Why don’t we break apart?
—Higgs boson and Dark Matter—

Hitoshi Murayama (Berkeley & Kavli IPMU)
Summer Institute 2019 Gangneung
August 18, 2019
Why don’t we break apart?

—Higgs boson and Dark Matter—

Hitoshi Murayama (Berkeley & Kavli IPMU)
Summer Institute 2019 @ Lakai Sandpine Resort
August 18, 2019
Standard Model

Quarks

Higgs

Leptons

Force Carriers

©Particle Fever
Standard Model
\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \gamma^\mu D_\mu \psi + \text{h.c.} \]

\[ + y_i y_{ij} x_j \phi + \text{h.c.} + |D_\mu \phi|^2 - V(\phi) \]
A Long History

• Since Fermi and Yukawa to the “Standard Model,” it took almost 40 years to build

• Since deep inelastic scattering and $J/\psi$ to precision measurements and Higgs, it took almost 40 years to test

• Now most ingredients experimentally verified except for Higgs couplings
Renormalizable Quantum Field Theory

- SU(3)$_C$ x SU(2)$_L$ x U(1)$_Y$ gauge theory

<table>
<thead>
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<th>Q</th>
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Spin and flavor representations are indicated by the appropriate symbols and numbers.
Anomaly Cancellation

- $\mathbf{U}(1)^3 - 6 \left( \frac{1}{6} \right)^3 + 3 \left( \frac{2}{3} \right)^3 + 3 \left( \frac{-1}{3} \right)^3 - 2 \left( \frac{1}{2} \right)^3 + (1)^3 = 0$
- $\mathbf{U}(1)(\text{gravity})^2 - 6 \left( \frac{1}{6} \right) + 3 \left( \frac{2}{3} \right) + 3 \left( \frac{-1}{3} \right) - 2 \left( \frac{1}{2} \right) + (1) = 0$
- $\mathbf{U}(1)(\mathbf{SU}(2))^2 - 3 \left( \frac{1}{6} \right) - 2 \left( \frac{1}{2} \right) = 0$
- $\mathbf{U}(1)(\mathbf{SU}(3))^2 - 2 \left( \frac{1}{6} \right) + \left( \frac{2}{3} \right) + \left( \frac{-1}{3} \right) = 0$
- $(\mathbf{SU}(3))^3 - 2 + 1 + 1 = 0$
- $(\mathbf{SU}(2))^3, (\mathbf{SU}(3))^2\mathbf{SU}(2), \mathbf{SU}(3)(\mathbf{SU}(2))^2 , \text{grav}^3$
- non-perturbative $\mathbf{SU}(2) 3 + 1 = \text{even}$

Non-trivial connection between $q & l$
The most general renormalizable Lagrangian with the given particle content:

\[ \mathcal{L} = -\frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a} \\
+ \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{e}_i i \not{D} e_i \\
+ Y_{ij} \bar{Q}_i u_j \tilde{H} + Y_{ij} \bar{Q}_i d_j H + Y_{ij} \bar{L}_i e_j H \\
- \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \]
Parameters

- 3 gauge coupling constants + $\theta_{\text{QCD}}$
- 2 parameters in the Higgs potential ($G_F, m_H$)

$$L = -\frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a}$$

$$+ \bar{Q}_i i\not{\! D} Q_i + \bar{u}_i i\not{\! D} u_i + \bar{d}_i i\not{\! D} d_i + \bar{L}_i i\not{\! D} L_i + \bar{e}_i i\not{\! D} e_i$$

$$+ Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_l^{ij} \bar{L}_i e_j H$$

$$- \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

$g' \sim 0.36, \ g \sim 0.65, \ gs \sim 1.2$

$G_F \sim (300 \text{ GeV})^{-2}, \ m_H = 125 \text{ GeV}, \ \theta_{\text{QCD}} < 10^{-10}$
Parameters

- 3x3 complex $Y_{uij}, Y_{dij}, Y_{lij}$: 54 real params
- reparameterization $SU(3)^5 \times U(1) = 41$

$$\mathcal{L} = -\frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a}$$

$$+ \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{e}_i i \not{D} e_i$$

$$+ Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_l^{ij} \bar{L}_i e_j H$$

$$- \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

$$54 - 41 = 13 = 3_u + 3_d + 3_l + (3 + 1)_{\text{CKM}}$$
Masses and Mixings

- Choose masses and mixings as observed

\[ V_{CKM} \approx \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho + i\eta) \\ -\lambda & 1 & A\lambda^2 \\ -\lambda^3(1 + \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \]

\[ \lambda \approx 0.22 \]

\[ A, \rho, \eta \approx O(1) \]
Standard Model is extremely successful

• Take Particle Data Group “Reviews of Particle Physics” with 400+ pages

• With only a few exceptions, all numbers in the book are consistent with the Standard Model with suitably chosen 19 parameters

• Some of them tested at $10^{-9} – 10^{-12}$ level

• Many at $10^{-3}$ level
Standard Model is extremely successful

- baryon and lepton number conserved (apart from anomaly \( \propto e^{-8\pi^2/g^2} \) giving rise to \( ^3\text{He} \rightarrow e^+\mu^+\bar{\nu}_\tau \))
- flavor approximately conserved (apart from small mixing in \( V_{CKM} \))
- especially flavor-changing neutral current small (e.g. \( s \rightarrow d \) vanishes at tree-level, suppressed by \( m_c^2/m_W^2 \) at one-loop)
So, what’s the problem?
Big Questions
–Horizontal–

- Why are there three generations?
- What physics determines the pattern of masses and mixings?
- Why do neutrinos have mass yet so light?
- What is the origin of CP violation?
- What is the origin of matter anti-matter asymmetry in Universe?
Big Questions
– Vertical –

- Why are there three unrelated gauge forces?
- Why is strong interaction strong?
- Charge quantization
- Anomaly cancellation
- Quantum numbers
- Is there a unified description of all forces?
- Why is $m_W \ll M_{Pl}$?

(Hierarchy Problem)
Big Questions
–From the Heaven–

- What is *Dark Matter*?
- What is *Dark Energy*?
- **Why now?** (Cosmic coincidence problem)
- What was *Big Bang*?
- Why is *Universe* so big? (flatness problem, horizon problem)
- How were galaxies and stars created?

HM, *Outlook*, Lepton Photon 2003
Big Questions
–From the Hell–

- What is the Higg boson?
- Why does it have negative mass-squared?
- Why is there only one scalar particle in the Standard Model?
- Is it elementary or composite?
- Is it really condensed in our Universe?

