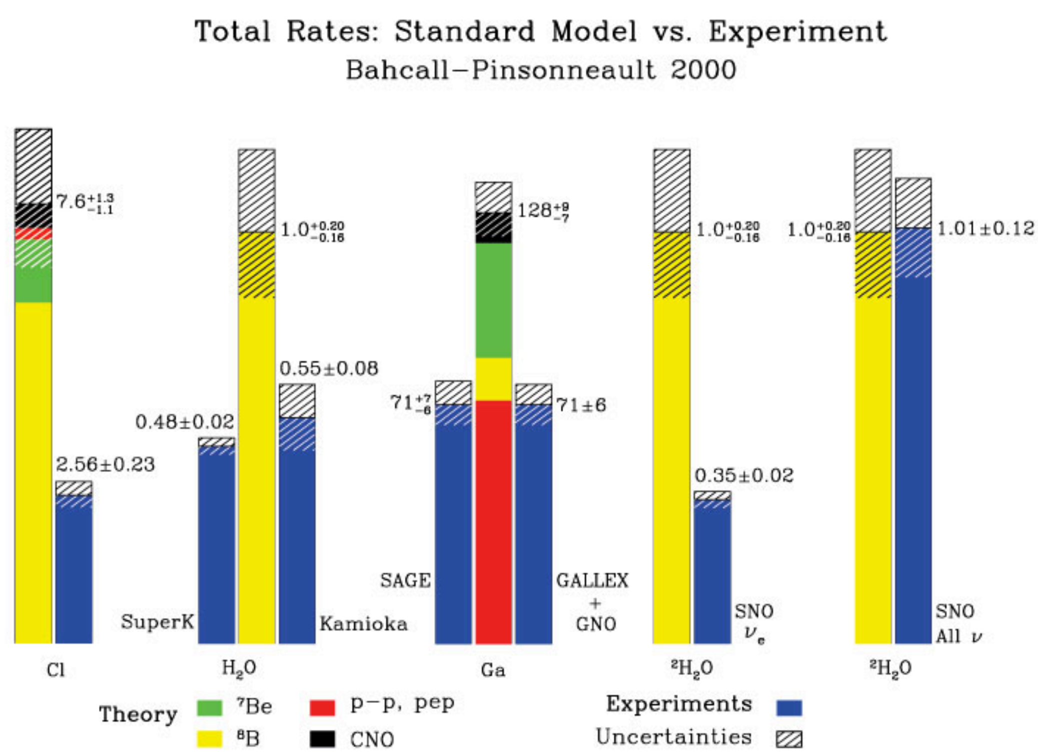
Some PPPs (particle physics puzzles)

- What's up with neutrinos?
- What is dark matter?
- What is dark energy?
- Where does inflation come from?
- Why is there more matter than antimatter?
- Are there even more fundamental entities than quarks and leptons?
- Are there unknown forces?

Neutrinos DISAPPEAR!

