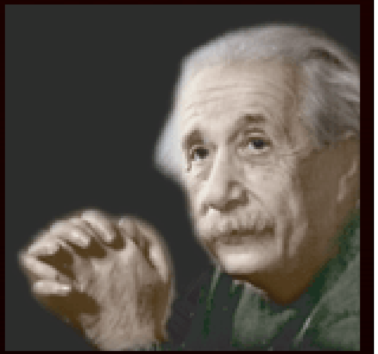
the new physics of dark matter and dark energy



Joseph Lykken
Fermilab/University of Chicago

Beyond Einstein 12-15 May 2004

outline

-philosophical introduction

-big ideas:

- supersymmetry
- extra dimensions
- neutrinos

how do you solve big mysteries in science?

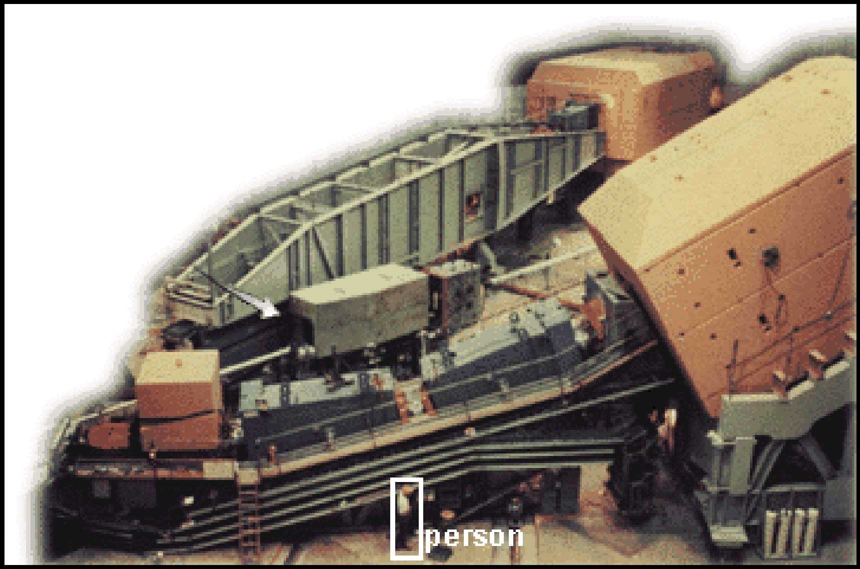
attack simultaneously from

top down

and bottom up

historical example:
the mystery of strong interactions

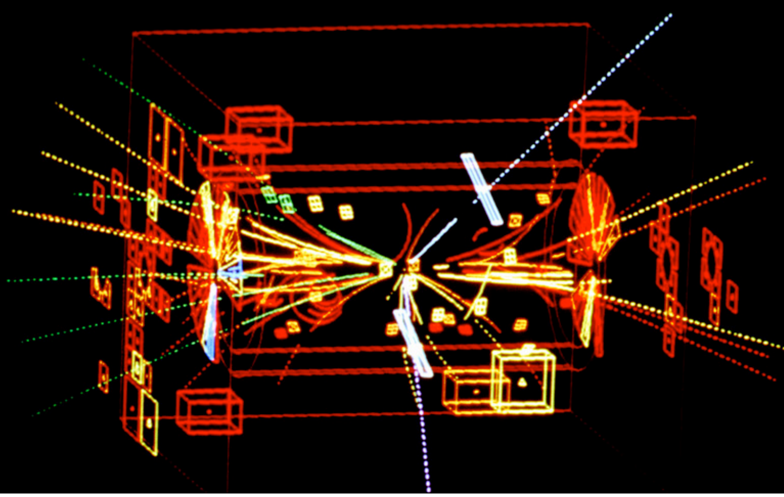
SLAC DIS experiments show protons have other particles inside of them



But these “partons” won’t come out...

Meanwhile:

Ivory tower theorists trying to understand renormalization of nonabelian gauge theories discover "asymptotic freedom" = infrared slavery of quarks in QCD



Same thing happening today on an even grander scale:

- **data, data, data, from space missions, earth observatories, particle accelerators, underground labs**
- **provocative results demand explanations**
- **big theoretical ideas are in play**

Daniele Amati in 1970's (as quoted by Ed Witten): "String theory was part of 21st century physics that fell by chance into the 20th century"

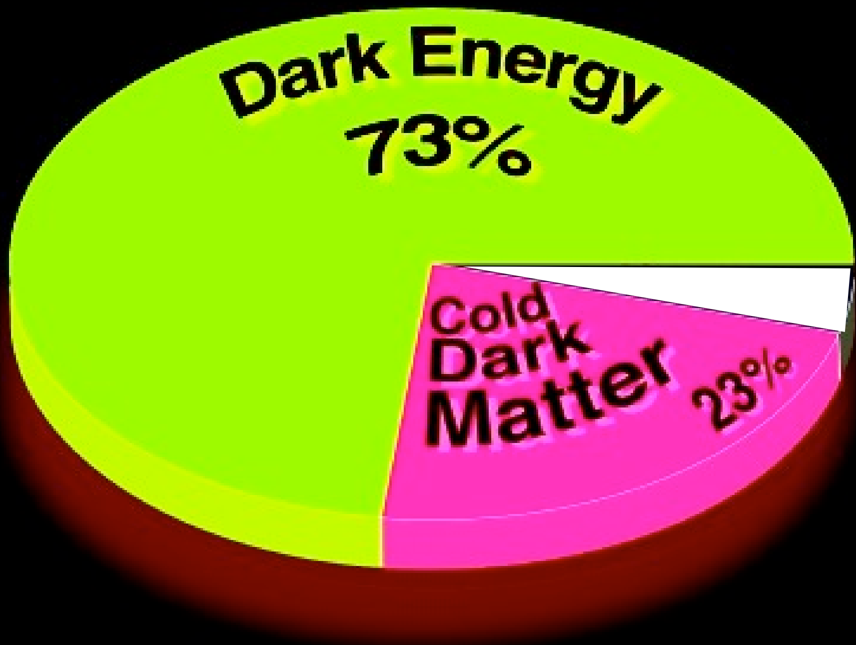
my claims:

- we are underestimating the scope of the dark matter and dark energy problems
- answers will come by combining many insights from many sources
- understanding DM+DE will mean understanding a whole new level of fundamental physics (maybe two).

- **we are underestimating the scope of the *dark matter* problem**

let's imagine a different history...

suppose that we were creatures of the dark...



what is
the mysterious
bright matter?

Source: Robert Kirshner
Source: NASA/WMAP Science Team

Answer:
57 elementary particles + 2 new forces
in this 4% slice!

- **we are underestimating the scope of the *dark energy* problem**

suppose that you found the perfect quintessence model

it predicts $\Lambda_{\mathrm{DM}},\ w,\ w'$ **exactly in terms of** π**,** α_{em}**, Barry Bond's batting average, etc**

Is the DE problem solved?

NO!

the dark energy problem is really an expanded version of the *cosmological constant* problem

i.e.: in the real theory of quantum gravity + matter
which goes Beyond Einstein
what are all quantum modifications and sources
in whatever replaces the Einstein equations
to describe the evolution of the universe?

part of the job is to put the
DM and DE mysteries into
the larger context of
big ideas in fundamental physics

this task was assigned to the
recent HEPAP committee
chaired by Persis Drell...

QUANTUM UNIVERSE

THE REVOLUTION IN 21ST CENTURY PARTICLE PHYSICS

EINSTEIN'S DREAM OF UNIFIED FORCES

1

ARE THERE UNDISCOVERED PRINCIPLES OF NATURE : NEW SYMMETRIES, NEW PHYSICAL LAWS?

The quantum ideas that so successfully describe familiar matter fail when applied to cosmic physics. Solving the problem requires the appearance of new forces and new particles signaling the discovery of new symmetries-undiscovered principles of nature's behavior.

2

HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

The dark energy that permeates empty space and accelerates the expansion of the universe must have a quantum explanation. Dark energy might be related to the Higgs field, a force that fills space and gives particles mass.

3

ARE THERE EXTRA DIMENSIONS OF SPACE?

String theory predicts seven undiscovered dimensions of space that give rise to much of the apparent complexity of particle physics. The discovery of extra dimensions would be an epochal event in human history; it would change our understanding of the birth and evolution of the universe. String theory could reshape our concept of gravity.

4

DO ALL THE FORCES BECOME ONE?

At the most fundamental level all forces and particles in the universe may be related, and all the forces might be manifestations of a single grand unified force, realizing Einstein's dream.

THE PARTICLE WORLD

5

WHY ARE THERE SO MANY KINDS OF PARTICLES?

Why do three families of particles exist, and why do their masses differ so dramatically? Patterns and variations in the families of elementary particles suggest undiscovered underlying principles that tie together the quarks and leptons of the Standard Model.

6

WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?

Most of the matter in the universe is unknown dark matter, probably heavy particles produced in the big bang. While most of these particles annihilated into pure energy, some remained. These remaining particles must have a small enough mass to be produced and studied at accelerators.

7

WHAT ARE NEUTRINOS TELLING US?

Of all the known particles, neutrinos are the most mysterious. They played an essential role in the evolution of the universe, and their tiny nonzero mass may signal new physics at very high energies.

THE BIRTH OF THE UNIVERSE

8

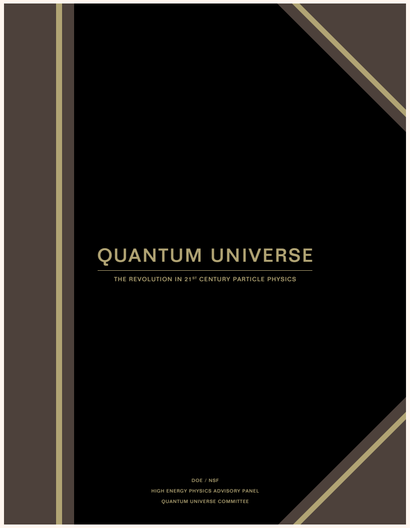
HOW DID THE UNIVERSE COME TO BE?

According to cosmic theory, the universe began with a singular explosion followed by a burst of inflationary expansion. Following inflation, the universe cooled, passing through a series of phase transitions and allowing the formation of stars, galaxies and life on earth. Understanding inflation requires breakthroughs in quantum physics and quantum gravity.

9

WHAT HAPPENED TO THE ANTIMATTER?

The big bang almost certainly produced equal amounts of matter and antimatter, yet the universe seems to contain no antimatter. How did the asymmetry arise?

