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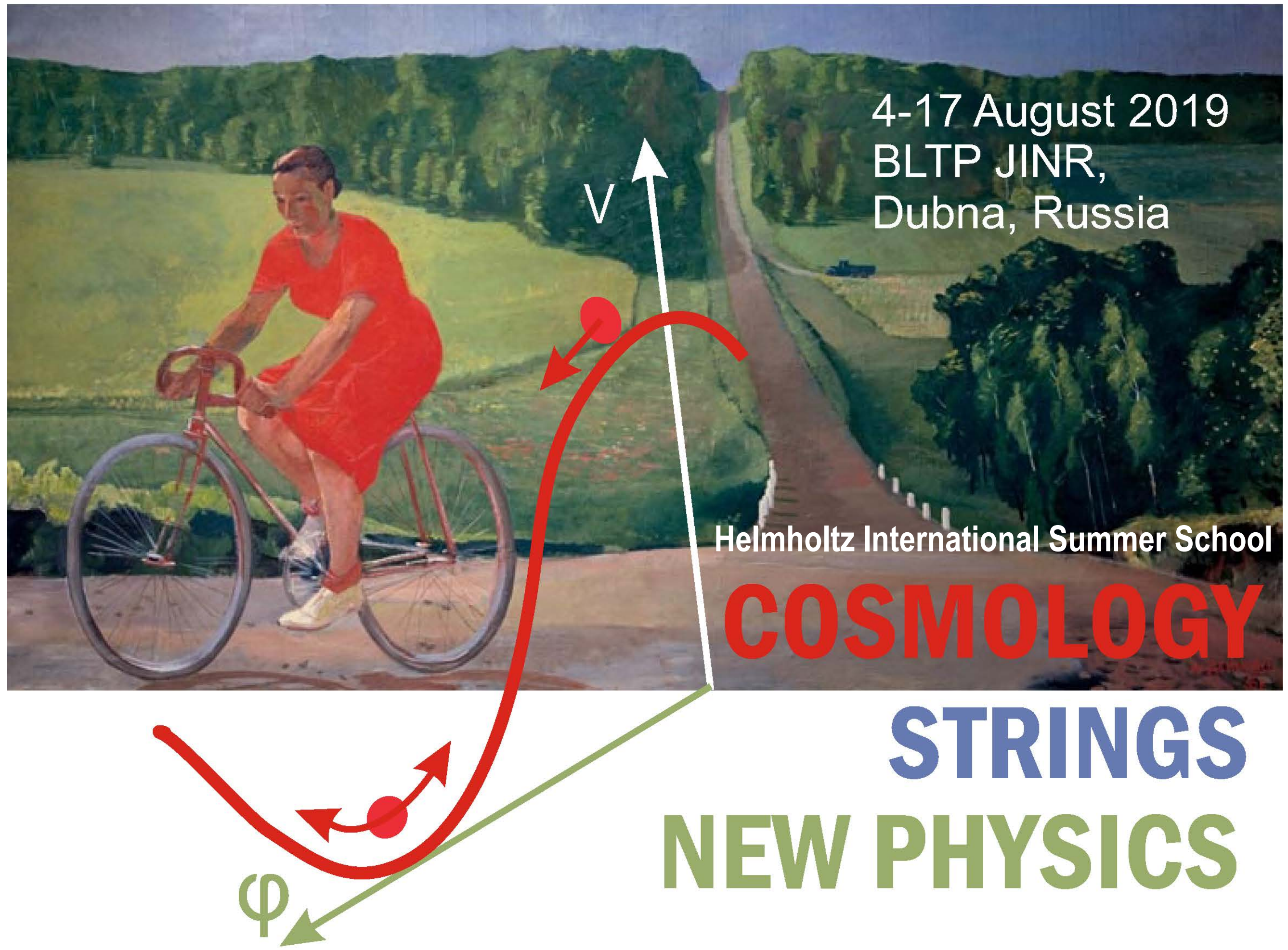


# Dark Side of the Universe II


*Alexander Vikman*


07.08.2019


FZU Institute of Physics of the Czech Academy of Sciences

CEICO

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

# Literature

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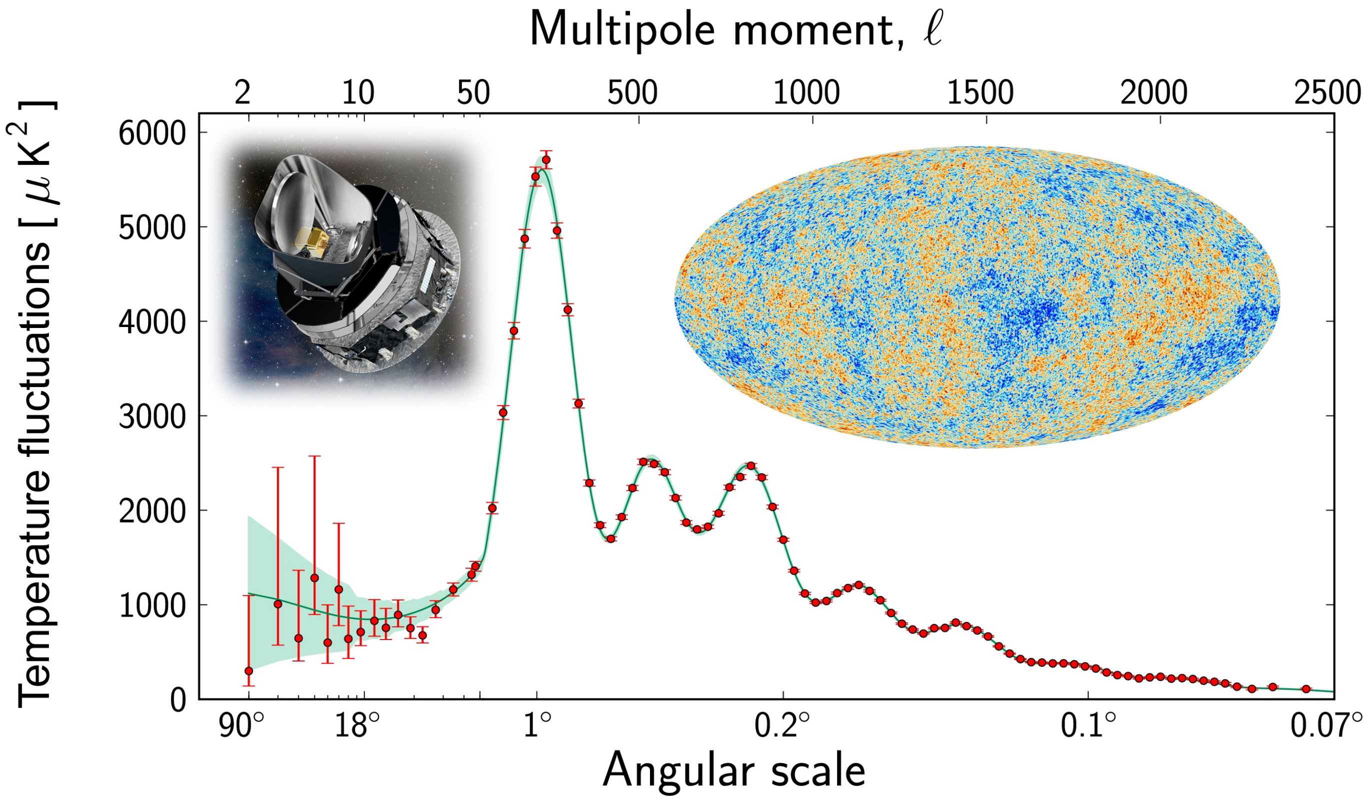
- *Lectures on the Cosmological Constant Problem*
  A. Padilla
  arXiv:1502.05296



Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [ $\mu K^2$ ]
6000
5000
4000
3000
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90°
18°
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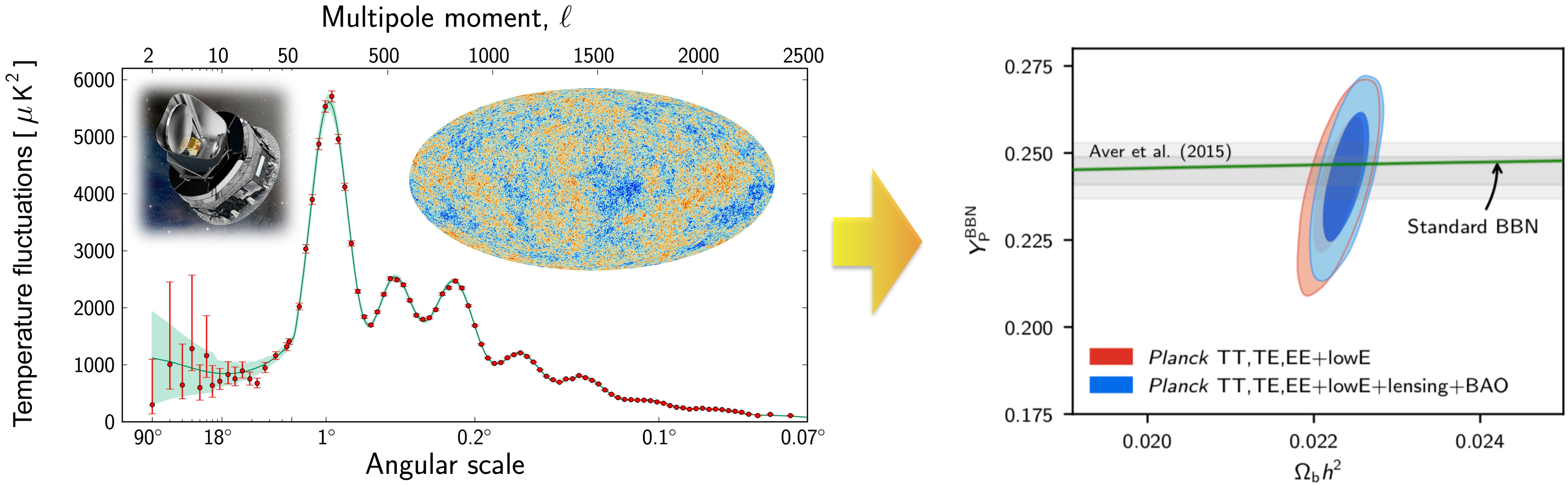
0.07°
Angular scale



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$Y_P^{BBN}$
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Standard BBN
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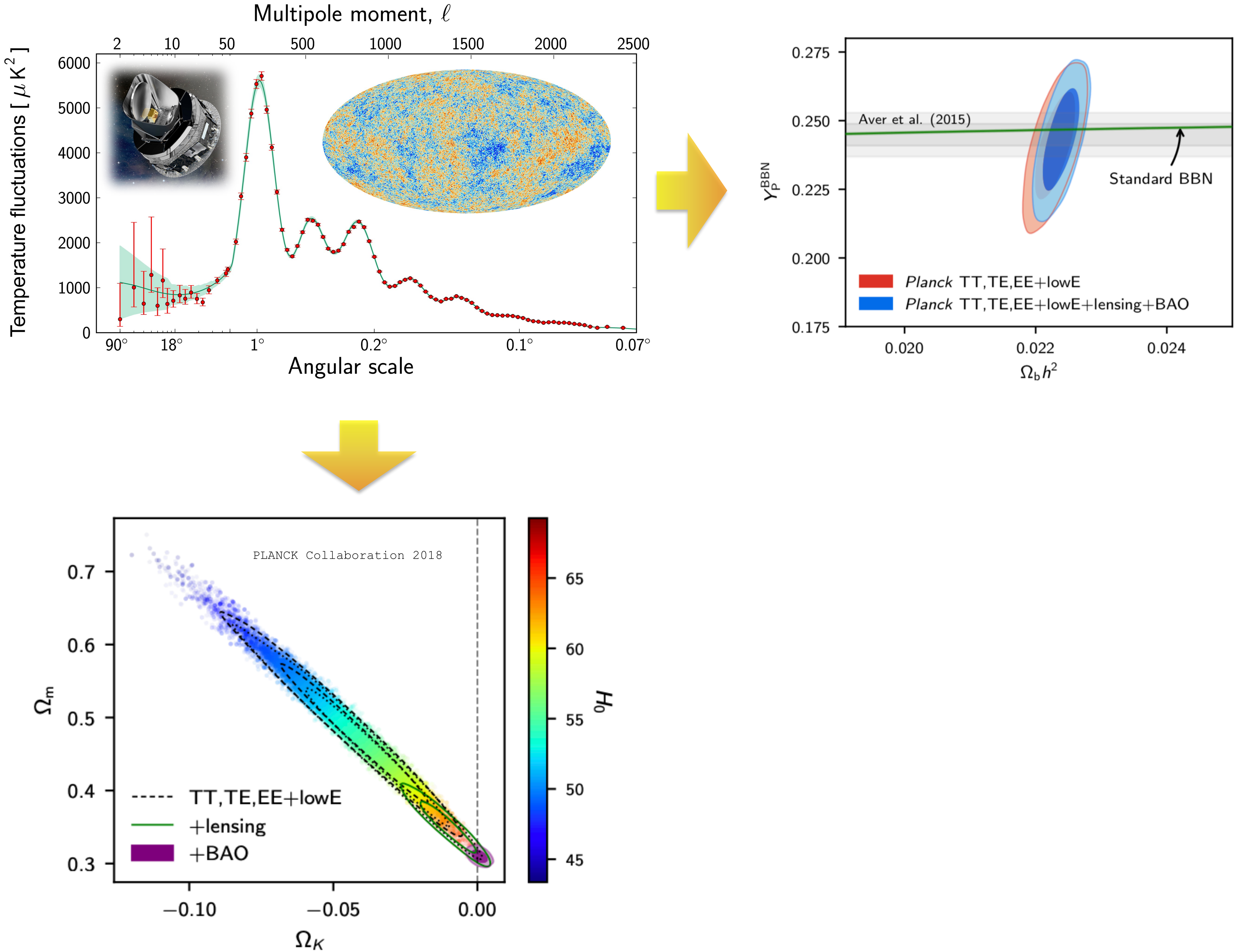
0.022
0.024
$\Omega_b h^2$



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PLANCK Collaboration 2018
0.7
0.6
0.5
0.4
0.3
$\Omega_m$
TT,TE,EE+lowE
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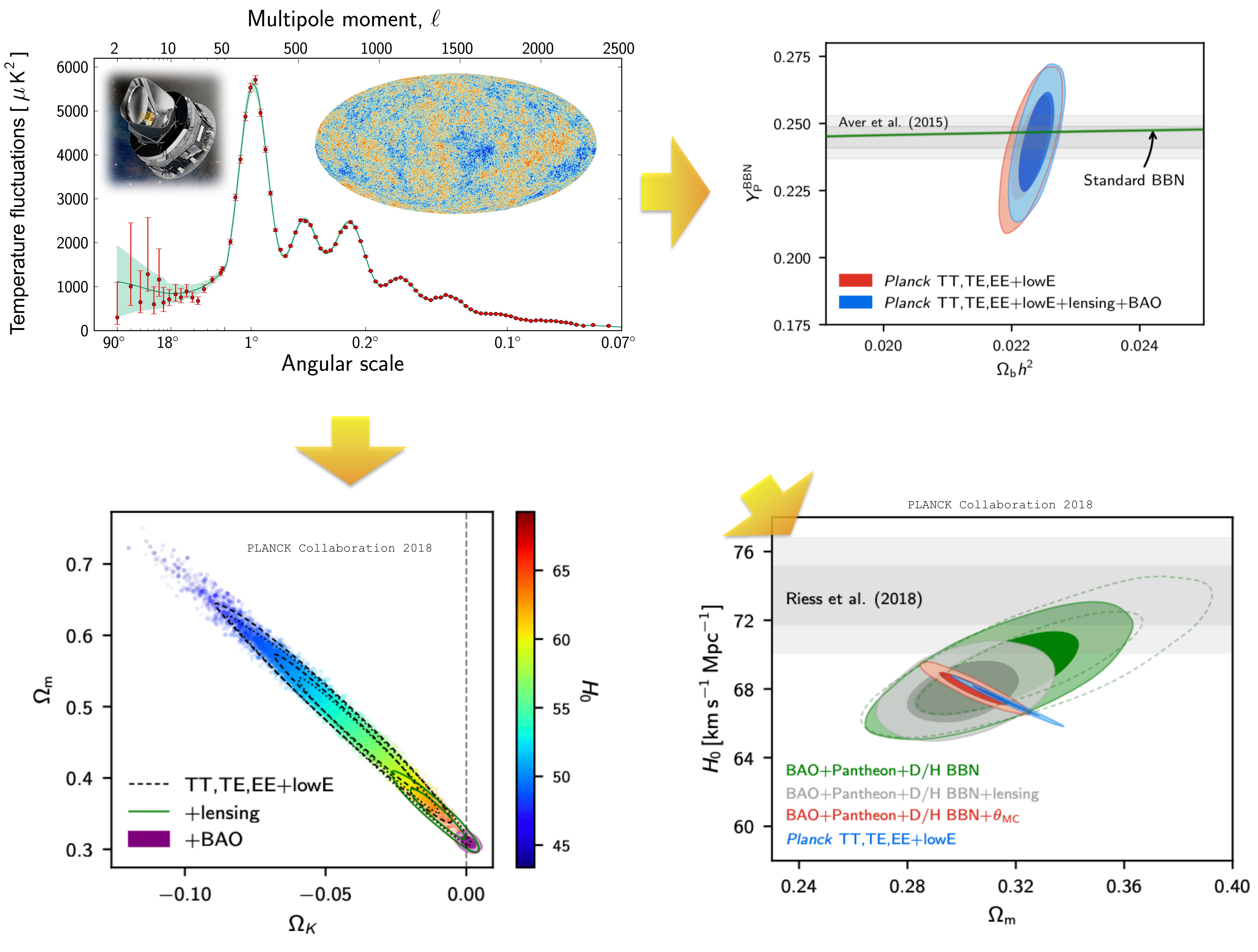
+BAO
−0.10
−0.05
0.00
$\Omega_K$
65
60
55
50
45
$H_0$



