Fundamental Physics from Future Spectroscopic Surveys

LBNL, May 2024

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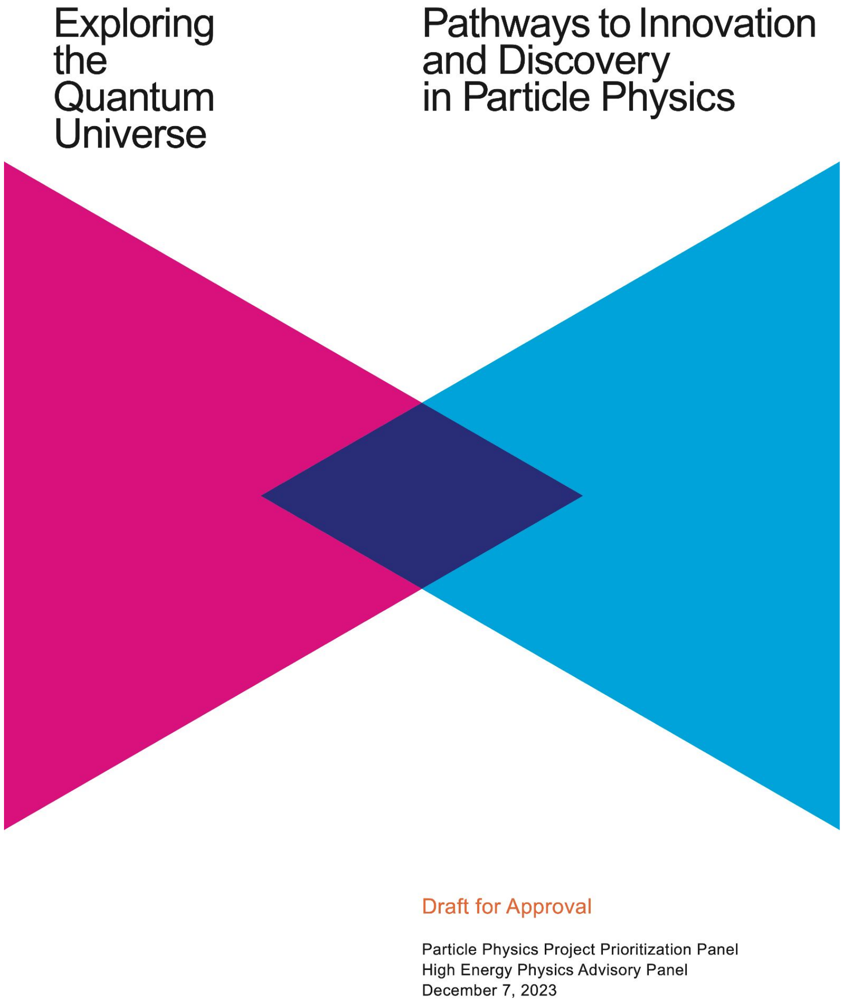
Spec-S5

Why this conference?

- Recent advances in detectors and experimental techniques have made it feasible to dramatically extend spectroscopic surveys with ‘modest’ cost.
- This opens the possibility that spectroscopic galaxy surveys could surpass even the CMB as a probe of fundamental physics.
- Spectroscopic surveys are inherently very powerful – the same instrument can study many different kinds of targets, different redshift ranges, different volumes of space.
    - Great potential to “optimize” for science return, prioritize one area or go for a broad portfolio of science.
    - **Theoretical input is incredibly important as we start to define S5.**

Report of the Particle Physics Project Prioritization Panel (P5) High Energy Physics Advisory Panel (HEPAP).

The flexibility of Spec-S5 to address multiple scientific goals (inflation, late-time cosmic acceleration, dark matter) depending on the priorities that emerge from DESI, early DESI-II, and Rubin Observatory LSST results makes it a crucial part of this 20-year vision.



Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Draft for Approval

Particle Physics Project Prioritization Panel
High Energy Physics Advisory Panel
December 7, 2023

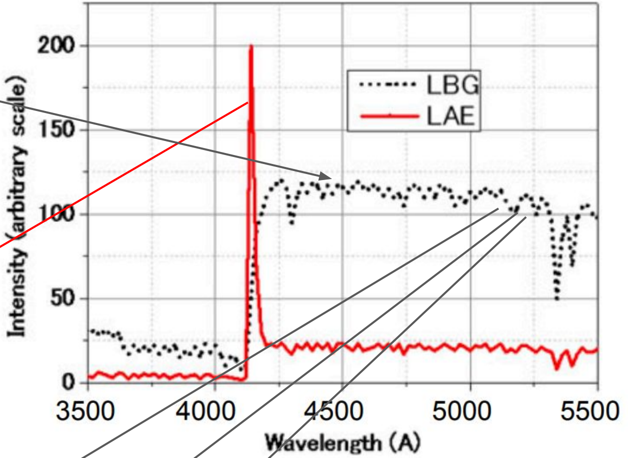
Spec-S5 is several "surveys" in one

- Milky Way and dwarfs.
- Low-z, high(er) number density.
- **High-z**
  - Precision cosmology.
  - EFT is the "unique large-scale solution".
  - Easy[†] to forecast, easy to optimize.

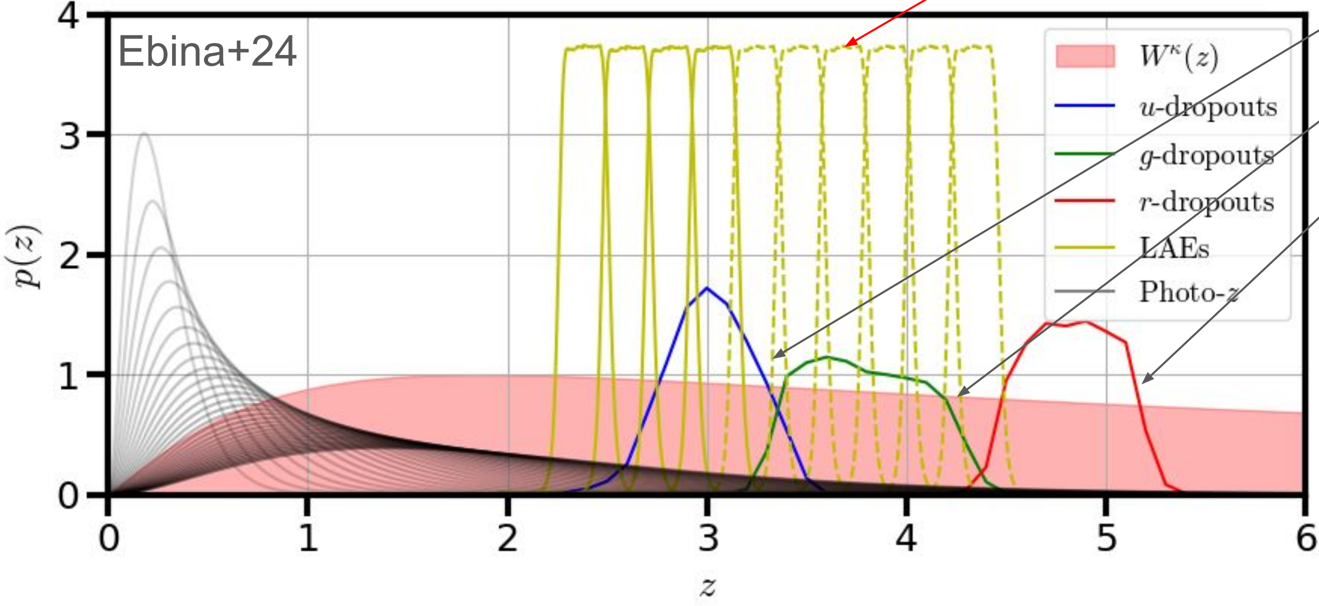
[†]The way dividing two 100 digit numbers by hand is easy, and quantum gravity isn't ...

