The connected universe

Relating Early, Intermediate and Late Universe with cosmological data

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Co-I of the Supernova Science group at WFIRST

Member of the High Latitude Survey group at WFIRST



A boa filha a casa retorna (the good daughter always returns home)



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KICP
Kavli Institute
for Cosmological Physics
at The University of Chicago

Penn
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Thanks Prof. Waga!



Ioav Waga

Being a student of Prof. Waga was an enormous privilege.

At UFRJ, I was in a crisis with physics before I met him. I could not find excitement in many physics classes.

He saw talent and determination in me. Discussing cosmology with him made me enjoy physics again!

Even after I left UFRJ, his doors were always open; he was still willing to advise me, to support me, to encourage me.

Thanks Prof. Waga! I will be forever in debt!

Without the <u>exceptional</u> education that Prof. Waga offered me, I would have never succeeded in being a P.h.D. student of Prof. Hu or a fellow at Upenn.

<u>My education was built on the shoulders of four giants in cosmology. I will be forever in debt</u>



Ioav Waga



Josh Frieman



Wayne Hu



Scott Dodelson

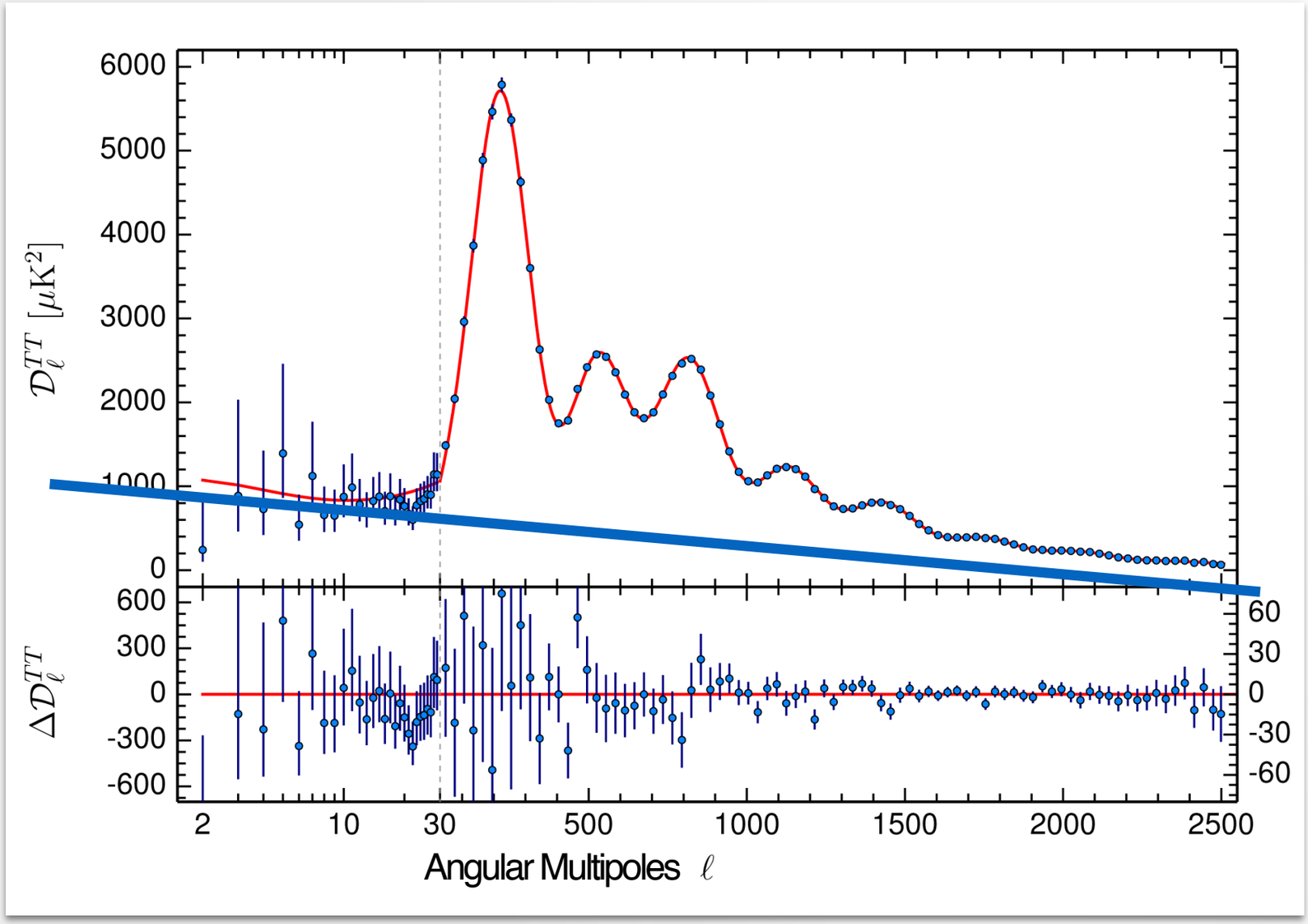
	FIW807	COMOLOGY Prof. Ioav Waga – (Doctorate)	4.0	60.0	A	4.0	12.0	AP
ASTR 41100 01	**Science of the Dark Energy Survey**		**J. F**			Autumn 2010		A
ASTR 32100 01	**Cosmology**		**W. H.**			Winter 2011		A
ASTR 44800 01	**Cosmic Microwave Background**		**W. H.**			Autumn 2012		A
ASTR 40600 01	**Gravitational Lensing**		**S. D.**			Winter 2014		A
ASTR 40800 01	**The Perturbed Universe**		**W. H.**			Autumn 2013		A

Thanks Prof. Waga! I will be forever in debt!



Part I: Early Universe

Basic cookbook of inflation: power law



Inflationary seeds

$$A_s \left(\frac{k}{k_0} \right)^{n_s - 1}$$

Transfer: physics of baryon-photon coupling

$$D_\ell^{TT} \propto \int d\ln k \; \text{Inflation} \times \text{Transfer}$$

Are there examples that violate the basic picture?

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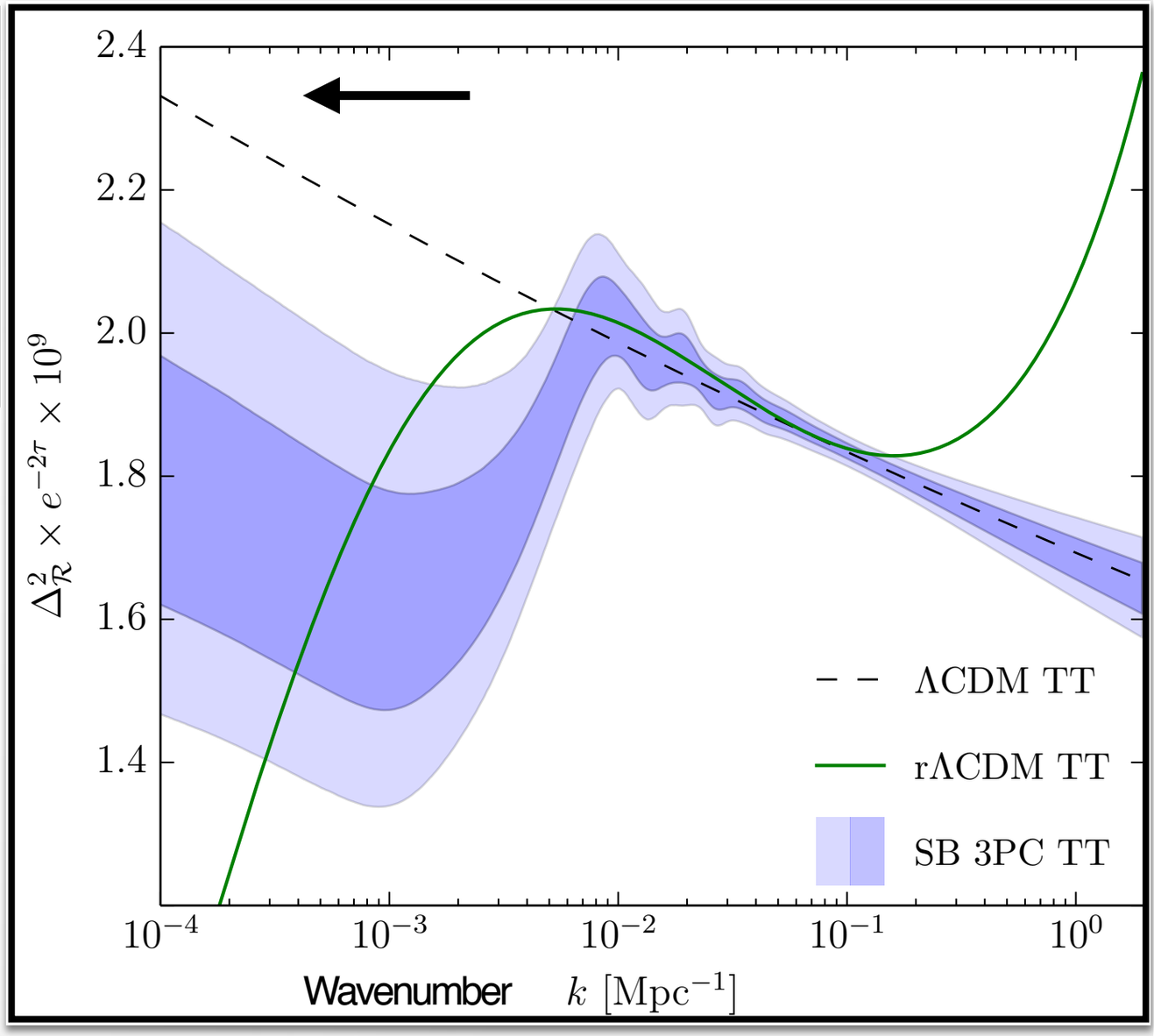
Inflationary features and shifts in cosmological parameters from *Planck* 2015 data

Georges Obied,[1] Cora Dvorkin,[1] Chen Heinrich,[2] Wayne Hu,[2] and Vinicius Miranda[3]

[1]*Harvard University, Department of Physics, Cambridge, Massachusetts 02138, USA*
[2]*Kavli Institute for Cosmological Physics, Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[3]*Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