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PLANCK Collaboration 2018
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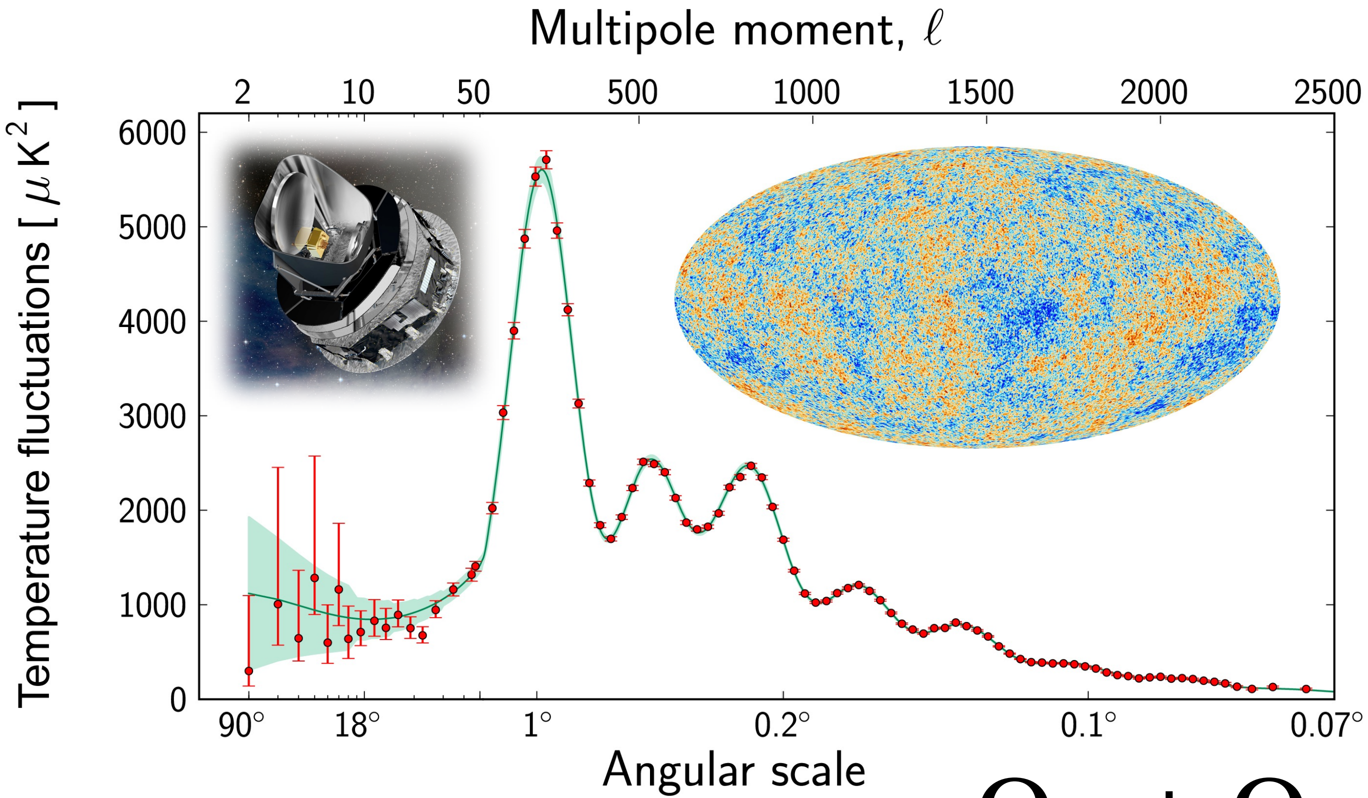
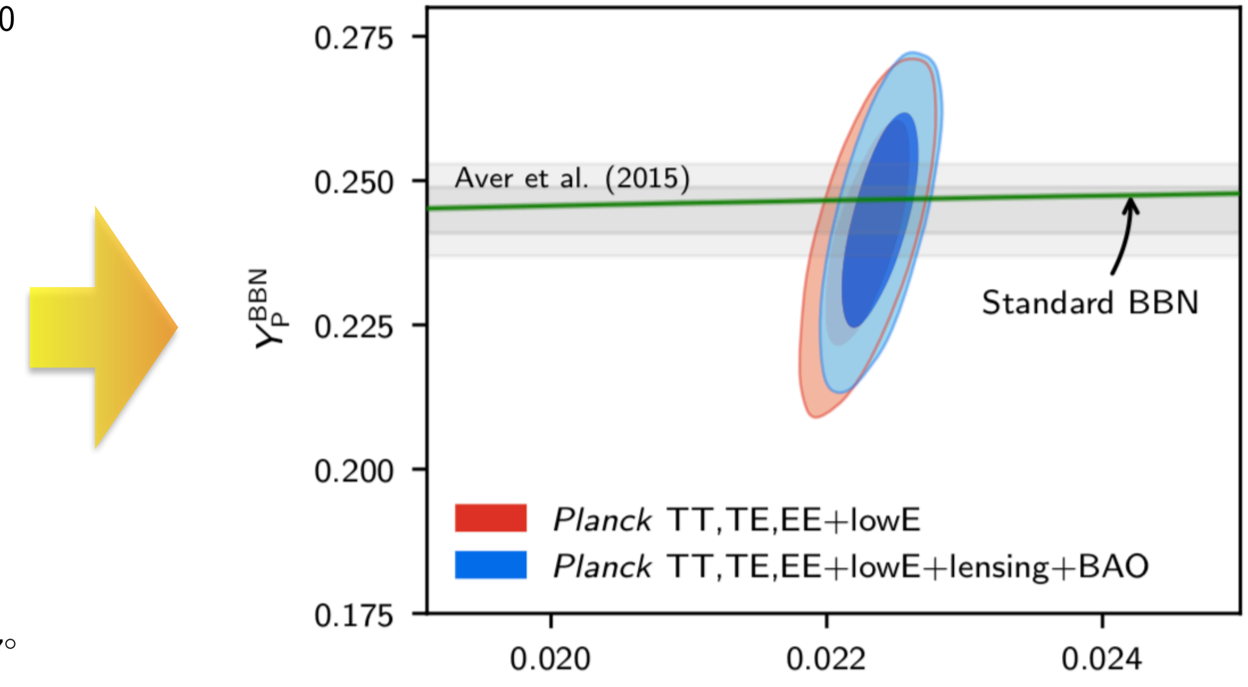
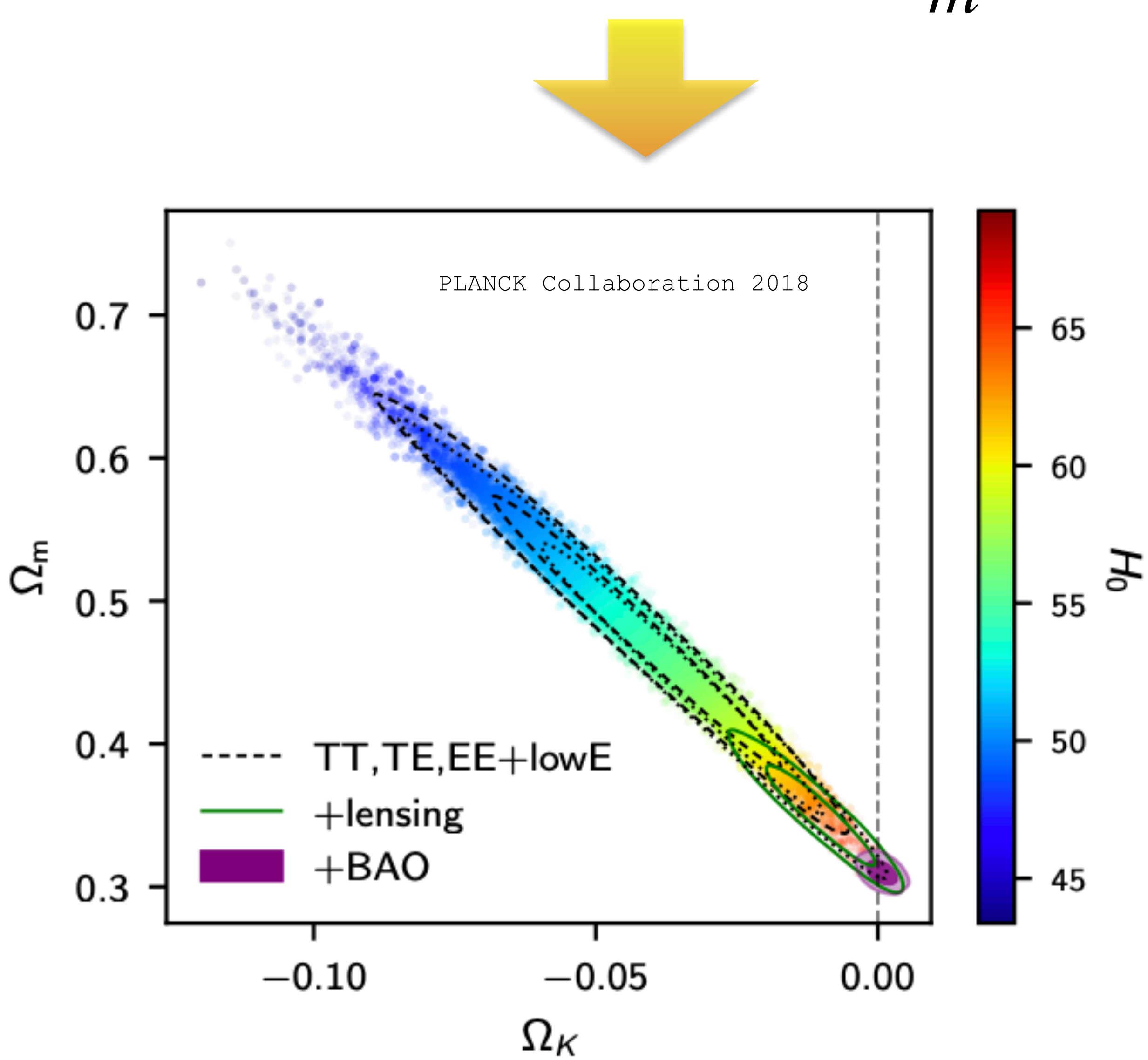
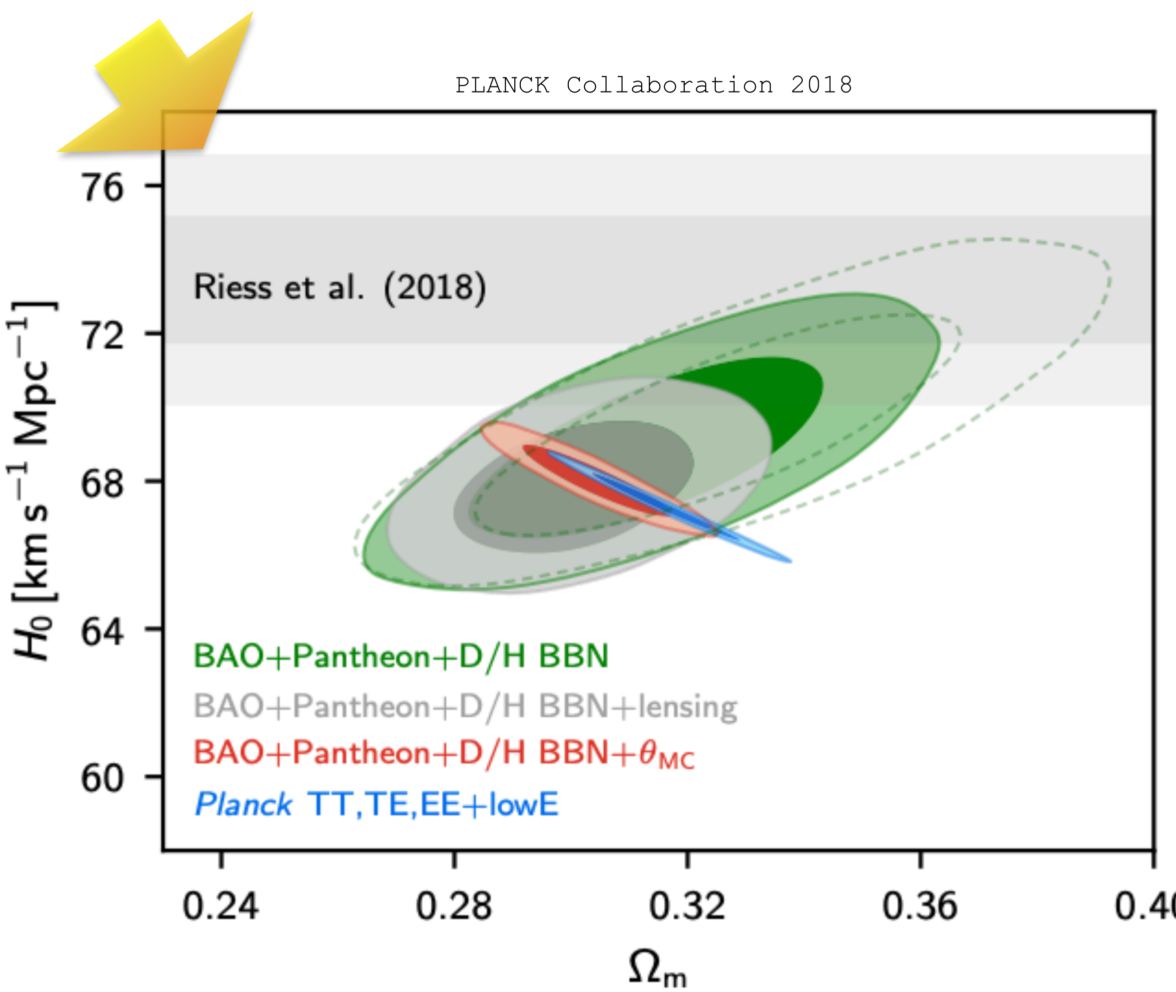
72
68
64
60
Riess et al. (2018)
$H_0$ [km s$^{-1}$ Mpc$^{-1}$]
BAO+Pantheon+D/H BBN
BAO+Pantheon+D/H BBN+lensing
BAO+Pantheon+D/H BBN+$\theta_{MC}$
Planck TT,TE,EE+lowE
0.24
0.28
0.32
0.36
0.40
$\Omega_m$

