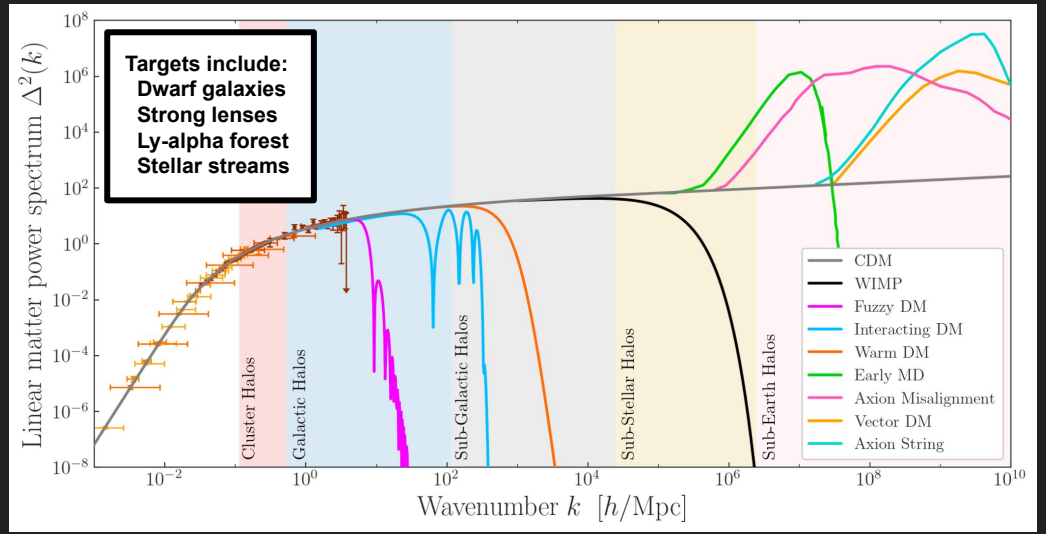
Dark Matter Physics in the Cosmos

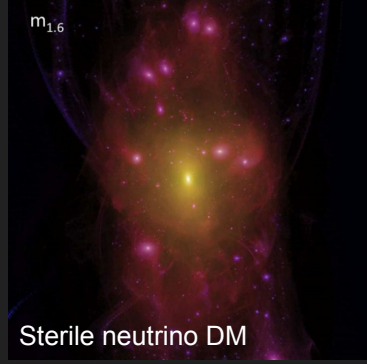
Alex Drlica-Wagner, Ethan Nadler, Annika Peter

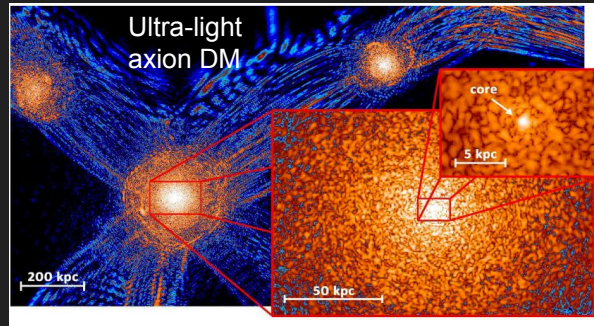
The particle properties of dark matter influence the growth and behavior of cosmic structure and astrophysical phenomena.

Cosmic probes are unique: they do not rely on the assumption that dark matter has interactions with normal matter beyond gravity.

Cosmic probes could be the only viable approach toward understanding the fundamental nature of dark matter.





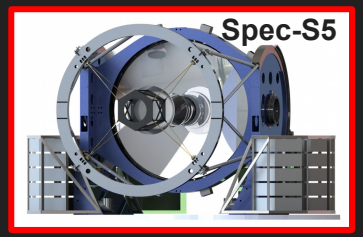


Cosmic probes are highly complementary to terrestrial dark matter searches, and there is strong experimental synergy between cosmic probes of dark matter, dark energy, and inflation.

- For example, funding for the Dark Matter Working Group within the LSST Dark Energy Science Collaboration (DESC) would enable it to contribute to and benefit from DESC infrastructure and science.

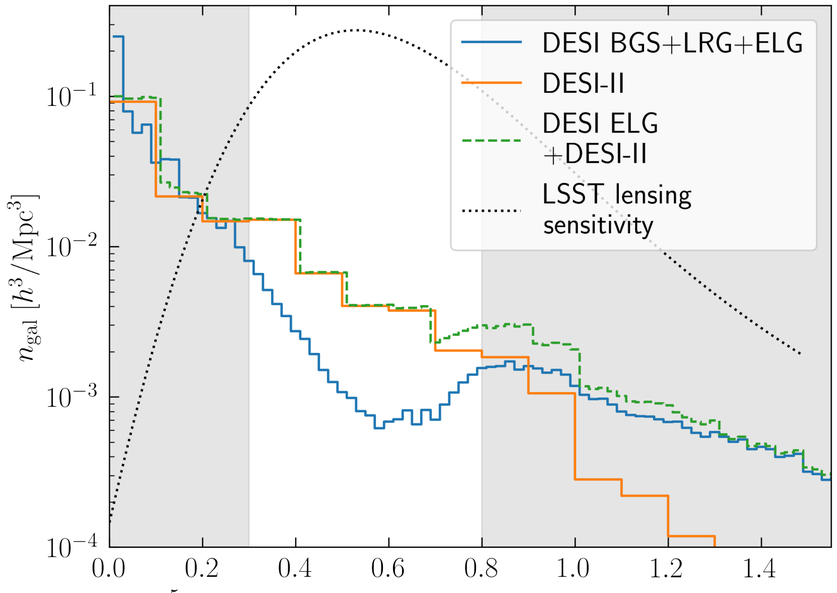
Cosmic probes represent an emergent field that requires strong synergy among particle theorists, dynamicists, simulators, observers, and experimentalists. Several things are needed to realize these opportunities:

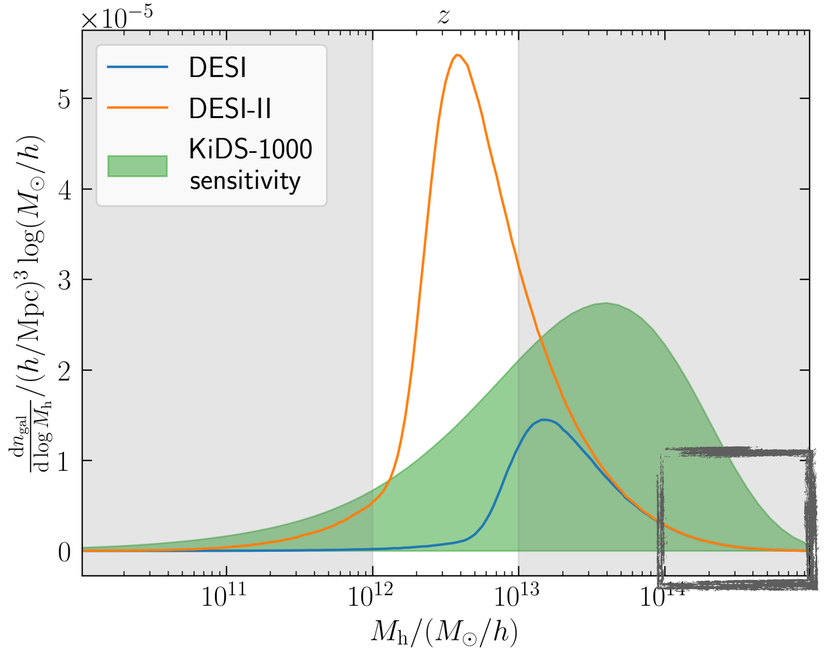
- Support HEP Cosmic Survey Projects to study dark matter in the cosmos.
- Support numerical simulations to interpret observations in the context of new dark matter physics.
- Support theorists to interpret new results in the context of new models.
- New funding mechanisms to support these emerging, collaborative efforts.



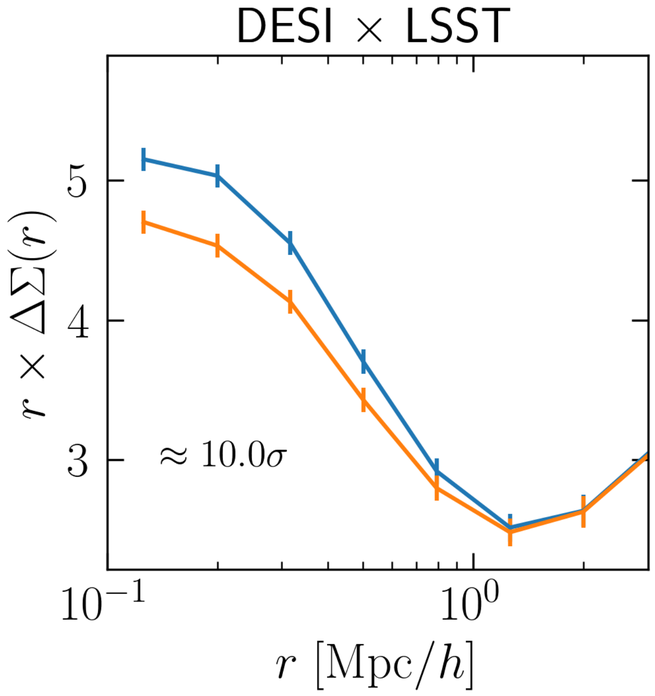
DESI-II + LSST = More than the sum of their parts

