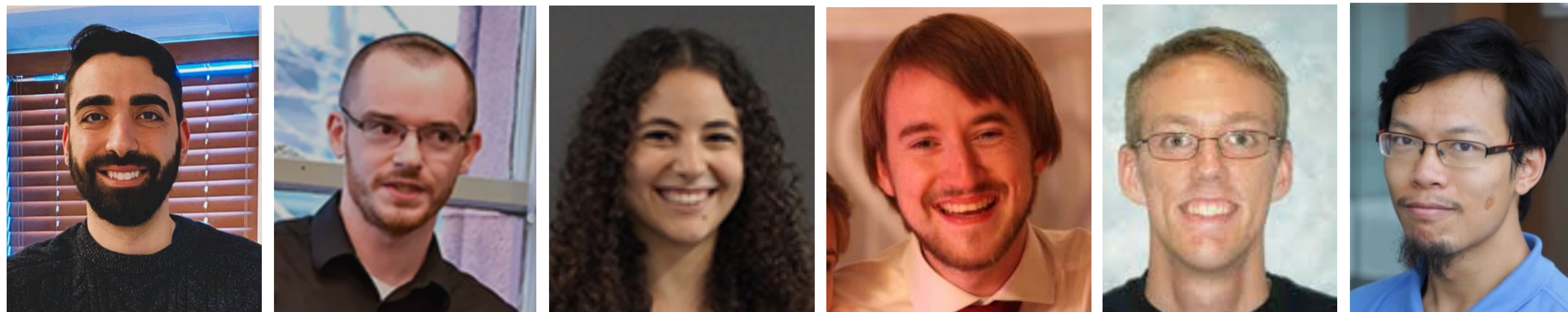


# Precision measurements and new problems

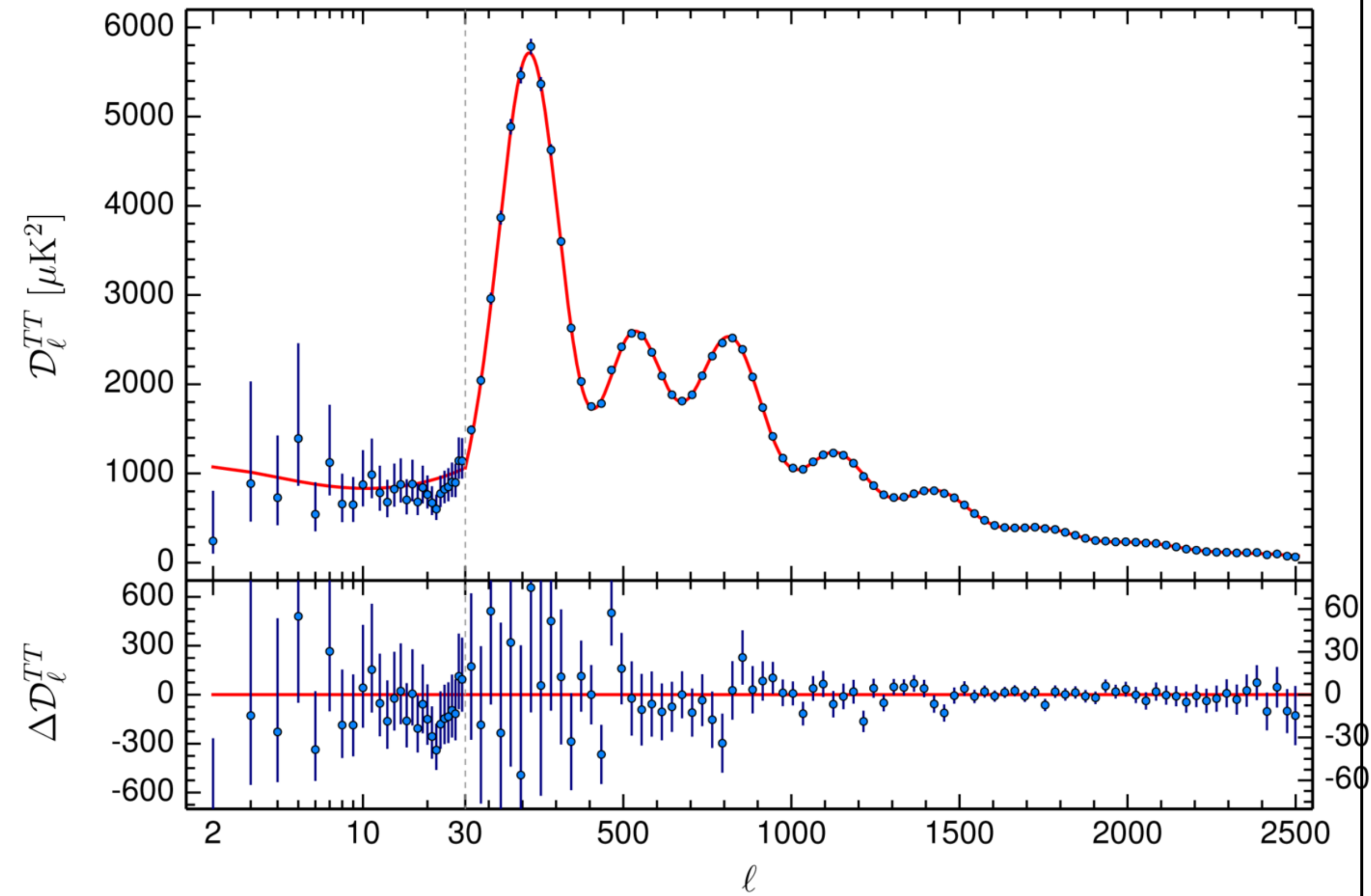
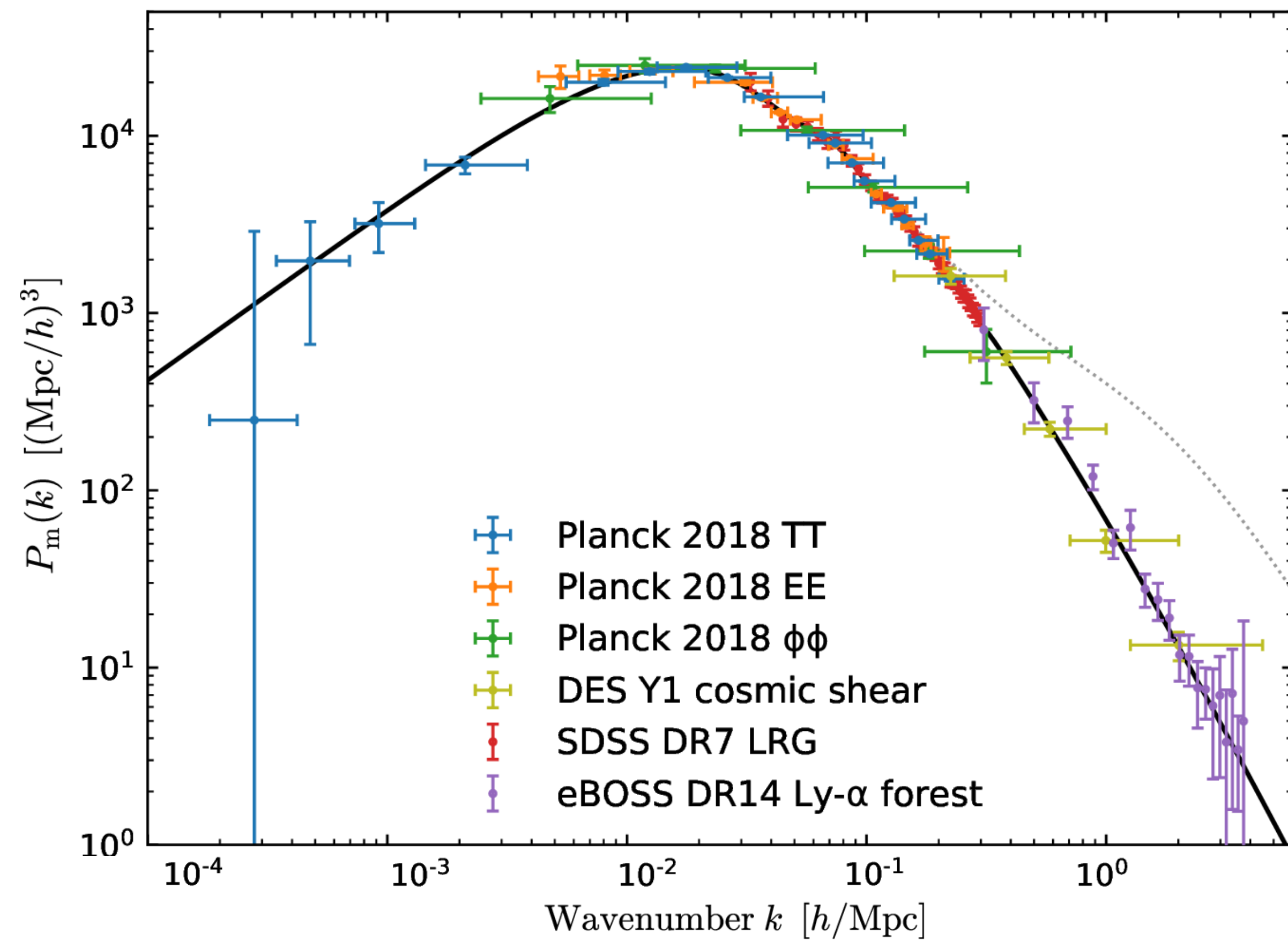
Savvas M. Koushiappas



Many thanks to colleagues Stephon Alexander, **Gordon Blackadder**, **Steven Clark**, Jiji Fan, **Isabelle Goldstein**, **Lingfeng Liu**, **Michael Toomey**, **Kyriakos Vattis**.



# $\Lambda$ CDM Cosmological model: very successful!



# Growing tensions in $\Lambda$ CDM cosmology...

Despite its successes, recent precision measurements show disagreements

- H0 tension  $H(a) \sim \sum \rho_i(a)$
- Large scale structure tension  $\sigma_8^2 = \int W(kR) k^3 P_M(k) d \log k$   $S_8 = \sigma_8 \sqrt{\Omega_M/0.3}$
- Sub-galactic dark matter structure problems (core/cusp, too big to fail, dwarf galaxies, etc.)

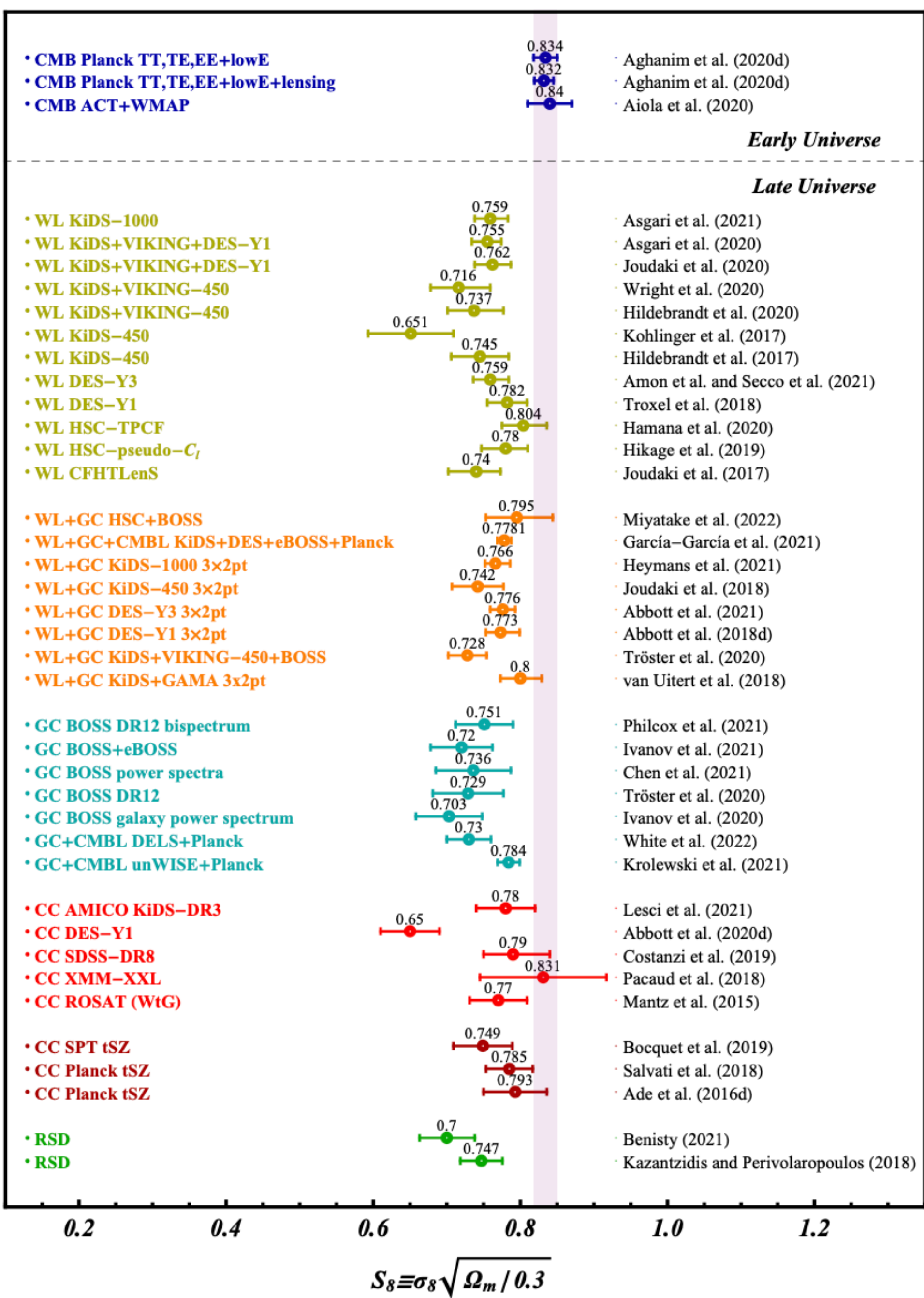
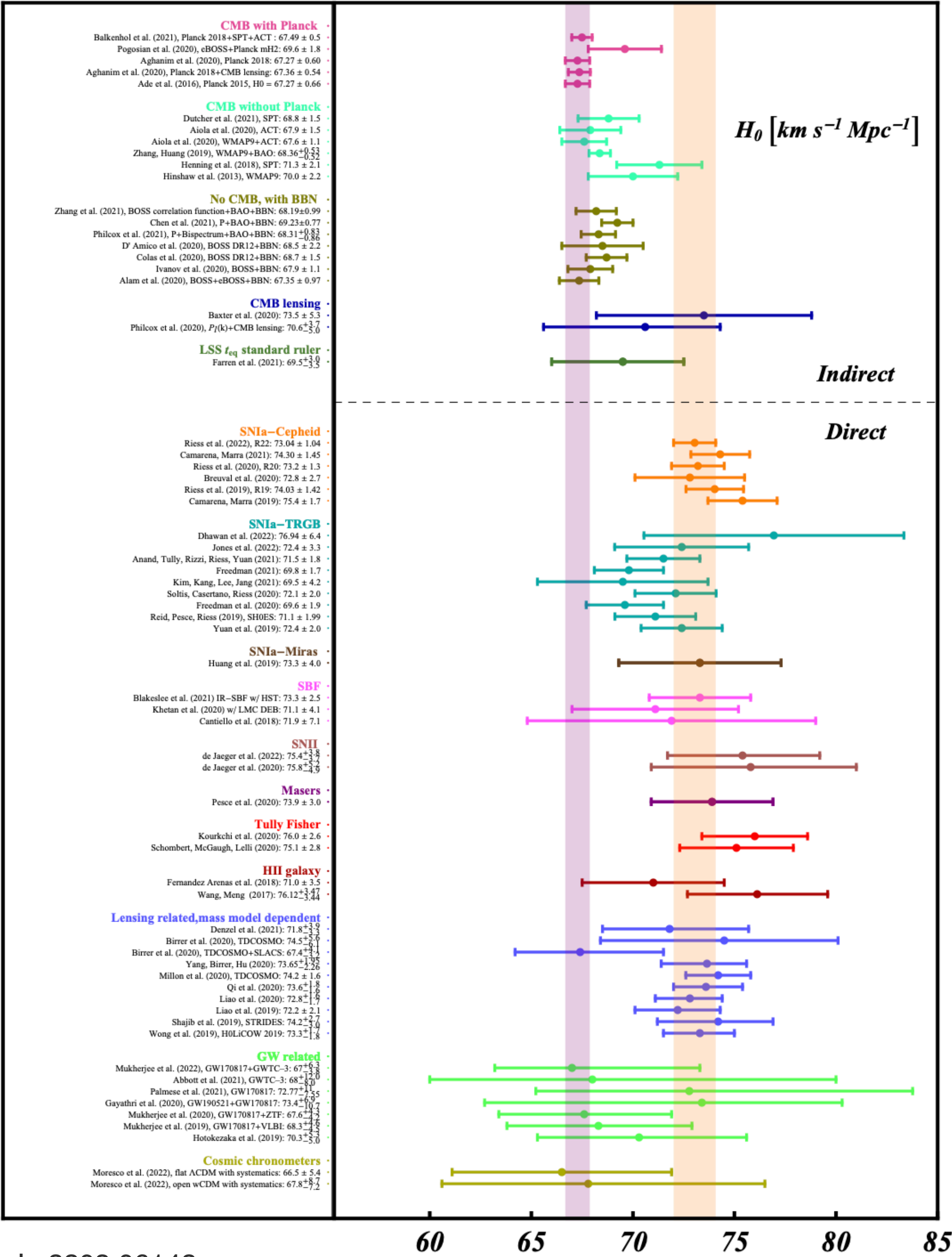
# Growing tensions in $\Lambda$ CDM cosmology...

