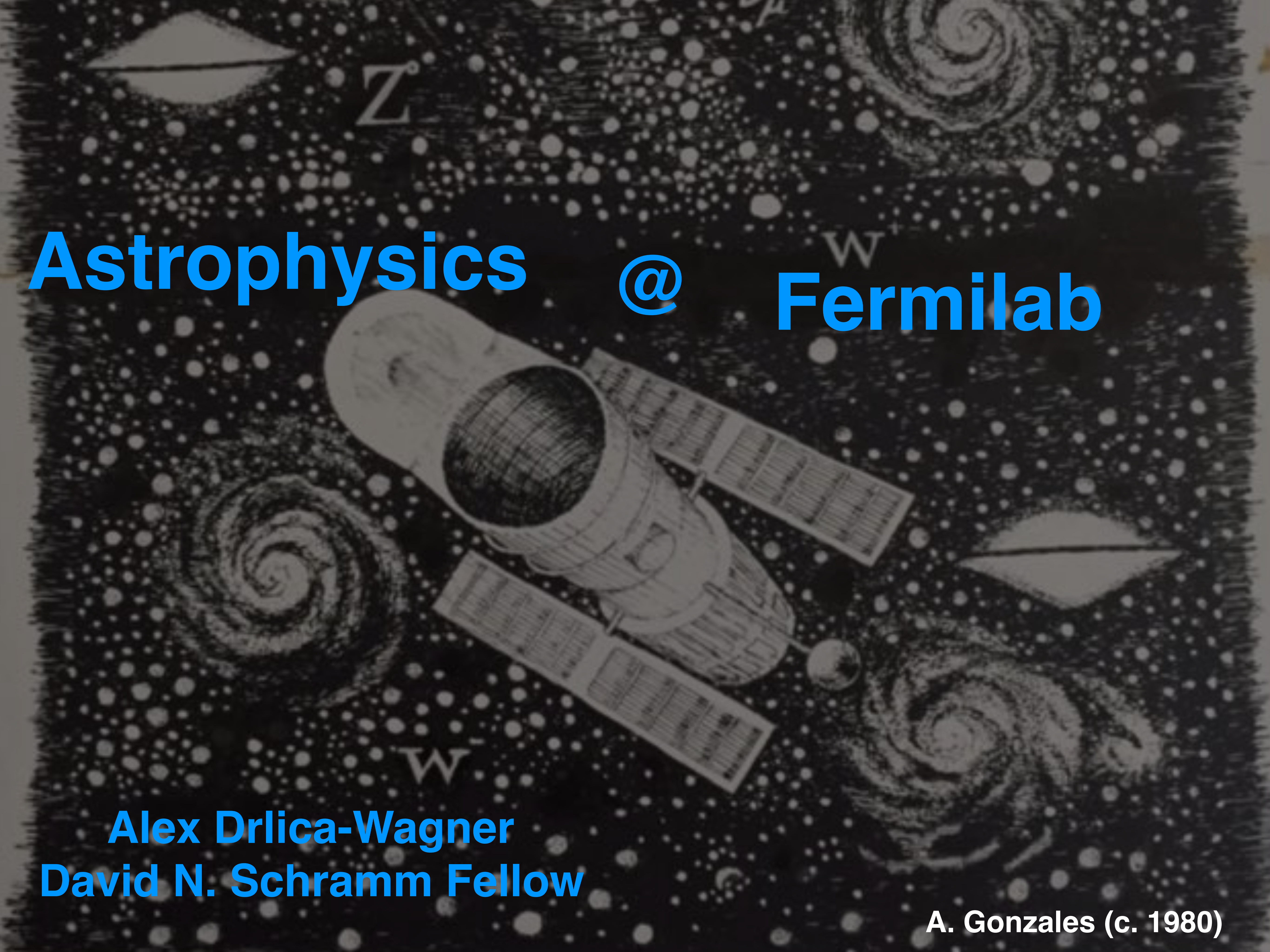
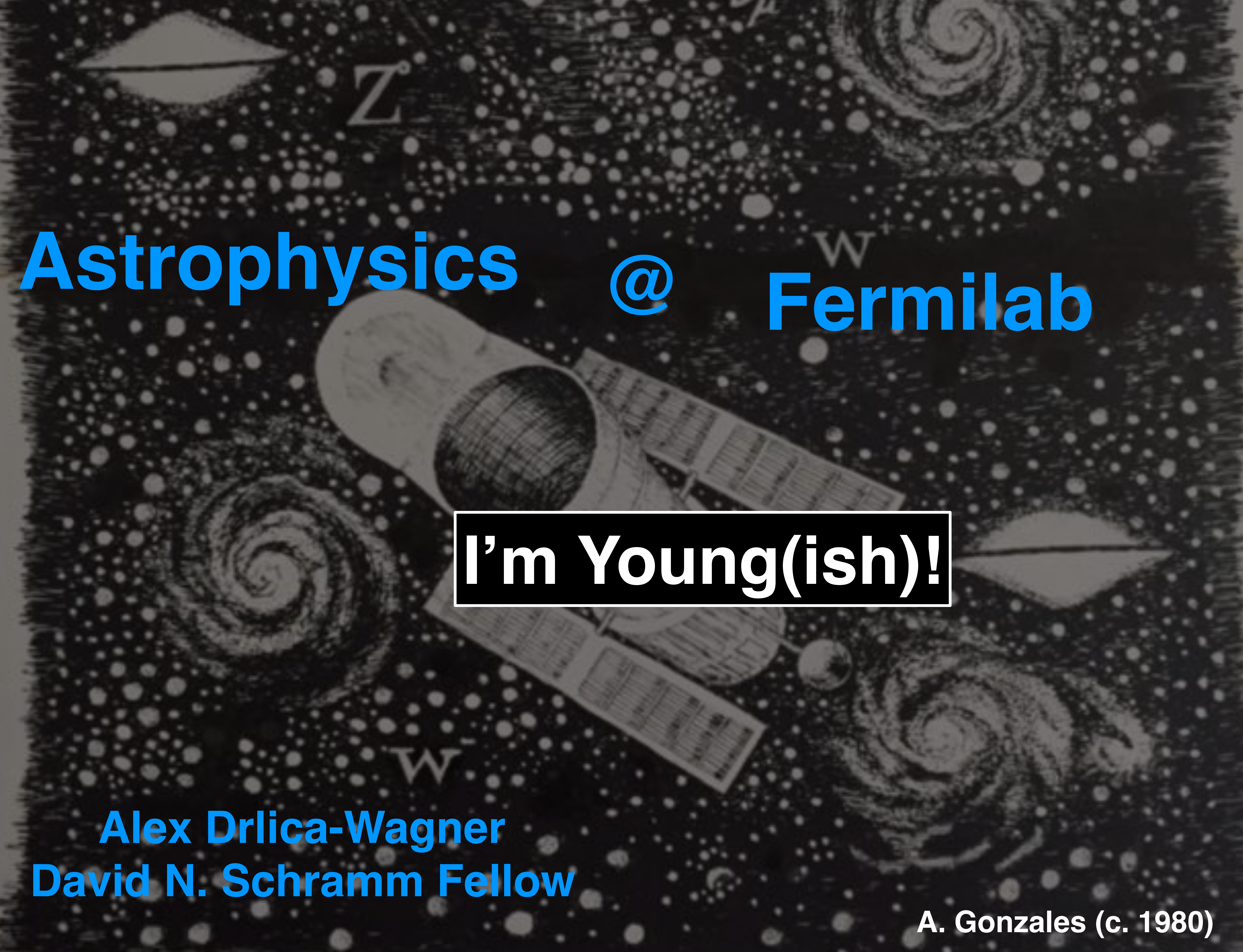
Astrophysics @ Fermilab

Alex Drlica-Wagner
David N. Schramm Fellow



A. Gonzales (c. 1980)

Astrophysics @ Fermilab

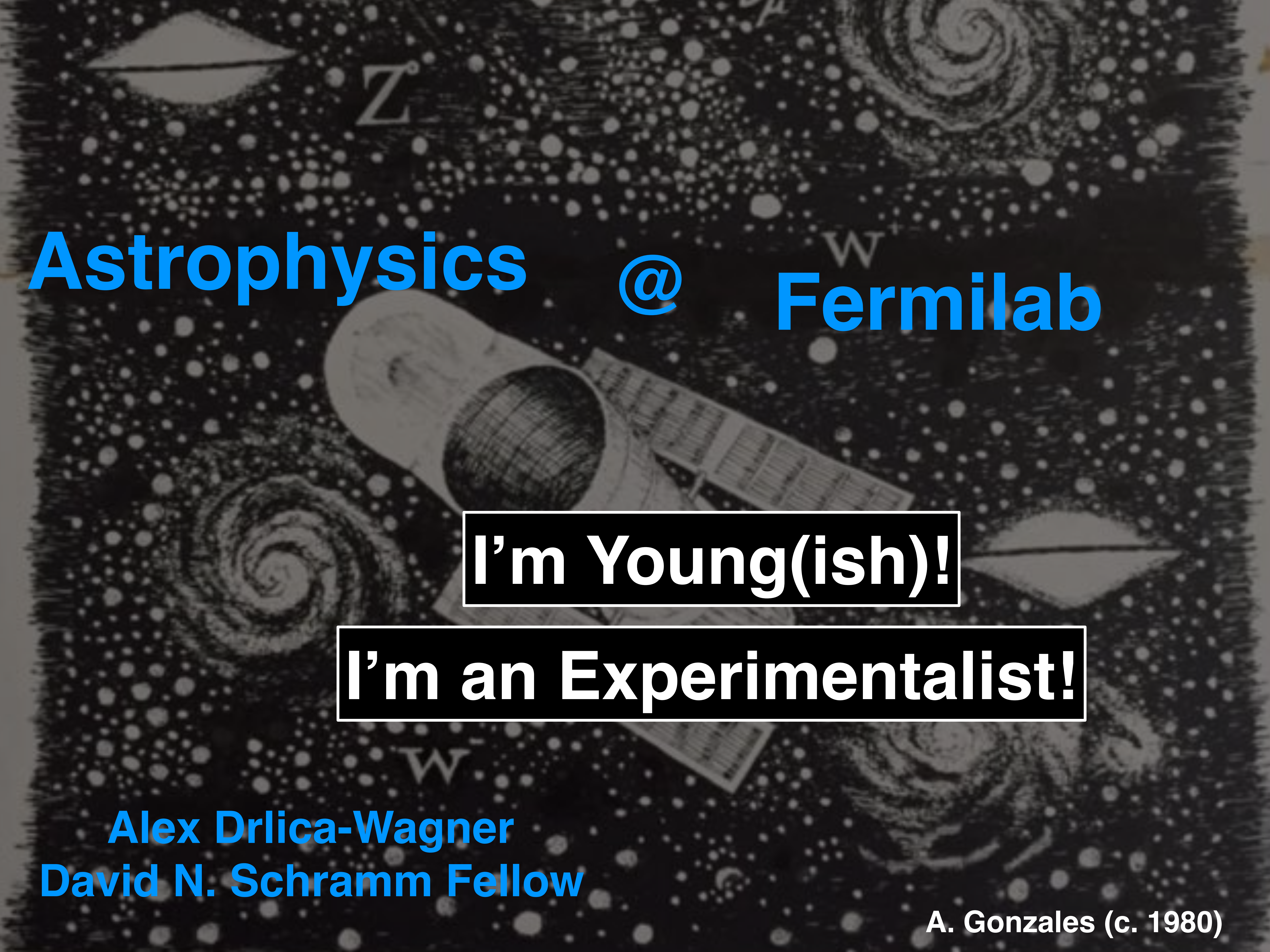


I’m Young(ish)!

Alex Drlica-Wagner
David N. Schramm Fellow

A. Gonzales (c. 1980)

Astrophysics @ Fermilab



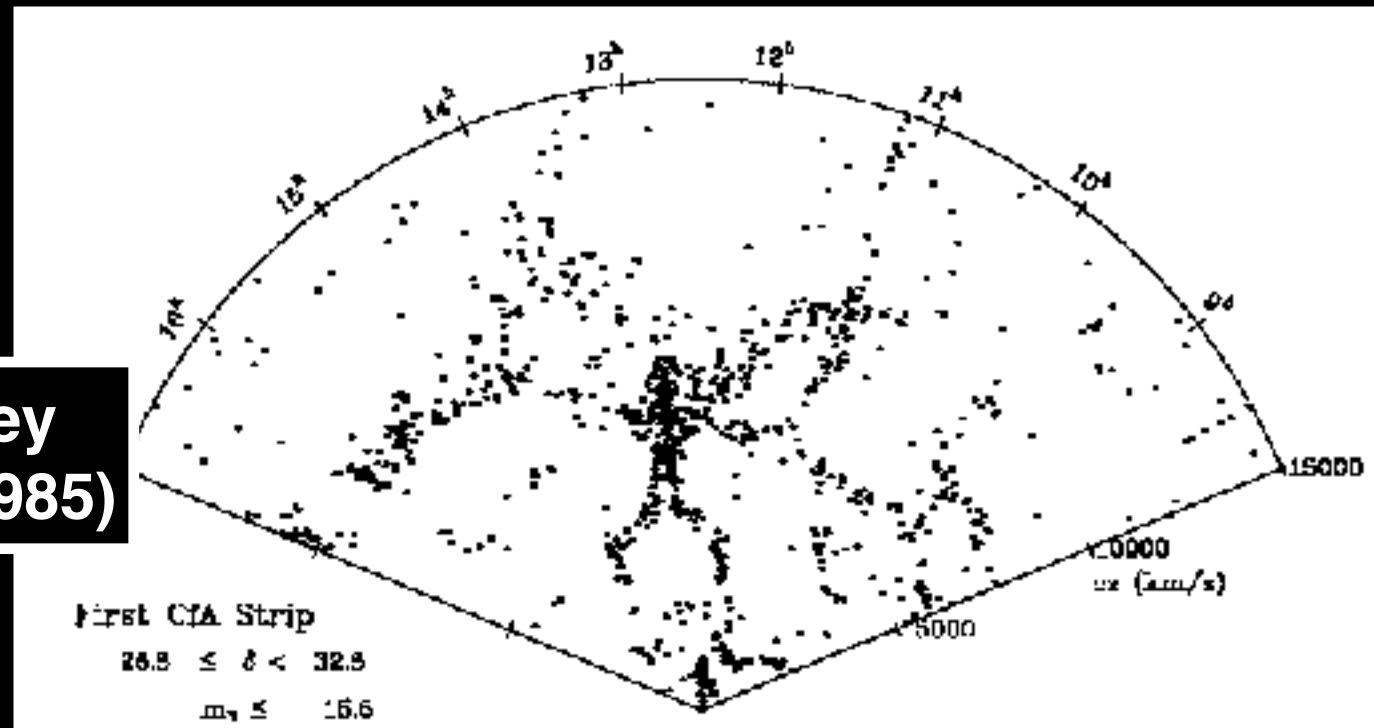
I'm Young(ish)!

I'm an Experimentalist!

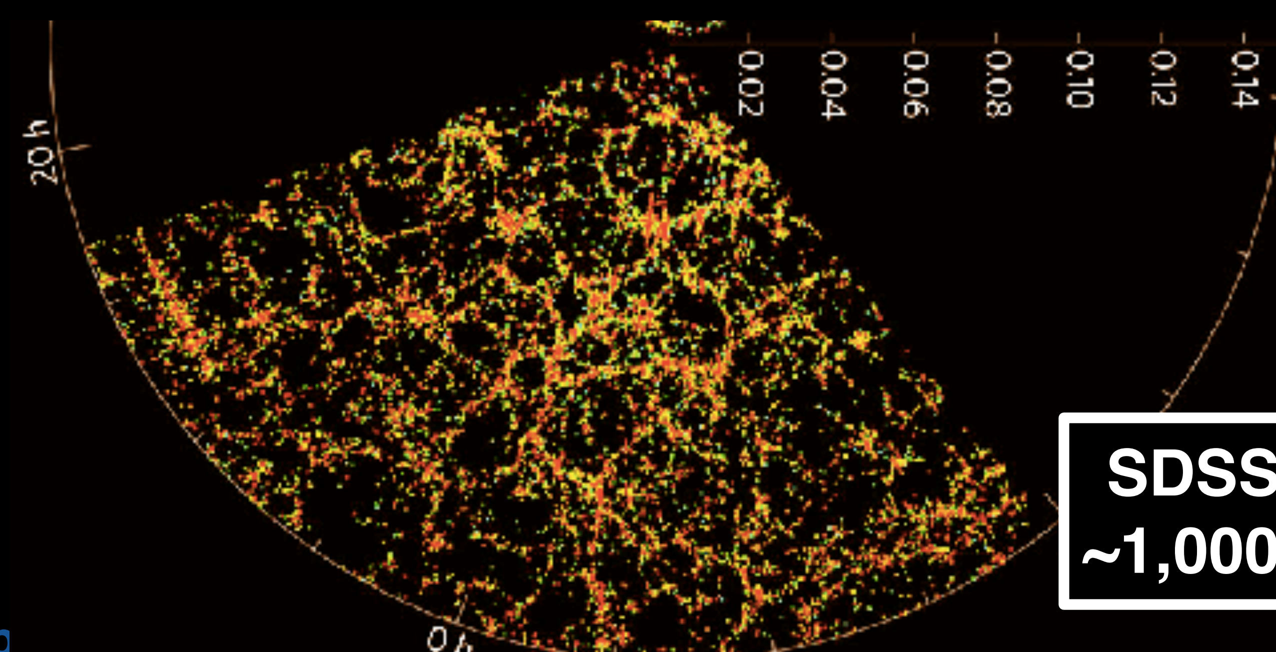
Alex Drlica-Wagner
David N. Schramm Fellow

A. Gonzales (c. 1980)

CfA Redshift Survey
~1000 Galaxies (c. 1985)



Over the last 50 years, thanks in large part to Fermilab, astrophysics and cosmology have gone from data starved to data rich.



SDSS DR7 Redshift Survey
~1,000,000 Galaxies (c. 2008)

Small Sample of Papers with >250 Citations

The Astronomical Journal, 120:1579–1587, 2000 September
© 2000. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE SLOAN DIGITAL SKY SURVEY: TECHNICAL SUMMARY

Donald G. York,[1] J. Adelman,[2] John E. Anderson, Jr.,[2] Scott F. Anderson,[3] James Annis,[2] Neta A. Bahcall,[4]

Selected for a Viewpoint in *Physics*
PRL **101,** 061101 (2008) PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2008

Observation of the Suppression of the Flux of Cosmic Rays above 4×10^{19} eV

J. Abraham,[1] P. Abreu,[2] M. Aglietta,[3] C. Aguirre,[4] D. Allard,[5] I. Allekotte,[6] J. Allen,[7] P. Allison,[8] J. Alvarez-Muñiz,[9]

ER

Particle dark matter: evidence, candidates and constraints

Gianfranco Bertone[a], Dan Hooper[b,*], Joseph Silk[b]

PHYSICAL REVIEW D VOLUME 55, NUMBER 12 15

Statistics of cosmic microwave background polarization

Marc Kamionkowski*
ia University, 538 West 120th Street, New York, New York 10027

Arthur Kosowsky†
Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138
Laboratory, Harvard University, Cambridge, Massachusetts 02138

Albert Stebbins‡
Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500

The Astronomical Journal, 137:4377–4399, 2009 May doi:10.1
© 2009. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

SEGUE: A SPECTROSCOPIC SURVEY OF 240,000 STARS WITH g = 14–20

Brian Yanny[1], Constance Rockosi[2], Heidi Jo Newberg[3], Gillian R. Knapp[4], Jennifer K. Adelm

---

Dark Energy and the Accelerating Universe

Joshua A. Frieman,[1,2] Michael S. Turner,[2] and Dragan Huterer[3]

The Astrophysical Journal, 633:560–574, 2005 November 10
© 2005. The American Astronomical Society. All rights reserved. Printed in U.S.A.

DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

Daniel J. Eisenstein,[1,2] Idit Zehavi,[1] David W. Hogg,[3] Roman Scoccimarro,[3] Michael R. Blanton,[3] Robert C. Nichol,[4]

Volume 65, Number 26 PHYSICAL REVIEW LETTERS 24 December 1990

Natural Inflation with Pseudo Nambu-Goldstone Bosons

Katherine Freese
Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Joshua A. Frieman and Angela V. Olinto
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510

Volume 72, Number 1 PHYSICAL REVIEW LETTERS 3 January 1994

Sterile Neutrinos as Dark Matter

Scott Dodelson[1,*] and Lawrence M. Widrow[2,†]
[1]*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60*

Selected for a Viewpoint in *Physics*
PRL **111,** 251301 (2013) PHYSICAL REVIEW LETTERS week ending 20 DECEMBER 2013

Silicon Detector Dark Matter Results from the Final Exposure of CDMS II

R. Agnese,[18] Z. Ahmed,[1] A. J. Anderson,[4] S. Arrenberg,[20] D. Balakishiyeva,[18] R. Basu Thakur,[2] D. A. Bauer,[2]

PHYSICAL REVIEW D **86,** 052001 (2012)

First dark matter search results from a 4-kg CF_3I bubble chamber operated in a deep underground site

E. Behnke,[1] J. Behnke,[1] S. J. Brice,[2] D. Broemmelsiek,[2] J. I. Collar,[3] A. Conner,[1] P. S. Cooper,[2] M. Crisler,[2,*] C. E. Dahl,[3] D. Fustin,[3] E. Grace,[1] J. Hall,[2] M. Hu,[2] I. Levine,[1] W. H. Lippincott,[2] T. Moan,[1] T. Nania,[1] E. Ramberg,[2] A. E. Robinson,[3]

Number 11 PHYSICAL REVIEW LETTERS 11 September 1995

Cosmology with Ultralight Pseudo Nambu-Goldstone Bosons

Joshua A. Frieman,[1,2] Christopher T. Hill,[3] Albert Stebbins,[1] and Ioav Waga[1,4]
[1]*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

Dark Matter Search Results from the CDMS II Experiment

The CDMS II Collaboration*†

ELSEVIER

The characterization of the gamma-ray signal from the central Milky Way: A case for annihilating dark matter

Tansu Daylan[a], Douglas P. Finkbeiner[a,b], Dan Hooper[c,d], Tim Linden[e,*], Stephen K.N. Portillo[b], Nicholas L. Rodd[f], Tracy R. Slatyer[f,g]

115, 231301 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

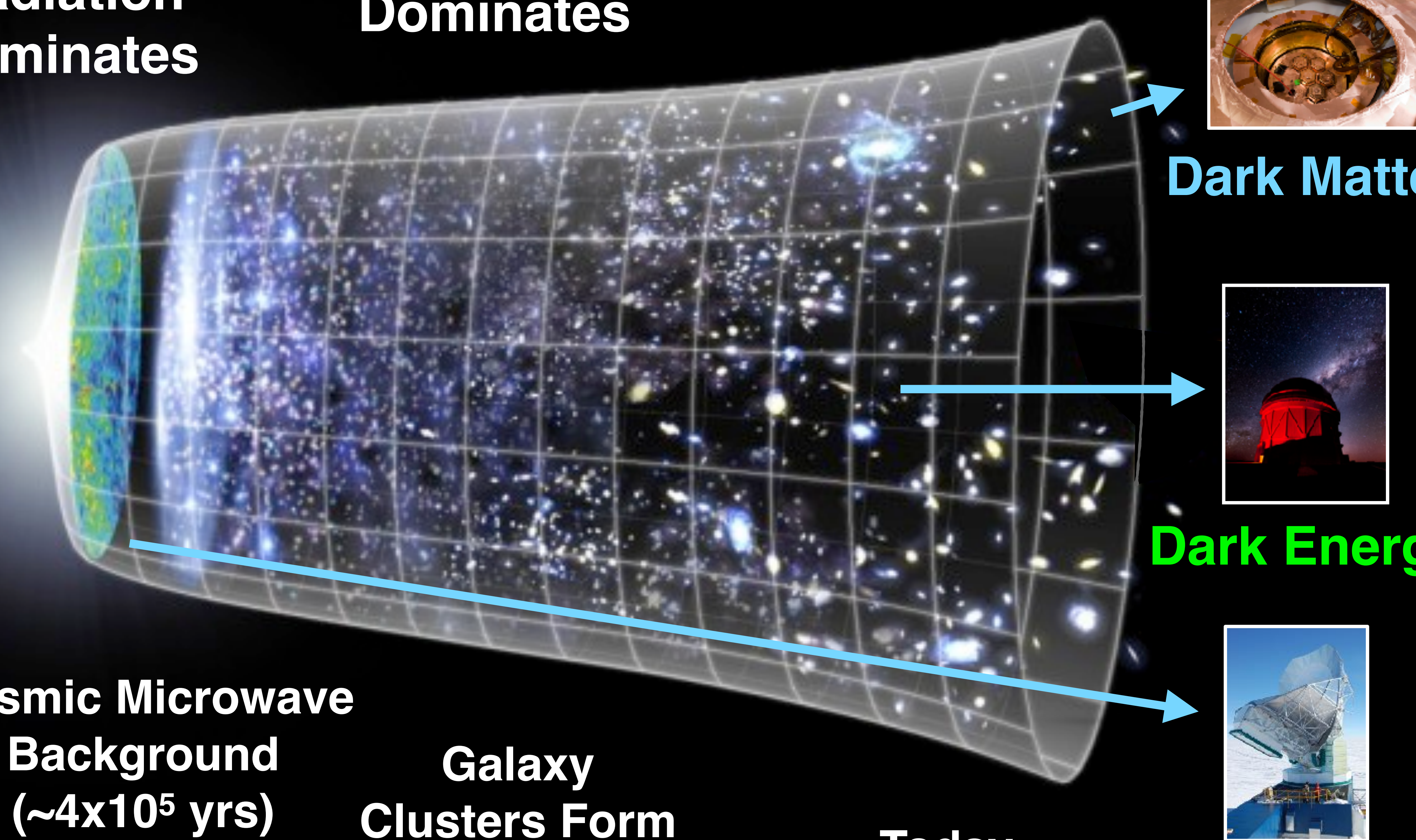
Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data

M. Ackermann,[1] A. Albert,[2] B. Anderson,[3,4,*] W. B. Atwood,[5] L. Baldini,[6,2] G. Barbiellini,[7,8] D. Bastieri,[9,10] K. Bechtol,[11]

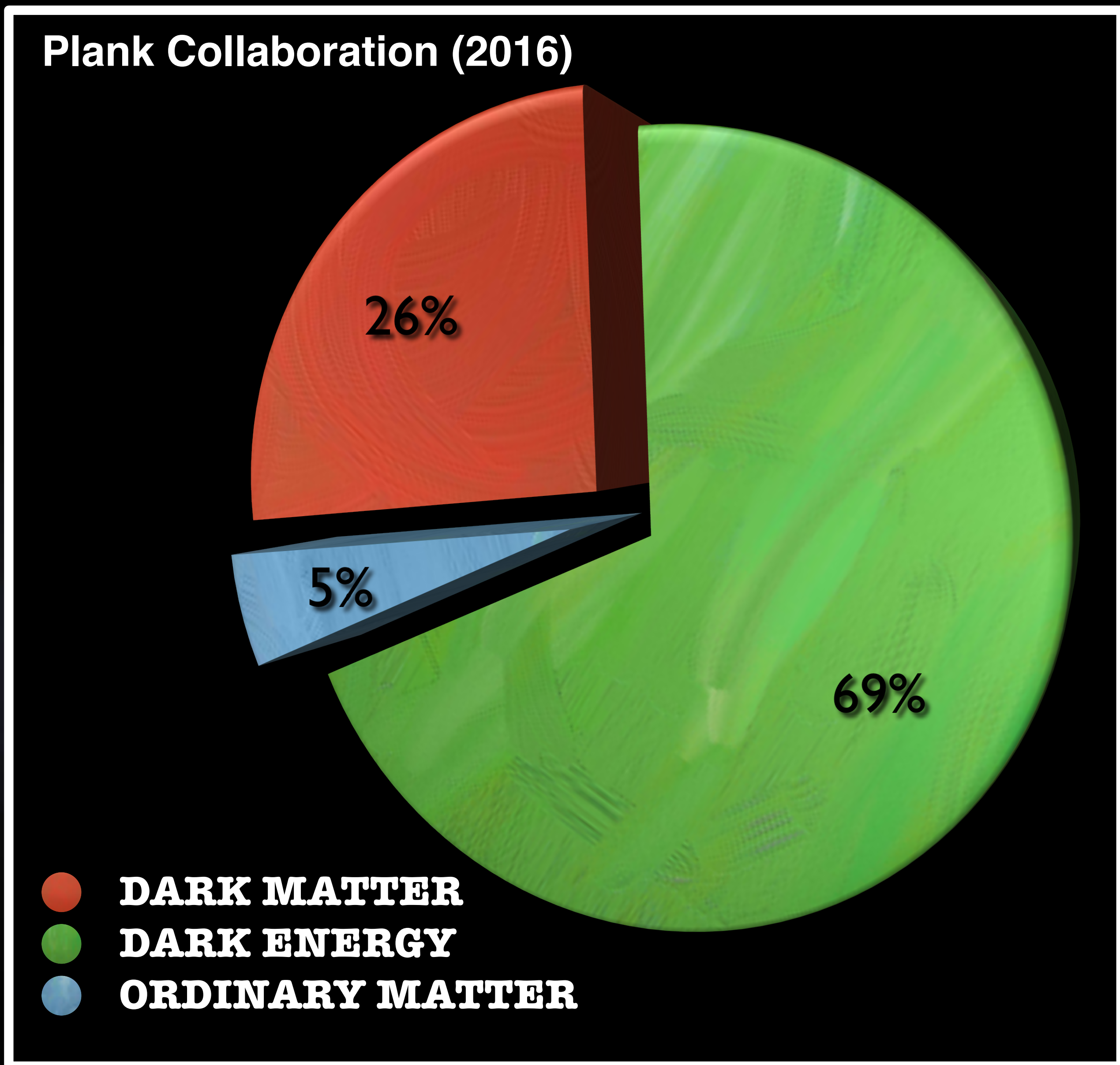
INNER SPACE OUTER SPACE
The Interface between Cosmology and Particle Physics
SDSS
MODERN COSMOLOGY
Scott Dodelson
COUPP
DES
SPT-3G
From Quarks to the Cosmos
Tools of Discovery
The Early Universe
Auger
GammeV
Darkside
Holometer
CDMS
DAMIC
1985
2015

DES
SuperCDMS
DESI
LSST
SSSI
?
SPT-3G
ADMX
LZ
SENSEI
CMB-S4
?
G3-DM
?
2015
2030

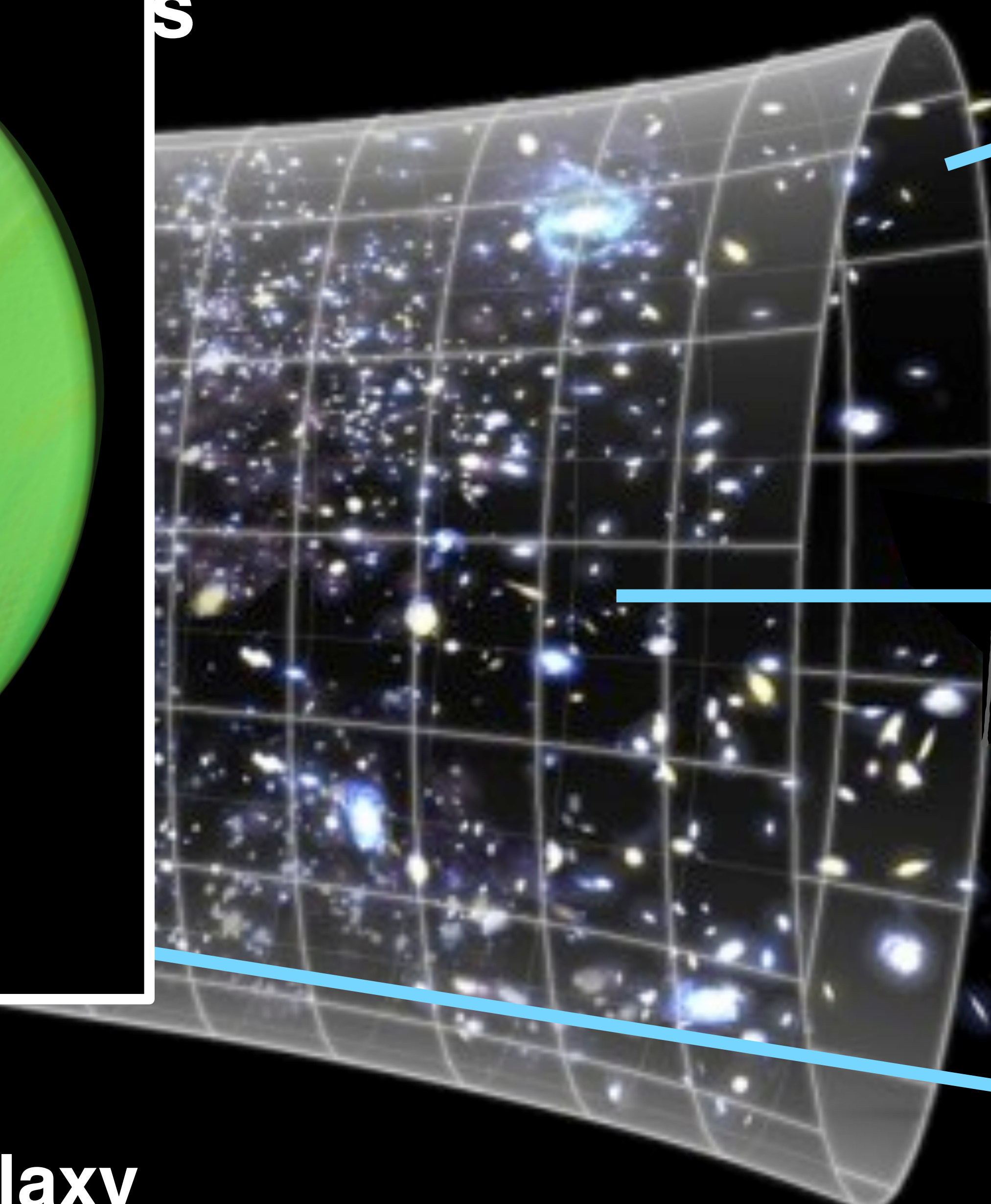
Standard Cosmological Model



Standard Cosmological Model

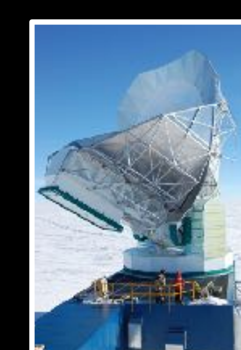


Dark Energy
Dominates



Dark Matter

Dark Energy



CMB/Inflation

Cosmic Microwave
Background
(~4x10^5 yrs)

Galaxy
Clusters Form
(~4x10^9 yrs)

Today
(13.8x10^9 yrs)

The Big Questions

- **Dark Matter** - What makes up the dominant gravitational influence in the Universe?
- **Dark Energy** - What powers the accelerated expansion of the Universe?
- **Inflation/CMB** - What is the mechanism for the initial rapid expansion of the Universe?

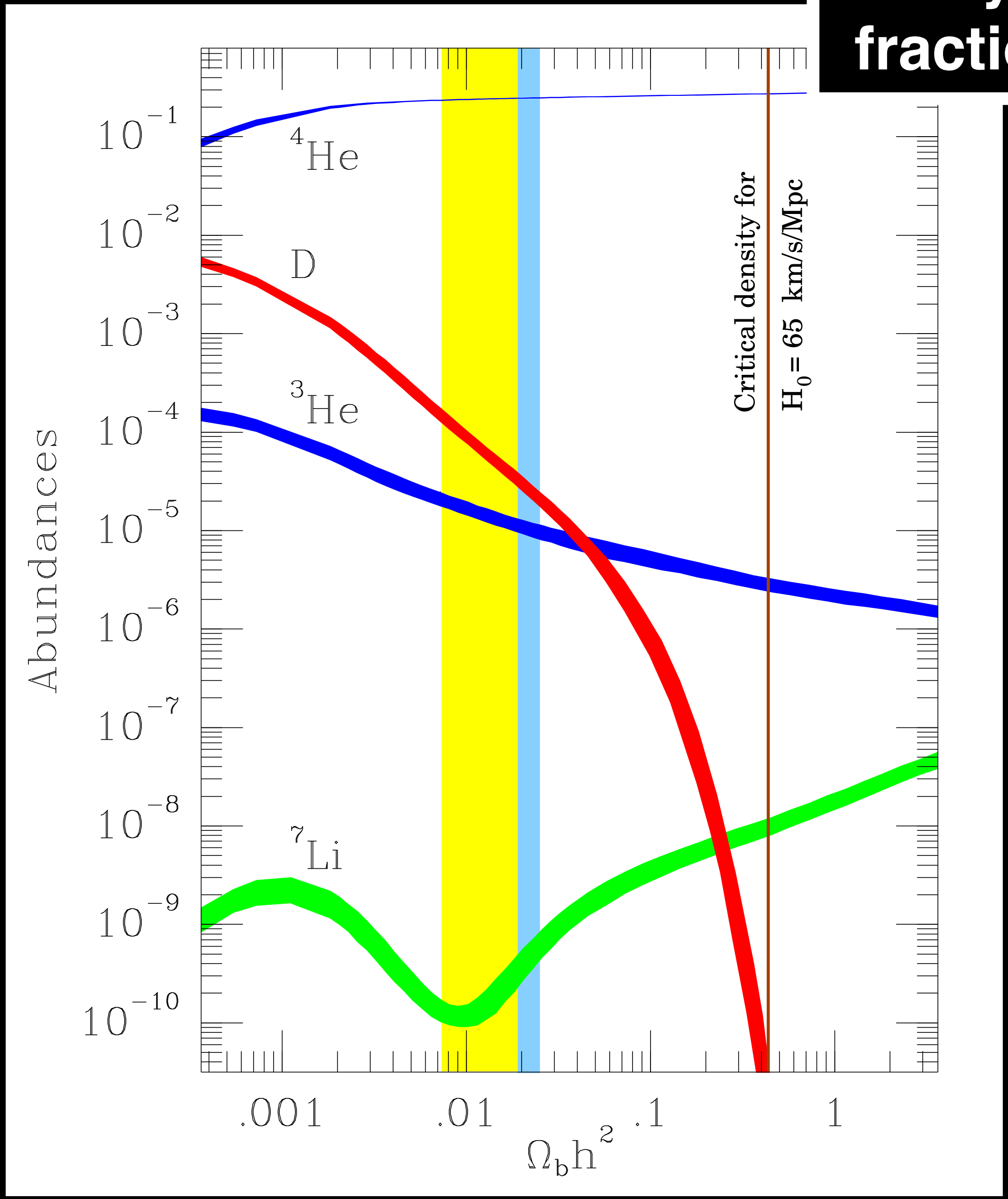
The Big Questions

- **Dark Matter** - What makes up the dominant gravitational influence in the Universe?

- **Dark Energy** - What powers the accelerated expansion of the Universe?

