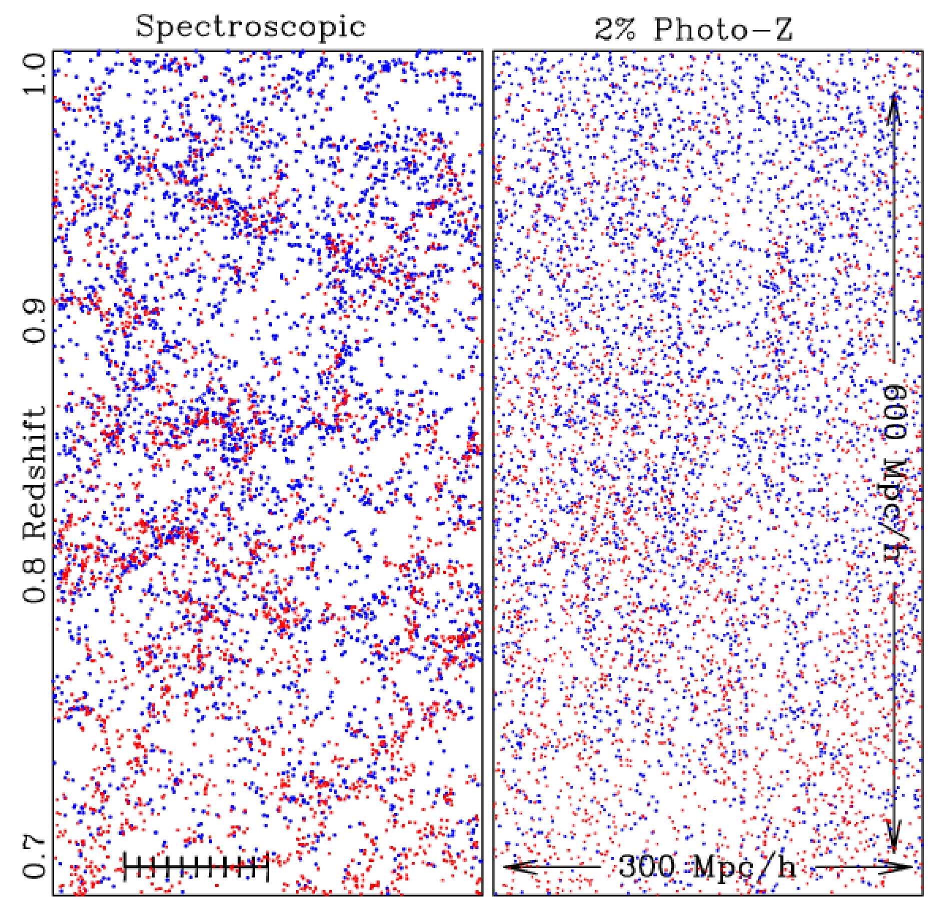
Seeing the Universe in 3-d

Daniel Eisenstein (Harvard)

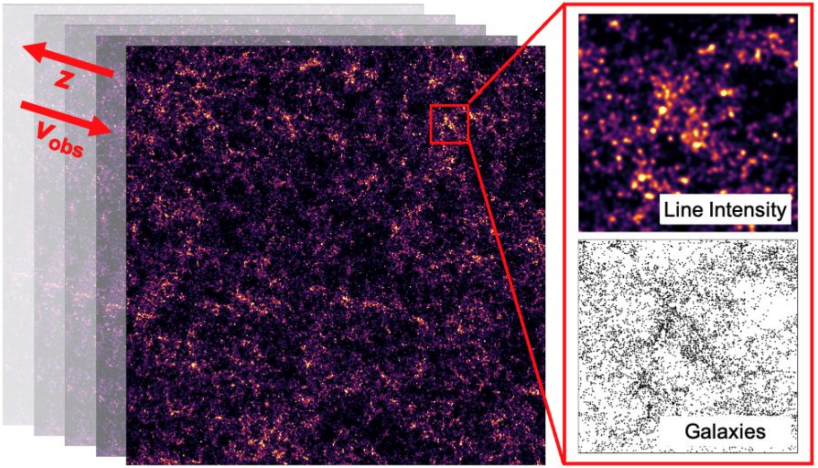
- Large-Scale Structure (LSS) allows us to explore a wide range of cosmological physics.
- We see LSS in many useful ways, but spectroscopic redshifts are by far the cleanest way to reveal the cosmic web.
  - More linear theory modes.
  - Access to peculiar velocities, groups, voids.
  - More robust!
- As we plan beyond Rubin/CMB-S4, both our statistical goals and our systematic requirements drive us toward a 3-d view of the Universe.



A small patch of DESI data (40 Mpc/h thick) showing red and blue galaxies. Even good photo-z's badly blur out the cosmic web. 10 Mpc/h is one tick on the ruler.

Millimeter-Wave Line Intensity Mapping: A Next-Generation Cosmological Probe

Kirit Karkare (SLAC), Adam Anderson (FNAL), Zhaodi Pan (ANL) – see Snowmass White Paper arXiv:2203.07258



Spec-hrs	Example	Time scale	$\sigma(M_\nu)$ [eV]	Primordial FoM
10^5	TIME, SPT-SLIM	2023		0.0015
10^6	TIME-Ext	2026	0.047	0.1
10^7	SPT-3G+, 1 tube	2028	0.028	1
10^8	SPT-3G+, 7 tubes	2031	0.013	10
10^9	CMB-S4, 85 tubes	2037	0.007	100

Low resolution, spectroscopic observations detect line emission from unresolved galaxies. Target far-IR lines such as CO/[CII] which redshift to the millimeter range. Reuse existing CMB facilities and detector heritage.

