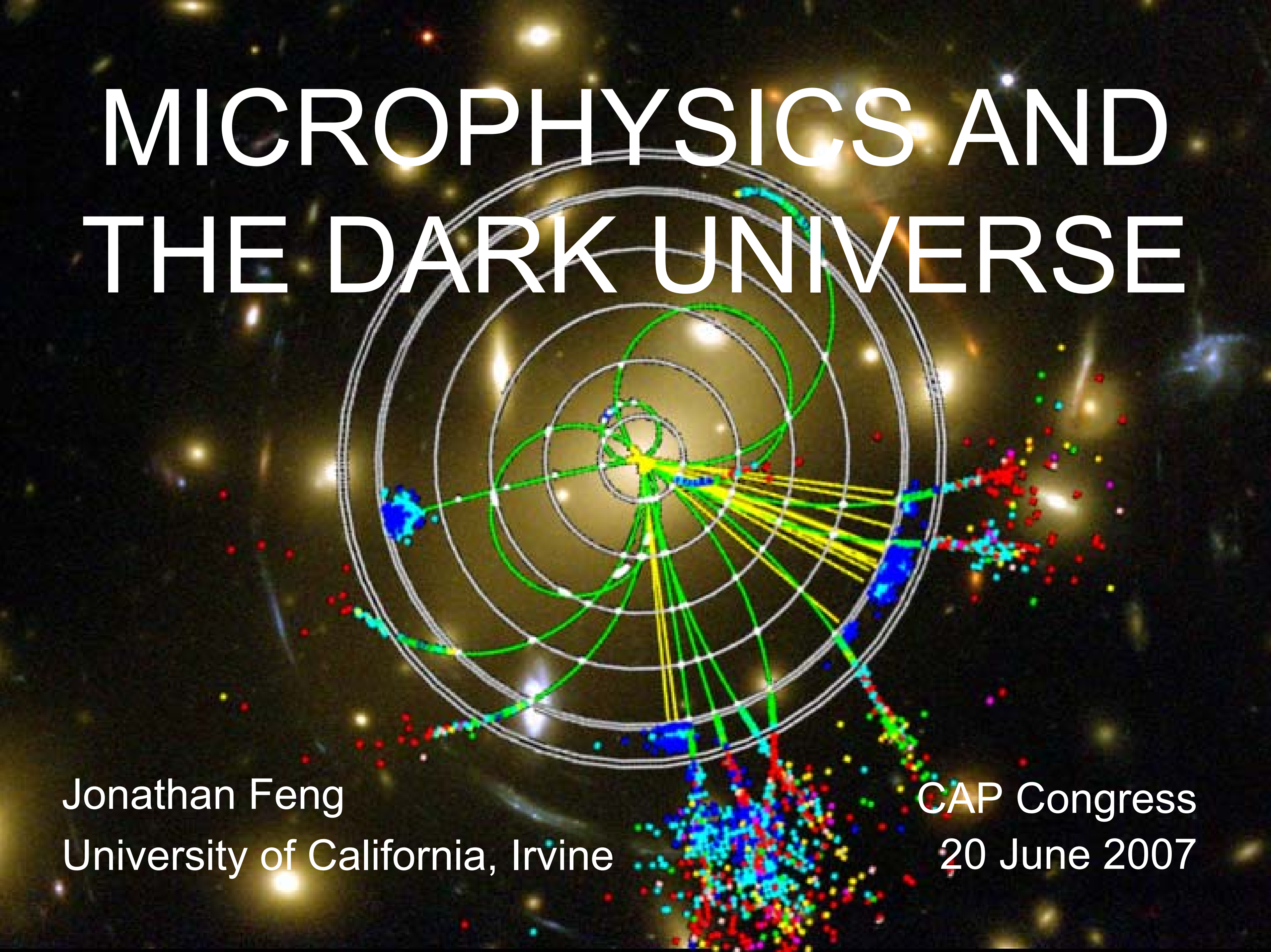
MICROPHYSICS AND THE DARK UNIVERSE



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University of California, Irvine

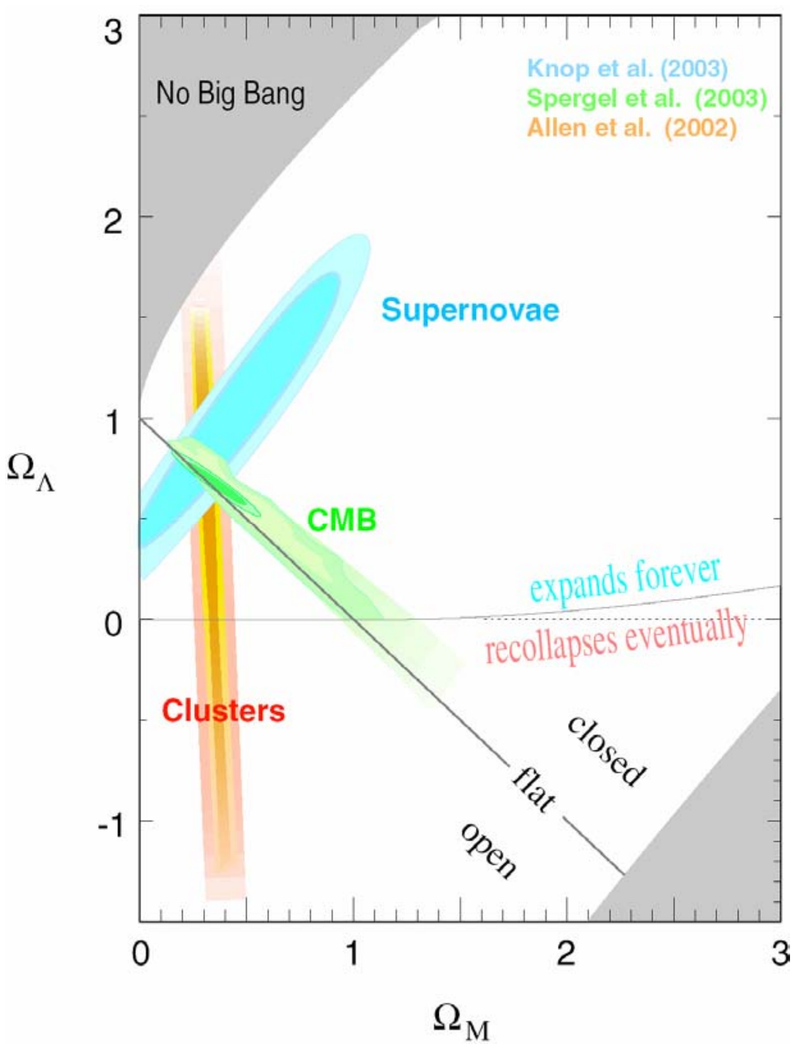
CAP Congress
20 June 2007

WHAT IS THE UNIVERSE MADE OF?

Recently there have been remarkable advances in our understanding of the Universe on the largest scales

We live in interesting times: for the first time in history, we have a complete "inventory" of the Universe

NEW ANSWERS



- Remarkable agreement

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  [Baryons: 4% ± 0.4%
  Neutrinos: 2% (Σm_ν/eV)]

- Remarkable precision

- Remarkable results

NEW QUESTIONS

DARK MATTER

- What is its mass?
- What are its spin and other quantum numbers?
- Is it absolutely stable?
- What is the symmetry origin of the dark matter particle?
- Is dark matter composed of one particle species or many?
- How and when was it produced?
- Why does Ω_{DM} have the observed value?
- What was its role in structure formation?
- How is dark matter distributed now?

