Quantum Universe

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三者若手夏の学校 Aug 19, 2008
COBE showed quantum origin of the universe.
Quantum Universe

To understand physics at the largest scale: Universe we need to understand the smallest scale: elementary particles

- What is the Universe made of?
- How did it come to be?
- Why do we exist?

Moving from philosophy to physics
There are many things we don’t see
Energy Budget of the Universe

- Stars and galaxies are only $\sim 0.5\%$
- $\nu \sim 0.1-1.5\%$
- Rest of ordinary matter (e, p & n) 4.4\%
- Dark Matter 23\%
- Dark Energy 73\%
- Anti-Matter 0\%
- Dark Field $\sim 10^{62}\%$?
What is Dark Matter?
What is Dark Energy?
Don’t be afraid of invisibles

Pauli regretted to have predicted neutrinos nobody can detect
Trillions of them go through our body every second

SuperKamiokande

The Origin of Solar Energy
taken 3000ft underground
Is there an underlying simplicity behind vast phenomena in Nature?

Einstein dreamed to come up with a unified description.

But he failed to unify electromagnetism and gravity (GR).
History of Unification

- planets
- apple
- gravity
- mechanics
- GR
- electromagnetism
- electric
- magnetic
- Special relativity
- Quantum mechanics
- Quantum ElectroDynamics
- Weak force
- β-decay
- γ-decay
- α-decay
- Strong Force
- String theory?
- Grand Unification?
We are just about to achieve another layer of unification

HERA ep collider

- Unification of electromagnetic and weak forces
  - $\Rightarrow$ electroweak theory
- Long-term goal since ‘60s
- We are getting there!
- The main missing link: Dark Field
major shift

- particle physics has been trying to understand matter and forces since 1897
- since 60’s, standard model has been verified experimentally. Great achievement of the 20th century physics. (*Higgs still needed!*)
- At the same time, we did not see the steps beyond, sense of suffocation
- Now totally changed: data require new physics beyond the standard model!
what we used to do

• Given lack of experimental evidence, we’ve focused on aesthetic reasons why we need physics beyond the standard model
  • hierarchy problem
  • why three generations?
  • masses and mixings?
  • why only one scalar multiplet?
  • why does it condense?
  • anomaly cancellations
  • why SU(3)>SU(2)>U(1)?
Experimental Facts

• Five facts standard model cannot explain
  • finite neutrino mass (1998, 2002)
  • accelerating universe (1998)
  • non-baryonic dark matter (2003)
  • acausal nearly Gaussian scale-invariant density fluctuation (2003)
  • baryon asymmetry (reconfirmed 2003)
Large Hadron Collider (LHC)

Recreating Big Bang

first beam on Sep 10
New Era

- **~1900** reached atomic scale $10^{-8}\text{cm} \approx \alpha/m_e$
- **~1970** reached strong scale $10^{-13}\text{cm} \approx M_e^{-2\pi/\alpha s b_0}$
- **~2010** will reach weak scale $10^{-17}\text{cm}$
- known since Fermi (1933), finally there!
- presumably it is also a derived scale more fundamental theory
- supersymmetry? extra dimensions? string theory?
- If so, we expect rich spectrum of new particles!
New Era

• ~1900 reached atomic scale $10^{-8} \text{cm} \approx \alpha/m_e$
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Outline

- Introduction
- Big Bang
- Dark Matter
- Dark Energy
- Dark Field
- Anti-Matter
- Inflation
- Conclusion
Big-Bang
• Approaching ambulance: higher key
• Moving-away ambulance: lower key
• Much the same way, moving-away stars: lower key (redder) in spectrum of light
• We see distant stars/galaxies are redder
Expansion of Space

- The spacetime itself is stretching, stars dragged away
- Universe getting colder as it expands
- It was much hotter earlier: Big Bang
History of the Universe

Key:
- W, Z bosons
- photon
- quark
- meson
- gluon
- ion
- electron
- baryon
- tau
- neutrino
- galaxy
- star
- atom
- black hole

Particle Data Group, LBNL, © 2008. Supported by DOE and NSF
elementary particles and early universe

- early universe: high temperature $T$
- high energy $E = kT$
- high momentum $p = E/c = kT/c$
- small distance $x = \hbar/p = \hbar c/kT$
- early universe: elementary particles play main roles!
Dark Matter
Evidence for non-baryonic dark matter
Solar system moves at 220km/sec
See the invisible DM through weak lensing
You don’t want to be there

collision at 4500 km/sec
You don’t want to be there.

