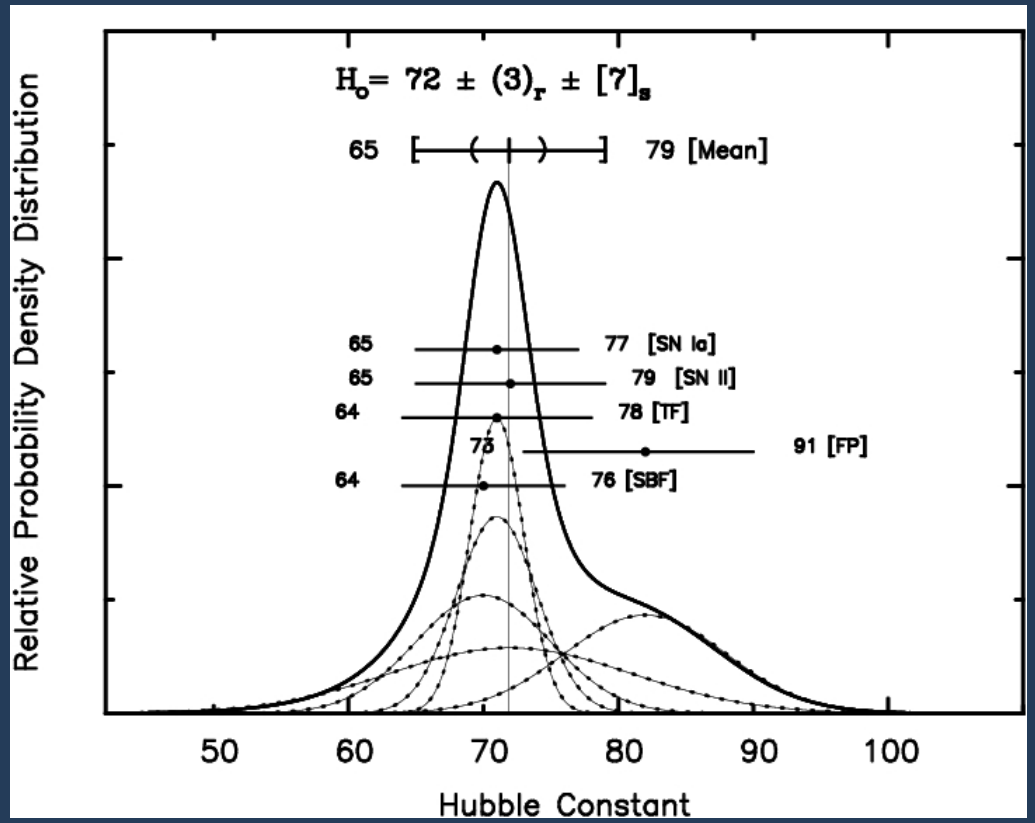
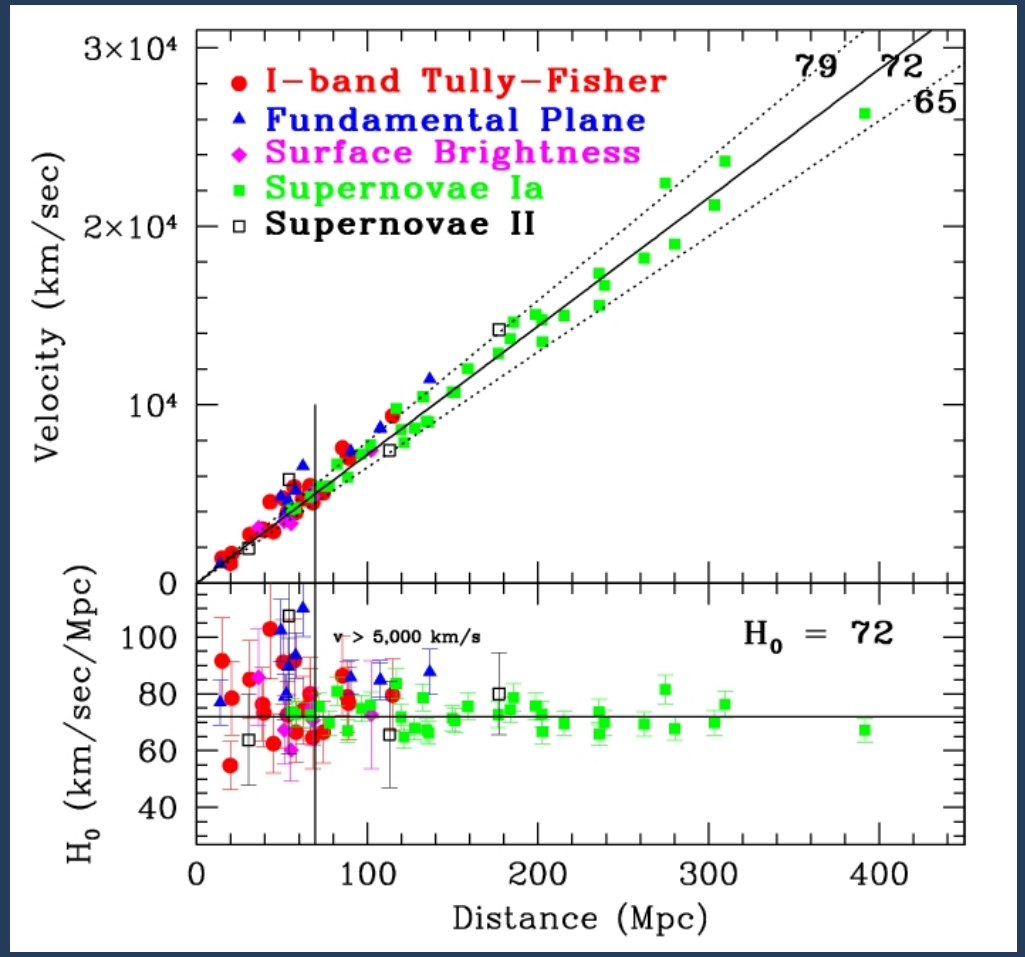
Final Key Project Combined Results