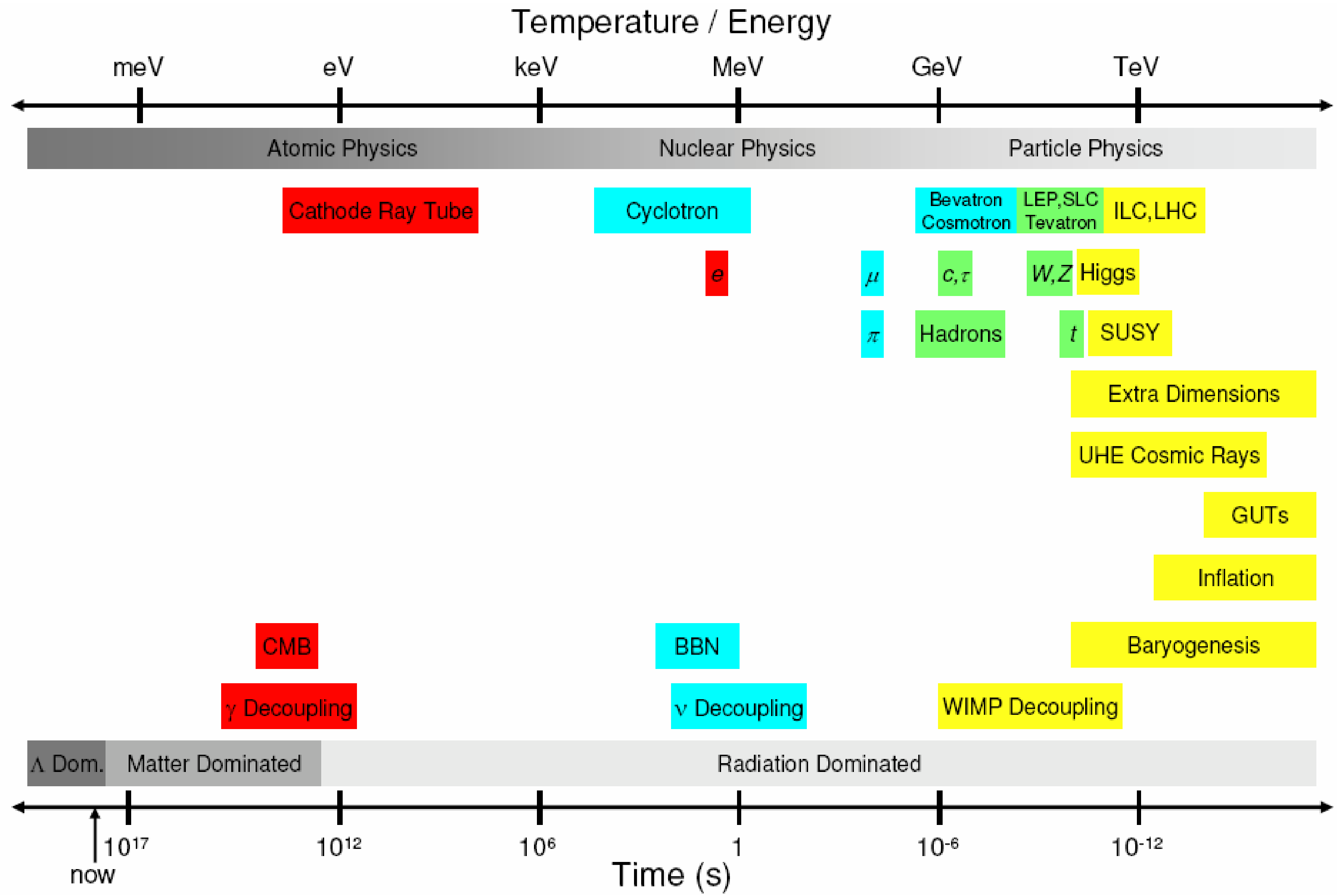
DARK ENERGY

- What is it?
- Why not $\Omega_\Lambda \sim 10^{120}$?
- Why not $\Omega_\Lambda = 0$?
- Does it evolve?

BARYONS

- Why not $\Omega_B \approx 0$?
- Related to neutrinos, leptonic CP violation?
- Where are all the baryons?

MICROPHYSICS AND COSMOLOGY



THE DARK UNIVERSE

The problems appear to be completely different

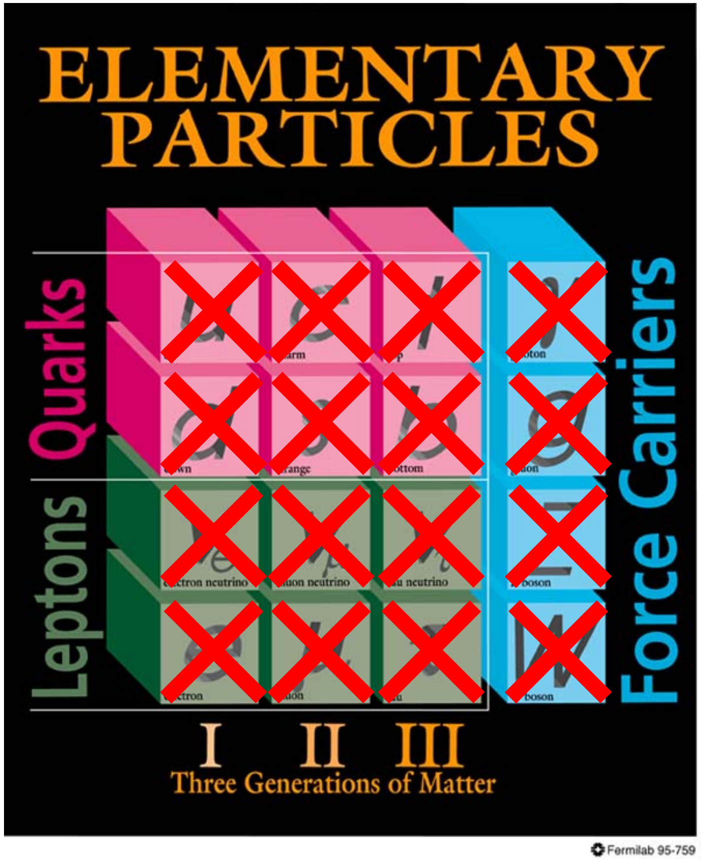
DARK MATTER

- No known particles contribute
- Probably tied to $M_{\text{weak}} \sim 100$ GeV
- Several compelling solutions

DARK ENERGY

- All known particles contribute
- Probably tied to $M_{\text{Planck}} \sim 10^{19}$ GeV
- No compelling solutions

DARK MATTER

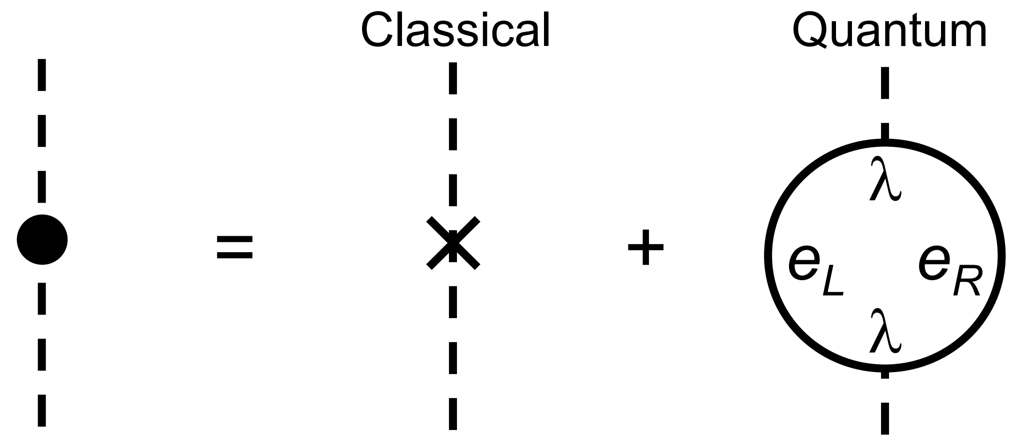


Known DM properties

- Not short-lived
- Not cold
- Not baryonic

Precise, unambiguous evidence for physics beyond the standard model

NEW PARTICLES AND NATURALNESS



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

m_h ~ 100 GeV, Λ ~ 10^{19} GeV → cancellation of 1 part in 10^{34}

At M_{weak} ~ 100 GeV we expect new particles:
supersymmetry, extra dimensions, something!

THE WIMP "MIRACLE"

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

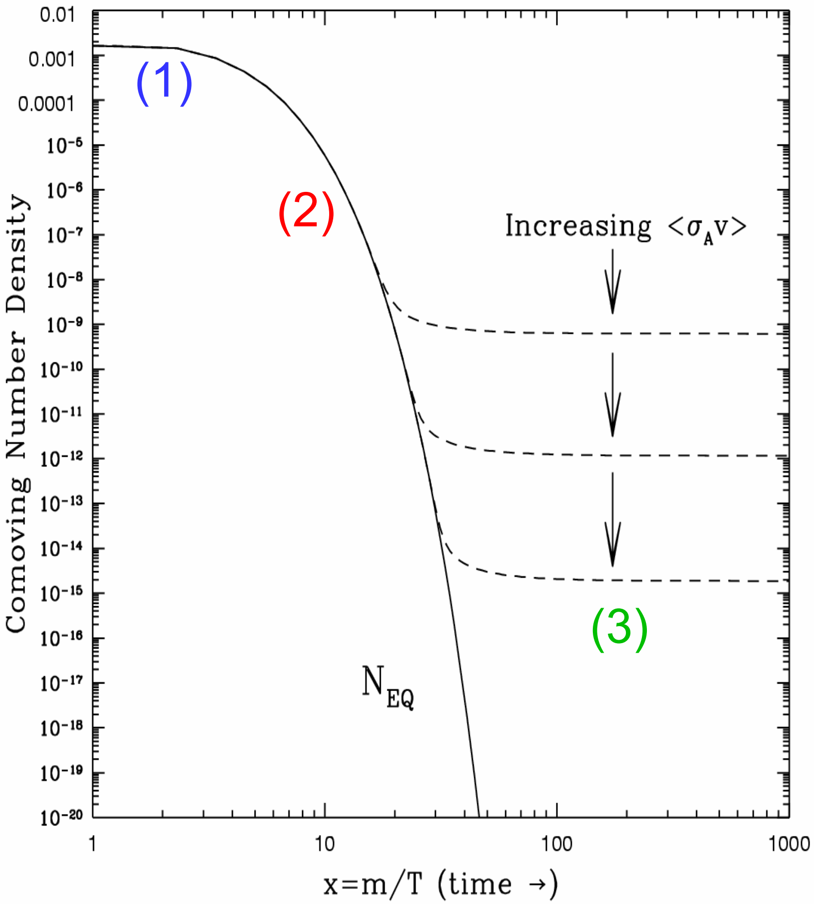
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