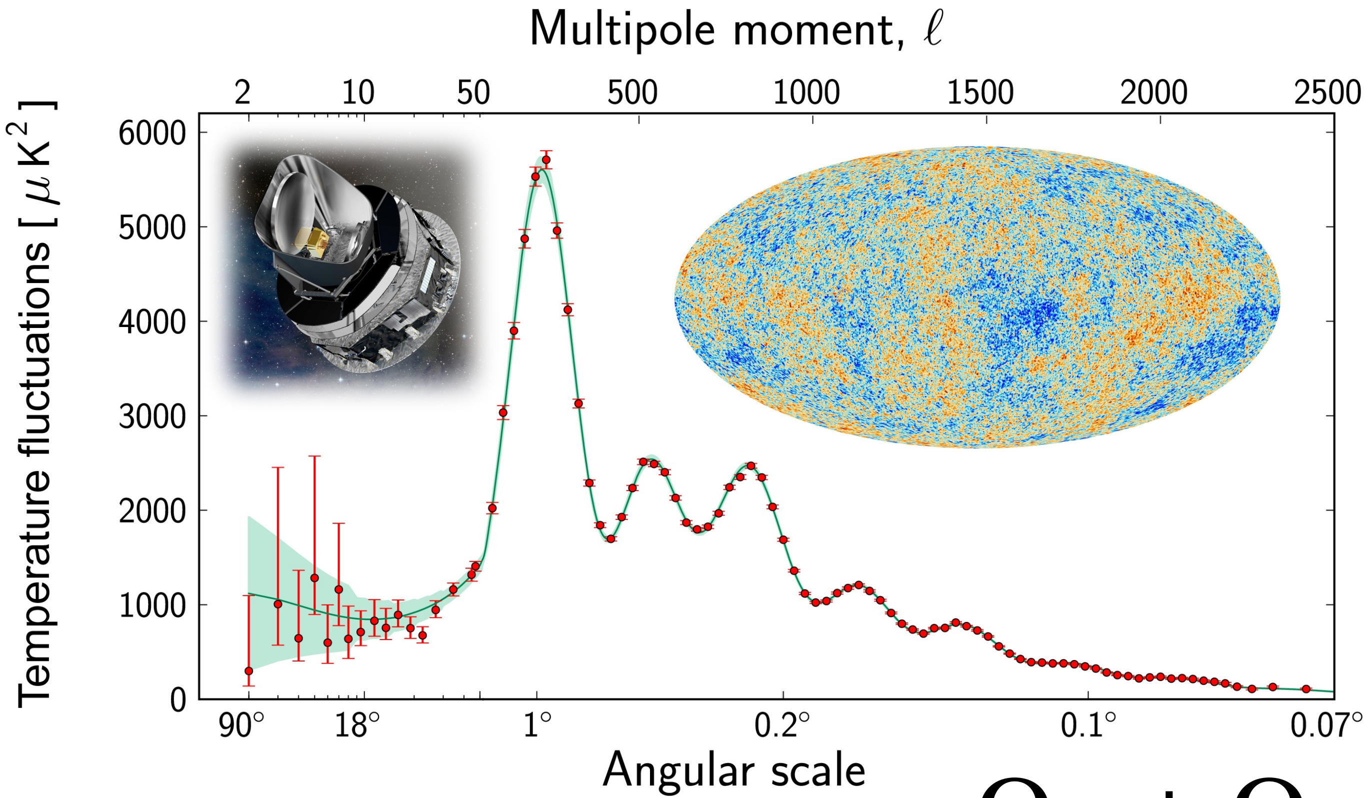


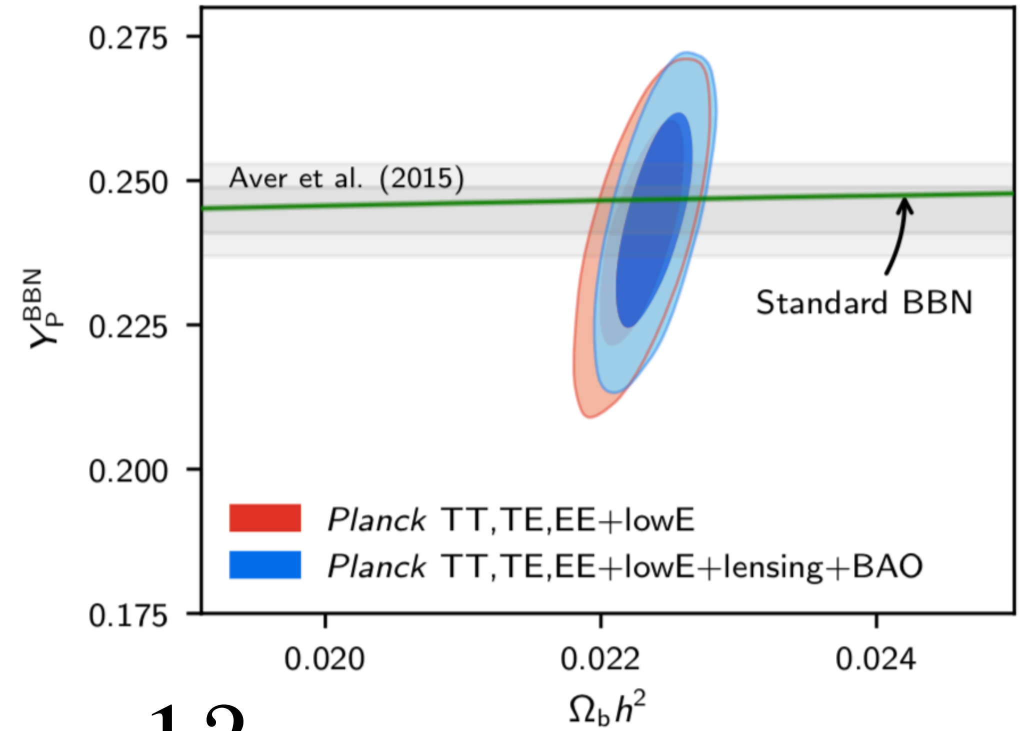




$$\Omega_m + \Omega_b + \Omega_k = 1?$$



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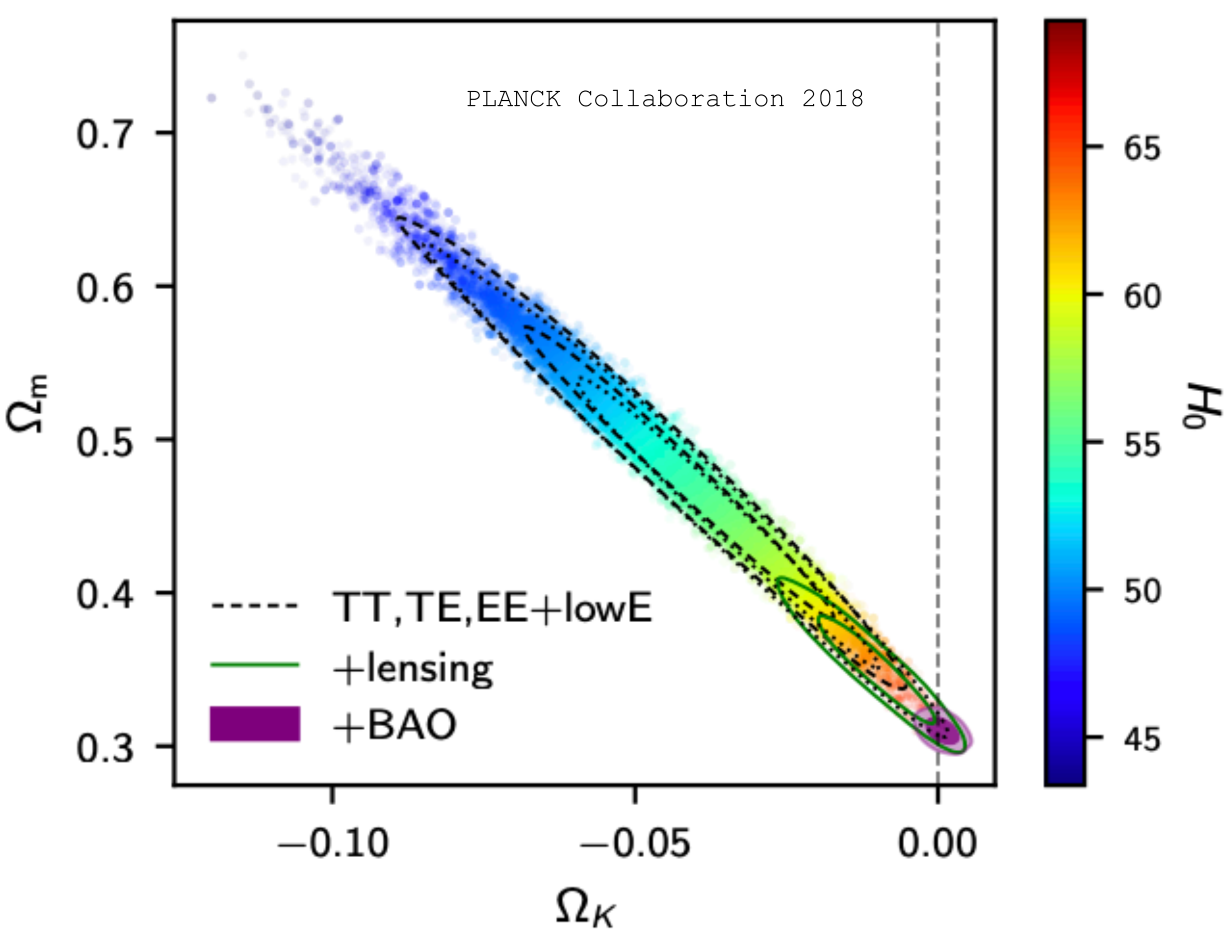