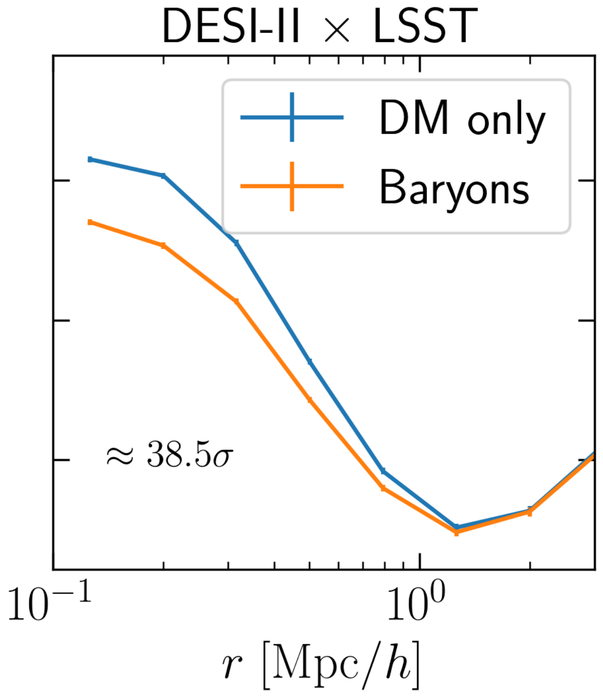
For the LBNL P5 town hall, 02/23/2023





1. Calibration of Baryonic effects over a mass range relevant for Cosmic Shear
2. Constraints on Intrinsic Alignment for a wide range in halo mass
3. Calibration of LSST Y1 redshifts





Sven Heydenreich, A. Leauthaud, E. Xhakaj, C. Blake, B. Dey, J. Newman

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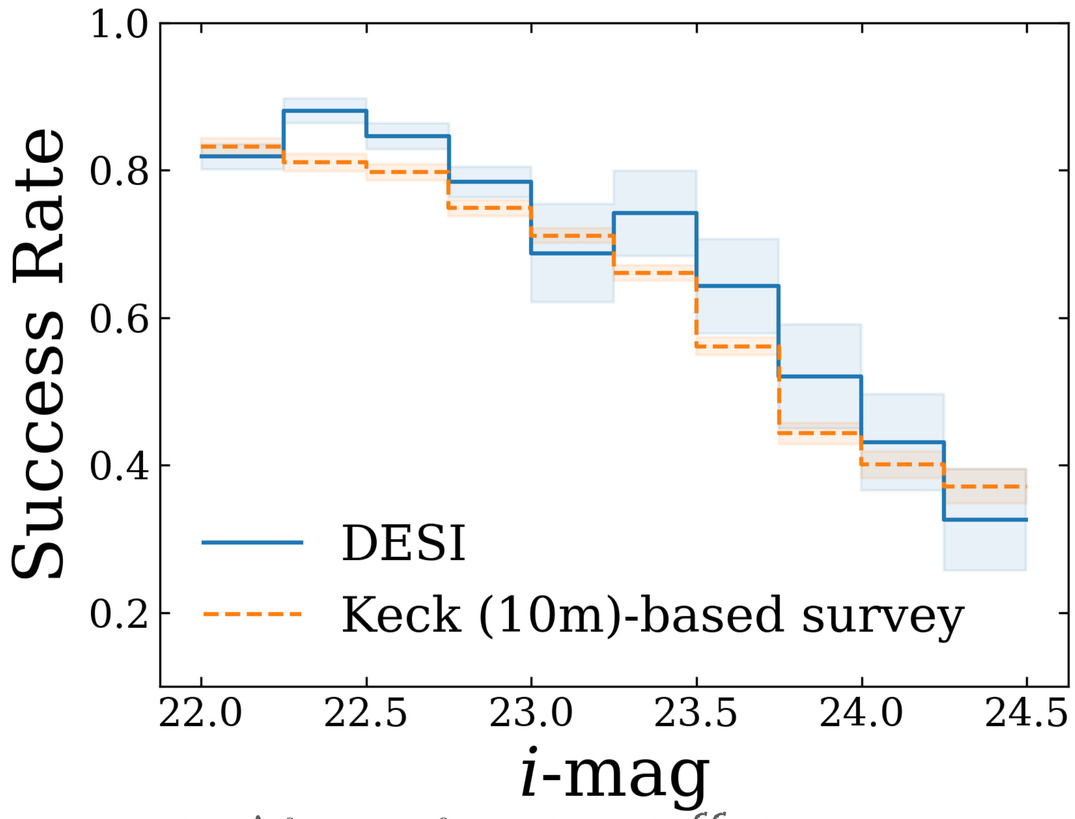


Credit: Biprateep Dey, Jeff Newman & DESI collaboration

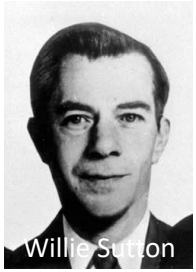
1. Calibration of Baryonic effects over a mass range relevant for Cosmic Shear
2. Constraints on Intrinsic Alignment for a wide range in halo mass
3. Calibration of LSST Y1 redshifts

DESI is extremely good at measuring redshifts of faint galaxies! We can target the overlap with LSST to create a redshift calibration sample.

Contact us at sven@ucsc.edu!

Sven Heydenreich, A. Leauthaud, E. Xhakaj, C. Blake, B. Dey, J. Newman

Training the Next Generation of Physicists and Engineers at Universities



- When the famous bank robber, Willie Sutton, was asked "Why do you rob banks" he replied, "because that's where the money is."
- If P5 is to advise the DoE and NSF on where to invest in infrastructure that supports workforce development, the answer is obvious: Universities, because that's where the students are.
- I have a bit of perspective on this, having been continuously funded by DoE at the University of Michigan for 37 years to participate in some of the largest Cosmic Frontier experiments ever built.
  - Monopole, Astrophysics and Cosmic Ray Observatory (MACRO) - 600 tonnes of liquid scintillator, ADC, TDC, trigger system
  - Dark Energy Survey (DES) - Filter Changer Mechanism
  - Dark Energy Spectroscopic Instrument (DESI) – >7500 Fiber Positioning Robots and control system. At peak production > 25 students were involved in some aspect of this.

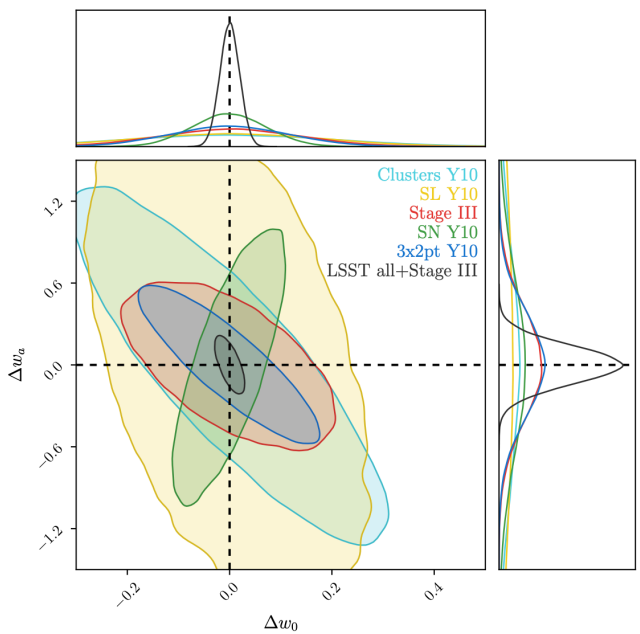
- Undergraduate and graduate students, postdocs and research scientists developed their skills in experimental physics on these projects. Many are now critical to the successful operation of large projects and will be the scientific leaders of tomorrow.
- Nearly everyone here, once "cut their teeth" on research projects at Universities.

Training the Next Generation of Physicists and Engineers at Universities

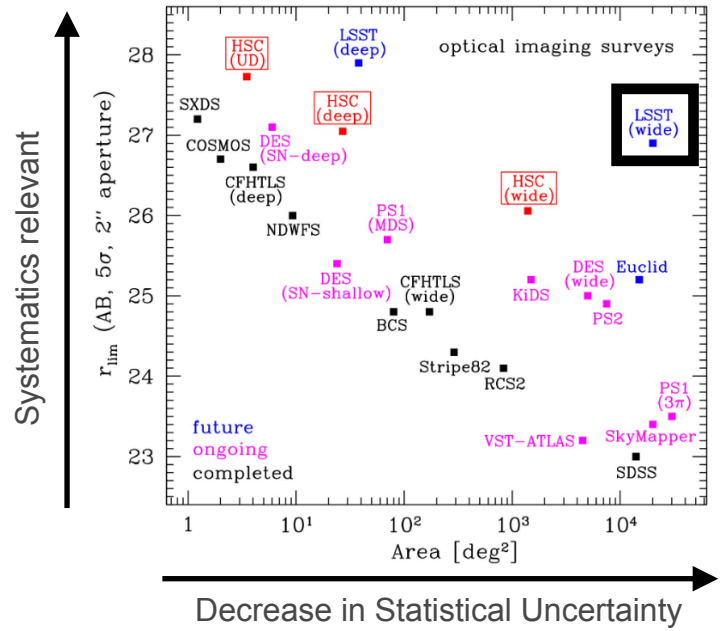
- Four decades developing novel instruments for HEP and cosmology experiments has taught me that great science comes from great scientific instruments!
- Many experimental physicists today are not familiar with the working end of a screwdriver or of an oscilloscope.
- Who will design and build the next generation of experiments?
- University research and the training of young scientists works best when there is a strong partnership between Universities and the National Labs. Some National Labs are better than others at promoting such partnerships.
- Continuity of funding at Universities is critical to maintaining the facilities and human infrastructure necessary to train the next generation of experimentalists.
- In recent decades, gaps between the end of one construction project and the beginning of another have made it difficult or impossible for many university groups to maintain capability to continue their participation in large scientific construction projects.
- We urge P5 to recommend that the agencies place a priority on sustaining vital infrastructure at our Universities to preserve capability to train our future experimental physicists and engineers.

