Nils Schöneberg Tuesday 08.11.2022 **nils.science@gmail.com**

European Research Council
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ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA
MARÍA
DE MAEZTU
2020-2023

BAO+BBN REVISITED

TOPICS

- Quick motivation
- The BAO principle
- The BBN principle
- Why do BAO+BBN combine so well?
- What aids this probe?
- What breaks this probe?

TOPICS

- Quick motivation
- The BAO principle
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- What aids this probe?
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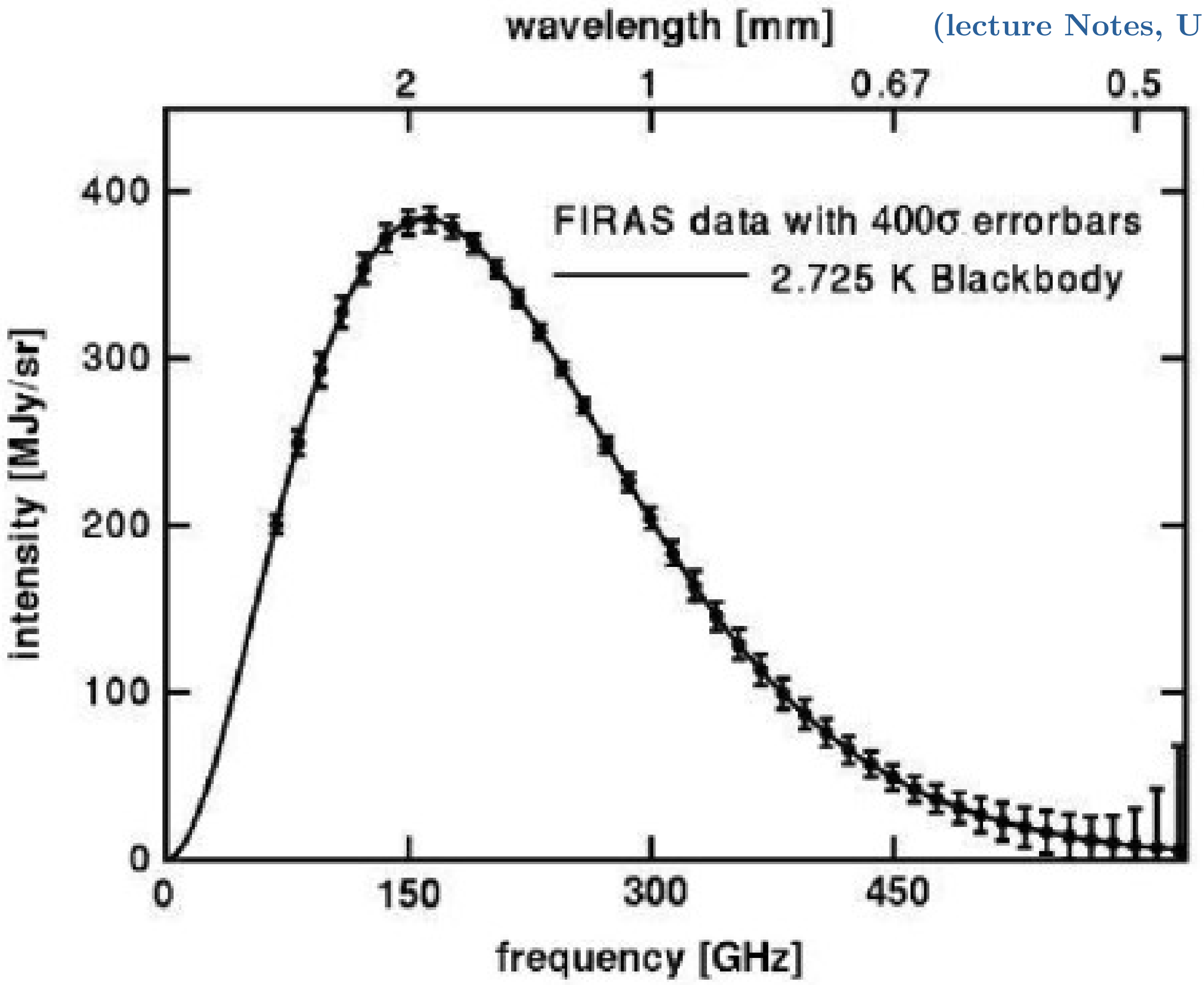
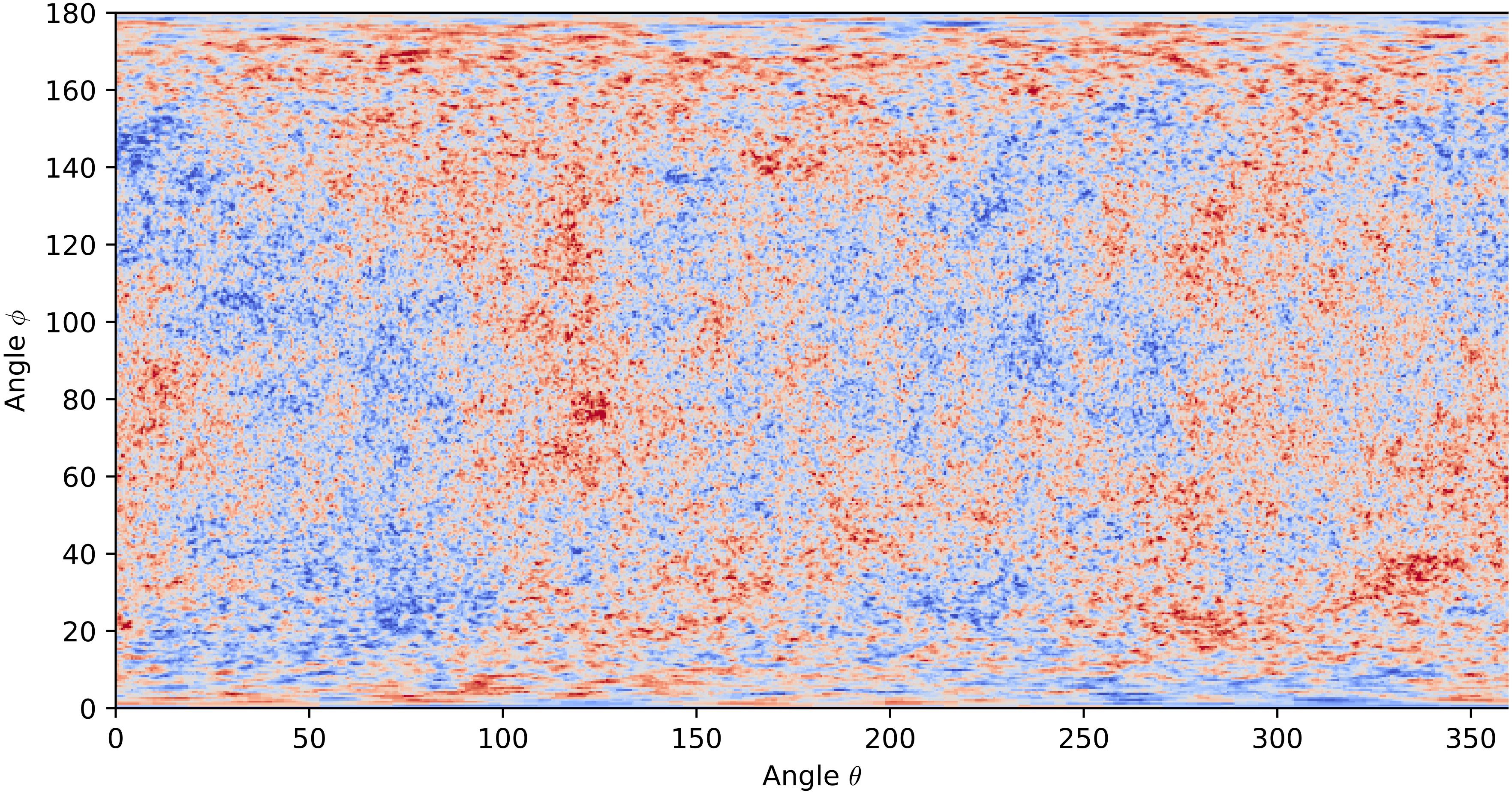
THE CMB

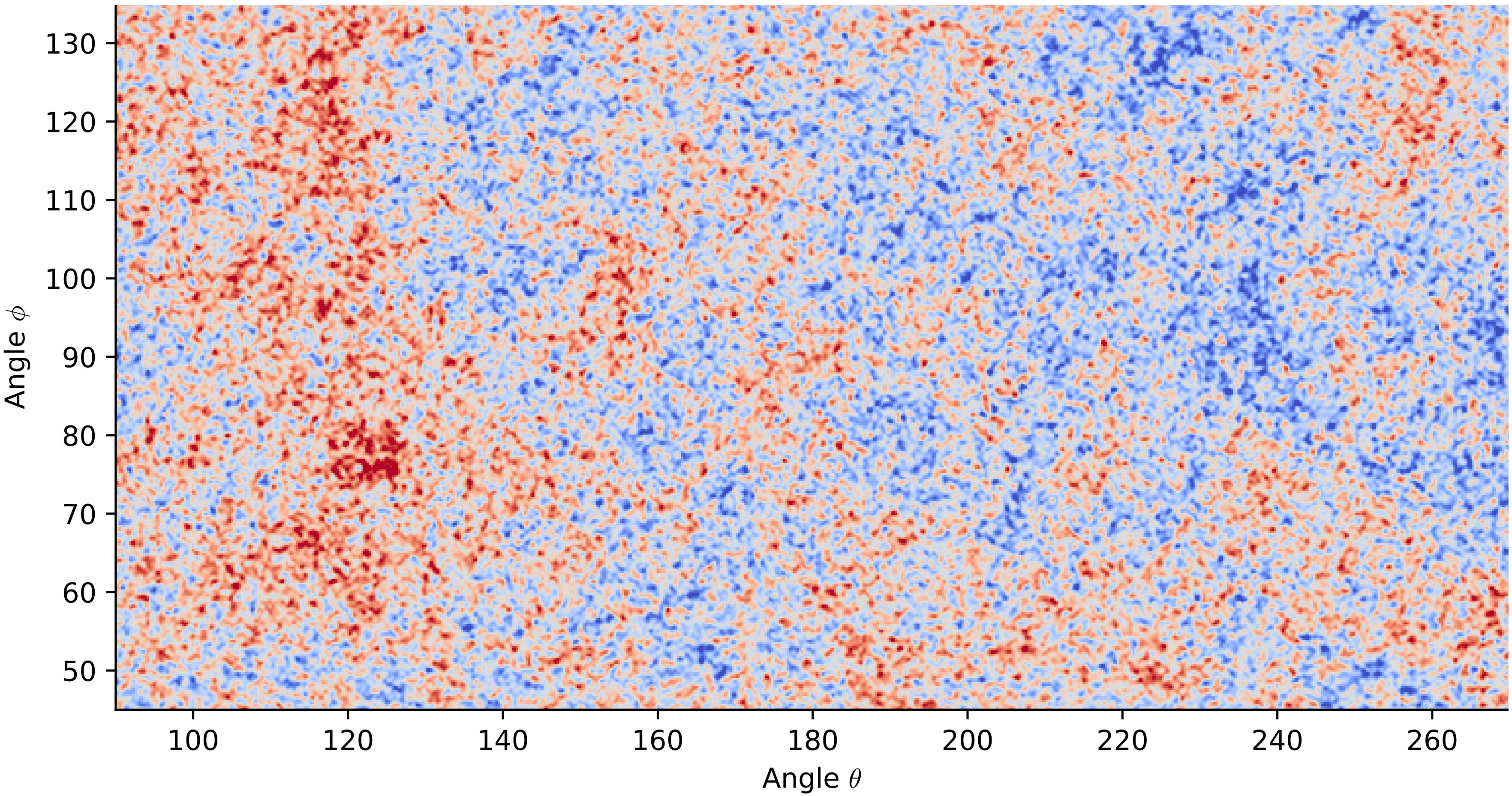
M. Bartelmann: Observing the Big Bang
(lecture Notes, University of Heidelberg)



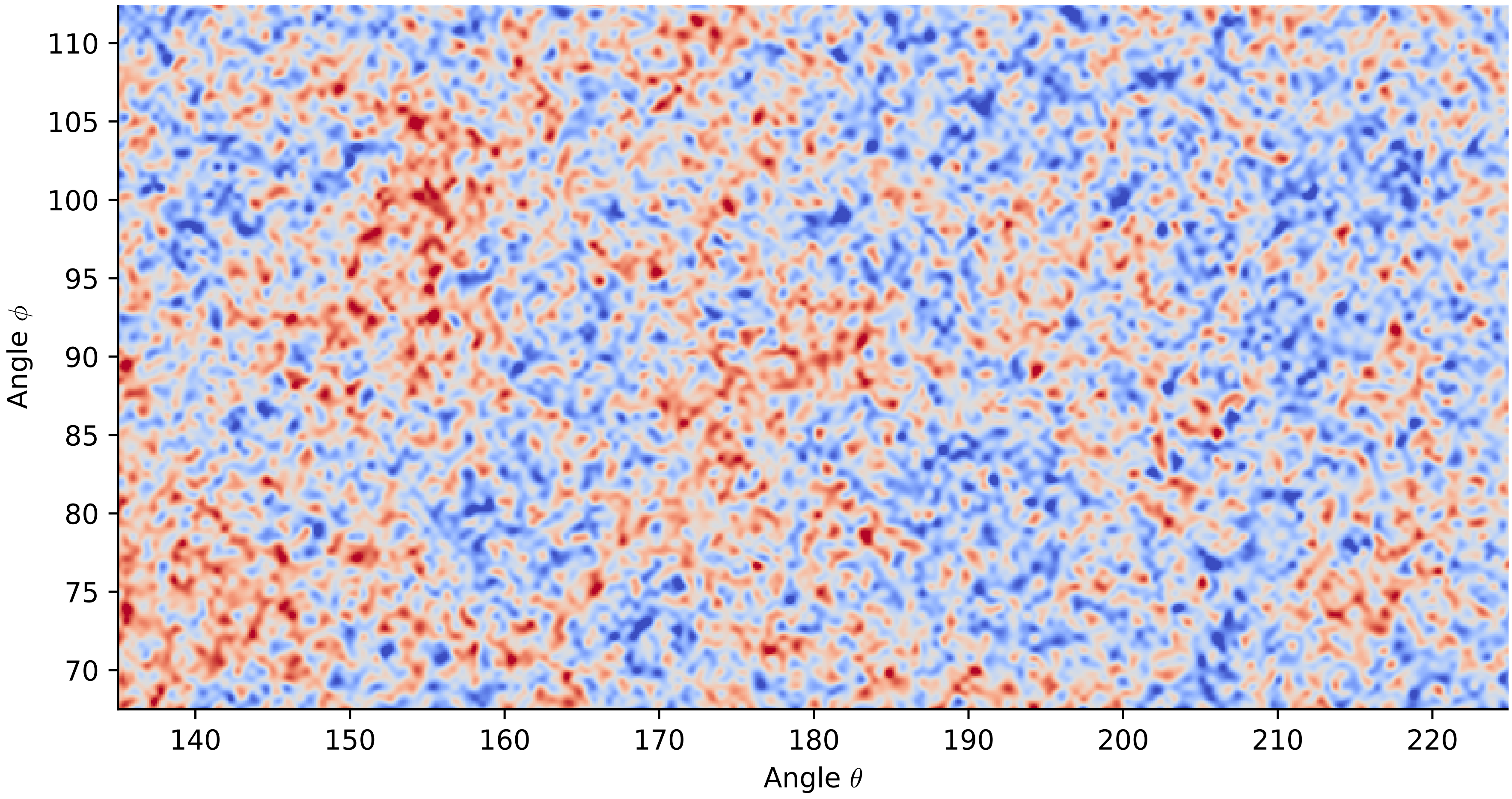
THE CMB


180
160
140
120
100
80
60
40
20
0
Angle ϕ
0
50
100
150
200
250
300
350
Angle θ

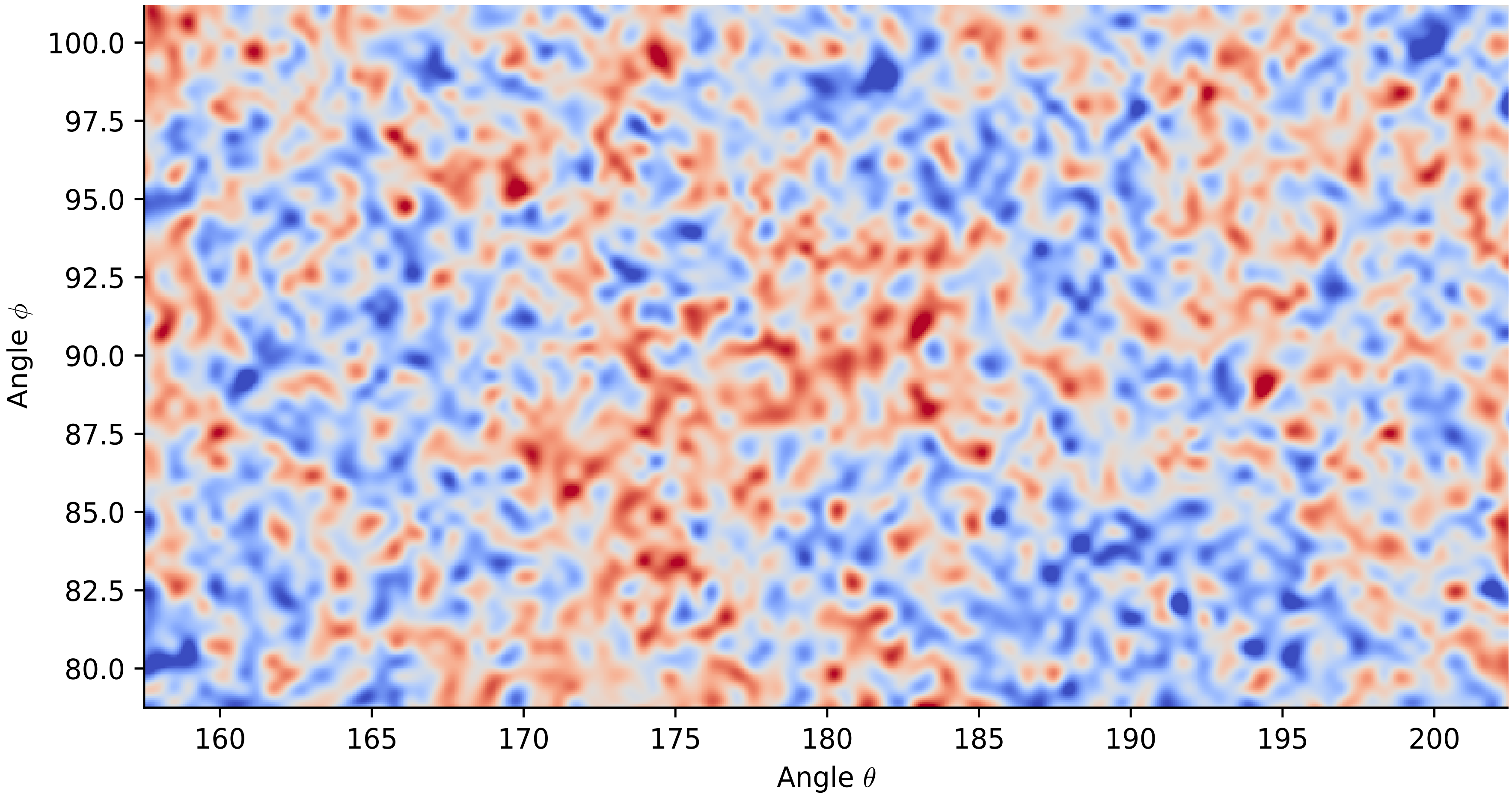
The CMB


Angle ϕ
130
120
110
100
90
80
70
60
50
100
120
140
160
180
200
220
240
260
Angle θ

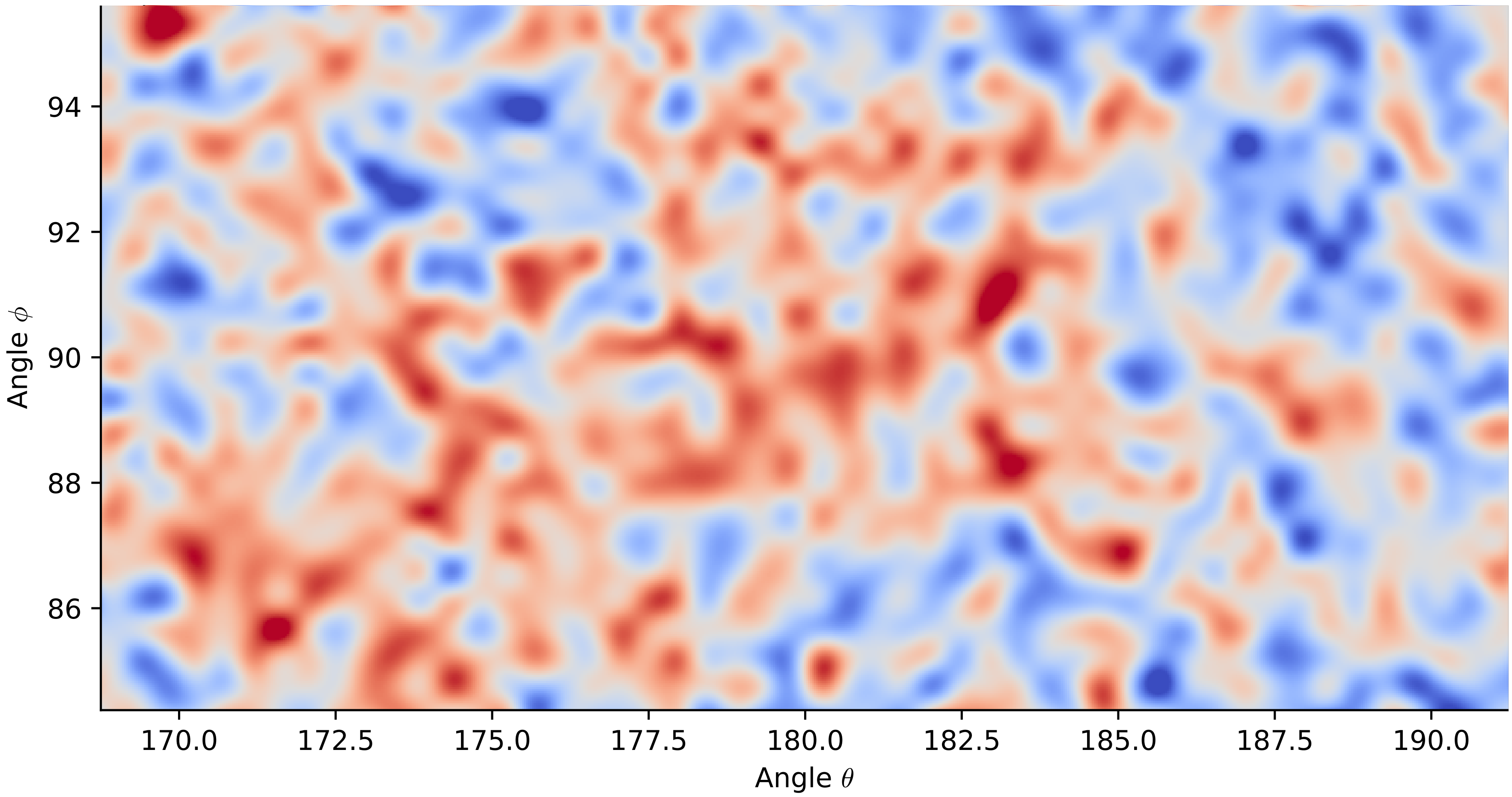
THE CMB


110
105
100
95
90
85
80
75
70
Angle ϕ
140
150
160
170
180
190
200
210
220
Angle θ