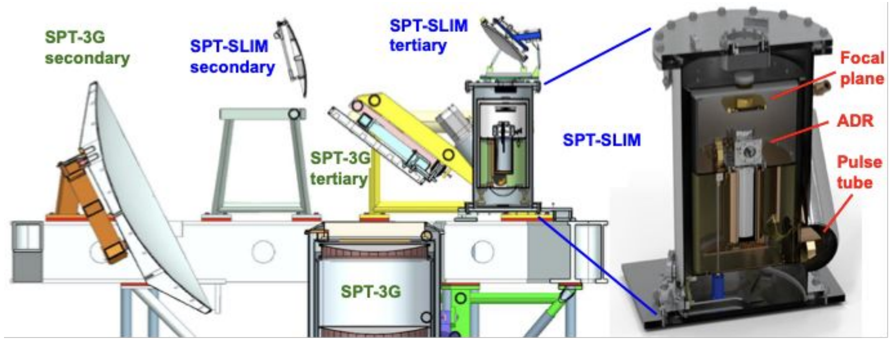
Efficiently measure LSS beyond the reach of optical surveys: a single instrument could detect $0 < z < 10$!

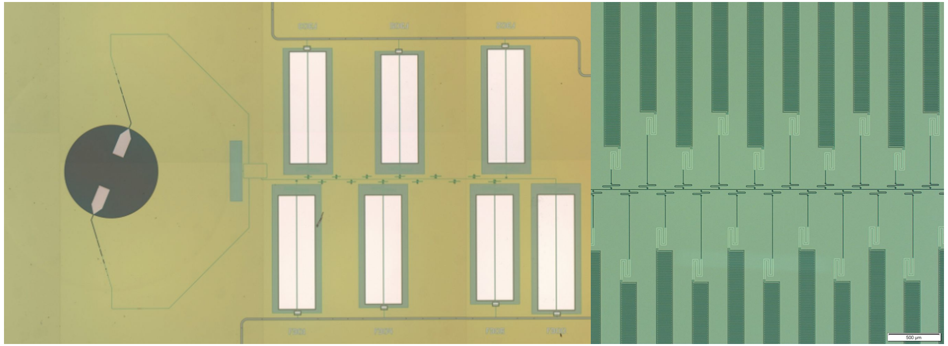
We need to improve sensitivity by several orders of magnitude for next-generation cosmological constraints.

Progress is driven by advances in detector technology (e.g., on-chip spectrometers) and pathfinder experiments that are now being fielded.

The SPT-SLIM Pathfinder and Detector R&D

Karkare et al. (arXiv:2111.04631)





Prototype SPT-SLIM spectrometer

On-chip filter bank (T. Cecil)

Small pathfinder experiments are *essential* for testing detector technology and measurement techniques in realistic on-sky conditions. SPT-SLIM is an example of such a pathfinder to demonstrate the on-chip spectrometer technology for mm-wave LIM, supported by NSF and Fermilab LDRD (~$2M total).

Will make sensitive measurements of the CO power spectrum using the South Pole Telescope in the 2023–24 austral summer.

Silicon wafers are ideal for building high-density integrated spectrometer arrays, based on CMB detector heritage. State of the art: O(10) spectrometers with O(100), R~100 spectral channels

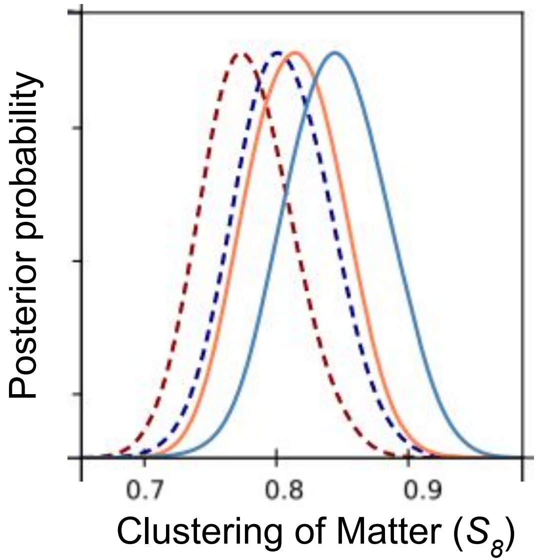
Challenges towards O(100-10000) spectrometer arrays: increased packing density, spectral resolution, optical efficiency, and sensitivity. DOE detector R&D support is critical for enabling this progression.

Survey synergies: Direct calibration of weak lensing surveys with spectroscopy

Noah Weaverdyck (LBNL)

- Cosmology with LSST needs accurate *p(z)*
- “Learn” *z* ~ *f* (photometry) from spectroscopy
    - Challenge: **spec samples not representative of photometric samples**
- DESI-II and Stage-5: measure LSST *p(z) directly*
    - Representative
    - Sidesteps systematics
    - Can *refine* samples
- **Other synergies**: characterizing spatial photo-z dependence, constraining baryonic effects, intrinsic alignments, etc

Systematic impact of different photo-z choices DES Y3, 2x2pt



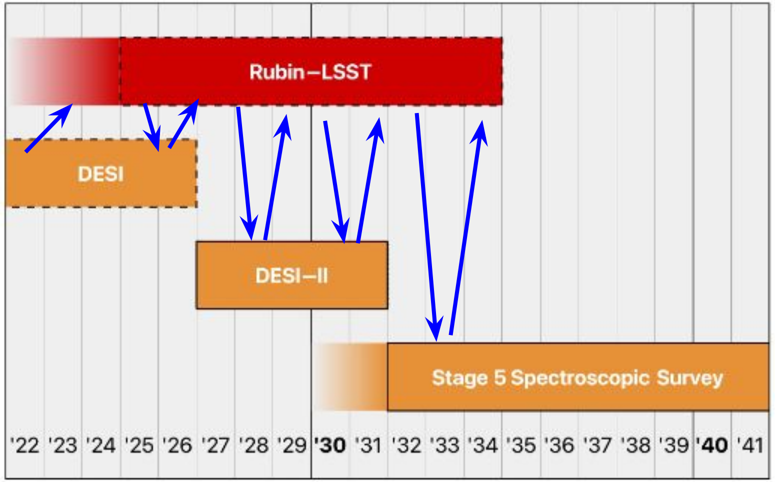
Giannini+, (DES Collaboration) 2022

NWeaverdyck@lbl.gov

Adapted from CF6 report

"A New Way to Do Science"

- Cross-collaboration analysis as a norm
- Requires support, policies, funding to facilitate
- Cultivate open access, regular public data sharing and release



*But perhaps as important as the science was **a new way to do science** [...]. The SDSS [has] produced **9,299** scientific papers to date, which have been cited half a million times.*

