The Opportunities of Stage-5 Spectroscopy

Probing both epochs of accelerated expansion

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P5 Cosmic Frontier Town Hall
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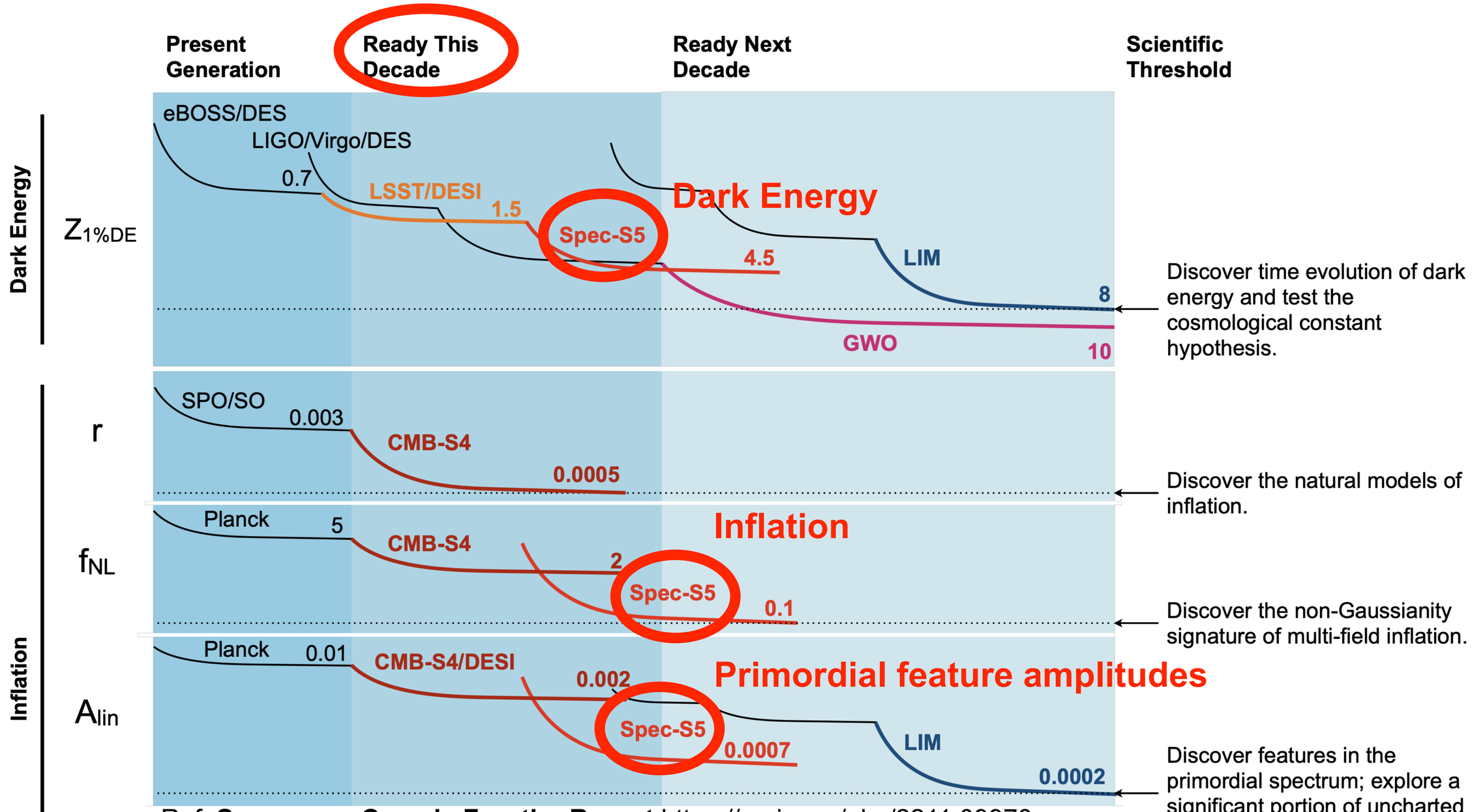
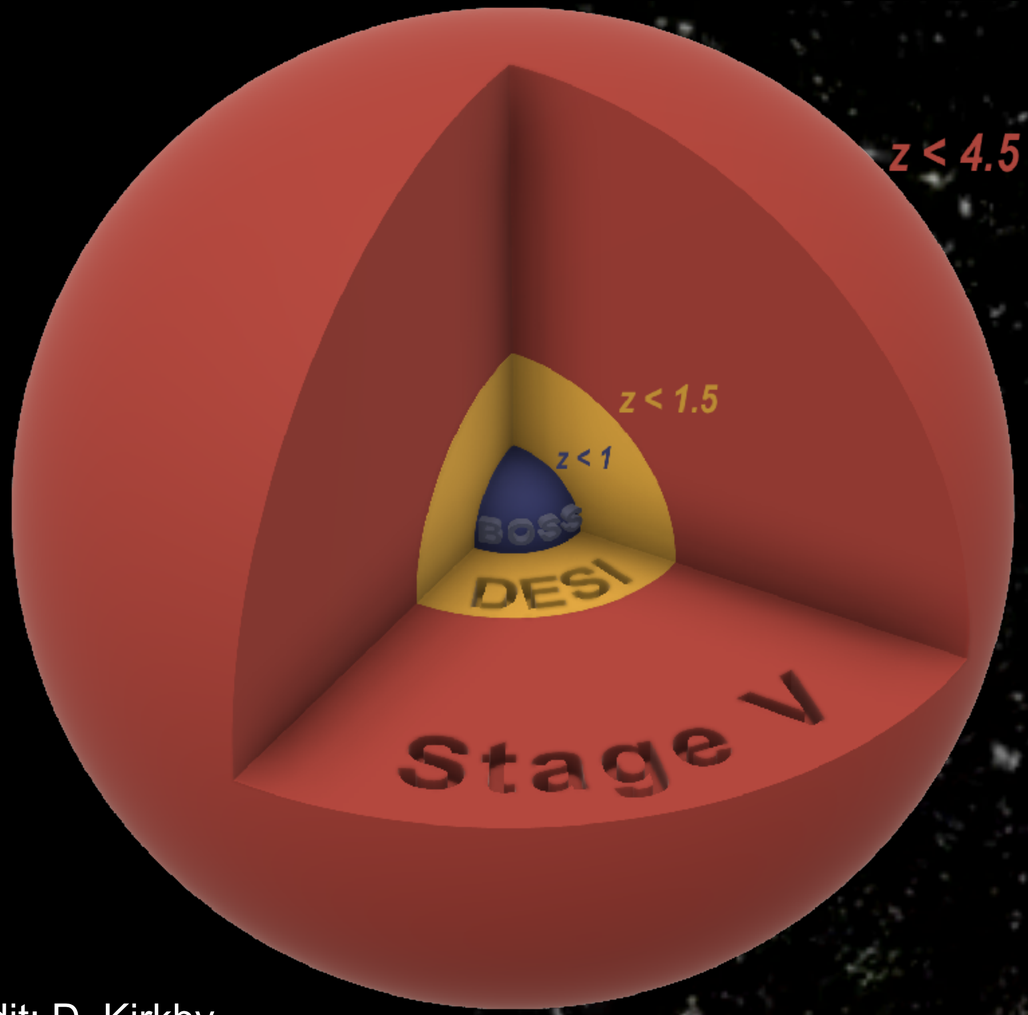
Stage 5 Spectroscopy will probe both epochs of accelerated expansion



Ref: **Snowmass Cosmic Frontier Report** https://arxiv.org/abs/2211.09978

What is the Stage 5 Spectroscopic experiment?

Newly-developed technologies to build the largest 3-dimensional galaxy map,
10X linear modes to be mapped by DESI + Rubin + CMB-S4



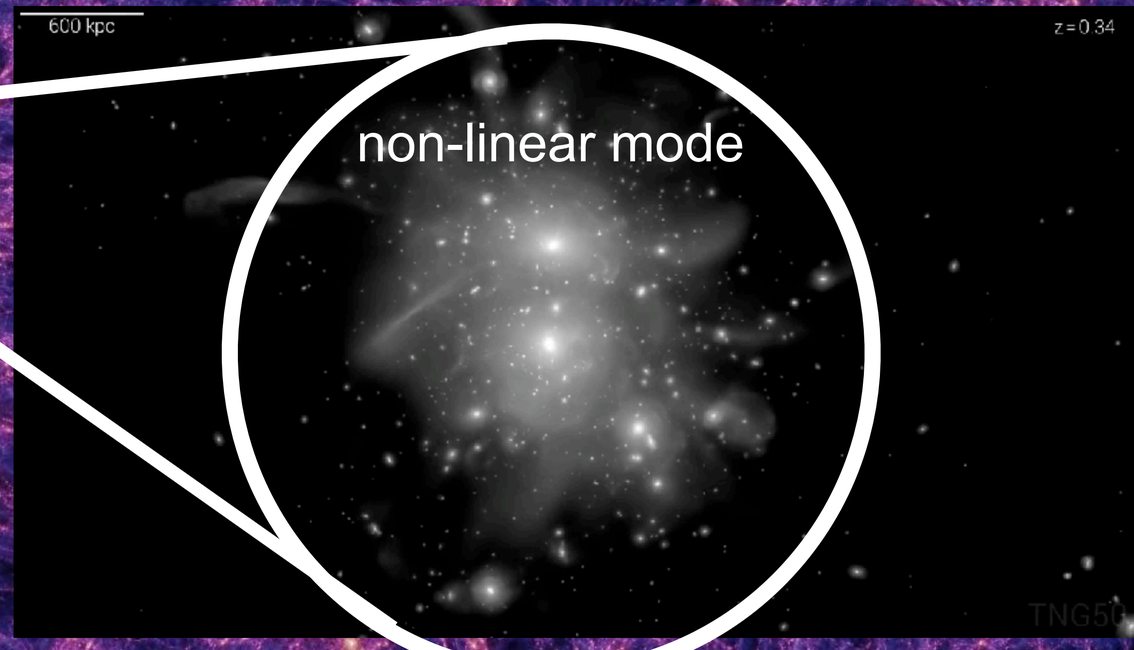
Credit: D. Kirkby

Credit: Aragon, Subbarao, Szalay for the SDSS collaboration

Stage 5 Spectroscopy reaches 10X the "Primordial Figure of Merit" by mapping 10X more linear modes than DESI

These are the quantum fluctuations imprinted on galaxy maps
Experimental signal-to-noise scale as √number of modes

125 Mpc/h



Credits: Millenium simulation, IllustrisTNG

What is a Stage 5 Spectroscopic experiment?