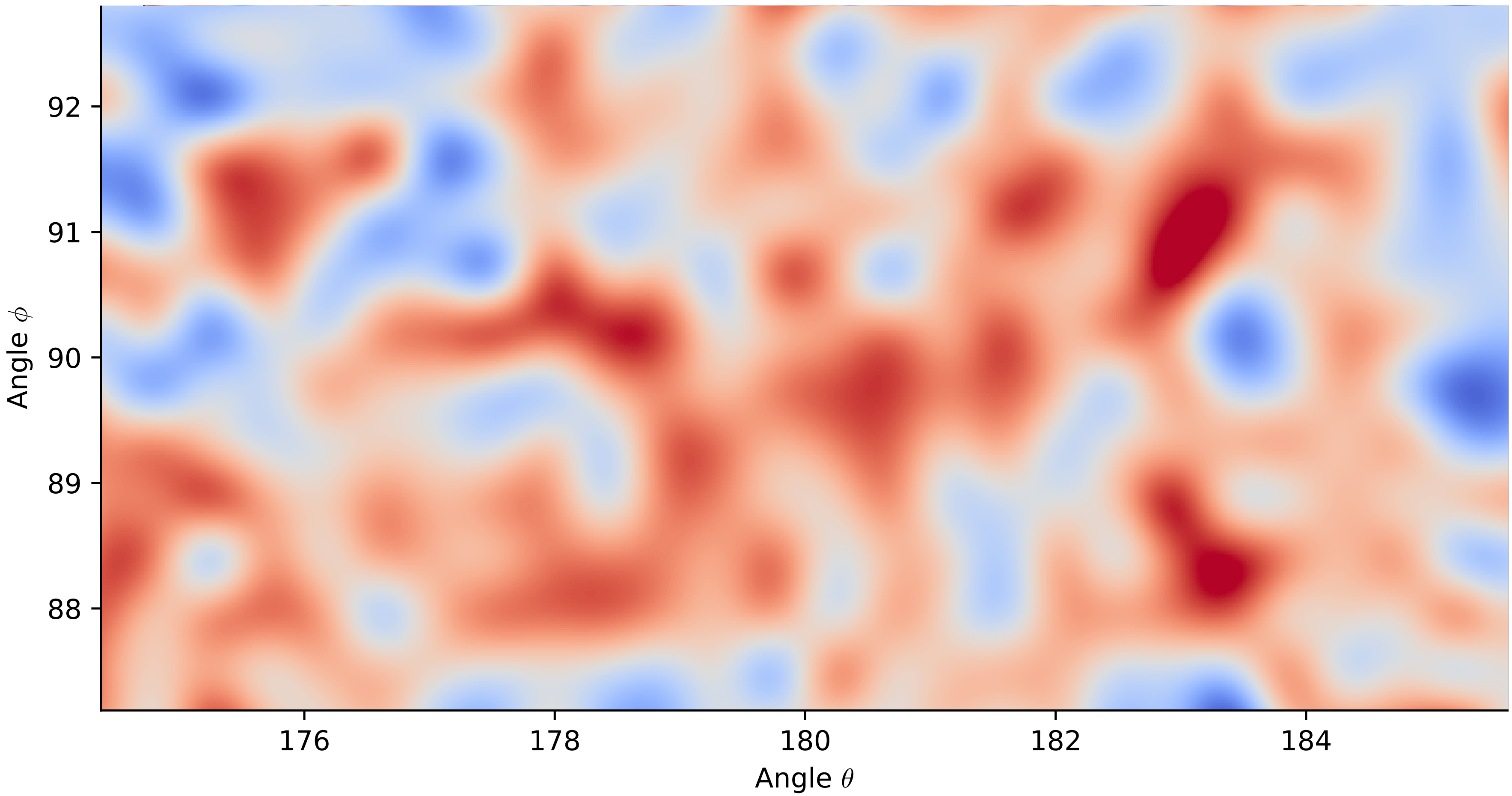
The CMB


100.0
97.5
95.0
92.5
90.0
87.5
85.0
82.5
80.0
Angle ϕ
160
165
170
175
180
185
190
195
200
Angle θ

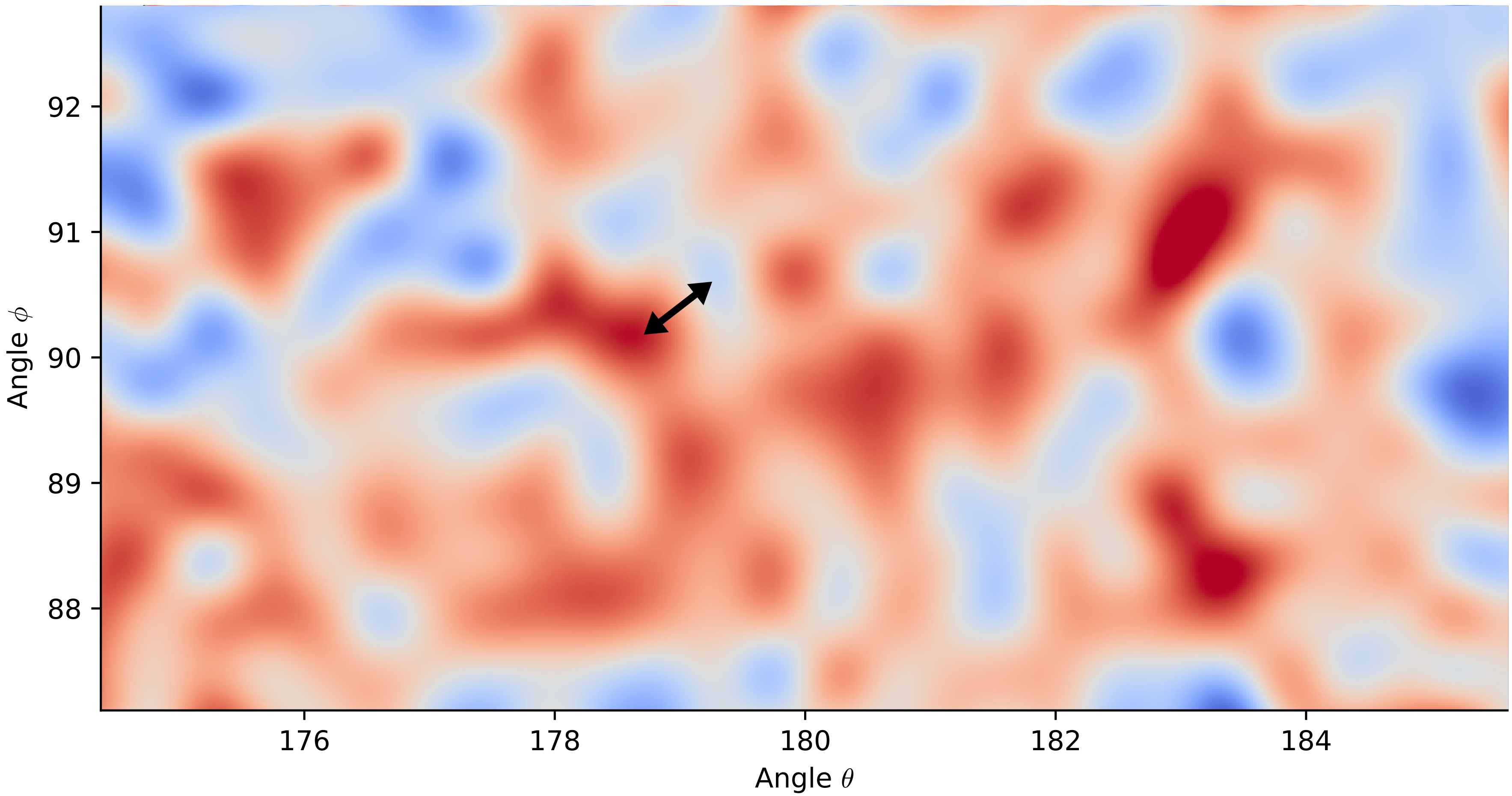
The CMB


94
92
90
88
86
Angle ϕ
170.0
172.5
175.0
177.5
180.0
182.5
185.0
187.5
190.0
Angle θ

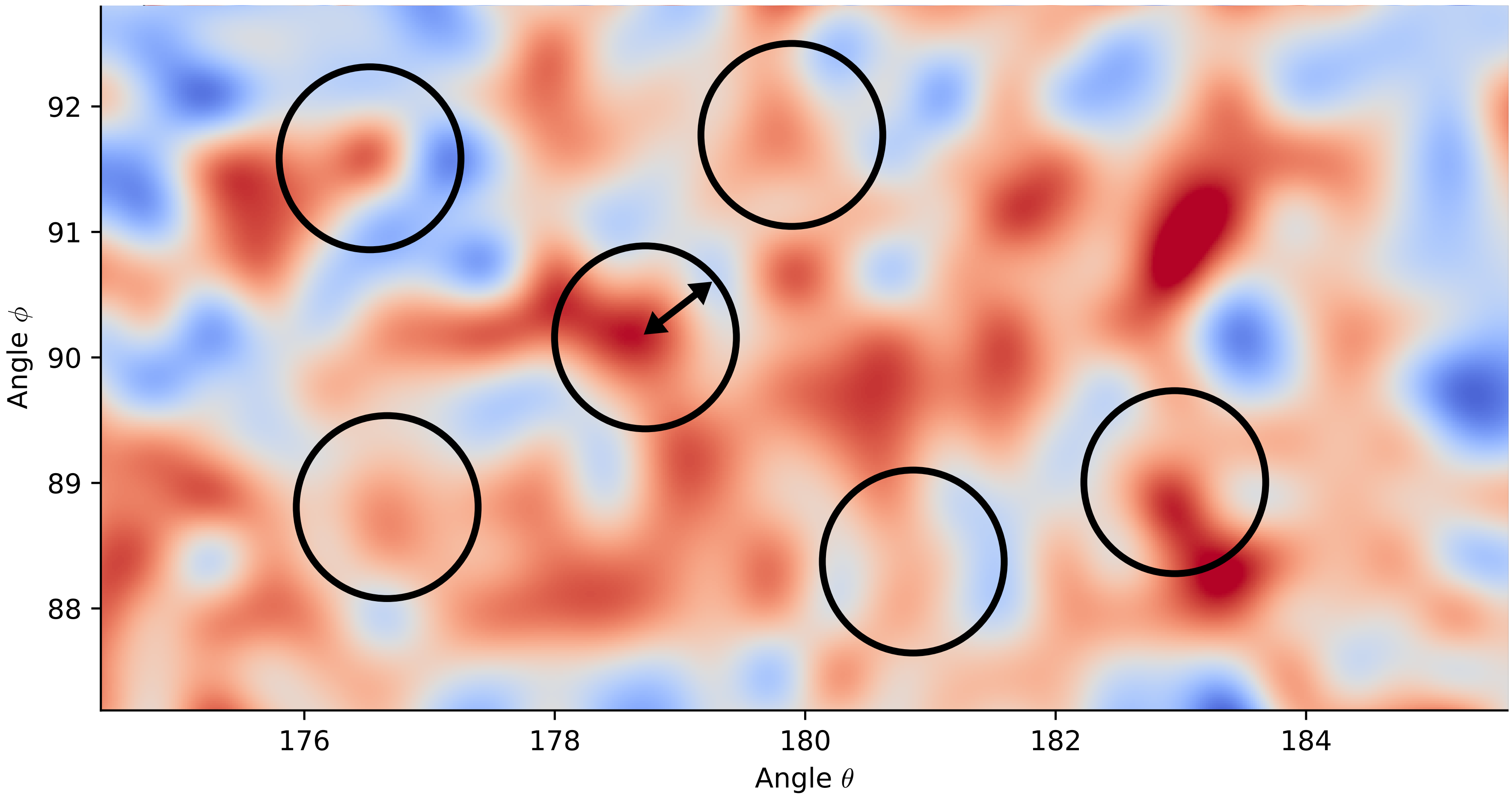
THE CMB



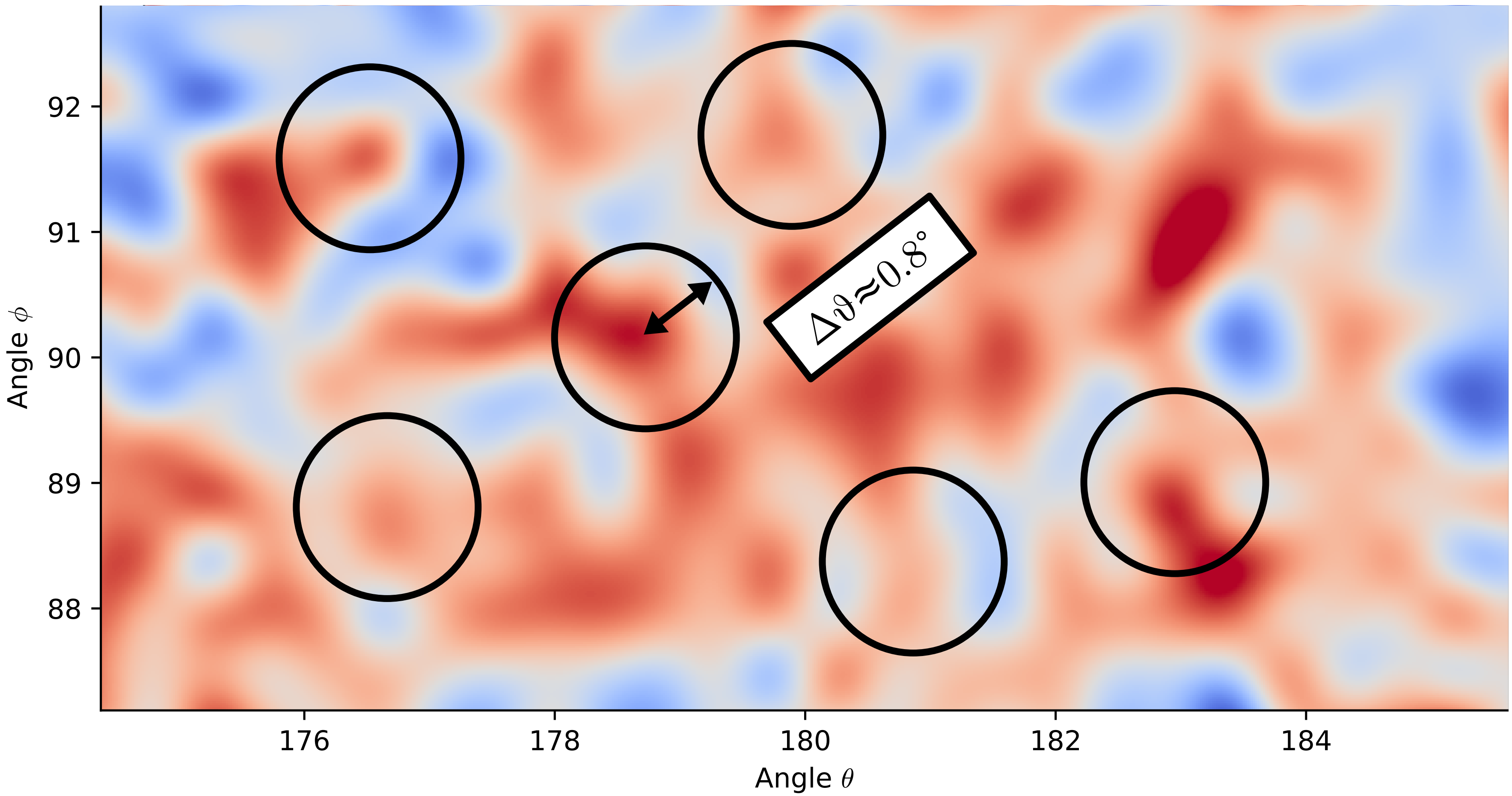
The CMB



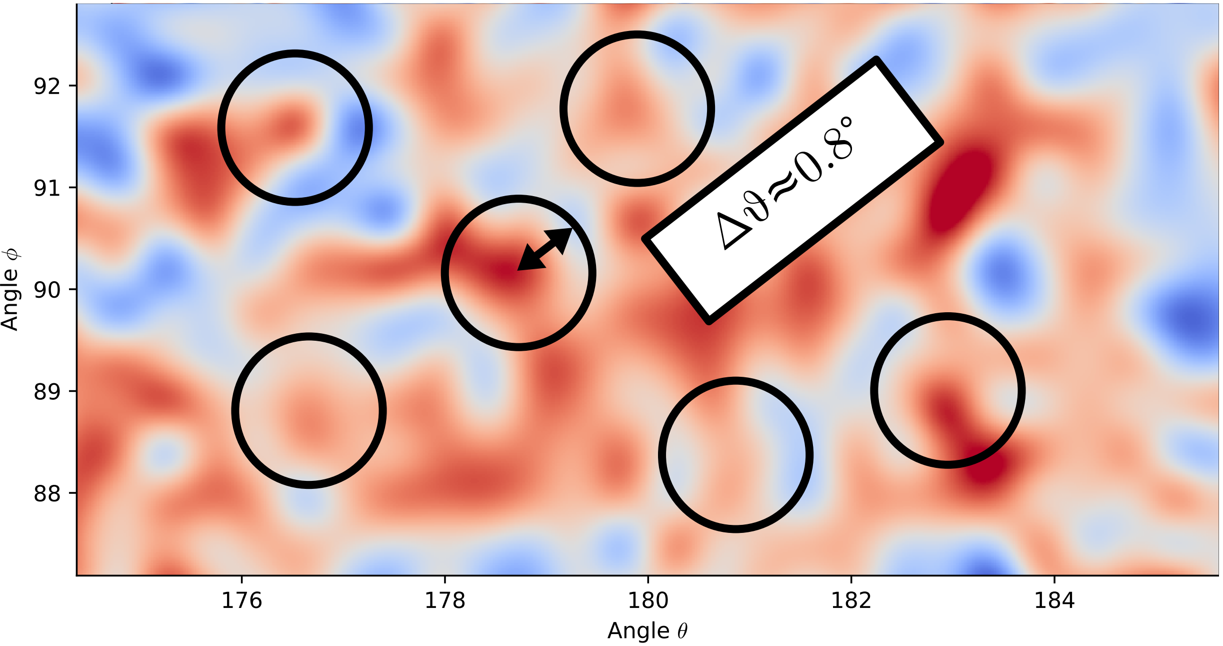
The CMB

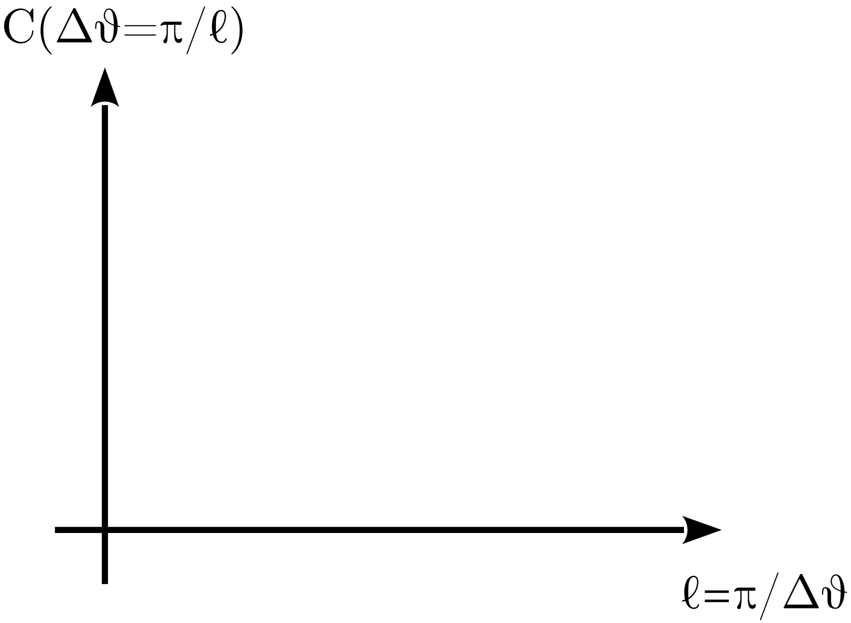


THE CMB

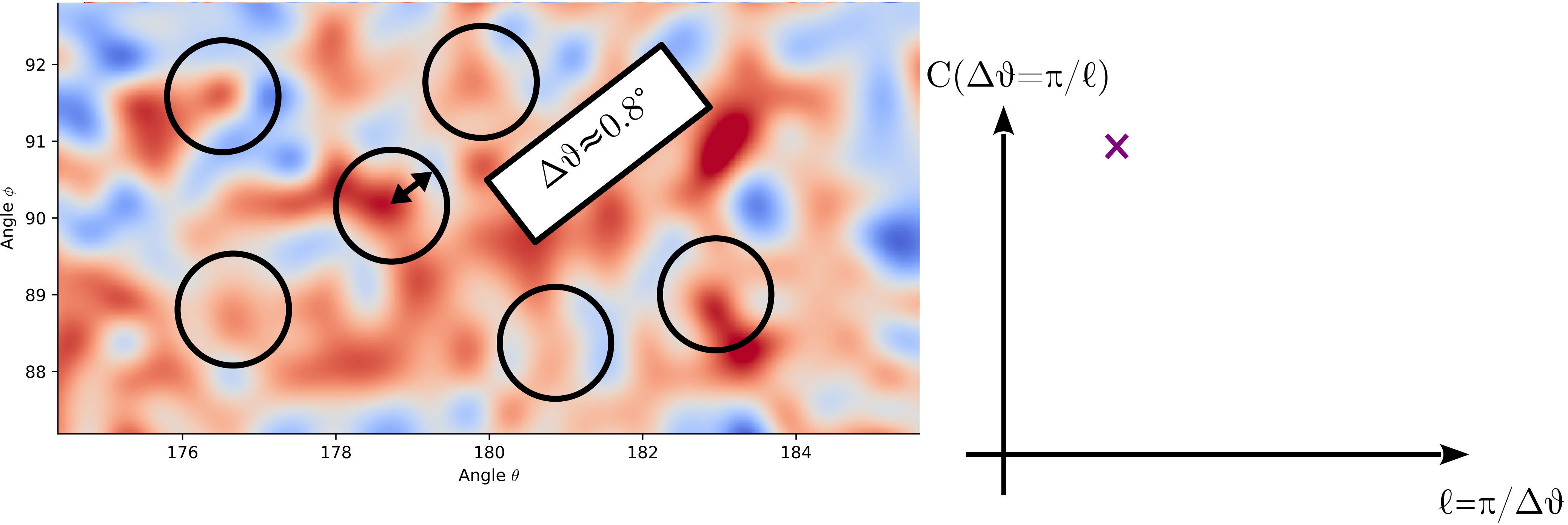

$\Delta\vartheta \approx 0.8°$
Angle ϕ
92
91
90
89
88
176
178
180
182
184
Angle θ