Despite its successes, recent precision measurements show disagreements

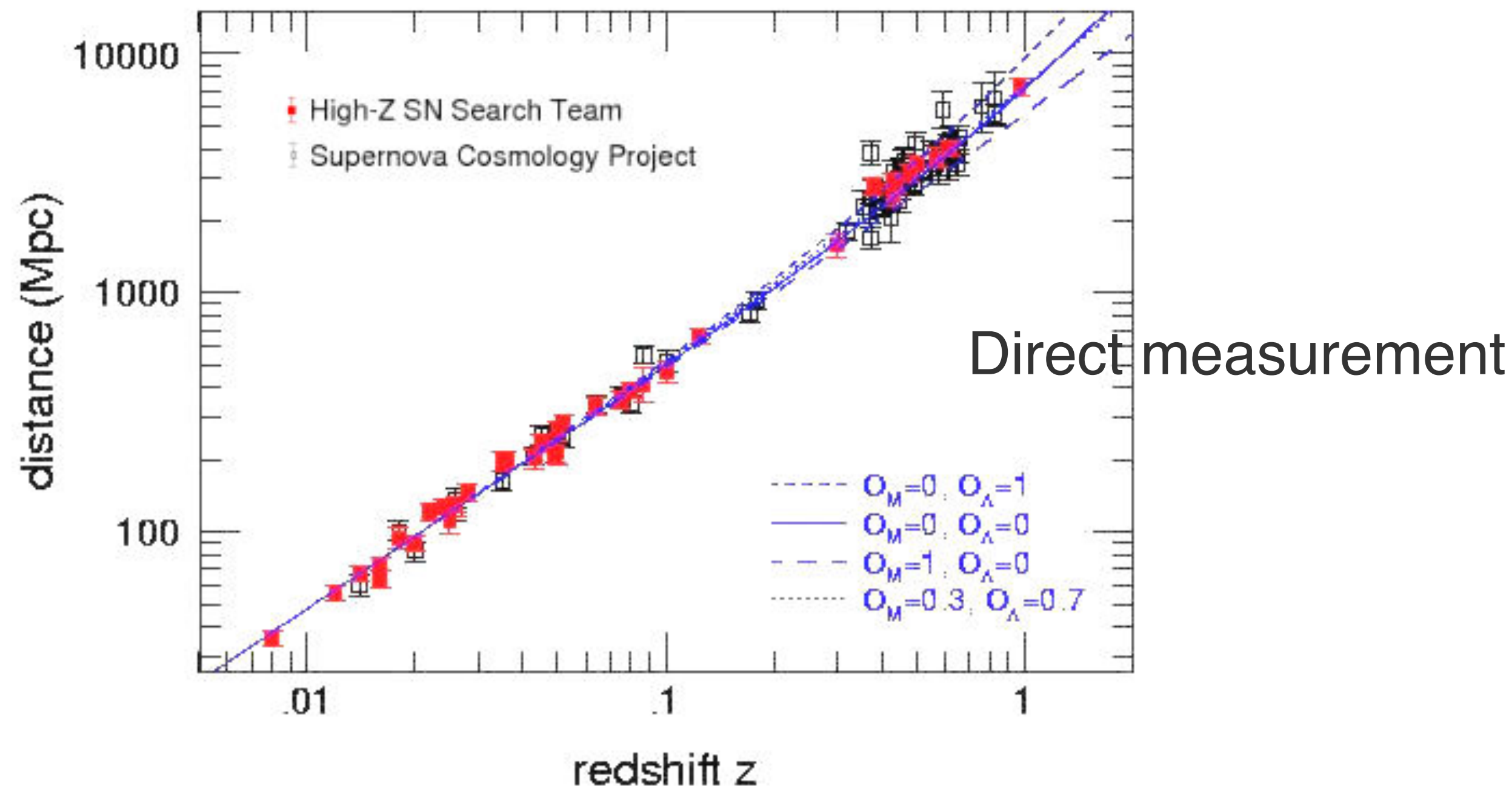
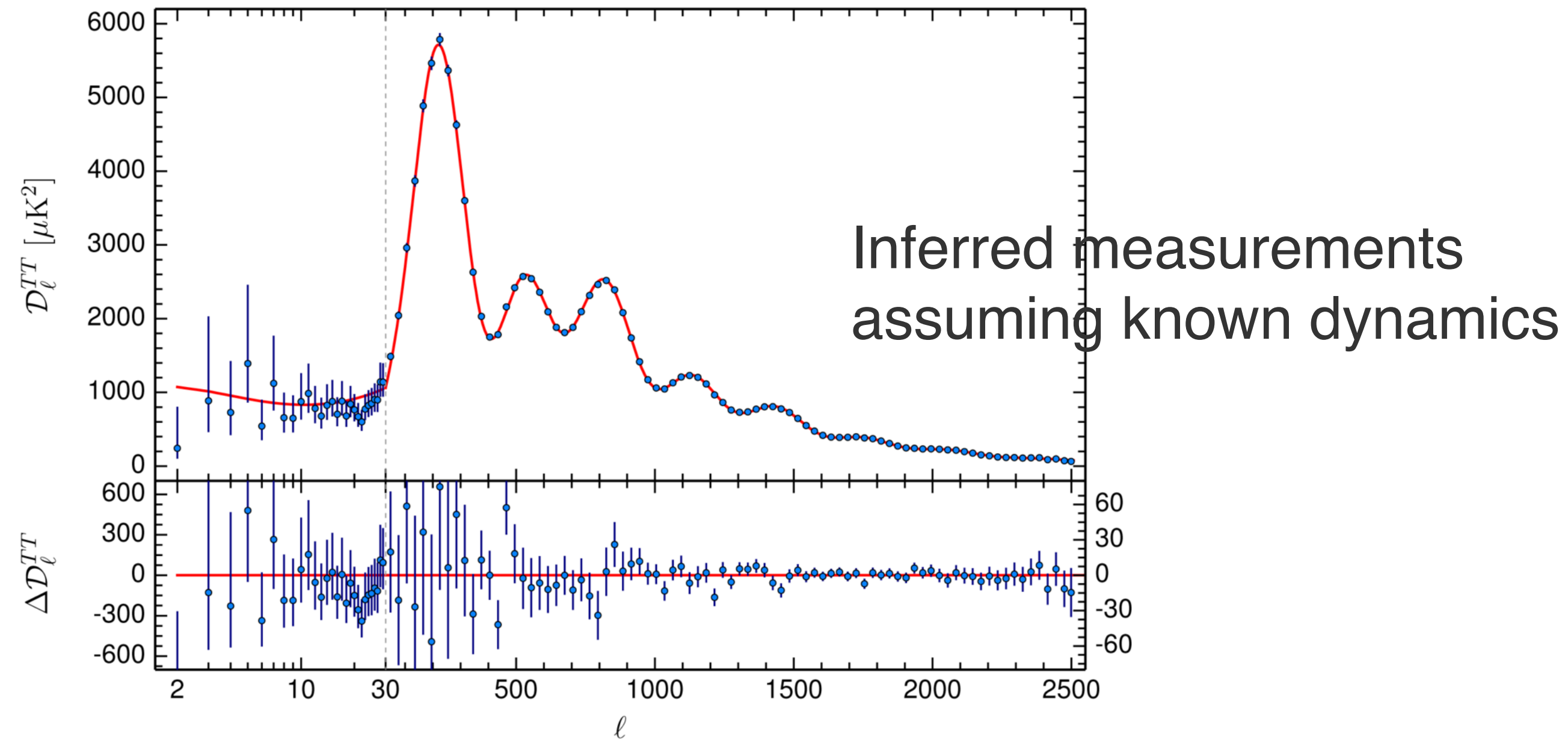
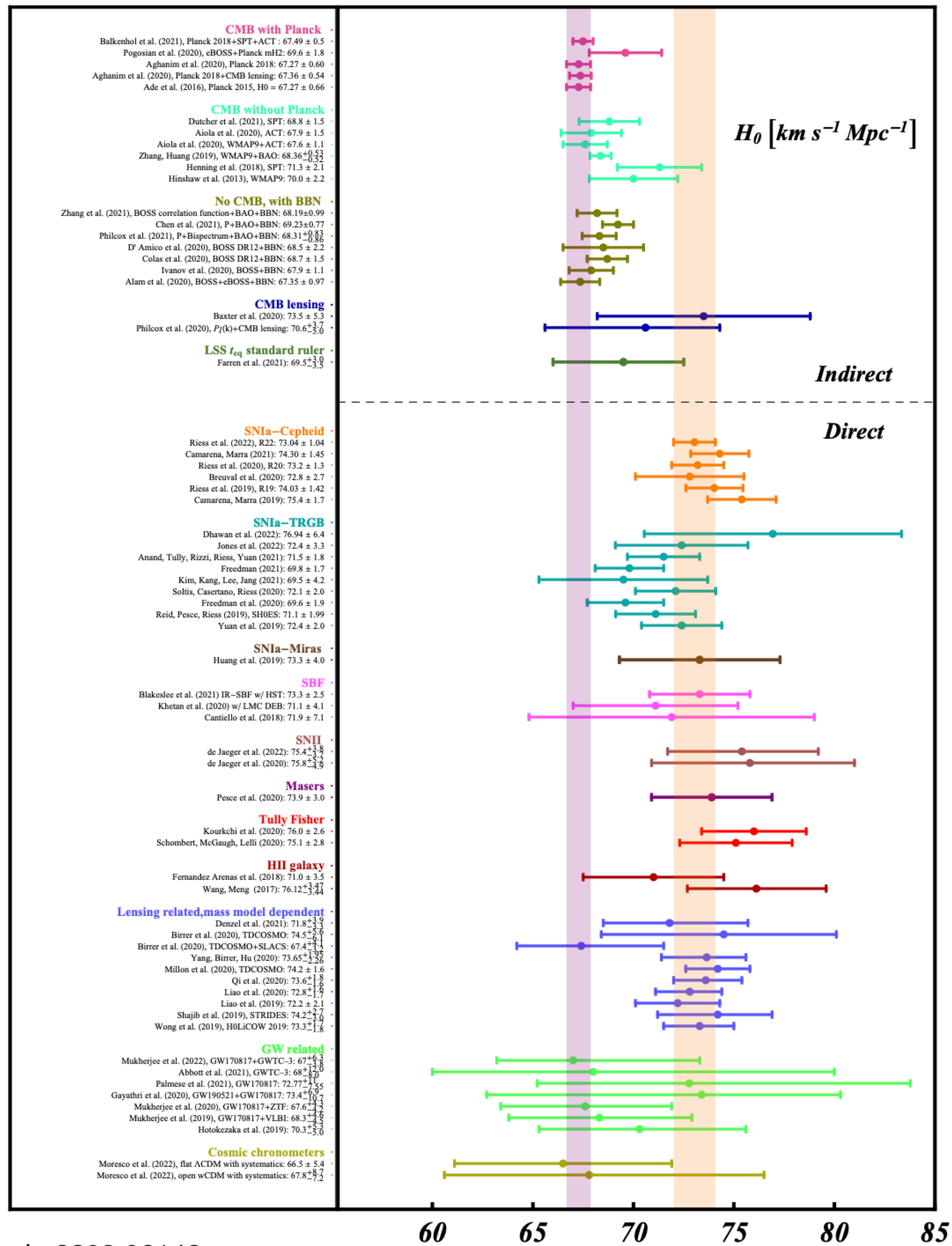
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Is it surprising we see tensions?

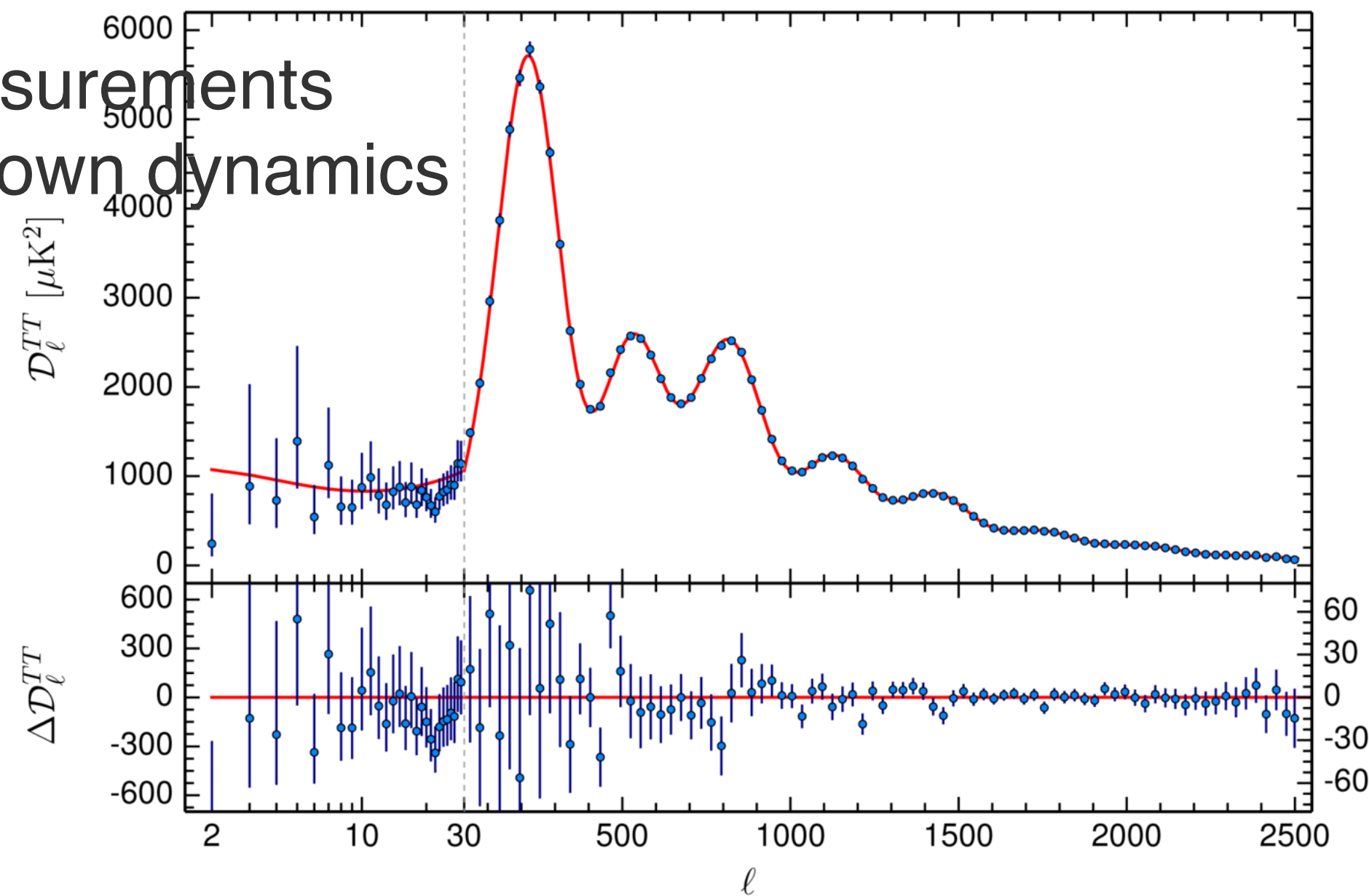
- $\Lambda$ CDM is only a macroscopic model
- Precision cosmology necessitates a microphysical model whose “coarse graining” should mimic  $\Lambda$ CDM.



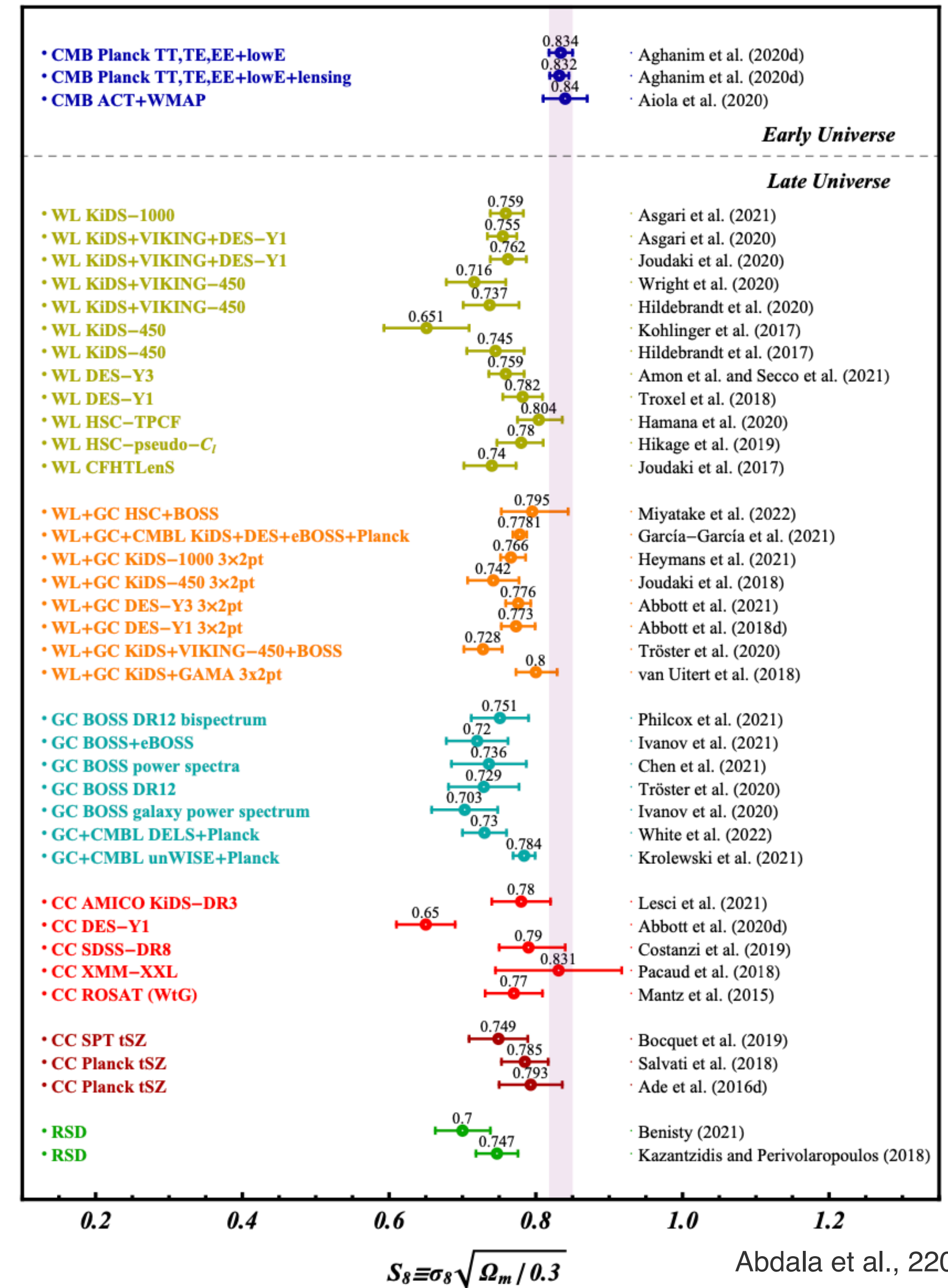
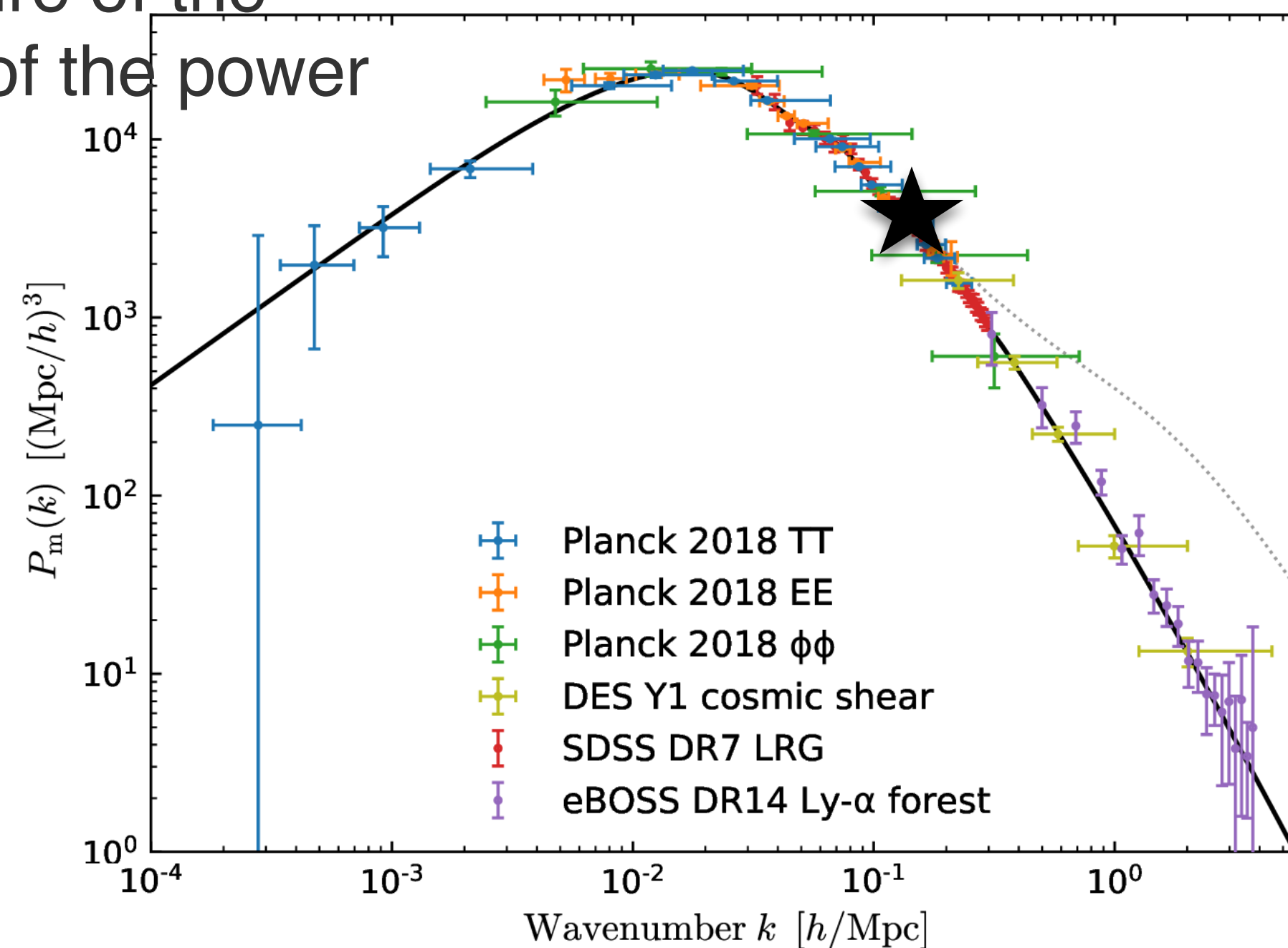
# H0 tension



Inferred measurements assuming known dynamics



A direct measure of the  
normalization of the power  
spectrum



# Stress

## Two forms of modifications to $\Lambda$ CDM

Early universe solutions (change the distance to the last scattering surface)

Late universe solutions (reshuffle the energy density of the universe at late times)

# Early dark energy solution

Increase the energy density by about 10% before recombination, i.e., move the sound horizon to earlier times.

