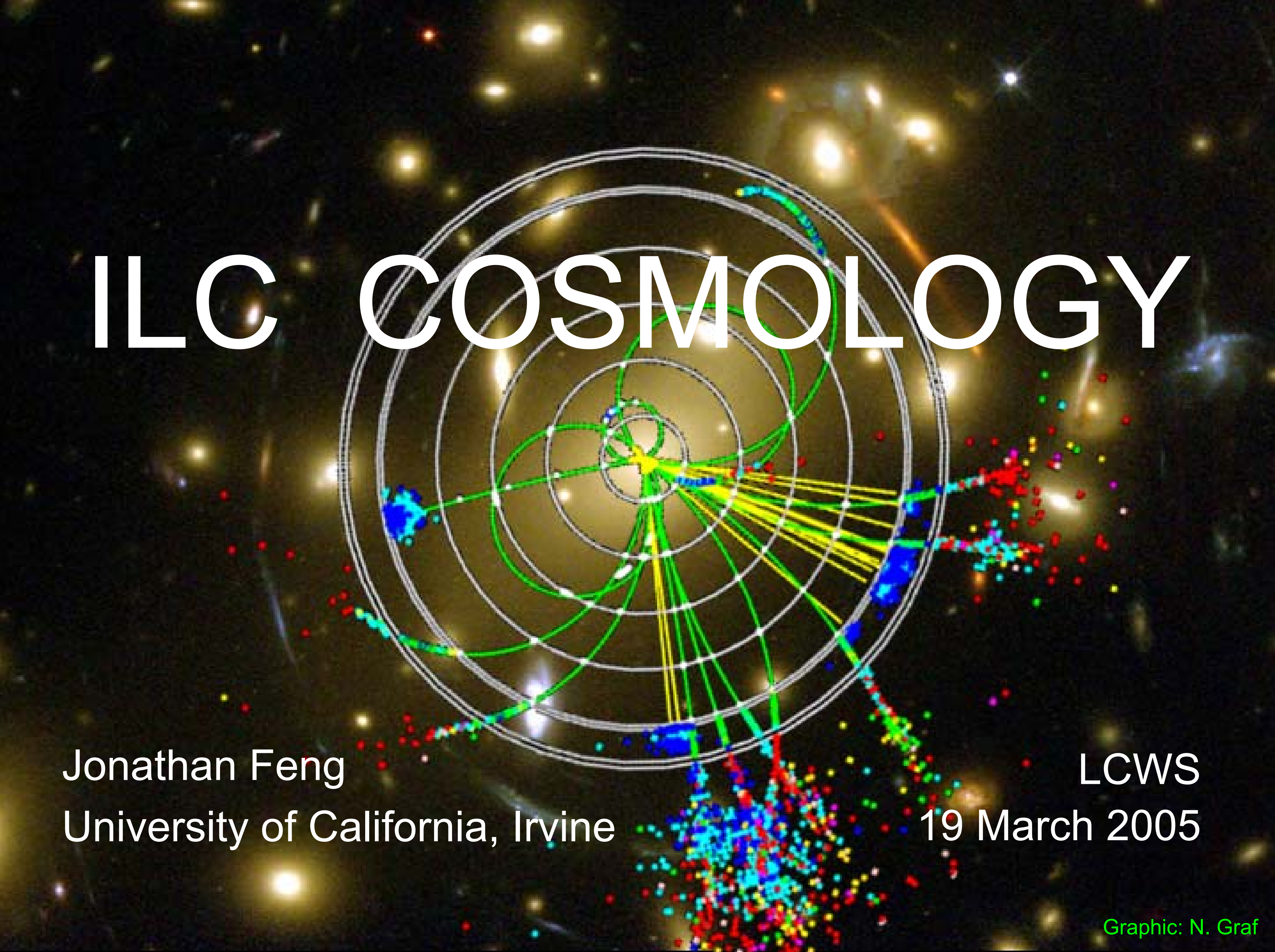


ILC COSMOLOGY

Jonathan Feng
University of California, Irvine

LCWS
19 March 2005

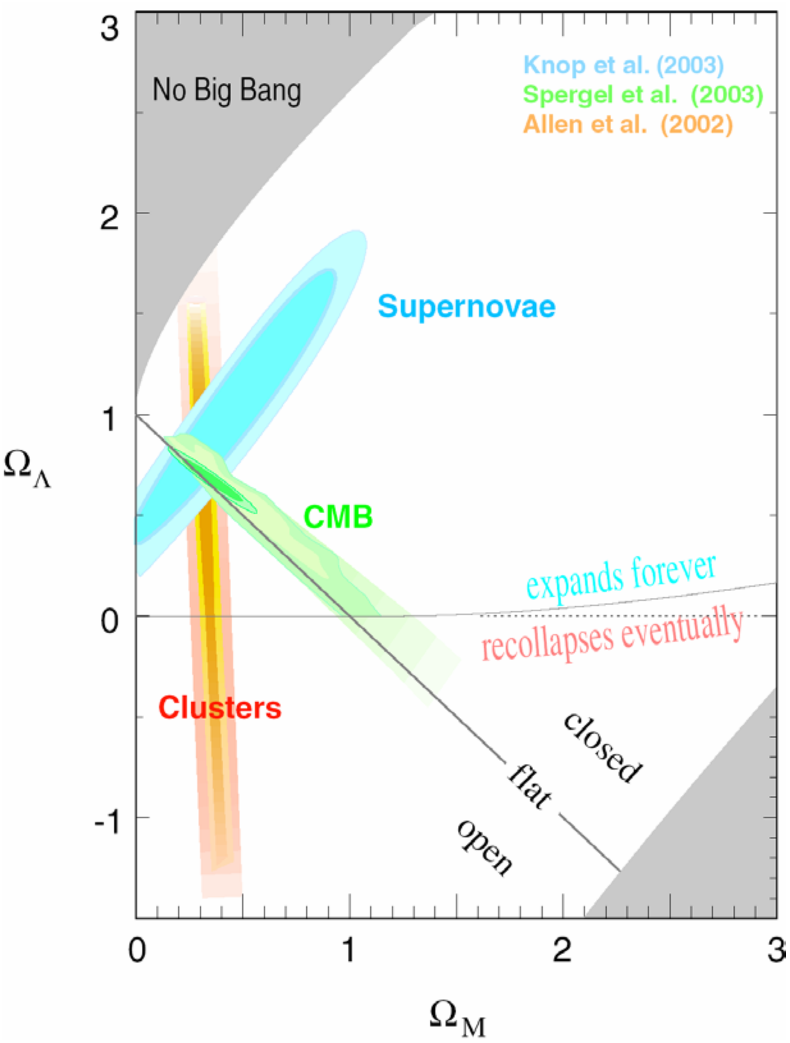
Graphic: N. Graf

COSMOLOGY NOW

We are living through a revolution in our understanding of the Universe on the largest scales

For the first time in history, we have a complete picture of the Universe

WHAT IS THE UNIVERSE MADE OF?



- Remarkable agreement

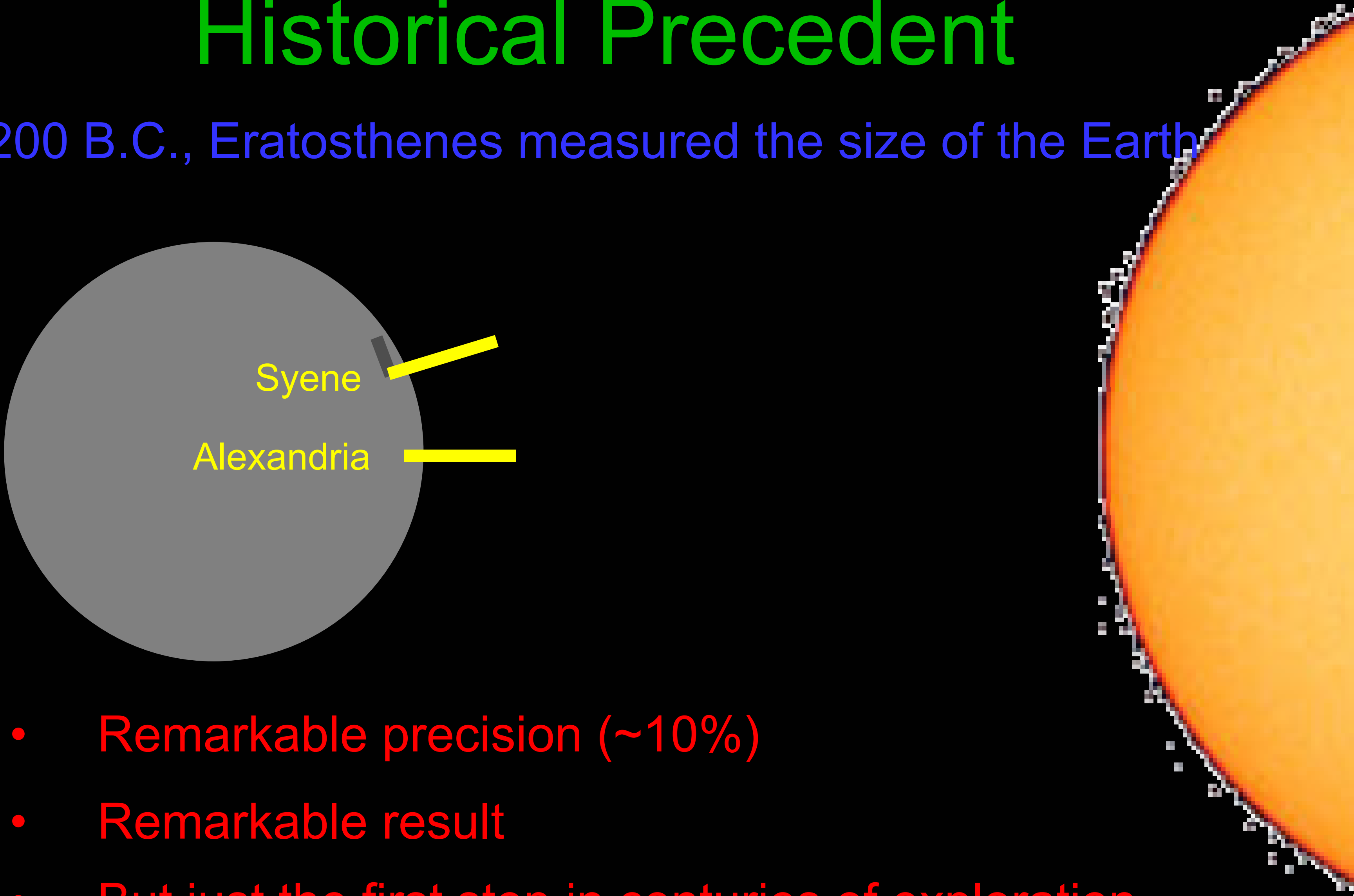
  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  [Baryons: 4% ± 0.4%
  Neutrinos: ~0.5%]

- Remarkable precision (~10%)