Lots of galaxies!

We have plenty of targets, and there is room to "sculpt" our survey (including integration time per source, number density, redshift reach and bias) to optimize desired science goals.



Credit: D. Schlegel



But resources are limited – we can do trades but we can't do everything!

Standard ~~ruler~~ spectrum

- As we push to higher z:
  - Fundamental mode moves to lower k
  - Non-linear scale moves to higher k
  - Longer lever arm in time.
  - Dynamic range in scale where we have highly precise measurements of $\delta(k)$ is much higher than we normally expect.
  - *We're sensitive to anything that deviates from "boring" spectra.*
  - (Could be primordial, could be bias, could be evolution, …)

Is there some way of turning this into "s, t & u"?

P5: Hidden Universe

- For many years now “galaxy redshift survey” has been synonymous with “Dark Energy” or “growth of structure”.
  - See the focus during this conference from many of the “cosmology speakers”.
- Growing realization that this barely scratches the potential of spectroscopy for fundamental physics.
  - Much like CMB-S4 is more than “just r”.
- During this conference we’ve also heard about inflation, non-Gaussianity, parity violation, cosmological collider, primordial features, axions, light relics, dark radiation, neutrino masses and interactions, and dark matter.
- Our task is to find compelling science targets that will help us to design S5 and convince the agencies to fund it!

Wide net vs. deep dive

- Our approach so far to designing our "straw-person" Spec-S5 survey has been "theory agnostic":
  - Many new ideas sound interesting, but none sound compelling.
  - To maximize S/N if you don't know where S peaks, try to lower N "everywhere"!
  - Design for broad discovery potential, with sensitivity to existing tensions.
- This can get us a long way, but to take the next steps we need to be able to say what science will come from Spec-S5 and how we will set priorities when it comes to flow-down.
  - Rule of thumb: if it's not required by something in level 1, it can be cut.
- We'd like to be making these decisions in the next year-ish (or so).

Science cases

Snowmass/P5 highlighted:

- Dark energy
- Growth of structure
- Neutrino mass
- Neff/light relics
- Modified gravity
- Primordial non-Gaussianity
- Primordial features
- Early dark energy

Further topics

- BSM is rich in phenomenology with cosmological signatures.
- Parity violation & anomalies.
- Cosmological collider
- Isocurvature modes
- Dark matter and dark radiation
- Long-range dark forces, 5th force
- Neutrinos “beyond mass” (heating, cooling, annihilation, decays, self-interaction, winds, …)

Cosmological tensions

- Several tensions have cropped up as we've lowered error bars to O(1%).
  - H0, S8, Lyα, …
  - These have been a focus of cosmological studies for several years now.
  - Rich experimental program investigating them.
  - **We can't ignore them!**
  - In addition to being "hints" of something exciting, they do have implications for other things we'd like to know (see previous list).
  - We have a <u>fairly</u> good idea how S5 would impact these sorts of topics.

Discovery space for Spec-S5, probe of eV-scale physics.
(Richer phenomenology than often assumed.)

Neutrino physics

- Neutrino effects already need to be included for existing experiments!
- Two "signatures" we use all the time: free streaming, mass.
  - First we've detected at $z \sim 10^3$, the second is a "goal".
- Non-standard neutrino physics that affects these could well be measurable.
  - Neutrino self-interactions, decays, …
  - These affects get tangled up in existing tensions.

Inflation

P5: Spec-S5 holds great promise to advance our understanding … inflationary physics via the statistical properties of primordial fluctuations

- There are numerous ways inflation could be different from our simplest models [based on a single, slowly rolling scalar field with simple V(ϕ)].
- In addition to "r": running of spectral index, higher-order functions, primordial features, isocurvature modes, cosmological collider, …
- Signatures of generic early Universe QFT go well beyond fNL-local …
- Two "threshold" values:
  - fNL-local~1 (probe of additional states)
  - fNL-equil~1 (probe of self/strong-coupling)
  - *Not clear either is a "driver" for S5* – will come back to this.
- It is clear that the phenomenology of scale-dependent bias, higher order "primordial" functions, etc. is much richer than a typical cosmologist thinks of.