$H_0 = 72 \pm 3$ (stat.)
± 7 (sys.)
km/sec/Mpc

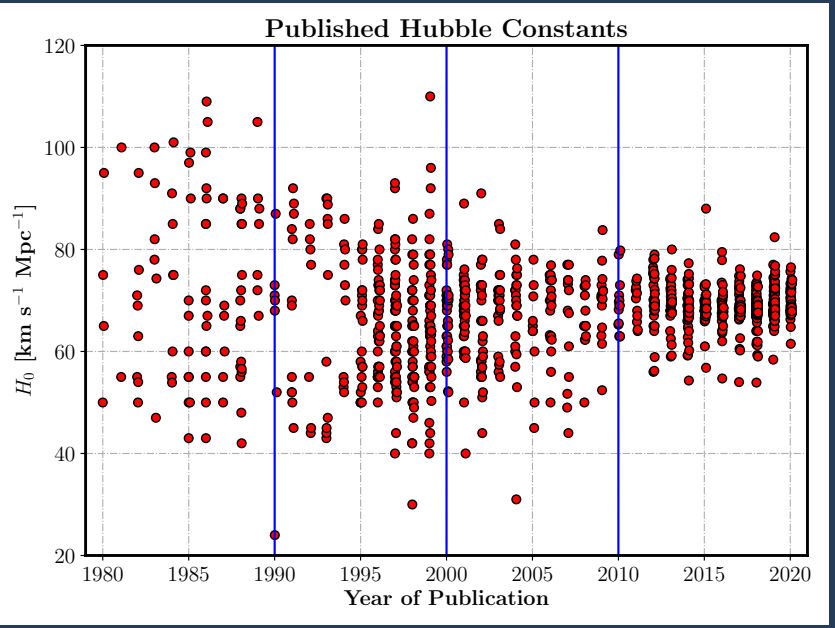
WLF et al. 2001

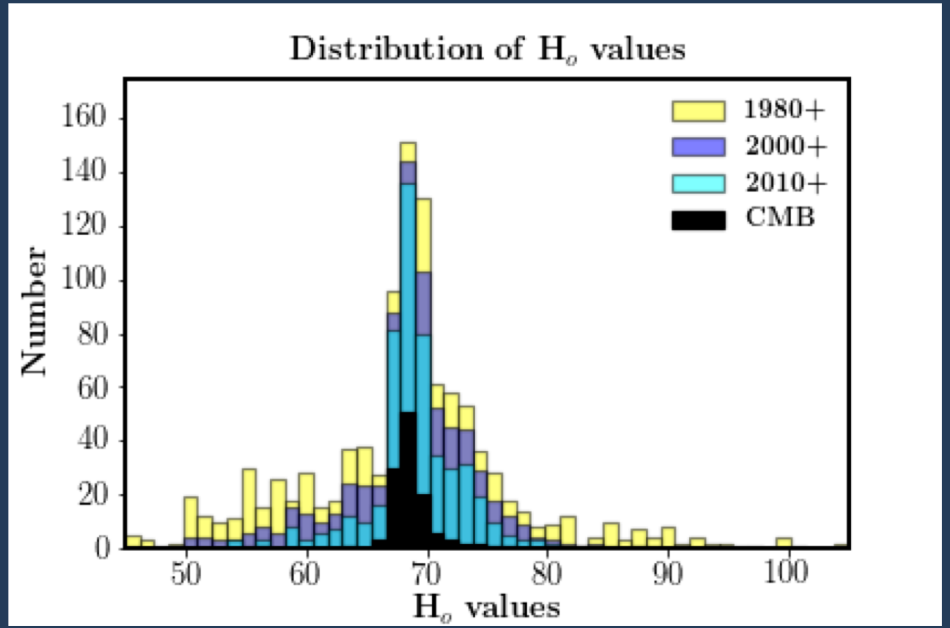
