Center for Cosmology and Gravity at the Quantum Frontier

Berkeley and Stanford
Physics Frontier Center Proposal

“Quantum Frontier Center”

Outline

• Science
• Value Added
• Education, Outreach and Diversity
• Management
Science

The Universe is a quantum question!

\[
\left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi}{3} \frac{G_N \rho}{c^2}
\]

WIMP dark matter?  
baryon asymmetry?  
vacuum dark energy?  
density fluctuation?  
quantum gravity?
Quantum Frontier

• **Aim:** fundamental understanding
  • necessarily quantum physics
• **Need:** quantum techniques
  • approach ultimate sensitivities
• **Pun:** quantum leap

Quantum Questions

• *Physics in the new millennium*
• Five Major Research Areas
  • Dark Matter
  • Dark Energy
  • Inflation
  • Matter Anti-Matter Asymmetry
  • Fundamental Gravity
• All *interwoven and connected!*
• **Need center approach**
Galaxies are held together by mass far bigger than all stars combined.

\[
\text{matter / all atoms} = 5.70^{+0.39}_{-0.61}
\]

New kind of matter

What is it??
Dark Energy

- Type-Ia Supernovae “standard candles”
- Apparent brightness ⇒ how far (time)
- Know redshift ⇒ expansion since then
- Expansion of Universe is accelerating

Dark Energy

- Einstein’s equation
  \[
  \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G N \rho}{3} - \frac{1}{c^2}
  \]
- 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”

- Einstein was wrong about gravity?
  \[
  R^\mu_\nu - \frac{1}{2} g^\mu_\nu R \neq 8\pi G N T^\mu_\nu
  \]
- quantum vacuum energy

- A negative pressure substance?
**Inflation**

- Different directions of the universe 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**

**Inflation:**
- Universe born small
- everybody communicated
- then exponentially stretched to the macroscopic size as we see

---

**Inflation:** 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
- **We have quantum origin!**
Matter and Anti-Matter
Early Universe

\[ \text{1,000,000,001} \quad \text{1,000,000,000} \]

\[ \text{matter} \quad \text{anti-matter} \]

Matter and Anti-Matter
Current Universe

\[ \text{1} \quad \text{us} \]

\[ \text{matter} \quad \text{anti-matter} \]

The Great Annihilation
**Fundamental Gravity**

- Gravity oldest force known to humankind
- yet its fundamental nature still obscure
- apparently incompatible with quantum mechanics
- dark energy: breakdown at long distances?
- string theory: modifications at short distances?

- Is it really $1/r^2$?
- Is it really composition independent?
- very difficult to test: *the weakest force!*
- need new quantum approaches to maximize sensitivity
- need quantum gravity theory to provide framework
Big Questions

• Need *attack on multiple fronts*
  • satellites, ground-based, underground, laboratory experiments
• Physics Frontier Center can’t do them all!
• Rather help synthesize results from existing efforts and spawn new directions
• Aim: *focused investment where high impact*
  • provide *context* to existing activities
  • seed money to *kickstart* new activities
  • *synergy* in experimental techniques
  • force *theorists* & *experimentalists* to talk

Three Pillars for Synergy

• *Theory* provides a framework in which to pose new questions
• *Phenomenology* makes data confront theory with careful attention to systematics
• apply novel *quantum techniques* to cosmology and gravity
They provide *vertical integration* to five science themes (Major Activities)
Interwoven science

- dark sector of same origin?
- cosmic coincidence
- dark energy and inflation both accelerate
- theory of everything?
- Old idea by Dirac: big numbers due to time evolution?