Collision at 4500 km/sec.
Cosmological scales

matter/all atoms=6.03±0.03

See Tegmark movie
Cosmological scales

matter/all atoms = 6.03 ± 0.03

See Tegmark movie
Known Facts about Dark Matter
Cold and Neutral

- By the time of matter-radiation equality and until now, dark matter must be non-relativistic and clump together by gravitational attraction.
- Must be electrically neutral.
Mass Limits

“Uncertainty Principle”

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- “Bohr radius”: $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won’t “fit” in a galaxy!
- $m > 10^{-22}$ eV “uncertainty principle” bound

(modified from Hu, Barkana, Gruzinov, astro-ph/0003365)
Dim Stars?

Search for MACHOs (Massive Compact Halo Objects)

Large Magellanic Cloud

Not enough of them!
Dim Stars?

Search for **MACHOs** *(Massive Compact Halo Objects)*

Large Magellanic Cloud

Not enough of them!
Mass Limits

• MACHO excluded $10^{-7} \, M_{\odot} < m < 20 \, M_{\odot}$

• Can’t make primordial blackholes (PBH) in a normal smooth Friedmann universe

• there can’t be anything violent since BBN

• maximum mass of PBH is horizon mass@BBN

\[
M_{\text{horizon}} \approx g_* T^4 \left( \frac{M_{Pl}}{g_*^{1/2} T^2} \right)^3 \approx 10^5 \, M_{\odot} \left( \frac{\text{MeV}}{T} \right)^2
\]

• And $m < 40 \, M_{\odot}$ from wide binaries

(Yoo, Chaname, Gould, astro-ph/0307437)
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Summary
Mass Limits

- $10^{-31}$ GeV to $10^{50}$ GeV
- narrowed it down to within 81 orders of magnitude
- a big progress in 70 years since Zwicky
• if self-coupling too big, will “smooth out” cuspy profile at the galactic center

• some people wanted it
  (Spergel and Steinhardt, astro-ph/9909386)

• need core < 35 kpc/h from data
  \[ \sigma < 1.7 \times 10^{-25} \text{ cm}^2 \text{ (m/GeV)} \]
  (Yoshida, Springel, White, astro-ph/0006134)

• bullet cluster:
  \[ \sigma < 1.7 \times 10^{-24} \text{ cm}^2 \text{ (m/GeV)} \]
  (Markevitch et al, astro-ph/0309303)
Lifetime

- At least of the order of age of the universe 14Gyr
- Beyond that, it depends on decay modes, branching fractions, all model-dependent
• It is probably WIMP (Weakly Interacting Massive Particle)
• Stable heavy particle produced in early Universe, left-over from near-complete annihilation
• Will focus on WIMPs for the rest of the talk
WIMP paradigm
thermal relic

- thermal equilibrium when $T > m_\chi$
- Once $T < m_\chi$, no more $\chi$ created
- if stable, only way to lose them is annihilation
- but universe expands and $\chi$ get dilute
- at some point they can’t find each other
- their number in comoving volume “frozen”

Using the above relations ($H = 1.66 g'^2 T^2/m_{pl}$ and the freezeout condition $r = Y_{\chi\chi}(G/2z) = H$), we find

$$n_{\chi 0} = n_{\chi f} = 1001 (m_\chi/m_{100 GeV}) (A/10^{-27} \text{cm}^3 \text{s}^{-1})^{-1},$$

where the subscript $f$ denotes the value at freezeout and the subscript 0 denotes the value today.

The current entropy density is $n_{\chi 0} \approx 4000 \text{ cm}^{-3}$, and the critical density today is $\rho_c \approx 10^{-5} h^2 \text{GeV cm}^{-3}$, where $h$ is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, so the present mass density in units of the critical density is given by

$$0, h^2 = m x n_{\chi 0}/\rho_c \approx 3 \times 10^{-27} \text{cm}^3 C_{10}^{-1}/(\sigma_A v).$$

The result is independent of the mass of the WIMP (except for logarithmic corrections), and is inversely proportional to its annihilation cross section.

Fig. 4 shows numerical solutions to the Boltzmann equation. The equilibrium (solid line) and actual (dashed lines) abundances per comoving volume are plotted as a function of $x = m/T_0$.
Freeze-out

- WIMP freezes out when the annihilation rate drops below the expansion rate
- Yield $Y = n/s$ constant under expansion
- Stronger annihilation $\Rightarrow$ less abundance

Mathematical expressions:

\[ H \approx g_*^{1/2} \frac{T^2}{M_{Pl}} \]

\[ \Gamma_{\text{ann}} \approx \langle \sigma_{\text{ann}} v \rangle n \]

\[ H(T_f) = \Gamma_{\text{ann}} \]

\[ n \approx g_*^{1/2} \frac{T_f^2}{M_{Pl} \langle \sigma_{\text{ann}} v \rangle} \]

\[ s \approx g_* T^3 \]

\[ Y = \frac{n}{s} \approx g_*^{-1/2} \frac{1}{M_{Pl} T_f \langle \sigma_{\text{ann}} v \rangle} \]

\[ \Omega_\chi = \frac{m_\chi Y s_0}{\rho_c} \]

\[ \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\text{ann}} v \rangle} \frac{s_0}{H_0^2} \]
Order of magnitude

