Summary of Snowmass Activities

Part b: CF5, CF6, Summary

S. Ritz and J. Feng
For the Cosmic Frontier Group
Detailed comparisons of different observations with much richer data sets will directly address these topics, and likely also provide more surprises.

**Inflation** at $t \approx 10^{-35}$ s (driven by ?) shapes the ...

...CMB map at $t \approx 300,000$ years, which, seeds structure formation driven by **Dark Matter** producing the growth of structure, which ...

...is then driven by **Dark Energy**...

...and Neutrinos ($N_{\text{eff}}$ and $(\sum m_{\nu}>0)$ have a significant impact on the growth of structure at small scales.
Dark Energy

• Highlights of Snowmass work include
  – Strategies to distinguish dark energy from modified gravity
  – Importance of upcoming complementary probes for determining the key cosmological parameters
  – Techniques and Issues
  – Facilities
  – “Why Study Dark Energy?”

• Stage III (next up!) a big advance.

• Stage IV not “just” improved Figure of Merit – it’s a new domain.
  – Stage III, IV plans result of intensive community processes
Much Better Data

Precision Cosmology

Michael Levi
Saul Perlmutter

Scale of the Universe Relative to Today’s Scale

Billions of Years from Today

Redshift

\( w = -1.0 \)
\( w = -0.97 \)

Alternative Universes for constant

\( w, \Omega_m = 0.27, \text{ and } \Omega_\Lambda = 0.73 \)

past \hspace{1cm} today \hspace{1cm} future

\( \bullet \) SNe (binned)
\( \bullet \) BOSS + SDSS (existing)
\( \bullet \) DESI (predicted)
Controlling Systematic Uncertainties

Optical Model +Tracking +Diffraction +Det Perturbations
+Lens Perturbations +Mirror Perturbations +Detector +Dome Seeing
+Low Altitude Atmosphere +Mid Altitude Atmosphere +High Altitude Atmosphere +Pixelization

Peterson et al 2013

LSST Photon Simulator
Mapping the Universe

- Two observable fields
  - Matter Density
    - Growth of structure
  - Velocities
    - Response to the matter density

- Imaging and Spectroscopic surveys give different, complementary views
  - Imaging surveys: Lensing
  - Spectroscopic surveys: BAO/Redshift Distortions

Plus other complementary techniques: clusters, Sne, …
Weak Gravitational Lensing

Galaxy shapes appear **sheared** due to **all matter** along line-of-sight

Measure **correlations** of those shears - not random
In the late 90’s the fraction of the budget devoted to projects was about 20%.
Progress in many fields require new investments to produce new capabilities.
The projects started in 2006 are coming to completion.
New investments are needed to continue US leadership in well defined research areas.
Possibilities for future funding growth are weak. Must make do with what we have.

Weak Budgetary Lensing

HEP budget - Recent Funding Trends

Trading Projects for more Research
Ramp up ILC and SRF R&D programs

Research
Facilities
Projects
Other
Dark Energy suppresses the growth of density fluctuations

The Virgo Consortium (1996)
Two (of many) Examples

Growth distinguishes MG from “new-stuff” DE

E.g. all models below have identical expansion history $H(z)$

At large scales ($>10$ Mpc, $l<300$) and early times, predictions based on linear perturbations considered highly reliable (high-$Q^2$ analogy) at level of $\sim 1\%$.

Smaller scales ($<1$ Mpc, $l>\mathcal{O}(1000)$) – also relevant to neutrino properties – more to do, but no show stoppers.

The same (DM) structures are probed in complementary ways.
It’s not just $w$!

- Study growth as a function of $k$
- Can decompose into “modes”, linear combinations of $D(k,z)$ that are best probed by surveys
- Failure in any one of these modes to agree with GR could signal a breakdown of the dark energy paradigm

Hojjati et al. 2012
Understand this new physics: strong plan internationally and across agencies often with US leadership

Photometric
- HSC

Spectroscopic
- eBOSS

CMB
- SPTPol
- Euclid

Large Synoptic Survey Telescope (LSST)

Cosmic Variance
Gravitational waves from Inflation leave an imprint on the CMB B-mode polarization

\[ E_{\text{inf}} = 1.06 \times 10^{16} \left( \frac{r}{0.01} \right)^{1/4} \text{ GeV} \]
Goals of $r=0.001$ Scale

- **Detection:**
  - Unambiguous confirmation of the Inflationary paradigm
  - Determine energy scale of inflation

- **Upper Limit:**
  - Rule out large field inflation

- **Two classes of Inflation Models**
  - Large Field -- $\Delta \phi > m_{pl}$
  - Small Field -- $\Delta \phi < m_{pl}$
Detection of $B$-mode Polarization in the Cosmic Microwave Background with Data from the South Pole Telescope

First measurement of lensing $B$ modes (last week!) using three-point $EB\phi$ from SPTpol + Herschel-SPIRE maps of the cosmic infrared background.