HM, Outlook, Lepton Photon 2003
Standard Model is fragile

- The minute you allow for additional fields and/or gauge groups, much of the success is destroyed
- Suppressed flavor-changing neutral currents
- No proton decay
- No neutrino mass either (good&bad)
- Consistency with precise electroweak data
- No excessive CP violation (e/n EDM)
- No charge/color breaking
Standard Model is fragile

- The minute you allow for parameters to vary, it exhibits very different physics
- take $m_d < m_u$, all protons decay to neutrons and there are no atoms
- take $m_e > 4m_p - m\alpha$, Sun doesn’t burn
- if $m_H^2 > 0$, EWSB still occurs by QCD, but the world is too radioactive to live
- If $m_c \sim m_t$, no $J/\psi$ before the end of cold war and no high-energy physics funding by now
Higgs
Mystery

- Weak force is basically the same kind as the electromagnetism
- But then why is its range much shorter than the size of nuclei?
Higgs is frozen in our Universe

The whole Universe is a kind of superconductor
This is why weak interaction is short-ranged
All elementary particles masses come from Higgs

Without Higgs, our body evaporates in a nanosecond!
Higgs boson decays into two photons
2012.7.4 discovery of Higgs boson

theory : 1964
design : 1984
construction : 1998
superconductors

Other ways of Shaking:
Hit the supercond. with femtosec. pulse of Terahz. radiation and probe the recovery of the gap by another optical pulse.
Watch oscillations as function of time at the Higgs freq.

Higgs Amplitude Mode in BCS Superconductors Nb$_{1-x}$Ti$_x$N induced by Terahertz Pulse Excitation

Ryusuke Matsunaga et al. (2013)

THz pulse

Ryo Shimano
\( <H> = 0 \) from gauge invariance (Elitzur)
\( <H^\dagger H> \) is not an order parameter

For \( m_h = 126 \text{GeV} \), it is crossover

No phase transition in the Minimal Standard Model
Higgs is too testy
Electron mass is natural by doubling #particles

- Electron creates a force to repel itself
  \[ \Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \text{GeV} \frac{10^{-17} \text{cm}}{r_e} \]
- quantum mechanics and anti-matter
  \[ \Rightarrow \text{only 10\% of mass even} \]
  for Planck-size \( r_e \sim 10^{-33} \text{cm} \)

\[ \Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e) \]
Higgs mass is natural by doubling #particles?

- Higgs also repels itself
- Double #particles again \( \Rightarrow \) superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies

\[ \Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H) \]

I still take it seriously
Scalar

- every elementary particles have spin
- electrons, photons, quarks, ....
- only Higgs boson doesn’t spin
- Faceless! A spooky particle
- I had proposed “Higgsless theories”
- Is it the only one?
- does it have siblings? relatives?
- Maybe it’s spinning in extra dimensions?
- maybe composite?
- why did it freeze in?
Nima’s anguish

$m_H=125$ GeV seems almost maliciously designed to prolong the agony of BSM theorists….
dream case for experiments

stupid not to do this!
no sign of new physics that explains Higgs!

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**ATLAS 8 TeV, 20.1 fb⁻¹**

<table>
<thead>
<tr>
<th>particle</th>
<th>mass [GeV]</th>
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<tr>
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</tr>
<tr>
<td>tt</td>
<td>1.2%</td>
</tr>
<tr>
<td>ee, µµ</td>
<td>0.2</td>
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<tr>
<td>ll</td>
<td>0.1</td>
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<tr>
<td>γγ</td>
<td>0.1</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Heavy Resonances**

- e⁺ e⁻, Λ = 2 TeV
- μ⁺ μ⁻, Λ = 2 TeV

- Z' (tt hadronic) width=1.2%
- Z' (tt lep+jet) width=1.2%
- Z' (ttbar hadronic) width=1.2%
- Z' (dijet) width=1.2%

**Compositeness**

- g ~ m, 200 GeV
- μ ~ m, 1000 GeV
- χ ~ m, 1200 GeV
- χ ~ m, 1400 GeV

**Extra Dimensions & Black Holes**

- Contact Interactions
- 4th Generation
- LeptoQuarks

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**ICA 95% CL Exclusion Limits (TeV)**

<table>
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<th>process</th>
<th>observed limit</th>
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<td>b⁺ b⁻ → g g</td>
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<tr>
<td>b⁺ b⁻ → b W</td>
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<td>τ⁺ τ⁻ → b W</td>
<td>1.1</td>
</tr>
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**CMS EXCLUSION LIMTS (TeV)**

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<td>b⁺ b⁻ → g g</td>
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<tr>
<td>b⁺ b⁻ → b W</td>
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</tr>
<tr>
<td>τ⁺ τ⁻ → b W</td>
<td>1.1</td>
</tr>
</tbody>
</table>
LHC score card

- origin of EWSB
- Higgs discovery: not only a partial answer
- naturalness
- None
- dark matter
- None
- EW baryogenesis
- No new CP violation
- unexpected
- Perhaps?? 750 GeV diphoton???
IF SUPERSYMMETRY DOESN’T PAN OUT, SCIENTISTS NEED A NEW WAY TO EXPLAIN THE UNIVERSE?
Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful...
Naturalness works!

- Why is the Universe big?
- Inflation
  - horizon problem
  - flatness problem
  - large entropy

Gaussianity

Planck
Scalar top mass $\geq 10\,\text{TeV}$ preferred

Predicted range for the Higgs mass

- Split SUSY
- High-Scale SUSY

Experimental favored

assumption: MSSM
Better Late Than Never

Even $m_{\text{SUSY}} \sim 10 \text{ TeV}$ ameliorates fine-tuning from $10^{-36}$ to $10^{-4}$
higher energies?

- Need to explore
- HL-LHC boosts reach
- We believe we should keep aiming at higher energies
- HE-LHC?
- 100 TeV pp would be great!
- Need to continue magnet R&D
- Possible first stage: FCCee from $m_Z$ upto 365 GeV
History of Colliders

1. precision measurements of neutral current (i.e. polarized e+e−) predicted \(m_W, m_Z\)
2. UA1/UA2 discovered \(W/Z\) particles
3. LEP *nailed* the gauge sector
   1. precision measurements of \(W\) and \(Z\) (i.e. LEP + Tevatron) predicted \(m_H\)
2. LHC discovered *a Higgs particle*
3. LC *nails* the Higgs sector?
   1. precision measurements at LC predict ???
Another staged path

- Start with 250 GeV
- guaranteed precision Higgs and top physics
- extendable 500 GeV to 1 TeV
- TDR exists
What is Higgs really?