THE CMB

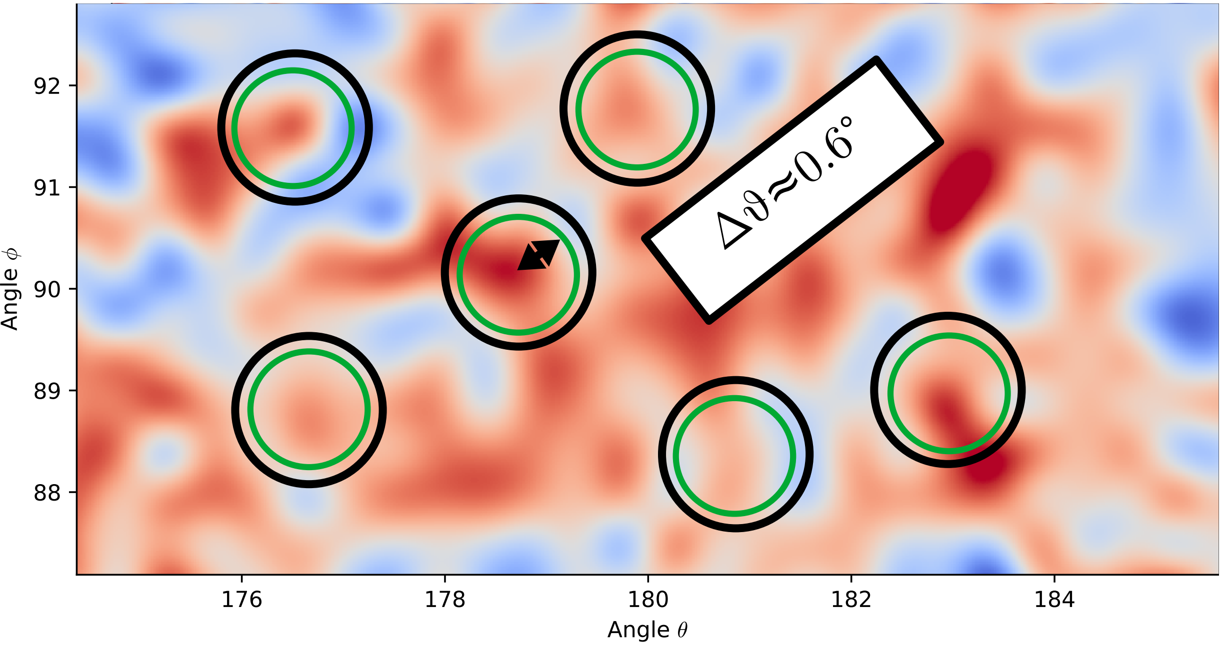

$\Delta\vartheta \approx 0.8°$
92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ

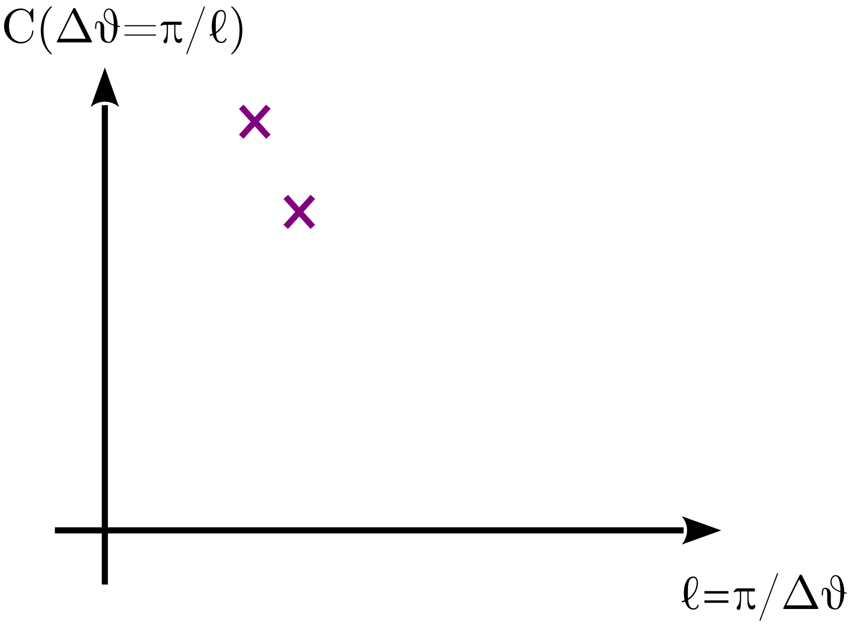

$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

THE CMB

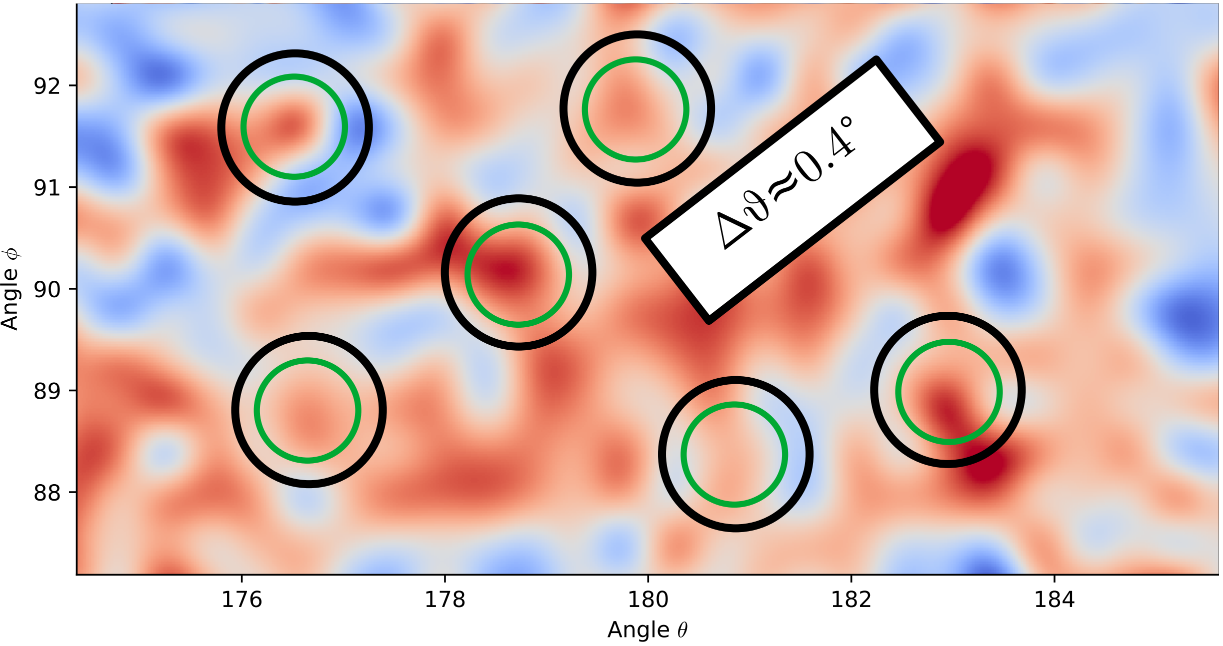

92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.8°$
$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

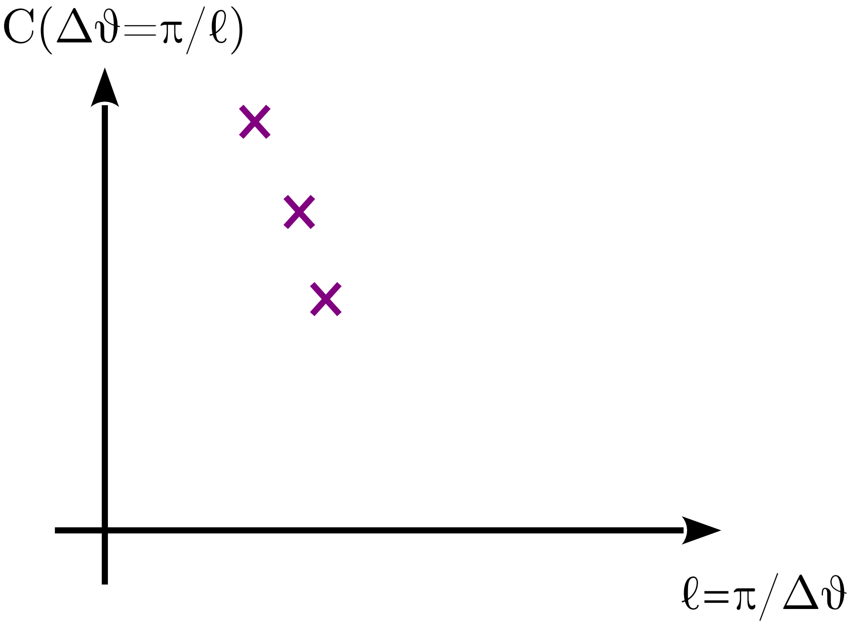
The CMB


92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta\approx 0.6°$

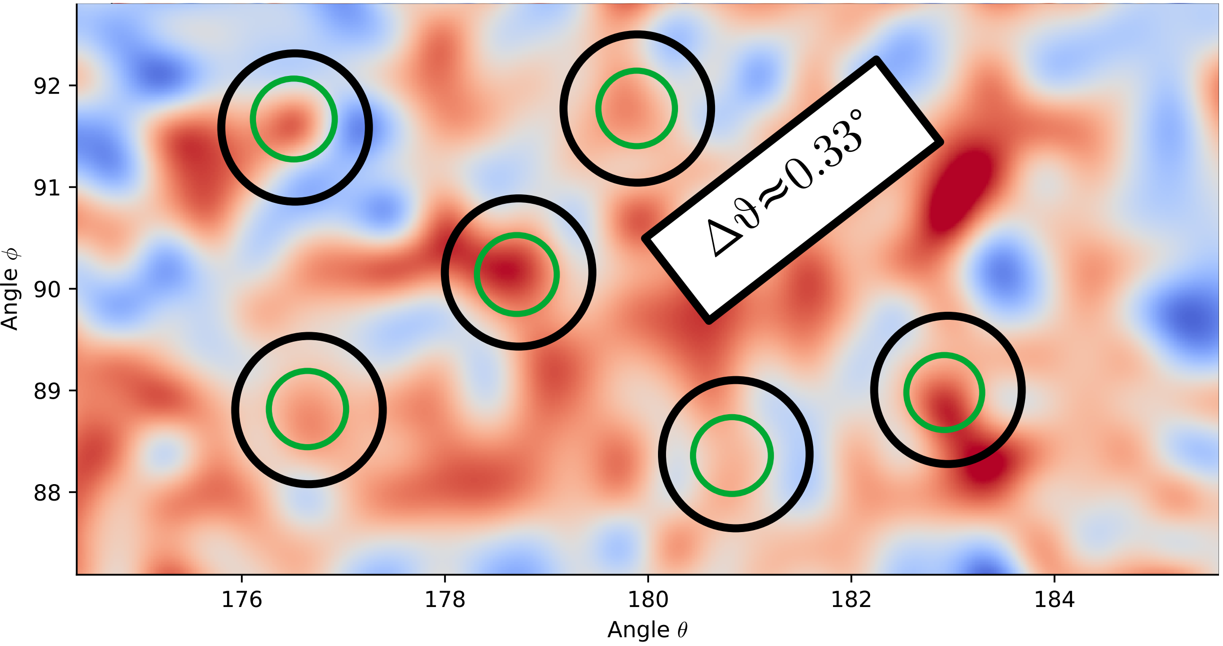

$C(\Delta\vartheta=\pi/\ell)$
$\ell=\pi/\Delta\vartheta$

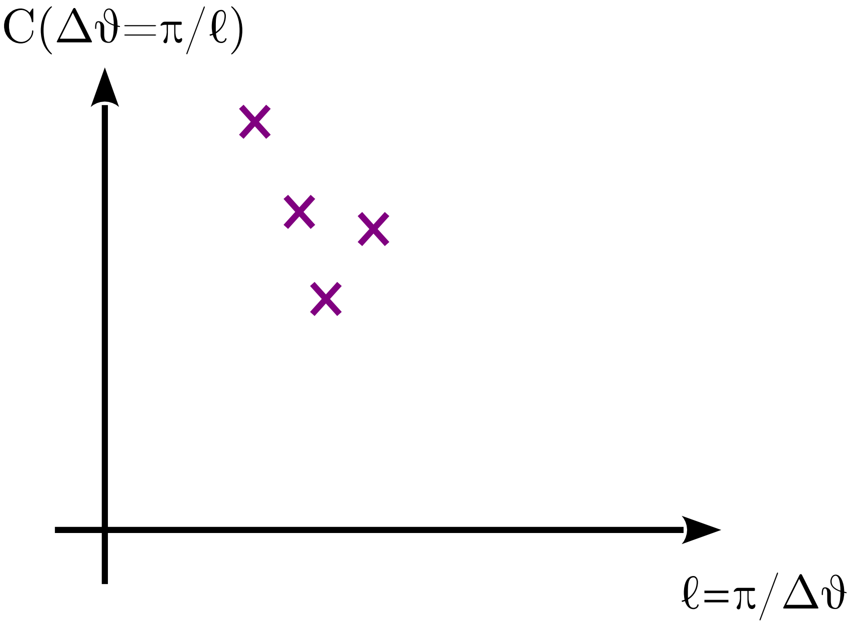
The CMB


$\Delta\vartheta \approx 0.4°$
92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ

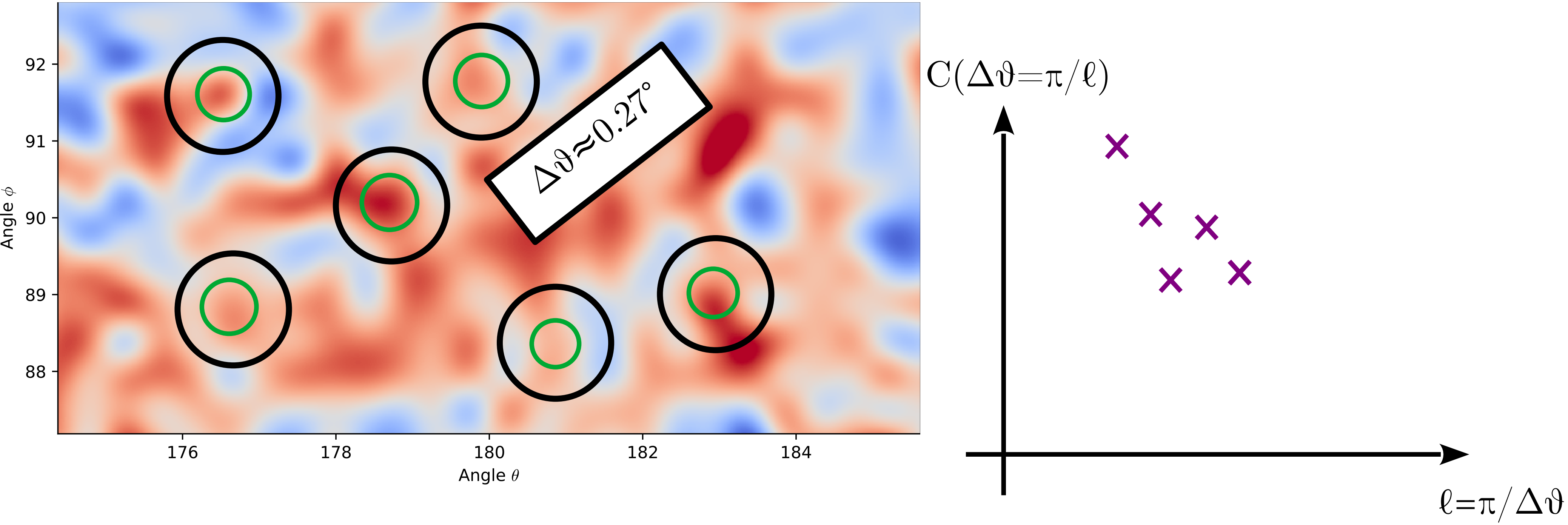

$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

THE CMB

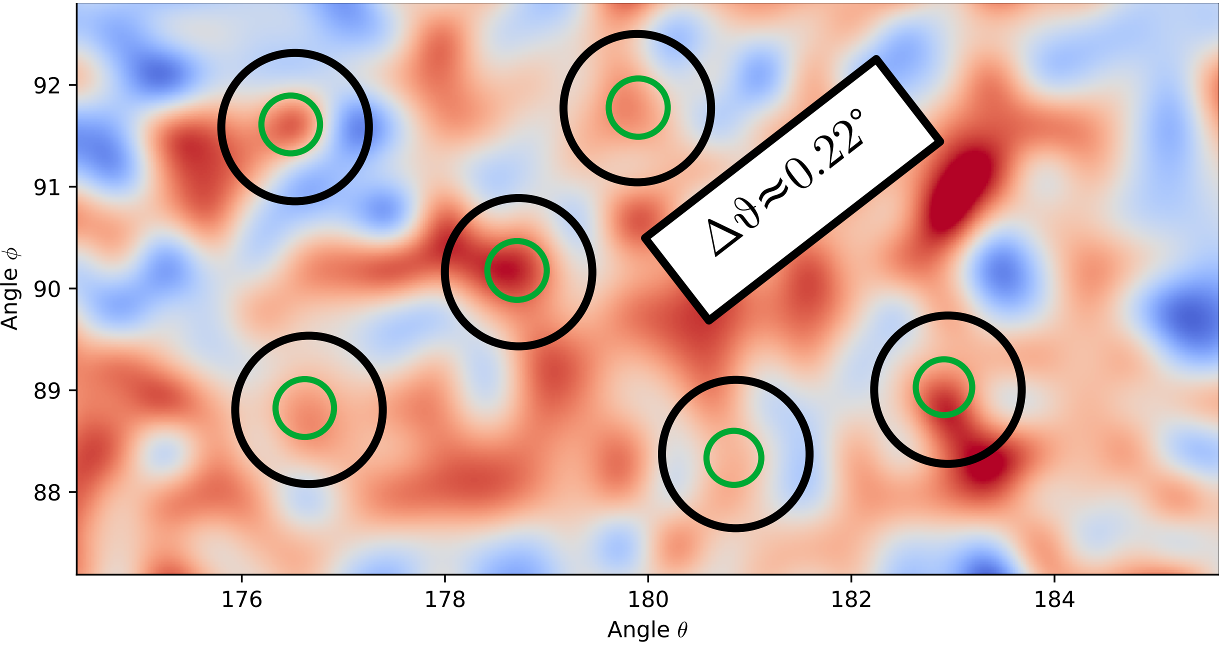

92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.33°$

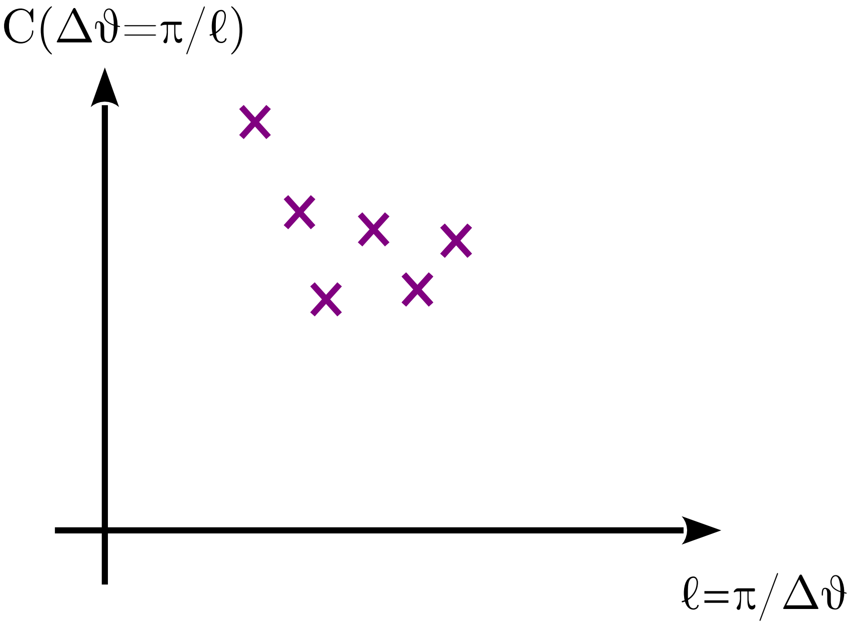

$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

THE CMB

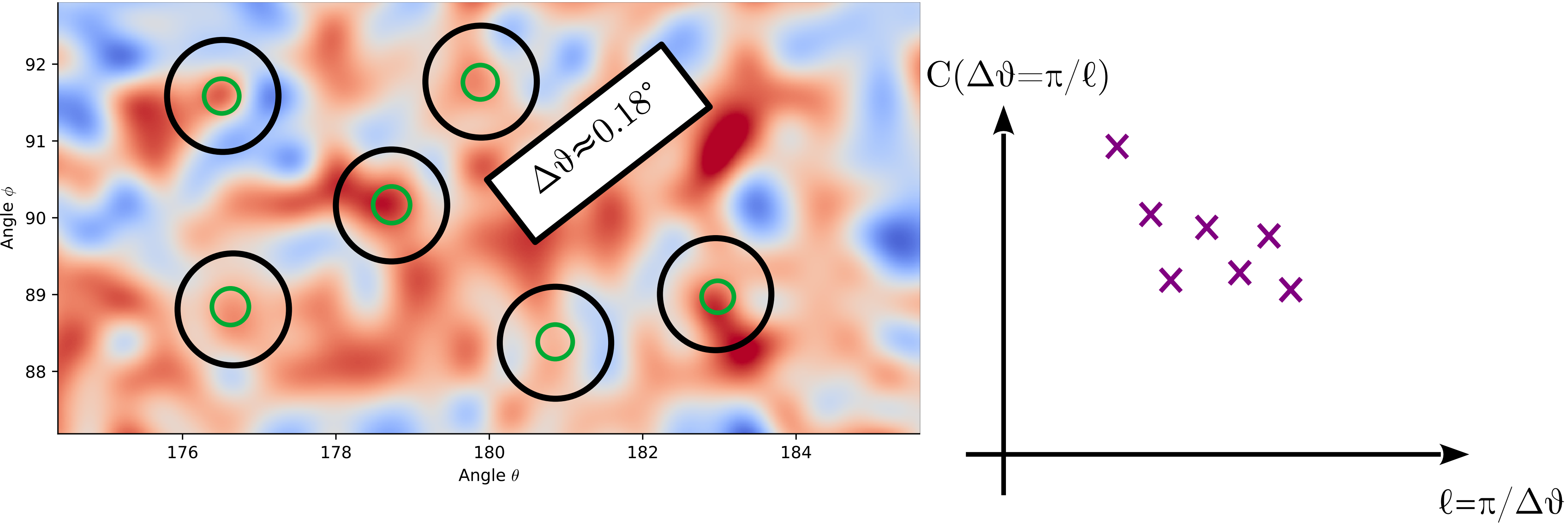

92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.27°$
$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

