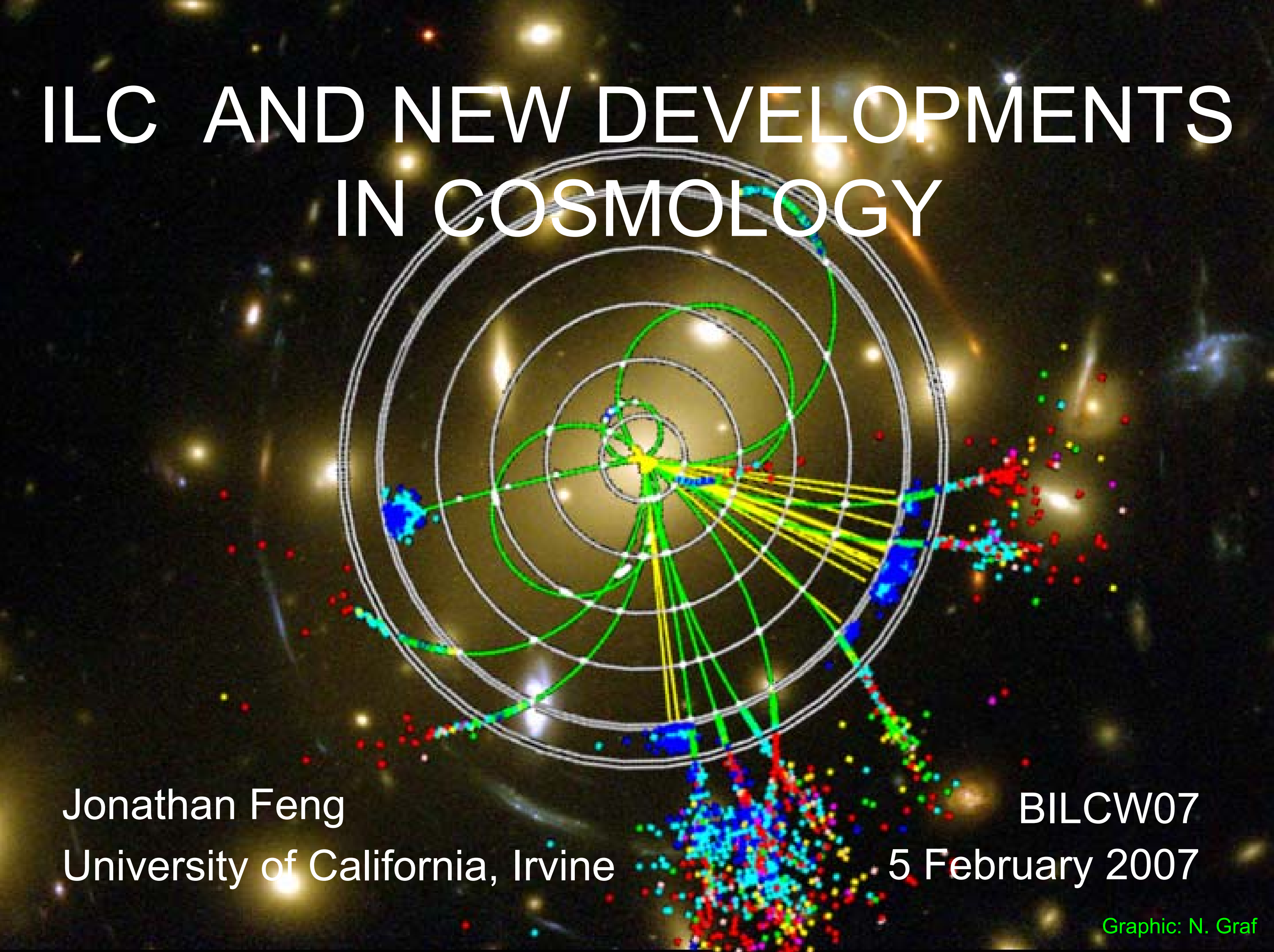


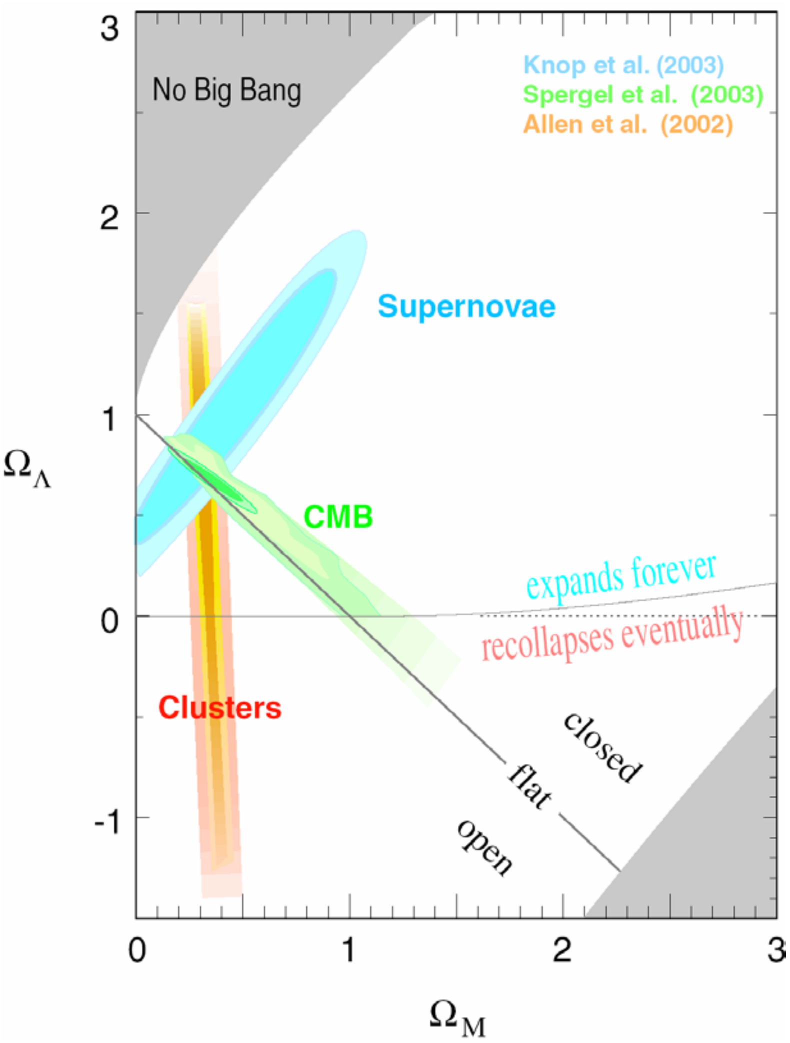
ILC AND NEW DEVELOPMENTS IN COSMOLOGY

Jonathan Feng
University of California, Irvine

BILCW07
5 February 2007

Graphic: N. Graf

COSMOLOGICAL REVOLUTION



- Remarkable agreement

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

- Remarkable precision (~10%)

- Remarkable results

DARK MATTER QUESTIONS

- What is its mass?
- What is its spin?
- What are its other quantum numbers and interactions?
- 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 was it produced?
- 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 QUESTIONS

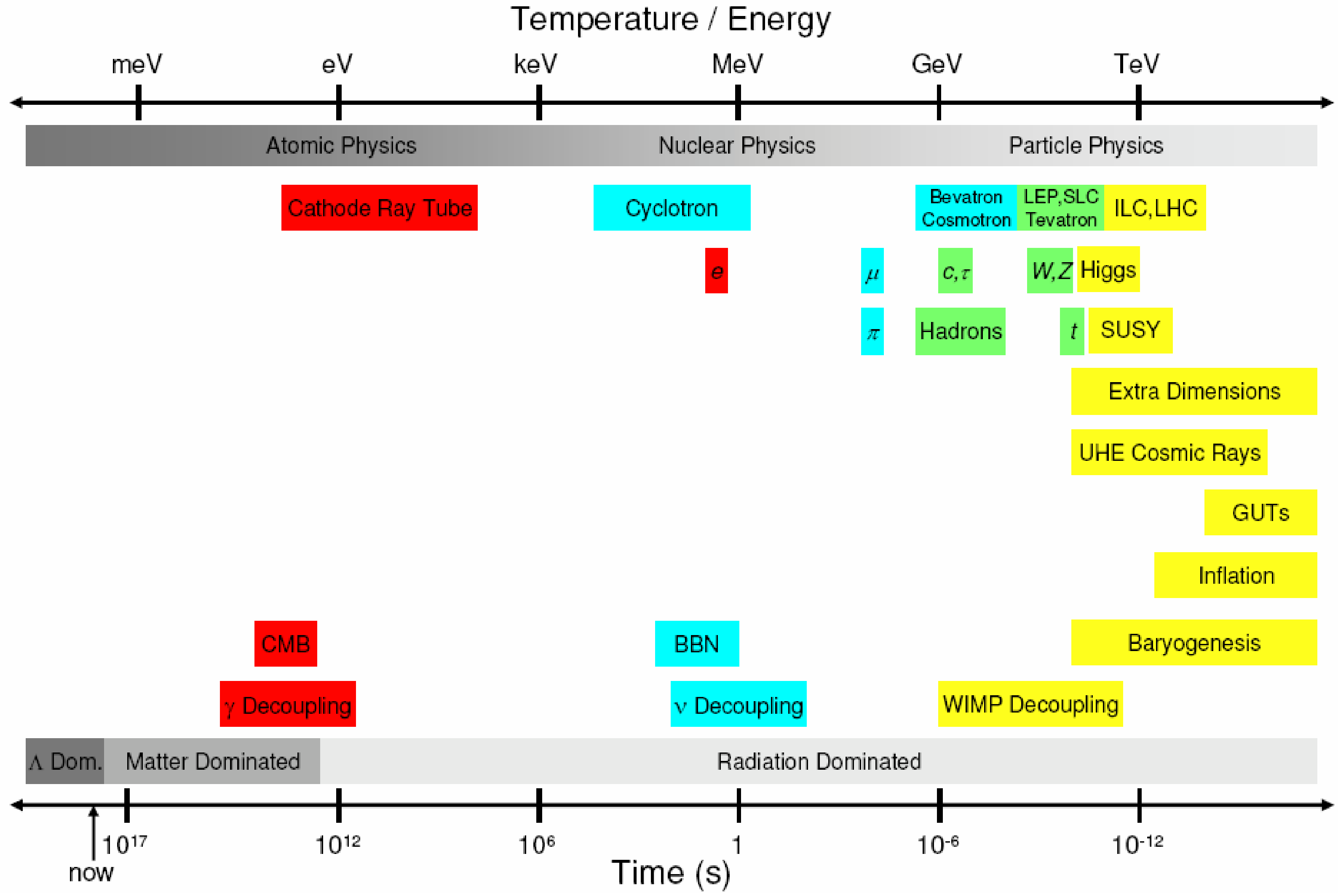
- What is it?
- Why not $\Omega_\Lambda \sim 10^{120}$?
- Why not $\Omega_\Lambda = 0$?
- Does it evolve?

BARYON QUESTIONS

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

What tools do we need to answer these?

PARTICLE PHYSICS AT THE ENERGY FRONTIER



DARK MATTER

- We know how much there is:

$$\Omega_{DM} = 0.23 \pm 0.04$$

- We know what it’s not:

Not short-lived: $\tau > 10^{10}$ years

Not baryonic: $\Omega_B = 0.04 \pm 0.004$

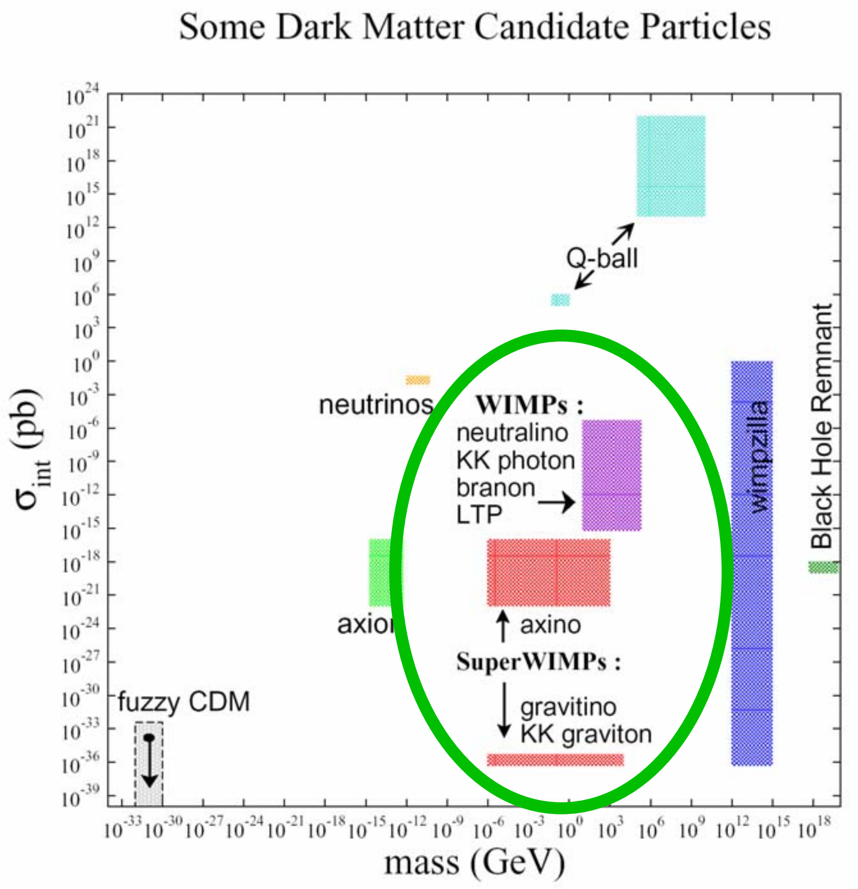
Not hot: must be “slow” to seed structure formation