Dark Energy Task Force (DETF) in 2005 advised DOE, NSF, NASA on the future of Dark Energy research

Four stages of spectroscopic experiments:

- Stage 1 & 2: SDSS — confirms Dark Energy
- Stage 3 SDSS/BOSS + eBOSS — precision Dark Energy at low redshift
- Stage 4: DESI — precision Dark Energy z=0->3

Stage 5 Spectroscopy moves us beyond the horizon of DETF,
addressing Dark Energy, primordial physics, neutrino mass, light relics, dark matter

—> All of this is physics beyond the standard model

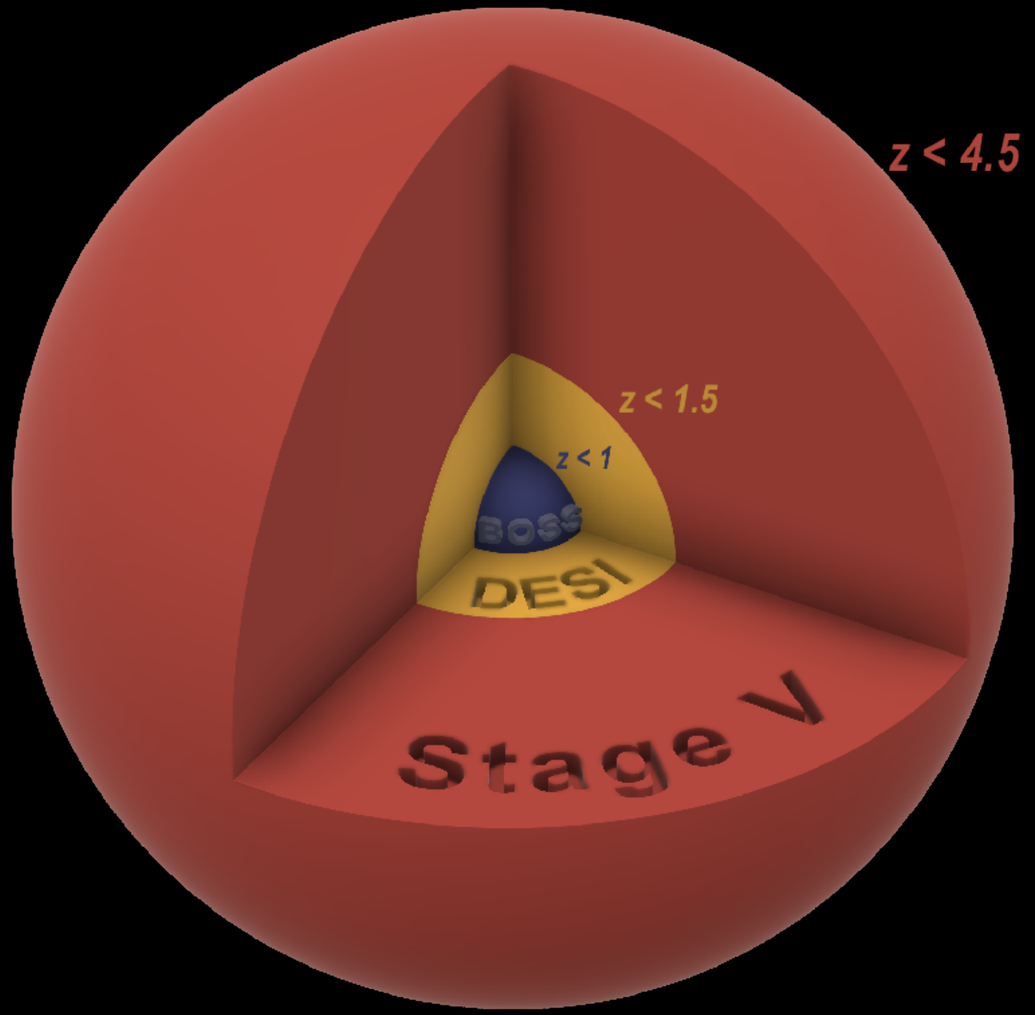
Stage 5 requires mapping the more distant universe at 2 < z < 6

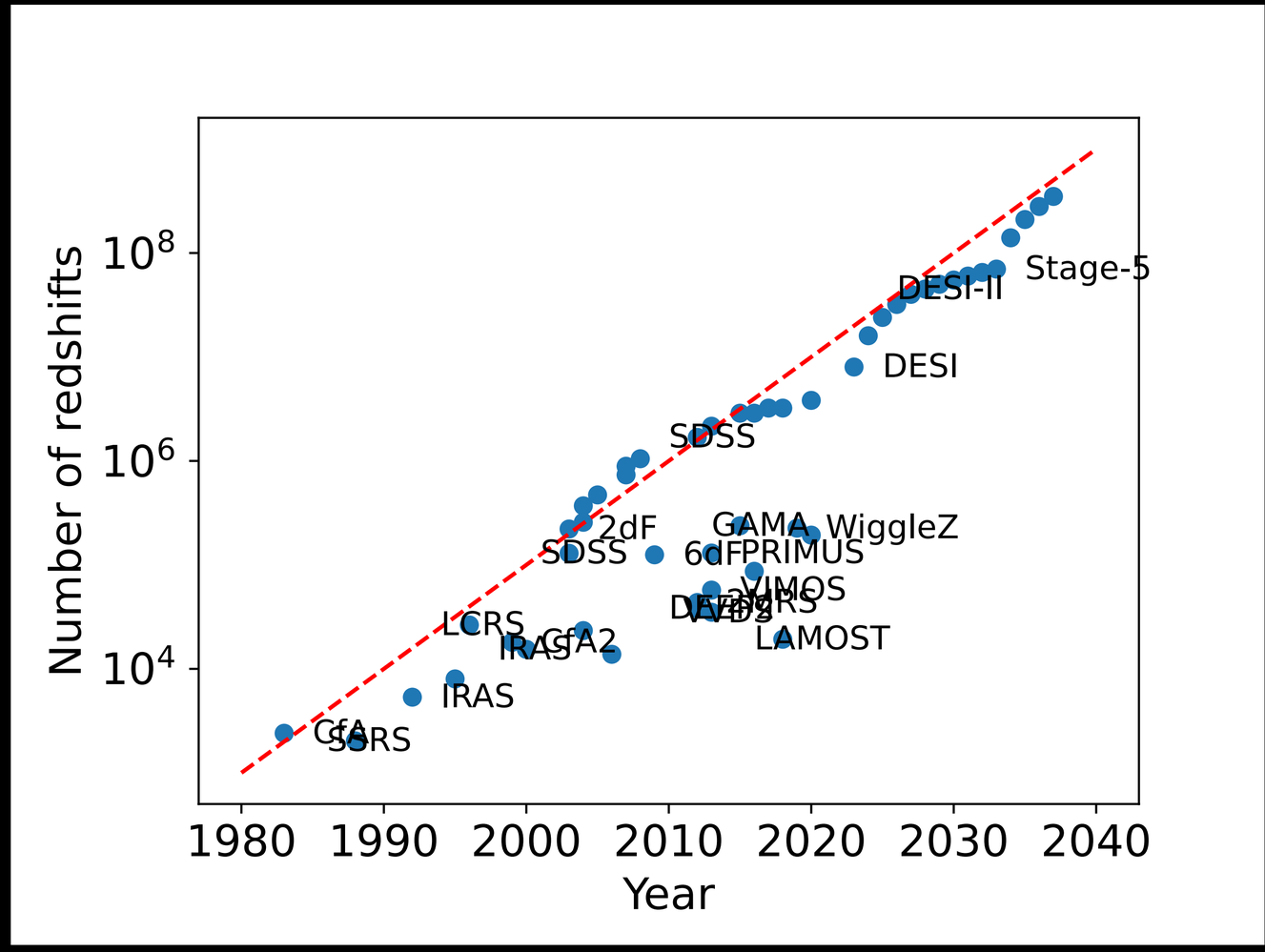
— Larger volume

linear modes well-correlated with init. cond., less affected by late-time astrophysics

