Chicago, October 2019

Cosmic controversies – boon or bane?

Simon White
Max Planck Institute for Astrophysics

Aristotle

Greece, 384 – 322 B.C.

Student of Plato

Tutor to Alexander the Great

The authoritative scientist in Europe for **1800 years**

"The speed at which an object falls is directly proportional to its weight"

Simon Stevin

Holland, 1548 – 1620

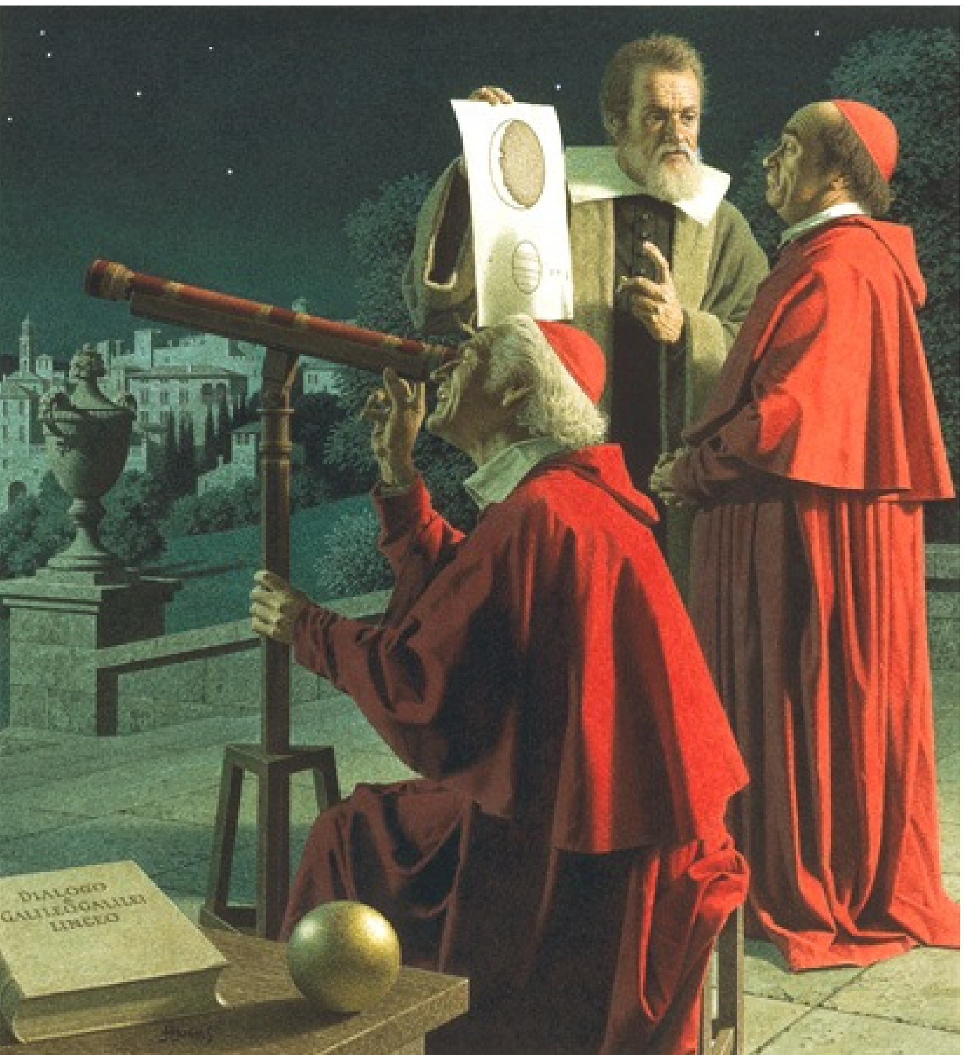
Experiment shows all objects fall at the same rate

Galileo Galilei

Italy, 1564 – 1642

Authority and the standard model *vs* discrepant observation;

an epistemological controversy over the primacy of “facts”

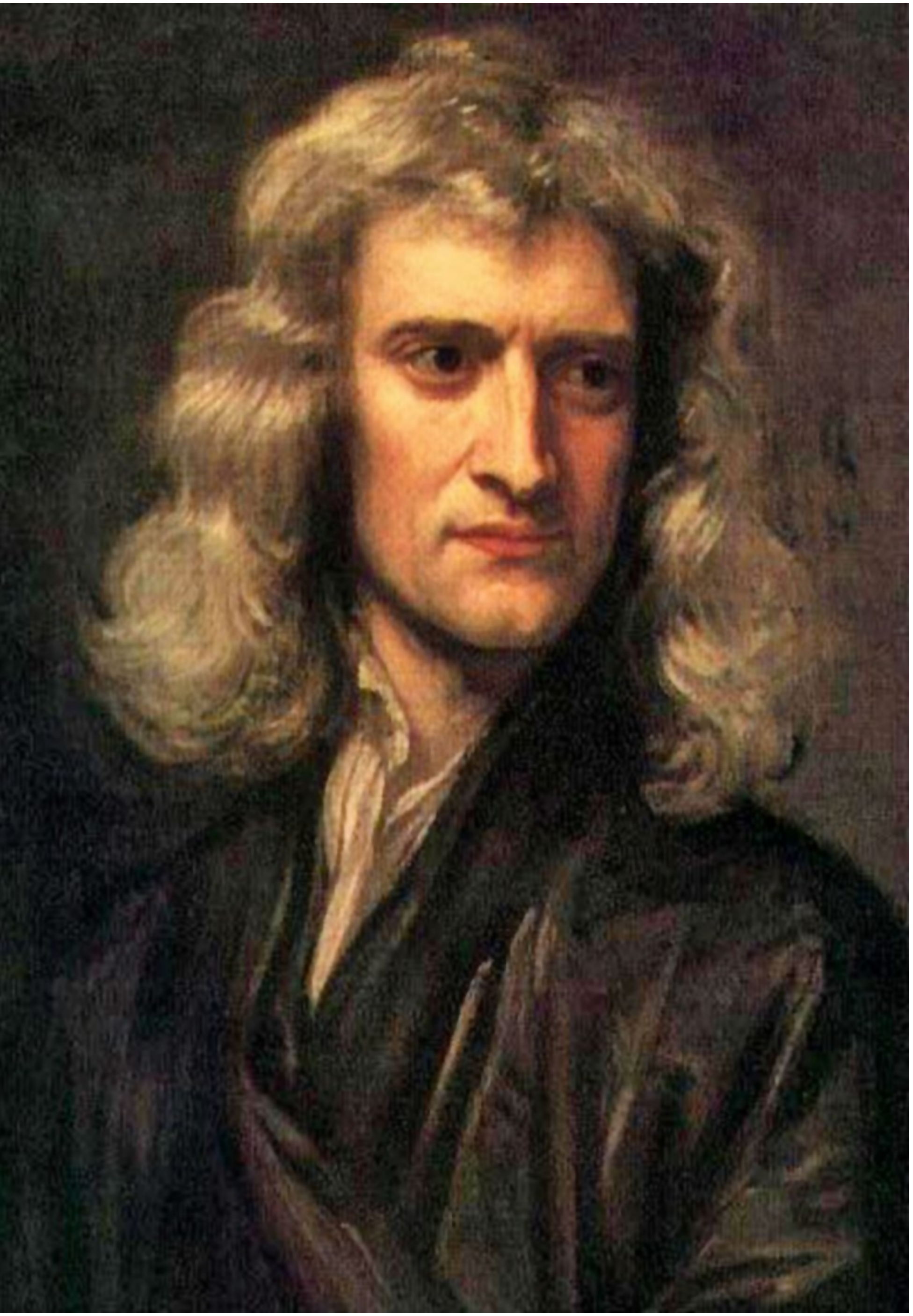


Galileo using his telescope to show the mountains of the Moon to two cardinals

The Copernican revolution

A controversy over interpretation, not over facts

Nicolaus Copernicus
Poland, 1473 – 1543



Isaac Newton: 1643 – 1727

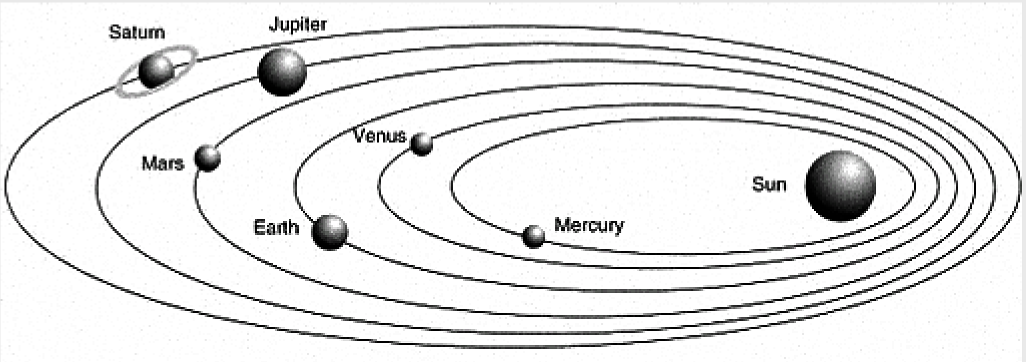
$F = m\,a$ Law of Motion

$F_{grav} = G\,m\,M_{\oplus} / R_{\oplus}^{2}$ Law of Gravity

→ $a_{grav} = G\,M_{\oplus} / R_{\oplus}^{2}$

Mathematics links the motion of the Moon and planets to the falling of objects

Is mathematical "beauty" relevant for establishing scientific truth?



Kepler's Laws

A controversy over the age of the Earth

Charles Lyell (1797 – 1895)
Erosion arguments lead to time-scales of hundreds of millions of years and an indefinite age.

Imprecise phenomenology

William Thomson (1824 – 1907)
Cooling arguments lead to ages of a few tens of millions of years for for the Earth and the Sun.

Rigorous physical calculation

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Rigorous physical calculation ✗

The Great Debate: 26 April 1920

Harlow Shapley   Heber Curtis

Agree that that van Maanen's inferred rotational proper motions for M31 and M31would require them to be galactic, if correct.

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

§ 5. Bemerkungen zur Streuung der Geschwindigkeiten im Coma-Nebelhaufen.

Wie aus der Zusammenstellung in § 3 hervorgeht, existieren im Comahaufen scheinbare Geschwindigkeitsunterschiede von mindestens 1500 bis 2000 km/sek. Im Zusammenhang mit dieser enormen Streuung der Geschwindigkeiten kann man folgende Überlegungen anstellen.

1. Setzt man voraus, dass das Comasystem mechanisch einen stationären Zustand erreicht hat, so folgt aus dem Virialsatz

$$\bar{\varepsilon}_k = -\tfrac{1}{2}\,\bar{\varepsilon}_p\,, \tag{4}$$

wobei $\bar{\varepsilon}_k$ und $\bar{\varepsilon}_p$ mittlere kinetische und potentielle Energien, z. B. der Masseneinheit im System bedeuten. Zum Zwecke der Abschätzung nehmen wir an, dass die Materie im Haufen gleichförmig über den Raum verteilt ist. Der Haufen besitzt einen Radius R von ca. einer Million Lichtjahren (gleich 10^{24} cm) und enthält 800 individuelle Nebel von je einer Masse entsprechend 10^9 Sonnenmassen. Die Gesamtmasse M des Systems ist deshalb

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45}\ \text{gr.} \tag{5}$$

Daraus folgt für die totale potentielle Energie Ω:

$$\Omega = -\frac{3}{5}\,\Gamma\,\frac{M^2}{R} \tag{6}$$

Γ = Gravitationskonstante

oder

$$\bar{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12}\ \text{cm}^2\,\text{sek}^{-2} \tag{7}$$

und weiter

$$\bar{\varepsilon}_k = \overline{v^2}/2 = -\varepsilon_p/2 = 32 \times 10^{12}\ \text{cm}^2\,\text{sek}^{-2}$$

$$(\overline{v^2})^{1/2} = 80\ \text{km/sek}\,. \tag{8}$$

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

This is the first statement of the **concept** of dark matter as we now understand it

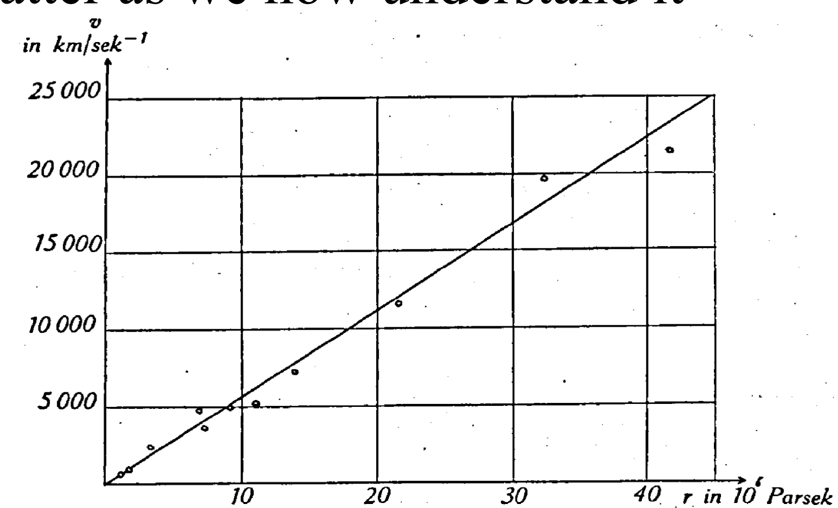


Fig. 2.