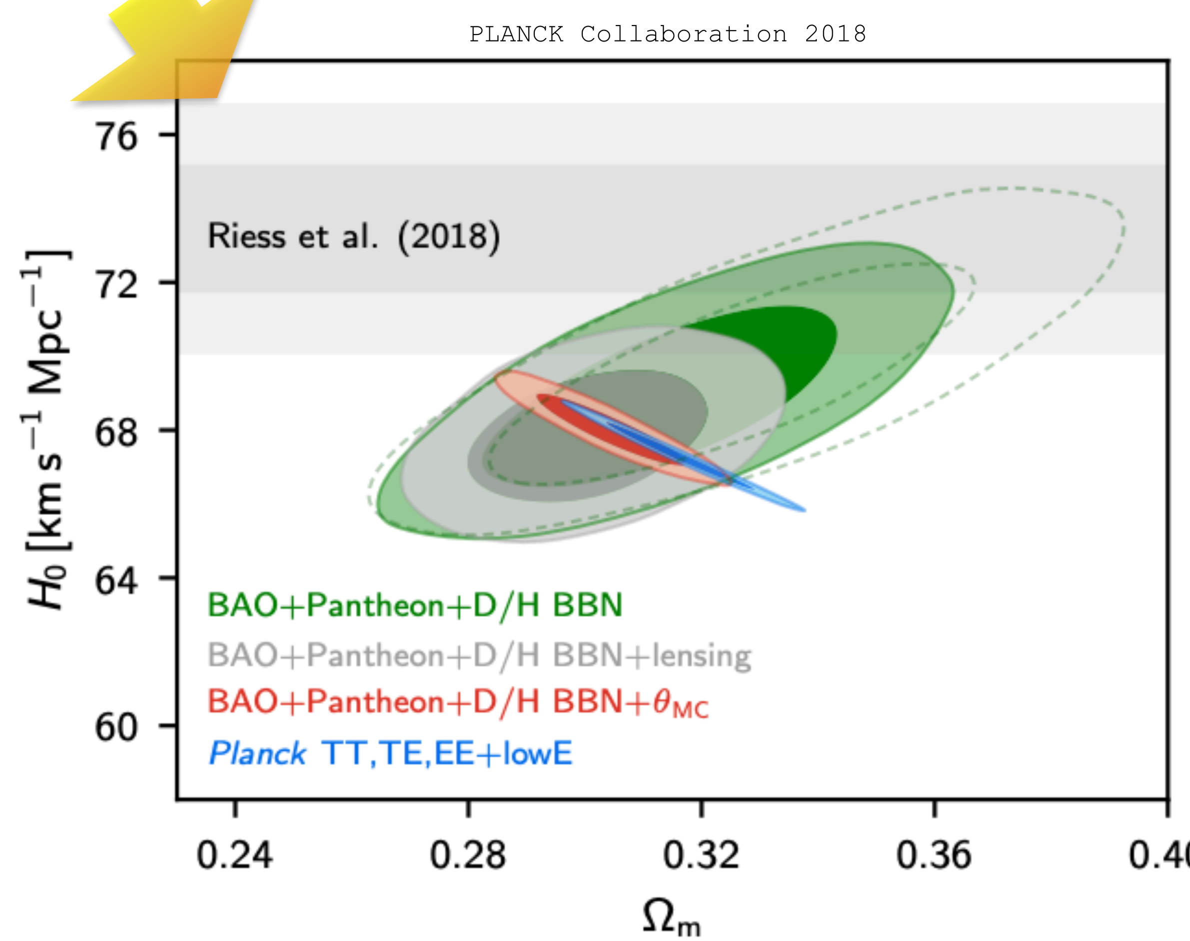

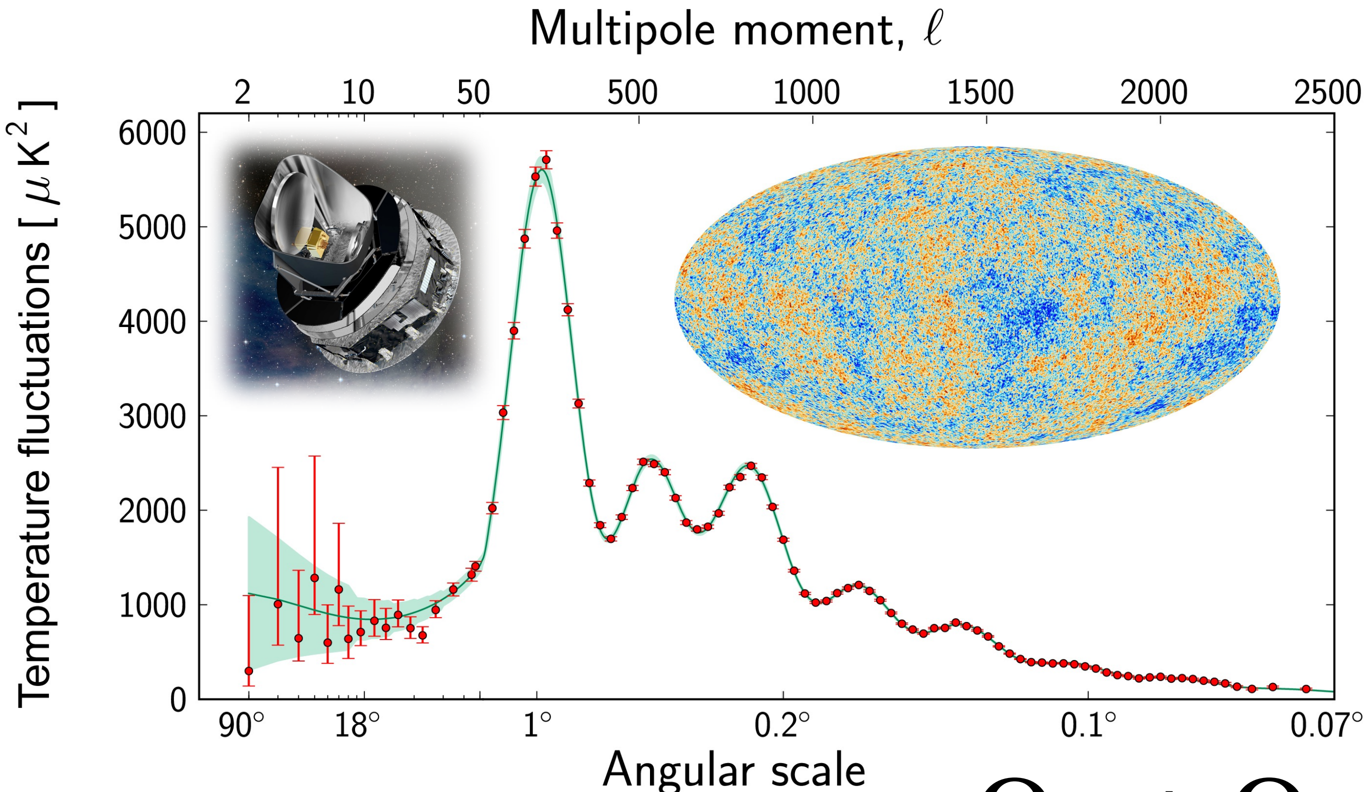


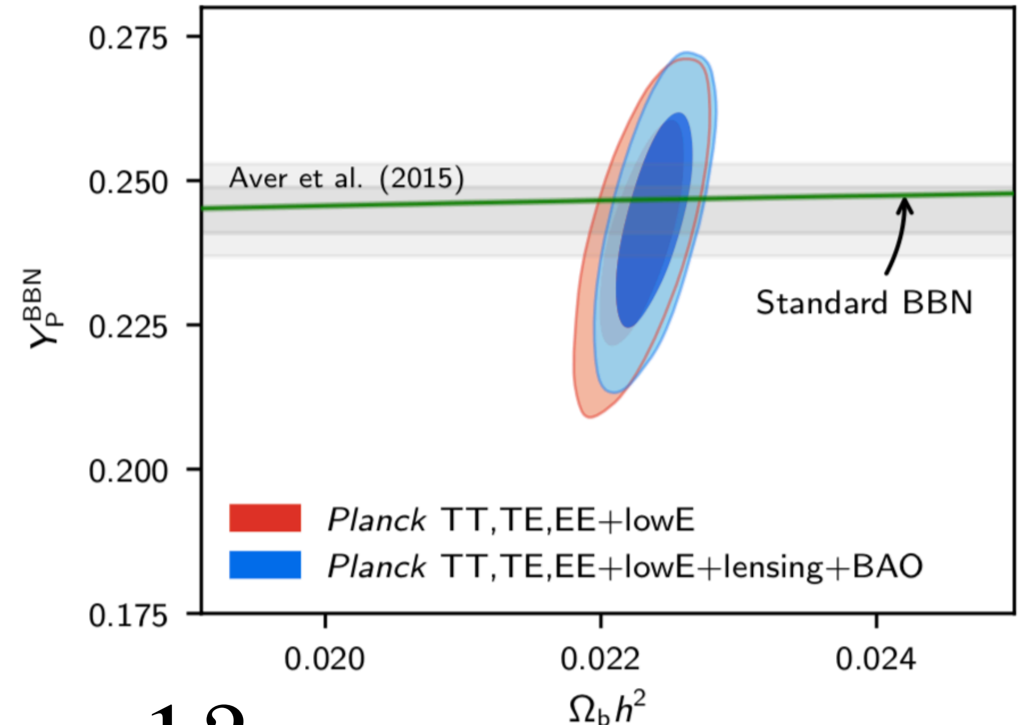


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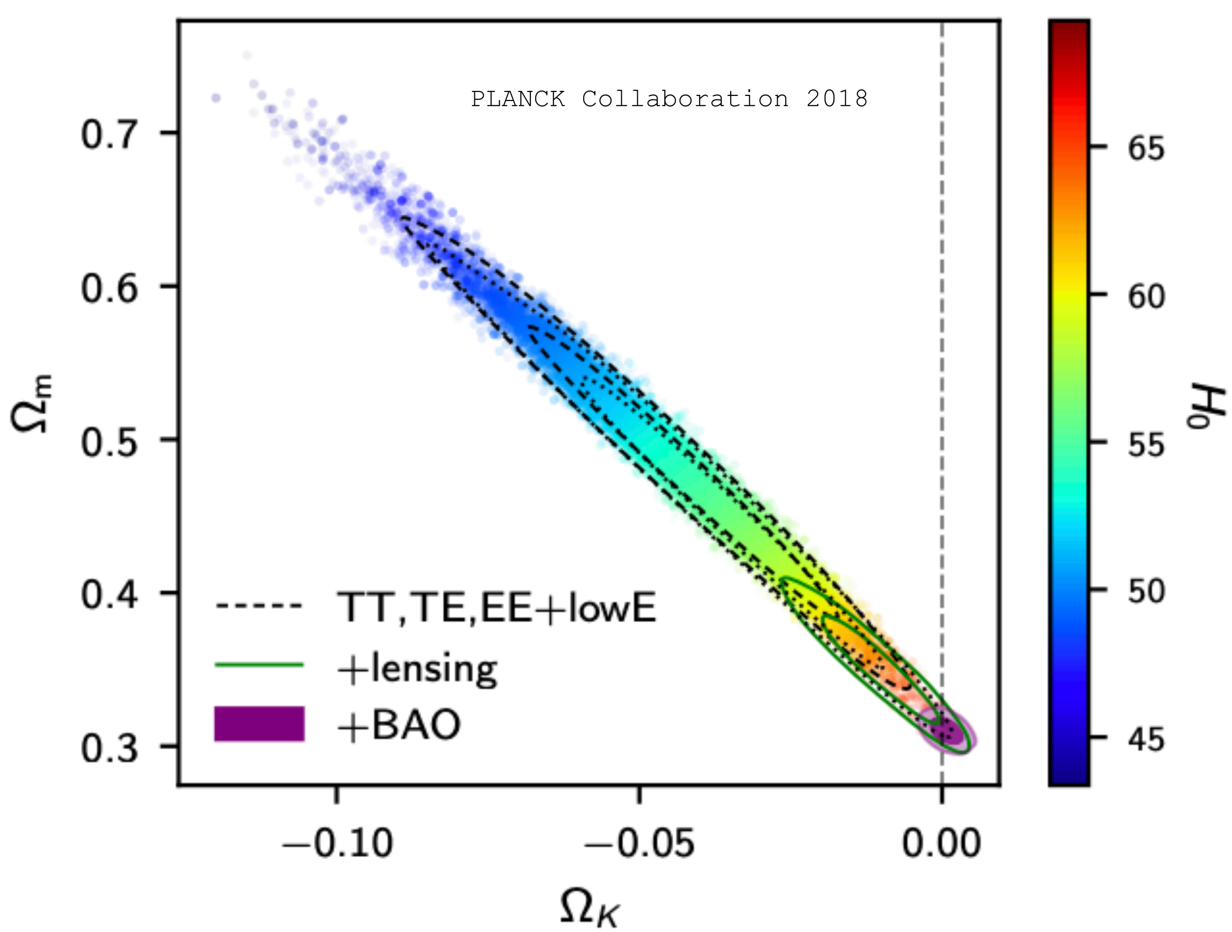
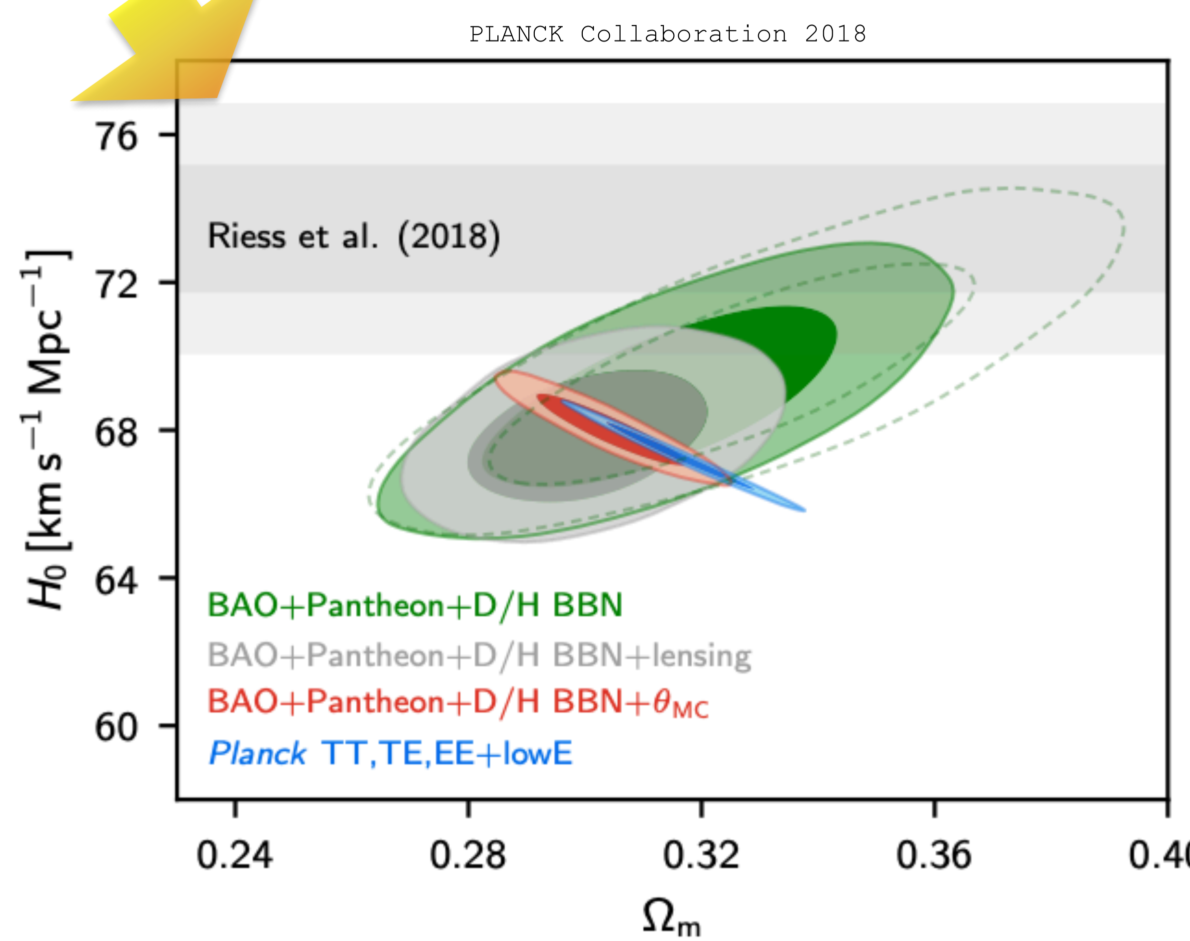
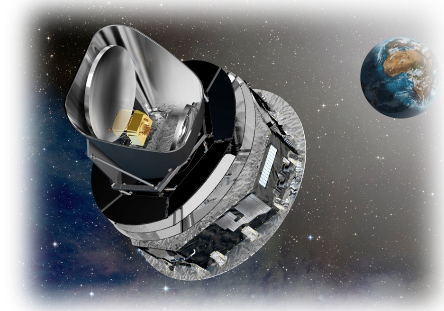
***Dark Energy!***



# Dark Energy equation of state



$$w = p/\varepsilon \qquad w(a) = w_0 + (1-a)\,w_a$$

PLANCK Collaboration 2013

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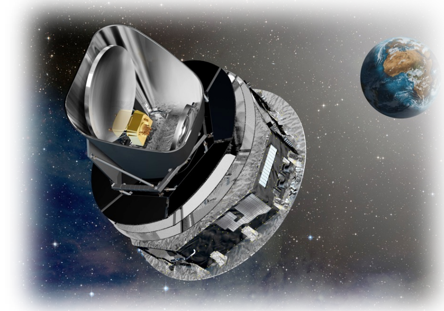

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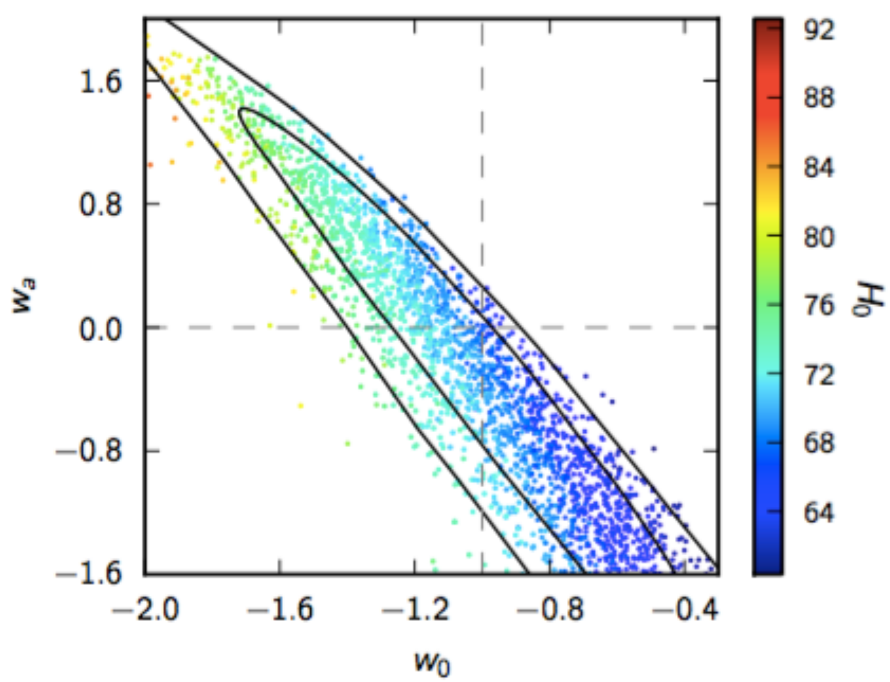


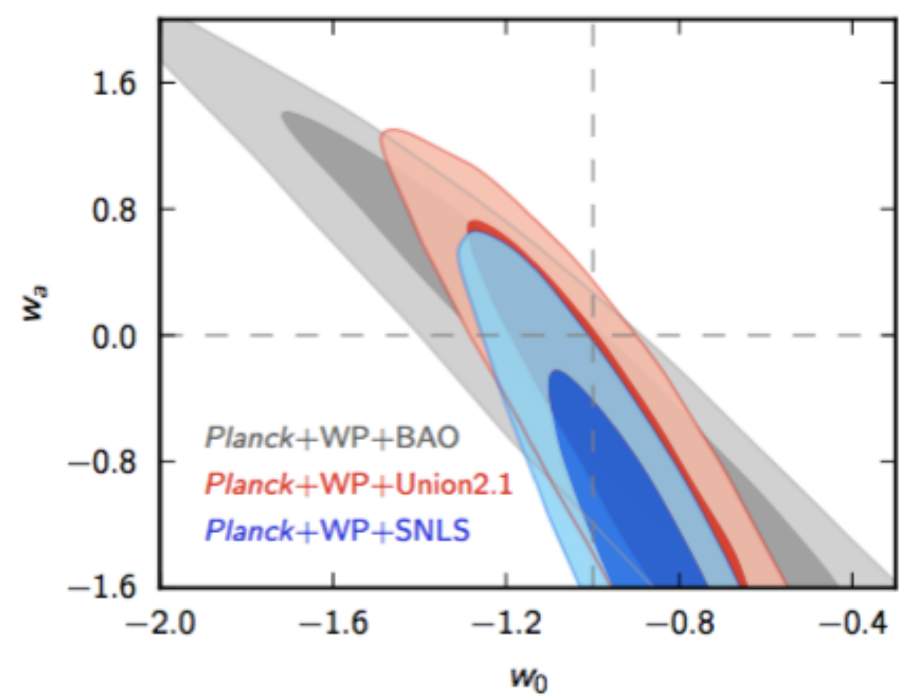

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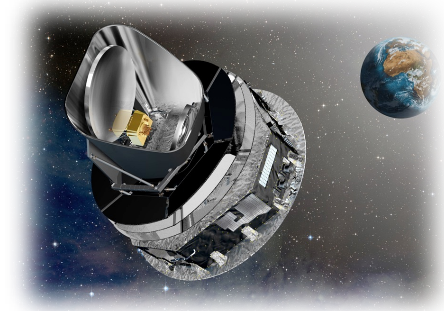

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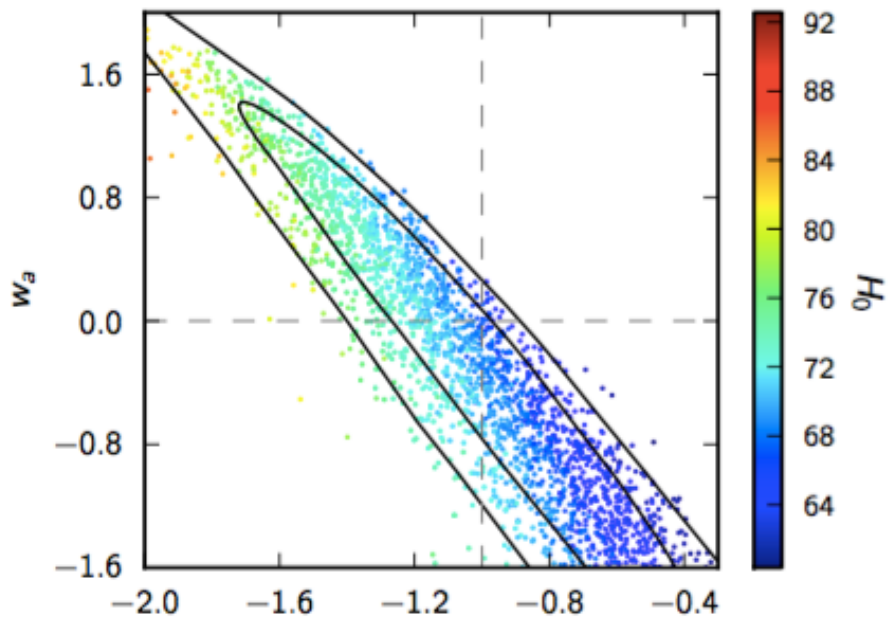


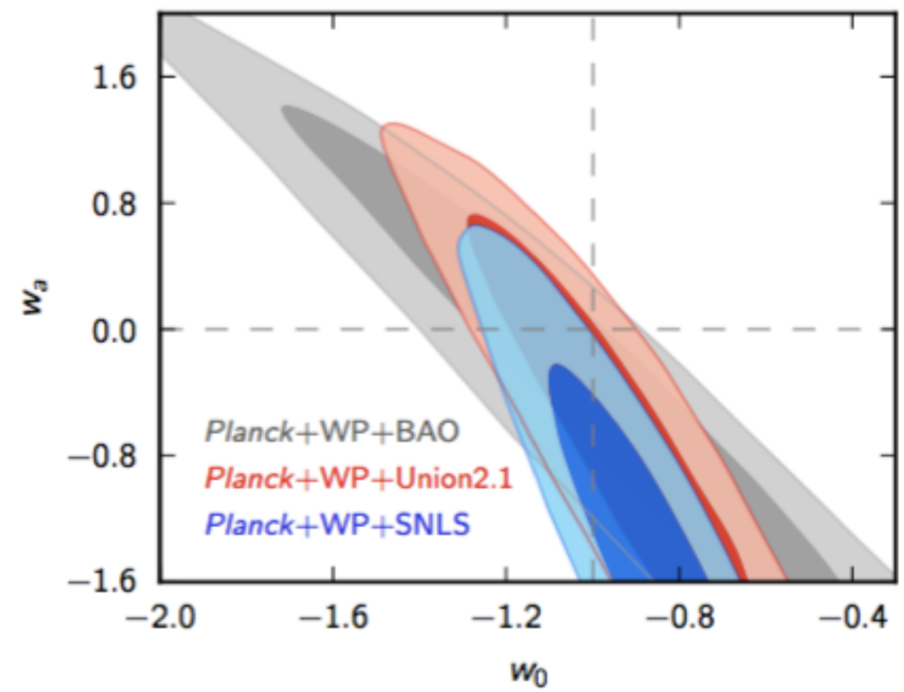


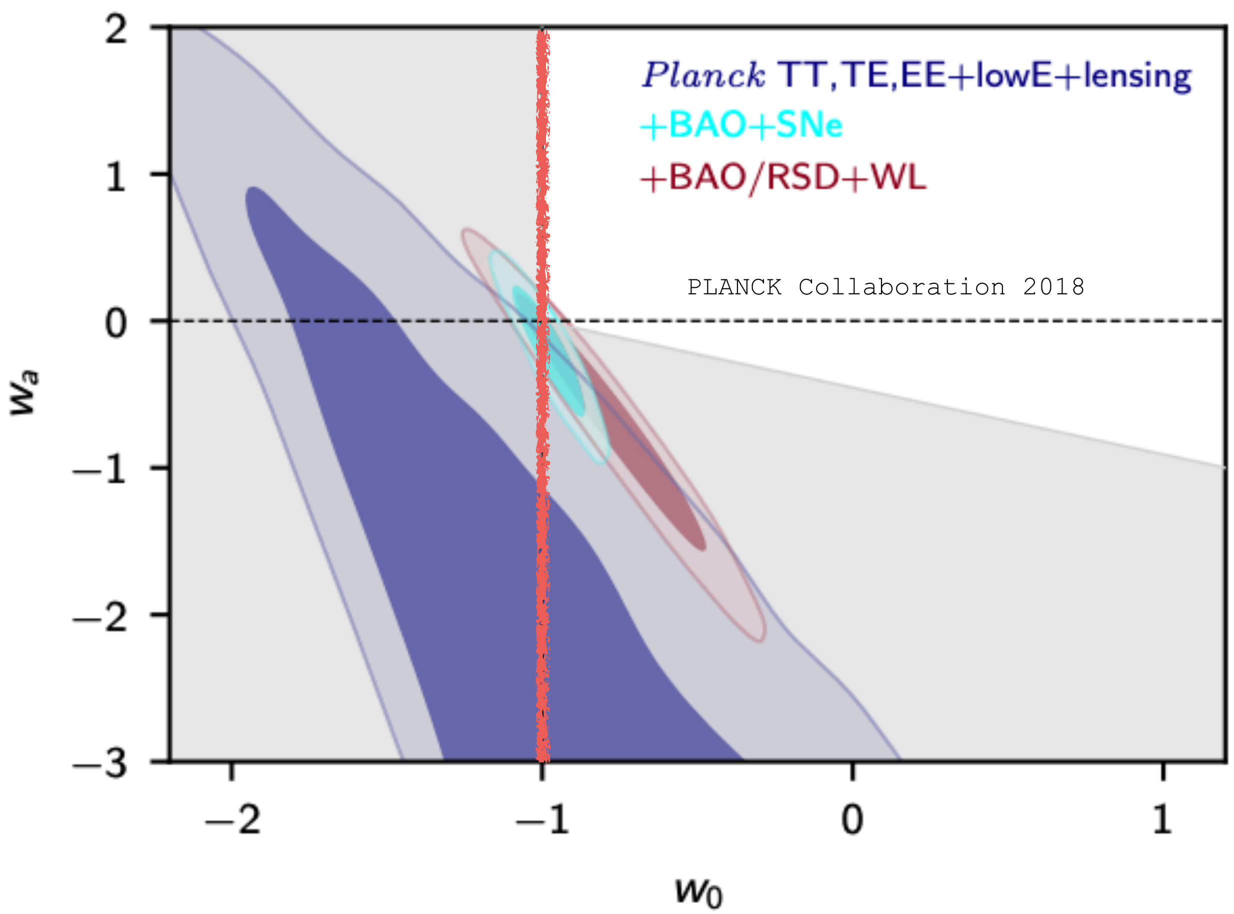

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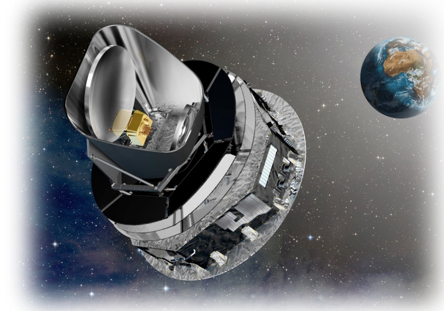