DARK MATTER CANDIDATES

- There are many candidates

- Masses and interaction strengths span many, many orders of magnitude

- But not all are equally motivated. Focus on:
  - WIMPs
  - SuperWIMPs



Dark Matter Scientific Assessment Group,
U.S. DOE/NSF/NASA HEPAP/AAAC Subpanel (2007)

WIMPS

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

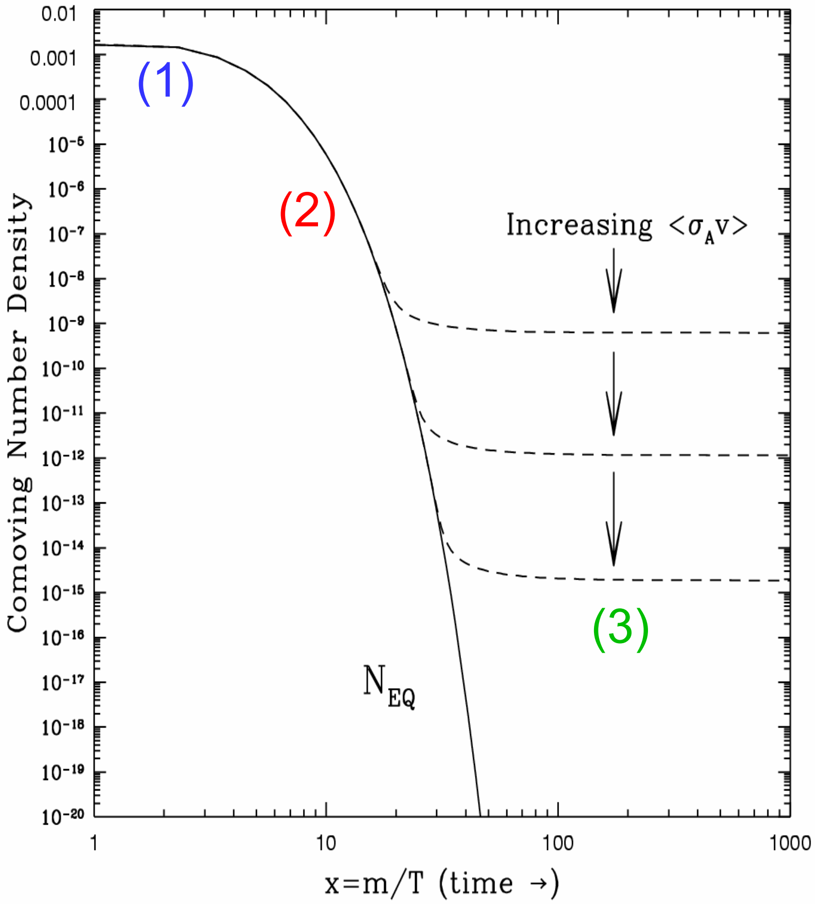
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \;\substack{\rightarrow \\ \not\leftarrow}\; \bar{f} f$$

(3) χs “freeze out”:

$$\chi\chi \;\substack{\not\rightarrow \\ \not\leftarrow}\; f f$$



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

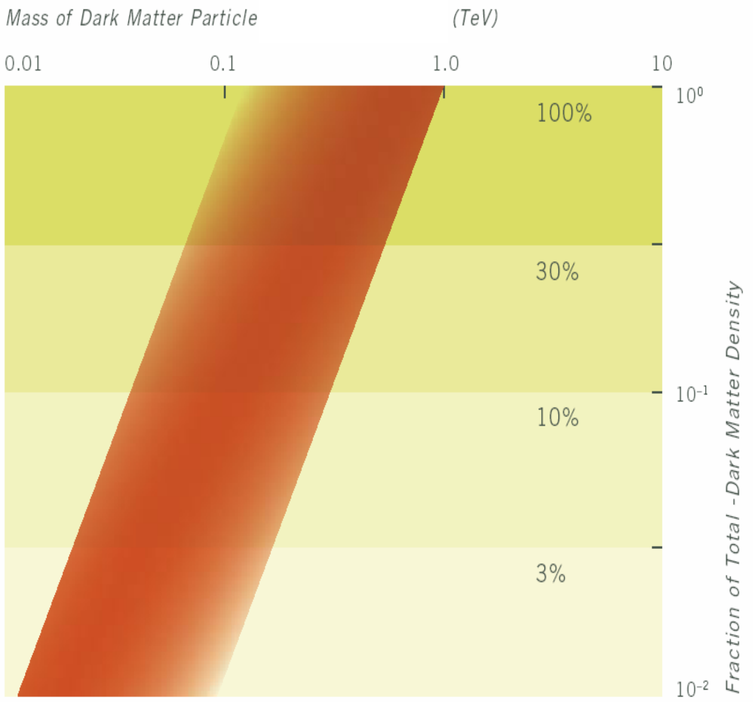
$$\Omega_{DM} \sim \langle \sigma_A v \rangle^{-1}$$

Scherrer, Turner (1986)

- 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]

Ω_{DM} ~ 0.1 for m ~ 100 GeV – 1 TeV

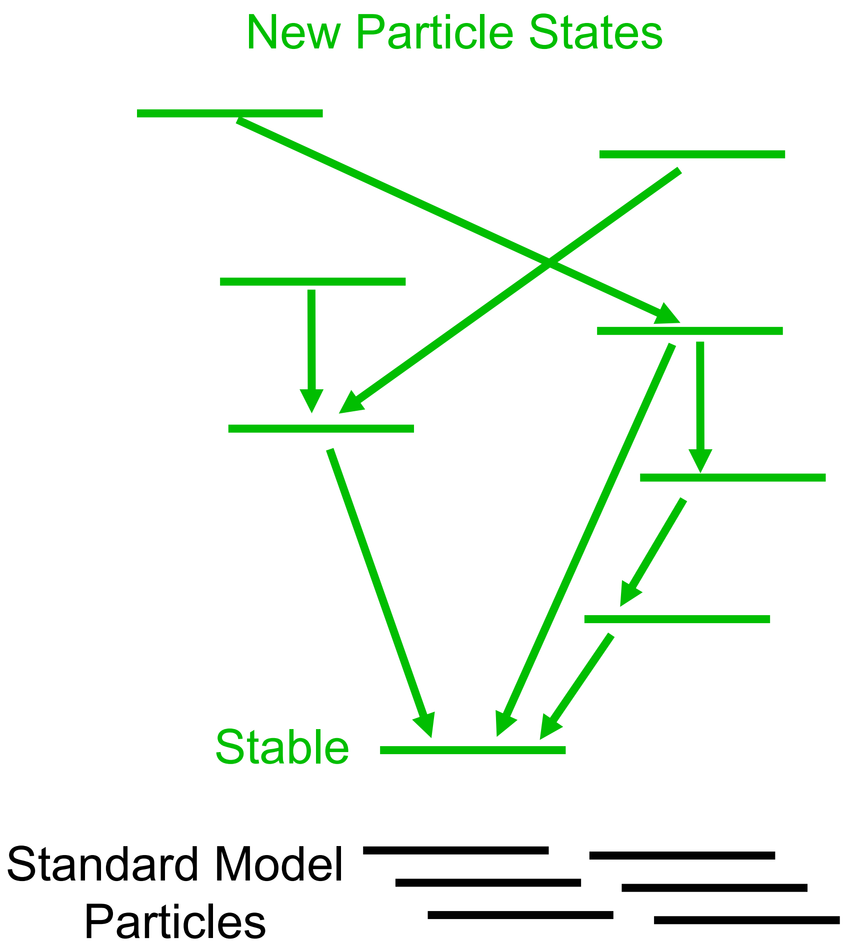
Cosmology alone tells us we should explore the weak scale

STABILITY

- This assumes a *stable* new particle, but this is generic:

Problems
(proton decay, extra particles,
EW precision constraints…)
↕
Discrete symmetry
↕
Stability

- Dark matter is easier to explain than no dark matter, and with the proliferation of EWSB models has come a proliferation of WIMP possibilities.



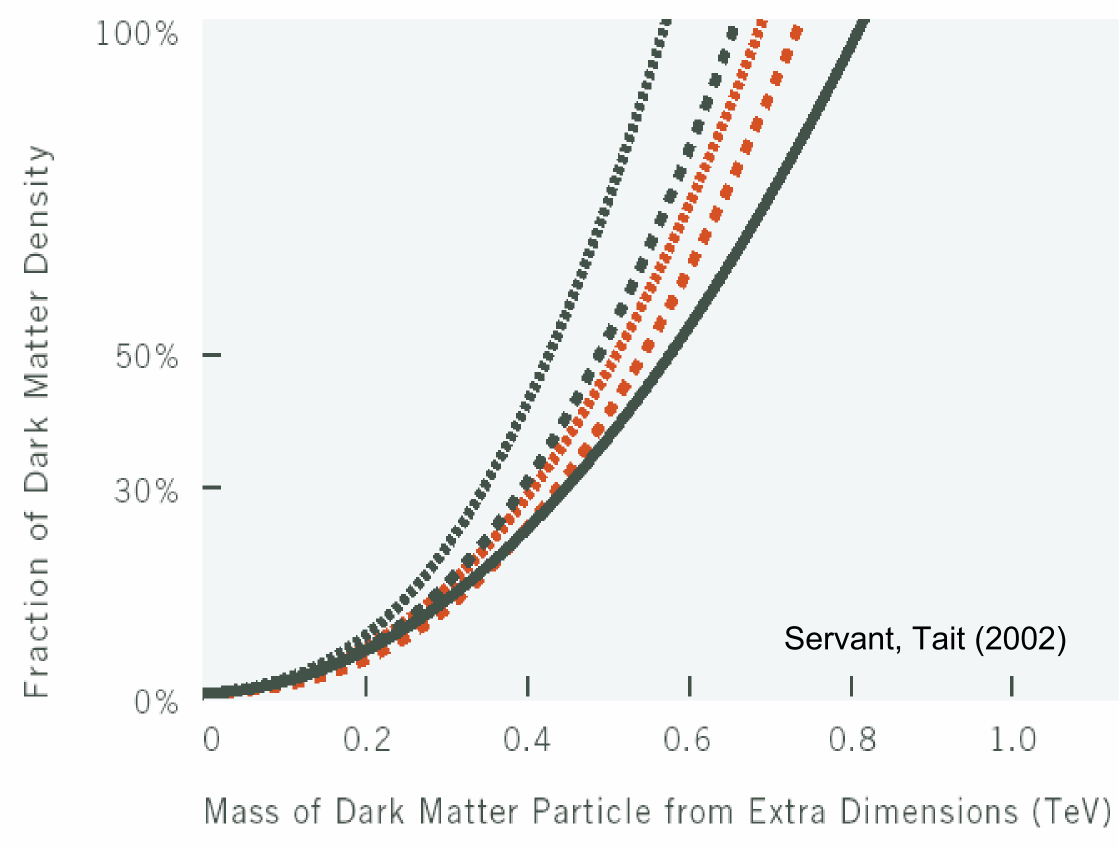
NON-DECOUPLING

- New physics does not decouple cosmologically:

  $$\Omega \sim m^2$$

  There are loopholes, but very heavy particles are disfavored, independent of naturalness.