- Remarkable results

Historical Precedent

In 200 B.C., Eratosthenes measured the size of the Earth



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

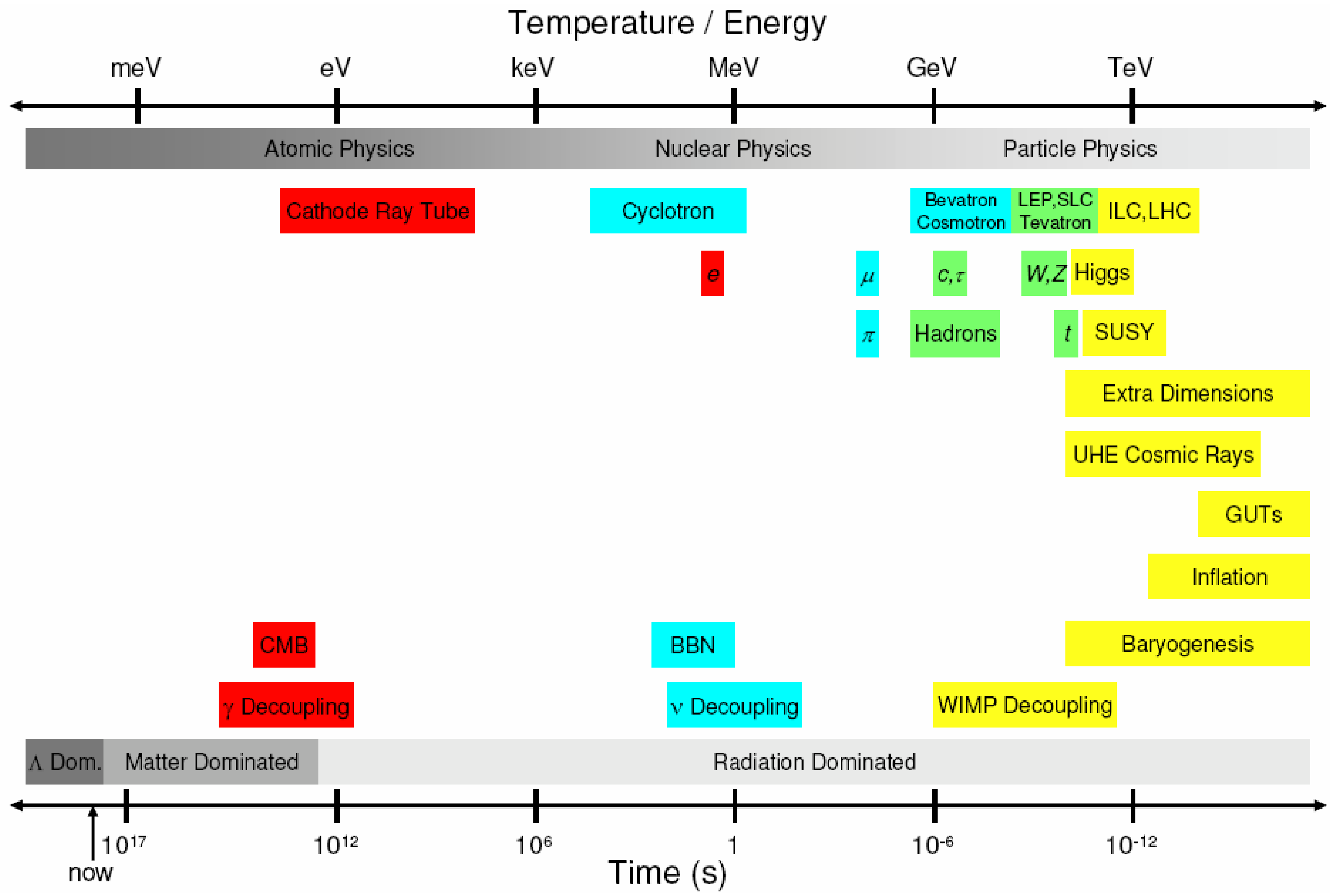
OUTSTANDING QUESTIONS

- Dark Matter: What is it? How is it distributed?
- Dark Energy: What is it? Why not $\Omega_\Lambda \sim 10^{120}$? Why not $\Omega_\Lambda = 0$? Does it evolve?
- Baryons: Why not $\Omega_B \approx 0$?
- UHE Cosmic Rays: What are they? Where do they come from?

…

What tools do we need to address these?

PARTICLE PHYSICS AT THE ENERGY FRONTIER



ALCPG COSMOLOGY SUBGROUP

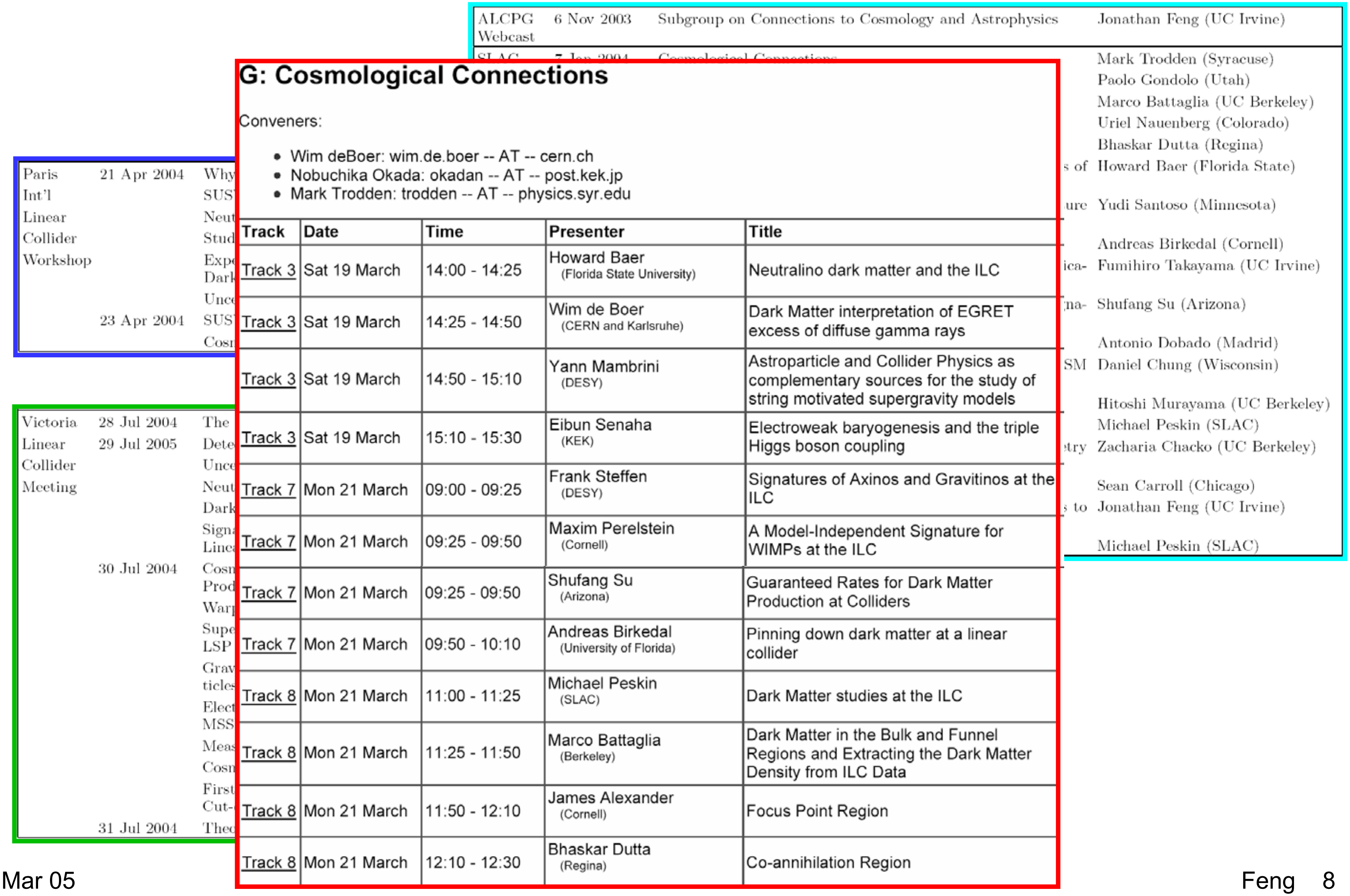
- Goals (Brau, Oreglia):
  - Identify cosmological questions most likely to be addressed by the ILC
  - Determine the role cosmology plays in highlighting specific scenarios for new physics at the ILC
  - Identify what insights the ILC can provide beyond those gained with other experiments and observatories

- Editors: Marco Battaglia, Jonathan Feng*, Norman Graf, Michael Peskin, Mark Trodden*

*co-conveners

- 30-50 contributors, international participation
  Preliminary results presented here

CONTRIBUTORS



G: Cosmological Connections

Conveners:

- Wim deBoer: wim.de.boer -- AT -- cern.ch
- Nobuchika Okada: okadan -- AT -- post.kek.jp
- Mark Trodden: trodden -- AT -- physics.syr.edu

Track	Date	Time	Presenter	Title
Track 3	Sat 19 March	14:00 - 14:25	Howard Baer (Florida State University)	Neutralino dark matter and the ILC
Track 3	Sat 19 March	14:25 - 14:50	Wim de Boer (CERN and Karlsruhe)	Dark Matter interpretation of EGRET excess of diffuse gamma rays
Track 3	Sat 19 March	14:50 - 15:10	Yann Mambrini (DESY)	Astroparticle and Collider Physics as complementary sources for the study of string motivated supergravity models
Track 3	Sat 19 March	15:10 - 15:30	Eibun Senaha (KEK)	Electroweak baryogenesis and the triple Higgs boson coupling
Track 7	Mon 21 March	09:00 - 09:25	Frank Steffen (DESY)	Signatures of Axinos and Gravitinos at the ILC
Track 7	Mon 21 March	09:25 - 09:50	Maxim Perelstein (Cornell)	A Model-Independent Signature for WIMPs at the ILC
Track 7	Mon 21 March	09:25 - 09:50	Shufang Su (Arizona)	Guaranteed Rates for Dark Matter Production at Colliders
Track 7	Mon 21 March	09:50 - 10:10	Andreas Birkedal (University of Florida)	Pinning down dark matter at a linear collider
Track 8	Mon 21 March	11:00 - 11:25	Michael Peskin (SLAC)	Dark Matter studies at the ILC
Track 8	Mon 21 March	11:25 - 11:50	Marco Battaglia (Berkeley)	Dark Matter in the Bulk and Funnel Regions and Extracting the Dark Matter Density from ILC Data
Track 8	Mon 21 March	11:50 - 12:10	James Alexander (Cornell)	Focus Point Region
Track 8	Mon 21 March	12:10 - 12:30	Bhaskar Dutta (Regina)	Co-annihilation Region

ALCPG Webcast | 6 Nov 2003 | Subgroup on Connections to Cosmology and Astrophysics | Jonathan Feng (UC Irvine)

Mark Trodden (Syracuse)
Paolo Gondolo (Utah)
Marco Battaglia (UC Berkeley)
Uriel Nauenberg (Colorado)
Bhaskar Dutta (Regina)
s of Howard Baer (Florida State)
ure Yudi Santoso (Minnesota)
Andreas Birkedal (Cornell)
ica- Fumihiro Takayama (UC Irvine)
na- Shufang Su (Arizona)
Antonio Dobado (Madrid)
SM Daniel Chung (Wisconsin)
Hitoshi Murayama (UC Berkeley)
Michael Peskin (SLAC)
try Zacharia Chacko (UC Berkeley)
Sean Carroll (Chicago)
s to Jonathan Feng (UC Irvine)
Michael Peskin (SLAC)

Paris Int'l Linear Collider Workshop
21 Apr 2004
23 Apr 2004

Victoria Linear Collider Meeting
28 Jul 2004
29 Jul 2005
30 Jul 2004
31 Jul 2004

DARK MATTER

- Requirements: cold, non-baryonic, gravitationally interacting

- Candidates: 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

THERMAL RELICS

(1) Initially, DM is in thermal equilibrium:

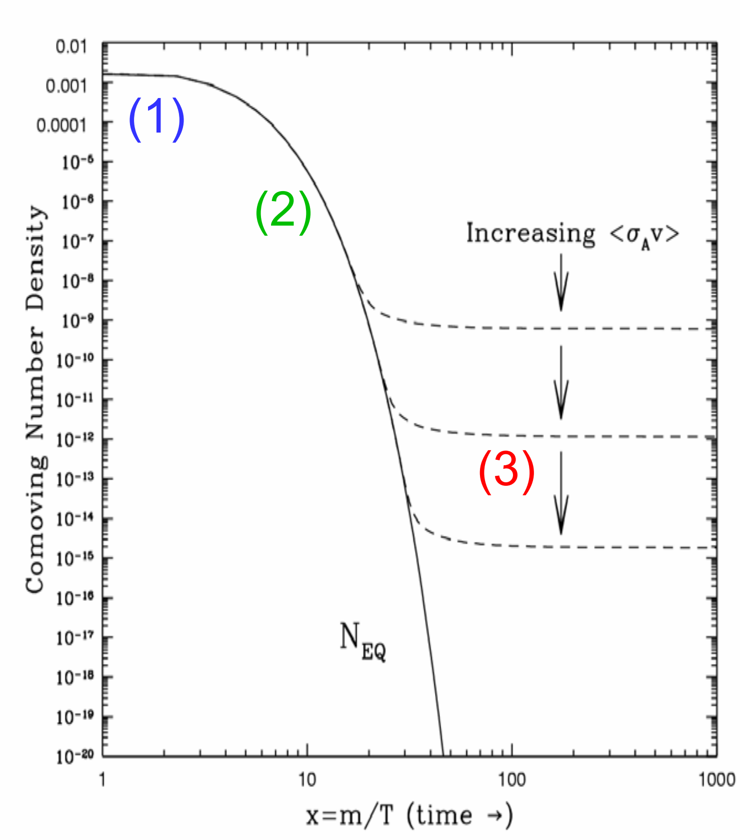
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

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

(3) χs “freeze out”:

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



$\Omega_{DM} \sim 0.1\ (\sigma_{weak} / \sigma_A)$ – just right for new weak scale particles!