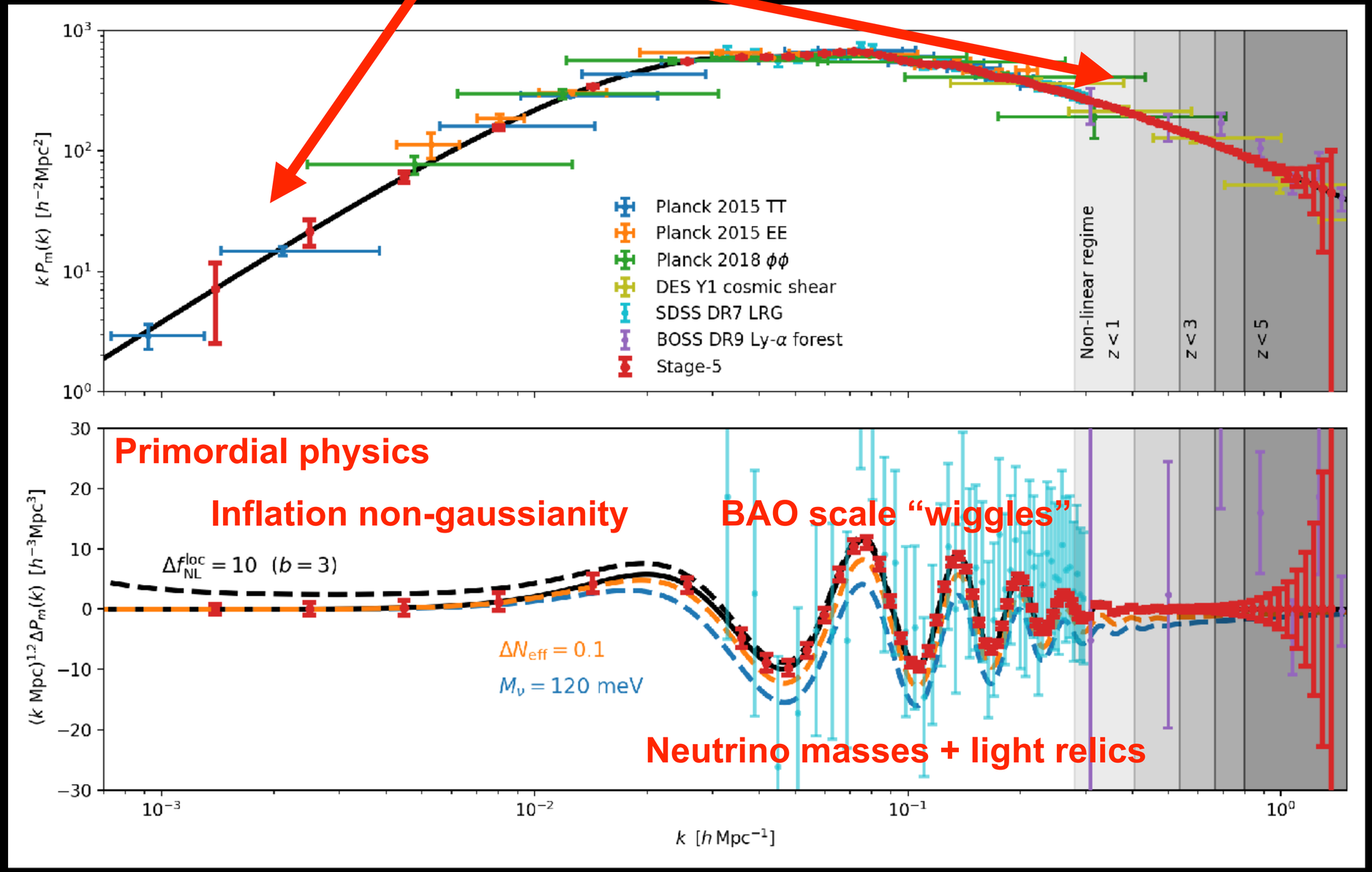
— Larger redshift range

degeneracy breaking, measures early->late Dark Energy





Stage 5 Spectroscopy extends to more volume + smaller scales than DESI



Based on Sailer, Castorina, Ferraro & White (2022)

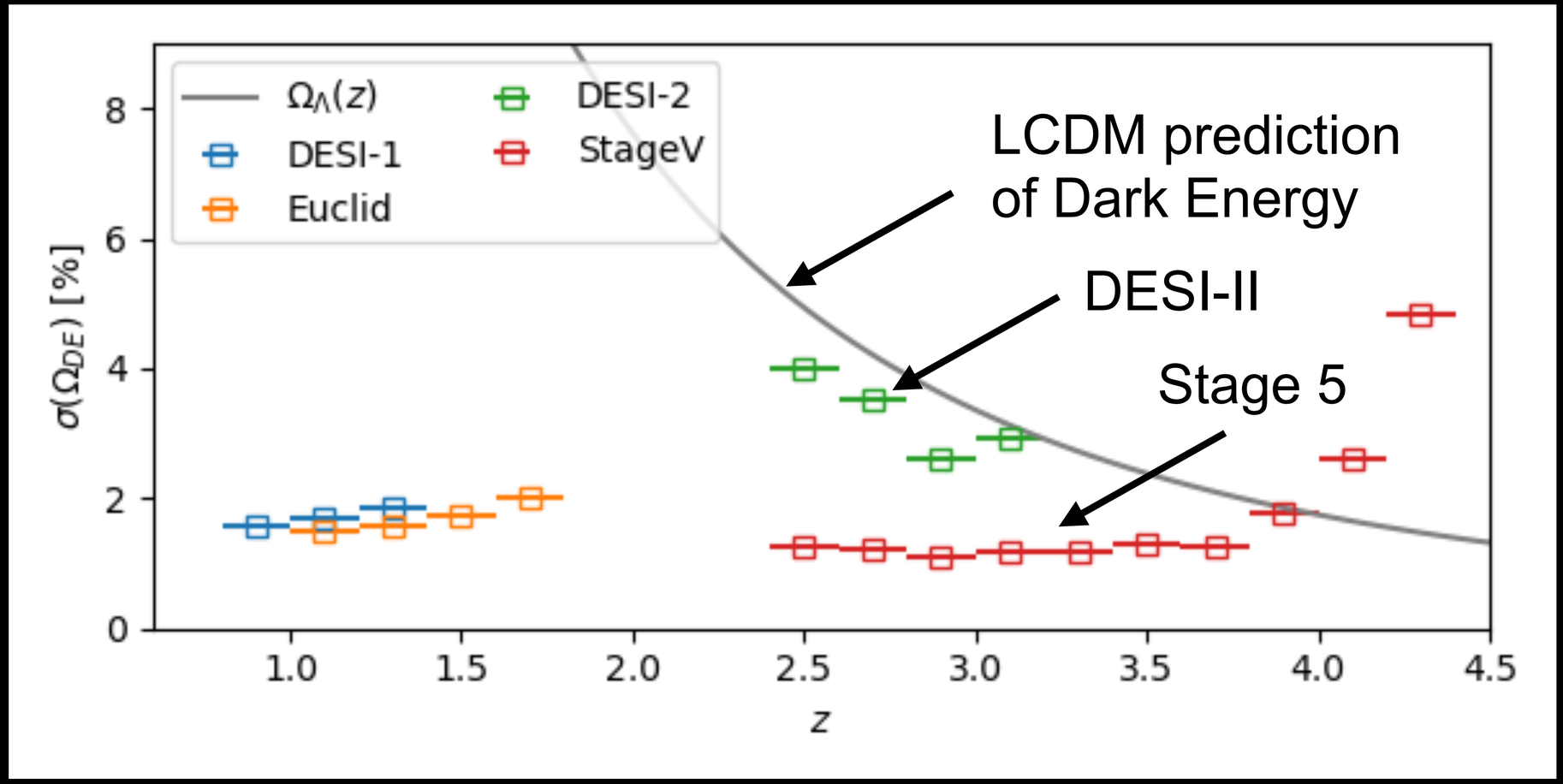
Stage 5 Spectroscopy : “Late” epoch of accelerated expansion

— direct, sub-percent Dark Energy density measurements to z=4 (matter-dominated era)

— indirect 1% expansion measurements to $z\sim10^5$

— search for extra relativistic species

— modified gravity + Dark Matter interactions



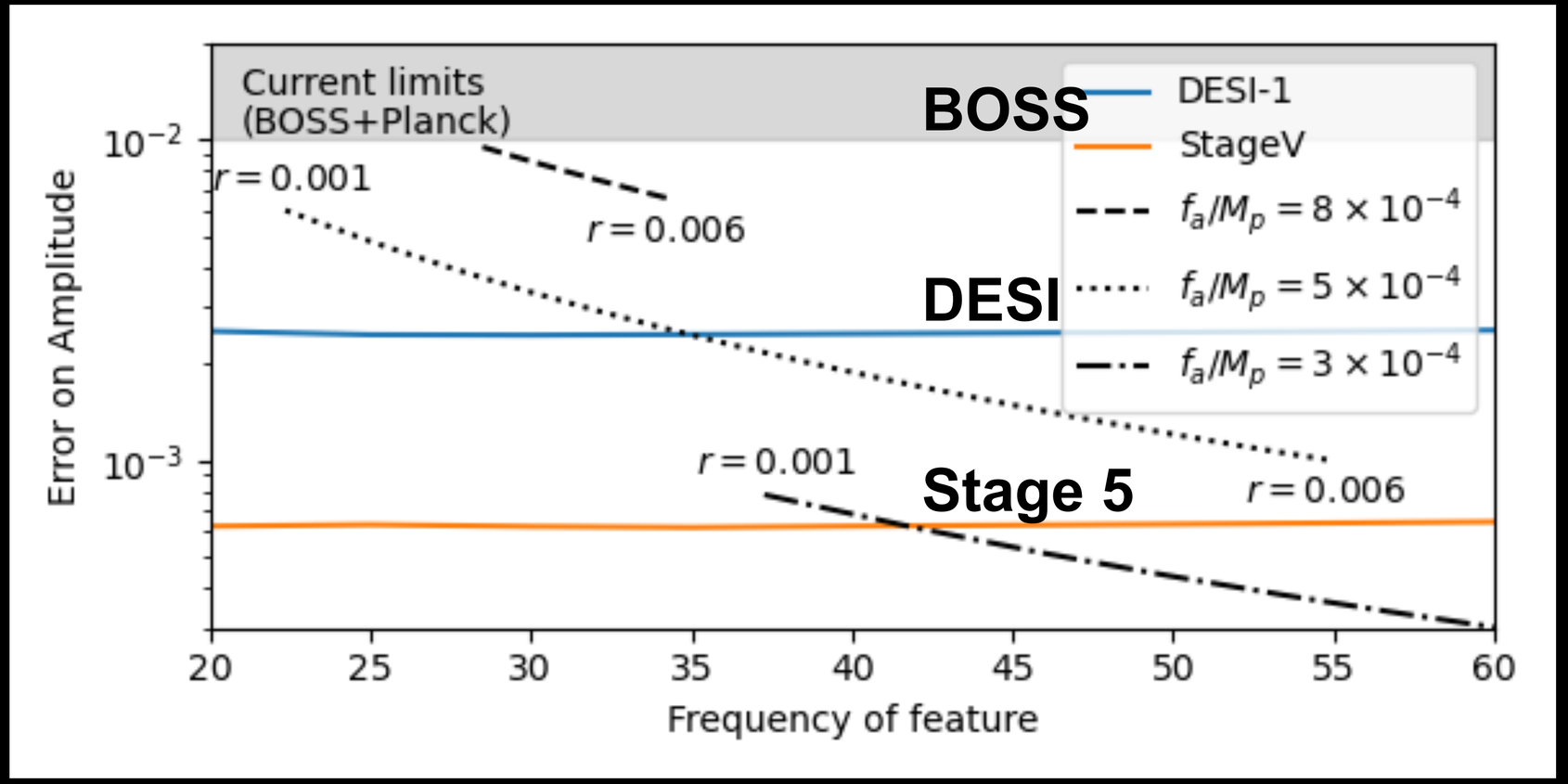
Based on Sailer, Castorina, Ferraro & White (2022)