- “Known” $\Omega_\chi = 0.23$ determines the WIMP annihilation cross section
- Simple estimate of the annihilation cross section
- Weak-scale mass!!!

\[
\Omega_\chi \approx g_*^{-1/2} \frac{xf}{M^3_{Pl} \langle \sigma_{ann} v \rangle} \frac{s_0}{H_0^2} \\
\langle \sigma_{ann} v \rangle \approx \frac{1.12 \times 10^{-10} \text{GeV}^{-2} x_f}{g_*^{1/2} \Omega_\chi h^2} \\
\approx 10^{-9} \text{GeV}^{-2} \\
\langle \sigma_{ann} v \rangle \approx \frac{\pi \alpha^2}{m^2_\chi} \\
m_\chi \approx 300 \text{ GeV}
\]
WIMP

- A stable particle at the weak scale with “EM-strength” coupling naturally gives the correct abundance
- This is where we expect new particles because of the hierarchy problem!
- Many candidates of this type: SUSY, little Higgs with T-parity, Universal Extra Dimensinos, etc
- If so, we may even create dark matter at accelerators
Minimal Model

- Dark Matter clearly a new degree of freedom
- The smallest degree of freedom you can add to the QFT is a real Klein-Gordon field $S$: $\text{dof}=1$
- Assign odd $Z_2$ parity to $S$, everything else even
- Most general renormalizable coupling

$$L_S = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2} |H|^2 S^2 - \frac{h}{4!} S^4.$$ 

Davoudiasl, Kitano, Li, HM
Consistency check

- correct Dark Matter abundance
- evades direct detection limits
- satisfies triviality/instability limits from RGE
- consistent with precision electroweak data
LSP

• The lightest Supersymmetric Particle is one of the best candidates for dark matter (assuming R-parity conservation)
• In the “Minimal Supergravity” or CMSSM, the LSP is bino-like
• Its annihilation cross section tends to be too small, abundance too large because it is P-wave suppressed \( \tilde{B} \tilde{B} \rightarrow e^+ e^- \)
• Coannihilation region \( \tilde{B} \tilde{\tau} \rightarrow \gamma \tau \)
• Funnel region where annihilation goes through a Higgs resonance.
Example

- exchange of Majorana fermions with a relative minus sign

\[
\mathcal{M}_{+-} = 8g'^2 \frac{M_B p_B}{M_B^2 + m_{\tilde{e}_R}^2} \cos^2 \frac{\theta}{2}
\]

\[
\mathcal{M}_{-+} = 8g'^2 \frac{M_B p_B}{M_B^2 + m_{\tilde{e}_R}^2} \sin^2 \frac{\theta}{2}
\]

\[
\mathcal{M}_{++} = 0
\]

\[
\mathcal{M}_{--} = 0
\]

- P-wave annihilation
- Final state J=1
- L=0, S=1 not possible
- L=1, S=1 allowed

\[
\sigma = \frac{4\pi \alpha^2 M_B^2 v_{rel}}{3c^4 W (M_B^2 + m_{\tilde{e}_R}^2)^2}
\]
A little too much

- You get the right order of magnitude!
- But in detail, a little too much beyond the collider limits
- Coannihilation region
  \[ \tilde{B}\tilde{\tau} \rightarrow \gamma\tau \]
- Funnel region where annihilation goes through a Higgs resonance
  \[ \tilde{B}\tilde{B} \rightarrow A^0, H^0 \]
Figure 1: The \((m_{1/2}, m_0)\) planes for (a) \(\tan \beta = 10\), \(\mu > 0\), (b) \(\tan \beta = 10\), \(\mu < 0\), (c) \(\tan \beta = 35\), \(\mu < 0\), and (d) \(\tan \beta = 50\), \(\mu > 0\). In each panel, the region allowed by the older cosmological constraint \(0.1 \leq \Omega \chi h^2 \leq 0.3\) has medium shading, and the region allowed by the newer cosmological constraint \(0.094 \leq \Omega \chi h^2 \leq 0.129\) has very dark shading. The disallowed region where \(m_{\tilde{\tau}_1} < m_\chi\) has dark (red) shading. The regions excluded by \(b \rightarrow s \gamma\) have medium (green) shading, and those in panels (a,d) that are preferred by \(g\mu - 2\) at the 2-\(\sigma\) level have medium (pink) shading. A dot-dashed line in panel (a) delineates the LEP constraint on the \(\tilde{e}\) mass and the contours \(m_\chi^\pm = 104\) GeV (\(m_h = 114\) GeV) are shown as near-vertical black (red dot-dashed) lines in panel (a) (each panel).
sample spectrum

\[ m_0 = 100, \ m_{1/2} = 250, \ A_0 = -100, \ \tan\beta = 10, \ \mu > 0 \]
sample spectrum