Only one? (SM)
has siblings? (2DHM)
not elementary?

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

MSSM (tanβ = 5, M_α = 700 GeV)

has siblings

MCHM5 (f = 1.5 TeV)

not elementary
Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other “sectors”

\[ \mathcal{L} = \mathcal{O}_{\text{hidden}} H^\dagger H \]
Twin Higgs

- Take two mirror copies of the SM:

\[(\text{SM}_A) \times (\text{SM}_B)\]

\[\mathbb{Z}_2\] An exchange symmetry. A ↔ B.

- Assume Higgs potential has an SU(4) or SO(8) global symmetry in the UV.

- Take a small hierarchy of Higgs vevs:

\[
\langle H_A \rangle = v \\
\langle H_B \rangle = f
\]

with \(v < f\).
In Mirror Twin Higgs models, the one loop quadratic divergences that contribute to the Higgs mass are cancelled by twin sector states that carry no charge under the SM gauge groups. Discovery of these states at LHC is therefore difficult. May explain null results.

Roni Harnik and Zackaria Chacko, JHU workshop 2017 in Budapest
• Fully exploit energy-momentum conservation
• Don’t lose information along the beam line
• Can use all final states
• Can “see” invisible states
• holistic use of all information

\[ m_{\text{recoil}}^2 = m_Z^2 + s - 2\sqrt{s}E_Z \]
Higgs exotic decay

Complementary to hadron collider searches

Liantao Wang, GRC 2019
# Personal View on Relative Timelines

<table>
<thead>
<tr>
<th>Timeline</th>
<th>~ 5</th>
<th>~ 10</th>
<th>~ 15</th>
<th>~ 20</th>
<th>~ 25</th>
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<td>Operation</td>
<td>Upgrade</td>
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<td>8~(11)T NbTi/(Nb3Sn)</td>
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<td>Construction</td>
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<tr>
<td>14~16T Nb3Sn</td>
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<td>Construction</td>
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</table>
Possible scenarios of future colliders

- **ILC**: 250 GeV
  - 2 ab⁻¹

- **500 GeV**
  - 4 ab⁻¹

- **1 TeV**
  - 4-5.4 ab⁻¹

- **3 TeV**
  - 5 ab⁻¹

- **10 TeV?**
  - 10 ab⁻¹

- **CepC**: 90/160/240 GeV
  - 16/2.6/5.6 ab⁻¹

- **SppC**: aim similar to FCC-hh

- **FCC-ee**: 90/160/250 GeV
  - 350-365 GeV 1.7 ab⁻¹

- **FCC hh**: 150 TeV = 20-30 ab⁻¹

- **FCC hh**: 100 TeV 20-30 ab⁻¹

- **HL-LHC**: 13 TeV 3-4 ab⁻¹

- **HE-LHC**: 27 TeV 10 ab⁻¹

- **LHeC**: 1.2 TeV
  - 0.25-1 ab⁻¹

- **FCC eh**: 3.5 TeV 2 ab⁻¹

- **CLIC**: 380 GeV
  - 1.5 ab⁻¹

- **1.5 TeV**
  - 2.5 ab⁻¹

- **3 TeV**
  - 5 ab⁻¹
Multiverse
Dark Matter
cluster of galaxies

Abell 2218
2.1B lyrs
more than 80% of matter in the Universe is not atoms
two clusters collided at 4500km/sec
4B lyrs away
Dark Matter
Dark Matter is our Mom

$10^{-5}$

without dark matter

with dark matter
largest 3D map ever ever

250 Million lyrs

1 Billion lyrs

8 Billion lyrs
Indeed, dark matter is our Mom!
Reenacting the Big Bang with Cal Marching Band
Miracles

\[ \frac{n_{\text{DM}}}{s} = 4.4 \times 10^{-6} \text{ GeV} \]

\[ m_{\text{DM}} \]

\[ \langle \sigma_{2\rightarrow2\nu} \rangle \approx \frac{\alpha^2}{m^2} \]

\[ \alpha \approx 10^{-2} \]

\[ m \approx 300 \text{ GeV} \]

WIMP miracle

We wanted new particles at this energy scale to address the naturalness problems anyway.

Supersymmetry
Extra dimensions
Composite models
Figure 5: Upper limits on the DM-nucleon cross section, at 90% CL, plotted against DM particle mass and compared with previously published results. Left: limits for the vector and scalar operators from the previous CMS analysis [10], together with results from the CoGeNT [60], SIMPLE [61], COUPP [62], CDMS [63, 64], SuperCDMS [65], XENON100 [66], and LUX [67] collaborations. The solid and hatched yellow contours show the 68% and 90% CL contours respectively for a possible signal from CDMS [68]. Right: limits for the axial-vector operator from the previous CMS analysis [10], together with results from the SIMPLE [61], COUPP [62], Super-K [69], and IceCube [70] collaborations.

Figure 6: Observed limits on the mediator mass divided by coupling, \( \frac{M}{p_{\gamma}} \), as a function of the mass of the mediator, \( M \), assuming vector interactions and a dark matter mass of 50 GeV (blue, filled) and 500 GeV (red, hatched). The width, \( G_{s} \), of the mediator is varied between \( \frac{M}{3} \) and \( \frac{M}{8} \). The dashed lines show contours of constant coupling \( p_{\gamma} \).

Figure 7 shows 95% CL limits at LO, compared to published results from ATLAS, LEP, and the Tevatron. Table 7 shows the expected and observed limits at LO and NLO for the ADD model.

Figure 8 shows the expected and observed 95% CL limits on the cross-sections for scalar un-
sociology

- in 1980s, dark matter was not as clear
- people tried to solve big problems in particle physics, i.e. naturalness, strong CP
- dark matter was optional, i.e. WIMP
- in 2010s, dark matter is a glaring problem
- but no sign of solution to naturalness
- perhaps naturalness is optional?
- rethinking: be more open-minded
Search for MACHOs (Massive Compact Halo Objects)

Large Magellanic Cloud

Dim Stars? Black Holes?

Not enough of them!
Best limit on Black Hole dark matter

Niikura, Takada et al., Nature Astronomy

observe Andromeda for one night
read out CCDs every 2 min

No detection \implies more stringent upper bound, than 2yr Kepler data (Griest et al.)
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 \( m \Rightarrow \) won’t “fit” in a galaxy!
- \( m > 10^{-22} \text{ eV} \) “uncertainty principle” bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)
SIMP: dark hadrons
\[ m \sim 0.3 \text{GeV}, \sigma \sim 10^{-24} \text{cm}^2 \]
Conclusions

• Particle Physics: exciting as ever!
• Higgs: need to understand it better
  • HL-LHC, ILC, CEPC, FCCee
• naturalness: higher energies, precision
  • HE-LHC, FCChh, CLIC, PWFA, μμ
• dark matter: open mind, broad search
  • cosmology, direct, indirect, collider
  • “table top” experiments
theorist

experiments
Why do we exist at all?

