Cosmology and Fundamental Physics Midterm Summary

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Scope of this talk (in 15 minutes or less…)

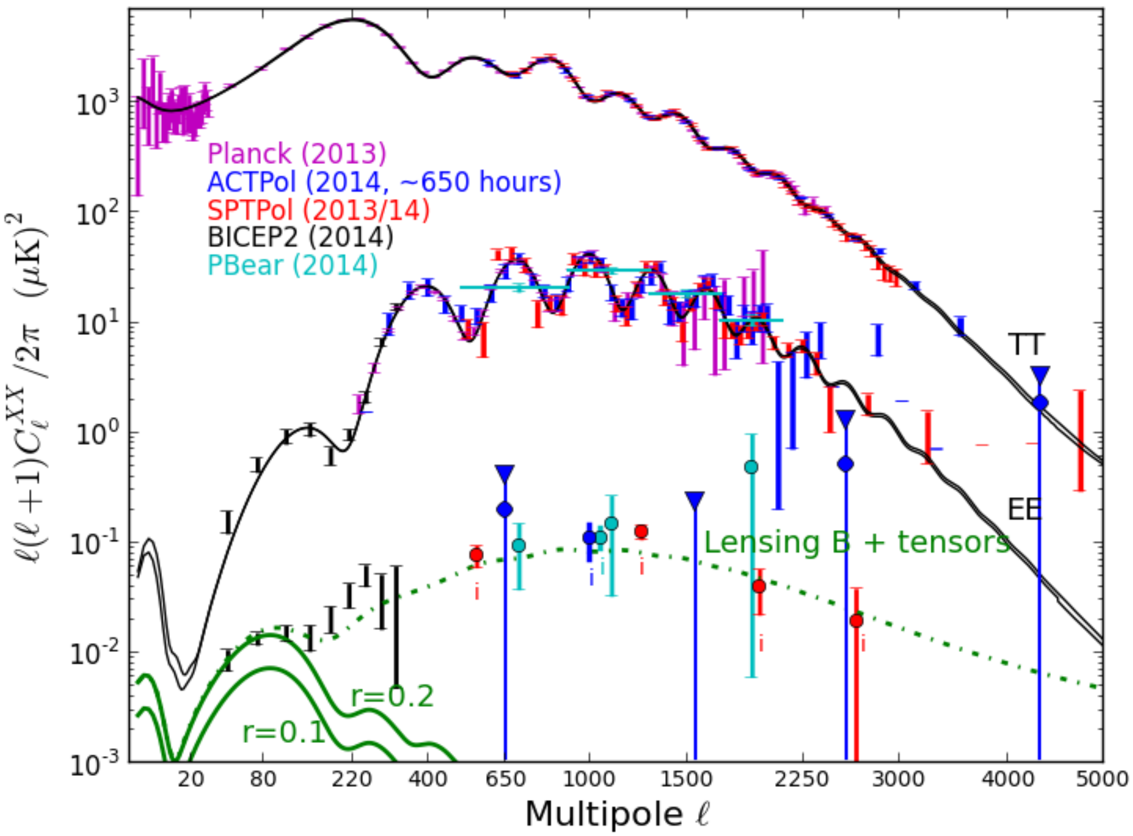
- 4 key science questions in the CFP report:
  - How did the universe begin?
  - Why is the universe accelerating?
  - What is dark matter?
  - What are the properties of neutrinos?
- Committee questions for CFP
  - How has the science landscape changed since NWNH? What have been the most important advances and discoveries?
  - Have we made progress with respect to the top science issues?What are the most important questions in your area now?
  - Have there been any technological advances that might enable rapid progress on particular topics?
  - What impact is the significantly smaller NSF/AST budget than was anticipated by NWNH having on this decade's science program?
  - **Is there consensus that WFIRST will advance CFP science beyond the state of the art expected in the early 2020s?**
  - **How do WFIRST capabilities for dark energy characterization compare and contrast with those from DESI, LSST, and Euclid?**
  - **How will future CMB or neutrino experiments affect CFP science?**

Conclusions, to start

- Investment in CFP flagship facilities, both in progress and in preparation, has the potential to deliver profound physical insights in CFP-centered science
  - Includes current and upcoming CMB, photometric and spectroscopic LSS surveys and direct and indirect DM surveys.
- The potential for order of magnitude or better improvements in inflationary, dark energy, dark matter and neutrino parameters that could reveal:
  - The inflationary energy scale
  - Properties of gravity (and perhaps deviations from GR) on Mpc-Gpc scales
  - Dark matter detection and constraints on the cross-section and mass
  - The neutrino mass sum and hierachy
- The significantly smaller budget does threaten CFP science
  - Lower grant funding limits US preparation and leadership in the science delivery from facilities in which the US has heavily invested, such as LSST.
  - Limits US participation in international projects, such as CTA.
- WFIRST, Euclid, LSST and DESI each provide valuable complementary datasets that comprise critical pieces needed to achieve percent level constraints on dark energy. Key factors are systematic error mitigation in weak lensing measurements and complementarity of gravitational constraints from peculiar motions & lensing.

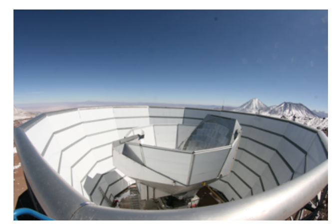
Progress in CMB measurements

- New regime of high precision spectra measurements to small scales
  - Plank 2015 cosmology consistent with WMAP ΛCDM with tighter constraints
  - First detection of cluster velocities from kinetic SZ (ACT+SDSS 2012)
  - First detection of CMB lensing (ACT 2011)
  - Boost in cluster science: Planck, SPT, ACT > 1000 thermal SZ clusters
- First detections of B-mode polarization

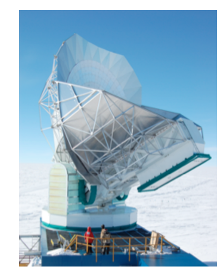


Planck satellite (ESA/NASA)

ACT (NSF)



SPT (NSF/DOE)