Universal Extra Dimensions



Servant, Tait (2002)

WIMPS FROM SUPERSYMMETRY

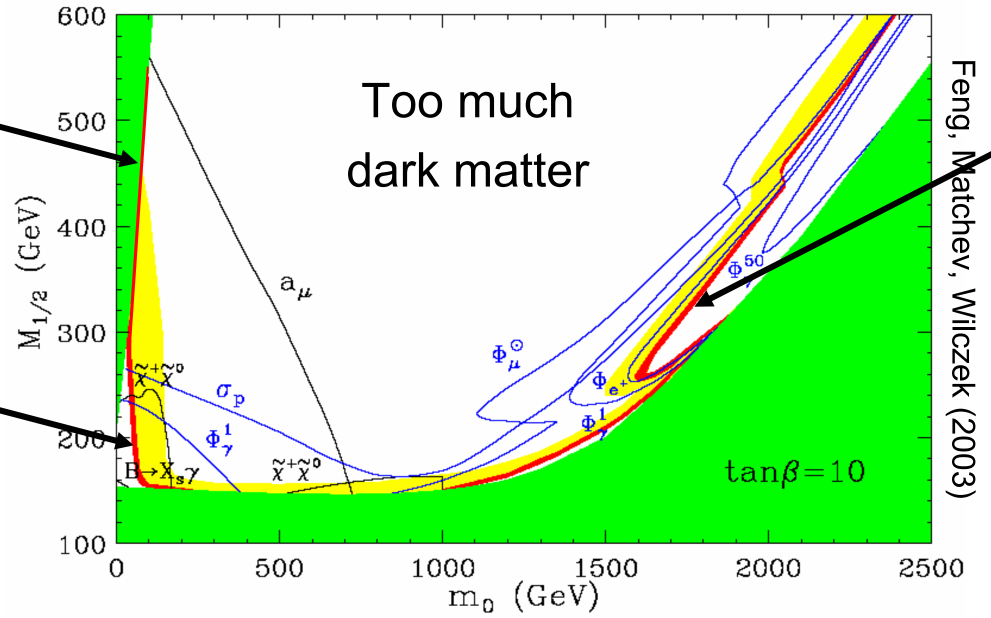
Goldberg (1983); Ellis et al. (1983)

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



Feng, Matchev, Wilczek (2003)

Co-annihilation region

Too much dark matter

Focus point region

Bulk region

Yellow: pre-WMAP
Red: post-WMAP

Cosmology excludes many possibilities, favors certain regions

WIMPS FROM EXTRA DIMENSIONS

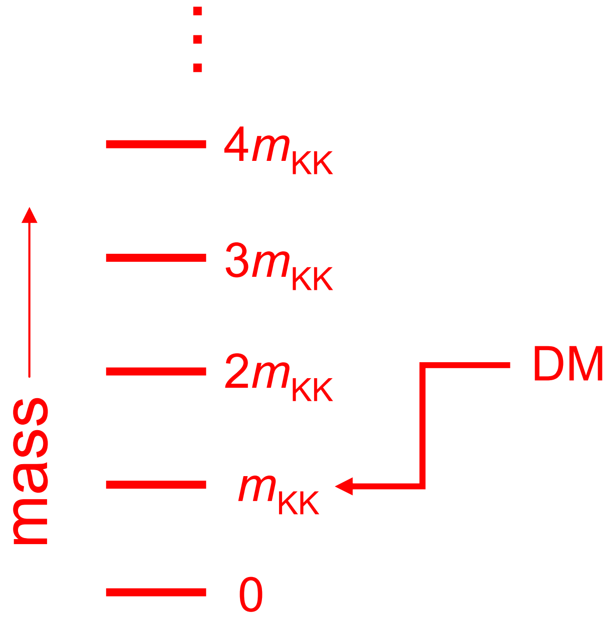
Servant, Tait (2002); Cheng, Feng, Matchev (2002)

- Extra spatial dimensions could be curled up into small circles of radius *R*

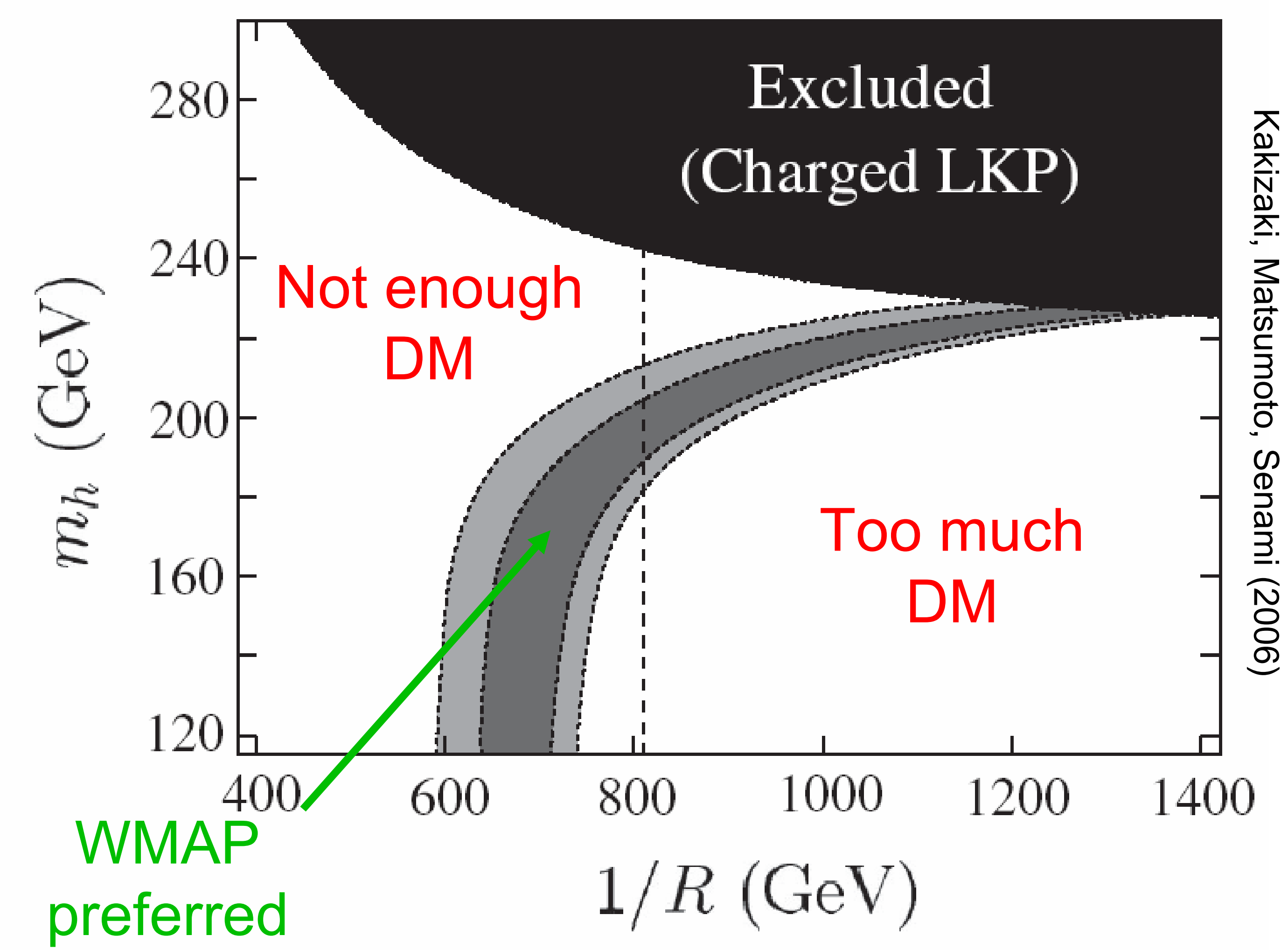
- Particles moving in extra dimensions appear as a set of copies of SM particles

- New particle masses are integer multiples of

$$m_{KK} = R^{-1}$$

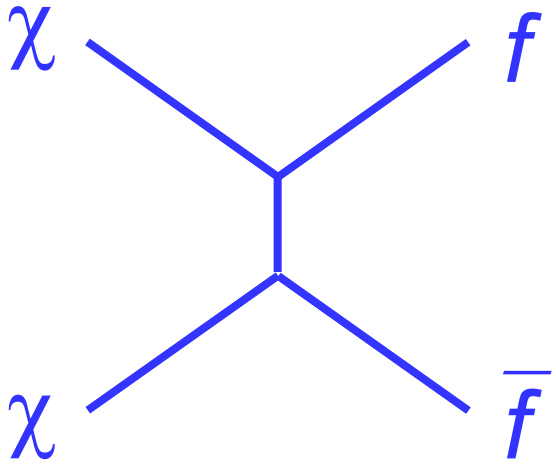


Minimal Universal Extra Dimensions



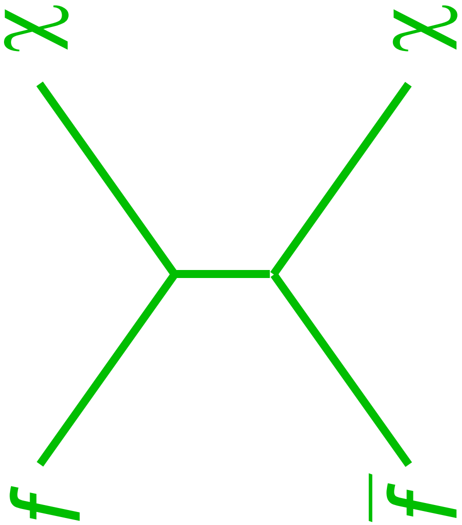
Kakizaki, Matsumoto, Senami (2006)

WIMP DETECTION



Annihilation

Crossing
$\longrightarrow$
symmetry



Scattering

Correct relic density → Efficient annihilation then

→ Efficient annihilation now

→ Efficient scattering now

DIRECT DETECTION

- WIMP essentials:

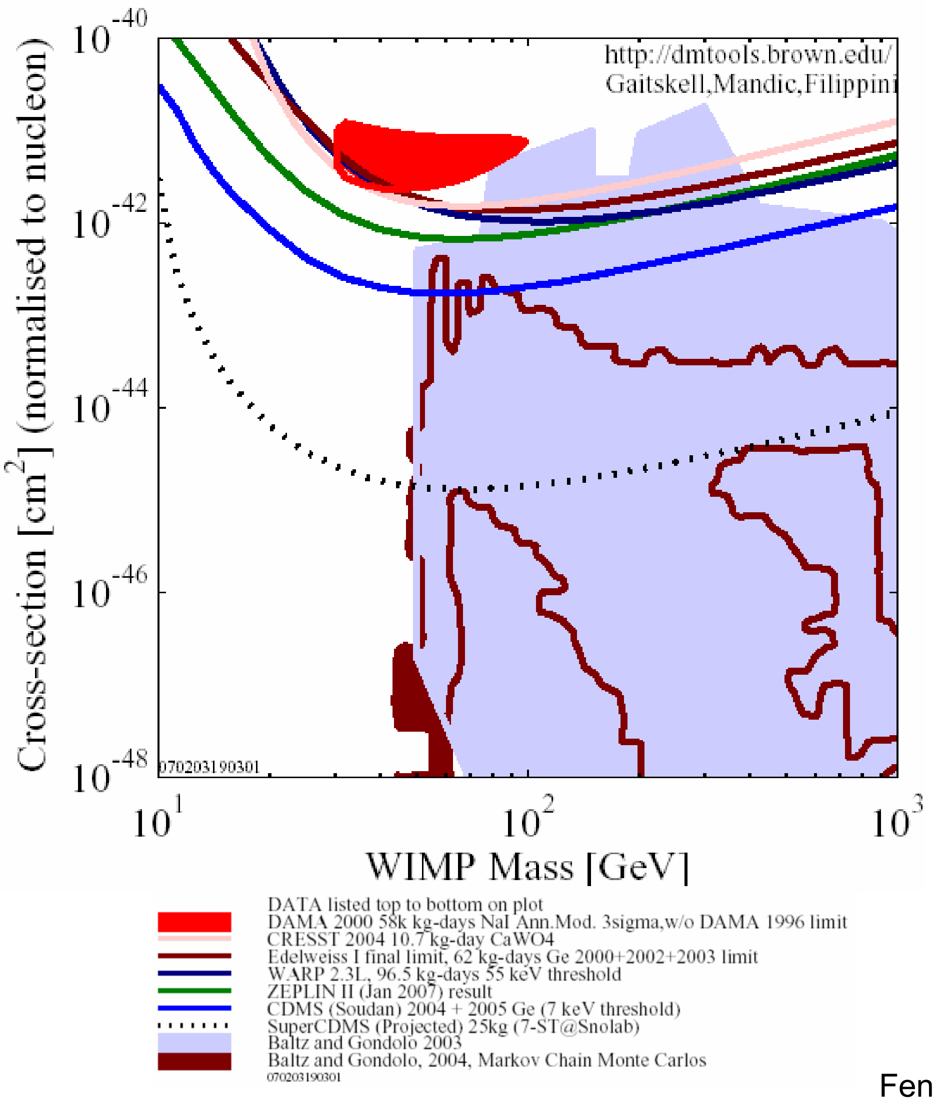
  $v \sim 10^{-3}\,c$

  Kinetic energy ~ 100 keV

  Local density ~ 1 / liter

- (Coherent) spin-independent scattering most promising for most WIMP candidates

- Theorists: χq scattering
  Expts: χ nucleus scattering
  Compromise: χp scattering