Final HST Key Project Combined Results



Freedman et al. 2001

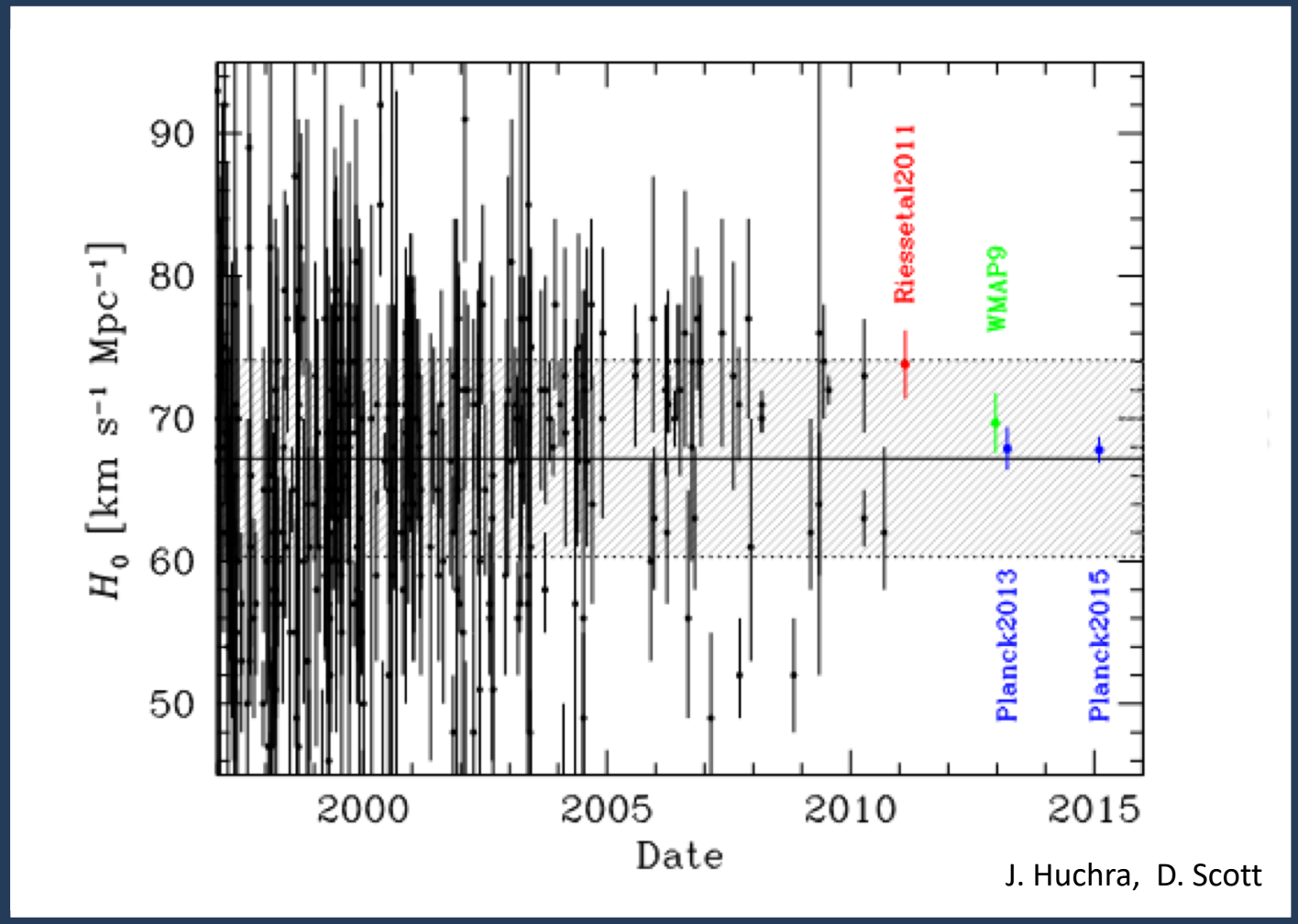
Published Values of the Hubble Constant (1980 – 2020)