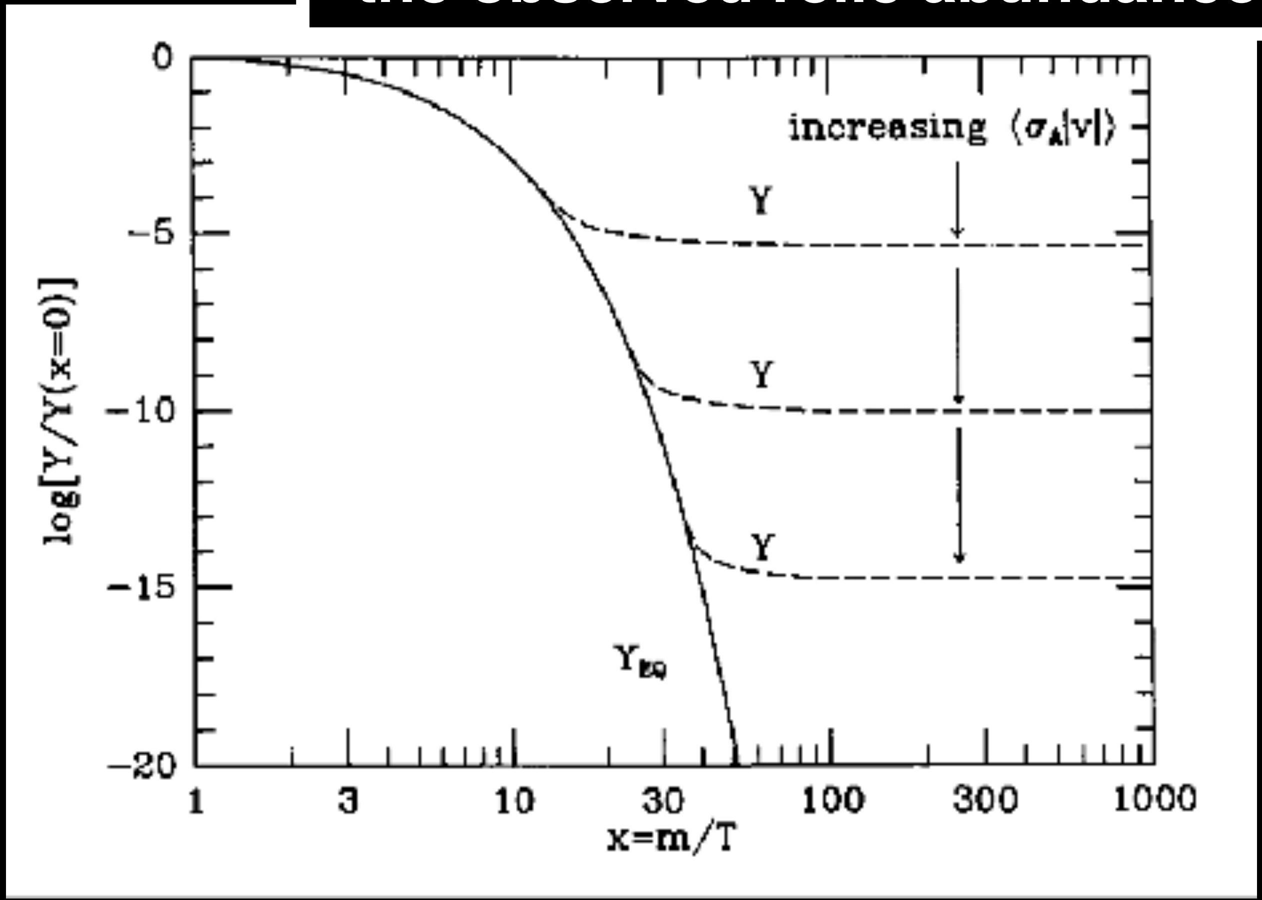
- **Inflation/CMB** - What is the mechanism for the initial rapid expansion of the Universe?

Non-Baryonic Dark Matter



Baryons make up only a fraction of the total matter

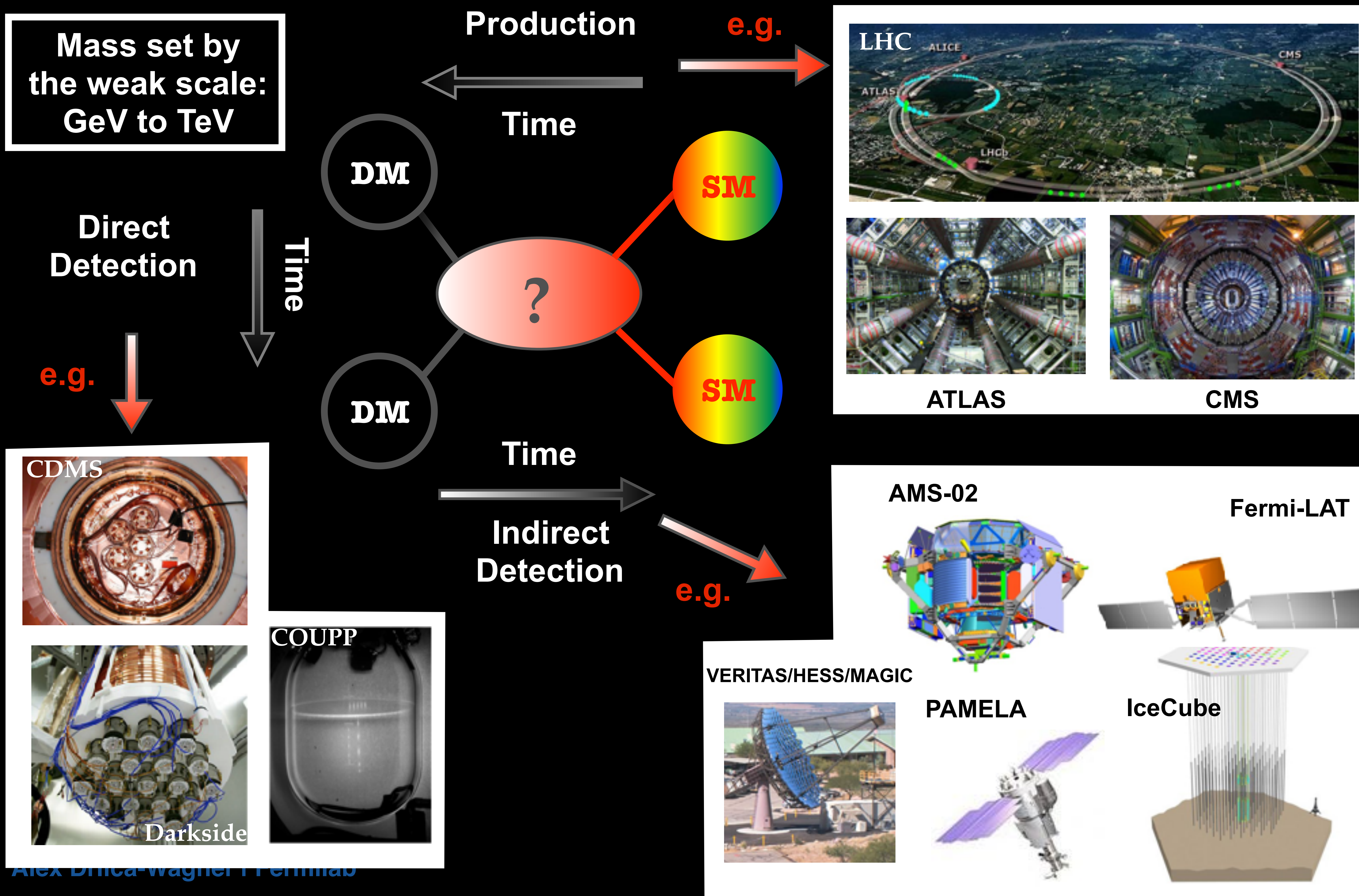
A weak cross section matches the observed relic abundance



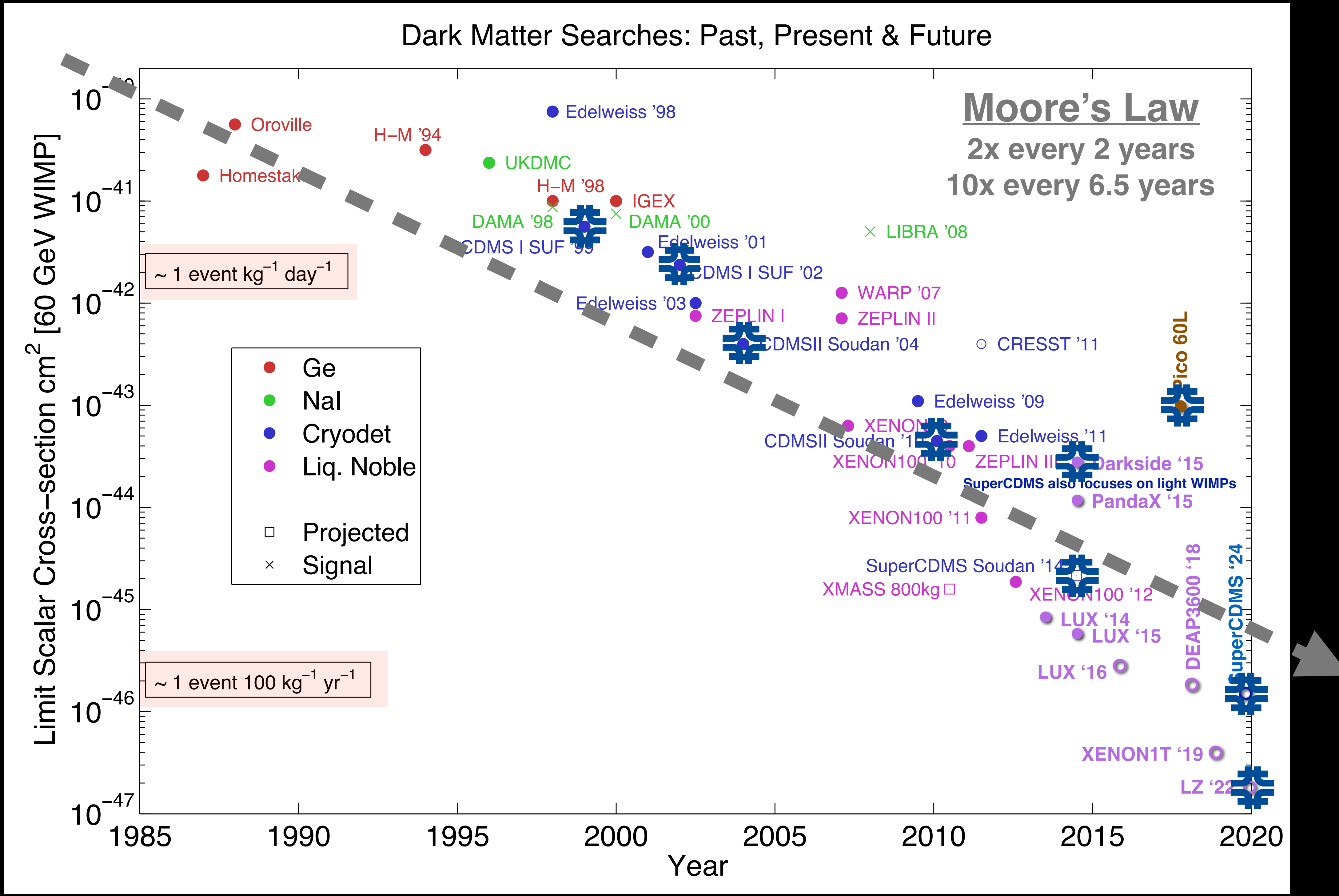
Schramm & Turner (1997)

Kolb & Turner (1990)

The Hunt for WIMPs

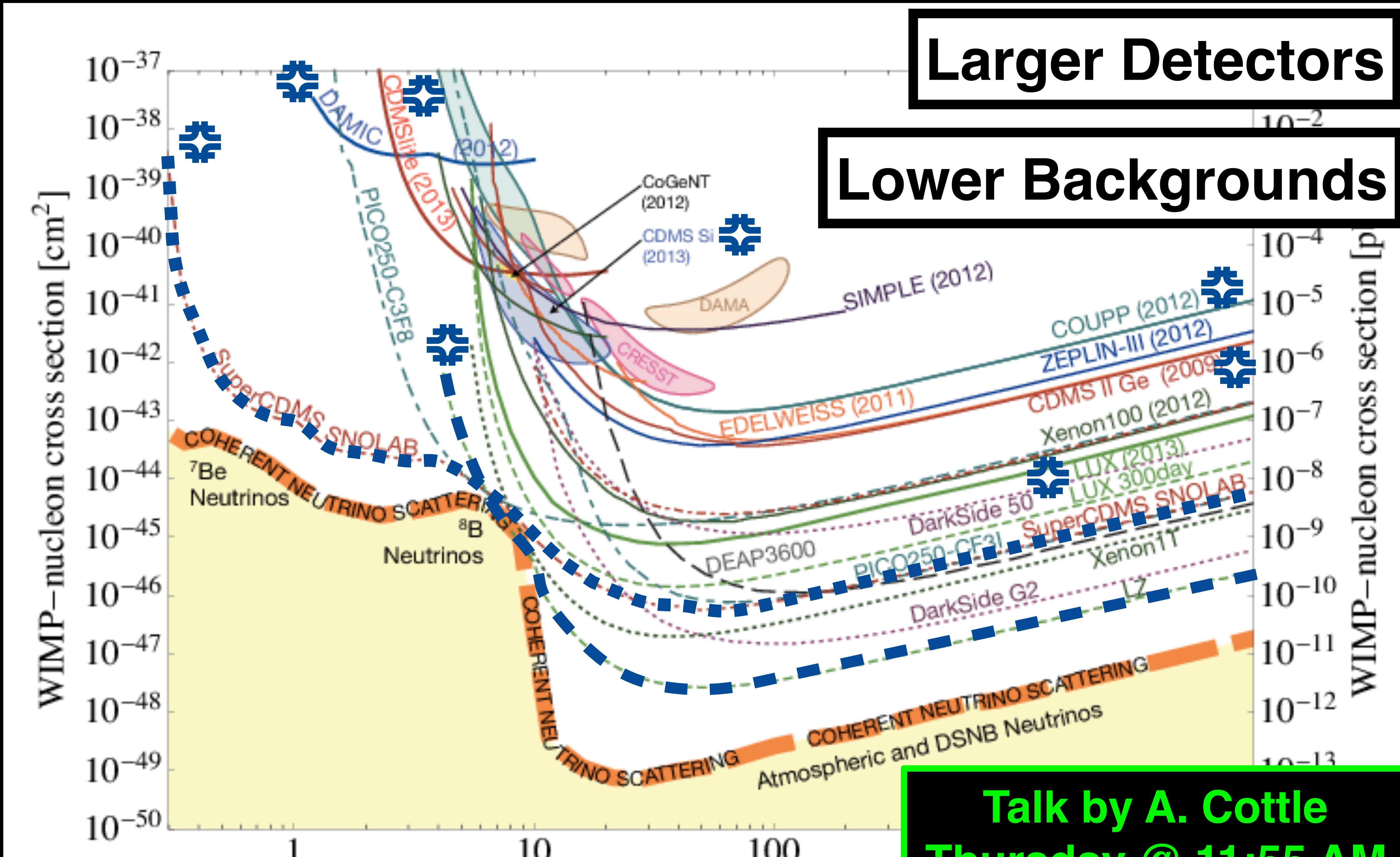


Moore's Law for Direct Detection



Modified from R. Gaitskill

The Landscape of Direct Detection

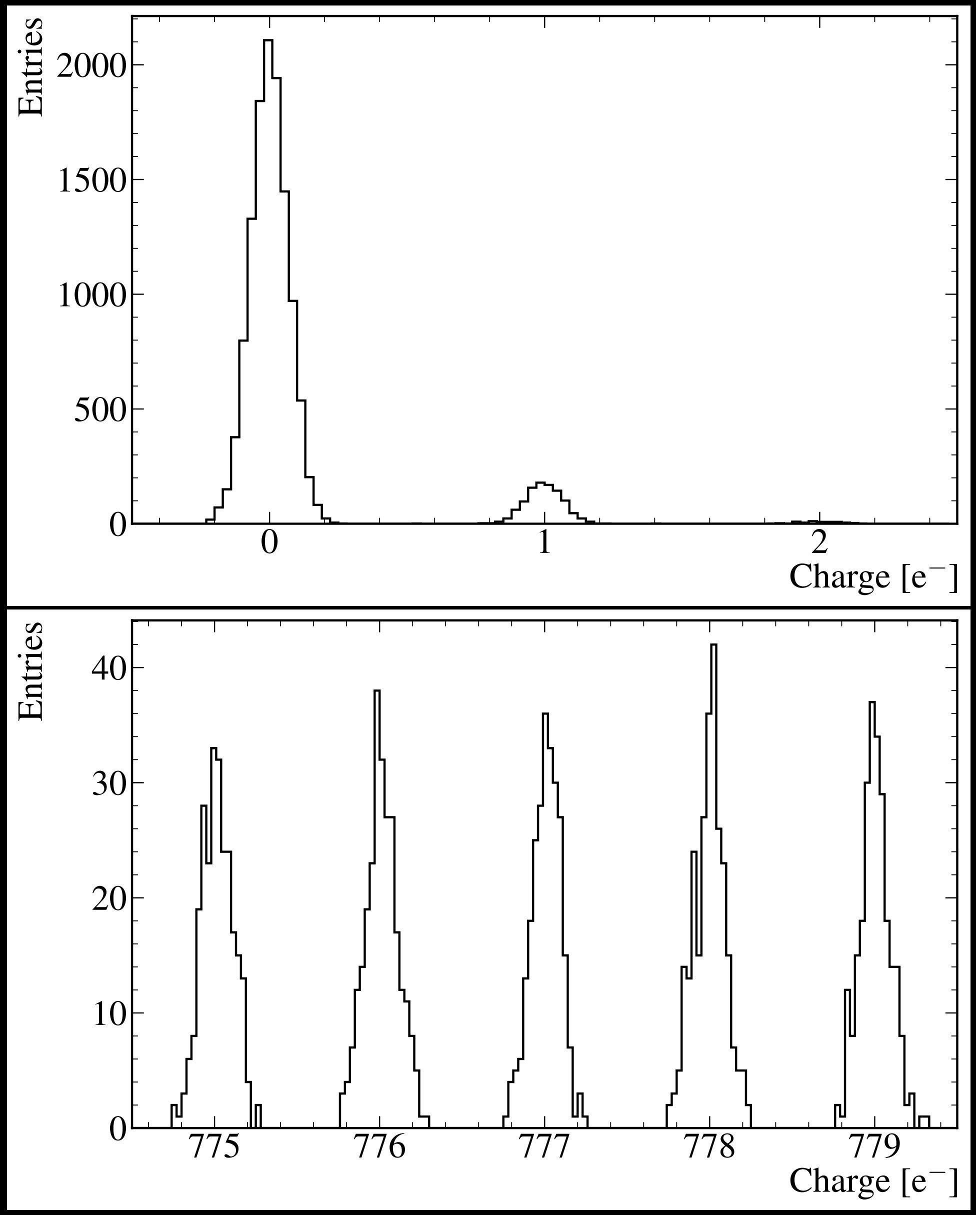


Billard et al. (2014)
Cooley (2014)