$m_0 = 1450, \ m_{1/2} = 300, \ A_0 = 0, \ \tan \beta = 10, \ \mu > 0$

SPS2 focus point region
sample spectrum

\[ m_0 = 90, \ m_{1/2} = 400, \ A_0 = 0, \ \tan \beta = 10, \ \mu > 0 \]
• 5D Dirac equation
  → vector-like spectrum
• Use orbifold to get a chiral spectrum in 4D
• $R^4 \times S^1/Z_2$
  $S^1$: $y \in [0,2\pi R]$
  $Z_2$: $y \rightarrow -y$
• BC: $\psi(-y) = -\gamma_5 \psi(y)$
• cuts the spectrum in a half
• as a result, there is a remaining $Z_2$ symmetry
  $y \rightarrow \pi - y$
• KK parity: $(-1)^n$
• Put all SM particles in the bulk

• 1st KK states m=1/R

• However, radiative corrections split their masses (Cheng, Matchev, Schmaltz, hep-ph/0205314)

• B(1) can be good DM (Servant, Tait, hep-ph/0206071)
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Many WIMP candidates

- Warped unification + proton stability (Agashe, Servant, hep-ph/0403143)
- Many, many, more....
- Conserved number + sub-TeV \(\Rightarrow\) good DM
WIMP Searches
Finding Dark Matter

Direct method

- neutralino
- underground laboratory
- nucleus
- phonon or photon
- detector
Limit

Cross-section [cm$^2$] (normalised to nucleon)

WIMP Mass [GeV/c$^2$]

http://dmtools.brown.edu/
Gaitskell, Mandic, Filippini

ZEPLIN-II, 2007
CDMS-II, 2005
XENON10, 2007
CDMS-II, 2008
> 8 sigma!

**Figure 2**: Model-independent residual rate of the single-hit scintillation events, measured by the new DAMA/LIBRA experiment in the (2 – 4), (2 – 5) and (2 – 6) keV energy intervals as a function of the time. The residuals measured by DAMA/NaI and already published in ref. [4, 5] are also shown. The zero of the time scale is January 1st of the first year of data taking of the former DAMA/NaI experiment. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves represent the cosinusoidal functions behaviours $A \cos (\omega (t - t_0))$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, with a phase $t_0 = 152.5$ day (June 2nd) and with modulation amplitudes, $A$, equal to the central values obtained by best fit over the whole data, that is: (0.0215 ± 0.0026) cpd/kg/keV, (0.0176 ± 0.0020) cpd/kg/keV and (0.0129 ± 0.0016) cpd/kg/keV for the (2 – 4) keV, for the (2 – 5) keV and for the (2 – 6) keV energy intervals, respectively. See text. The dashed vertical lines correspond to the maximum of the signal (June 2nd), while the dotted vertical lines correspond to the minimum. The total exposure is 0.82 ton$\times$yr.
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XMASS

- Trying to *detect dark matter directly*
- PIs Suzuki and Nakahata lead the project
- adding Kai Martens to the project
- start data taking ~2009
Finding Dark Matter

*Indirect method*
*Icecube, Antares, Nestor, Nemo, Baikal*

\[
\chi \chi \rightarrow \nu \nu X
\]
Finding Dark Matter

*Indirect method*

Icecube, Antares, Nestor, Nemo, Baikal

\[ \chi \chi \rightarrow \nu \nu \]

Earth → Sun
Future Limits

- SUSY (Bergström, Edsjö, Gondolo, hep-ph/98060293)
- UED (Hooper and Kribs, hep-ph/0208261)

![Graph showing limits on the muon flux from the Sun as a function of neutralino mass.](image)
Other possibilities

• Given that dark matter is supposed to be in the halo of the galaxy, WIMPs annihilation may lead to signals in *gammas*, *positrons*, *anti-protons*, *neutrinos*

• look for them from the galactic center, the entire halo, substructures in the halo
Adiabatic compression and indirect detection of supersymmetric dark matter