The CMB

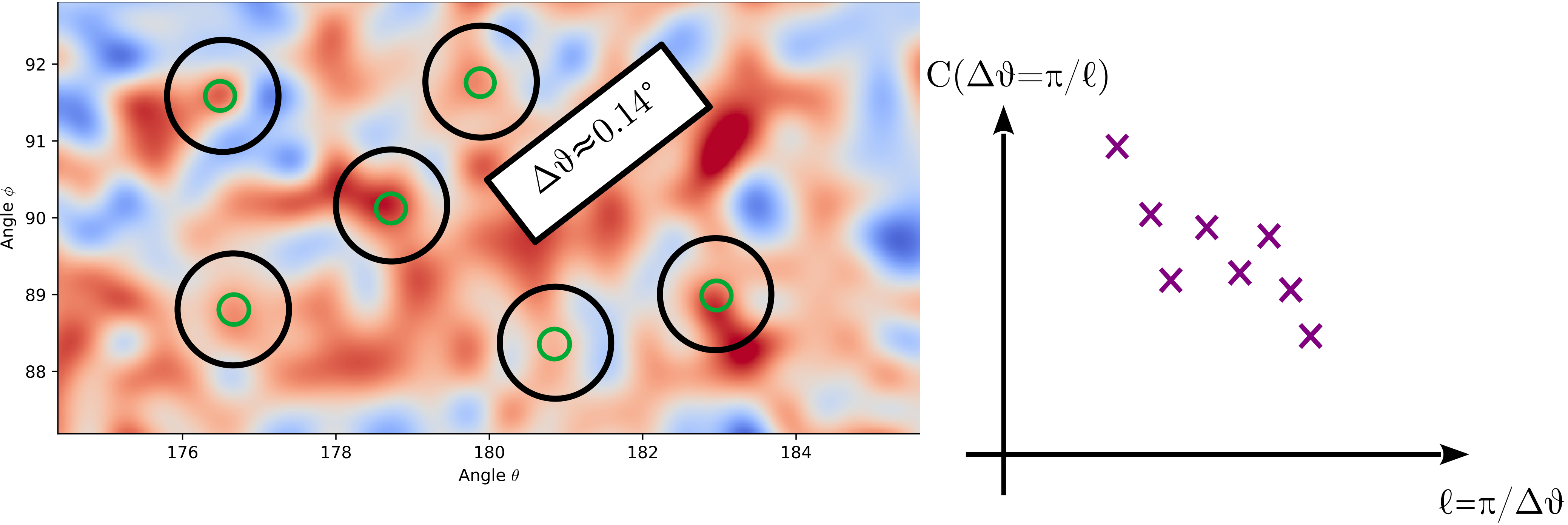

92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.22°$


$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

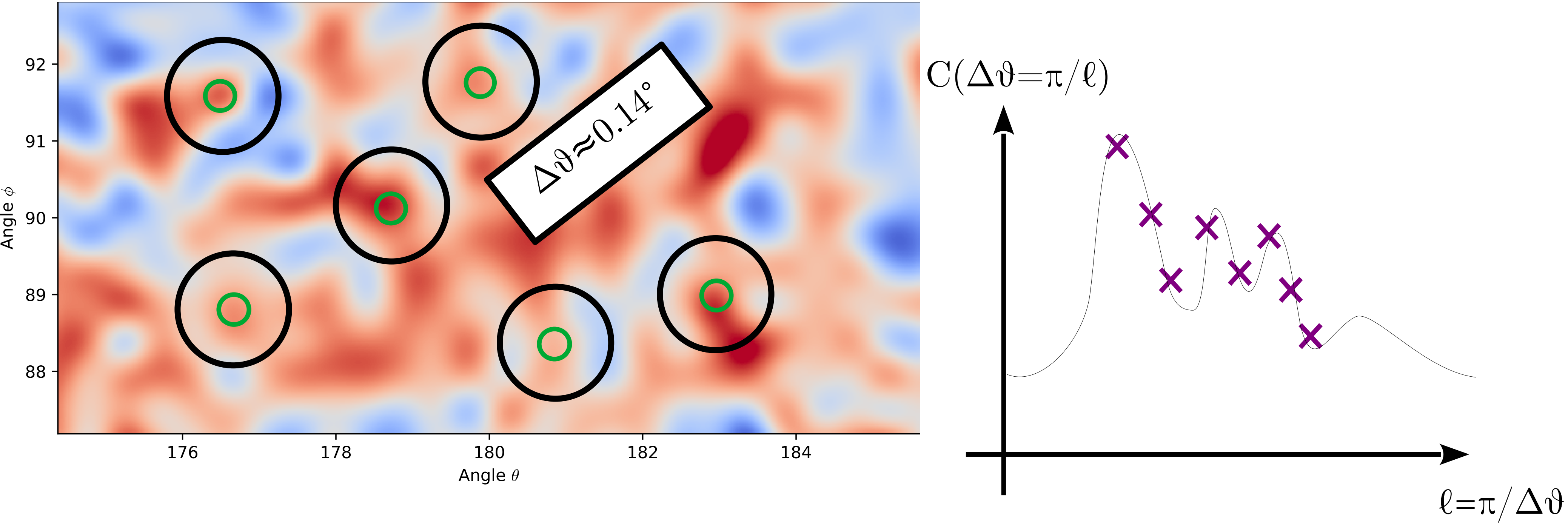
THE CMB


92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.18°$
$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

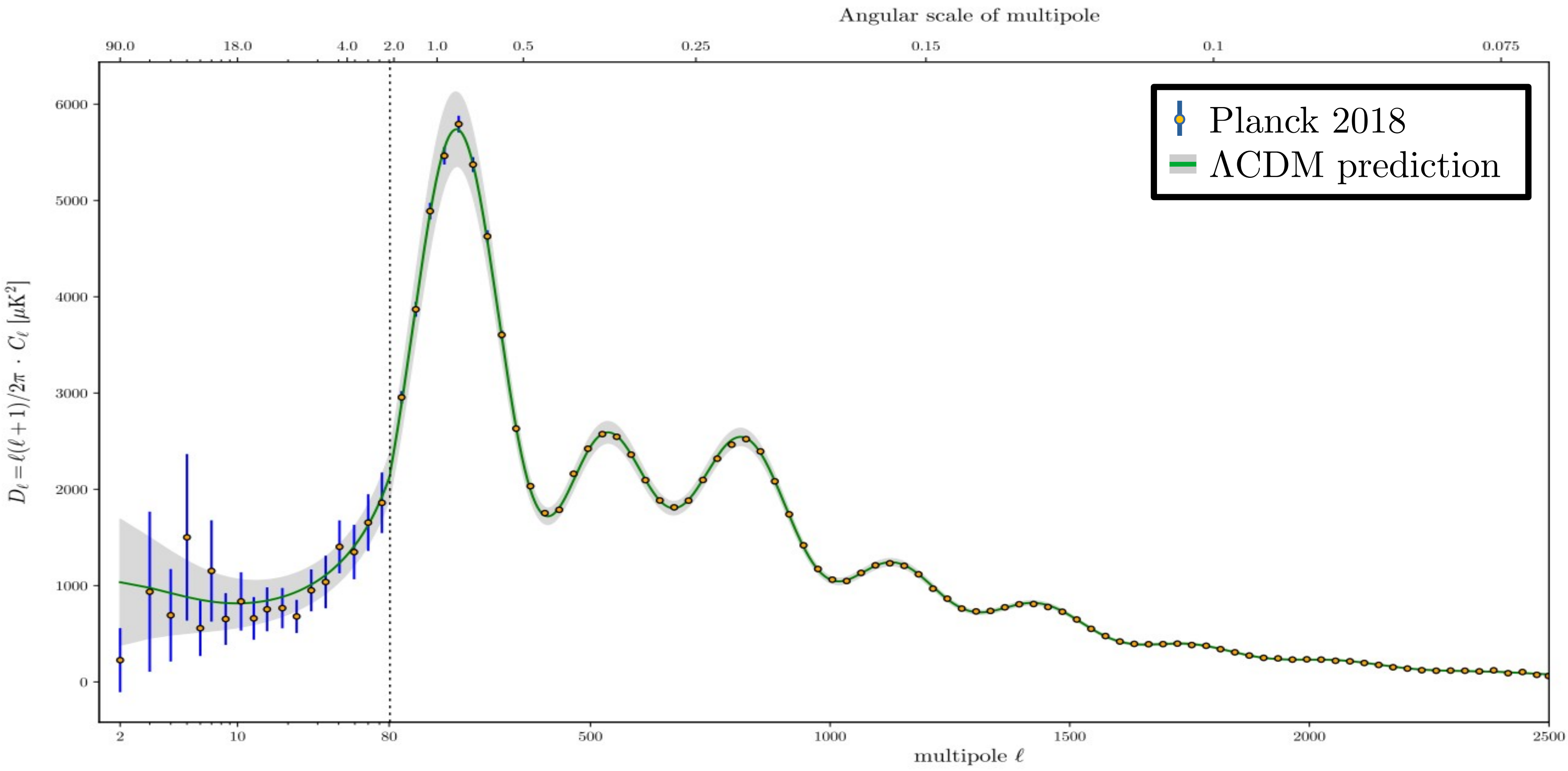
THE CMB


92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.14°$
$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

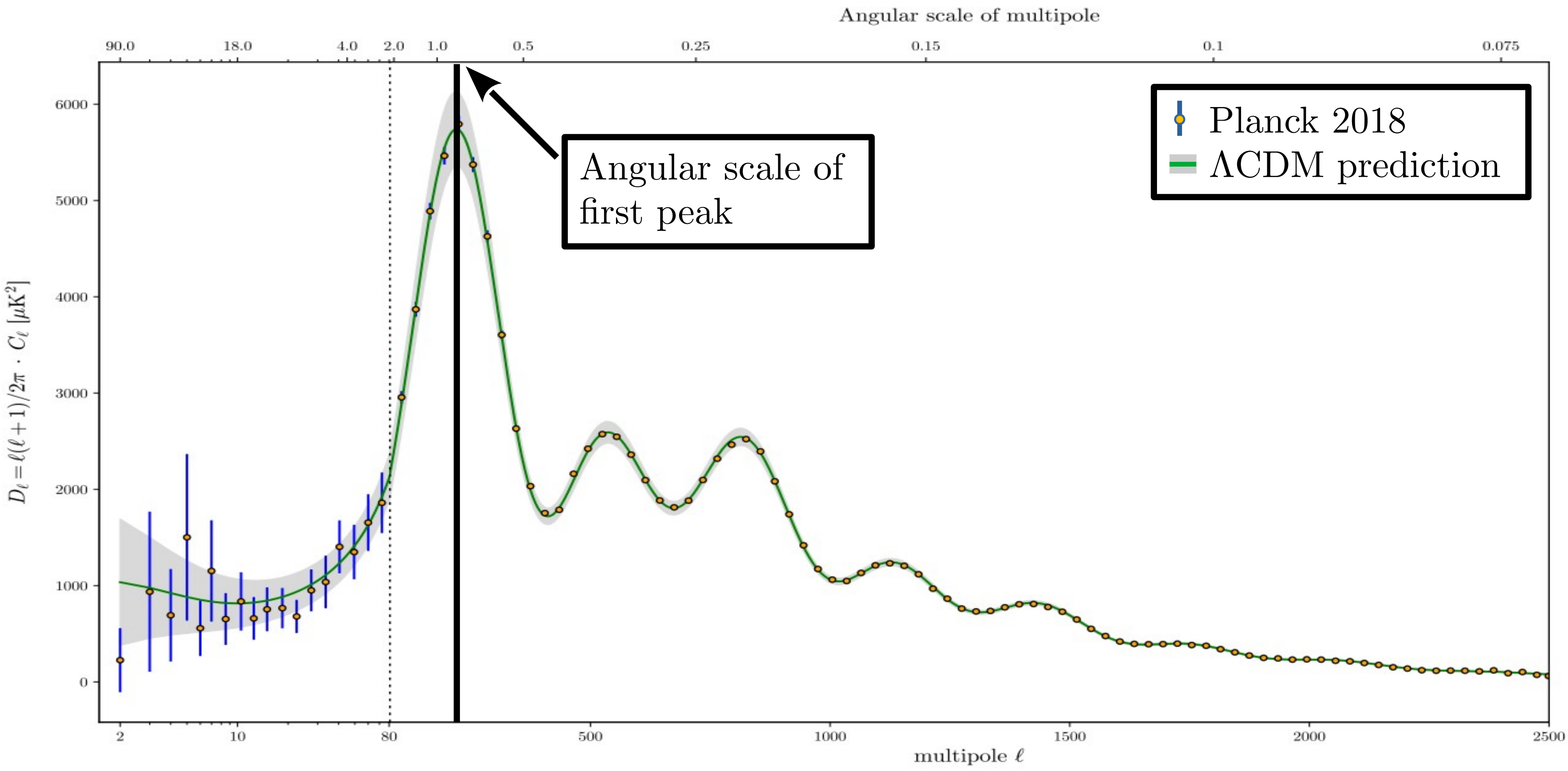
THE CMB


92
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.14°$
$C(\Delta\vartheta = \pi/\ell)$
$\ell = \pi/\Delta\vartheta$

The CMB

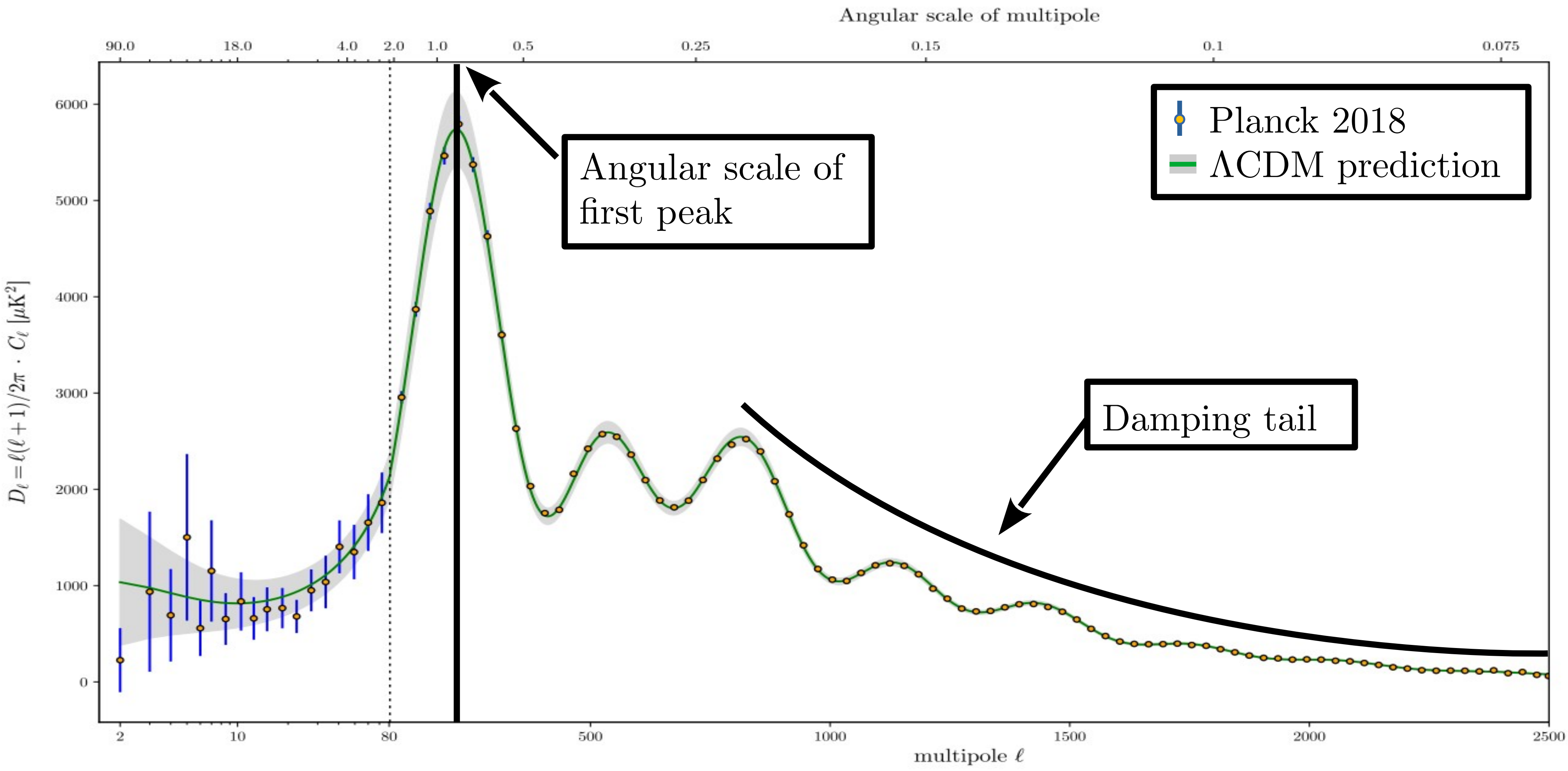

Angular scale of multipole
90.0
18.0
4.0
2.0
1.0
0.5
0.25
0.15
0.1
0.075
Planck 2018
ΛCDM prediction
$D_\ell = \ell(\ell+1)/2\pi \cdot C_\ell\ [\mu K^2]$
6000
5000
4000
3000
2000
1000
0
2
10
80
500
1000
1500
2000
2500
multipole ℓ

The CMB



Angular scale of first peak

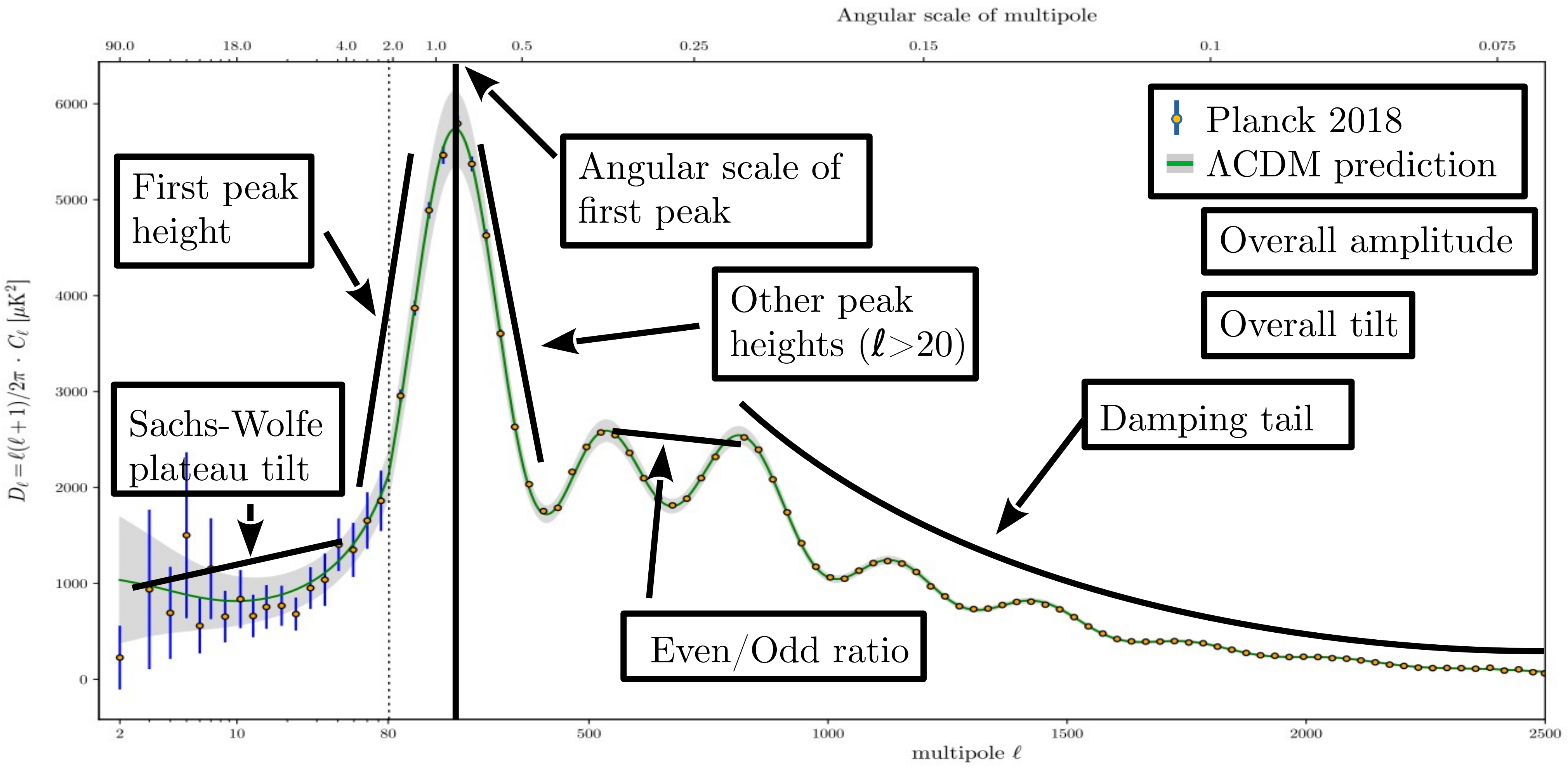
THE CMB



Angular scale of first peak

Damping tail

THE CMB



First peak height

Angular scale of first peak

Overall amplitude

Overall tilt

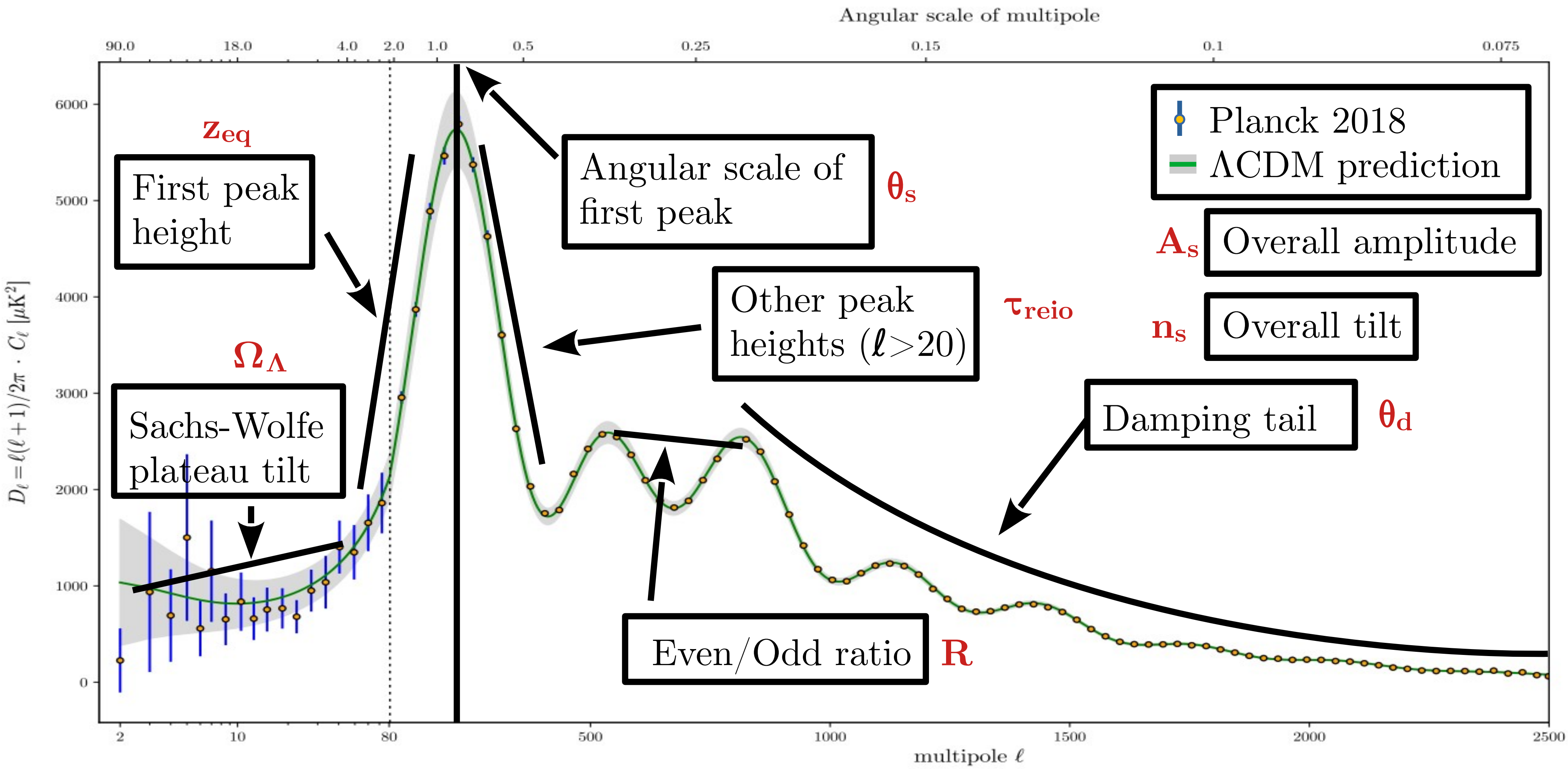
Other peak heights (ℓ>20)