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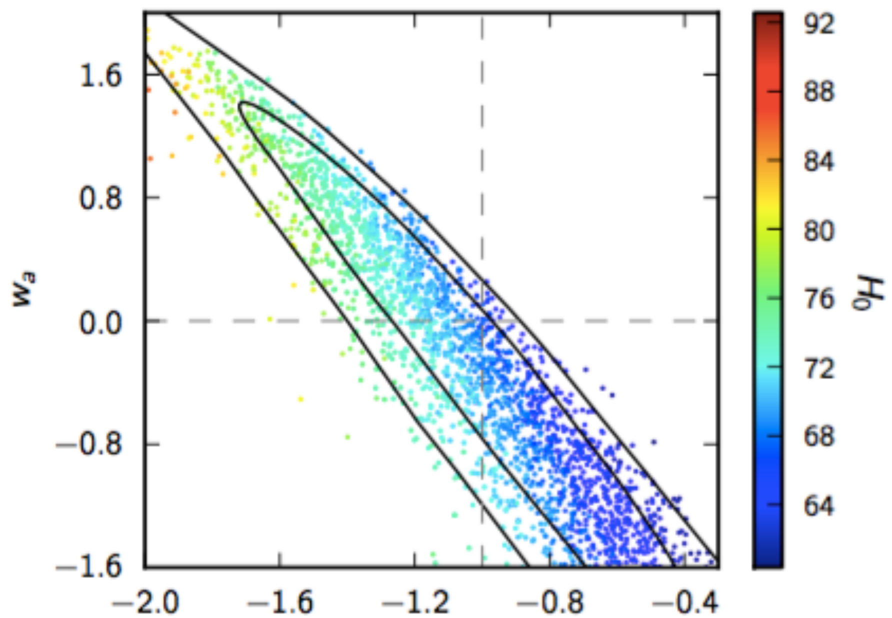


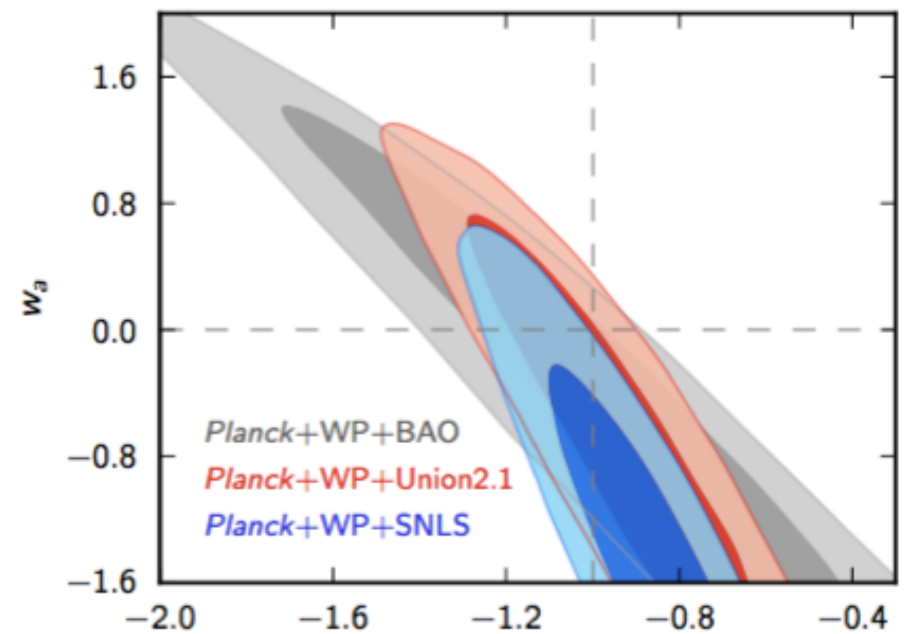


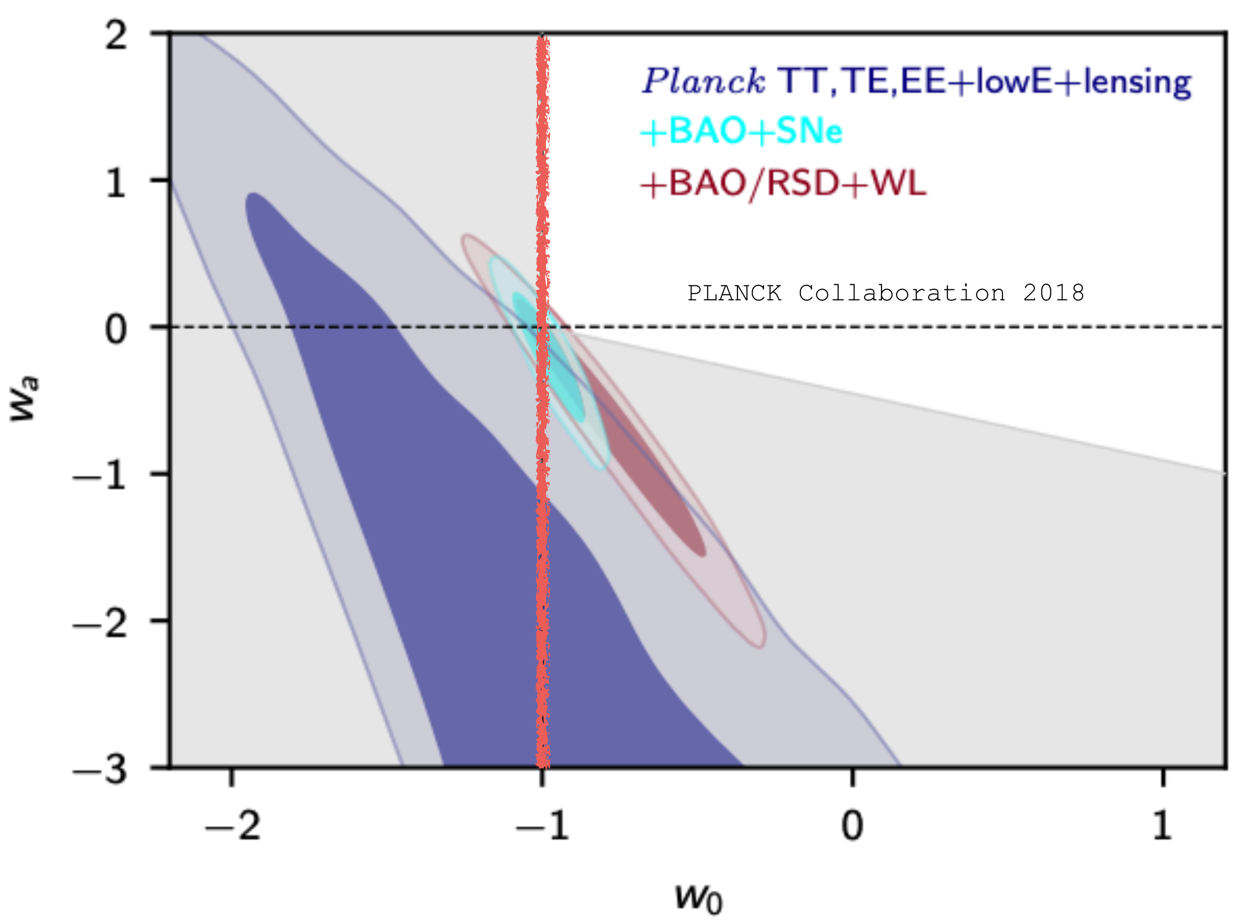


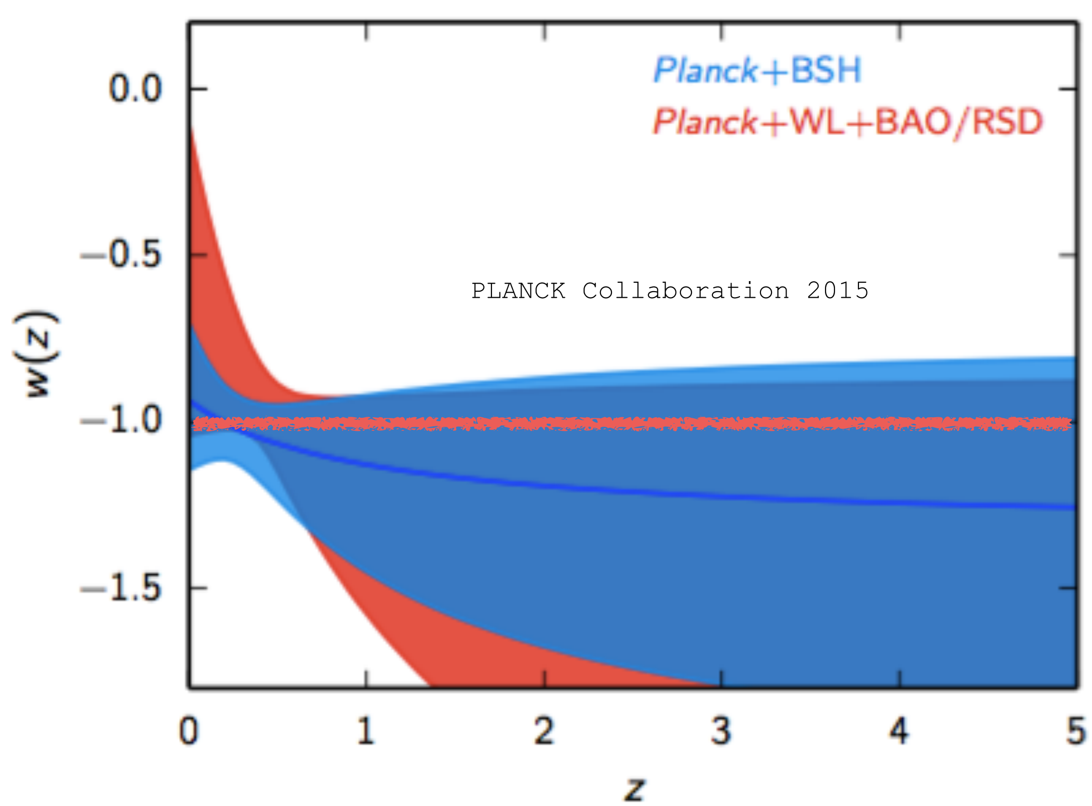

# **Dark Energy** Nobel Prize 2011

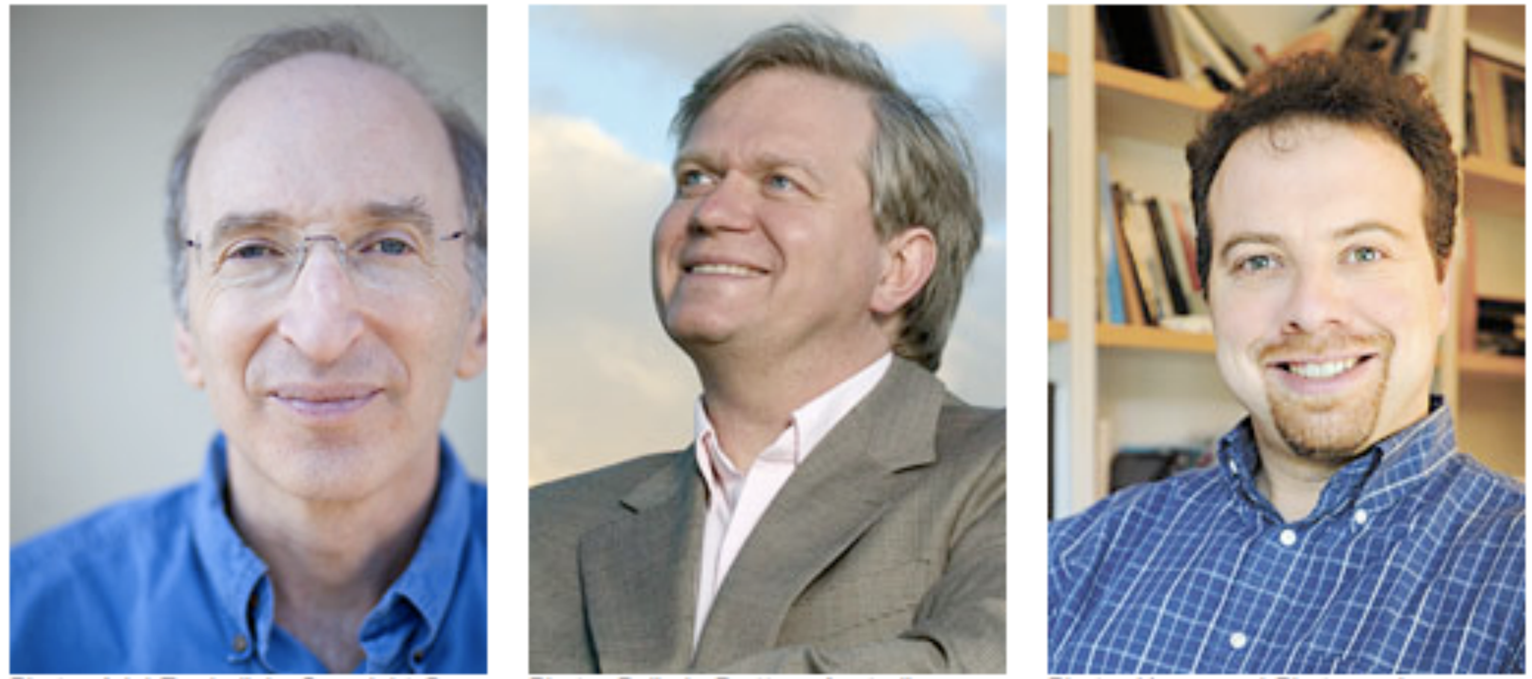

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Photo: Belinda Pratten, Australian National University — Brian P. Schmidt

Photo: Homewood Photography — Adam G. Riess

image from Nobelprize.org

in 1998 found that now

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$$\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\varepsilon + 3p)$$