***Far fewer than half** of these papers have arisen **from within the collaboration**, **even while the original survey was active**. A **secret of its success**, as important or more than the optics and detectors and software, was the **openness of the data** and the **open tools to access, organize, and work with the data**.*

- James Gunn [Annu. Rev. Astron. Astrophys. 2020.58:1-25]

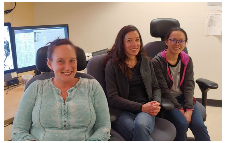
DESI: A Successful University - National Laboratory Partnership

Klaus Honscheid, Paul Martini (Ohio State University)

University of Michigan **EPFL (Swiss)**

IFAE, ICE, CIEMAT, IFT (Spanish)

Boston University



The Ohio State University

UC Irvine

University of Arizona

UC Berkeley

CEA Saclay, CPPM, LAM, OHP, LPNHE (French)

LBNL

LPNHE (French)

Fermilab

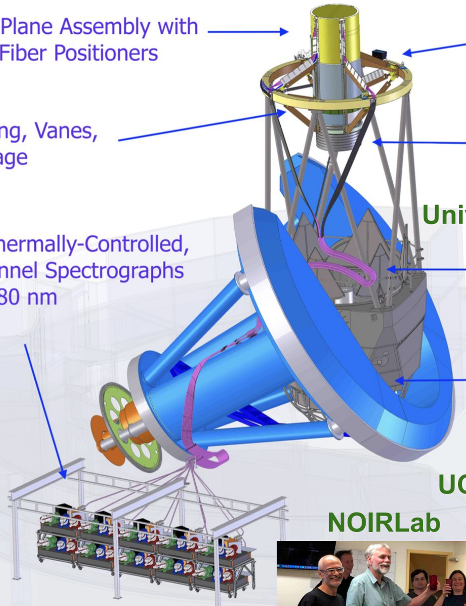
University College London

Durham University

Yale University

UC Santa Cruz

NOIRLab



DESI Institutional Contributions

Institution	Responsibilities
LBNL	Project Management; Project Office; Design; Lead for Focal Plane, Fiber System, Spectrographs, and Data Systems; NERSC; NIR Detectors and Electronics; Positioner R&D
University of Arizona	Blue Detectors
UC Berkeley	Optical design; Spectrograph Acquisition; Dichroics; VPH gratings; Corrector Lens Acquisition
Boston University	Petal Fabrication and Metrology
CEA Saclay	Cryostats
Durham University	Fiber System
EPFL	Positioner Components
Fermilab	Corrector Support System and Hexapod; Telemetry Database; PlateMaker, Detectors
IFAE, ICE, CIEMAT, IFT	Guide/Focus/Alignment Arrays
LPNHE	Calibration System, Spectrograph Testing
University of Michigan	Positioners Assembly and Testing; Petal Electronics
NOIRLab	Installation; Mayall Upgrades; Facility Operations; Data Transfer and Backup
Ohio State University	Instrument Control System; Commissioning Instrument; Spectrograph Mechanisms; Rack and Shack; Sky Monitor
CPPM, LAM, OHP	Spectrograph Testing
UC Irvine	Dynamic Exposure Time Calculator; Sky Monitor
UC Santa Cruz	Lead for Commissioning
University College London	Corrector
Yale University	Fiber View Camera; Fiducials; Focal Plane Imaging

NOTE—Contributions to instrumentation by institution through CD-4. For each institution listed in Column (1), their contribution(s) are listed in Column (2). Acronyms are: LBNL: Lawrence Berkeley National Laboratory; CEA Saclay: Commissariat à l'énergie atomique at Saclay; EPFL: École polytechnique fédérale de Lausanne; Fermilab: Fermi National Accelerator Laboratory; IFAE: Institut de Física d'Altes Energies; ICE: Institut de Ciències de l'Espai; CIEMAT: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas; IFT: Instituto de Física Teórica; LPNHE: Laboratoire de Physique Nucleaire et de Hautes Energies; NOIRLab: NSF's National Optical-Infrared Astronomy Research Laboratory; CPPM: Centre de Physique des Particules de Marseille; LAM: Laboratoire d'Astrophysique de Marseille; OHP: Observatoire de Haute-Provence (now the Observatoire des Sciences de l'Univers Institut Pythéas).