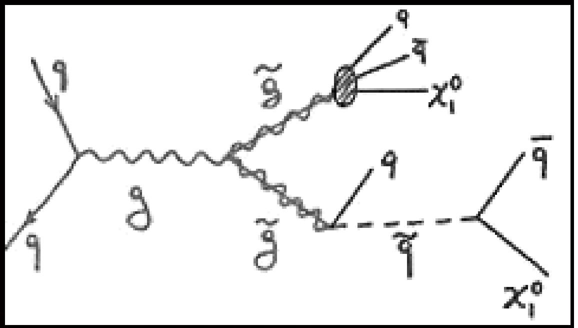



big idea #1
supersymmetry

space-time symmetries have profound implications:

- **conservation of E, p, J**
- **all particles have *antiparticle partners* with identical mass and |spin|**
- **makes quantum mechanics consistent with special relativity**

→ quantum field theory



space-time symmetries could be increased:

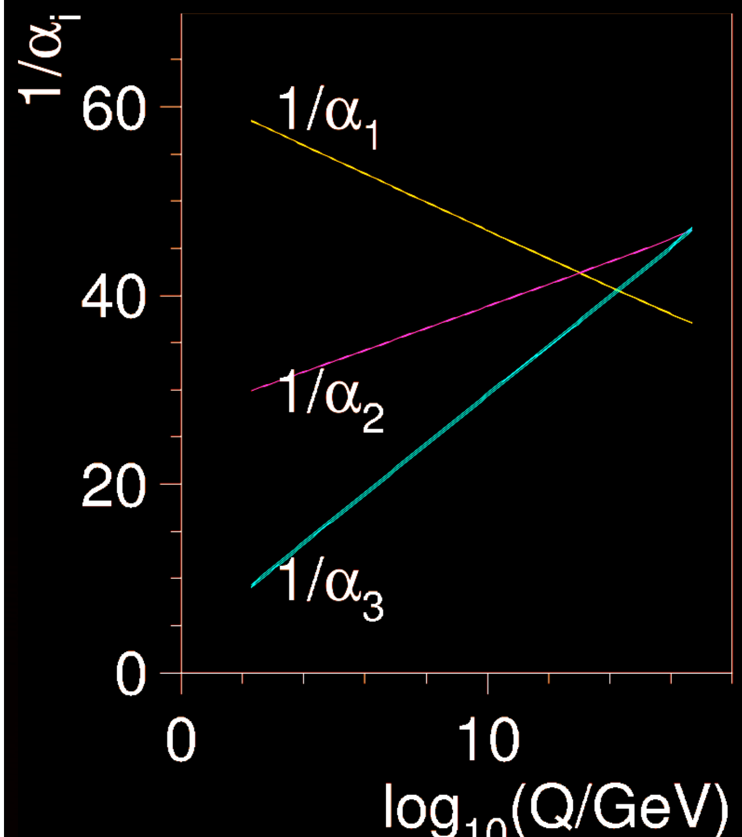
- if extra space-time dimensions
- if extra *quantum* (fermionic) dimensions
- 4 “bosonic” spacetime dims
  + 4 “fermionic” spacetime dims
  = “simple” supersymmetry
- “extended” supersymmetries too

supersymmetry
has profound implications:

- all particles have *superpartners* with identical mass and *different* |spin|
- suppresses quantum fluctuations
- with other ingredients, makes quantum mechanics consistent with gravity

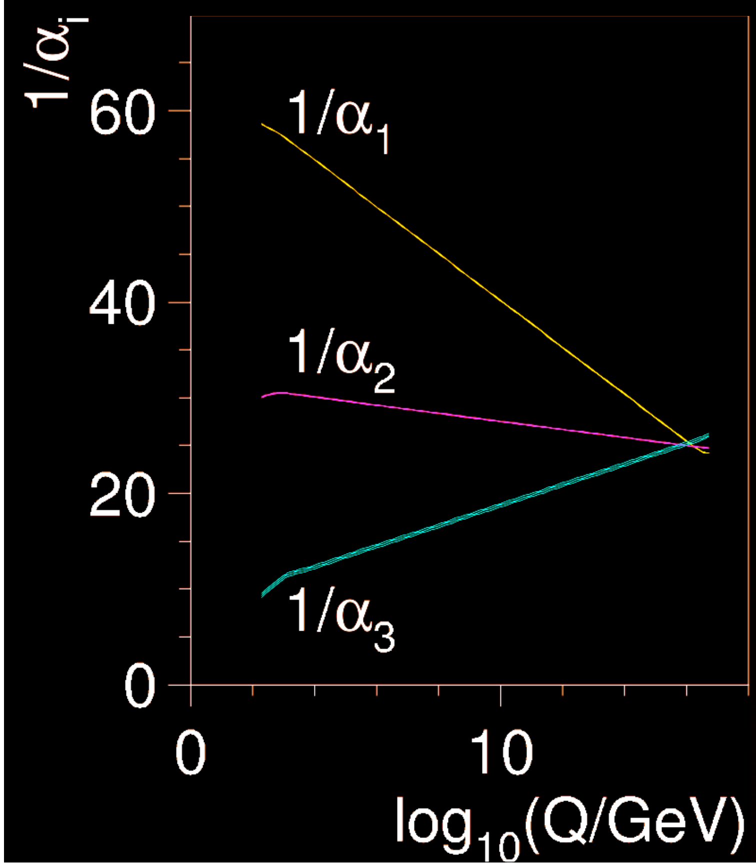
→ superstrings

almost grand unification:



- **extrapolating gauge couplings suggests SU(5) grand unification at ~ 10^{14} GeV**
- **then a <GUT> field breaks SU(5) at ~ 10^{14} GeV, and <Higgs> field breaks electroweak at 174 GeV**
- **but quantum corrections drive <Higgs> -> 10^{14} GeV!**
- **a naturalness + hierarchy problem**

SUSY grand unification:



- **supersymmetry eliminates this problem by suppressing quantum fluctuations**
- **makes it natural to have a "tiny" <Higgs>=174 GeV**
- **and the couplings unify better**
- **and the unification scale goes up**

Supersymmetry and

- in flat space, superpartners cancel quantum vacuum energy
- SUSY is the only symmetry that does this
- but SUSY is not an exact symmetry:
  electron mass = 0.5 MeV
  selectron mass > 100,000 MeV

- **we don't know what is the new physics responsible for breaking SUSY**
- **broken SUSY *seems* to imply**

$$\Lambda \sim (M_{\cancel{\mathrm{SUSY}}})^4 \;\sim (100\ \mathbf{GeV})^4$$

SUSY is our best idea relating to dark energy

SUSY-Higgs interplay is suggestive

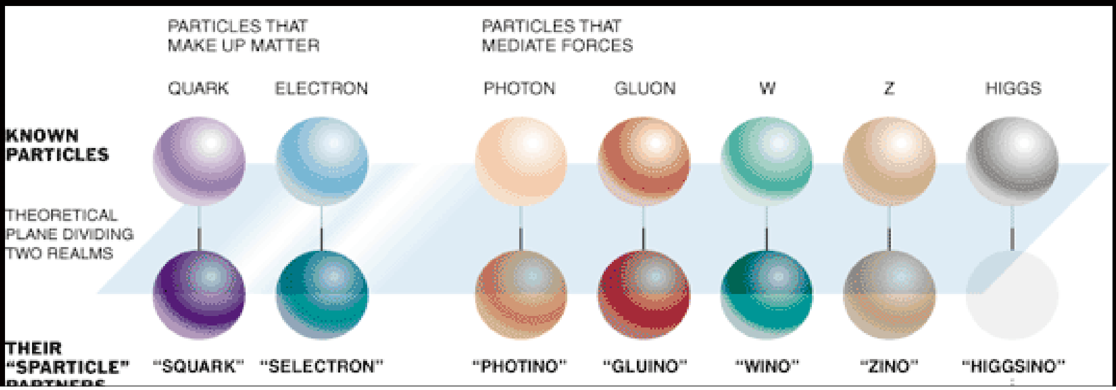
progress requires understanding how SUSY is broken and how gravity sees this, e.g.

$$\Lambda \sim (M_{\not{S}USY})^4 \left[c_0 + c_1 \frac{M^2_{\not{S}USY}}{M^2_{Planck}} + c_2 \frac{M^4_{\not{S}USY}}{M^4_{Planck}} + \ldots \right]$$

if $\mathbf{c_0 = c_1 = 0}$**, we are happy!**

supersymmetry and dark matter

- SUSY is a symmetry, not a model!
- SUSY predictions for DM depend sensitively upon:
  - how SUSY is broken in your model
  - how your model extends the SM



simplest viable framework=MSSM

- minimal particle content
- proton decay suppressed by new global charge = R parity
- electroweak breaking via top quark
- consistent with grand unification

produces many DM candidates:

- neutralino
- sneutrino
- gravitino
- axino
- Q balls
- LOP (Kumar+JL 2004)

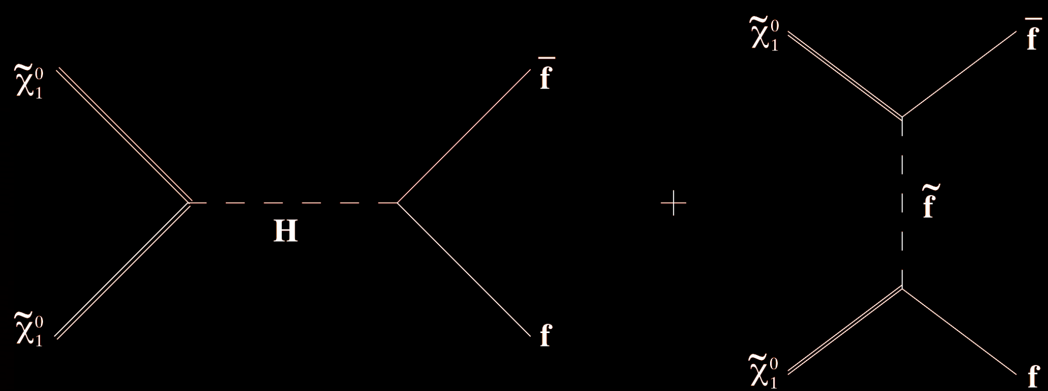
neutralino

- lightest neutralino
- $$\tilde{\chi}_1^0 \sim \tilde{\gamma} + \tilde{\mathrm{Z}} + \tilde{\mathrm{H}}_1 + \tilde{\mathrm{H}}_2$$
- in large fraction of models, is the stable LSP
- EWSB -> mass ~ 100-1000 GeV
- for electroweak strength annihilation cross section:

$$\Omega_{\mathrm{CDM}} \mathrm{h}^2 = 10^{-6} \left(\frac{\mathrm{m_{wimp}}}{\mathrm{GeV}} \right)^2$$