WLF (2021)
Database from Huchra, updated by Steer

History of the Hubble Constant…



J. Huchra, D. Scott

With error bars

VOLUME 999 NUMBER 1, PART 1

THE ASTROPHYSIOLOGICAL JOURNEY

1986 APRIL 1

STEPS TO THE HUBBLE CONSTANT. LXXXVII. IT'S 55, DAMMIT, 55, AND THAT'S ALL THERE IS TO IT! ..... *A. Sandage and E. T. Al*

SORRY AL, IT'S MORE LIKE 100 ..... *G. de Vaucouleurs and A. Student*

WELL, 90 OR SO MAYBE ..... *M. Aaronson, J. Huchra, J. Mould, and J. Huchra*

ON HOW ANY TWO QUASARS CAN BE FIT TO A STRAIGHT LINE AND HOW THAT CONCLUSIVELY PROVES QUASARS ARE LOCAL ..... *H. C. Arp*

NO IT DOESN'T, CHIP ..... *Almost the entire astronomical community*

HEY, QUIT PICKING ON CHIP! ..... *G. R. Burbidge*

OH NO, NOT ANOTHER SILLY WOLF-RAYET STAR. XXIV. ..... *P. Massey*

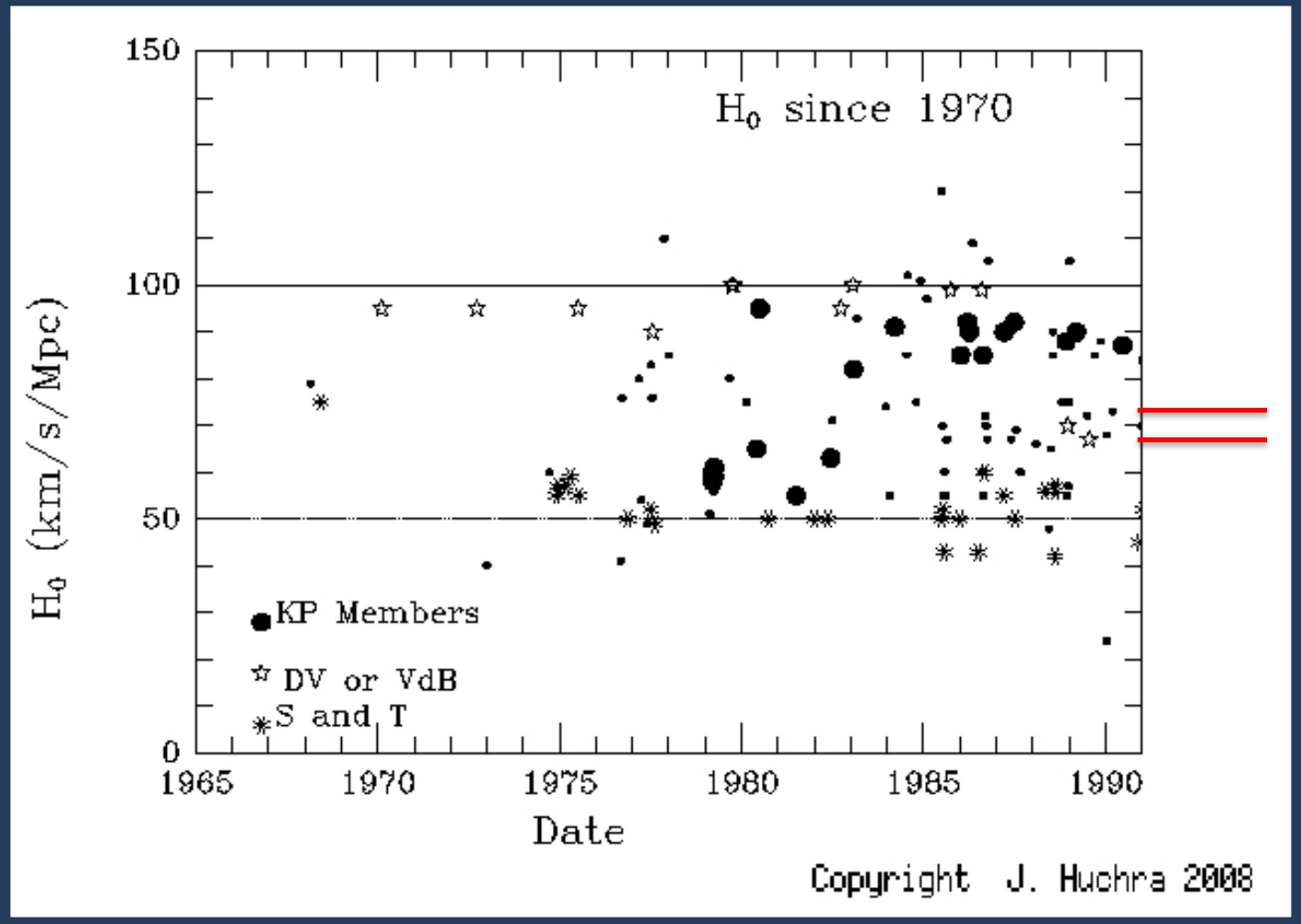
YET STILL MORE VELOCITY DISPERSIONS ..... *G. Illingworth and R. Davies*

ON A NEW MULTICOLOR PHOTOMETRIC SYSTEM ..... *J. Black, R. E. White, R. L. White, R. Green, R. Brown*

PAIR PRODUCTION IN ASTROPHYSICS ..... *D. Elmegreen, B. Elmegreen, G. R. Burbidge, E. M. Burbidge, J. Goad, L. Goad, W. L. W. Sargent, A. Sargent, D. Cesarsky, C. Cesarsky, B. Twarog, B. Anthony-Twarog*

Before the Hubble Key Project…

History of the Hubble Constant…



… Is a history of overcoming systematic effects (e.g., factor of 2)

The improvements have been enormous.

But challenges remain.

Lecture 2

Precision vs Accuracy

Precision

Accuracy

Current Status of Strong Lensing H_0 Measurements

- **Without assumptions on the radial mass density profile - and relying exclusively on stellar kinematics to break the mass-sheet degeneracy - the precision drops from 2% to 8%; i.e., insufficient to resolve the H_0 tension.**

- **The precision can improve to 2.5% with the further addition of kinematics for 50 non-time-delay lenses. Expanding the samples to 40 time-delay and 200 non-time-delay lenses will improve the precision to 1.5% and 1.2%, respectively.**