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

(3) χs "freeze out":

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

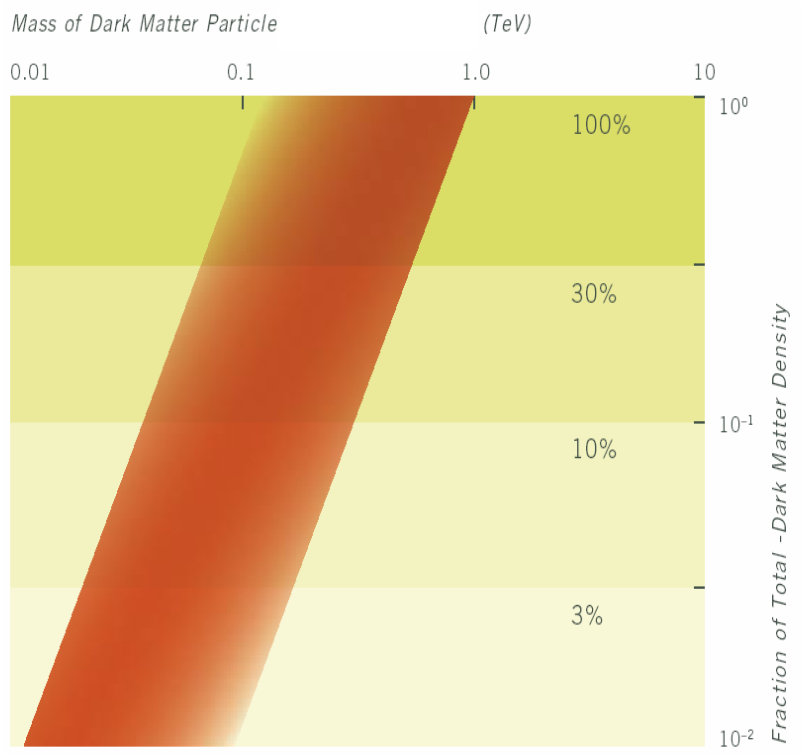


- The amount of dark matter left over is inversely proportional to the annihilation cross section:

$$\Omega_{DM} \sim \langle \sigma_A v \rangle^{-1}$$

- What is the constant of proportionality?
- Impose a natural relation:

$$\sigma_A = k\alpha^2/m^2 \text{ , so } \Omega_{DM} \sim m^2$$



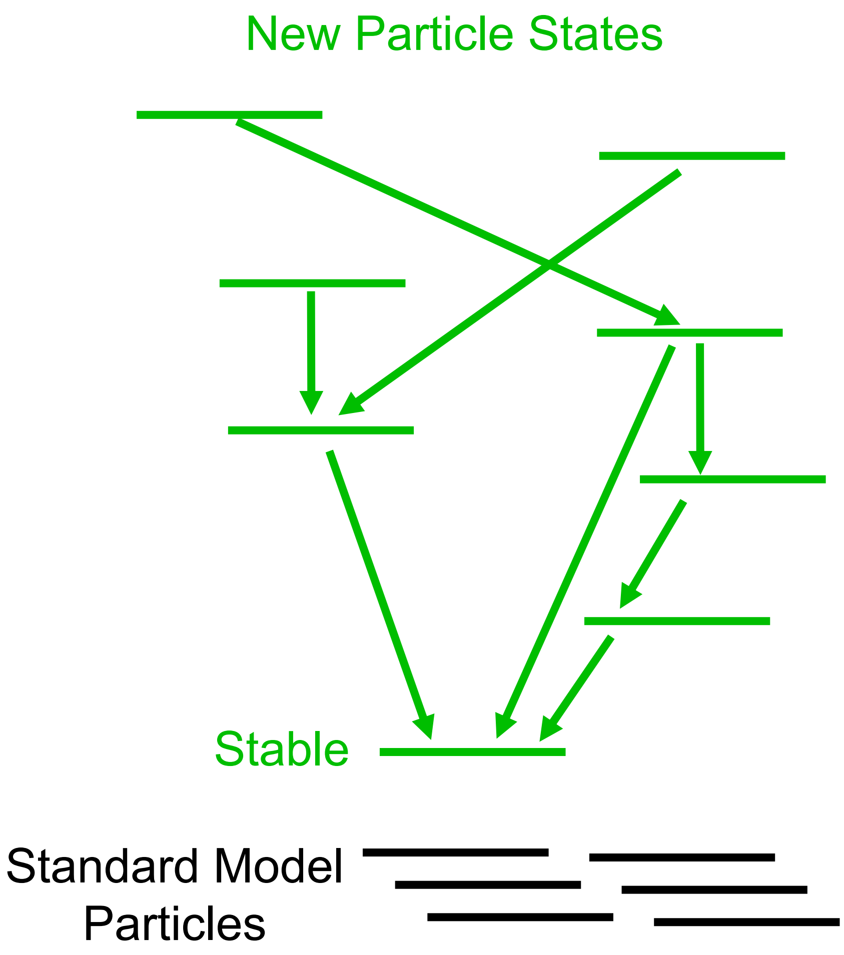
HEPAP LHC/ILC Subpanel (2006)

[band width from k = 0.5 – 2, S and P wave]

Remarkable "coincidence": $\Omega_{DM} \sim 0.1$ for m ~ 100 GeV – 1 TeV

STABILITY

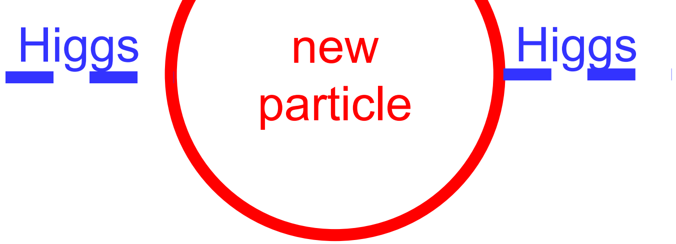
- This all assumes the new particle is stable
- How natural is this?



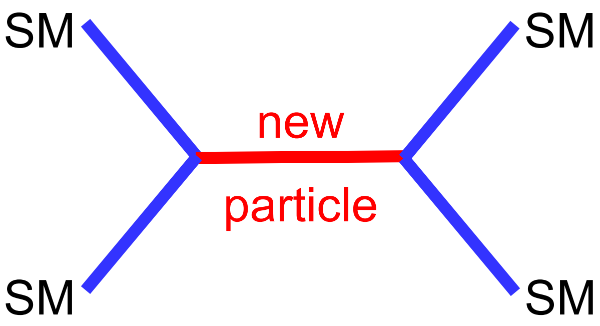
LEP'S COSMOLOGICAL LEGACY

- Large Electron Positron Collider at CERN, 1989-2000
- Confirmed the standard model, stringently constrained effects of new particles through precision measurements

Good: Naturalness

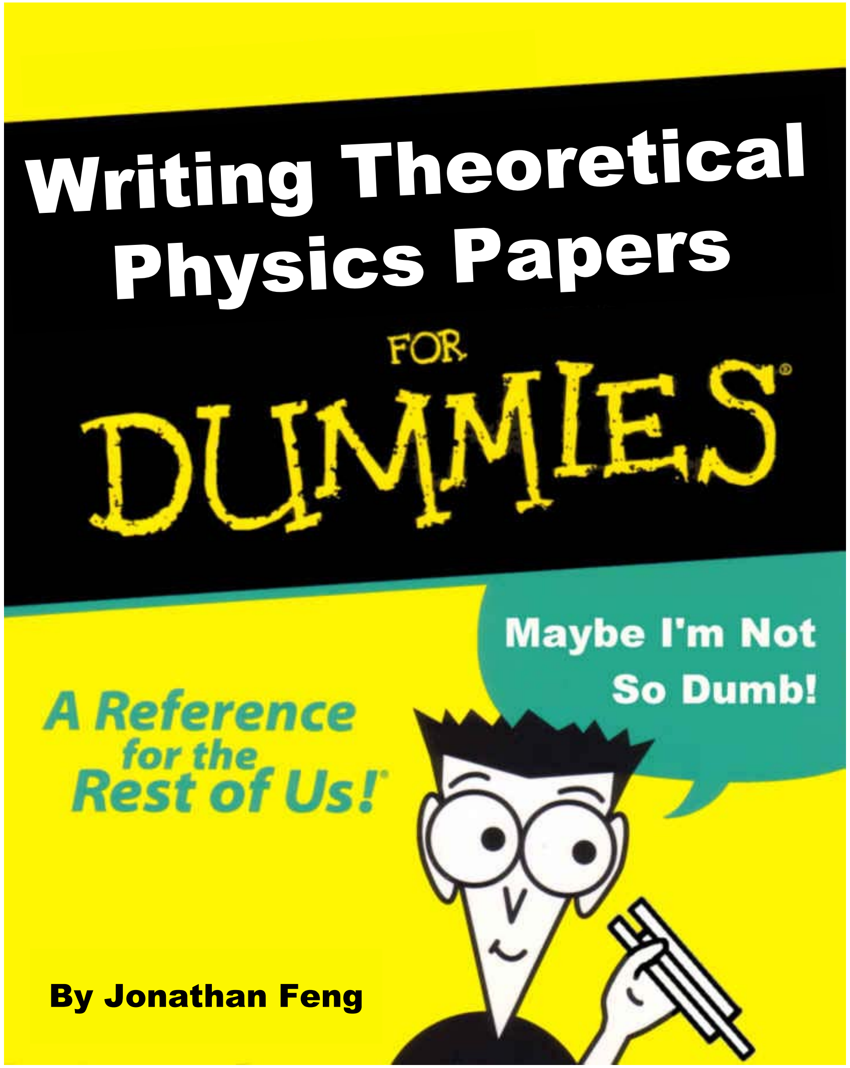


Bad: Precision Constraints



- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This makes the lightest new particle stable → Dark Matter! DM is easier to explain than no DM.