Sachs-Wolfe plateau tilt

Damping tail

Even/Odd ratio

THE CMB



z_{eq}

First peak height

Angular scale of first peak θ_s

A_s Overall amplitude

Other peak heights (ℓ>20) τ_{reio}

n_s Overall tilt

Ω_Λ

Sachs-Wolfe plateau tilt

Damping tail θ_d

Even/Odd ratio **R**

The CMB

$\mathbf{z_{eq}}$

$\boldsymbol{\theta_s}$

$\mathbf{A_s}$

$\boldsymbol{\tau_{reio}}$

$\mathbf{n_s}$

$\boldsymbol{\Omega_\Lambda}$

$\boldsymbol{\theta_d}$

$\mathbf{R}$

The CMB

$\mathbf{z_{eq}}$

$\mathbf{\Omega_\Lambda}$

$\mathbf{\theta_s}$

$\mathbf{R}$

$\mathbf{\theta_d}$

$\mathbf{A_s}$

$\mathbf{n_s}$

$\mathbf{\tau_{reio}}$

The CMB

$\mathbf{z_{eq}}$

$\mathbf{\Omega_\Lambda}$

$\boldsymbol{\theta_s}$

$\mathbf{R}$

$\boldsymbol{\theta_d}$

$\mathbf{A_s}$

$\mathbf{n_s}$

$\boldsymbol{\tau_{reio}}$

Primordial information
+ Reionization

THE CMB

z_{eq} → $\omega_m/\omega_r \to \Omega_m h^2$

Ω_Λ → $\Omega_\Lambda \to \Omega_m$

θ_s → $r_s/D_A(z_*) \to \Omega_m h^3, \Omega_b h^2$

R → $\omega_b/\omega_\gamma \to \Omega_b h^2$

θ_d → $r_{\mathrm{silk}}/D_A(z_*) \to \Omega_m h^{3.4}, \Omega_b h^2$

A_s

n_s

τ_{reio}

Primordial information
+ Reionization

THE CMB

z_{eq} → $\omega_m/\omega_r \to \Omega_m h^2$

Ω_Λ → $\Omega_\Lambda \to \Omega_m$

θ_s → $r_s/D_A(z_*) \to \Omega_m h^3, \Omega_b h^2$

R → $\omega_b/\omega_\gamma \to \Omega_b h^2$

θ_d → $r_{\text{silk}}/D_A(z_*) \to \Omega_m h^{3.4}, \Omega_b h^2$

A_s
n_s
τ_{reio}

Primordial information
+ Reionization

THE CMB

$\mathbf{z_{eq}} \longrightarrow \omega_m/\omega_r \to \boxed{\Omega_m} h^2$

$\mathbf{\Omega_\Lambda} \longrightarrow \Omega_\Lambda \to \boxed{\Omega_m}$

$\mathbf{\theta_s} \longrightarrow r_s/D_A(z_*) \to \boxed{\Omega_m} h^3, \Omega_b h^2$

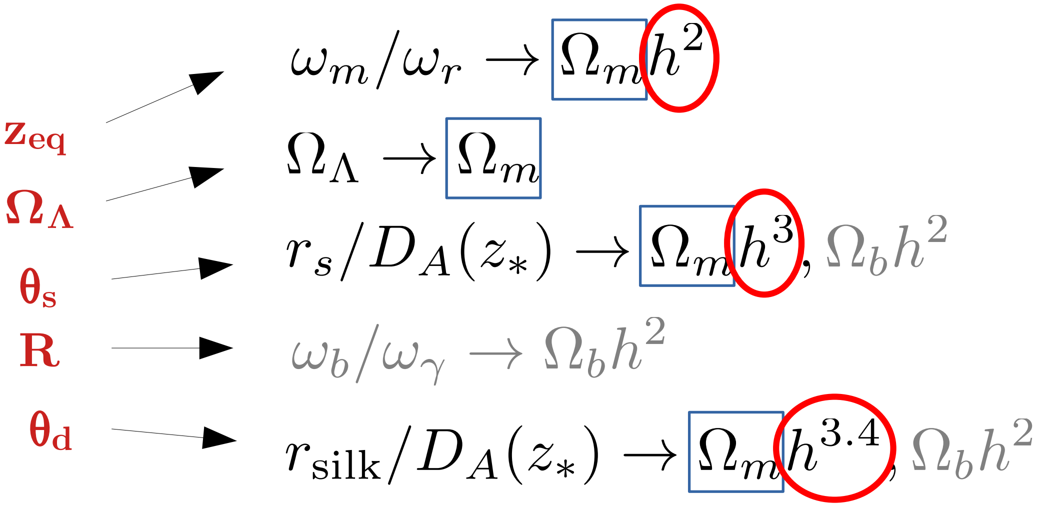
$\mathbf{R} \longrightarrow \omega_b/\omega_\gamma \to \Omega_b h^2$

$\mathbf{\theta_d} \longrightarrow r_{\rm silk}/D_A(z_*) \to \boxed{\Omega_m} h^{3.4}, \Omega_b h^2$

$\mathbf{A_s}$
$\mathbf{n_s}$
$\mathbf{\tau_{reio}}$

Primordial information
+ Reionization

THE CMB



z_{eq} → $\omega_m/\omega_r \rightarrow \boxed{\Omega_m} h^2$

Ω_Λ → $\Omega_\Lambda \rightarrow \boxed{\Omega_m}$

θ_s → $r_s/D_A(z_*) \rightarrow \boxed{\Omega_m} h^3, \Omega_b h^2$ [0.03% precision]

