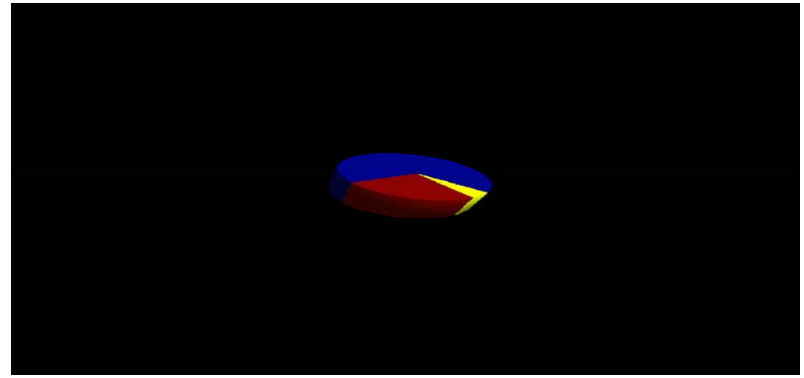


Colloquium
Thursday, August 11, 3:00 PM
Flug Forum

Gordon Kane
University of Michigan

A Unifying Supersymmetry/Superstring Perspective on Cosmology

Cosmologists and astronomers have now provided a description of the universe with baryons and dark matter and dark energy, beginning with an inflationary phase. From the perspective of string theory and its supersymmetric 4D world all these features and others may be related, perhaps very closely. Current research is probing these connections in a number of ways.

Everyone is invited to this informative talk
especially designed for physicists not in this field.

Refreshments will be served outside after the talk.

- Universe has baryonic matter, dark matter, dark energy, neutrinos, photons

- Baryonic matter – why not matter and antimatter? -- why observed amount?
- Dark matter – clumps gravitationally, but doesn't form stars – what is it (stable lightest superpartner? axions? other wimp?) -- why observed amount?
- Dark energy – what is it?

- Looks very arbitrary to astronomers, cosmologists, formal string theorists, other physicists, real people, reporters
- But with an underlying theory all forms may be connected! – and connected to other phenomena! – need a rich theory that addresses many phenomena
- In fact, potentially realistic models usually have baryons, wimps, axions – question is how much of each – maybe one dominates – probably dark energy is also typical

- All beyond the Standard Model – SM an amazing and wonderful theory that does describe the world we see, quarks (so hadrons, nuclei), leptons (electron, muon, tau), strong and weak and electromagnetic interactions, but it *cannot* explain matter asymmetry, dark matter, dark energy, inflation

