

# PUZZLES IN PARTICLE PHYSICS AND COSMOLOGY

QuarkNet Summer Workshop

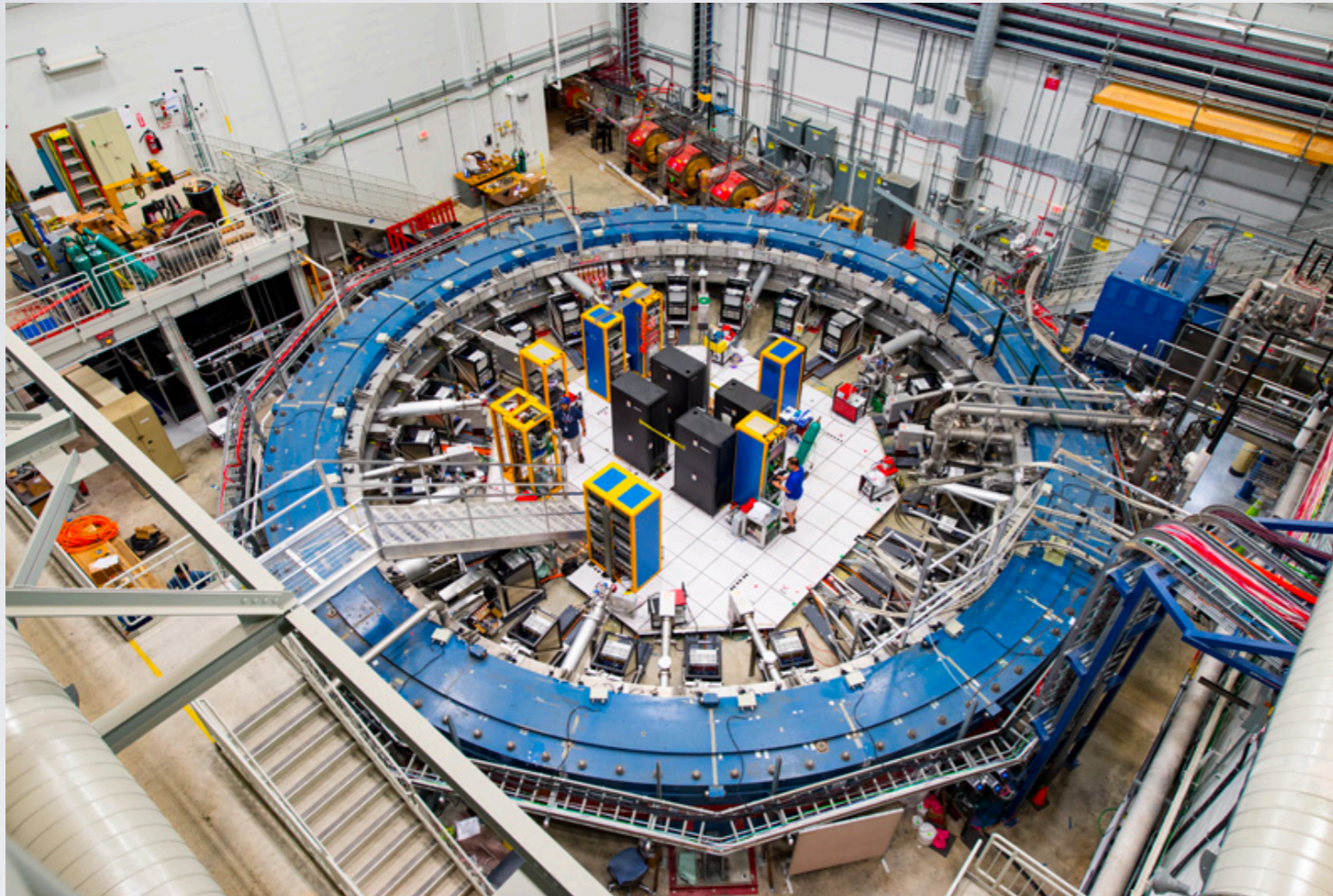
Josh Erlich

William & Mary