An important milestone
θ\text{d} is the angular diffusion length at recombination.

Photon has a mean free path and diffuses. So, oscillations on small scales are damped exponentially. (Silk damping)

Note \( \frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H^{0.5} \) so ratio is sensitive energy density.
**Constraining model extensions:**

*joint $N_{\text{eff}}$ and $\Sigma m_\nu$ constraints*

\[ N_{\text{eff}} \]

\[ \Sigma m_\nu \text{ [eV]} \]

$\sigma(N_{\text{eff}}) = 3.30 \pm 0.27$

$\sigma(\Sigma m_\nu) < 0.23 \text{eV}$

at 95% C.L.

$N_{\text{eff}}$ is the effective number of relativistic species.

For standard 3 neutrinos $N_{\text{eff}} = 3.046$.

It measures the extra energy relative to the photons.
Aside: Neutrino Mass Measurements

To measure the mass of a feather…
…get a large number of them and measure their combined effects
...get a large number of them and measure their combined effects
<table>
<thead>
<tr>
<th>DATASET</th>
<th>$\sigma(\sum m_\nu)$ [meV]</th>
<th>$\sigma(N_{\text{eff}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TODAY:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planck + BOSS BAO</td>
<td>100</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>2020:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planck + eBOSS galaxy clustering</td>
<td>36/52</td>
<td>0.13/0.16</td>
</tr>
<tr>
<td>Stage-III CMB + BOSS BAO</td>
<td>60</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>2025:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planck + DESI galaxy clustering</td>
<td>17/24</td>
<td>0.08/0.12</td>
</tr>
<tr>
<td>Planck + LSST</td>
<td>23</td>
<td>0.07</td>
</tr>
<tr>
<td>Stage-IV CMB + DESI BAO</td>
<td>16</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Cosmic constraints are complimentary to terrestrial experiments, and will be at a sensitivity that they can precisely test predictions; either confirming the standard model or indicating new physics.
Terrestrial $\Delta m_{23} = 0.049$ eV (PDG 2011)

Current Cosmology (95% U.L.)

Future Cosmology

KATRIN c. 2020 (95% U.L.)

Inverted Hierarchy

Long Baseline $\nu$

Normal Hierarchy

$\Sigma m_\nu > 0.098$ eV

MS-DESI 1σ error on $\Sigma m_\nu > 0.049$ eV

Normal hierarchy $\Sigma m_1 > 0.049$ eV

Inverted hierarchy $\Sigma m_2 > 0.008$ eV

Also see CF6: PINGU potential to determine hierarchy arXiv:1306.5846v1
**CMB timeline**

- **2009:** $r < 0.7$ (BICEP) Chiang et al, 0906.1181

- **2013:** $r \lesssim 0.1$ from Inflationary B-modes (BICEP 2)?
- **2013:** Stage II experiments detect lensing B-modes
- **2013-2016:** Stage II experiments
  $\sigma(r) \sim 0.03$, $\sigma(N_{\text{eff}}) \sim 0.1$, $\sigma(\Sigma m_\nu) \sim 0.1\text{eV}$
- **2016-2020:** Stage III experiments
  $\sigma(r) \sim 0.01$, $\sigma(N_{\text{eff}}) \sim 0.06$, $\sigma(\Sigma m_\nu) \sim 0.06\text{eV}$;

- **2020-2025:** **Stage IV goal to reach**
  $\sigma(r) = 0.001$, $\sigma(N_{\text{eff}}) = 0.025$, $\sigma(\Sigma m_\nu) = 16\text{ meV}$

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**Approximate raw experimental sensitivity (µK)**

- **Space based experiments**
- **Stage–I – 100 detectors**
- **Stage–II – 1,000 detectors**
- **Stage–III – 10,000 detectors**
- **Stage–IV – 100,000 detectors**