1. What is the inflaton?
   -- several candidates

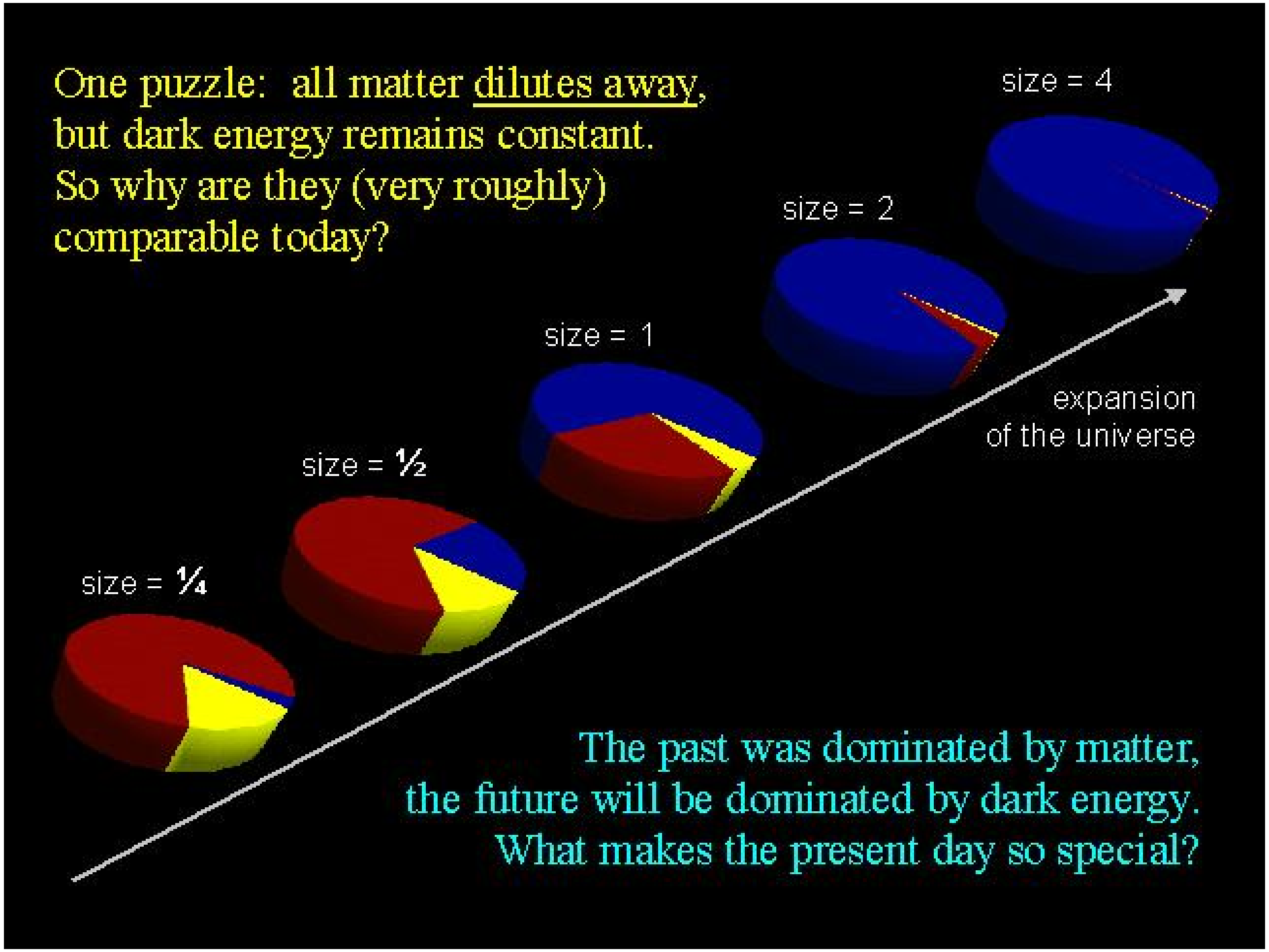
2. What is the origin of the matter-antimatter asymmetry?
   -- several candidates

3. What is the dark matter and how is it produced?
   -- several candidates, several mechanisms

4. What is the dark energy?
   -- several possibilities

5. Why about the same amounts of baryons, DM, DE today? – note density of matter decreases as scale factor grows, density of dark energy constant -- big problem? – coincidence? – profound problem? – note the forms of energy density can interact

From Sean Carroll



Some assumptions:

Default: universe came into existence, 3 space dimensions inflated because of quantum fluctuations or scalar energy density – decayed into particles in big bang

Presumably 4D theory supersymmetric Standard Model, so initial particles include quarks, leptons, gauge bosons, superpartners

(supersymmetry – all the SM particles have a superpartner with same quantum numbers except spin – Lagrangian, interactions known except for masses)

Presumably there is an underlying string theory

Most of what I talk about not much affected by the “defaults” and “presumably’s”

A proper job on citations would take many for each topic, so restrict to locals who started approaches -- apologies

INFLATON?

- Inflation works very well – for our purposes assume it happened – so we have a description -- accomodates all data
- Won't really understand it until we identify the physics of the energy density that makes inflation happen, i.e. the quantum numbers and interactions of the inflaton
  - Quantum theory says the structure of the vacuum is describable by simple harmonic oscillators – like a spring, with negative pressure

    $$dU=-pdV=+kxdx$$

    so non-zero vacuum energy would provide inflation
  - Scalar fields, e.g. Higgs-like fields (but not our Higgs), can provide inflation
  - RH sneutrino – if neutrinos get mass by seesaw need heavy RH Majorana neutrino, its superpartner
  - String theory moduli, scalars that parameterize e.g. sizes of small dimensions – that inflaton might be moduli considered soon after beginning of string theory, but problems – recently major progress
  - Distances between branes embedded in higher dimensional space

All promising, none completely successful

MATTER ASYMMETRY

- o Dirac and Pauli worried about it, 1933
- o Andrei Sakharov, 1967 – a theory can give a matter asymmetry if it violates B, CP, C, and is not in thermal equilibrium
- o SM satisfies conditions, but resulting asymmetry far too small
- o Today several good approaches – probably all need supersymmetry