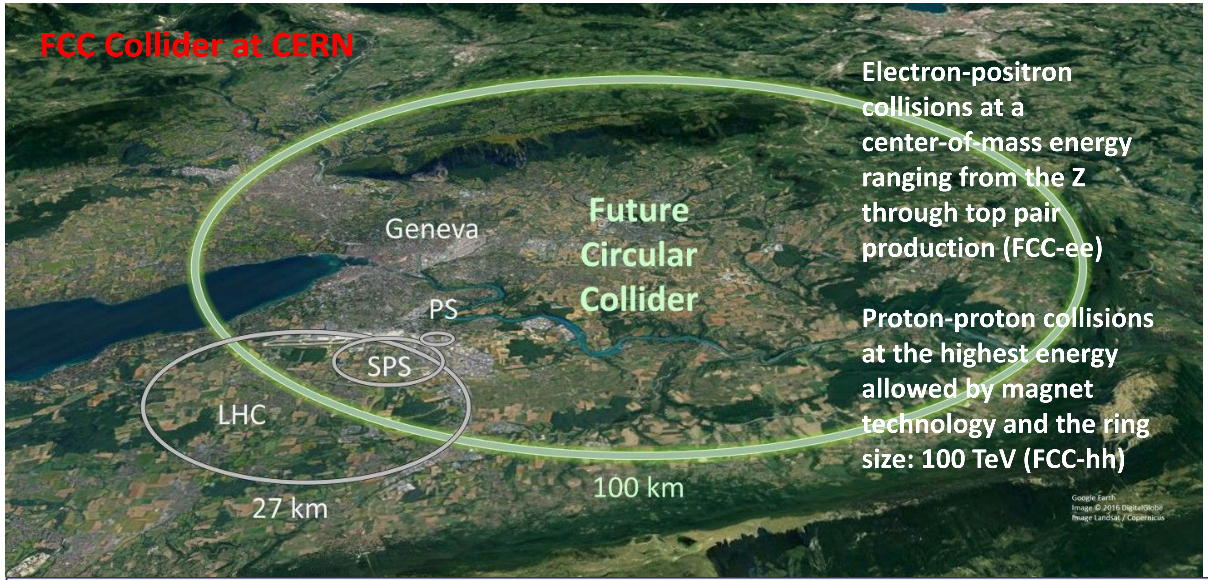
DESI Collaboration (2022), AJ, 164, 207

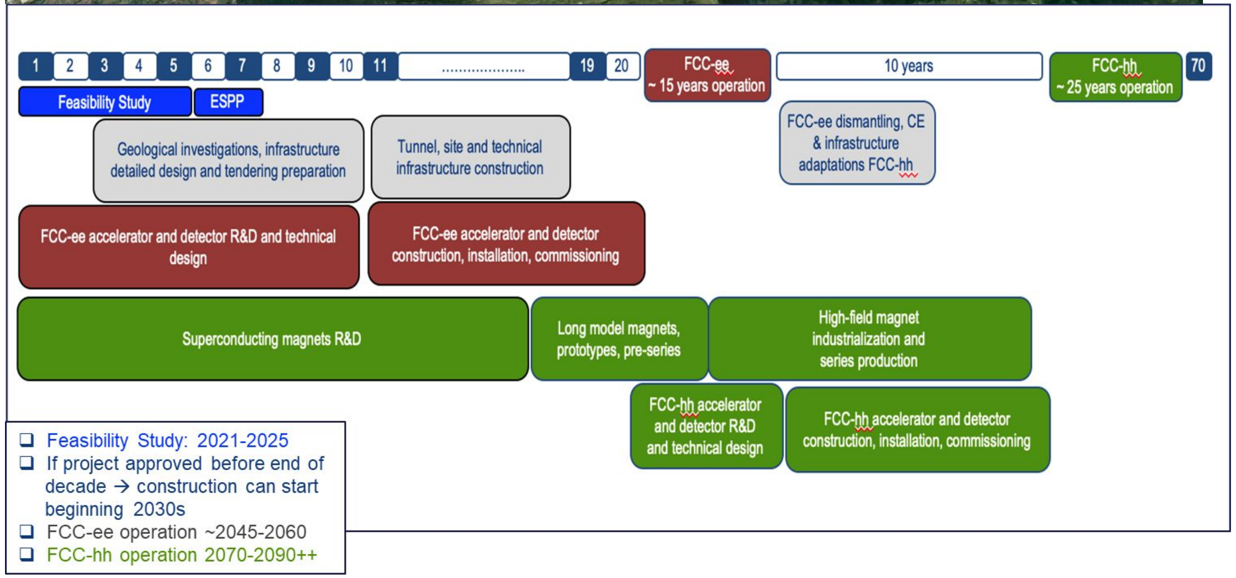
Synergy between cosmological research and the FCC program

There have long been deep synergies between collider-based studies of particles and understanding our universe at a fundamental level. Examples include the interplay between constraints on the number of neutrinos from studies at the LEP collider at CERN and from CMB measurements, or of dark matter searches at CERN's LHC program and space or other non-collider searches

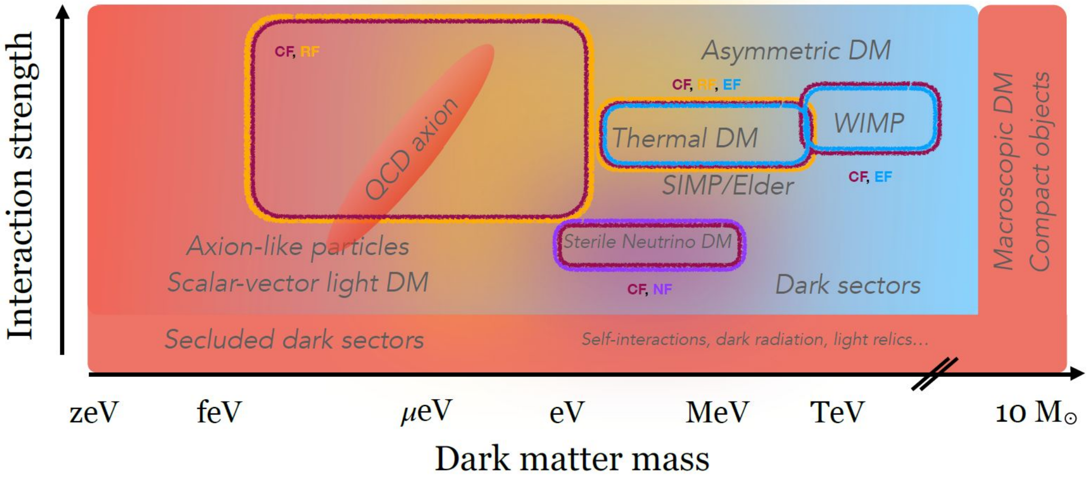
Observational astronomy has given particle physics a great gift: proof of the existence of dark matter.

We believe that **a program of precision and energy frontier physics enabled by the FCC program at CERN is an exciting new partnership between cosmology and accelerator-based particle physics**. (See also Snowmass 2021 Dark Matter Complementarity Report https://arxiv.org/abs/2211.07027)