R → $\omega_b/\omega_\gamma \rightarrow \Omega_b h^2$

θ_d → $r_{\rm silk}/D_A(z_*) \rightarrow \boxed{\Omega_m} h^{3.4}, \Omega_b h^2$

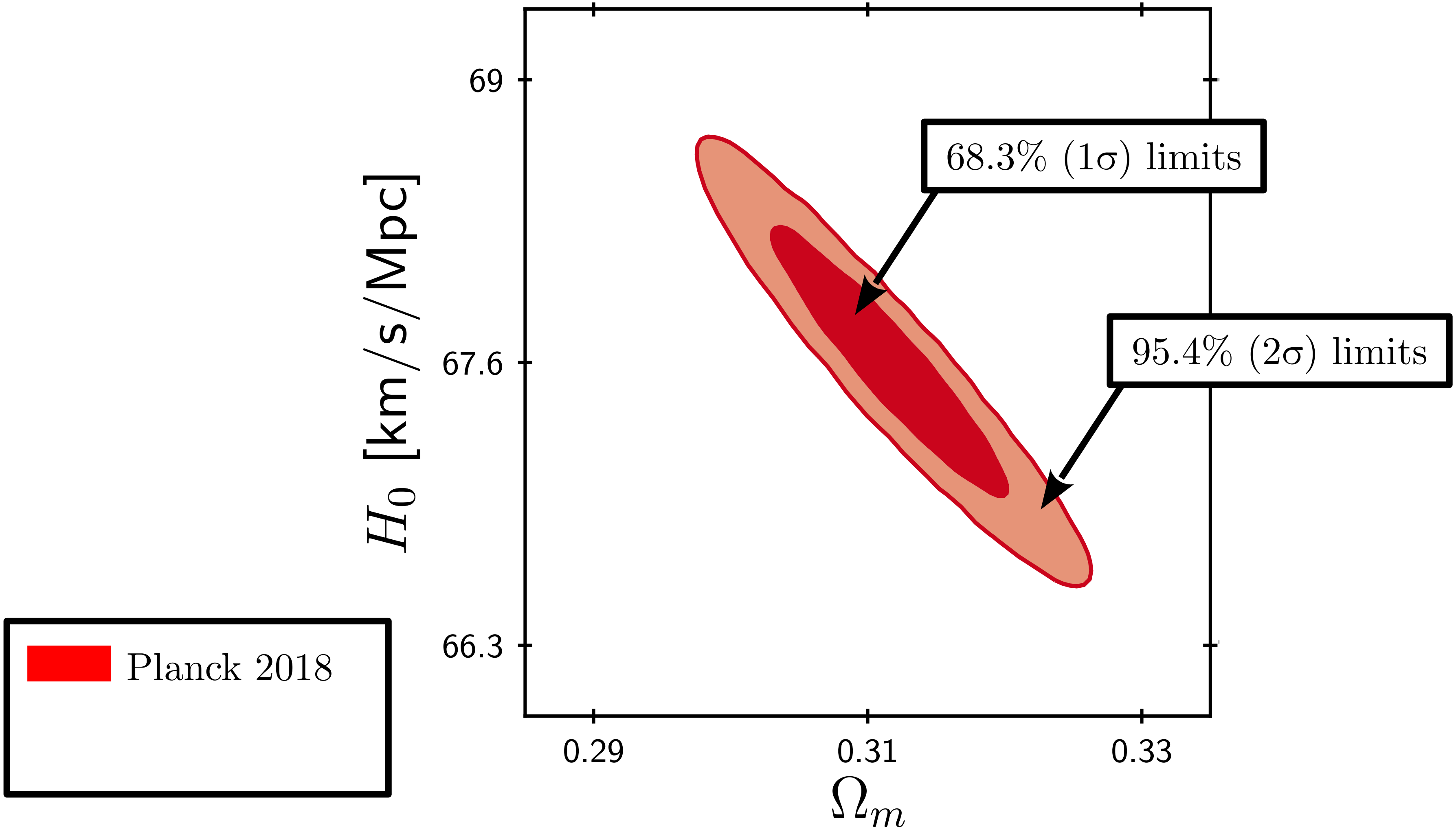
A_s

n_s

τ_{reio}

Primordial information
+ Reionization

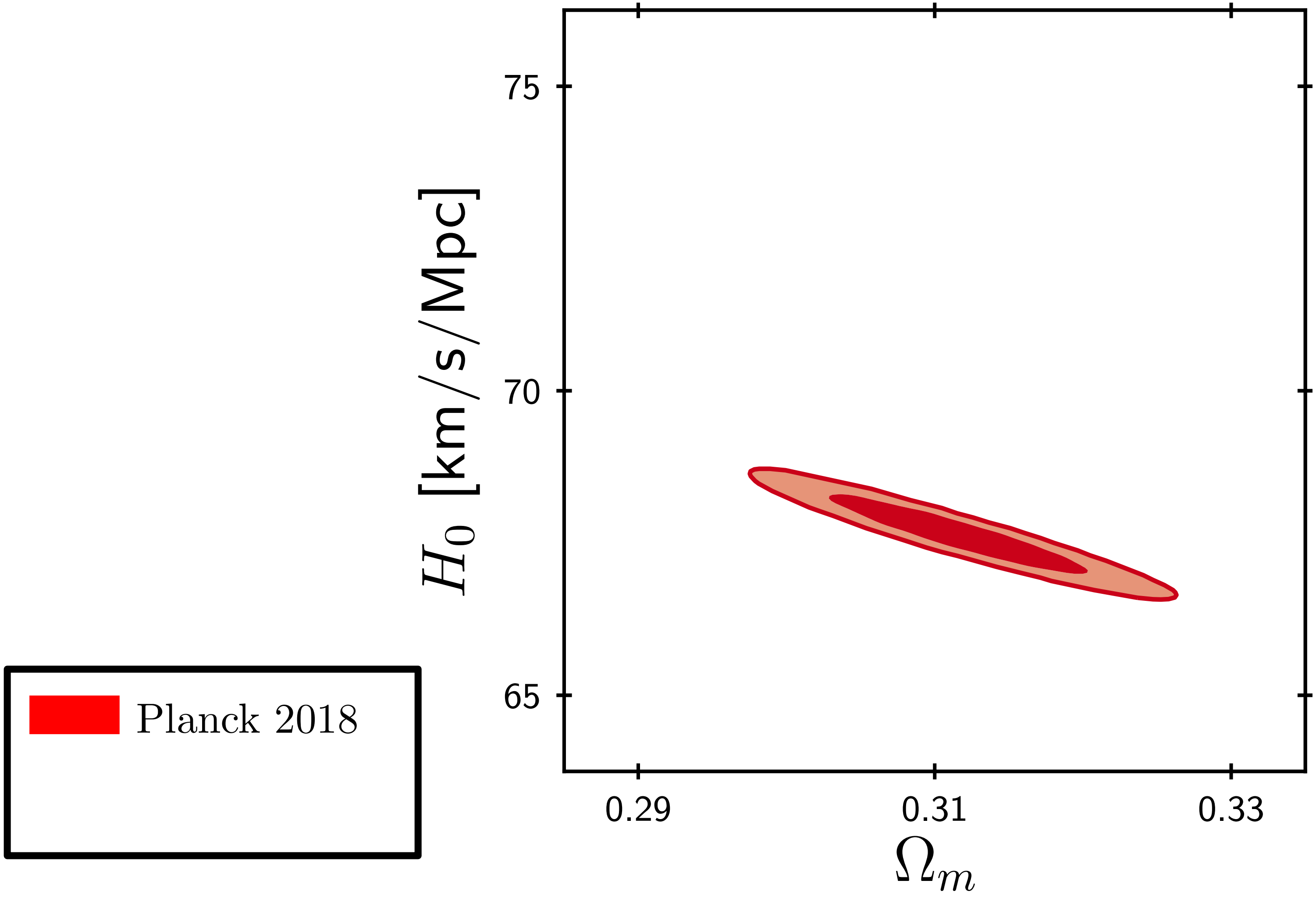
THE CMB



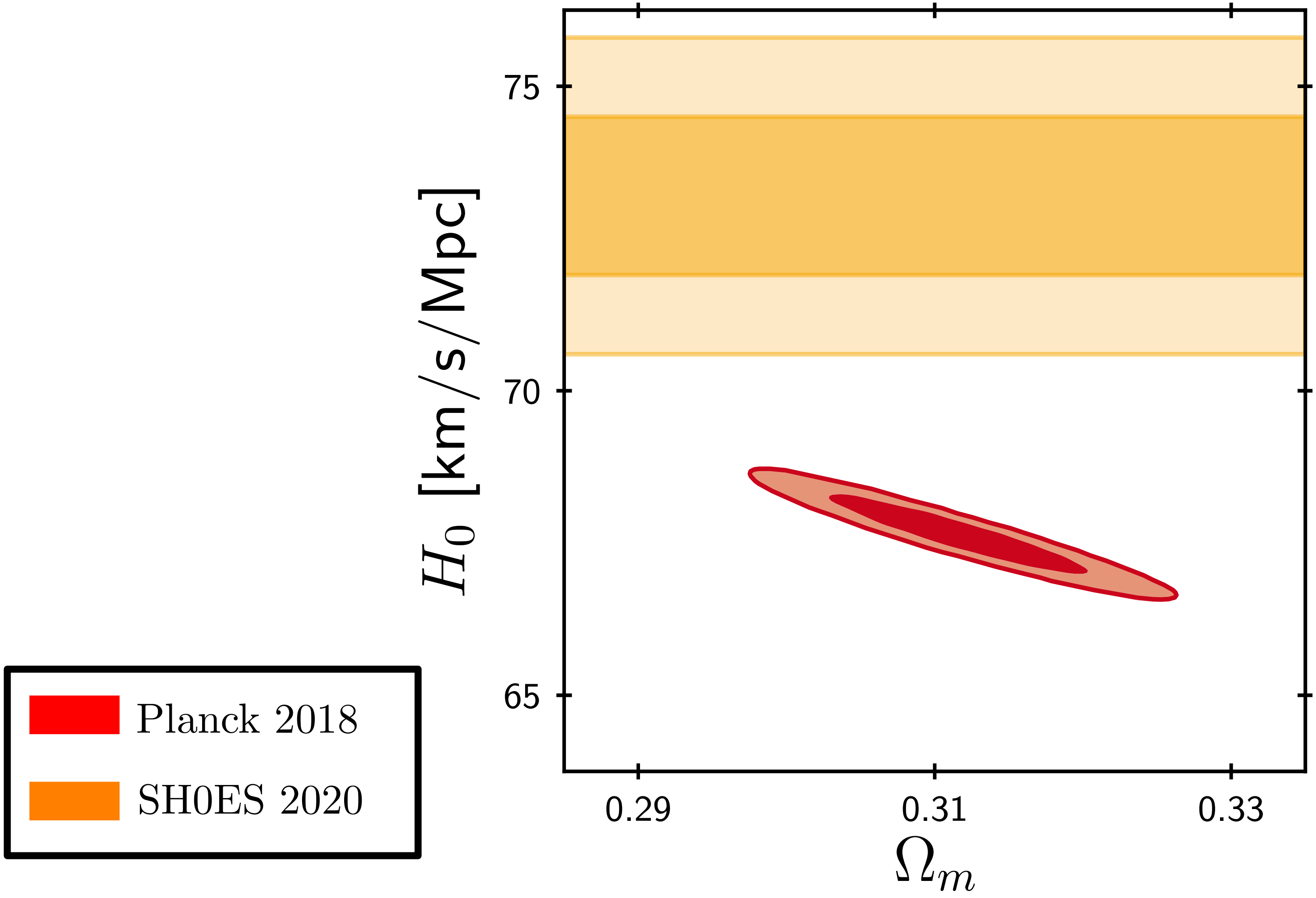
68.3% (1σ) limits

95.4% (2σ) limits

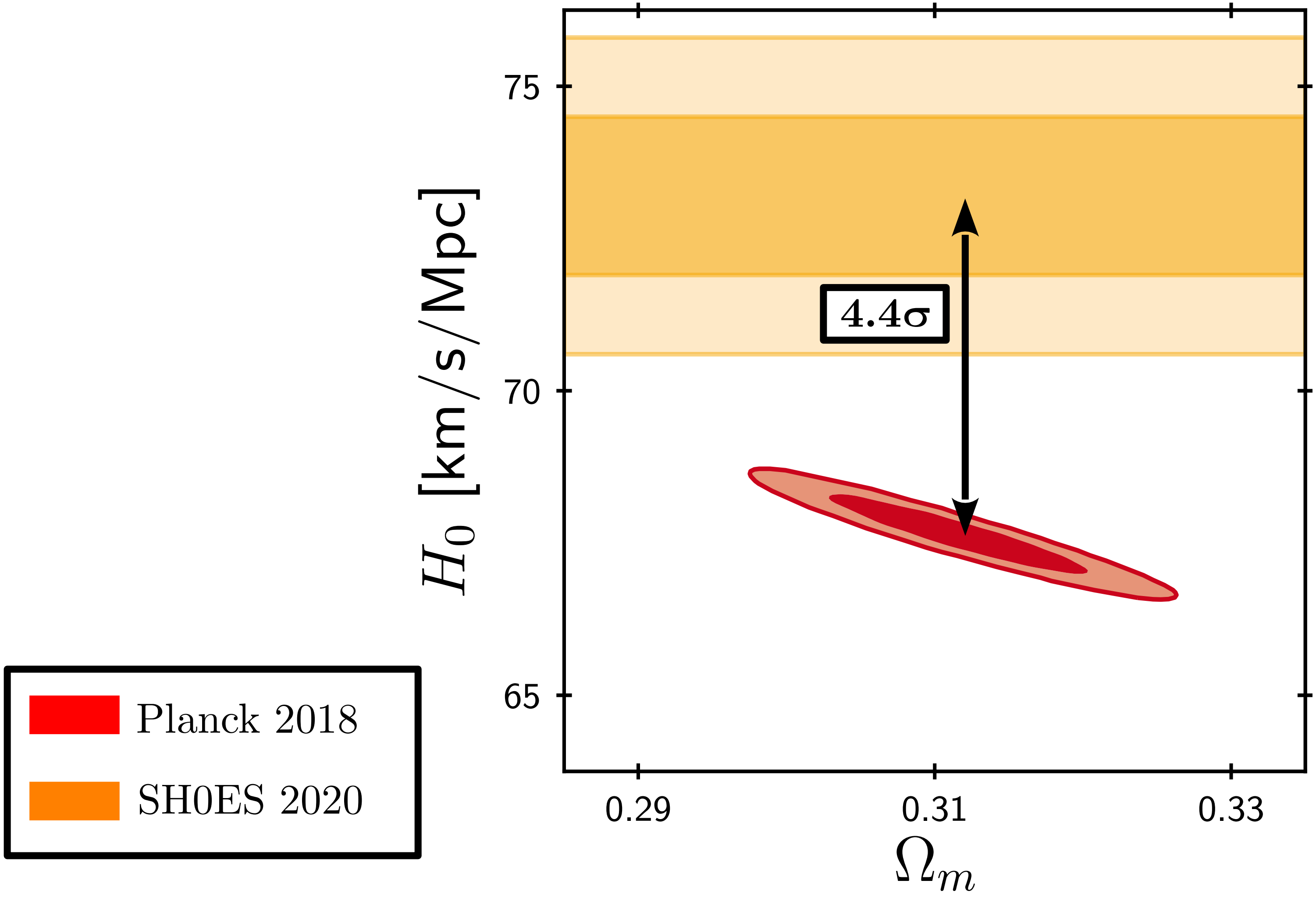
The Hubble Tension



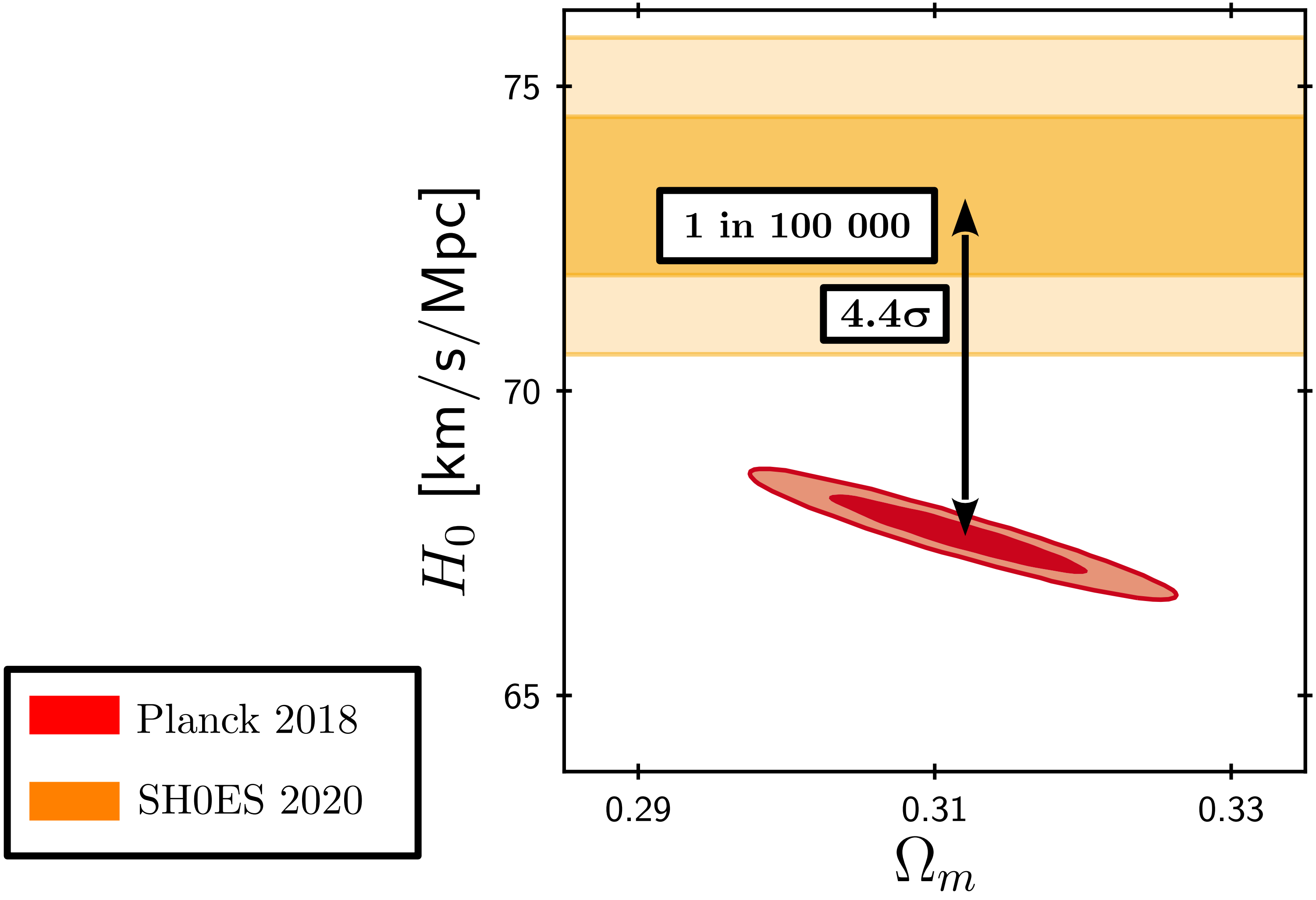
THE HUBBLE TENSION



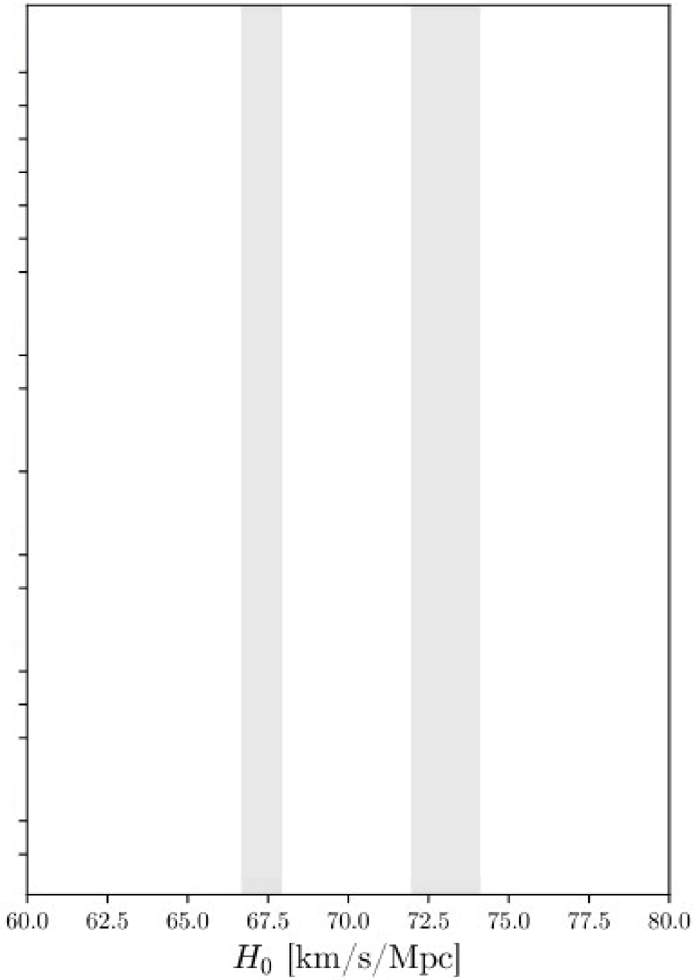
THE HUBBLE TENSION



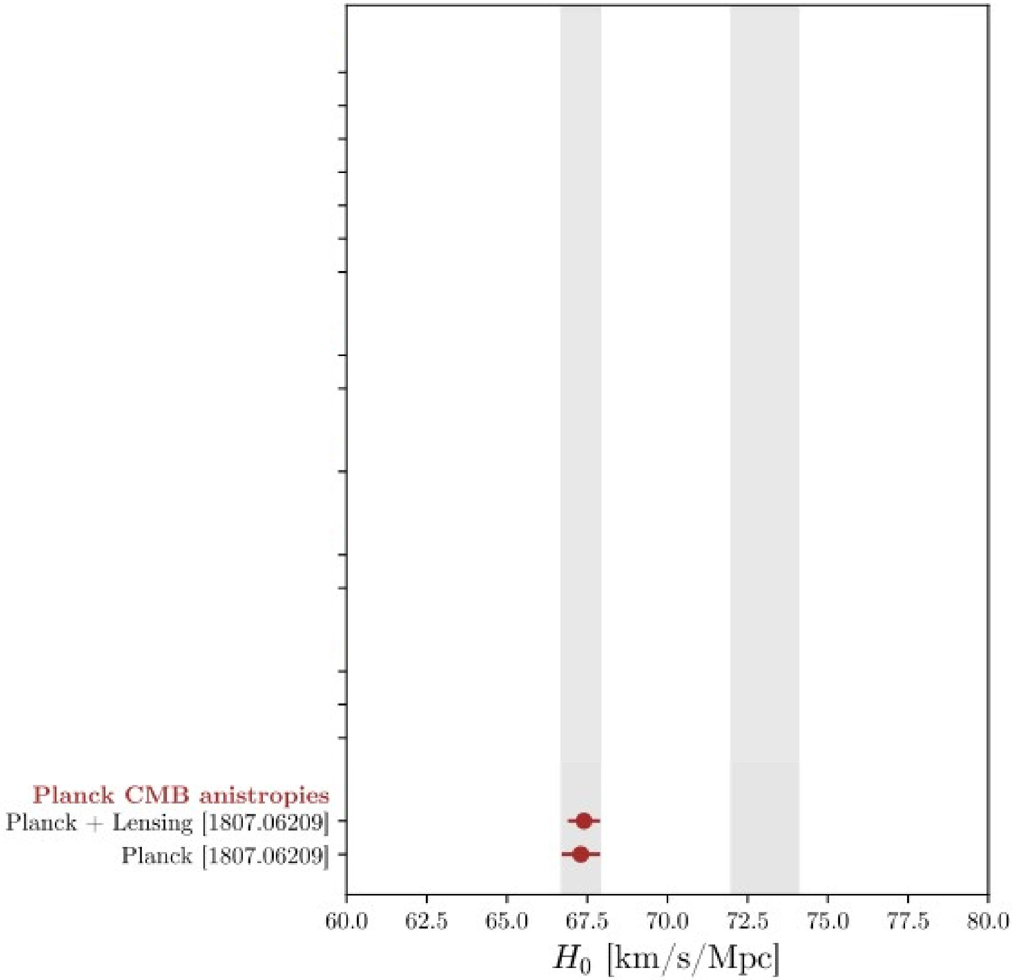
THE HUBBLE TENSION



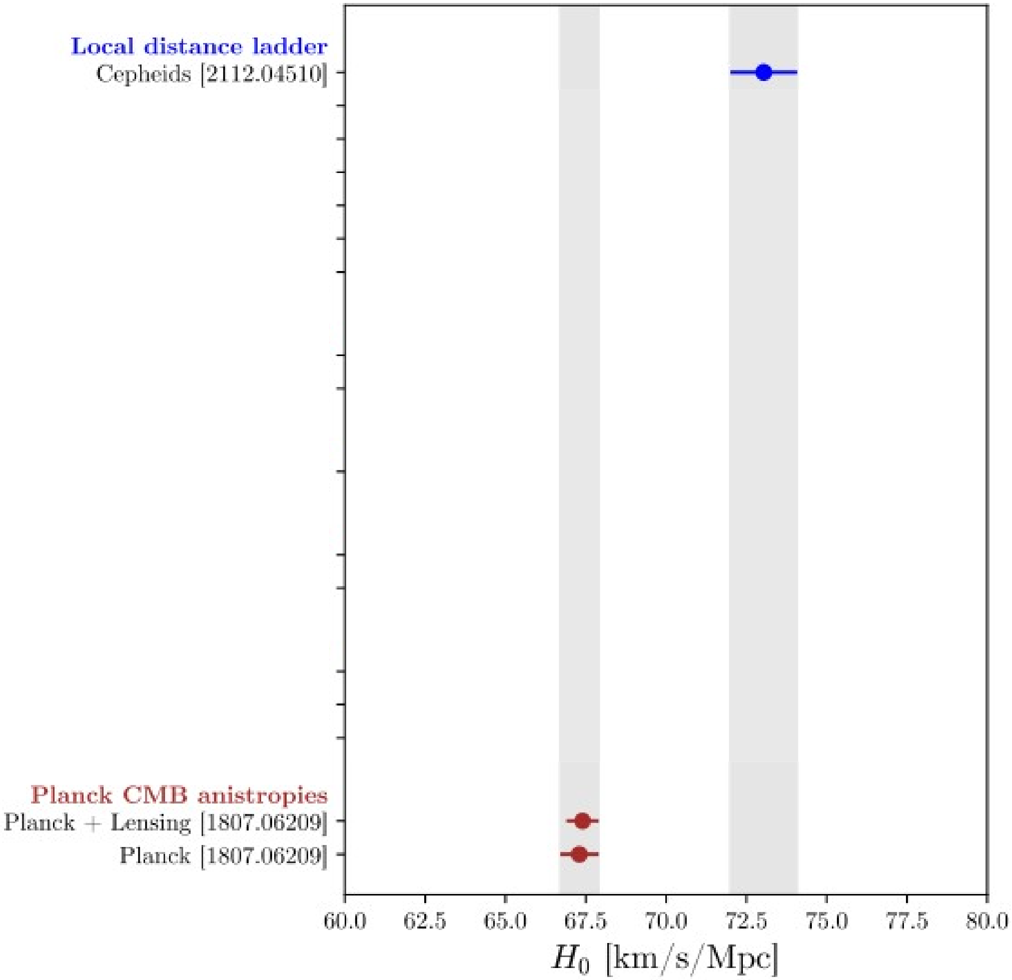
ALTERNATIVE PROBES OF HUBBLE



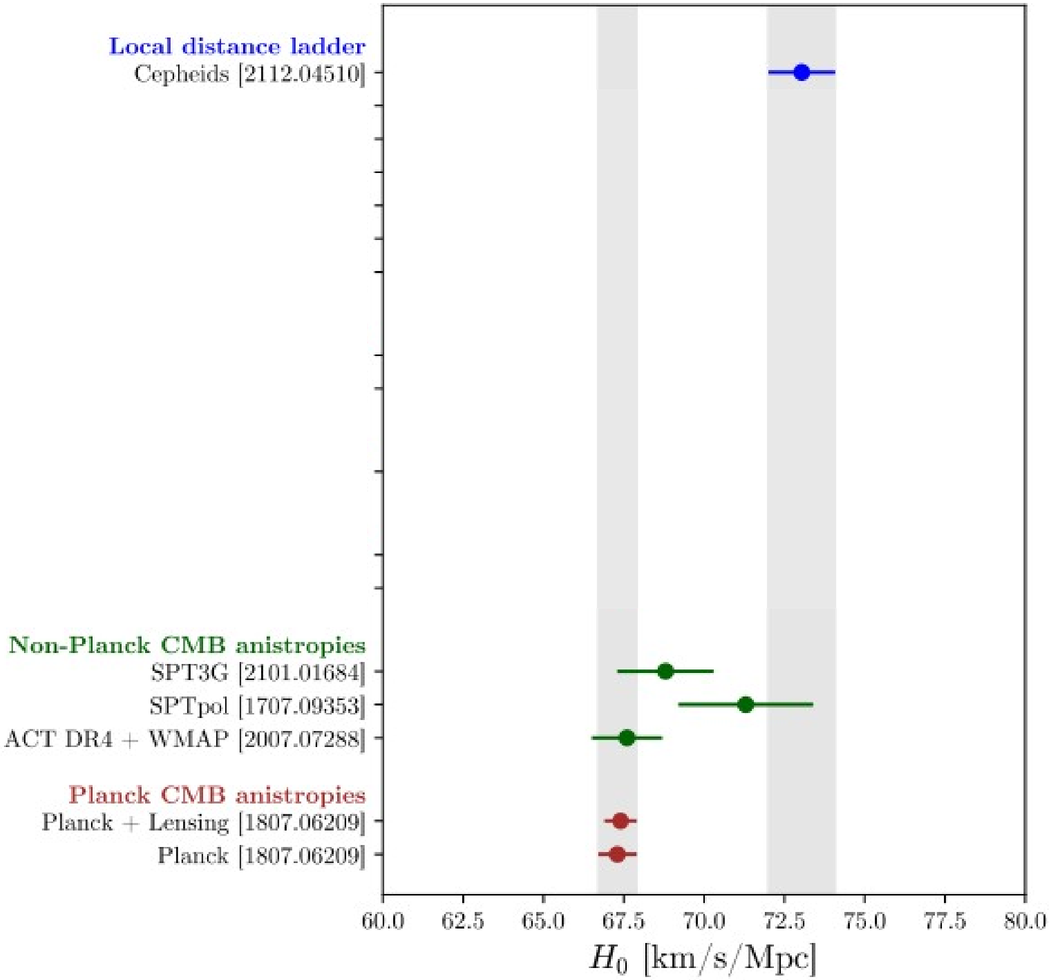
ALTERNATIVE PROBES OF HUBBLE



ALTERNATIVE PROBES OF HUBBLE

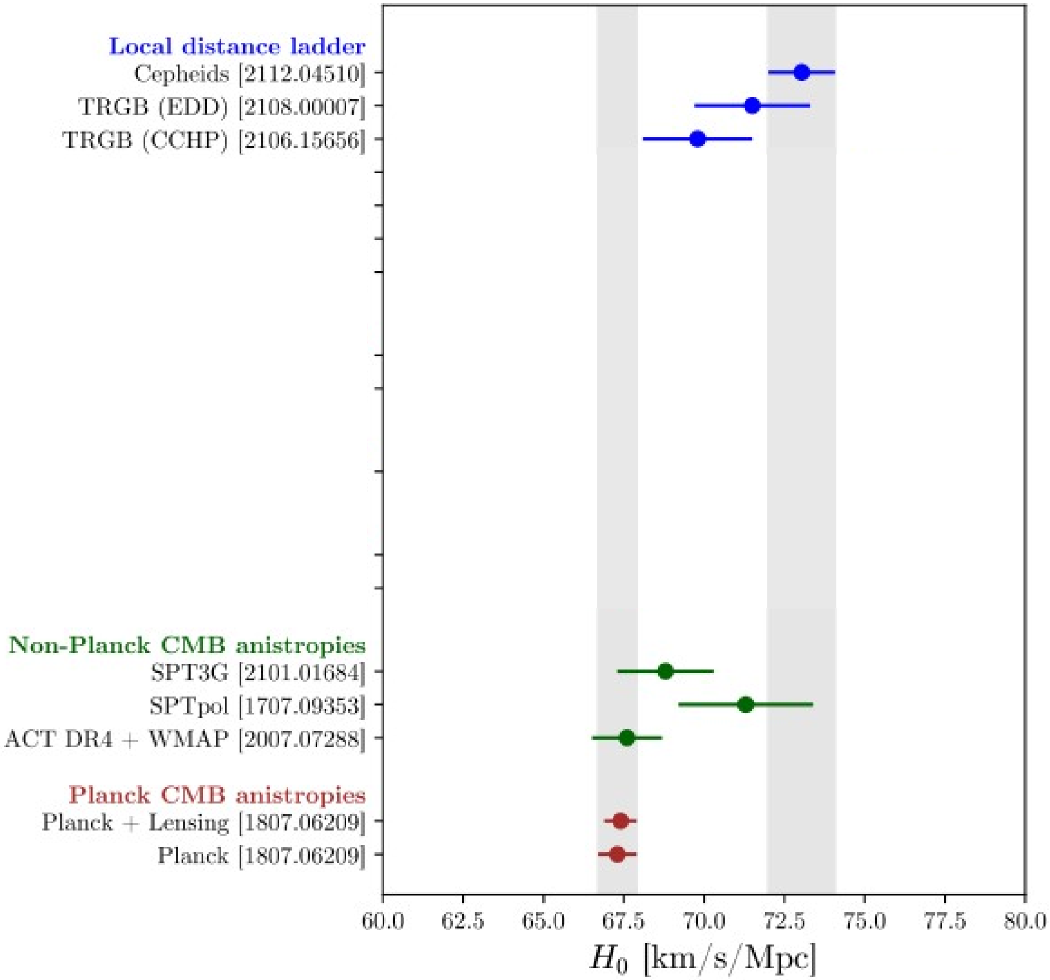


ALTERNATIVE PROBES OF HUBBLE



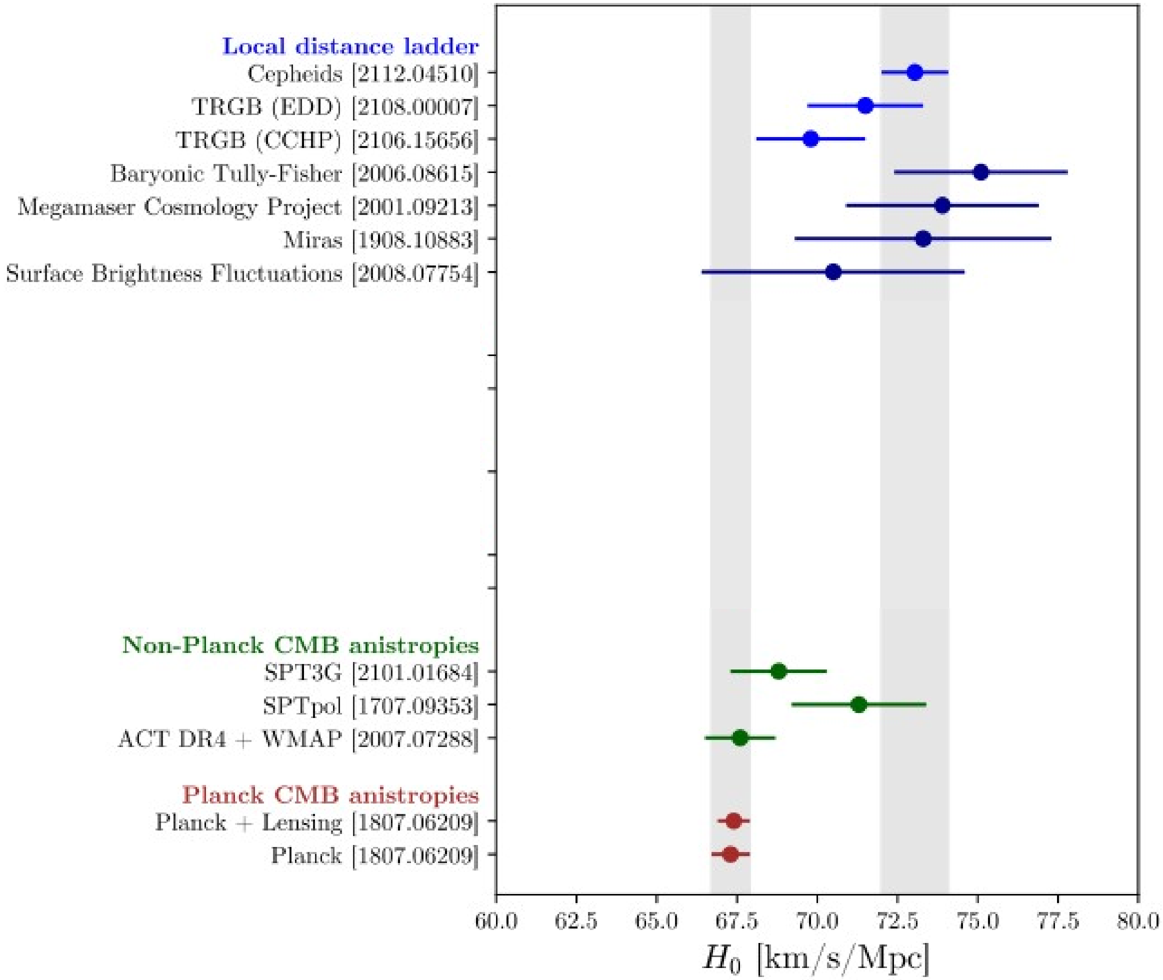
- CMB similar

ALTERNATIVE PROBES OF HUBBLE



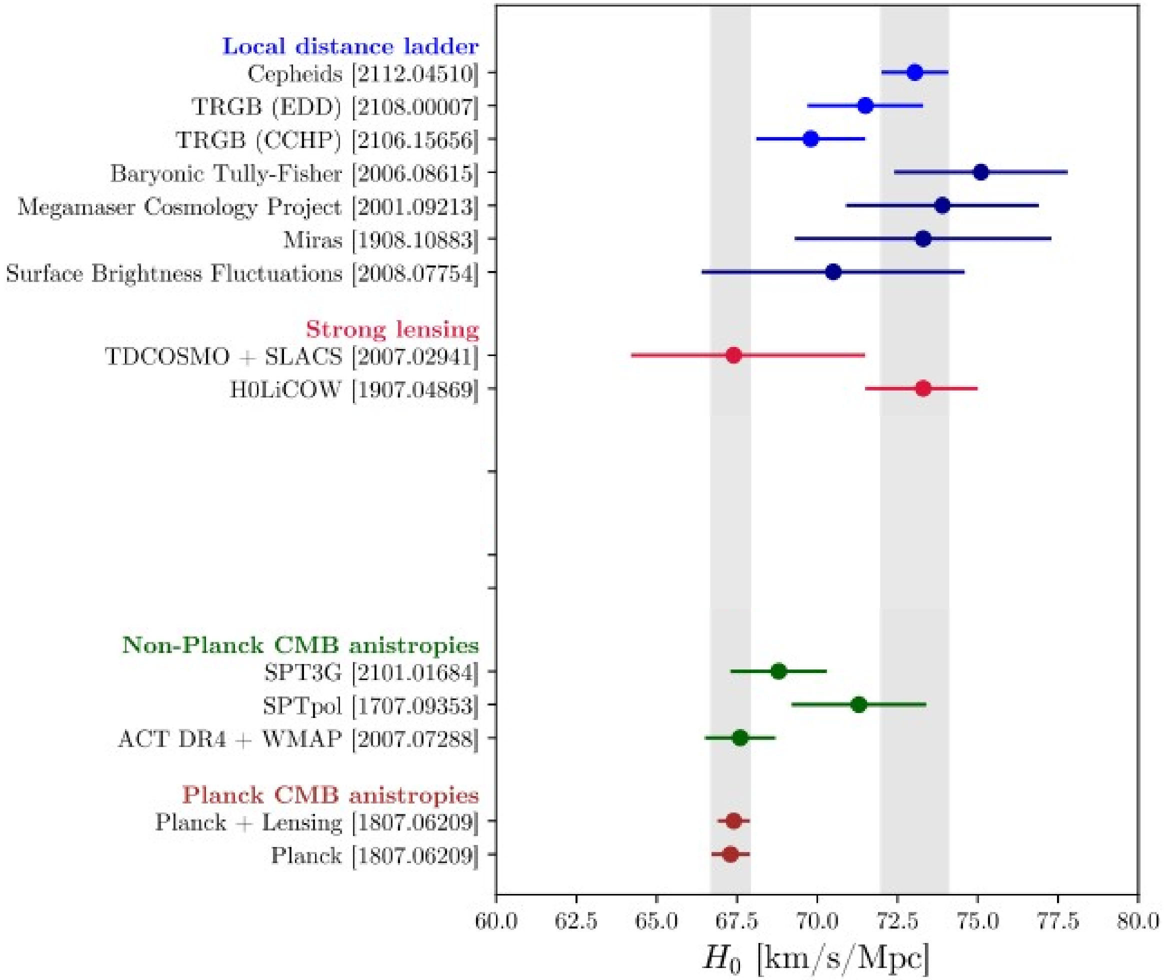
- CMB similar
- Distance ladder consistent (up to CCHP TRGB)