Ann. Rev. Astron. Astrophys. 1979. 17: 135–87

MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES[1]

S. M. Faber[2]
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

J. S. Gallagher
Department of Astronomy, University of Illinois, Urbana, Illinois 61801

1 INTRODUCTION

Is there more to a galaxy than meets the eye (or can be seen on a photograph)? Many decades ago, Zwicky (1933) and Smith (1936) showed that if the Virgo cluster of galaxies is bound, the total mass must considerably exceed the sum of the masses of the individual member galaxies; i.e. there appeared to be "missing mass" in the cluster.

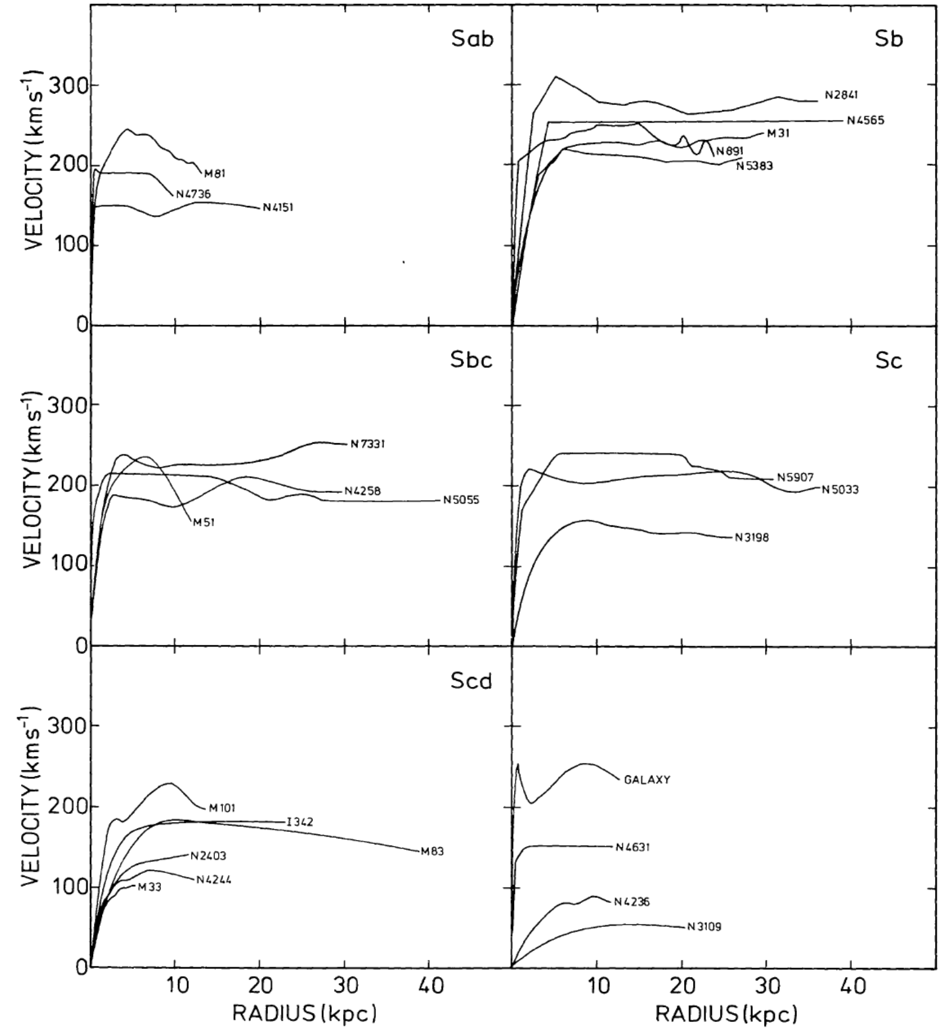


Figure 2 Rotation curves of 25 galaxies of various morphological types from Bosma (1978).

- Extended dark matter halos became part of the mainstream in the 1970's
- Rotation curves were a small part of the justification (9/54 pages in F&G79)
- The rotation curves used were mostly 21cm, rather than optical

BULLETIN OF THE ASTRONOMICAL INSTITUTES
OF THE NETHERLANDS

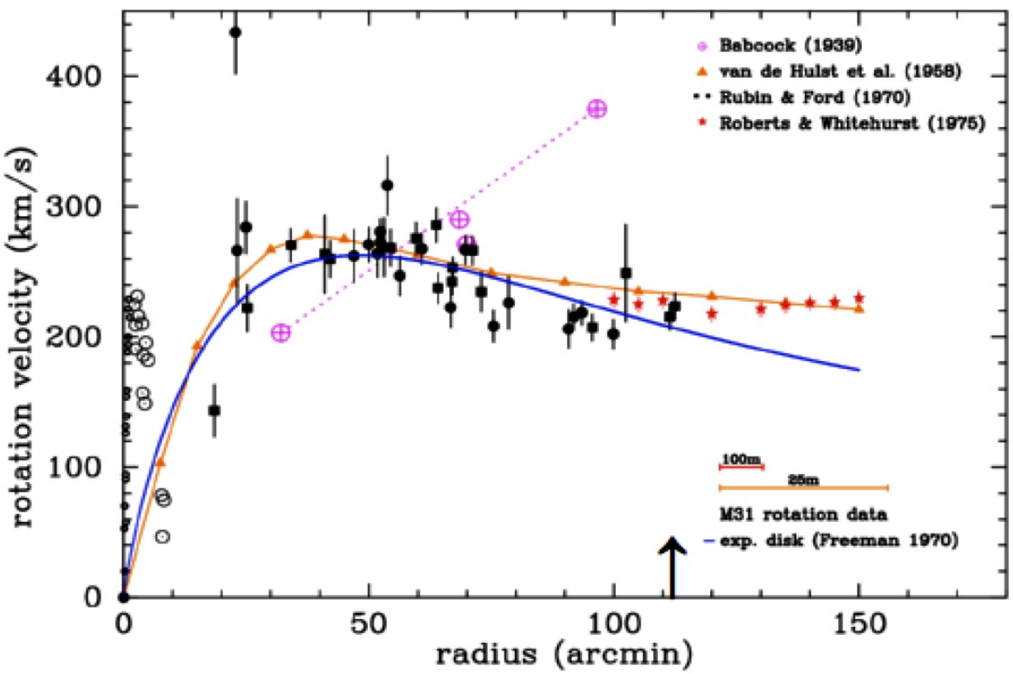
1957 NOVEMBER 9 VOLUME XIV NUMBER 480

COMMUNICATIONS FROM THE NETHERLANDS FOUNDATION FOR RADIO
ASTRONOMY AND THE OBSERVATORY AT LEIDEN

ROTATION AND DENSITY DISTRIBUTION OF THE ANDROMEDA NEBULA DERIVED FROM OBSERVATIONS OF THE 21-cm LINE

BY H. C. VAN DE HULST, E. RAIMOND AND H. VAN WOERDEN

The atomic hydrogen emission from the Andromeda nebula (M31) was observed with the 25-metre telescope at Dwingeloo; the beamwidth was 0°.6. Line profiles were measured at 20 points of the major axis (Figure 5). The mean error of the brightness temperature measured at one frequency in one direction was 0.2 to 0.3°K except in the frequency range contaminated by galactic foreground radiation. The line was observable to 2°.5 at either side of the centre. The central velocity with respect to the local standard of rest is — 296 km/sec. The velocity of rotation slowly falls from 278 km/sec at 0°.6 from the centre to 221 km/sec at 2°.5



- The earliest reliable flat rotation curves (for M31) are usually credited to Rubin & Ford 1970 (optical) and Roberts & Whitehurst 1975 (radio)
- The 21cm goes to larger radius
- The 1957 Dwingeloo curve is just as good and goes just as far

The mid-century cosmological controversy

Georges Lemaitre

Fred Hoyle

A primeval atom
An evolving universe with finite age and a singularity

No ugly “Big Bang”, rather a steady state universe with continuous creation

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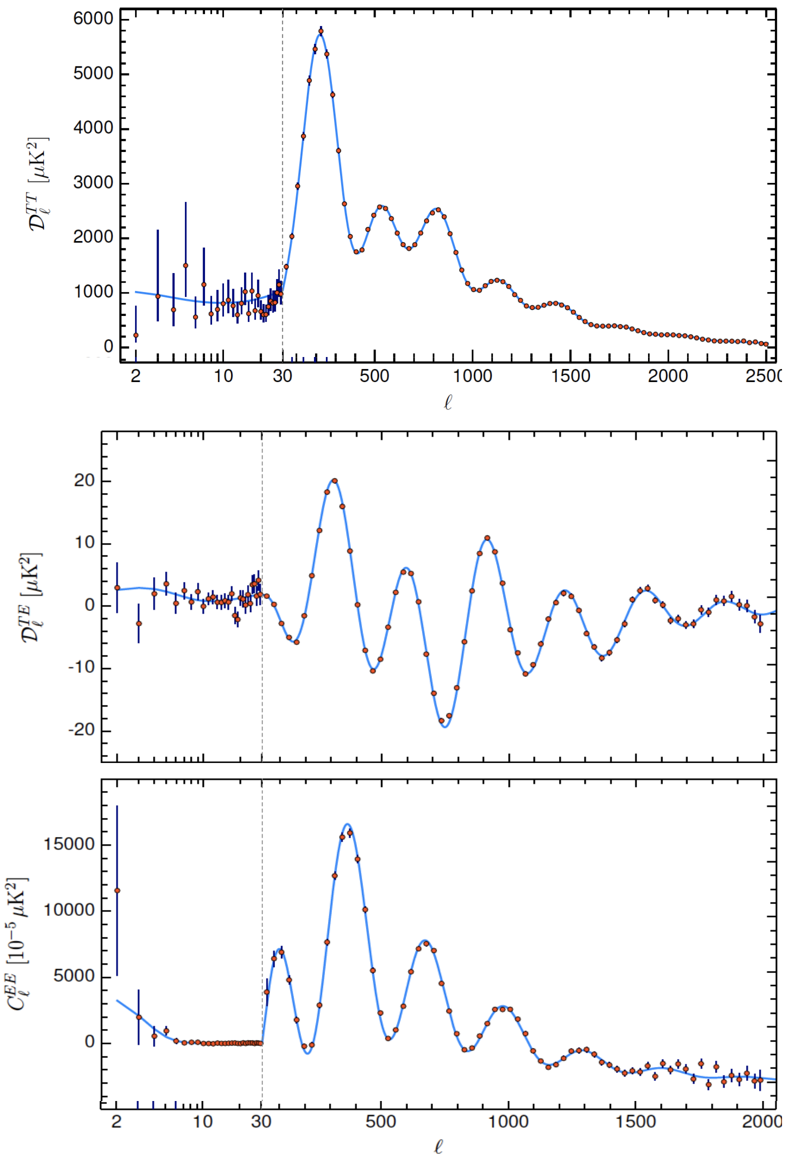
Observations decided!