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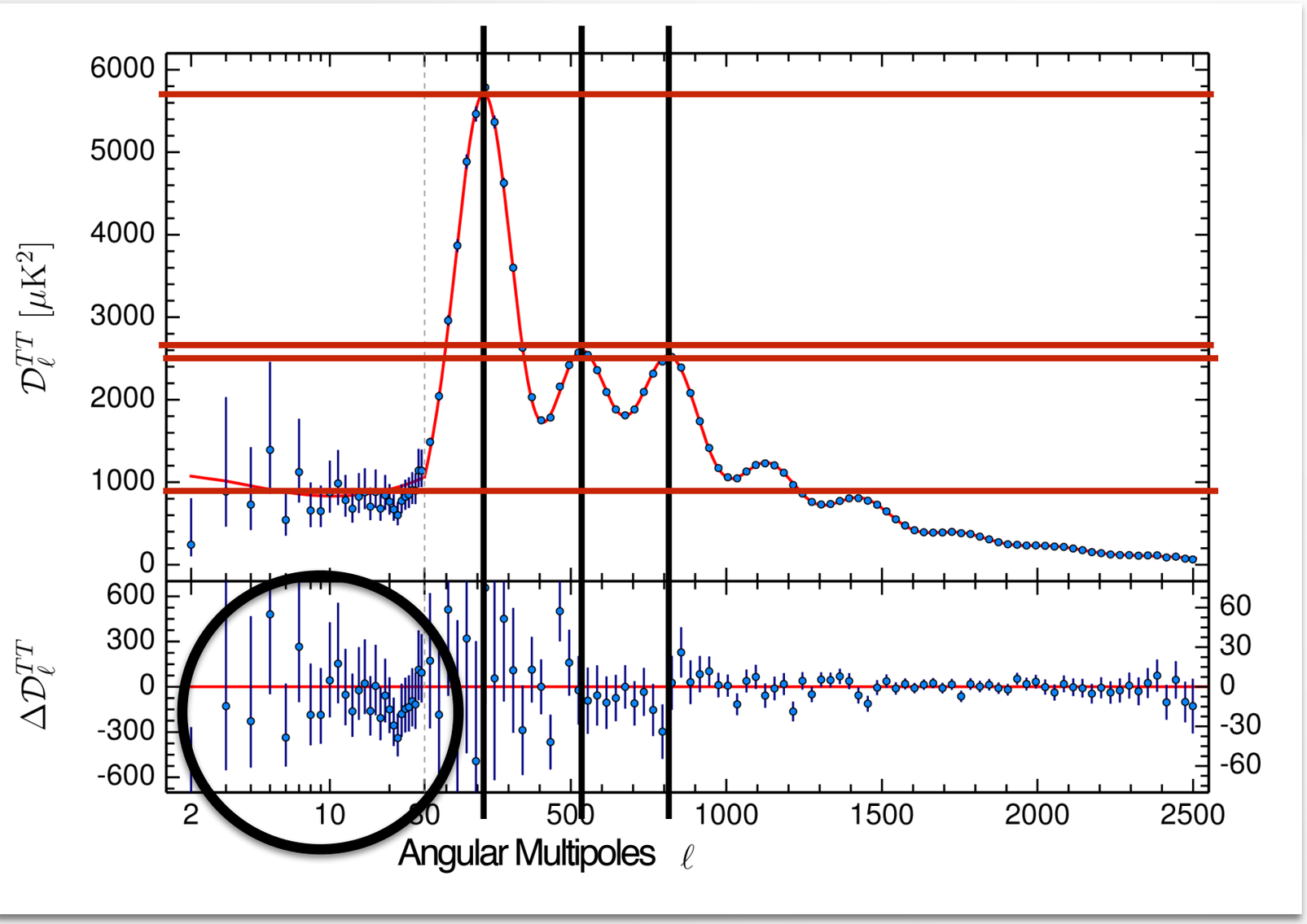
CMB prefers less power at large scales



Inflation can be complicated

How can it be connected with the Late Universe?

How CMB mixes inferences about inflation x dark energy



Peak Positions
(assuming DE model)

$$\Omega_m h^{3.4}$$

+ Peak amplitudes

$$\Omega_m h^2$$

= Prediction on

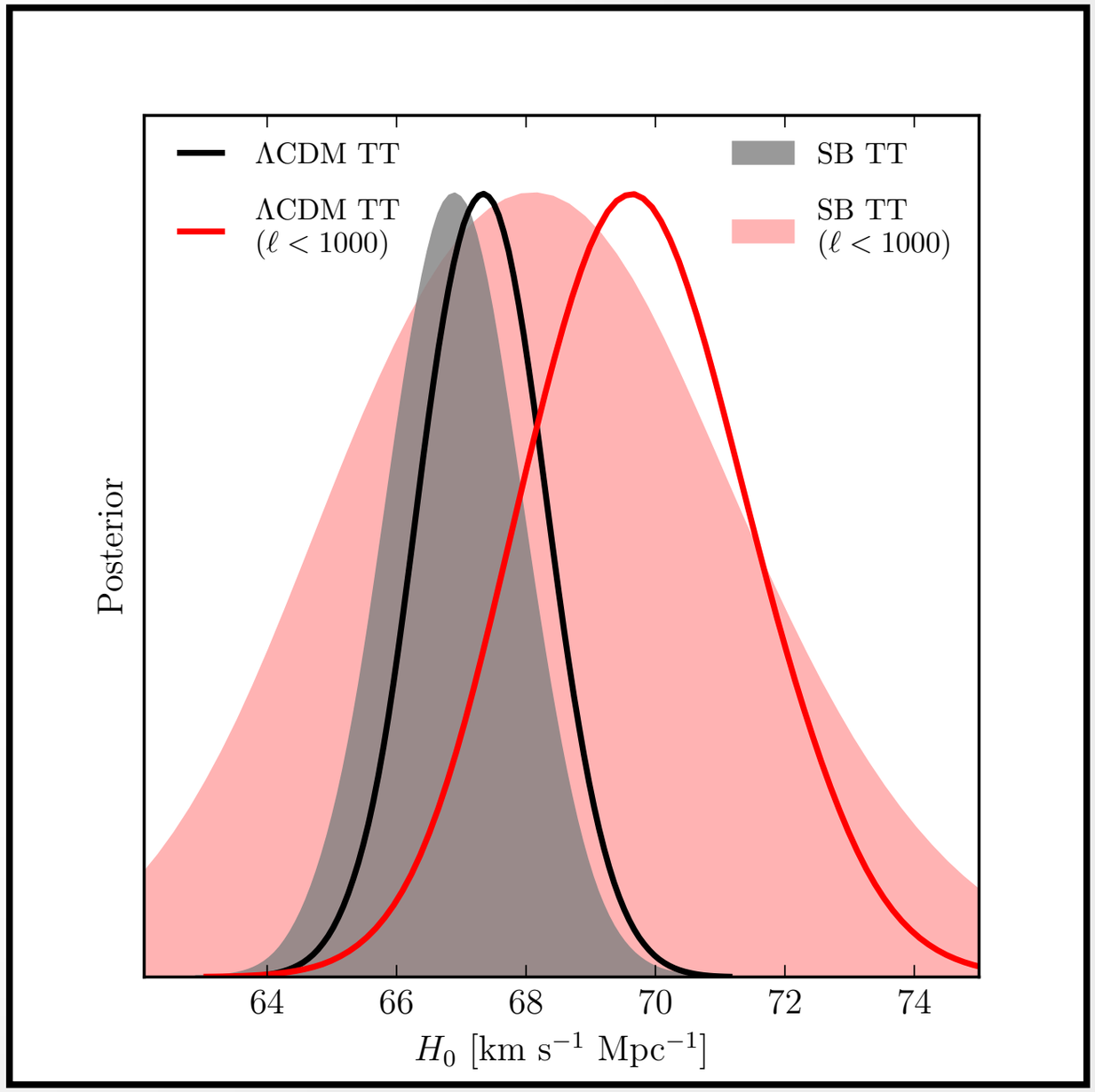
$$h = H_0 / 100$$

CMB mixes inferences on inflation vs dark energy

H0 = Hubble Constant

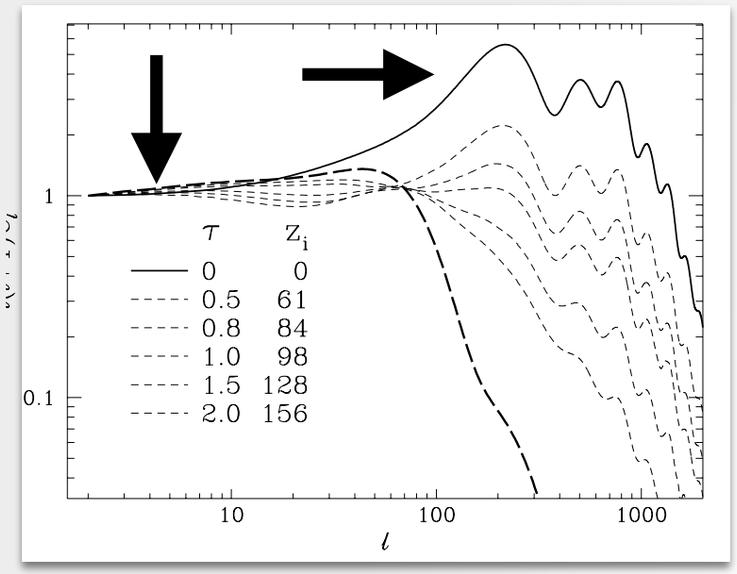
H0 problem: stringent test to LCDM (4.3 sigma tension!)