Two-point function

- Primordial curvature 2-point function: primarily kinematic information on inflaton.
- Late time physics gives access to Neff, Mnu, etc.
- Studying galaxies (or gas) gives access to “bias”
- Scale dependent bias has a rich phenomenology!
    - Light particles, massive-ish particles during inflation, isocurvature modes, equivalence principle, …
    - Think beyond fNL/k^2.
    - Understanding any signals we find will be … fascinating and complex!

(Monotonic) Scale-dependent bias

- Is b(k) the "killer app" for a future spectroscopic survey???
- Spec-S5 will come after SPHEREx, LSST and SO/S4 and will prioritize excellent radial resolution, "# modes"
  - If SPHEREx/LSST/CMB find something, would we do Stage-5 to confirm it or something else?
  - If SPHEREx/LSST/CMB don't, would it remain a compelling target?
- Could be if
  - Can't use very low k due to systematics
  - Are forced to rely on higher-order information at higher k rather than scale-dependence of 2-point function at very low k OR
  - Combinations of high-k power that have $1/k^2$ bias (large-small coupling).
- Can we achieve interesting benchmarks in this scenario?
  - Simple calculation: do we agree on how forecasts depend upon kmin?

Oscillations from b(*k*)

- Some models of scale-dependent bias produce oscillations
  - “Cosmological collider”
- I will return to these later, when we consider “primordial” features.

Tails of the distribution

- Massive particles – heavy, non-Gaussian tails.
- Position-space analysis could increase the reach for m>>H.
- What is the right way to search for these?
- What are the appropriate thresholds or “special model signals”?
- How does this drive survey design?
  - I, for one, have no good idea what to trade against what to optimize this science!

To what extent would this drive survey design?
What are the theoretical targets/templates?
What should we be optimizing for?

Higher-order functions

- In principle provide huge amount of information!
- Self-interactions, new particles, thermal initial states, dissipative systems, particle scattering, isocurvature modes, …
- 3D information gives much tighter errors on “many tens of Mpc” scales.
- We need new ideas for meeting theoretical “thresholds”

Can we achieve interesting thresholds?

Primordial features

- Primordial dynamics may exhibit significant departure from scale-invariance.
- Generic and ubiquitous in "non minimal" models.
    - EFT with discrete shift symmetry, UV complete dynamics, multi-field landscapes, …
    - Complex, high-dimensional "landscapes" …
- Features in V(ϕ) lead to oscillatory features in P(k).
- Interactions with other fields modify V(ϕ), can lead to features.
- Can have isolated features.
- Features can be in 2-point or higher-point functions, can be correlated.
- Heavy fields (60H) – position-space feature.
- Even upper limits inform model building efforts (not too different than "r").

Not-so-primordial features

- Many post-inflationary but “early” Universe cases give features:
    - Running of spectral index
    - Dark Acoustic Oscillations
    - Cosmological collider
    - Self-interactions in dark matter, neutrinos, …
    - Other things …

(Quasi-)Primordial features

- This is a signal for which LSS, in 3D, really shines.
  - Already “beating” the CMB
- Easier to disentangle from astrophysics and non-linear evolution.
- Features drives us to large #modes.
  - For large ω, what requirements on survey uniformity does this imply?
- ***Science driver that pushes a design allowing many other science cases.***

Amplitudes, scale-dependence very theory dependent!
Hard to motivate thresholds.
Should we have “interesting models”?

Dark sector(s)

- There's no reason the Universe has to make the dark sector simple.
- Could have multiple DM particles, dark radiation, interactions, …
- Several of these models impact large-scale structure.
- Solutions interact with existing tensions in "interesting" ways.
- Wasn't highlighted in Snowmass/P5, could be worth developing …

DM case – fractional DM?