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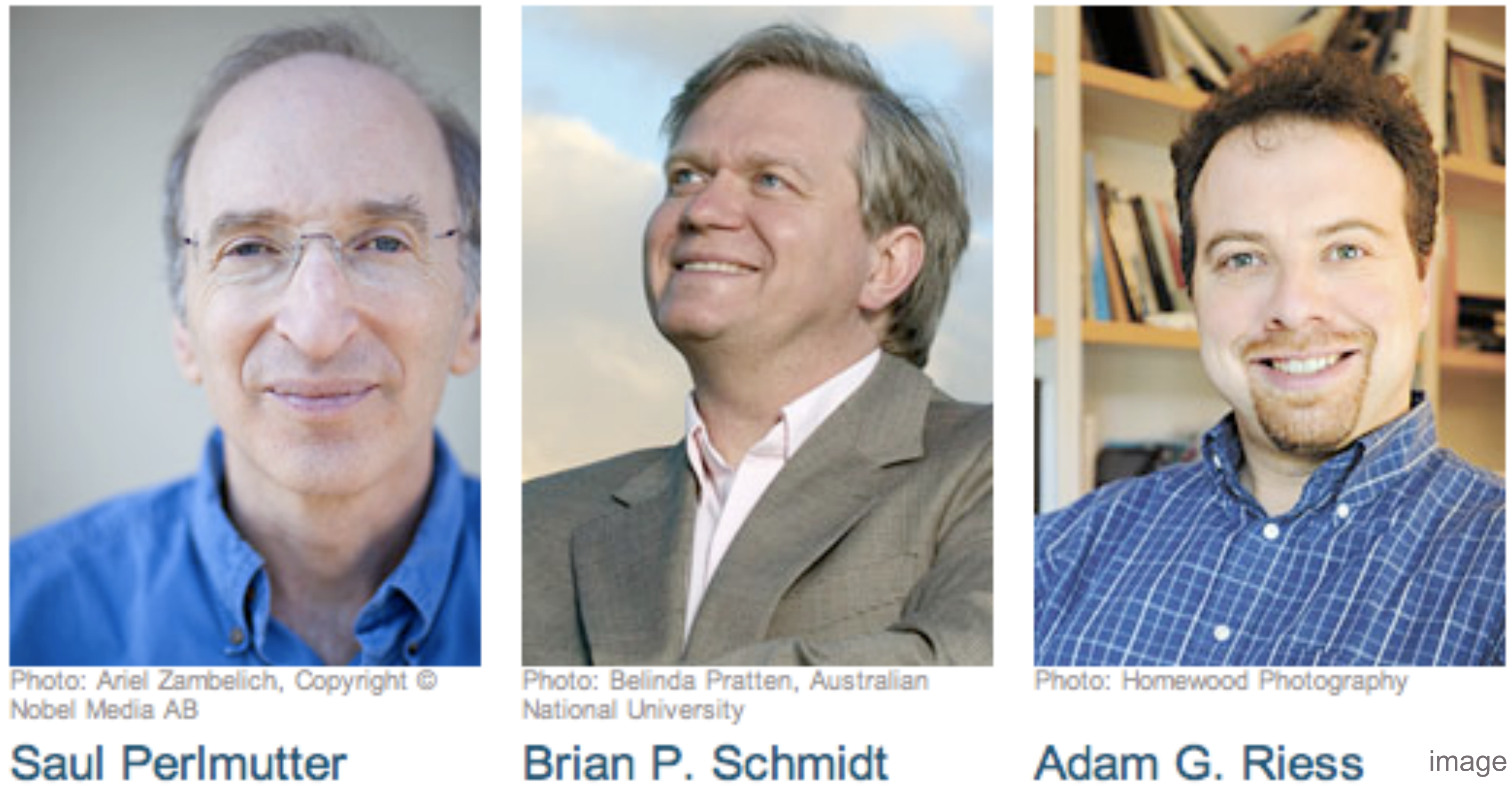


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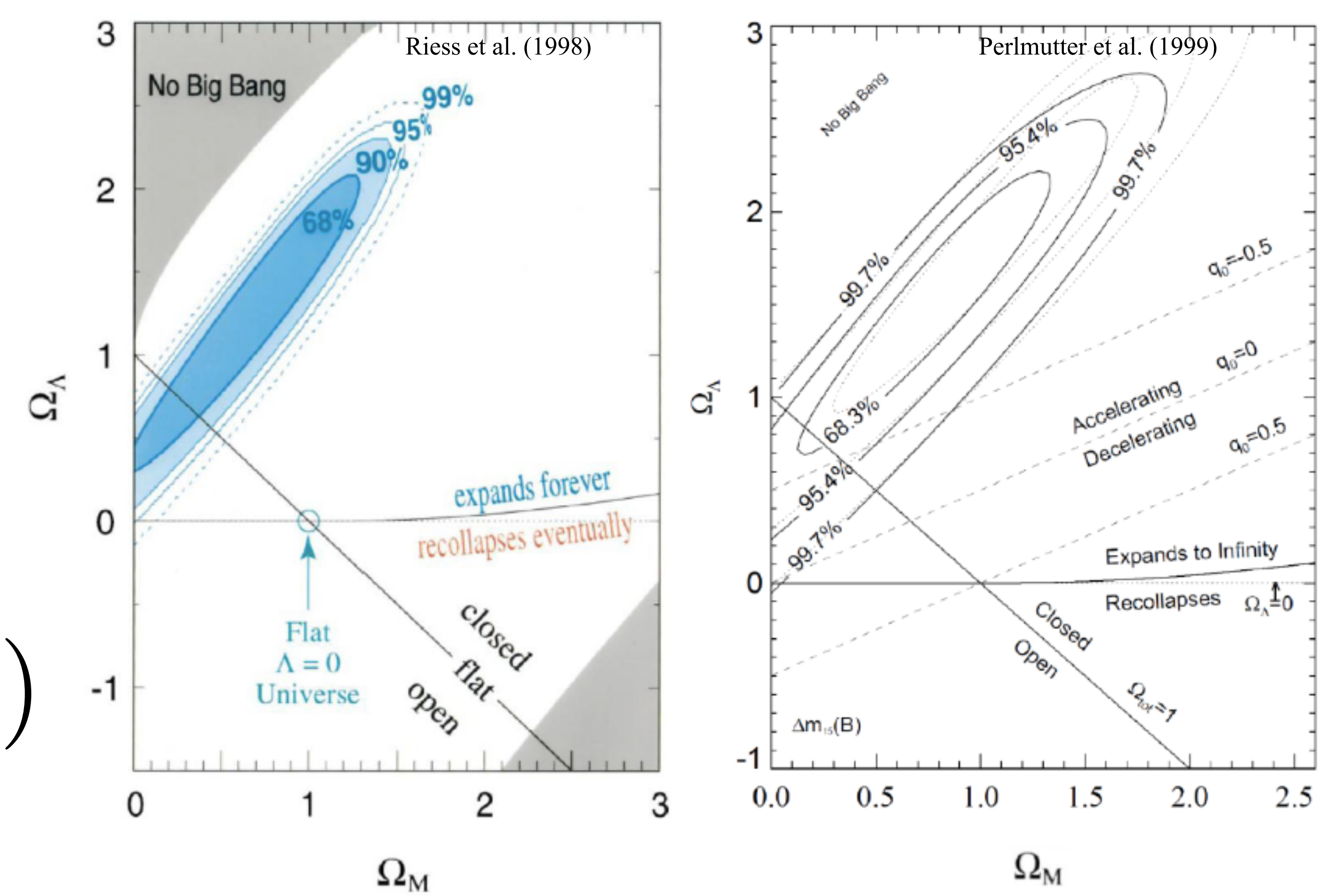

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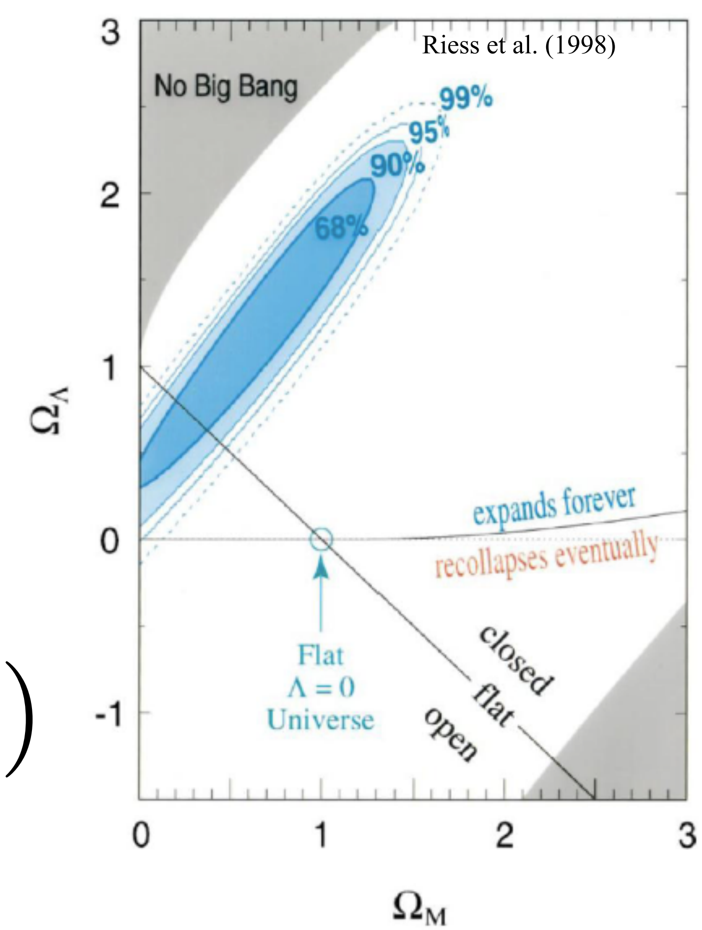


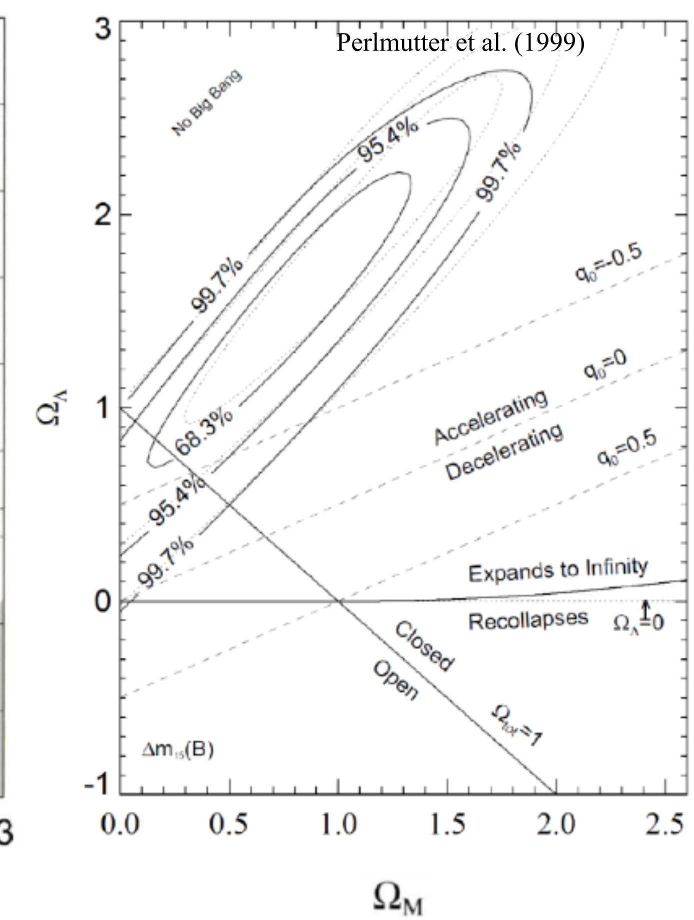

# Negative pressure and Vacuum

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$$\delta E = \delta\left(\varepsilon V\right) = V\delta\varepsilon + \varepsilon\delta V = -p\delta V$$

$$V\delta\varepsilon = -\left(\varepsilon + p\right)\delta V$$

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$$\varepsilon = Ts + \mu n - p$$

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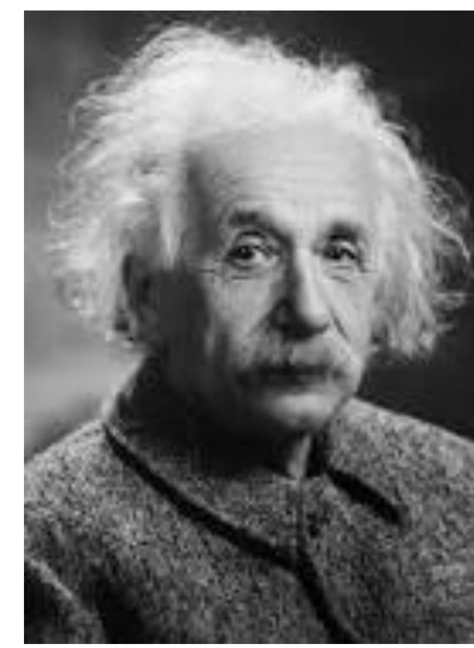
Cosmological constant: $\varepsilon = \Lambda$



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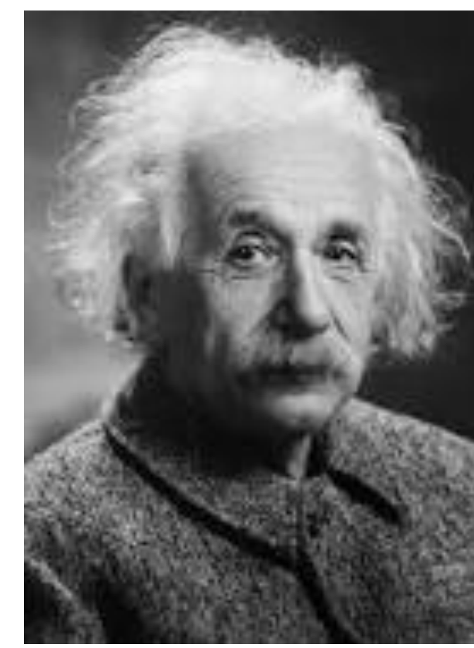

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$$T_{\mu\nu} = \Lambda g_{\mu\nu}$$

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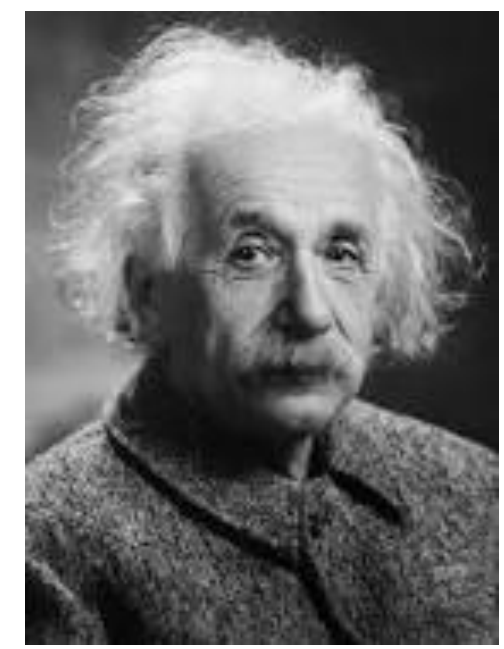

(1917)

Cosmological constant: $\varepsilon = \Lambda$

$$T_{\mu\nu} = \Lambda g_{\mu\nu} \qquad w = -1$$

# Quantum Fluctuations

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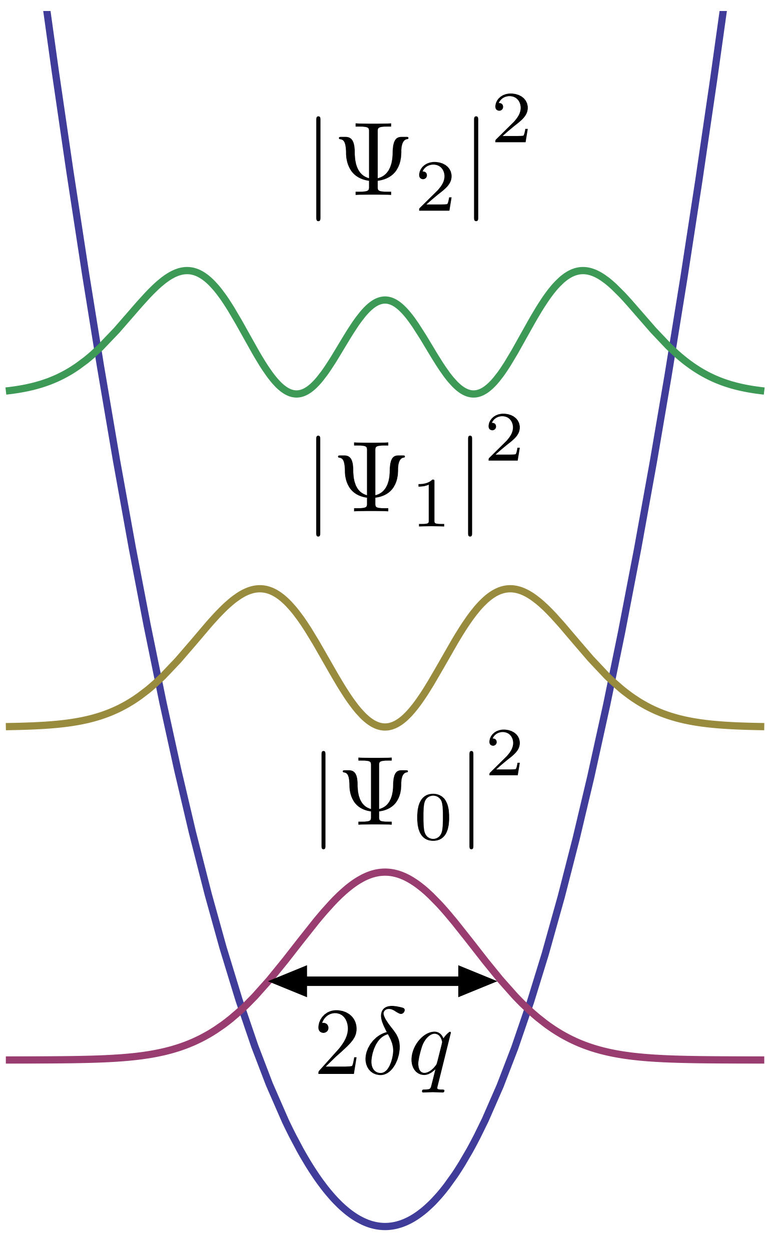
Heisenberg uncertainty relation