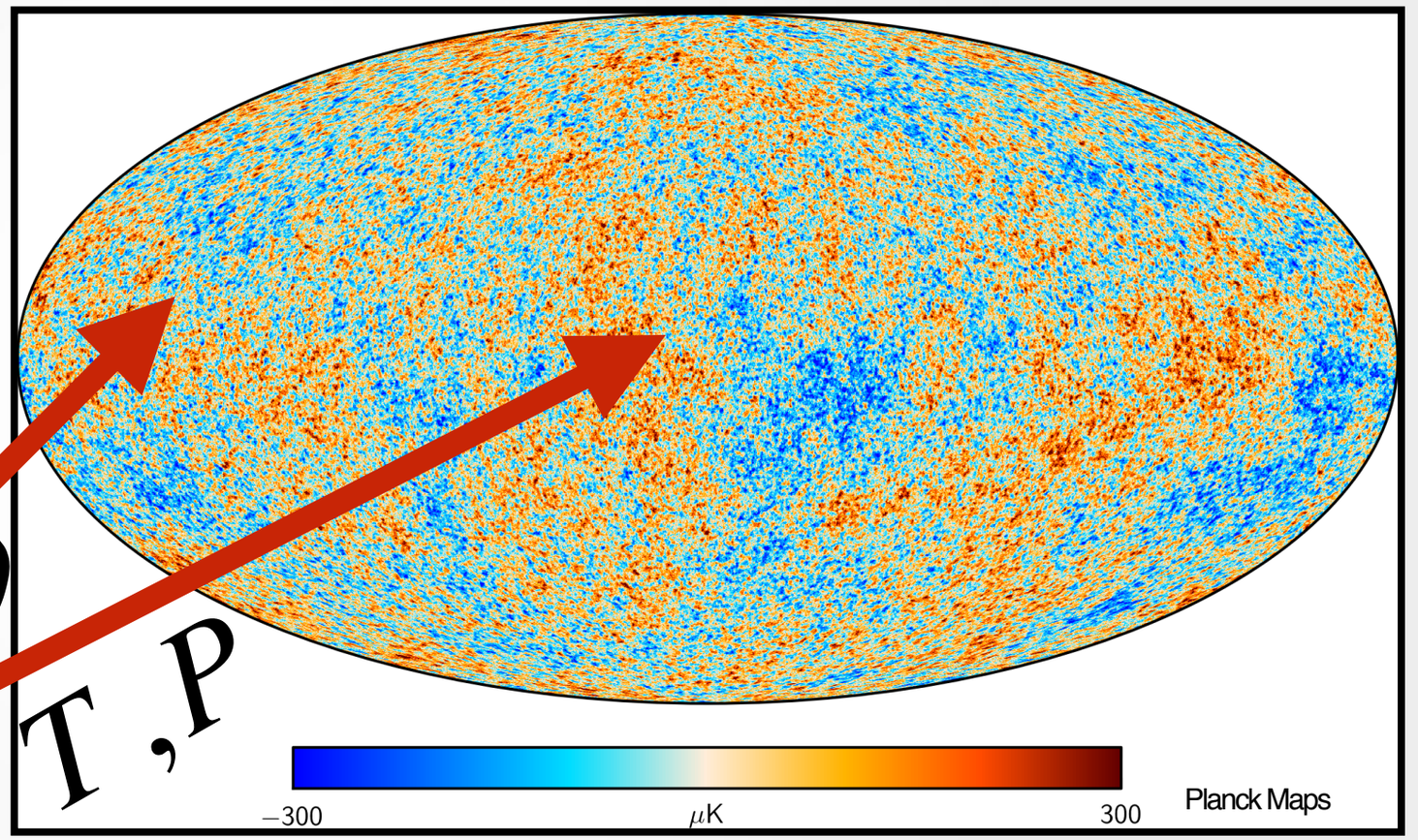
Hypotheses on inflation impact CMB constraints on Dark Energy!



Part II: Intermediate Universe

How can we probe the Epoch of Reionization?





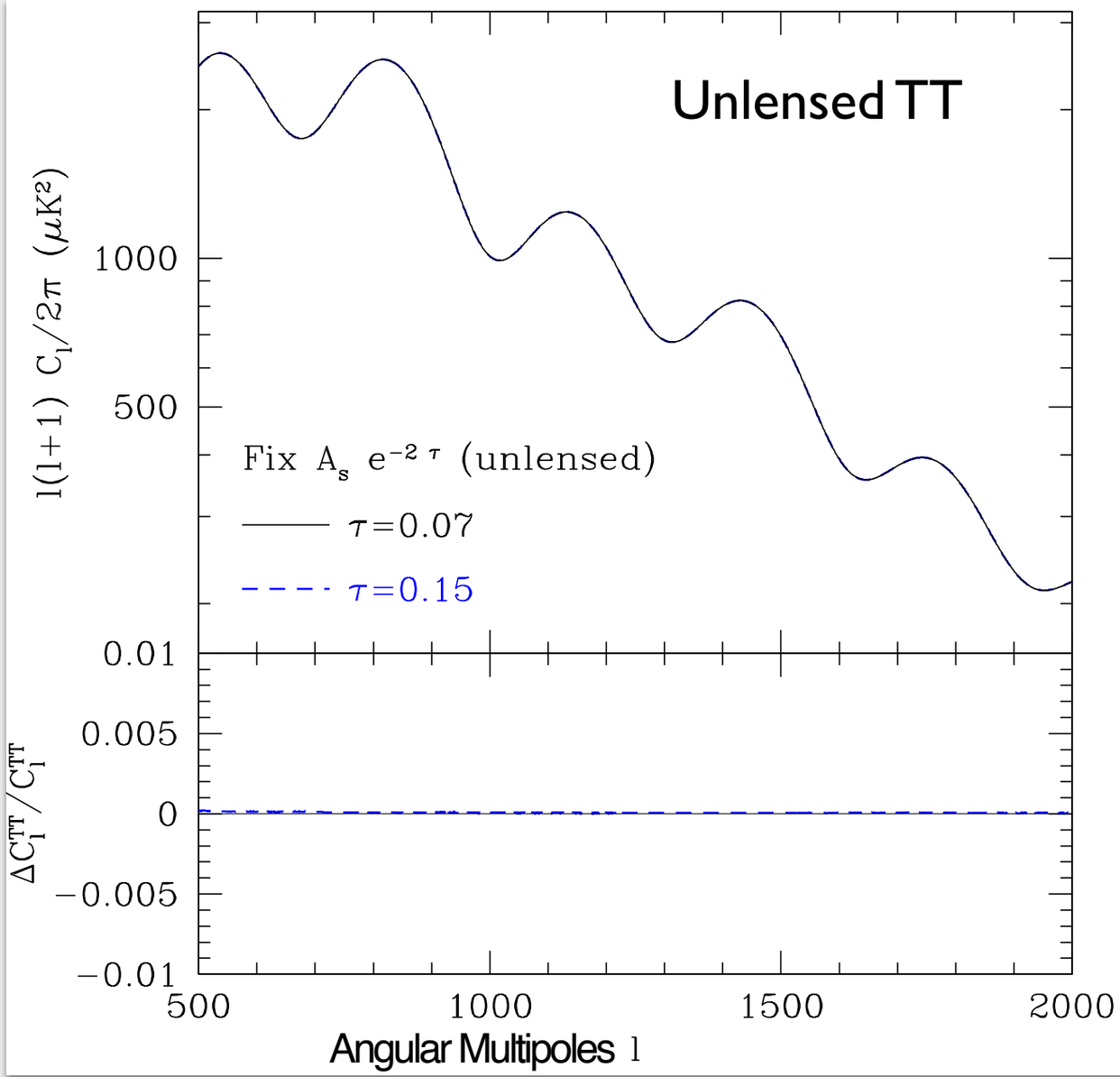


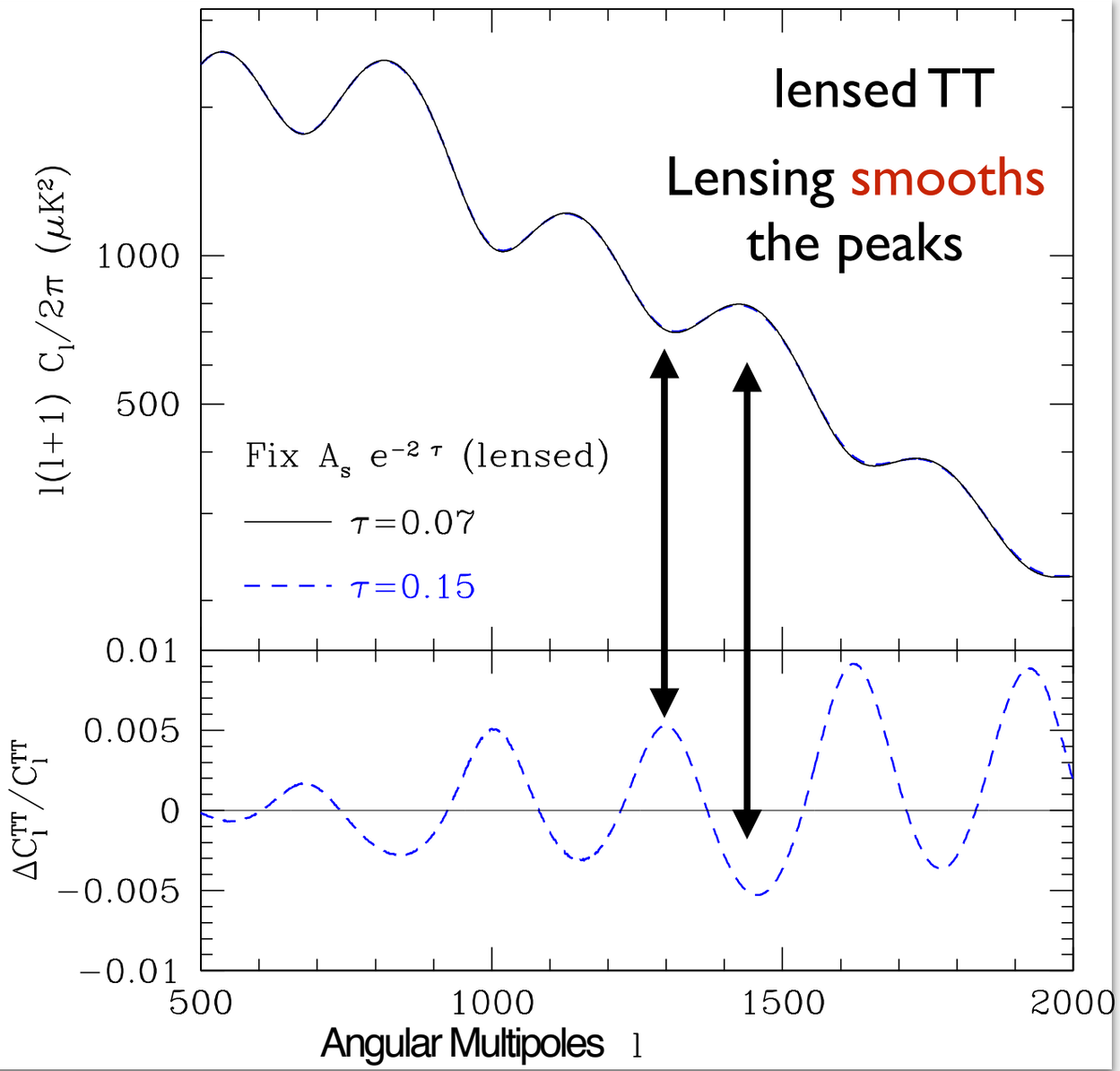
free electrons: damps temperature,

enhances polarization!