5 August 2013
National lab and HEP community involvement in CMB-S4

• CMB-S4 requirements exceed capabilities of University-based experiments
  – Focal-plane Arrays and Readout
    • Improved Production Reliability
    • Increased Production Volume and Throughput
      – 500,000 detectors ~ 300 silicon arrays
    • Multiplexed TES Readout
    • Large Cryogenic Optics
  – Computing Infrastructure and Analysis tools
    • ~10,000 x Planck data size (~ 3 TB/day)
  – Project Organization/Management
CF5 Findings

- Cosmic Surveys are sensitive to fundamental physics
  - discovery of the accelerating universe
  - strong evidence for an epoch of early expansion near GUT scale
  - indirect detection of cosmic neutrino background
  - compelling evidence for non-baryonic dark matter
- To date only a tiny fraction of the available information has been explored
- Strategic, valuable information, accessible to experiments, remains unmined…but that will soon change.
- Great potential to discover something fundamentally new
CF5 Main Messages

• **Remain a Leader in Dark Energy**
  – A combination of imaging and spectroscopic surveys is needed to pinpoint the new physics driving the accelerations.
  – Current suite of surveys, Stage III, will be the first to implement the vision of multiple probes and small systematics.
  – The next stage is needed to complete this program and to achieve percent-level uncertainties.

• **Build a Stage IV CMB Polarization Experiment**
  – The community understands that next generation experiment will require a nation-wide coherent effort.
  – Moving to hundreds of thousands of detector elements will require the involvement of the National Labs working with the university community.

• **Extend the Reach**
  – With small investments the DE program can be augmented in important ways.
EeV Neutrino Beam: the GZK Process

\[ p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

Discovery of GZK neutrinos within reach over the next decade
- to measure 100 TeV c.m. neutrino interactions via ratio of upward to downward neutrino showers.
- to determine the Origin of the Highest Energy Particles
Next Generation GZK Neutrino Detectors

Current Limits

Next Generation

Flux Lower Limit
**Have the first High Energy Astrophysical Neutrinos been observed by IceCube?**

28 events with a spectrum harder than that expected for any atmospheric backgrounds.

Cascade-dominated as expected.

Southern events more abundant as expected due to Earth attenuation.

Spectrum slightly softer than $E^{-2}$.

Insufficient statistics to identify sources; currently compatible with isotropy.

More to come as IceCube runs...
Atmospheric neutrinos provide many values of L and E
Very large baselines for probing matter effects (~12,700 km)
Add ~40 strings inside DeepCore
20-25m string spacing (73 for DC and 125 for IC)

Could provide very significant hierarchy information with a few years of running, improving $\delta_{CP}$ range probed by NOvA + T2K
Photon Dispersion Limits from GRB 090510

Fermi, Nature, vol 462, p331 (plus comment on p291)

Table 2 | Limits on Lorentz Invariance Violation

| # | $t_{\text{start}} - T_0$ (ms) | Limit on $|\Delta t|$ (ms) | Reasoning for choice of $t_{\text{start}}$ or limit on $|\Delta t|$ or $|\Delta t/\Delta E|$ | $E_1$ (MeV) | Valid for $s_{\pi^*}$ | Lower limit on $M_{QG}/M_{\text{Planck}}$ |
|---|---|---|---|---|---|---|
| (a)$^\bullet$ | -30 | < 859 | start of any < 1 MeV emission | 0.1 | 1 | > 1.19 |
| (b)$^\bullet$ | 530 | < 299 | start of main < 1 MeV emission | 0.1 | 1 | > 3.42 |
| (c)$^\bullet$ | 648 | < 181 | start of main > 0.1 GeV emission | 100 | 1 | > 5.63 |
| (d)$^\bullet$ | 730 | < 99 | start of > 1 GeV emission | 1000 | 1 | > 10.0 |
| (e)$^*$ | — | < 10 | association with < 1 MeV spike | 0.1 | ±1 | > 102 |
| (f)$^*$ | — | < 19 | If 0.75 GeV$^2$ γ-ray from 1st spike | 0.1 | ±1 | > 1.33 |
| (g)$^*$ | $|\Delta t/\Delta E|$ < 10 ms/GeV | lag analysis of > 1 GeV spikes | — | ±1 | > 1.22 |

Next-generation facilities could push factor ~10 higher using AGN variability

PKS 2155-304
Z = 0.116
E$\text{max}$ ~ 500 GeV
Variability ~minutes

$E_{1\text{LIV}}$ > $2.1 \times 10^{18}$ GeV
$E_{2\text{LIV}}$ > $6.4 \times 10^{10}$ GeV

H.E.S.S. Astrop. Phys 34 (2011) 738
How many UHECRs > 60 EeV?