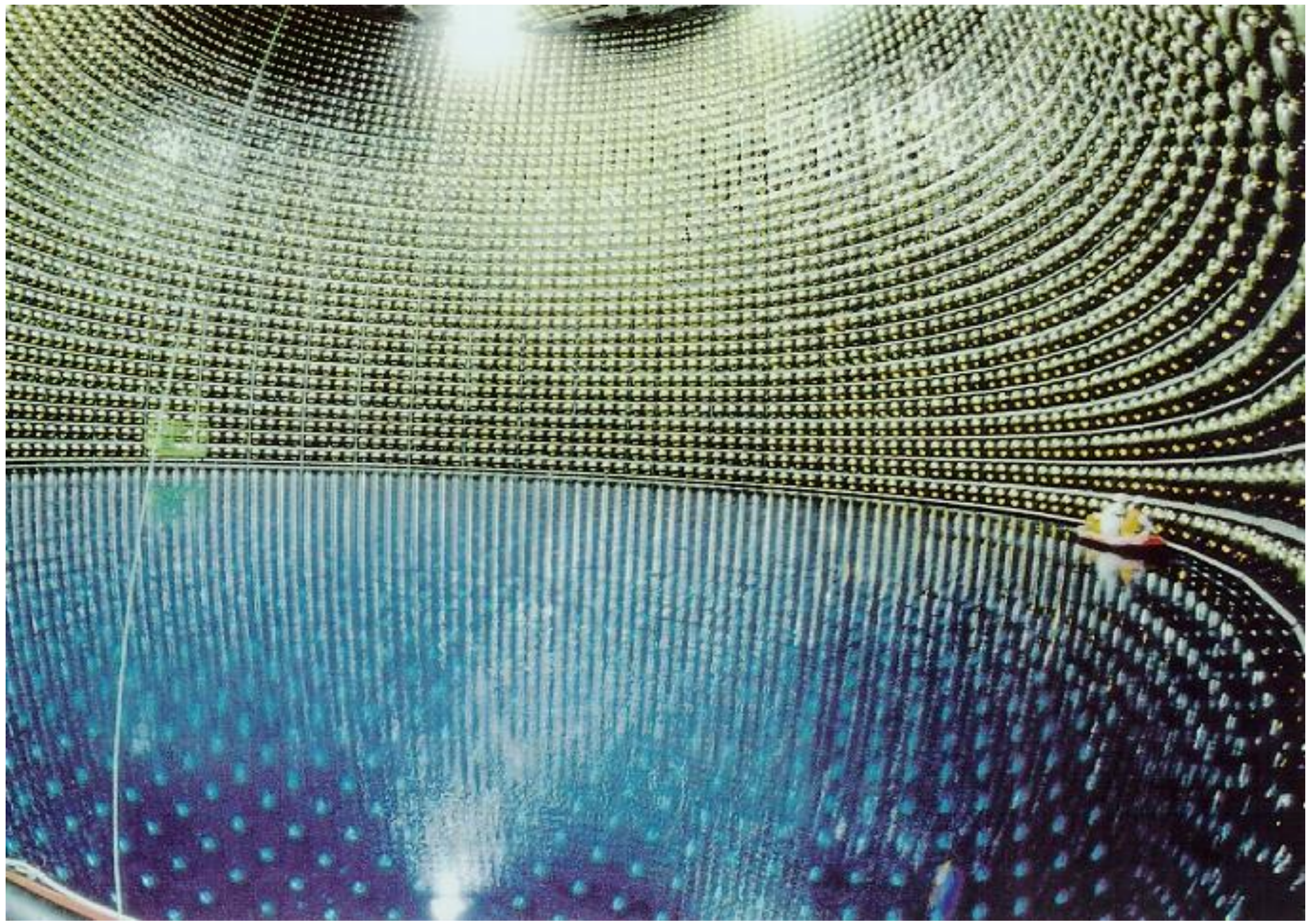
- Originally discovered by Ray Davis: there are too few neutrinos coming from the sun

- Original experiment in Homestead Mine (Cl): Only 1/3 of expected flux
- Confirmed by Sage, Gallex, Super-K, SNO, …
- Confirmed with reactors: Bugey, Chooz, KamLand,… and accelerator neutrinos (T2K, NOνA,…)
- Also found disappearance of μ-neutrinos in atmosphere: Super-K.



Kamiokande, Super-K

- Detect neutrinos from sun and atmospheric neutrinos
- Only 50% of solar νs
- Detection via Cherenkov Light



Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

SNO

- Heavy Water Cherenkov detector
- Sensitive to all 3 types of ν's with different observables:
  $d + \nu_e \rightarrow p + p + e^-$;
  $d + \nu_\mu \rightarrow p + n + \nu_\mu$
- First unambiguous confirmation that total number of ν's from sun is as expected -
  only flavor
  changes

Nobelpr
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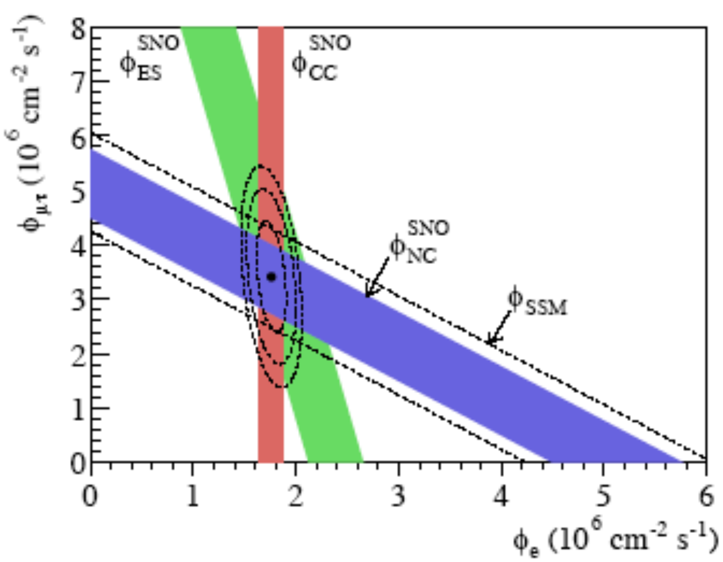
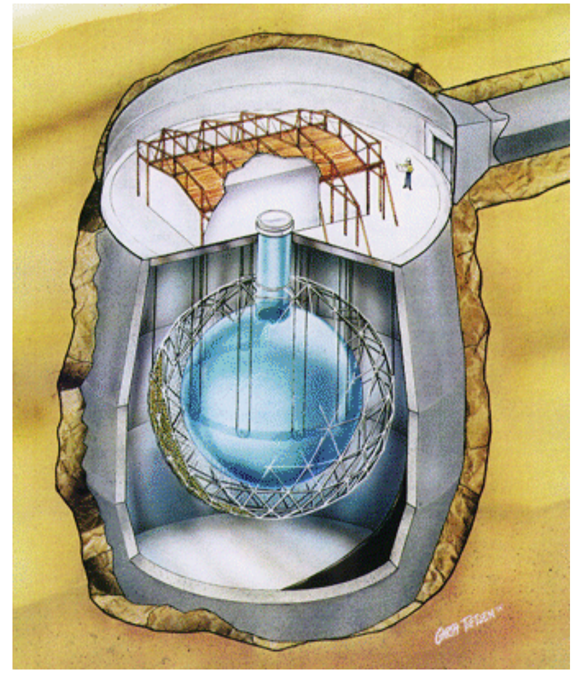