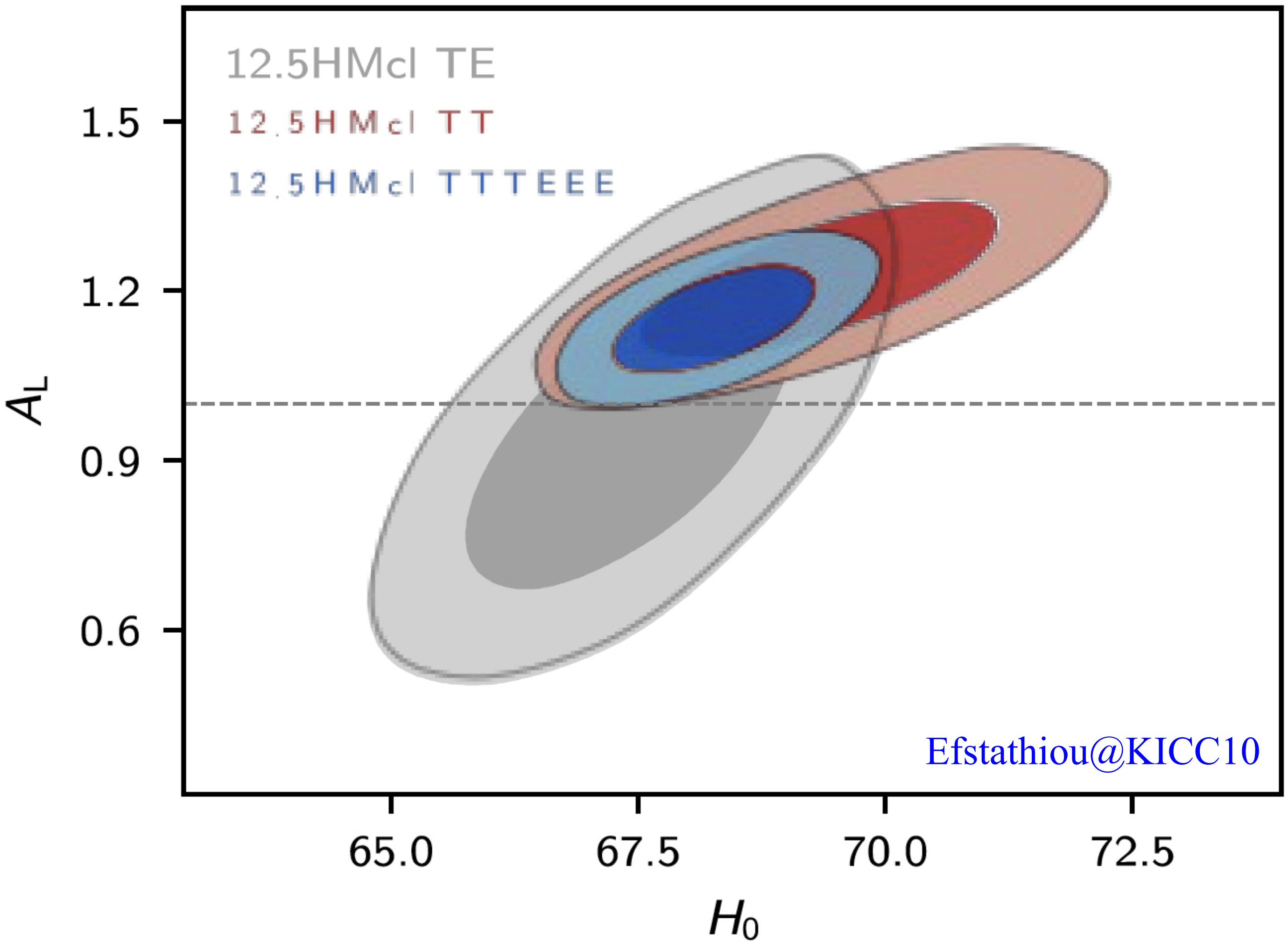
<u>Precise</u> astrophysical evidence for dark matter?



Planck Collaboration 2018

Parameter	Combined
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042
$\Omega_m h^2$	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.37 ± 0.54
Ω_m	0.3147 ± 0.0074
Age [Gyr]	13.801 ± 0.024
σ_8	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.830 ± 0.013
z_{re}	7.64 ± 0.74
$100\theta_*$	1.04108 ± 0.00031
r_{drag} [Mpc]	147.18 ± 0.29

- Results from a single instrument (Planck/HFI)
- <u>No</u> local/low-redshift data are used
- Linear perturbation of a homogeneous medium
- No exotic/HE physics needed to set pattern
- No measurable primordial non-gaussianity
- Good fit to minimal 6-parameter ΛCDM



- Peaks in the Planck TT power spectrum are slightly broader than expected
- This can be parametrised as more lensing than expected/measured directly
- No corresponding effect is seen in the TE power spectrum

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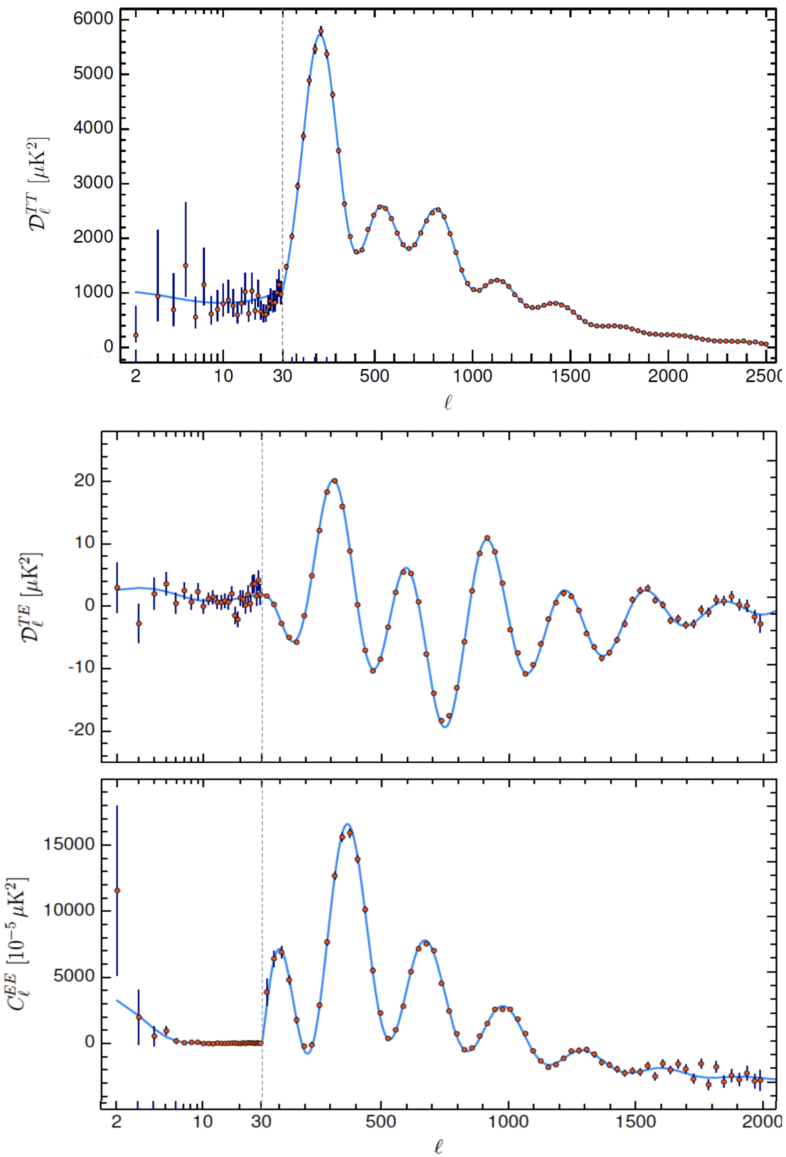

Planck Collaboration 2018

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$\Omega_c h^2$	0.1198 ± 0.0012	dynamics, lensing
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τ	0.0540 ± 0.0074	reionization
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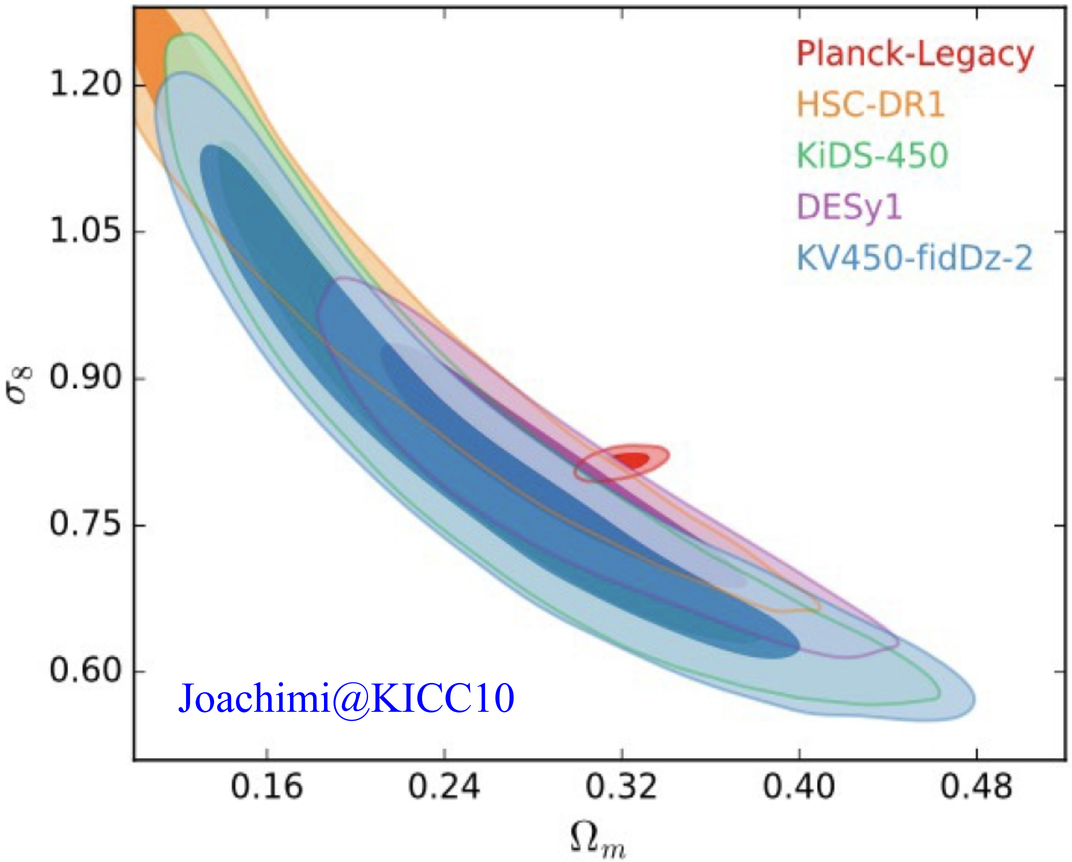
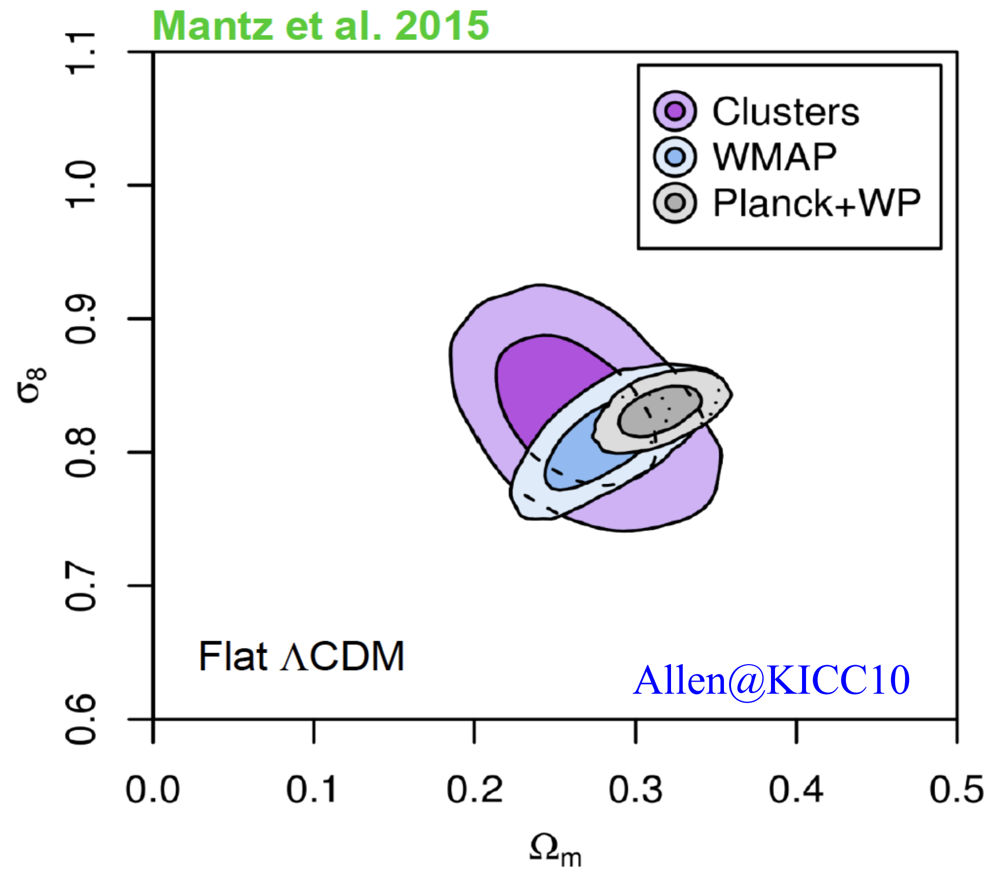
- Some “tensions” with other data

