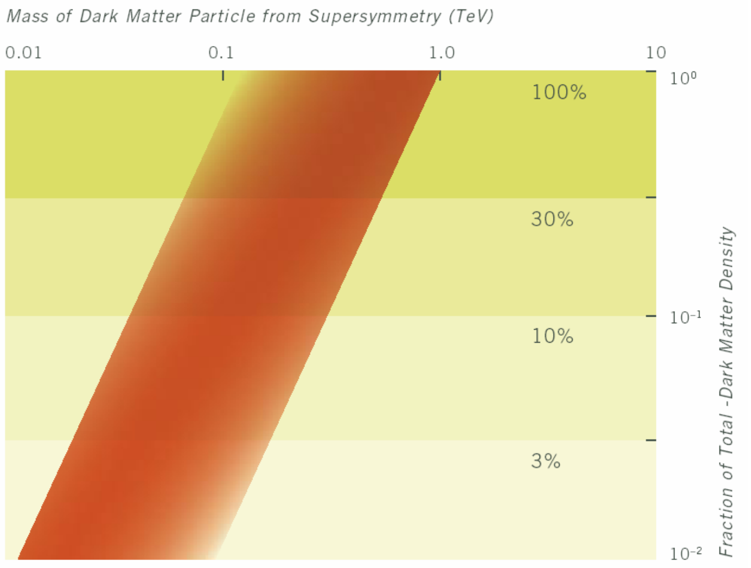




- Final $N \sim 1/\sigma_A$.

What's the constant of proportionality?

- Impose a natural relation: $\sigma_A \sim g^2/m^2$



Matchev (2005)

Remarkable "coincidence": even without the hierarchy problem, cosmology tells us we should explore the weak scale

STABILITY

- We’ve assumed the new particle is stable. Why should it be?

- Problems (proton decay, extra particles, …)

↕

Discrete symmetry

↕

Stability

- In many theories, dark matter is easier to explain than no dark matter

WIMP COSMOLOGY

- Weakly-interacting massive particles: “Candidates you could take home to mother.” – V. Trimble

- Many examples, some even qualitatively different

- The prototypical WIMP: neutralinos in supersymmetry

Goldberg (1983)