Stage 5 Spectroscopy: “Early” epoch of accelerated expansion

— probe the inflationary potential with primordial non-gaussianity
Primordial Figure-of-Merit increases from 0.9 (DESI) to 10 (Stage 5)

— inflationary features — 10X more sensitive than Stage 4 (DESI,CMB-S4)

— tests of parity-violating physics



Courtesy Dan Green, Eva Silverstein, Martin White

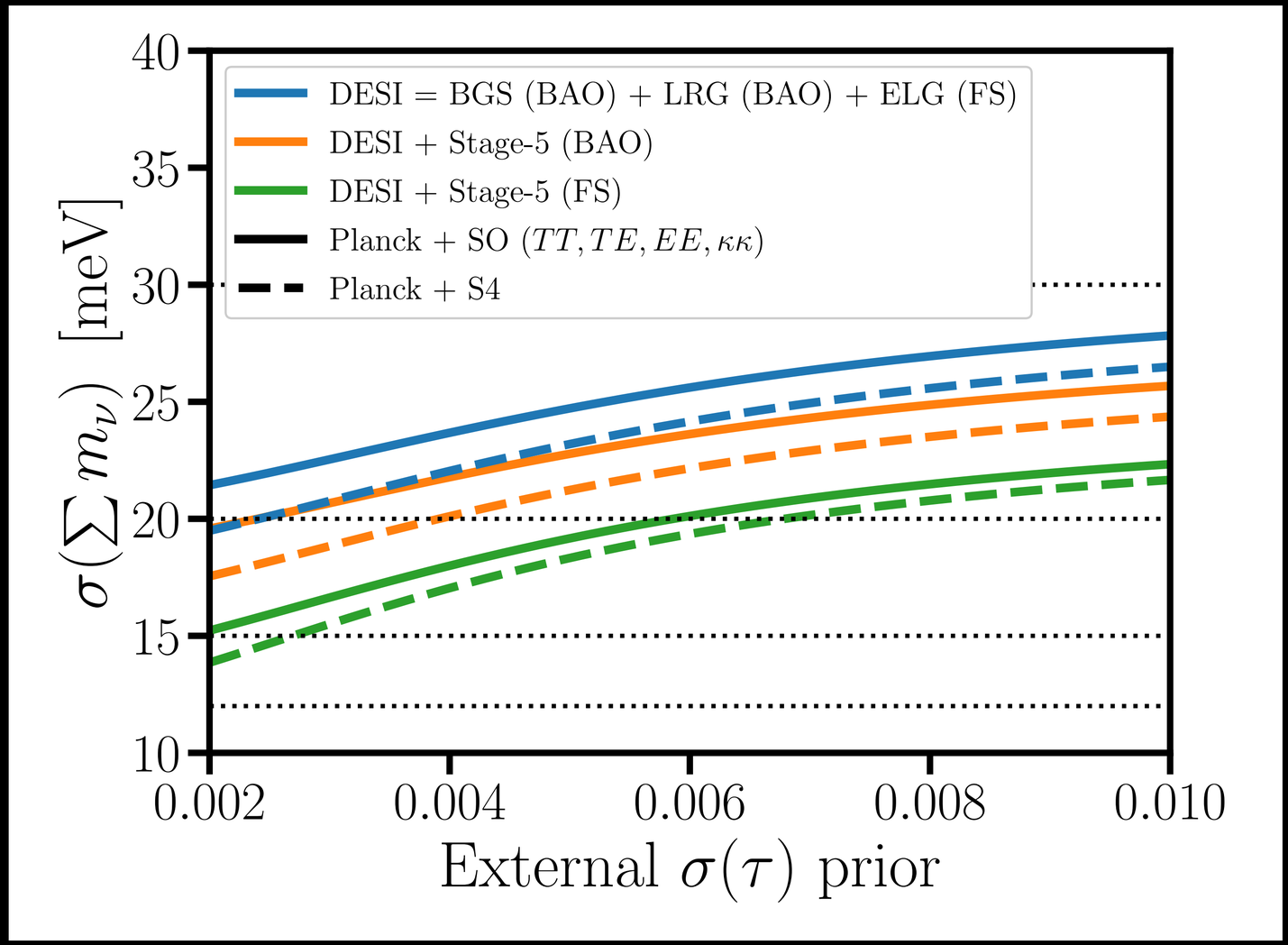
Inflaton potential of the form sin(ϕ/f), ϕ=inflaton, f=energy scale

Stage 5 Spectroscopy: neutrino masses + light relics

— Current constraints from Planck (CMB) + BOSS (Stage 3 spectroscopy)

— Massive neutrinos ($\sum m_\nu$) to 15-25 meV (dependent upon LiteBIRD τ)

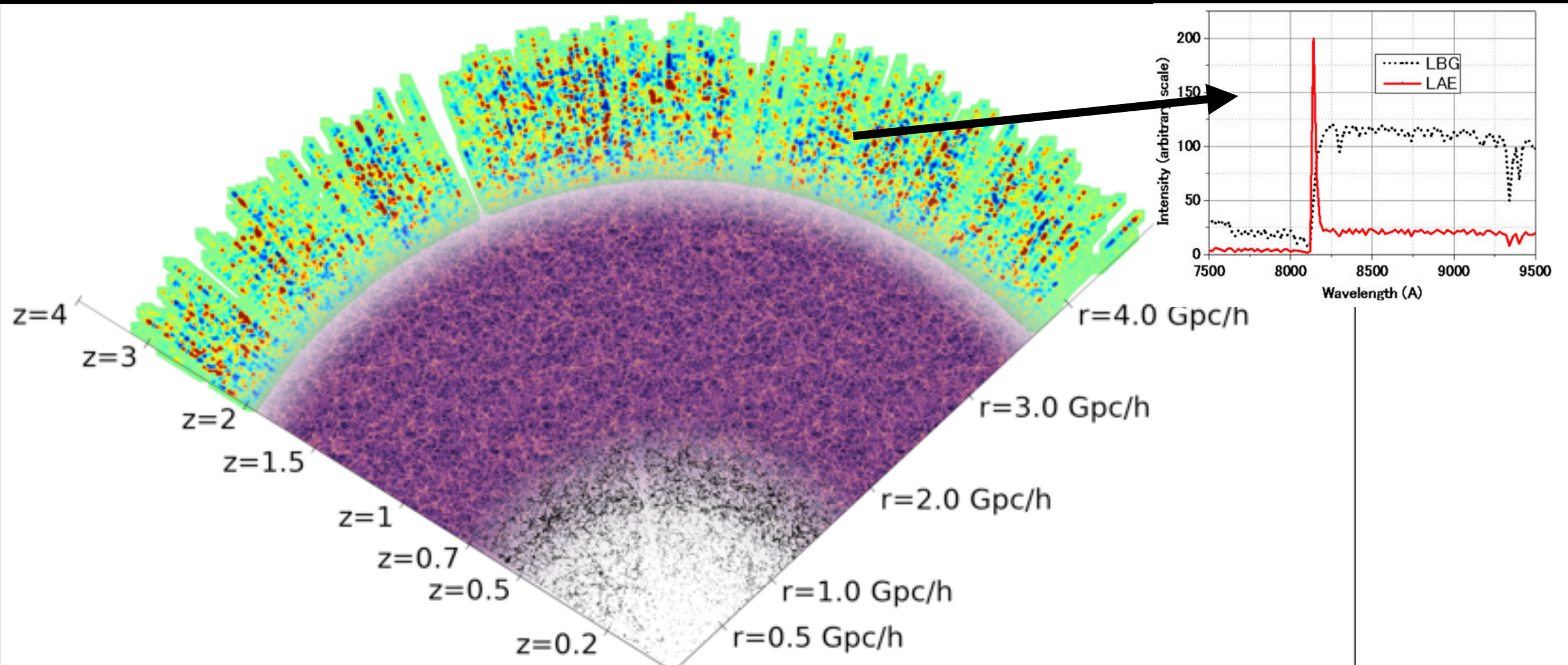
— Light relics (ΔN_{eff}) to 0.024 (with BBN prior, otherwise 0.08)



Based on Sailer, Castorina, Ferraro & White (2022)

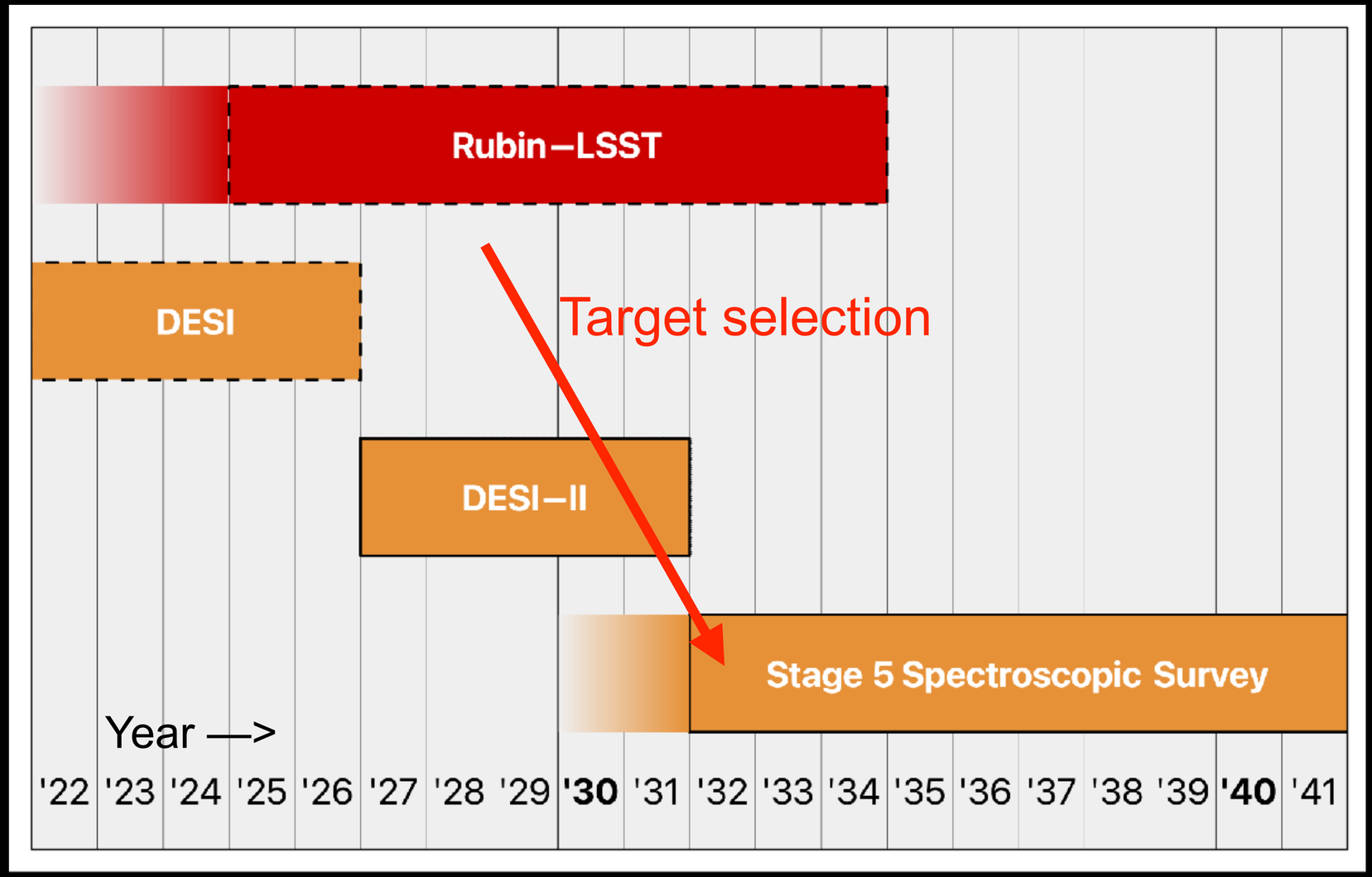
The Universe (+Rubin Observatory) kindly provides compact galaxies at all redshifts