SYNERGIES OF SURVEY PROGRAMS FOR COSMIC FRONTIER (MMRAU)

DESC SRD arXiv:1809.01669



HSC SSP



Photometric Survey teams like LSST-DESC derive cosmological information using images in broad optical filters to **maximize cosmological information. Systematics,** like e.g. error in distance or redshift measurements, **can be difficult to mitigate.**

Spectroscopic or narrow filter multi-band surveys complement these survey programs in current analyses. Future analyses will concentrate on multi-survey analyses exploiting complementary survey designs. Increase effort in development of necessary statistical methodology and experimental infrastructure.

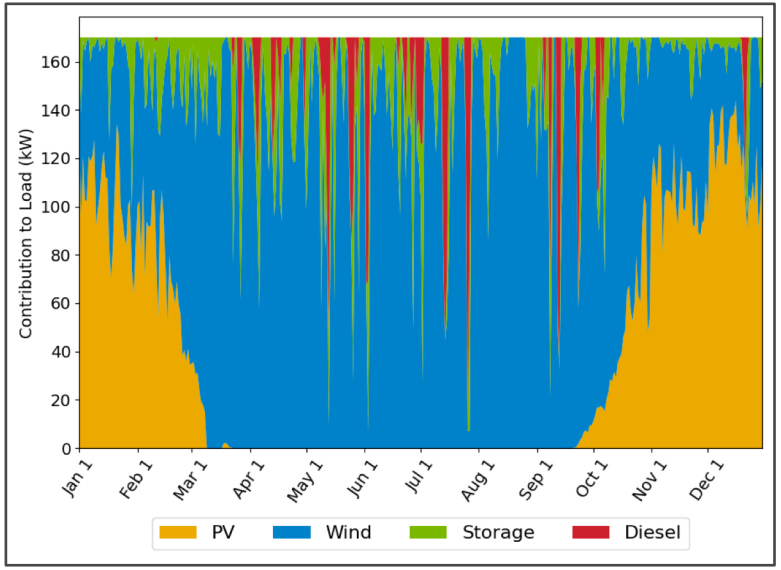
RENEWABLE ENERGY IS VIABLE FOR HEP INFRASTRUCTURE

- Renewable energy (RE) technology is reliable and affordable. RE should be a normal part of HEP infrastructure to mitigate our environmental impact.
- Argonne & NREL have collaborated on a feasibility study for RE at the South Pole (cosmic frontier experimental site)
  - Expert multidisciplinary team evaluated both technical challenges and economic viability given unique site constraints
  - Results indicate RE is good opportunity at the South Pole!

Argonne NATIONAL LABORATORY

NREL Transforming ENERGY

Renewable System at South Pole



Optimization result for example load using solar, wind, lithium-ion energy storage, & diesel. Solar and wind modeled from South Pole NOAA weather data.

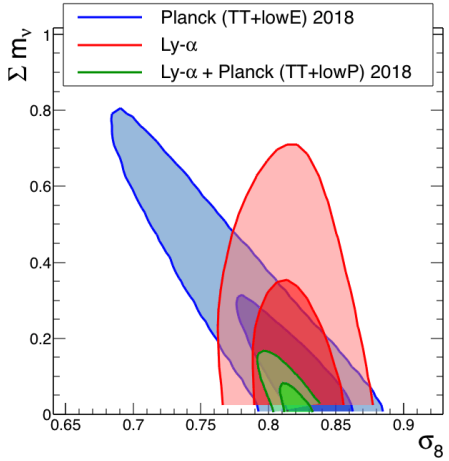
Diesel consumption and associated carbon footprint reduced by 95.5%!

15 years of fruitful collaboration between French and DOE labs

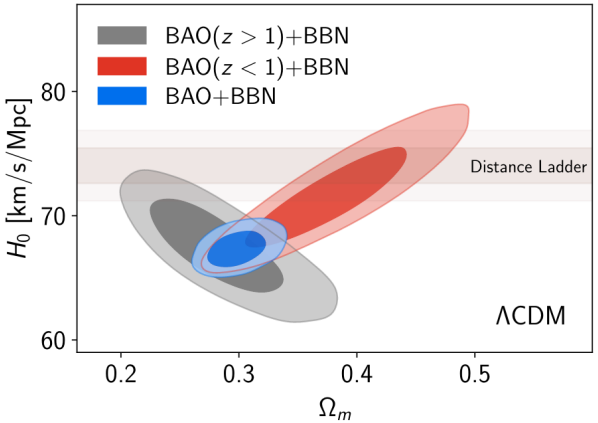
Ch. Yèche
CEA-Saclay

- Five French labs supported by three funding agencies (CEA, CNRS and ANR)
- Science: clustering of galaxies, quasars, Ly-α forests, and voids

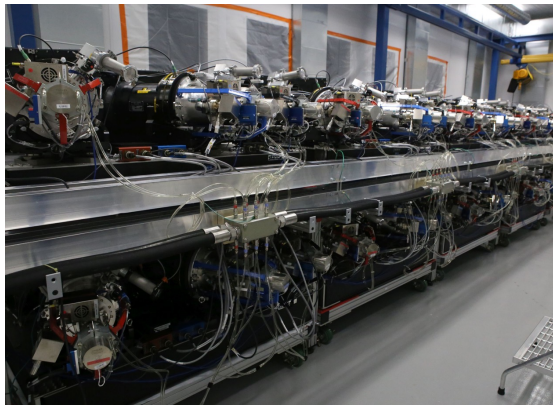
Target selection of quasars



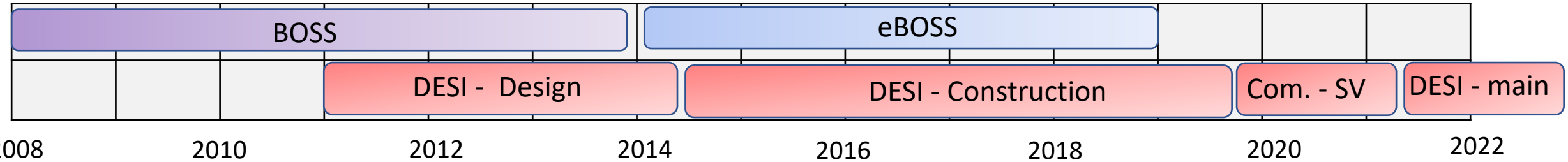
Neutrinos mass with Ly-α forests of quasars



BAO with quasars and Ly-α forests of quasars



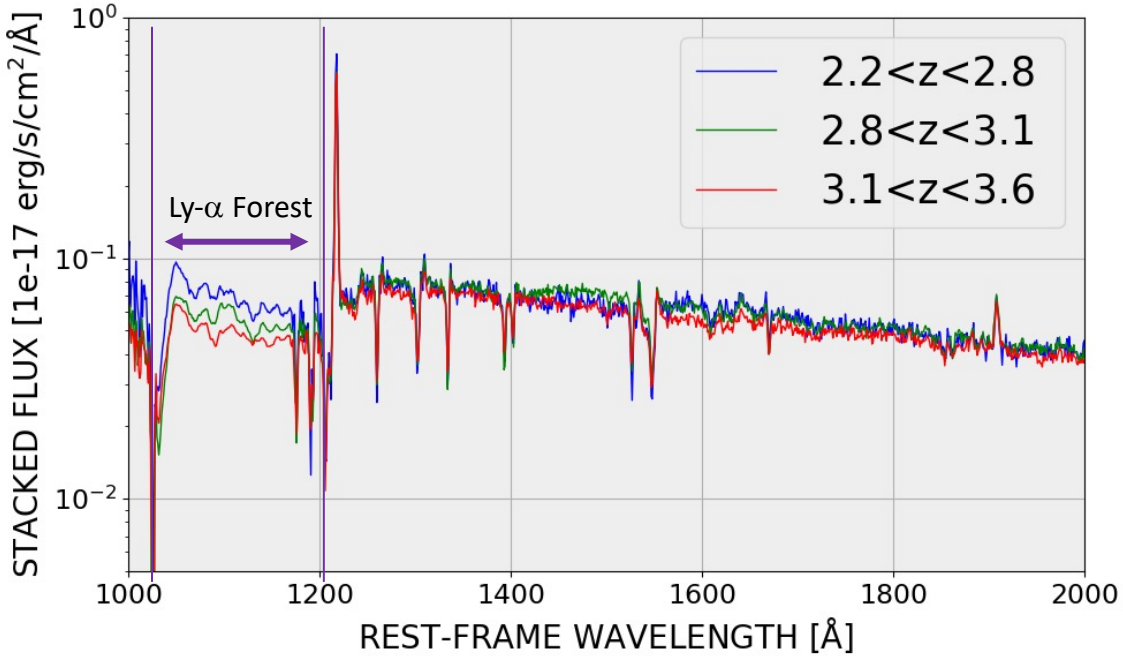
Construction of DESI spectrographs



Continued Collaboration with DESI-II and Beyond

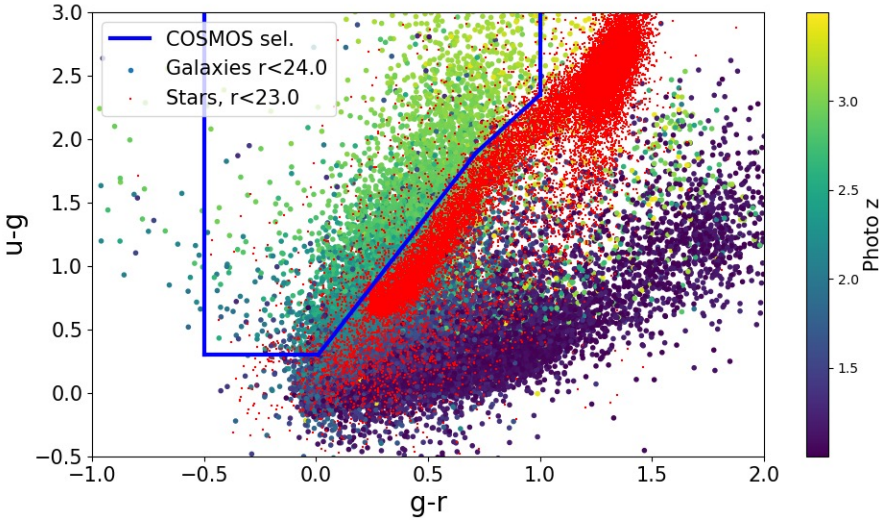
Lyman-Break Galaxies (LBGs)