  - As universe cools have phase transition at ~ 100 GeV, where electroweak symmetry is broken

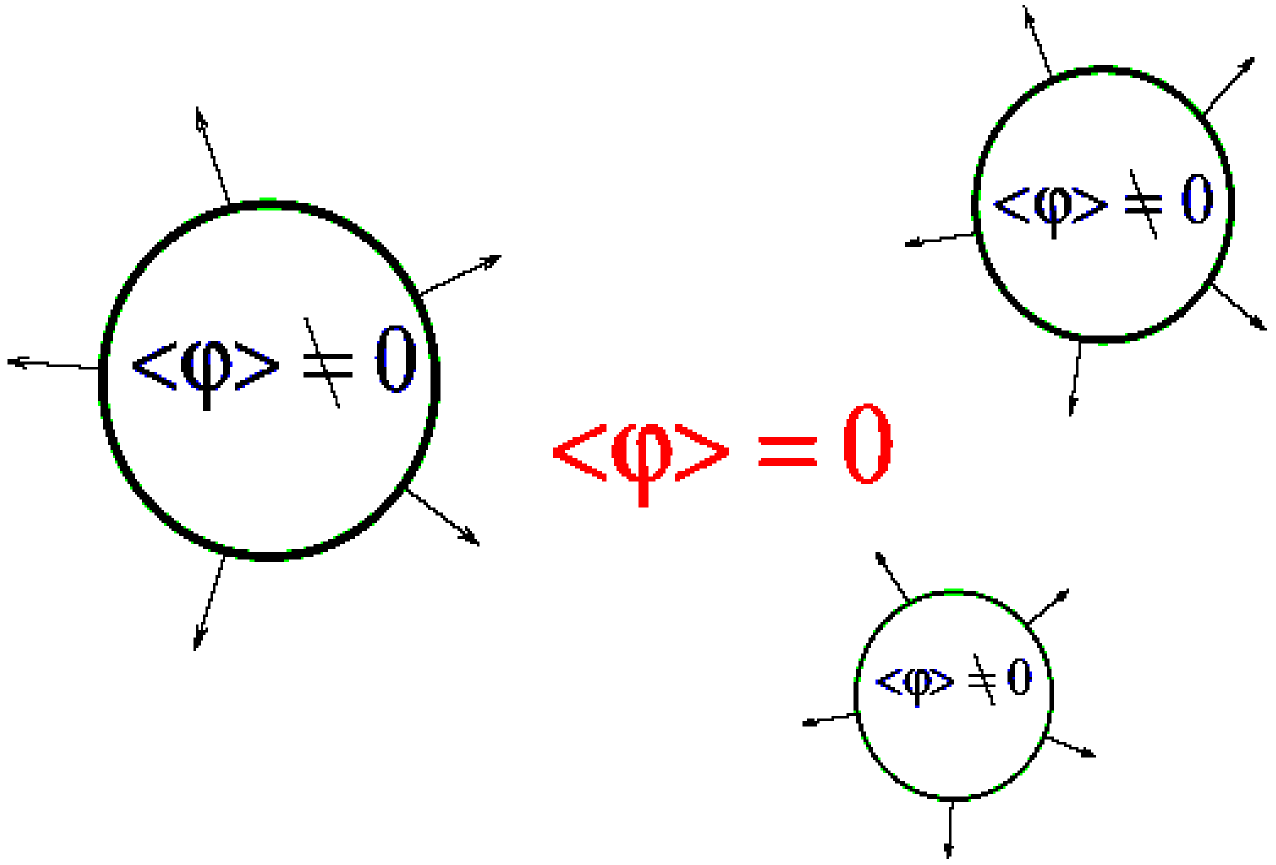
  - Leptogenesis – get difference in decays of heavy RH Majorana neutrinos or sneutrinos – Majorana fermions are their own charge conjugate so violate lepton number conservation – generate lepton matter asymmetry – SM and many theories that contain the SM conserve B-L so generate B asymmetry

  - Squarks, superpartners of quarks, are scalar fields that can oscillate in early universe and generate squark asymmetry → quark asymmetry (Affleck-Dine mechanism)

All can get right answer – all have some tests – EW phase transition soon testable, needs supersymmetric Higgs boson with M_h<115-120 GeV, top quark superpartner not heavier than top quark, …

All will contribute, perhaps one dominates

Baryon number is generated by reactions in and around the bubble walls.