How can we probe the Epoch of Reionization?

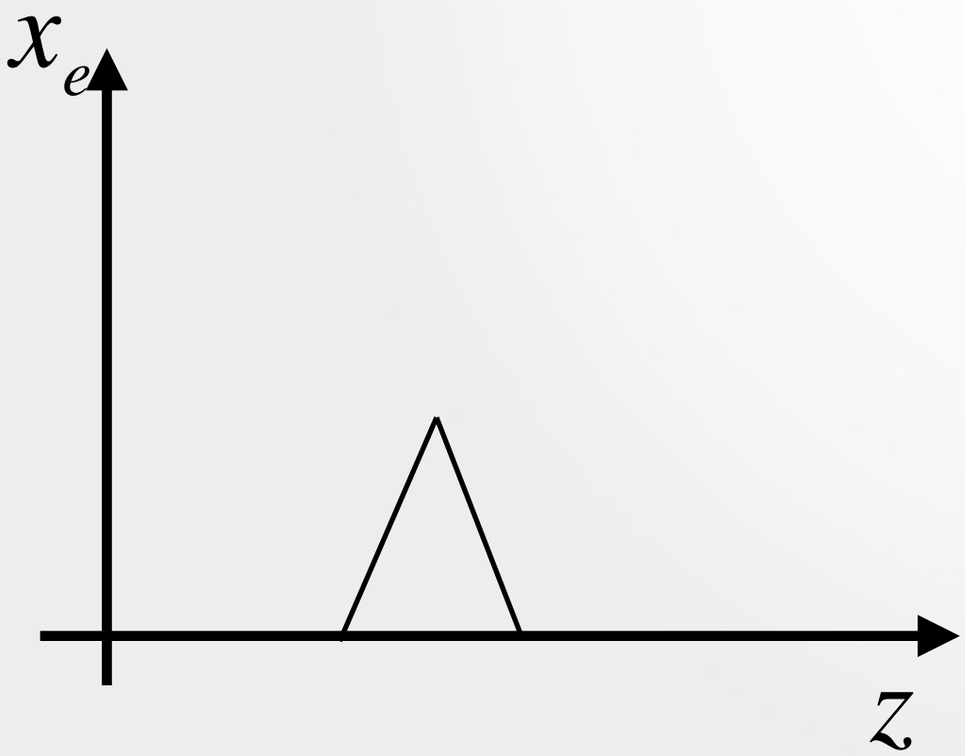
Not quite: gravitational lensing partially breaks this degeneracy

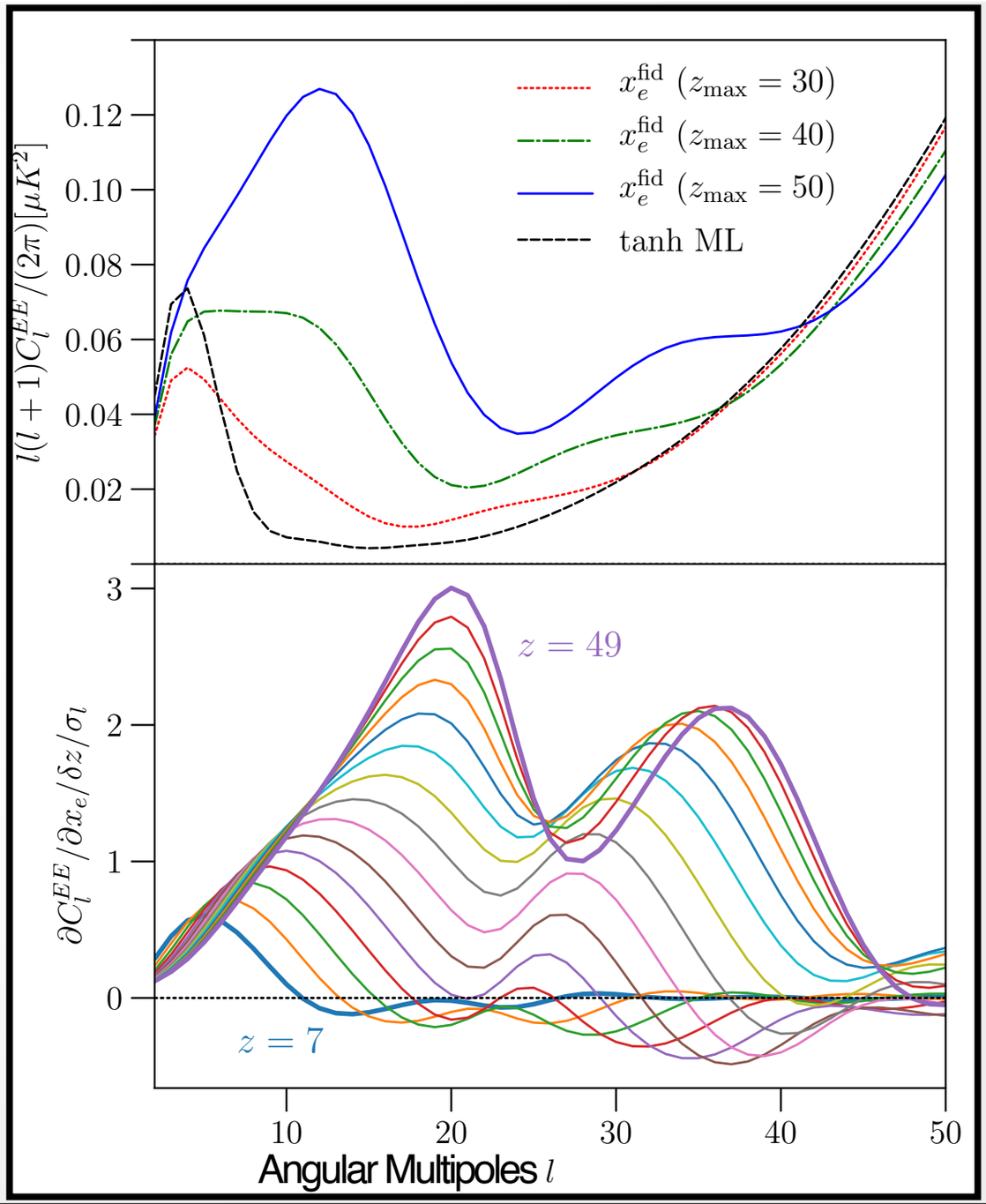




How can we probe the Epoch of Reionization?

CMB Polarization: can measure the evolution of the total optical depth





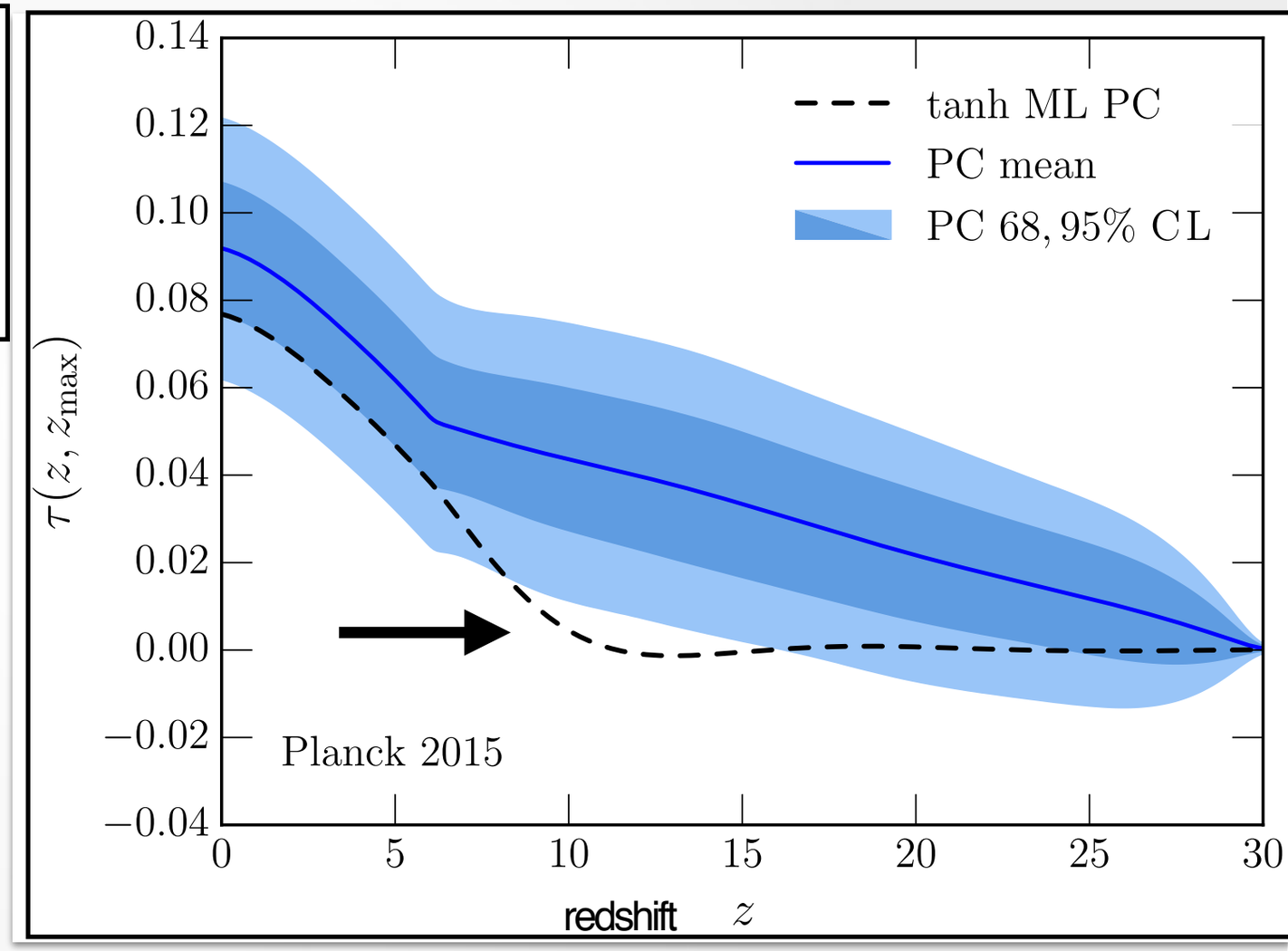
Test that Pop-II stars are the only source of radiation?