- Tracers of the high-z Universe
  2.<z<4
- Galaxy clustering
- Tomography with Ly-α Forest



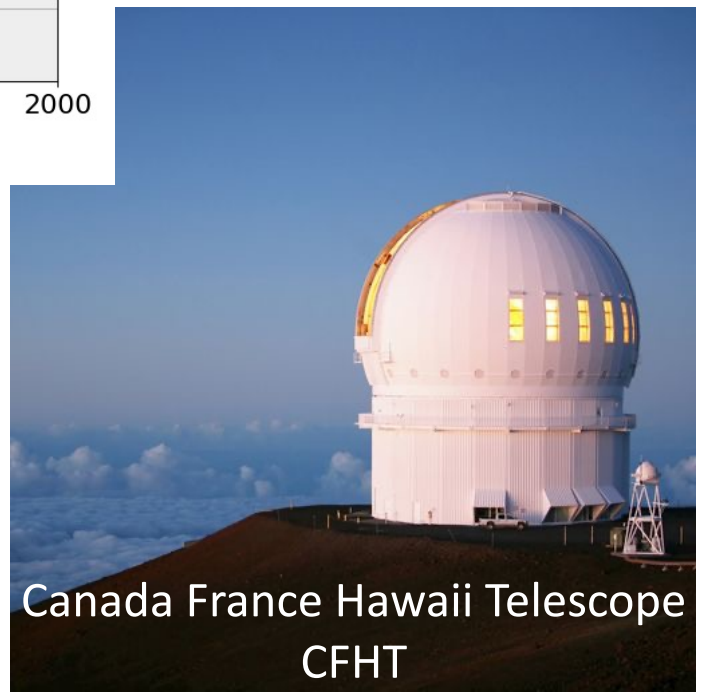
Primordial Physics

- Neutrino mass
- Inflation



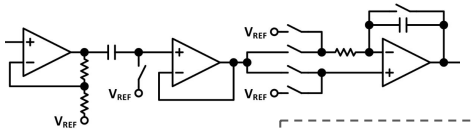
Selection of LBGs

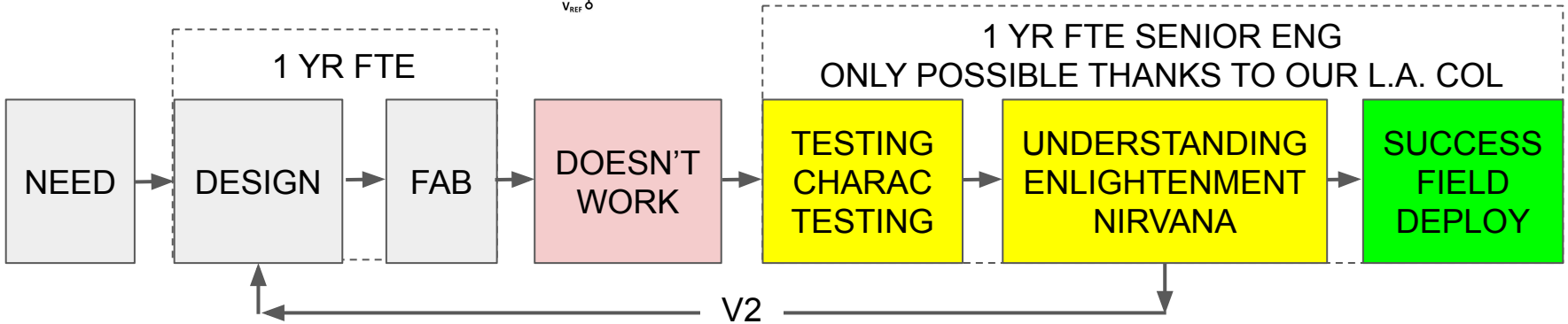
- Pilot surveys with DESI
- Use very deep u-band provided by CFHT



Leveraging Microelectronics through Dedicated Support for Implementation in HEP Experiments

CASE STUDY: MIDNA





- ➔ Compensate for fabrication uncertainties
- ➔ Develop and implement PCB circuits for readout and control
- ➔ Engineer and build packages for the ASICs
  - ◆ Mechanical design
  - ◆ Flex circuits or similar
  - ◆ Train technicians and build custom tools (packaging rigs, etc)
- ➔ Link with other users and help with the deployment and tech transfer

Take home message:

NO CHARAC & TESTING = NO ASIC

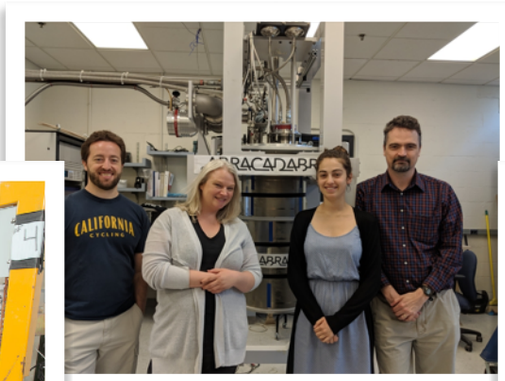
- It's critical to have dedicated resources to support testing and implementation of ASICs
- People leading the implementation and testing should participate in the design process

Yonatan Kahn

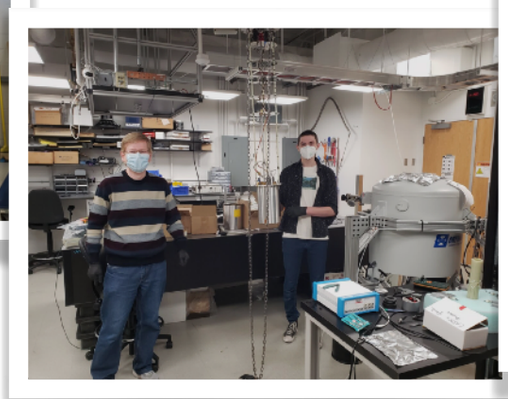
Small-scale R&D: from theory to the lab since last P5

DarkSRF:
theory 2014,
data 2023

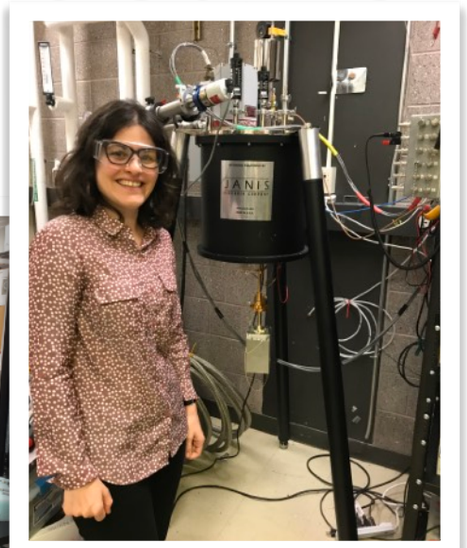
SENSEI:
theory 2015, data 2018



ABRACADABRA:
theory 2016,
data 2018



SHAFT:
theory 2016, data 2020

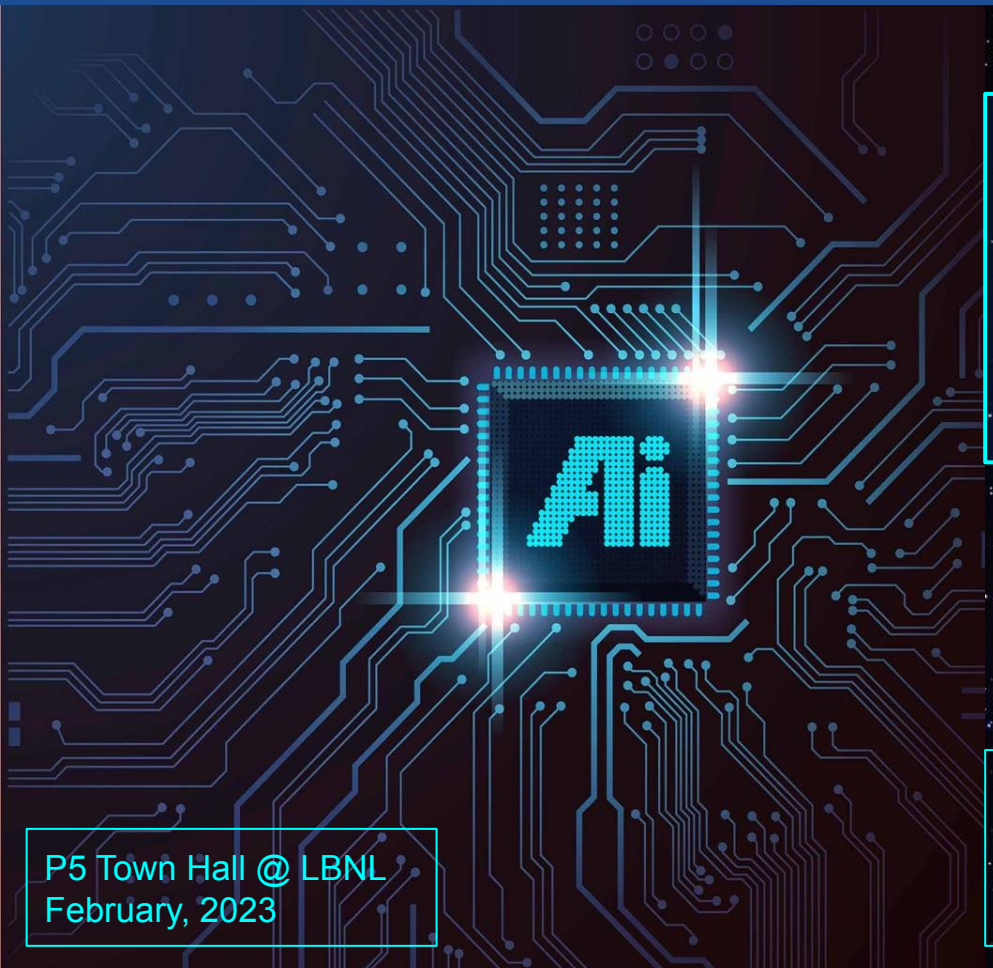


LAMPOST:
theory 2018,
data 2021

Requests for P5 recommendations:

- Expand scope and funding for detector R&D to include **personnel-level funding, multi-institutional collaborations, and science goals** (not just instruments)
- **Continue DMNI program on ~3-year cycles** to allow new ideas to "graduate" from prototype to larger-scale

The next generation of DM graduate students can go from blackboard to world-leading sensitivity during a Ph.D.!