Figure 6. Scatter plot of the gamma-ray flux $\Phi_\gamma$ for a threshold of 1 GeV as a function of the neutralino mass $m_\chi$ for the SUGRA cases discussed in equation (3.4), and for the same parameter space used in figure 5. An NFW profile with adiabatic compression is used with $\Delta \Omega \sim 10^{-5}$ sr. All points in the figure fulfil the $b\rightarrow s\gamma$ bounds. For $\tan \beta = 5$ all points have $\Delta \chi < 7.1 \times 10^{-10}$. For the other values of $\tan \beta$, $\Delta \chi > 7.1 \times 10^{-10}$ is fulfilled for the points located on the arrow side of the dashed lines, and $B(B_s \rightarrow \mu^+\mu^-) < 2.9 \times 10^{-9}$ for those on the arrow side of the dot–dashed lines. Points depicted with light grey (magenta) triangles have $0.129 < \Omega \tilde{\chi}_0^1 h^2 < 0.3$, those with black stars have $0.094 < \Omega \tilde{\chi}_0^1 h^2 < 0.129$, and finally those with dark grey (blue) boxes have $0.03 < \Omega \tilde{\chi}_0^1 h^2 < 0.094$ with the appropriate rescaling of the density of neutralinos in the galaxy as discussed in the text. Solid lines denote the 5 $\sigma$ sensitivity curves for satellites. From top to bottom, the first solid line corresponds to the signal reported by EGRET, and the upper area bounded by the second solid line will be analysed by the GLAST experiment.
• Collision of high-energy particles mimic Big Bang
• We hope to create Dark Matter particles in the laboratory
• Look for events where energy and momenta are unbalanced
  “missing energy” $E_{\text{miss}}$
• Something is escaping the detector
• electrically neutral, weakly interacting
  $\Rightarrow$ Dark Matter!? 
• need to know the model!
  $\Rightarrow$ spin & mass measurements
Concordance model of Dark Matter?

- **cosmological** measurement of dark matter
  \[ \Rightarrow \text{abundance } \propto (\text{annihilation cross section})^{-1} \]
- **detection** experiments
  \[ \Rightarrow \text{scattering cross section} \]
- **production at colliders**
  \[ \Rightarrow \text{mass, couplings} \]
  \[ \Rightarrow \text{can calculate cross sections} \]
- **Will know what Dark Matter is**
- **Will understand universe back to } t \sim 10^{-10} \text{sec**}
• Electron-positron collider
• Super-high-tech machine
• Accelerate the beam over ten miles
• Focus beam down to a few nanometers and make them collide
• Precisely measure the dark matter properties
Omega from colliders

SUSY case study
Baltz, Battaglia, Peskin, Wizansky hep-ph/0602187
Cross check

abundance
direct cross section

**ILC**
**LHC**
**Planck (~2010)**
**WMAP (Current)**

**ALCPG Cosmology Subgroup**

**Dark Matter Mass from Supersymmetry (GeV)**

**Fraction of Dark Matter Density**

**Dark Matter Mass (TeV)**

**CDMS-II**
**ILC**
**CDMS-II projection**

**SUPERSYMMETRIC MODELS**

**-1ton Detector**

**Interaction Strength (cm²)**
Experimental Facts

- Five facts standard model cannot explain
  - accelerating universe (1998)
  - acausal nearly Gaussian scale-invariant density fluctuation (2003)
  - baryon asymmetry (reconfirmed 2003)
Dark Energy
Type-IA Supernovae

- Type-IA Supernovae “standard candles”
- Apparent brightness ⇒ how far (time)
- Know redshift ⇒ expansion since then
- Expansion of Universe is accelerating
• Einstein’s equation
\[
\left( \frac{\ddot{R}}{R} \right)^2 = \frac{8\pi}{3} G_N \rho
\]
• If the energy dilutes as Universe expands, it must slow down
• Need something that gains in energy as Universe stretches i.e, negative pressure
• The cosmological constant \( \Lambda \) has the equation of state \( w = p/\rho = -1 \)
• Generically called “Dark Energy”
Embarrassment

- A naïve estimate of the cosmological constant in Quantum Field Theory:

\[ \rho_\Lambda \sim M_{Pl}^4 = G_N^{-2} \sim 10^{120} \text{ times observation} \]

The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero

- But now it seems finite???
Cosmic Coincidence Problem

• Why do we see matter and cosmological constant almost equal in amount?
• “Why Now” problem
• Actually a triple coincidence problem including the radiation
• If there is a deep reason for $\rho_\Lambda \sim ((\text{TeV})^2/M_{pl})^4$, coincidence natural

Arkani-Hamed, Hall, Kolda, HM
Does the Universe end?

- If $w < -1$, the Universe ends in a Big Rip
- Expansion becomes so fast that galaxies, stars, eventually atoms and even nuclei get ripped apart
- **Universe ends** with an infinite speed and empty!
- We need to know the equation of state
What is Dark Energy?