STABILITY

- This assumes the new weak-scale particle is stable
- Problems (p decay, extra particles, large EW corrections)

↕

Discrete symmetry

↕

Stability

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

EXAMPLES

- Supersymmetry
  - Superpartners
  - R-parity
  - Neutralino χ with significant Ω_{DM}

Goldberg (1983)

- Universal Extra Dimensions
  - Kaluza-Klein partners
  - KK-parity
  - Lightest KK particle with significant Ω_{DM}

Appelquist, Cheng, Dobrescu (2000)

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

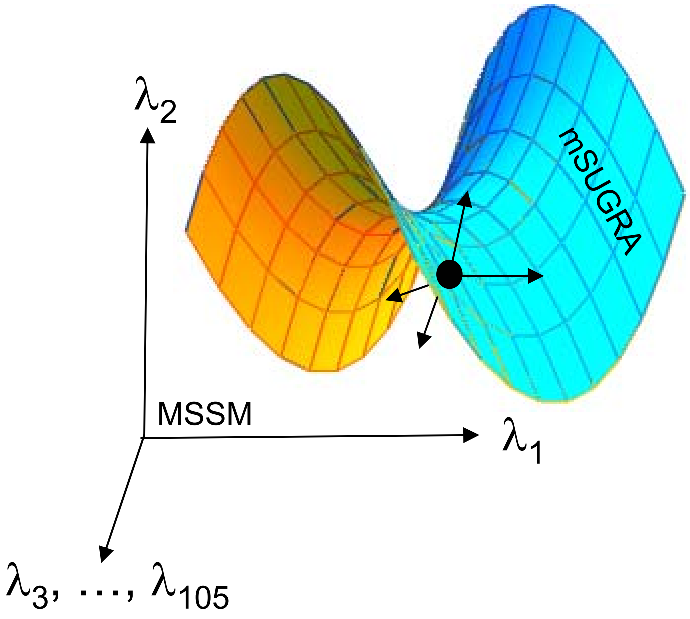
- Branes
  - Brane fluctuations
  - Brane-parity
  - Branons with significant Ω_{DM}

Cembranos, Dobado, Maroto (2003)

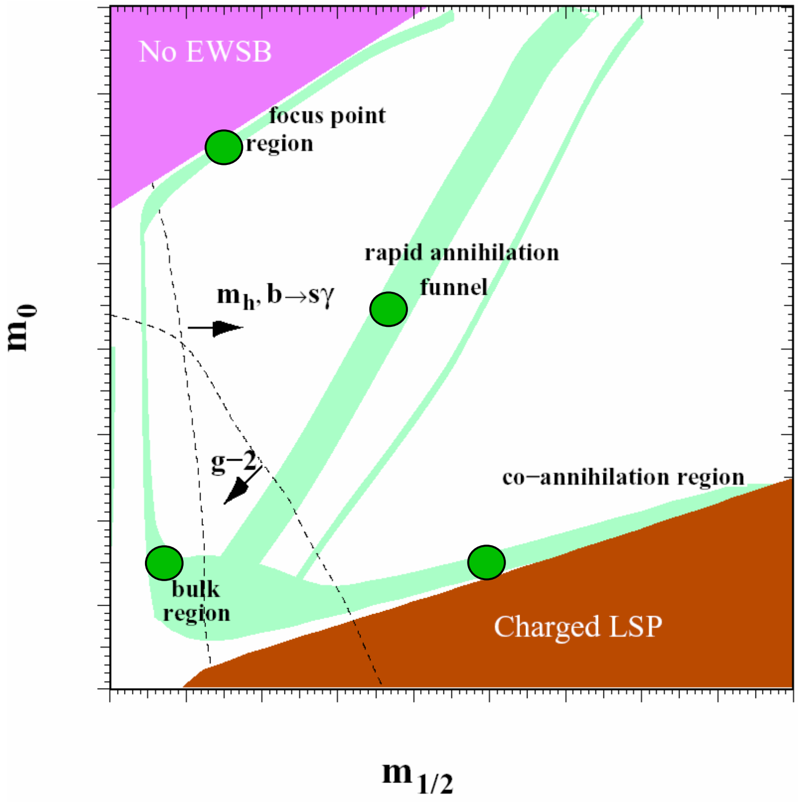
QUANTITATIVE ANALYSIS OF DM

The Approach:

- 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)

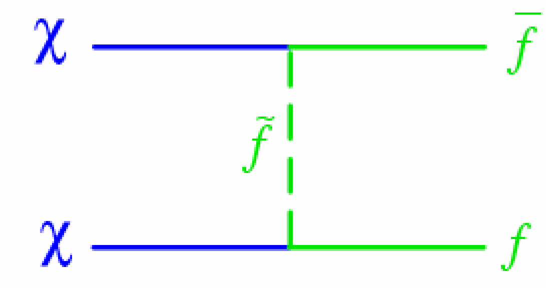
Choose 4 representative points for detailed study

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

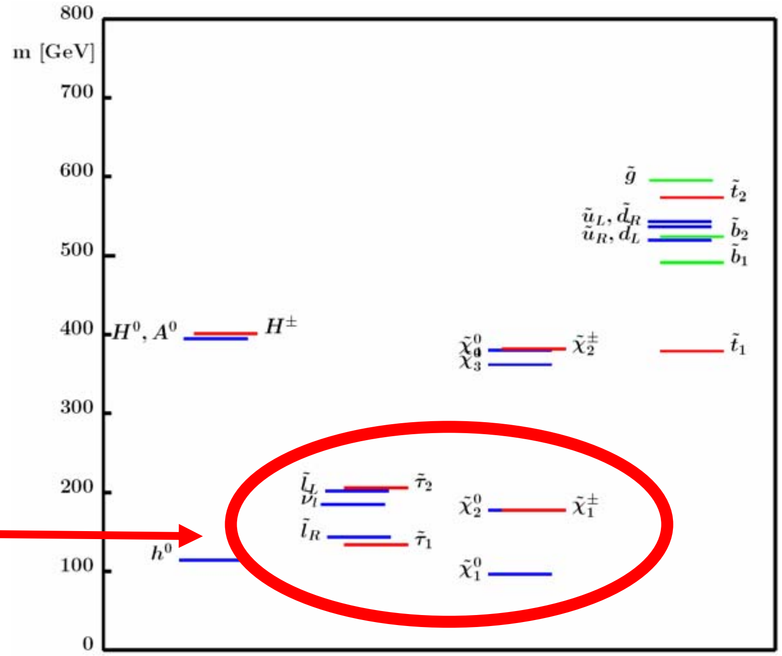
BULK REGION LCC1 (SPS1a)

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

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



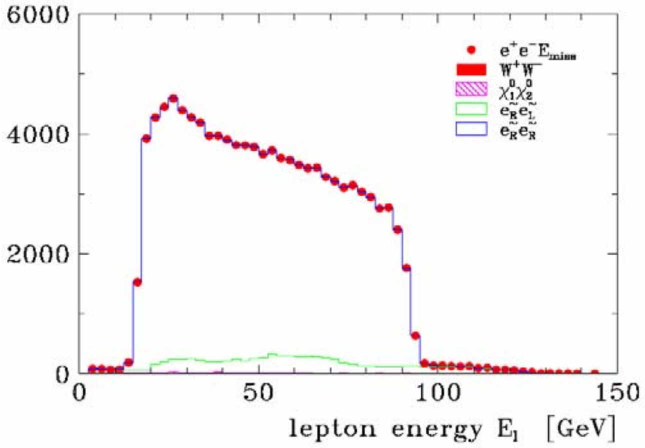
- Motivates SUSY with light $\chi, \tilde{l}$

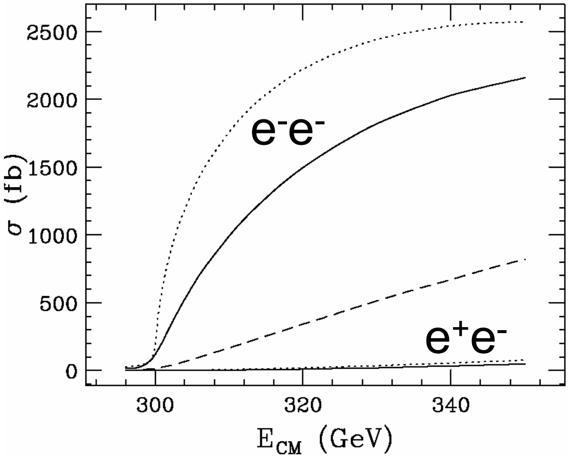


Allanach et al. (2002)

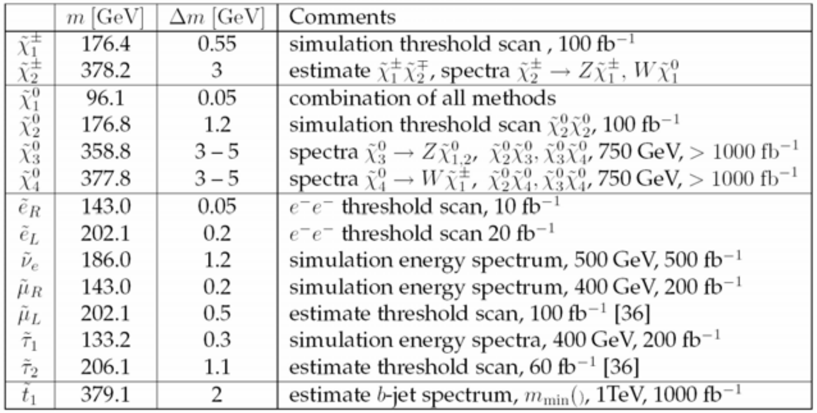
PRECISION MASSES

- Kinematic endpoints, threshold scans:
  - variable beam energy
  - e^- beam polarization
  - e^-e^- option





Feng, Peskin (2001)
Freitas, Manteuffel, Zerwas (2003)



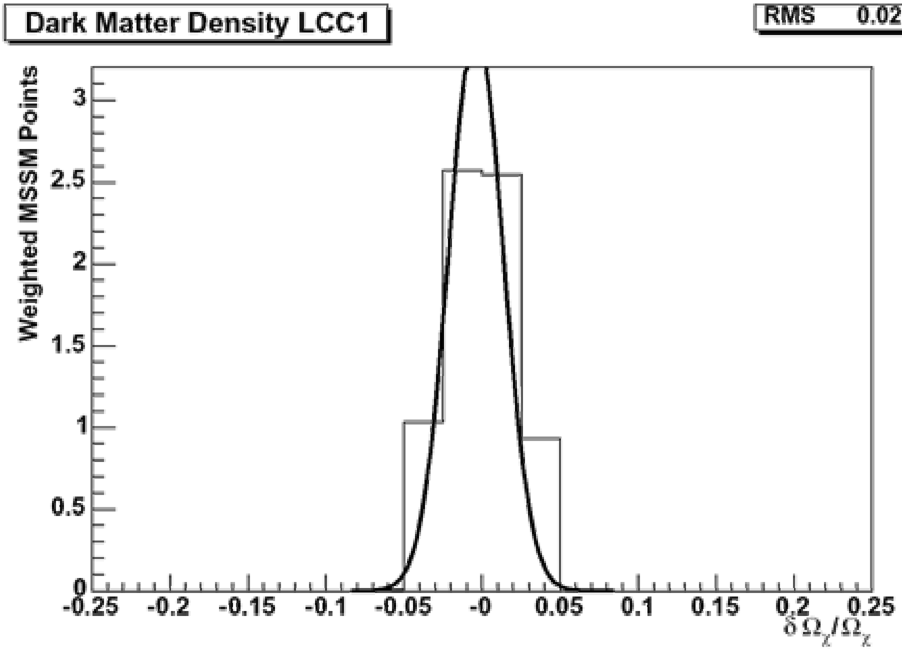
	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^\pm$	378.2	3	estimate $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$, spectra $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm, W\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	176.8	1.2	simulation threshold scan $\tilde{\chi}_2^0\tilde{\chi}_2^0$, 100 fb^{-1}
$\tilde{\chi}_3^0$	358.8	3 – 5	spectra $\tilde{\chi}_3^0 \to Z\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, > 1000 fb^{-1}
$\tilde{\chi}_4^0$	377.8	3 – 5	spectra $\tilde{\chi}_4^0 \to W\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0\tilde{\chi}_4^0$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$, 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}