Tensions with low-redshift large-scale structure

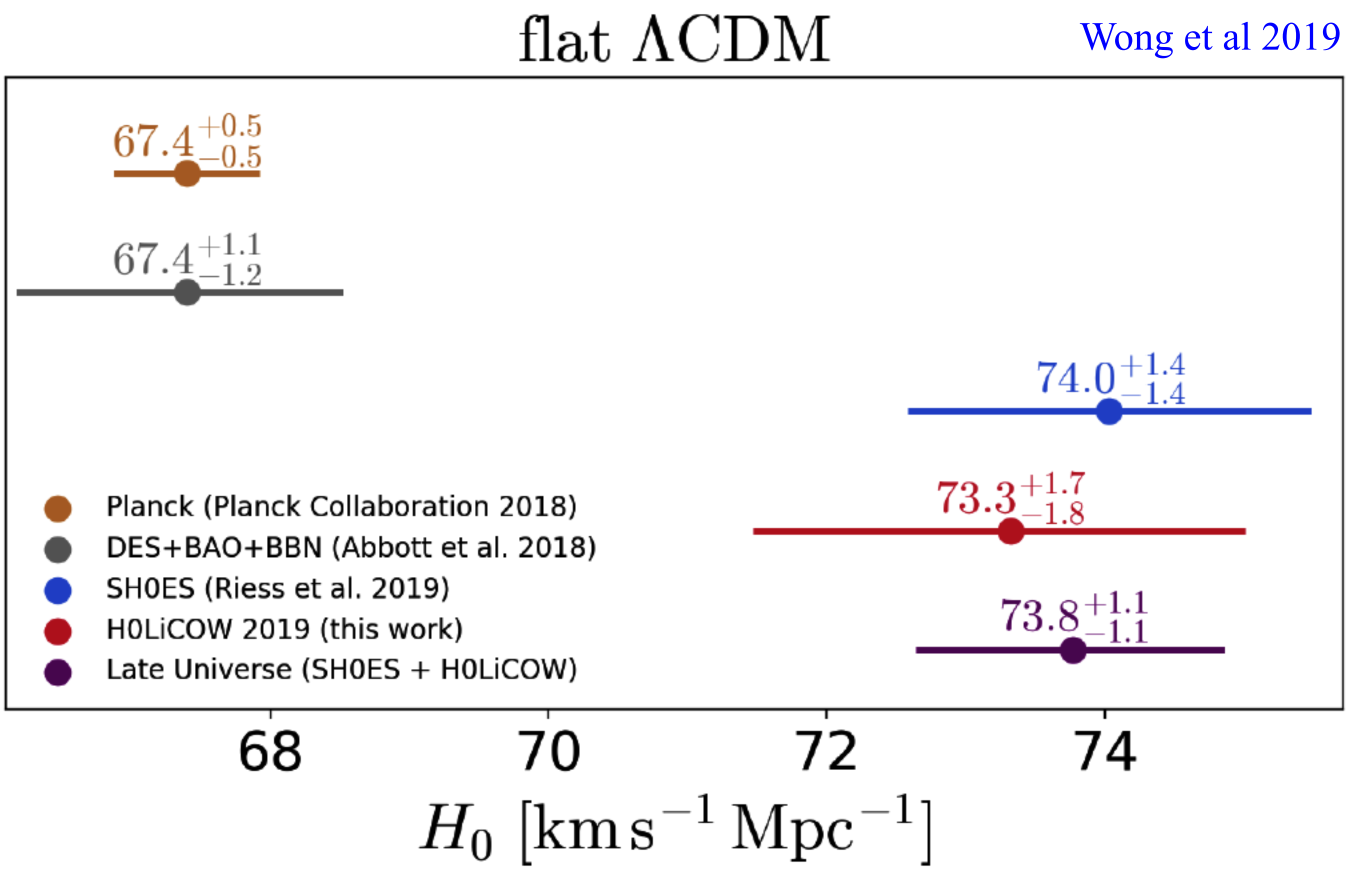




Shear measurement sensitive to the redshift distribution of background galaxies

Cluster abundance measurement sensitive to the mass calibration of the clusters

Another H_0 controversy



- Low and high redshift estimates of H_0 disagree by 10%

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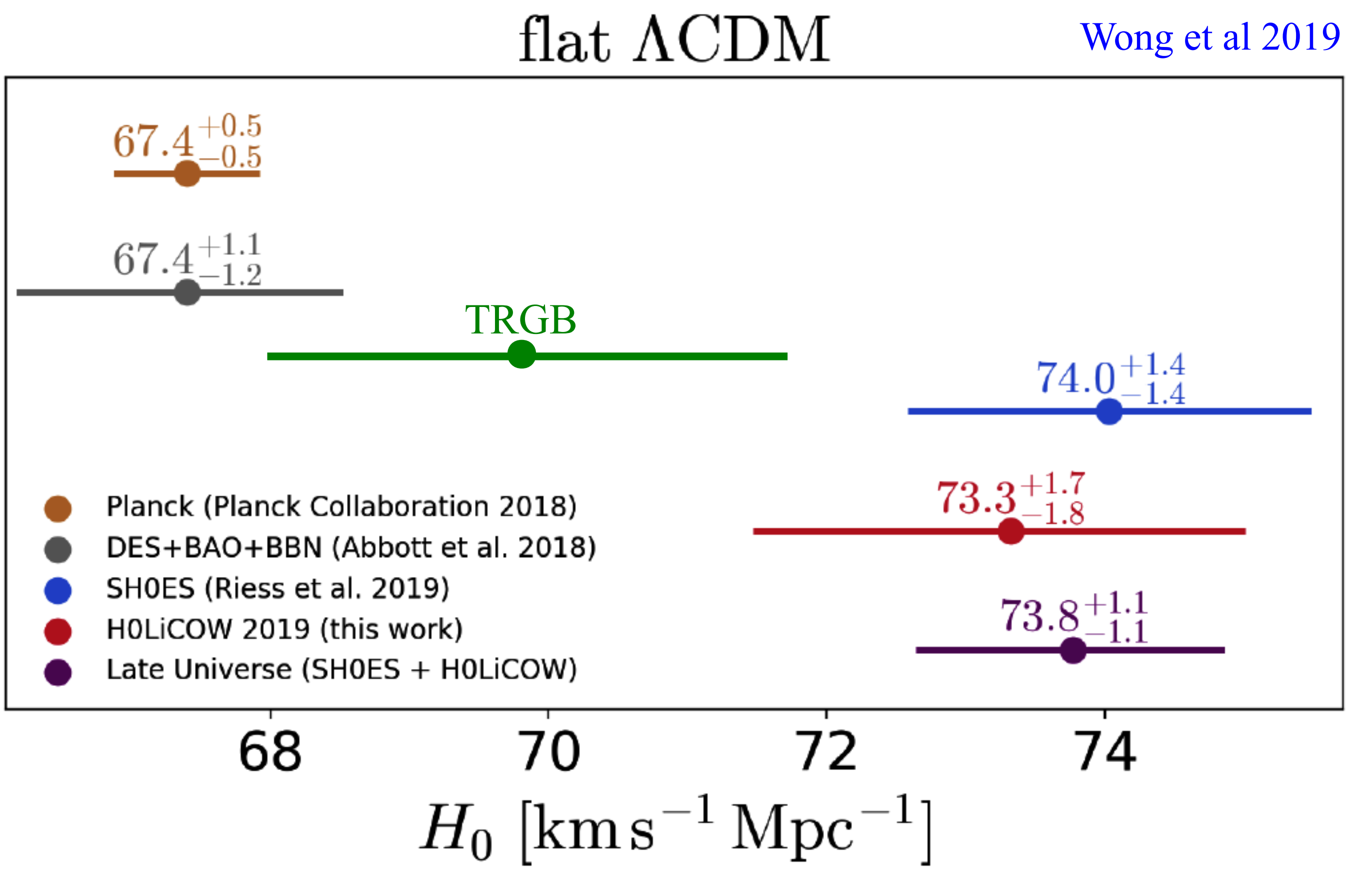

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- Tip of the Red Giant Branch estimate is intermediate (Freedman et al 2019)

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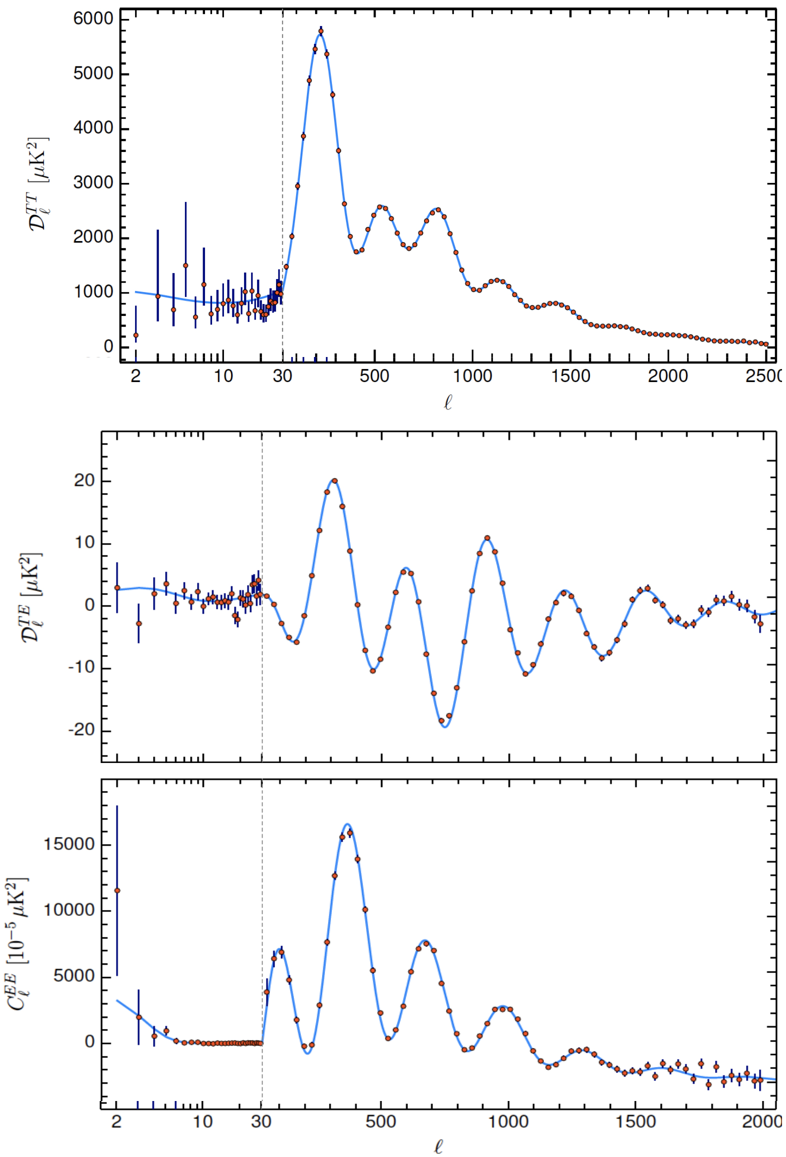