Artificial Intelligence as a Core Component of the Cosmology Research

Aleksandra Ćiprijanović
(she/her/hers)

Fermilab, DSSL
aleksand@fnal.gov

P5 Town Hall @ LBNL
February, 2023

Vision of the Future - Cosmology with Big Data

- Major Cosmic Frontier dark energy experiment for the next decade (~$70M operations per year for 10 years, split between DOE & NSF).

- Fermilab - major role in project operations and data management; transfers expertise from DES and SDSS, LSST Dark Energy Science Collaboration (DESC).

LSST DESC
Dark Energy Science Collaboration

Fermilab

Vision of the Future - Cosmology with Big Data

- Synergies with other surveys: DESI, DES, Roman, JWST, CMB-S4 etc.

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DARK ENERGY SURVEY

CMB-S4
Next Generation CMB Experiment

THE NANCY GRACE ROMAN SPACE TELESCOPE

LSST DESC
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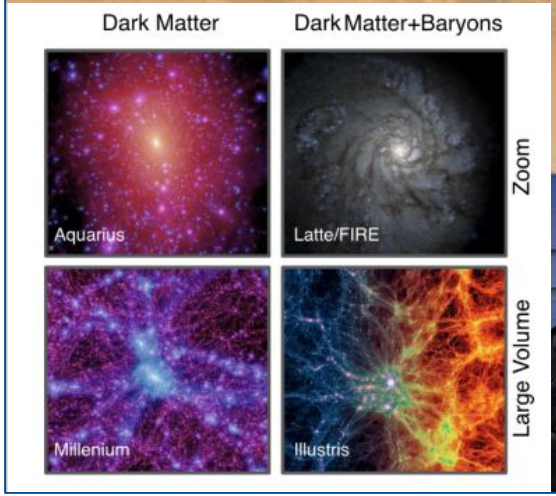
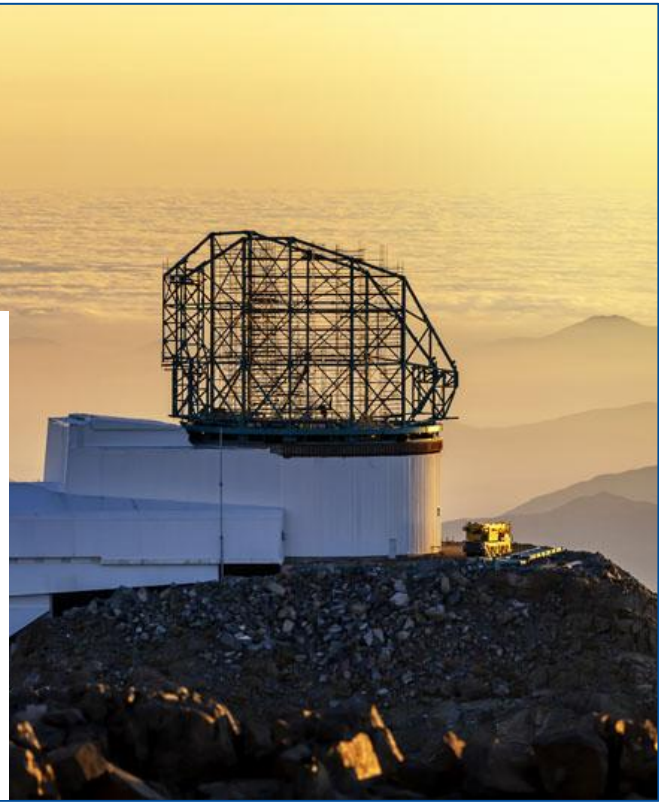
LSST DESC
Dark Energy Science Collaboration

Rubin LSST

~ 20 TB / day
~ 114x4 TB / month (raw)
~ 650 PB / year





Fermilab

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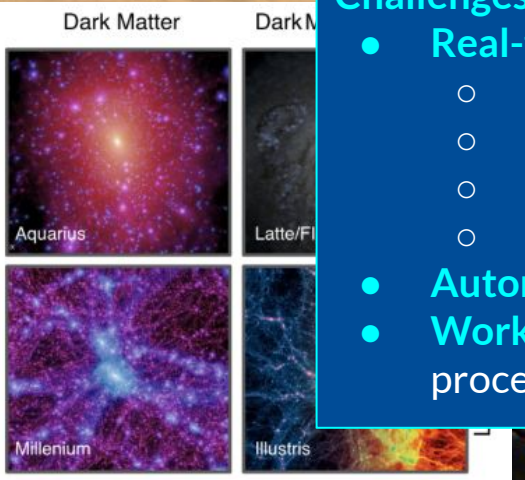


Challenges:

- **Real-time:**
  - data handling,
  - decision making
  - detection of interesting events
  - inference
- **Automated experiments**
- **Working with big data** later in the process -> cosmology

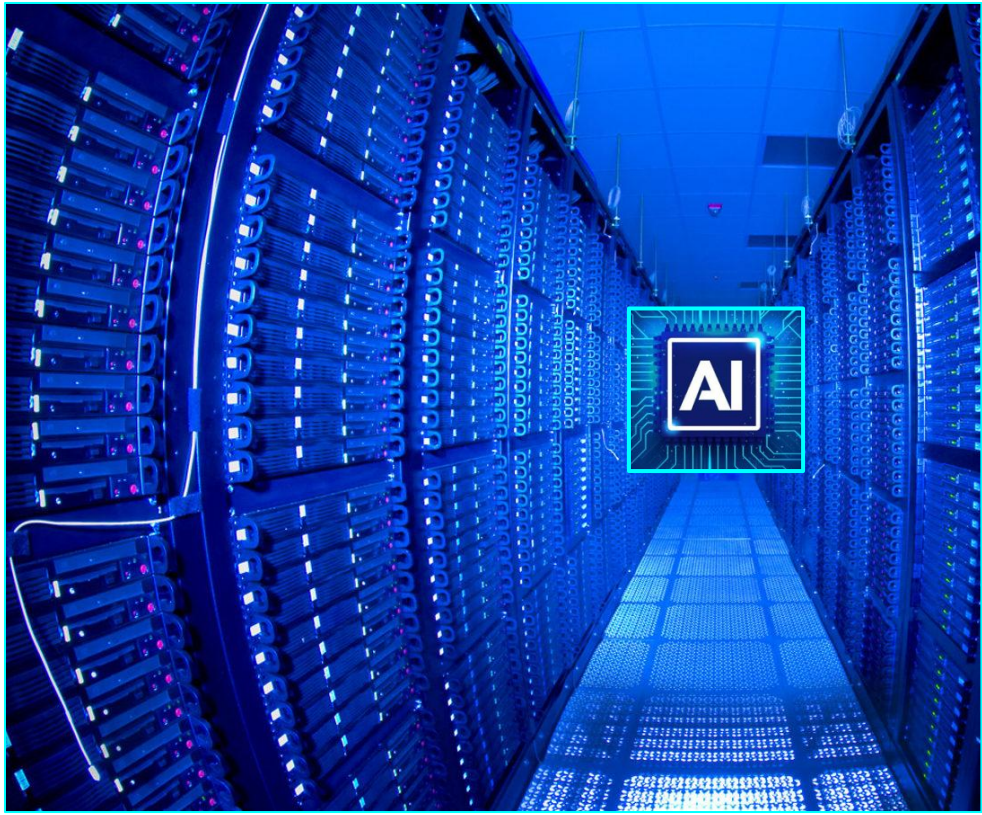
Fermilab

Artificial Intelligence for Precision Cosmology

- **AI will increase our capabilities** for real-time data handling, decision making, anomaly detections, and enable cross-dataset learning.

- Easier and faster work with big datasets, no approximations and data-driven models, no MCMC and other slow and limiting methods, **going beyond summary statistics for cosmology** etc.

- Recognising the need for the development of science-specific AI methods. AI should be **recognized as a core component of cosmology research**.