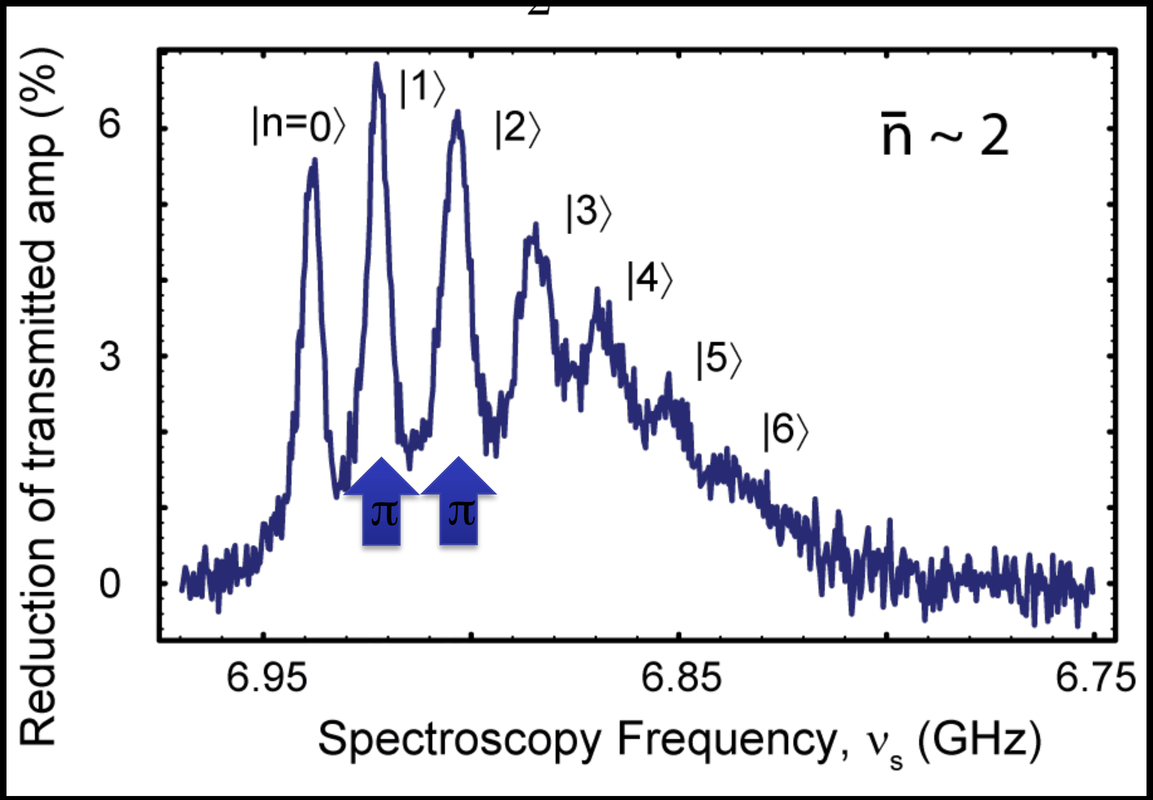
Quantum Detectors

Dark Matter and dark photon searches with single electron counting with CCDs

Axion Searches using single microwave photon detection with qubits



Tiffenberg et al. (2017)



Schuster et al. (2007)

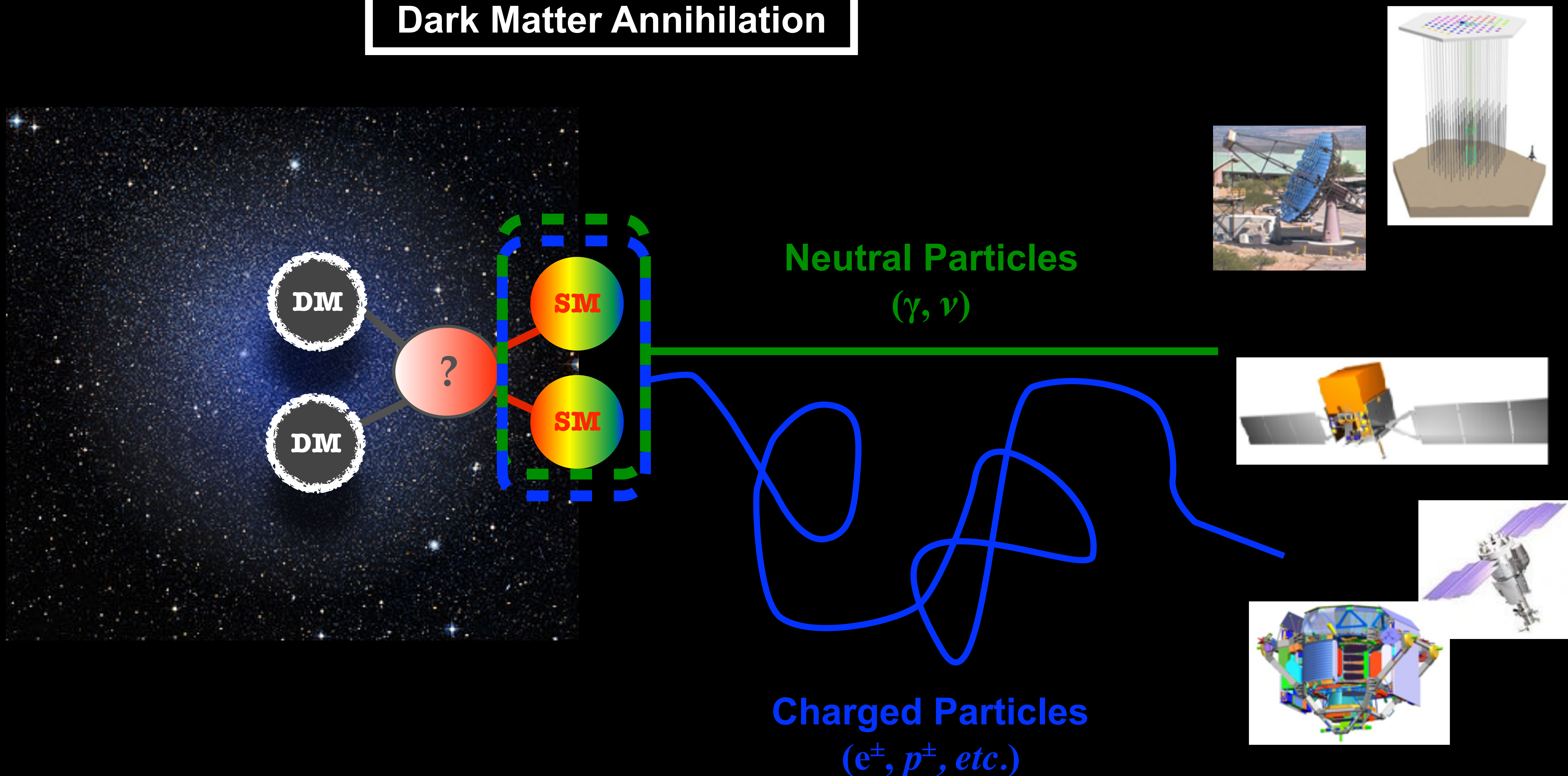
Indirect Detection

Dark Matter Distribution

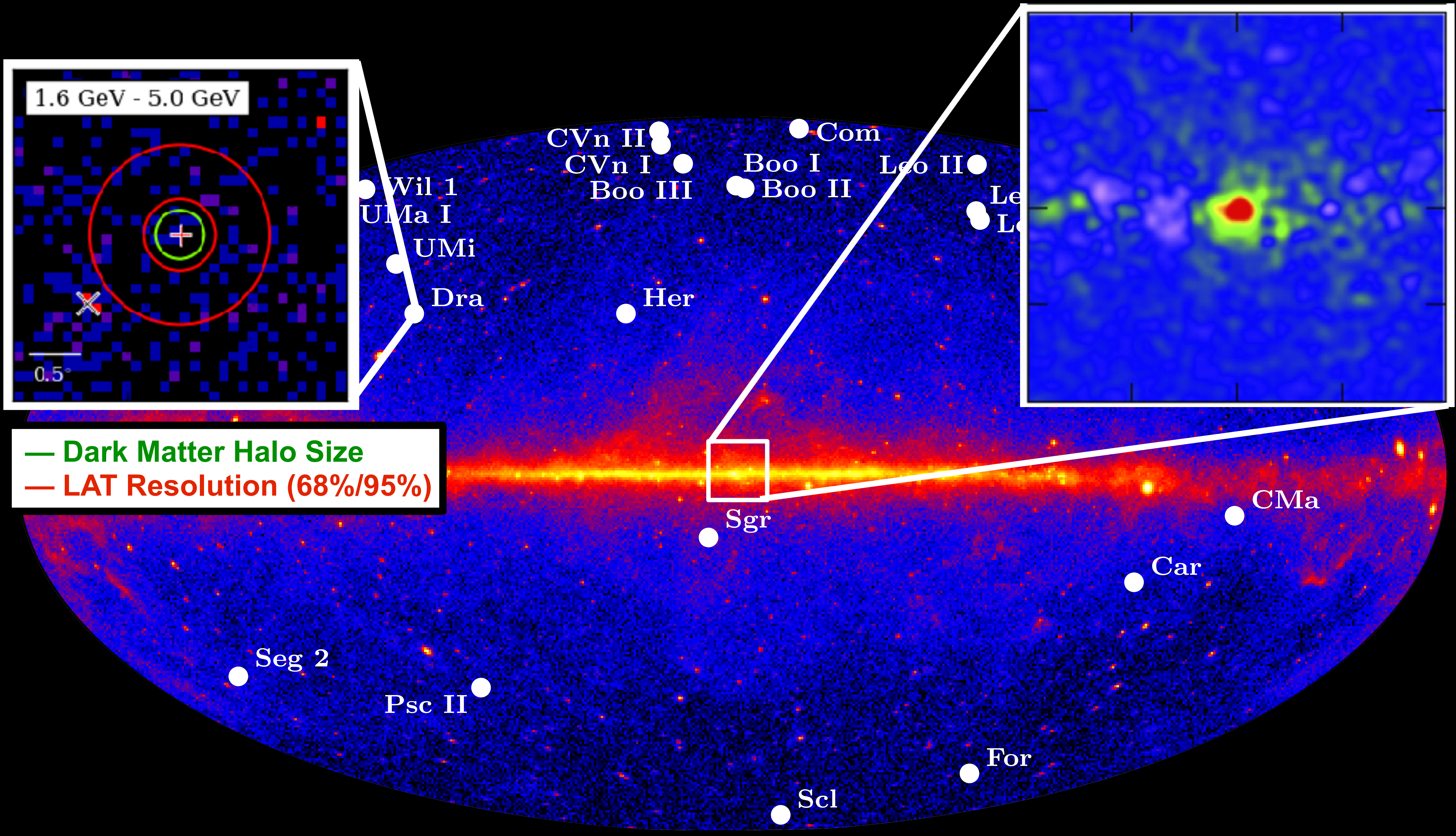
Particle Propagation

Particle Detection

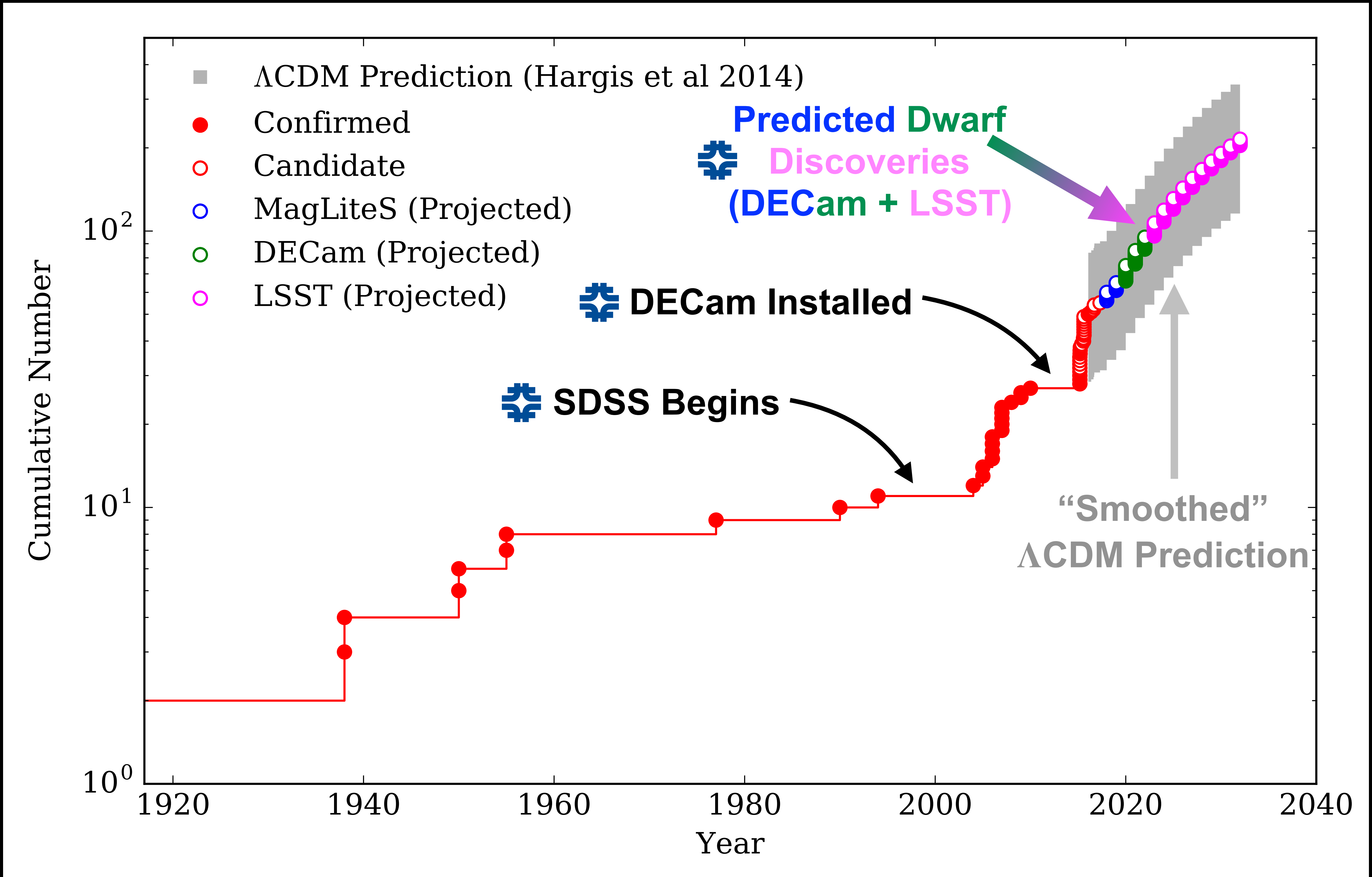
Dark Matter Annihilation



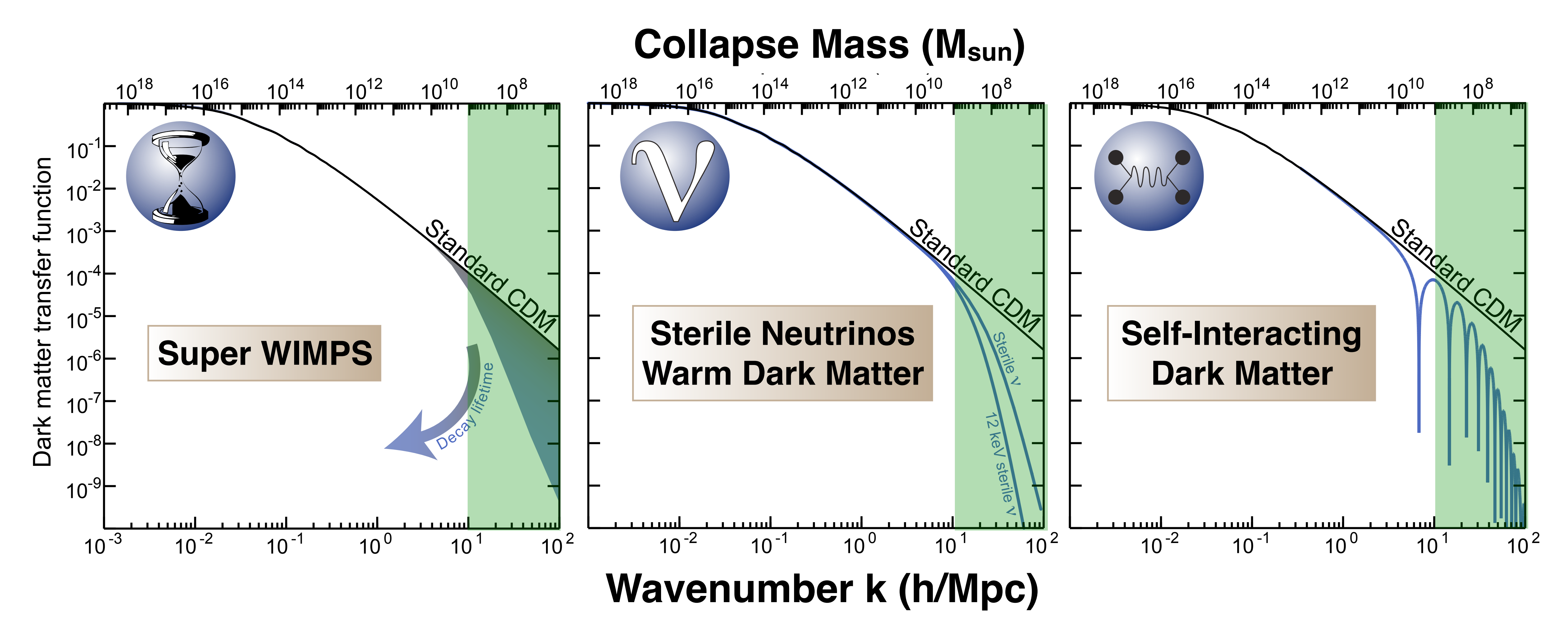
Dark Matter Particle Annihilation



More Dwarf Galaxies!



Astrophysical Probes



Deviations from Cold Dark Matter would be detected in the abundance of the smallest structures.

Image Credit: Massey & Moustakas

The Big Questions

- **Dark Matter** - What makes up the dominant gravitational influence in the Universe?
- **Dark Energy** - What powers the accelerated expansion of the Universe?
- **Inflation/CMB** - What is the mechanism for the initial rapid expansion of the Universe?

Rocky & Mike's Prediction from "The Early Universe" (c.1993)

abandoning $\Omega_0 = 1$ or invoking a cosmological constant, both, equally unpalatable to us. Therefore, we remain steadfast in our prediction that the Hubble constant is $50 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.[10]

Rocky & Mike's Prediction from "The Early Universe" (c.1993)

abandoning $\Omega_0 = 1$ or invoking a cosmological constant, both, equally unpalatable to us. Therefore, we remain steadfast in our prediction that the Hubble constant is $50 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.[10]

[10]We acknowledge a generous contribution to the Chicago Cosmologists' Retirement Fund from Allan Sandage.

Rocky & Mike's Prediction from "The Early Universe" (c.1993)

abandoning $\Omega_0 = 1$ or invoking a cosmological constant, both, equally unpalatable to us. Therefore, we remain steadfast in our prediction that the Hubble constant is $50 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.[10]

[10]We acknowledge a generous contribution to the Chicago Cosmologists' Retirement Fund from Allan Sandage.

discovery to change cosmology. We would be most surprised if the future did not include a revolutionary idea or unexpected discovery. In fact, our biggest disappointment would be if, ten years from now, we did not have to write another book.

Rocky & Mike's Prediction from "The Early Universe" (c.1993)

abandoning $\Omega_0 = 1$ or invoking a cosmological constant, both, equally unpalatable to us. Therefore, we remain steadfast in our prediction that the Hubble constant is $50 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.[10]

[10] We acknowledge a generous contribution to the Chicago Cosmologists' Retirement Fund from Allan Sandage.

discovery to change cosmology. We would be most surprised if the future did not include a revolutionary idea or unexpected discovery. In fact, our biggest disappointment would be if, ten years from now, we did not have to write another book.