Weiglein, Martyn et al. (2004)

- Must also verify insensitivity to all other parameters

BULK RESULTS

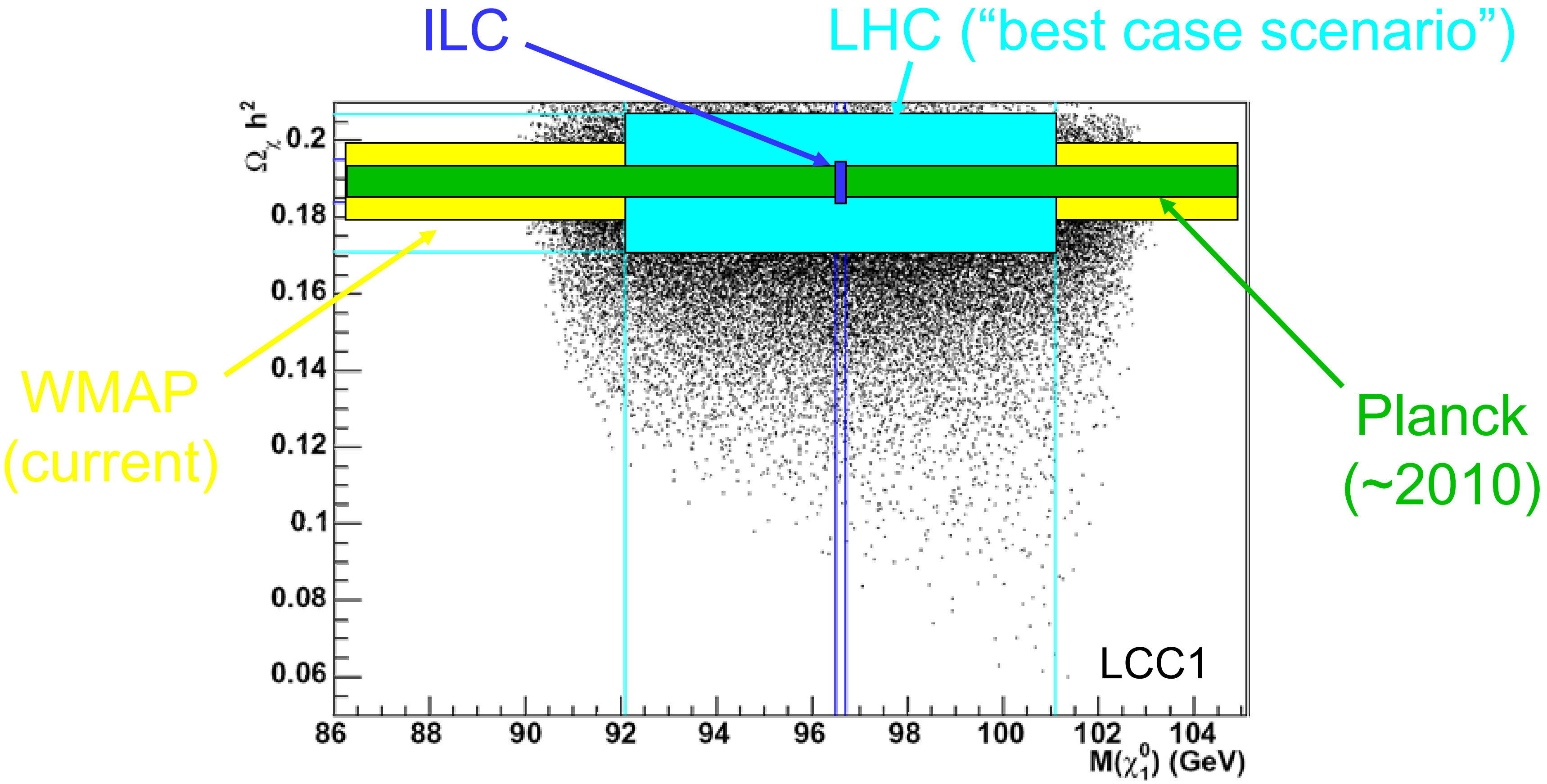
- Scan over ~20 most relevant parameters
- Weight each point by Gaussian distribution for each observable
- ~50K scan points



Battaglia (2005)

- (Preliminary) result: $\Delta\Omega_\chi/\Omega_\chi$ = 2.2% ($\Delta\Omega_\chi h^2$ = 0.0026)

RELIC DENSITY DETERMINATIONS



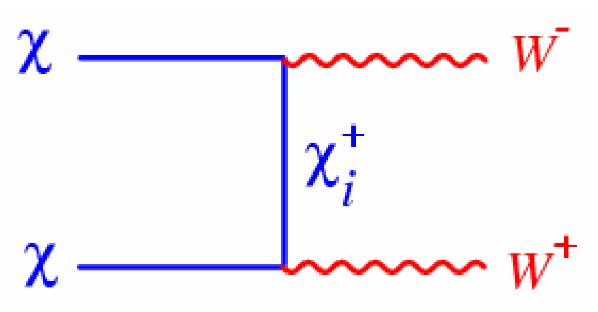
Parts per mille agreement for Ω_χ → discovery of dark matter

FOCUS POINT REGION LCC2

$m_0, M_{1/2}, A_0, \tan\beta = 3280, 300, 0, 10$ [$\mu>0$, $m_{3/2}>m_{LSP}$]

- Correct relic density obtained if χ is mixed, has significant Higgsino component to enhance

Feng, Matchev, Wilczek (2000)



$$\mathcal{M}_N = \begin{pmatrix} M_1\cos^2_W + M_2\sin^2_W & (M_2-M_1)\sin_W\cos_W & 0 & 0 \\ (M_2-M_1)\sin_W\cos_W & M_1\sin^2_W + M_2\cos^2_W & m_Z & 0 \\ 0 & m_Z & \mu\sin 2\beta & -\mu\cos 2\beta \\ 0 & 0 & -\mu\cos 2\beta & -\mu\sin 2\beta \end{pmatrix}$$

Gauginos

Higgsinos

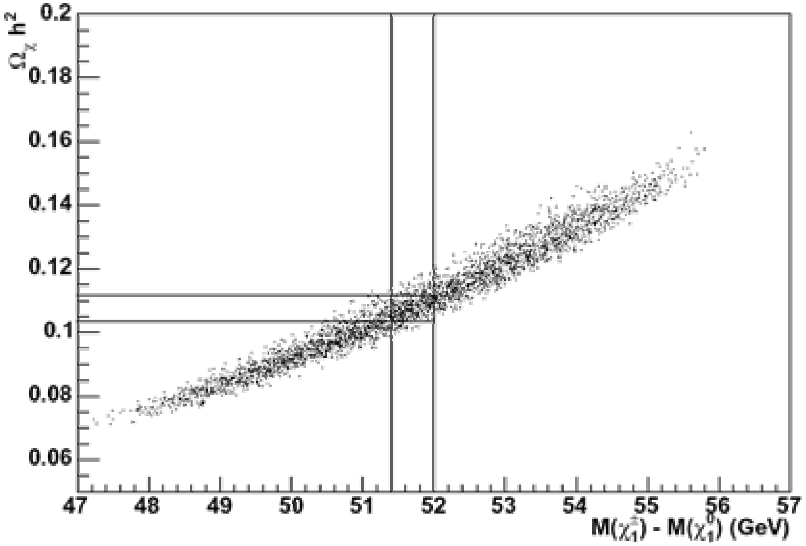
$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2}m_W\cos\beta \\ \sqrt{2}m_W\sin\beta & \mu \end{pmatrix}$$

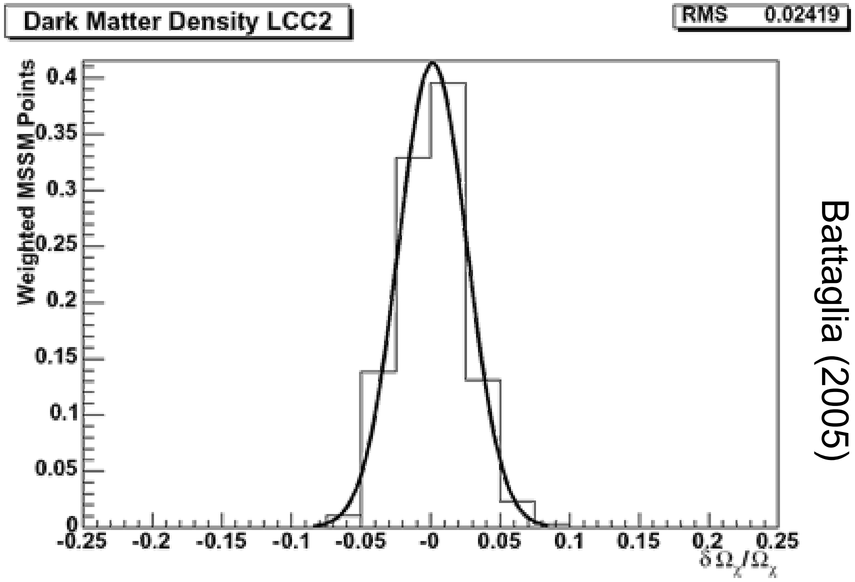
- Motivates SUSY with light neutralinos, charginos

FOCUS POINT RESULTS

- Ω_χ sensitive to Higgsino mixing, chargino-neutralino degeneracy

Alexander, Birkedal, Ecklund, Matchev et al. (2005)

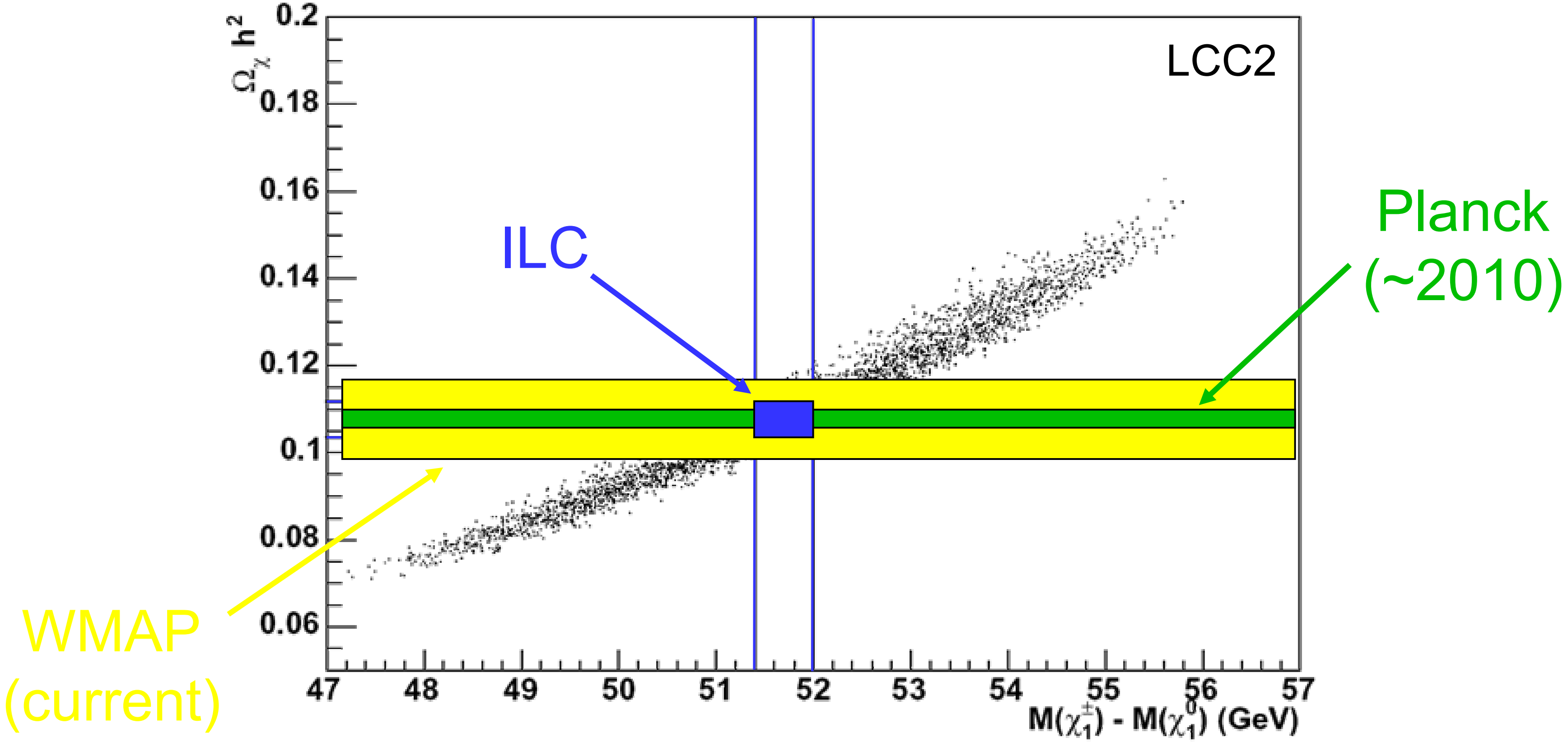




Battaglia (2005)