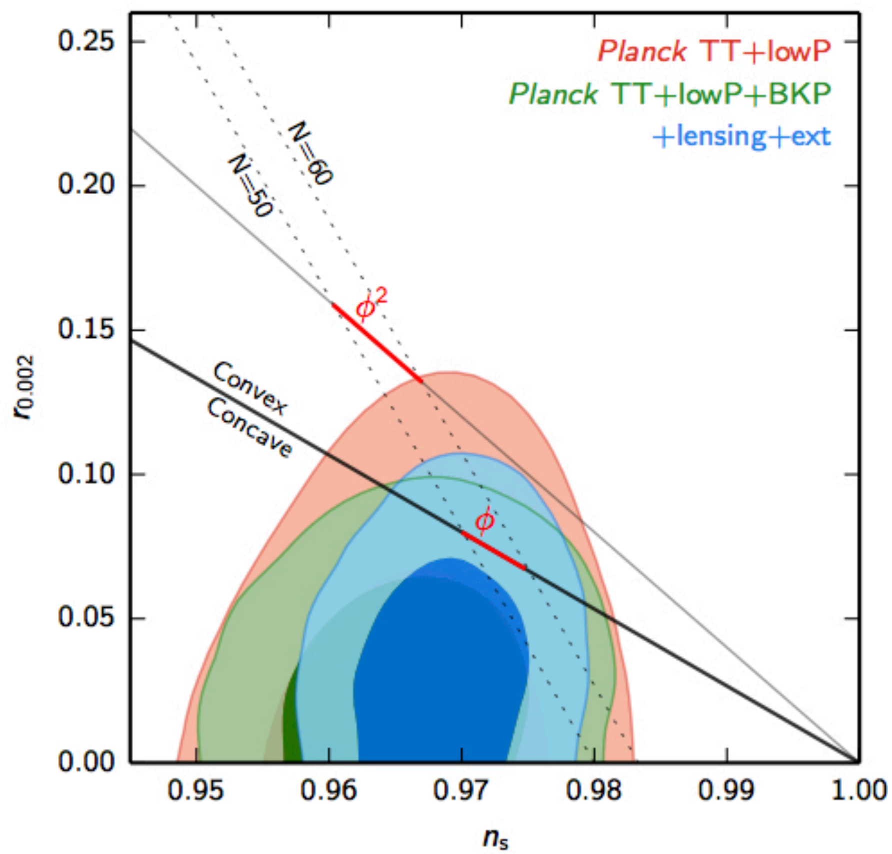
BICEP2/Keck (NSF/private)

Polarbear (NSF/private)

Courtesy Michael Niemack

How did the universe begin?

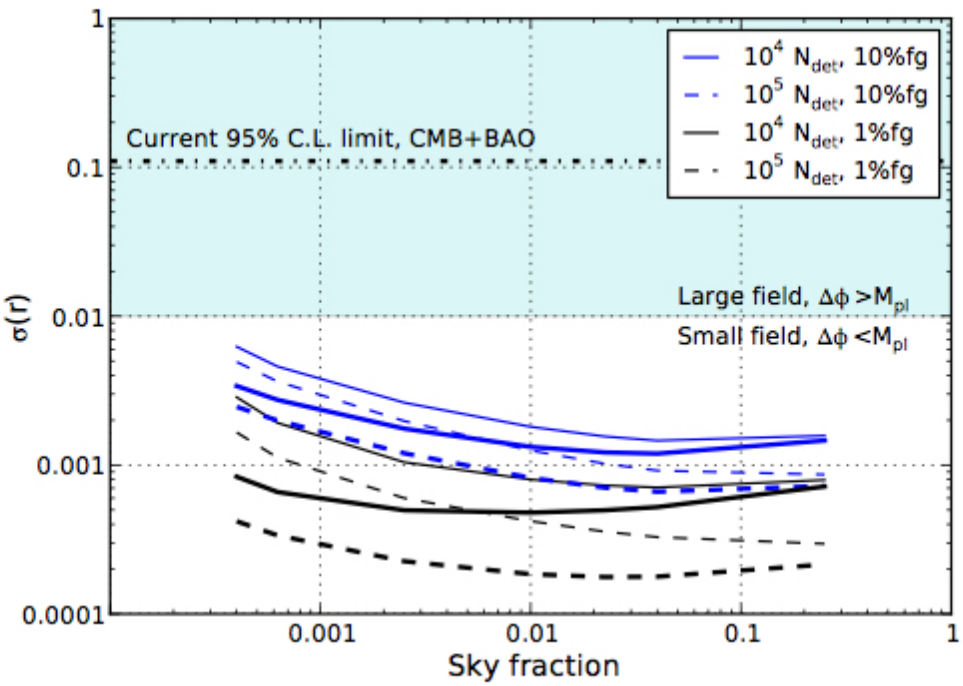
- Aims:
  - Detect gravitational waves, and infer the inflationary energy scale.
  - Test the physics of inflation and distinguish among models.
- Progress: Planck, ACT and SPT T and E-mode polarization
  - Consistent with single field inflation, no detection of isocurvature modes/ non-Gaussianity
- Progress: B-mode measurements
  - PolarBear and BICEP2 results
  - Highlight important dust foregrounds.
  - BICEP2 +Keck+ Planck yielded tighter constraints on r upper bound.



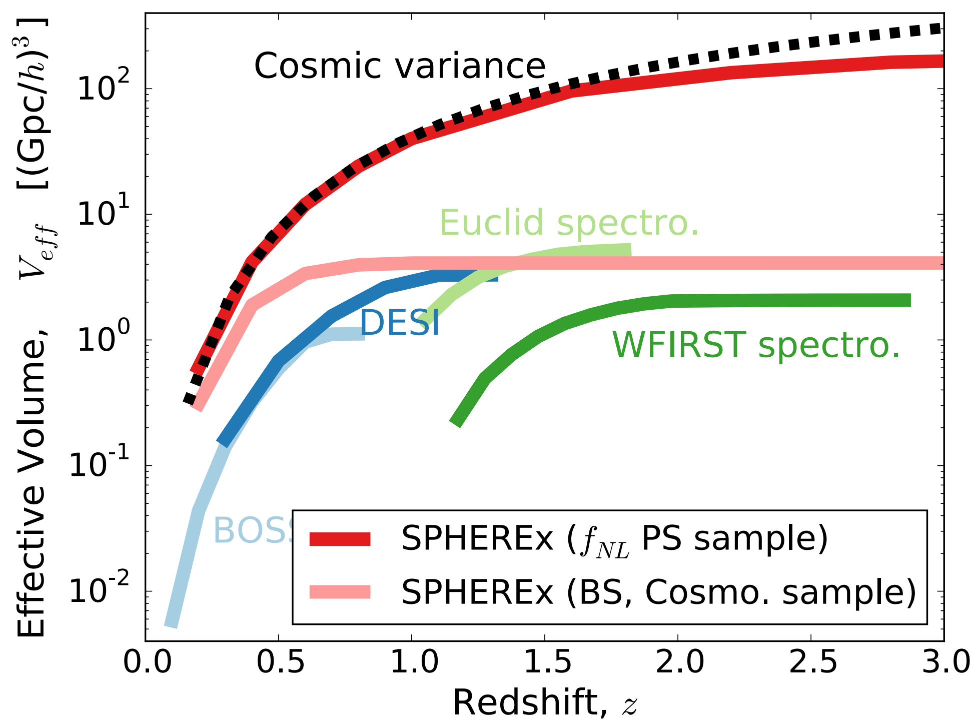
Ade et al (Planck 2015 XIII)

How did the universe begin?