The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

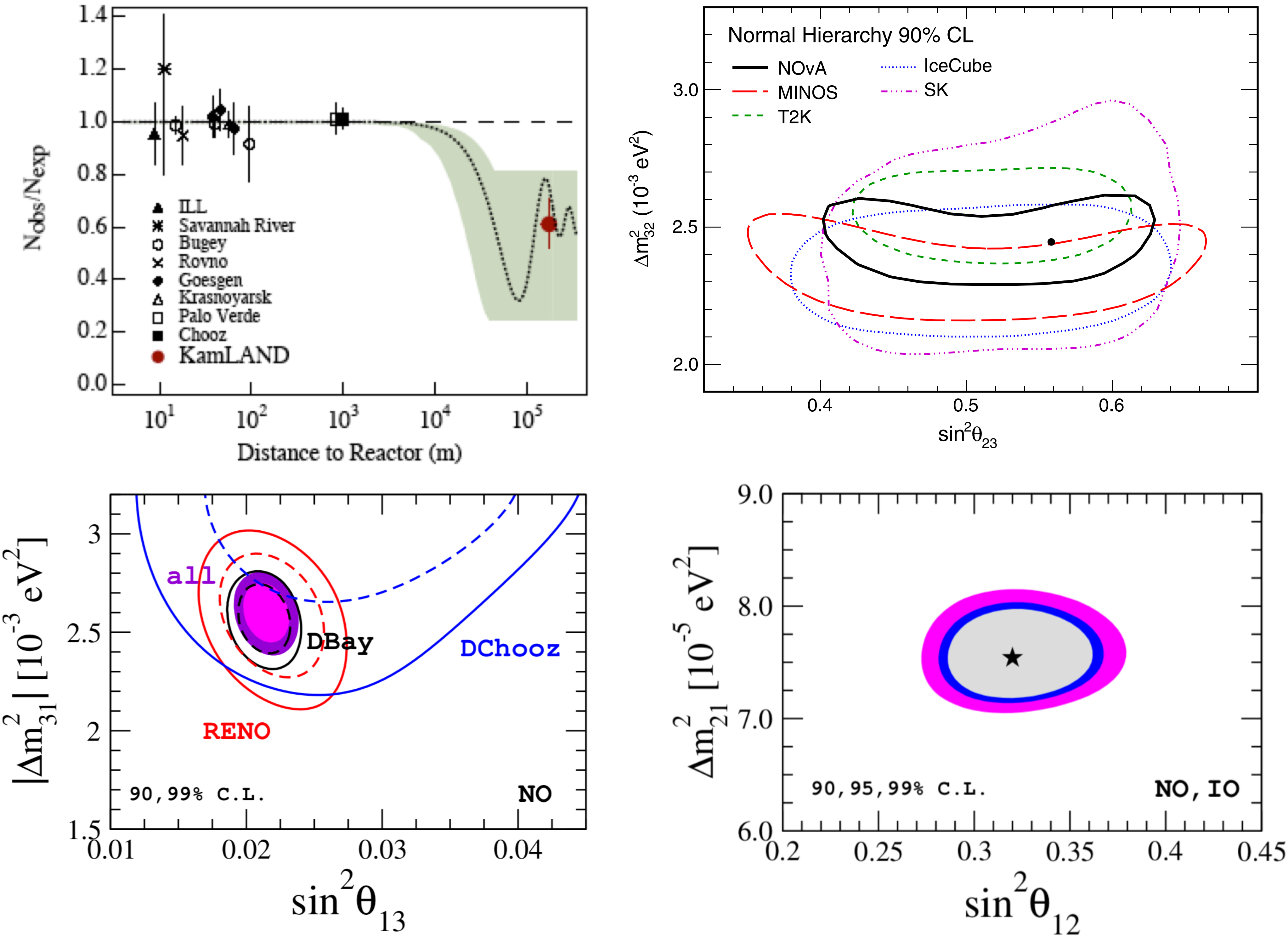
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Explanation: 2 –neutrino model