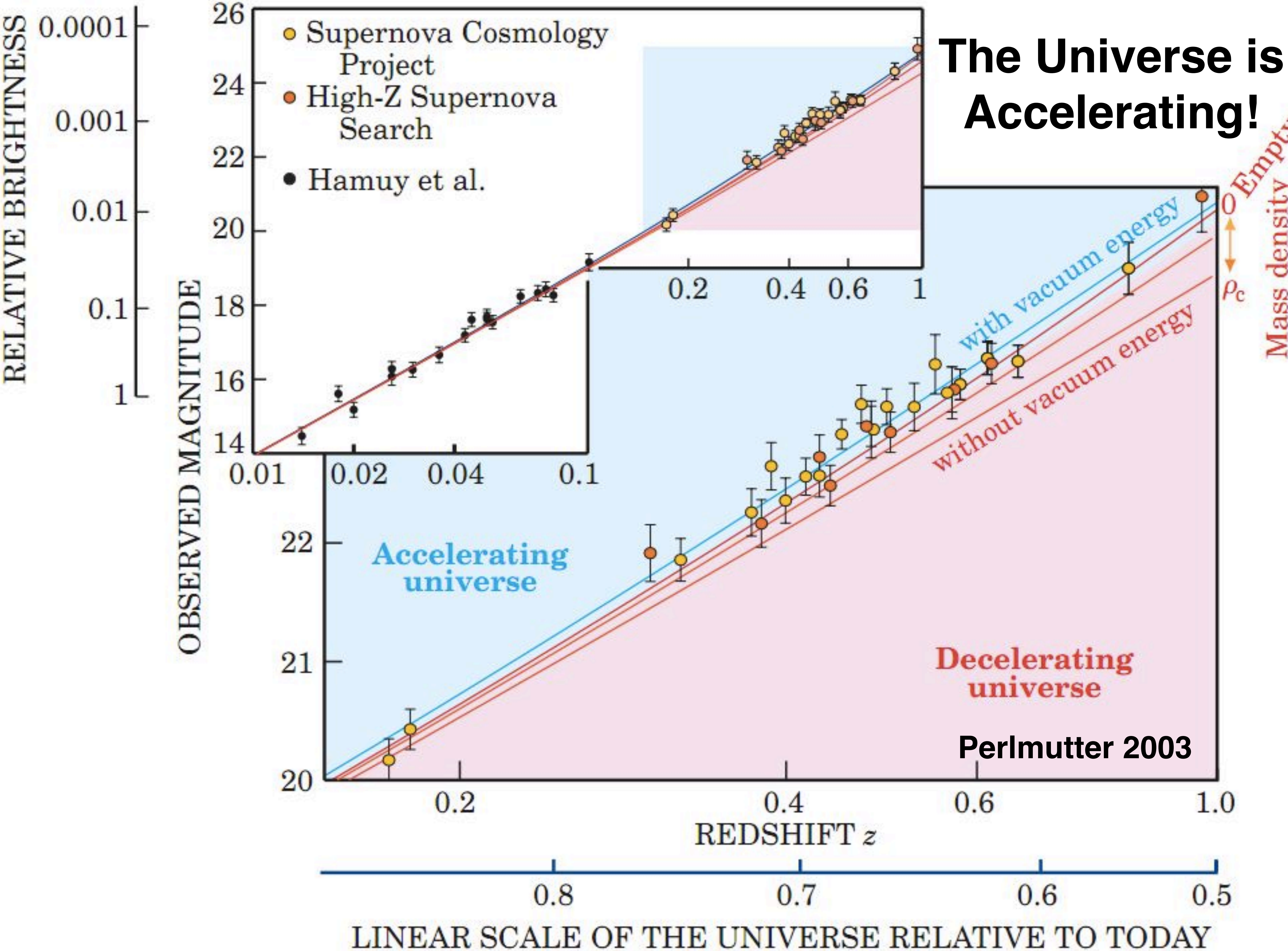
As the camera-ready book goes to press, it is completly free of any typographical errors, errors of physics, or errors of judgment. Any errors present in the final product must have crept in during the production process, and are wholly the fault of the publisher.

Rocky and Mike

Warrenville & Hinsdale, Illinois

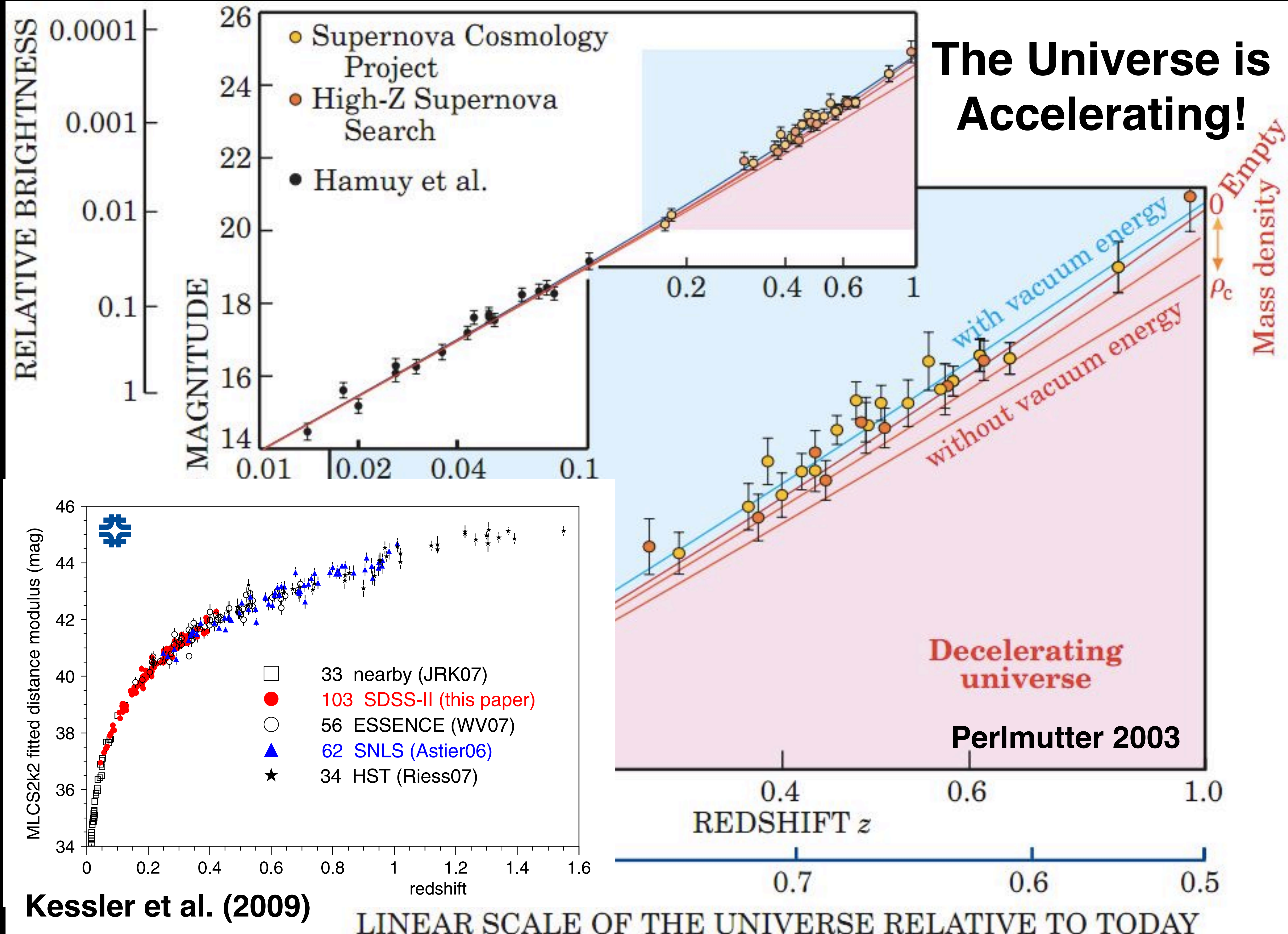
September, 1993

The Universe is Accelerating!



Perlmutter 2003

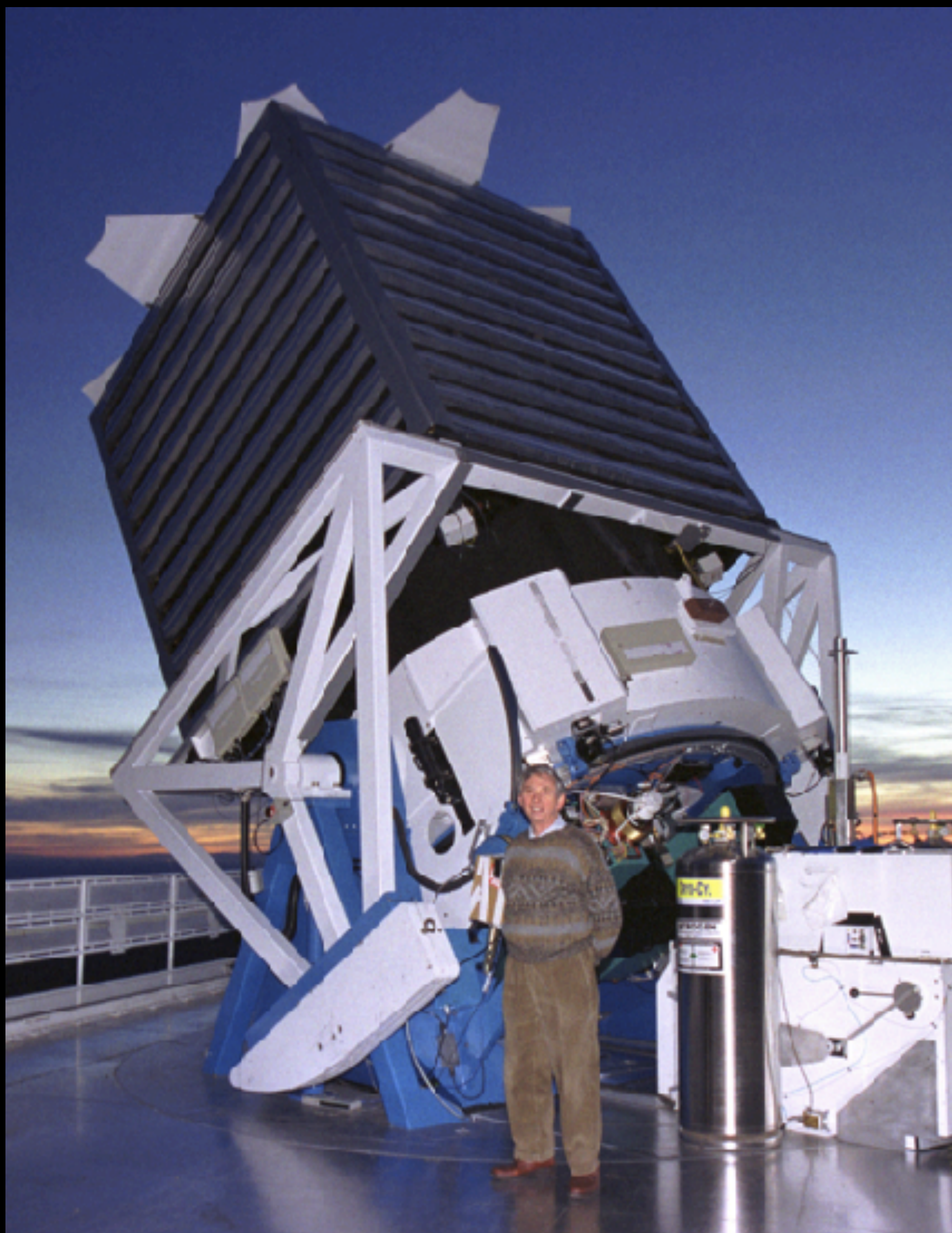
The Universe is Accelerating!



Perlmutter 2003

Kessler et al. (2009)

Sloan Digital Sky Survey



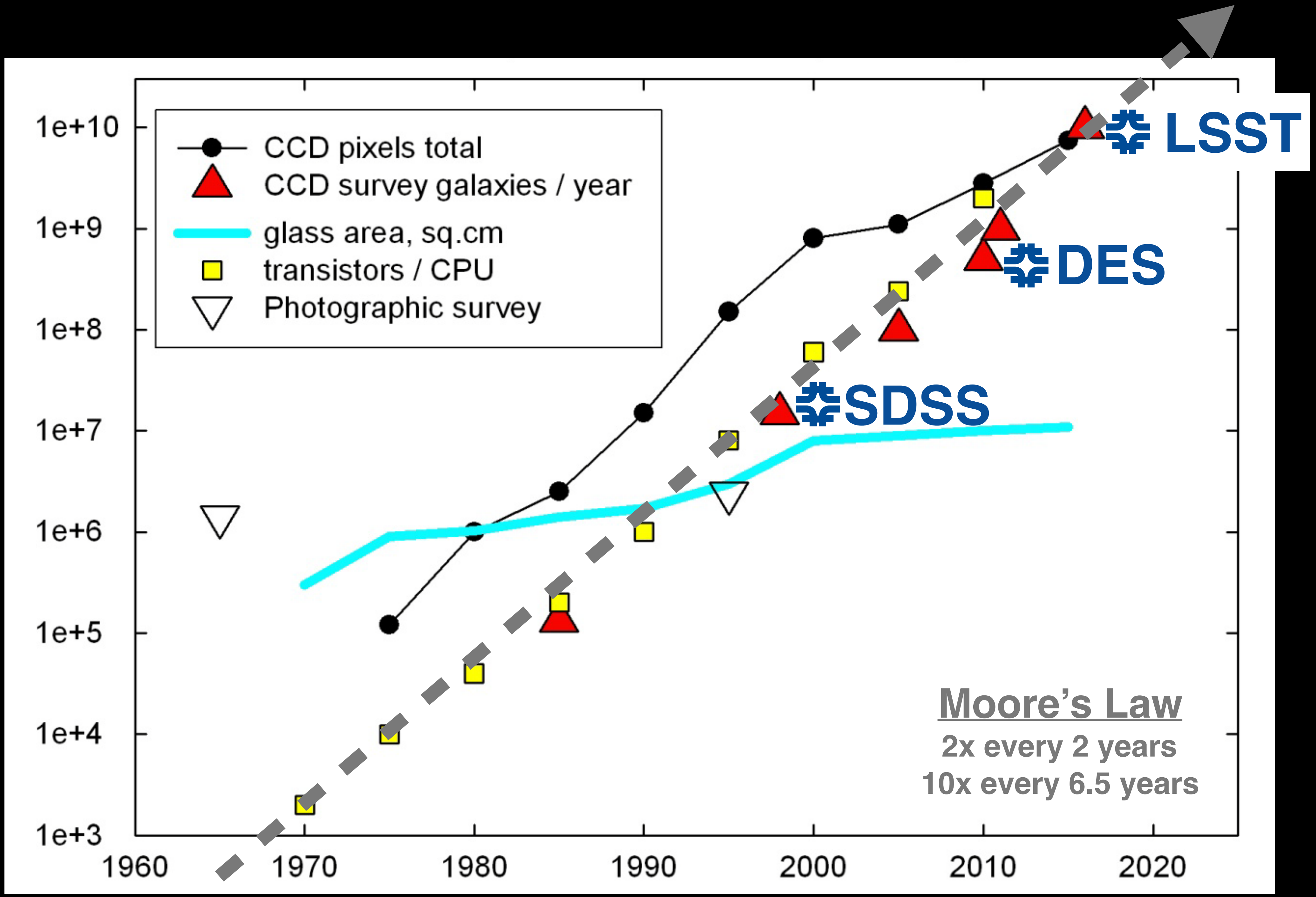
High-Impact Astronomical Observatories

Juan P. Madrid[1] and F. Duccio Macchetto[2]
[1] *McMaster University, Hamilton, Canada*
[2] *Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218*

TABLE 1
HIGH-IMPACT OBSERVATORIES

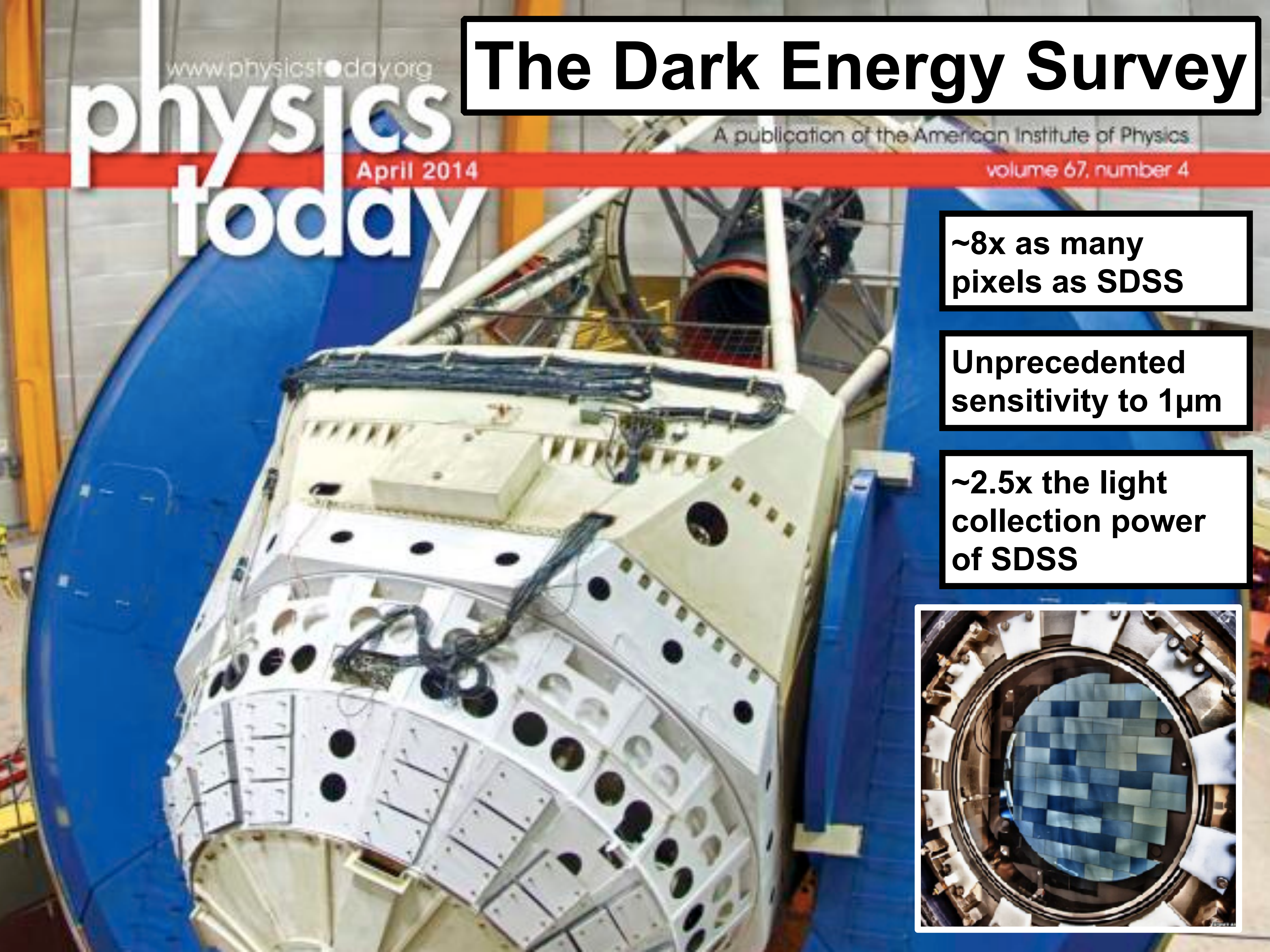
Rank	Facility	Citations	Participation
1	SDSS	1892	14.3%
2	Swift	1523	11.5%
3	HST	1078	8.2%
4	ESO	813	6.1%
5	Keck	572	4.3%
6	CFHT	521	3.9%
7	Spitzer	469	3.5%
8	Chandra	381	2.9%
9	Boomerang	376	2.8%
10	HESS	297	2.2%