Indirect Detection

Dark matter annihilates in ____________________ to

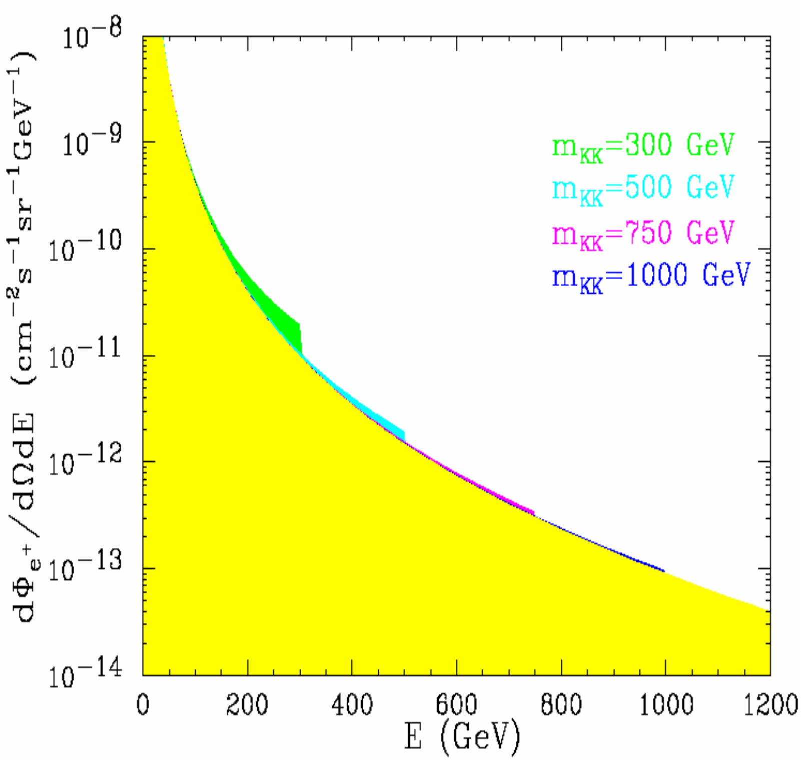
a place

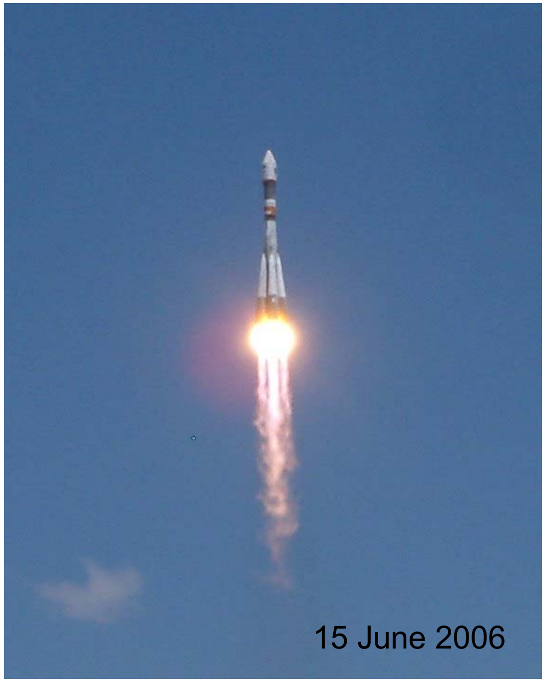
____________ , which are detected by ________________ .

particles   an experiment

Dark Matter annihilates in ______the halo______ to
a place

__positrons__ , which are detected by __PAMELA__.
some particles an experiment




15 June 2006

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

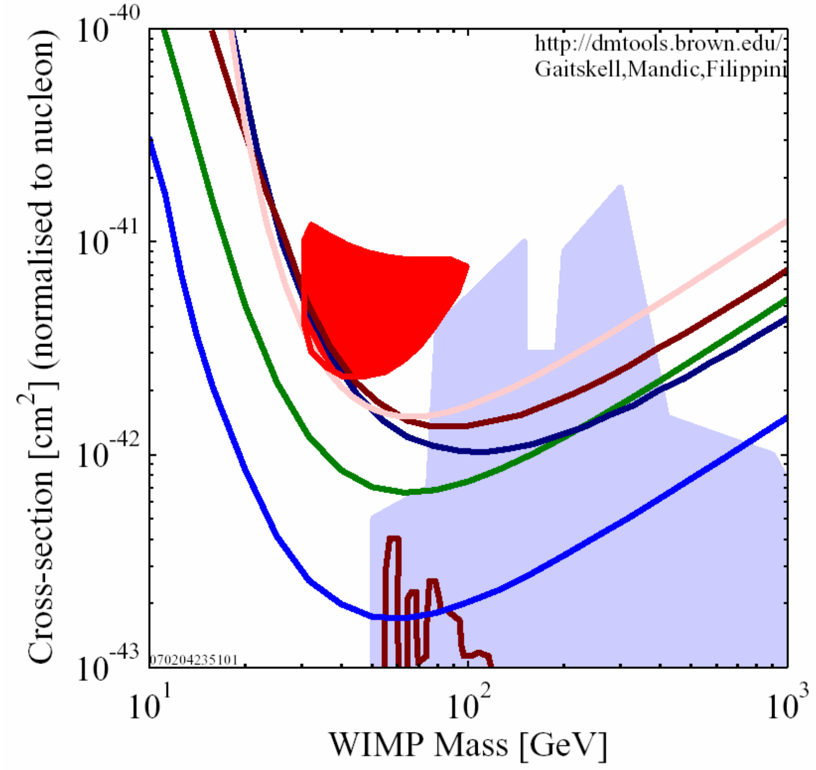
Indirect dark matter searches

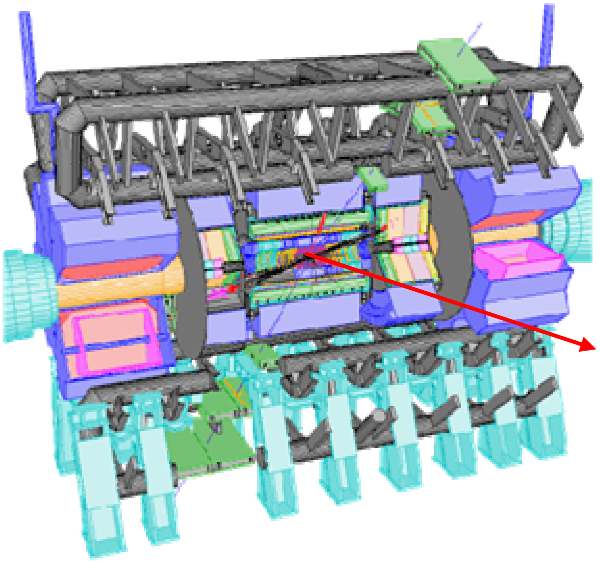
The Tevatron at Fermilab

The Large Hadron Collider at CERN

What then?

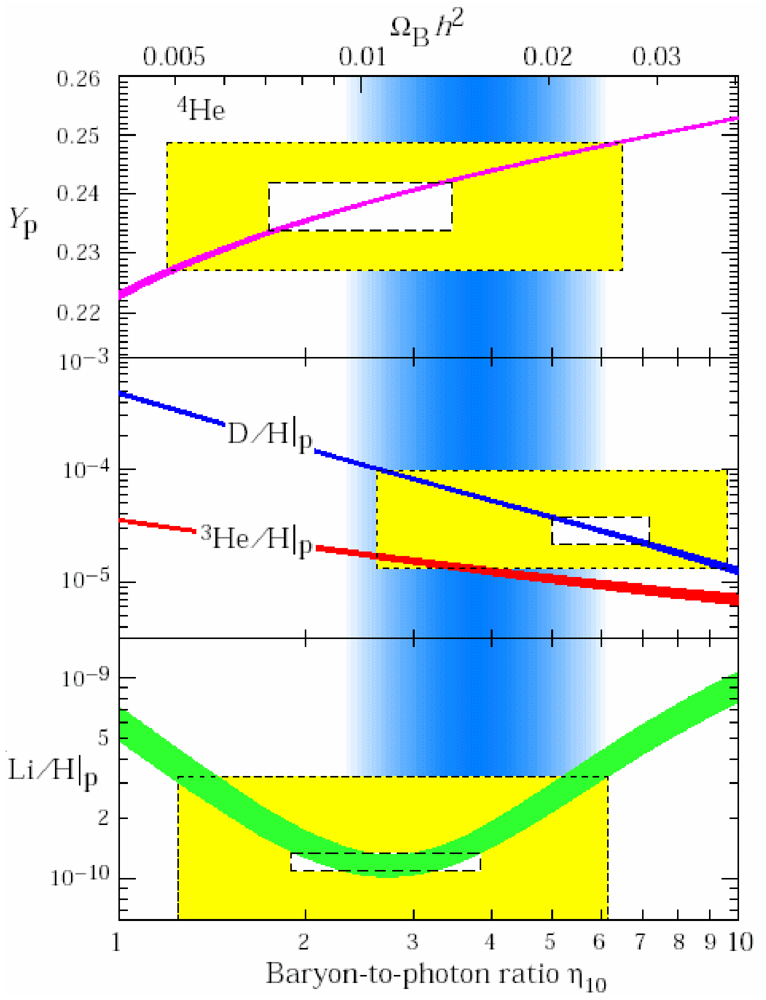
- Cosmology can't discover SUSY
- Particle colliders can't discover DM





Lifetime > 10^{-7} s → 10^{17} s ?

THE EXAMPLE OF BBN

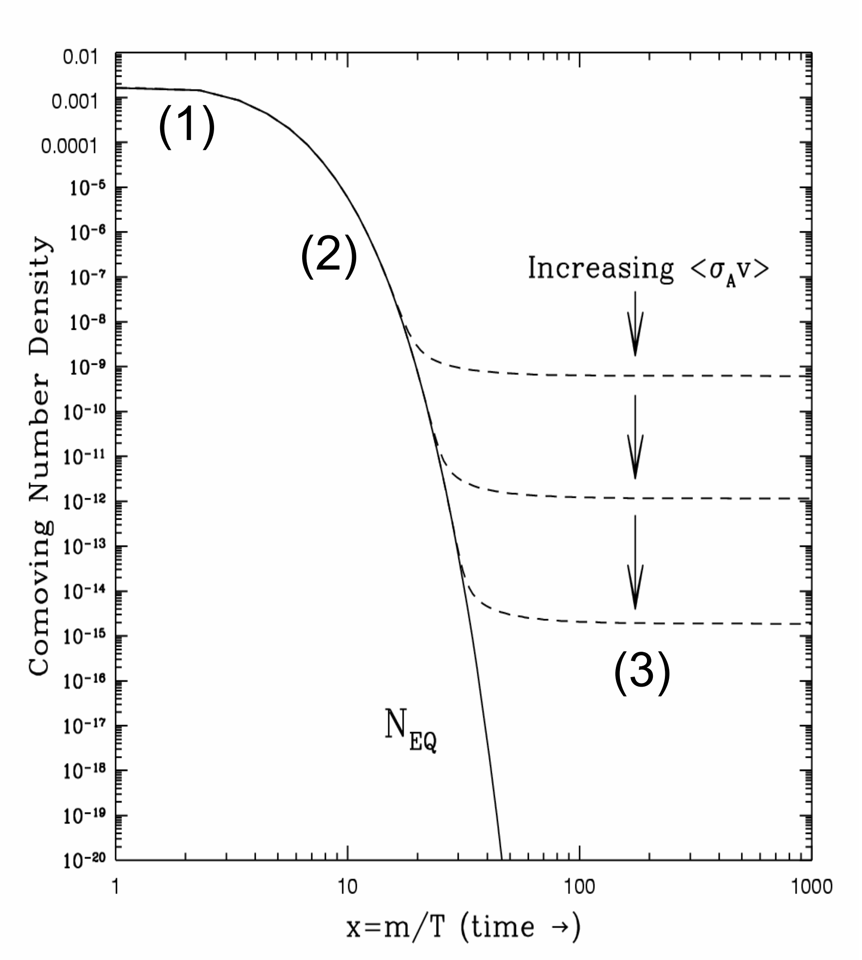


- Nuclear physics → light element abundance predictions
- Compare to light element abundance observations
- Agreement → we understand the universe back to

  T ~ 1 MeV

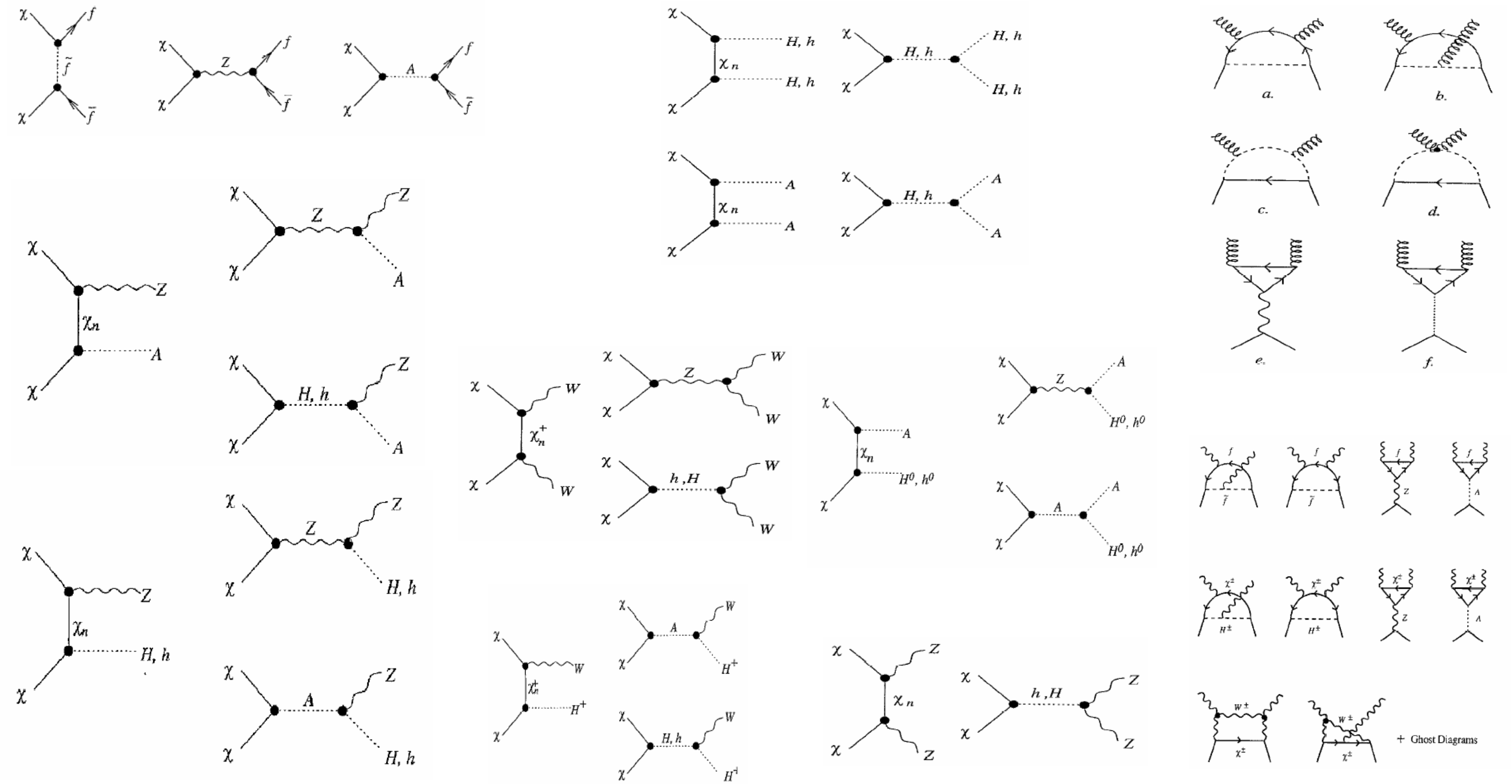
  t ~ 1 sec

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)