The Matrix

Targeted areas ➞ Theory ➞ Phenomenology ➞ Quantum techniques ➞ Seed

<table>
<thead>
<tr>
<th>Major research areas</th>
<th>Targeted areas</th>
<th>Theory</th>
<th>Phenomenology</th>
<th>Quantum techniques</th>
<th>Seed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Matter Total yr 2: $1,026,077</td>
<td>SUSY</td>
<td>Inter-comparison</td>
<td>WIMP detectors</td>
<td>Seif</td>
<td></td>
</tr>
<tr>
<td>Dark Energy Total yr 2: $683,854</td>
<td>Vacuum Fluctuations</td>
<td>Large Scale Structure</td>
<td>Large supercond. det. arrays</td>
<td>Sunayev Zeldovich arrays</td>
<td>Cavty free axion search</td>
</tr>
<tr>
<td>Inflation Total yr 2: $1,00514</td>
<td>Field Theory</td>
<td>SCP, Sloan II, SNAP</td>
<td>WIMP searches</td>
<td>Arrays for next generation of BOSD CMBR</td>
<td>Kinetic inductance array</td>
</tr>
<tr>
<td>Neutrinos Baryon-Antibaryon asymmetry Total yr 2: $446,738</td>
<td>GUTs Leptogenesis</td>
<td>EXO COWRE</td>
<td>Double beta decay</td>
<td>Electric Dipole moment with atomic interferometry</td>
<td>Probe of forces at nanoscale</td>
</tr>
<tr>
<td>Fundamental Gravity Total yr 2: $719,269</td>
<td>Strings, Quantum gravity</td>
<td>Current experimental limits on deviation of gravity</td>
<td>1/f&lt;sup&gt;2&lt;/sup&gt; at small distance</td>
<td>Electric Dipole moment variation of physical constants</td>
<td>Electric Dipole Moment with atomic interferometry</td>
</tr>
</tbody>
</table>

Sum by column:
- Dark Matter: $1,026,077
- Dark Energy: $683,854
- Inflation: $1,00514
- Neutrinos Baryon-Antibaryon asymmetry: $446,738
- Fundamental Gravity: $719,269

Total:
- $383,032
- $546,996
- $501,452
- $1,132,974
- $808,576
- $201,475
<table>
<thead>
<tr>
<th>Dark Matter</th>
<th>Berkeley</th>
<th>Stanford</th>
</tr>
</thead>
<tbody>
<tr>
<td>experiment, observation</td>
<td>Battaglia, Blitz, Clarke, Heinemann, Nygren, Sadoulet, Siddiqi</td>
<td>Allen, Bloom, Cabrera, Kahn, Michelson, Romani</td>
</tr>
<tr>
<td>theory, phenomenology</td>
<td>Davis, Hall, Hinchliffe, Ma, Murayama, Nomura, Seljak, White</td>
<td>Blandford, Dixon, Peskin, Shenker, Wacker, Wechsler</td>
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<td>Church, Kahn, Kuo</td>
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<td>theory, phenomenology</td>
<td>Bousso, Cohn, Hall, Horava, Linder, Ma, Murayama, Nomura, Quataert, Seljak, White</td>
<td>Blandford, Kachru, Kallosh, Lind, Shenker, Silverstein, Susskind</td>
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<td>Budker, Freedman, Heinemann, Luk, Kolomensky, Nygren</td>
<td>Gratta</td>
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<tr>
<td>theory, phenomenology</td>
<td>Bauer, Hall, Hinchliffe, Murayama, Nomura, Seljak, White</td>
<td>Dimopoulos, Susskind</td>
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<th>Stanford</th>
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<tr>
<td>experiment, observation</td>
<td>Backer, Blitz, Budker, Heinemann, Smoot, Stamper-Kurn</td>
<td>Kapitulnik, Kasevich, Romani</td>
</tr>
</tbody>
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**Focus**

- a **broad and strong** team
- **wide and deep** intellectual landscape, helping & synthesizing a broad set of results
- **yet focused and controlled** investment to create new directions, enabling new science
Value Added
Value Added

- bring **coherence**, coordinated attack to make progress
- fill the gaps in activities needed for science
- **phenomenology** and **theory** tie so far disconnected efforts
- **novel quantum techniques** for cosmology and gravity
- share facilities
- **seed money** for emerging areas
- now discuss some possible examples

Possible scenario I after the launch of Center fall 2009

⇒ LHC discovers missing energy and CDMS discovers a DM candidate
⇒ refine QCD for LHC: consistency worsens
⇒ refine simulations for the structure of Milky Way halo
  look for gamma-rays at GLAST, neutrinos at ICECUBE
⇒ **phenomenologists** cannot find consistent picture of the nature of dark matter
⇒ **new effort on multiplexing**, X-ray on warm baryons in cluster, multiplex low-T Ge detector for WIMPs
⇒ correlation between baryon, weak lensing from large-area optical surveys demonstrate they are not proportional
⇒ **new systematics** in dark energy parameters
  affect combination of LSS, weak & strong lensing, supernova
⇒ no concordance:
  test equivalence principle using atom interferometer,
  variation of coupling constants?
Possible scenario II after the launch of Center fall 2009