(Preliminary) result: $\Delta\Omega_\chi/\Omega_\chi$ = 2.4% ($\Delta\Omega_\chi h^2$ = 0.0029)

RELIC DENSITY DETERMINATIONS



ILC

Planck (~2010)

WMAP (current)

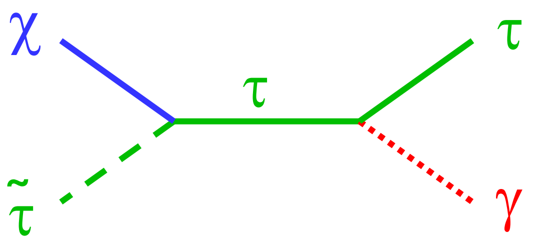
Parts per mille agreement for Ω_χ → discovery of dark matter

CO-ANNIHILATION REGION LCC3

$m_0, M_{1/2}, A_0, \tan\beta = 210, 360, 0, 40$ [$\mu>0, m_{3/2}>m_{LSP}$]

- If other superpartners are nearly degenerate with the χ LSP, they can help it annihilate

Griest, Seckel (1986)



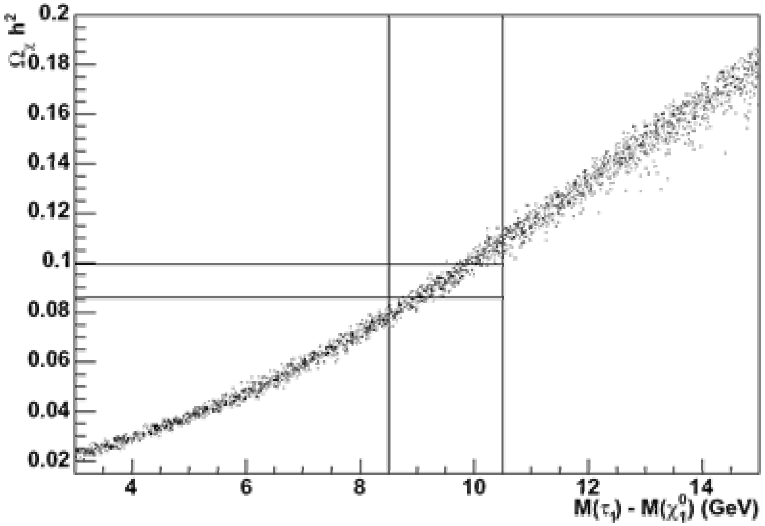
- Requires similar $e^{-m/T}$ for χ and $\tilde{\tau}$, so (roughly)

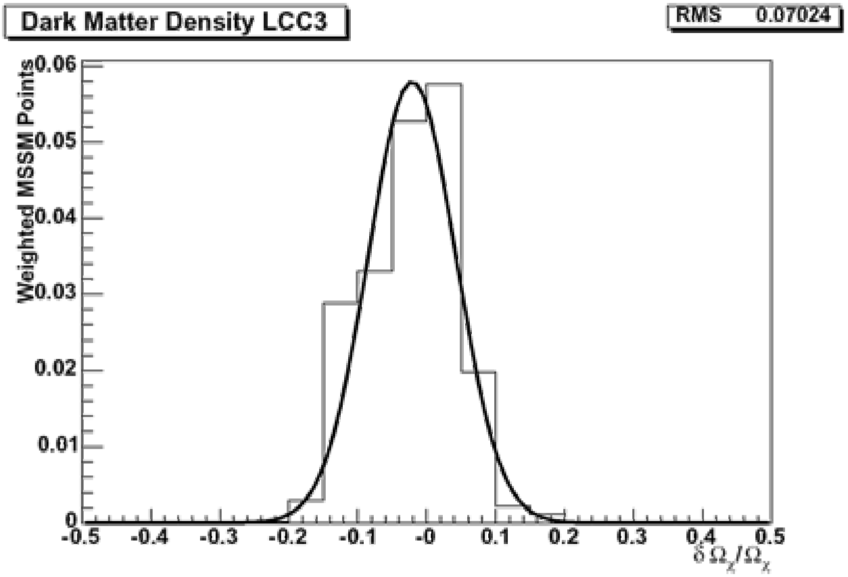
$$\Delta m < T \sim m_\chi/25$$

- Motivates SUSY with $\tilde{\tau} \rightarrow \tau\chi$ with Δm ~ few GeV

CO-ANNIHILATION RESULTS

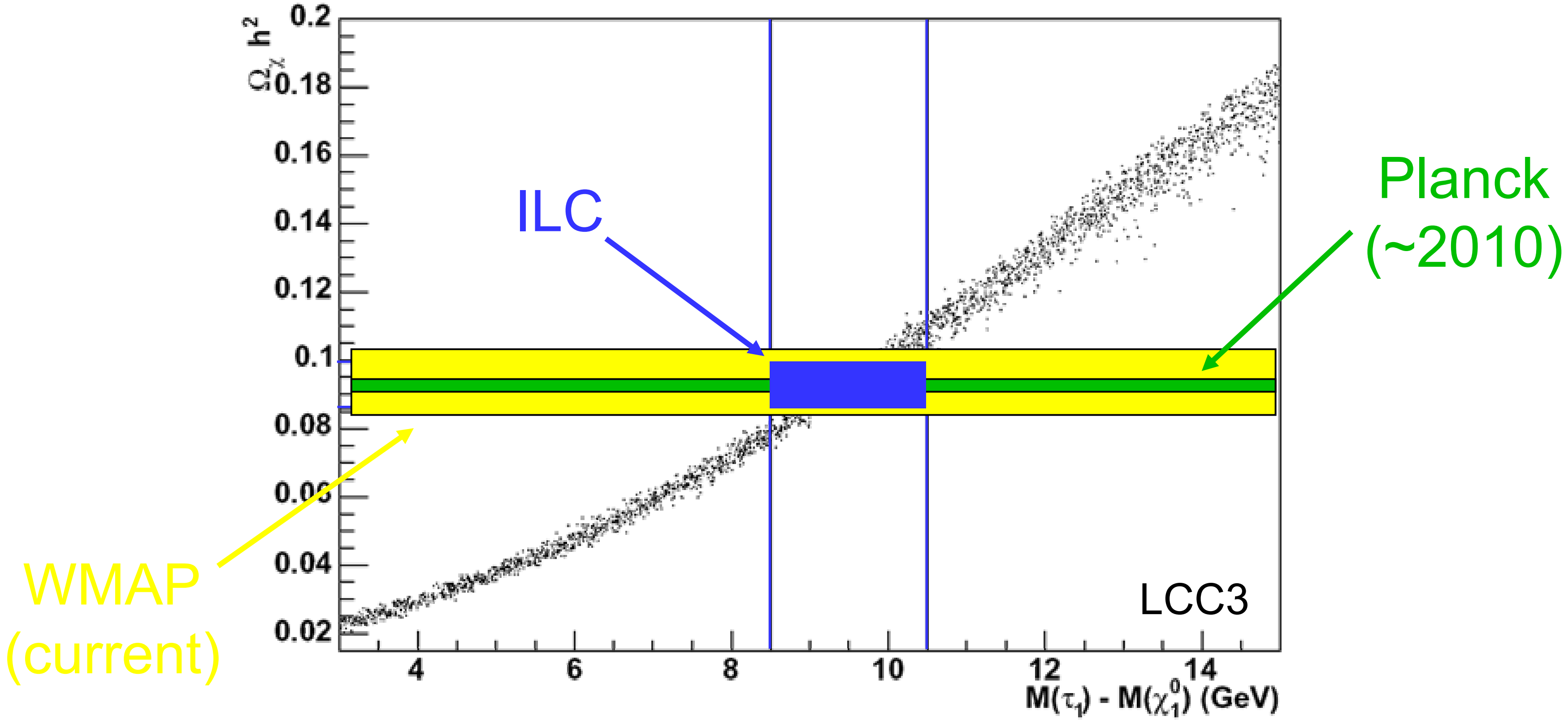
Dutta, Kamon; Nauenberg et al.; Battaglia (2005)





(Preliminary) result: $\Delta\Omega_\chi/\Omega_\chi$ = 7.0% ($\Delta\Omega_\chi h^2$ = 0.0084)

RELIC DENSITY DETERMINATIONS



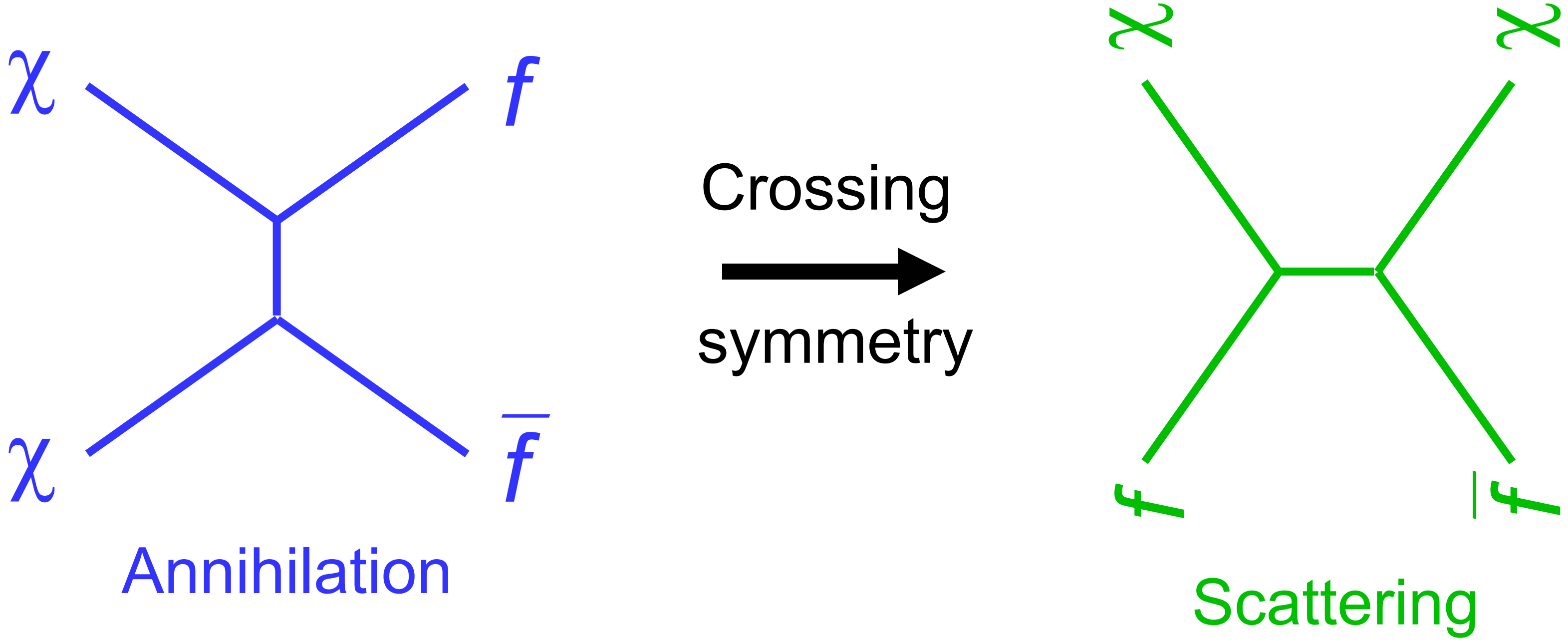
ILC

Planck (~2010)