$$\delta q \cdot \delta p \geq \frac{1}{2}\hbar$$

# Quantum Fluctuations

m=1 Oscillator

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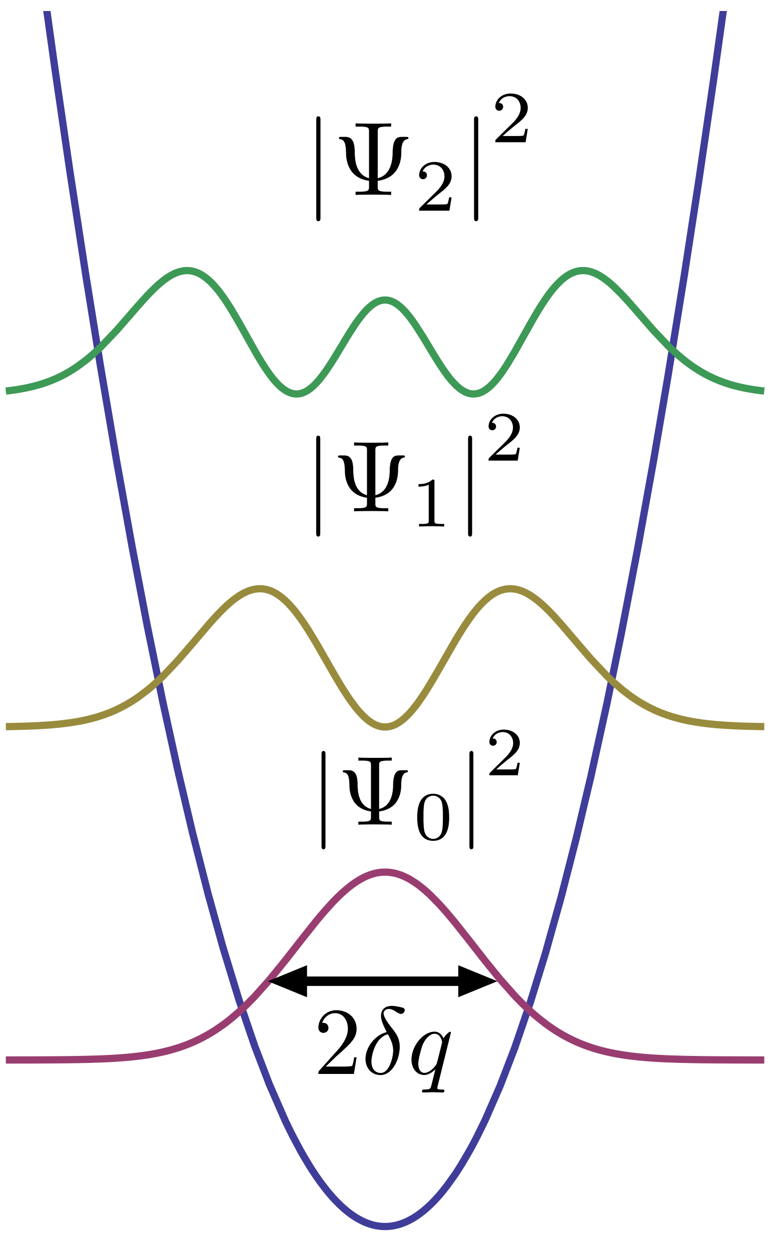


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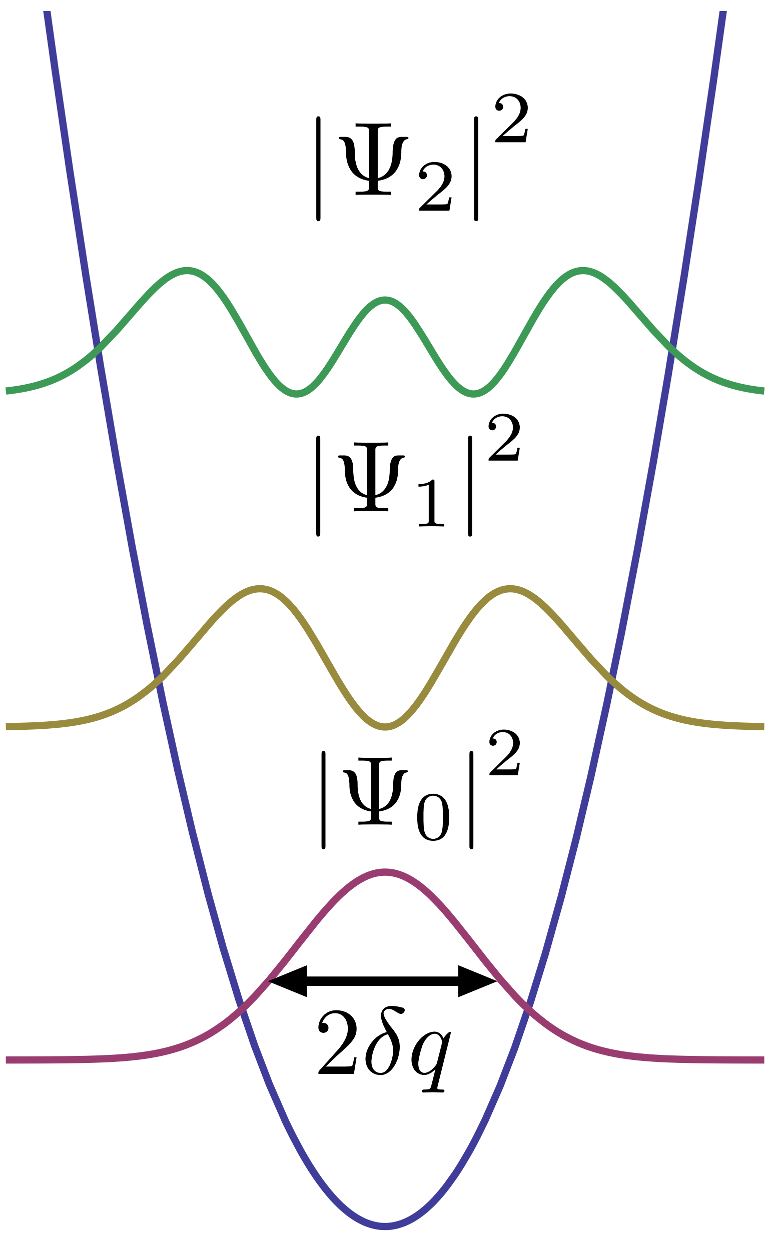


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$$\delta p = \omega \delta q \quad \Rightarrow \quad \delta q = \sqrt{\frac{\hbar}{2\omega}}$$

$$\Downarrow$$

$$E_0 \simeq \frac{1}{2}\left(\delta p^2 + \omega^2 \delta q^2\right) = \omega^2 \delta q^2 = \frac{\hbar\omega}{2}$$

minimal possible "vacuum" energy

# Measuring Fields

- Every device has a *finite* resolution
- One cannot measure a field at a point in *space*
- Every measurement of a field yields a smoothed/ *space-averaged / coarse grained* on some scale $\ell$ field $\phi_\ell\,(x)$

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# Averaging fields

- A device with *finite adjustable* resolution $\ell$ measures eigenvalues of the field operator

$$\hat{\phi}_\ell(\mathbf{x},t) = \int \mathrm{d}^d\mathbf{x}'\, W_\ell^\phi(\mathbf{x}-\mathbf{x}')\,\hat{\phi}(\mathbf{x}',t)$$

smeared by a family of window functions

$$W_\ell^\phi(\mathbf{x}) = \ell^{-d}\cdot w^\phi\left(\frac{\mathbf{x}}{\ell}\right)$$

# Averaging fields

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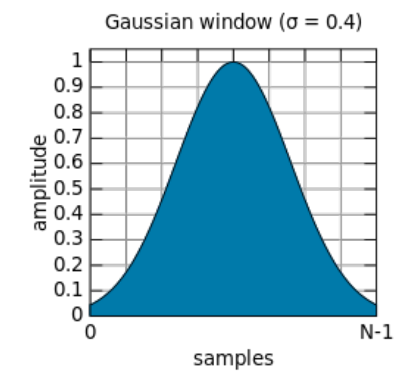
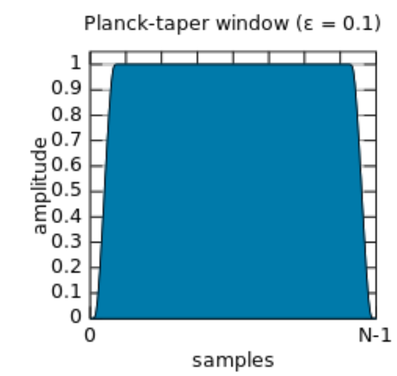



$$\hat{\phi}_\ell\,(\mathbf{x}, t) = \int \mathrm{d}^d\mathbf{x}'\, W_\ell^\phi\,(\mathbf{x} - \mathbf{x}')\, \hat{\phi}\,(\mathbf{x}', t)$$

smeared by a family of window functions

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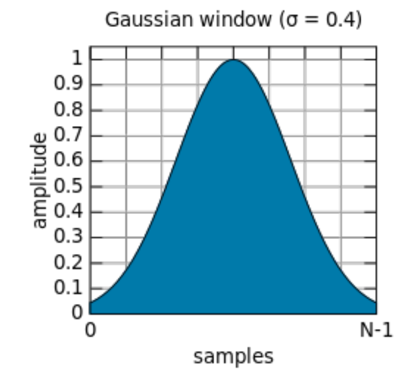


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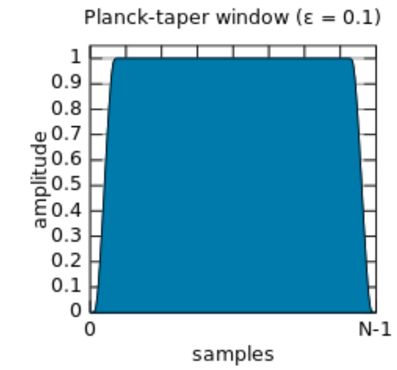


- Another device which we put *at the same place* measures canonical momentum $\hat{p}(t,\mathbf{x})$ averaging it with some other family of window functions with the same scaling property above. Suppose that the resolution is the same.

# Canonical Quantisation

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where

$$\mathscr{D}\left(\mathbf{r}\right)=\int\mathrm{d}^{d}\mathbf{r}'\,w^{\phi}\left(\mathbf{r}-\mathbf{r}'\right)w^{p}\left(\mathbf{r}'\right)$$

dimensionless

this convolution of shapes does not depend on scale $\ell$ but only on the way of averaging

# Uncertainty Relations, QFT

fluctuations *on scale* $\ell$:

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$$\delta\phi_\ell\left(\mathbf{x}\right) \cdot \delta p_\ell\left(\mathbf{x}\right) \geq \frac{\hbar}{2} \cdot \mathscr{D}_0 \cdot \ell^{-d}$$

for two Gaussian window functions $\mathscr{D}_0 = \left(2\sqrt{\pi}\right)^{-d}$

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the shorter is the scale at which we look, the more quantum is the world

# Two -Point Function / Correlator and the Power Spectrum

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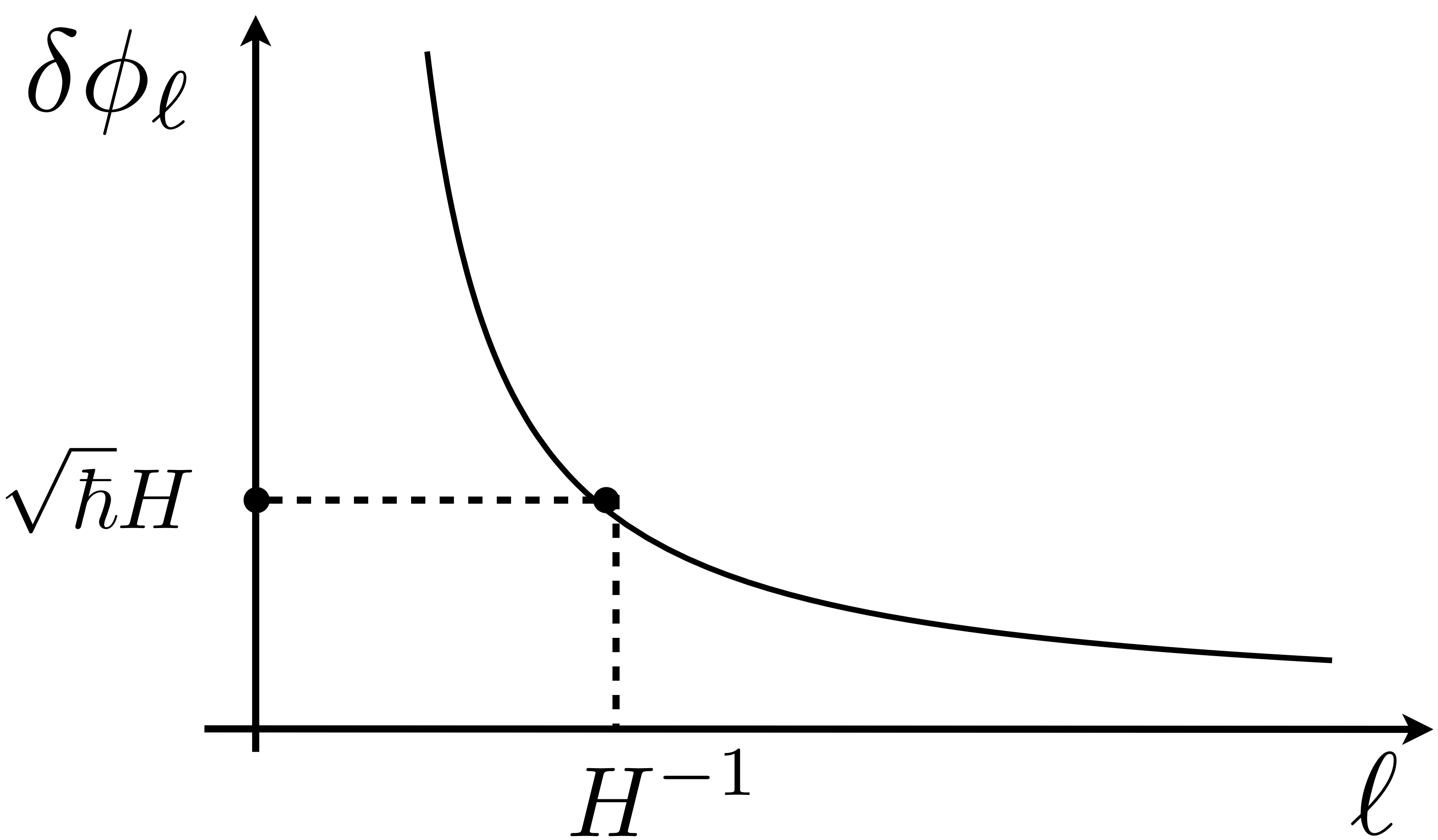

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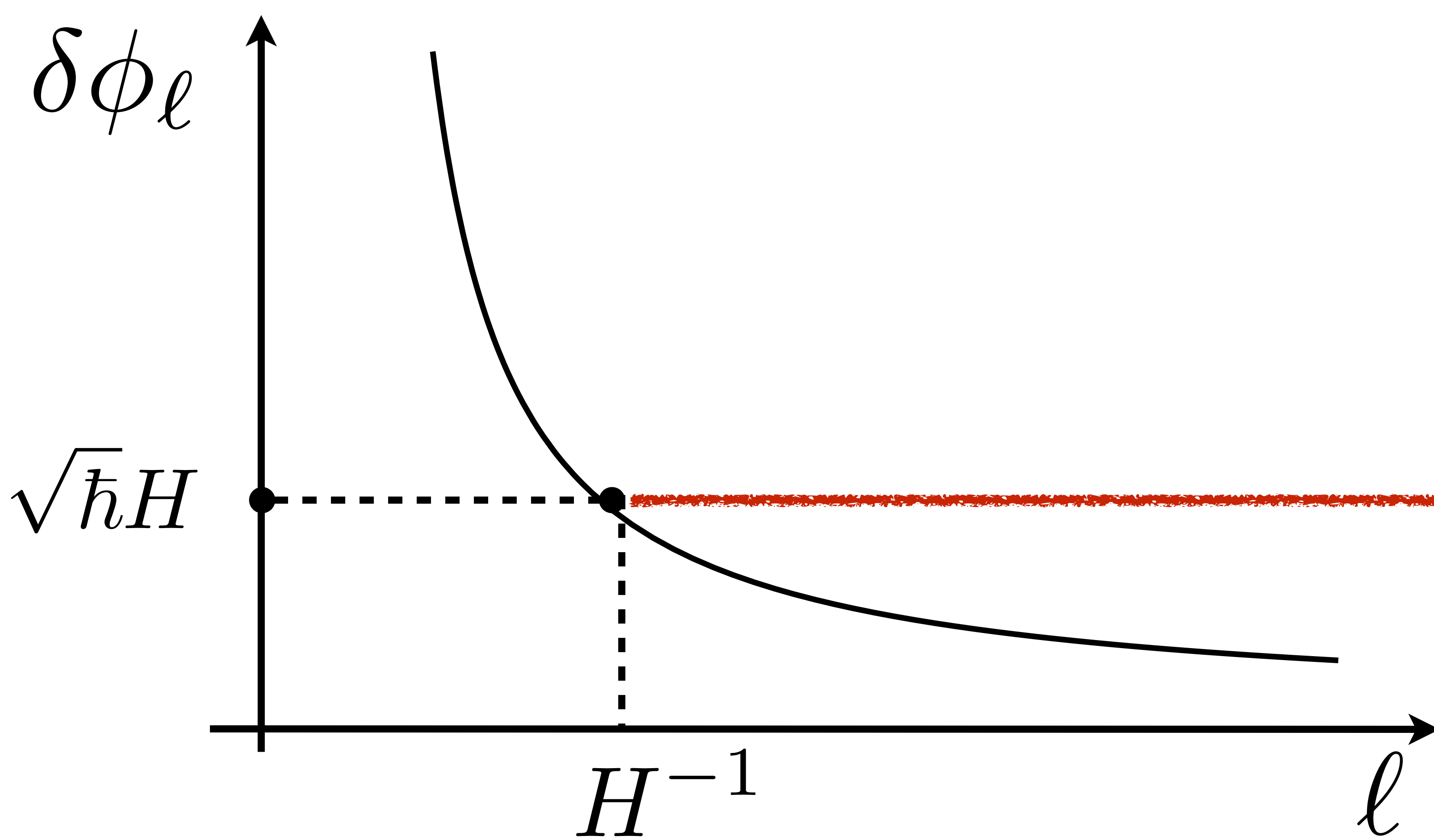