Cheng, Low (2003); Wudka (2003)


Writing Theoretical
Physics Papers
FOR
DUMMIES
Maybe I'm Not
So Dumb!
A Reference
for the
Rest of Us!
By Jonathan Feng

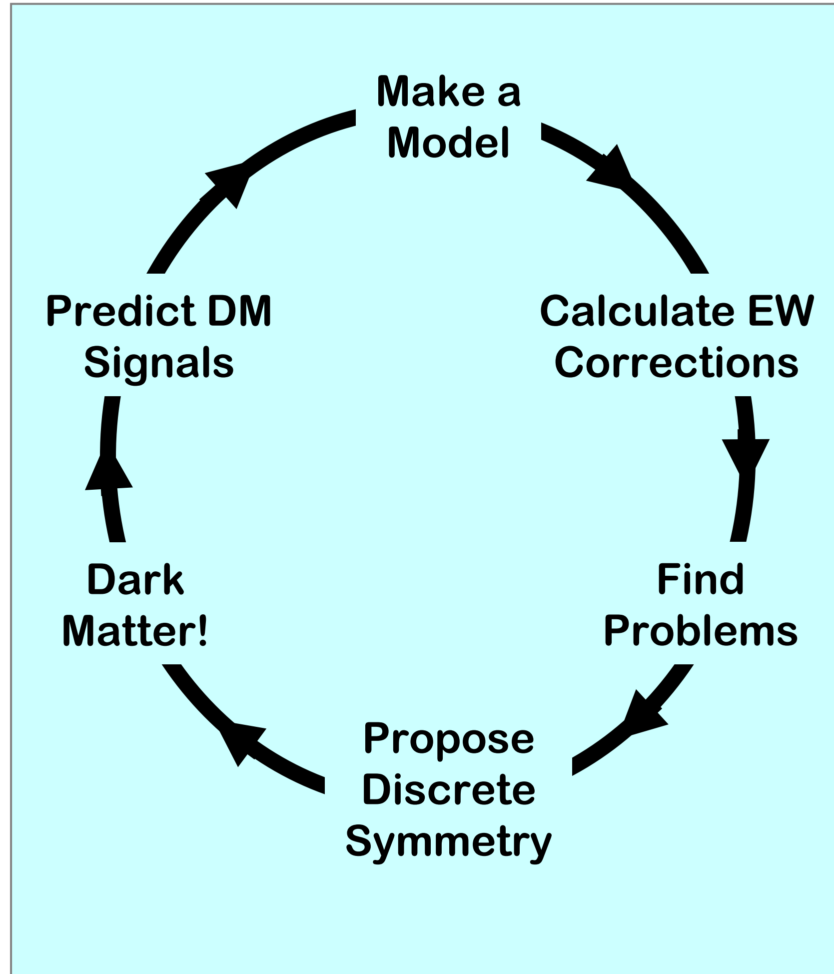

Make a
Model
Calculate EW
Corrections
Find
Problems
Propose
Discrete
Symmetry
Dark
Matter!
Predict DM
Signals

Fig. 1

SUMMARY SO FAR

- Cosmological data strongly suggest
  - Dark Matter exists
- Microphysical Data strongly suggest
  - New particles (WIMPs) exist
  - They are stable
  - They have the right relic density

WIMPS FROM SUPERSYMMETRY

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

Supersymmetry: many motivations. For every known particle X, predicts a partner particle $\tilde{X}$

Neutralino $\chi \in (\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d)$

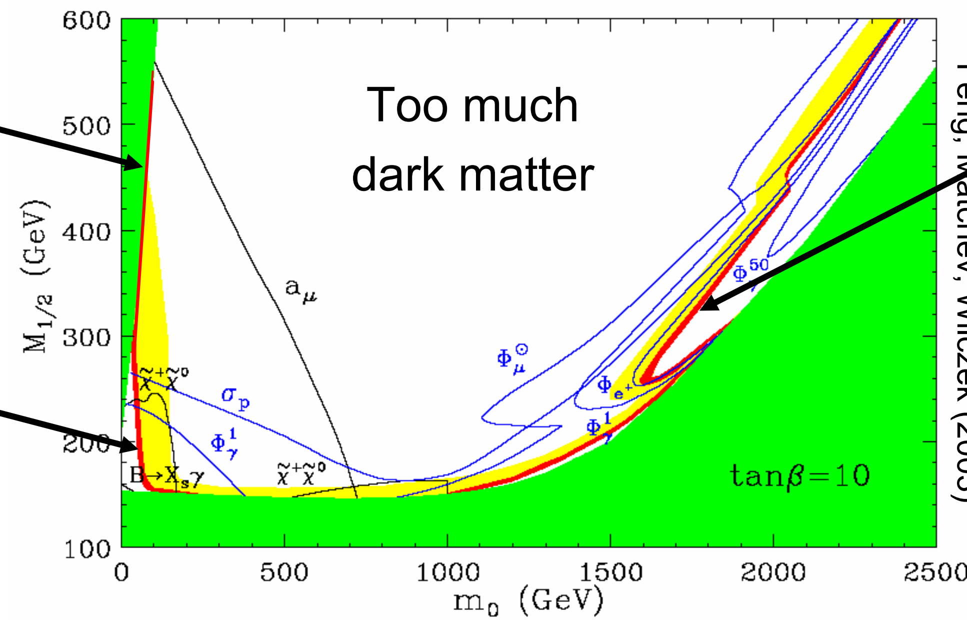
In many models, χ is the lightest supersymmetric particle, stable, neutral, weakly-interacting, mass ~ 100 GeV. All the right properties for WIMP dark matter!

Minimal Supergravity

Co-annihilation region

Bulk region

Too much dark matter



Feng, Matchev, Wilczek (2003)

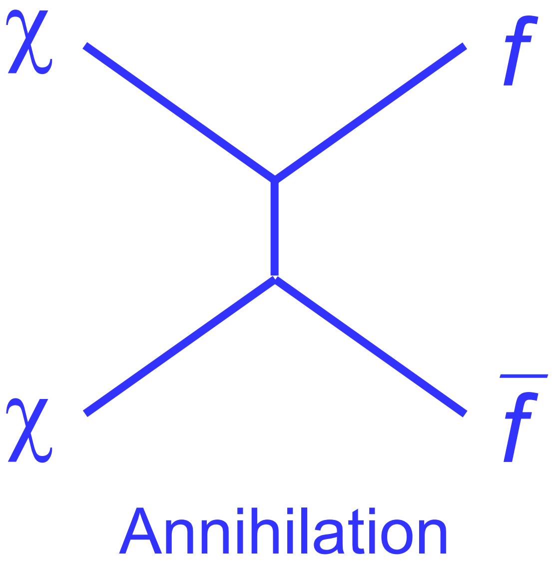
Focus point region

Yellow: pre-WMAP

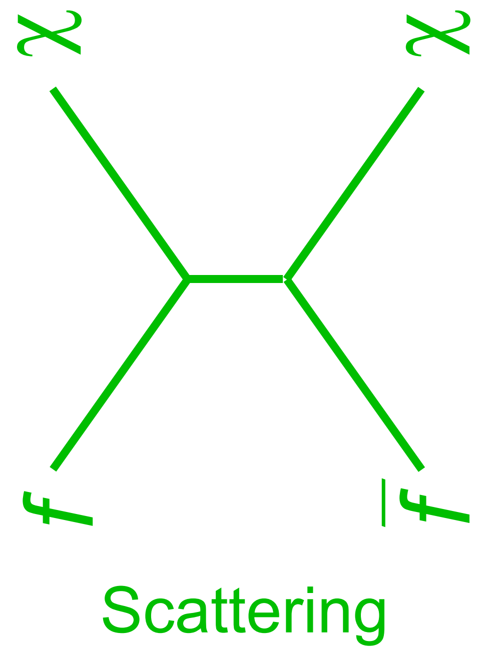
Red: post-WMAP

Relic density favors regions where detection is promising

WIMP DETECTION



Crossing
symmetry



Correct relic density → Efficient annihilation then

→ Efficient annihilation now (indirect detection)

→ Efficient scattering now (direct detection)