WMAP (current)

% level agreement for Ω_χ → discovery of dark matter

IMPLICATIONS FOR ASTROPARTICLE PHYSICS

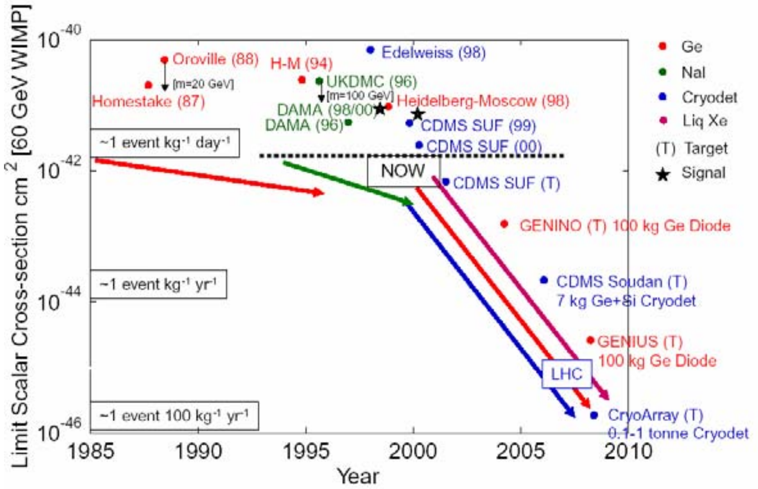


Correct relic density → Efficient annihilation then

→ Efficient scattering now

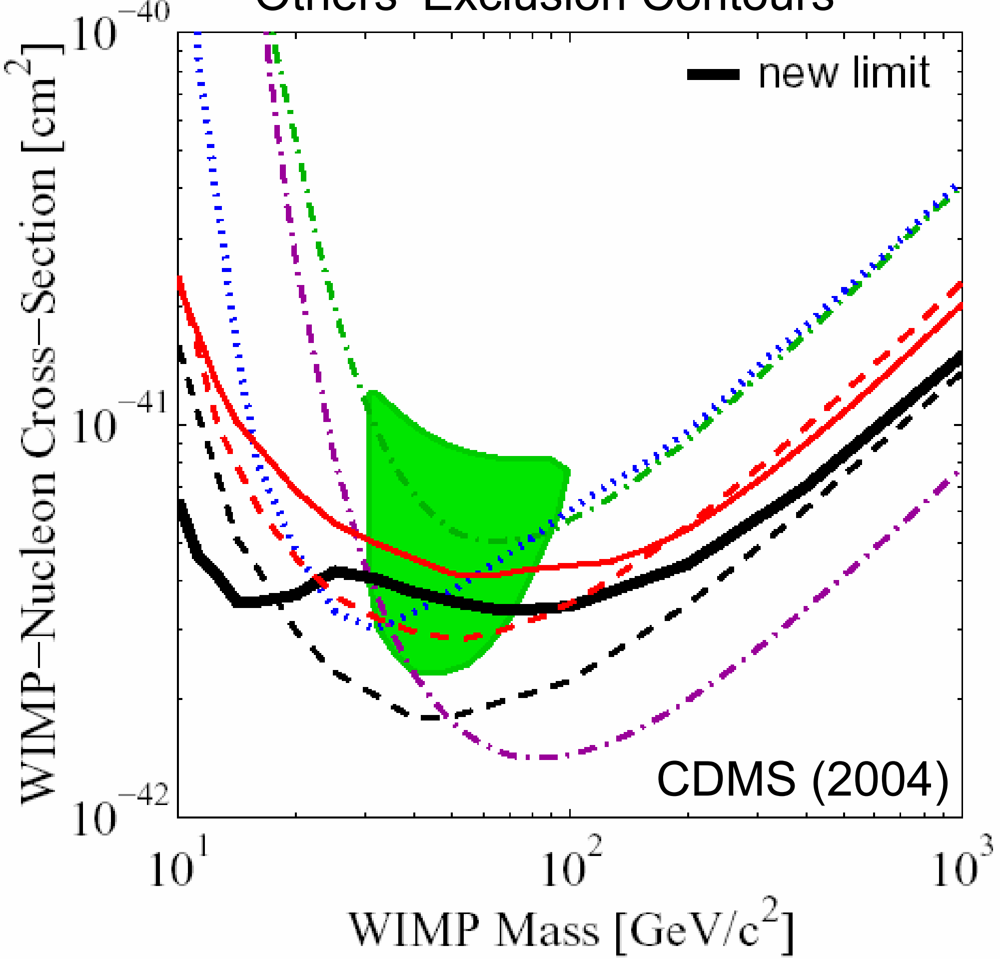
→ Efficient annihilation now

Direct Detection



Gaitskell (2001)

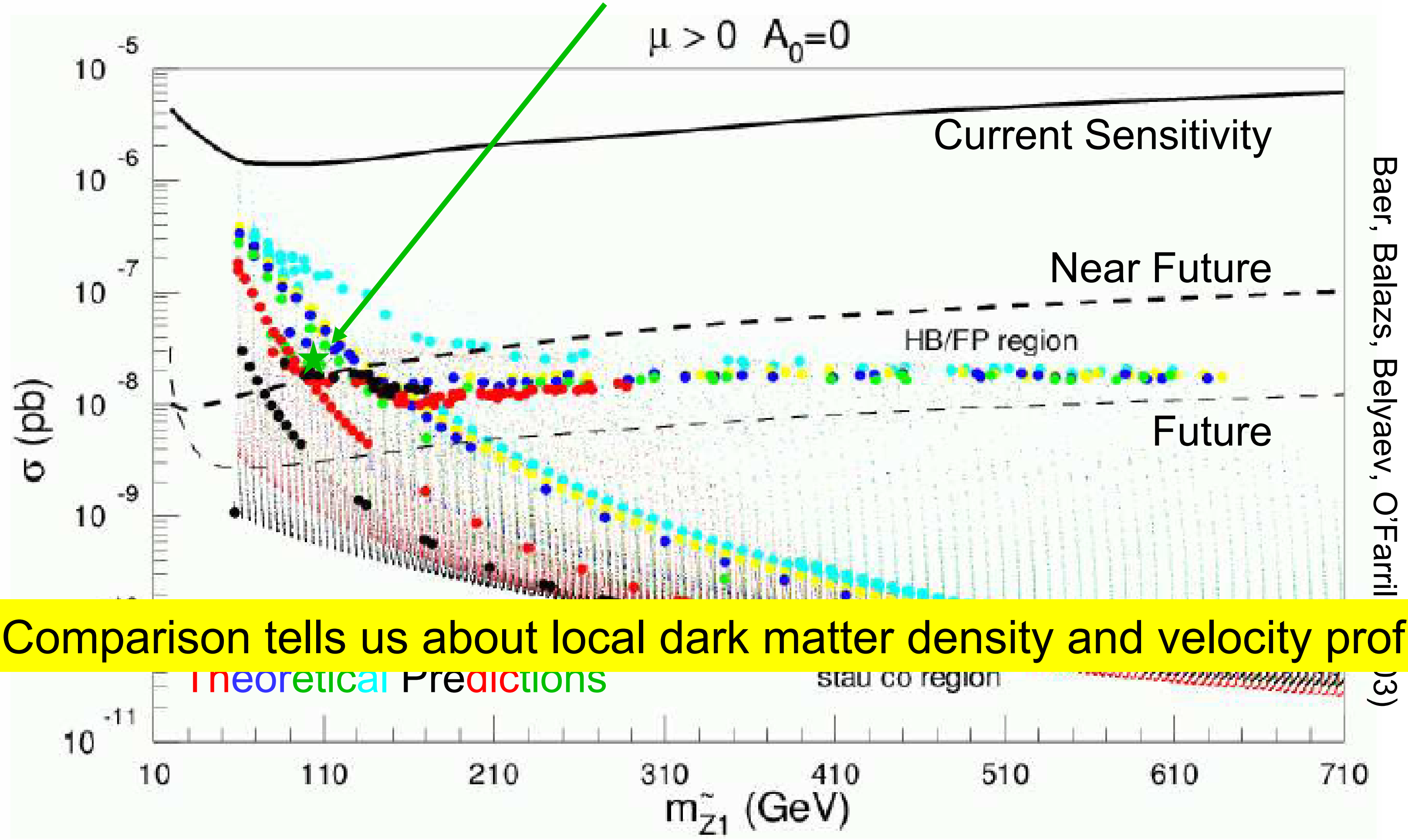
DAMA Signal and
Others' Exclusion Contours



CDMS (2004)

ILC IMPLICATIONS

LCC2 → m < 1 GeV, $\Delta\sigma/\sigma$ < 10%



Baer, Balazs, Belyaev, O'Farril

3)

Comparison tells us about local dark matter density and velocity profiles

INDIRECT DETECTION

Dark Matter Madlibs!

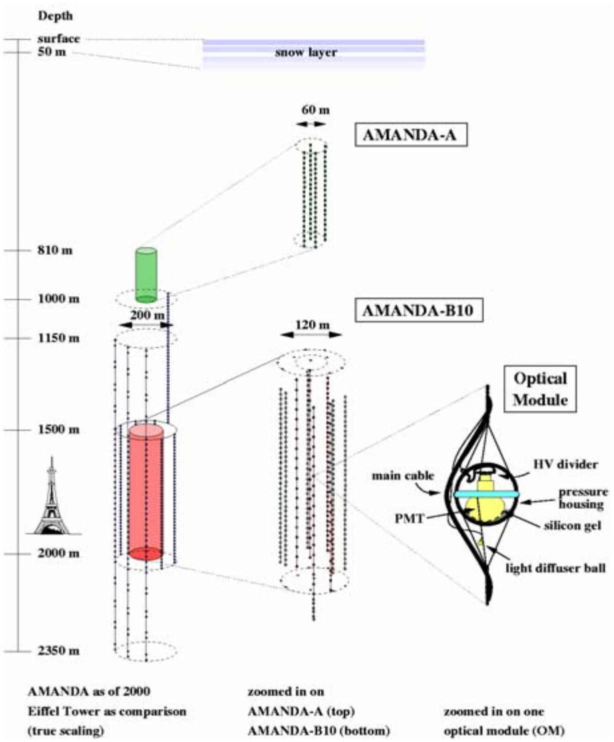
Dark matter annihilates in ____________________ to
a place

_____________ , which are detected by ________________ .
particles an experiment

Dark Matter annihilates in center of the Sun to
a place

neutrinos , which are detected by AMANDA, IceCube .
some particles an experiment

- Comparison with colliders constrains dark matter density in the Sun, capture rates



AMANDA in the Antarctic Ice

Dark Matter annihilates in __the galactic center__ to
a place

__photons__ , which are detected by _GLAST, HESS, …_ .
some particles an experiment

Comparison with colliders constrains DM density at the center of the galaxy

Dark Matter annihilates in ______the halo______ to
a place

__positrons__ , which are detected by _AMS on the ISS_ .
some particles an experiment

- Comparison with colliders constrains dark matter density profiles in the halo

ASTROPHYSICS VIEWPOINT:
ILC ELIMINATES PARTICLE PHYSICS UNCERTAINTIES,
ALLOWS ONE TO DO REAL ASTROPHYSICS

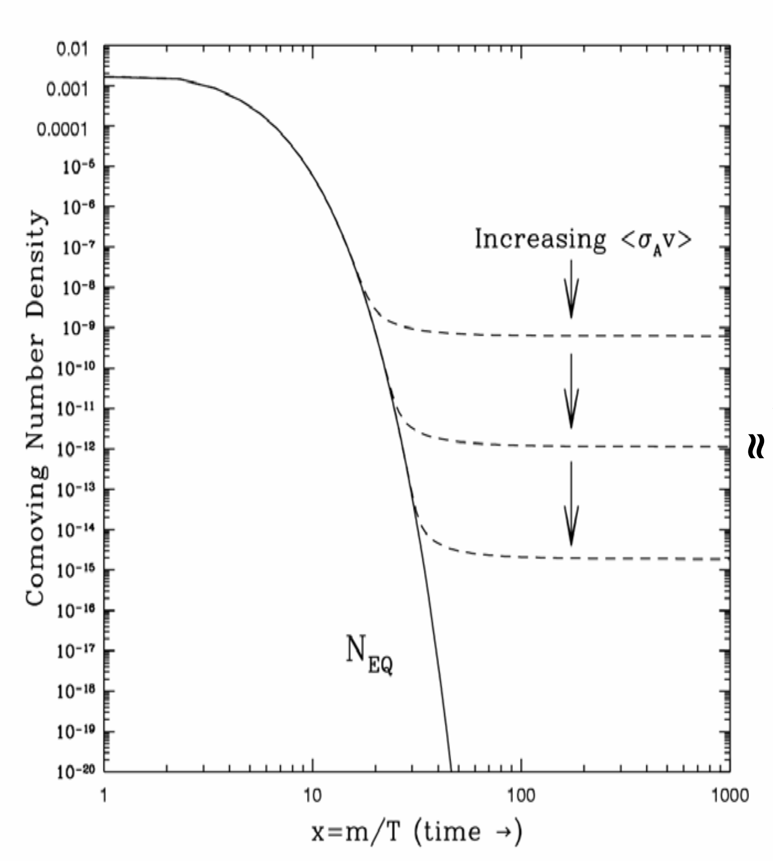
ALTERNATIVE DARK MATTER

- All of these signals rely on DM having electroweak interactions. Is this required?
- No – the only required DM interactions are gravitational (much weaker than electroweak).
- But the relic density argument strongly prefers weak interactions.