At z > 2, we have Lyman Alpha Emitters (LAEs) and Lyman Break Galaxies (LBGs)



Stage V Spectroscopy Timeline advocated in the Snowmass reports

Rubin imaging will provide the target-selection incl. >30M LBG and >50M LAE galaxies



Adapted from Snowmass CF6 report

Stage 5 Spectroscopic Survey implementation options

Operate DESI for ~100 years

- (not actually proposed)

Option A: DESI-Upgrade in the north+south (twin 4-m telescopes)

- Upgrade DESI in Arizona from 5,000 ➔14,000 fiber robots
- DESI spectrographs
- Upgrade the detectors + electronics to low-noise Skipper CCDs
- Replicate at the twin telescope in Chile
- Operate both telescopes for ~10 years

Option B: MegaMapper (6.5-m telescope)

- New or re-purpose existing 6.5-m primary mirror
- New wide-field optical corrector
- DESI spectrographs
- Operate for ~5 years

Larger-aperture telescope (SpecTel/WST, MSE)

- Facility + instrument would be shared with other astronomy projects
- Uncosted

R&D for Stage 5 Spectroscopic Survey is well-underway

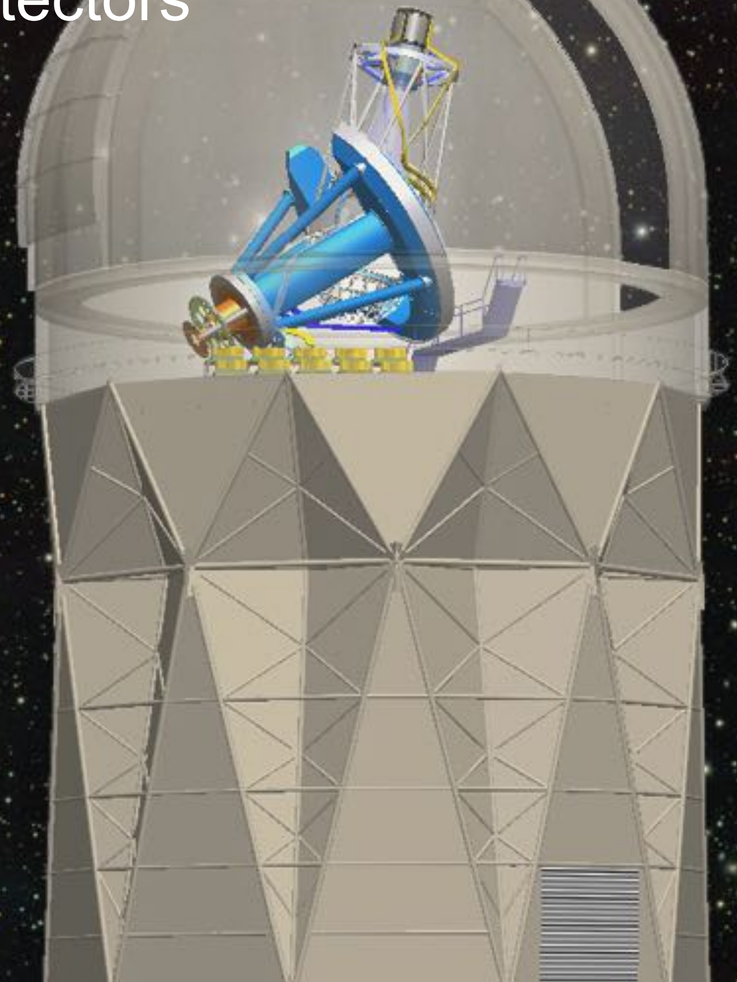
What upgrades from DESI?

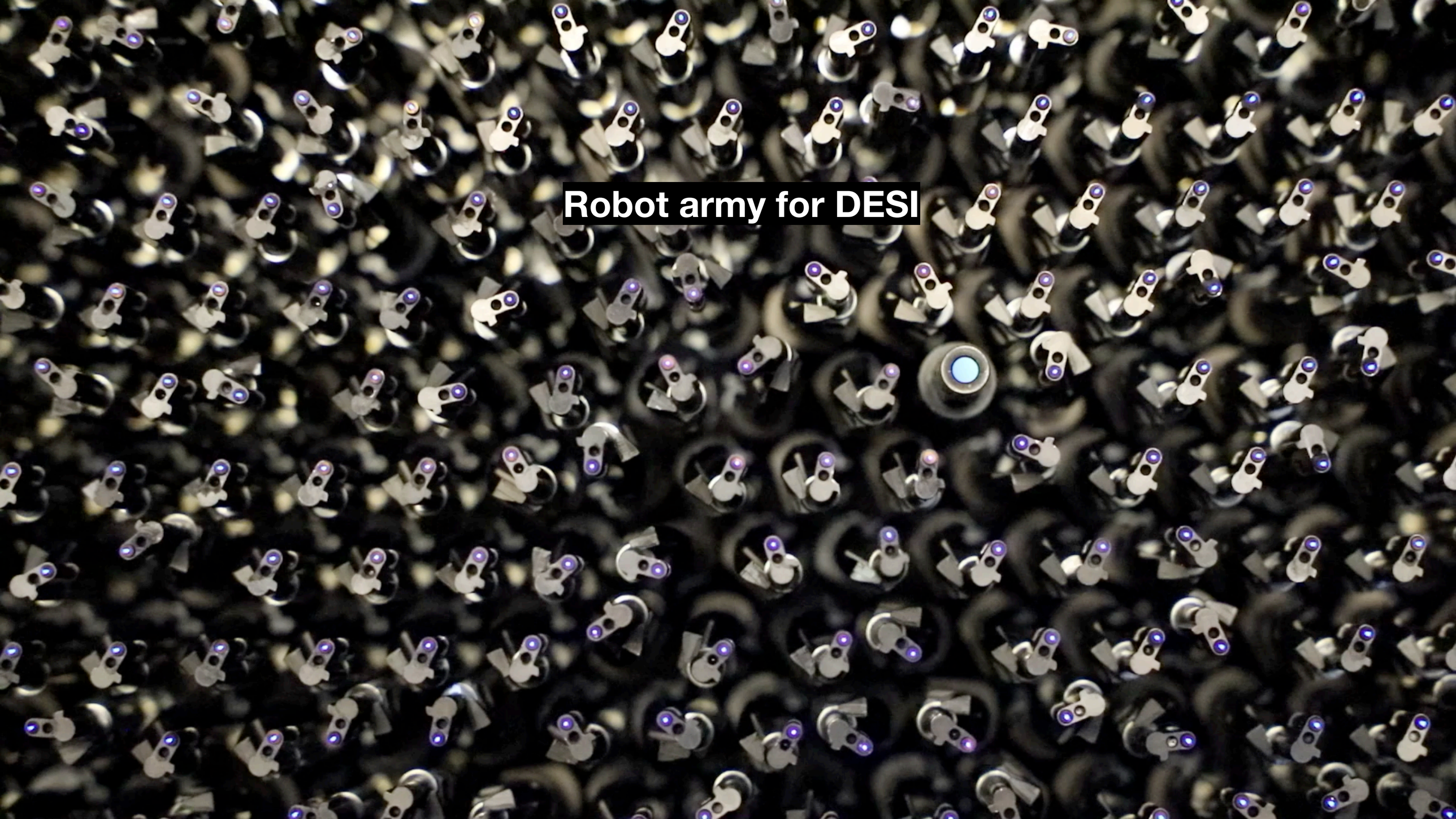
- robots — smaller, higher-density robot army
- fibers — higher fiber density
- CCDs & FEEs — low-read-noise (Skipper) detectors

Heritage from DESI

- targeting
- spectrographs
- telescope operations
- instrument operations
- data systems
- analysis pipelines
- the collaboration!