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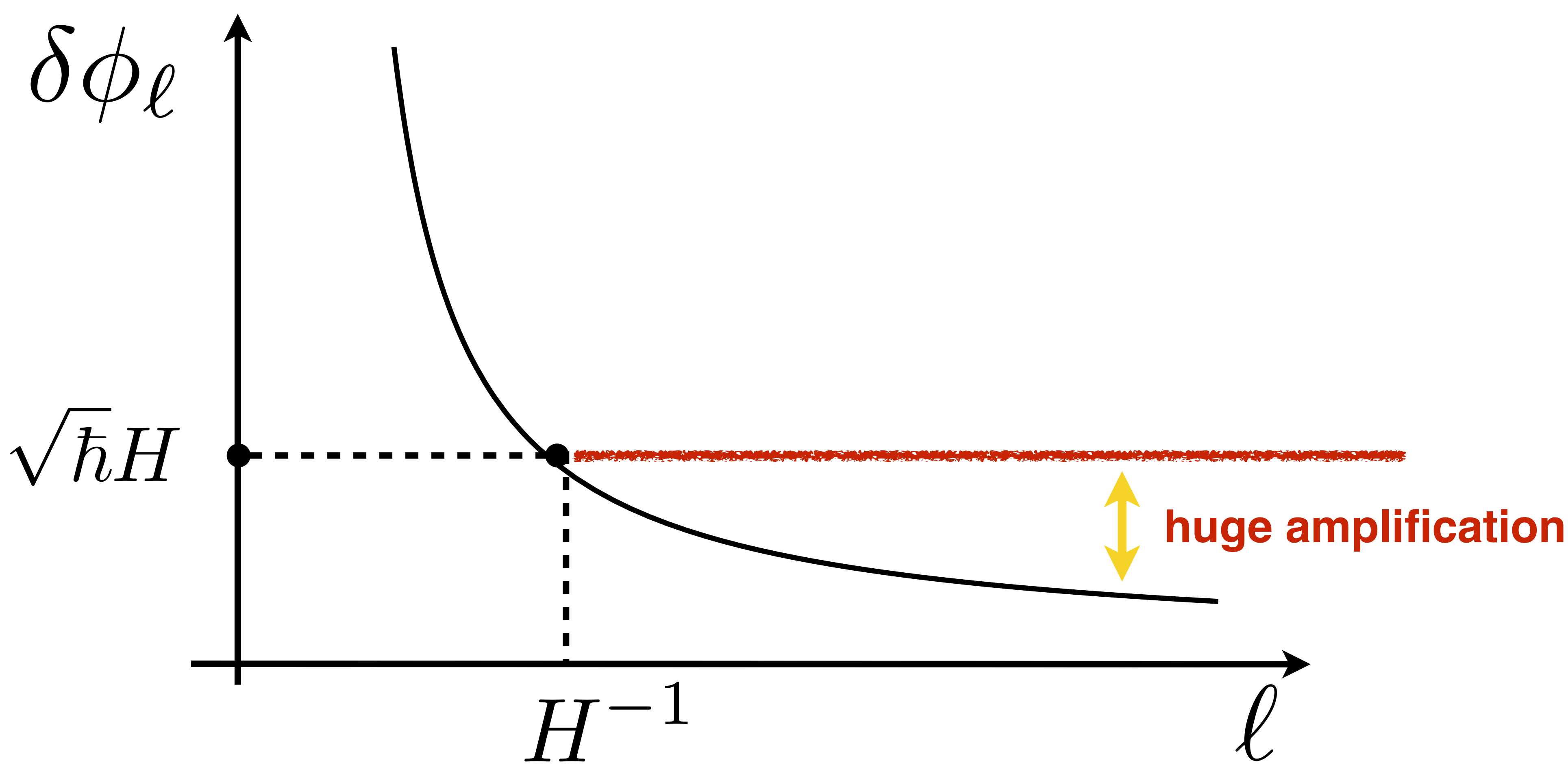

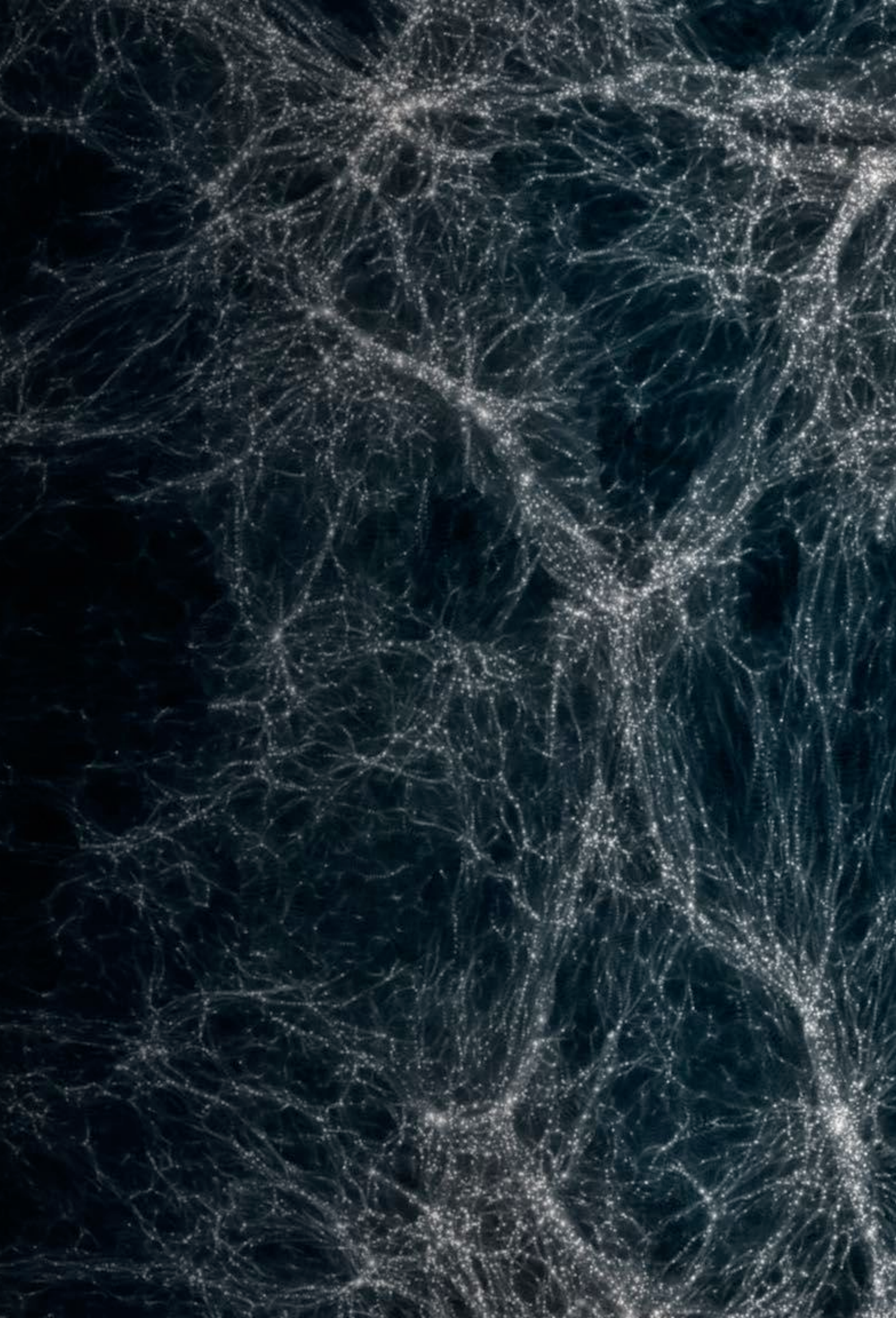

For short range of scales one
can parametrise
the resulting Newtonian
potential as a power law

$$\Phi_\ell \propto \ell^{(1-n_S)/2}$$

$$n_S < 1$$

spectral index,
prediction slightly red

Galaxies and
Large Scale Structure
do gravitate!

But all of them appeared out of
quantum fluctuations!!!

quantum fluctuations should
gravitate!!!

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## Should vacuum really weigh?

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$$\Downarrow$$

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Die dargelegten Schwierigkeiten werden dadurch beseitigt, daß man an die Stelle der Feldgleichungen (1) die Feldgleichungen

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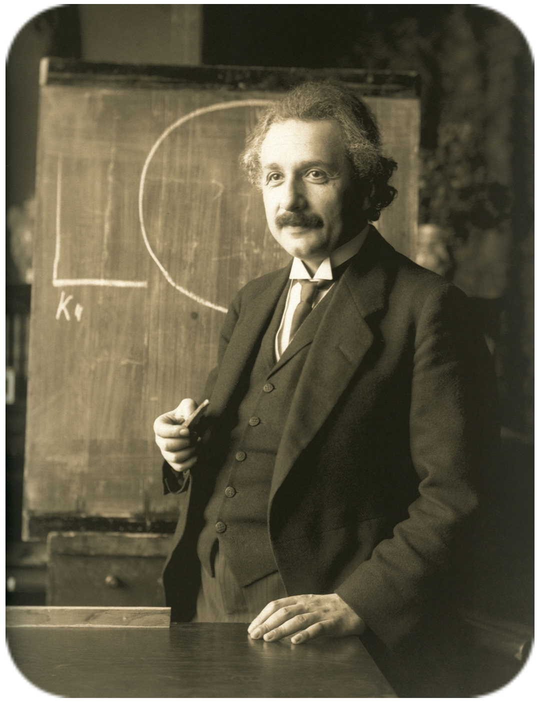

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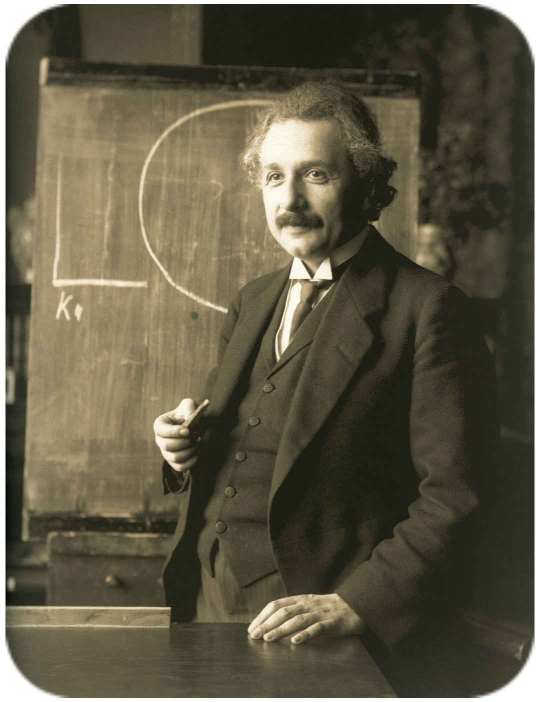

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Einstein: Gravitationsfelder im Aufbau der materiellen Elementarteilchen 349

In: *Königlich Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* (1919): 349–356.

**Spielen Gravitationsfelder im Aufbau der materiellen Elementarteilchen eine wesentliche Rolle?**

Von A. Einstein.

Weder die Newtonsche noch die relativistische Gravitationstheorie hat bisher der Theorie von der Konstitution der Materie einen Fortschritt gebracht. Demgegenüber soll im folgenden gezeigt werden, daß Anhaltspunkte für die Auffassung vorhanden sind, daß die die Bausteine der Atome bildenden elektrischen Elementargebilde durch Gravitationskräfte zusammengehalten werden.

§ 1. Mängel der gegenwärtigen Auffassung.

Die Theoretiker haben sich viel bemüht, eine Theorie zu ersinnen, welche von dem Gleichgewicht der das Elektron konstituierenden Elektrizität Rechenschaft gibt. Insbesondere G. Mie hat dieser Frage tiefgehende Unternehmungen gewidmet. Seine Theorie, welche bei den Fachgenossen vielfach Zustimmung gefunden hat, beruht im wesentlichen darauf, daß außer den Energietermen der Maxwell-Lorentzschen Theorie des elektromagnetischen Feldes von den Komponenten des elektrodyna-

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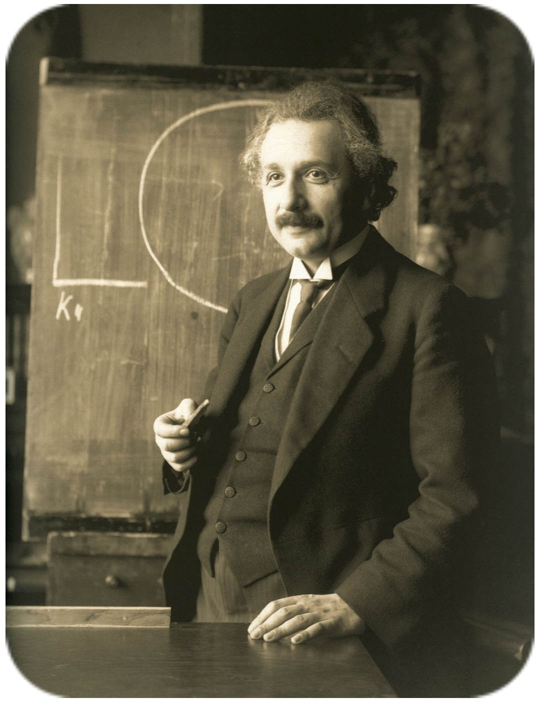

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Weder die NEWTONsche noch die relativistische Gravitationstheorie hat bisher der Theorie von der Konstitution der Materie einen Fortschritt gebracht. Demgegenüber soll im folgenden gezeigt werden, daß Anhaltspunkte für die Auffassung vorhanden sind, daß die die Bausteine der Atome bildenden elektrischen Elementargebilde durch Gravitationskräfte zusammengehalten werden.

§ 1. Mängel der gegenwärtigen Auffassung.

Die Theoretiker haben sich viel bemüht, eine Theorie zu ersinnen, welche von dem Gleichgewicht der das Elektron konstituierenden Elektrizität Rechenschaft gibt. Insbesondere G. MIE hat dieser Frage tiefgehende Unternehmungen gewidmet. Seine Theorie, welche bei den Fachgenossen vielfach Zustimmung gefunden hat, beruht im wesentlichen darauf, daß außer den Energietermen der MAXWELL-LORENTZschen Theorie des elektromagnetischen Feldes von den Komponenten des elektrodyna-

§ 2. Die skalarfreien Feldgleichungen.

Die dargelegten Schwierigkeiten werden dadurch beseitigt, daß man an die Stelle der Feldgleichungen (1) die Feldgleichungen

$$R_{i\kappa} - \frac{1}{4} g_{i\kappa} R = -\kappa T_{i\kappa} \qquad (1a)$$

setzt, wobei $(T_{i\kappa})$ den durch (3) gegebenen Energietensor des elektromagnetischen Feldes bedeutet.

# Bianchi identity + energy-momentum conservation

$$\nabla_\mu G^{\mu\nu} = 0 \quad + \quad \nabla_\mu T^{\mu\nu} = 0 \quad \Rightarrow \quad \partial_\mu (G - T) = 0$$

neue universelle Konstante λ eingeführt werden mußte, die zu der Gesamtmasse der Welt (bzw. zu der Gleichgewichtsdichte der Materie) in fester Beziehung steht. Hierin liegt ein besonders schwerwiegender Schönheitsfehler der Theorie.

$$G_{\mu\nu} - T_{\mu\nu} - \Lambda g_{\mu\nu} = 0$$

# Decoupling vacuum energy from spacetime curvature

$$G_{\mu\nu} - T_{\mu\nu} - \frac{1}{4} g_{\mu\nu} (G - T) = 0$$

# Decoupling vacuum energy from spacetime curvature

$$G_{\mu\nu} - T_{\mu\nu} - \frac{1}{4} g_{\mu\nu} (G - T) = 0$$

## invariant under vacuum shifts of energy-momentum

$$T_{\mu\nu} \rightarrow T_{\mu\nu} + \Lambda g_{\mu\nu}$$

# What is the action for the *traceless* Einstein field equations ?

$$G_{\mu\nu} - T_{\mu\nu} - \frac{1}{4} g_{\mu\nu} (G - T) = 0$$