Is there an exception to this rule?

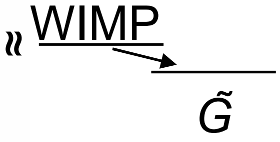
SUPERWIMPS

Feng, Rajaraman, Takayama (2003)



- Consider SUSY again:

  Gravitons → gravitinos $\tilde{G}$
- What if the $\tilde{G}$ is the lightest superpartner?



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

- A month passes…then all WIMPs decay to gravitinos – a completely natural scenario with long decay times

Gravitinos naturally inherit the right density, but they interact only gravitationally – they are “superWIMPs”

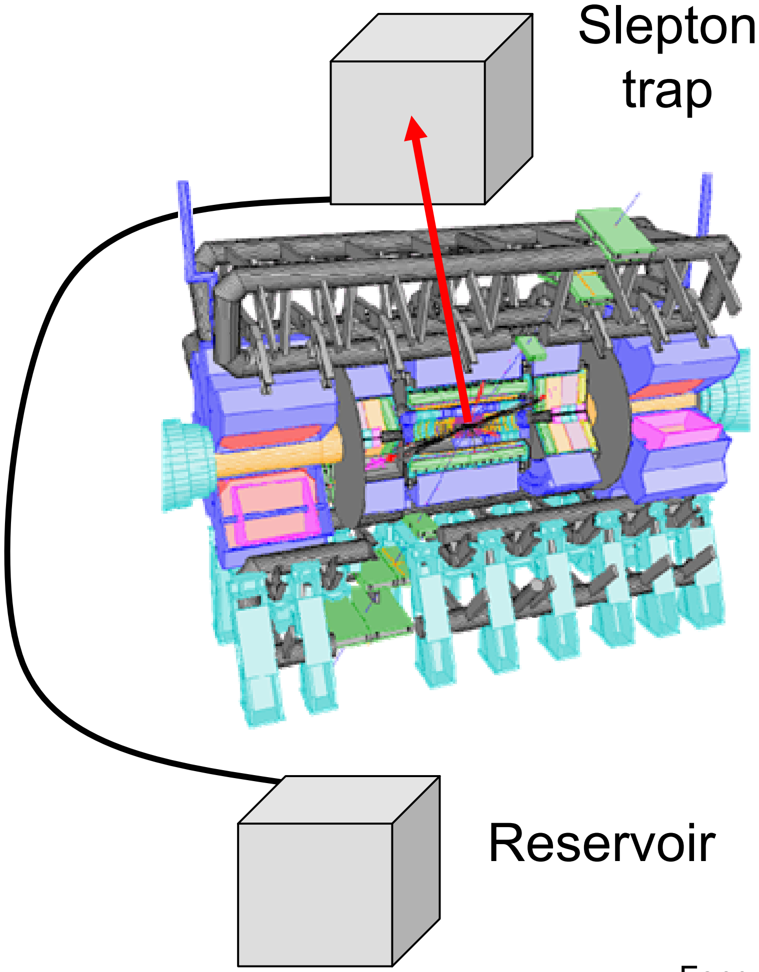
WORST CASE SCENARIO?

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

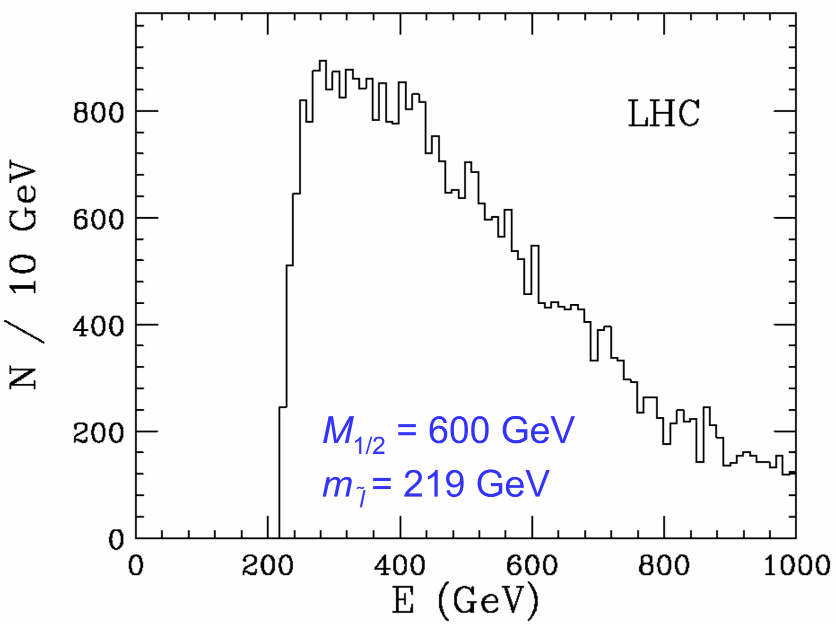
But, cosmology → decaying WIMPs are sleptons: heavy, charged, live ~ a month – can be trapped, then moved to a quiet environment to observe decays.

How many can be trapped?

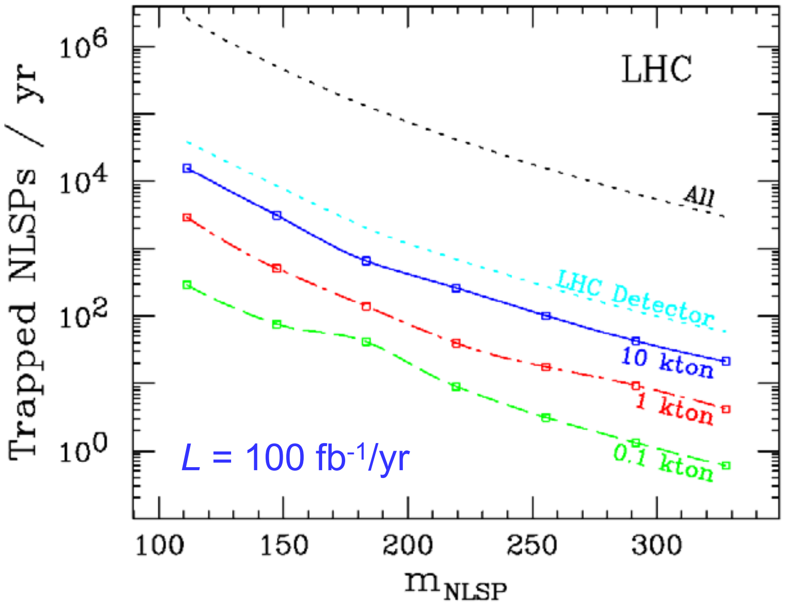
Hamaguchi, Kuno, Nakaya, Nojiri (2004)
Feng, Smith (2004)



Large Hadron Collider



$M_{1/2}$ = 600 GeV
$m_{\tilde{l}}$ = 219 GeV

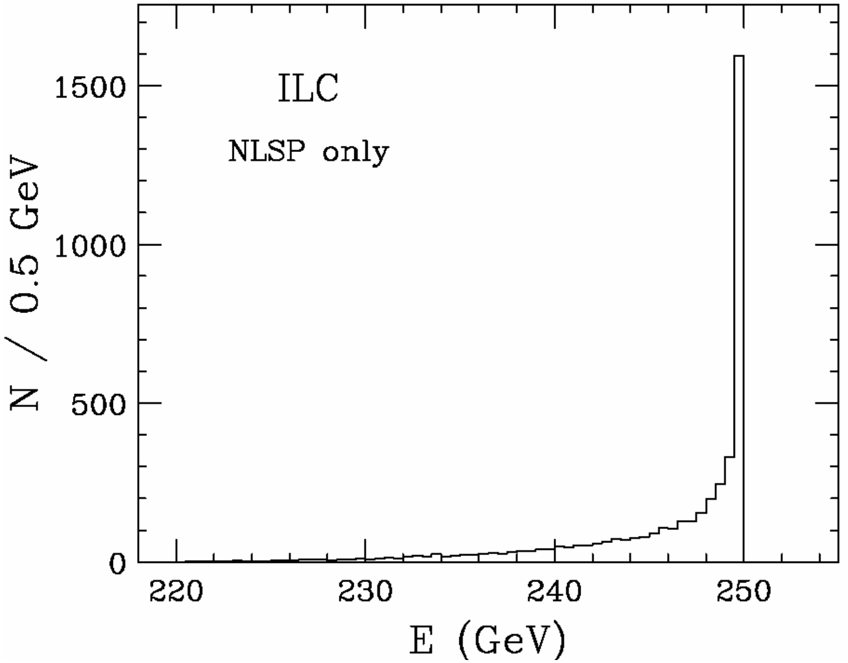


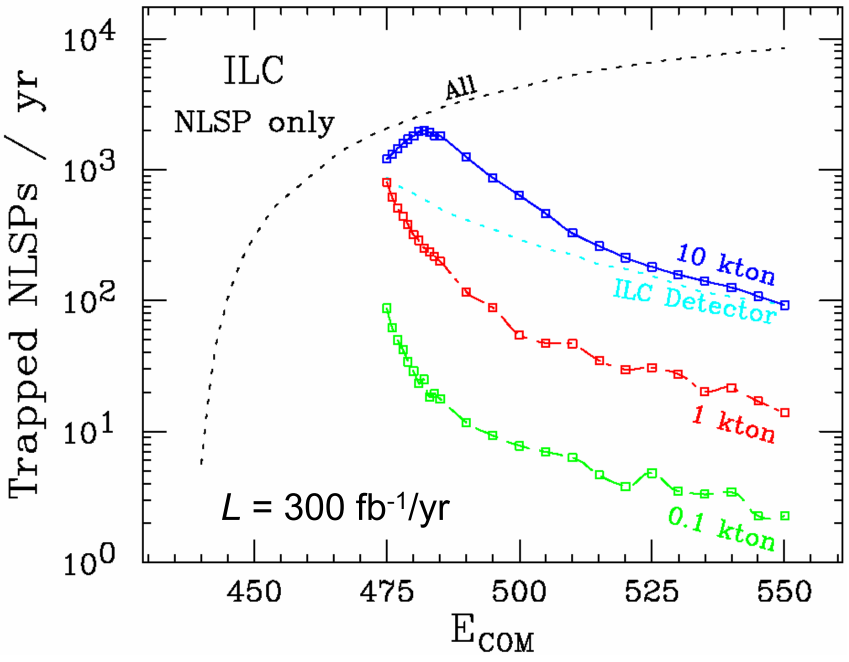
L = 100 fb^{-1}/yr

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





Can tune beam energy to produce slow sleptons:

75% are caught in 10 kton trap

Shufang Su, LCWS05

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* $E_l \rightarrow m_{\tilde{G}}$ *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
  - BBN, CMB in the lab

  - Determines $\Omega_{\tilde{G}}$: SuperWIMP contribution to dark matter
  - Determines *F* : supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