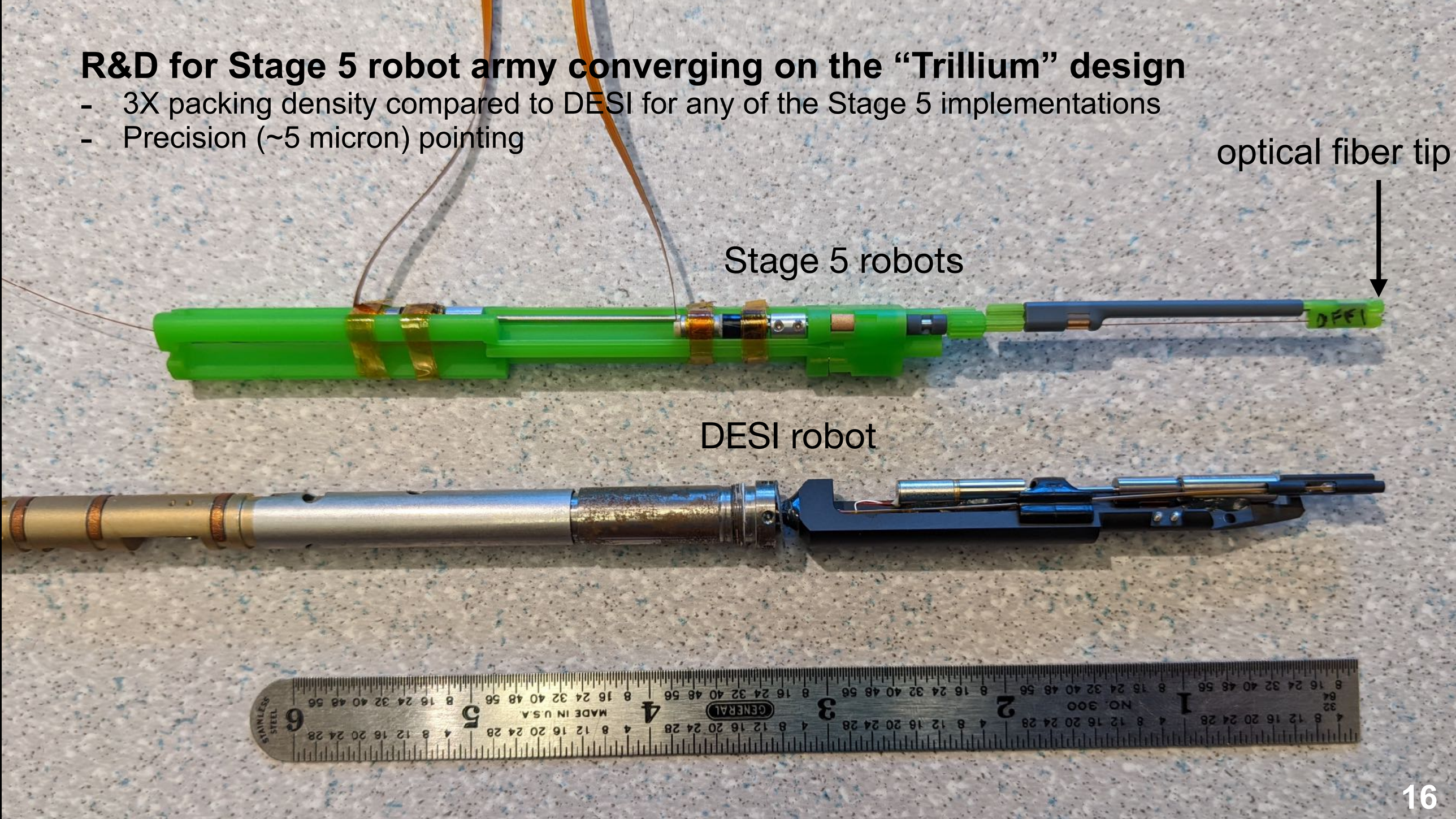
AA




Robot army for DESI

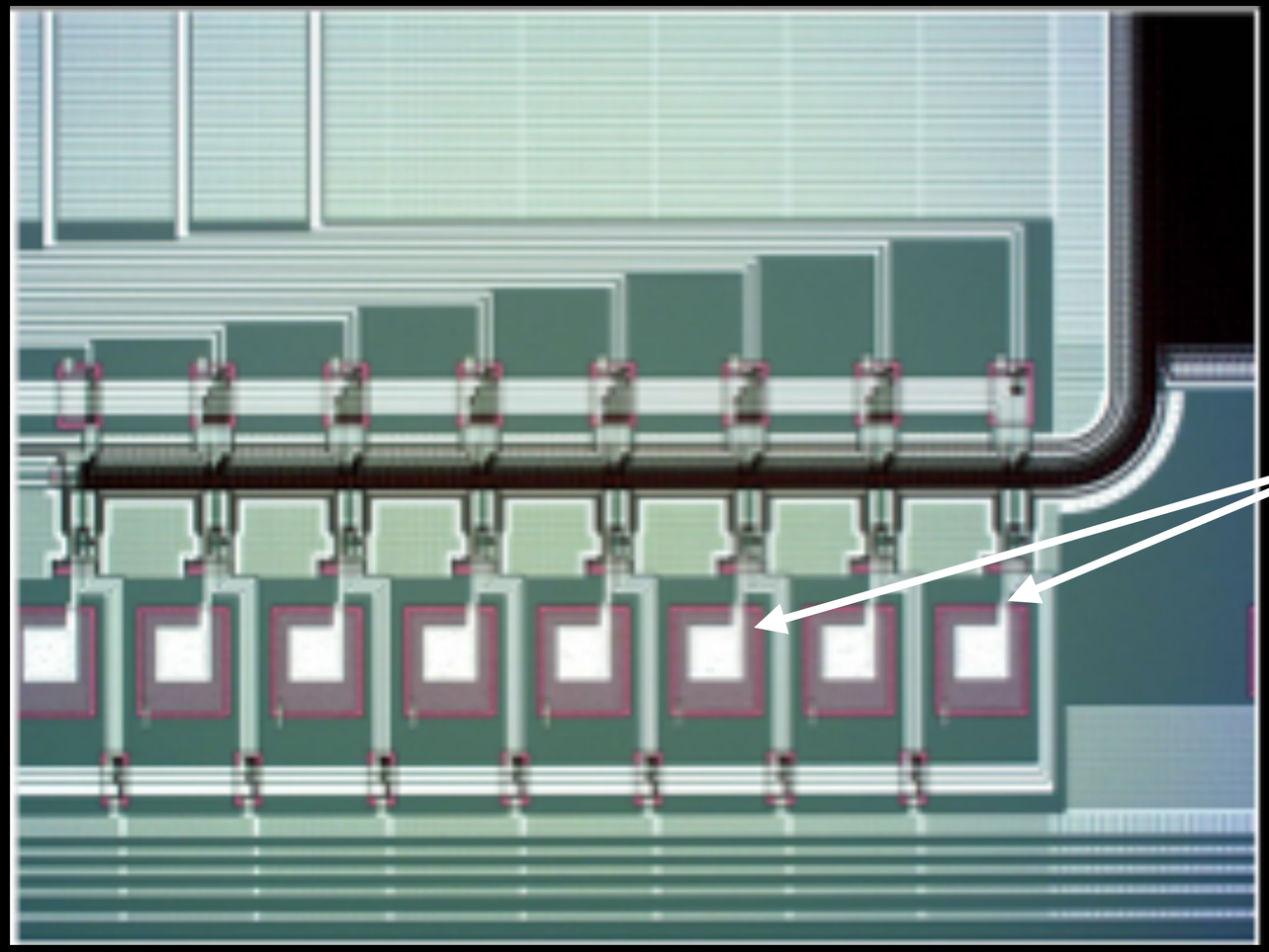
R&D for Stage 5 robot army converging on the “Trillium” design

- 3X packing density compared to DESI for any of the Stage 5 implementations
- Precision (~5 micron) pointing



R&D for Stage 5 detectors to use “Skipper” CCDs

- increases signal-to-noise for faint galaxies with ~few photons per spectral resolution
- Dark matter experiments developed Skipper (non-destructive-read) amplifiers
- Astronomical Skipper CCDs use many Skipper amplifiers for fast readout
- First “astronomical Skipper” CCDs to be deployed by FNAL this year



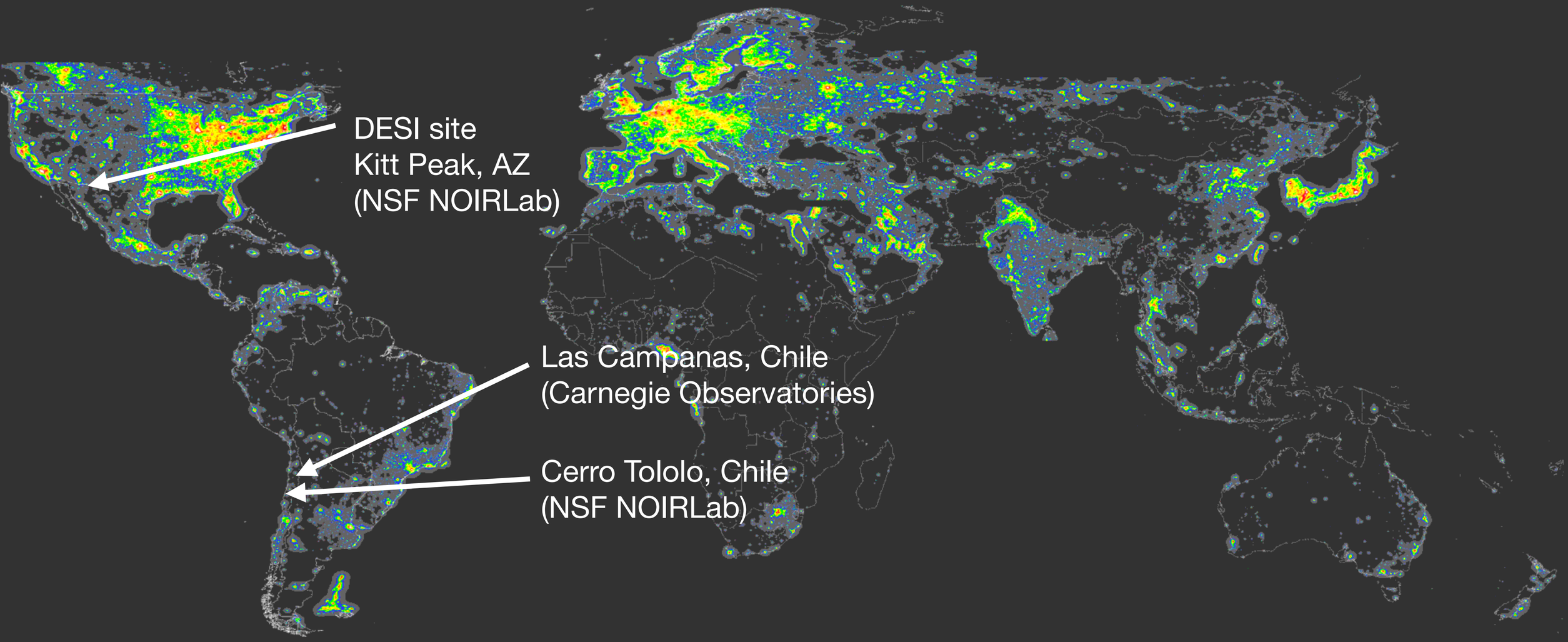
16 Skipper amplifiers
(on one corner of the CCD)