August 1, 2022



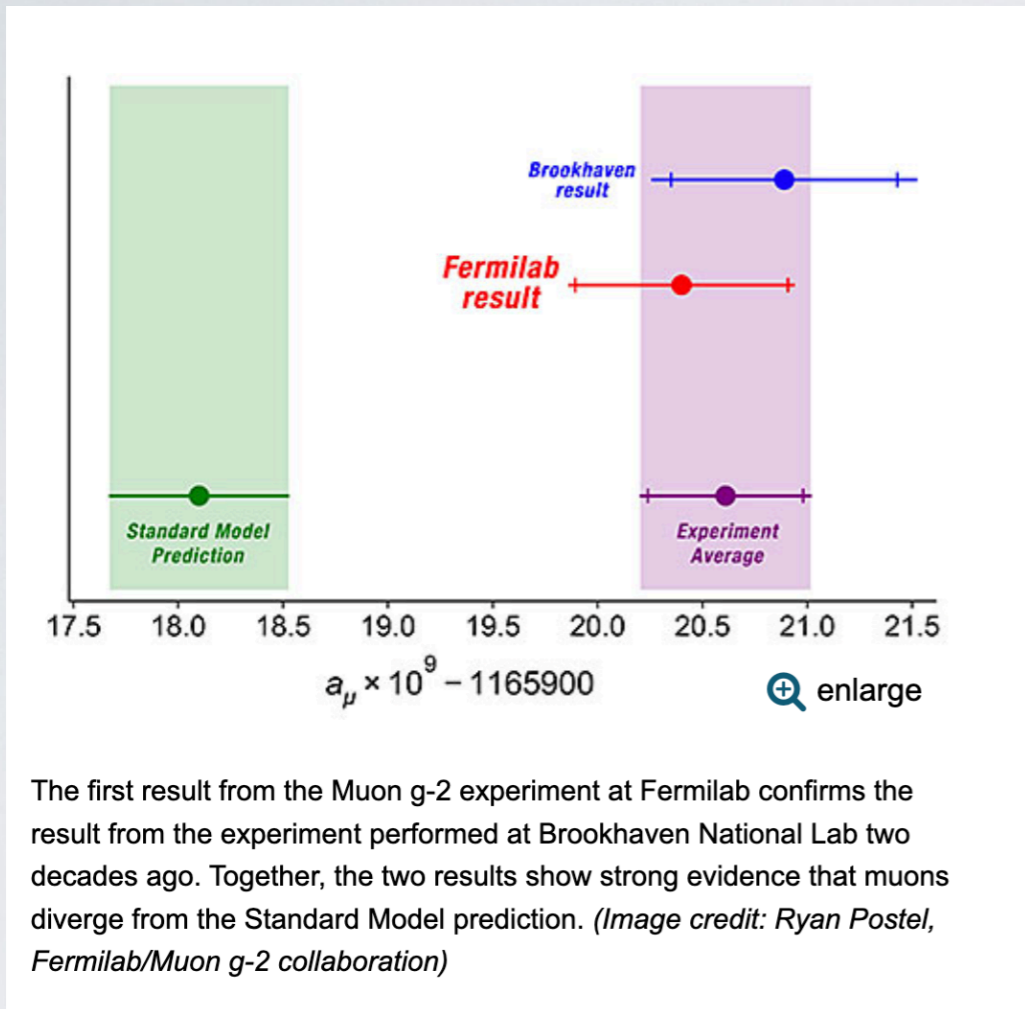
# Muon g-2



$$\mu = \frac{e}{2m} (\mathbf{L} + g\mathbf{S})$$