DIRECT DETECTION

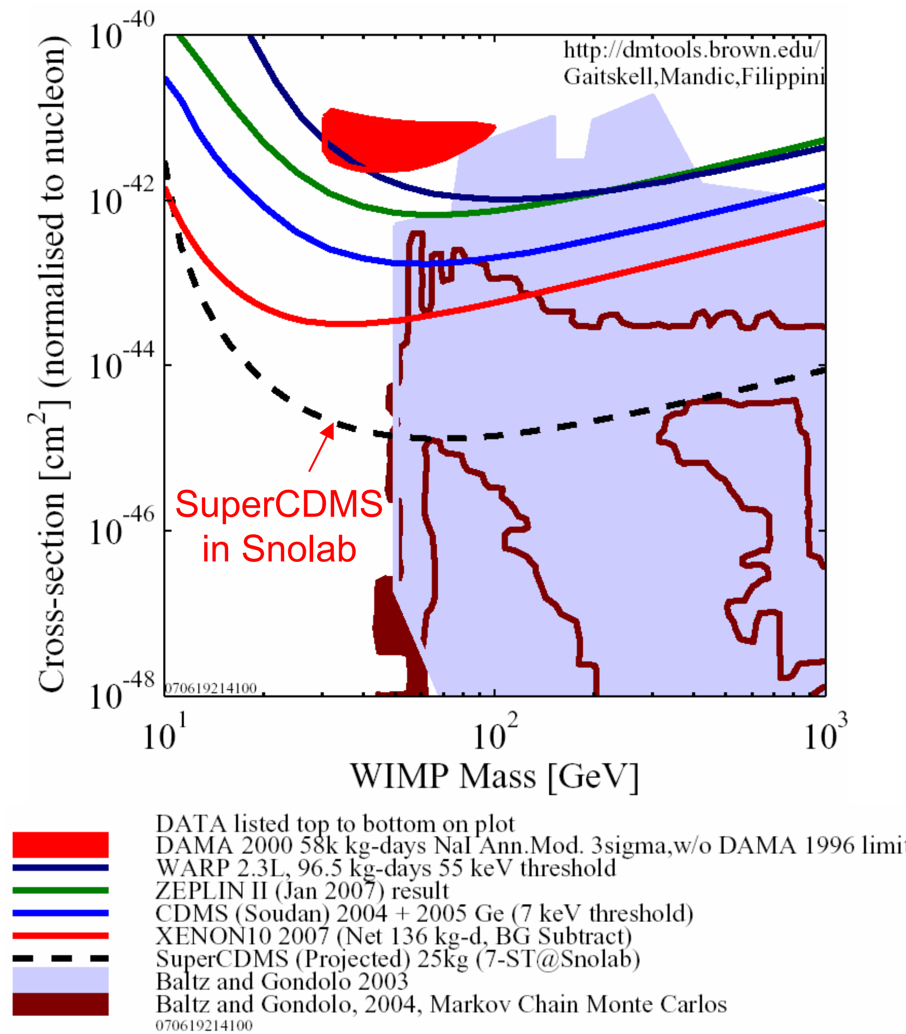
- WIMP essentials:

  $v \sim 10^{-3}$ c

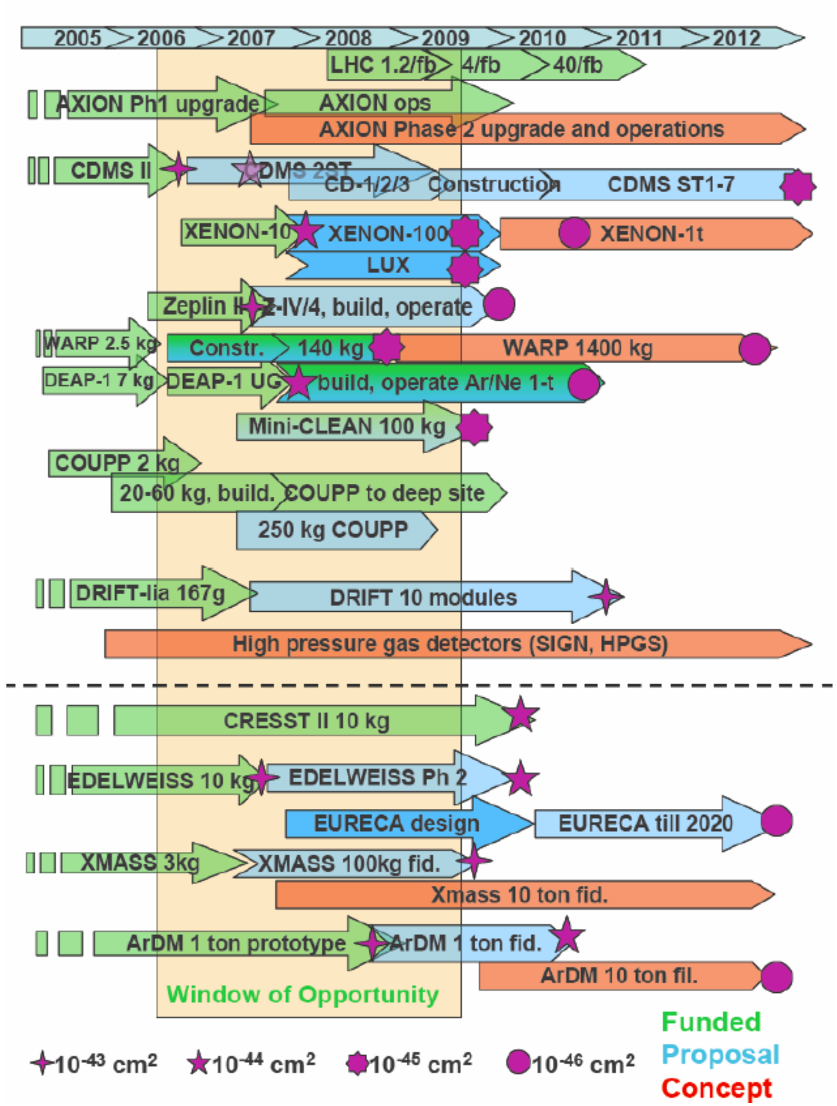
  Kinetic energy ~ 100 keV

  Local density ~ 1 / liter

- Detected by recoils off ultra-sensitive underground detectors



FUTURE DIRECT DETECTION



HEPAP/AAAC DMSAG Subpanel (2007)

PROSPECTS

If the relic density “coincidence” is no coincidence and DM is WIMPs, the new physics behind DM will very likely be discovered in the next few years:

Direct dark matter searches

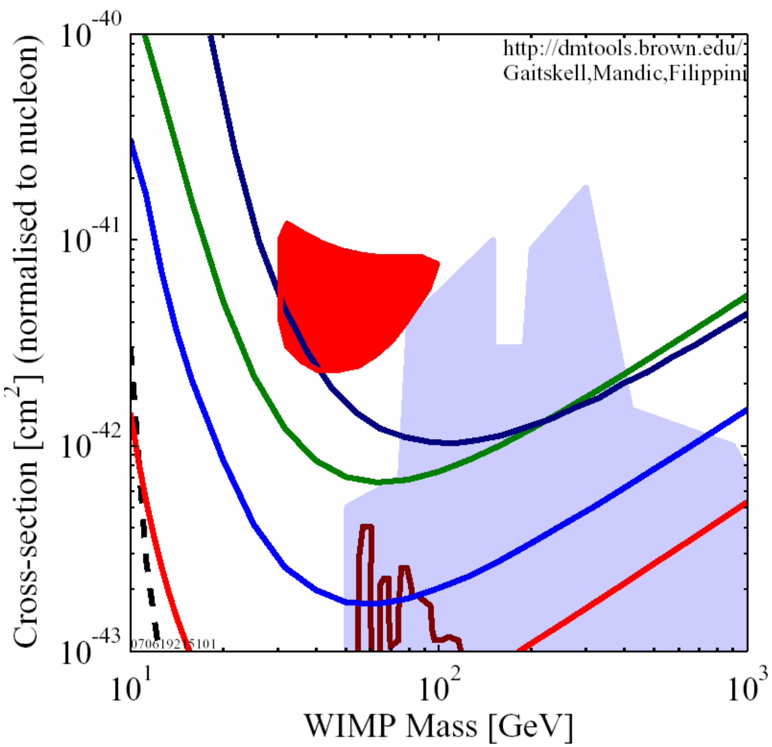
Indirect dark matter searches

The Tevatron at Fermilab

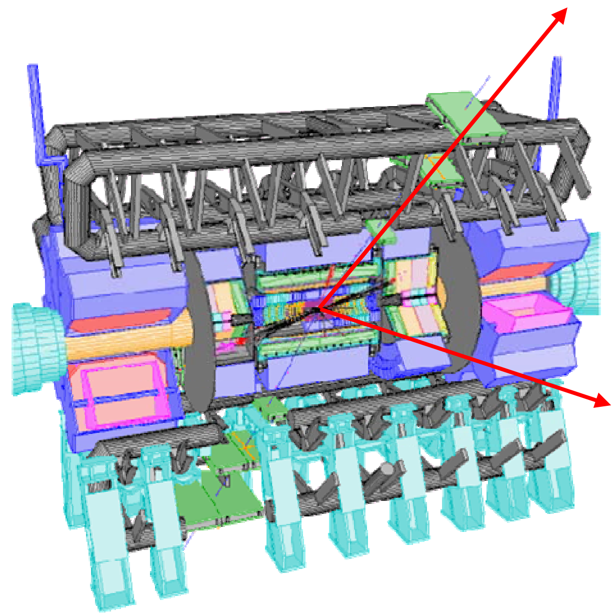
The Large Hadron Collider at CERN

What then?