Complete reionization constraints from Planck 2015 polarization

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[1] *Kavli Institute for Cosmological Physics, Enrico Fermi Institute, University of Chicago, Illinois 60637*
[2] *Department of Physics, University of Chicago, Illinois 60637, USA**
[3] *Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[4] *Kavli Institute for Cosmological Physics, Enrico Fermi Institute, University of Chicago, Chicago Illinois 60637, USA*
[5] *Department of Astronomy & Astrophysics, University of Chicago, Illinois 60637, USA*

(Dated: April 10, 2017)



Our state of the art analysis showed hints of high redshift signal

$$\tau(15 < z < 30) = 0.033$$

Theoretical priors on the Planck analysis prevented them from seeing this signal!

Reionization can be complicated

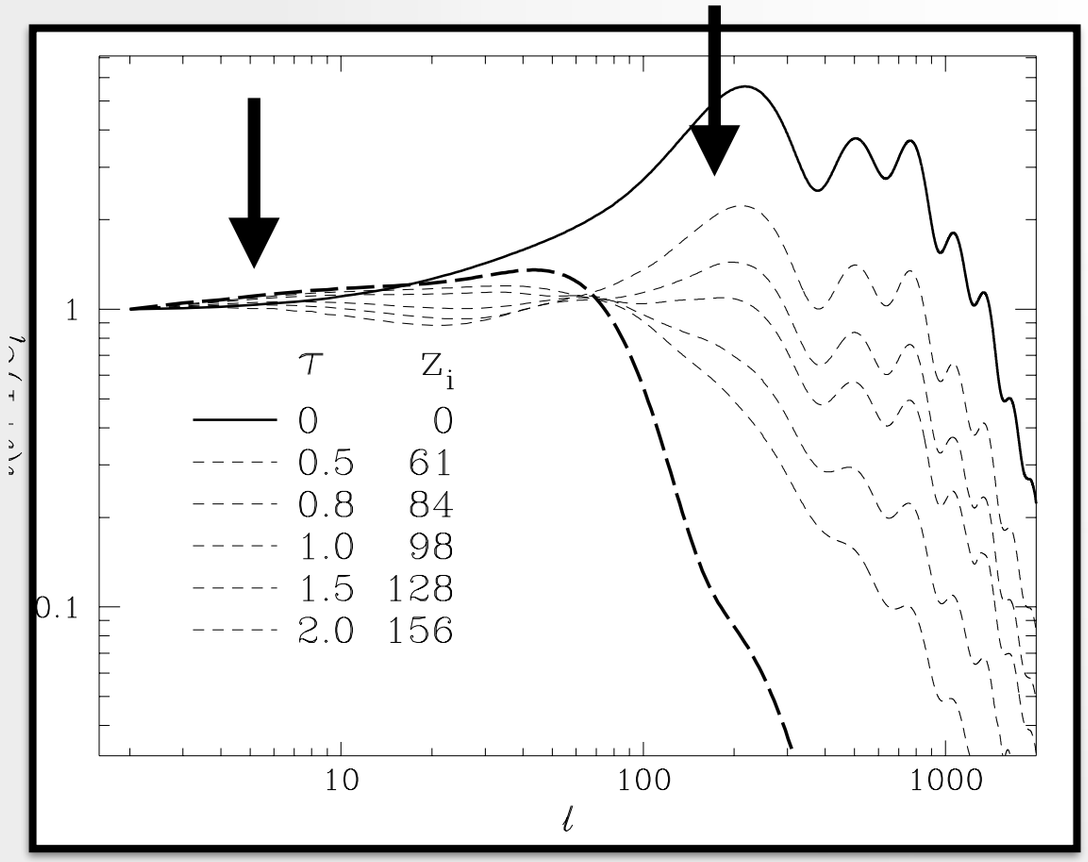
How can it be connected with the Early Universe?

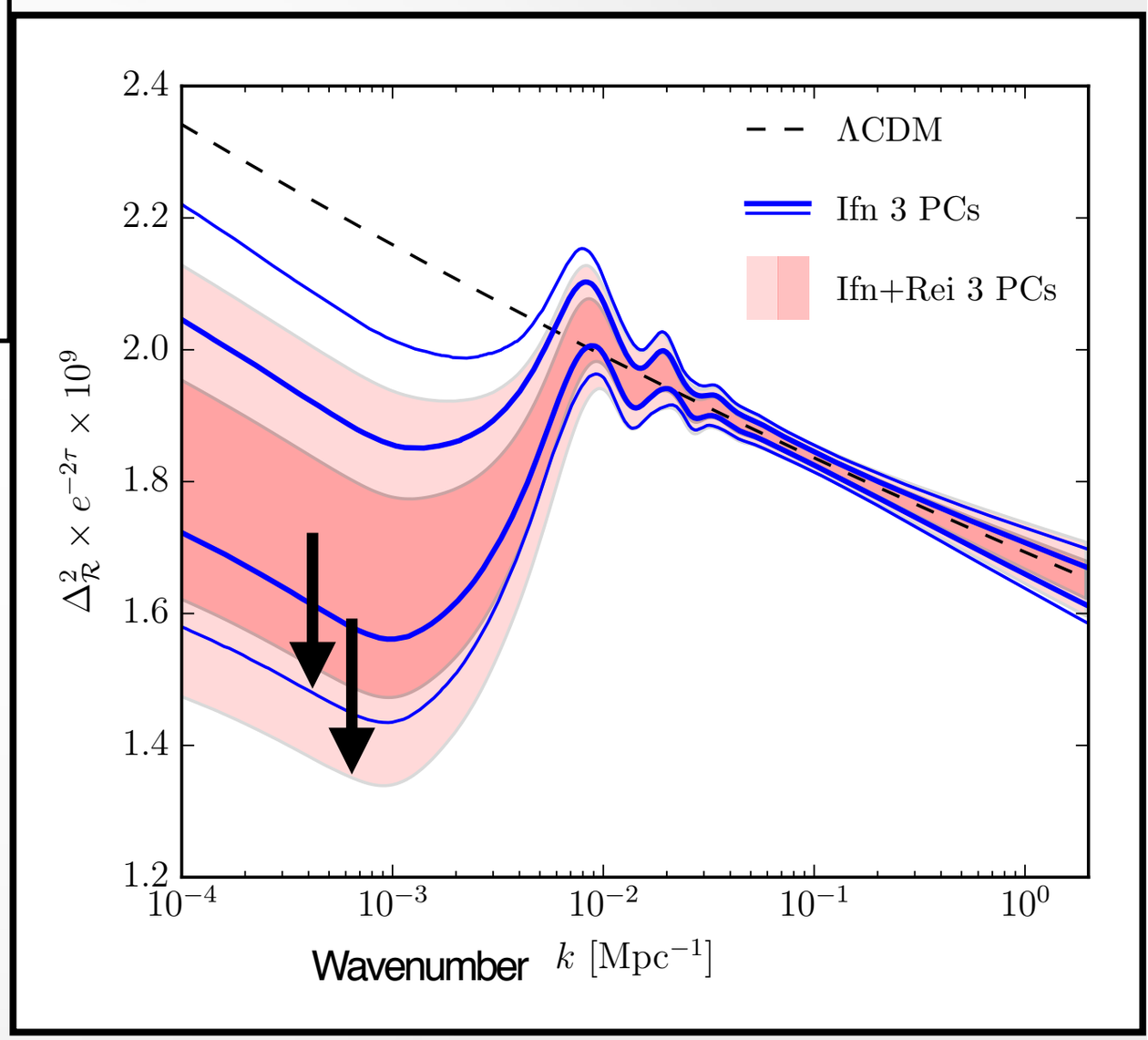
How degenerate is this signal with early universe?

Inflationary vs. Reionization Features from *Planck* 2015 Data

Georges Obied,[1] Cora Dvorkin,[1] Chen Heinrich,[2,3] Wayne Hu,[4] and Vinicius Miranda[5]

[1] *Harvard University, Department of Physics, Cambridge, MA 02138, USA*
[2] *California Institute of Technology, Pasadena California 91125*
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[4] *Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*
[5] *Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*





H0 solution: Dark Energy or Dark Matter?