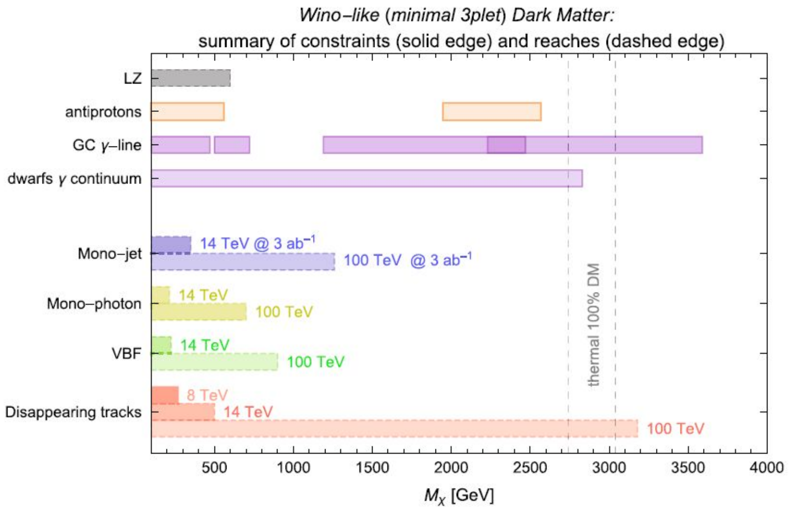




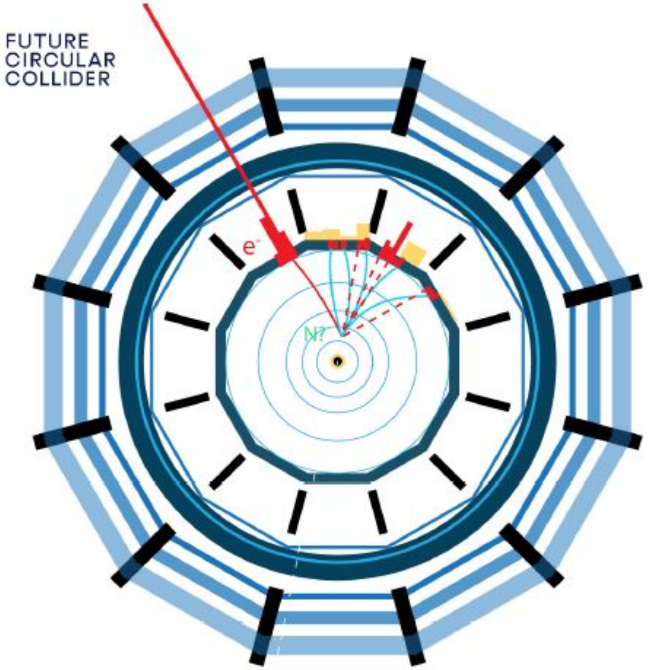
Sensitivity of FCC program to dark matter



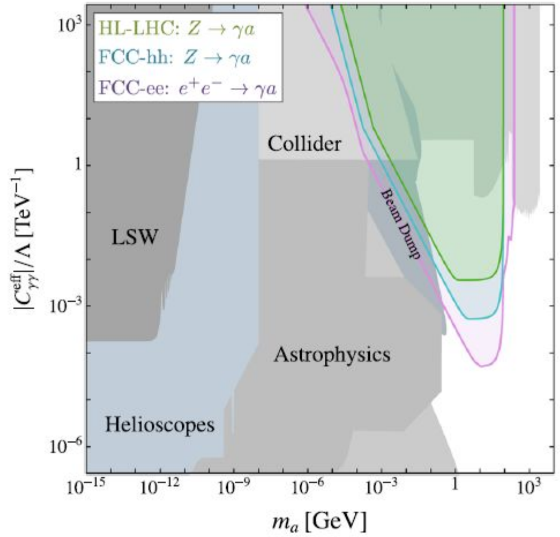
Examples from the wide variety of potential models of dark matter of the complementarity of FCC dark matter searches and other search methods
learn more at https://fcc-cdr.web.cern.ch/



FCC-hh can cover the entire allowed mass range of doublet and triplet WIMP DM



Any collider-based discovery will be independent of astrophysical uncertainties, and give significant information to improve cosmological models



FCC-ee, FCC-hh can extend searches for axion-like particles

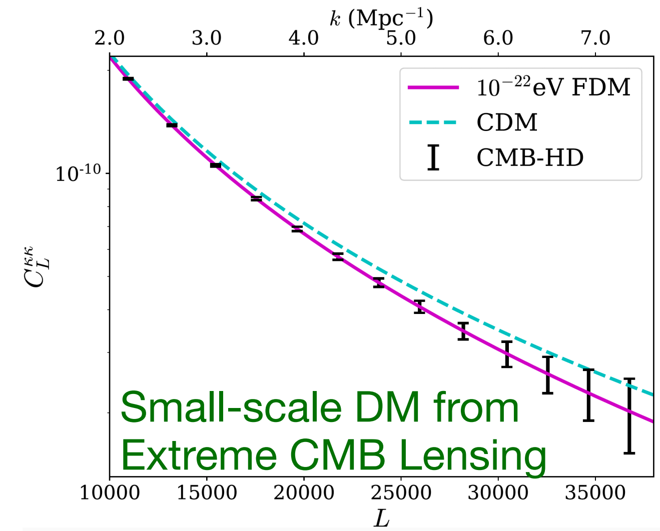
Neelima Sehgal (Stony Brook)

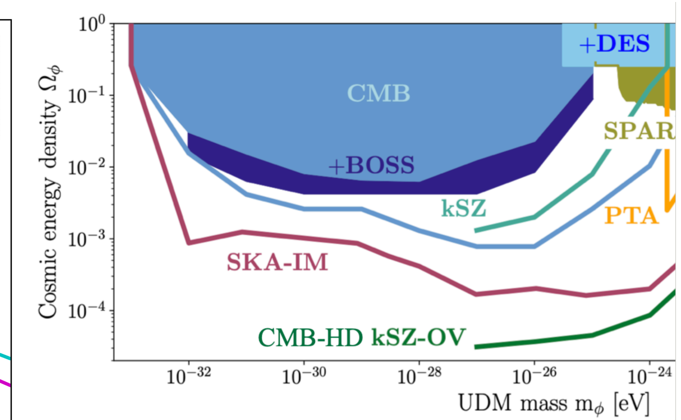
The Need for R&D Towards a Stage 5 CMB Facility

- CMB experiments have a strong track record of informing particle physics
- Simons Observatory and CMB-S4 are poised to extend progress
- A Stage 5 CMB facility, with 6x higher resolution and 3x lower noise than CMB-S4 can cross several critical thresholds (see figures)
- Snowmass Cosmic Frontier Report said:
  - “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 future surveys (e.g. LIM and CMB-S5)”
- It is essential to support R&D this decade, on both the theory and instrumental fronts, to enable a future Stage 5 CMB facility and the wealth of discoveries it can provide