QUANTITATIVE ANALYSIS OF DM

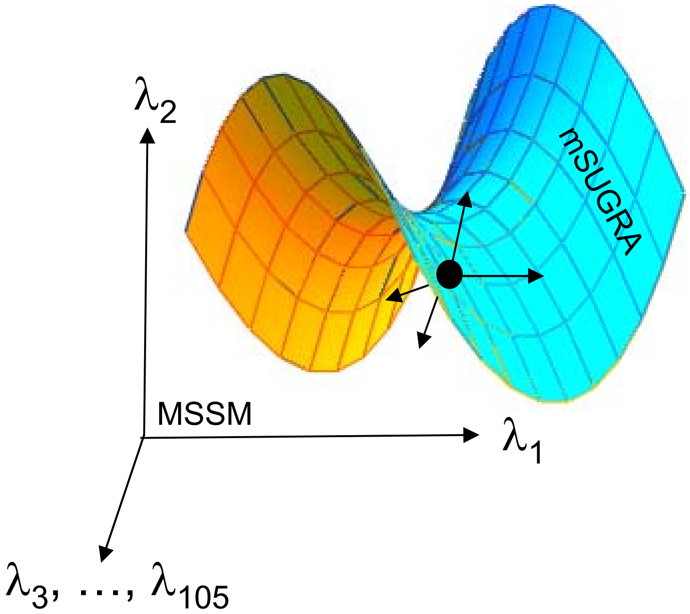
The Approach of the ALCPG Cosmology Group:

- Choose a concrete *example*: neutralinos

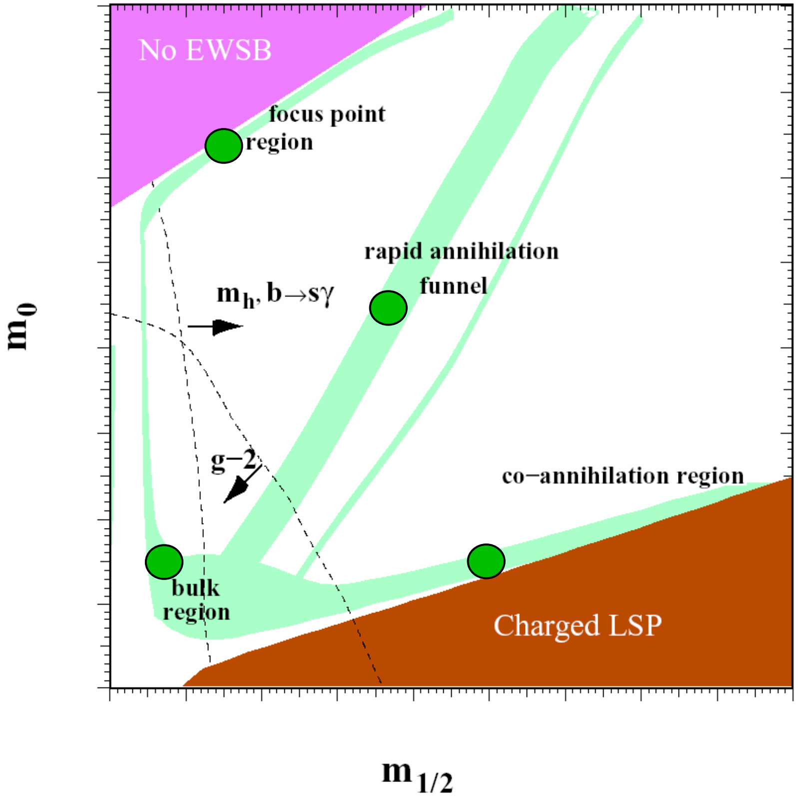
- Choose a simple model framework that encompasses many qualitatively different behaviors: mSUGRA

- Relax model-dependent assumptions and determine parameters

- Identify cosmological, astroparticle implications



Neutralino DM in mSUGRA



Cosmology excludes much of parameter space (Ω_χ too big)

Cosmology focuses attention on particular regions (Ω_χ just right)

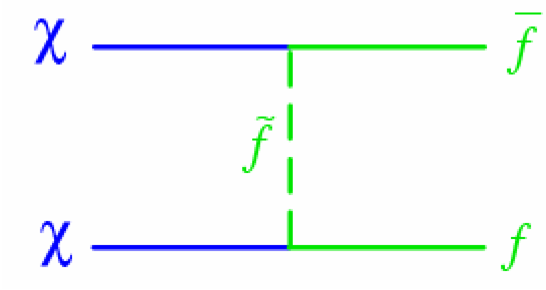
Choose 4 representative points for detailed study

Baer et al., ISAJET Gondolo et al., DARKSUSY Belanger et al., MICROMEGA

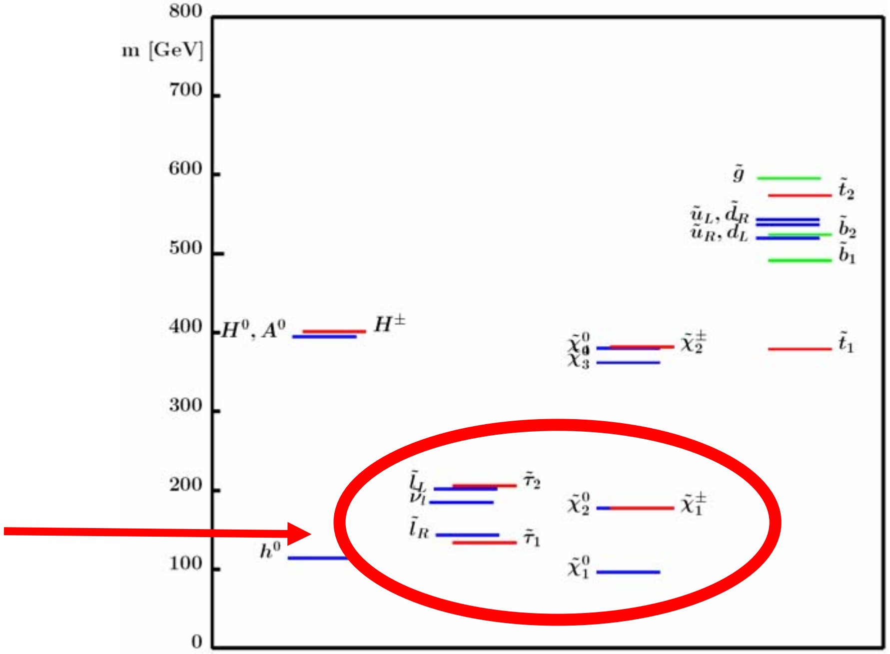
BULK REGION LCC1 (SPS1a)

$m_0, M_{1/2}, A_0, \tan\beta = 100, 250, -100, 10$ [$\mu>0, m_{3/2}>m_{LSP}$]

- Correct relic density obtained if χ annihilate efficiently through light sfermions:



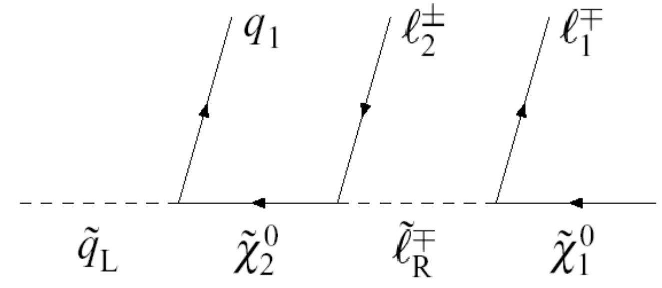
- Motivates SUSY with light $\chi, \tilde{l}$



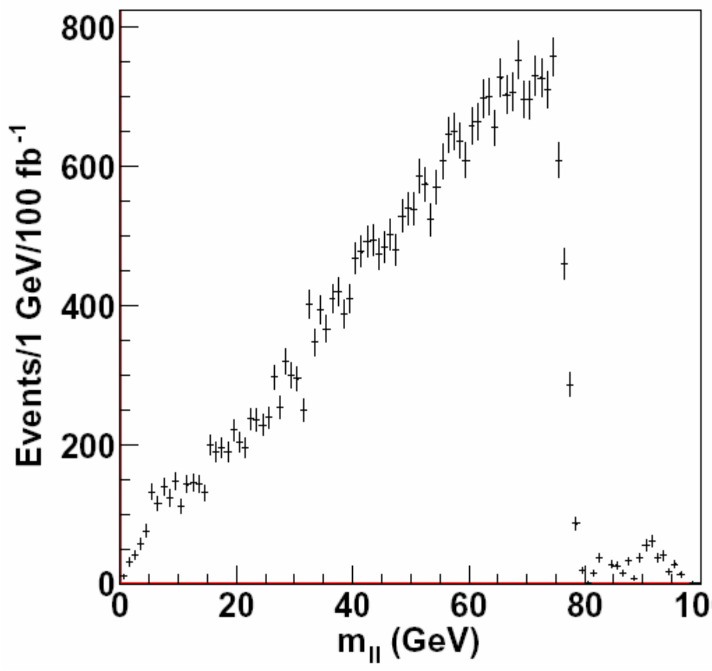
Allanach et al. (2002)

PRECISION SUSY @ LHC

- LHC produces strongly-interacting superpartners, which cascade decay



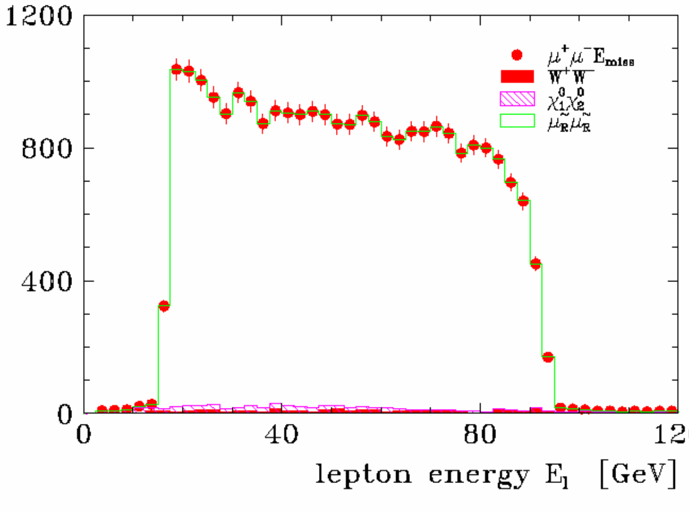
$$\begin{aligned}
\left(m_{ll}^2\right)^{\text{edge}} &= \frac{\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{l}_R}^2} \\
\left(m_{qll}^2\right)^{\text{edge}} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{\chi}_2^0}^2} \\
\left(m_{ql}^2\right)_{\text{min}}^{\text{edge}} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)}{m_{\tilde{\chi}_2^0}^2} \\
\left(m_{ql}^2\right)_{\text{max}}^{\text{edge}} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{l}_R}^2} \\
\left(m_{qll}^2\right)^{\text{thres}} &= [(m_{\tilde{q}_L}^2 + m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2) \\
&\quad -(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)\sqrt{(m_{\tilde{\chi}_2^0}^2 + m_{\tilde{l}_R}^2)^2(m_{\tilde{l}_R}^2 + m_{\tilde{\chi}_1^0}^2)^2 - 16 m_{\tilde{\chi}_2^0}^2 m_{\tilde{l}_R}^4 m_{\tilde{\chi}_1^0}^2} \\
&\quad +2m_{\tilde{l}_R}^2(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)]/(4m_{\tilde{l}_R}^2 m_{\tilde{\chi}_2^0}^2)
\end{aligned}$$