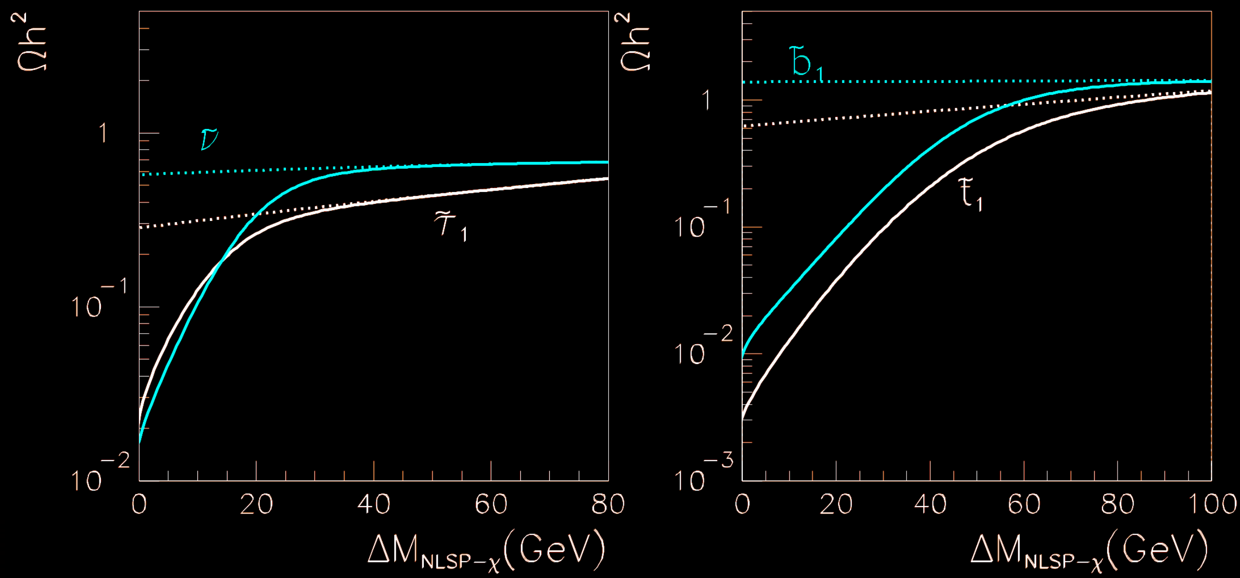
so SUSY neutralino is a “natural” DM candidate

but the real situation is complicated:



+ coannihilation channels

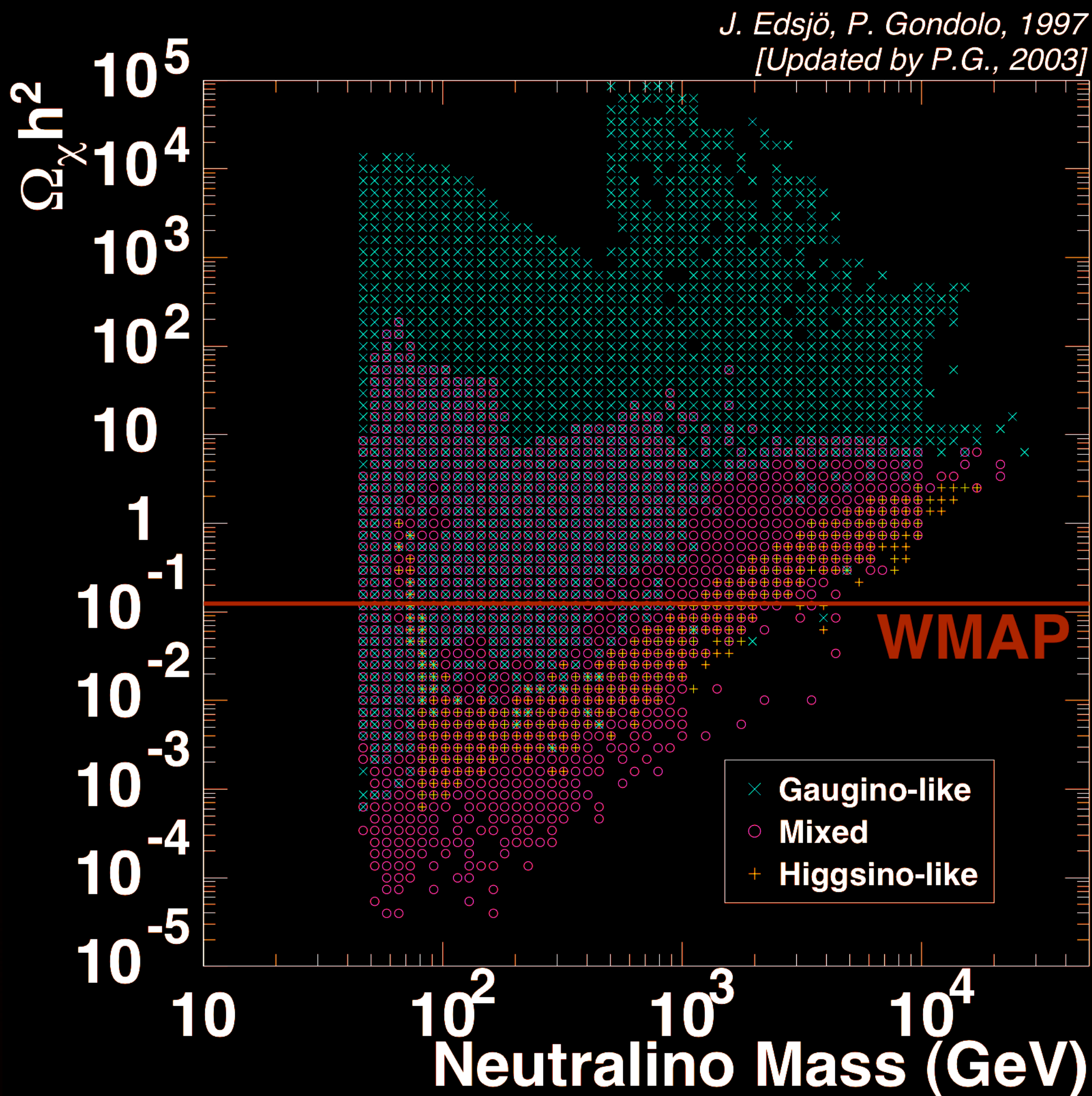
- **depends on relation of $m_{\tilde{\chi}_1^0}$ to sfermion masses**
- **depends on how gaugino vs higgsino $\tilde{\chi}_1^0$ is.**



(Belanger 2002)

the most extreme model/parameter sensitivity is from the possibility of LSP+NLSP coannihilations, e.g.

$$\tilde{\chi}_1^0 + \tilde{\tau} \rightarrow \tau + \gamma$$

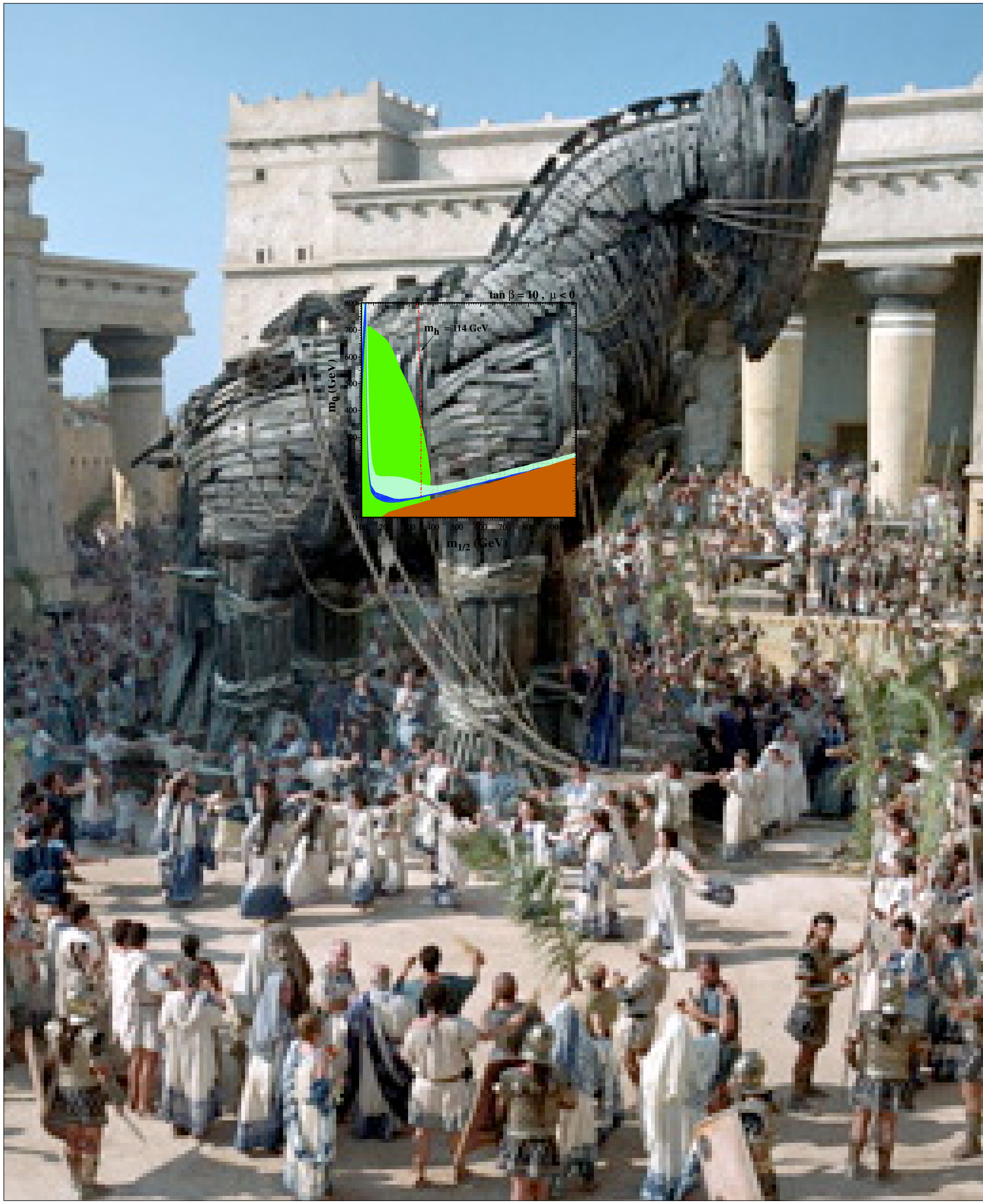


scanning over the 7 most relevant of the 124 parameters in the MSSM

so does SUSY "naturally" give

$$0.094 < \Omega_\chi h^2 < 0.129 \text{ ?}$$

- no, but this is not the fault of SUSY
- precision data shrinks the parameter space of SUSY models, as it should
- eliminates models with very heavy superpartners (good!) or close LSP-NLSP mass degeneracies (good!)
- the fact that colliders have not seen superpartners, and have not seen the Higgs below 114 GeV, is also quite constraining -> either heavy superpartners, or Higgs ~ 114 GeV, or non-minimal SUSY