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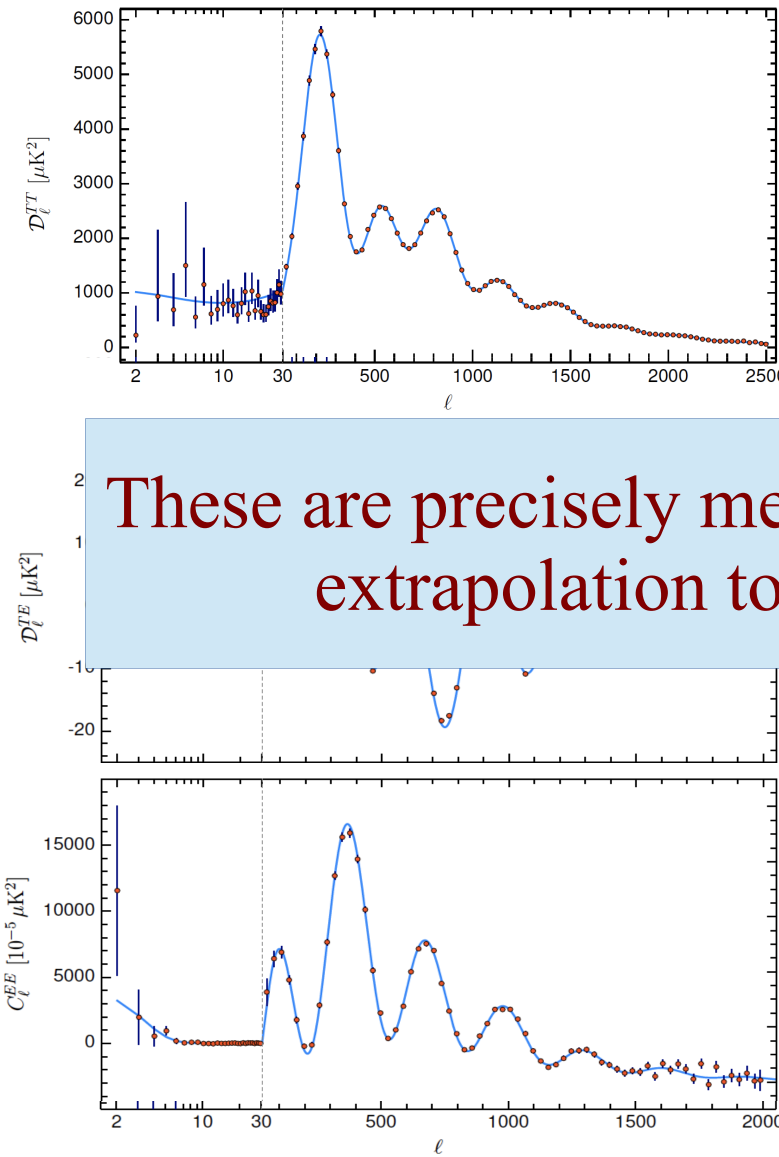

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These are precisely measured initial conditions, but they need extrapolation to the scales which form galaxies

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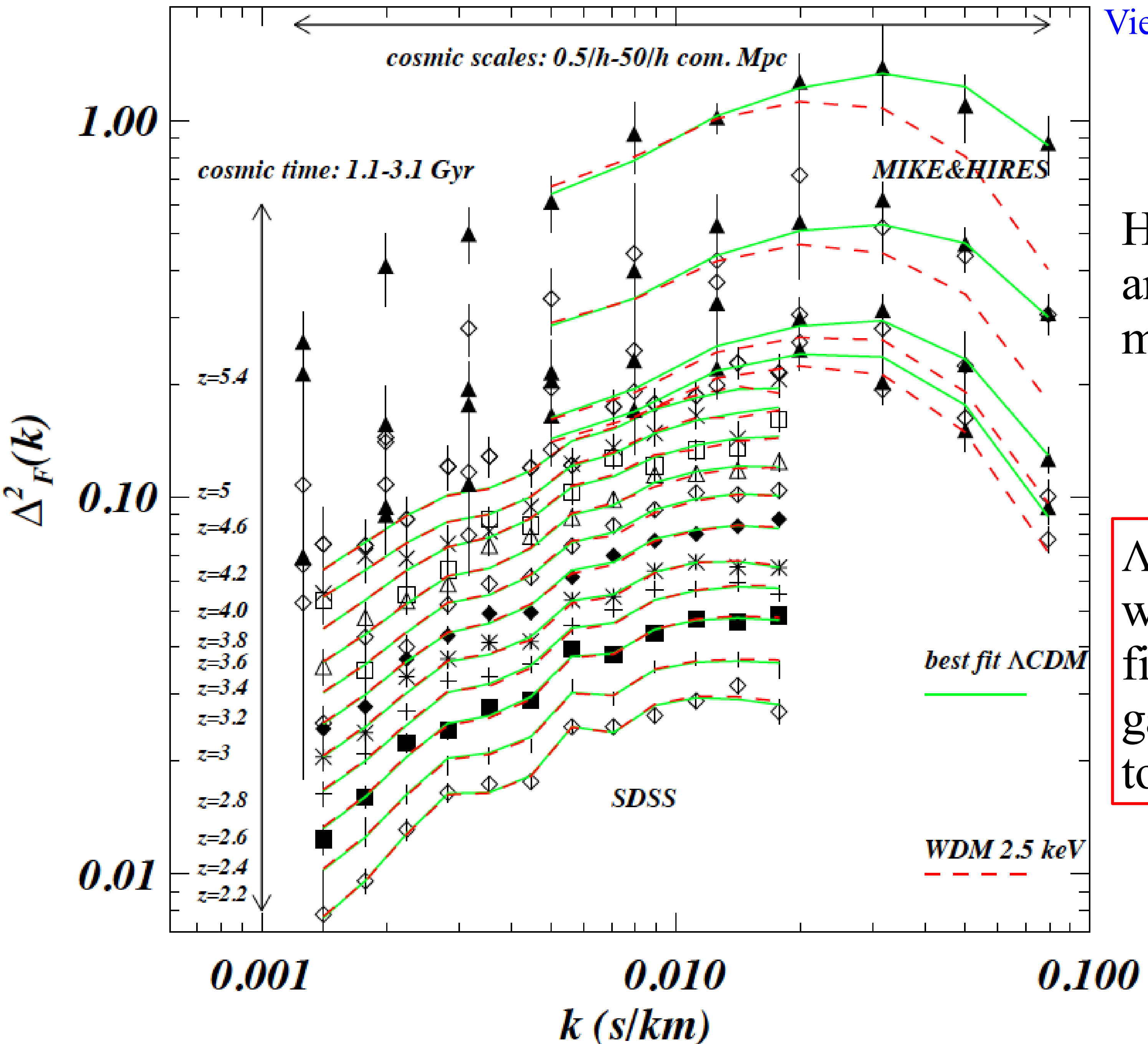
Lyman α forest spectra compared to ΛCDM predictions



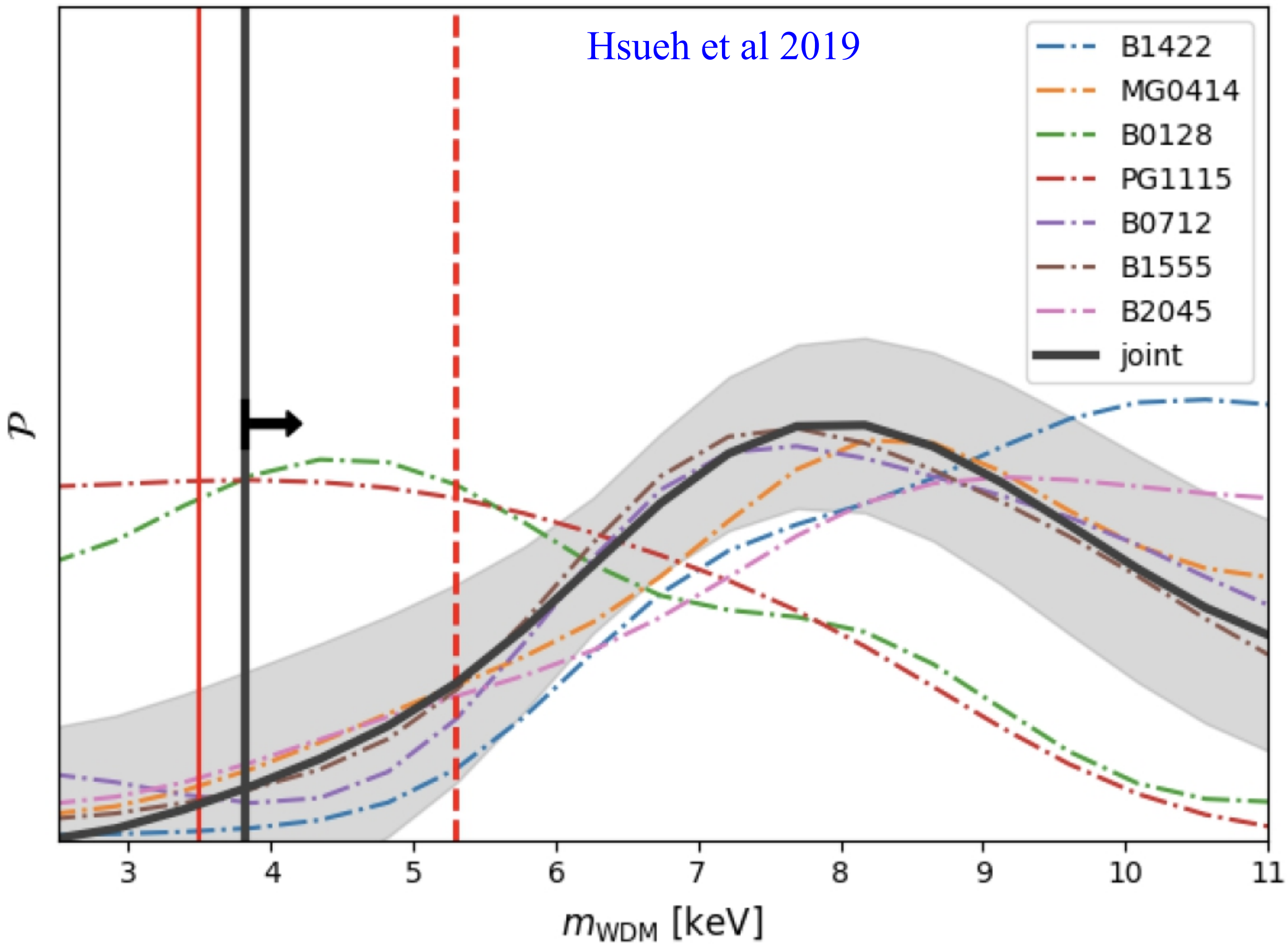
Viel, Becker, Bolton & Haehnelt 2013

High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4

ΛCDM initial conditions with CMB parameters fit structure in the pre-galactic medium down to dwarf galaxy scales

$m_{WDM} > 3.3$ keV

Strong lensing constraints on WDM



- Flux ratio anomalies in multiply imaged quasars constrain the mass of thermal relic WDM to be $m_{WDM} > 3.8$ keV