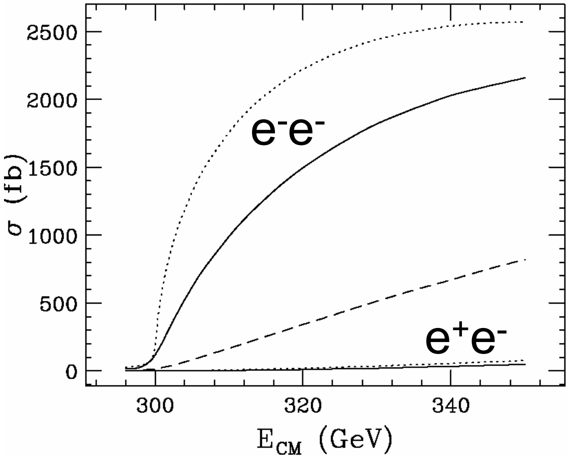
Weiglein et al. (2004)

PRECISION SUSY @ ILC

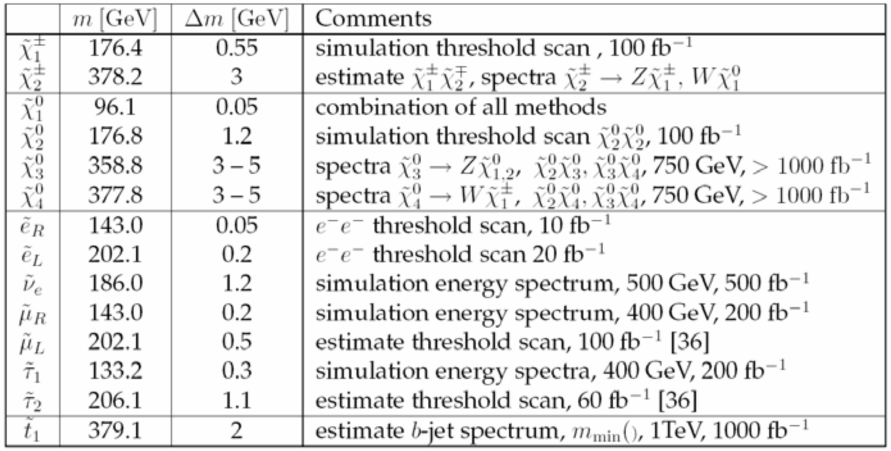
- Exploit all properties
  - kinematic endpoints
  - threshold scans
  - e^- beam polarization
  - e^-e^- option



Martyn et al. (2004)



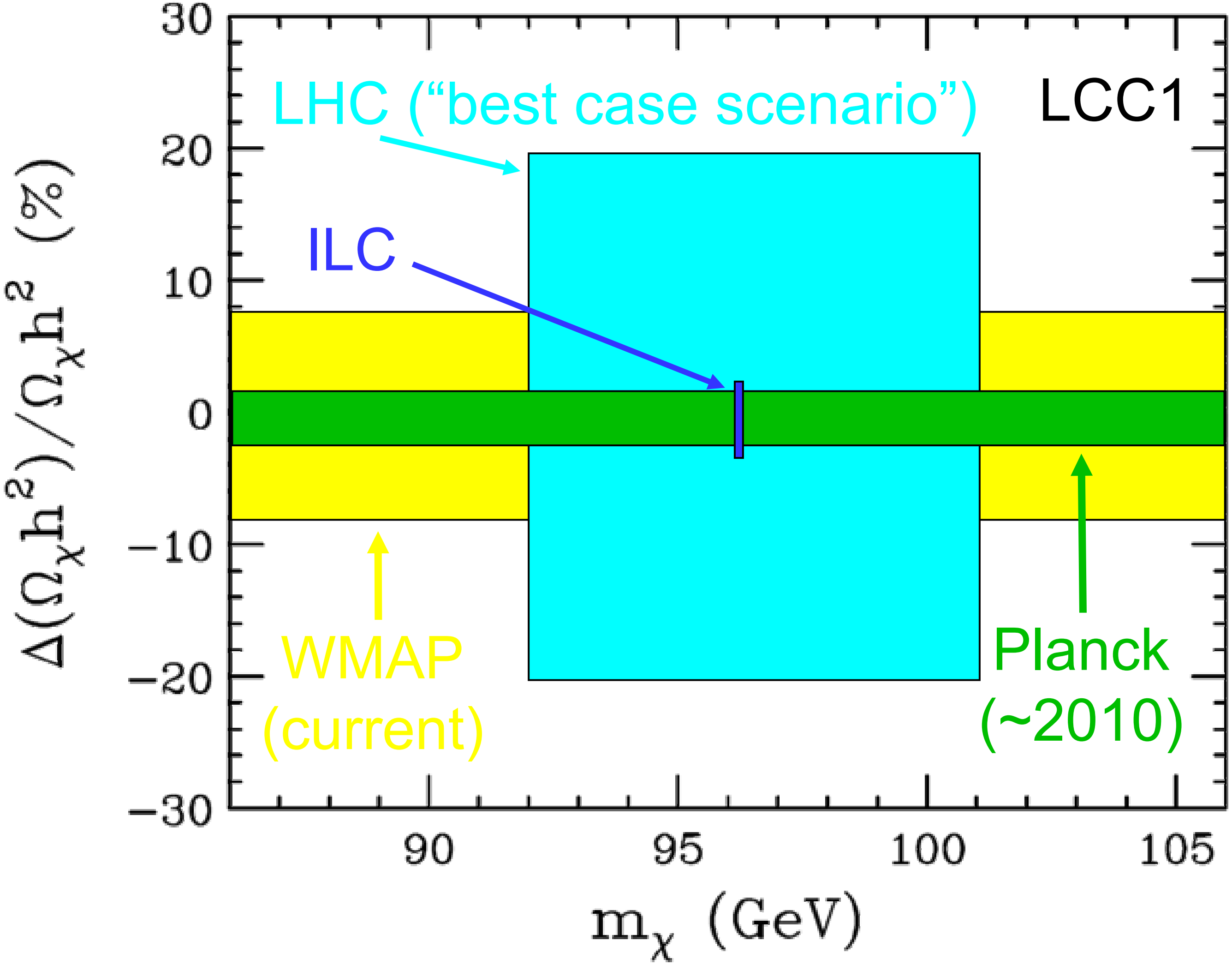
Feng, Peskin (2001)



	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}^\pm_1$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}^\pm_2$	378.2	3	estimate $\tilde{\chi}^\pm_1\tilde{\chi}^\mp_2$, spectra $\tilde{\chi}^\pm_2 \to Z\tilde{\chi}^\pm_1, W\tilde{\chi}^0_1$
$\tilde{\chi}^0_1$	96.1	0.05	combination of all methods
$\tilde{\chi}^0_2$	176.8	1.2	simulation threshold scan $\tilde{\chi}^0_2\tilde{\chi}^0_2$, 100 fb^{-1}
$\tilde{\chi}^0_3$	358.8	3 – 5	spectra $\tilde{\chi}^0_3 \to Z\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^0_2\tilde{\chi}^0_3, \tilde{\chi}^0_3\tilde{\chi}^0_4$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{\chi}^0_4$	377.8	3 – 5	spectra $\tilde{\chi}^0_4 \to W\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2\tilde{\chi}^0_4, \tilde{\chi}^0_3\tilde{\chi}^0_4$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{e}_R$	143.0	0.05	e^-e^- threshold scan, 10 fb^{-1}
$\tilde{e}_L$	202.1	0.2	e^-e^- threshold scan 20 fb^{-1}
$\tilde{\nu}_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde{\mu}_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde{\mu}_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1} [36]
$\tilde{\tau}_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde{\tau}_2$	206.1	1.1	estimate threshold scan, 60 fb^{-1} [36]
$\tilde{t}_1$	379.1	2	estimate b-jet spectrum, $m_{\min}()$, 1TeV, 1000 fb^{-1}

- Must also verify insensitivity to all other parameters

RELIC DENSITY DETERMINATIONS



ALCPG Cosmology Subgroup

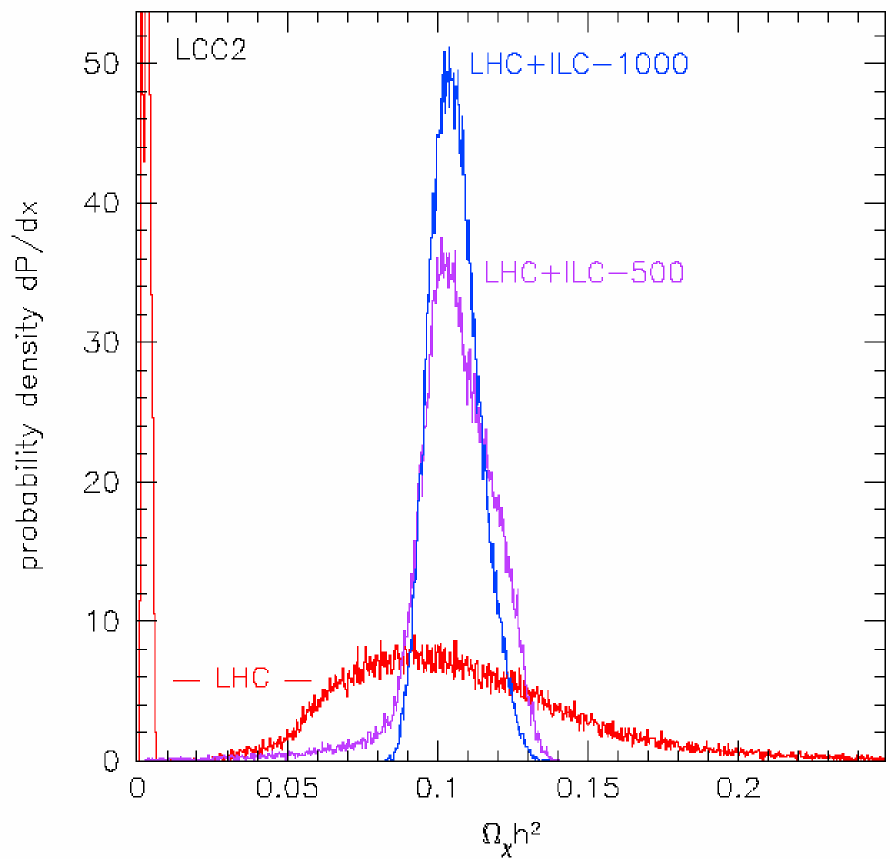
% level agreement → Identity of dark matter

MODEL DEPENDENCE

- LHC/ILC determination of relic densities has now been studied by many groups.

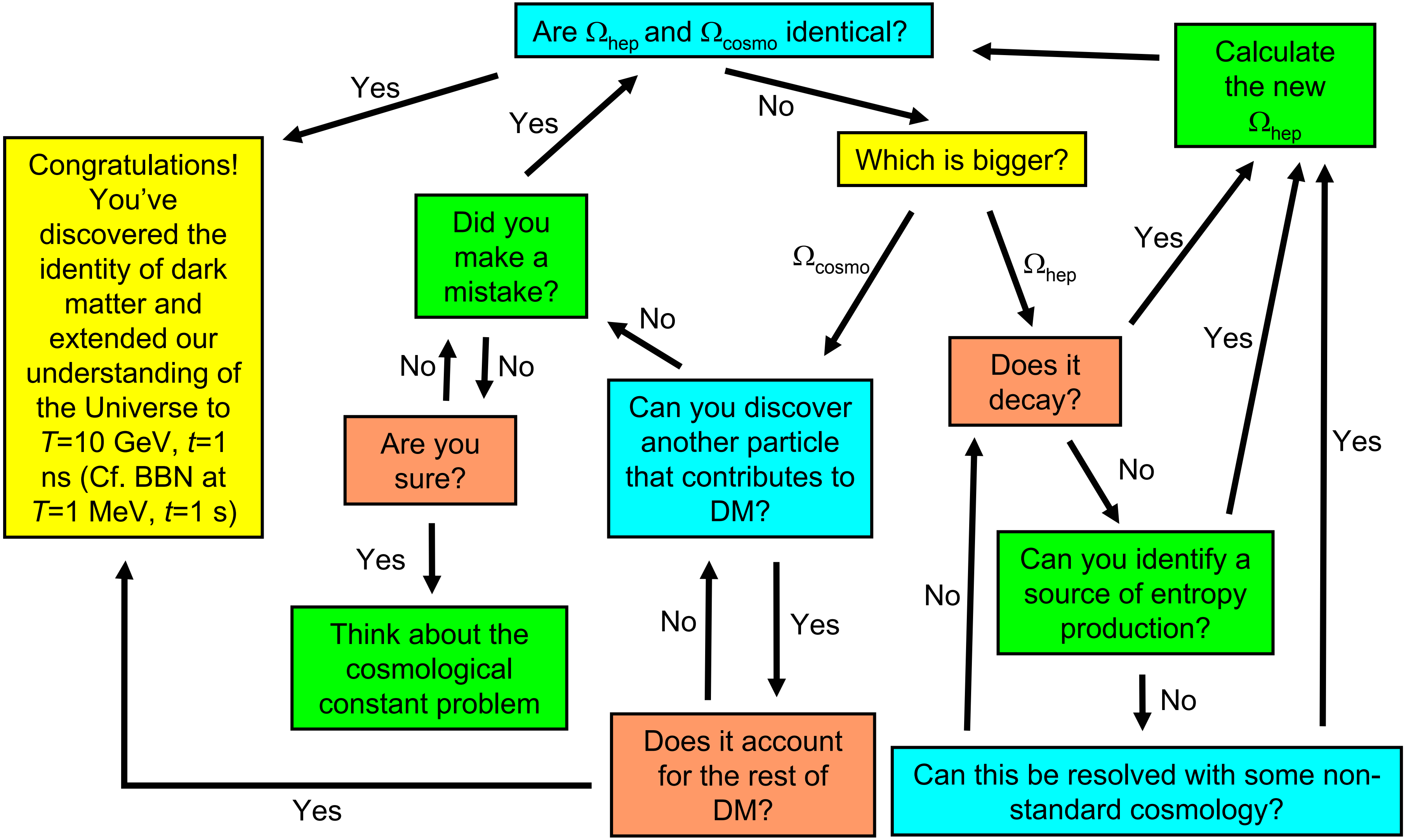
Allanach, Belanger, Boudjema, Pukhov (2004)
Moroi, Shimizu, Yotsuyanagi (2005)
Baltz, Battaglia, Peskin, Wizansky (2006)

- Bottom line: LHC results are not always good, but ILC removes degeneracies



Baltz, Battaglia, Peskin, Wizansky (2006)

IDENTIFYING DARK MATTER



Are Ω_{hep} and Ω_{cosmo} identical?