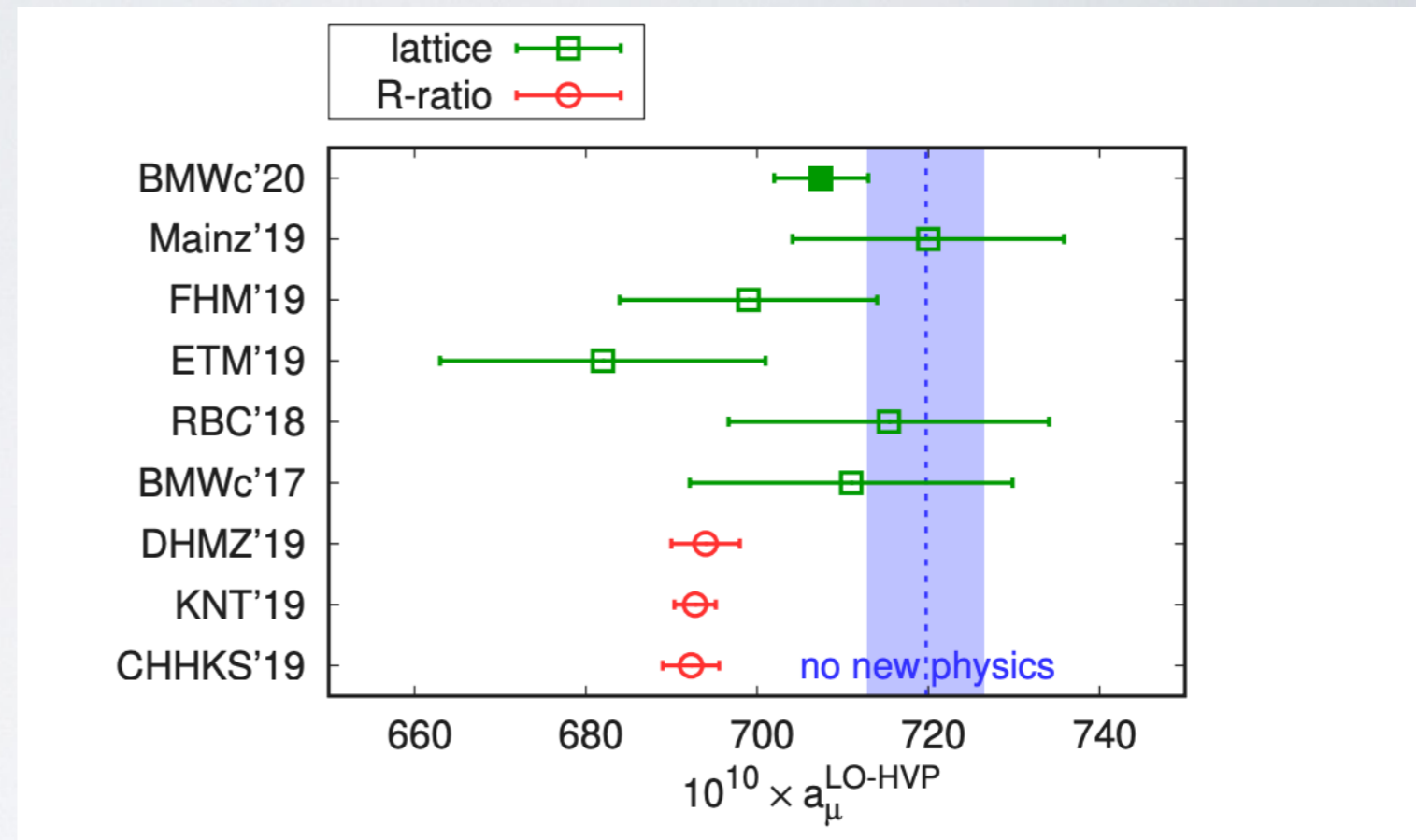
Muon g-2 ring, Fermilab

# Muon g-2



Fermilab

4.2 sigma discrepancy



BMW Lattice QCD collaboration  
(Zoltan Fodor)