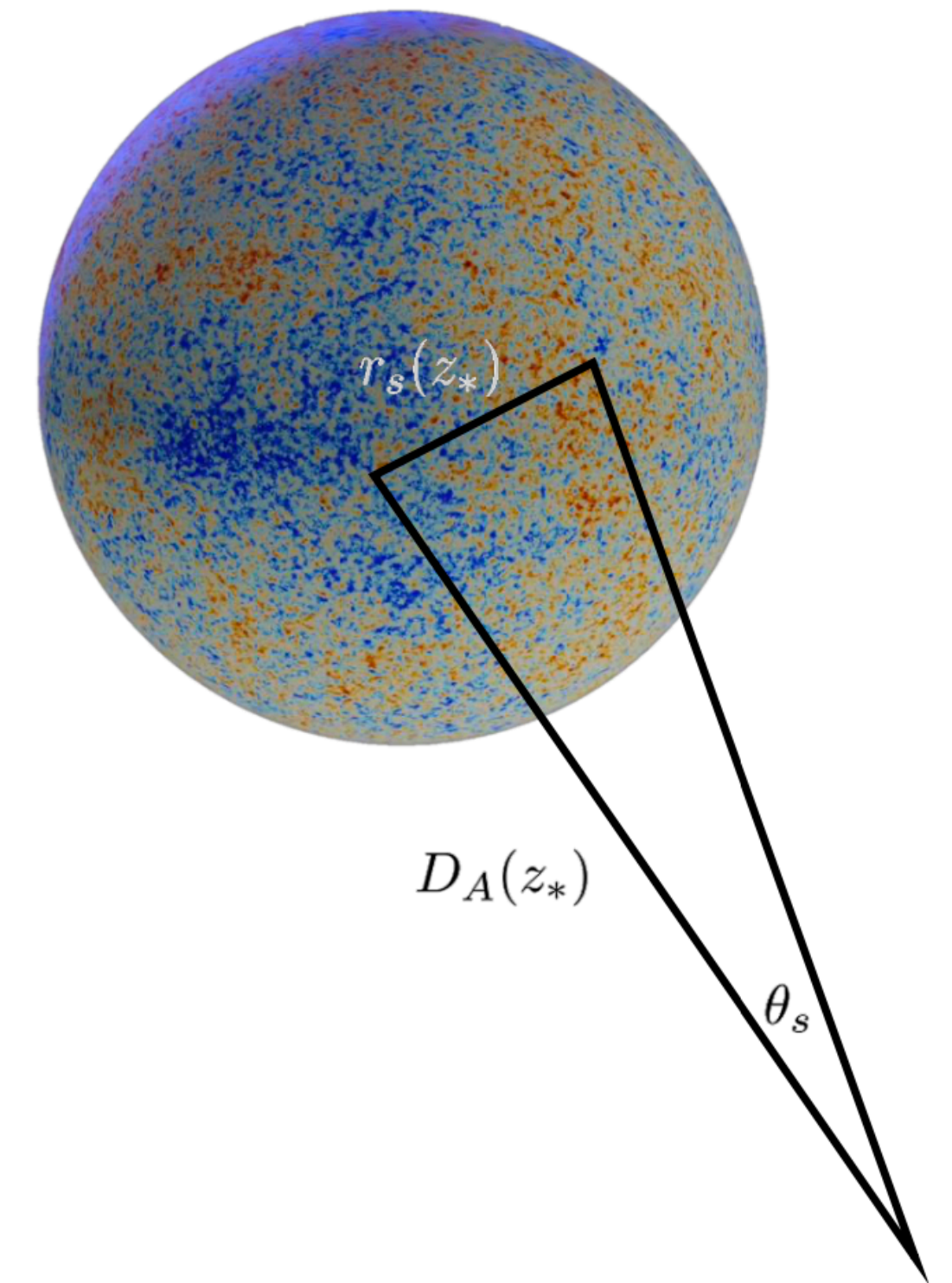
Requirement:  $\theta_s = \frac{r_s(z_\star)}{D_A(z_\star)}$   $r_s(z_\star) = \int_{z_\star}^{\infty} \frac{c_s(z)}{H(z)} dz$

$$D_A(z_\star) = \int_0^{z_\star} \frac{dz}{H(z)}$$

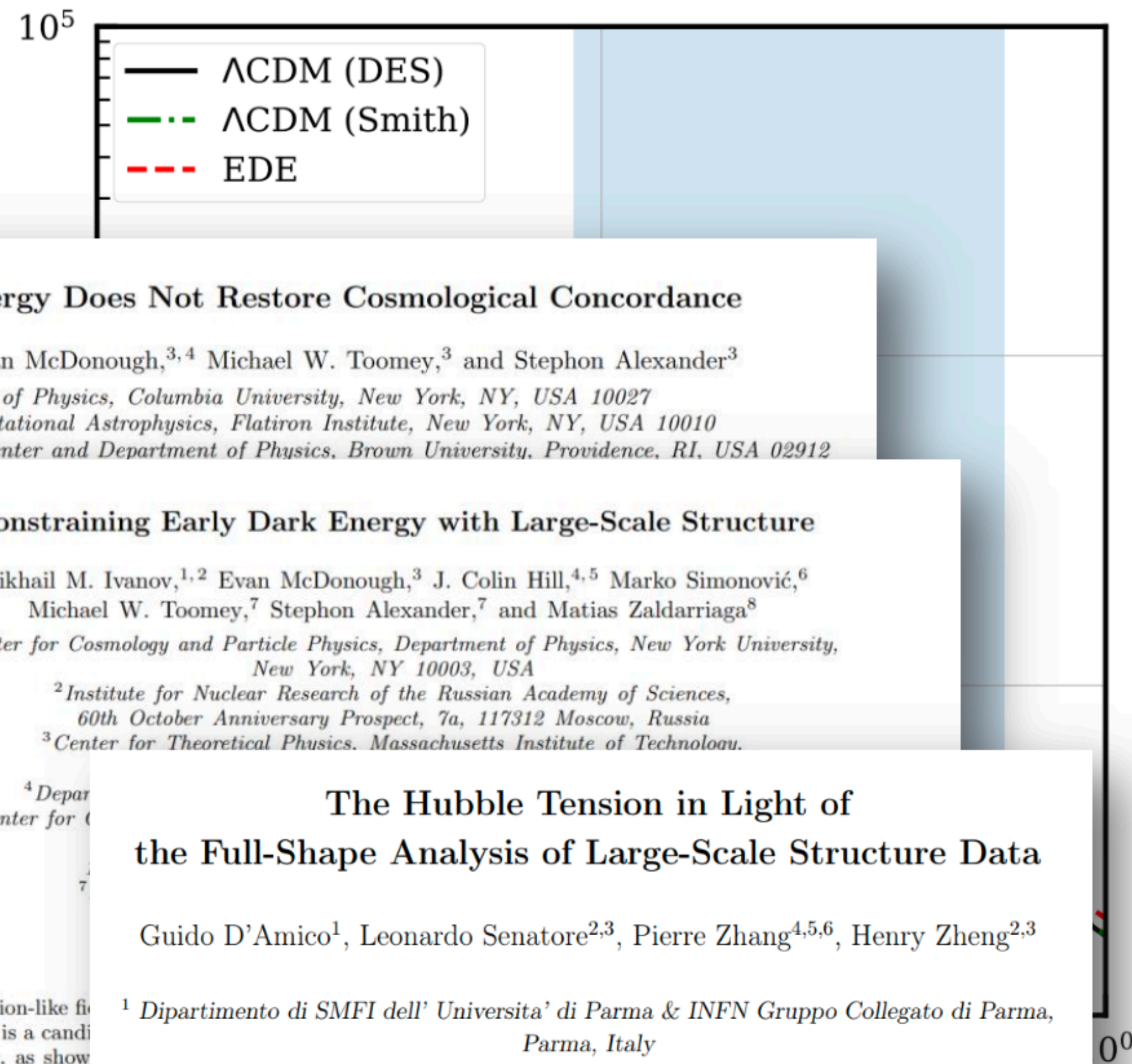
A light scalar field can act as dark energy (Early Dark energy)  $\ddot{\phi} + 3H\dot{\phi} + V_\phi = 0$

Equation of state  $w_\phi = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$   $V = V_0[1 - \cos(\phi/f)]^n, \quad V_0 \equiv m^2 f^2$   
Axion-like potential

For  $H > m$  we have  $w \approx -1$



# EDE in significant conflict with large scale structure



**Early Dark Energy Does Not Restore Cosmological Concordance**

J. Colin Hill,<sup>1,2</sup> Evan McDonough,<sup>3,4</sup> Michael W. Toomey,<sup>3</sup> and Stephon Alexander<sup>3</sup>

<sup>1</sup>Department of Physics, Columbia University, New York, NY, USA 10027  
<sup>2</sup>Center for Computational Astrophysics, Flatiron Institute, New York, NY, USA 10010  
<sup>3</sup>Brown Theoretical Physics Center and Department of Physics, Brown University, Providence, RI, USA 02912  
<sup>4</sup>Center for

**Constraining Early Dark Energy with Large-Scale Structure**

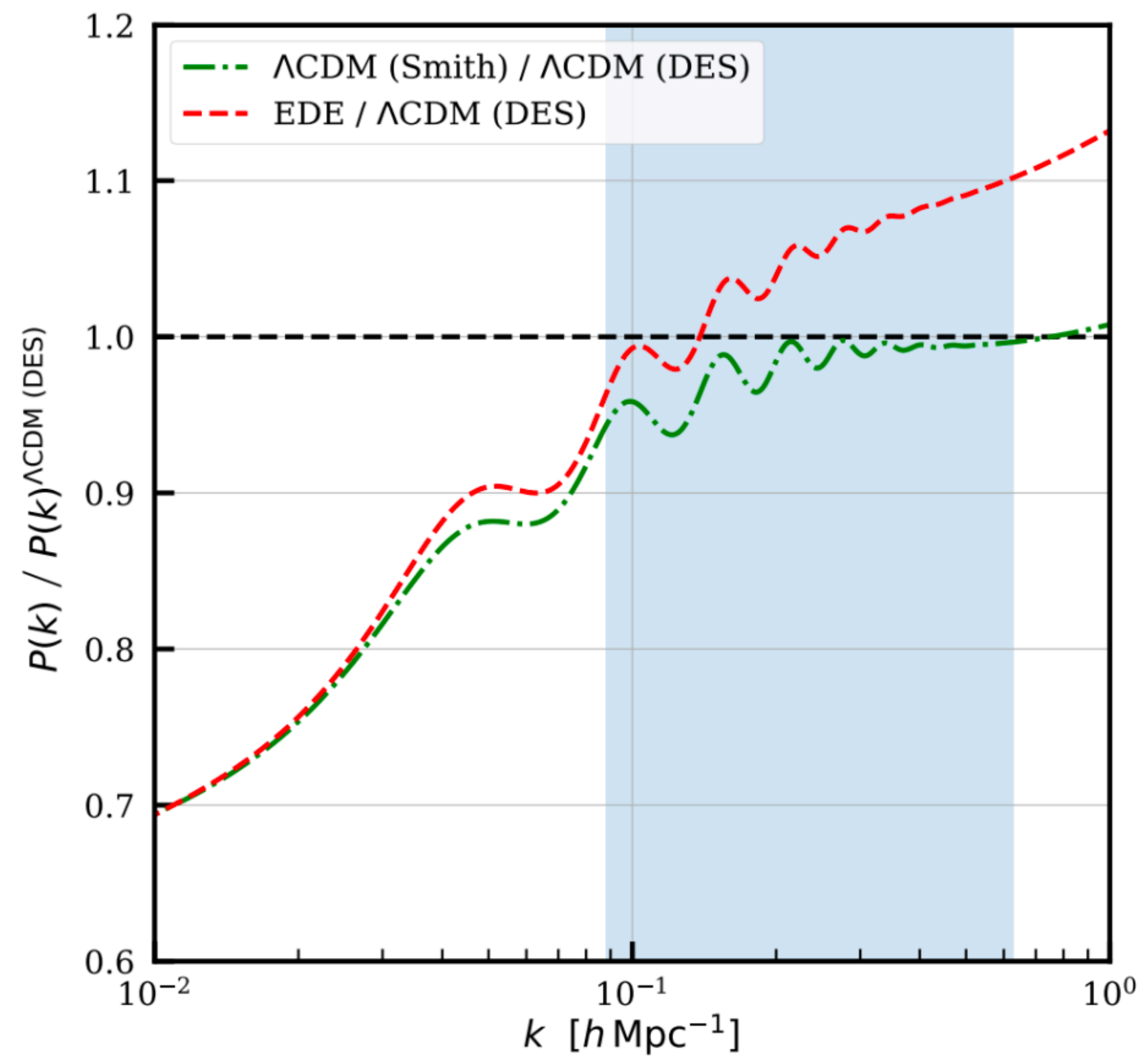
Mikhail M. Ivanov,<sup>1,2</sup> Evan McDonough,<sup>3</sup> J. Colin Hill,<sup>4,5</sup> Marko Simonović,<sup>6</sup> Michael W. Toomey,<sup>7</sup> Stephon Alexander,<sup>7</sup> and Matias Zaldarriaga<sup>8</sup>

<sup>1</sup>Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA  
<sup>2</sup>Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect, 7a, 117312 Moscow, Russia  
<sup>3</sup>Center for Theoretical Physics, Massachusetts Institute of Technology,

**The Hubble Tension in Light of the Full-Shape Analysis of Large-Scale Structure Data**

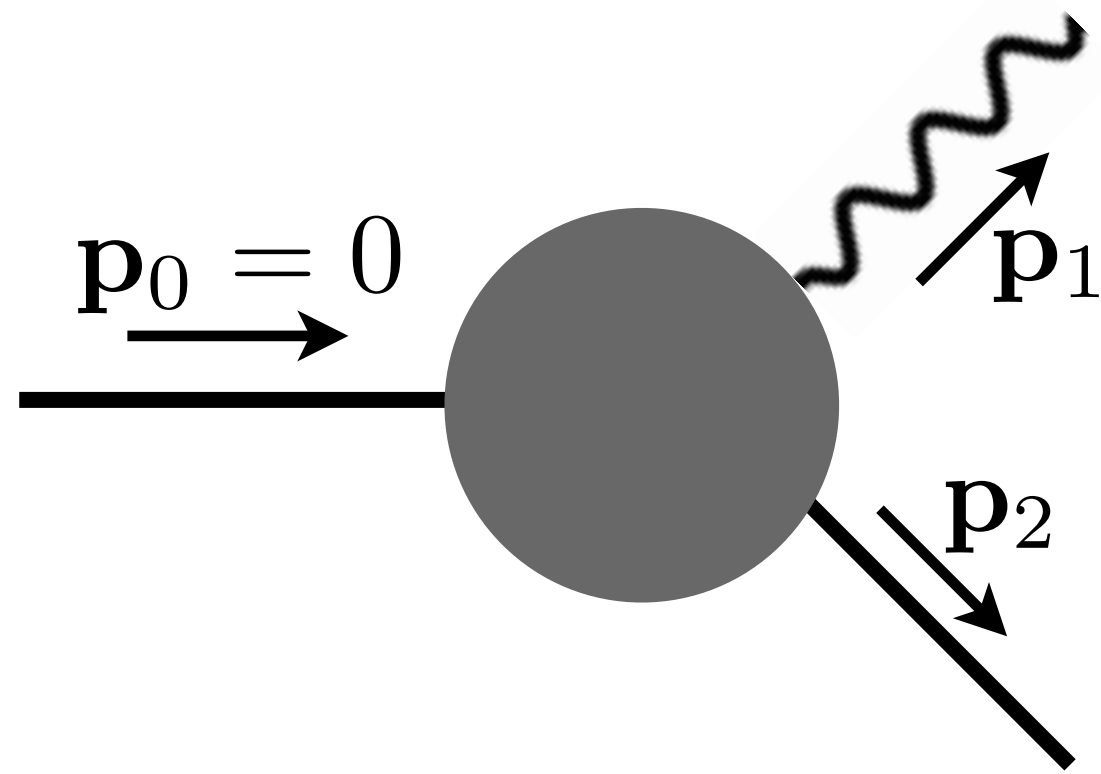
Guido D'Amico<sup>1</sup>, Leonardo Senatore<sup>2,3</sup>, Pierre Zhang<sup>4,5,6</sup>, Henry Zheng<sup>2,3</sup>

<sup>1</sup> Dipartimento di SMFI dell' Università di Parma & INFN Gruppo Collegato di Parma, Parma, Italy  
<sup>2</sup> Stanford Institute for Theoretical Physics, Physics Department, Stanford University, Stanford, CA 94306  
<sup>3</sup> Kavli Institute for Particle Astrophysics and Cosmology, SLAC and Stanford University, Menlo Park, CA 94025