- Next steps: $\sigma(r)\sim10^{-3}$ constraints
  - requires multiple frequencies needed to extract out backgrounds
  - Ground, e.g. CMB-S4, Space explorer-class e.g. Litebird, PIXIE, and ongoing balloon, e.g. Spider, to access higher frequencies than ground
- Next steps: $\sigma\sim10^{-3}$ constraints on n_s and running and non-Gaussianity $\sigma(f_{NL})\sim1$
  - requires mapping of the 3D P(k).
  - DESI and Euclid and prospective spectroscopic missions e.g. SPHEREx



Wu et al (1402.4108)



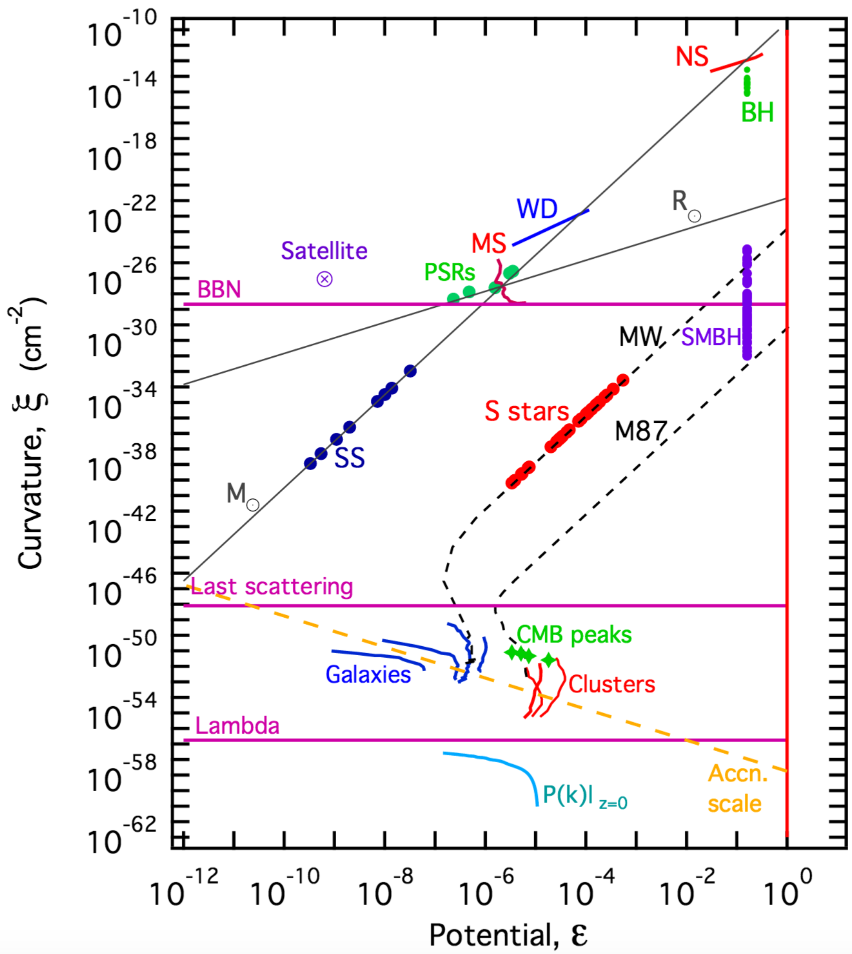
Dore et al (1412.4872)

Why is the universe accelerating?

- Aims:
  - Use geometric tests to constrain the dark energy equation of state
  - Use the growth of structure to test GR on cosmic scales
  - Connect phenomenological constraints to underlying theories

Category	Theory
Horndeski Theories	Scalar-Tensor theory (incl. Brans-Dicke)
	$f(R)$ gravity
	$f(\mathcal{G})$ theories
	Covariant Galileons
	The Fab Four
	K-inflation and K-essence
	Generalized G-inflation
	Kinetic Gravity Braiding
	Quintessence (incl. universally coupled models)
	Effective dark fluid
Lorentz-Violating theories	Einstein-Aether theory
	Hořava-Lifschitz theory
$>$ 2 new degrees of freedom	DGP (4D effective theory)
	EBI gravity
	TeVeS

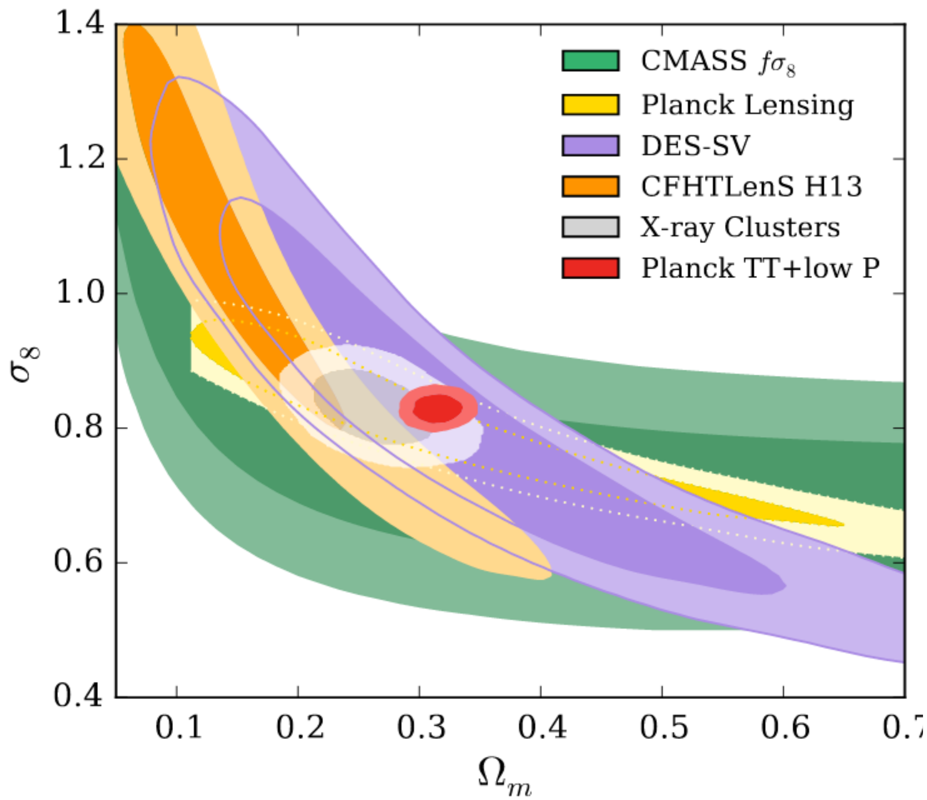
Baker et al (1107.0491)