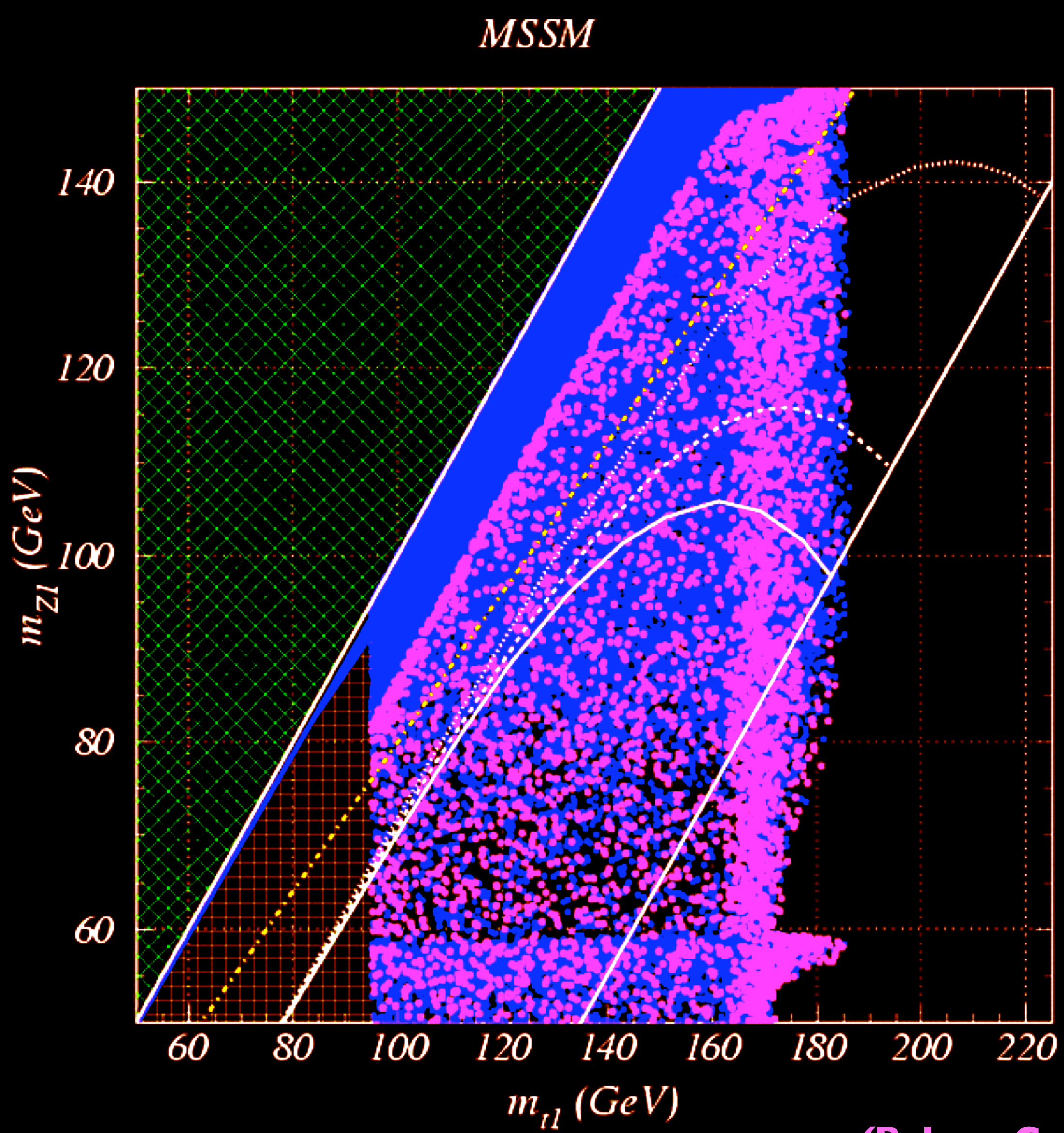


Beware theorists bearing plots!

Since the post-WMAP CDM constraint is tight, you had better look at the whole MSSM, not just random subsets of models

E.g. plots based on mSUGRA or CMSSM can be very misleading!

- **however, it is OK to start with reduced SUSY parameter space if you want SUSY to do an extra job**
- **e.g. SUSY can provide a very natural mechanism for electroweak baryogenesis**
- **in the MSSM, requires CP violating phases, and requires a light stop to make the EW phase transition sufficiently first order**
- **also requires Higgs mass < 120 GeV**



scanning over stop and neutralino masses for MSSM regions that produce EW baryogenesis

magenta points satisfy WMAP CDM constraint

inside white lines means stop will be seen at Tevatron!

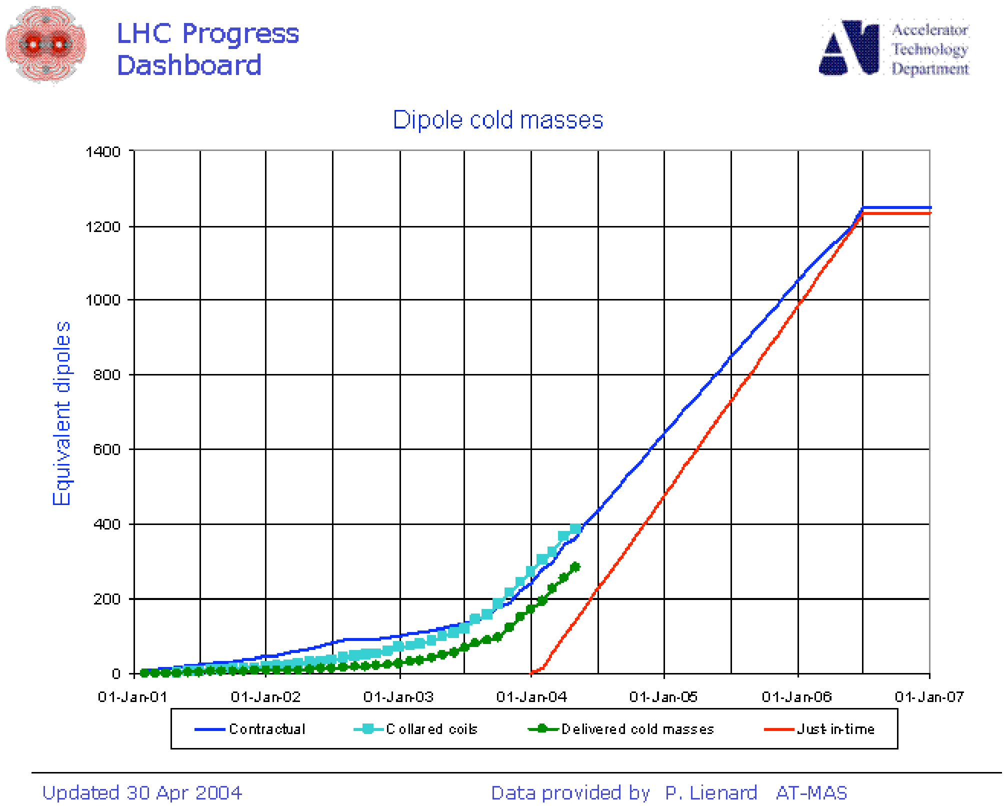
(Balazs, Carena, Wagner 2004)

other SUSY DM candidates

- sneutrinos are ruled out as primary CDM
- gravitinos are ruled out as primary CDM if they are thermal relics, but not as nonthermal "superWIMPS"
- this is important because gravitino LSP is a *generic* prediction of low scale SUSY breaking
- "LOP" is example of stable particle from the *SUSY breaking sector* acting as CDM
- Q-balls? axinos? ...

outlook for supersymmetry

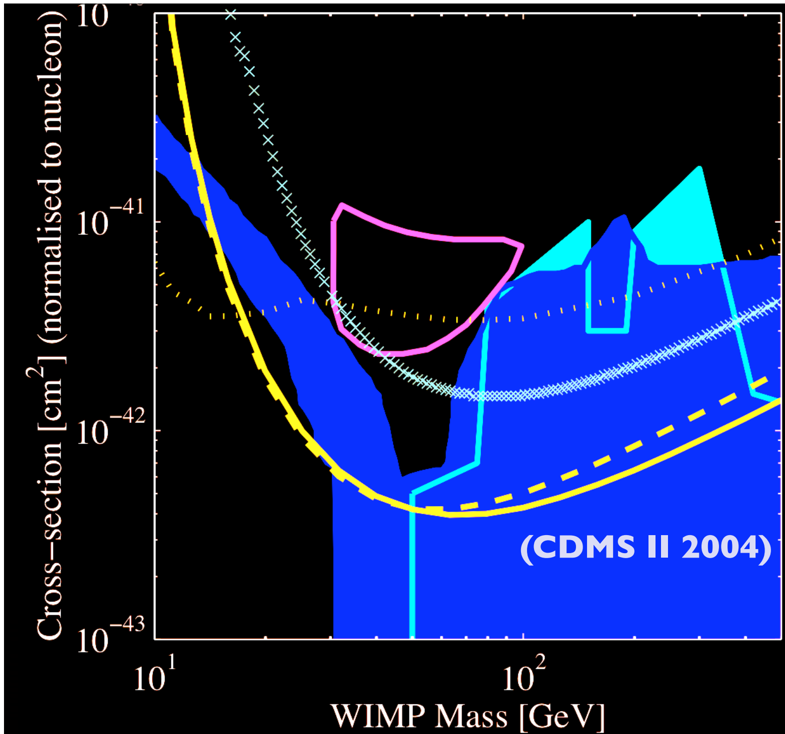
- LHC will turn on in 2007, with 10 times current mass reach for superpartners
- by 2010, may have SUSY discovery + first hints about physics of SUSY breaking (Planck scale?)
- make the SUSY<->dark energy connection explicit