See Snowmass WP arXiv:2203.05728

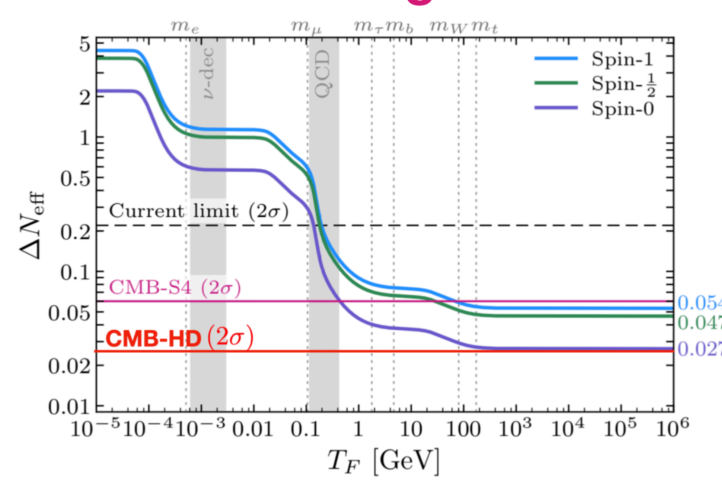
Discover Dark Matter Properties



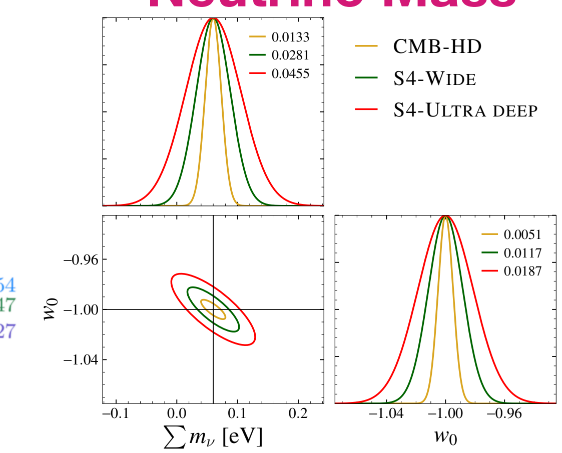


Ultra-light DM from Extreme kSZ

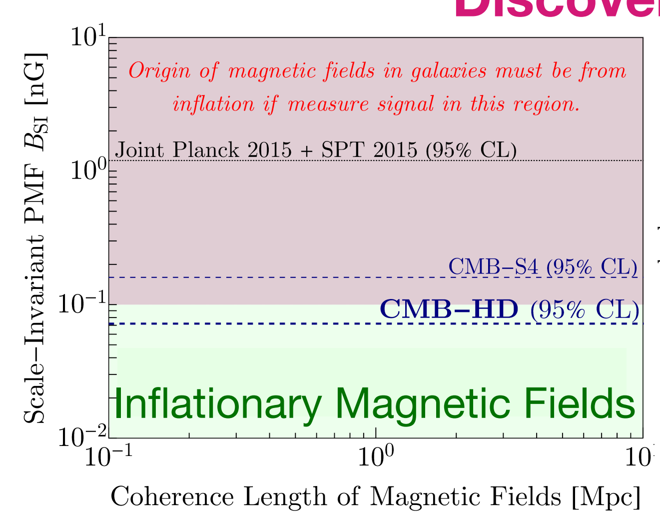
Discover Light Relics

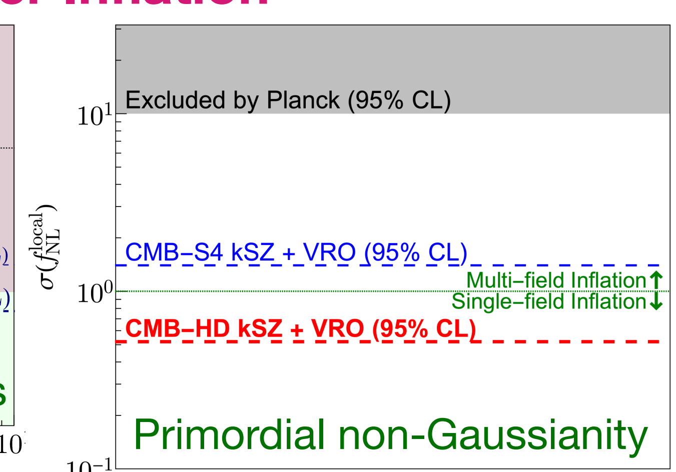


Measure Dark Energy/ Neutrino Mass



Discover Inflation



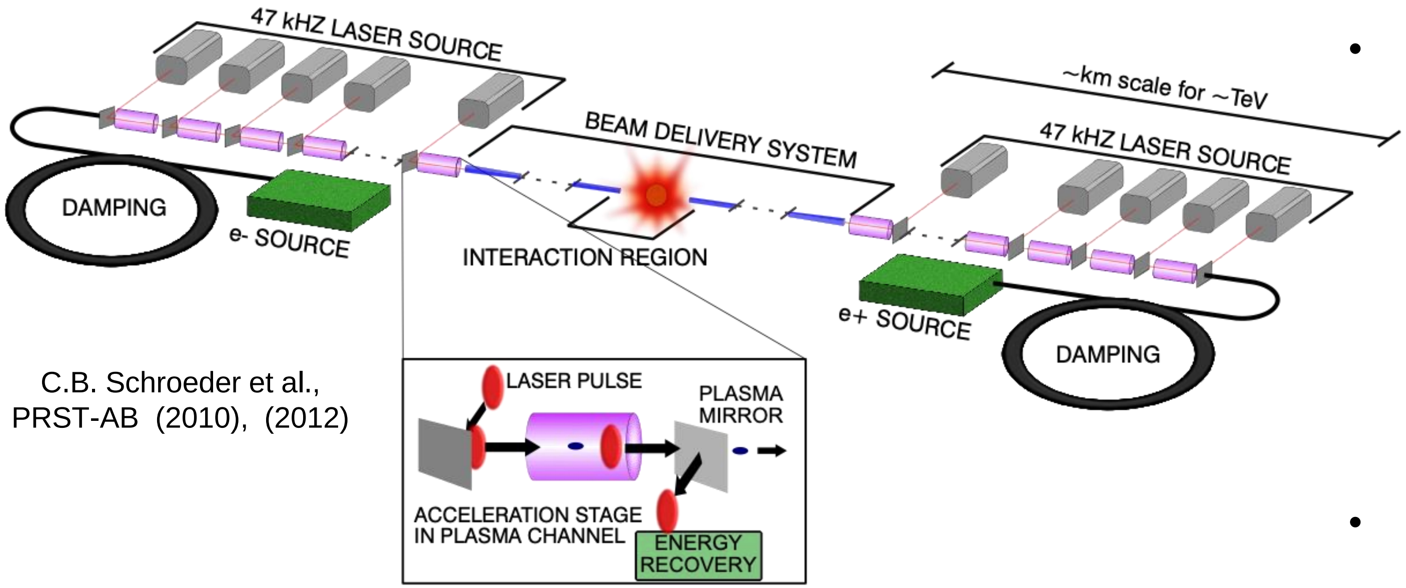


+ Gastrophysics, Transients, Planetary Studies…

Laser-Plasma Accelerators for Multi-TeV Lepton or Gamma-Gamma Colliders

Lieselotte Obst-Huebl, Early Career Scientist, BELLA Center, LBNL

- Laser-plasma accelerators (LPAs)
  - Ultrahigh fields 10-100 GV/m (1000x conventional)
    - Small footprint, reduced cost
  - Ultrashort bunches ~ few fs
  - Rapidly evolving laser tech (2018 Nobel Prize)
  - Vigorous international research program (100s papers/yr)
    - 8 GeV high quality e^- bunches (BELLA)
    - Stable operation many hours (DESY)
    - LPA driven FEL (China, Italy, Germany)



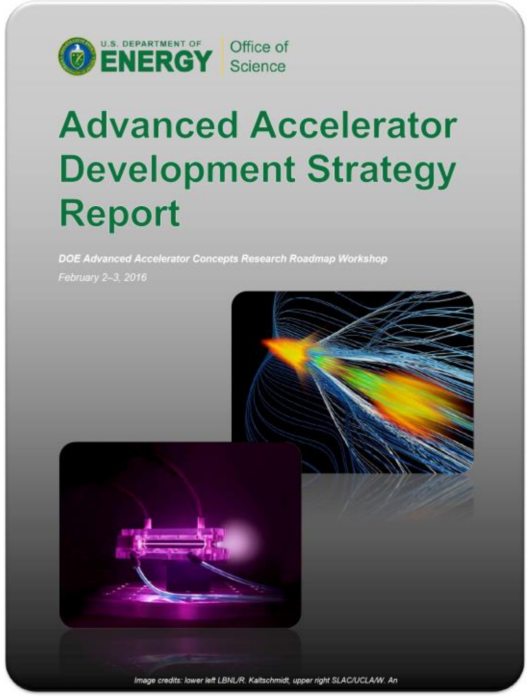
C.B. Schroeder et al., PRST-AB (2010), (2012)

- Collider based on staged LPAs
  - Stages (~10 GeV in 1 m) with compact coupling
  - Each stage: ~10 J laser driver
  - Few GV/m average gradient: compact linacs
  - Short bunches improve interaction and reduce overall power required (reduced Beamstrahlung)
  - Laser and plasma energy recovery proposed
  - Rep-rate for luminosity: ~10's of kHz
    - Fiber lasers: high efficiency + high average power
- Additional R&D required
  - More efficient methods for positron acceleration
  - Low emittance injectors + emittance preservation
  - Compact cooling methods
  - Compact beam delivery systems
  - High-average power laser technology
  - Integrated design study
- Serious investments overseas
  - Challenges US leadership

Competitive Progress along LPA-Collider R&D Roadmap Requires Investments

The Advanced Accelerator Community recommends (see Snowmass White Papers)

- Continue and enhance the General Accelerator R&D program
- Upgrades to the US Beam Test Facilities that serve the community
  - BELLA at LBNL
    - *kBELLA: mid-scale project*
    - *kHz precision LPA facility proposed*
  - FACET II at SLAC
  - Argonne Wakefield Accelerator at ANL
  - Accelerator Test Facility at BNL
  - University programs
- Enhanced support for high power laser drivers
- Initiation of an integrated design study for an advanced collider