Auger + TA ~ 30 events/yr
40 years to reach 1,000

JEM-EUSO

~200 events > 60 EeV/yr

Earth - surface ~ 5 $10^8$ km$^2$

~3.4 $10^6$ events/yr
The Matter – anti-Matter asymmetry

- Physics beyond the standard model to explain why $10^8 + 1$ quarks for every $10^8$ antiquarks in very early universe
- Possibilities within popular theories beyond the standard model
  - Leptogenesis: decay of very heavy right handed neutrinos
  - Electroweak Baryogenesis: new bosons providing 1st order phase transition (light right handed top squark, 2 Higgs doublets, …)
  - Affleck-Dine: evolution and decay of squark/slepton condensate
  - many others
- Need nonstandard CP violation: → look for new source
  - Electric Dipole Moments
  - CPV in long baseline neutrino oscillations
- A 3 Frontier Problem
Holometer

from Craig Hogan

Planckian quantum-geometrical position uncertainty
Gravitational theory suggests that quantum geometrical degrees of freedom have information with Planck area density.
Information on spatial position is much less than in field theory; limits angular or transverse degrees of freedom.
Quantum geometry may not respect locality or separation of scales; geometrical position uncertainty may be much larger than the Planck length.
Introduces new source of noise in macroscopic position detectable with nonlocal measurements of position of massive bodies in two directions.
May be relevant to new physics of Dark Energy.

There may be no such thing as a massive body at rest.

- Expect results soon!

Fermilab Holometer Experimental Concept

Measure correlated optical phase fluctuations in a pair of isolated but collocated power recycled 40-meter Michelson interferometers.
Exploit the spatial coherence of entangled quantum-geometrical noise measured at high frequencies (MHz) where other correlated noise is small.
Sensitvity goal: measure or rule out spectral density of transverse position noise given by the Planck time:

\[ h^2 \approx \frac{\langle \hat{x}^2 \rangle}{cL_{\alpha}} = \frac{t_P}{\sqrt{4\pi}} = (1.23 \times 10^{-22} \text{Hz}^{-1/2})^2 \]

World lines of beamsplitters

Overlapping spacetime volumes ↔

Correlated fluctuations

Experiment is now built, currently in commissioning stage.
CF-6 Summary

• Baryogenesis: EDMs, CP violation in neutrino sector, and inflation scale are key measurements
• Neutrino mass hierarchy possible with SN neutrinos (LBNE) and atmospheric neutrinos (PINGU)
• Origin of highest energy particles in the universe (multi-messenger campaign)
• Fundamental physics accessible with next generation instruments
• Control of astrophysical systematics in era of precision VHE gamma-ray astrophysics (CTA)
• Neutrino interactions at high energies to be measured with GZK neutrinos (ARIANNA, ARA, …)
• 300 TeV C-M interactions to be measured with UHECRs (JEM-EUSO)
• Probing Planck scale physics is now possible
Cosmic Frontier Challenges

- **UHE-CR**
  - Low rates at high energy
  - R&D: Radio Detection, detection of air shower from space

- **UHE-neutrinos**
  - R&D: Need development of new antennas, low noise amplifiers for detection of Cherenkov radio emission

- **Gamma rays**
  - R&D: Cherenkov and water tank arrays, Low-cost photosensors/low-power digitizers
  - Distributed timing across large arrays

- **Dark Energy**
  - R&D path: Low-resolution spectroscopy and spectroscopic capability to wide field optical surveys

- **Dark Matter**
  - Large program looking for larger mass, lower thresholds and directionality

- **CMB**
  - R&D path towards readout of large cryogenic multi-chroic arrays

Instrumentation Investments Important!
A Big Message

• **Together with the other Frontier areas**, the “Cosmic Frontier” provides to Particle Physics:
  – Clear evidence for physics Beyond the Standard Model
  – Profound questions of popular interest.
  – Frequent new results, surprises, with broad impacts.
  – Large discovery space with unique probes.
  – Important cross-frontier topics
  – Full range of project scales, providing flexible programmatic options.
  – **US Leadership**
Particle Physics Using Cosmic Frontier Techniques

Activities at the Cosmic Frontier are marked by rapid, surprising, and exciting developments.

- Planck-scale physics constraints
- Axion searches through the favored DM region
- WIMP detection to background and to early-universe production
- Neutrino properties, mass, Neff
- Inflation probes
- DE detailed properties and probes of modified gravity
- Origin of HE CR, cosmic accelerators
- GZK neutrinos