DARK MATTER

- Two candidates proposed before need for non-baryonic dark matter established from astronomy

  -- lightest superpartner, generally stable, e.g. photino or higgsino or zino (really linear combination) – or sneutrino – “LSPs”, “wimps”

  -- axions, goldstone bosons from breaking of global symmetries, get (small) mass from “other” interactions – lots of broken symmetries

- Lots of others – more “wimps”

- Present number depends on production, annihilation as universe cools, entropy – so can calculate in a definite model, but not model-independent

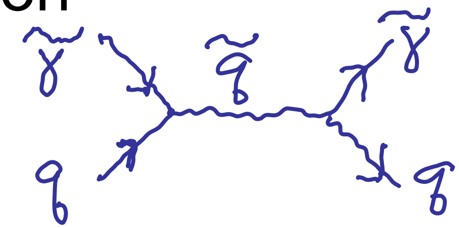
  -- number might be in thermal equilibrium as universe cooled, until a freeze-out

  -- or arise from decay of other states, gravitinos or moduli

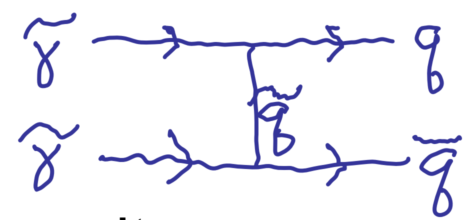
  -- in presence of some forms of dark energy, thermal equilbrium calculation can change dramatically

- Most forms of DM directly or indirectly testable, often detectable in lab experiments

  -- wimps scatter on nuclei in detectors, deposit detectable recoil energy, “direct detection”

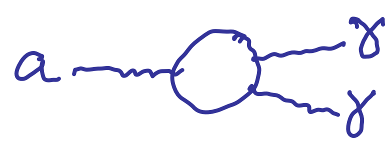


  -- wimps accumulate at center of earth, sun – annihilate into SM particles → very energetic neutrinos which react in underground detectors, produce muons