Stage 5 Spectroscopy exploring site alternatives

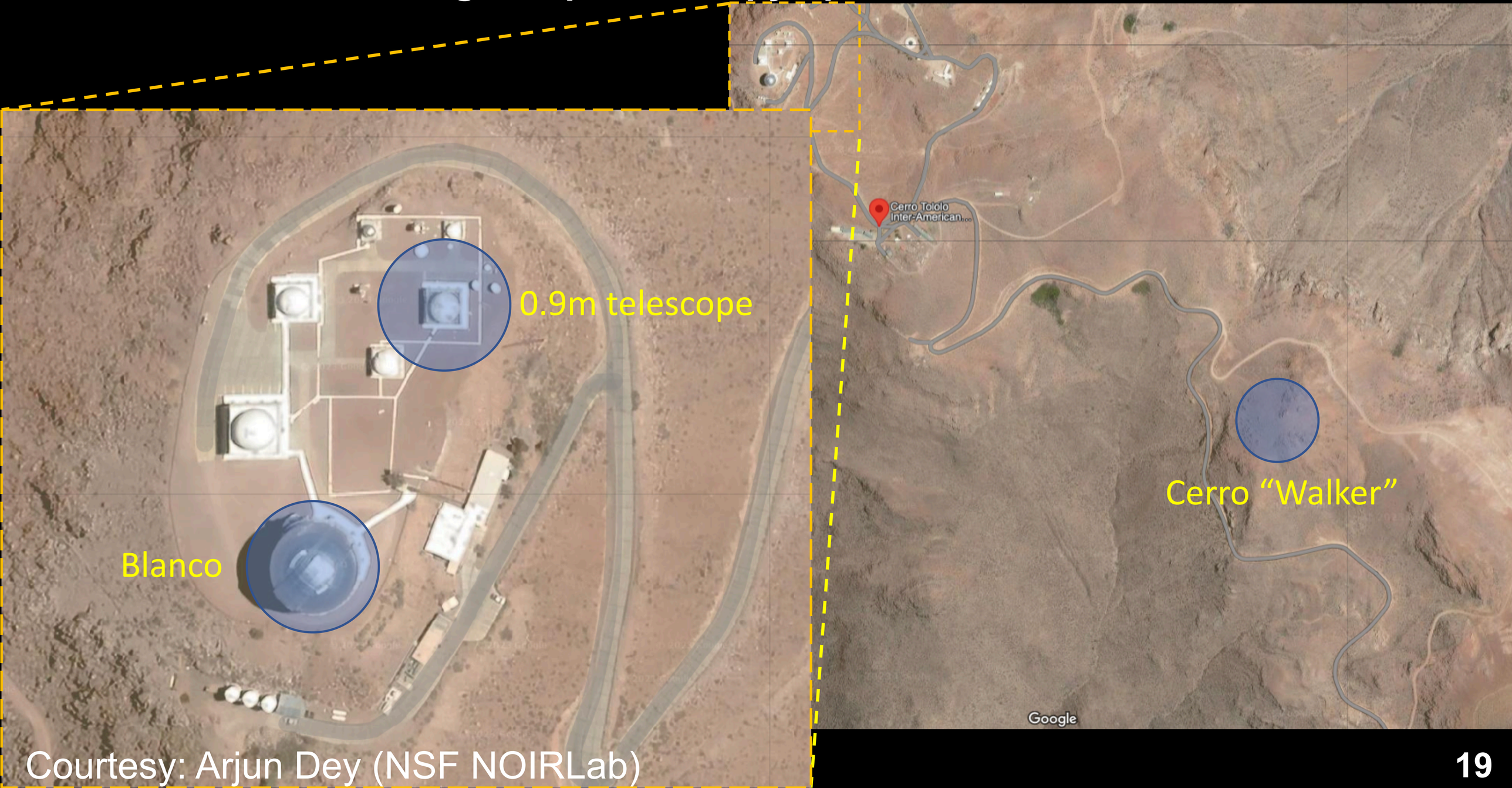
Partnership will partly depend upon telescope platform

NSF NOIRLab is the partner for DESI — partner at Kitt Peak & Cerro Tololo for Options A or B

Carnegie Observatories — partner at Las Campanas for Option B

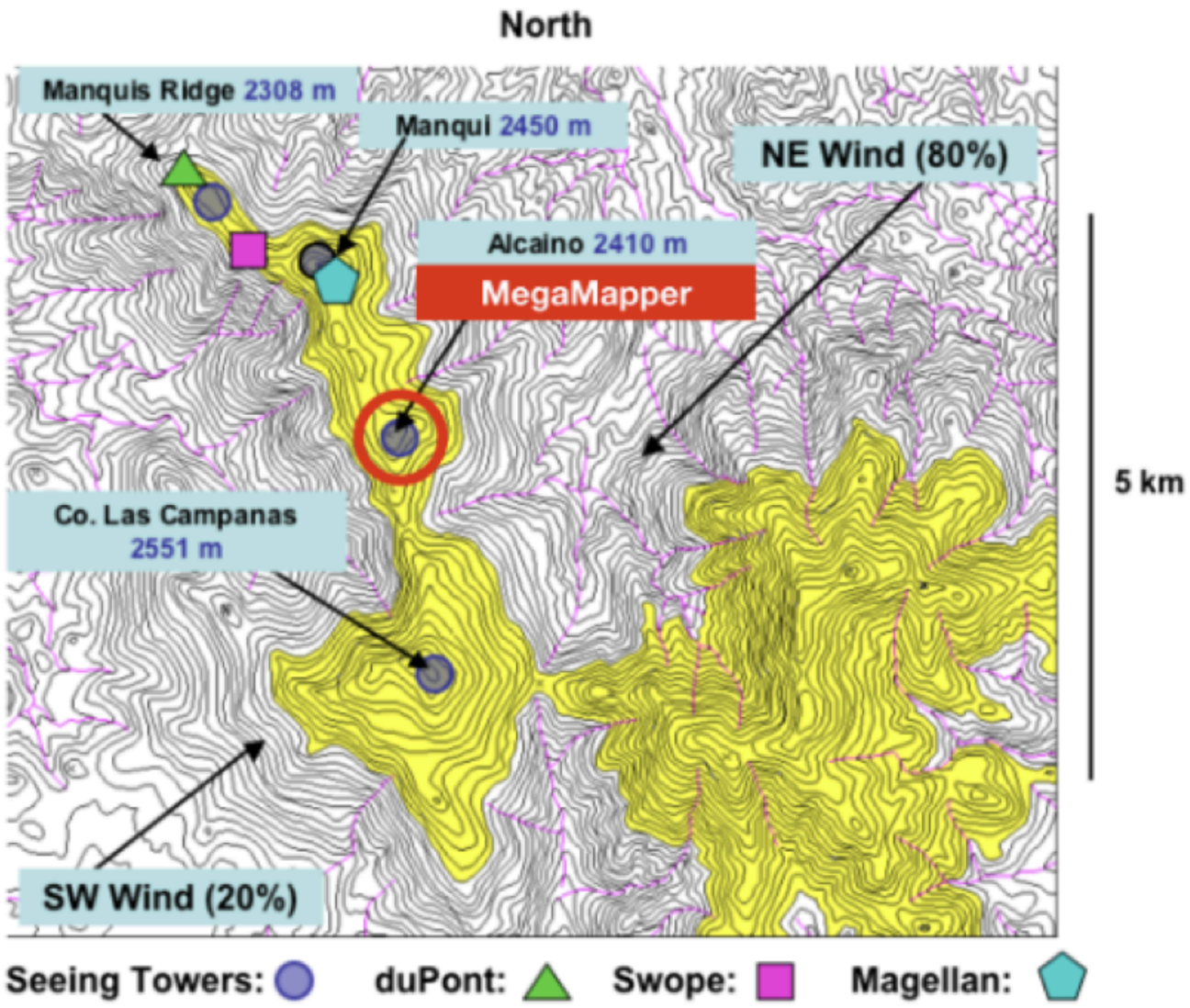


Potential sites for Stage 5 Spectroscopy options A or B at or near Cerro Tololo



Courtesy: Arjun Dey (NSF NOIRLab)

Potential sites for Stage 5 Spectroscopy Option B at or near Las Campanas



Courtesy: Juna Kollmeier (Carnegie Observatories & CITA)