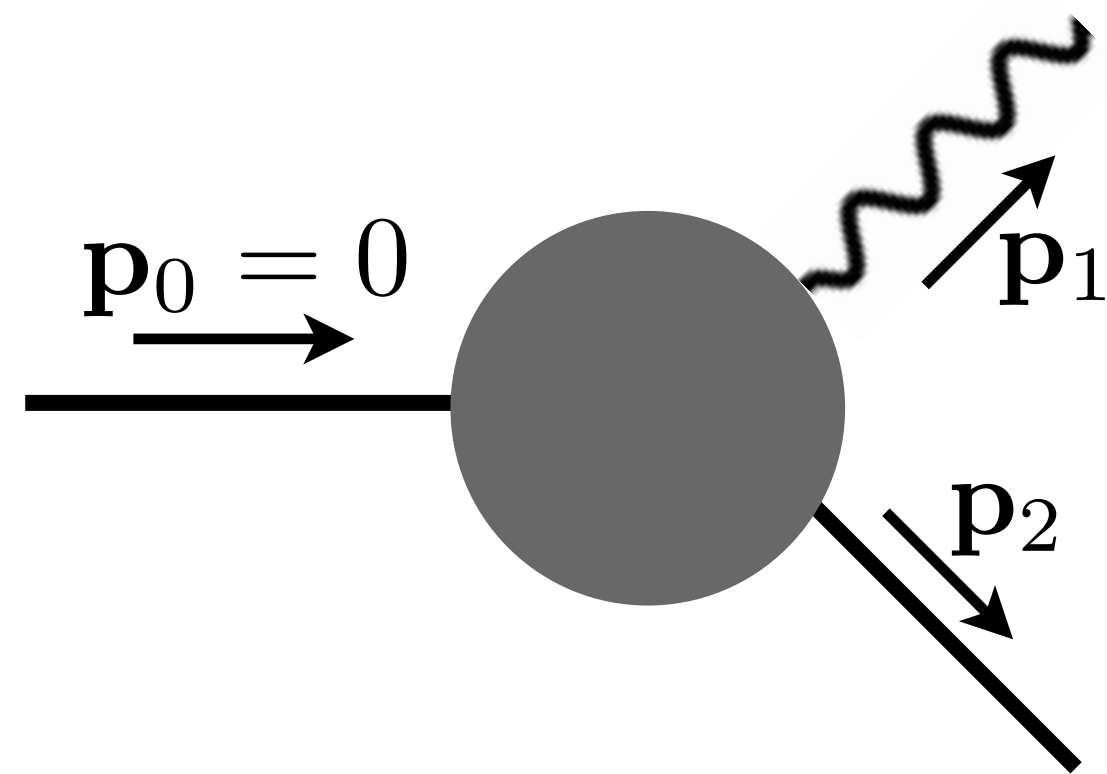
To solve this problem: Decaying dark matter

$$\psi \rightarrow \chi \gamma$$



To solve this problem: Decaying dark matter

$$\psi \rightarrow \chi \gamma$$



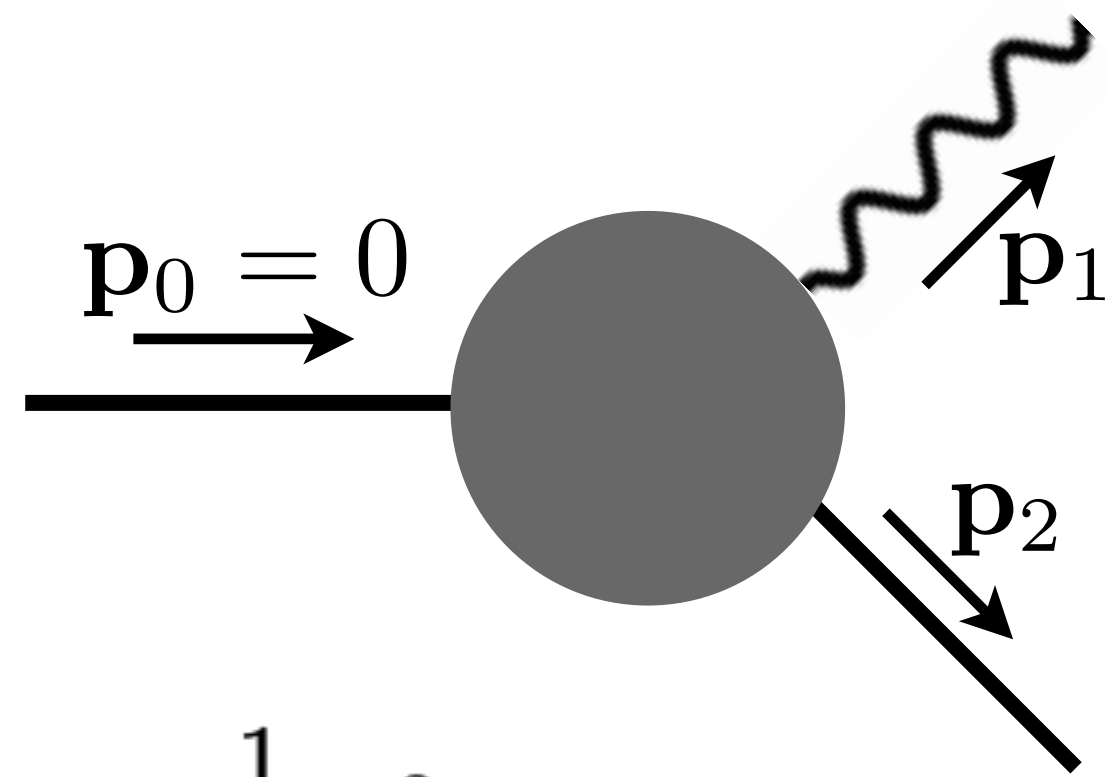
$$\dot{\bar{\rho}}_0 = -3\mathcal{H}\bar{\rho}_0 - a\Gamma\bar{\rho}_0,$$

$$\dot{\bar{\rho}}_1 = -4\mathcal{H}\bar{\rho}_1 + \epsilon a\Gamma\bar{\rho}_0,$$

$$\dot{\bar{\rho}}_2 = -3(1 + w_2)\mathcal{H}\bar{\rho}_2 + (1 - \epsilon)a\Gamma\bar{\rho}_0$$

# To solve this problem: Decaying dark matter

$$\psi \rightarrow \chi \gamma$$

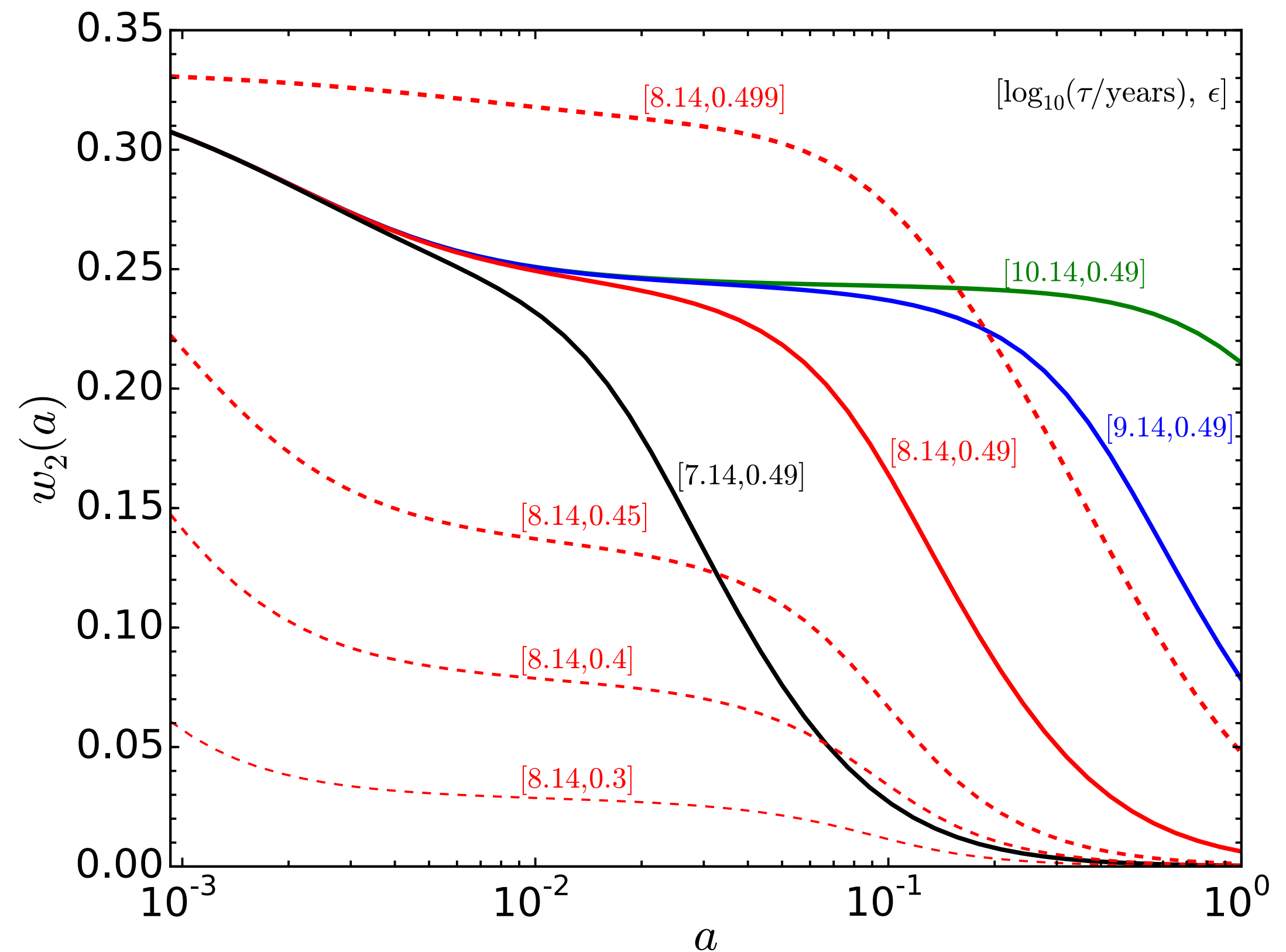


$$w_2(a) = \frac{1}{3} \langle v_2^2(a) \rangle$$

$$\langle v^2(\eta) \rangle = \int_{\eta_*}^{\eta} v^2(\tilde{a}) \dot{n}_2 d\eta_D / \int_{\eta_*}^{\eta} \dot{n}_2 d\eta_D$$

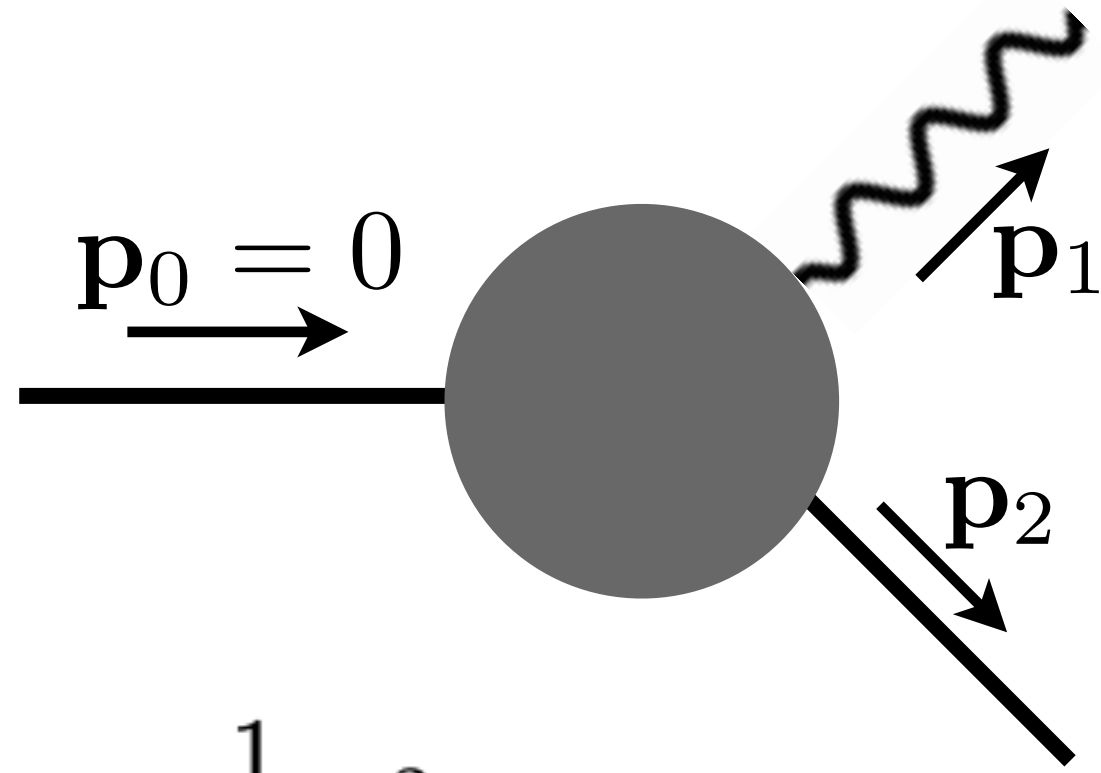
$$v^2(\tilde{a}) = \frac{\tilde{a}^2 \beta_2^2}{1 + \beta_2^2 [\tilde{a}^2 - 1]},$$

$$\begin{aligned} \dot{\bar{\rho}}_0 &= -3\mathcal{H}\bar{\rho}_0 - a\Gamma\bar{\rho}_0, \\ \dot{\bar{\rho}}_1 &= -4\mathcal{H}\bar{\rho}_1 + \epsilon a\Gamma\bar{\rho}_0, \\ \dot{\bar{\rho}}_2 &= -3(1+w_2)\mathcal{H}\bar{\rho}_2 + (1-\epsilon)a\Gamma\bar{\rho}_0 \end{aligned}$$



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$$w_2(a) = \frac{1}{3} \langle v_2^2(a) \rangle$$

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$$v^2(\tilde{a}) = \frac{\tilde{a}^2 \beta_2^2}{1 + \beta_2^2 [\tilde{a}^2 - 1]},$$

$$(\delta_1 \dot{r}_1) = -\frac{4}{3} r_1 \theta_1 - \frac{2}{3} r_1 \dot{h} + \dot{r}_1 \delta_0,$$

$$\frac{4}{3k} (\theta_1 \dot{r}_1) = \frac{k}{3} \delta_1 r_1 - \frac{4k}{3} r_1 \sigma_1,$$

$$2(\sigma_1 \dot{r}_1) = \frac{8}{15} \theta_1 r_1 + \frac{4}{15} r_1 (\dot{h} + 6\dot{\eta}) + \text{h.o.}$$

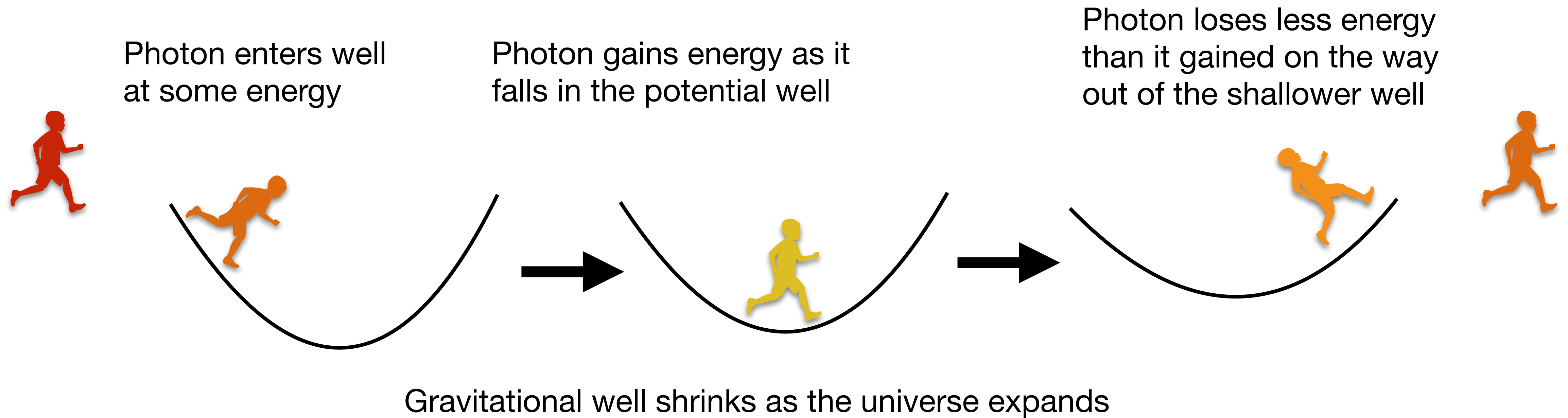
$$\dot{\delta}_2 = -3\mathcal{H}(c_{sg}^2 - w_2)\delta_2 - (1 + w_2) \left( \theta_2 + \frac{\dot{h}}{2} \right)$$

$$+ (1 - \epsilon) a \Gamma \frac{\bar{\rho}_0}{\bar{\rho}_2} (\delta_0 - \delta_2),$$

$$\dot{\theta}_2 = -\mathcal{H}(1 - 3c_g^2)\theta_2 + \frac{c_{sg}^2}{1 + w_2} k^2 \delta_2 - k^2 \sigma_2$$

$$- (1 - \epsilon) a \Gamma \frac{1 + c_g^2}{1 + w_2} \frac{\bar{\rho}_0}{\bar{\rho}_2} \theta_2.$$

# Decays and the Integrated ISW effect

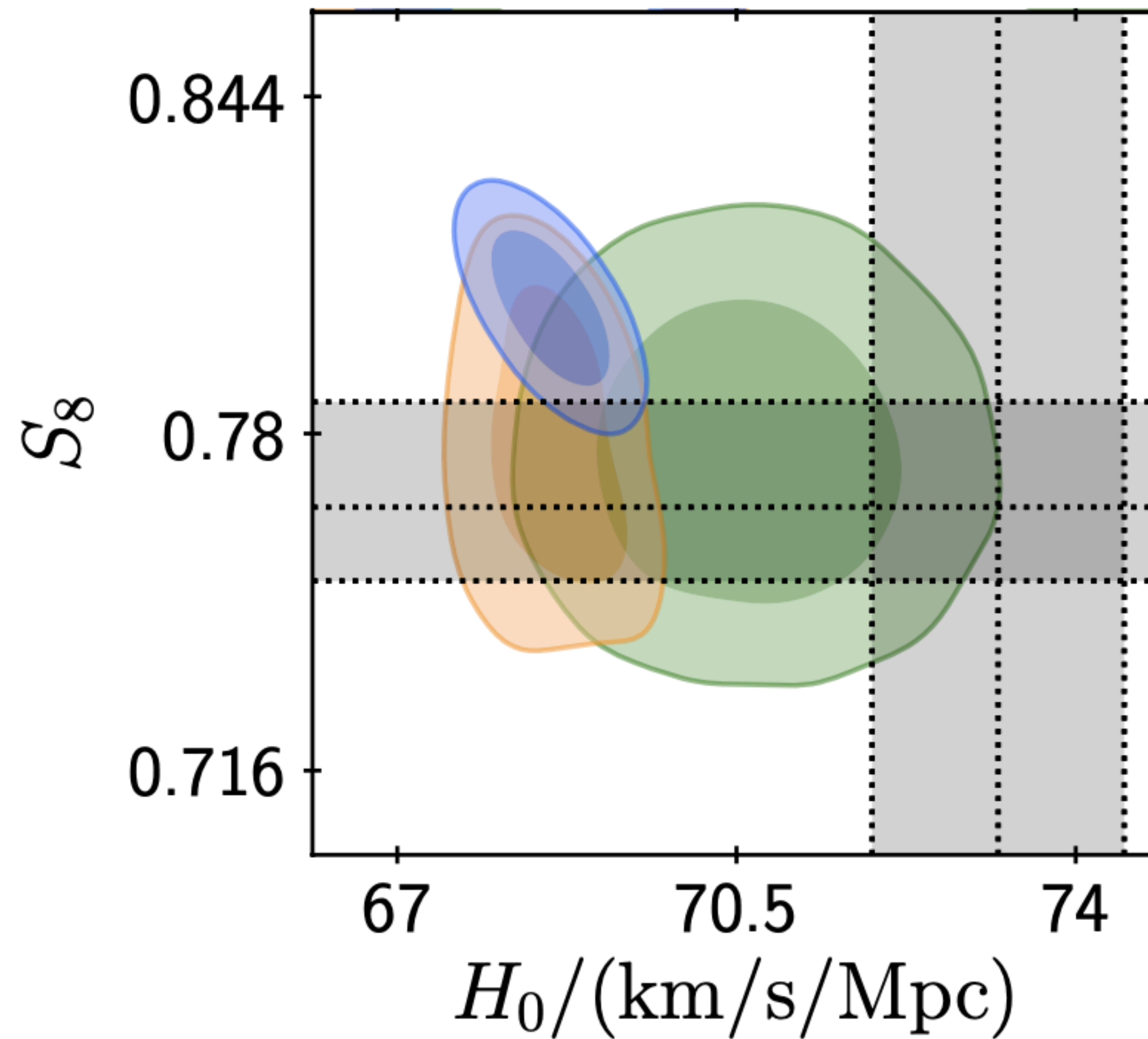


$$\Theta_{\text{ISW}}(\hat{\mathbf{p}}) \equiv \frac{\Delta T^{(s)}(\hat{\mathbf{p}})}{T} \sim \int \frac{\partial \Phi}{\partial \eta} d\eta.$$