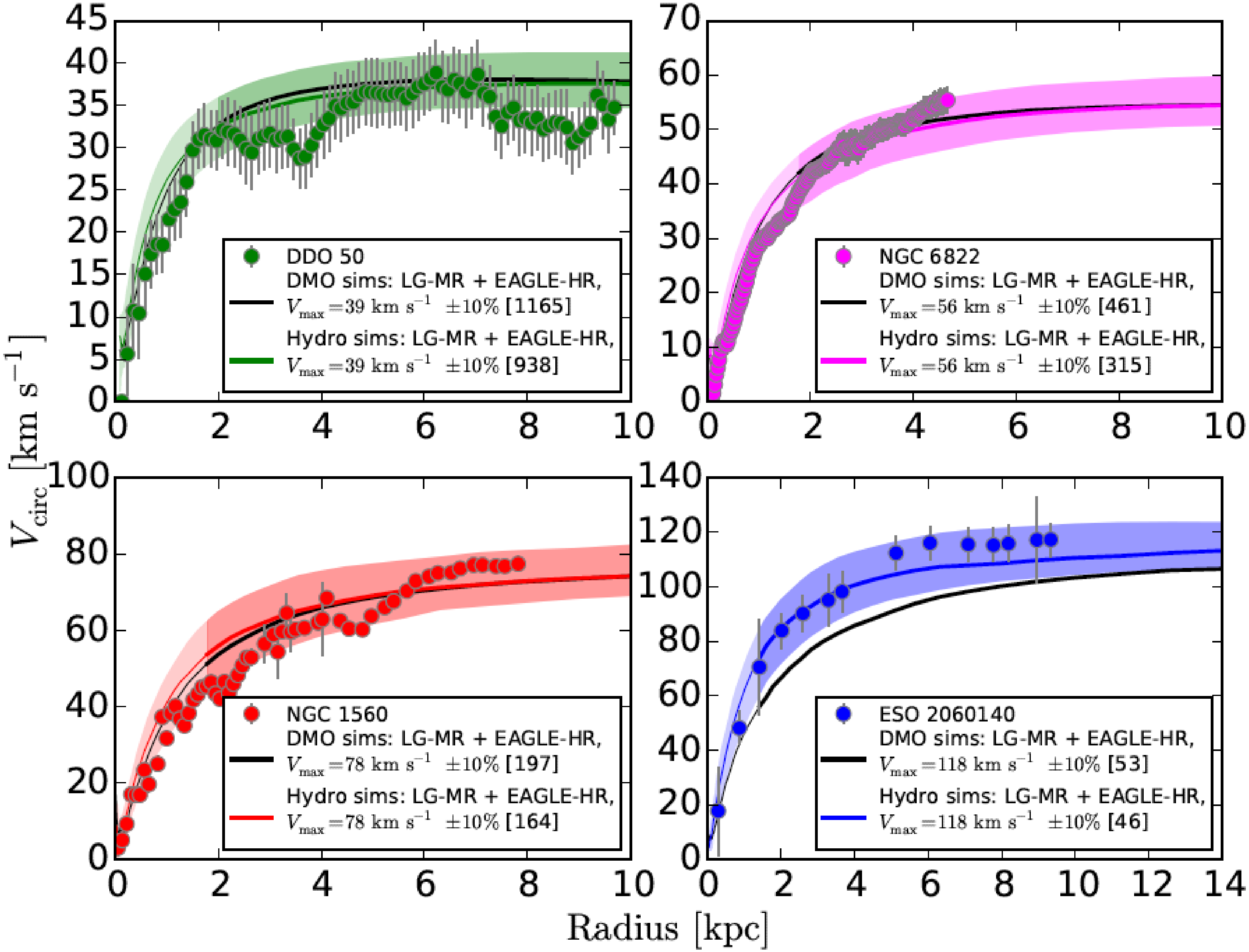
Small-scale controversies over ΛCDM

- The core-cusp problem
- The missing satellite problem "Solved" by baryonic processes?
- The Too-Big-To-Fail problem

DM "solutions" have other problems or are insufficiently understood

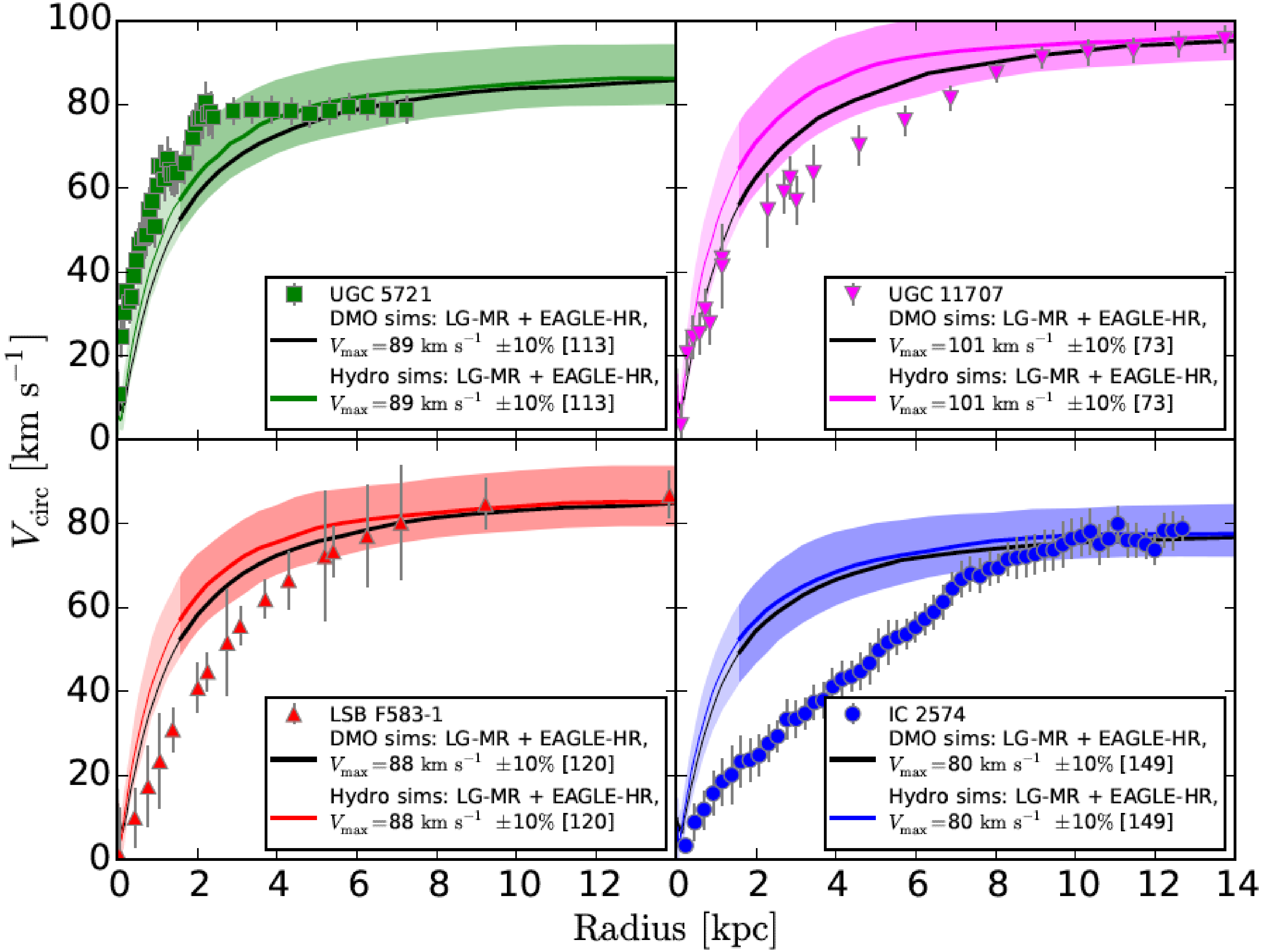
- **WDM** Abundance of hi-z galaxies? Ly-α forest? flux-ratio anomalies?
- **SIDM** V-dependent X-section needed, complex interaction with G.F.
- **FDM** Not yet explored enough to know
- **Emergent DM** A fully calculable theory has yet to emerge

Dwarf galaxy rotation curves: cusps vs cores



Many dwarf galaxies have rotation curves that fit ΛCDM predictions well

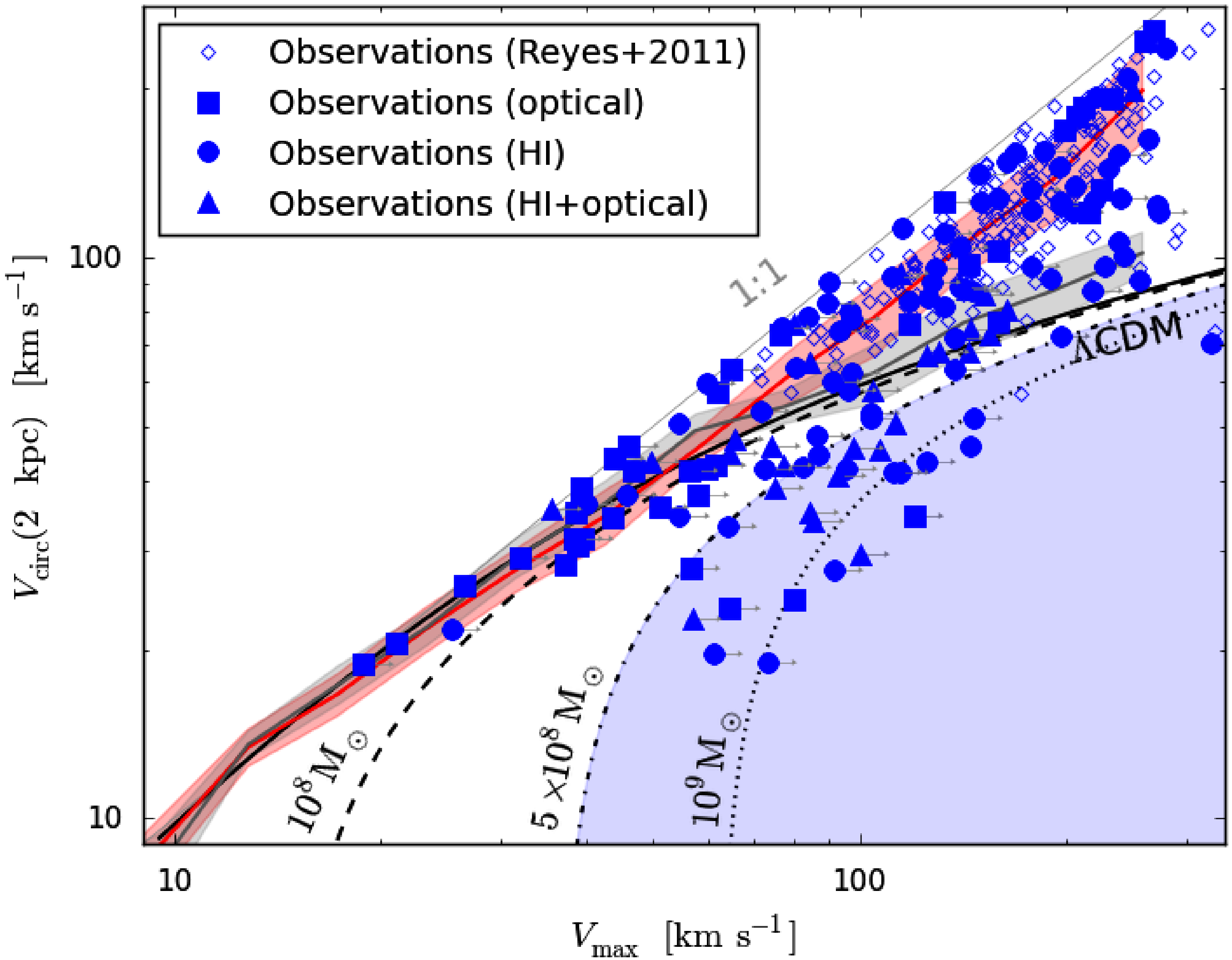
Dwarf galaxy rotation curves: cusps vs cores



Many others fail dramatically to fit ΛCDM predictions.

"Cores" from: (i) DM properties? (ii) Baryon effects? (iii) Incorrect modelling?

V_{circ}(2 kpc) versus V_{max} for observed dwarfs



Enormous apparent <u>diversity:</u>

Too large for baryon effects proposed so far?

Too large to reflect DM properties alone?

Oman et al 2015

ΛCDM rules!

ΛCDM rules!

Is dark energy really a cosmological constant?
When do we accept that w = -1 to astro-physical accuracy?

ΛCDM rules!

Is dark energy really a cosmological constant? When do we accept that $w = -1$ to astro-physical accuracy?

Is the dark matter really cold to astrophysical accuracy? Does it have other measurable interactions?

ΛCDM rules!

Is dark energy really a cosmological constant?
When do we accept that w = -1 to astro-physical accuracy?

Is the dark matter really cold to astrophysical accuracy? Does it have other measurable interactions?

Is the dark matter really dark?
Has decay or annihilation emission been seen?

ΛCDM rules!

Is dark energy really a cosmological constant?
When do we accept that w = -1 to astro-physical accuracy?