No significant discrepancy

# $M_W$

## Abstract

The mass of the  $W$  boson, a mediator of the weak force between elementary particles, is tightly constrained by the symmetries of the standard model of particle physics. The Higgs boson was the last missing component of the model. After observation of the Higgs boson, a measurement of the  $W$  boson mass provides a stringent test of the model. We measure the  $W$  boson mass,  $M_W$ , using data corresponding to 8.8 inverse femtobarns of integrated luminosity collected in proton-antiproton collisions at a 1.96 tera-electron volt center-of-mass energy with the CDF II detector at the Fermilab Tevatron collider. A sample of approximately 4 million  $W$  boson candidates is used to obtain

$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4 \text{ MeV}/c^2$ , the precision of which exceeds that of all previous measurements combined (stat, statistical uncertainty; syst, systematic uncertainty; MeV, mega-electron volts;  $c$ , speed of light in a vacuum). This measurement is in significant tension with the standard model expectation.

CDF Collaboration

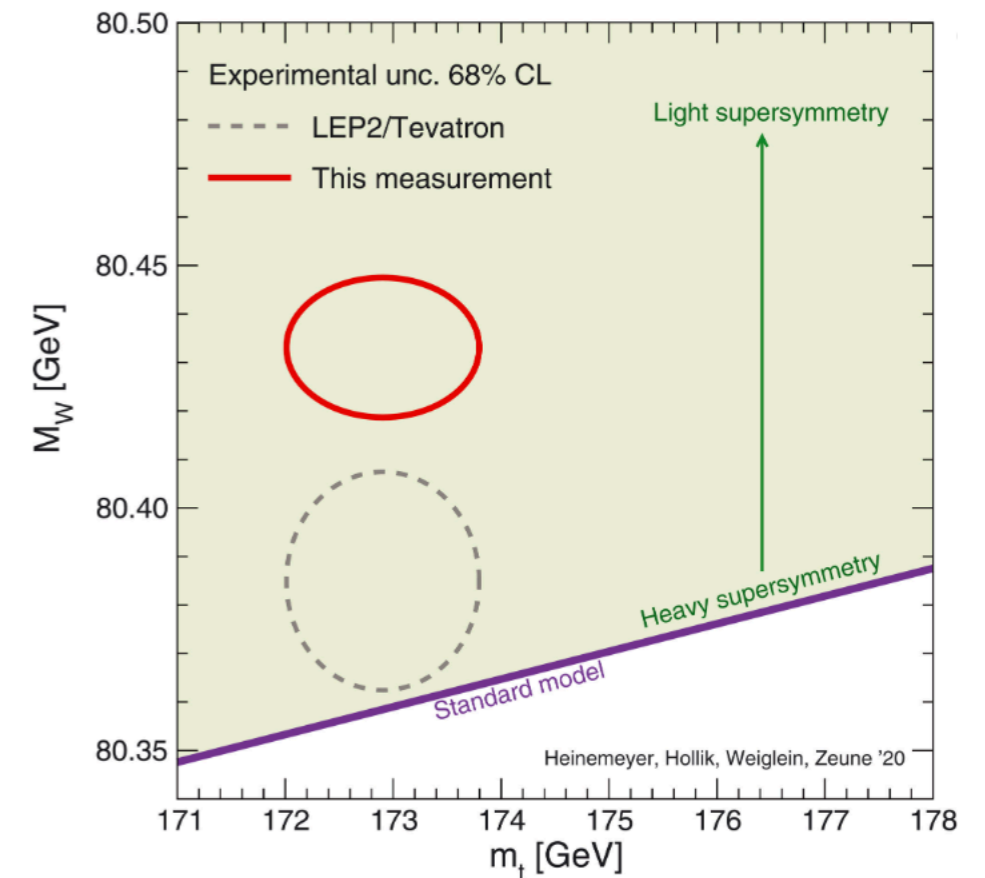


Fig. 1. Experimental measurements and theoretical predictions for the  $W$  boson mass.