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)\ \text{(natural units)}.$$

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\text{eV}^2]\,[\text{km}]}{[\text{GeV}]}\right).$$

- The mass differences, Δm^2, are known to be on the order of 1×10^{-4} eV^2
- Oscillation distances, L, in modern experiments are on the order of kilometers
- Neutrino energies, E, in modern experiments are typically on order of MeV or GeV.

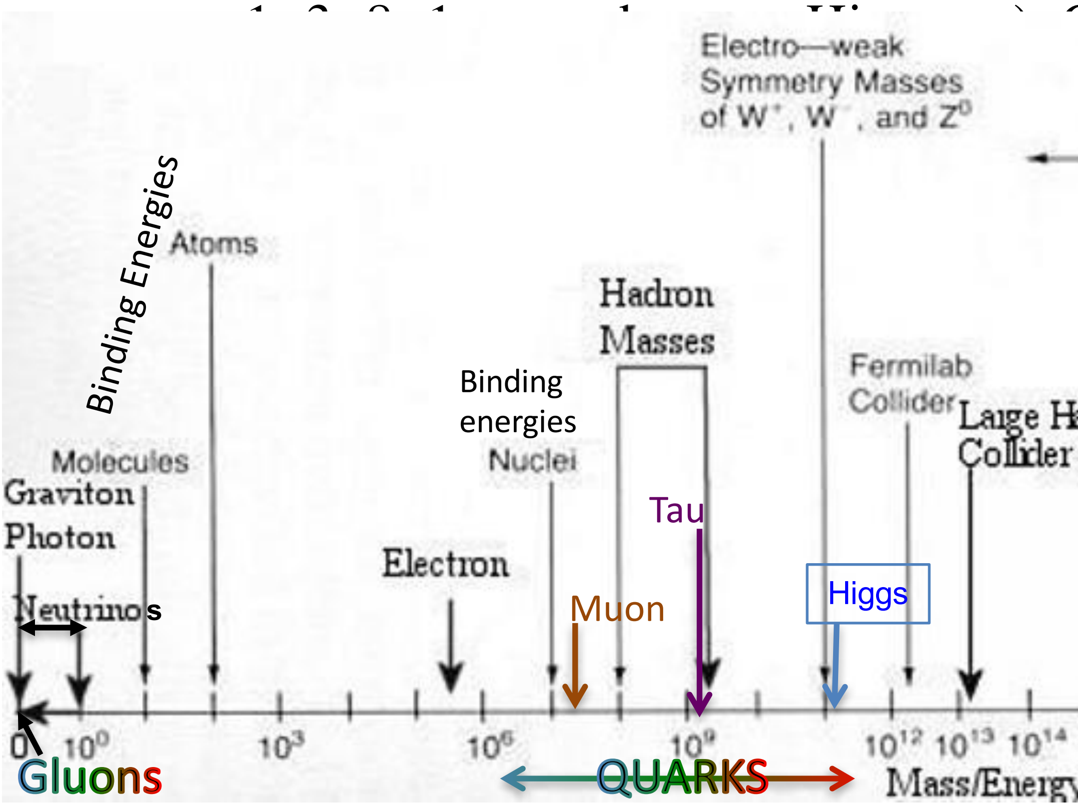


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Nobs/Nexp
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)
Normal Hierarchy 90% CL
NOvA
MINOS
T2K
IceCube
SK
3.0
2.5
2.0
Δm^2_{32} (10^{-3} eV^2)
0.4
0.5
0.6
$\sin^2\theta_{23}$
3
2.5
2
1.5
$|\Delta m^2_{31}|$ [10^{-3} eV^2]
all
DBay
DChooz
RENO
90,99% C.L.
NO
0.01
0.02
0.03
0.04
$\sin^2\theta_{13}$
9.0
8.0
7.0
6.0
Δm^2_{21} [10^{-5} eV^2]
90,95,99% C.L.
NO, IO
0.2
0.25
0.3
0.35
0.4
0.45
$\sin^2\theta_{12}$