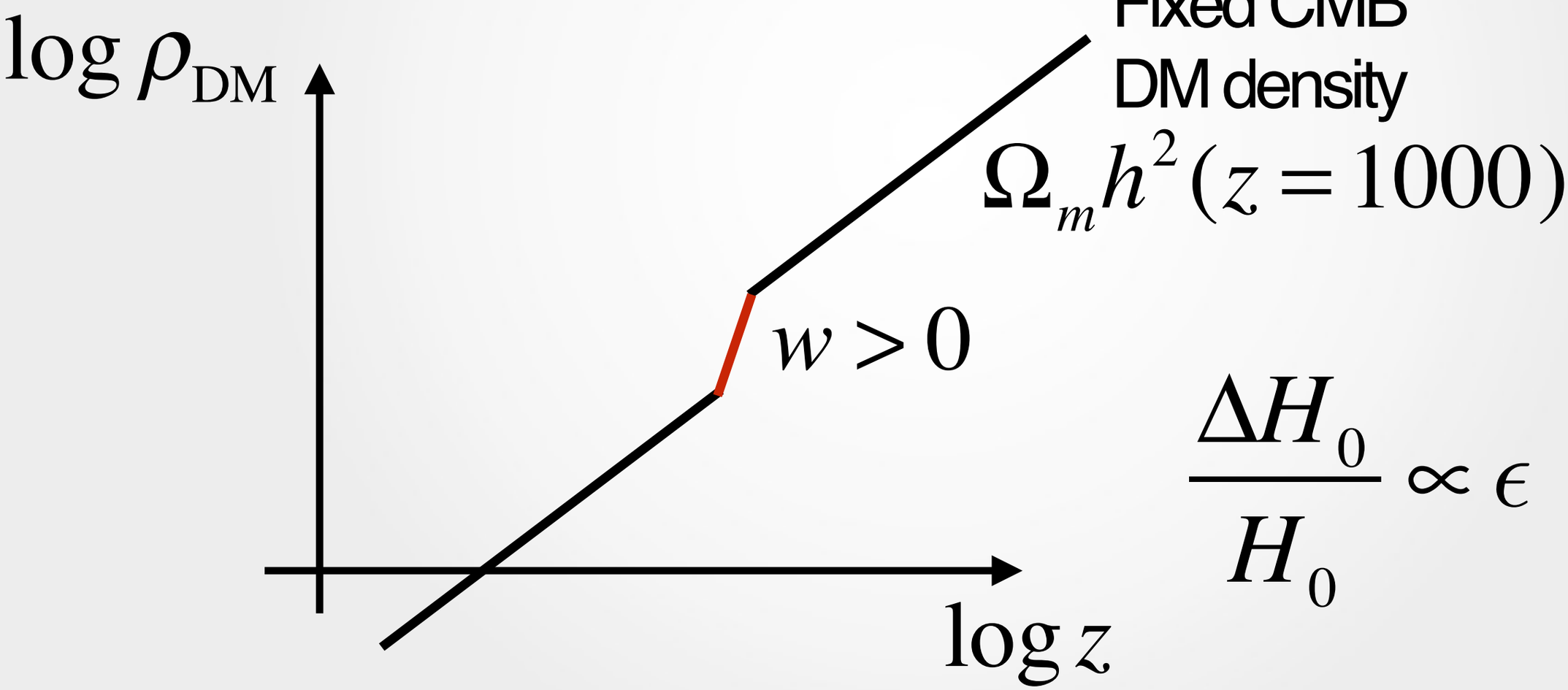
Dark Matter decay



V. Miranda



Justin Khoury

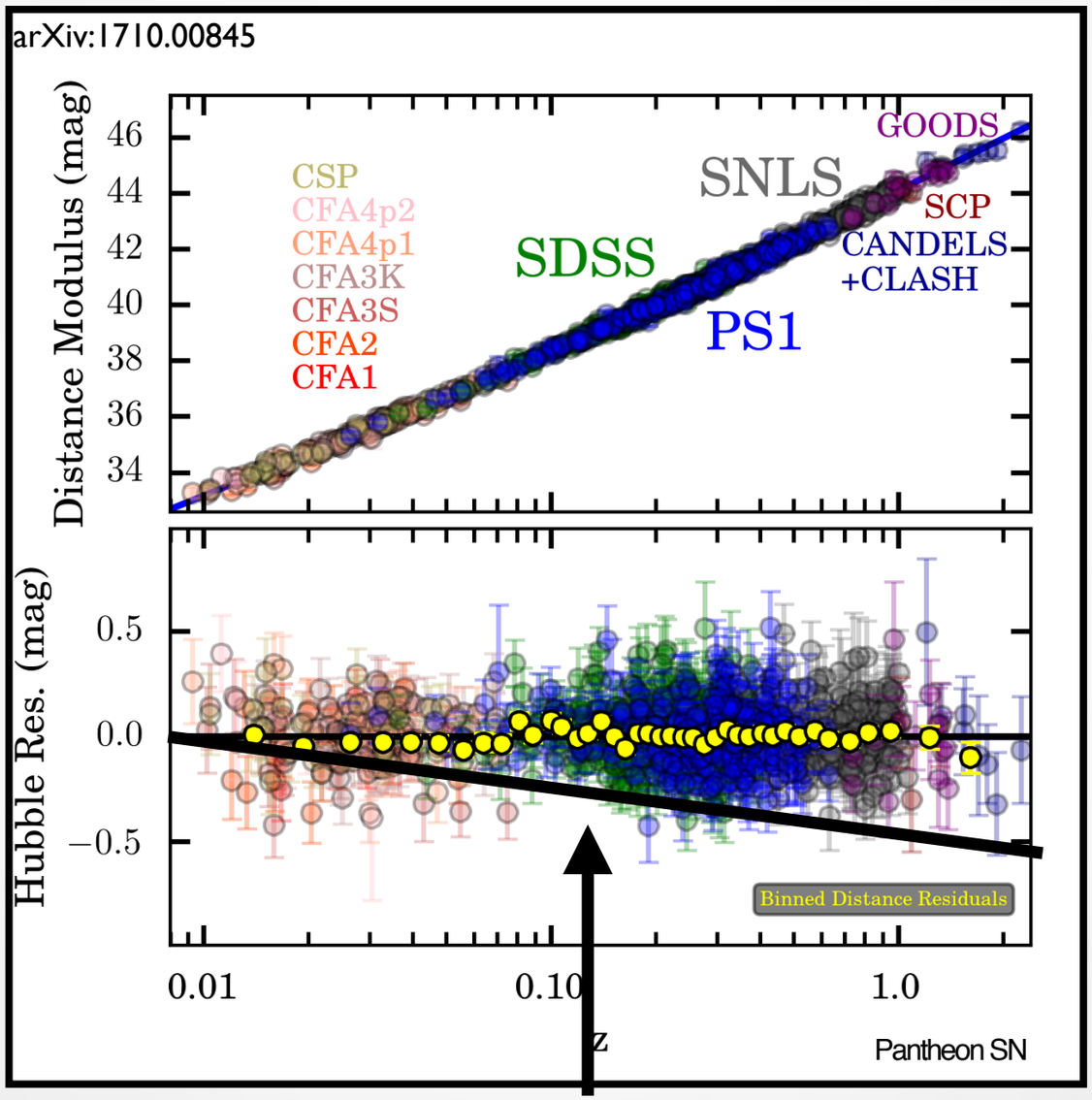


$$\frac{\Delta H_0}{H_0} \propto \epsilon$$

That explains why massive neutrinos don't work! (rad -> CDM at z~200)

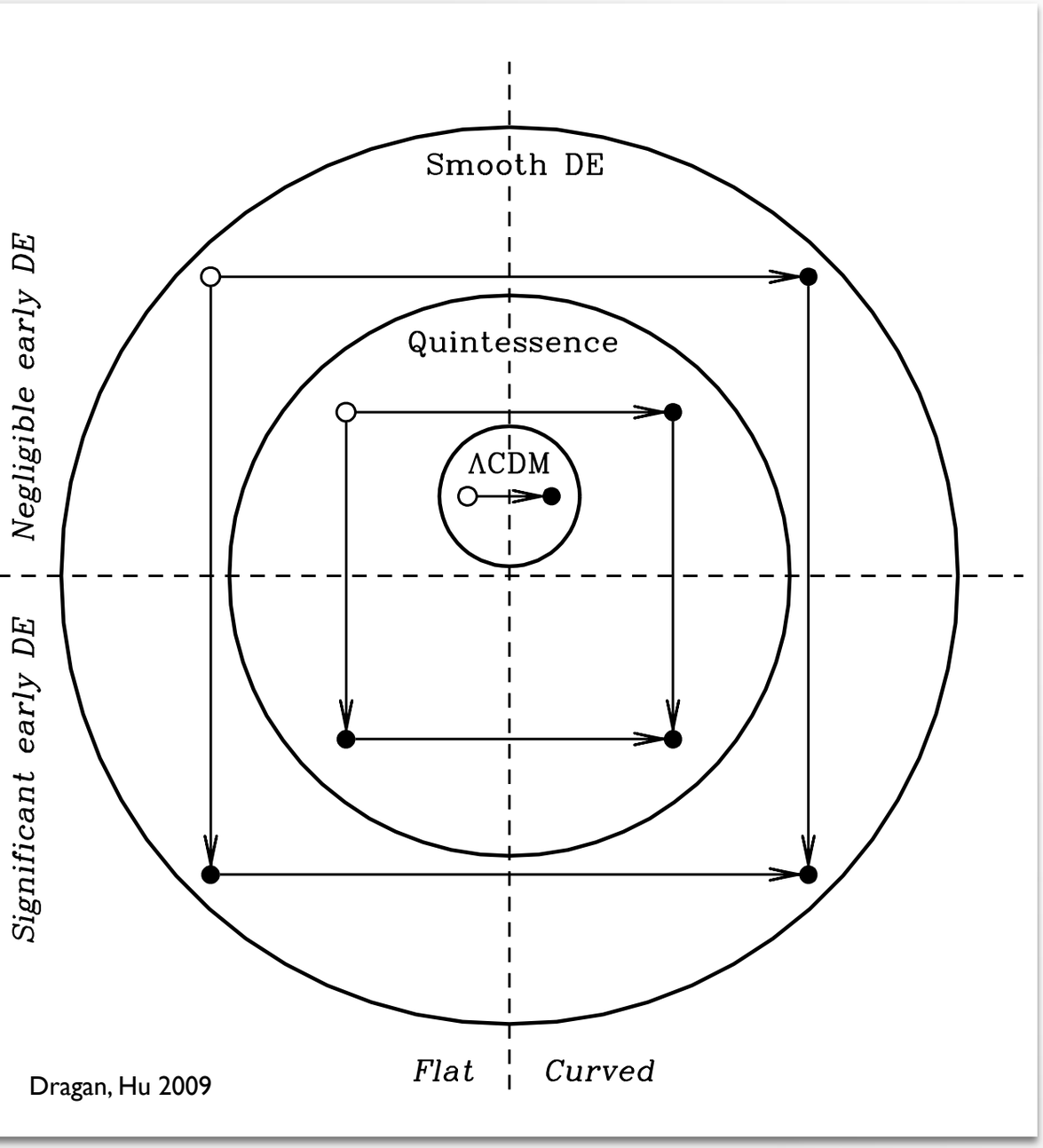
Part III: Late Universe

Habemus Acceleration: Candles are too dim



$$\Omega_m = 1 \Rightarrow \Delta m(z=1) \sim -0.5$$

Generic approach to the problem



How can we falsify the simplest Paradigm of Cosmic Acceleration?