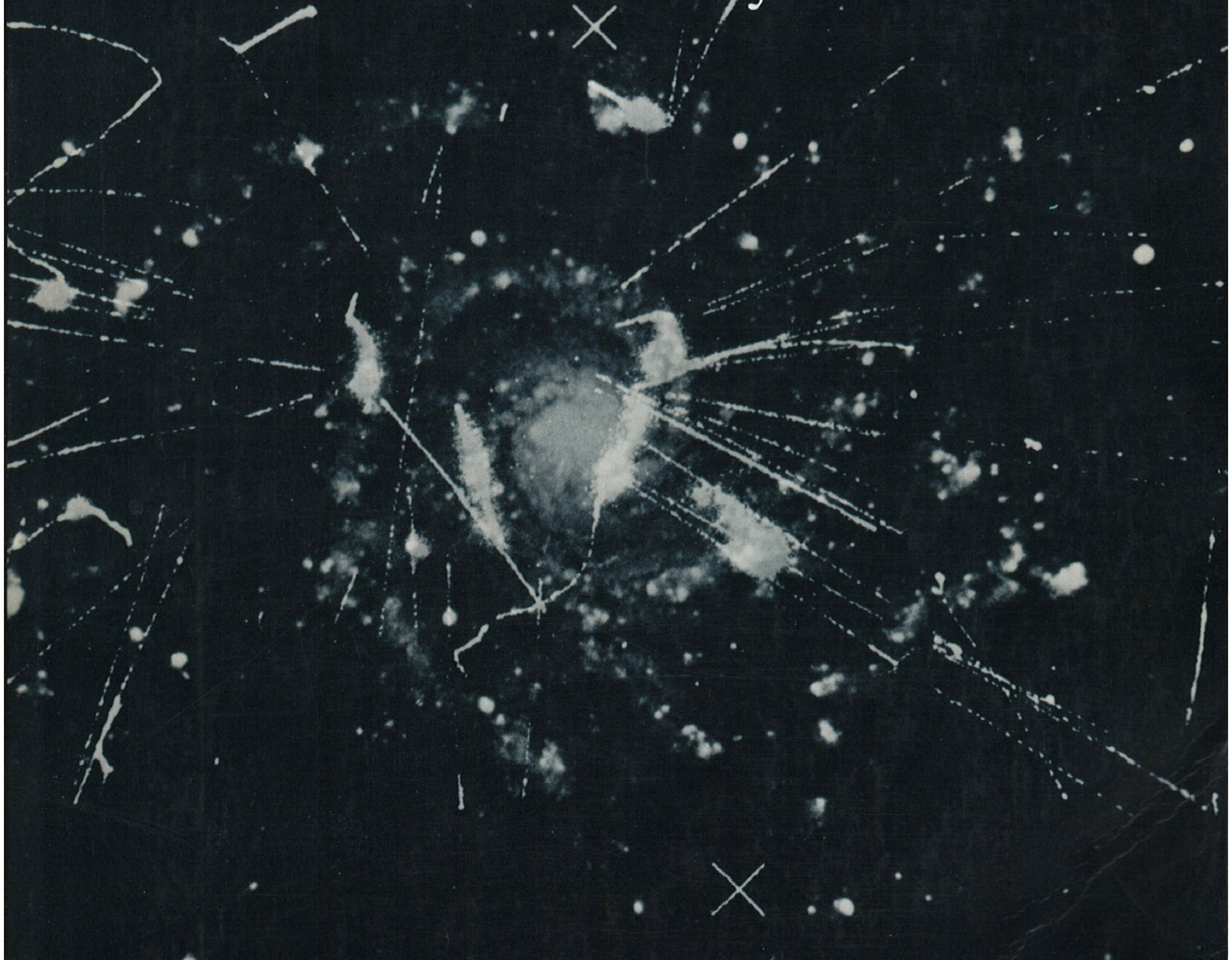
Is the dark matter really cold to astrophysical accuracy? Does it have other measurable interactions?

Is the dark matter really dark?
Has decay or annihilation emission been seen?

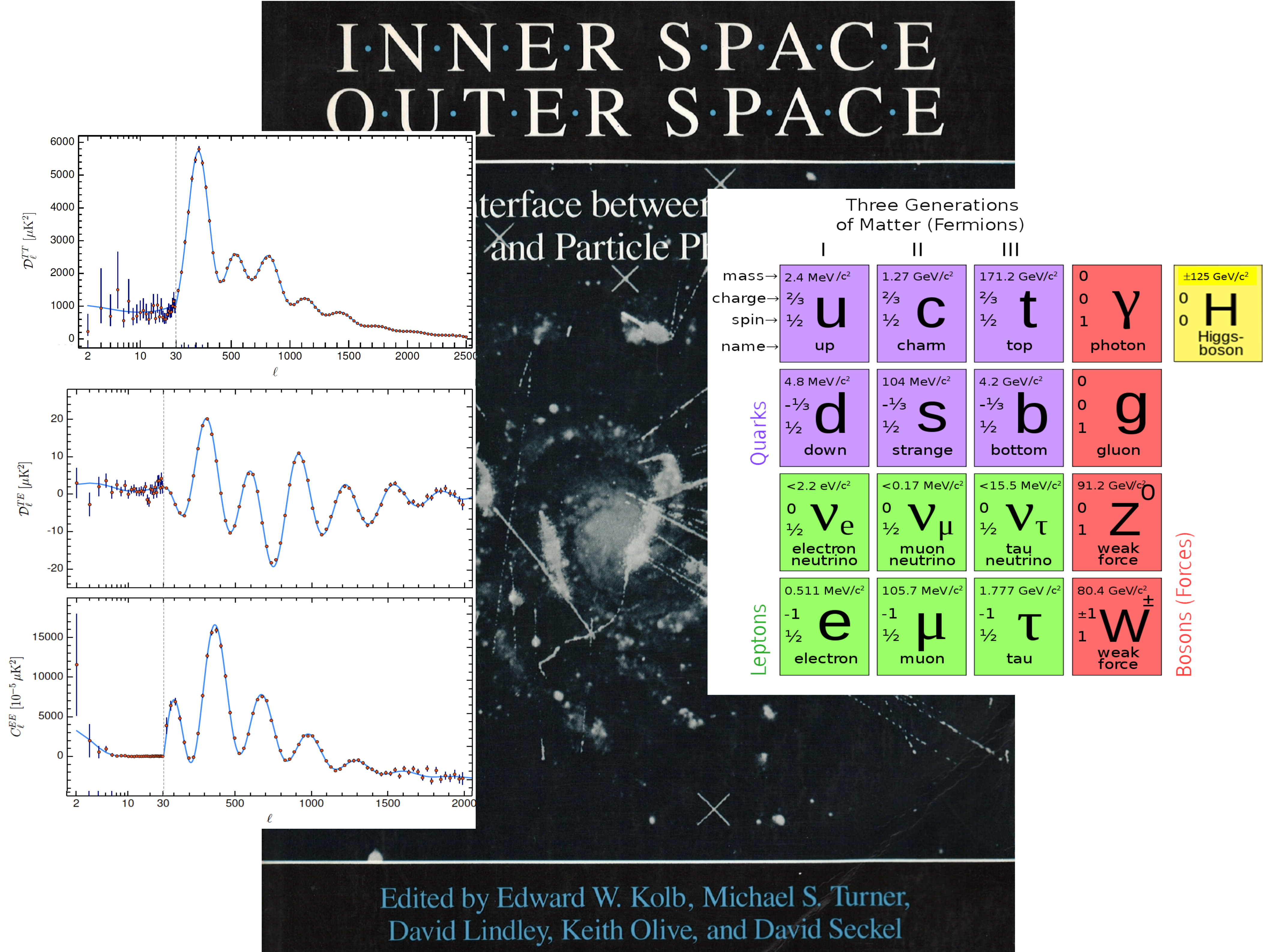
Does the dark matter phenomenon indicate "funny gravity"?

INNER SPACE OUTER SPACE

The Interface between Cosmology and Particle Physics



Edited by Edward W. Kolb, Michael S. Turner, David Lindley, Keith Olive, and David Seckel