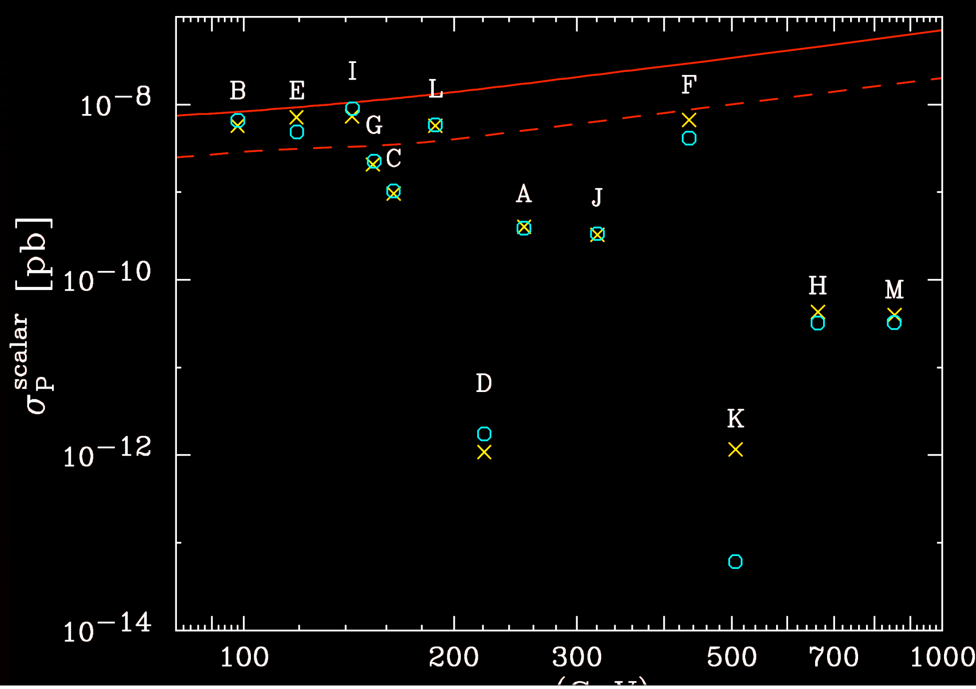


LHC is on-track for pp collisions at 14 TeV in 2007

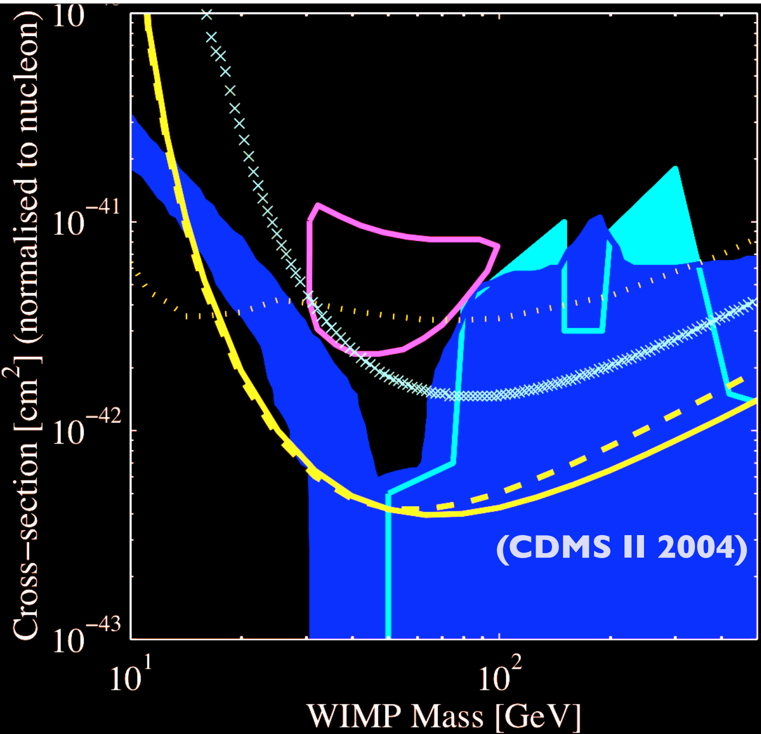
outlook for supersymmetry

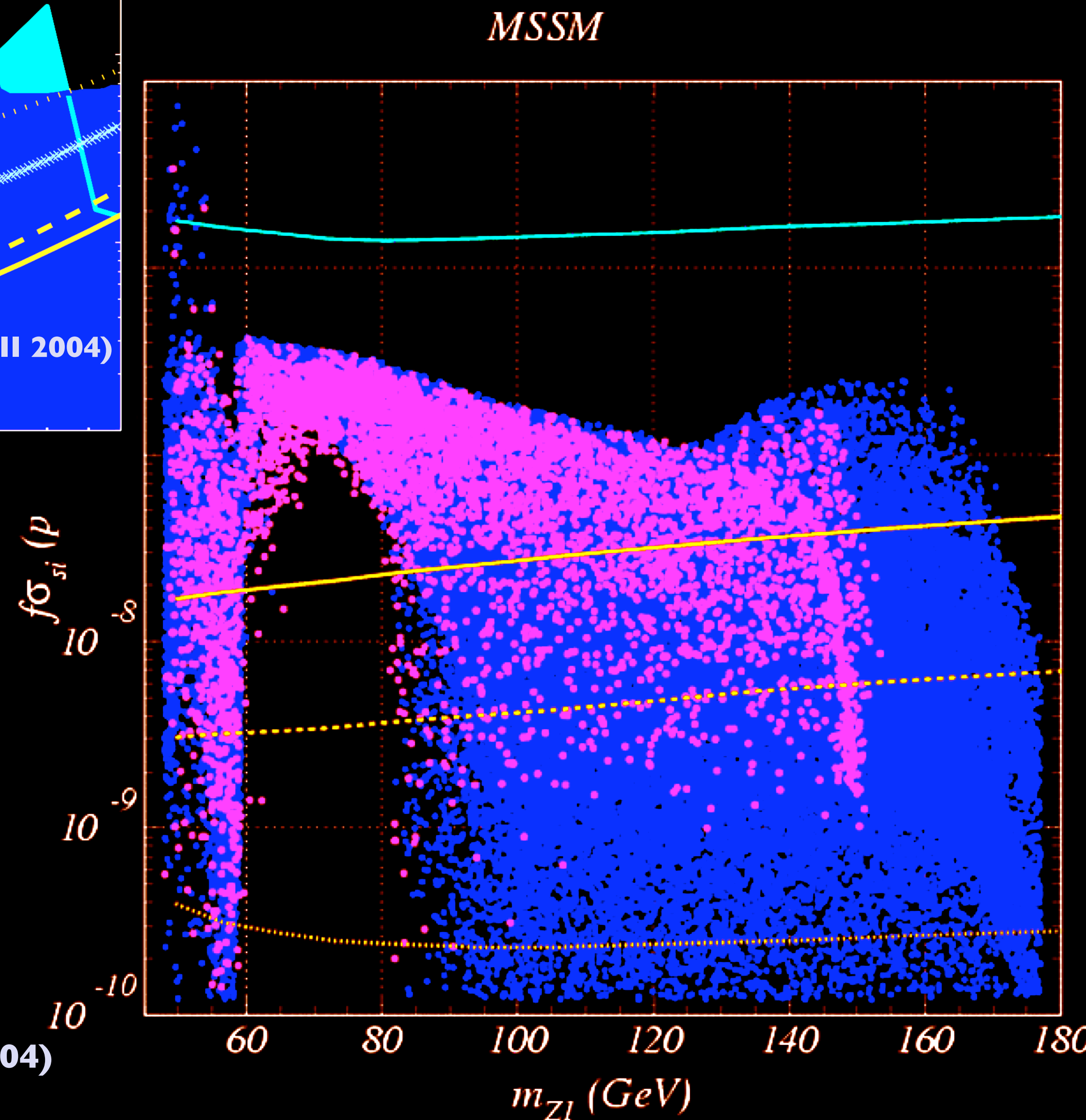
- compare LHC SUSY with direct+indirect WIMP signals
- “closing the circle”, i.e. 1% calculation of LSP relic density from collider data, will require a Linear Collider





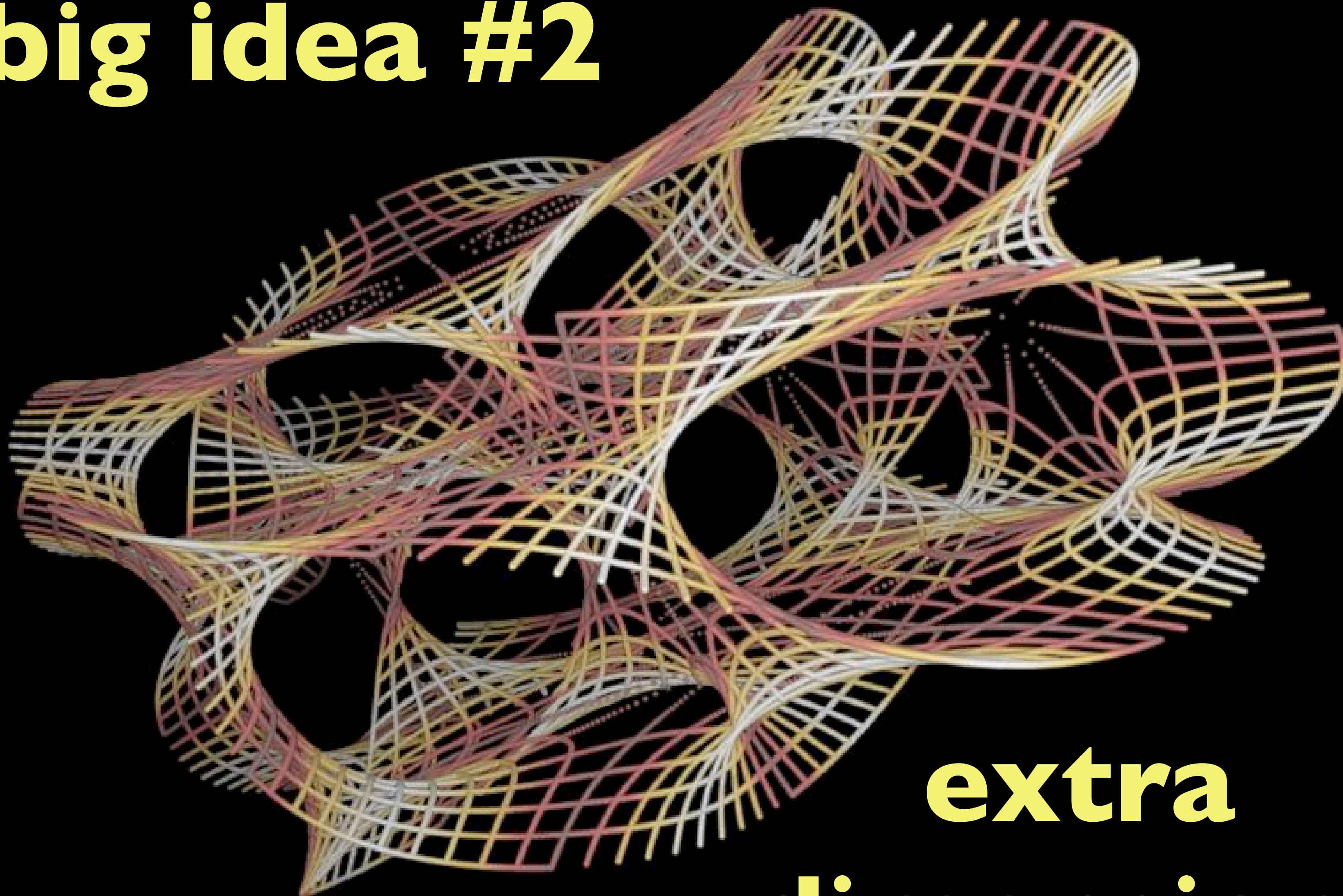
(Ellis, Feng, Ferstl, Matchev, Olive 2004)