Birrer, Treu 2019, 2021

Refsdal 1964

- Used Time-delay of lensed supernovae

$$\Delta t = \frac{d_s d_B}{d_s - d_B} \frac{\alpha(\alpha_1 - \alpha_2)}{c}$$

$$d_B = \frac{Z_B c}{H_0} \qquad d_S = \frac{Z_S c}{H_0}$$

$$H_0 = \frac{Z_s Z_B}{Z_s - Z_B} \frac{\alpha(\alpha_1 - \alpha_2)}{\Delta t}$$

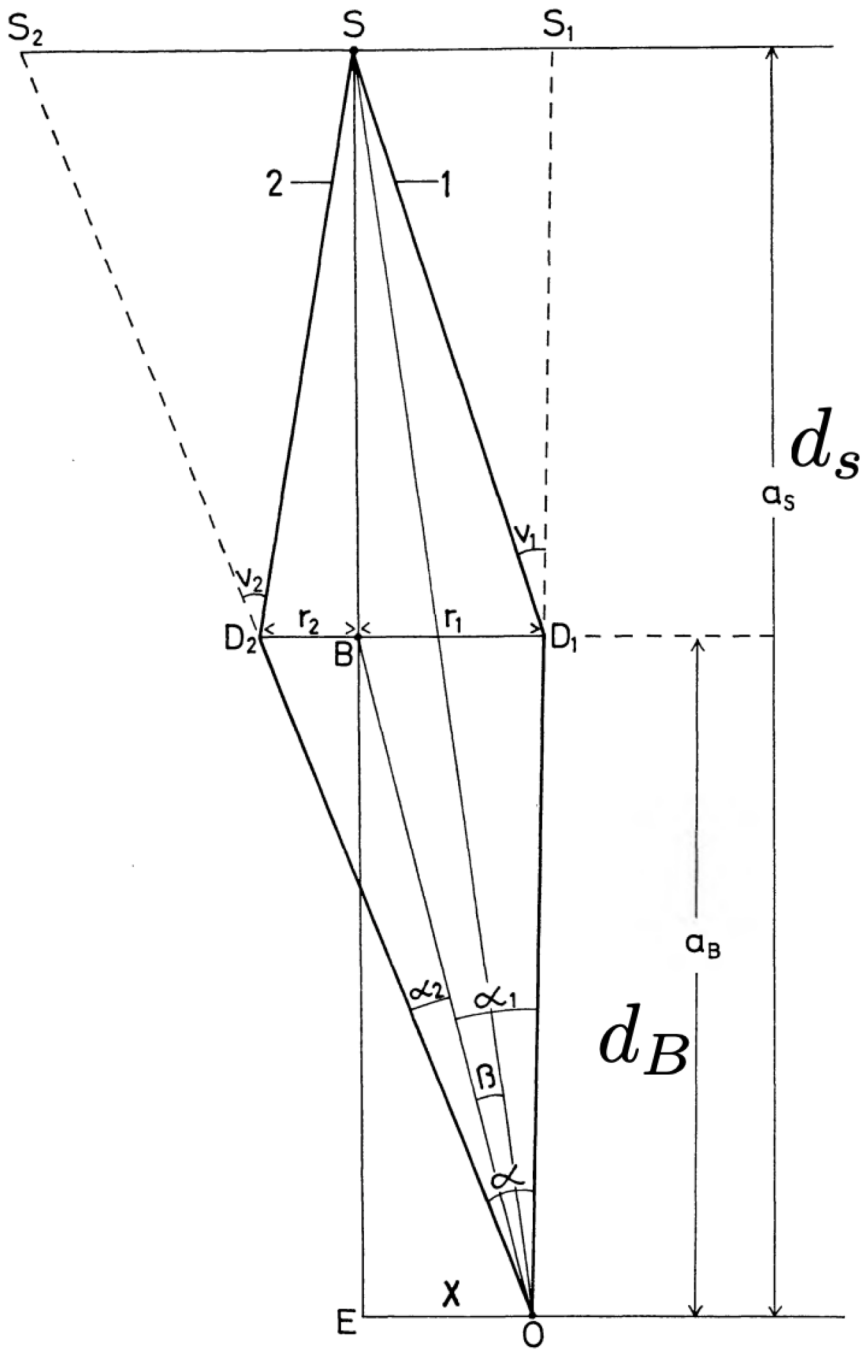
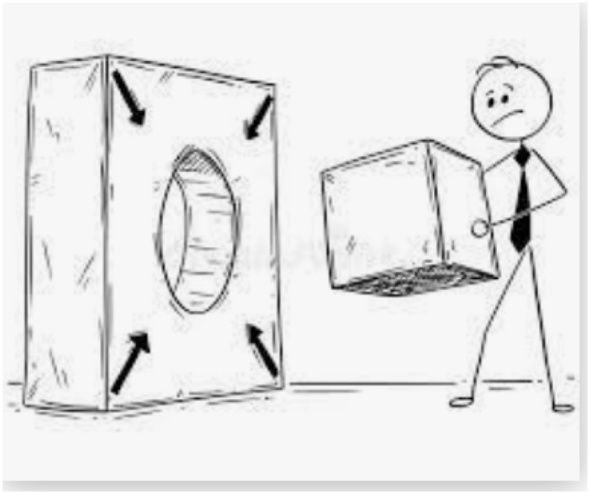