- Cosmology can't discover SUSY

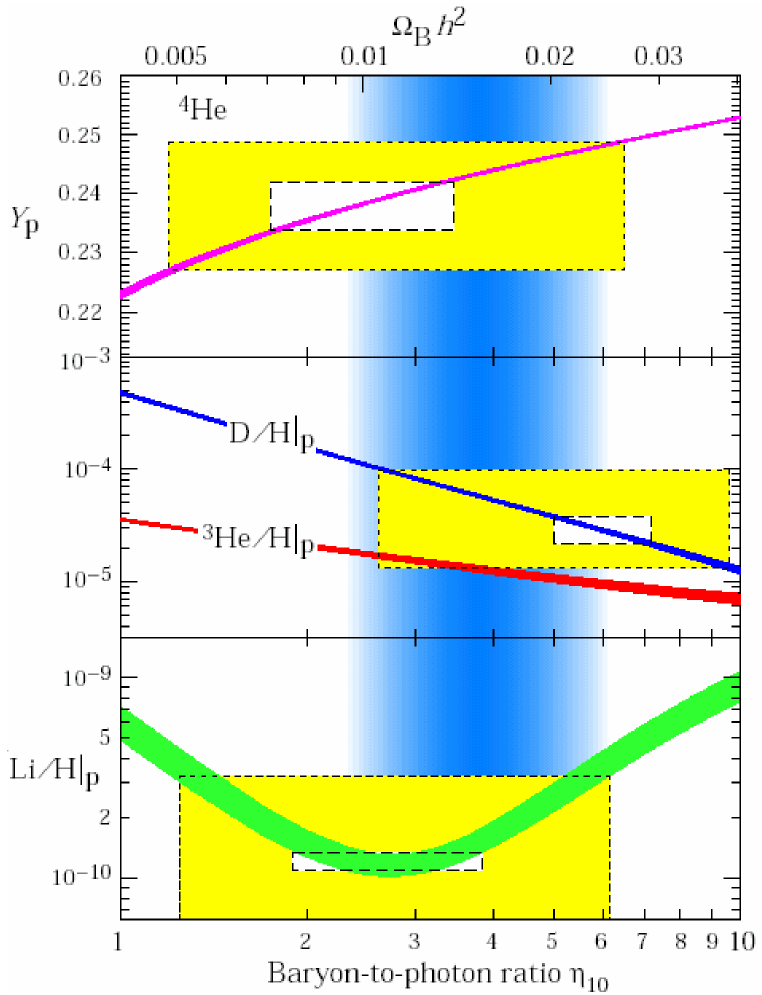


- Particle colliders can't discover DM



Lifetime > 10^{-7} s → 10^{17} s ?