Moore’s Law for Surveys



Tyson 2010

The Dark Energy Survey

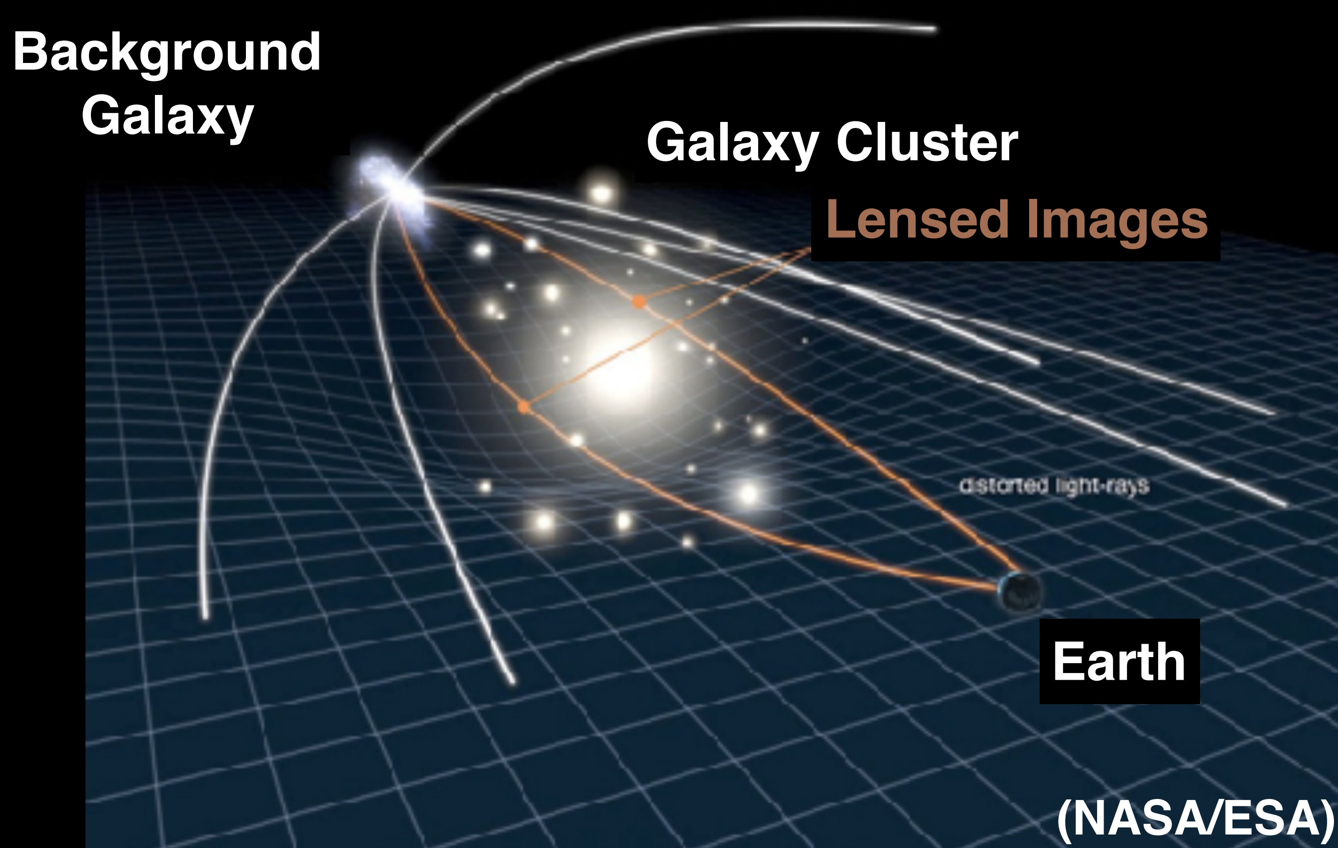


~8x as many pixels as SDSS

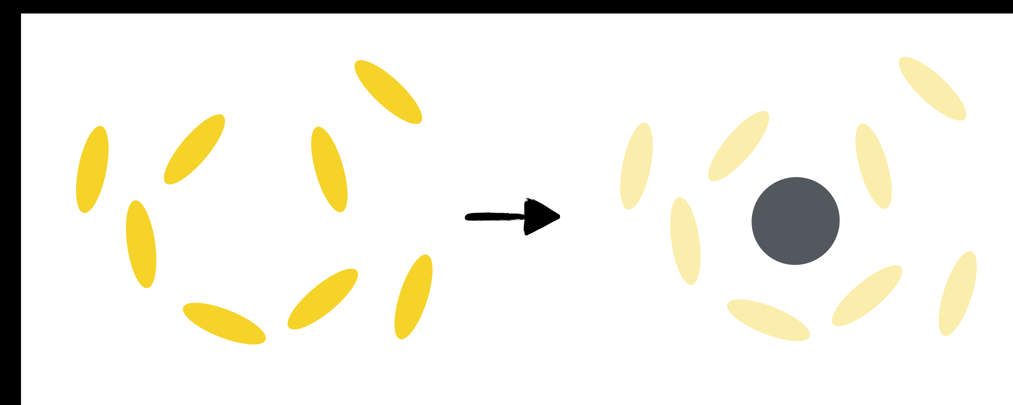
Unprecedented sensitivity to 1μm

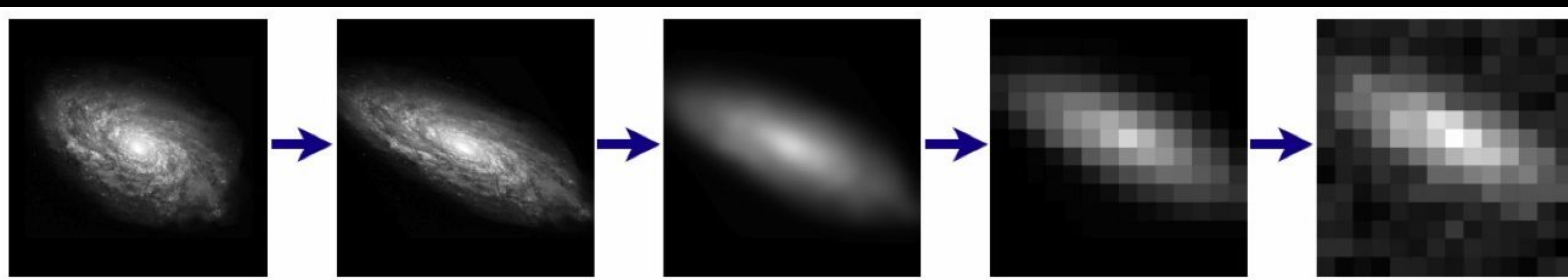
~2.5x the light collection power of SDSS

Dark Energy Survey: A Weak Lensing Machine!



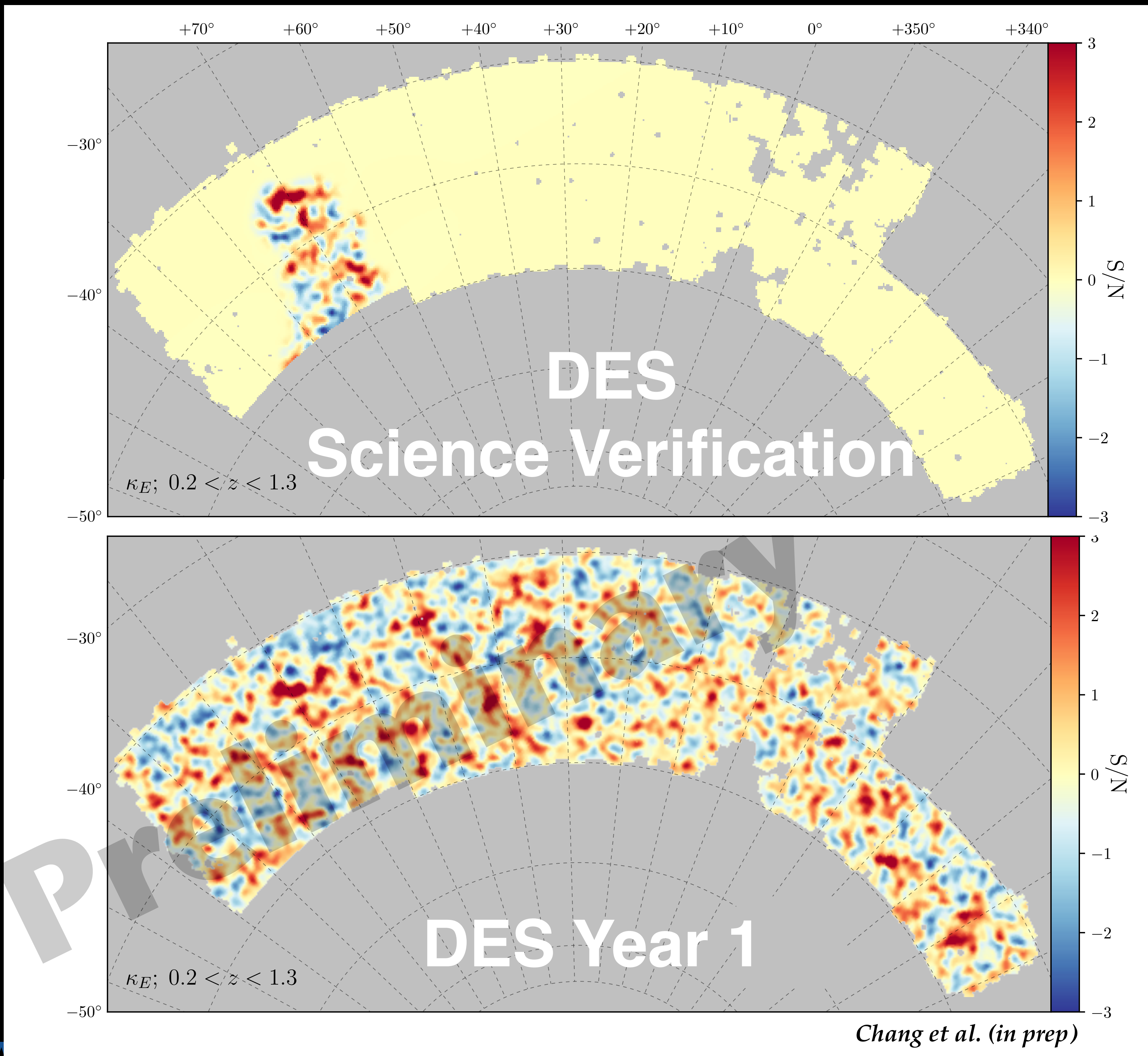
Lensing measures mass directly!





Intrinsic galaxy (shape unknown) → Gravitaional lensing causes a ***shear (g)*** → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise

Wide-Field Mass Map



Largest map of *mass* (independent of light)

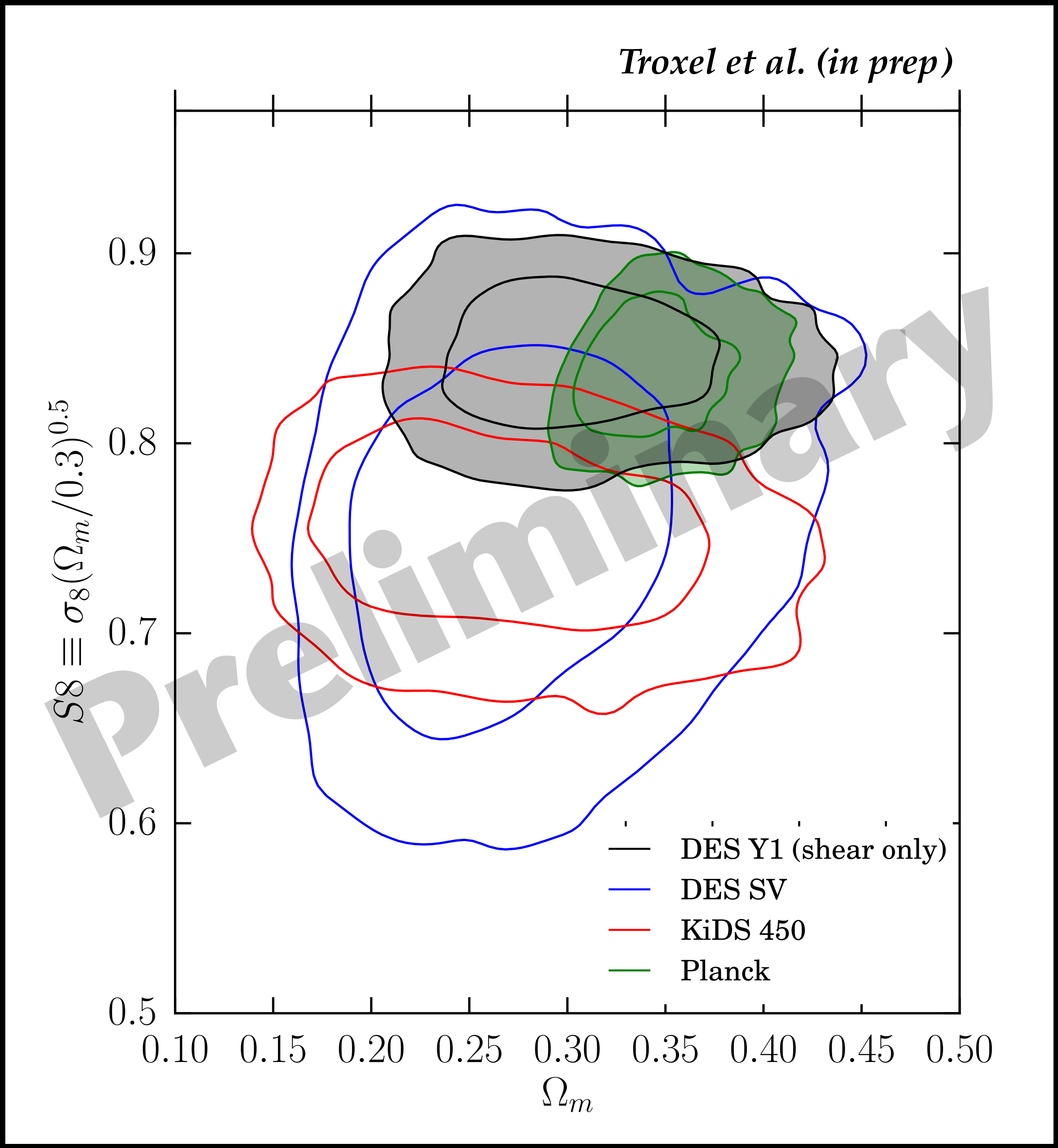
10x area of DES SV

4x area of KIDS predecessor

Only 2/5th of the total DES area and depth!

Talk by C. Chang Thursday @ 4:05PM

Weak Lensing Constraints



Results are still blinded!
(Contour center may shift)

Systematics uncertainties reduced to the level required by the *next-generation* of surveys

Within striking distance of Planck (contours ~2x larger)

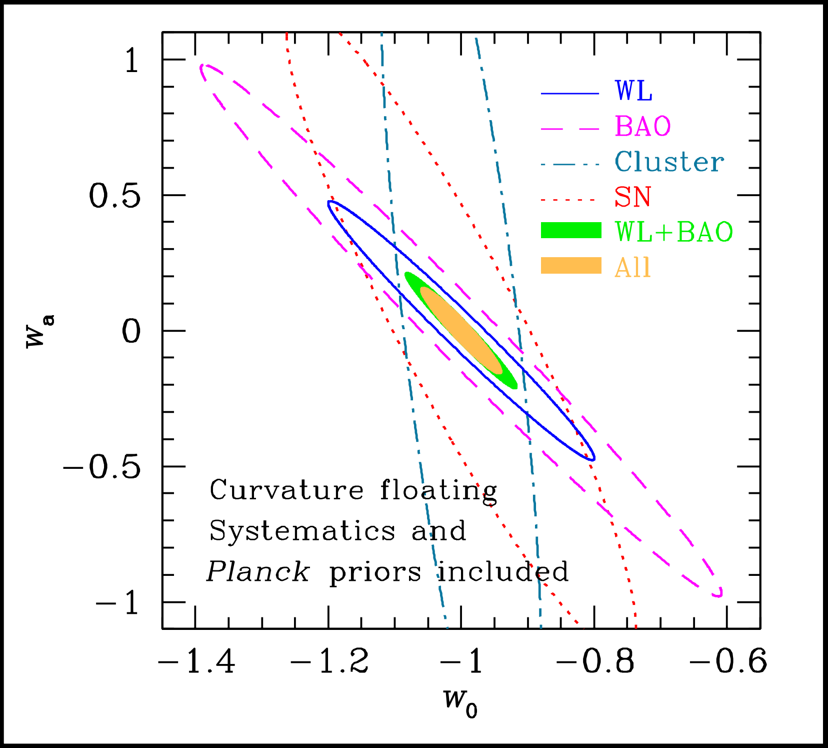
DES is transforming weak lensing into a tool for precision cosmology

LSST Coming!

Full DES depth in 15s; entire visible sky every 3 nights

7x10[12] detections of 3x10[9] unique objects; Nearly an Exabyte of data!

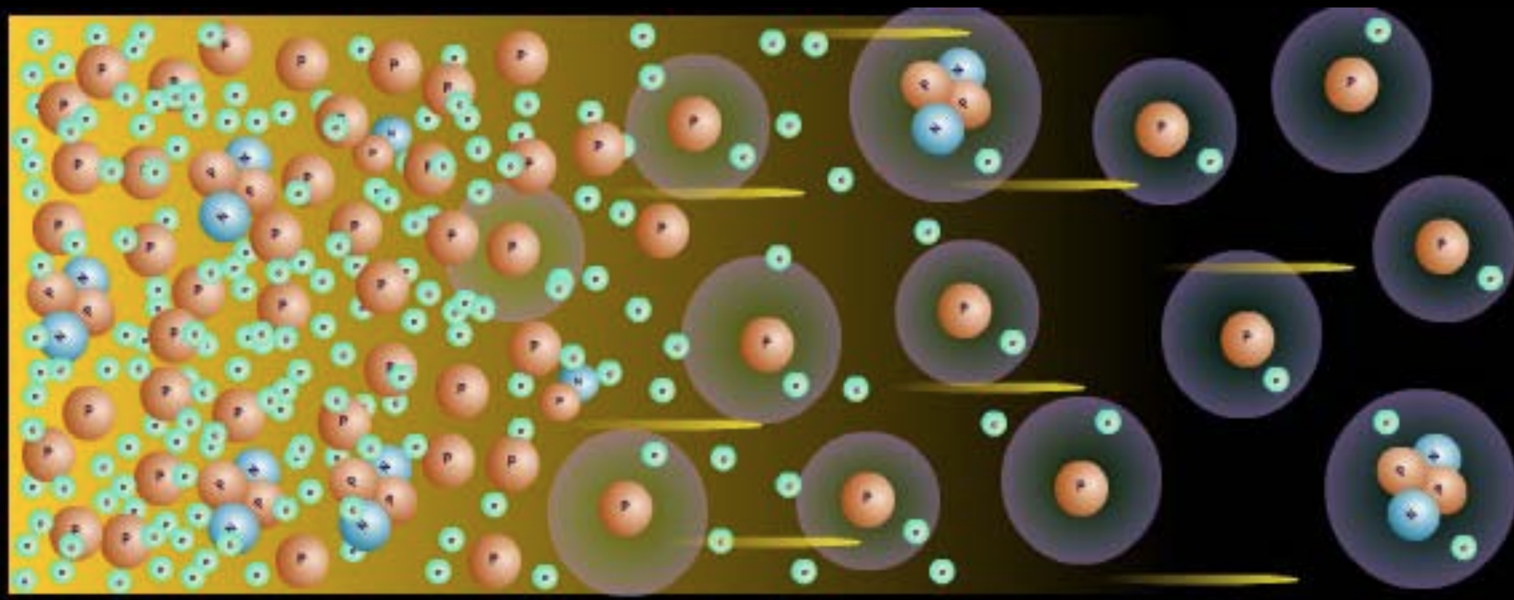
~10x more sensitive than DES to the dark energy equation of state.