- General Relativity
- Minimal coupling to Dark Matter
- Minimal coupling to the standard model
- Smooth Dark Energy (no clustering)

Pantheon SN

$$\Delta^2_m(k,a) \propto \left[\frac{G^2(a)a}{\Omega^2_m}\right]\left[T^2(k)\right]\left[\Delta^2_{\mathcal{R}}(k)\right]$$

Matter Power Spectrum

Growth Factor

Physics inside the horizon

Power Spectrum from Inflation

Dark Energy can be complicated

LSS can be connected with

everything

WFIRST - Wide Field Infrared Survey Telescope



WFIRST - Wide Field Infrared Survey Telescope

We released the state-of-the-art analysis of what WFIRST can do

Simulations of the *WFIRST* Supernova Survey and Forecasts of Cosmological Constraints

PI

R. Hounsell[1,2,*] D. Scolnic[3], R. J. Foley[1], R. Kessler[3], V. Miranda[4], A. Avelino[5]
R. C. Bohlin[6], A. V. Filippenko[7], J. Frieman[3,8], S. W. Jha[9], P. L. Kelly[7],
R. P. Kirshner[5,11], K. Mandel[5], A. Rest[6], A. G. Riess[6,12], S. A. Rodney[10], L. Strolger[6]



Rebekah Hounsell



Dan Scolnic



Richard Kessler



V. Miranda

WFIRST - Wide Field Infrared Survey Telescope

Expanded the analysis to general smooth dark energy paradigm

Model-Independent Predictions for Smooth Cosmic Acceleration Scenarios

Vinicius Miranda[1] and Cora Dvorkin[2]

[1] *Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[2] *Harvard University, Department of Physics, Cambridge, MA 02138, USA*



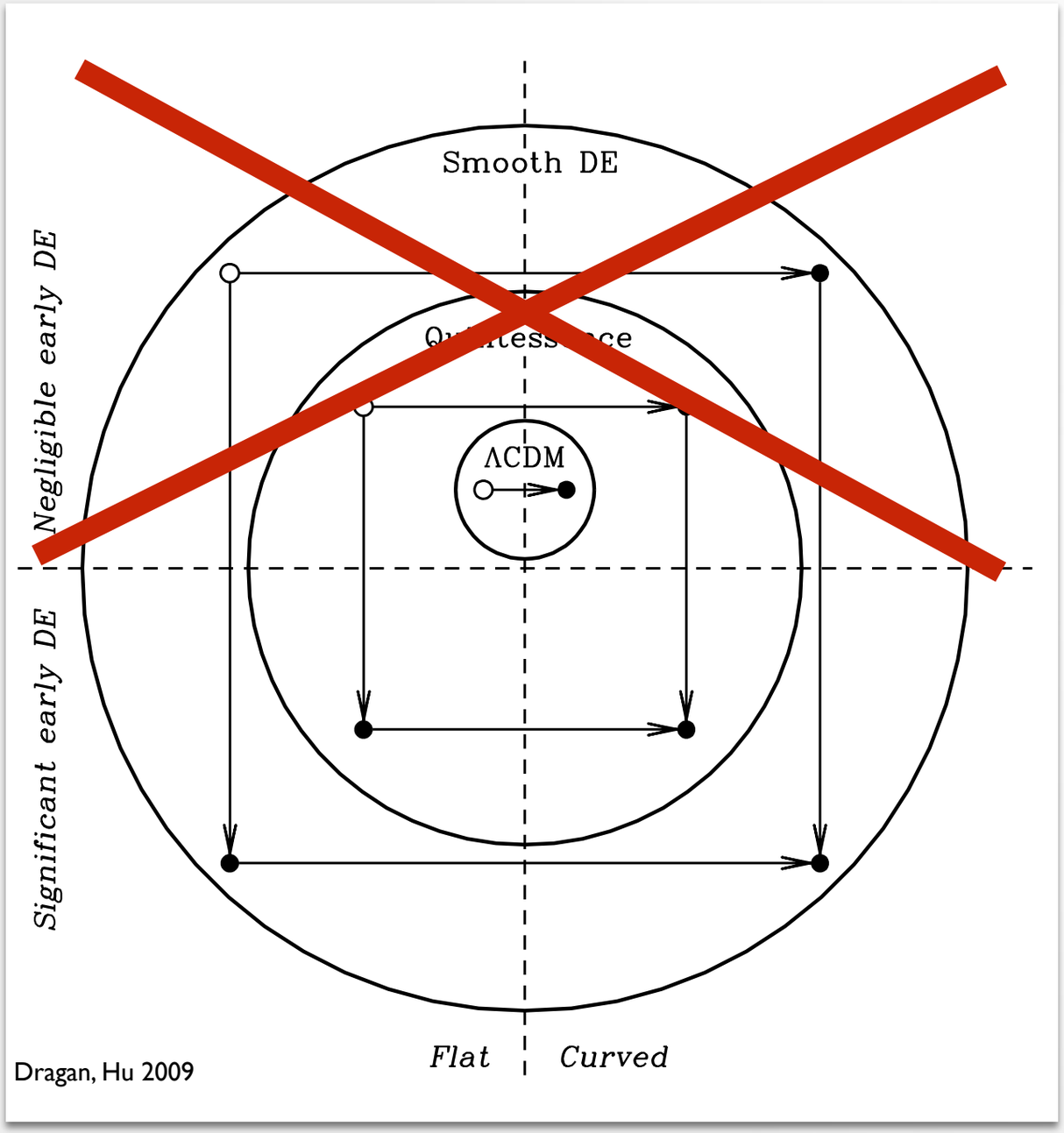
V. Miranda



Cora Dvorkin

If smooth dark energy paradigm fails, something quite exotic will become the standard model!

WFIRST - Wide Field Infrared Survey Telescope



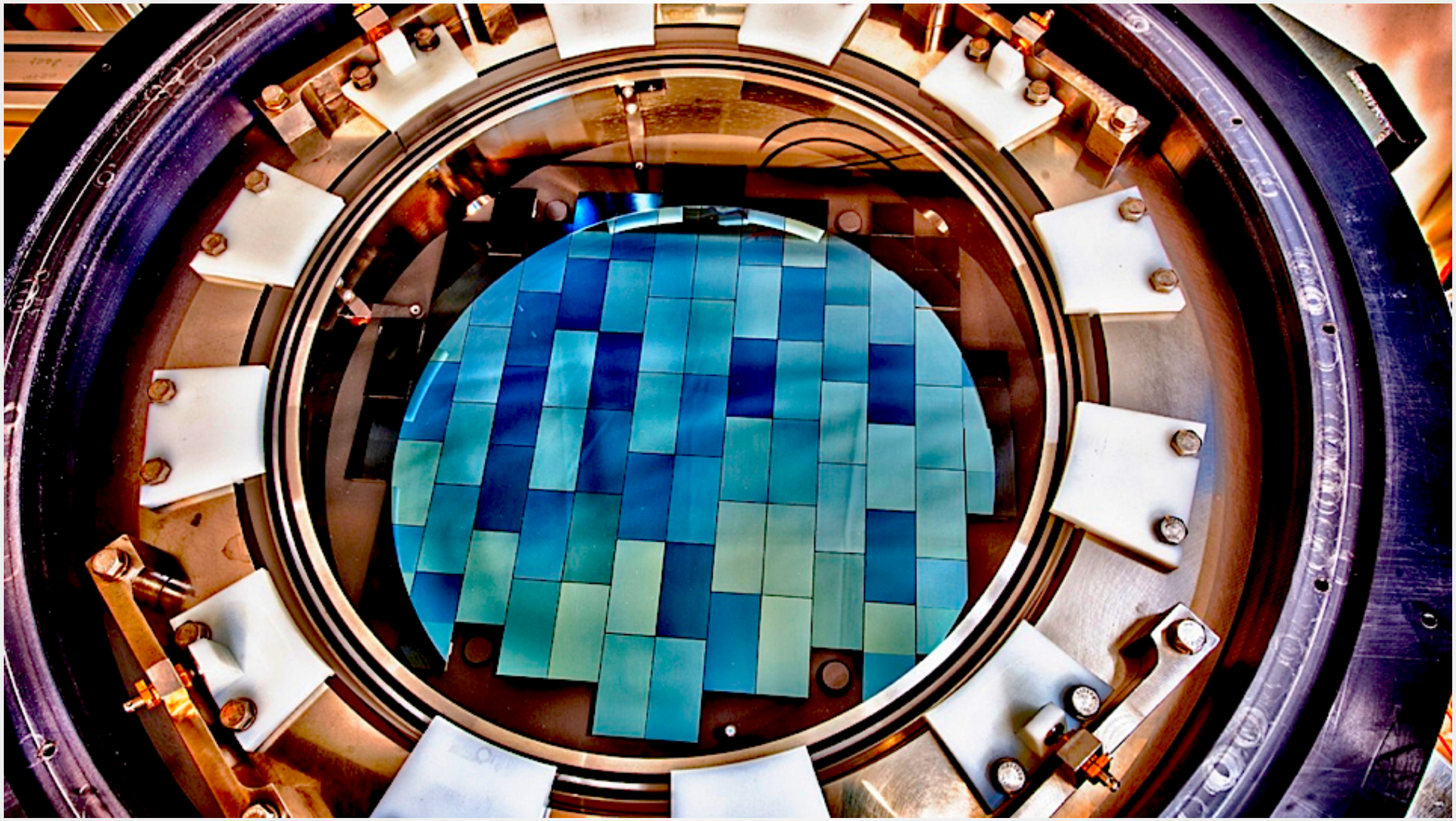
Dragan, Hu 2009

If growth deviates from LCDM

by more than +-5%

Currently, we are investigating how future CMB lensing probes can constrain early dark energy