(Balazs, Carena, Wagner 2004)

big idea #2



extra dimensions

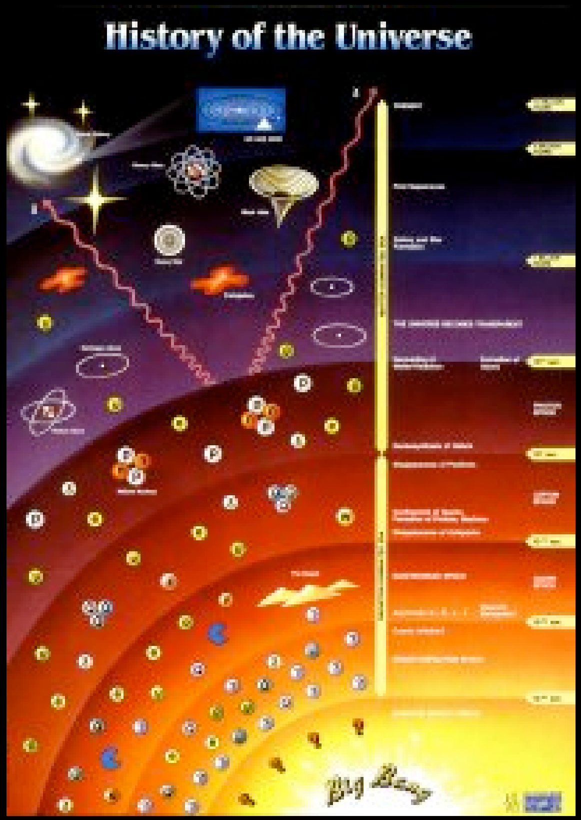
three strong arguments for extra dimensions

- cosmology
- the SM of particle physics
- string theory

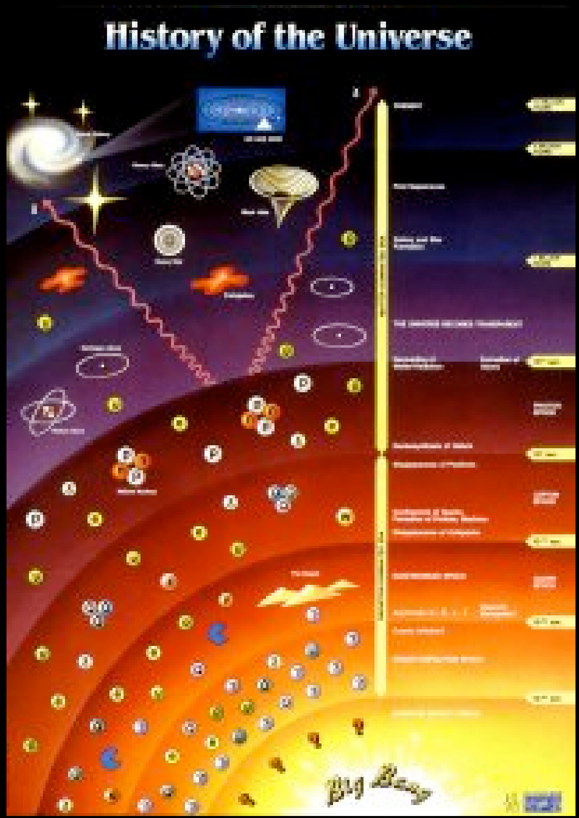
classical general relativity already tells us that spacetime is dynamical

the three spatial dimensions that we see are changing – expanding- and we don't understand it!

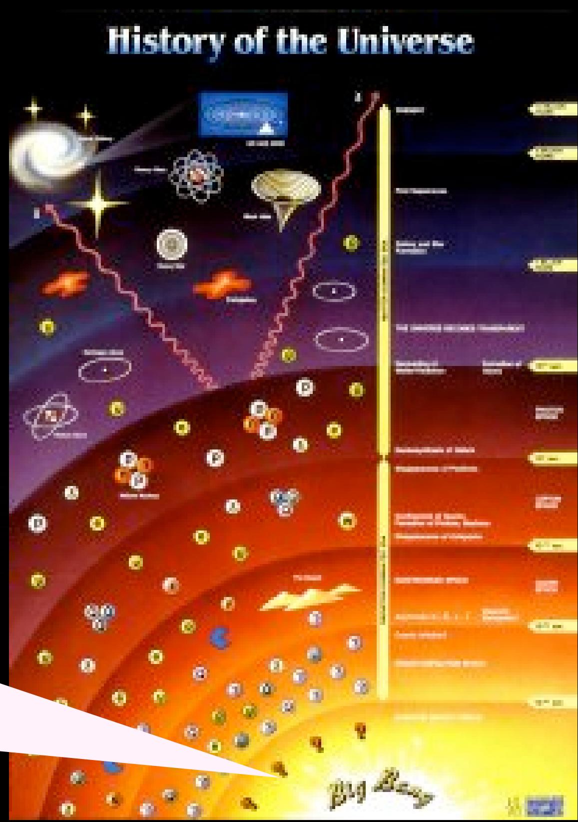
we don't understand what is the dark energy driving the expansion today



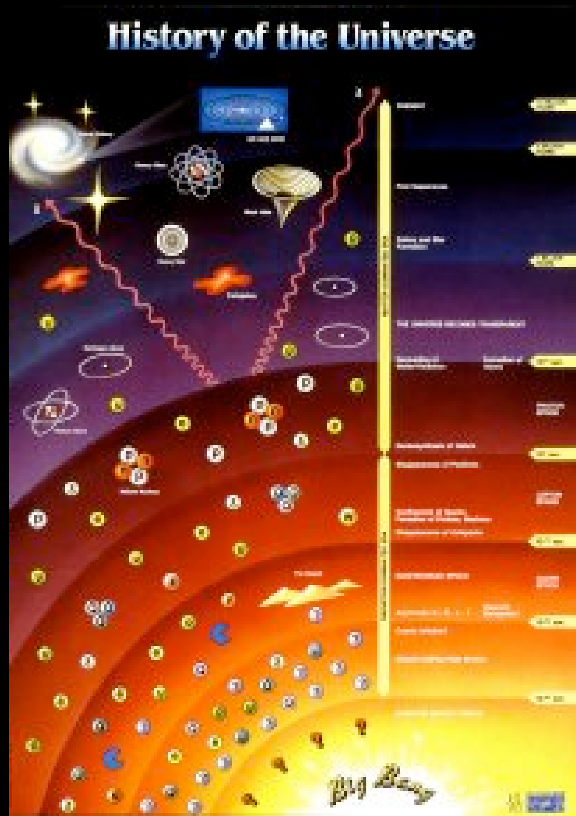
we don't understand what drove cosmic inflation in the early universe



we don’t understand what
this was

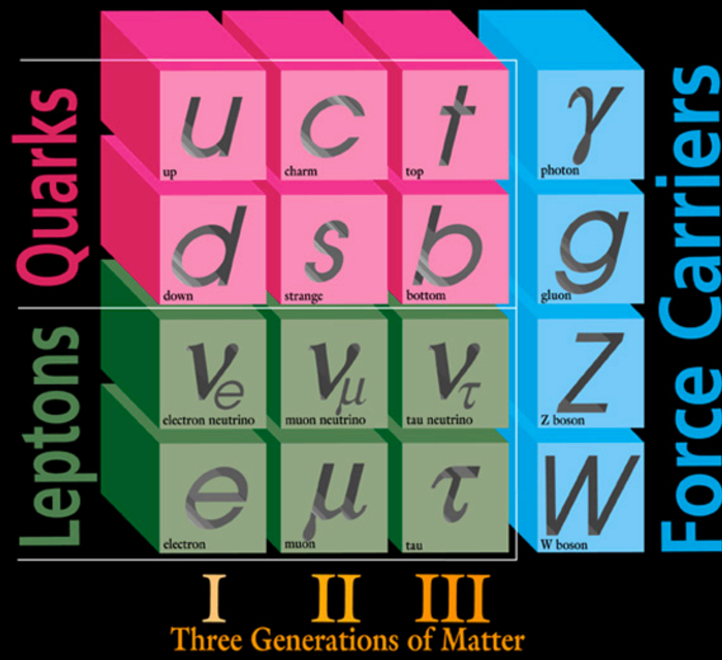


extra dimensions may be the extra ingredient that explains the dynamical evolution of the universe



the Standard Model

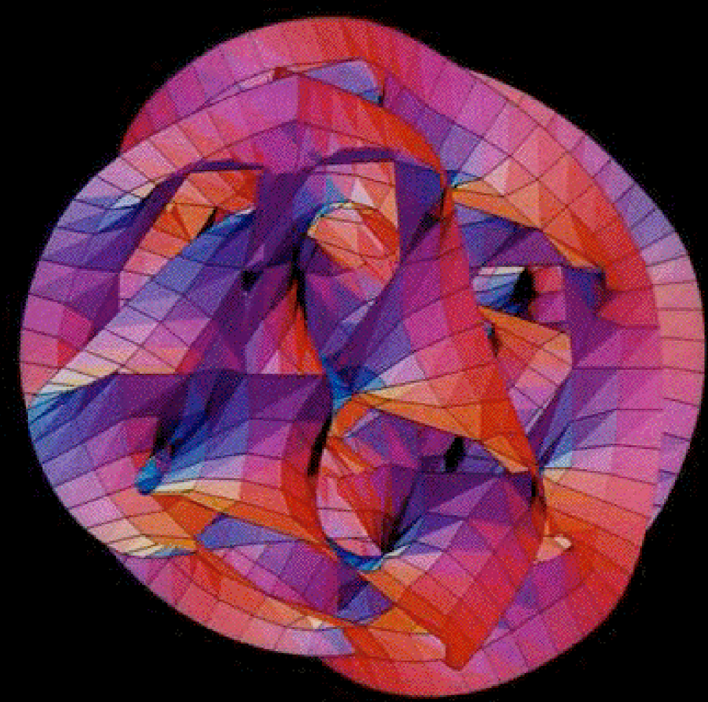
- 57 elementary particles?
- $\frac{m_{\rm top}}{m_\nu} > 10^{12}$?
- etc



the Standard Model
flavor structure is too complicated
for a theory of "elementary" constituents

the shape, content, and dynamics
of extra dimensions
may account for complexities
of particle physics

slice of a
6 dimensional Calabi-Yau manifold



string theory

- it is not surprising that when you quantize a relativistic extended object it turns out to have a critical dimension
- for superstrings the critical dimension is 10, not 4, and this is very fortunate

what is the physics that hides extra dimensions?