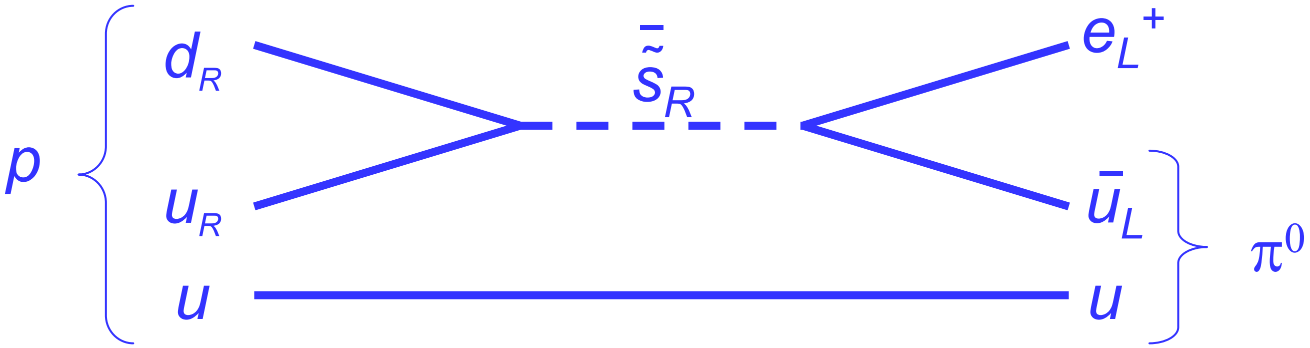
Neutral SUSY Particles

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

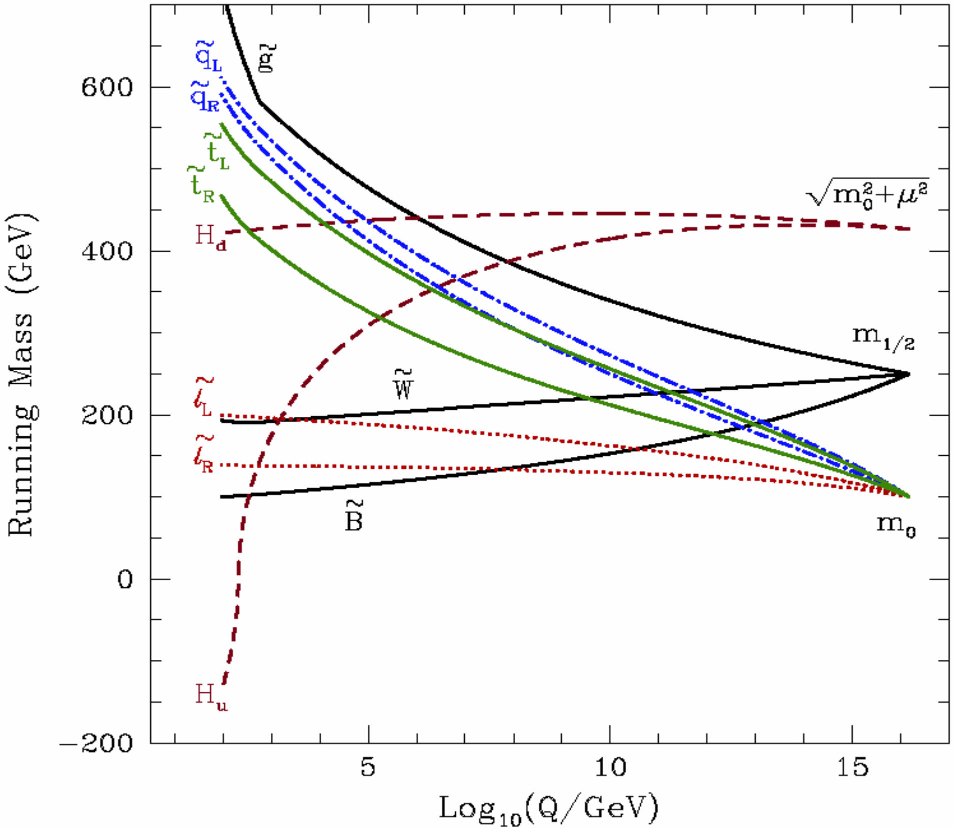


- Forbid this with R-parity conservation: $R_p = (-1)^{3(B-L)+2S}$
  - SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
  - Require $\Pi\ R_p = 1$ at all vertices
- Consequence: the lightest SUSY particle (LSP) is stable!

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

Cosmologically Preferred Supersymmetry

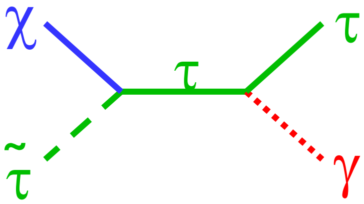
Typically get too much DM, but there are generic mechanisms for reducing it

Excluded:
Stau LSP

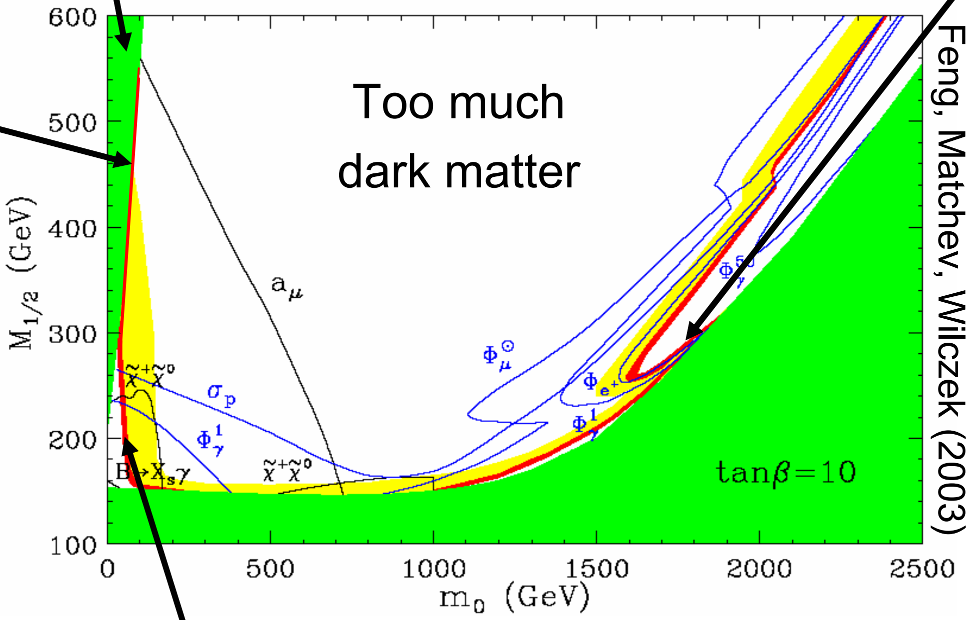
Yellow: pre-WMAP
Red: post-WMAP

Focus point
region

Co-annihilation
region

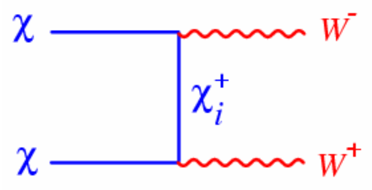


Degenerate
χ and stau



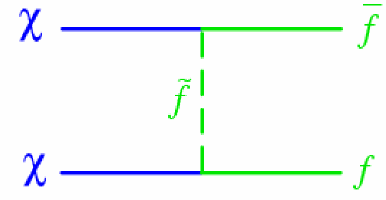
Too much
dark matter

Feng, Matchev, Wilczek (2003)