- Searching for decay products (e.g. ɣ) allows us to extract a small fraction of the rest-mass energy of the DM particle to obtain a signal.
- Looking at impact on LSS requires us to extract a fraction of the momentum.
- Already have tight constraints over much of the *k*-range LSS is sensitive to.
- Heard several times during this meeting that “large scale” LSS is useful if DM is not a single particle (e.g. axiverse).
- Have well-controlled theory with minimal astrophysical assumptions, so we can search for “small departures” from standard model.
- By contrast small scales are good when the expected signal is O(1) e.g. exponential suppression of small-scale power by warm dark matter.
  - Then can still argue that our (current) O(1) uncertainty due to astrophysics can be tolerated.
  - What Spec-S5 does in this regime is the topic of a different conference (that we should organize!)
- Open questions around going beyond EFT, but possibly big gains …

Fifth forces

- LSS already doing much, much better than earlier limits.
  - Long-range forces to 0.1% level – orders of magnitude better than earlier limits.
- Small violations of the EP over a long time can really add up!
  - log(a/aeq) ~ 8
- CMB is disadvantaged compared to LSS in constraining 5th forces – another area where Spec-S5 could shine.
- May be one case where we want high number density.

Role of simulations

- Spec-S5 is planned to have "sub surveys"
  - High redshift, large volume
  - Low redshift, high number density
- High-z part is easier[†] for theorists but particularly challenging to simulators:
  - Require large volume (though don't have to evolve all the way to z=0)
  - Require very high mass resolution
  - Working with extremely tiny (statistical) error bars.
- High number density isn't exactly trivial
  - Statistical errors are high k are ridiculously small (<0.1%)!
- Heard many different ways to improve simulations.
- **How do we combine theory, AI and simulations in a Spec-S5 (+LSST+SO/S4+...) world?**

What lives "inside" a collaboration vs. what work is "inspired by" the science of S5?

Synergies with other probes

- Cosmology is entering a multi-survey decade (or so). Very promising!
- Thinking across surveys is hard, working across surveys is harder.
- Can help mitigate systematics for “core science” of each survey.
- Provide opportunities to extend the science reach:
  - CMB lensing, kSZ tomography, intrinsic alignments, moving lens, delensing B-modes, …
  - Strong constraints on ν physics, scale-dependent bias, …

Spec-S5 is planned to cover northern and southern hemispheres – maximize overlap with other surveys!
It is powerful enough to do many thing “in support of” other surveys …
Are there “joint” goals that are noteworthy?

Next steps?

- During Snowmass we made the case on "fundamental physics", prominently featuring inflation (PNG, features, …) in presentations.
- Inflation science was included in the P5 report, but in quite a generic way.
- We have to lay out the specifics of the Spec-S5 science case early
  - This will then flow down to science requirements and design considerations.
  - For DESI this was "dark energy", roughly a <u>decade</u> before DESI first light!
- We would like to write a science book to lay out a more specific science case than what is in P5.
  - We hope to use the information from this meeting to inform that writing.
  - Ideally this would come together over the next year, possibly with future meetings/conferences.
  - **If you're interested in contributing to this, or think you have a science case that should inform the design, please contact us! Be prepared to iterate 😀.**

And finally …

Thanks to … our hardworking staff

Without whom absolutely none of this would have been possible!

- Tami Blackwell
- Liz Worthy
- Adam Foote
- Jeff Anderson
- Jill Stark (in conference services)

Thanks to … LOC

- Satya Gontcho A Gontcho (Chair)
- Edmond Chaussidon
- Roger de Belsunce
- Noah Weaverdyck

Thanks to … SOC

- Kyle Dawson
- Simone Ferraro
- Vera Gluscevic
- Daniel Green
- Marilena Loverde
- David Schlegel
- Martin White

Thanks to … our speakers and panelists

(too many to list individually, but you know who you are!)

And last but not least …
Thanks to all the participants!

For a productive and engaging meeting which brought a lot of new ideas to the table with healthy and enthusiastic discussion!

Carpe Noctum!

The End

(we will post the slides to the conference website for archiving and the video on YouTube)