ALTERNATIVE PROBES OF HUBBLE



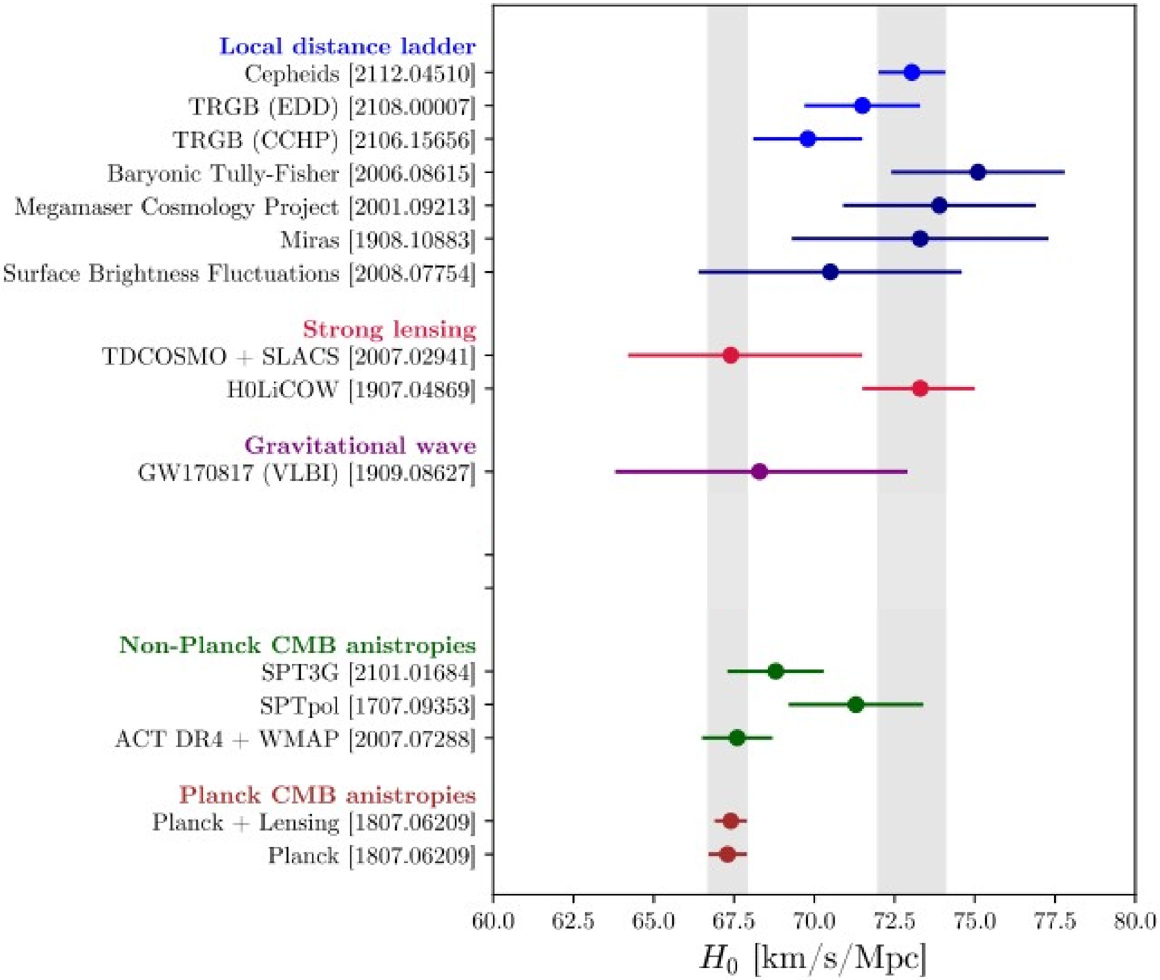
- CMB similar
- Distance ladder consistent (up to CCHP TRGB)
- Other standard candles agree

ALTERNATIVE PROBES OF HUBBLE



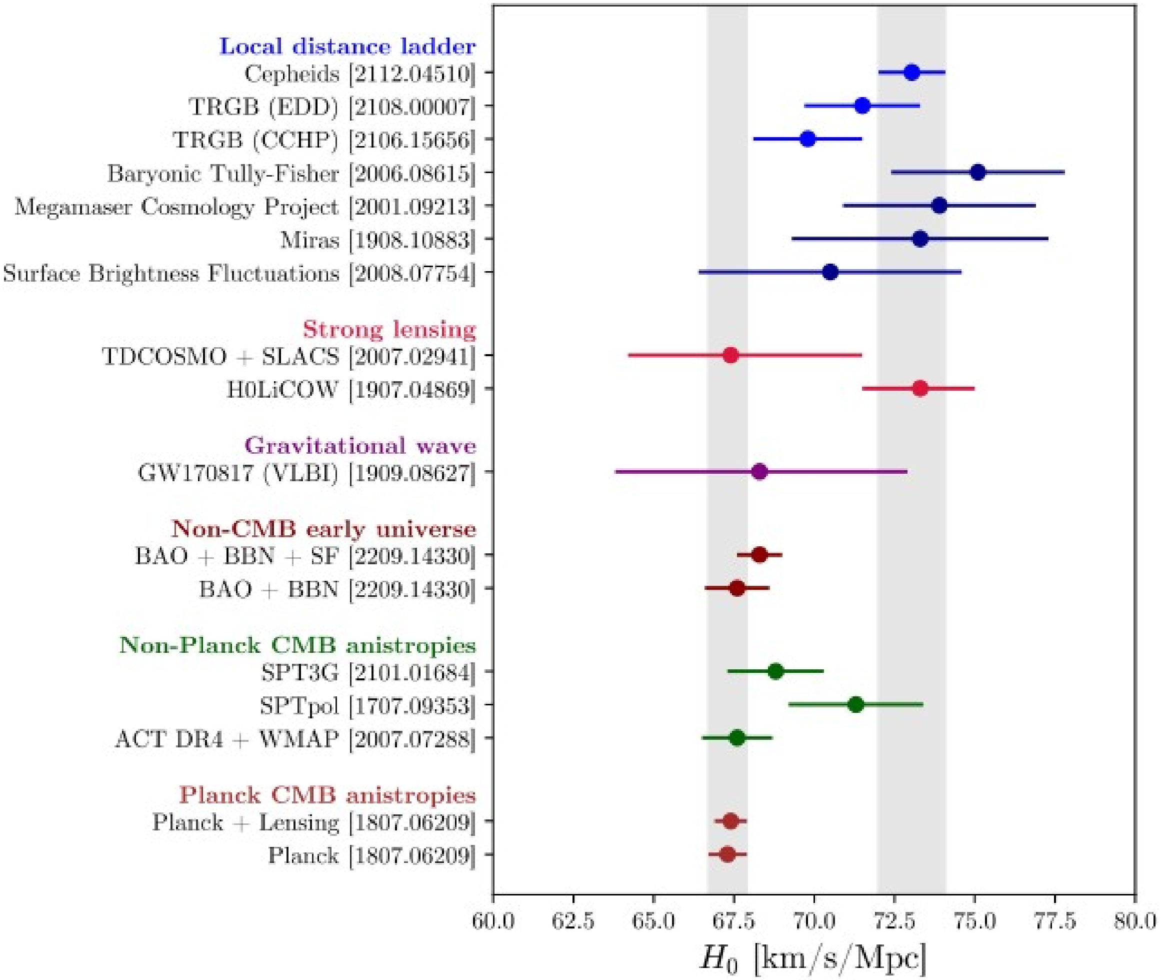
- CMB similar
- Distance ladder consistent (up to CCHP TRGB)
- Other standard candles agree
- Strong lensing disputed, but points high Hubble

ALTERNATIVE PROBES OF HUBBLE



- CMB similar
- Distance ladder consistent (up to CCHP TRGB)
- Other standard candles agree
- Strong lensing disputed, but points high Hubble
- GW not yet enough precision

ALTERNATIVE PROBES OF HUBBLE



- CMB similar
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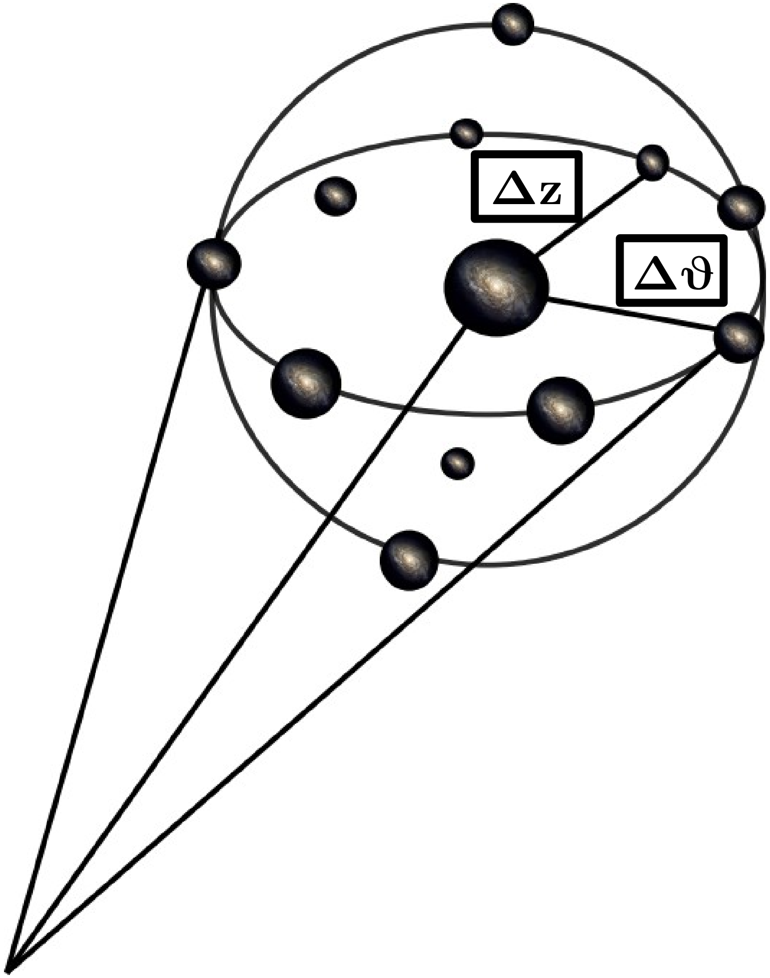
TOPICS

- Quick motivation
- The BAO principle
- The BBN principle
- Why do BAO+BBN combine so well?
- What aids this probe?
- What breaks this probe?

BAO AND THE SOUND HORIZON

GENERAL IDEA:

1) BAO determines Ω_m and $H_0 \, r_s$

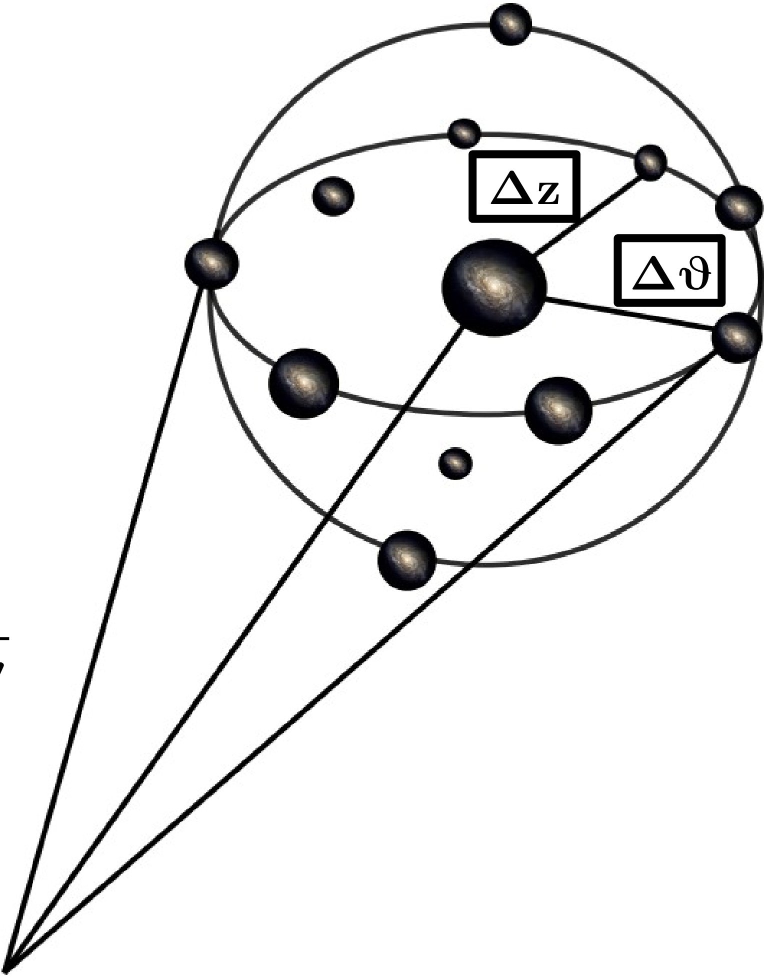


BAO AND THE SOUND HORIZON

GENERAL IDEA:

1) BAO determines Ω_m and $\mathrm{H}_0\ \mathrm{r_s}$

$$\Delta z \approx \frac{h r_s}{1/E(z)} \quad \Delta\vartheta \approx \frac{h r_s}{\int_0^z E(z')\mathrm{d}z'}$$



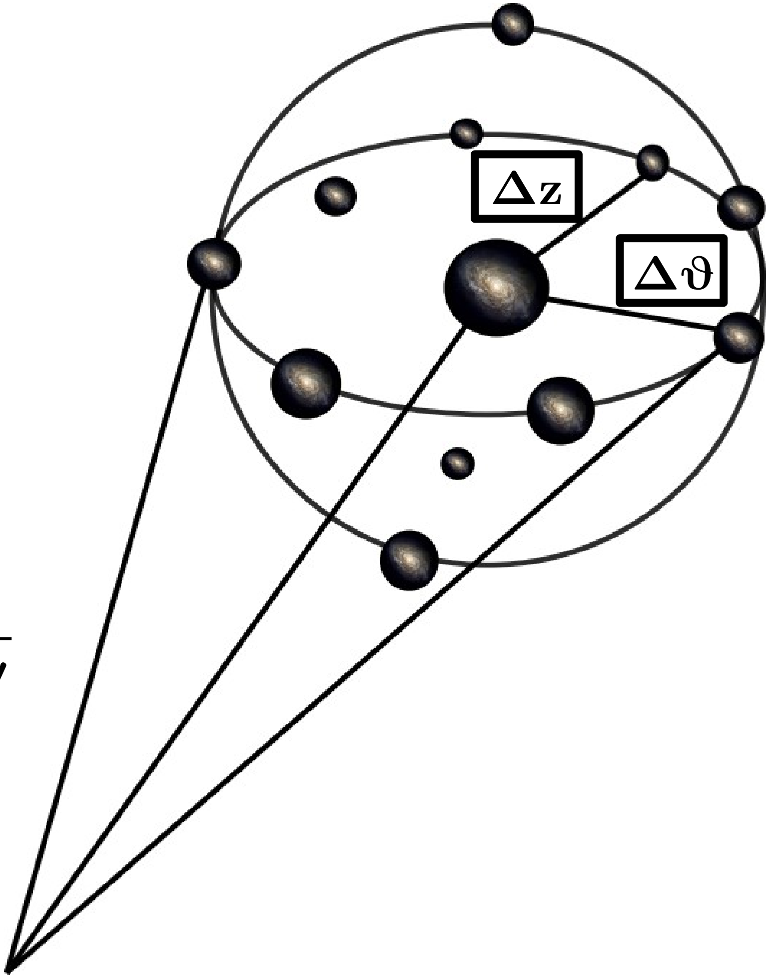
BAO AND THE SOUND HORIZON

GENERAL IDEA:

1) BAO determines Ω_m and $\boxed{\mathrm{H_0\ r_s}}$

$$\Delta z \approx \frac{\boxed{hr_s}}{1/E(z)} \quad \Delta\vartheta \approx \frac{\boxed{hr_s}}{\int_0^z E(z')\mathrm{d}z'}$$

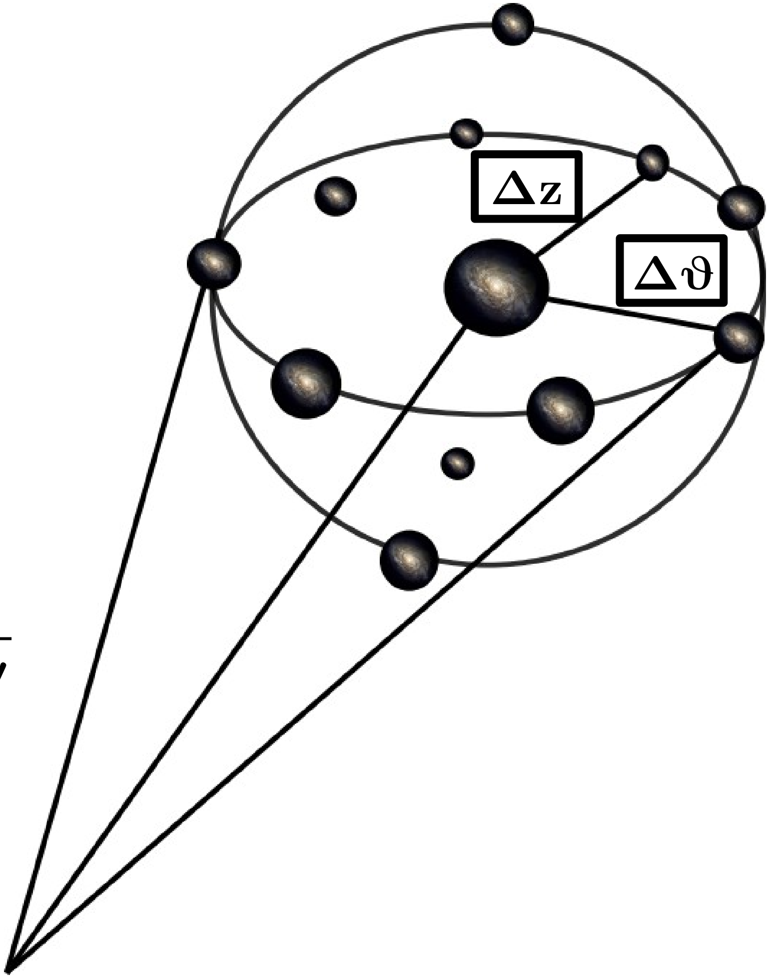
$$E(z) \equiv H(z)/h \approx 100\mathrm{km/s/Mpc} \cdot \sqrt{\Omega_m((1+z)^3-1)+1}$$



BAO AND THE SOUND HORIZON

GENERAL IDEA:

1) BAO determines $\boxed{\Omega_\mathrm{m}}$ and $\boxed{\mathrm{H}_0\ \mathrm{r}_\mathrm{s}}$



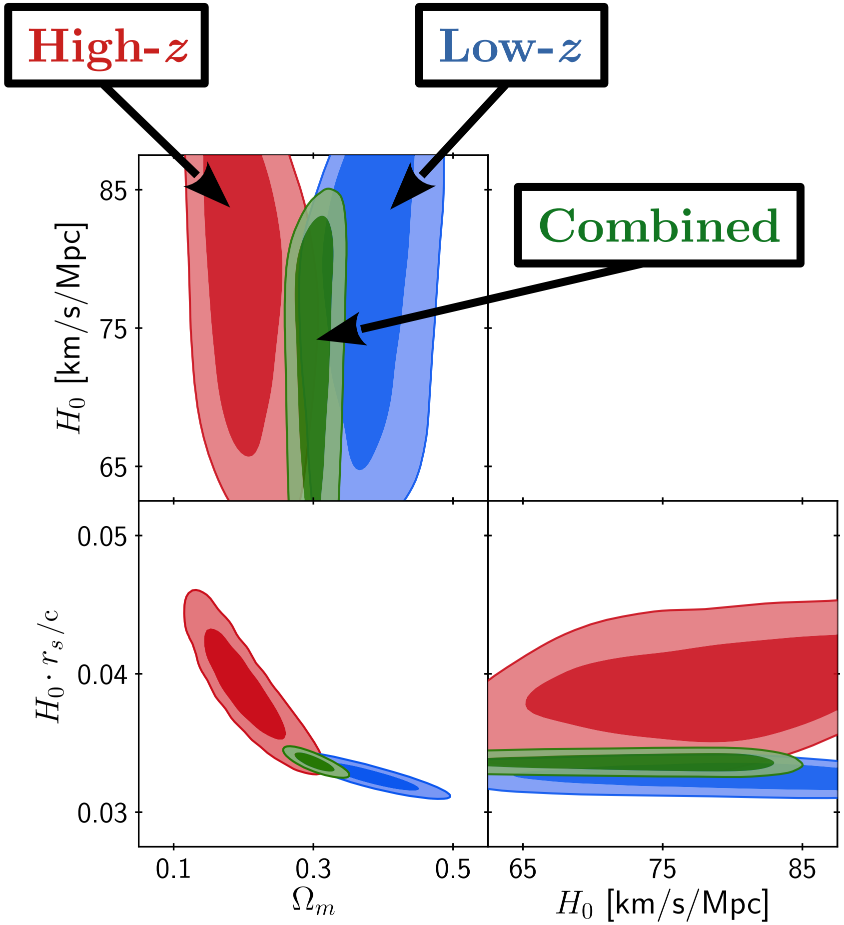
$$\Delta z \approx \frac{\boxed{hr_s}}{1/\boxed{E(z)}} \quad \Delta\vartheta \approx \frac{\boxed{hr_s}}{\int_0^z \boxed{E(z')}\mathrm{d}z'}$$

$$\boxed{E(z)} \equiv H(z)/h \approx 100\mathrm{km/s/Mpc} \cdot \sqrt{\boxed{\Omega_m}((1+z)^3-1)+1}$$