if extra spatial dimensions exist, they must be (for some reason) difficult to probe

there are several possible explanations:

e.g. the extra spatial dimensions are compact and small



Nordstrom, Kaluza, and Klein, circa 1920

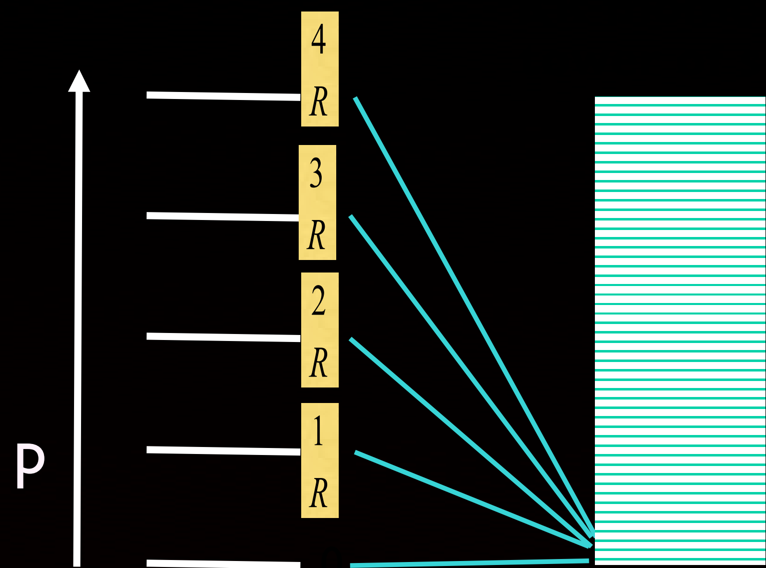
Kaluza-Klein modes

if spatial dimension is compact
then momentum in that
dimension is quantized:

$$p = \frac{n}{R}$$

from our point of view we see new massive particles

$$m^2 = m_0^2 + \frac{n^2}{R^2}$$

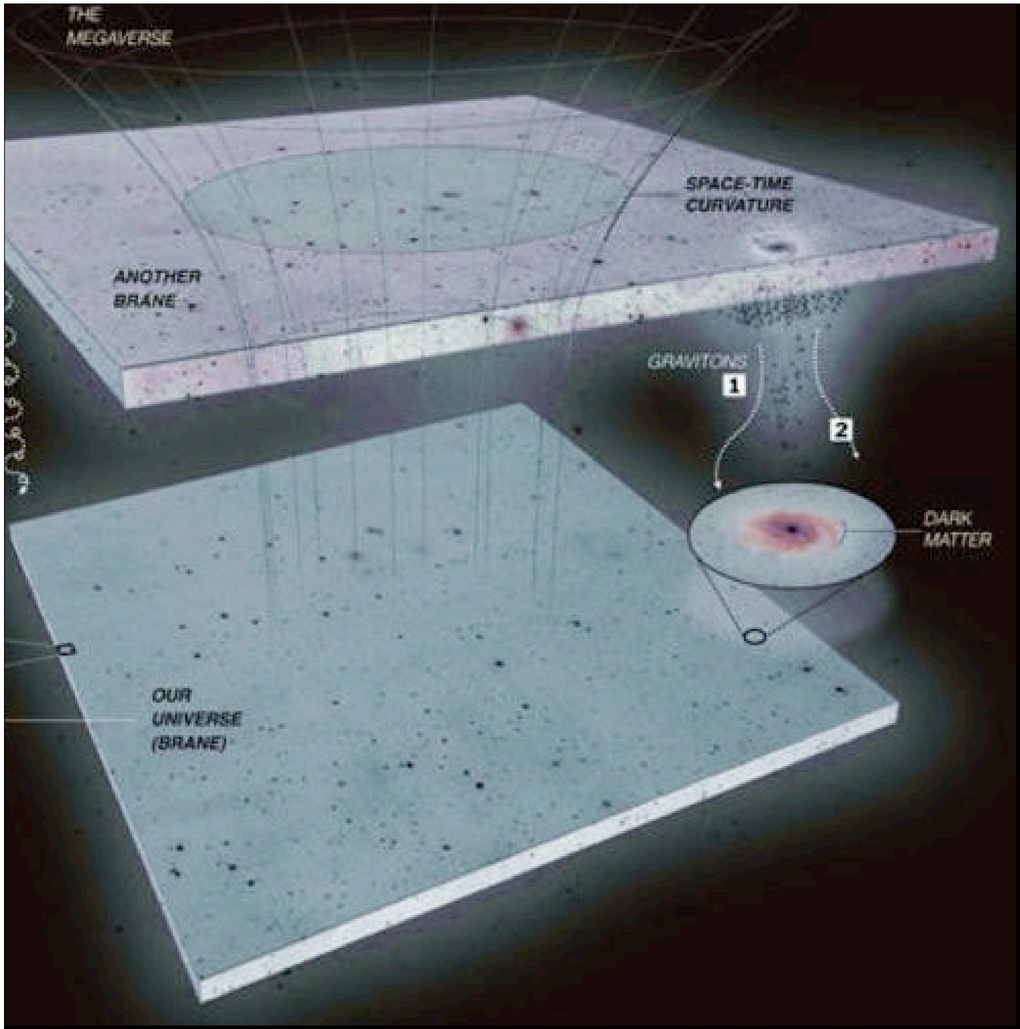


hidden dimensions

e.g. it may be that not all particles
(in a certain energy range)
move, probe, or see
the same number of spatial dimensions

a dramatic realization of this is called

the braneworld



the braneworld

only gravitons and exotics move in the "bulk" of the extra dimensional universe

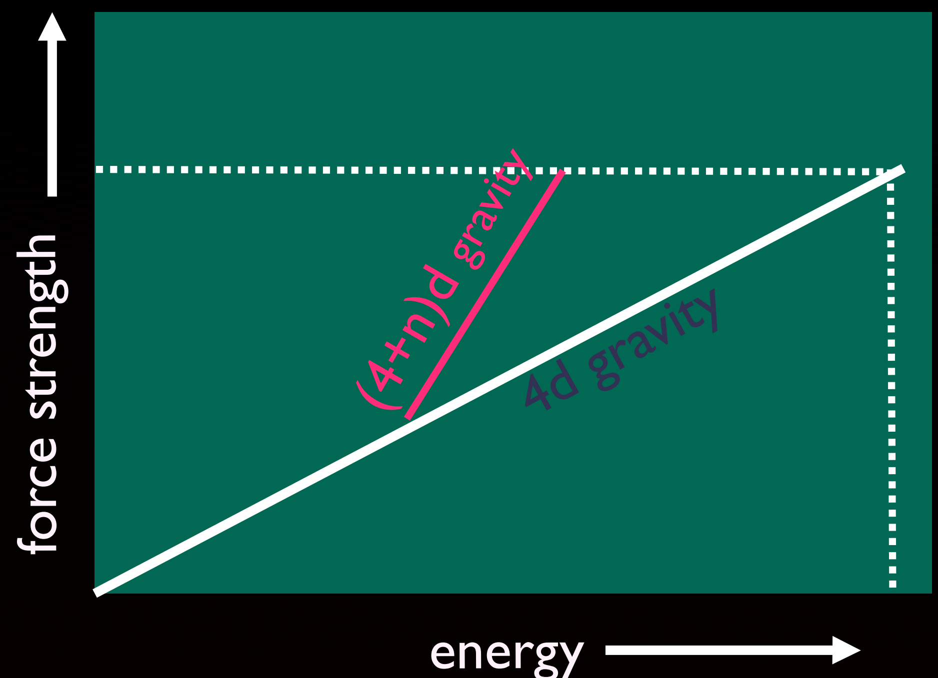
Standard Model particles are trapped on a brane and can't move in the extra dimensions

extra dimensions change gravity

gravity gets stronger at extremely high energies

$$M_{Planck} = 10^{19}\ \mathrm{GeV}$$

it gets stronger at not-so-high energies
(not-so-short distances) if there are extra dimensions….



ADD braneworld models

Arkani-Hamed, Dimopoulos, Dvali

assume that only gravity sees n <u>large</u> extra compact dimensions with common size R:

$$M_{\mathrm{Planck}}^2 = M_*^{n+2}\, R^n$$

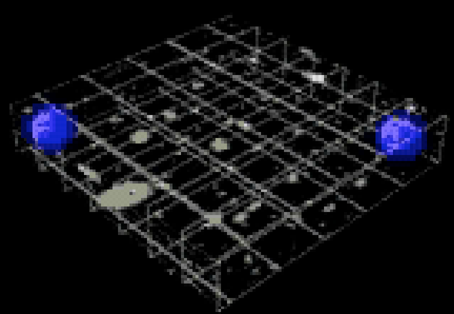
	δ			
	2	3	4	5
Supernova Cooling (68)	30	2.5		
Cosmic Diffuse γ-Rays:				
Cosmic SNe (69)	80	7		
$\nu\bar{\nu}$ Annihilation (71)	110	5		
Re-heating (72)	170	20	5	1.5
Neutron Star Halo (73)	450	30		
Overclosure of Universe (71)	$6.5/\sqrt{h}$			
Matter Dominated Early Universe (75)	85	7	1.5	
Neutron Star Heat Excess (73)	1700	60	4	1

lower bounds on M_* , in TeV

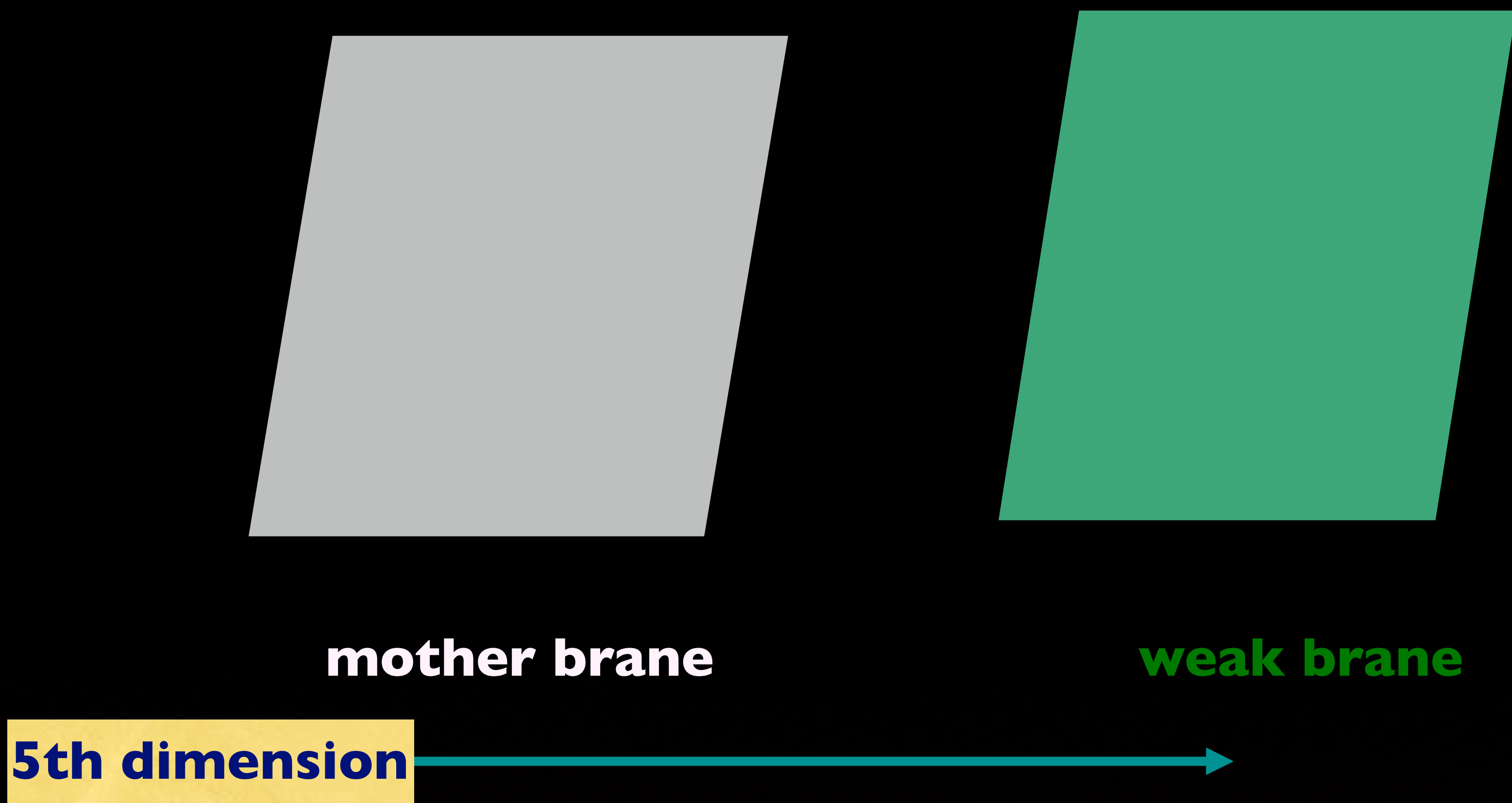
astrophysics and cosmology constrains ADD (or other) models with too many low mass KK gravitons

quantum gravity at colliders

if ADD is correct, collider expts should see effects of both real and virtual massive KK gravitons



$$\sigma_{KK} \sim \frac{1}{M_{\mathrm{Planck}}^2}(ER)^n \sim \frac{1}{M_*^2}\left(\frac{E}{M_*}\right)^n$$



Randall–Sundrum warped space

zero mode graviton likes to be near mother, but Kaluza-Klein graviton modes do not

extra dimensions can do a lot

ED’s have been invoked to:

- explain electroweak symmetry breaking
- break supersymmetry
- explain flavor properties of the SM
- explain or eliminate the hierarchy
- improve grand unification

what defines an ED scenario?