THE EXAMPLE OF BBN

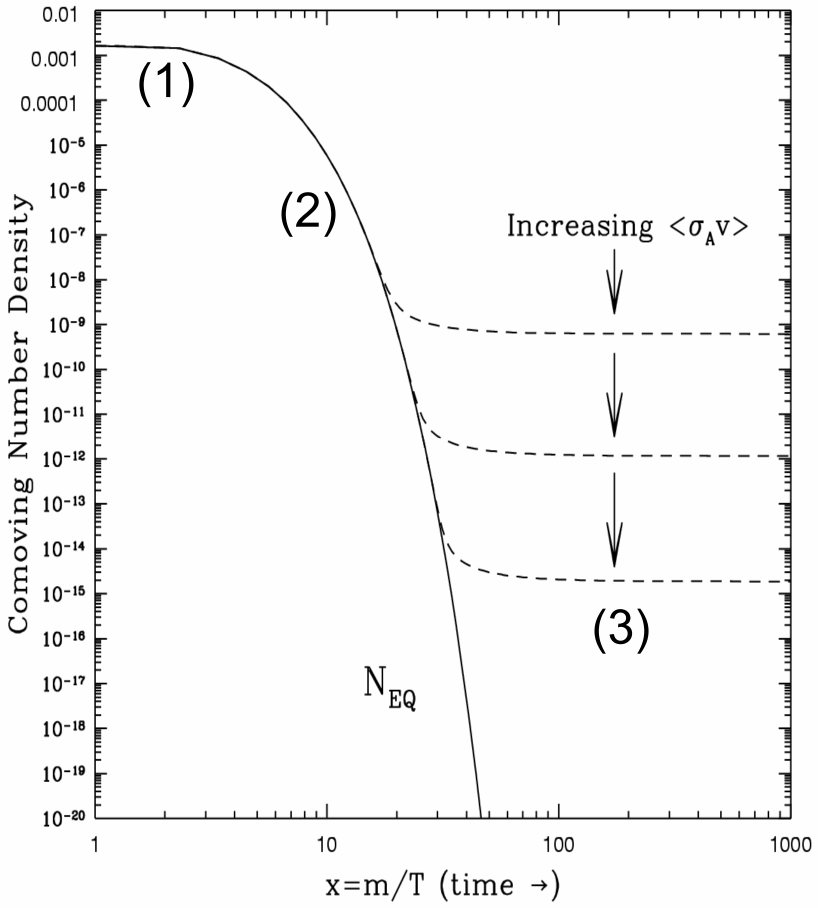


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

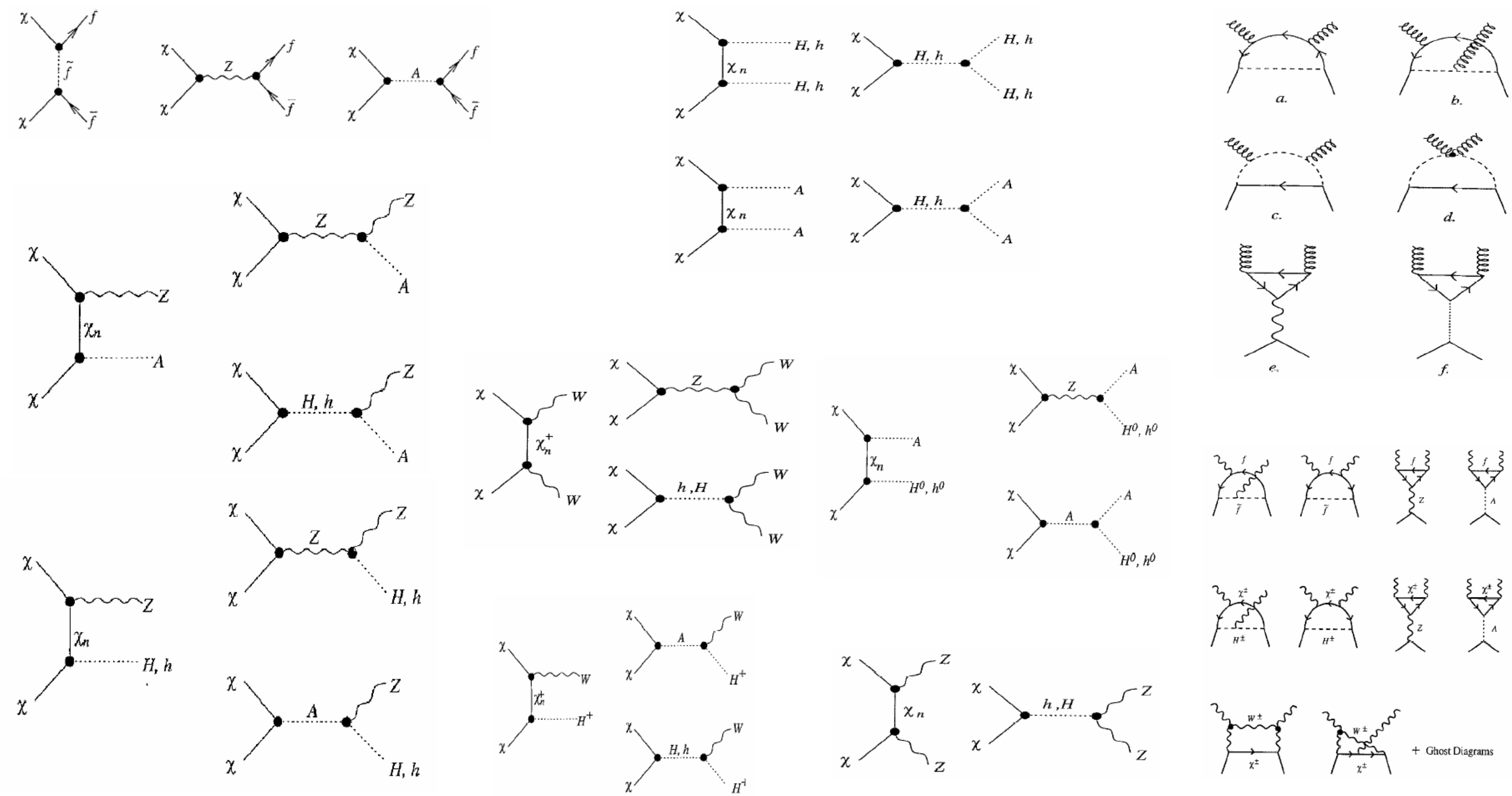
  t ~ 1 sec

DARK MATTER ANALOGUE



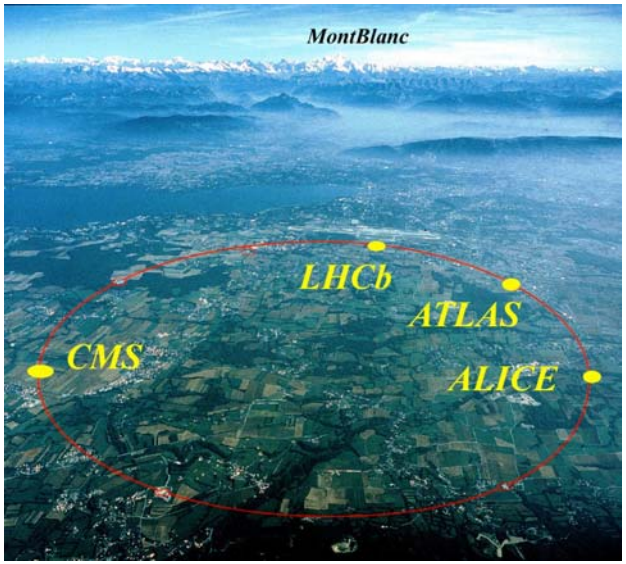
- Particle physics → dark matter abundance prediction
- Compare to dark matter abundance observation
- How well can we do?

Contributions to Neutralino WIMP Annihilation

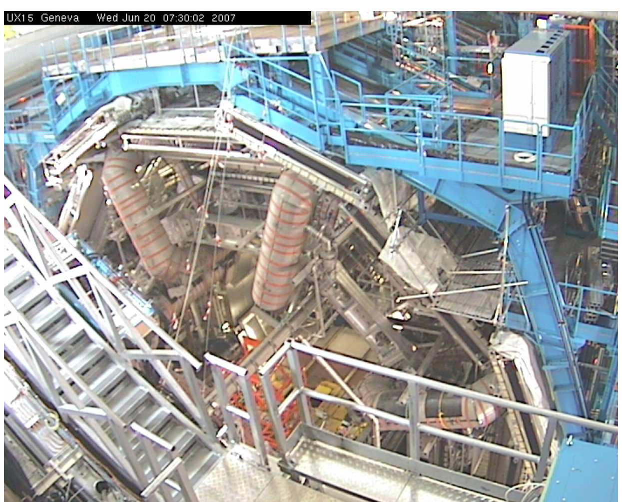


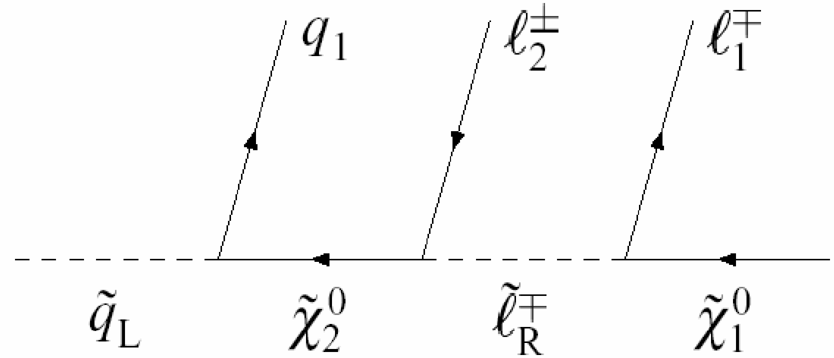
Jungman, Kamionkowski, Griest (1995)

LARGE HADRON COLLIDER

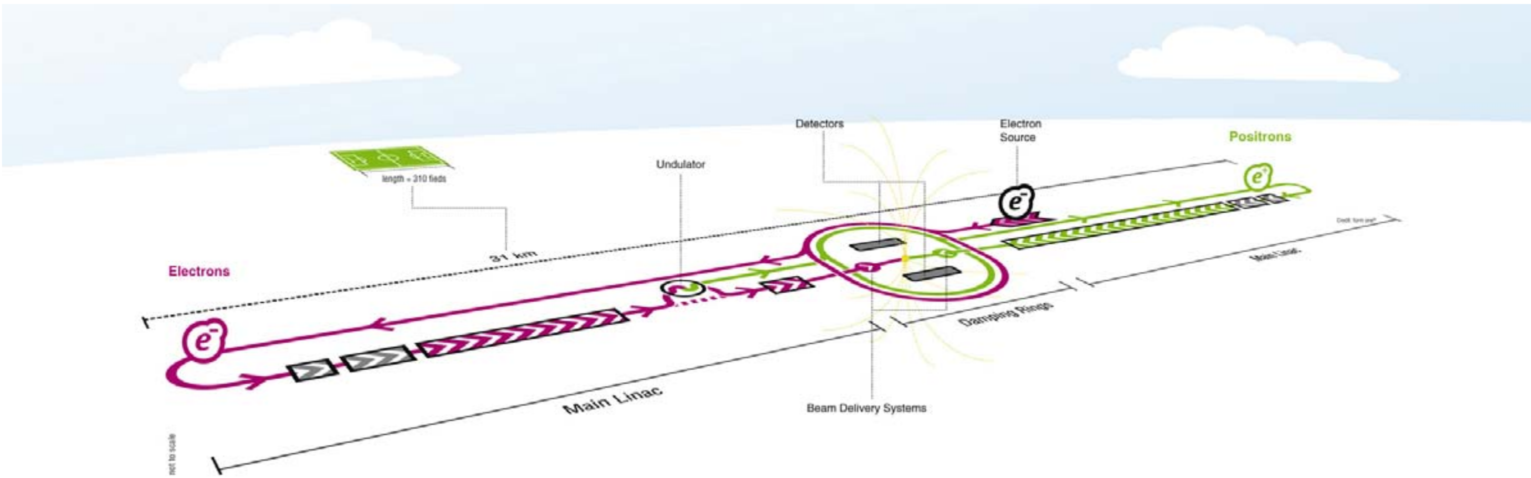


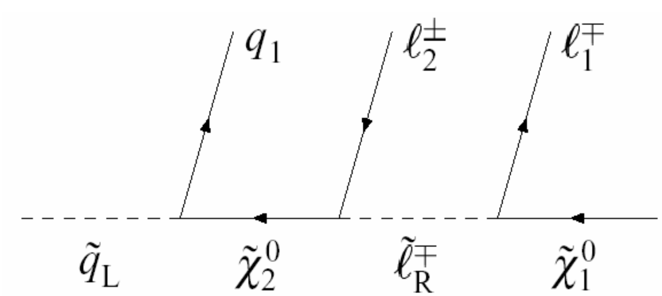
- Collides protons (bags of quarks)
- Produces particles that cascade decay to neutralinos
- Fixed beam energies
- Starts 2008