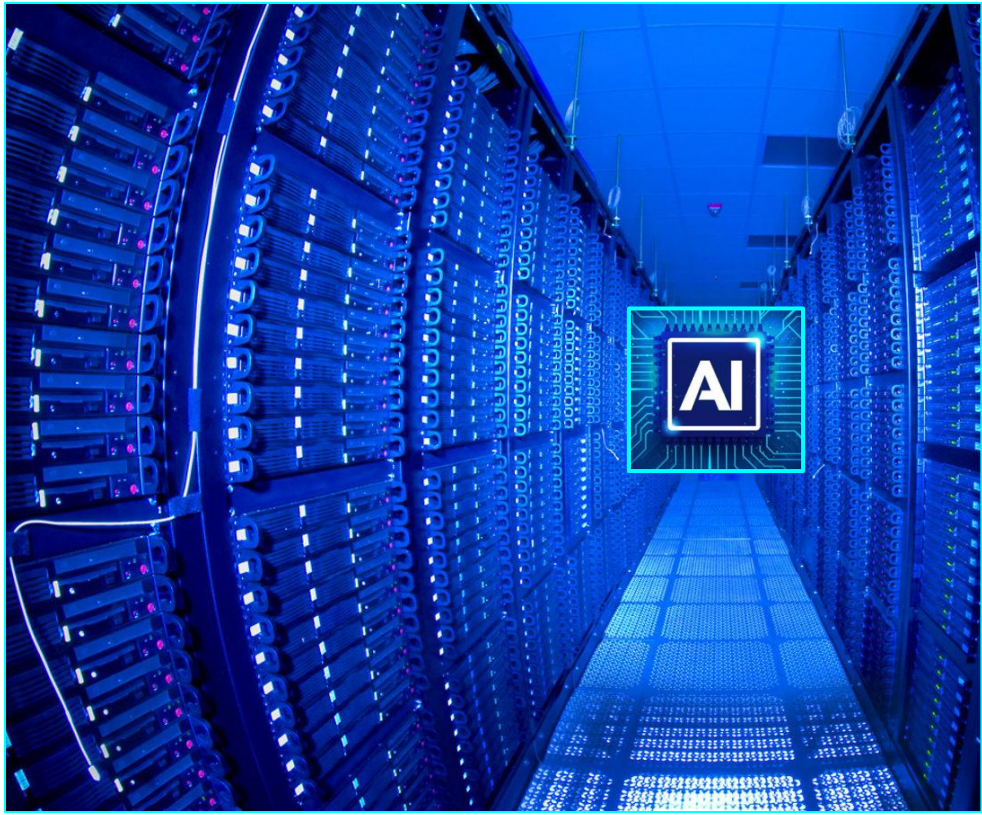


Artificial Intelligence for Precision Cosmology

AI for Physics, Physics for AI

- Fermilab has established **Computational Science and Artificial Intelligence Directorate** and **AI Office.**

- Build a community around our cross-cutting problems and guide the development of much needed physics-driven AI methods.



Hugh Lippincott (UCSB)
Rick Gaitskell (Brown)

Research Funding in Cosmic Frontier (CF) and throughout HEP

- Incredible progress in CF (and HEP) research over last decade.
  - CF points to new physics!
- University research support appears to be at long-term low
  - Program managers do what they can but have constrained budgets
  - e.g. Current target for new DOE faculty in CF after multiple rounds of successful review is 1 PD/1GS. More established grants have also been brought down to this level. [See July 2022 - Report on Status & Funding Opportunities to Snowmass])
- Faculty struggle to maintain groups to contribute to design, construction, and particularly exploitation phases of experiments
  - Lack of continuity in physics programs because so little opportunity for overlap of personal and development of specializations
  - Limitation on graduate training
  - Limitation in diversity within groups
- Faculty driven to seek additional funding joining multiple projects in parallel, distracting from key mission of agencies
  - Negative impact on experimental science exploitation/follow-through

Research Funding in Cosmic Frontier (CF) and throughout HEP / 2

- Past panels (2014 P5, 2020 CoV) have looked at the question of research funding
  - P5 2014 p8 “the budget fraction invested in construction of projects to the 20%–25% range”
  - P5 2014 p9 “the community has been coping with a sequence of recent cuts in the research program budgets, and there is a strong sense that further erosion without careful evaluation will cause great damage.”
  - 2020 Committee of Visitors recommend increase of research back to pre-P5 level. Research and Technology program funding trends mean that the “ability of the university and laboratory groups to design and build, operate and analyze, and theoretically interpret the experimental data is at risk.” If allowed to continue, the consequences will become severe…

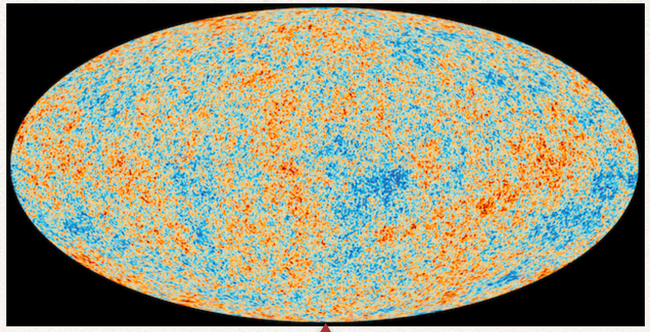
- We ask P5 to use the resources at their disposal to gather comprehensive data on university funding to understand the issue with all agencies
  - Historical university support across each frontiers including PI #.
  - What is the most effective level of personnel support for a successful research group?

- New physics is there to be discovered, but it will not happen without appropriate investment

Leveraging Cross Correlations to Detect New Physics

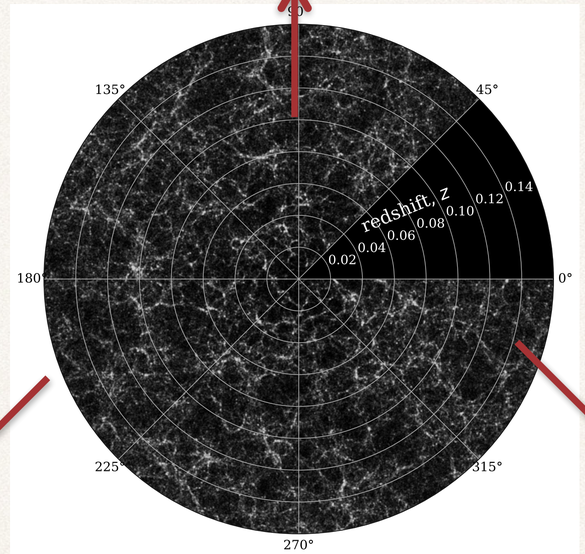
Andrina Nicola (AIfA) & Joe DeRose (LBNL)

The CMB

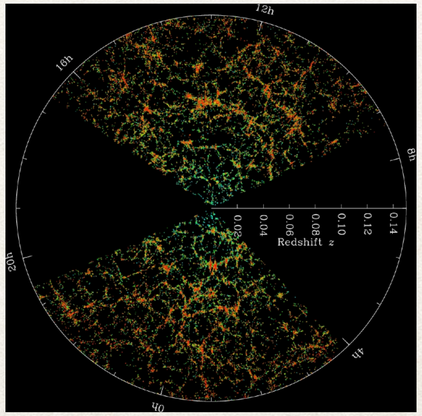


CMB-galaxy lensing
Sunyaev-Zel'dovich effect

CMB-galaxy lensing
shear calibration
redshift calibration
Sunyaev-Zel'dovich effect
CMB de-lensing

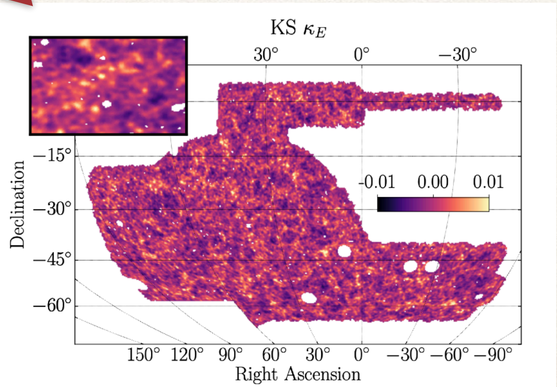


Spectroscopy



galaxy-galaxy lensing
intrinsic alignments
redshift calibration

Photometry



Leveraging Cross Correlations to Detect New Physics

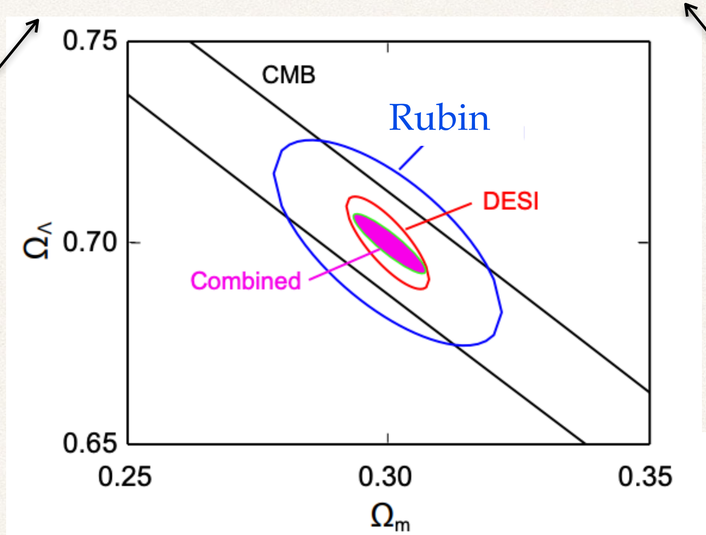
Andrina Nicola (AIfA) & Joe DeRose (LBNL)

The CMB

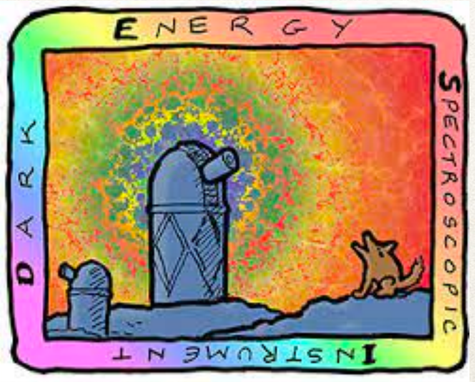
CMB-S4
Next Generation CMB Experiment

We currently lack the simulation capabilities required to take full advantage of cross-survey analyses.

We need to facilitate cross-talk and code sharing between collaborations and we need to train students and postdocs in techniques relevant to cross-survey work.