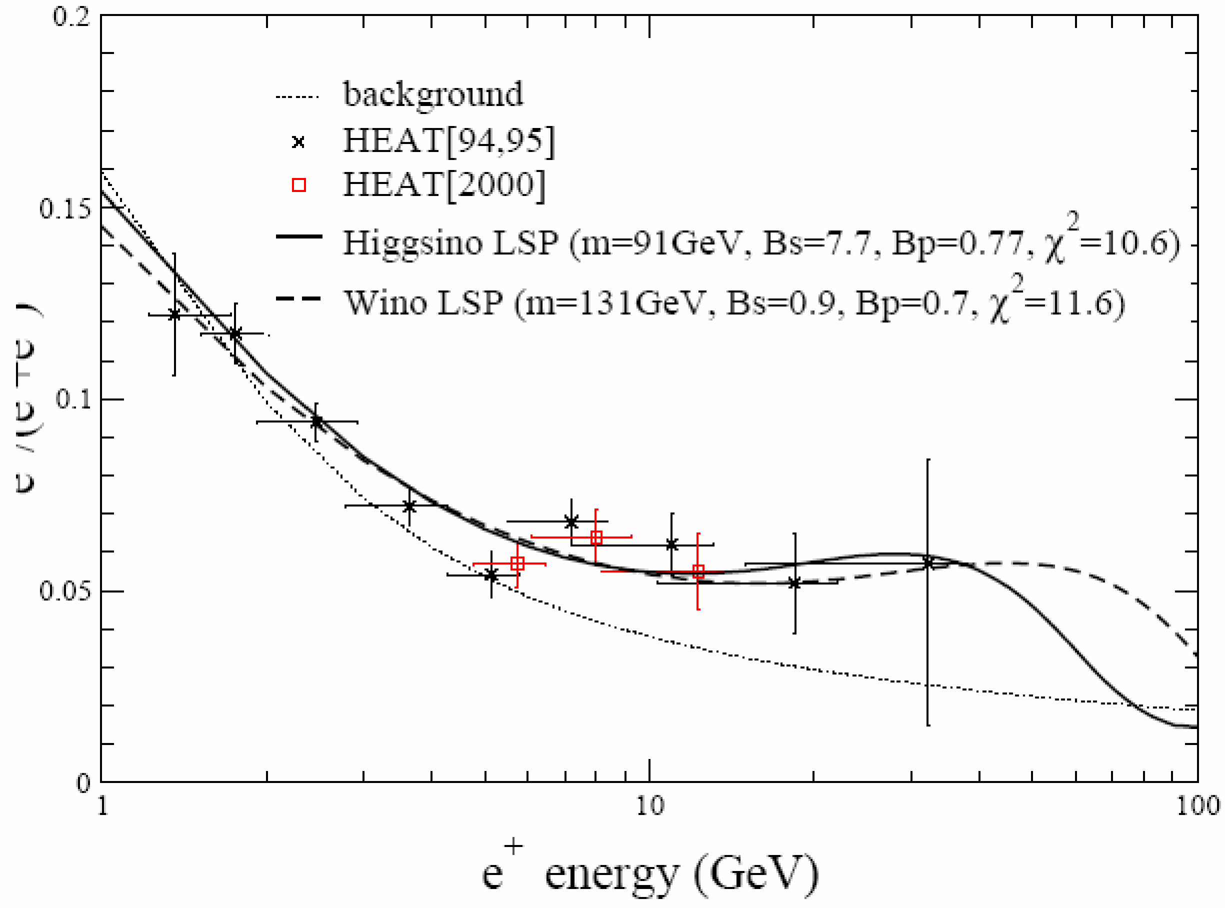


  -- wimps annihilate in galaxy → excess positrons, antiprotons, photons – HEAT – Pamela, AMS

  -- axions couple to photons so can produce photons in strong magnetic field



HEAT data, description with LSP



WHAT IS THE DARK ENERGY?

Part of the cosmological constant problem

- Sometimes people say this is the most important problem in particle physics…

  -- Naïve quantum fluctuations generate energy density

$$\sim M_{pl}^{4}$$

- In fully supersymmetric theory bosonic and fermionic quantum fluctuations cancel → zero CC
- If supersymmetry broken, estimate is

$$(M_{susy}^{2} - M_{SM}^{2})M_{pl}^{2} \approx M_{susy}^{2} M_{pl}^{2}$$

  and for early universe the susy breaking scale is set by the Hubble parameter H which may be a few orders of magnitude below the Planck mass, so problem is slightly ameliorated

- So many string theorists, cosmologists think more clever symmetry needed to get zero after susy breaking, expect solution will affect strongly the rest of particle physics
- MAYBE

DARK ENERGY

魔 MAGIC

[MAGIC CARD ✚]

SDK-020

A Fiend-Type monster equipped with this card increases its ATK and DEF by 300 points.

04614116

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- Really two problems:
  -- eliminate large naïve energy density
  -- explain small observed energy density

    (associated mass scale ~ 3×10^{-4}eV)

- Sometimes people say we have no clue about how to solve either of these

- Several new approaches
  -- extra dimensions
  -- scalar fields, perhaps with different dynamics ("quintessance")
  -- modify Einstein/Freidman equations
  -- less naïve quantum fluctuations
  -- many vacua, approximately degenerate – ours OK to give carbon
    - o Sort of anthropic – give up normal understanding, but not stronger than that – fine tuned rather than natural
    - o Landscape – similar but coming from opposite direction

    Having many vacua arose as implication of inflation, string theory before needed

Consider one incomplete approach to maybe less naïve estimate of effect of vacuum fluctuations (GK, Perry, Zytkow, Phys Lett (2005)B609)

(also see Tye, Sarrangi analysis on wave function of universe)

→ small, non-zero, non-anthropic CC

At beginning of inflation universe is in de Sitter space

Assume many degenerate string theory vacua, but not usual "landscape"

(Cartoon: think of two levels and degenerate levels in quantum theory – levels mix, one pushed up, one down – system falls into lowest level, which is ground state)

In deS space tunneling between minima is not significantly suppressed -- Hawking-Moss tunneling – tunneling absent in Minkowski and AdS spaces

Crudely, ground state is lowered by $1/N_{vacua}$

Better, cannot put ground state in any particular vacuum – must form quantum mechanical superposition of vacua -- like Bloch wavefunction – system will relax to ground state