- number of ED’s at each scale
- what is the compactification:

  - what is the geometry?

  - are there background fields,
  e.g. gauge fluxes, in the EDs?

  - what symmetries are broken/unbroken?

  - is there curvature in the bulk?

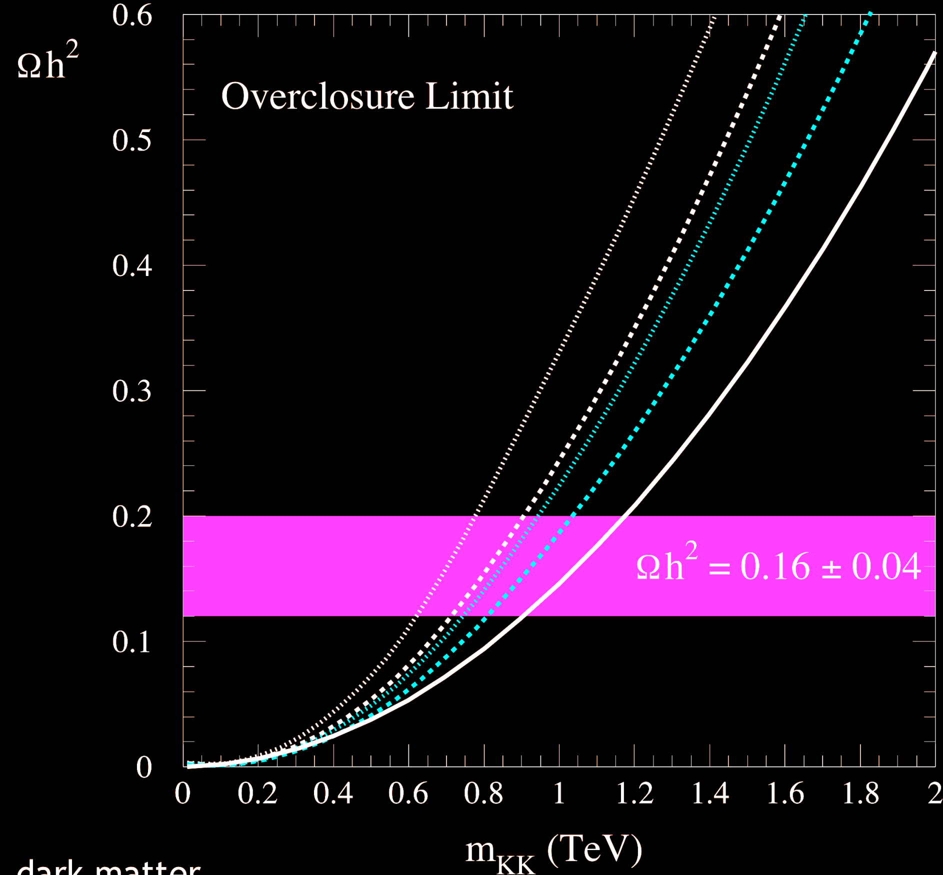
  - are there “visible” radions or other moduli fields?

what defines an ED scenario?

- what is gravity doing?
- who is on the branes and who is in the bulk?
  - who has KK modes?
  - who gets volume-suppressed couplings?
- what about stability+consistency?

extra dimensions and dark matter

- new ideas!
- Universal Extra Dimensions: we live in the bulk of an orbifold compactification
- is this case the LKP is stable



B_1 dark matter

Servant and Tait

these LKPs will be show up at LHC and in direct+indirect searches

extra dimensions and dark energy

- new ideas!
- (1) self-tuning branes
- (2) late-time self-accelerating braneworlds

self-tuning branes

- *usual problem:* even if vacuum energy is 0 after inflation, gets huge contributions later from e.g. EWSB, QCD
- *new idea:* if we are on a brane, these effects contribute just to brane tension
- *strategy:* try to find brane+bulk setup where 4d brane is flat *independent* of the value of the brane tension

self-tuning branes

- solves part of the bigger DE problem
- seems to work better in 6D than in 5D
- requires strong model assumptions

Kachru, Schulz, Silverstein (2000)
Arkani-Hamed, Dimopoulos, Kaloper, Sundrum (2000)
Forste, Lalak, Lavignac, Nilles (2000)
Chen, Luty, Ponton (2000)
Carroll, Guica (2003)
Navarro (2003)
Aghababaie, Burgess, Parameswaran, Quevedo (2003)
Nilles, Papazoglou, Tasinato (2003)

self-accelerating braneworlds

- *usual problem*: why is expansion accelerating, and why now?
- *new idea*: instead of a new source, change the Friedmann equation
- *strategy*: start with 5D DGP braneworld, derive 4D effective Friedmann eqn

Dvali, Gabadadze, Porrati (2000)
Dvali, Gabadadze (2001)
Dvali, Gabadadze, Kolanovic, Nitti (2002)
Deffayet, Dvali, Gabadadze (2002)
Dvali and Turner (2003)

self-accelerating braneworlds

- **DGP braneworld: assume we live on 4D tensionless brane in 5D space with**
- $S_{grav} = \frac{M^2_{Planck}}{r_c} \int d^5x \sqrt{g} R_5 + M^2_{Planck} \int d^4x \sqrt{g} R_4$
- **for** $r << r_c$ **observer on brane sees 4D gravity**
- **but 4D Friedmann eqn becomes**

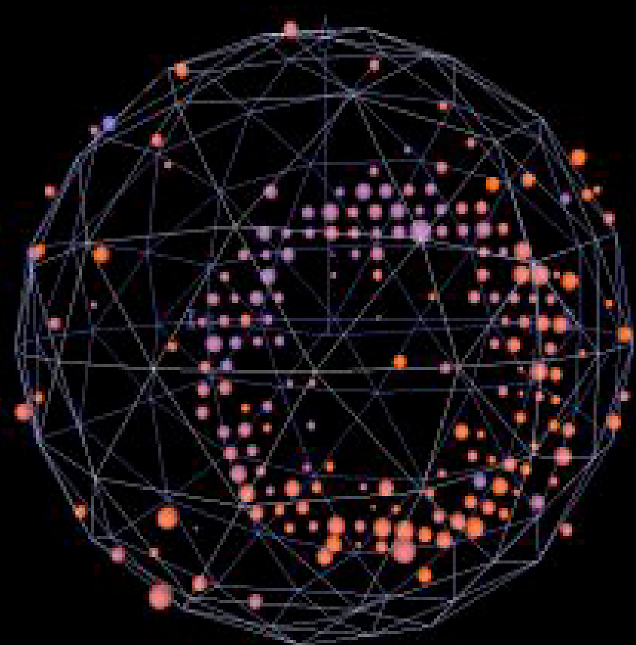
$$H^2 + \frac{H}{r_c} = \frac{\rho_{brane}}{3M_{Planck}}$$

4D expansion self-accelerates for $r_c \sim H_{now}$

self-accelerating braneworlds

- solves part of the bigger DE problem
- seems to work better in 5D than in 6D
- requires strong model assumptions

big idea #3



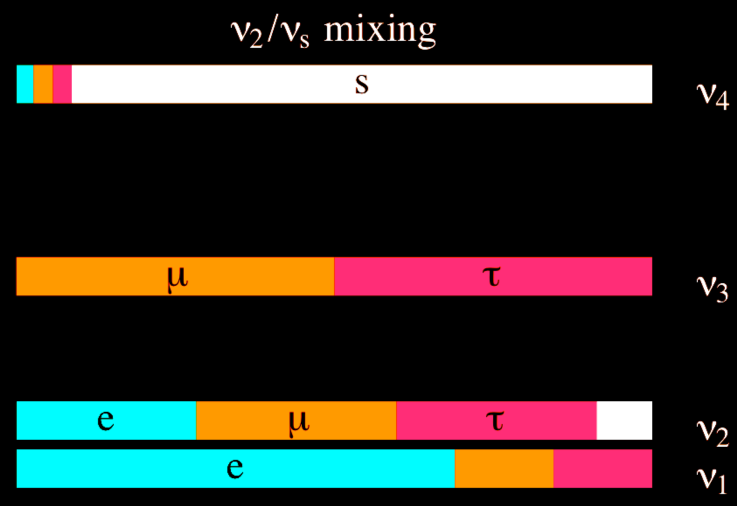
neutrinos

- *neutrinos are particles, not ideas*
- *but the neutrino sector is full of surprises*
- *could be source of unexpected insights about e.g. dark energy*
- *currently experiments have seen 3 different neutrino oscillation lengths -not possible if only 3 neutrino species*

- *only unconfirmed result is LSND, which sees the largest neutrino mass difference, ~ 1 eV*

- *LSND is being checked by the MiniBooNE expt at Fermilab now, results next year*

- *A MiniBooNE signal -> sterile neutrinos or exotic new physics*



neutrinos and dark energy

$$\Lambda_{\mathrm{DE}} \sim (2 \times 10^{-3}\ \mathrm{eV})^4$$
$$\delta \mathrm{m}_\nu^2 \sim (10^{-2})^2$$

- is this a coincidence or a clue?
- are both DE and the neutrino sector sensitive to Planckian physics?

  Barenboim and Mavromatos (2004)
- do neutrinos get mass by coupling to the quintessence field?

  Fardon, Nelson, Weiner (2003)
  Kaplan, Nelson, Weiner (2004)
- both cases predict a signal for MiniBooNE

conclusion:
there is more than one way to catch a big fish