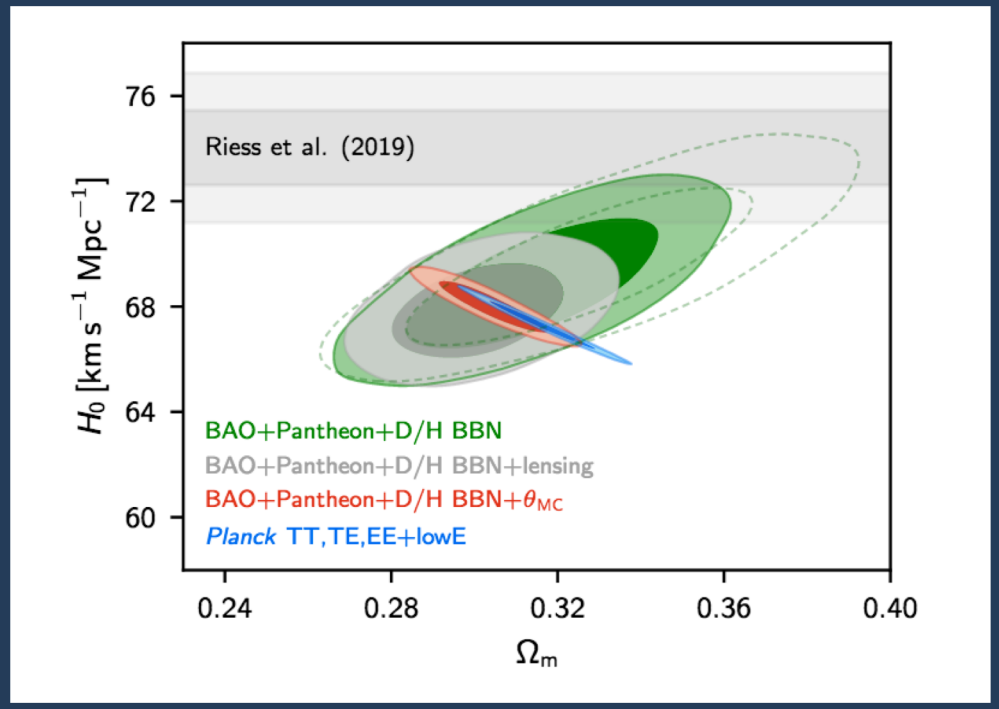
FIG. 1.—*The two light rays from S to O.*

Potential New Physics Beyond ΛCDM, If Real

- Another relativistic species (e.g., an additional neutrino or other 'dark radiation')
- A different equation of state for dark energy from w = -1
- A decaying relic massive dark matter particle
- Interacting dark matter and dark energy
- Modified gravity
- Non-zero spatial curvature
- Additional early-universe physics (prior to recombination)



CMB+BAO+SNe+BBN vs CMB



CMB constraints are orthogonal.

There is no single parameter that can simultaneously bring all of the data into agreement.

Planck Cosmology 2018

Suggested Tensions in the Standard Model: Are There Effects at Greater than 2 to 3 sigma?

- Amplitude (σ_8) differences between the CMB and cluster abundance
- WMAP versus Planck TT power spectra
- Planck high-ℓ versus low -ℓ data
- Planck $A_L > 1$ value
- Core/cusp; satellite galaxies
- Discrepancy between local direct and CMB estimates of the Hubble constant