As universe cools, tunneling suppressed by cooling, decoherence – eventually system in single superposition vacuum – Bloch wavefunction includes many vacua, so system likely to collapse to vacuum with small energy density

To calculate actual energy density of ground state presently too hard – get observed answer if $N_{vacua} \sim 10^{100}$ – reasonable from stringy estimates where estimates ~ $10^{300\text{-}500}$

Presumably only vacua important in superposition have 3 families, SM gauge group, etc – very interesting question – what can be superimposed also determined by 6 small dimensions

Examining whether inflation could be caused by quantum fluctuations in this approach – automatically turns off as approach ground state – maybe

Still an approach because much has to be calculated, confirmed

Not obviously wrong, worth considerable study since does give small positive non-anthropic CC

Conservative, just a quantum theory estimate of effect of quantum fluctuations if world is a stringy one with large number of approximately degenerate vacua

May be more general but at beginning of inflation definitely in deS space where approach is technically OK

WHAT DATA MIGHT HELP?

- Baryogenesis?

  -- ratio of matter to DM known well enough, sign known

  -- residual antimatter in universe?

  -- to test EW baryogenesis need to know weak scale superpartners exist, masses of stop and lightest higgs boson, relative phase of chargino and higgsino masses

  -- no reason to think phases in rotation between quark mass and weak eigenstates (the CKM matrix) connected to baryogenesis phase

  -- phase of matrix (MNS matrix) that relates symmetry and mass eigenstates for neutrinos? – maybe, not clear since may have little connection with high scale phases -- leptogenesis has constraints, depends also on thermal history of universe

  -- Afflect-Dine mechanism requires supersymmetry

- Dark Matter?

  -- Don’t need to know amount better

  -- Cosmology, astronomy data probably won’t help, except maybe photons

  -- Need collider data about what wimps could exist, need direct detection, underground lab detection of neutrinos, space detection of positrons, antiprotons, photons

  -- Need axion detection experiments

  -- Detection of wimp or axion *does not imply* the dark matter has been detected – actual relic density must be calculated, it cannot be measured – for LSP need to measure mass, composition to calculate relic density, and other susy parameters – LSP mass cannot be measured at hadron collider – collider plus direct detection may allow mass to be measured

- Dark energy?

-- Don’t need to know amount better

-- Knowing equation of state better could be very important, $w=p/\rho$

-- CC → w=-1, other explanations w>-1,

-- CC → w=constant, so important to learn about time dependence

-- present data, w=-1± about 0.15, consistent with no time dependence

CONCLUDING REMARKS

- If there is a real theory, then all the cosmological phenomena are related – if the theory has input parameters then they determine more than one part of the cosmology in general – ratios of baryons, DE, DM calculable
- E.g., string theory – moduli may be inflaton, same physics that gives moduli potentials also determines susy breaking so give LSP mass (crucial for DM), and also predicts collider physics
- Or – consider neutrino+sneutrino sector – LH tau sneutrino can be the LSP and DM, assuming non-thermal production --- RH sneutrino can be inflaton – decay of RH Majorana neutrinos or sneutrinos can give leptogenesis → baryogenesis – can have see-saw mechanism giving small neutrino masses – all parts of this have been worked out, though not combined

PARTICLE COSMOLOGY IS AT AN EXCITING TIME, POISED FOR LARGE PROGRESS IN UNDERSTANDING – LIKELY TO CONNECT CLOSELY TO STRING PHENOMENOLOGY* IN SEVERAL WAYS

* STRING PHENOMENOLOGY IS AN EMERGING NEW SUBFIELD OF PHYSICS

String phenomenology attempts to **explain** at least:
(definition of string phenomenology)

No other subfield focuses on these

- No large cosmological constant
- Dark energy—what, how much
- What is the dark matter
- Baryon asymmetry – amount, origin
- Inflation, big bang
- Standard model (why quarks and leptons, their charges, gauge group)
- Electroweak symmetry breaking – calculate M_Z, $\tan\beta$
- Unification of forces
- Supersymmetry
- Supersymmetry breaking
- Superpartner masses – collider data
- Number of families – why not 1?
- Quark and lepton and neutrino masses
- Origin and pattern of CP violation
- Flavor changing interactions – size, chirality