DES - The Dark Energy Survey



DES - The Dark Energy Survey

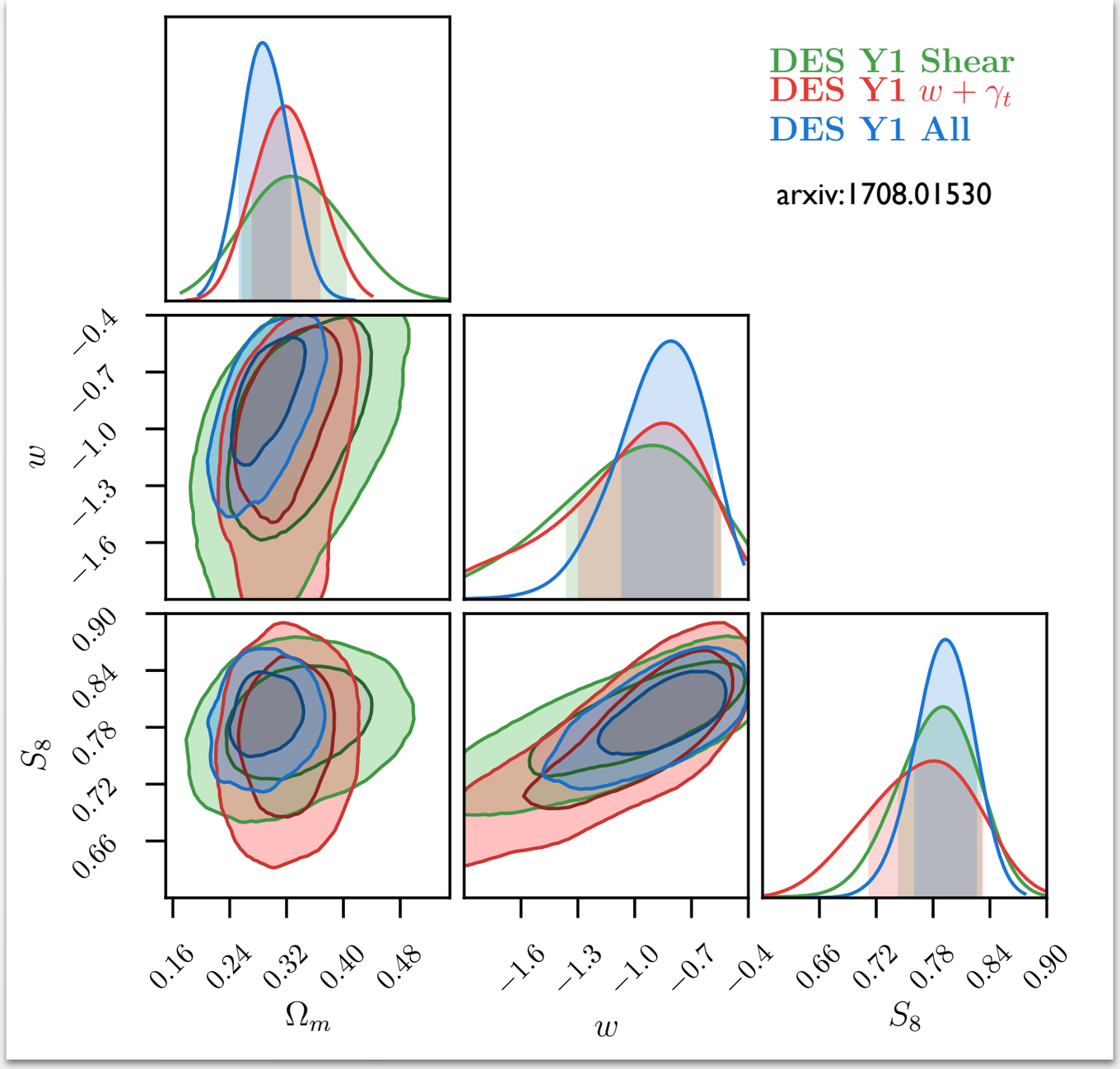
Cosmic Shear

Galaxy-Galaxy Lensing

Galaxy/Cluster Clustering

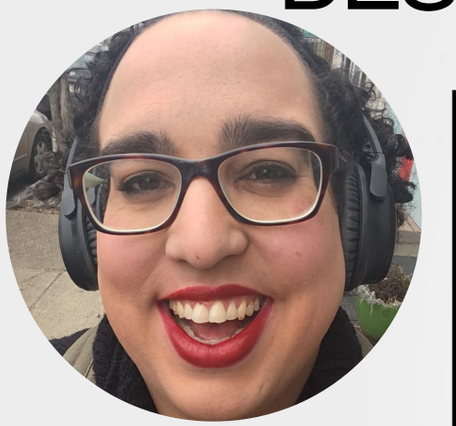
Advantage of multiple probes?

Degeneracy breaking!



DES - The Dark Energy Survey

DES Extensions - leading participation in all extensions!



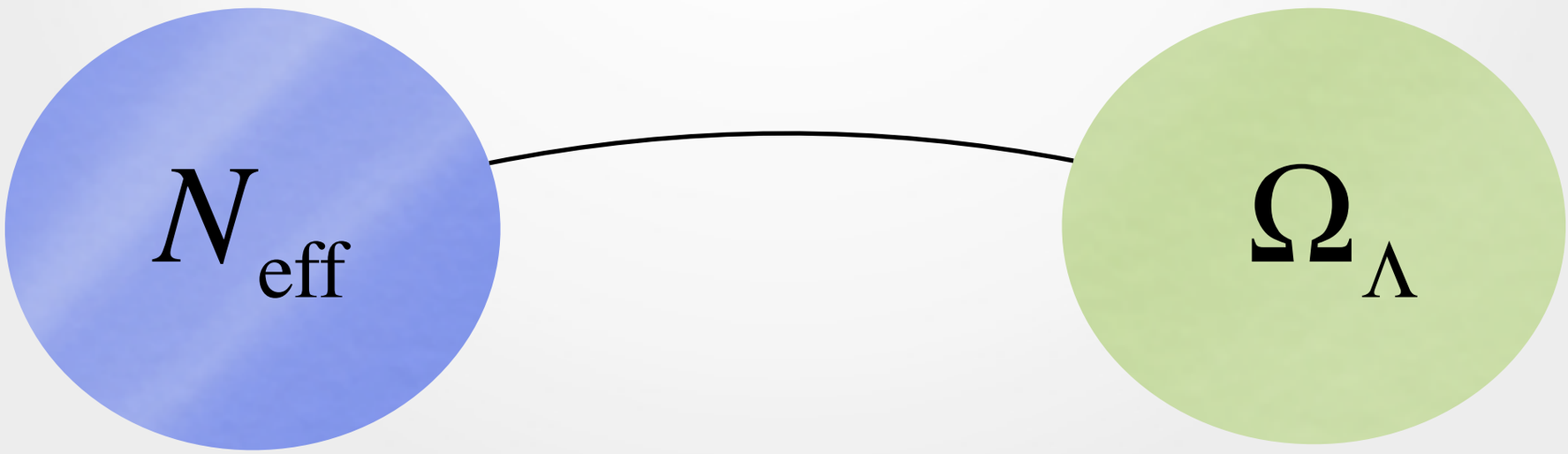
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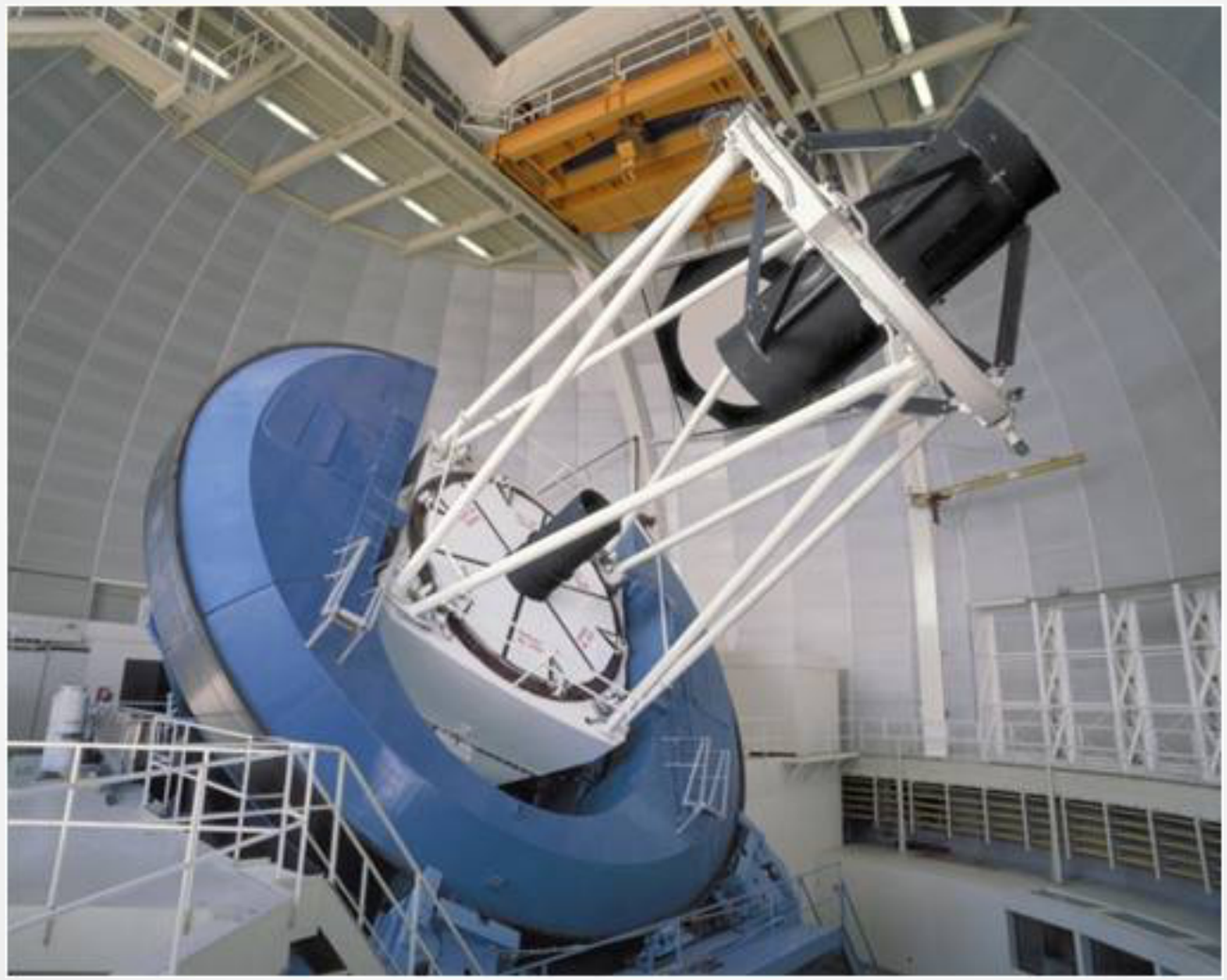
Dark Energy Survey Year 1 Results:
Constraints on Extended Cosmological Models from Galaxy Clustering and Weak Lensing

Key paper authors[1]
(Dark Energy Survey Collaboration)*
[1] *Universities*
(Dated: September 20, 2018)

Example of one relation between Early and Late Universe I explored



DESI - Dark Energy Spectroscopic Instrument



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It is the nature of things that they *are* ties to each other.

***Chuang-tzu* (300BC)**

V. Miranda et al (2012, 2014(a), 2014(b))
V. Miranda et al (2015)
Adshead, Hu, V. Miranda (2013)

Early

He, V. Miranda & Hu (2017)
V. Miranda et al (2017)

Intermediate

V. Miranda et al (2009, 2017(a), 2017(b))
Orbied et al (2017, 2018)
Vega et al (2017),
DES-WFIRST papers,

Late