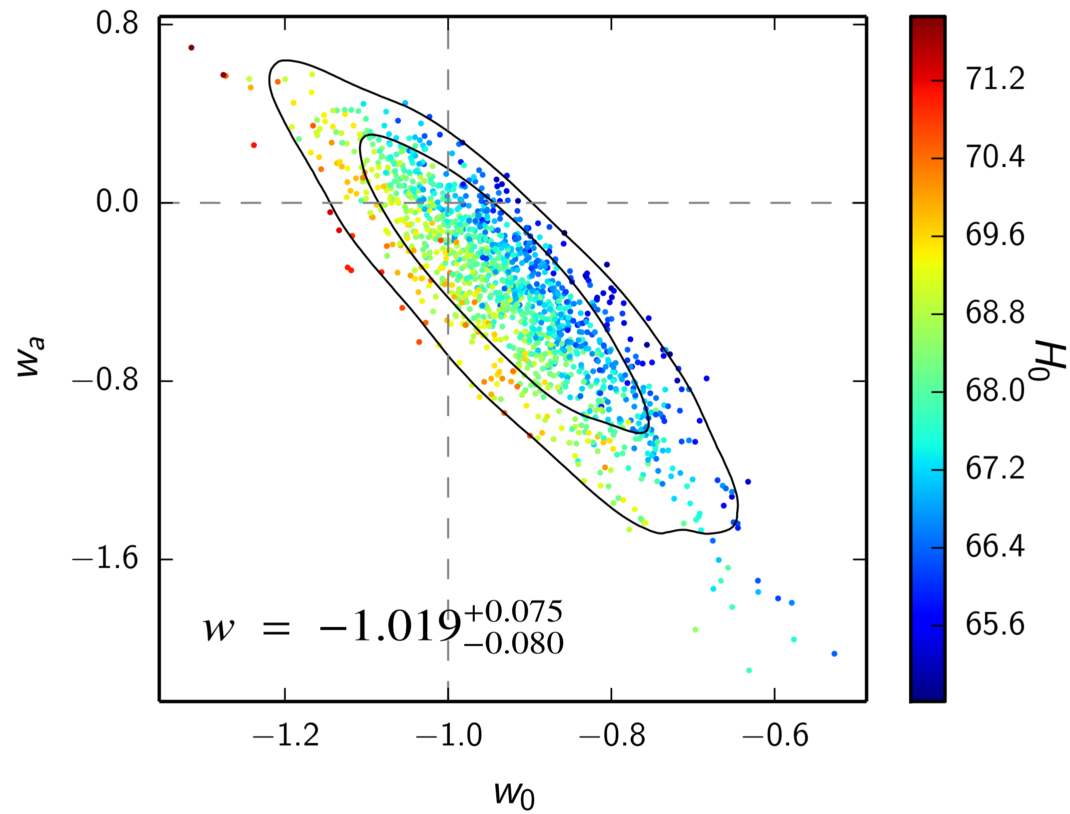
Baker et al (1412.3455)

Why is the universe accelerating?

- Progress: Combined Planck, BOSS BAO and SDSS/SNLS SN yield constraints on w consistent with ΛCDM.
- Progress: DES and HSC taking data and early science verification results



DES Collaboration 1507.05552



Ade et al (Planck 2015 XIII)

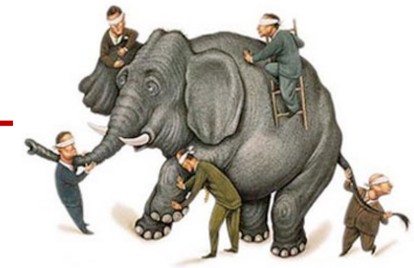
Why is the universe accelerating?

- Next steps: Sub-percent precision on w and few percent accuracy on growth rate exponent γ or G_{mat}/G_{light}

$$k^2\Psi = -4\pi G_{\rm matter}a^2\rho\Delta \qquad k^2(\Psi+\Phi) = -8\pi G_{\rm light}a^2\rho\Delta\,,$$

- To achieve: Future distinct and complementary surveys
  - Careful control of instrumental and astronomical systematics
  - Multiple projects and approaches (lensing, motions, positions): LSS surveys (DESI, LSST, Euclid, WFIRST and others) and CMB lensing
  - Techniques: SN1a, BAO, RSD, gravitational lensing.
- Need multiple surveys to:
  - Balance photometric speed (billions of galaxies) vs. spectroscopic precision and angular and spectral resolution (millions of galaxies)
  - Provide complementary tracers (LRGs, ELGs, Lya/QSOs, clusters), redshifts, scales and environs (cluster vs dwarf galaxies)
  - Leverage cross-correlations e.g. galaxy-CMB lensing, CMB-LSS kinetic SZ
  - Provide trade offs in survey area vs depth (repeat imaging, dithering, cadence and survey area overlap/configuration) for systematic control.

Why is the universe accelerating?



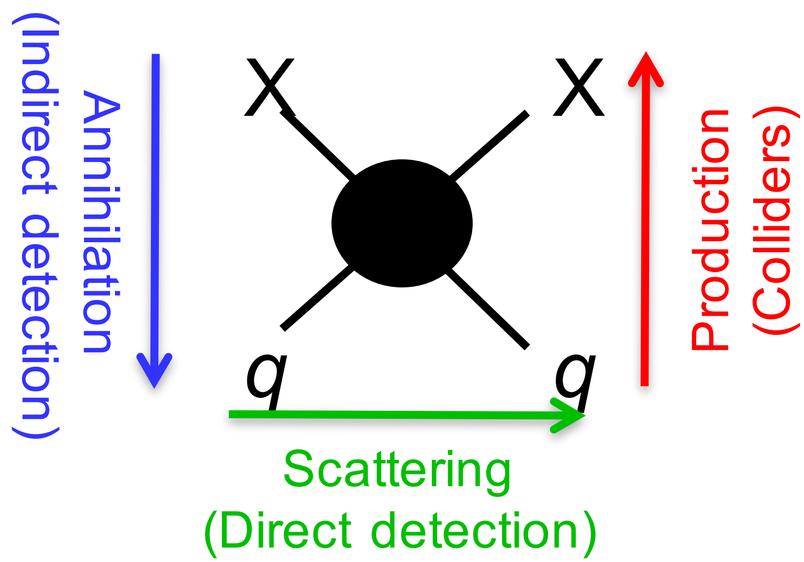
- Upcoming Surveys: Different strengths & systematics

Based on publicly available data

Stage IV	DESI	LSST	Euclid	WFIRST-AFTA
Starts, duration	~2018, 5 yr	2020, 10 yr	2020 Q2, 7 yr	~2023, 5-6 yr
Area (deg^2)	14,000 (N)	20,000 (S)	15,000 (N + S)	2,400 (S)
FoV (deg^2)	7.9	10	0.54	0.281
Diameter (m)	4 (less 1.8+)	6.7	1.3	2.4
Spec. res. $\Delta\lambda/\lambda$	3-4000 (N_{fib}=5000)		250 (slitless)	550-800 (slitless)
Spec. range	360-980 nm		1.1-2 mm	1.35-1.95 mm
BAO/RSD	20-30m LRGs/[OII] ELGs 0.6 < z < 1.7, 1m QSOs/Lya 1.9<z<4		~20-50m Hα ELGs z~0.7-2.1	20m Hα ELGs z = 1–2, 2m [OIII] ELGS z = 2–3
pixel (arcsec)		0.7	0.13	0.12
Imaging/ weak lensing (0<z<2.)		~30 gal/$arcmin^2$ 6 bands 320-1080 nm	30-35 gal/$arcmin^2$ Broad visible band 550– 900 nm	68 gal/$arcmin^2$ 3 bands 927-2000nm
SN1a		10^4-10^5 SN1a/yr z = 0.–0.7 photometric		2700 SN1a z = 0.1–1.7 IFU spectroscopy

What is dark matter?