⇒ multiplexing developed for CMB, WIMP, X-ray
⇒ CMB B-mode discovered
⇒ large-field models! probe to trans-Planck physics
⇒ cyclic universe: lot of public attention
⇒ atom interferometer for gravitational waves
⇒ while better limit on EDM
⇒ phenomenology of LHC, EDM, B-mode:
  - inflaton=sneutrino does baryogenesis?
⇒ atomic methods in ν-less double beta decay
⇒ significant dark matter component in neutrinos despite Lyman-α (SDSS)
⇒ To resolve the discrepancy: may need inhomogeneous large extra dimension?
⇒ testing gravity down to microns and below using BEC/nanomachines

Another possible (science fiction) story ≈ 2014

The Center makes progress in measuring forces and their fluctuations at micron scale.

• Kapitulnik and X, (a new Berkeley hire, specialist of quantum mechanical noise) have been collaborating in understanding noise in their mechanical devices with optical and capacitive readout respectively. No doubt, there is a contribution additional to phonon and electromagnetic (Casimir/Van der Waals) noise!

• Stamper-Kurn and Kasevich, who have put in common a number of quantum measuring tricks see also an unexpected phase noise which seem to appear at the micron scale.

Meanwhile, there has been considerable progress made theoretically in the understanding of metric fluctuations

• The excessively naive questions that Sadoulet kept asking about zero point fluctuations of $T^{μν}$ have been answered rigorously in a semi classical approximation framework in a common paper with Dimopoulos, Murayama and X and experimental tests are sketched.

• An interpretation of the holographic principle and the possible experimental tests of these ideas with Sagnac interferometers are better understood. A summer visitor resulted in several papers with Susskind, Bouso, Silverstein, Horava, Stamper-Kurn and Kasevich on string theory interpretation and possible tests with atomic beams.
2014 science fiction story (continued)

At a Center workshop in Stanford, groups from Saclay (France) and Kyoto (Japan) report also unexplained noise. The possibility dawns on us that we may be observing fluctuations of the local metric $g_{\mu\nu}$. Numerous theoretical interpretations are proposed and possible experimental consequences for missing energy at LHC, the effective value of $w$ in the dark energy and inflation tests with CMBR are worked out. Strong intellectual contribution of the Center and support of the community synthesis through topical workshops and moderation of a wiki web site. The experimental program shapes up rapidly: Spatial and time spectrum and multipolar character of metric fluctuations? Other tests

• Clarke and Siddiqi become involved with Kapitulnik, Cabrera, Sadoulet and X in an experiment to measure the multipole components, bringing quantum limited charge amplifier and their experience with e.m. fluctuations. Following an earlier Center seed funding, COINS scientists contribute nanowires to suspend devices.
• Kasevich and Stamper Kurn manage to bring in interference two counter rotating BEC rings and map both the spatial and temporal spectrum.
• The Stanford and Berkeley LHC group rapidly reanalyses its missing energy data and finds the predicted correlations with jets.

A CalTeach master teacher gets fascinated by the whole story and proposes to focus the 2014 Teacher Academy on uncertainty and noise. Center postdocs, pre-service and in service teachers and LHS specialists collaborate on curriculum units adapted to California standards.

Vertical Integration

- theory, phenomenology, quantum techniques cut across science themes
- e.g. large supercond array:
  - X-ray to look for dark warm baryons
  - microwave to study CMB B-mode, SZ
  - WIMP detectors
  - Church, Kahn, Kuo, Cabrera (Stanford)
  - Lee, Holzapfel, Sadoulet (Berkeley)
- similar integration for quantum amplifiers, atomic methods
Experimental Projects

- capitalize from existing efforts technically, phenomenologically (interpretation), and theoretically (new questions)
- seed on emerging areas, common R&D
- bring coherence, coordinate efforts
- share facilities, techniques
- don’t fund ongoing projects, but engage scientists, provide intellectual support in analysis & interpretation
- incubate new proposals

New Ideas & Synergy

- New ideas in past examples
  - Low-T detectors for dark matter search (CDMS, TES) @ CfPA/Stanford
  - supernova cosmology @ CfPA
  - atom interferometer @ Stanford
  - identify dark matter at colliders @ BCTP
- synergy from postdocs in close contact, draw senior people in, build critical mass
  - CMB theory (Silk, Sugiyama, Hu, White, Scott) @ CfPA
  - MAXIMA/Boomerang @ CfPA
Seed Money