—Baryogenesis and Inflation—

Hitoshi Murayama (Berkeley & Kavli IPMU)
Summer Institute 2019 Gangneung
August 19, 2019
Why don’t we break apart?
—Higgs boson and Dark Matter—

Hitoshi Murayama (Berkeley & Kavli IPMU)
Summer Institute 2019 Gangneung
August 19, 2019
SIMP: dark hadrons
$m \sim 0.3 \text{GeV}, \sigma \sim 10^{-24} \text{cm}^2$
What to choose?

• We need a broad experimental search
• for me, I need some guidance from data
• the only one astrophysical data that points to nature of dark matter is issue with small-scale structure
  ➡ self-interacting dark matter (Spergel & Steinhardt 2000)
• still controversial
• baryonic feedback?
FIG. 4: Left: Observed rotation curve of dwarf galaxy DDO 154 (black data points) compared to models with an NFW profile (dotted blue) and cored profile (solid red). Stellar (gas) contributions indicated by pink (dot-)dashed lines. Right: Corresponding DM density profiles adopted in the fits. NFW halo parameters are $r_s \varpi 3.4 \text{kpc}$ and $\varpi s \varpi 1.5 \times 10^7 \text{M}_\odot/\text{kpc}^3$, while the cored density profile is generated using an analytical SIDM halo model developed in [116, 118].

Recent high-resolution surveys of nearby dwarf galaxies have given further weight to this discrepancy. The H I Near Galaxy Survey (THINGS) presented rotation curves for seven nearby dwarfs, finding a mean inner slope $\varpi = 0.29 \pm 0.07$ [96], while a similar analysis by LITTLE THINGS for 26 dwarfs found $\varpi = 0.32 \pm 0.24$ [167]. These results stand in contrast to $\varpi \ll 1$ predicted for CDM. However, this discrepancy may simply highlight the inadequacy of DM-only simulations to infer the properties of real galaxies containing both DM and baryons. One proposal along these lines is that supernova-driven outflows can potentially impact the DM halo gravitationally, softening cusps [78, 168], which we discuss in further detail in §II E. Alternatively, the inner mass density in dwarf galaxies may be systematically underestimated if gas pressure—due to turbulence in the interstellar medium—provides radial support to the disk [169, 170]. In this case, the observed circular velocity will be smaller than needed to balance the gravitational acceleration, as per Eq. (5), and purported cores may simply be an observational artifact.

In light of these uncertainties, LSB galaxies have become an attractive testing ground for DM halo structure. A variety of observables—low metallicities and star formation rates, high gas fractions and mass-to-light ratios, young stellar populations—all point to these galaxies being highly DM-dominated and having had a quiescent evolution [171]. Moreover, LSBs typically have larger circular velocities and therefore deeper potential wells compared to dwarfs. Hence, the effects of baryon feedback and pressure support are expected to be less pronounced. Rotation curve studies find that cored DM profiles are a better fit for LSBs compared to cuspy profiles [54, 58, 59, 63, 64]. In some cases, NFW profiles can give reasonable fits, but the required halo concentrations are systematically lower than the mean value predicted cosmologically. Although early H I and long-slit H observations carried concerns that systematic effects—limited resolution (beam-smearing), slit misalignment, halo triaxiality and noncircular motions—may create cores artificially, these issues have largely been put to rest with the advent of high-resolution H I and optical velocity fields (see Ref. [148] and references therein). Whether or not baryonic feedback can provide the solution remains actively debated [67, 172, 173, 174]. Cored DM profiles have been further inferred for more luminous spiral galaxies as well [65, 175, 176].
DDO 154 dwarf galaxy

\[ V_{\text{circ}}(\text{km/s}) \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \]

\[ \text{Radius (kpc)} \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \]

\[ \text{Stars} \]

\[ \text{Gas} \]

\[ \text{Core} \]

\[ \text{Cusp} \]

\[ \text{Dark Matter Density (M}_\odot/\text{kpc}^3) \]

\[ 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \]

\[ 0.1 \quad 0.5 \quad 1 \quad 5 \quad 10 \]

\[ \text{Radius (kpc)} \]

\[ 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \quad 10^{10} \]

\[ \text{Cores} \]

\[ \text{Cusps} \]

\[ \text{DDO 154} \]

\[ \text{Gas} \]

\[ \text{Stars} \]

\[ \text{Dark Matter Density} (\text{M}_\odot/\text{kpc}^3) \]

\[ 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \]

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\[ \text{Observed rotation curve of dwarf galaxy DDO 154 (black data points) [167] compared to models with an NFW profile (dotted blue) and cored profile (solid red). Stellar (gas) contributions indicated by pink (dot-)dashed lines. Right: Corresponding DM density profiles adopted in the fits. NFW halo parameters are } r_s \sim 3.4\,\text{kpc} \text{ and } \rho_s \sim 1.5 \times 10^7\,\text{M}_\odot/\text{kpc}^3, \text{ while the cored density profile is generated using an analytical SIDM halo model developed in [116, 118].} \]

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Diversity in stellar distribution

Similar outer circular velocity and stellar mass, but different stellar distribution

- compact → redistribute SIDM significantly
- extended → unchange SIDM distribution

NGC 6503, c_{200}: median, M_{200}: 2.5 \times 10^{11} M_\odot

UGC 128, c_{200}: median, M_{200}: 3.8 \times 10^{11} M_\odot

Stars
Gas
Halo

compact stellar disk

extended stellar disk

\[ M_* : 0.83 \times 10^{10} M_\odot \]

\[ M_* : 0.57 \times 10^{10} M_\odot \]

Ayuki Kamada

AK, Kaplinghat, Pace, and Yu, PRL, 2017
PFS pointings for MW satellites
~ HSC imaging data are available for all samples ~

Ursa Minor
Draco
Sextans
Bootes I

Sculptor
Fornax
NGC6822

tidal radius of stellar comp.
velocity dependence

S1: $\tilde{m} = 22$ GeV
$v_R = 120$ km/s
$(m_R/m-2=10^{-7.4})$
$\gamma = 10^{-4.5}$
$\sigma_0/m = 0.1 \text{cm}^2/\text{g}$