Deficiencies of the Standard Model

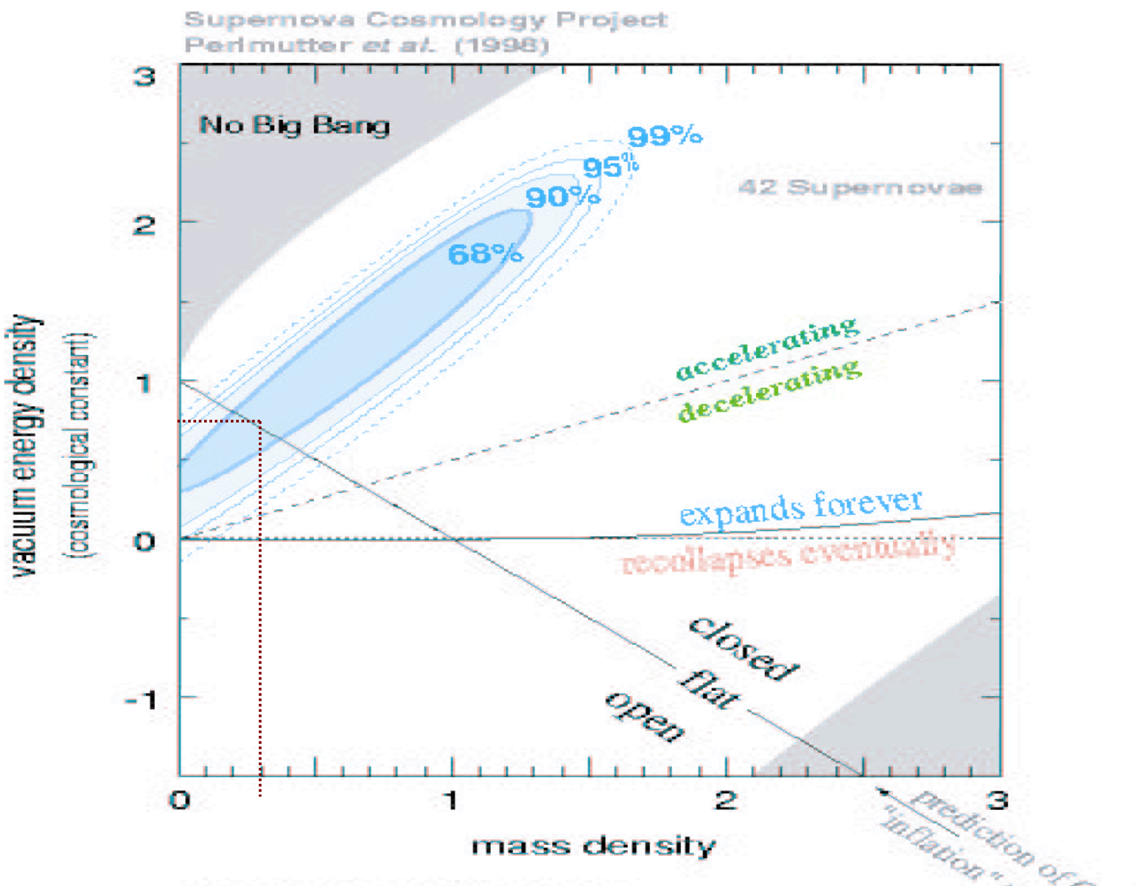
The Standard Model is really successful, but…

- Does (fundamental particle rest) mas
    - Why are the masses so vastly di
      Lowest mass neutrino eigenstate
      quark t (top quark) $\rightarrow$ 170,000,0
- Why are there so many "fundamenta

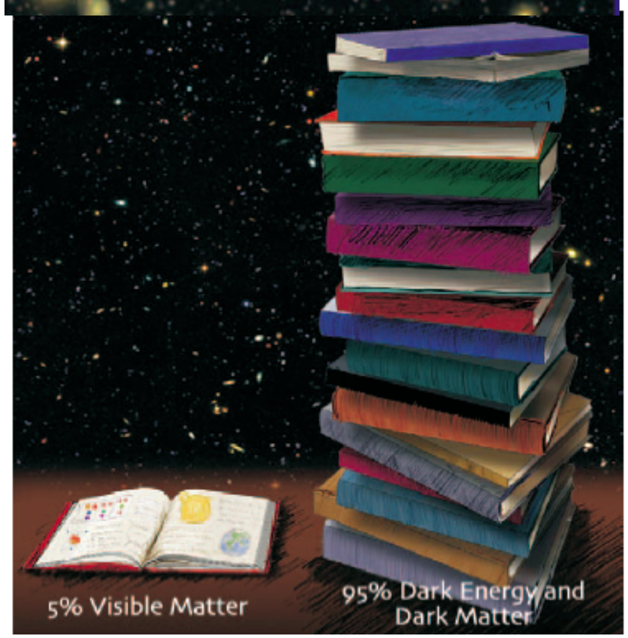


Deficiencies of the Standard Model

We observe much more gravitation in the Universe than can be explained by visible mass (and even by **all** hadronic and leptonic mass left over from the big bang) → WIMPs.