Spectroscopy



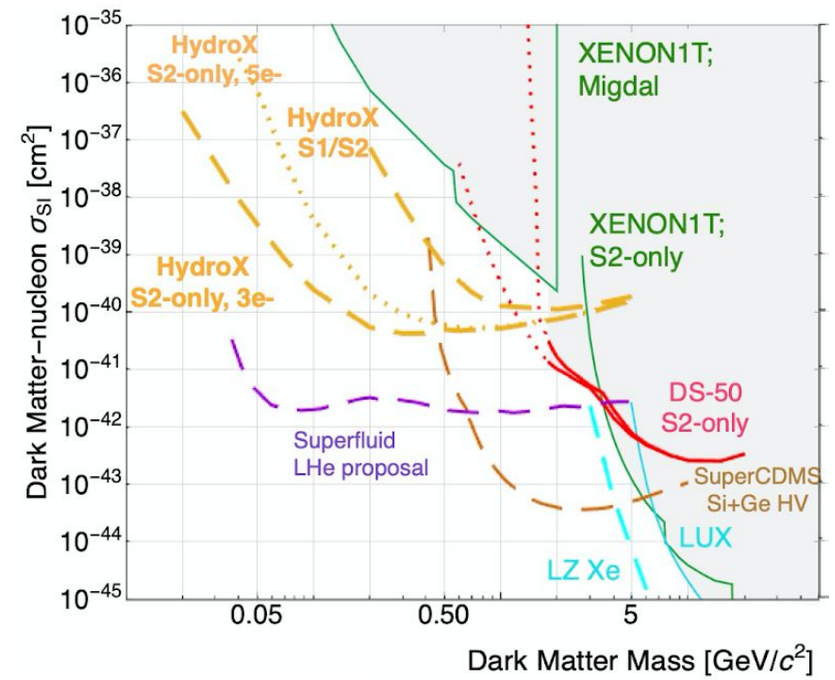
Photometry

VERA C. RUBIN
OBSERVATORY

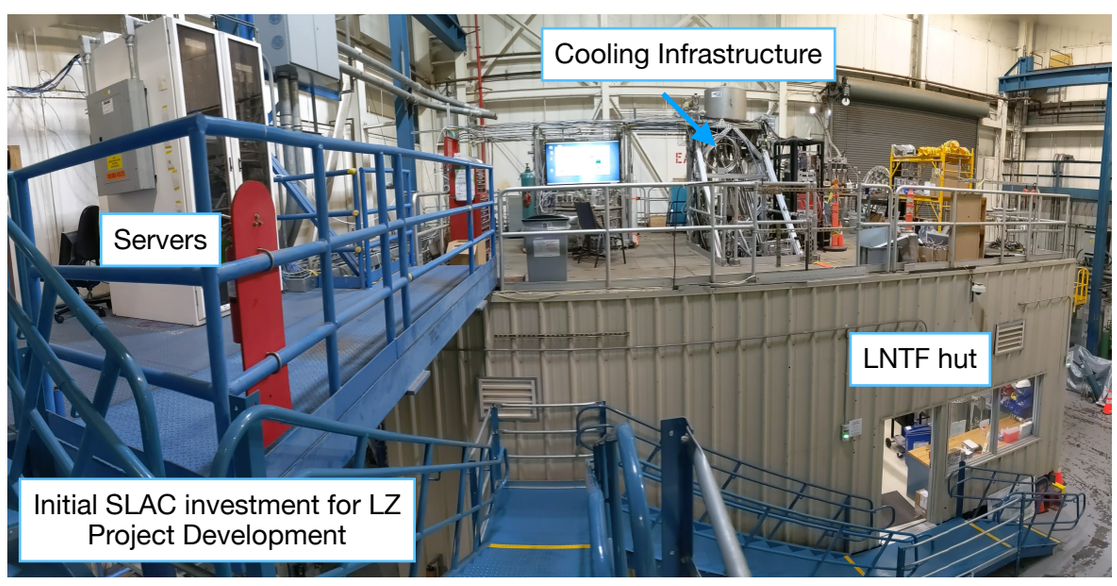
Expanding the reach of current dark matter experiments through xenon R&D & technology-centered facilities

- World-leading sensitivity of dark matter experiments such as LZ has been enabled by a strong foundation in liquid xenon detector R&D
- New areas in xenon detector R&D can lead to dramatic **improvements in current and future xenon experiment sensitivity**
  - HydroX: doping xenon with light atoms
  - CrystaLiZe, Liquid Xe Chromatography: radon mitigation

Ref: Snowmass HydroX LOI



Liquid Noble Test Facility (LNTF)



Picture from Yun-Tse Tsai

- **Technology-centered facilities** can help support needed R&D programs across HEP
  - Many sub-areas of HEP share common detector techniques/ tools
  - Provide common infrastructure and place to share ideas

Increased investment into R&D and dedicated facilities

- Support **increased investment in xenon detector R&D at universities and labs** to upgrade existing dark matter experiments

- As these R&D efforts mature, supporting potential **upgrades to existing experiments** can greatly improve sensitivity
  - Also fills the timeline gap between G2 & G3 dark matter experiments

- Investing in **technology-centered facilities** can enable R&D work across areas of HEP

- R&D and related facilities serve as an important **training ground for early career experimentalists** as projects grow in scale

As an early career member of a large experiment, smaller R&D programs and facilities have been vital for me to learn about detector design, so I can help build the next generation experiment

DESI-II and S5 spectroscopic surveys can test dark matter particle predictions in the Milky Way and its satellites

Connie Rockosi
UC Santa Cruz, SCIPP

- Large area + high sensitivity; same drivers as cosmic structure surveys
- Surveys of 1000s of square degrees, 10s of millions of stars can make comprehensive tests of predictions, now and as DM models evolve

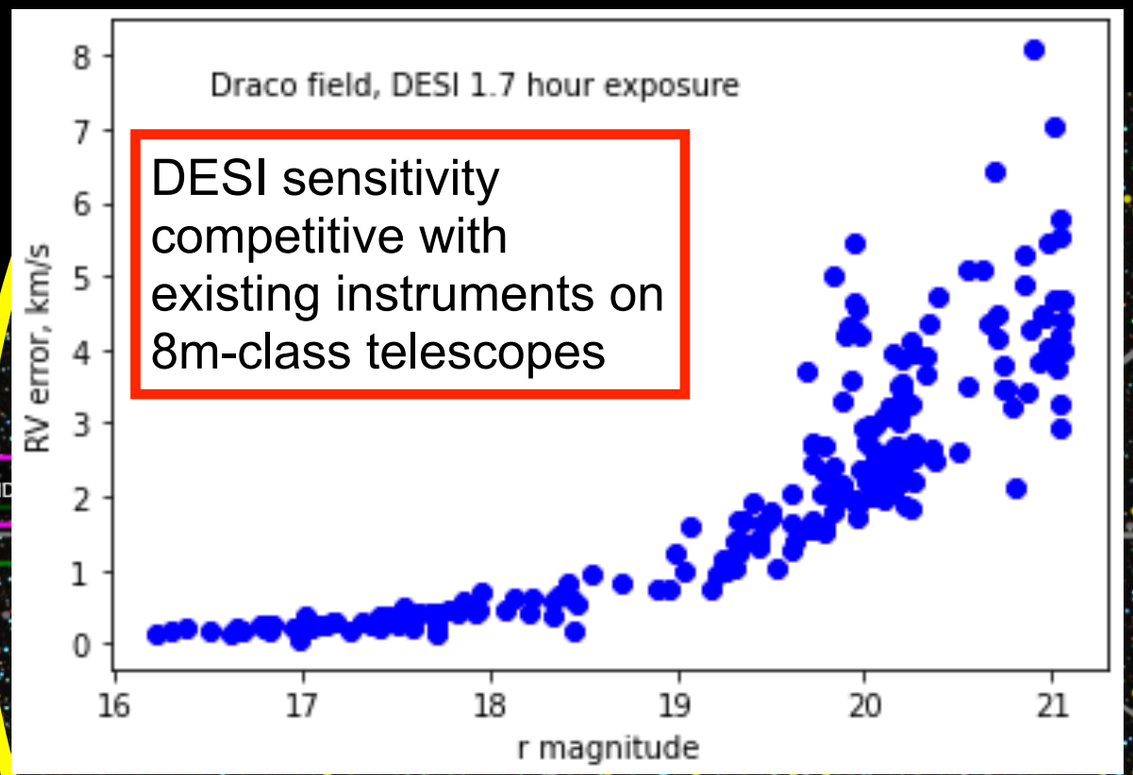
Velocities of thousands of stars in MW dwarf satellites