Congratulations! You've discovered the identity of dark matter and extended our understanding of the Universe to *T*=10 GeV, *t*=1 ns (Cf. BBN at *T*=1 MeV, *t*=1 s)

Did you make a mistake?

Are you sure?

Think about the cosmological constant problem

Which is bigger?

Can you discover another particle that contributes to DM?

Does it account for the rest of DM?

Does it decay?

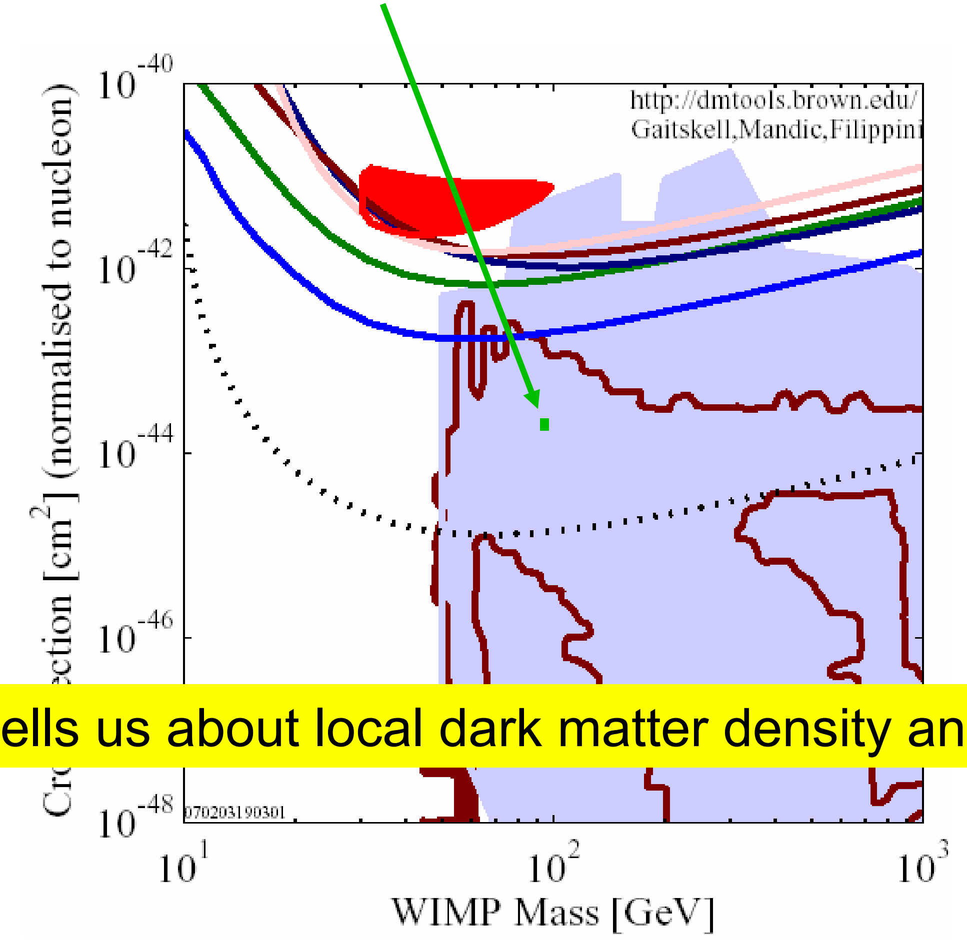
Can you identify a source of entropy production?

Can this be resolved with some non-standard cosmology?

Calculate the new Ω_{hep}

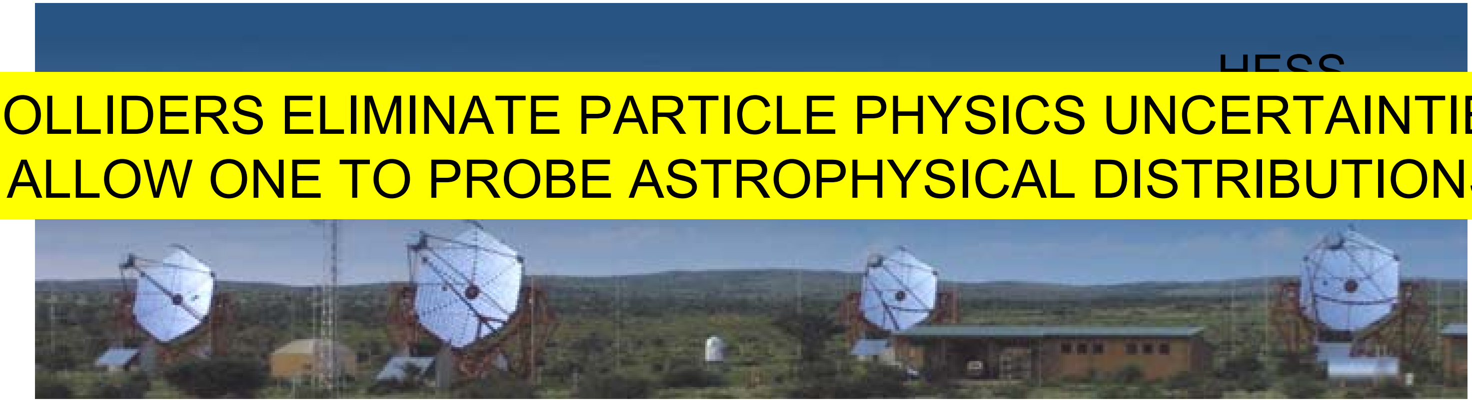
DIRECT DETECTION IMPLICATIONS

LHC + ILC → Δm < 1 GeV, Δσ/σ < 20%



Comparison tells us about local dark matter density and velocity profiles

INDIRECT DETECTION IMPLICATIONS



COLLIDERS ELIMINATE PARTICLE PHYSICS UNCERTAINTIES, ALLOW ONE TO PROBE ASTROPHYSICAL DISTRIBUTIONS

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

Very sensitive to halo profiles near the galactic center

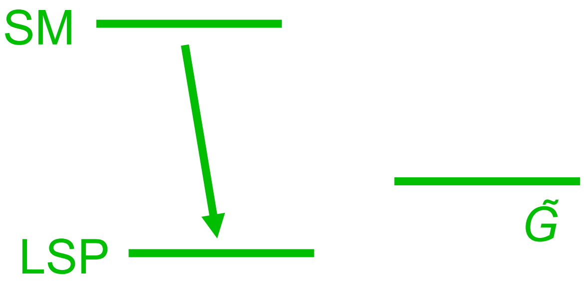
SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

- Consider gravitinos (also KK gravitons, axinos, quintessinos, …):
  spin 3/2, mass ~ M_W, couplings ~ M_W/M_*

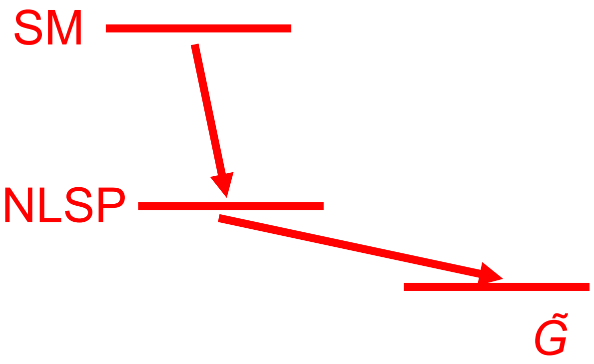
Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Roszkowski et al. (2004); …

- $\tilde{G}$ not LSP



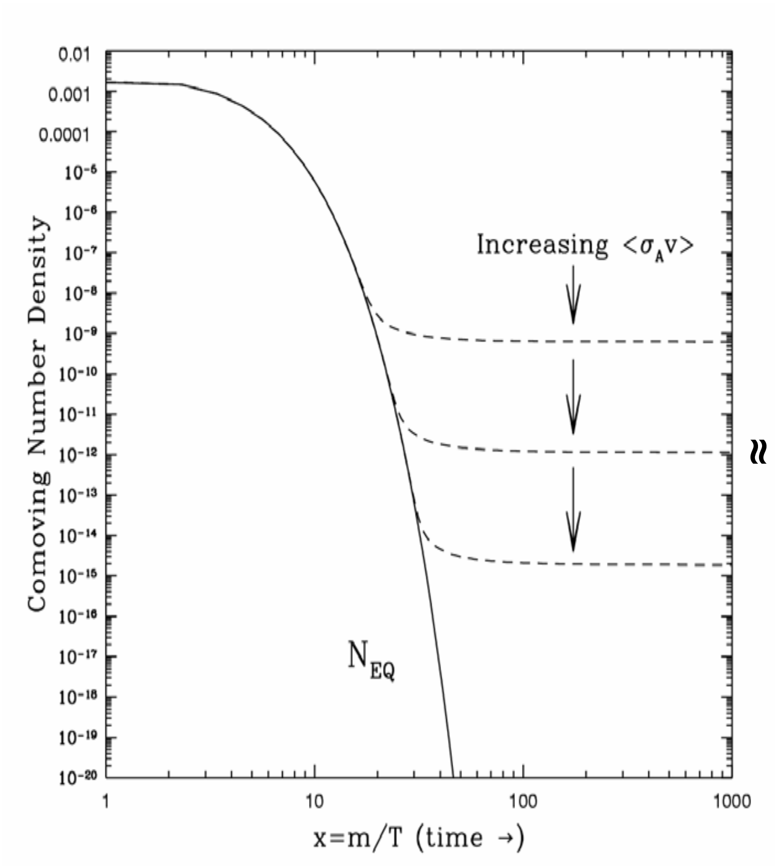
- Assumption of most of literature

- $\tilde{G}$ LSP



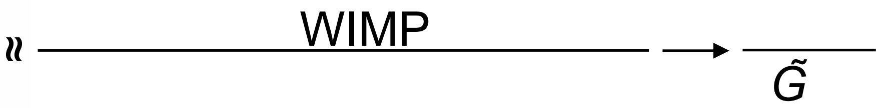
- Completely different cosmology and physics

SUPERWIMP RELICS



- Suppose gravitinos $\tilde{G}$ are the LSP.

- WIMPs freeze out as usual



- But then all WIMPs decay to gravitinos after

  M_{Pl}^2/M_W^3 ~ hours to month

Gravitinos naturally inherit the right density, but interact only gravitationally – they are superWIMPs, impossible to detect directly

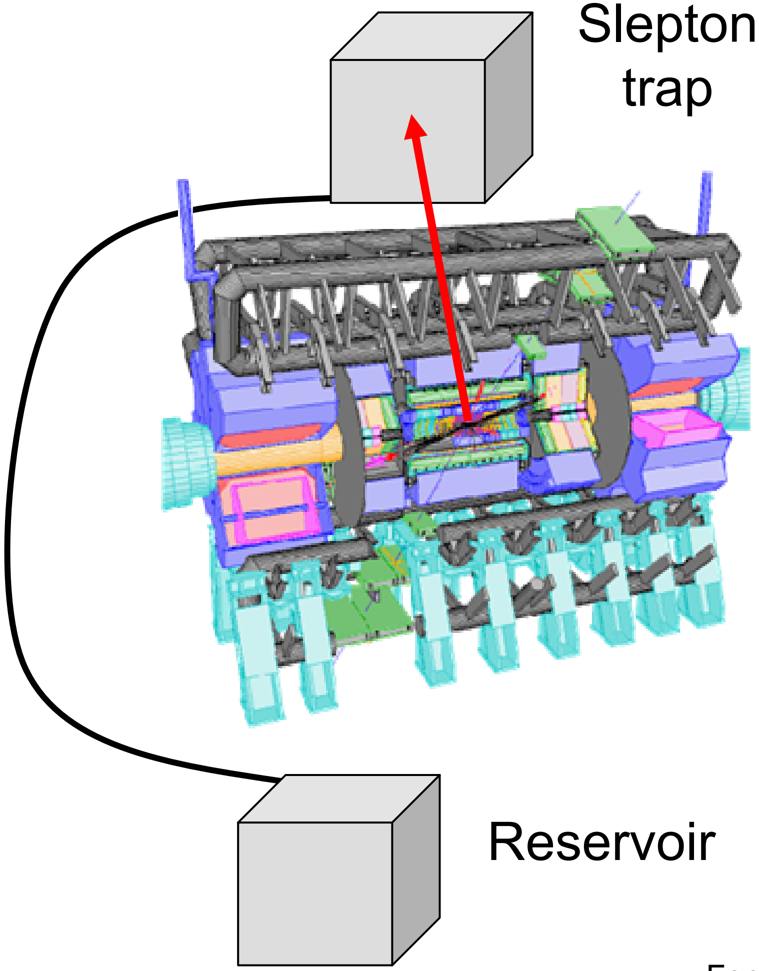
WORST CASE SCENARIO?