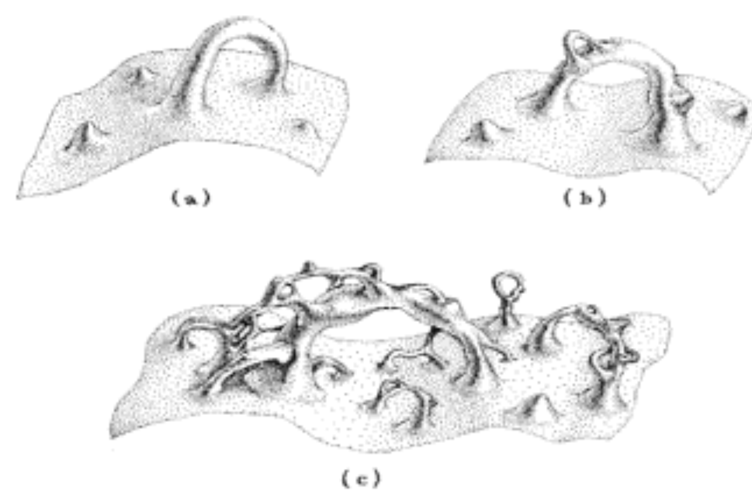
Frank Wilczek



Deficiencies of the Standard Model

Gravitation - what happens at the Planck Scale?

- The Planck Scale - a universal size, time and energy scale
  - Einstein: $E^2 = m^2c^4 + p^2c^2 \Rightarrow E \geq pc$
  - Heisenberg: $\Delta p \cdot \Delta x \geq \hbar/2 \Rightarrow E \geq pc \geq \hbar c/2\Delta x$
  - Newton: $U_{\mathrm{grav}} = m\, GM/r \Rightarrow$ Escape velocity $v_{\mathrm{esc}} = (2GM/r)^{1/2} \leq c \Rightarrow$ Black hole: Schwartzschild radius $R = 2GM/c^2$
  - Einstein: $M \leftarrow E/c^2 \Rightarrow R = 2GE/c^4 \geq 2G\hbar/(2c^3 R)$
  - $\Rightarrow$ Planck length: $\mathrm{R} = (G\hbar/c^3)^{1/2} = 1{\cdot}6.10^{-35}$ m;
    Planck Mass 22μg (10^{19} GeV)
    Planck Energy $2{\cdot}10^9$ J
- What happens at the Planck Scale?
  - Space-Time becomes "frothy"
  - Pointlike interactions make no sense
  - Pointlike particles make no sense



Supersymmetry

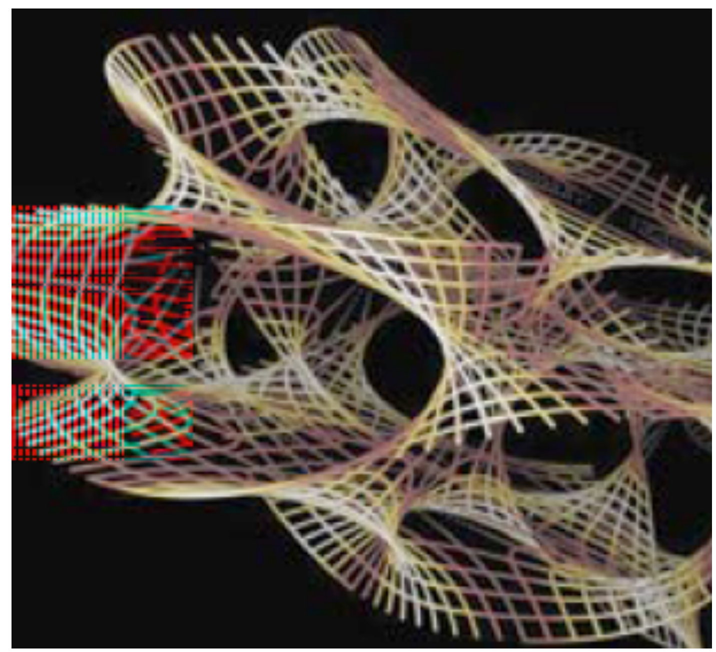
- Fundamental Space-Time-Spin symmetry
- Every Particle has a Super-Partner of different spin (different statistics!):
  - Fermions (S = 1/2) ⇔ sFermions (S = 0)
    - sneutrinos, selectrons, smus, staus, squarks
  - Bosons (S = 0,1,2) ⇔ Bosinos (S = 1/2)
    - winos, zino, photino, gluino, gravitino, higgsino
- May explain dark matter (WIMPs = lightest Super-partner)
- Supersymmetry is broken at high energy scale (1 TeV?) - should be accessible at LHC