INNER SPACE
OUTER SPACE
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and Particle Ph
Edited by Edward W. Kolb, Michael S. Turner,
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6000
5000
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$\mathcal{D}_\ell^{TT}$ [μK^2]
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15000
10000
5000
0
C_ℓ^{EE} [$10^{-5}\mu$K^2]
2
10
30
500
1000
1500
2000
ℓ
Three Generations
of Matter (Fermions)
I
II
III
mass→
charge→
spin→
name→
2.4 MeV/c²
⅔
½
u
up
1.27 GeV/c²
⅔
½
c
charm
171.2 GeV/c²
⅔
½
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photon
±125 GeV/c²
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H
Higgs-boson
Quarks
4.8 MeV/c²
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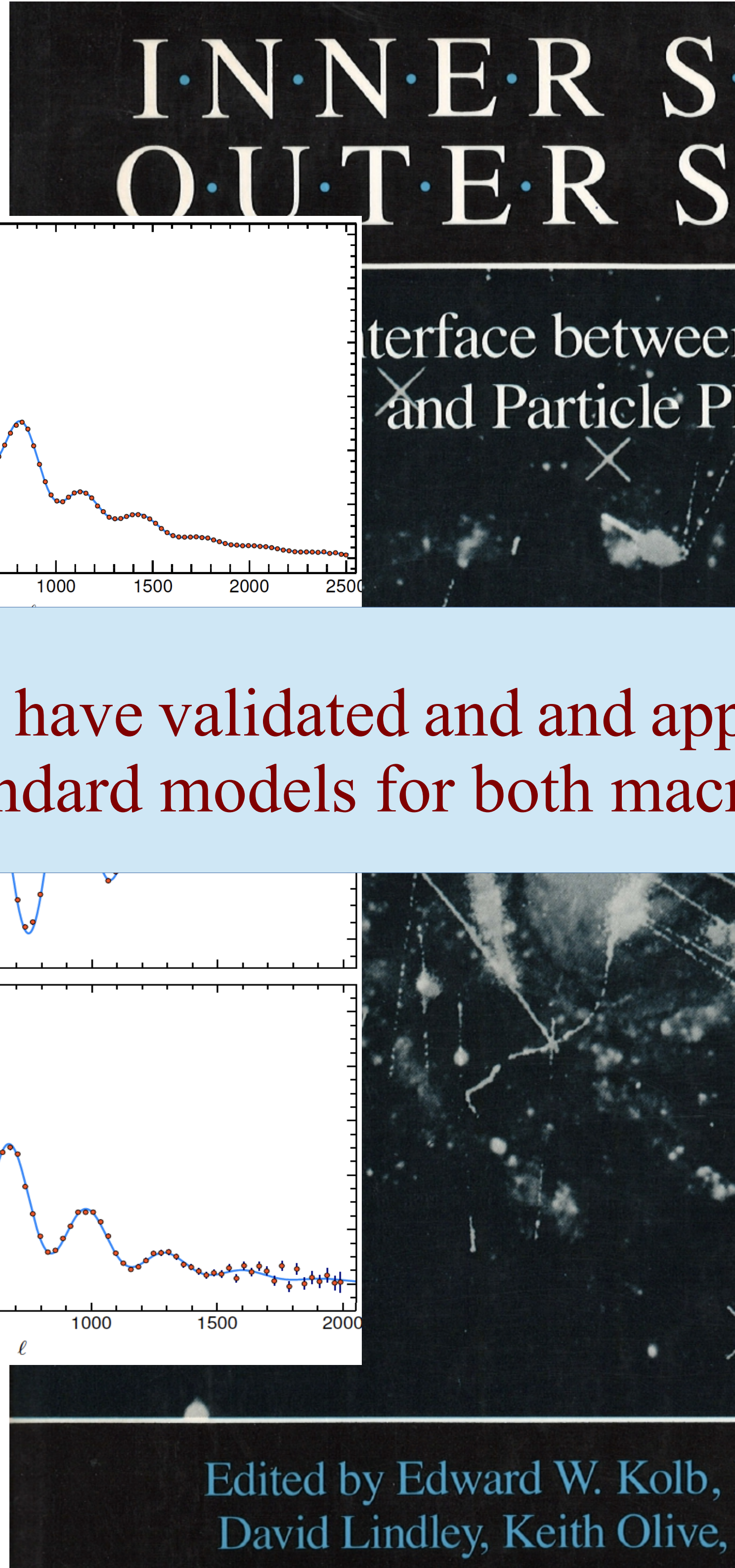
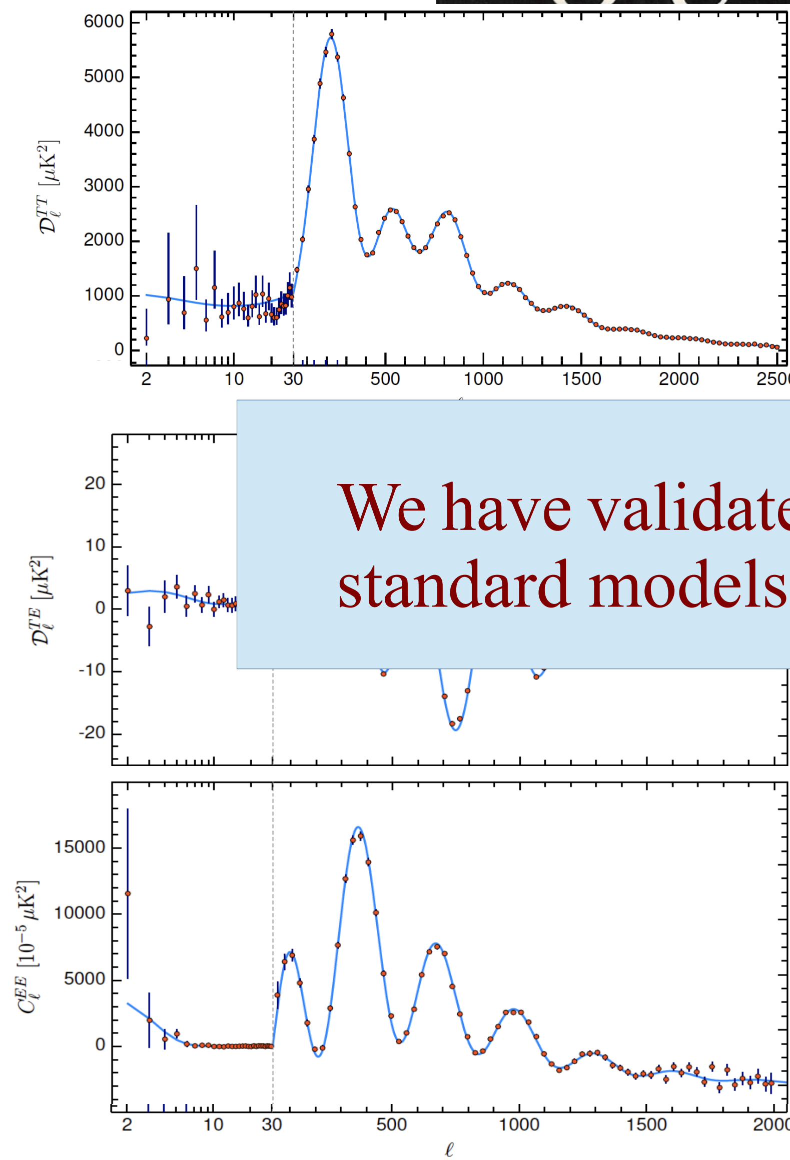
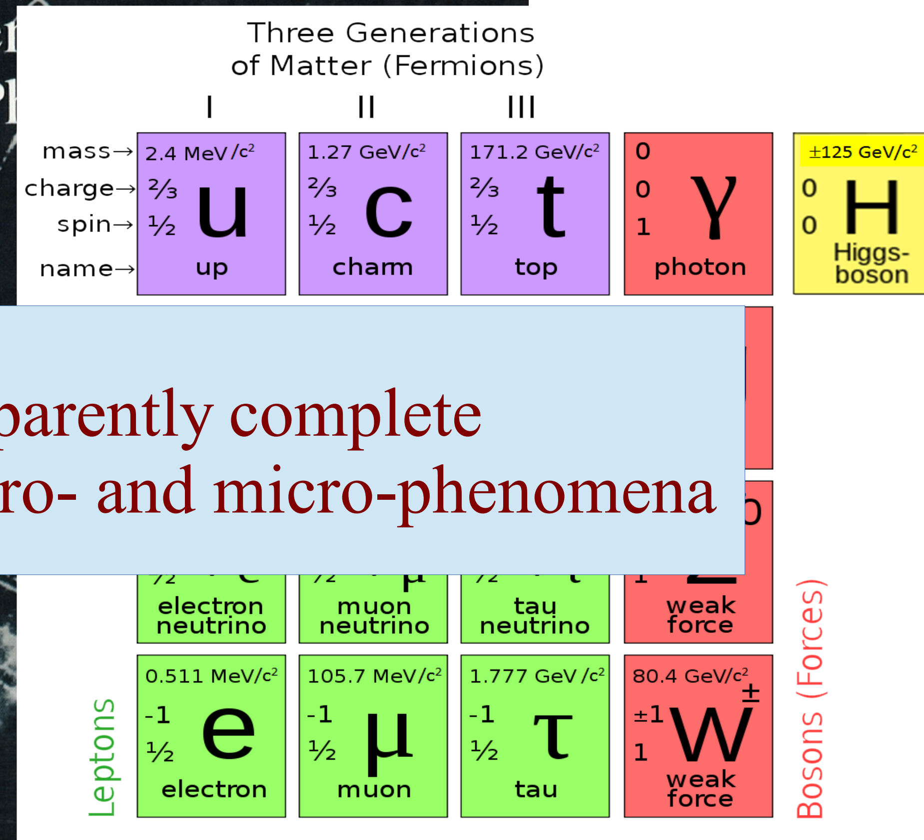
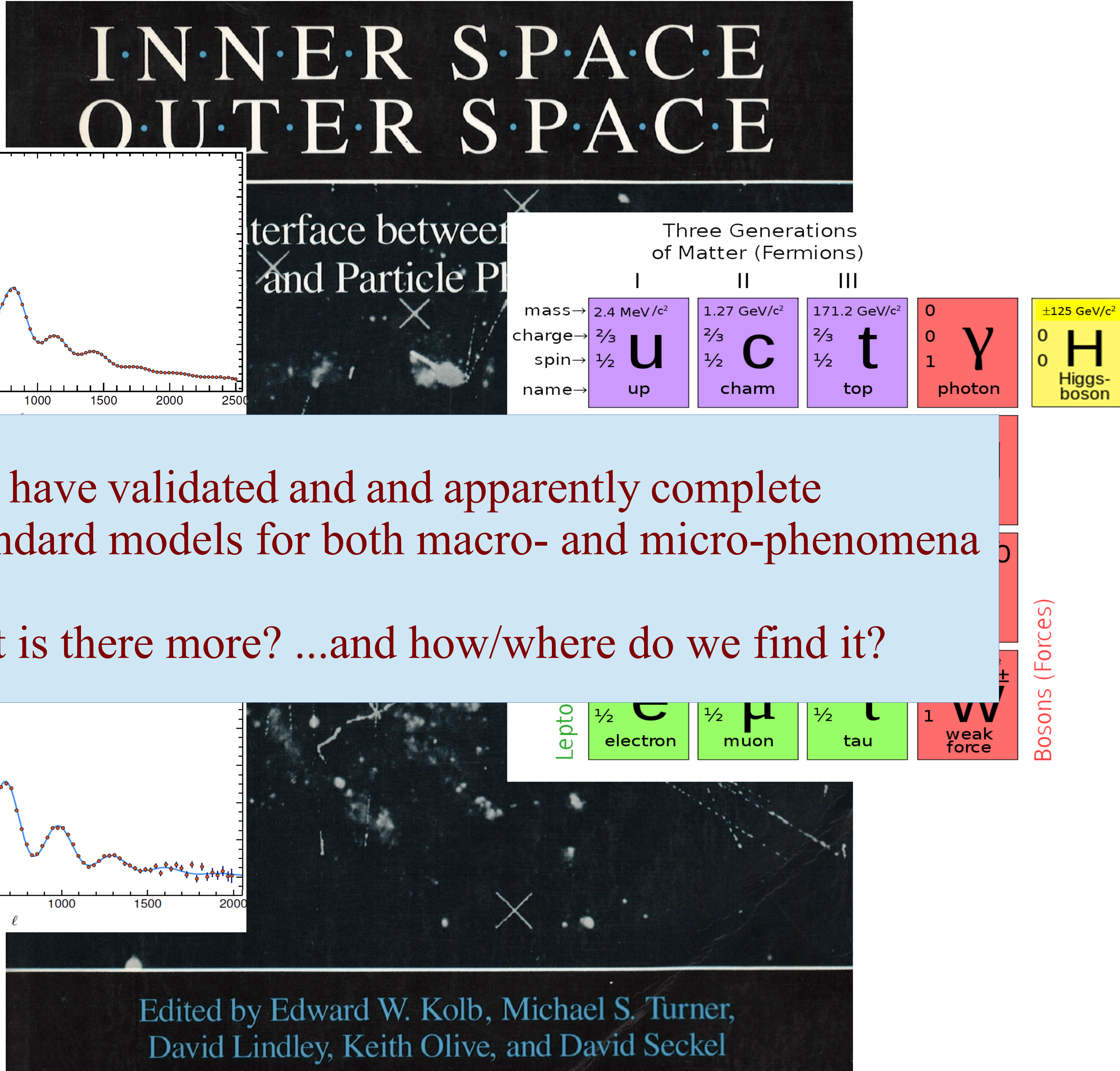
d
down
104 MeV/c²
-⅓
½
s
strange
4.2 GeV/c²
-⅓
½
b
bottom
0
0
1
g
gluon
<2.2 eV/c²
0
½
ν_e
electron neutrino
<0.17 MeV/c²
0
½
ν_μ
muon neutrino
<15.5 MeV/c²
0
½
ν_τ
tau neutrino
91.2 GeV/c²
0
1
Z^0
weak force
Leptons
0.511 MeV/c²
-1
½
e
electron
105.7 MeV/c²
-1
½
μ
muon
1.777 GeV/c²
-1
½
τ
tau
80.4 GeV/c²
±1
1
$W^\pm$
weak force
Bosons (Forces)

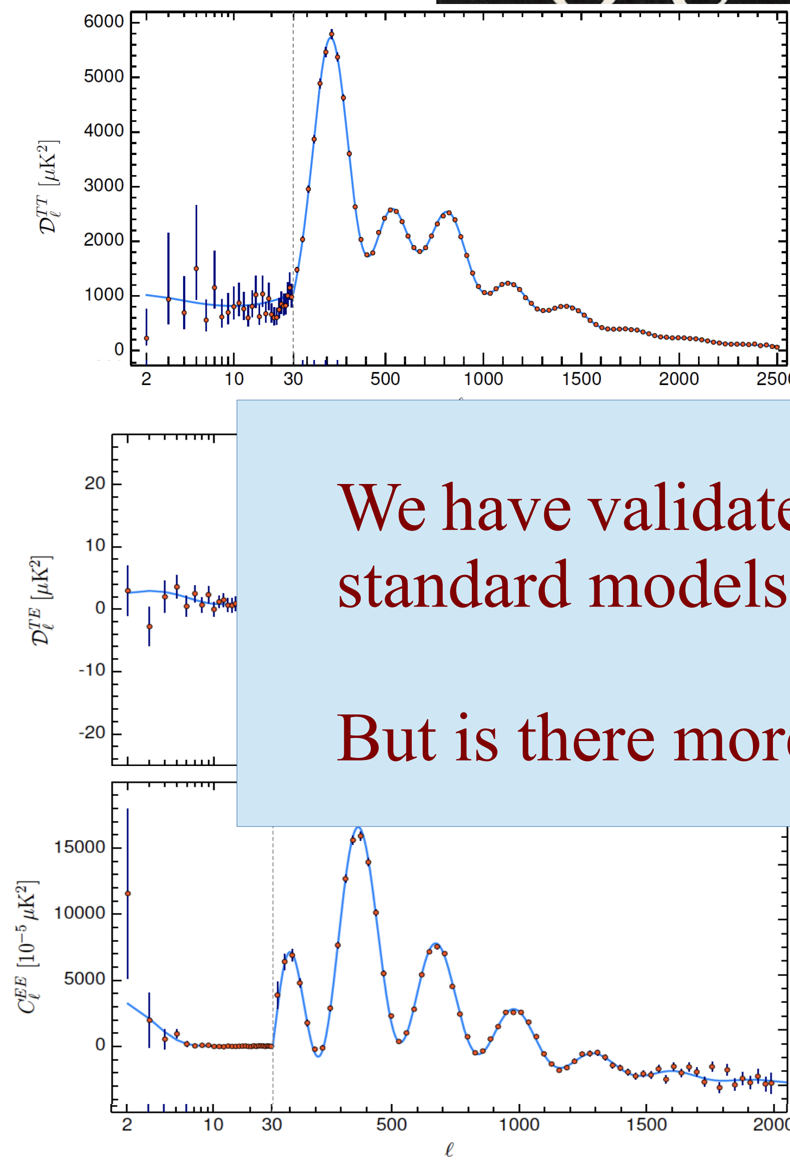






We have validated and and apparently complete standard models for both macro- and micro-phenomena





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But is there more? ...and how/where do we find it?