Looks bad – dark matter couplings suppressed by 10^{-16}

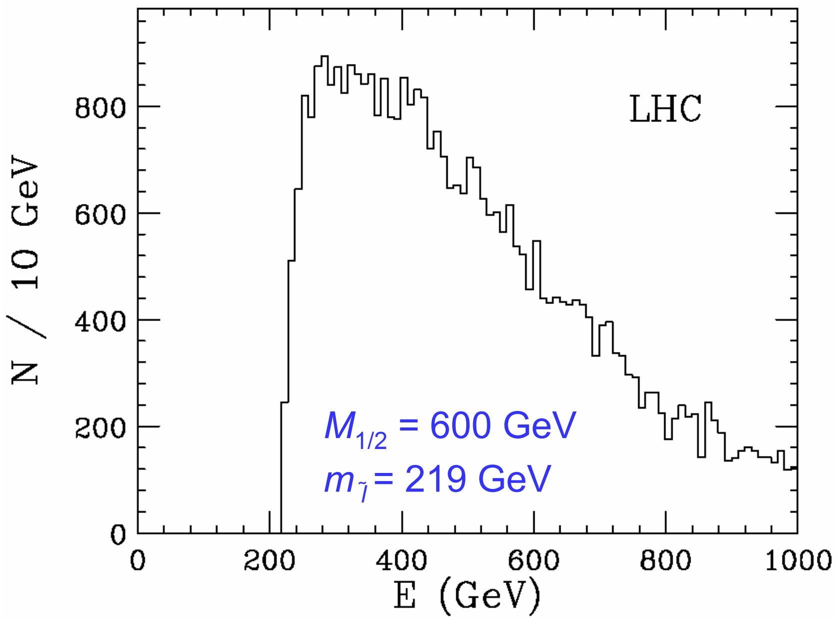
But, cosmology → decaying WIMPs are sleptons: heavy, charged, live ~ a month – can be trapped, then moved to a quiet environment to observe decays.

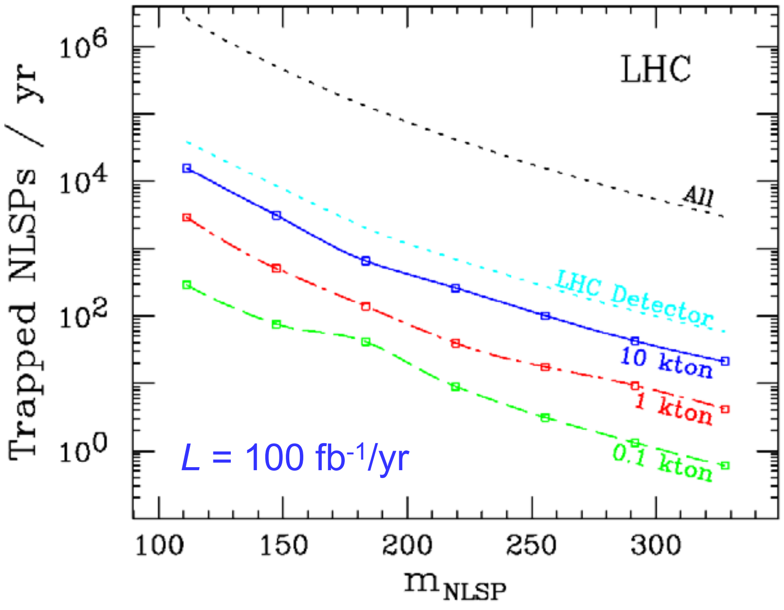
How many can be trapped?

Hamaguchi, Kuno, Nakaya, Nojiri (2004)
Feng, Smith (2004)
De Roeck et al. (2005)
Martyn (2006)



Large Hadron Collider

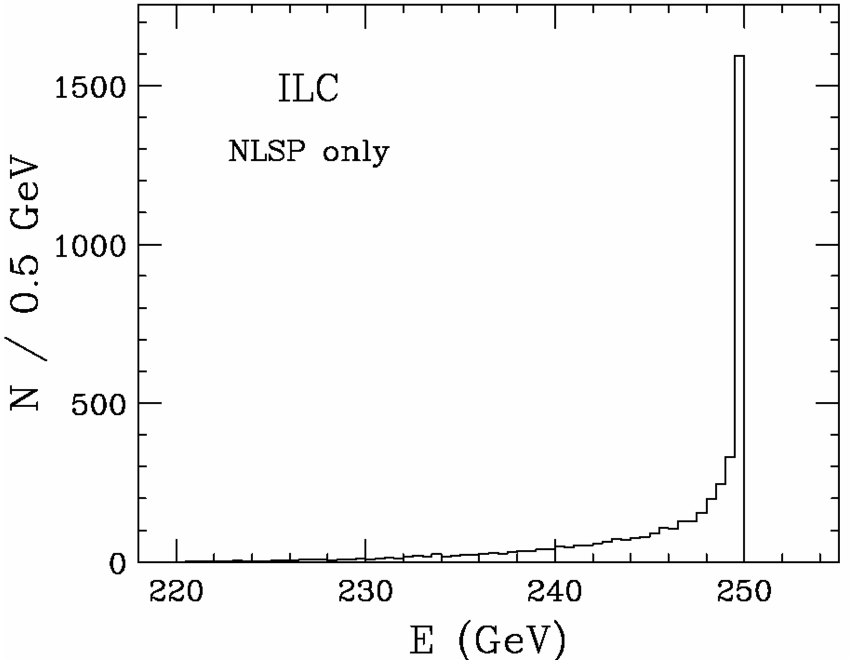


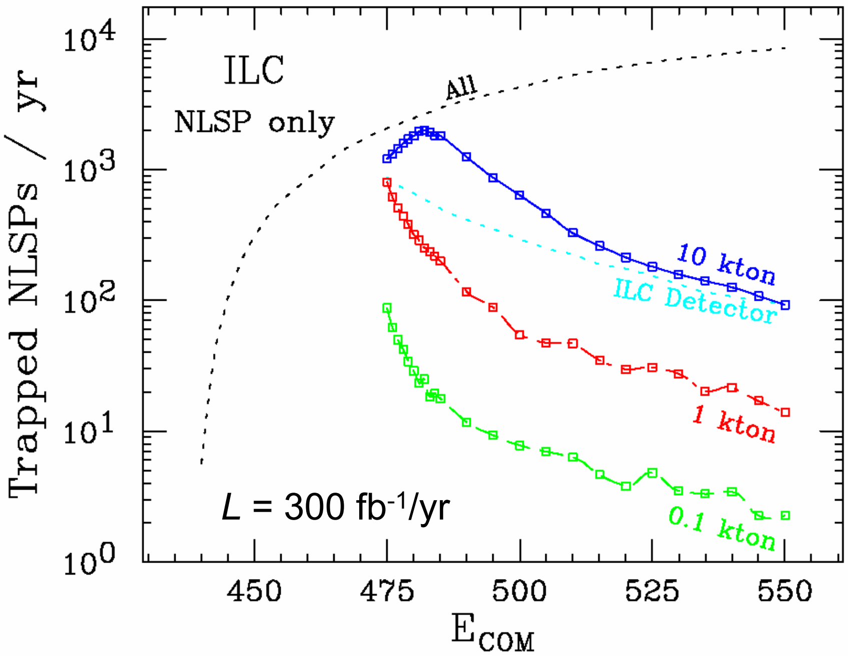


If squarks, gluinos light, many sleptons, but most are fast:
O(1)% are caught in 10 kton trap

International Linear Collider

$m_{\tilde{\tau}_R}$ 219.3 GeV } NLSP only





Novel use of tunable beam energy: adjust to produce slow sleptons, 75% are caught in 10 kton trap

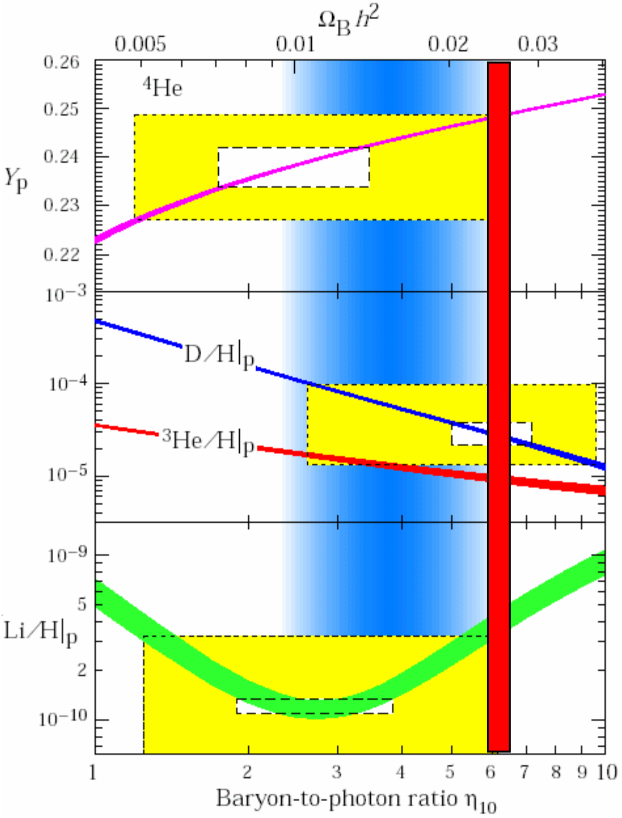
IMPLICATIONS FROM SLEPTON DECAYS

$$\Gamma(\tilde{\ell} \to \ell \tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{\ell}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\ell}}^2}\right]^4$$

- Measurement of Γ *and* E_l → $m_{\tilde{G}}$ *and* M_*
  - Probes gravity in a particle physics experiment!
  - Measurement of G_{Newton} 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
  - Early universe cosmology in the lab

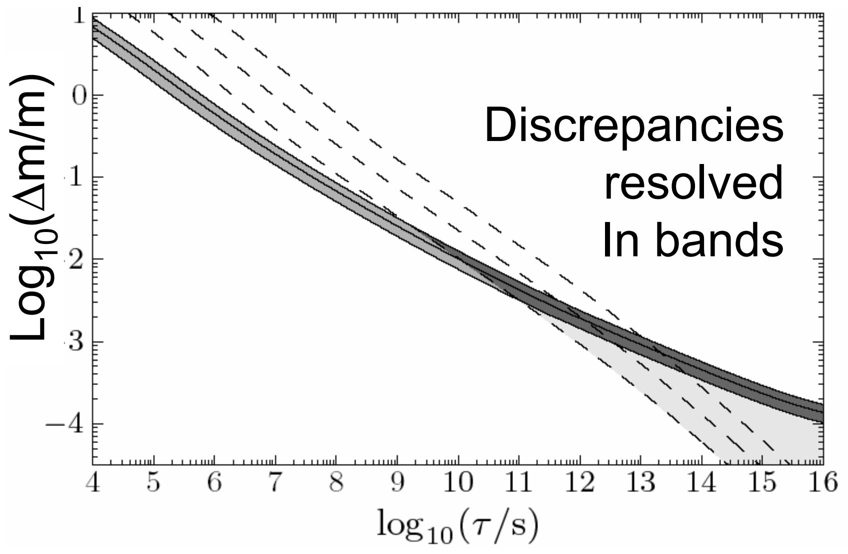
Resolve cosmological discrepancies?

BBN ^{7}Li problem:
Late decays can modify BBN



Fields, Sarkar, PDG (2002)

CDM is too cold:
Late decays warm up DM



Discrepancies
resolved
In bands

Lin, Huang, Zhang, Brandenberger (2001)
Sigurdson, Kamionkowski (2003)
Profumo, Sigurdson, Ullio, Kamionkowski (2004)
Kaplinghat (2005)
Cembranos, Takayama et al. (2005)
Bringmann, Borzumati, Ullio (2006)
…

CONCLUSIONS

- Cosmology now provides sharp problems that are among the most outstanding in basic science today.
- They require new particle physics, cannot be solved by cosmological tools alone.
- In many cases, the quantitative precision of ILC is essential to determine qualitative answers.