- CMB has established that there were two fluids: non-baryonic dark matter + baryon/photon fluid
- CMB galactic foreground generated interest as potential DM signature
- Aim: Detect dark matter, determine their mass and cross-section.
  - 3 Main Approaches to detect WIMPs and related candidates
  - Indirect detection: DM pair annihilation or decay in our galactic neighborhood into positrons, high-energy photons, neutrinos…



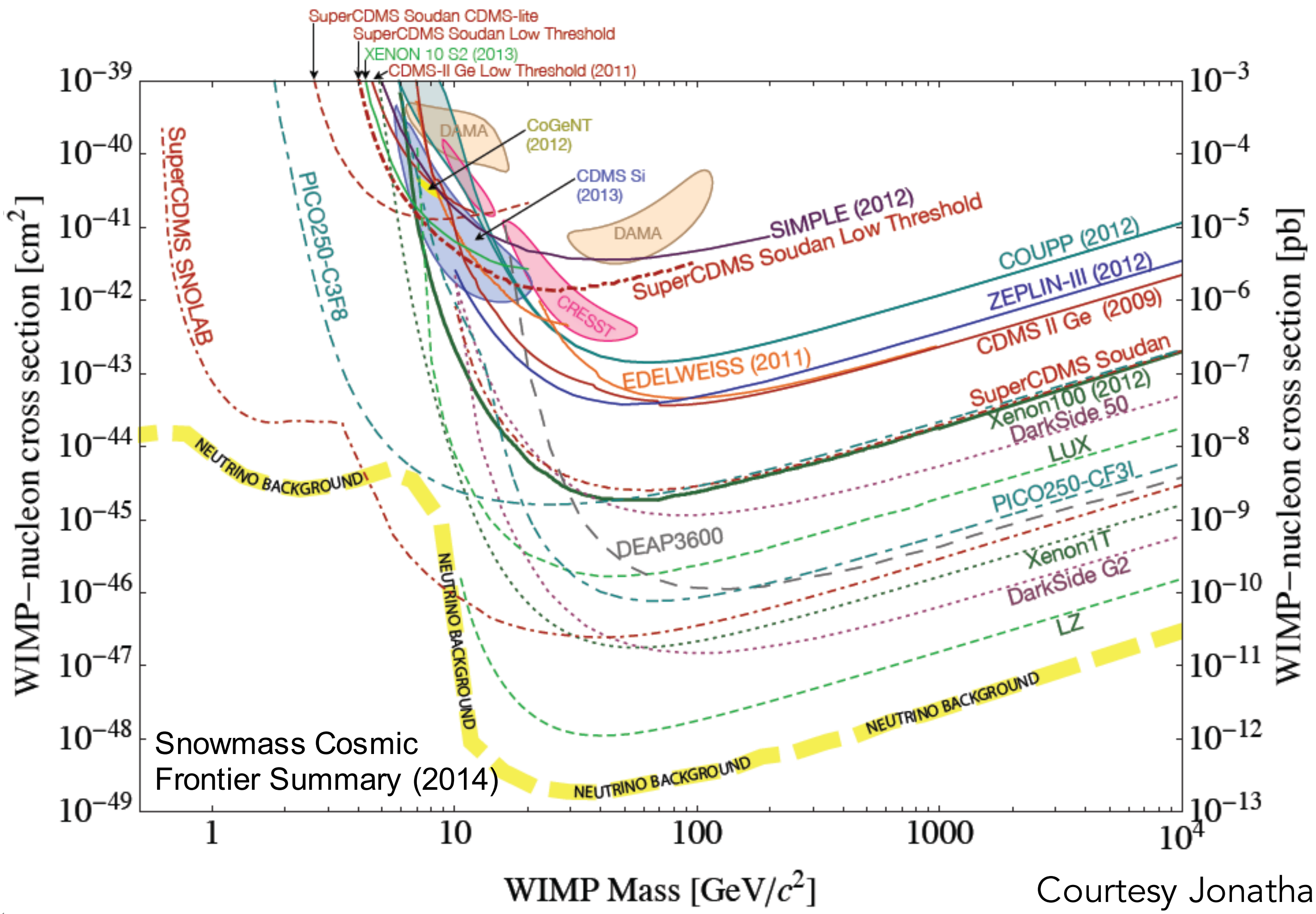
- Progress: No direct detections, but improvements on DM constraints

Courtesy Jonathan Feng

What is dark matter?

Direct Detection

- Progress: since 2010, sensitivity improved by ~100 (for m ~ 100 GeV)
- Next steps: 2-3 orders of magnitude improoemenexpected by a suite of experiments world-wide