Supersymmetry - some (minor?) problems

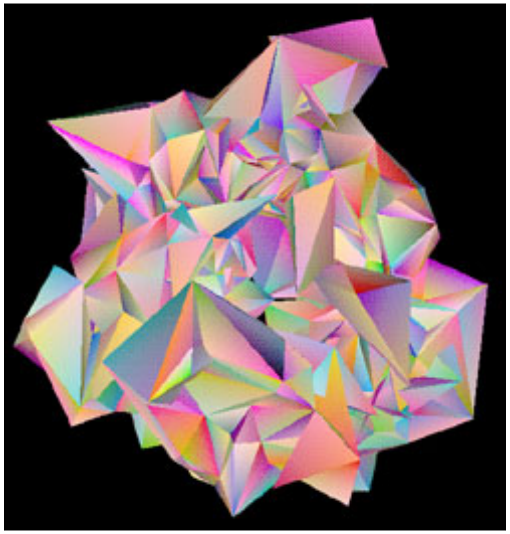
- Now we are supposed to **double** the number of particles (not a single one has been detected yet)? First LHC run came up empty!
- Add to that a whole bunch of other parameters and possibly new interactions (sfermion decays, quark decays -> proton should be unstable, but so far only upper limits have been found)
- Why is supersymmetry broken, and why is it broken at yet another mass scale?

Super-Strings

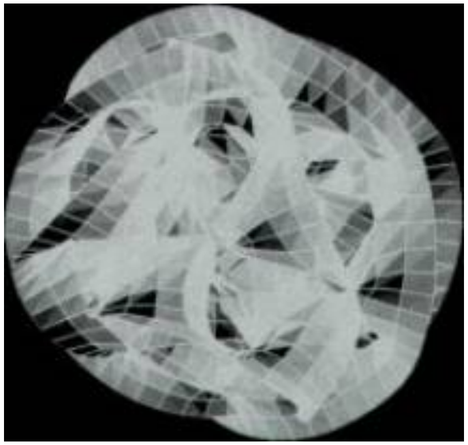
- All particles are vibrations of incredibly tiny strings (of size of the Planck scale, 10^{17} times smaller than resolution of present accelerators). Tension = 10^{9}J/10^{-35}m = 10^{40} tons
- They are “wrapped” around extra dimensions
- Their vibrational energies determine their masses.
- Vibration patterns determine charges and spin (determined by geometry of extra dimensions).
- Original idea: Kaluza-Klein.