S2: $\tilde{m} = 16$ GeV
$v_R = 5035$ km/s
$(m_R/m-2=10^{-4.1})$
$\gamma = 10^{-1.1}$
$\sigma_0/m << 0.1 \text{cm}^2/\text{g}$

P1: $\tilde{m} = 400$ MeV
$v_R = 108$ km/s
$(m_R/m-2=10^{-7.5})$
$\gamma = 10^{-3}$
$\sigma_0/m = 0.1 \text{cm}^2/\text{g}$
Self interaction classical regime

- (semi-)long-range force with light mediator
- analog of Rutherford scattering (classical regime)
- cross section can be large with many partial waves
- but annihilation of dark matter into light mediator
- asymmetric dark matter?
Self interaction
quantum regime

• low-energy scattering typically dominated by S-wave ($\sigma \sim k^2$)
• unitarity limit $\sigma_0 \leq 4\pi/k^2 \sim 4\pi/(mv)^2$ (quantum regime)
• to have $\sigma_0/m \sim 1\text{ cm}^2/\text{g}$ for $v \sim 100\text{ km/s}$, we need $m < 30\text{ GeV}$
• typically light dark matter with strong interaction preferred
• a new strongly interacting sector?
Miracles

\[
\frac{n_{\text{DM}}}{s} = 4.4 \times 10^{10} \text{ GeV} \quad m_{\text{DM}}
\]

\[
\langle \sigma_{2\rightarrow2\nu} \rangle \approx \frac{\alpha^2}{m^2}
\]

\[
\alpha \approx 10^{-2}
\]

\[
m \approx 300 \text{ GeV}
\]

WIMP miracle\(^2\)

\[
\langle \sigma_{3\rightarrow2\nu^2} \rangle \approx \frac{\alpha^3}{m^5}
\]

\[
\alpha \approx 4\pi
\]

\[
m \approx 300\text{MeV}
\]

SIMP miracle\(^2\)

Hochberg, Kuflik, Volansky, Wacker

arXiv:1402.5143
SIMPlest Miracle

Yonit Hochberg, Eric Kuflik, HM, Tomer Volansky, Jay Wacker

- SU(2) gauge theory with four doublets
- SU(4)=SO(6) flavor symmetry
- $\langle q^i q^j \rangle \neq 0$ breaks it to Sp(2)=SO(5)
- coset space SO(6)/SO(5)=$S^5$
- 5 stable pions
- $\pi_5(S^5)=\mathbb{Z} \Rightarrow$ Wess-Zumino term
  - $L_{WZ} = \varepsilon_{abcde} \varepsilon^{\mu\nu\rho\sigma} \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$

SIMP miracle³
Wess-Zumino term

- SU($N_c$) gauge theory
- $\pi_5(SU(N_f))=\mathbb{Z} \ (N_f \geq 3)$
- Sp($N_c$) gauge theory
- $\pi_5(SU(2N_f)/Sp(N_f))=\mathbb{Z} \ (N_f \geq 2)$
- SO($N_c$) gauge theory
- $\pi_5(SU(N_f)/SO(N_f))=\mathbb{Z} \ (N_f \geq 3)$

also vector SIMP  Soo-Min Choi, Yonit Hochberg, Eric Kuflik, Hyun Min Lee, Yann Mambrini, Hitoshi Murayama, Mathias Pierre
**LAGRANGIANS**

**Quark theory**

\[
\mathcal{L}_{\text{quark}} = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a} + \bar{q}_i i \gamma_\mu q_i - \frac{1}{2} m_Q J^{ij} q_i q_j + \text{h.c.}
\]

**Sigma theory**

\[
\mathcal{L}_{\Sigma} = \frac{f_\pi^2}{16} \text{Tr} \partial_\mu \Sigma \partial^\mu \Sigma^\dagger - \frac{1}{2} m_Q \mu^3 \text{Tr} J \Sigma + \text{h.c.} - \frac{i N_c}{240 \pi^2} \int \text{Tr} (\Sigma^\dagger d\Sigma)^5
\]

**Pion theory**

\[
\mathcal{L}_{\text{pion}} = \frac{1}{4} \text{Tr} \partial_\mu \pi \partial^\mu \pi - \frac{m_\pi^2}{4} \text{Tr} \pi^2 + \frac{m_\pi^2}{12 f_\pi^2} \text{Tr} \pi^4 - \frac{1}{6 f_\pi^2} \text{Tr} \left( \pi^2 \partial_\mu \pi \partial_\mu \pi - \pi \partial_\mu \pi \pi \partial_\mu \pi \right)
\]

\[
+ \frac{2N_c}{15 \pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \text{Tr} [\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi] + \mathcal{O}(\pi^6)
\]
The Results

Solid curves: solution to Boltzmann eq.
Dashed curves: along that solution

\[ \frac{m_\pi}{f_\pi} \propto m_\pi^{3/10} \]
\[ \frac{\sigma_{\text{scatter}}}{m_\pi} \propto m_\pi^{-9/5} \]
The Results

$3\text{SU}(N_f)\times\text{SU}(N_f) / \text{SU}(N_f)$ (SU($N_f$) broken)

$m_\pi \sim 2\pi f_\pi$

$\sigma_{\text{scatter}} / m_\pi \text{[cm}^2/\text{g]}$

$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$

$\frac{\sigma_{\text{scatter}}}{m_\pi} \propto m_\pi^{-9/5}$

can be a part of twin QCD with $N_f=4$

Hochberg, Kuflik, HM, arXiv:1805.09345

Solid curves: solution to Boltzmann eq.

Dashed curves: along that solution
The Results

Solid curves: solution to Boltzmann eq.

Dashed curves: along that solution

\[ \frac{m_\pi}{f_\pi} \propto m_\pi^{3/10} \]

\[ \frac{\sigma_{\text{scatter}}}{m_\pi} \propto m_\pi^{-9/5} \]
The hidden sector may generally contain a multitude of hidden photons for some additional scenarios. The mediators generically couple to SM fermions through mixing, with a Higgs boson, and consequently their couplings to electrons is proportional to the electron Yukawa, which, with low-energy constraints, is realistically unlikely to be sensitive to them.

In this paper, we discuss this prototype model as well as its implications for low-energy colliders. In Section IV we describe the production in profusion of these four parameters are relevant for comparisons to other experimental constraints, as well as for the values of the couplings of the mediator to other SM particles. For instance, it does not necessarily indicate a (pseudo-)scalar, and does not have to be a (dominant) component of ordinary matter through a light, neutral boson (the DM mass). (Note that in this paper, the symbol $\L$ stands for the mediator.)