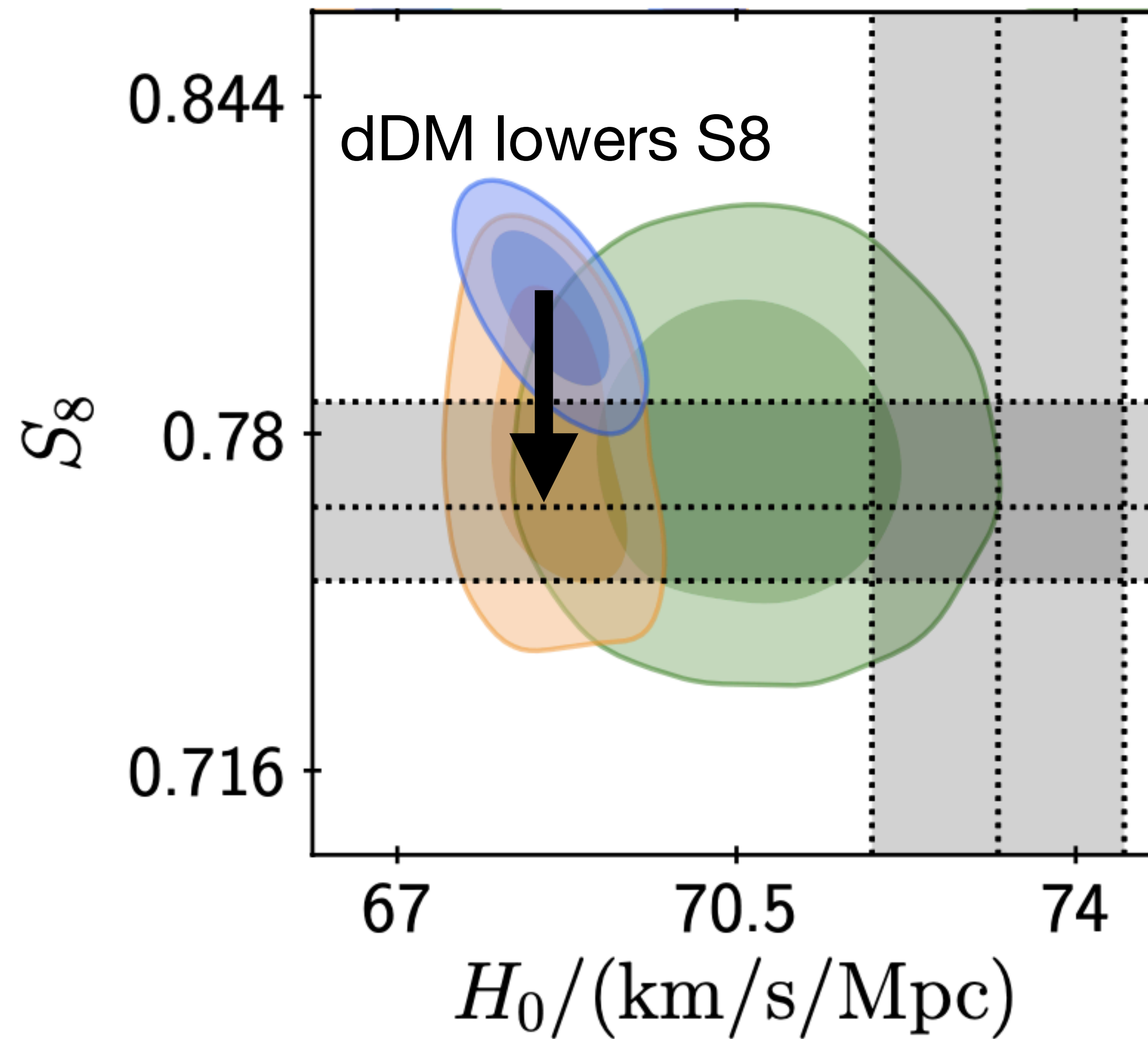
$$C_\ell = \langle \Theta_{\ell m} \Theta_{\ell m}^* \rangle$$

$$\sim \int dk P(k) \left[ \int d\eta a^2 \left( \frac{\partial \lambda}{\partial \eta} + 2\mathcal{H}\lambda \right) \right]^2$$

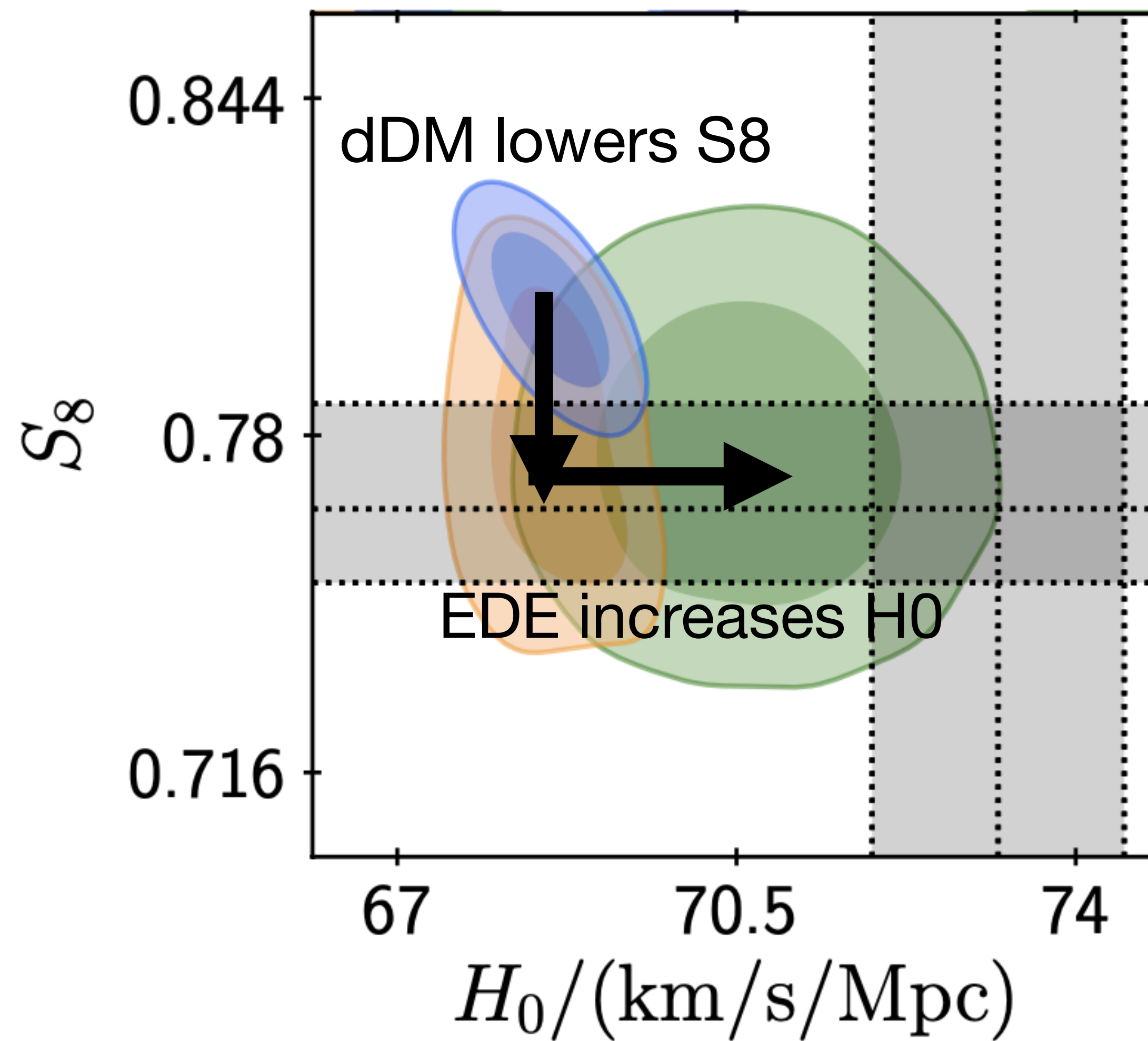
# EDE + dDM as an example of 2-level modification of $\Lambda$ CDM to solve tensions



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# EDE + dDM as an example of 2-level modification of $\Lambda$ CDM to solve tensions



Alternatively, are we observing effects of quantum gravity?

## Quantum Gravity Signatures in the Late-Universe

Michael W. Toomey,<sup>1,2</sup> Savvas Koushiappas,<sup>1,2</sup> Bruno Alexandre,<sup>3</sup> and João Magueijo<sup>3</sup>

<sup>1</sup> *Department of Physics, Brown University, Providence, RI 02912-1843, USA*

<sup>2</sup> *Brown Theoretical Physics Center, Brown University, Providence, RI 02912-1843, USA*

<sup>3</sup> *Theoretical Physics Group, The Blackett Laboratory, Imperial College,  
Prince Consort Rd., London, SW7 2BZ, UK*

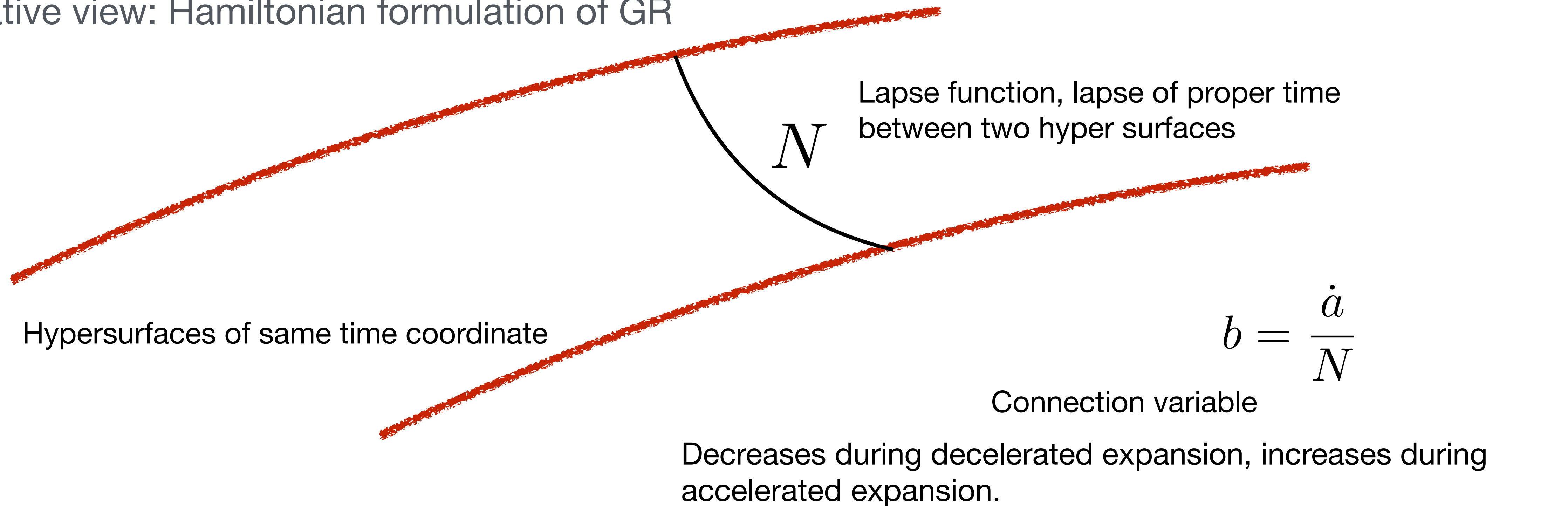


Michael Toomey (PhD 2023, off to MIT)

# Alternatively, are we observing effects of quantum gravity?

The transition from dark matter to dark energy domination is well understood in the metric formulation of GR.

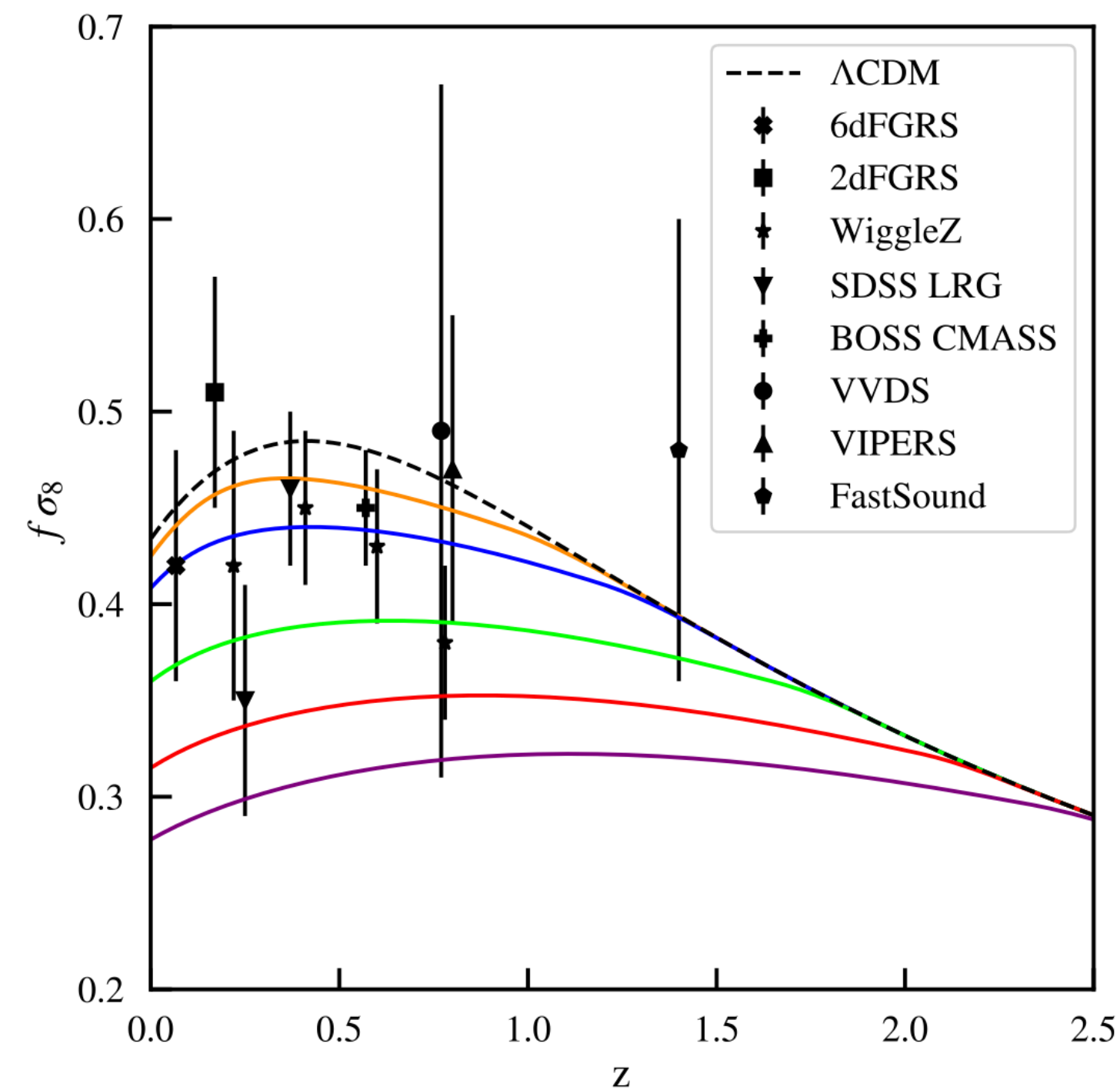
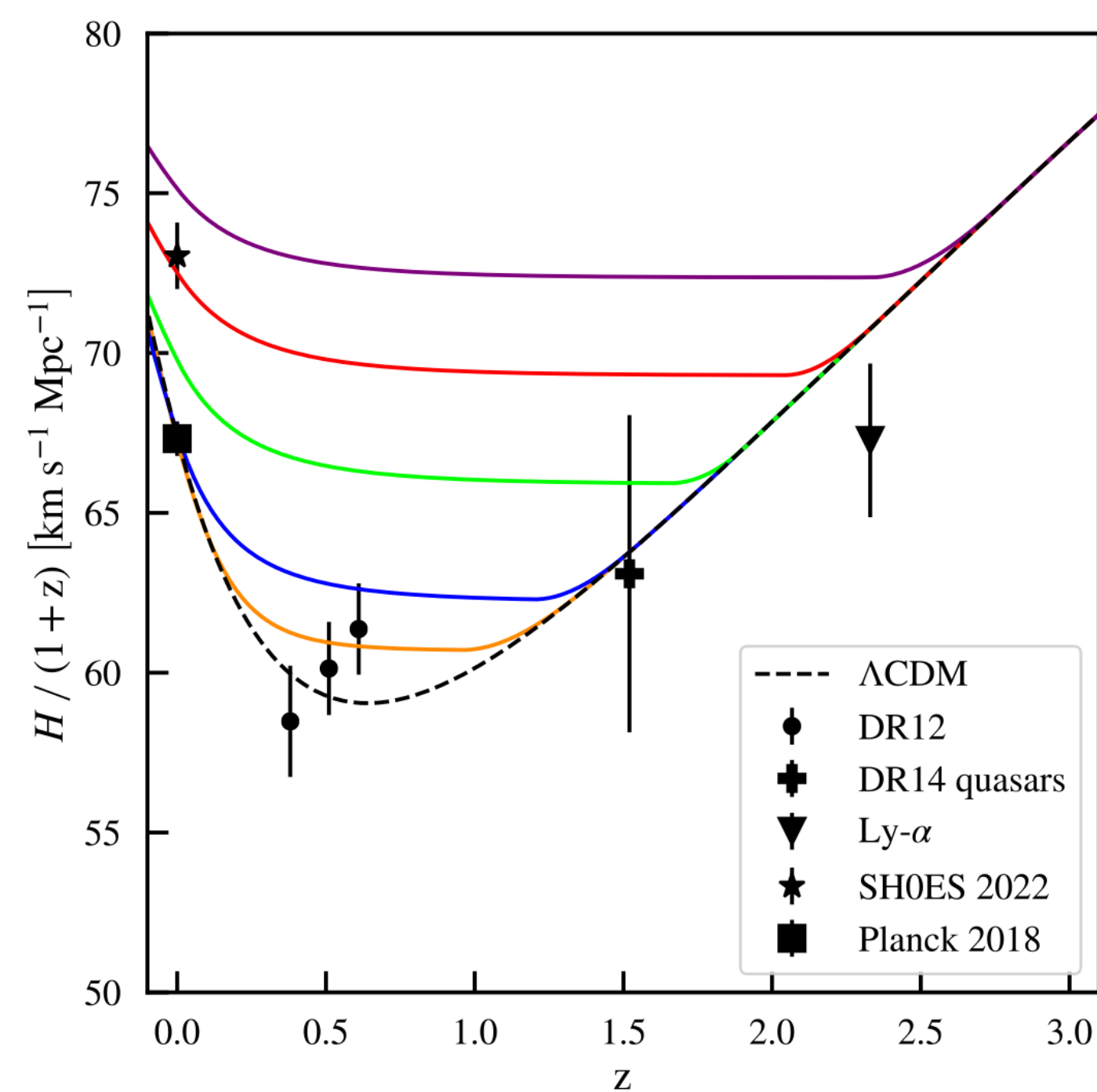
Alternative view: Hamiltonian formulation of GR



Connection must have “reflected” off a minimum at matter — dark energy transition

# Alternatively, are we observing effects of quantum gravity?

Interference effects at the matter—dark energy transition can lead to deviations in the evolution of the hubble parameter