- We have to measure $w$
- For example with a dedicated satellite experiment

SNAP
- or on the ground: DES, BOSS, LSST, etc

$w = -1/3$

range of "Quintessence" models

$w = -1$

99% 95% 90% 68%

D.E.

equation of state $w = \frac{p_u}{\rho_u}$

Flat Universe Constant $w$

network of cosmic strings $w = -1/3$

Domain wall

SNAP Satellite
Target Statistical Uncertainty

$\Omega_M = 1 - \Omega_D.E.$

Supernova Cosmology Project
Perlmutter et al. (1999)

Friedland, HM, Perelstein
HyperSuprimeCam

- New camera at Subaru
- IPMU, NAOJ, KEK, Princeton
- IPMU leads the design (Aihara)
- IPMU leads the analysis team (Takada, Yoshida)
- map out distribution of dark matter
- constrain dark energy properties
Power of Combination

- SDSS and HSC with very different systematics
give confidence to the result
- How fast is dark energy creating energy?
- Is dark energy "alive"?

How fast dark energy is increasing
How much dark energy there is
string theory prediction?

- Bousso’s covariant entropy bound says de Sitter universe has only finite entropy
- how can it be consistent with infinite number of dof in string theory?
- de Sitter must tunnel to Minkowski
- create bubbles
- no dark energy in bubble
- “eternal inflation”? 
- need criteria!
string theory prediction?

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Dark Field

= Cosmic Superconductor
Mystery of the weak force

- **Gravity** pulls two massive bodies (long-ranged)
- **Electric** force repels two like charges (long-ranged)
- **Weak force** pulls protons and electrons (short-ranged) acts only over 0.000000001 nanometer
- We know the energy scale: \(~0.3\,\text{TeV}\)
We are swimming in Dark Field

- There is quantum liquid filling our Universe
- It doesn’t disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- otherwise no atoms!
- What is it??
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- What is it??
Cosmic Superconductor

• In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the “penetration length”

⇒ Magnetic field is short-ranged!

• Imagine a physicist living in a superconductor
• She finally figured:
  • magnetic field must be long-ranged
  • there must be a mysterious charge-two condensate in her “Universe”
  • But doesn’t know what the condensate is, nor why it condenses
  • Doesn’t have enough energy (gap) to break up Cooper pairs

That’s the stage where we are!
Solving the Dark Field Problem

Large Hadron Collider (LHC)

Tevatron

International Linear Collider (ILC)
Higgs at ATLAS

Robust discovery

\[ \mathcal{L}dt = 30 \text{ fb}^{-1} \]
(no K-factors)

ATLAS

Signal significance

- \( H \rightarrow \gamma \ell \)
- \( ttH \ (H \rightarrow bb) \)
- \( H \rightarrow ZZ^{(*)} \rightarrow 4\ell \)
- \( H \rightarrow WW^{(*)} \rightarrow \ell\nu\nu \)
- \( qqH \rightarrow qqWW^{(*)} \)
- \( qqH \rightarrow qq\tau\tau \)

Total significance

5\( \sigma \)

\( m_H \) (GeV/c\(^2\))

100 120 140 160 180 200

1 10 100
Post-Higgs Problem

• We see “what” is condensed

• But we still don’t know “why”

• Two problems:
  ▪ Why anything is condensed at all
  ▪ Why is the scale of condensation
    \( \sim \text{TeV} \ll M_{\text{Pl}} = 10^{15} \text{TeV} \)

• Explanation most likely to be at \( \sim \text{TeV} \) scale because
  this is the relevant energy scale
Three Directions

History repeats itself
- Crisis with electron solved by anti-matter
- Double #particles again ⇒ supersymmetry

Learn from Cooper pairs
- Cooper pairs composite made of two electrons
- Higgs boson may be fermion-pair composite
  ⇒ technicolor

Physics as we know it ends at TeV
- Ultimate scale of physics: quantum gravity
- May have quantum gravity at TeV
  ⇒ hidden dimensions (0.1 mm to 10^{-17} cm)
More Directions

- Higgs boson as a **Pseudo-Nambu-Goldstone boson** (Little Higgs)
- Higgs boson as an **extra-dimensional gauge boson** (Gauge-Higgs Unification)
- **Fat Higgs** (Composite)
- **Higgsless** and **$W^\pm$** as Kaluza-Klein boson
- technicolorful supersymmetry
Supersymmetry

Tevatron/LHC will discover supersymmetry

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New physics looks alike

missing $E_T$, multiple jets, $b$-jets, (like-sign) di-leptons

4th generation  SUSY  technicolor

+Universal extra dimension, little Higgs with T-parity
Need absolute confidence for a major discovery

As an example, supersymmetry

“New-York Times level” confidence
As an example, supersymmetry

“New-York Times level” confidence still a long way to

“Halliday-Resnick” level confidence

“We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances.”
Prove Superpartners have different spin

Discovery at Tevatron Run II and/or LHC

Test they are really superpartners
  - Spins differ by 1/2
  - Same SU(3)×SU(2)×U(1) quantum numbers
  - Supersymmetric couplings

\[
\cos \theta
\]