- Competitive funding within the Center
- CfPA had many successful examples
  - MACHO
  - AMANDA
  - DEIMOS/DEEP
  - high electron mobility transistors (CMB)
- critical reviews by a committee, even off-ramps

MACHO search
CfPA legacy

MACHOs
(Massive Compact Halo Objects)
Large Magellanic Cloud

Not enough of them!
Shared Facilities

- General infrastructure of LBNL, SLAC, Stanford, Berkeley, SSL, ...
- **acquire common fabrication equipments** (specialized superconducting large-scale integration)
- Already, Lee (Berkeley) goes to Stanford microlab for complementary machines
- CDMS detector fabricated in Stanford, tested in Berkeley
- Stamper-Kurn and Kasevich want to use each other’s lab

Broader Impact

- Direct impact on a broad set of fundamental sciences
- Strong interactions with large federal projects, e.g.
  - ★ DUSEL
  - ★ LSST/JDEM
- Cross fertilization with
  - ★ Condensed matter
  - ★ Atomic, Molecular and Optical Physics
  - ★ Quantum Computing
Broader Impact

- Development of enabling technologies for a number of fields and industry
  - Atomic methods: DUSEL gravitational wave with atom interferometry in vertical shaft
  - + industrial applications: e.g. gyroscopes
  - Photon Sensors: Large number of pixels $10^3 \rightarrow 10^4 \rightarrow 10^5$ will multiply applications
  - cf. what already happened with TES (Transition Edge-Sensor) developed by CDMS now used heavily for CMB, X-ray including industry (surface contamination)

Broader Impact

- The Center is a unique position to promote international collaboration
  - Japan: close link with IPMU, exchange of postdocs
  - Capitalizing on a number of existing partnership, build collaborations on large future projects (e.g. Dark Matter joint study groups with EURECA and ASPERA)
Education, Outreach and Diversity

How was the universe formed?  
What is it made of?  
How is it evolving?

These fundamental questions are proven hooks that motivate and engage students and the public at all levels of learning.

Key Strategies:

• Direct support and engagement of underserved minorities at critical points in the educational pathway
• Collaborative environment that values diversity and involves Center scientists, students, and professional educators
• Partnerships with existing successful programs to maximize efficiency and leveraging of resources
• Independent evaluation to assess and measure program impact

EO&D Partners: UC Berkeley – CalTeach, LHS, and SSL; LBNL – BCCP; Stanford University – Office of Science Outreach; Chabot Space & Science Center
**Objective 1:** Recruit, Retain, and Directly Support a diverse cadre of undergrad and graduate students, postdocs, and high school students

**Recruitment, retention and advancement** of underrepresented students pursuing doctoral-level degrees in science: *Berkeley Edge Program*

**Research internships and courses** for local undergrads and high school students from underserved schools: *Research Experiences at Center Laboratories at Berkeley (SMASH) and Stanford (REU)*

**Development of skills and content support** for undergrads as early as possible in their studies to increase the percentage of students who matriculate in science: *Compass Program at Berkeley*

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**Objective 2:** Engage middle & high school teachers & students in Center-related science, increasing their science knowledge, skills, and career awareness

*Research Opportunities and Fellowships* for in-service educators: *CalTeach (Berkeley); Research Program for Teachers (Stanford).*

*Professional Development Workshops* in coordination with our partners for educators. The Center will recruit participants and provide science content and support.

*Science Enrichment* at Chabot and *Internships* at Stanford and Berkeley for underserved students in grades 4 through 12.

*Development and Nat’l Distribution of Two Science Books* on gravity and cosmology for middle and high-school levels by LHS, filling a significant curricular gap.

*Career-Awareness* events for students and teachers featuring Center science.
**Objective 3:** Increase the scientific literacy of the general public and their participation in science learning opportunities

*Planetarium Show* by LHS, to be included in Planetarium Activities for Student Success (PASS) series presented in school-based and community-based planetariums nationally and worldwide

*Community Science Festivals* presented by SSL to engage local Hispanics, featuring Center science and career opportunities, along with activities related to multi-cultural science

*Public Lectures* to engage Center scientists in dialogue with diverse public audiences at venues such as East Bay Science Café, Stanford Summer Lecture Series, and Chabot

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**EO&D Budget Percentage and Reach by Function**