DARK ENERGY

- Quantum mechanics:

$$\tfrac{1}{2}\hbar\omega, \qquad \omega^2 = k^2 + m^2$$

- Quantum field theory:

$$\int^E d^3k\,(\tfrac{1}{2}\hbar\omega) \sim E^4,$$

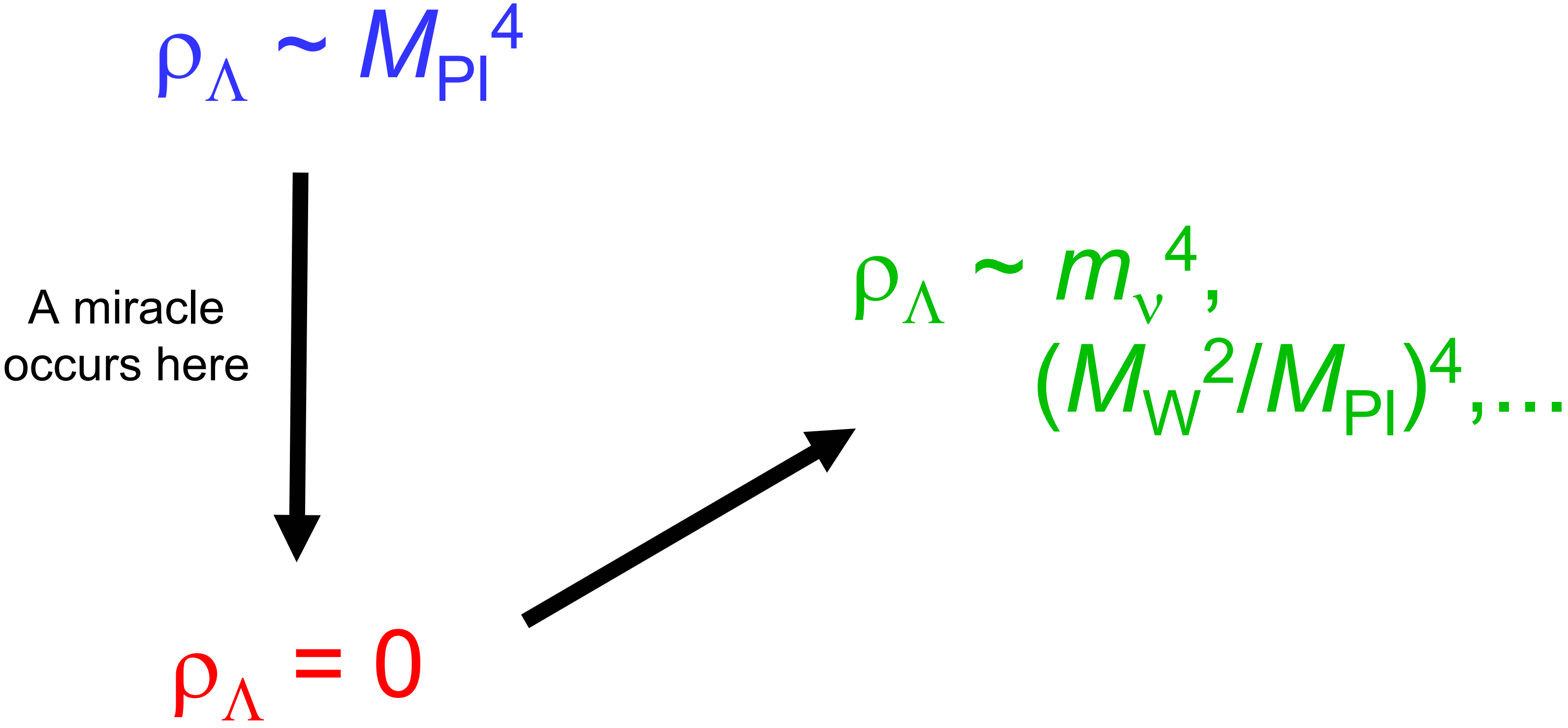
where E is the energy scale where the theory breaks down

- All fields contribute to Λ. We expect

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

ONE APPROACH

- Small numbers ↔ broken symmetry



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

A miracle
occurs here

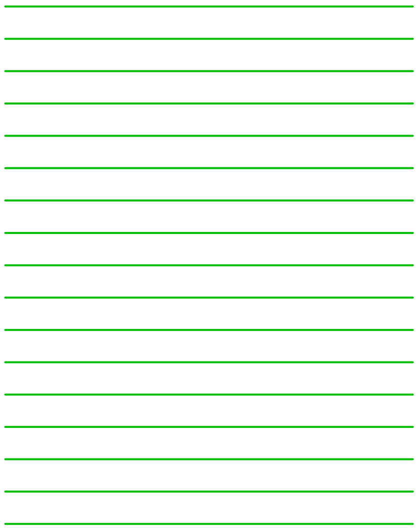
$\rho_\Lambda = 0$

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

ANOTHER APPROACH

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

Many, densely spaced vacua (string landscape, many universes, etc.)



Anthropic principle:

$-1 < \Omega_\Lambda < 100$

Weinberg (1989)

- Two very different approaches. There are others, but none is compelling.

- Ways forward:
  1) Discover a fundamental scalar particle (Higgs would be nice)
  2) $(M_{\text{weak}})^4 \sim 10^{60}\ \rho_\Lambda$: map out the EW potential
  3) $(M_{\text{SUSY}})^4 \sim 10^{90}\ \rho_\Lambda$: understand SUSY breaking (see above)
  4) $(M_{\text{GUT}})^4 \sim 10^{108}\ \rho_\Lambda$: extrapolate to GUT scale
  5) $(M_{\text{Planck}})^4 \sim 10^{120}\ \rho_\Lambda$: …

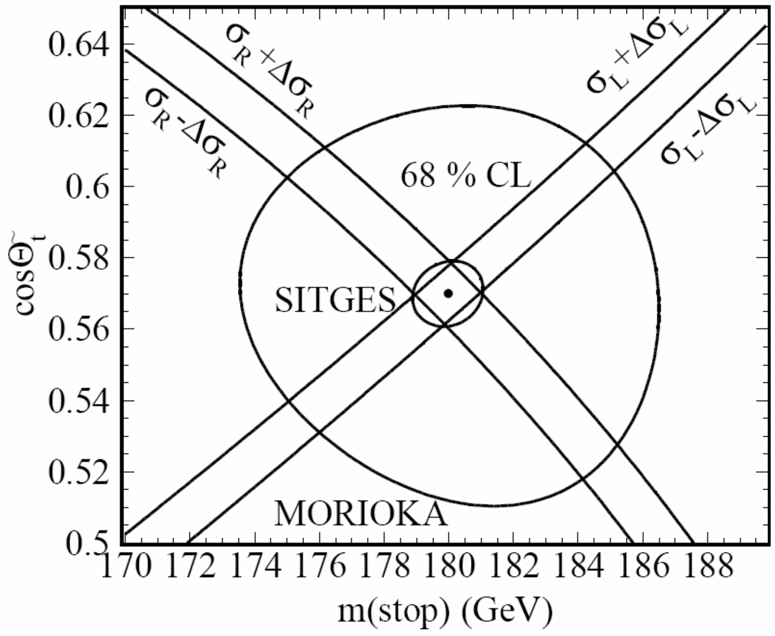
- ILC will be an essential tool for at least 2, 3, and 4.

BARYOGENESIS

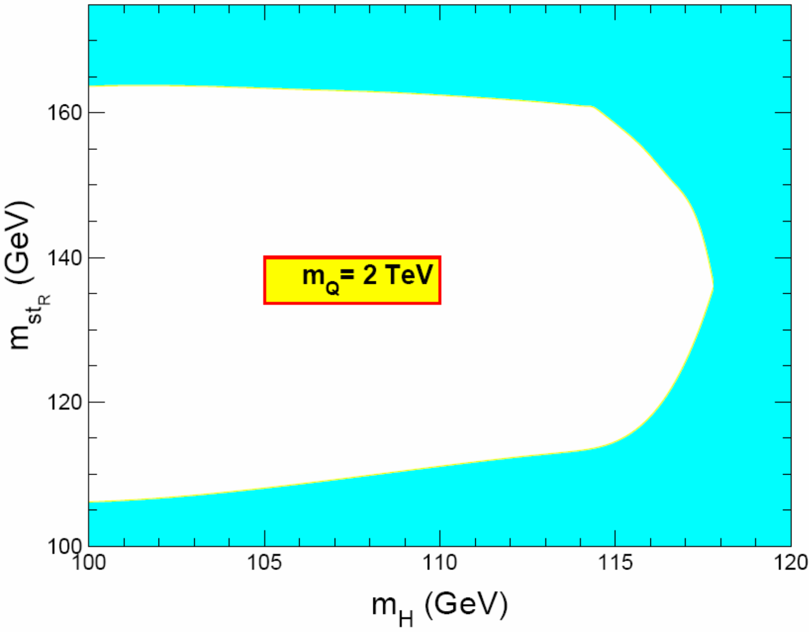
- Requires
  - B violation
  - CP violation
  - Departure from thermal equilibrium

- All possible at the electroweak scale with new physics

- For SUSY, requires precise determination of Higgs and top squark parameters, and CP violating phases



Berggren, Keranen, Nowak, Sopczak (1999)



Carena, Quiros, Wagner (2001)

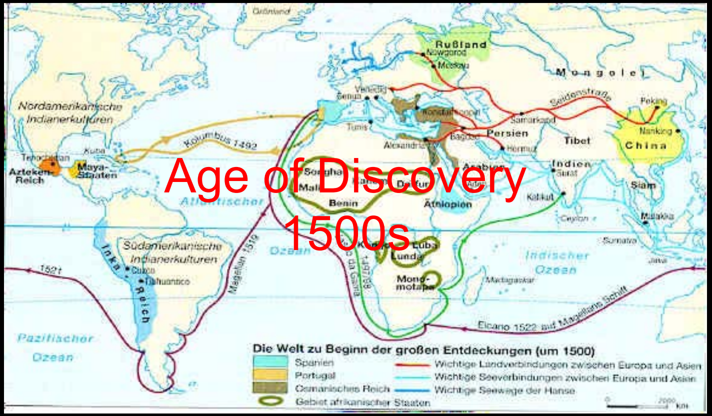
- ILC will quickly establish whether EW Baryogenesis is possible
- CP violation: Bartl et al., Zerwas et al., Barger et al., and others
- LCC5: Graf, Strube et al.

CONCLUSIONS

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

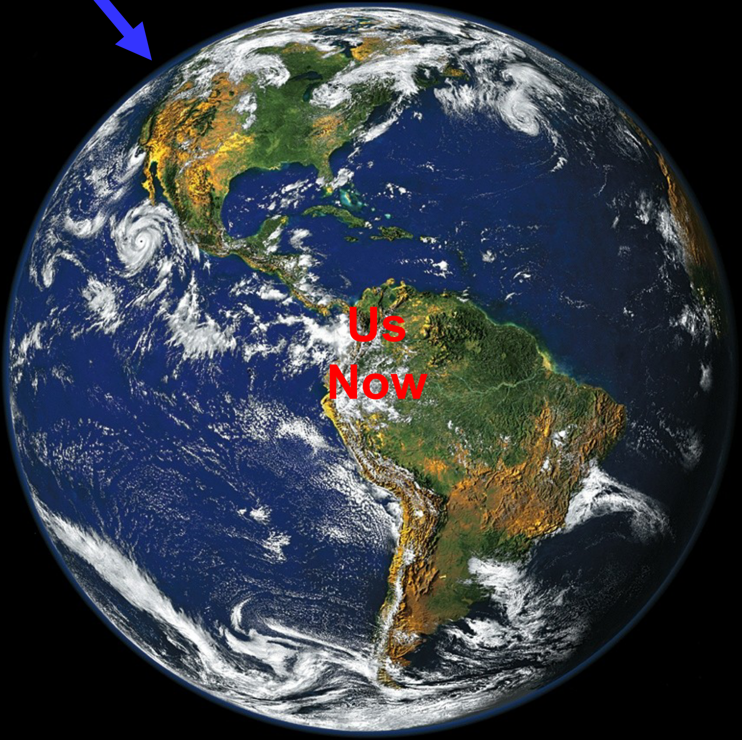
- They require new particle physics, cannot be solved by cosmological tools alone.

- In many cases, the ILC provides an essential tool for discovering the answers.



Age of Discovery
1500s

Eratosthenes
200 B.C.



Us
Now

AN EQUALLY EXCITING AGE OF DISCOVERY AHEAD