2010

Now

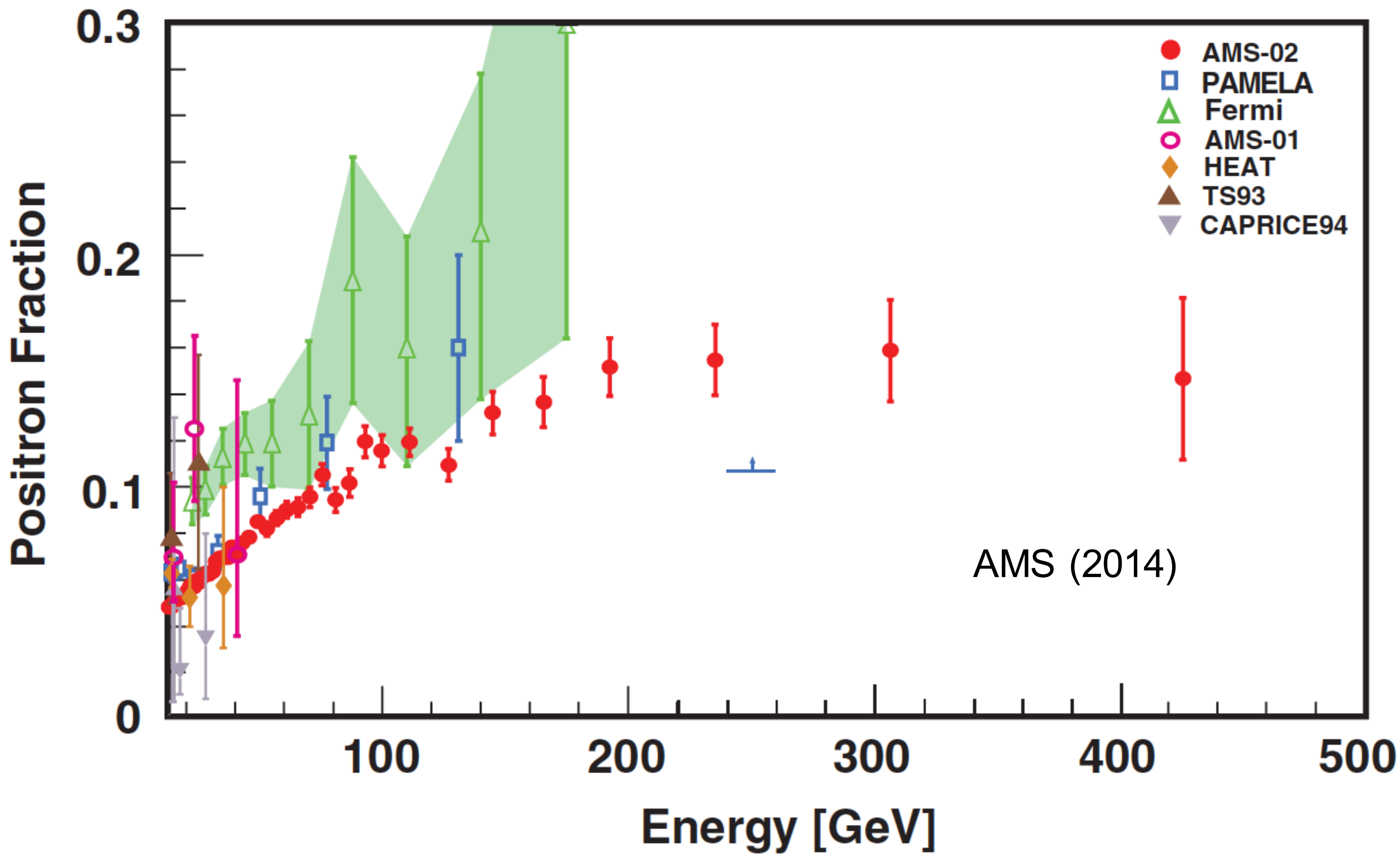
LZ 2021 start…

Courtesy Jonathan Feng

What is dark matter?

Indirect Detection with positrons

- Progress: since 2010, electron and positron fluxes have been measured by AMS with remarkable precision, constrained up to ~400 GeV
- Next steps: 2-3 orders of magnitude improvement expected by a suite of experiments world-wide

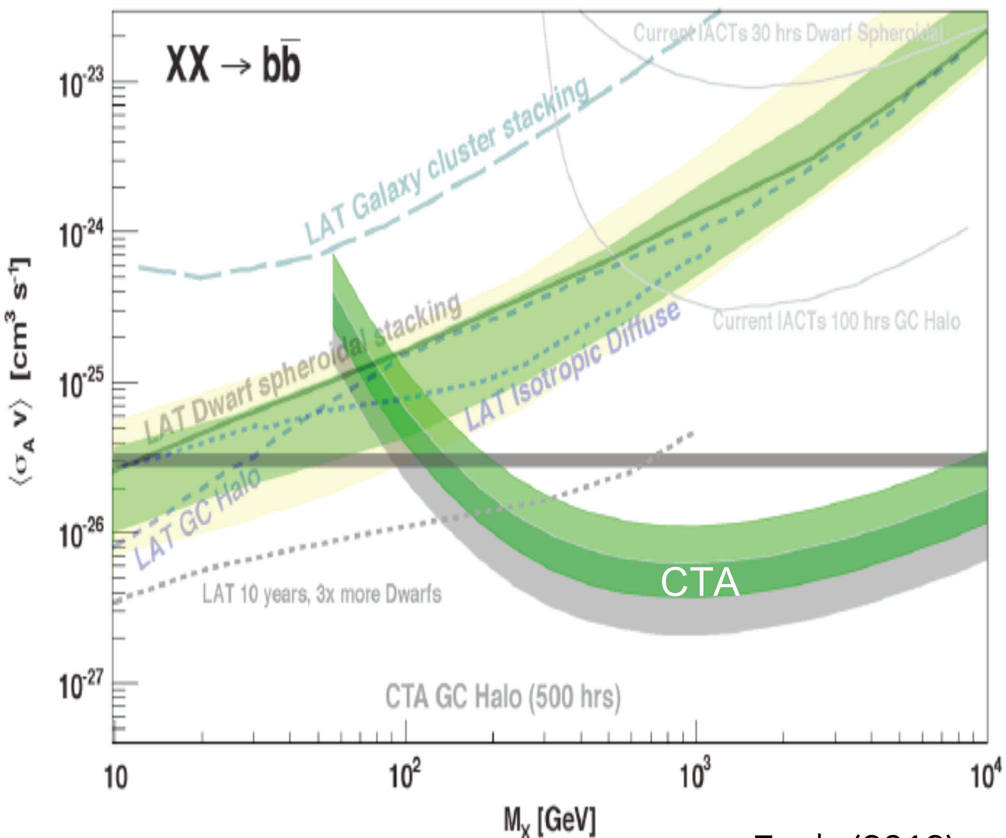


Courtesy Jonathan Feng

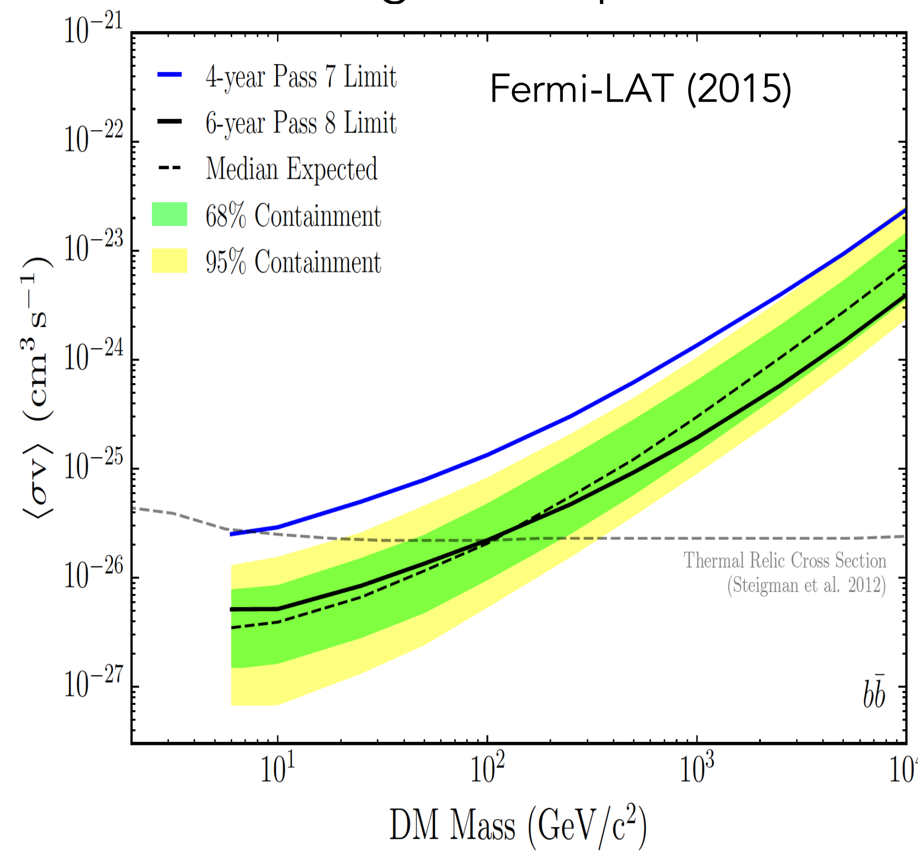
What is dark matter?