<table>
<thead>
<tr>
<th>EO&amp;D Activity</th>
<th>% of Total Budget</th>
<th># People Served / 5 yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Support of Underserved Postdocs</td>
<td>37%</td>
<td>100</td>
</tr>
<tr>
<td>(&amp; Students)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engage K-12 Students &amp; Teachers</td>
<td>25%</td>
<td>5500</td>
</tr>
<tr>
<td>Inspire Families and General Public</td>
<td>7%</td>
<td>50250</td>
</tr>
<tr>
<td>Overall EO&amp;D Coordination</td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td>Evaluation</td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100%</strong></td>
<td><strong>55850</strong></td>
</tr>
</tbody>
</table>

Our statistics are based on the current reach of the existing programs with which we are partnering, as well as the resources budgeted for stipends and internships.
Management

Center for Cosmology and Gravity at the Quantum Frontier

Center Director
Hitoshi Murayama

Deputy Director
Bernard Sadoulet

Deputy Director for Education, Outreach & Diversity
Isabel Hawkins

Program Coordinator
Rachel Winheld

Major Activities

Education, Outreach & Diversity Programs

Figure: Center Organization. Solid lines indicate lines of responsibility, dotted lines indicate advisory roles.

Members of the PAC:
- Chosen locally by the Director
- Consultant on decisions regarding budgets and seed projects

Members of the EAB:
- Chosen internationally by the universities and approved by the NSF
- Meet annually to review the Center's programs and management
- Submit a report to university administrations and the NSF

The External Advisory Board includes:
- Three education and diversity specialists with nationwide influence
- Scientists from industry

Our past experience indicates that such an external committee of senior scientists and educators provides invaluable aid for the Center to define policies, define priorities, and keep sight of its fundamental goals.

Four internal committees are constituted:
- Visitor Committee and Fellow Selection and Support Committee, chaired by rotating scientists
- Education and Diversity Committee, chaired by the Deputy Director for Education and Diversity
- Broader Impact Committee, chaired by the Deputy Director for Operation

These committees meet at least twice a year, and ad hoc committees with junior and senior scientists are constituted as needed.

All of these functions are supported by a small staff:
- Executive Assistant: A high level individual supported directly by UC Berkeley for the Director and Deputy Director for Operation with experience in scientific grant management and program development
- Person for event organization, visitor and Center Fellow support (including visa questions)
- Program coordinator

Other administrative functions like payroll and Education Diversity and Outreach support programs are subcontracted to appropriate UCB or Stanford units.

From past experience, we understand the importance for Center management as well as for the individual researchers of receiving accurate and timely financial reports.

One of the first priorities of the Center's administrative staff will be to work with the Berkeley and Stanford accounting departments to set up a financial reporting system that meets the Center's needs.
Berkeley & Stanford

- In many ways, complementary strengths
- One hour drive, doable with enough scientific motivation
- successful examples: Sadoulet and Cabrera
- CfPA was multi-institutional (Berkeley, Stanford, Santa Barbara, Caltech, Santa Cruz)
- send each other’s postdocs, possibly shared
- seminars over video, virtual walls, joint workshops

Budget

- Focused investment to reach critical mass ≠ dispersion of our resources ≠ equal division of the pie
- Oriented towards future: No funds for pre-existing efforts (e.g. LHC, CDMS, Polar Bear)
- Balance evolves with time
• International center from ground up
• IPMU commits $350K/year for exchange, shared postdocs

Institutional Commitments

• Berkeley
  • VCR: $1M over 5 years
  • Dean L&S UCB: $125K over 5 years
  • space from physics & astronomy
• Stanford
  • lab space in Physics & Astrophysics bldg
  • strong support from KIPAC, SITP (from Stanford and SLAC)
\[
\left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G_N \rho}{3} \frac{G_N \rho}{c^2}
\]
dark matter WIMPs?  
baryon asymmetry?  
vacuum dark energy?  
density fluctuation?  
quantum gravity?

Universe is a quantum question!

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Quantum Techniques  
Novel approaches  
feed data  
Integration / Phenomenology  
Focuses  
Questions  
Diverse Community  
Public  
Inspires  
Converges  
Fundamental Laws of Nature
Value Added

- bring coherence, coordinated attack to make progress
- fill the gaps in activities needed for science
- phenomenology and theory tie them
- novel quantum techniques for cosmology and gravity
- share facilities
- seed money for emerging areas

Quantum Frontier

- Aim: fundamental understanding
- necessary quantum physics
- Need: quantum techniques
- approach ultimate sensitivities
- Pun: quantum leap