#Events

\[
e^+e^- \rightarrow \mu^+\mu^-
\]
\[\sqrt{s} = 350 \text{ GeV}\]

Tsukamoto, Fujii, HM, Yamaguchi, Okada
Hidden Dimensions

- Hidden dimensions
- Can emit graviton into the bulk
- Events with apparent energy imbalance

⇒ How many extra dimensions are there?
Superpartners as probe

- Most exciting thing about superpartners beyond existence:
  
  They carry information of small-distance physics to something we can measure

  “Are forces unified?”

```

LHC+LC

M3

M2

M1

Energy (GeV)

gaugeino mass (GeV)

10^2 10^5 10^8 10^11 10^14 10^16

0

100

200

300

400

500
```
Why neutrino mass?

- Neutrino mass likely comes from physics at $>10^{10}$ GeV
- How will we ever know?
- Precision measurements at LHC/ILC determine boundary conditions at $10^{16}$ GeV
- With both ends fixed, we can constrain physics in between

Buckley, HM
1955 anti-proton in Berkeley
STAR TREK
DEEP SPACE NINE
ANTIMATTER

With a dangerous cargo at stake, Commander Sisko must battle a band of hijackers!

John Vornholt

BESTSELLING AUTHOR OF DIGITAL FORTRESS

ANGELS & DEMONS

“A breathless, real-time adventure… Exciting, fast-paced, with an unusually high IQ.” — San Francisco Chronicle

DAN BROWN

A NOVEL
Matter and Anti-Matter

Early Universe

1,000,000,001

matter

1,000,000,000

anti-matter
Matter and Anti-Matter
Current Universe

The Great Annihilation

matter  anti-matter
Baryogenesis

• What created this tiny excess matter?

• *Necessary* conditions for baryogenesis (Sakharov):
  
  • Baryon number non-conservation
  
  • CP violation
    (subtle difference between matter and anti-matter)
  
  • Non-equilibrium
    \[ \Gamma(\Delta B > 0) > \Gamma(\Delta B < 0) \]

• It looks like it is the matter of quarks...
CP Violation

- Is anti-matter the exact mirror of matter?
- 1964 discovery of CP violation
- But only one system, hard to tell what is going on.
- 2001, 2002 Two new CP-violating phenomena
- But no CP violation observed so far is not large enough to explain the absence of anti-matter
Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass

\[
\begin{pmatrix}
\nu_L & \nu_R
\end{pmatrix}
\begin{pmatrix}
m_D
\end{pmatrix}
\begin{pmatrix}
\nu_L \\
\nu_R
\end{pmatrix}
\]
Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, **but $\nu_R$ SM neutral**

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\begin{pmatrix}
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\end{pmatrix}
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m_D & m_D \\
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m_D & m_D \\
M & M
\end{pmatrix}
\begin{pmatrix}
\nu_L \\
\nu_R
\end{pmatrix}
\]

\[
m_\nu = \frac{m_D^2}{M} << m_D
\]

To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}, m_D \sim m_\tau, M_3 \sim 10^{15}\text{GeV} \ (\text{GUT!})$
Grand Unification

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become the same at $10^{16}$ GeV if supersymmetry
- To obtain $m_3 \sim (\Delta m_{atm}^2)^{1/2}$, $m_D \sim m_t$
  $\Rightarrow M_3 \sim 10^{15}$ GeV!

Neutrino mass may be probing unification:

$Einstein's$ $dream$
Electroweak Anomaly

- Actually, SM converts $L$ ($\nu$) to $B$ (quarks).
- In Early Universe ($T > 200\text{GeV}$), $W$ is massless and fluctuate in $W$ plasma.
- Energy levels for left-handed quarks/leptons fluctuate correspondingly.

$$\Delta L = \Delta Q = \Delta Q = \Delta Q = \Delta B = 1 \Rightarrow \Delta (B - L) = 0$$
Leptogenesis

• You generate *Lepton Asymmetry* first.
• Generate $L$ from the direct CP violation in right-handed neutrino decay

$$\Gamma(N_1 \rightarrow \nu_i H) - \Gamma(N_1 \rightarrow \bar{\nu}_i H) \propto \text{Im}(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

• $L$ gets converted to $B$ via EW anomaly
  ⇒ More matter than anti-matter
  ⇒ *We have survived “The Great Annihilation”*
Leptogenesis

- Neutrinos have mass (1998-2002)
- Neutrinos may be their own anti-particles
- They can transform matter to anti-matter and vice versa
- Maybe they are responsible for our existence!