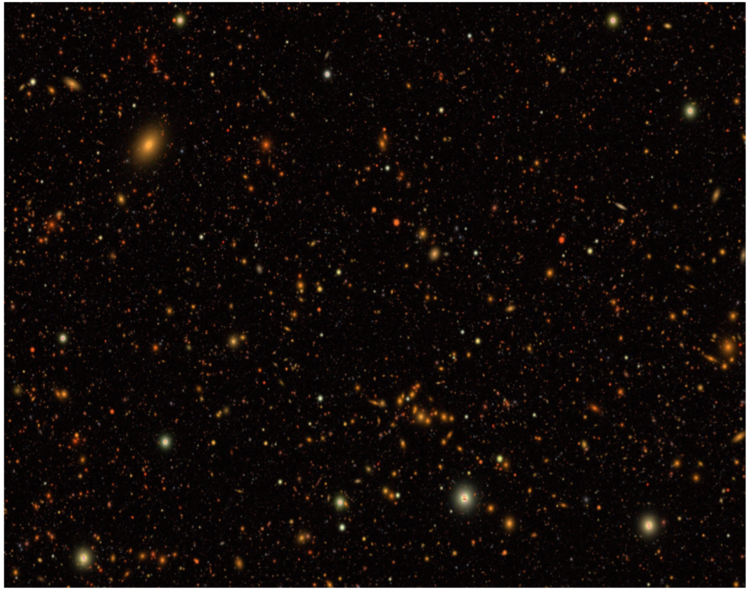


2016 R&D Roadmap

Please join us for a tour of the BELLA PW laser facility Friday afternoon

Significance of Simulation Development

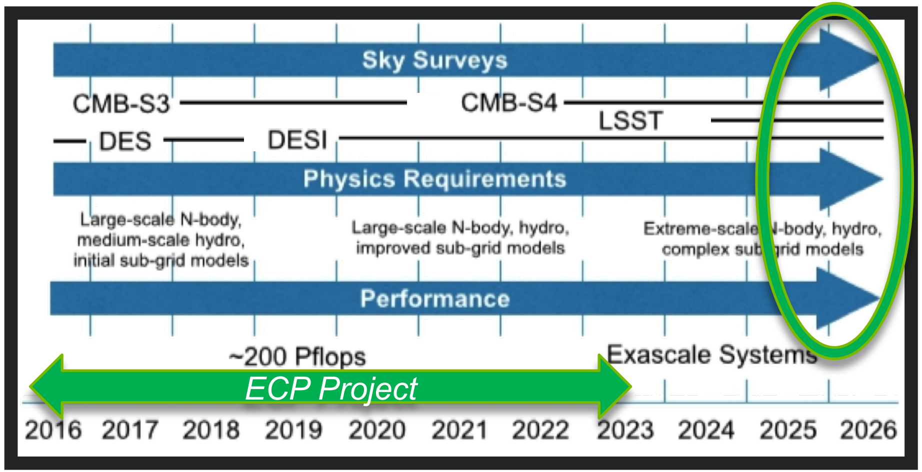
- **Simulations** are an essential component of Cosmic Frontier observations
  - Provide theoretical predictions and constraints for cosmic probes including cross-correlations
  - Characterize systematics necessary for the planning, calibration and validation of surveys
- **Enhanced Modeling** is important to match the sensitivities of future experiments
  - Baryonic effects, Astrophysical Processes, Neutrinos, etc.
  - New exascale supercomputers are arriving, allowing us to significantly expand the complexity and science reach of simulations
  - Over the next decade, post-exascale architectures will provide even more opportunities. But will we be able to use them?



Simulated Sky Image
LSST DESC DC2 Team

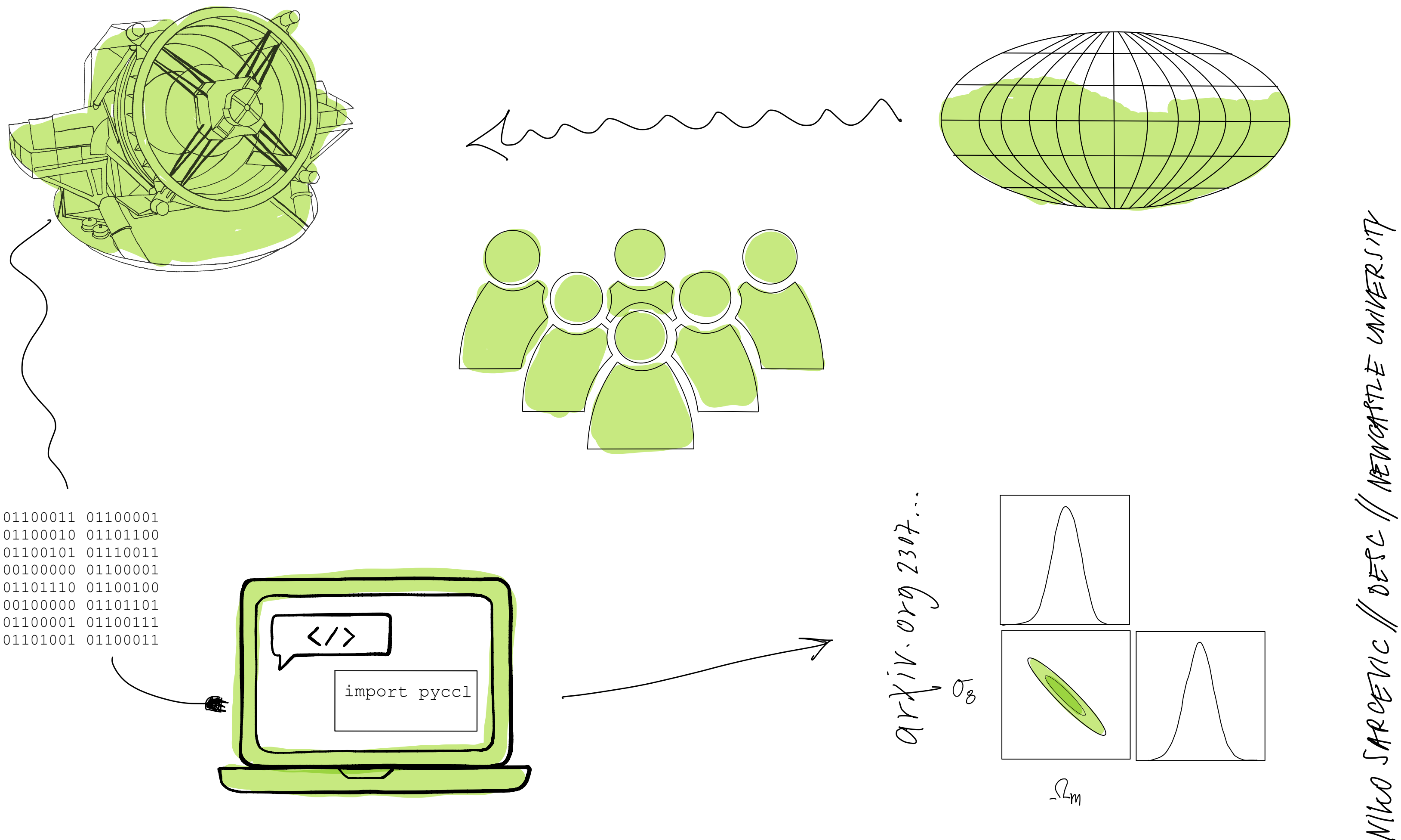
Significance of Simulation Development Cont.

- **Computational Readiness** is required to fully utilize the next era of computing
  - The landscape of compute facilities is changing (most notably with accelerators) and there is no indication that we are reaching a stability point beyond exascale
  - The compute and data accumulation/analysis requirements of observations are growing
  - Exascale Computing Project (ECP) and SciDAC program are a good examples of the success and importance of supporting scientific codes to effectively run on new machines
- **Supporting** simulation research will be critical to the success of future surveys



What models and compute requirements are needed for the next decade in Cosmic Frontier research?

What will machines look like in the post exascale era and will we be ready to use them for science?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RE-EVALUATE AS

individual / working group / collaboration

OBVIOUS POINTS

- analysis choices
- mitigation techniques
- biases
- cross pollination

LESS OBVIOUS

- communication
- coding practices
- upgrades
- documentation

SUPER OBSCURE

- meetings
- workshops
- presentation
- legacy

ULTIMATELY, science is done by people

& all the pieces matter

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