The rest of the paper is organized as follows. In Section II we introduce the model, Sec. III outlines the production mechanisms, Sec. IV discusses the constraints on invisibly decaying mediators, and Sec. V compares our results to existing limits. In Sec. VI we discuss the implications for direct detection experiments. In Sec. VII we discuss some of the implications for indirect detection scenarios. We will refer in the following to this restriction as perturbativity, which is necessary for the calculation of the model. Such a calculation in order to guarantee calculability of the model. Such a notation of these four parameters are relevant for calculations in LDM scenarios. The channel shown on the left of Fig. 1 is the resonant production of a neutralino, followed by decay to a photon (the coupling of the mediator to DM).
$SU(2), N_f = 2$

$\alpha_D = 1/4\pi$

$m_\pi = 300$ MeV

Hochberg, Kuflik, HM, arXiv:1512.07917
Super KEK B & Belle II

$E_\gamma = \frac{\sqrt{s}}{2} \left(1 - \frac{M_{\text{inv}}^2}{s}\right)$
abuse of notation, may refer to a generic (pseudo-)vector, 

states with complicated interactions among themselves. 

tal attention in recent years, see e.g. [38–55] and refer-

hidden photons for some additional scenarios. 

appendix discusses the constraints on invisibly decaying 
collider such as Belle II. We conclude in Sec. VII. A short 
estimate the reach of a similar search in a future 
iments, and direct detection experiments. In Sec. VI we 
on LDM. In Sec. V we compare our results to existing 
search [37], and extend the results to place constraints 
tailed discussion of the production of such LDM at low-
we give a brief theoretical overview of LDM coupled 
taking 
a mono-photon trigger during the entire course of data 
(diators.) 

FIG. 1: (iii)

(right)

A LDM particle, in a hidden sector that couples weakly 

The hidden sector may generally contain a multitude of 

A LDM f i eld shown on the left of Fig. 1 is the resonant production 
selectron exchange). In these, the mediator would be 

mediator (such as light neutralino production through 

very minor. We do not consider models with a t-channel 

rferences between fermion and scalar production are 

Nonetheless, since more intricate scalar sectors may al-

pling to electrons is proportional to the electron Yukawa, 

ing with a Higgs boson, and consequently their cou-

ators generically couple to SM fermions through mix-

UV complete models, scalar and pseudo-scalar medi-

ation. We will refer in the following to this restriction as 

which is necessary for the 

constraint is also equivalent to imposing 

gs/50 MeV

Events/50 MeV

Belle II projection

\( \sqrt{s} = 10 \text{ GeV}, \ 50 \text{ ab}^{-1} \)

\( \sigma_{E_{\gamma}} / E_{\gamma} = 1\% \)

\( m_{\gamma_d} = 12 \text{ GeV}, \ \epsilon_{\gamma} = 10^{-2} \)

\( \psi_d(2S) \)

\( J/\psi_d \)

\( \phi_d \)

4.2

4.4

4.6

4.8

5.0

\( \chi \)

\( A^{(*)} \)

\( \gamma \)

\( e^- \)

\( e^+ \)

\( \nu \nu \gamma \)

Mirror QCD

\( \frac{\sigma_{E_{\gamma}}}{E_{\gamma}} = 1\% \)

Binned

Hochberg, Kuflik, HM, 1706.05008
BES III projection

\[ \sqrt{s} = 4 \text{ GeV}, \ 100 \text{ fb}^{-1} \]

\[ \frac{\sigma_{E\gamma}}{E\gamma} = 2\% \]

\[ m_{\gamma_d} = 3 \text{ GeV}, \ \varepsilon_\gamma = 8 \times 10^{-4} \]
Resonant scattering

S1: $\tilde{m} = 22$ GeV
$\nu_R = 120$ km/s
$(m_R/m-2 = 10^{-7.4})$
$\gamma = 10^{-4.5}$
$\sigma_0/m = 0.1 \text{cm}^2/\text{g}$

S2: $\tilde{m} = 16$ GeV
$\nu_R = 5035$ km/s
$(m_R/m-2 = 10^{-4.1})$
$\gamma = 10^{-1.1}$
$\sigma_0/m << 0.1 \text{cm}^2/\text{g}$

P1: $\tilde{m} = 400$ MeV
$\nu_R = 108$ km/s
$(m_R/m-2 = 10^{-7.5})$
$\gamma = 10^{-3}$
$\sigma_0/m = 0.1 \text{cm}^2/\text{g}$

Xiaoyong Chu, Camilo Garcia-Cely, HM,
large low-energy velocity-dependent $\sigma$

$np \rightarrow np$

Unified description of SIDM

- Hans Bethe: effective range theory
- only two parameters to describe scattering at low velocities
- fully unitary and non-perturbative
- covers bound state, resonance, virtual level
- one more parameter accommodates continuum, anti-resonance
- ideal for simulations!

\[ \cot \delta = -\frac{1}{a} + \frac{1}{2} r e k^2 + O(k^4) \]

\[ V = -\alpha \frac{e^{-m\phi r}}{\alpha m/m_\phi r} \]

Xiaoyong Chu, Camilo Garcia-Cely, HM, appeared today
Why do we exist at all?

—Baryogenesis and Inflation—

Hitoshi Murayama (Berkeley & Kavli IPMU)
Summer Institute 2019 Gangneun
August 19, 2019
no sign of new physics that explains Higgs!
Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM:
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry

We don’t really know their energy scales...
Power of Expedition

Experimental reach [GeV] (with significant simplifying assumptions)

- proton decay
- neutrino
- lepton flavor
- quark flavor
- EDM
- dark matter
- LHC

Unified Theories

with Zoltan Ligeti
Rare effects from high energies

• Effects of high-energy physics mostly disappear by power suppression

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots \]

• can be classified systematically

\[ \mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_\nu \nu \nu \]

\[ \mathcal{L}_6 = QQQL, \tilde{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W^a_\nu W^b_\nu W^c_\lambda, \]
\[ (H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots \]
unique role of $m_\nu$

- **Lowest order** effect of physics at short distances
- **tiny effect**: $(m_\nu/E_\nu)^2 \approx (0.1 \text{eV/GeV})^2 \approx 10^{-20}$!
- interferometry (e.g. Michaelson-Morley)
  - need a coherent source
  - need a long baseline
  - need interference (i.e. large mixing angle)
- **Nature was kind to provide them all**!
- neutrino interferometry (a.k.a. oscillation) a unique tool to study physics at very high $E$
  - probing up to $\Lambda \approx 10^{14}$ GeV
• At $T > \text{MeV}$, the soup of $e^+, e^-, \nu, \bar{\nu}$
• small amount of $p, n$
• they start to fuse, forming light elements
• abundance of light elements depends on amount of baryon
• baryon asymmetry consistent with $T \sim \text{MeV}$ and $T \sim 0.3 \text{eV}$