The Big Questions

- **Dark Matter** - What makes up the dominant gravitational influence in the Universe?
- **Dark Energy** - What powers the accelerated expansion of the Universe?
- **Inflation/CMB** - What is the mechanism for the initial rapid expansion of the Universe?

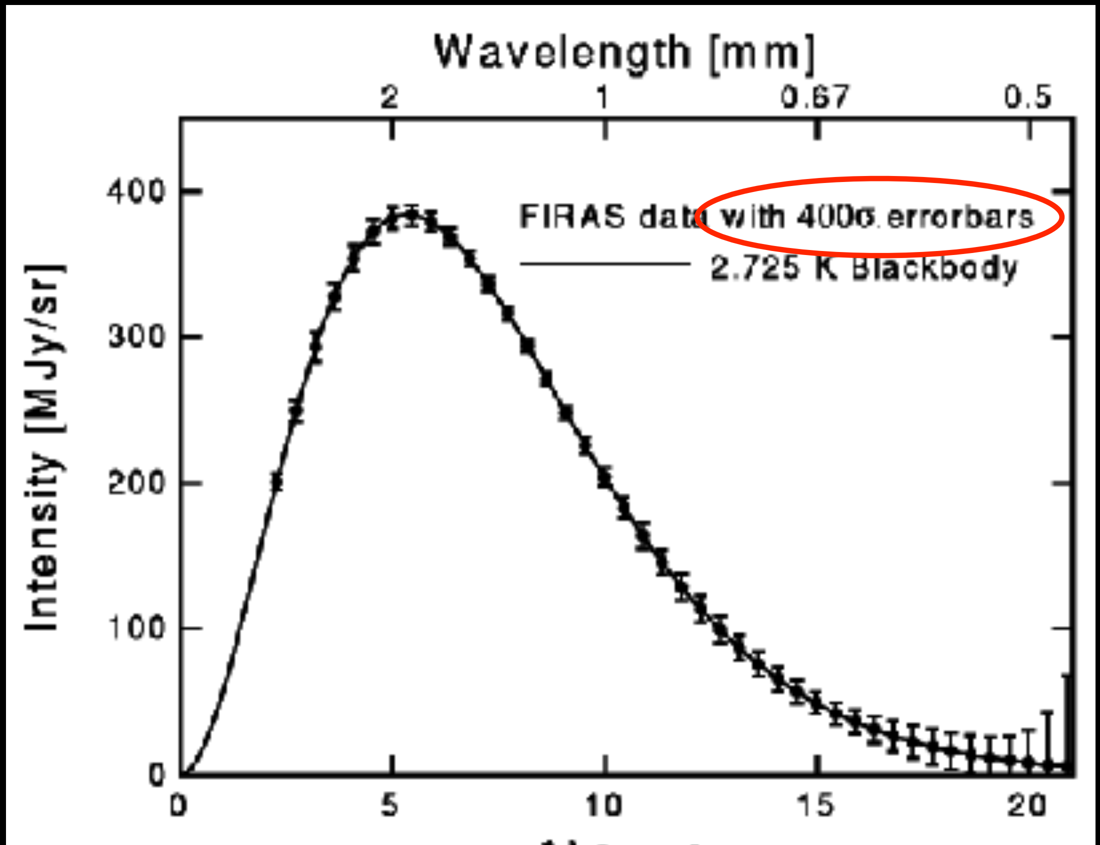
Cosmic Microwave Background Radiation



CMB photons emitted when first atoms formed (t ~ 380,000 years)

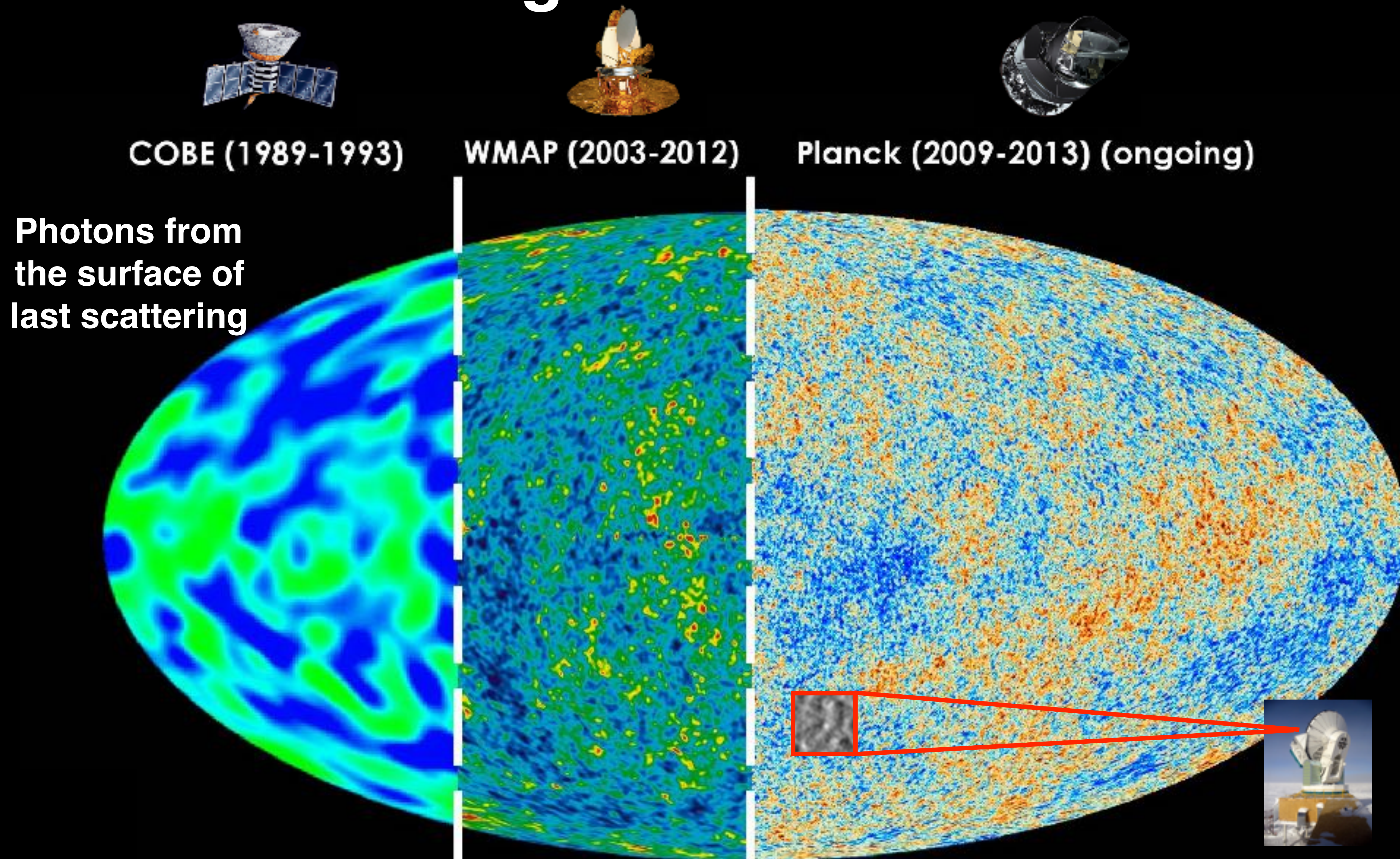
Redshifted from a temperature of ~3000K to 2.725K today (λ ~ cm)

Density fluctuations imprinted as small temperature fluctuations $\Delta T/T \sim 10^{-5}$

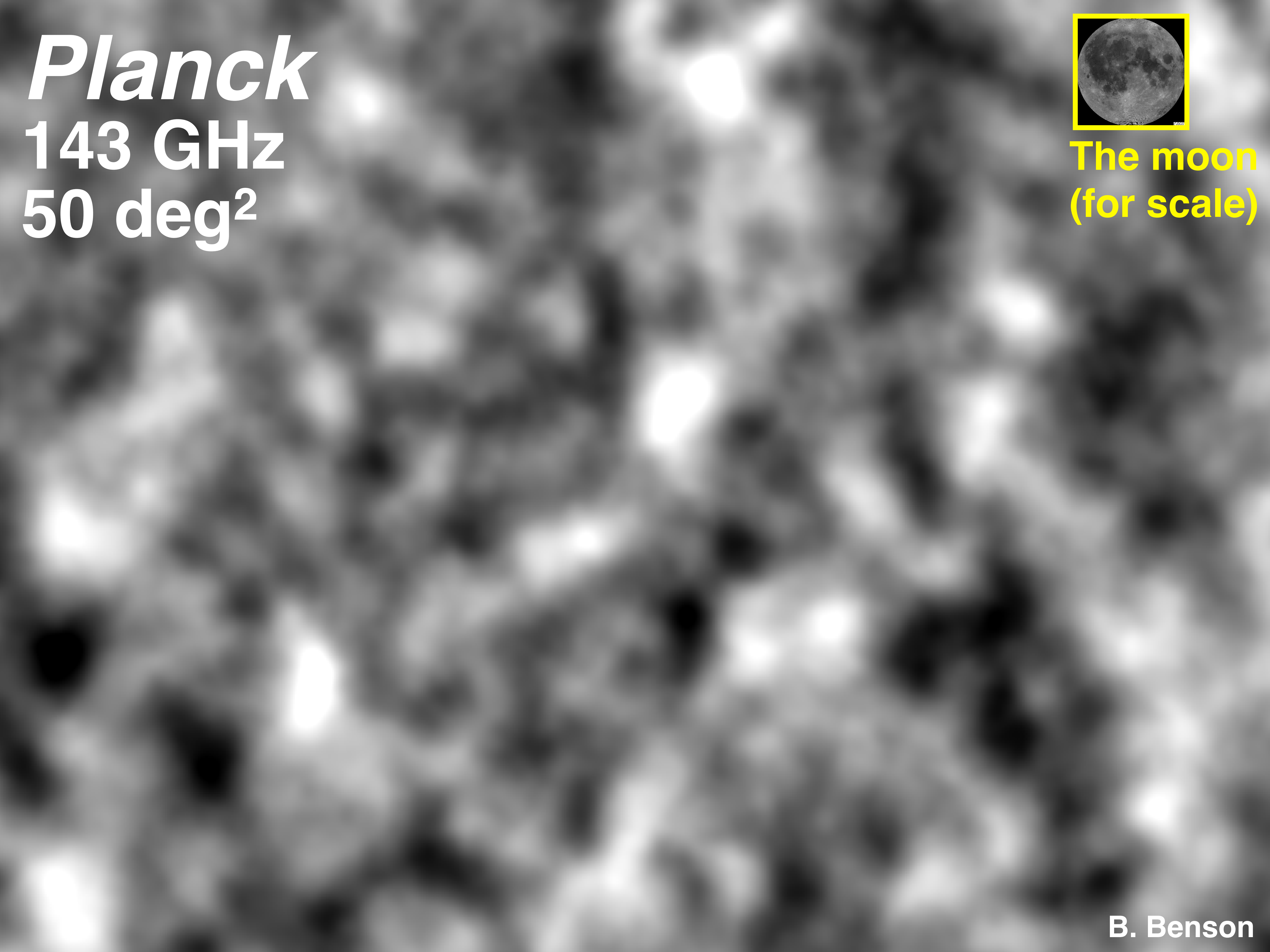


Mather et al. 1994

Cosmic Microwave Background Radiation



SPT (2006 - present)
(ongoing w/ upgrades)


Planck
143 GHz
50 deg²
The moon
(for scale)
B. Benson

South Pole Telescope

150 GHz
50 deg^2

The moon
(for scale)

6x deeper

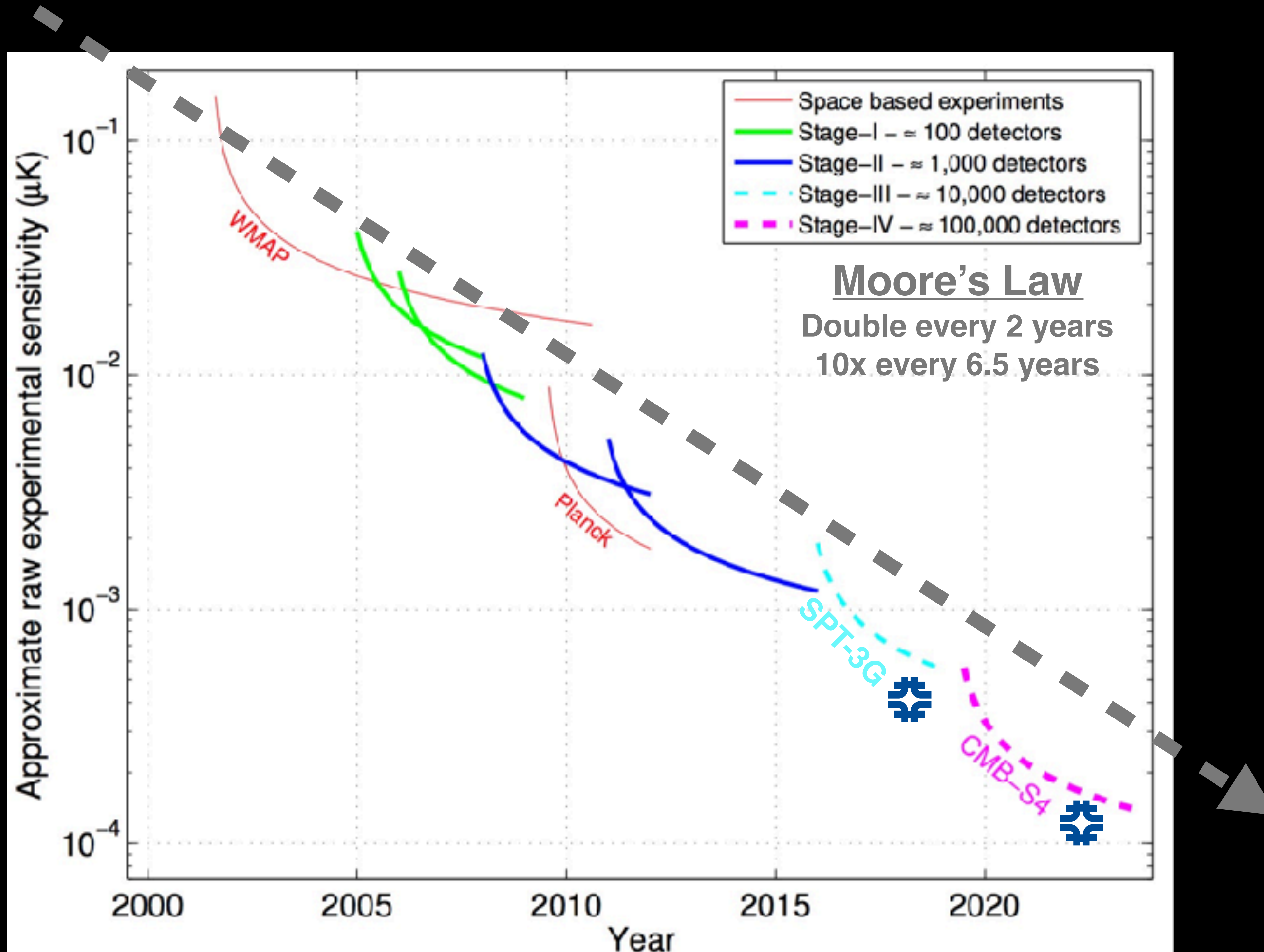
6x finer angular resolution

Clusters of Galaxies

"Shadows" in the microwave background from clusters of galaxies (the **Sunyaev-Zel'dovich**)

B. Benson

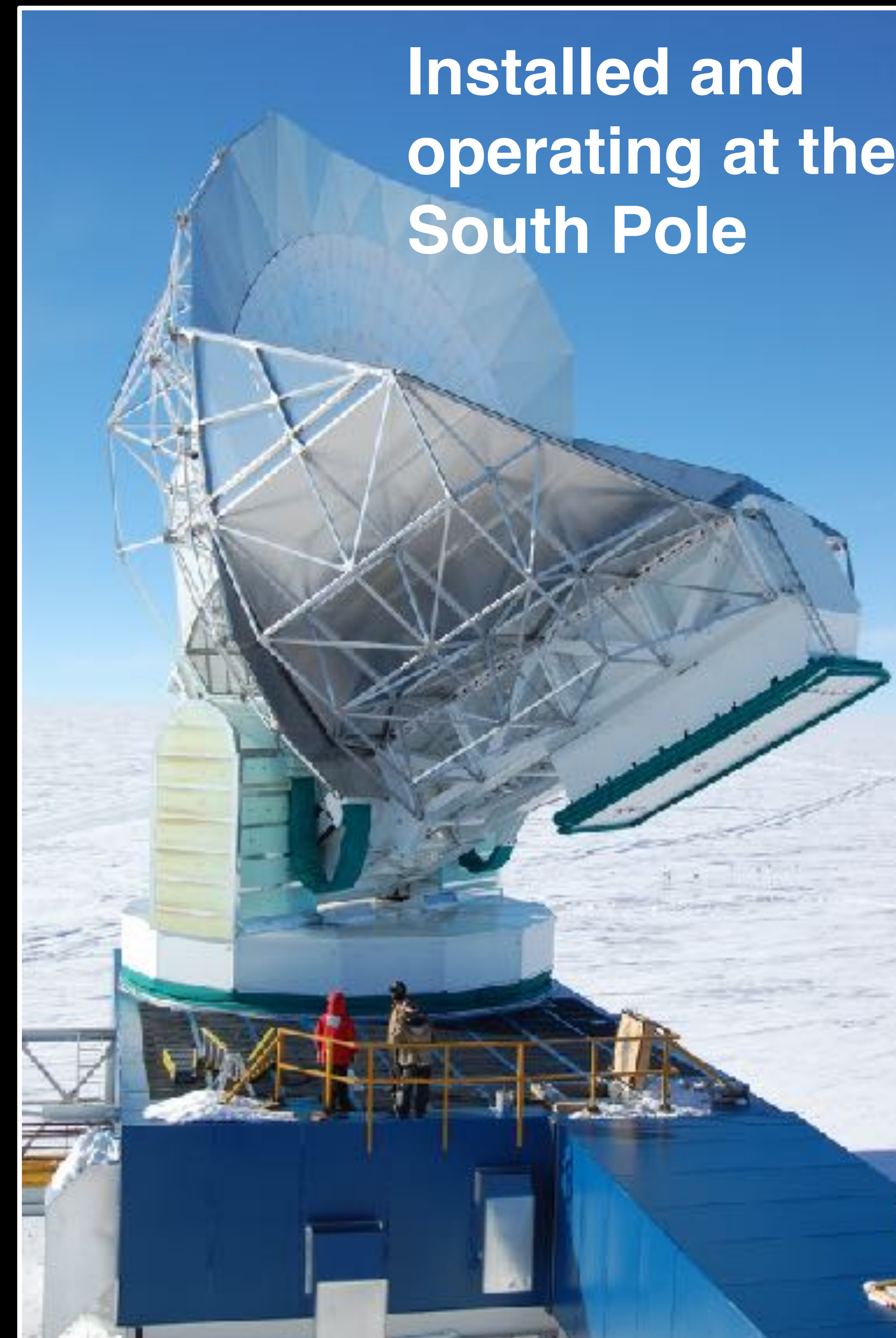
Moore's Law for CMB



South Pole Telescope (SPT-3G)