Indirect Detection with photons

- Progress: since 2010, rapid improvements, Fermi-LAT now excludes WIMP masses up to ~100 GeV for certain annihilation channels
- Next steps: the Cerenkov Telescope Array (CTA), will extend reach to masses ~ 10 TeV; with dwindling U.S. support, this frontier is moving to Europe



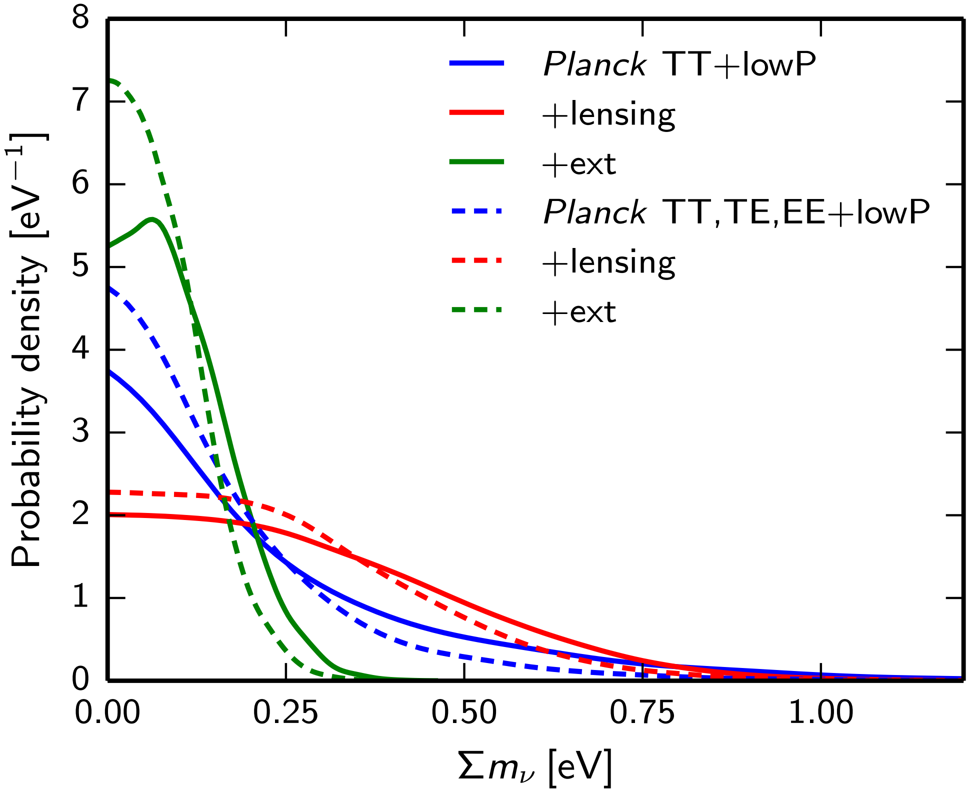
Funk (2013)

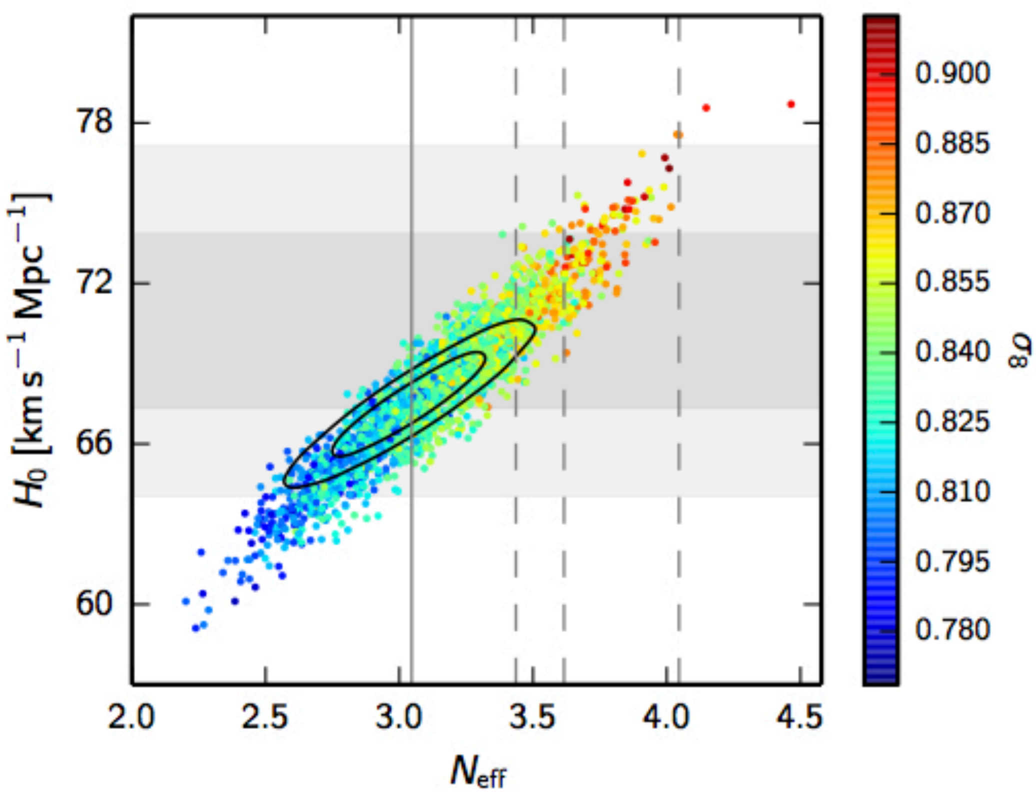


Courtesy Jonathan Feng

What are the properties of neutrinos?