7 sigma discrepancy

# Hubble Tension

- CMB with Planck**
- Balkenhol et al. (2021), Planck 2018+SPT+ACT :  $67.49 \pm 0.53$
  - Pogosian et al. (2020), eBOSS+Planck  $\Omega_m H^2$ :  $69.6 \pm 1.8$
  - Aghanim et al. (2020), Planck 2018:  $67.27 \pm 0.60$
  - Aghanim et al. (2020), Planck 2018+CMB lensing:  $67.36 \pm 0.54$
  - Ade et al. (2016), Planck 2015,  $H_0 = 67.27 \pm 0.66$

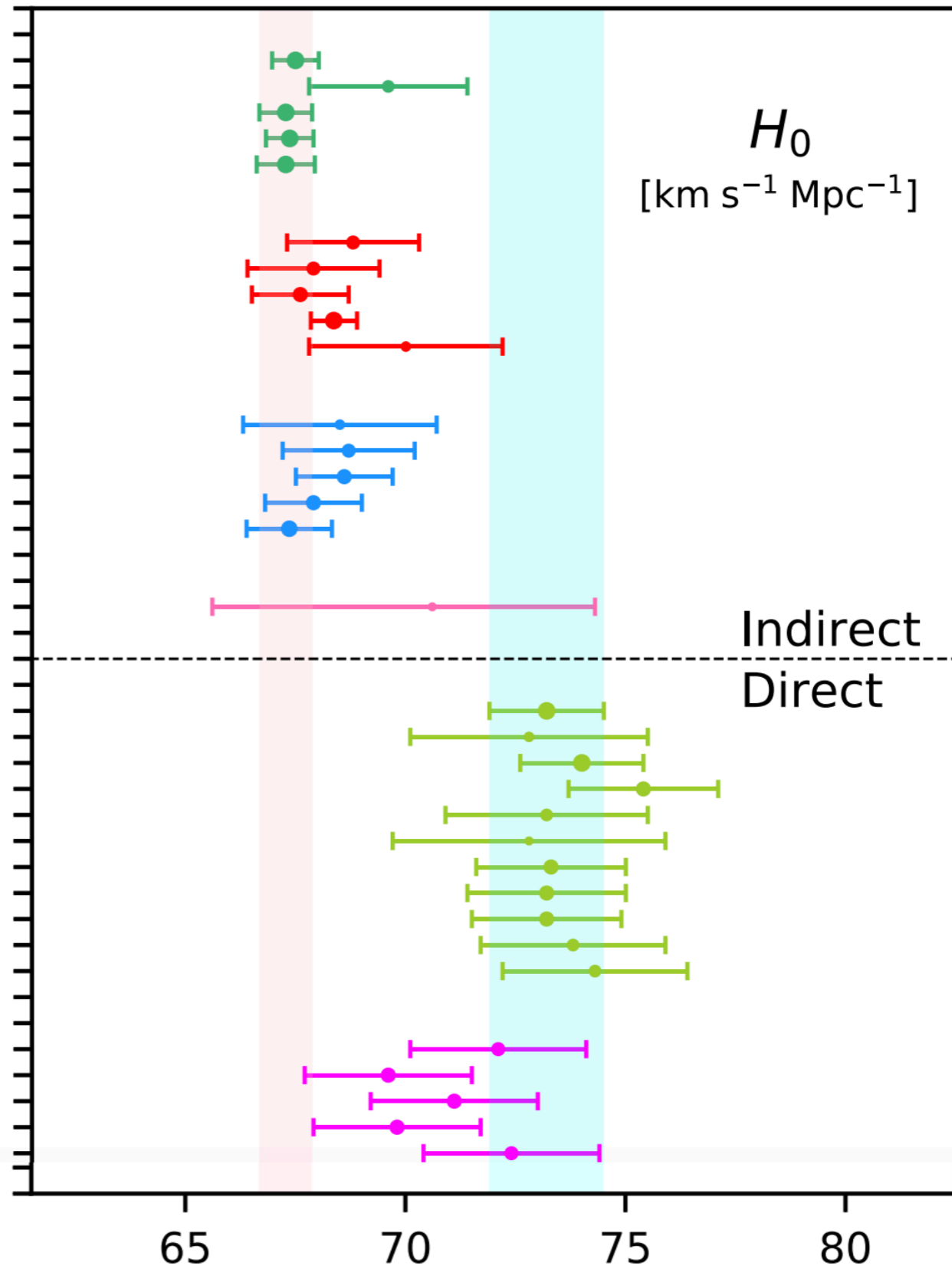
- CMB without Planck**
- Dutcher et al. (2021), SPT:  $68.8 \pm 1.5$
  - Aiola et al. (2020), ACT:  $67.9 \pm 1.5$
  - Aiola et al. (2020), WMAP9+ACT:  $67.6 \pm 1.1$
  - Zhang, Huang (2019), WMAP9+BAO:  $68.36^{+0.53}_{-0.52}$
  - Hinshaw et al. (2013), WMAP9:  $70.0 \pm 2.2$