Mixed
Neutralinos

Bulk
region



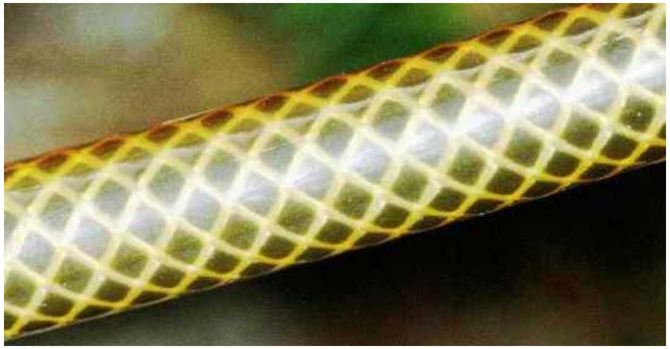
Light sfermions

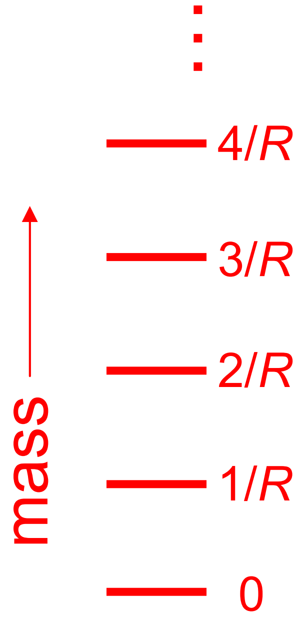
Extra Dimensional Dark Matter

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

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

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





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

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

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

- A solution…

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

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

- Unwanted scalar is projected out:

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

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

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

Appelquist, Cheng, Dobrescu (2001)

KK-Parity

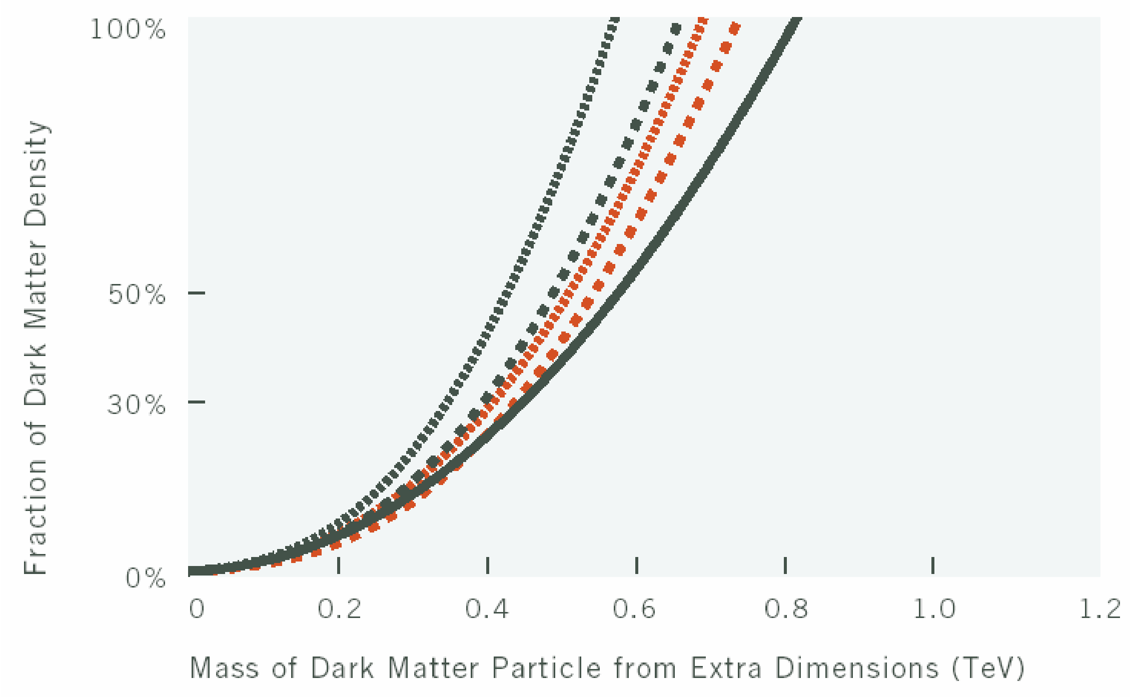
- An immediate consequence: conserved KK-parity $(-1)^{KK}$ Interactions require an even number of odd KK modes

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

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

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

KK Dark Matter Relic Density



Servant, Tait (2002)

LECTURE 1 SUMMARY

- The revolution in cosmology has produced remarkable progress and remarkable problems
- Cosmology and particle physics both point to the weak scale for new particles
- Ω_{DM} highly constraining
- Searches not yet constraining, but prospects promising
- Next time: what will colliders tell us?