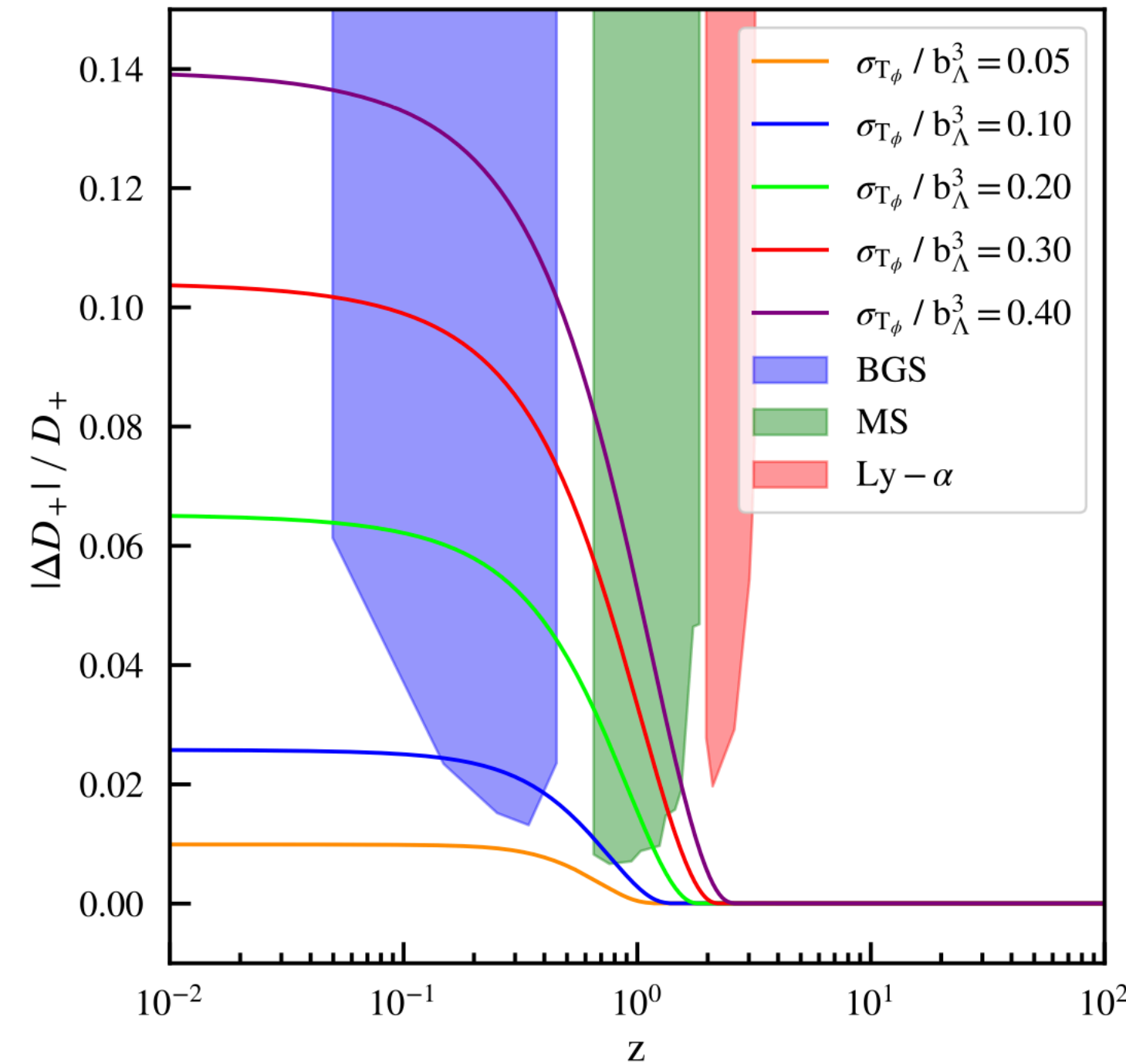
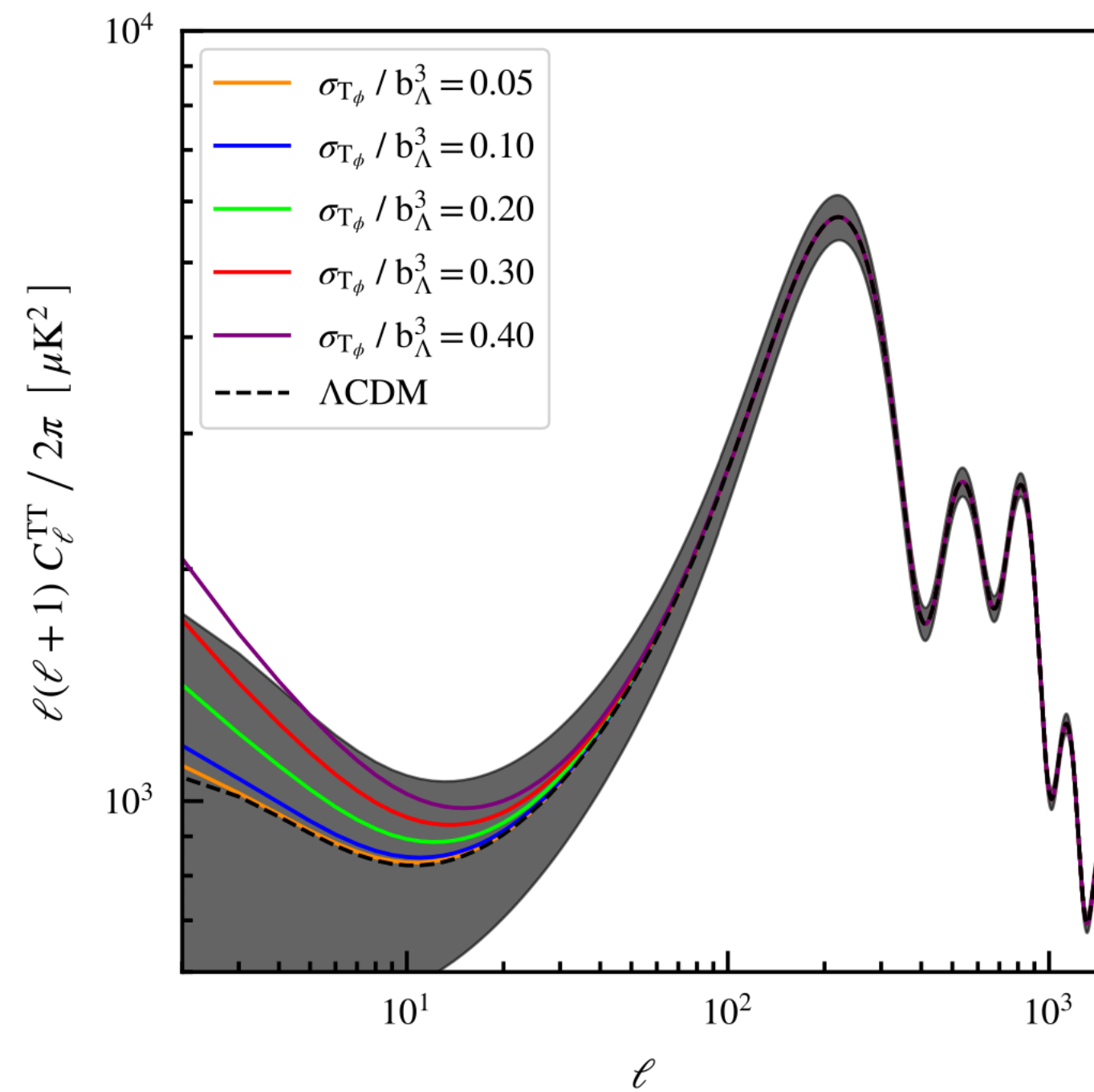


$$f\sigma_8 \equiv \sigma_8 \frac{d \ln D}{d \ln a}$$

$$D'' = -aH D' + \frac{3}{2}a^2 \rho_M D$$

# Alternatively, are we observing effects of quantum gravity?

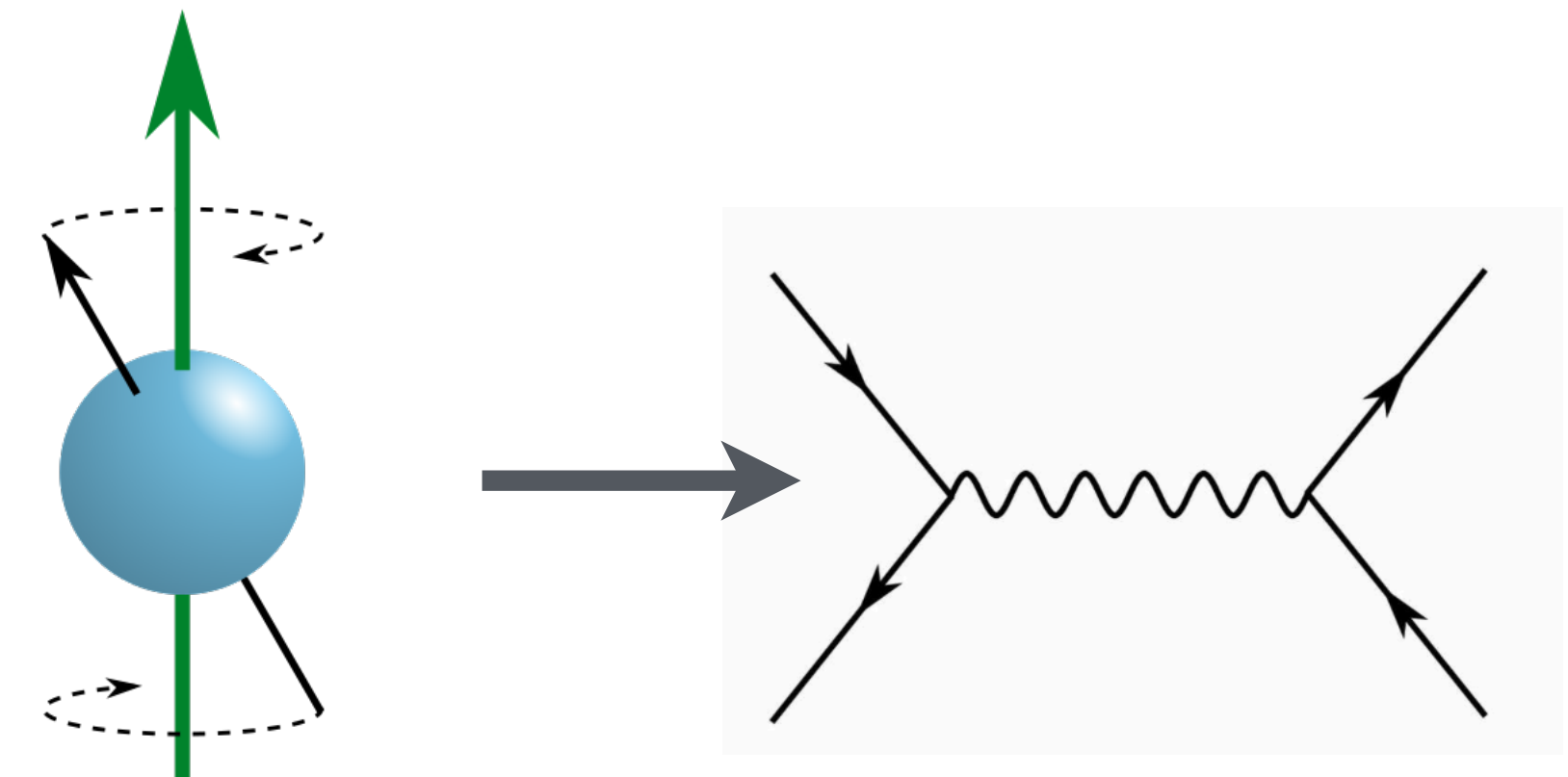
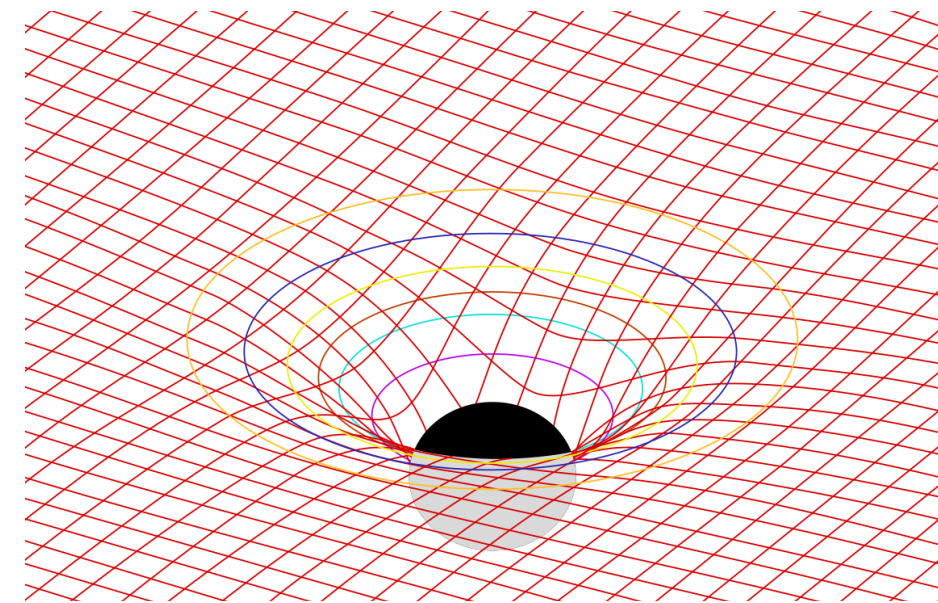
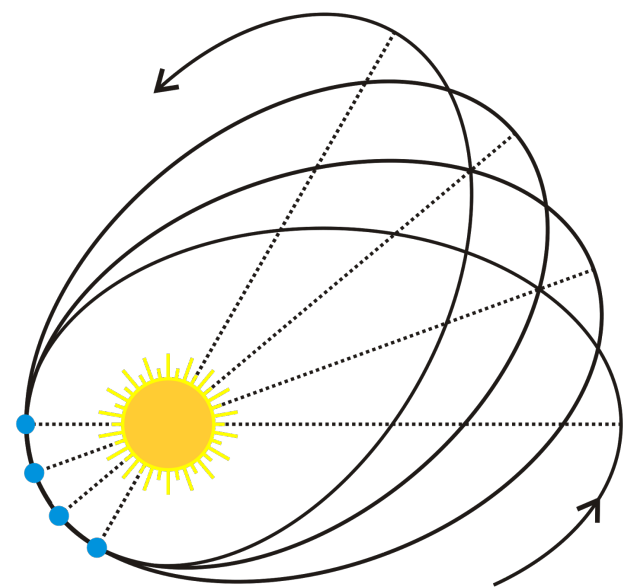
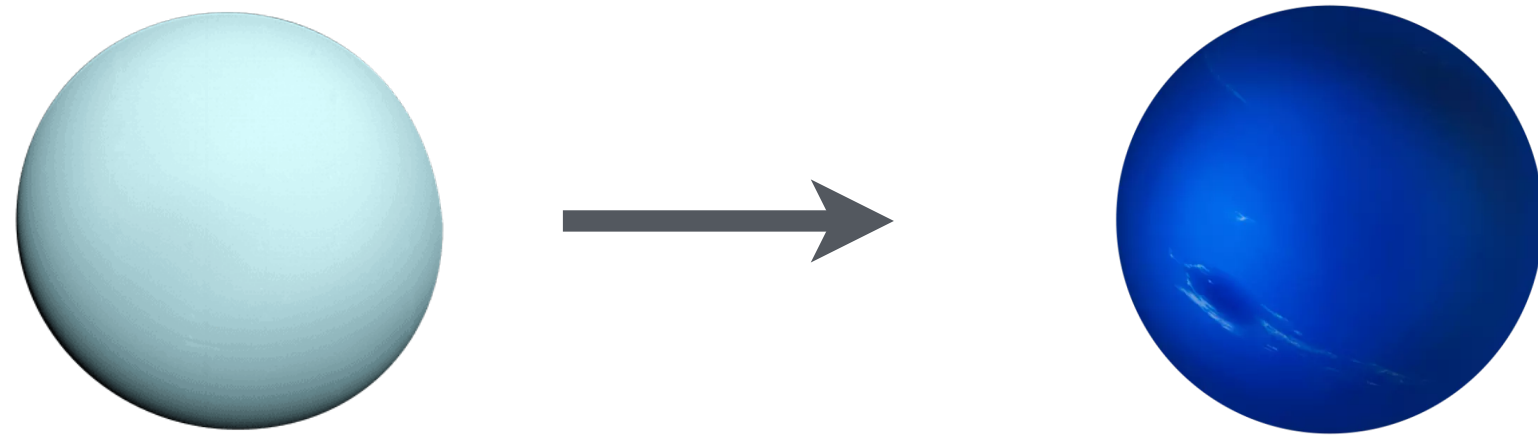
Interference effects at the matter—dark energy transition can lead to deviations in the evolution of the hubble parameter



$$f\sigma_8 \equiv \sigma_8 \frac{d \ln D}{d \ln a}$$

$$D'' = -aH D' + \frac{3}{2}a^2 \rho_M D$$

Precision always leads to breakthroughs...



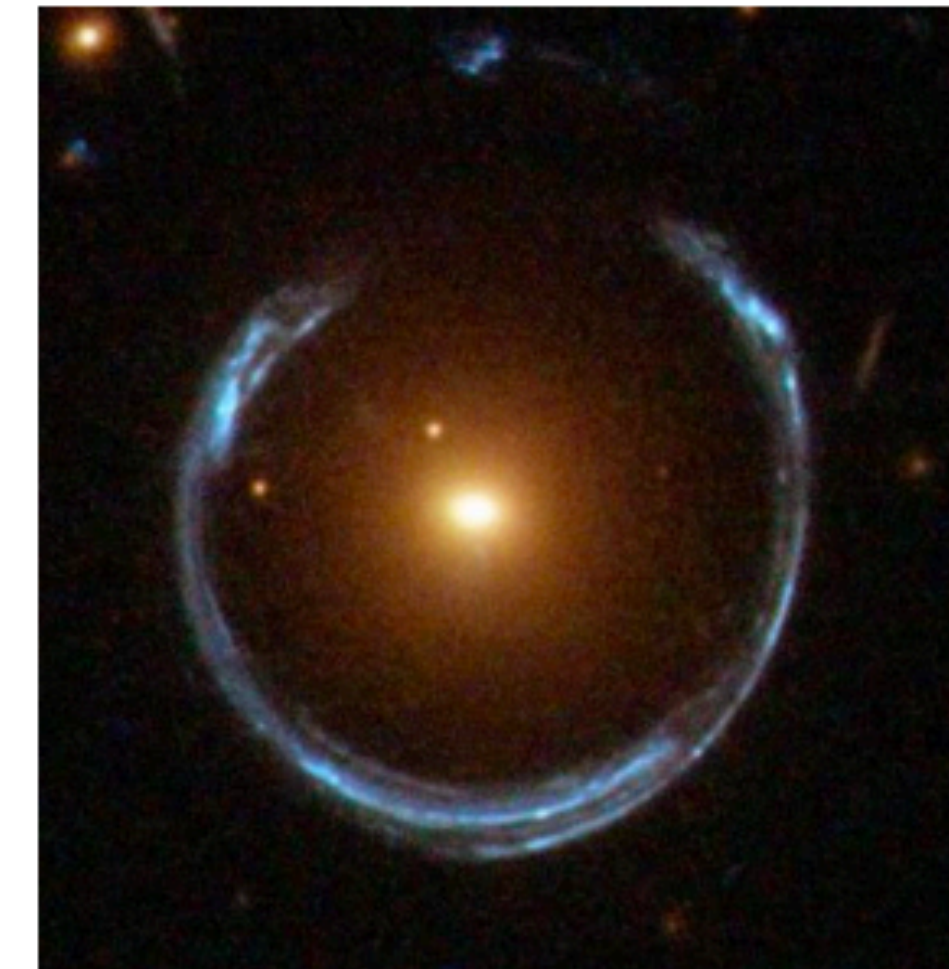
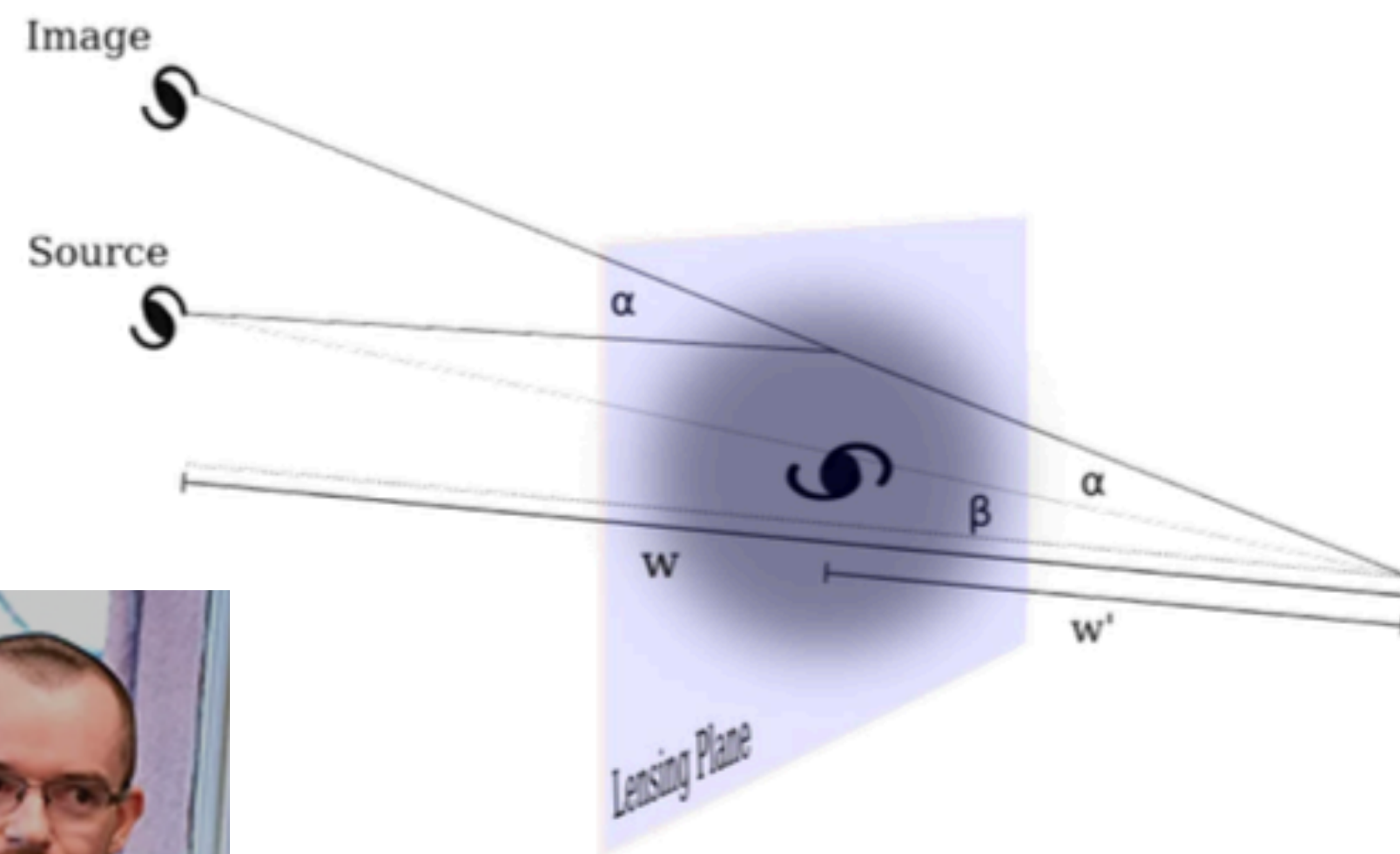
..it seems we may be heading in the same direction in cosmology today.