SDSS & DESI collaborations have developed expertise across many institutions

- Aix-Marseille University Regional Participation Group
  - Centre de Physique des Particules de Marseille (CCPM)
  - Laboratoire d'Astrophysique de Marseille (LAM)
  - Observatoire des Sciences de l'Univers – Institut Pythéas
- Argonne National Laboratory
- Barcelona-Madrid Regional Participation Group
  - Institut de Física d'Altes Energies
  - Institut de Ciències de l'Espai (ICE-CSIC, IEEC)
  - Centro de Investigaciones Energéticas, Madioambientales y Tecnológicas
  - Instituto de Física Teórica (IFT, UAM)
- Brookhaven National Laboratory
- Boston University
- Carnegie Mellon University
- CEA-IRFU, Saclay
- China Participation Group
  - National Astronomical Observatories, Chinese Academy of Sciences
  - Peking University
  - Tsinghua University
- Cornell University
- Durham University
- École Polytechnique Fédérale de Lausanne
- Eidgenössische Technische Hochschule, Zürich
- Fermi National Accelerator Laboratory
- Granada-Madrid-Tenerife Regional Participation Group
  - Universidad Autónoma de Madrid (Campus de Excelencia Internacional CIE/UAM + CSIC)
  - Instituto de Astrofísica de Andalucía
  - Instituto de Astrofísica de Canarias
- Harvard University
- Kansas State University
- Korea Astronomy and Space Science Institute
- Korea Institute for Advanced Study
- Lawrence Berkeley National Laboratory
- Laboratoire de Physique Nucléaire et de Hautes Energies
- Laboratório Interinstitucional de e-Astronomia (LIneA)
- Ludwig Maximilians University
- Max Planck Institute
- Mexico Regional Participation Group
  - Universidad Nacional Autónoma de México (UNAM-Instituto de Física, UNAM-Instituto de Astronomía, UNAM-Instituto de Ciencias Nucleares)
  - Universidad de Guanajuato (División de Ciencias e Ingenierías)
  - Instituto Nacional de Investigaciones Nucleares (ININ)
  - Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (CINVESTAV)
- National Optical-Infrared Astronomy Research Laboratory (NSF NOIRLab)
- National Taiwan University
- New York University
- Ohio University
- Perimeter Institute
- Shanghai Jiao Tong University
- Siena College
- SLAC National Accelerator Laboratory
- Southern Methodist University
- Swinburne University
- The Ohio State University
- Universidad de los Andes
- University of Arizona
- University of Barcelona
- University of California, Berkeley
- University of California, Irvine
- University of California, Santa Cruz
- University College London
- University of Edinburgh
- University of Florida
- University of Michigan at Ann Arbor
- University of Pennsylvania
- University of Pittsburgh
- University of Portsmouth
- University of Queensland
- University of Rochester
- University of Toronto
- University of Utah
- University of Waterloo
- University of Wyoming
- University of Zurich
- UK Regional Participation Group
  - The Royal Observatory, Edinburgh
  - University of Cambridge
  - University of Saint Andrews
  - University of Warwick
- Yale University

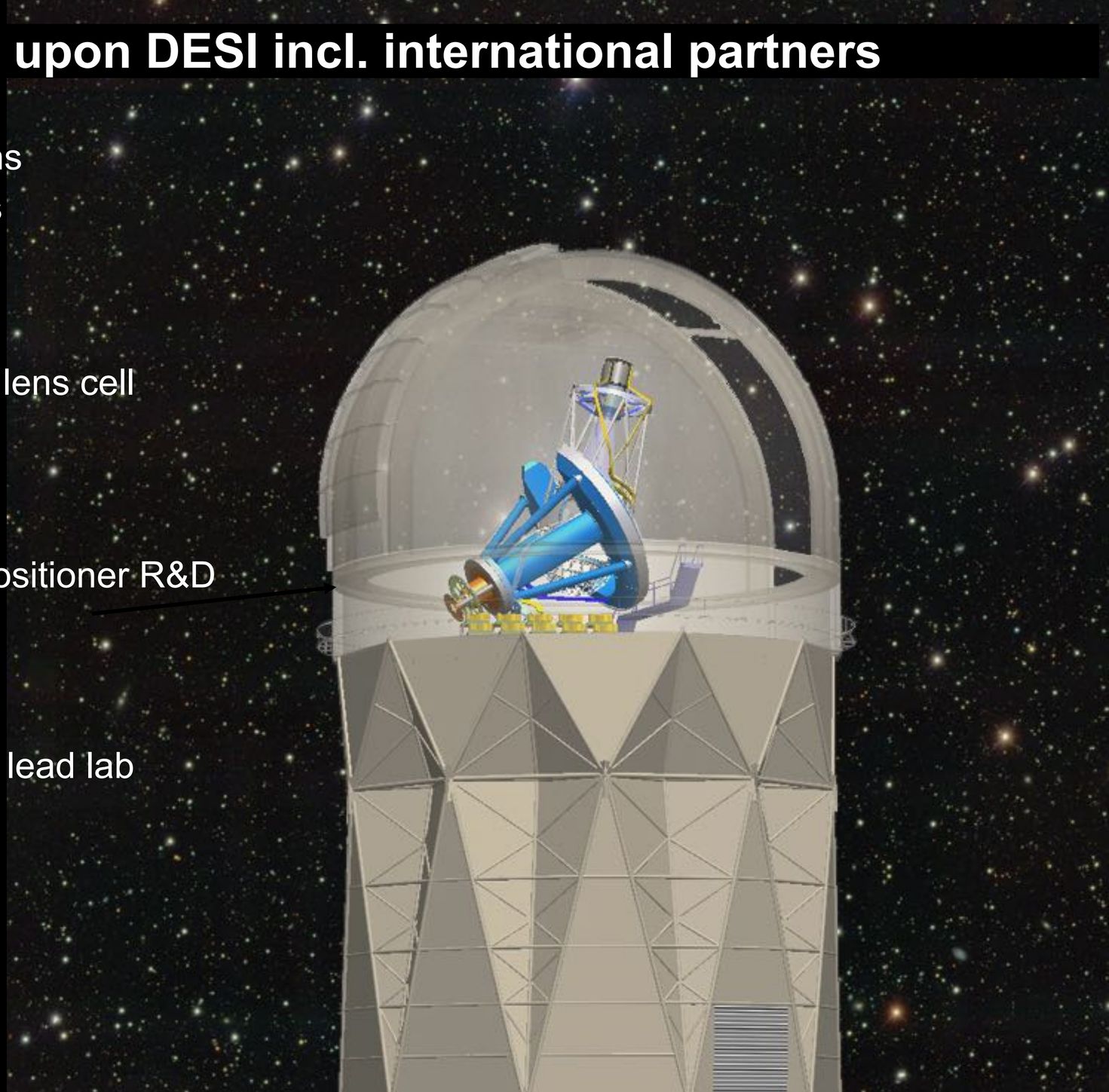
Stage 5 collaboration would build upon DESI incl. international partners

LAM + CPPM (France): Spectrographs
LPNHE (France): Calibration systems
CEA (France): Cryo systems

Fermilab (U.S.): Telescope top-end + lens cell
w/ UCL (U.K.): Telescope optics

AAO, USTC, Spain: Fiber positioner R&D

Efforts managed + coordinated by LBNL as the lead lab



Stage 5 costing

DESI management estimates based upon DESI construction 2016-2021
with 35% (labor) or 46% (materials) escalation to FY23 dollars

DESI partners have (enthusiastically!) expressed interest in Stage 5

Option A: Twin DESI north+south
- $145M for Arizona site upgrade
- $175M for Chile site upgrade (including new wide-field corrector)
- $320M total w/out contingency

Option B: MegaMapper instrument on a 6.5-m telescope platform
- Would require a contributed telescope
- $340M for instrument+corrector w/out contingency

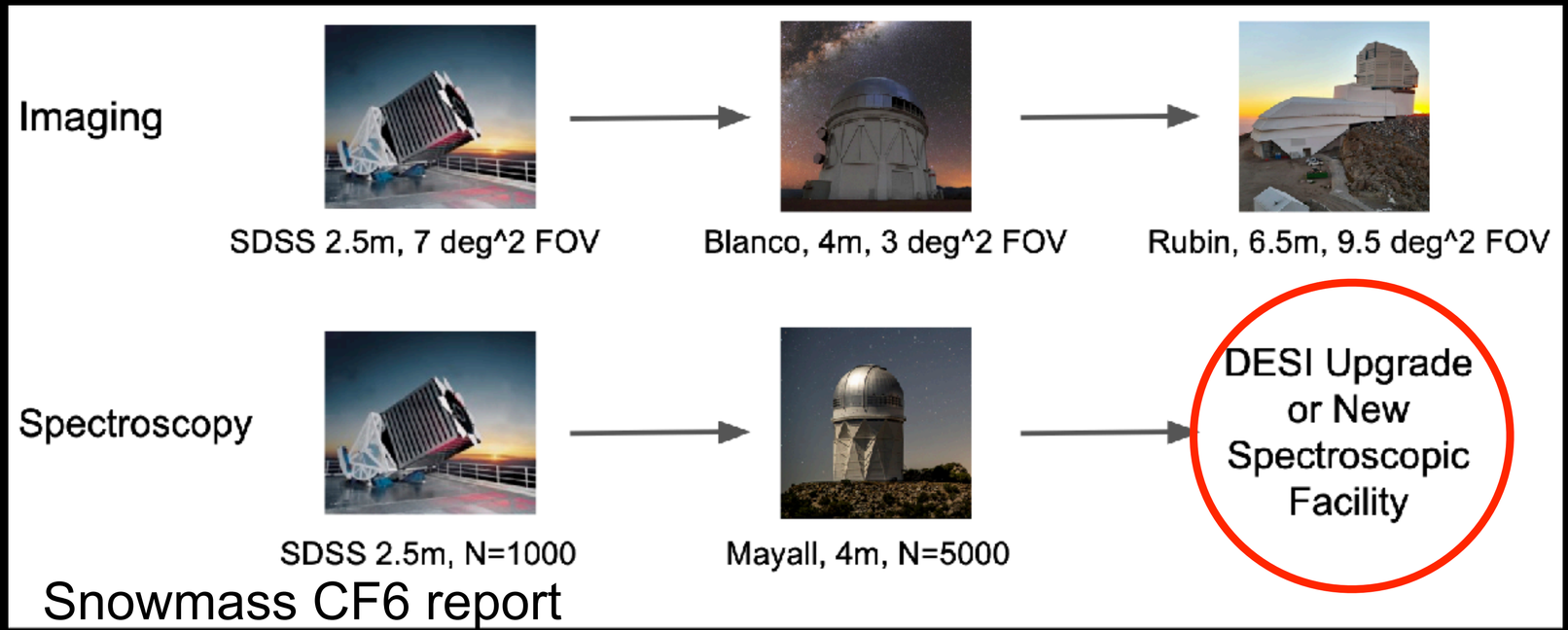
Operations costs would scale from DESI at $11M/year,
plus continued DOE grant support for ~40 US university PIs

Summary: The Opportunites of Stage 5 Spectroscopy

Next-generation will probe both epochs of accelerated expansion
- Direct Dark Energy density measurements to z=4
- Primordial Figure-of-Merit increases from 0.9 (DESI) to 10 (Stage 5)

Snowmass report: “CMB-S4 and Spec-S5 are ready to be immediately implemented”
- instrument continues iterative upgrades from DESI, increasing capability by 10X
- BOSS, DES, DESI collaborations have built the analysis tools

Continues broad participation in the US HEP community & international participation



Snowmass CF6 report