- No CMB, with BBN**
- D'Amico et al. (2020), BOSS DR12+BBN:  $68.5 \pm 2.2$
  - Colas et al. (2020), BOSS DR12+BBN:  $68.7 \pm 1.5$
  - Philcox et al. (2020),  $P_l$ +BAO+BBN:  $68.6 \pm 1.1$
  - Ivanov et al. (2020), BOSS+BBN:  $67.9 \pm 1.1$
  - Alam et al. (2020), BOSS+eBOSS+BBN:  $67.35 \pm 0.97$

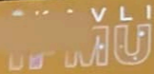

- $P_l(k)$  + CMB lensing**
- Philcox et al. (2020),  $P_l(k)$ +CMB lensing:  $70.6^{+3.7}_{-5.0}$

- Cepheids – SNIa**
- Riess et al. (2020), R20:  $73.2 \pm 1.3$
  - Breuval et al. (2020):  $72.8 \pm 2.7$
  - Riess et al. (2019), R19:  $74.0 \pm 1.4$
  - Camarena, Marra (2019):  $75.4 \pm 1.7$
  - Burns et al. (2018):  $73.2 \pm 2.3$
  - Dhawan, Jha, Leibundgut (2017), NIR:  $72.8 \pm 3.1$
  - Follin, Knox (2017):  $73.3 \pm 1.7$
  - Feeney, Mortlock, Dalmaso (2017):  $73.2 \pm 1.8$
  - Riess et al. (2016), R16:  $73.2 \pm 1.7$
  - Cardona, Kunz, Pettorino (2016), HPs:  $73.8 \pm 2.1$
  - Freedman et al. (2012):  $74.3 \pm 2.1$

- TRGB – SNIa**
- Soltis, Casertano, Riess (2020):  $72.1 \pm 2.0$
  - Freedman et al. (2020):  $69.6 \pm 1.9$
  - Reid, Pesce, Riess (2019), SH0ES:  $71.1 \pm 1.9$
  - Freedman et al. (2019):  $69.8 \pm 1.9$
  - Yuan et al. (2019):  $72.4 \pm 2.0$
  - Jang, Lee (2017):  $71.2 \pm 2.1$

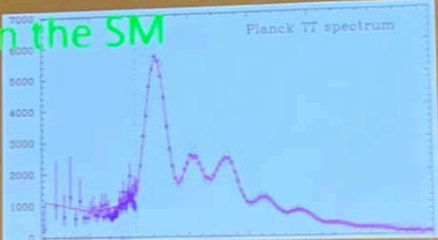


# Evidence for New Physics

Talking Itocho  

## Five evidences for physics beyond SM

- at least five missing pieces in the SM
- dark matter
- neutrino mass
- dark energy
- apparently acausal density fluctuations
- baryon asymmetry



Unusual in science: the problems are clear!

- theoretical problems:
  - hierarchy problem
  - origin of flavor

also anomalies ( $H_0$  tension,  $\sigma_8$ )

are many other theoretical problems we want to understand, like the

n of matter and forces gravity

Hitoshi Murayama, Snowmass 2022

Photo, Alexey Petrov