# Deep learning the astrometric signature of dark matter substructure

Kyriakos Vattis<sup>ID,\*</sup>, Michael W. Toomey<sup>ID,†</sup> and Savvas M. Koushiappas<sup>ID,‡</sup>

*Department of Physics, Brown University, Providence, Rhode Island 02912-1843, USA  
and Brown Theoretical Physics Center, Brown University, Providence, Rhode Island 02912-1843, USA*

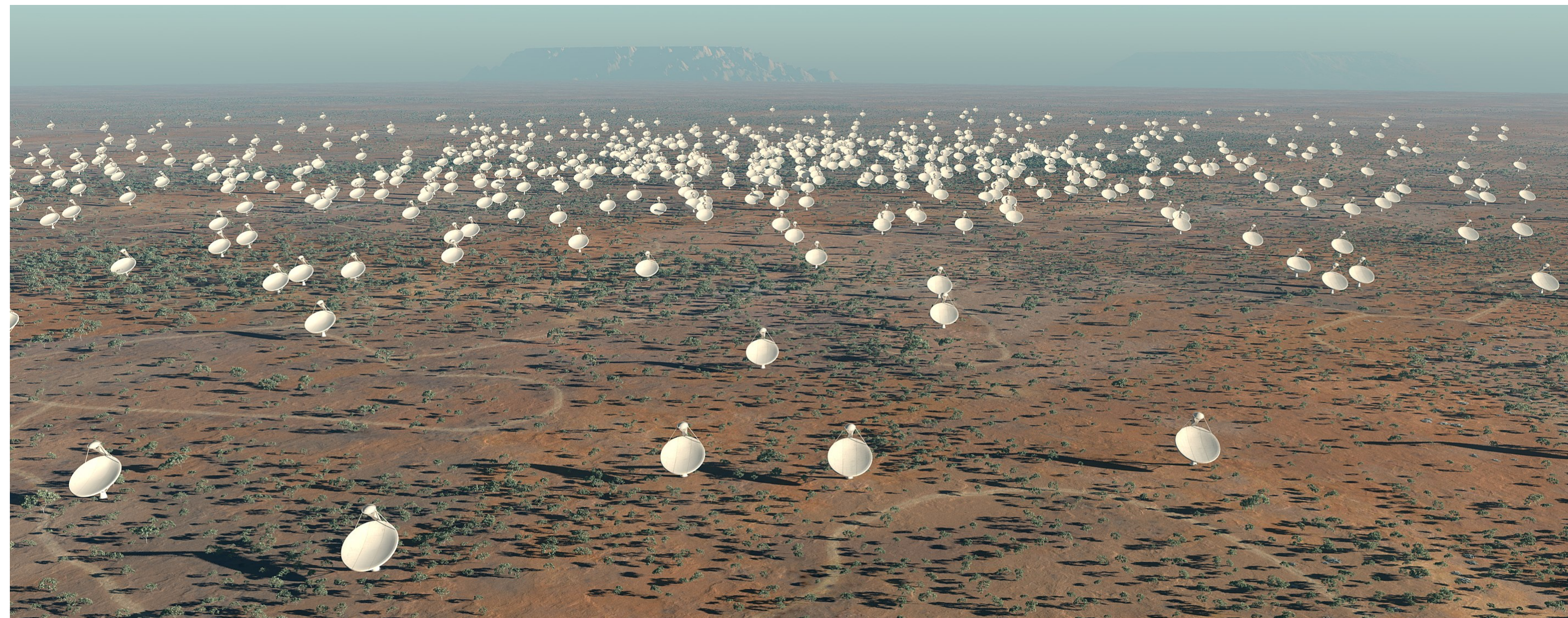
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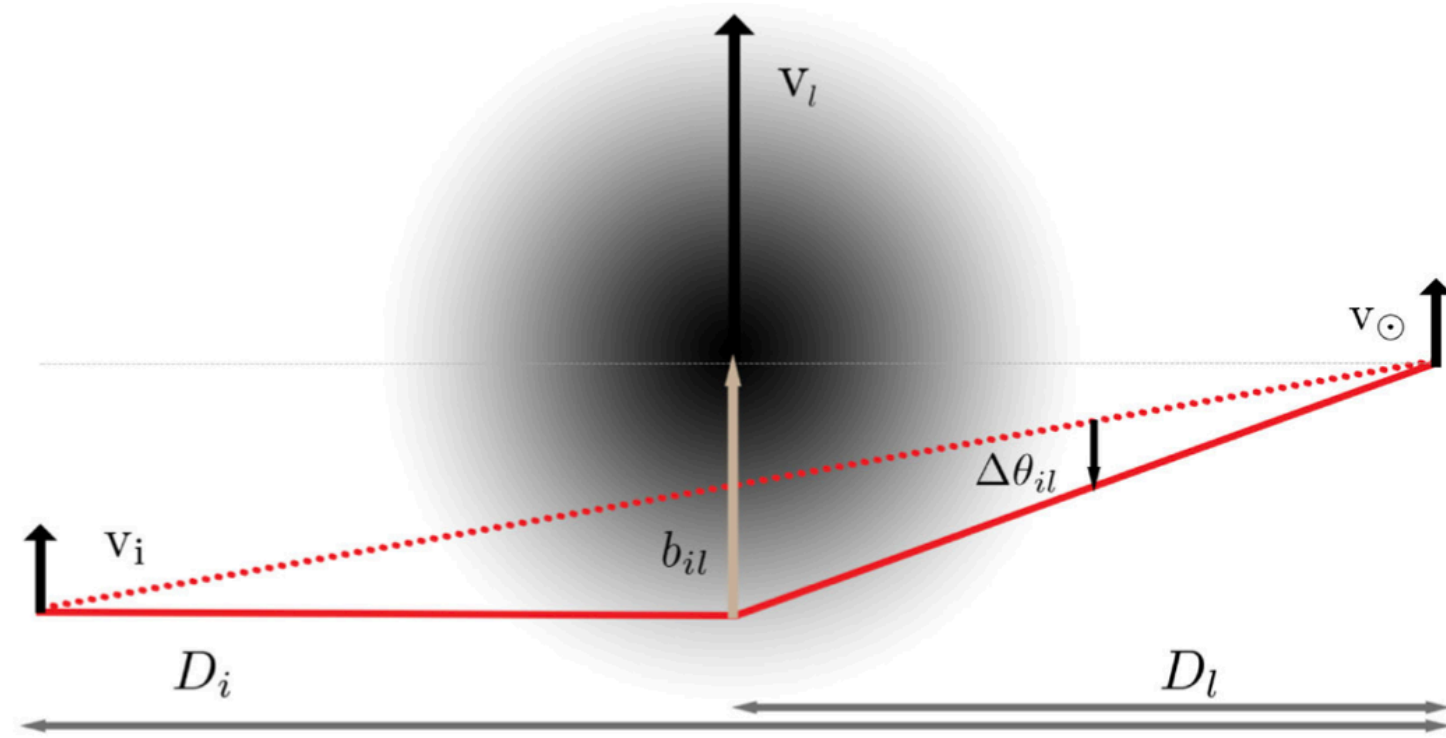
Here is an outline of how deep learning can be utilized to study the astrometric signature of dark matter substructure:

- **Data Collection:** Gather astrometric data from telescopes or observational surveys. This data may include precise measurements of positions, velocities, redshifts, or lensing effects of galaxies, stars, or other astrophysical sources.

No data yet, but we can assume that a survey like SKA can observe a large number of quasars. We call them background sources.



- **Simulated Training Data:** Generate simulated astrometric data that incorporates the effects of dark matter substructure. Numerical simulations or theoretical models can be used to create a training dataset that accurately represents the astrometric signature of dark matter substructure.



$$\Delta\theta_{il} = -\left(1 - \frac{D_l}{D_i}\right) \frac{4G_N M(b_{il})}{c^2 b_{il}} \hat{\mathbf{b}}_{il}$$

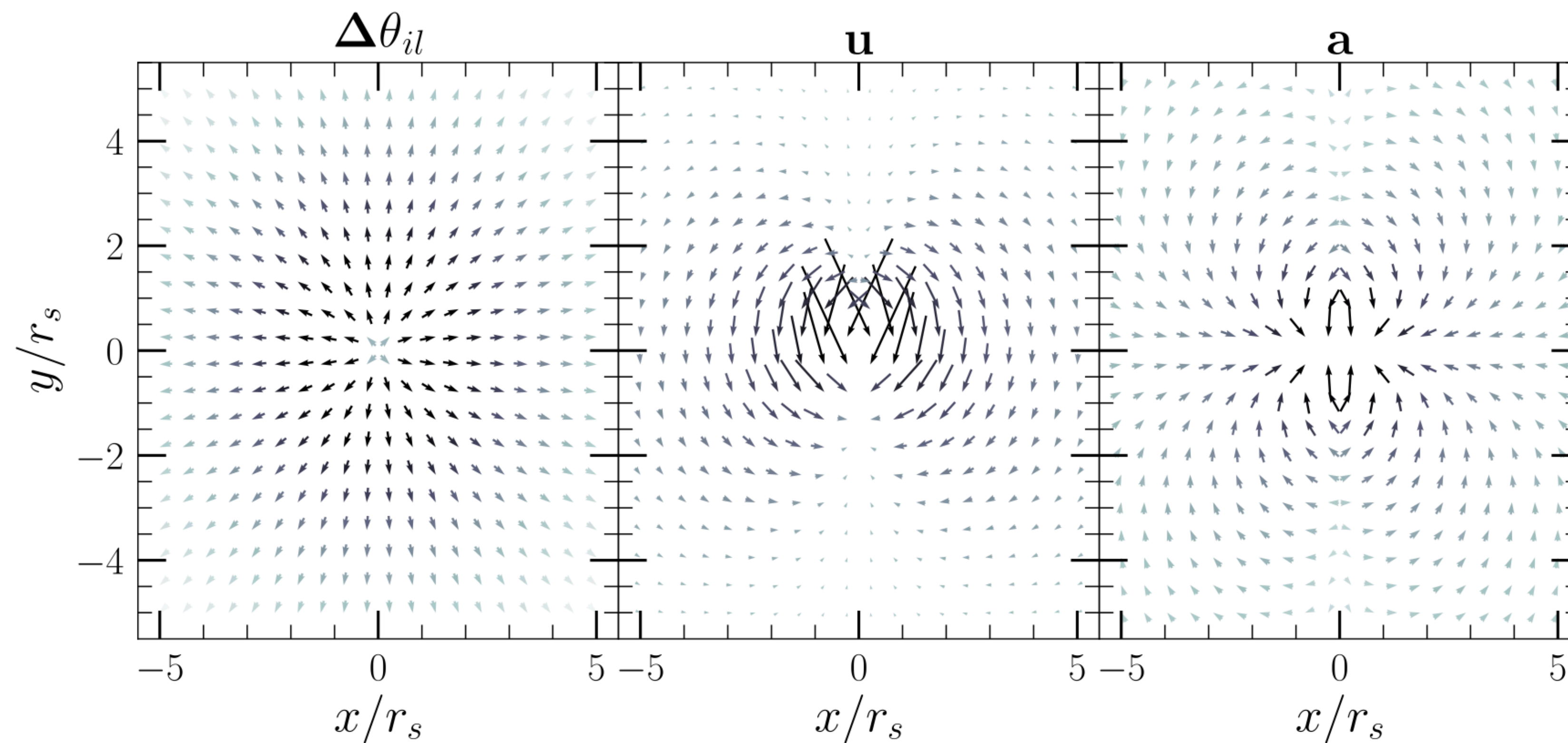
$$\mathbf{u} = \dot{\Delta\theta}_{il}$$

$$= -\left(1 - \frac{D_l}{D_i}\right) \frac{4G_N}{c^2} \left\{ \frac{M'(b_{il}) |\dot{b}_{il}|}{b_{il}} \hat{\mathbf{b}}_{il} + \frac{M(b_{il})}{b_{il}^2} [\mathbf{v}_{il} - 2|\dot{b}_{il}| \hat{\mathbf{b}}_{il}] \right\}$$

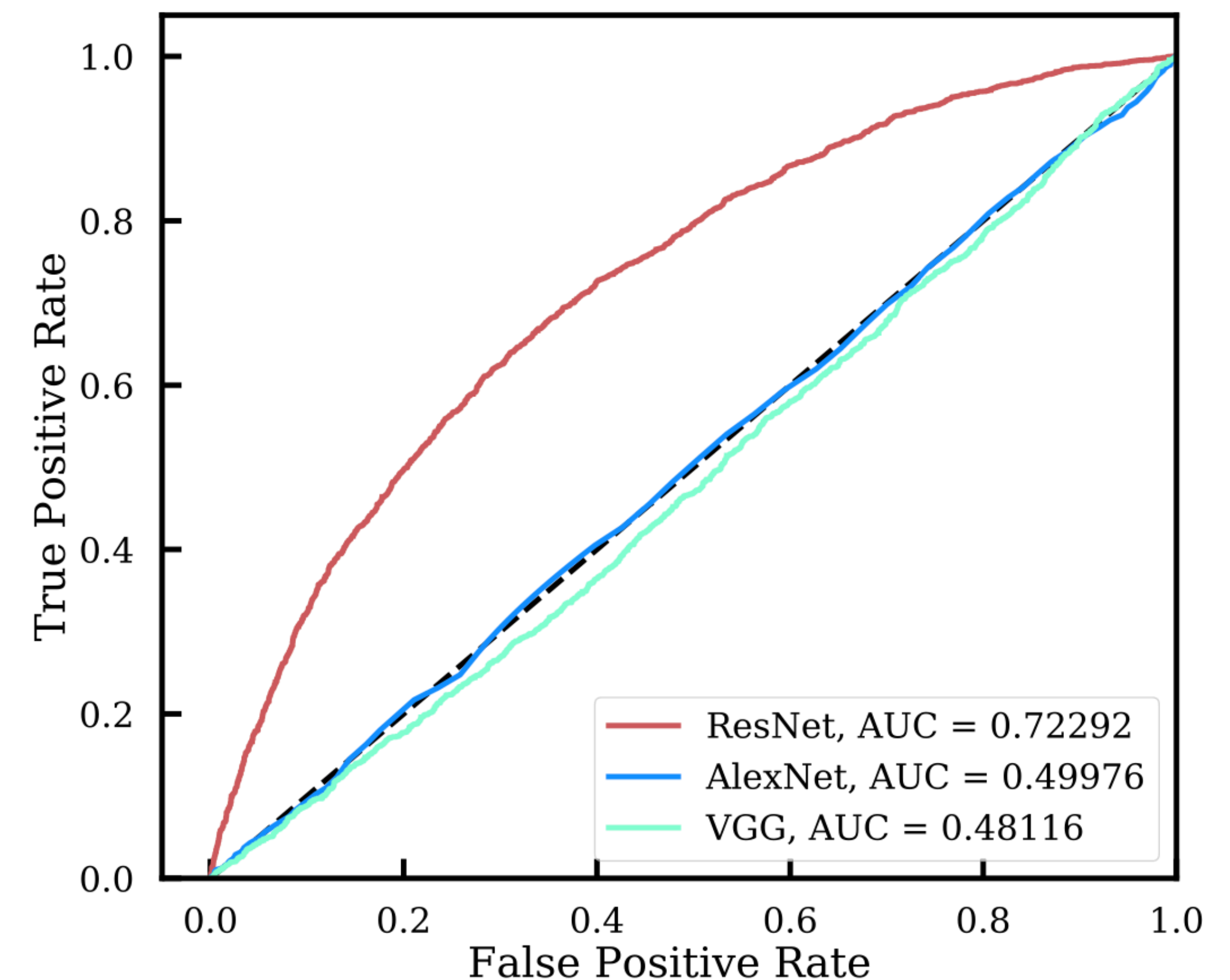
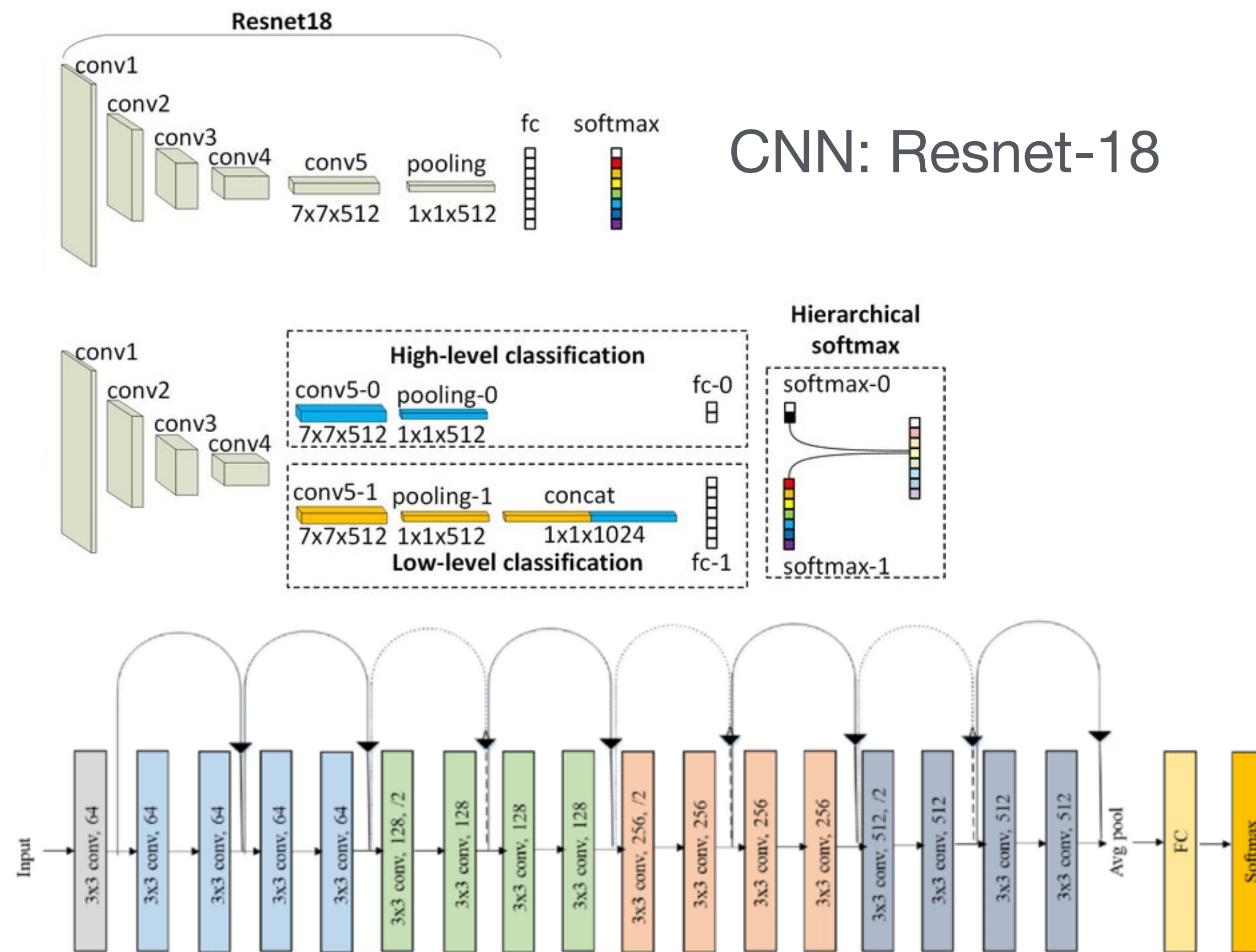
$$\mathbf{a} = \ddot{\Delta\theta}_{il}$$

$$= -\left(1 - \frac{D_l}{D_i}\right) \frac{4G_N}{c^2} \left\{ \frac{M''(b_{il}) |\dot{b}_{il}|^2}{b_{il}} \hat{\mathbf{b}}_{il} + \frac{M'(b_{il})}{b_{il}^2} [2|\dot{b}_{il}| \mathbf{v}_{il} + |\ddot{b}_{il}| \mathbf{b}_{il} - 4|\dot{b}_{il}|^2 \hat{\mathbf{b}}_{il}] - \frac{2M(b_{il})}{b_{il}^3} [2|\dot{b}_{il}| \mathbf{v}_{il} + |\ddot{b}_{il}| \mathbf{b}_{il} + 3|\dot{b}_{il}|^2 \hat{\mathbf{b}}_{il}] \right\}$$