- Aims: Determine the neutrino mass sum, heirarchy & relativistic species number
- Progress: Planck CMB + SDSS BAO sub-eV constraints on neutrino mass. N_{eff} consistent with no extra relativistic species

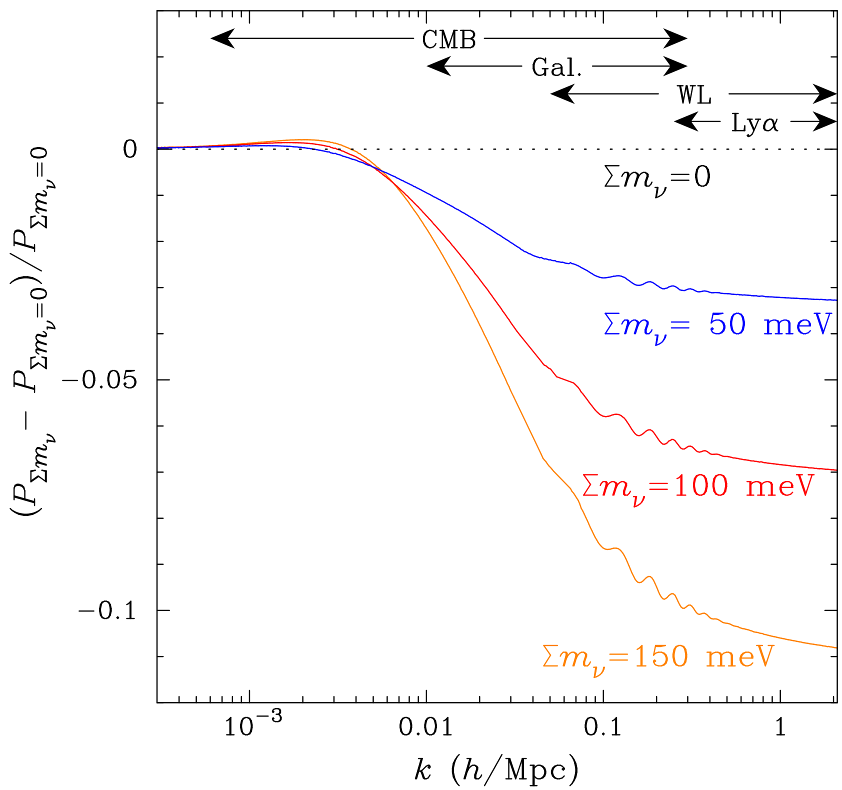




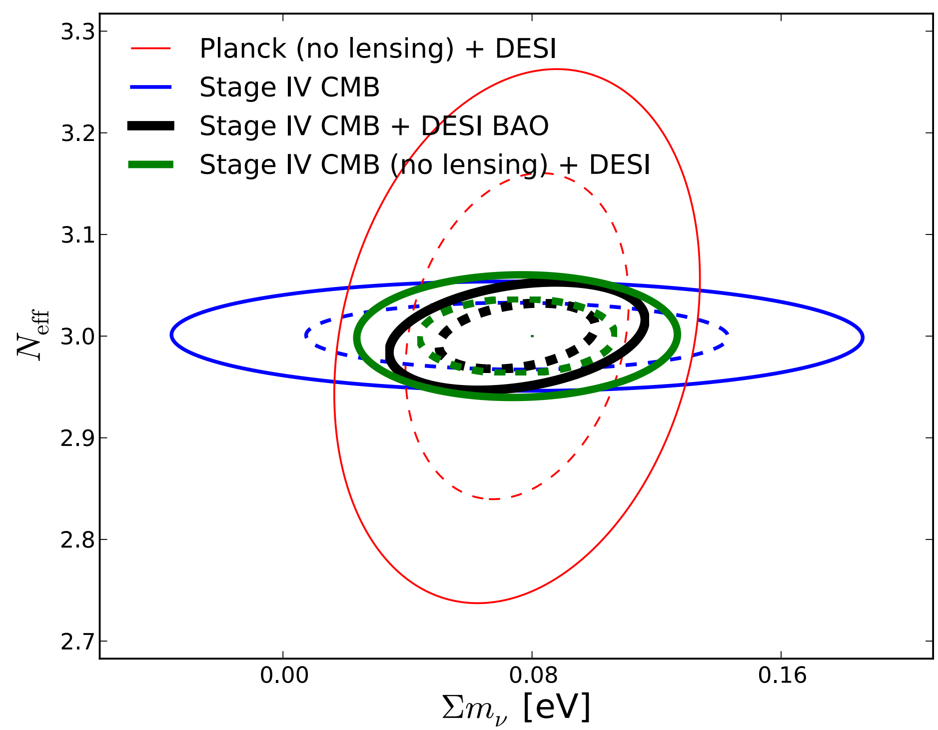
Ade et al (Planck 2015 XIII)

What are the properties of neutrinos?

- Next steps: Order of magnitude improvement, to ~15-20 meV, constraints on m_ν to determine the mass hierarchy, and 1.5% on N_{eff} to test Beyond-Standard-Model (BSM) physics
- Multiple probes (e.g. DESI BAO/RSD, LSST WL/galaxy, CMB-S4 lensing) promise 20meV constraints. In combination we might how to achieve 15meV complementary constraints from CMB-lensing and BAO.



Abazjian et al 1309.5383



Wu et al 2014 (1402.4108)

Maintaining US leadership in survey science

- We want to ensure there is sufficient funding for the delivery of science to reap the return on the major US (NSF, DOE and NASA) investments in key astrophysical facilities in the coming decade.
- e.g. LSST Facility
  - Facility investment: NSF MREFC $473M, DOE MIE Camera $168M + $38 commissioning + Operations ~75% of $40M/year (2013 USD)
  - Facility produces "science-ready" Level 1 nightly alerts and Level 2 object catalogs. Science analysis wholly falls to the (international) community.
  - Broad recognition across the science collaborations at the LSST All-hands meeting that significant preparatory work is needed, in advance of first light, to deliver science from data.
- Low funding levels:
  - Creates challenges for peer-review process to prioritize preparatory work.
  - Needs funding models that encourage advance preparation. Common in HEP projects in DOE and NSF physics, newer in the astronomy community.

Maintaining US leadership in survey science

- An example: The LSST Dark Energy Science Collaboration (DESC) has just completed a major planning exercise, the Science Roadmap*, to lay out the critical tasks, now through first light, to be ready to fully leverage LSST data for dark energy science.
  - An incremental, data-challenge led approach is to be used to build and validate the analysis pipeline infrastructure.
  - The work requires ~40-50FTEs effort/year, now through first light.

Scope of the 2015 Science Roadmap

	2015		2016				2017				2018				2019				2020				2021			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
DC1		RQ	DG	DG	DG	DA	DA	DA																		
DC2						RQ	DG	DG	DG	DG	DA	DA	DA	DA												
DC3											RQ	DG	DG	DG	DG	DA	DA	DA	DA							
Verification							PrV				PrV															
ComCam																			PrC	PrC						
SV																									PrC	PrC

RQ	Data Challenge: Simulation Requirements
DG	Data Challenge: Simulated Data Generation
DA	Data Challenge: Data Analysis
PrV	LSST Project Verification Datasets: Anticipated Availability of DM-Processed External Precursor Products
PrC	LSST Project Commissioning Data Products: Anticipated Availability of ComCam & Science Verification (SV) Data

*http://lsst-desc.org/sites/default/files/DESC_SRM_V1.pdf

Conclusions (again)

- Investment in CFP flagship facilities, both in progress and in preparation, has the potential to deliver profound physical insights in CFP-centered science
  - Includes current and upcoming CMB, photometric and spectroscopic LSS surveys and direct and indirect DM surveys.
- Have the potential for order of magnitude or better improvements in inflationary, dark energy, dark matter and neutrino parameters that could reveal:
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