EW baryogenesis?
$\implies$ Chang Sub Shin
Beginning of Universe

matter

anti-matter
fraction of second later

turned an anti-matter out of a billion to matter
This must be how we survived the Big Bang!
Seesaw mechanism explains

- small but finite neutrino masses \( m_\nu \sim v^2 / M_R \)
- baryon asymmetry of the Universe through leptogenesis

\[
\Gamma(N_1 \rightarrow \nu_i H) - \Gamma(N_1 \rightarrow \bar{\nu}_i H^*) \propto \Im(m_{1j} h_{1k} h_{lk}^* h_{ij}^*)
\]

- the dominant paradigm in neutrino physics
- probe to very high-energy scale
- notoriously difficult to test
Anomaly!

- $W$ and $Z$ bosons massless at high temperature
- $W$ field fluctuates just like in thermal plasma
- Solve Dirac equation in the presence of the fluctuating $W$ field

$\Delta q = \Delta q = \Delta q = \Delta L$
Leptogenesis

\[ \tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} \]

di Bari, Plümacher, Buchmüller
How do we test it?

build a $10^{14}$ GeV collider
how do we test it?

• possible three circumstantial evidences
  • $0\nu\beta\beta$
  • CP violation in neutrino oscillation
  • other impacts e.g. LFV (requires new particles/interactions < 100 TeV)
• archeology
• any more circumstantial evidences?
Excitement

- CP violation in neutrino sector may be observable with conventional technique

\[ P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}\]

\[ \sin \delta \sin \frac{\Delta m_{12}^2}{4E} L \sin \frac{\Delta m_{13}^2}{4E} L \sin \frac{\Delta m_{23}^2}{4E} L \]

- 1998 Super-K
- 2002 KamLAND
- SNO
- 2012 Daya Bay
- RENO
Hyper-K

Sun

Supernova

ν

ν

ν

Proton Decays

\[ \sin \delta_{CP} = 0 \] exclusion

- 8σ for \( \delta_{CP} = -90° \) (T2K best fit)
- 80% coverage of \( \delta_{CP} \) parameter space for CPV discovery w/ >3σ
- Test of CPV origin
- \( \delta_{CP} \) precision measurement
- 22° for \( \delta_{CP} = -90° \)
- 7° for \( \delta_{CP} = 0° \)

CPV sensitivity

\[ \sigma = \sqrt{\chi^2} \]

\[ \sin^2 \theta_{13} = 0.1 \]
\[ \sin^2 \theta_{23} = 0.5 \]

Normal mass hierarchy

HK 1 tank 10 years

1.3 MW beam

1 year = 10^7 s

Hyper-K

Supernova

Sun

Atmospheric ν

Proton Decays
DUNE Sensitivity
Normal Ordering
\( \sin^2 2\theta_{13} = 0.085 \pm 0.003 \)
\( \theta_{23} \) : NuFit 2016 (90% C.L. range)

- 7 years (staged)
- 10 years (staged)

\( \sin^2 \theta_{23} = 0.441 \pm 0.042 \)
Concerning the Start of Hyper-Kamiokande

Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

**The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project’s importance and value both nationally and internationally.**

The neutrino research that lead to Nobel prizes for Special University Professor Emeritus Koshiba and Distinguished University Professor Kajita has entered a new era. The international community has demonstrated the need for Hyper-Kamiokande. The considerable expertise and achievements of the University of Tokyo and Japan, and unique and invaluable contributions from national and international collaborators will ensure the project will make significant contributions to the intellectual progress of the world.

Makoto Gonokami
President, The University of Tokyo
Kolmogorov-Smirnov test (de Gouvêa, HM)
nature has 47% chance to choose this kind of numbers
Prefers maximal CPV
no direct connection to CP violation in oscillation
but a plausibility test

Hierarchical $m_R$

$N_i=0$ unitD=30

random mass matrices

$N_1(+2), N_2(+1), N_3(0)$

$L_1(0), L_2(0), L_3(0)$

$\epsilon(-1) \approx 0.1$

Xiaochuan Lu, Murayama
Can anti-matter turn into matter?

- Proton is positively charged, anti-proton negatively.
- Can never turn into each other.
- But neutrinos or anti-neutrinos do not have electric charge.
- Neutrinoless double beta decay: \( n_n \rightarrow p_p e^- e^- \)
- Can we look for anti-matter turning into matter?
Not easy

- anarchy prefers normal hierarchy
- quite difficult to reach the sensitivity levels
- but if LBL discovers inverted hierarchy, it is in a much better shape!
Neutrino masses, mixing, and oscillations

Neutrinos are predicted to be of Majorana nature by the see-saw mechanism of neutrino mass generation [3]. The observed patterns of neutrino mixing and of neutrino mass squared differences can be related to Majorana massive neutrinos and the existence of an approximate flavour symmetry in the lepton sector (see, e.g., Ref. 96). Determining the nature of massive neutrinos $\nu_j$ is one of the fundamental and most challenging problems in the future studies of neutrino mixing.

The effective Majorana mass $|\langle m \rangle|$ (including a $2\sigma$ uncertainty), as a function of $\min(m_j)$. The figure is obtained using the best fit values and the $1\sigma$ ranges of allowed values of $\Delta m_{21}^2$, $\sin^2 \theta_{12}$, $\sin^2 \theta_{13}$ and $|\Delta m_{31}^2(32)|$ from Ref. 58 (see Table 14.1), propagated to $|\langle m \rangle|$ and then taking a $2\sigma$ uncertainty.

The phases $\alpha_{21}$ and $(\alpha_{31} - 2\delta)$ vary in the interval $[0, 2\pi]$. The predictions for the NH, IH and QD spectra as well as the GERDA-II, KamLAND-Zen and the combined CUORE+CUORICINO limits, Eq. (14.20) and Eq. (14.21), are indicated.