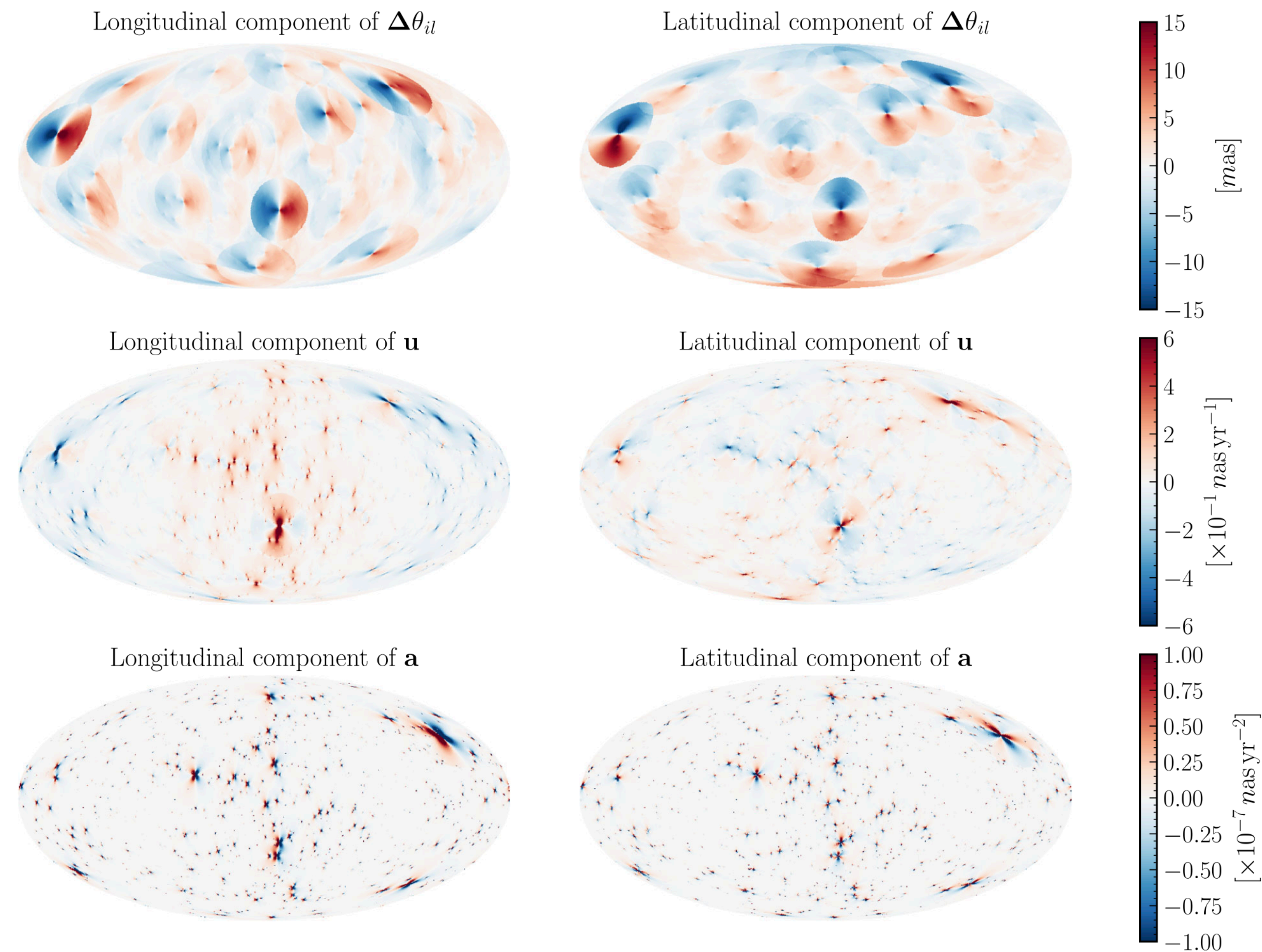
- **Feature Extraction:** Extract relevant features from the collected or simulated data that are likely influenced by dark matter substructure. These features could include deviations in the observed positions or motions of celestial objects, distortions in their shapes due to gravitational lensing, or clustering patterns in their distribution.



- **Deep Learning Model Design:** Design a deep learning architecture suitable for capturing the astrometric signature of dark matter substructure. Convolutional neural networks (CNNs), recurrent neural networks (RNNs), or other architectures can be used depending on the specific features and data characteristics.



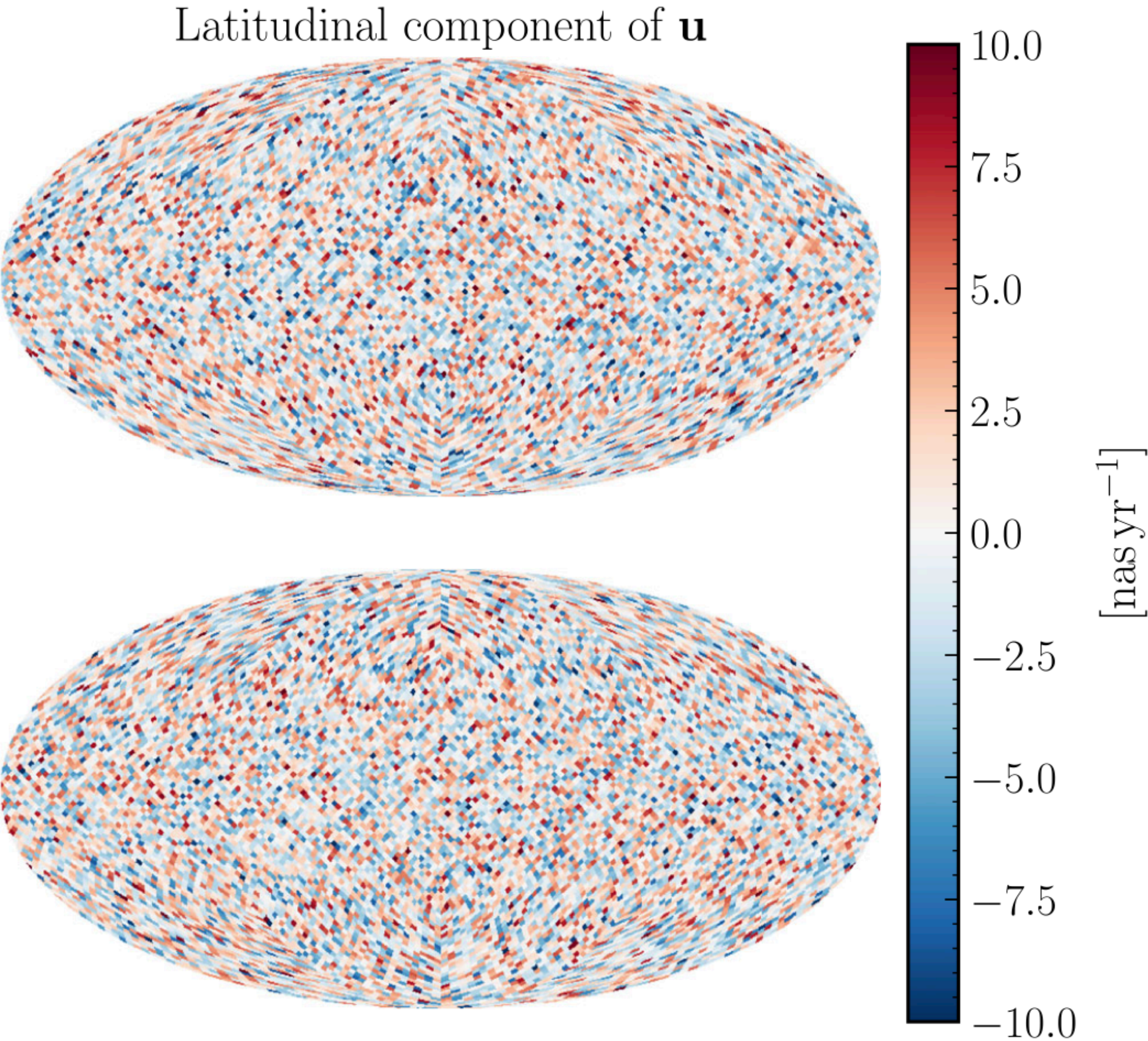
- **Model Training:** Train the deep learning model using the simulated training dataset. This involves feeding the data through the network, adjusting the model's parameters using backpropagation, and optimizing the model's performance through appropriate loss functions and optimization algorithms.



- **Model Evaluation:** Evaluate the trained model using validation data to assess its performance in capturing the astrometric signature of dark matter substructure. This evaluation helps ensure the model's generalization capability and its ability to accurately predict the astrometric effects of substructure.

Designed SKA

Scenario	$N_q$	$\sigma_u(\mu\text{as/yr})$
A	$10^8$	1
B	$10^8$	0.1
C	$10^9$	1
D	$10^9$	0.1
E	$3 \times 10^9$	1

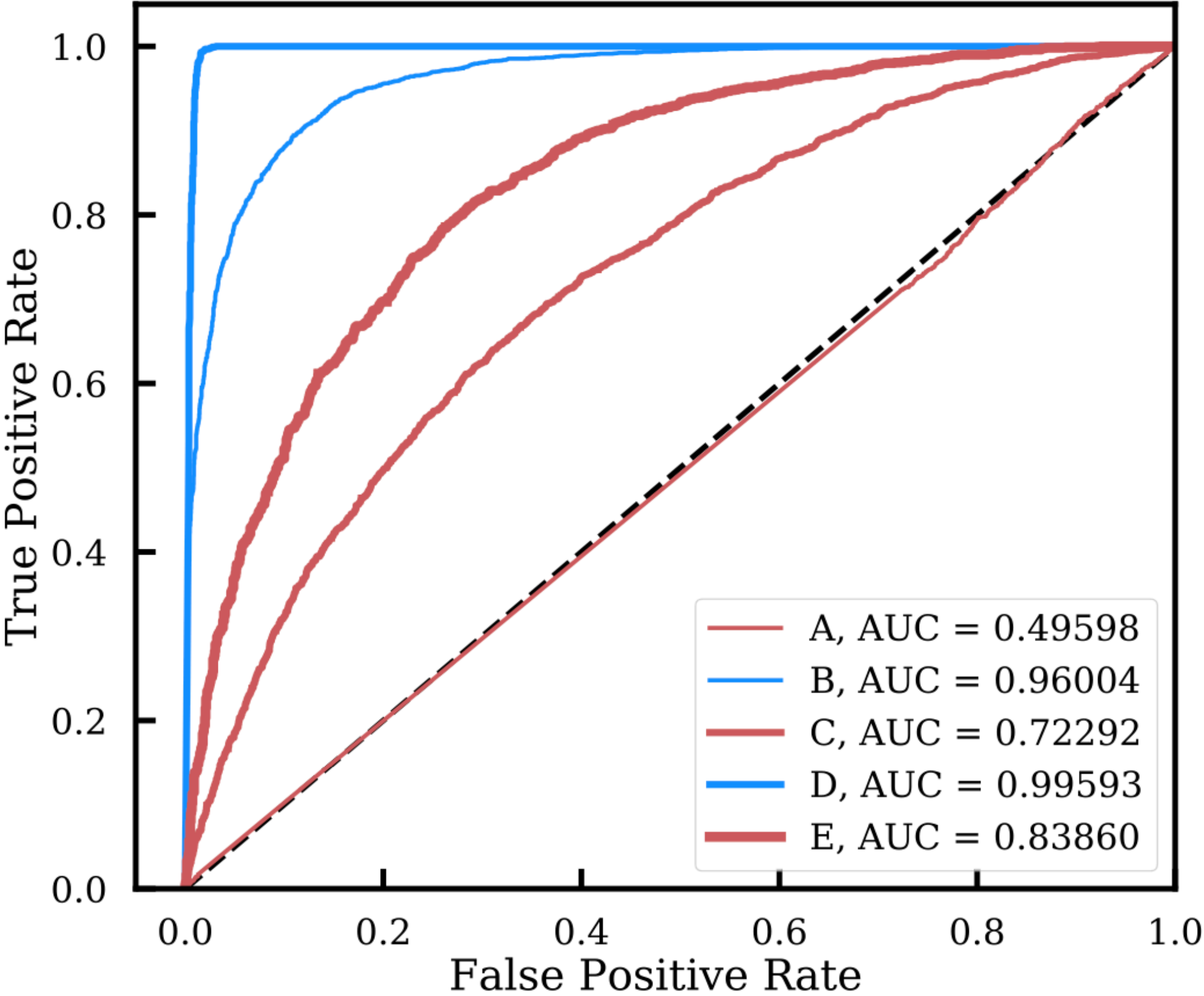


- **Astrometric Signature Inference:** Apply the trained deep learning model to real astrometric data to infer the presence and characteristics of dark matter substructure. The model can predict the astrometric signature associated with substructures and provide insights into their distribution, abundance, or other properties.

Designed SKA

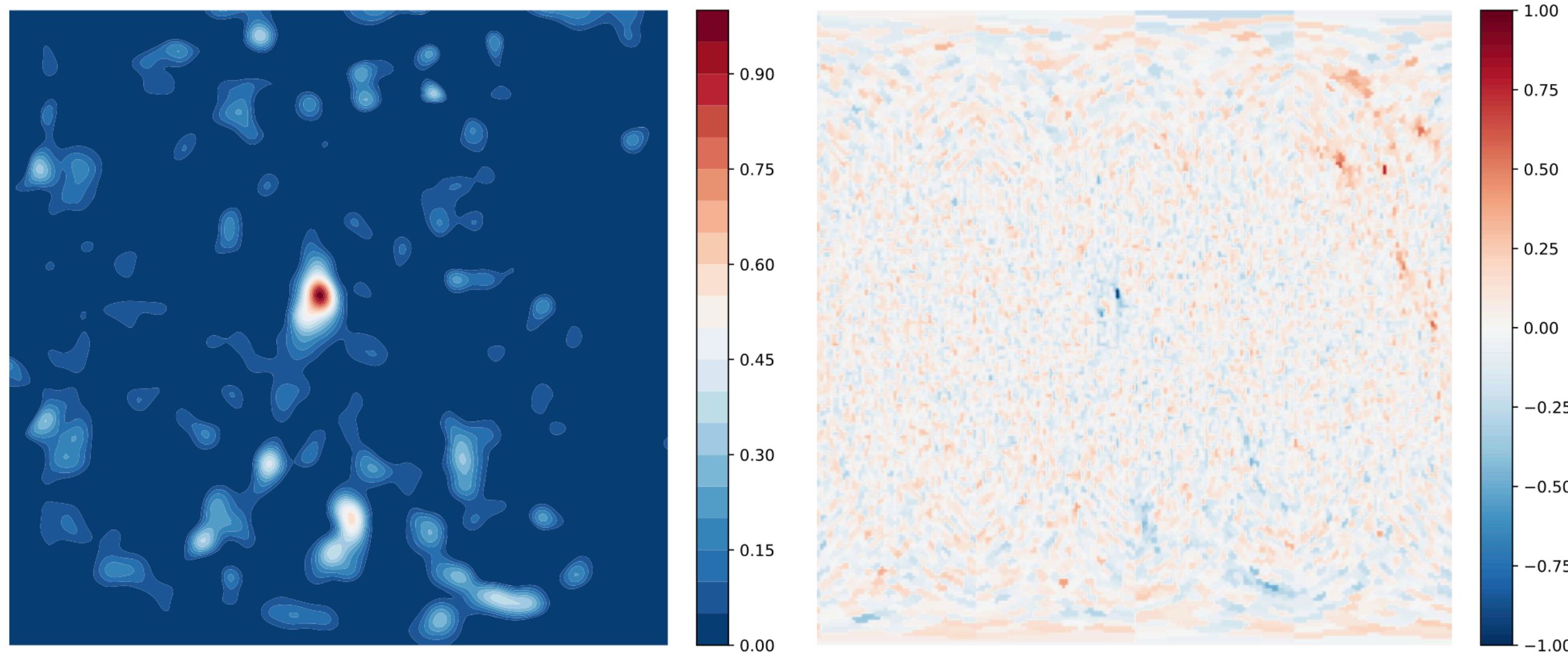
Scenario	$N_q$	$\sigma_u(\mu\text{as/yr})$
A	$10^8$	1
B	$10^8$	0.1
C	$10^9$	1
D	$10^9$	0.1
E	$3 \times 10^9$	1

Doubling the operational time of SKA allows for a reliable probe of the substructure content of the Milky Way through astrometry.



- **Astrometric Signature Inference:** Apply the trained deep learning model to real astrometric data to infer the presence and characteristics of dark matter substructure. The model can predict the astrometric signature associated with substructures and provide insights into their distribution, abundance, or other properties.

Use of Integrated Gradients (path integral of gradients of baseline and desired inputs) allows deterministic localizations of substructure.



$$IG_i(x, x') ::= (x_i - x'_i) \int_{\alpha=0}^1 \frac{\partial F(x' + \alpha(x - x'))}{\partial x_i} d\alpha.$$

# ChatGPT



deep learning the astrometric signature of dark matter substructure



Deep learning techniques can be employed to learn and analyze the astrometric signature of dark matter substructure. Dark matter substructure refers to smaller clumps or concentrations of dark matter within larger dark matter halos, and its astrometric signature refers to the measurable effects it produces in the positions, motions, or gravitational lensing of celestial objects. Applying deep learning to understand and extract this astrometric signature can aid in the detection and characterization of dark matter substructures.



Here is a general outline of how deep learning can be utilized to study the astrometric signature of dark matter substructure:

Fin