Map shape and density DM halos
Low mass, DM dominated regime

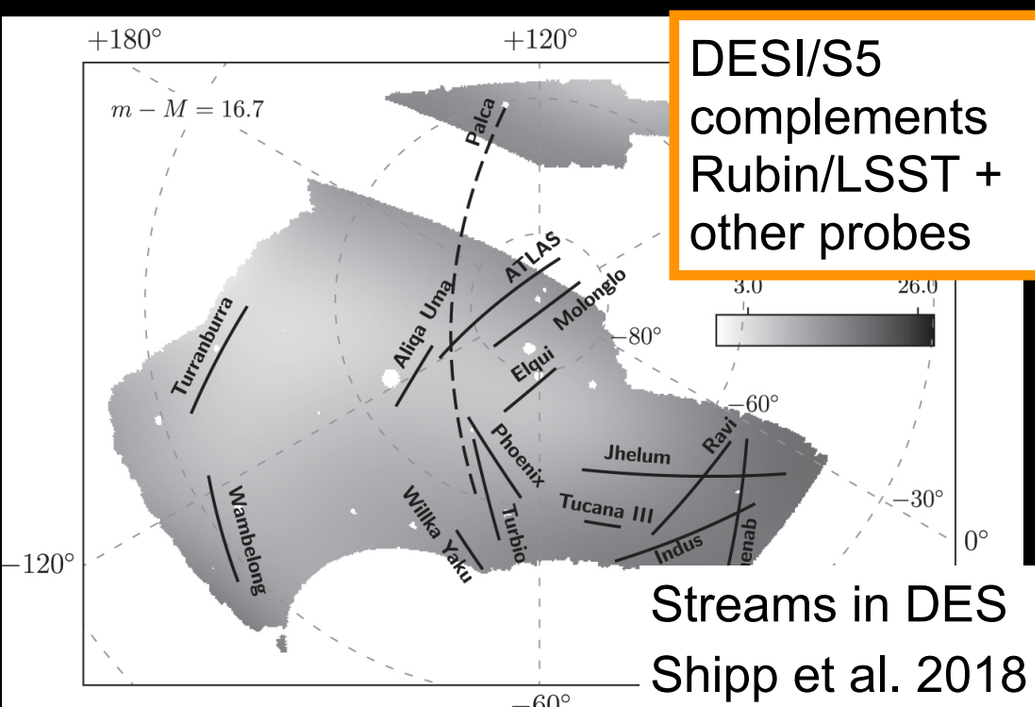
Kinematic maps of MW stellar streams

~100 known (so far), large on the sky

Perturbations constrain spectrum of lowest mass DM halos

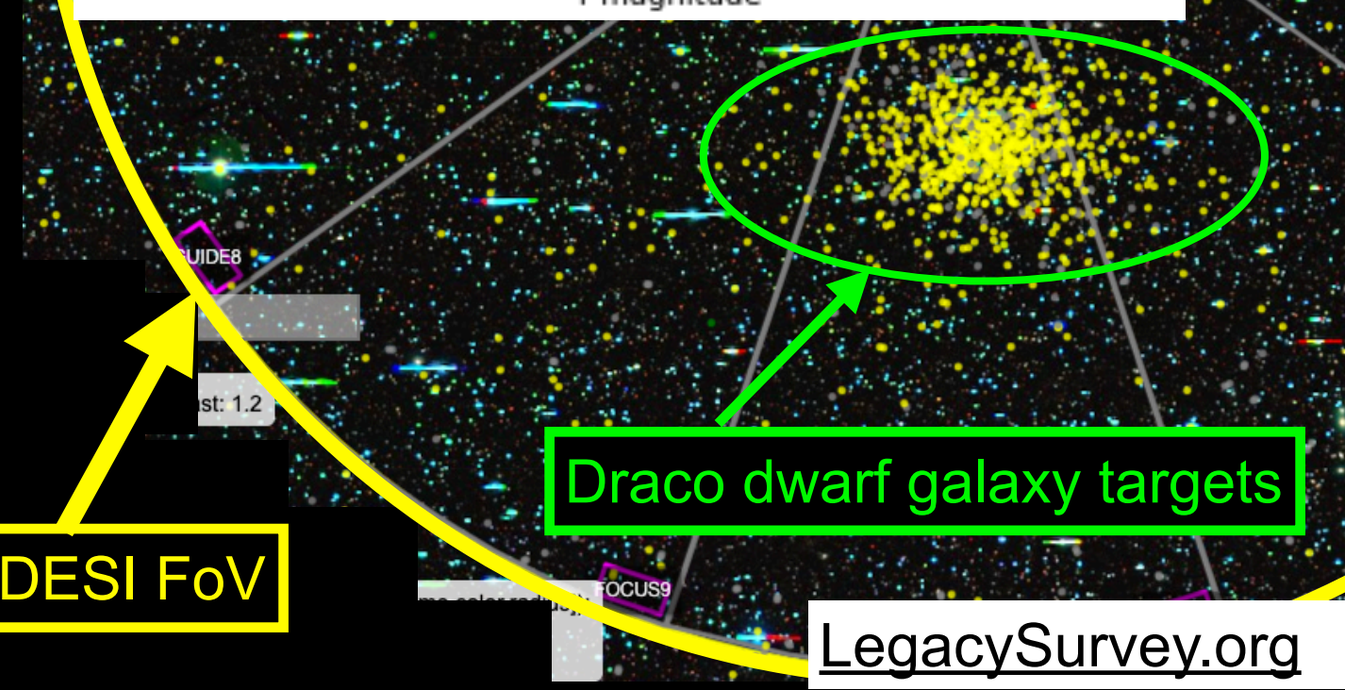


DESI sensitivity competitive with existing instruments on 8m-class telescopes



DESI/S5 complements Rubin/LSST + other probes

Streams in DES
Shipp et al. 2018



DESI FoV

Draco dwarf galaxy targets

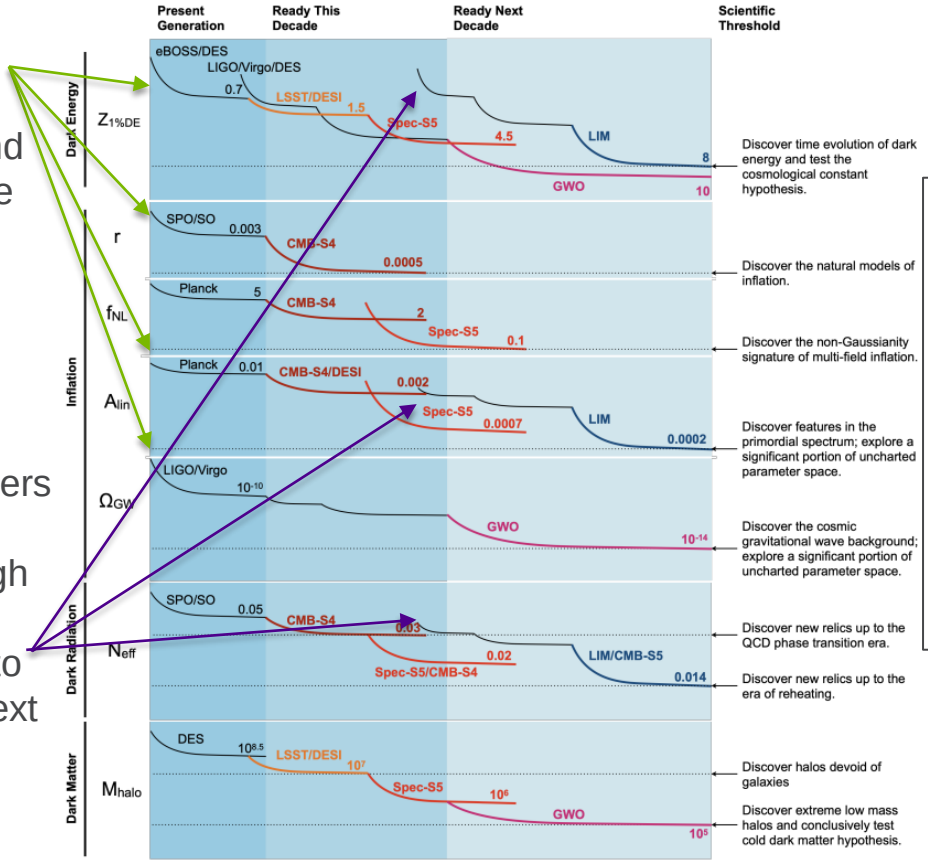
LegacySurvey.org

SUPPORT DEVELOPMENT TOWARD THE NEXT GENERATION FLAGSHIPS

Katie Harrington
mm-wave / CMB instrumentation

Pathfinders + Stage-3 instruments have enabled the technological development and understanding we need for the upcoming flagships.

Support for R&D and pathfinders that take new technology and measurement methods through to on-sky observations is necessary for us to be ready to use their results to plan the next generation of flagships.



Snowmass Report:
Longer-term Efforts

Support R&D and pathfinder studies for a next-generation CMB experiment (at the Stage V or VI level).

Support R&D and small projects to develop technologies and methods that can enable a future surveys (e.g., LIM and CMB-S5) and new precision probes of cosmology.

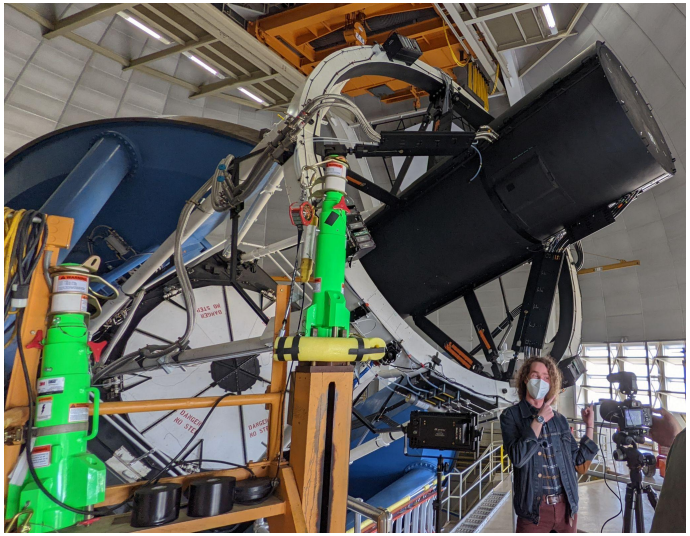
Reflections on DESI construction from early career scientists

Claire Poppett (SSL)
Kevin Fanning (OSU)

- 2012: Joined the project as a PostDoc, 2014: Lead Fiber scientist (L2 manager), 2020: DESI observing operations lead and lead observer(L2 manager)
- DESI is the most powerful redshift survey instrument ever built
  - Significant early investment in R&D.
  - Every design decision was optimized resulting in throughput equivalent to 10m-class telescopes and incredible point-spread function stability

" I strongly believe that the future of Cosmology relies on training and retaining instrument builders like me who rely on the prospect of future world-class survey instruments"

DESI is powerful because of the investment in both early R&D and in people



Kevin Fanning| Ohio State| Graduating 2023
"Much of my training as a scientist has been through working on DESI construction, commissioning and early analysis of data. Following the development of a project in one's early career is a unique and formative experience. Similar opportunities for early career scientists to involve themselves with developing projects should continue to be cultivated within the community for future projects."

Abby Bault | UC Irvine | 5th year PhD
"Being involved in DESI throughout my years as a grad student has afforded me unique opportunities to become a more well-rounded scientist. I have been able to work hands-on with the robotic fiber positioners and continue to do science during my PhD. I believe these different experiences are essential for success as a grad student, and am excited to see what opportunities lie ahead."