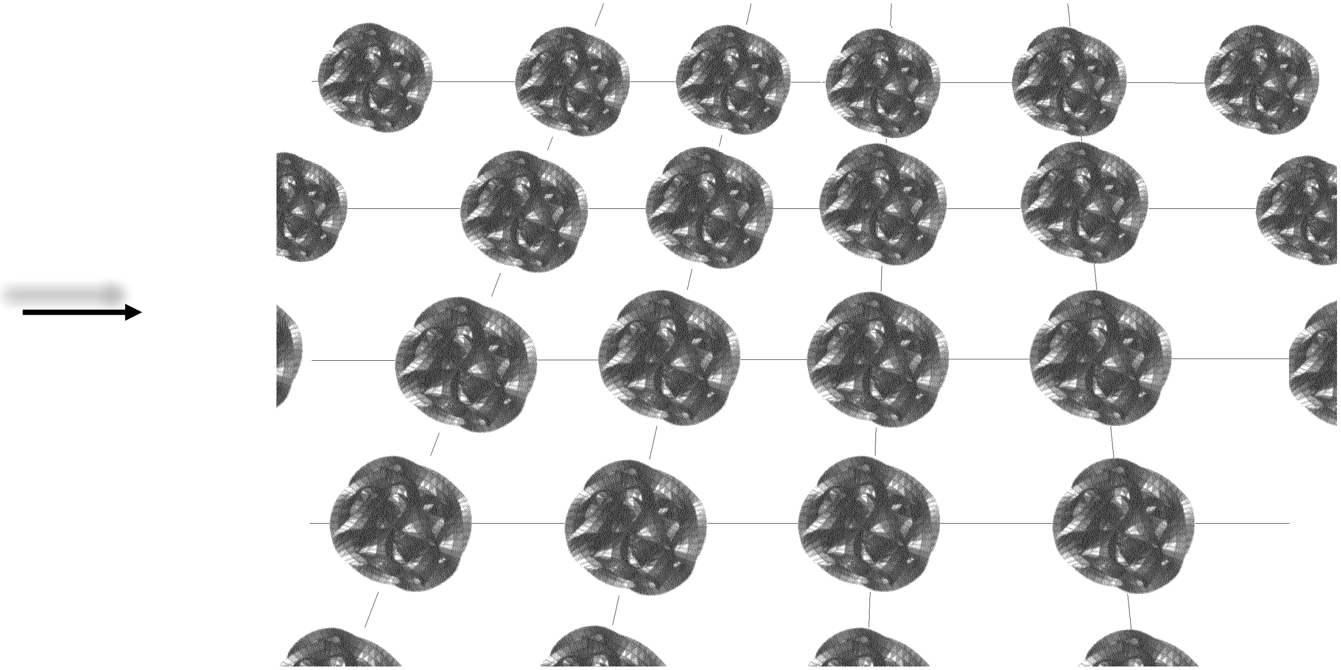


Super-Strings



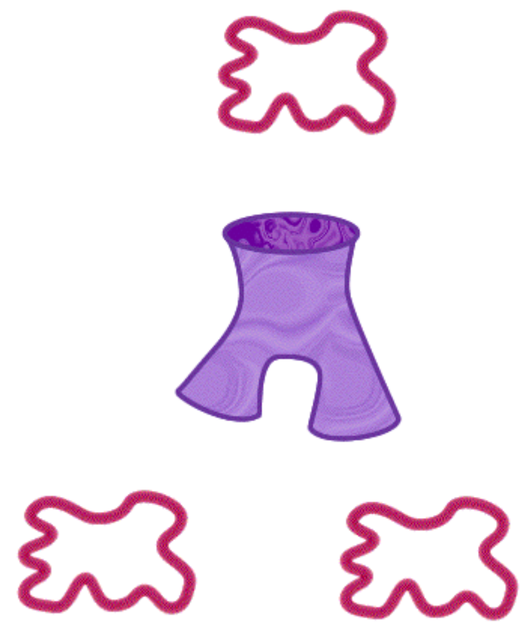
- Require 9+1 dimensions to avoid negative probabilities
- Extra dimensions "curled up"
- "Calabi Yau Spaces"
- Compare to ants on a hose





Super-String Theory

- Unified picture of all four interactions
- Avoids singularities in particle interactions - you can't make them smaller than the Planck Length
- Includes Supersymmetry "automatically"
- Could be compatible with all 4 forces uniting in strength at the Planck scale
- Might explain beginning of Universe



Super-Strings - some (minor?) Problems

- Nobody can write down the exact theory (equations aren't fully known)
- Only approximate solutions known
- Many competing versions (Brane theory…) -> too many solutions
- Presently hard to see how we can test them experimentally

The New York Times
nytimes.com

September 2, 2003

One Cosmic Question, Too Many Answers

By DENNIS OVERBYE

Call it the theory of anything.

But the same calculations confirmed that string theory could have a vast number of solutions, each representing a different universe with slightly different laws of physics. The detailed characteristics of any particular one of these universes — the laws that describe the basic forces and particles — might be decided by chance.

As a result, string theorists and cosmologists are confronted with what Dr. Leonard Susskind of Stanford has called "the cosmic landscape," a sort of metarealm of space-times. Contrary to Einstein's hopes, it may be that neither God nor physics chooses among these possibilities, Dr. Susskind contends. Rather it could be life.

Only a fraction of the universes in this metarealm would have the lucky blend of properties suitable for life, Dr. Susskind explained. It should be no surprise that we find ourselves in one of these. "We live where we can live," he said.

Dr. Susskind conceded that many colleagues who harbor the Einsteinian dream of predicting everything are appalled by that notion that God plays dice with the laws of physics.

Among them is **Dr. David Gross**, director of the Kavli Institute of Theoretical Physics in Santa Barbara, Calif., who said, "I'm a total Einsteinian with respect to the ultimate goal of science." Physicists should be able to predict all the parameters of nature, Dr. Gross said, adding, "They're not adjustable."

Nobel Laureate 2004