Shoot the beams over thousands of kilometers to see CP violation in neutrinos
T2KK (T2K to Korea)

Detecting neutrinos from T2K in Korea → T2KK

Studied OA from 1.0° to 2.5° in Korea (Kamioka fixed at 2.5°)
neutrinoless double beta decay

- seesaw mechanism implies Majorana neutrinos
- lepton number is violated
- look for neutrinoless double beta decay
- e.g. dissolve Xe into KamLAND

Sasha Kozlov
History of the Universe

Key:
- W, Z bosons
- photon
- quark
- meson
- gluon
- electron
- muon
- tau
- neutrino
- galaxy
- star
- ion
- atom
- black hole

- 400Kyr
- 13.7Byr
- 1min
- 10sec
- acceleration
- observation
- CMB
- BBN
- DM
- baryon
Inflation
Why do they all look the same?

- Like having discovered two remote islands in very different parts of the world, speaking the same language
- even the accents are nearly the same: one part in 100,000
- we suspect they had communication
Seeds for structure

- Cosmic Inflation stretched the new-born microscopic space to our entire visible universe
- Observed density fluctuation is due to quantum fluctuation of inflaton
- E-mode polarization consistent with this picture
How do we know it really happened?

- everything gets quantum fluctuation, including gravitons
- Gravitons from quantum fluctuation gives B-mode polarization in CMB
- The size is directly proportional to the inflationary energy scale ⇒e.g., POLARBEAR
Putting them together

- Superpartner of a heavy neutrino
- displaced from the minimum at the beginning
- rolls down slowly: inflation
- quantum fluctuation source of later structure
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter

H. Murayama et al, PRL 70, 1912
Origin of the Universe

- Right-handed scalar neutrino: $V = m^2 \phi^2$
- $n_s \sim 0.96$
- $r \sim 0.16$
- Need $m \sim 10^{13}$GeV
- Still consistent with latest WMAP
- But $V = \lambda \phi^4$ is excluded
- Verification possible in the near future
Conclusions

• Consistent picture of the universe emerged
• Yet, unknown components: Dark matter, Dark Energy
• Where did the anti-matter go?
• What is Dark Field? Why is it there?
• Universe emerged from quantum physics
• New experiments gearing up to solve these puzzles
TeV: rich energy scale?

- **Dark Matter**
  \[ \Omega_M = \frac{0.756(n + 1)x_f^{n+1}}{g^{1/2}\sigma_{\text{ann}}M_{\text{Pl}}^3} \times \frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(\text{TeV})^2}{\sigma_{\text{ann}}} \]

- **Fermi (Higgs) scale**
  \[ G_F^{-1/2} = 0.3\text{TeV} \]

- **Dark Energy**
  \[ \rho_\Lambda \sim (2\text{meV})^4 \text{ vs } (\text{TeV})^2/M_{\text{Pl}} \sim 0.5\text{meV} \]

- **Neutrino**
  \[ (\Delta m_{\text{LMA}}^2)^{1/2} \sim 7\text{meV} \text{ vs } (\text{TeV})^2/M_{\text{Pl}} \sim 0.5\text{meV} \]

TeV-scale physics likely to be rich

We are now getting there!
IPMU
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

- New intl research institute in Japan
  - astrophysics
  - particle theory
  - particle expt
  - mathematics
- official language: English
- >30% non-Japanese
- $14M/yr for 10 years
- launched Oct 1, 2007

- ≈20 now, ≈40 in fall
- excellent new faculty hires, young and dynamic!
- will hire about 30 more scientists
- support visitors!
- new building in 2009
- intl guest house in 2009
- wkshp about a month
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Director
Hitoshi Murayama

Scientific Advisory Committee

Internal Advisory Committee

Administrative Director
Takao Nakamura

Deputy Directors
Hiroaki Aihara
Yoichiro Suzuki

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- M. Fukugita (Tokyo)
- H. Aihara (Tokyo)
- K. Sato (Tokyo)
- K. Nomoto

T. Yanagida (Tokyo)
M. Jimbo (Tokyo)
T. Kohno (Tokyo)
N. Sugiyama (Nagoya)
A. Tsuchiya
H. Ooguri (Caltech)
D. Spargel (Princeton)

H. Sobel (Irvine)
S. Katsanevas (Paris 7)

@Kamioka Satellite

- K. Inoue (Tohoku)
- Y. Suzuki (Tokyo)
- M. Nakahata (Tokyo)

Astronomers

14 PIs in 40s & 50s

14 PIs in 40s & 50s
Winter 2009 occupancy
\(~5900\text{m}^2\)
emphasis on large interaction area
“like a European town square” \( \sim 400 \text{ m}^2 \)
On Site Scientists

number of scientists

- Japanese
- Asian
- European
- American
- Australian

non-Japanese 50%

10/1/07 1/1/08 3/1/08 5/1/08 7/1/08 9/1/08 11/1/08