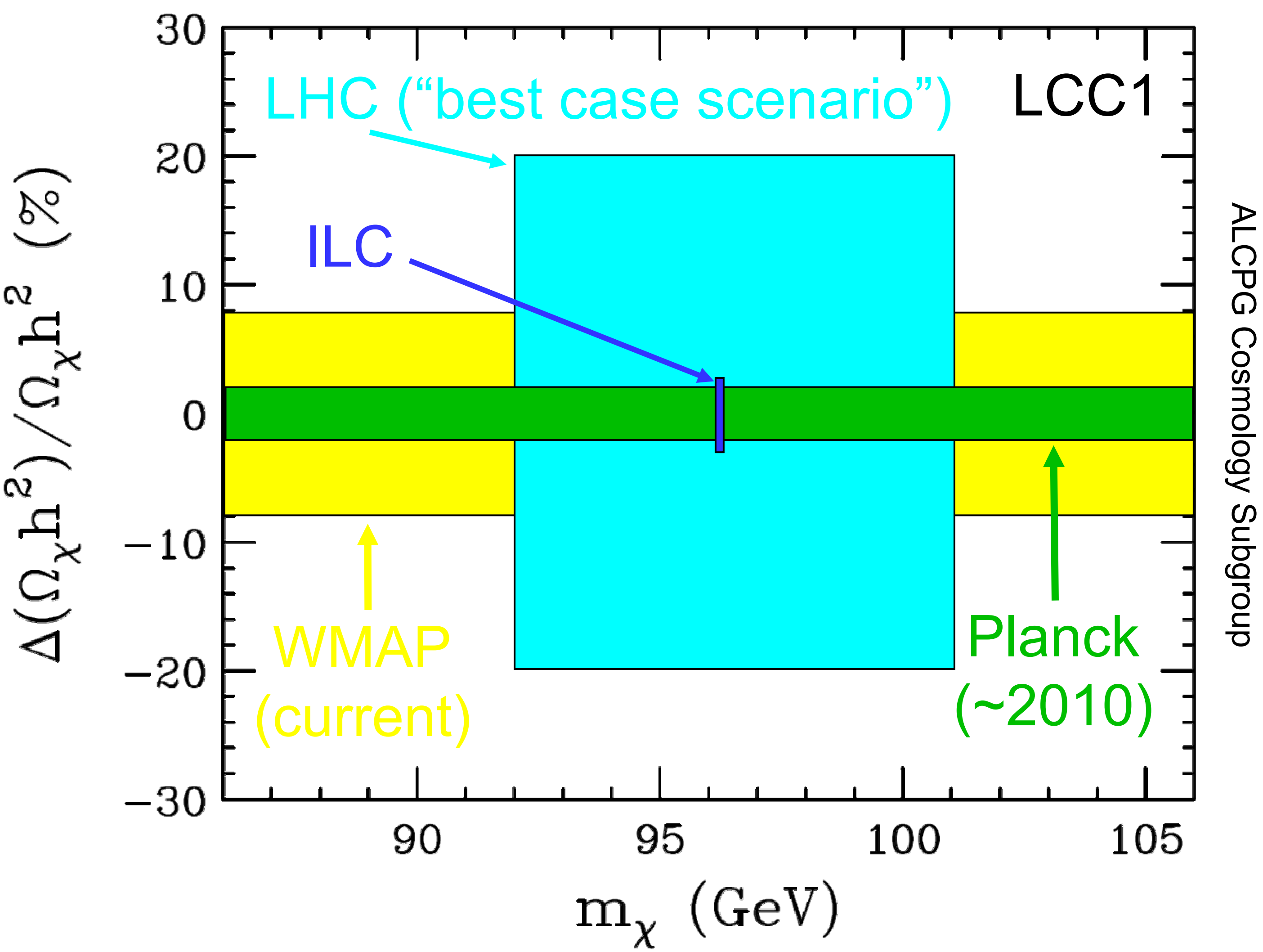
INTERNATIONAL LINEAR COLLIDER





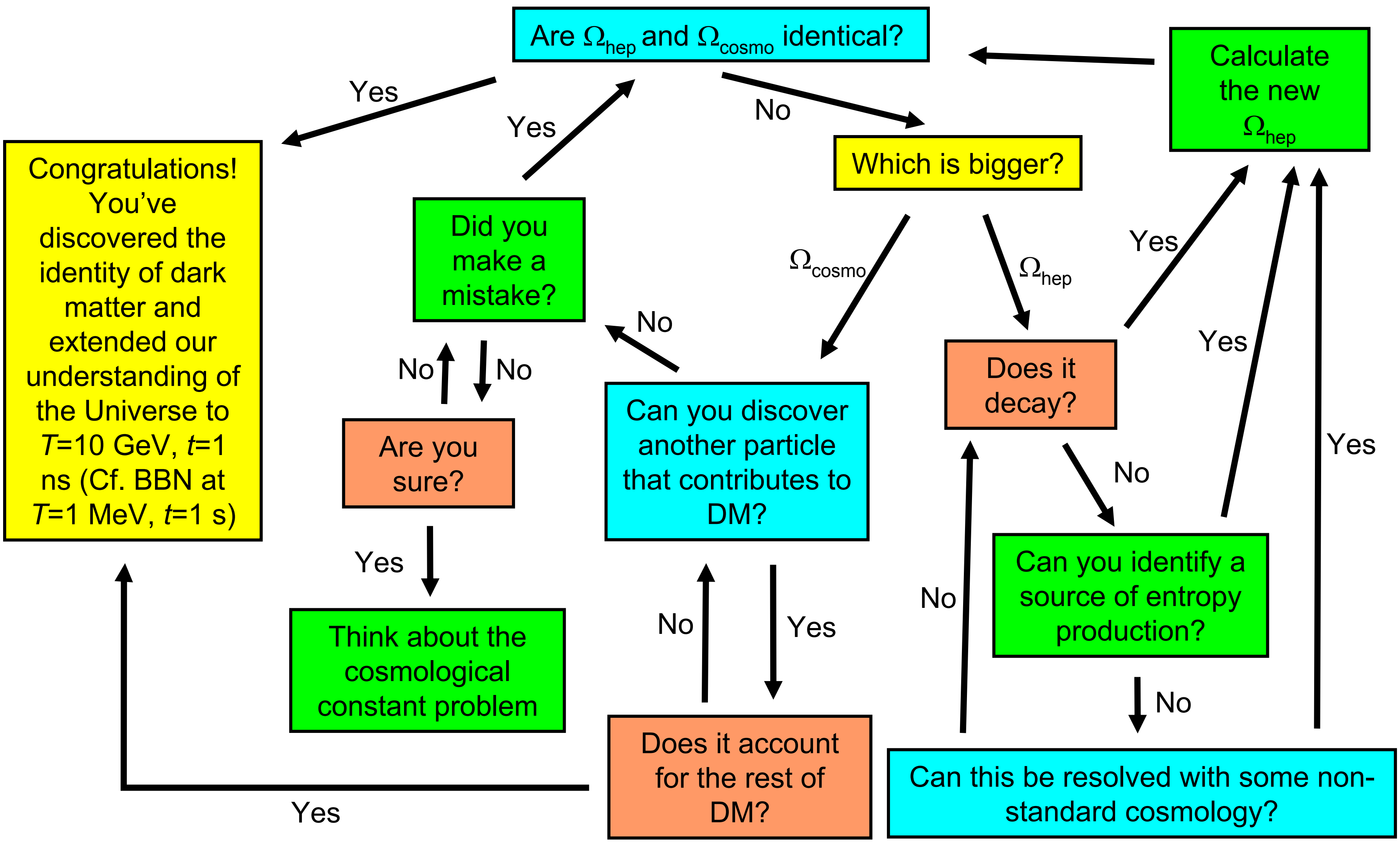
- Collides e^+e^-
- Variable beam energies
- Polarizable e^- beam
- Option to collide e^-e^-
- Starts 20??

RELIC DENSITY DETERMINATIONS



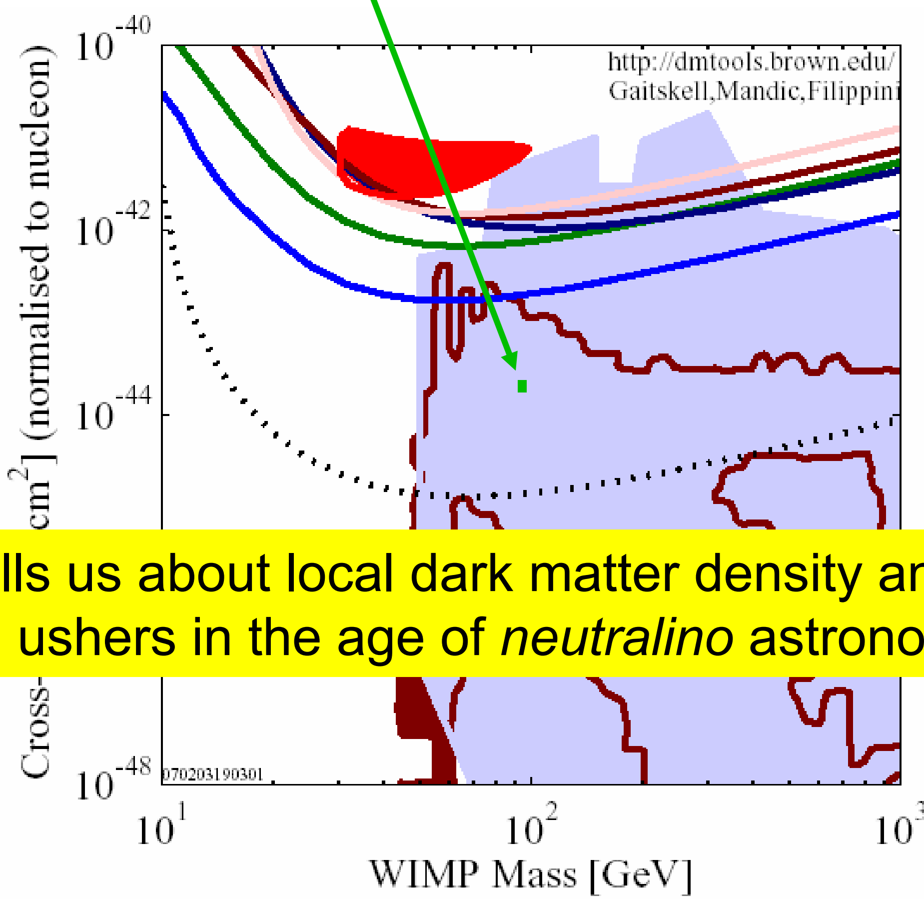
% level comparison of predicted Ω_{hep} with observed Ω_{cosmo}

IDENTIFYING DARK MATTER



DIRECT DETECTION IMPLICATIONS

LHC + ILC → Δm < 1 GeV, $\Delta\sigma/\sigma$ < 20%



Comparison tells us about local dark matter density and velocity profiles, ushers in the age of *neutralino* astronomy

CONCLUSIONS

- Cosmology now provides sharp problems that are among the most outstanding in basic science today.

- They require new microphysics, solutions rely on the intimate connection between large and small

- This field may be transformed by the end of this decade