SPT-3G Camera Cryostat Designed and Integrated at Fermilab

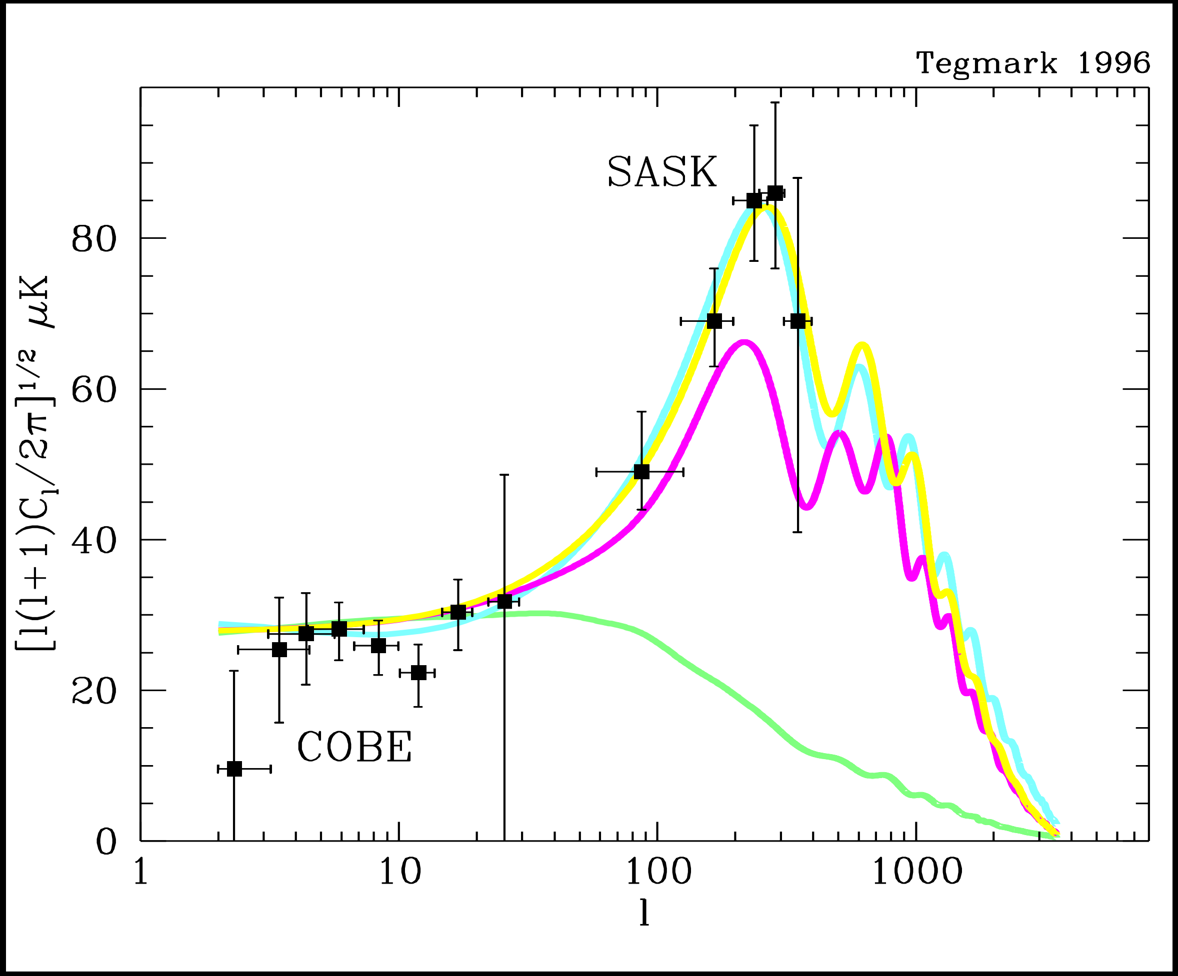
Installed and operating at the South Pole



Talk by S. Rahlen
Thursday @ 16:50 PM

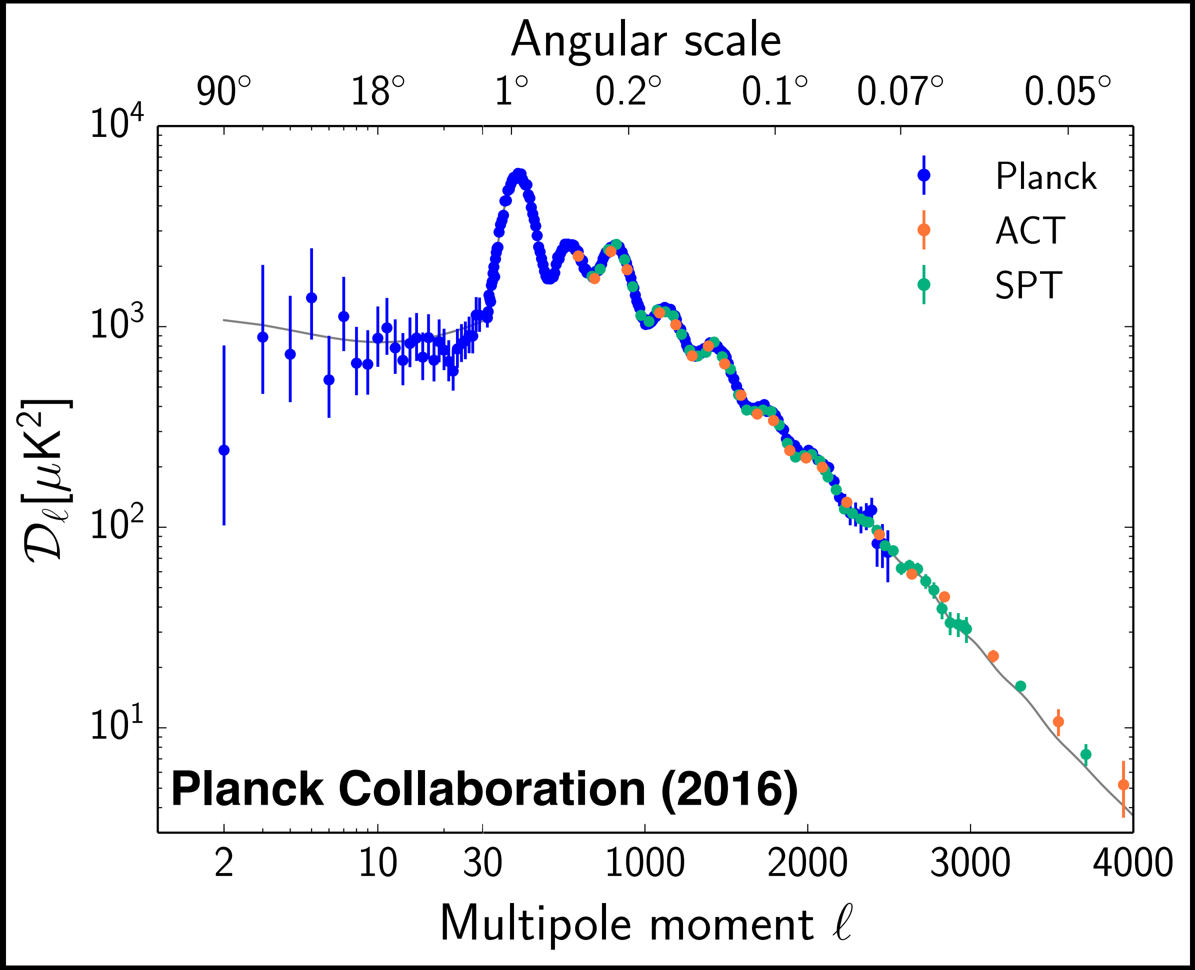
CMB Angular Power Spectrum

1 Acoustic Peak



9 Acoustic Peaks + Polarization!

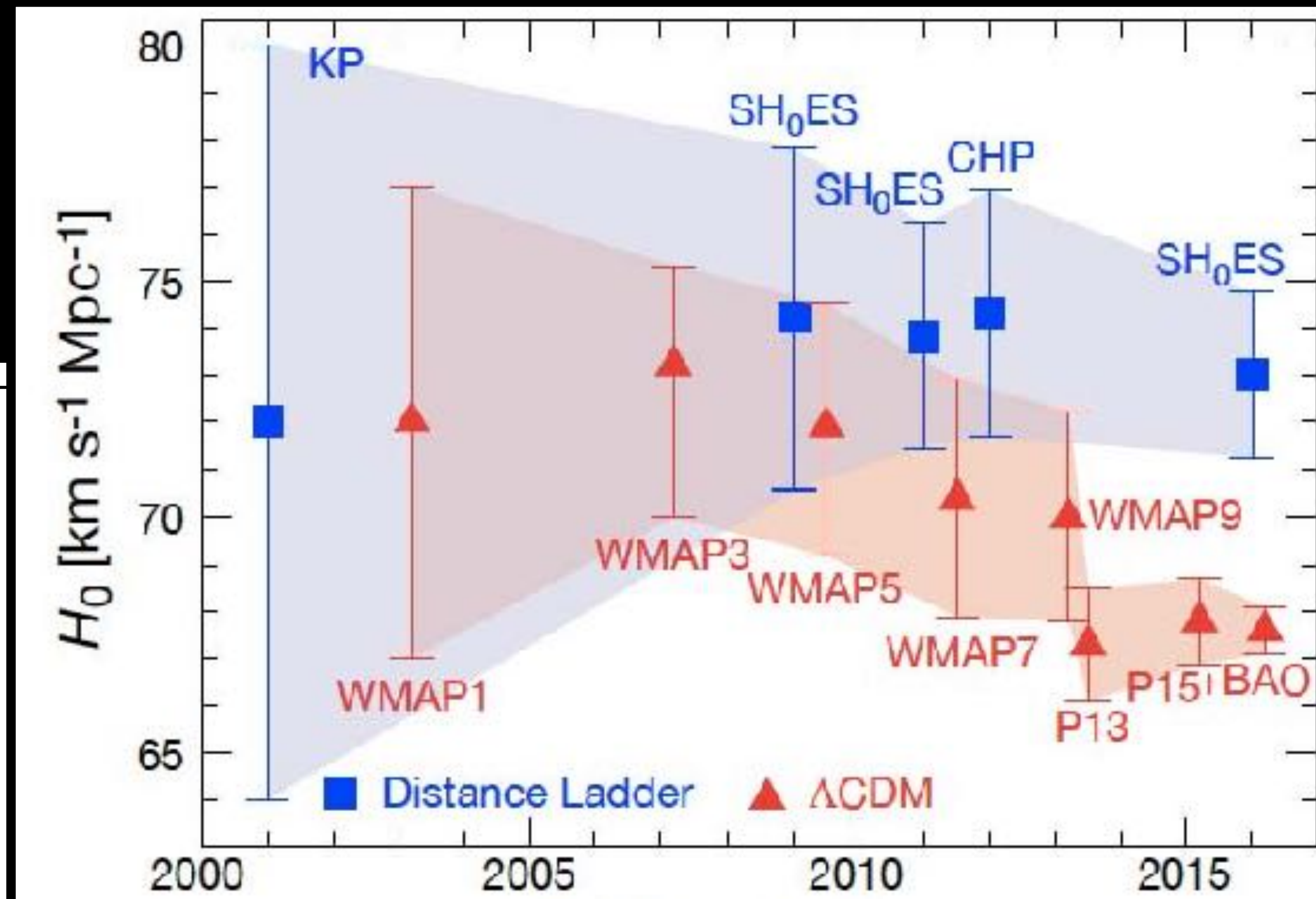
(Kamionkowski, Kosowsky & Stebbins, 1996)



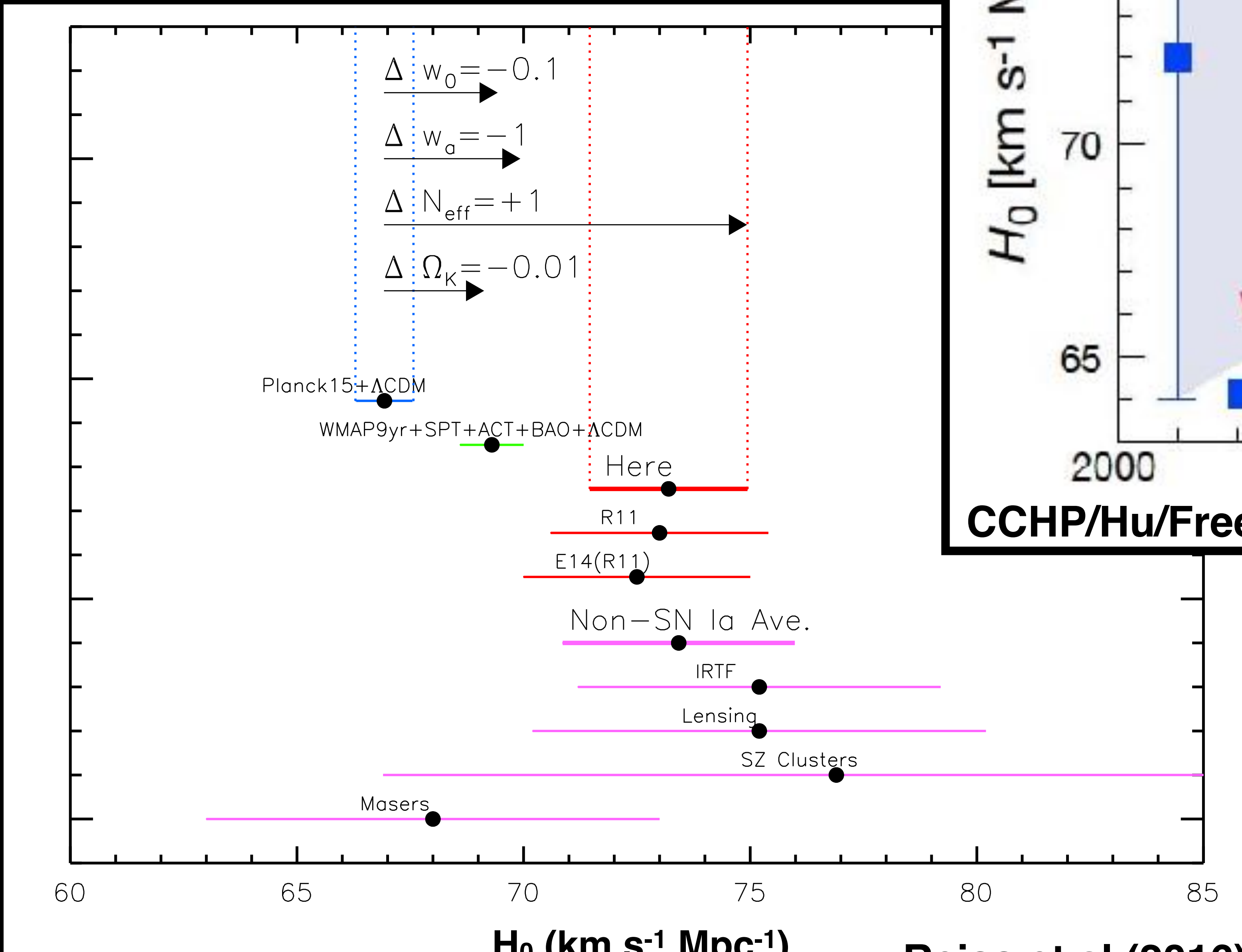
The ΛCDM model yields a precise and accurate fit to the data with only 6 parameters. Flat, accelerating Universe, dominated by dark energy and dark matter.

Trouble with Hubble?

The Hubble constant has a long and "disagreeable" history.



CCHP/Hu/Freedman



Reiss et al (2016)

CMB and distance ladder disagree at 3.4σ.

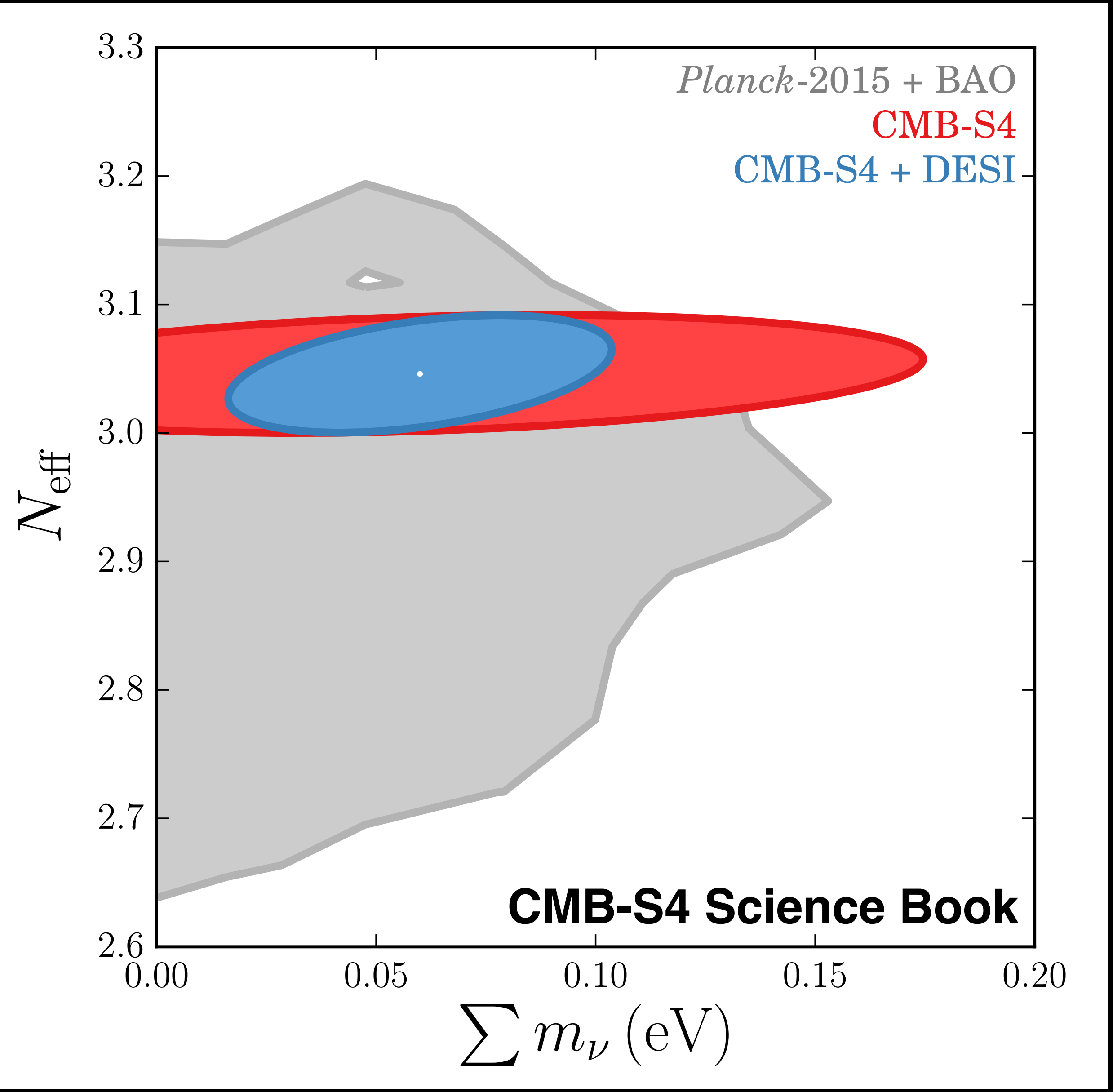
A hint that maybe ΛCDM is not enough?

CMB-S4 Experiment

Inflation

Dark Energy

Neutrinos



What is to come?

- **Dark Matter** - Are we entering a post-WIMP era? How will searches be influenced by quantum detectors? What will we learn from astrophysical observations?
- **Dark Energy** - Is dark energy a cosmological constant? Is there some extension to the laws of gravity? Is there really “Trouble with Hubble”?
- **Inflation/CMB** - Will we see signs of non-standard inflation? Will cosmological and accelerator neutrino measurements agree? Are there sterile neutrinos?


BIG BANG