The Majorana nature of massive neutrinos $\nu_j$ manifests itself in the existence of processes in which the total lepton charge $L$ changes by two units: $K^+ \rightarrow \pi^- + \mu^+ + \mu^+$, $\mu^- + (A, Z) \rightarrow \mu^+ + (A, Z - 2)$, etc. Extensive studies have shown that the only $\Sigma m_{\nu i} < 0.2\text{eV}$.
Leptogenesis

\[ \tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} \]

di Bari, Plümacher, Buchmüller
$U(1)_{B-L}$

- $\nu_R < 10^{15}$ GeV for leptogenesis is much below $M_{Pl}$
- Consider $<\phi> \neq 0$
  - $M_R$ from $<\phi>\nu_R\nu_R$ or $<\phi^2>\nu_R\nu_R/M_{Pl}$
- $U(1)$ breaking produces cosmic strings because $\pi_1(U(1))=Z$
cosmic strings

$G \mu \sim v^2 / M_{Pl}^2$

$v \sim 10^{15} \text{GeV}$
probably $M_{R\nu R\nu R}$ forbidden

$\langle \phi \rangle v_{R\nu R} \text{ or } \langle \phi \rangle^2 v_{R\nu R}/M_{Pl}$

Jeff Dror, Takashi Hiramatsu, Kazunori Kohri, HM, Graham White

arXiv:1908.03227
Semi-simple unified groups

- $G_{SM} \times Z_4$
- $G_{SM} \times U(1)_{B-L}$
- $SU(3)_L \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- $SU(4)_{PS} \times SU(2)_L \times SU(2)_R \times U(1)_R$
- $SU(5) \times U(1)_X$

Symmetries that forbid right-handed neutrino mass

- Inflation that wipes out magnetic monopoles
- Two monopoles

Thermal leptogenesis

- Domain walls
- Cosmic string
- Texture
- None
intermediate gauge symmetry

- intermediate gauge symmetry $G$ protects $\nu_R$ mass
- breaks either with or without matter parity
- matter parity always leads to stable $\mathbb{Z}_2$ string
- $U(1)_{B-L}$ string breaks by monopole creation if embedded in $SO(10)$

$$G_{\text{disc}} = G_{\text{SM}} \times \mathbb{Z}_N,$$
$$G_{B-L} = G_{\text{SM}} \times U(1)_{B-L},$$
$$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L},$$
$$G_{421} = SU(4)_{PS} \times SU(2)_L \times U(1)_Y,$$
$$G_{\text{flip}} = SU(5) \times U(1).$$

<table>
<thead>
<tr>
<th>$G$</th>
<th>$H = G_{\text{SM}}$</th>
<th>$H = G_{\text{SM}} \times \mathbb{Z}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{\text{disc}}$</td>
<td>defects</td>
<td>Higgs</td>
</tr>
<tr>
<td>$G_{B-L}$</td>
<td>domain wall*</td>
<td>$B - L = 1$</td>
</tr>
<tr>
<td>$G_{LR}$</td>
<td>abelian string*</td>
<td>$B - L = 1$</td>
</tr>
<tr>
<td>$G_{421}$</td>
<td>texture*</td>
<td>$(1, 1, 2, \frac{1}{2})$</td>
</tr>
<tr>
<td>$G_{\text{flip}}$</td>
<td>none</td>
<td>$(4, 1, 1)$</td>
</tr>
<tr>
<td></td>
<td>none</td>
<td>$(10, 1)$</td>
</tr>
</tbody>
</table>
Schwinger

- Schwinger computed the production of $e^+e^-$ pairs in a constant electric field in 3+1 dimension
- adopt it to 1+1 dimension
- dualize it to magnetic field
- cross section of the string $A \sim (g \nu)^{-2}$
- $B A \sim 2\pi/(g Q)$
- length of the string $L \sim H^{-1}$
- strings get cut when $H \sim \Gamma/L \times L \sim \Gamma/L \times H^{-1}$
- string network persists until $H^2 \sim (\Gamma/L)^2 \sim (g \nu)^2 \exp(-\pi m^2/gB)$
- monopole mass $m \sim V/g$
- survives to date if $\nu < 10^{15}\text{GeV}$
covers pretty much the entire range for leptogenesis!
based on Jose J. Blanco-Pillado, Ken D. Olum arXiv:1709.02693
caveat: particle emission from cosmic strings
Inflation
fly-by simulation based on real data

about ten trillion times faster than light
practically the same no matter how far you go
How do they know each other?

- Like having discovered two remote islands in very different parts of the world, but people speak the same language
- We suspect they were together at some point
History of the Universe

The Hot Big Bang

Inflation

Gravitational waves

Telescope

Key:
- $W, Z$ bosons
- $q$ quark
- $g$ gluon
- $e$ electron
- $\mu, \tau$ muon, tau
- $\nu$ neutrino
- Photon
- Meson
- Galaxy
- Star
- Ion
- Atom
- Black hole

Particle Data Group, LBNL, © 2008. Supported by DOE and NSF
vacuum is active

http://www.youtube.com/watch?v=uxlOMa6pdr4
Seeds for structure

\[ \Delta E \Delta x \gtrsim \hbar c \]
History of the Universe

380 kyr
13.8 Byr
CMB
ν
dark matter
Big Bang
string theory?

Chosen by JAXA for 2027 launch last May
Foreground emission

From Planck

The 2015 Planck view of the sky

30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

We are living in the Galaxy.

T. Matsumura, Kavli IPMU
We need to observe in multiple bands to subtract the foreground reliably.

T. Matsumura, Kavli IPMU

Andromeda@NASA
Why modulator for LiteBIRD?

- The goal is to measure the fluctuation of the polarization signal at nano-Kelvin level over the large angular scale.
- The instrument is required to
  - be stable enough to make a distinction between the fluctuation from the sky signal and fluctuation from the instrument.
  - minimize the conversion from the temperature signal leaking into the B-mode signal.
polarization modulator@IPMU
zero-contact mechanism
Development results

Brodest AR and achromatic HWP using sapphire

R. Takaku
Univ. of Tokyo

K. Komatsu
Okayama Univ.
Role of IPMU in LiteBIRD

**JAXA**
- Launch
- Satellite system
- Low frequency telescope (LFT)

**Kavli IPMU**
- Polarization modulator for LFT
- Data analysis lead in Japan

**KEK**
- Ground calibration

**Europe**
- Middle and high frequency telescope
- Sub-K cooler

**US**
- Superconducting detector (TES) array
- Sub-K cooler

**Canada**
- Warm readout electronics

**JAXA H3 rocket**
Conclusions

- Particle Physics: exciting as ever!
- **dark matter: open mind, broad search**
- cosmology, direct, indirect, collider
- “table top” experiments
- may learn from astrophysical surveys PFS
- **baryogenesis: leptogenesis?**
- need many fossils to get convinced
- cosmic strings quite generic
- **inflation: CMB B-mode**
- LiteBIRD launch in 2027!
Dark Matter is Mom
Inflation is Dad
Neutrino is superhero