BAO + BBN

GENERAL IDEA:

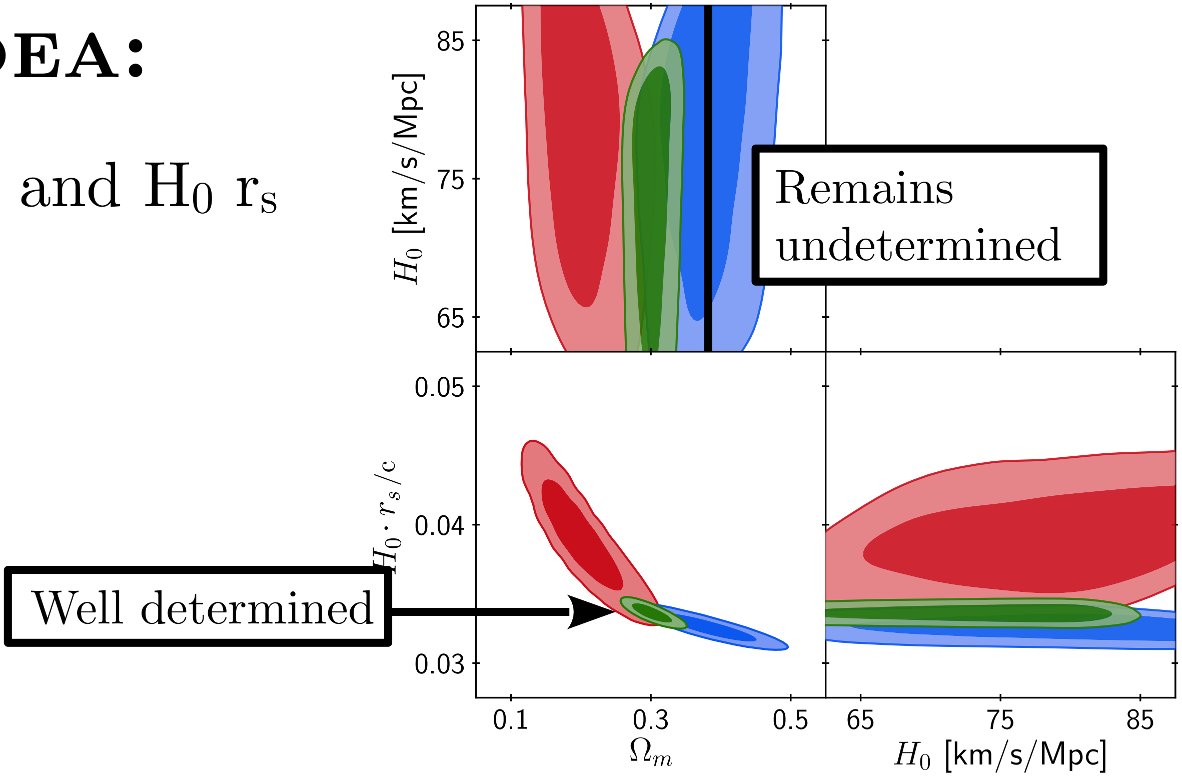
1) BAO determines Ω_m and $H_0\, r_s$



BAO + BBN

GENERAL IDEA:

1) BAO determines Ω_m and $\mathrm{H}_0\ \mathrm{r}_\mathrm{s}$



Remains undetermined

Well determined

BAO + BBN

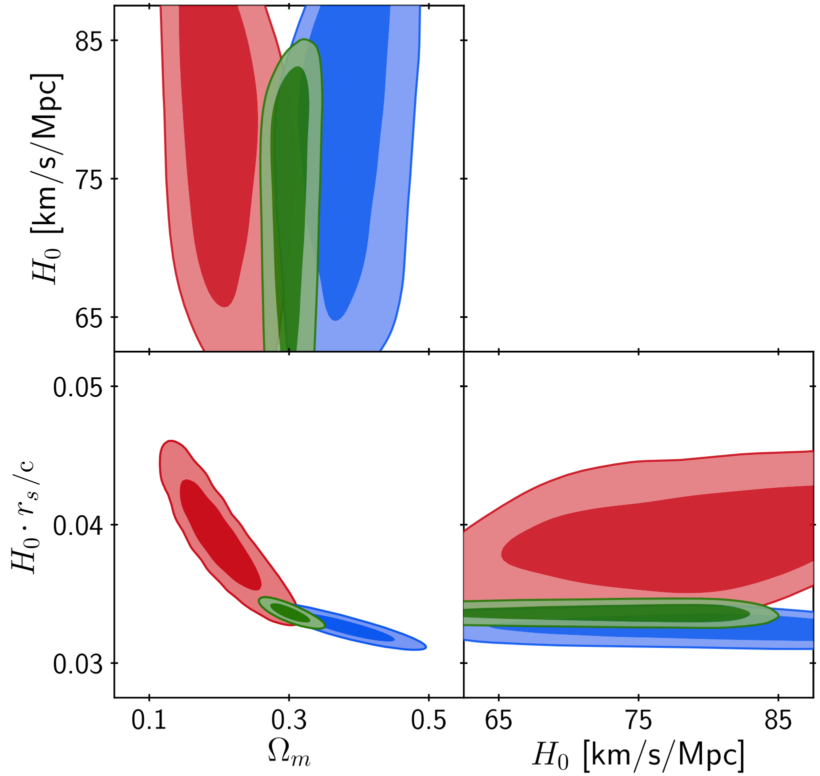
GENERAL IDEA:

1) BAO determines Ω_m and $\mathrm{H_0\ r_s}$

$\mathbf{T_0\ ,\ \Omega_b\ h^2}$

$$H_0 r_s = \int_{z_\mathrm{rec}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

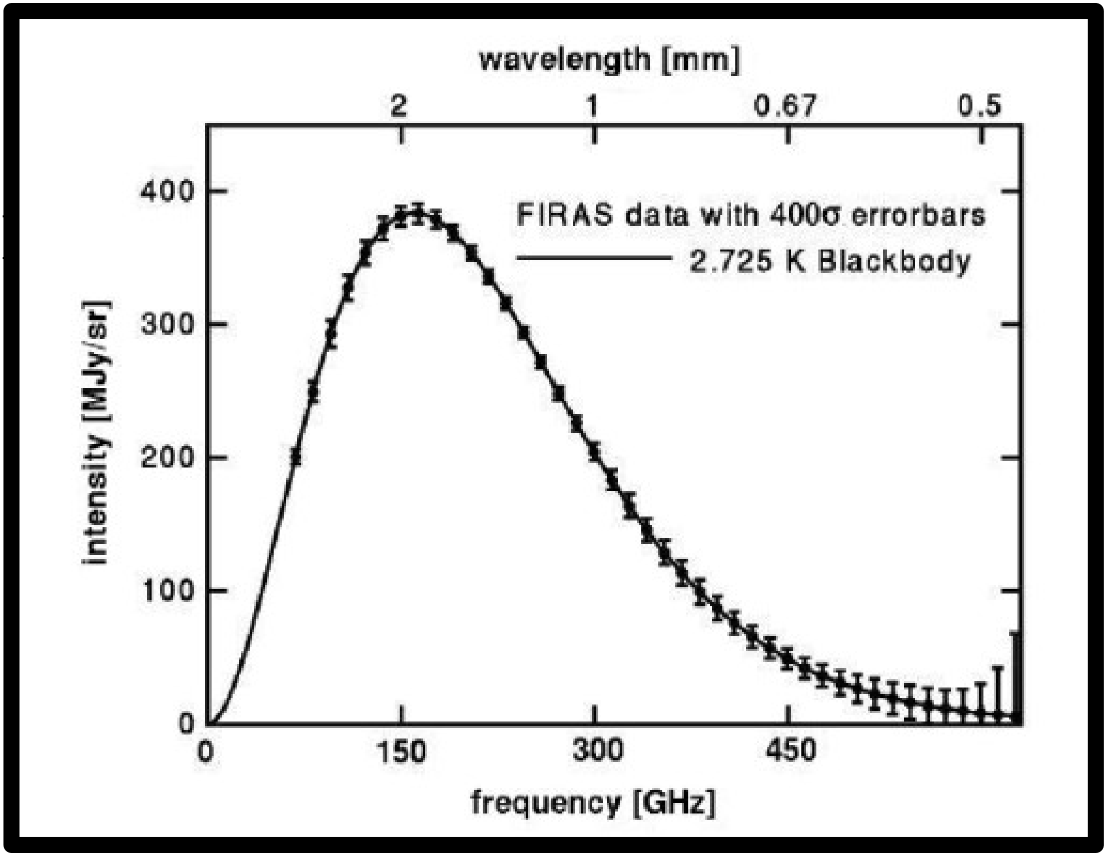
$\mathbf{\Omega_m\ ,\ \Omega_r\ h^2,\ H_0}$



BAO + BBN

GENERAL IDEA:

1) BAO determines Ω_m and



$\mathrm{T_0}$, $\Omega_\mathrm{b}\,\mathrm{h}^2$

$$H_0 r_s = \int_{z_\mathrm{rec}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

Ω_m , $\Omega_\mathrm{r}\,\mathrm{h}^2$, $\mathrm{H_0}$

BAO + BBN

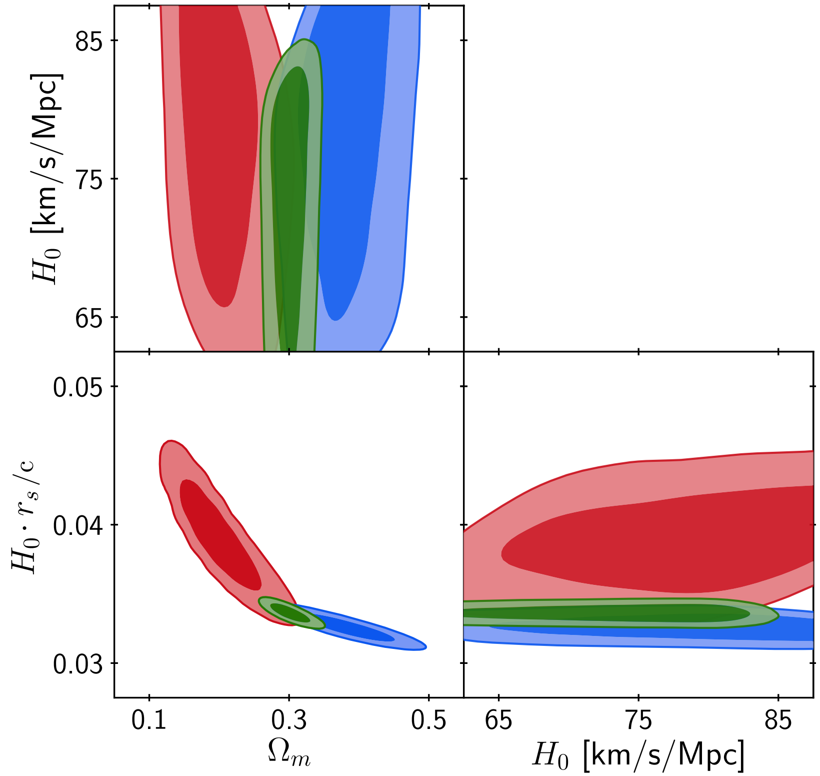
GENERAL IDEA:

1) BAO determines Ω_m and $\mathrm{H}_0\ \mathrm{r}_\mathrm{s}$

✓ $\boxed{\mathbf{T_0\ ,\ \Omega_b\ h^2}}$

$$H_0 r_s = \int_{z_\mathrm{rec}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

$\boxed{\mathbf{\Omega_m\ ,\ \Omega_r\ h^2,\ H_0}}$ ✓



BAO + BBN

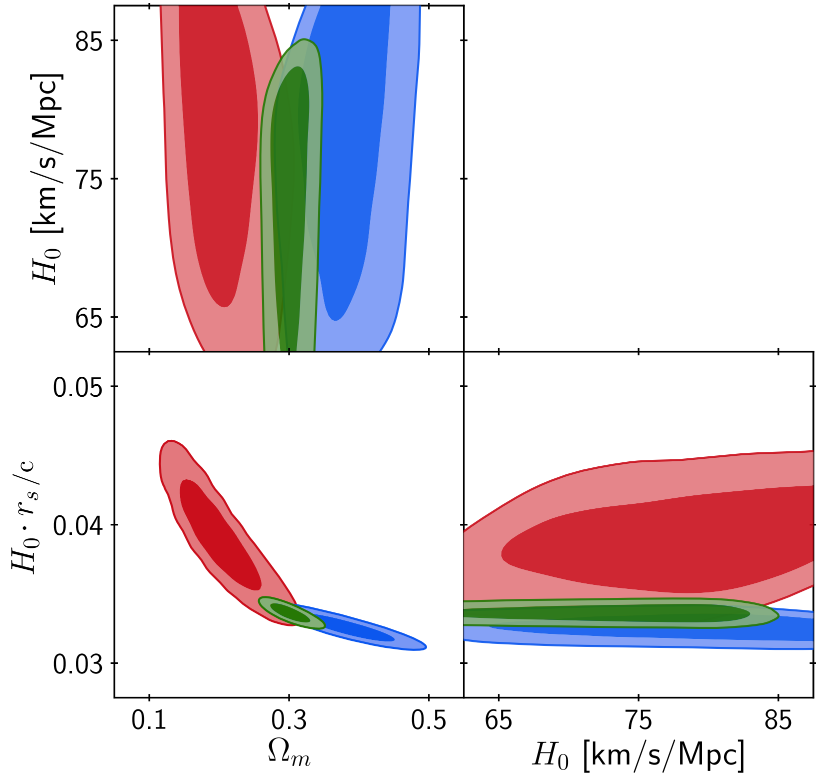
GENERAL IDEA:

1) BAO determines Ω_m and $\mathrm{H_0\ r_s}$

$\mathrm{T_0\ ,\ \Omega_b\ h^2}$ ✓

$$H_0 r_s = \int_{z_\mathrm{rec}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

$\mathrm{\Omega_m,\ \Omega_r\ h^2,\ H_0}$ ✓



BAO + BBN

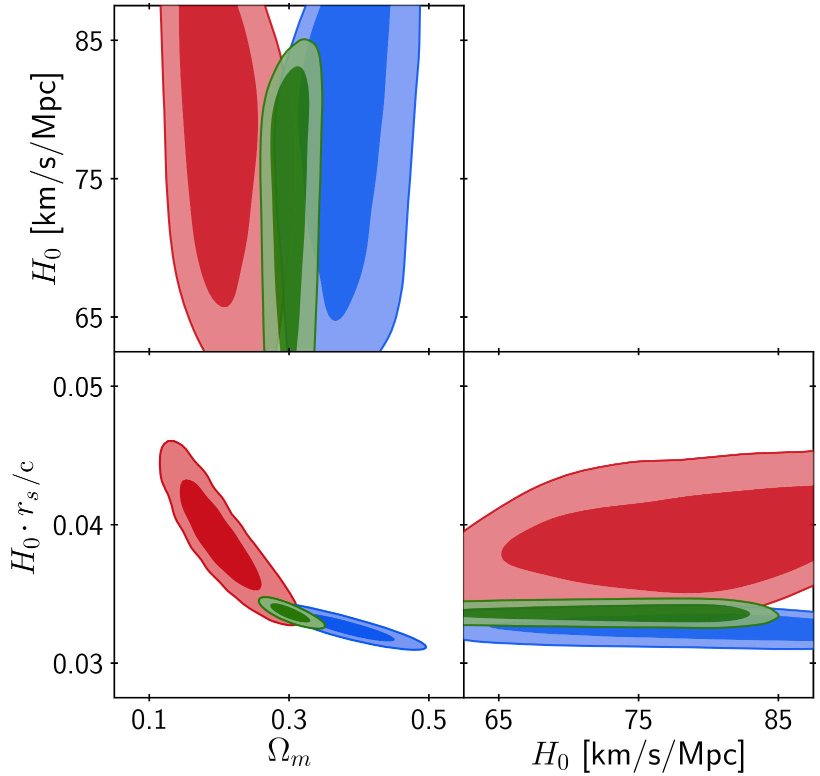
GENERAL IDEA:

1) BAO determines Ω_m and H_0 r_s

✓ T_0 , $\Omega_b h^2$

$$H_0 r_s = \int_{z_{\mathrm{rec}}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

Ω_m, $\Omega_r h^2$, H_0 ✓ ✓

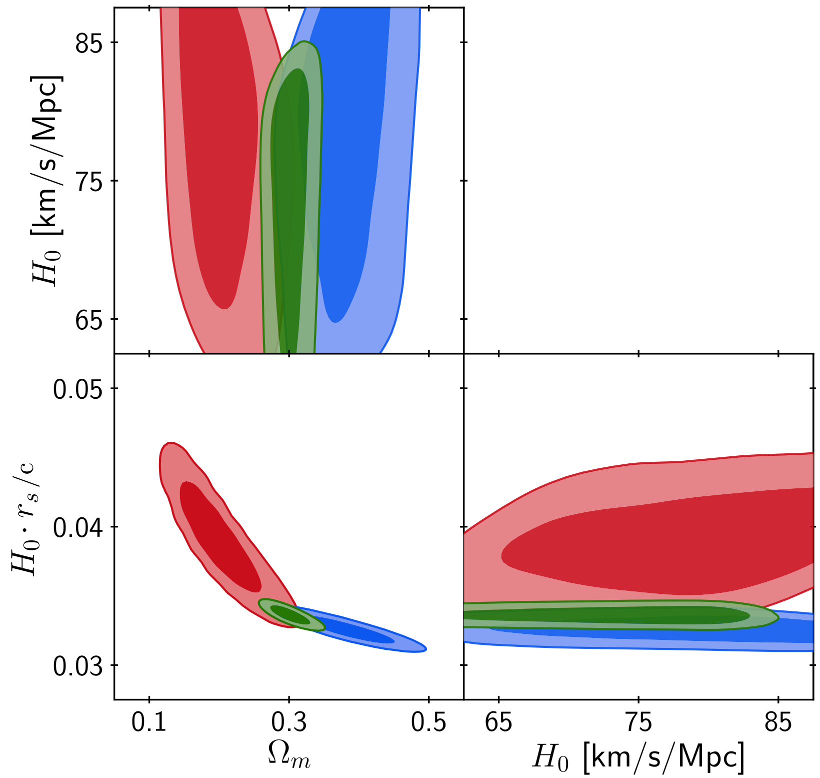


BAO + BBN

GENERAL IDEA:

1) BAO determines Ω_m and $\mathrm{H_0\ r_s}$

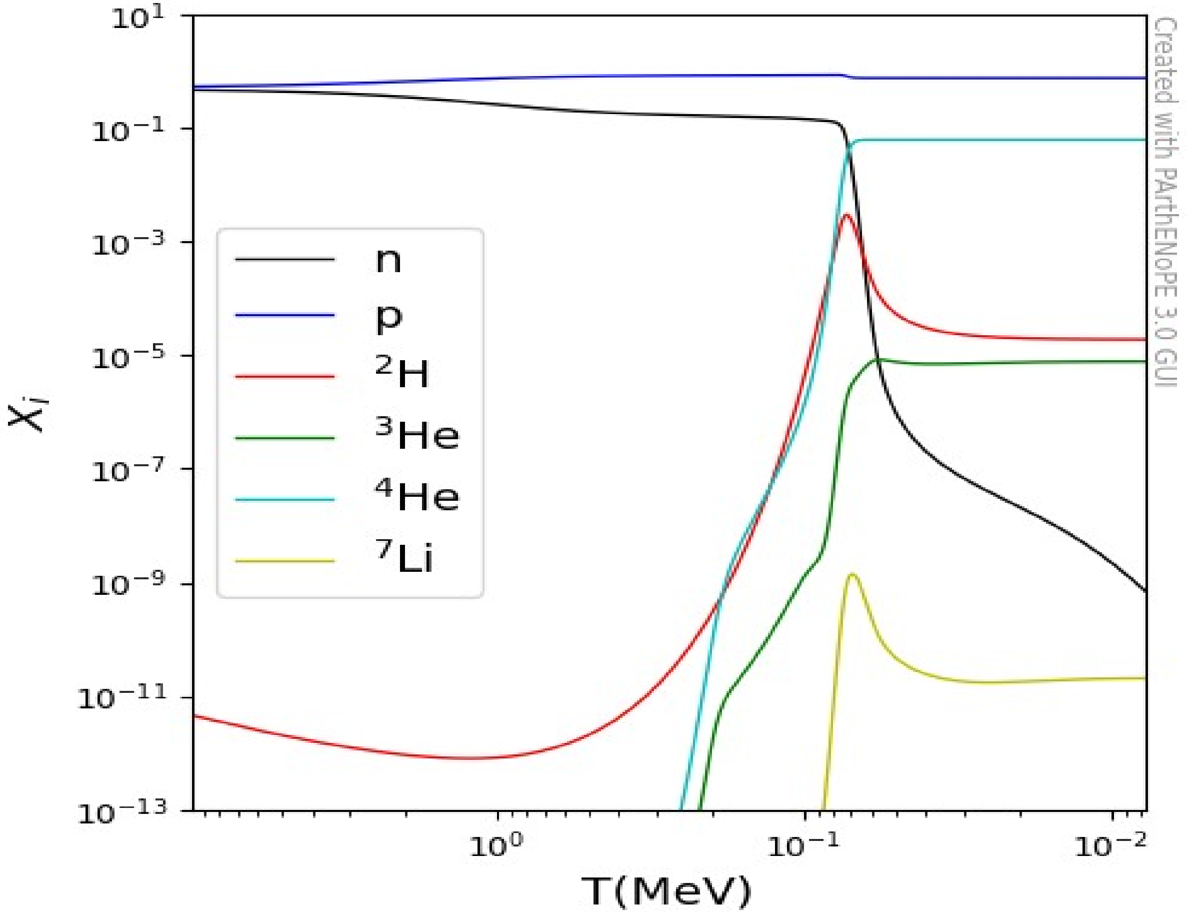
$$H_0 r_s = \int_{z_\mathrm{rec}}^{\infty} \frac{\overset{\boxed{\mathrm{T_0}\checkmark,\ \Omega_\mathrm{b}\,\mathrm{h}^2}}{c_s(z)}\,\mathrm{d}z}{\underset{\boxed{\Omega_\mathrm{m}\checkmark,\ \Omega_\mathrm{r}\,\mathrm{h}^2\checkmark,\ \mathrm{H_0}}}{H(z)/H_0}}$$



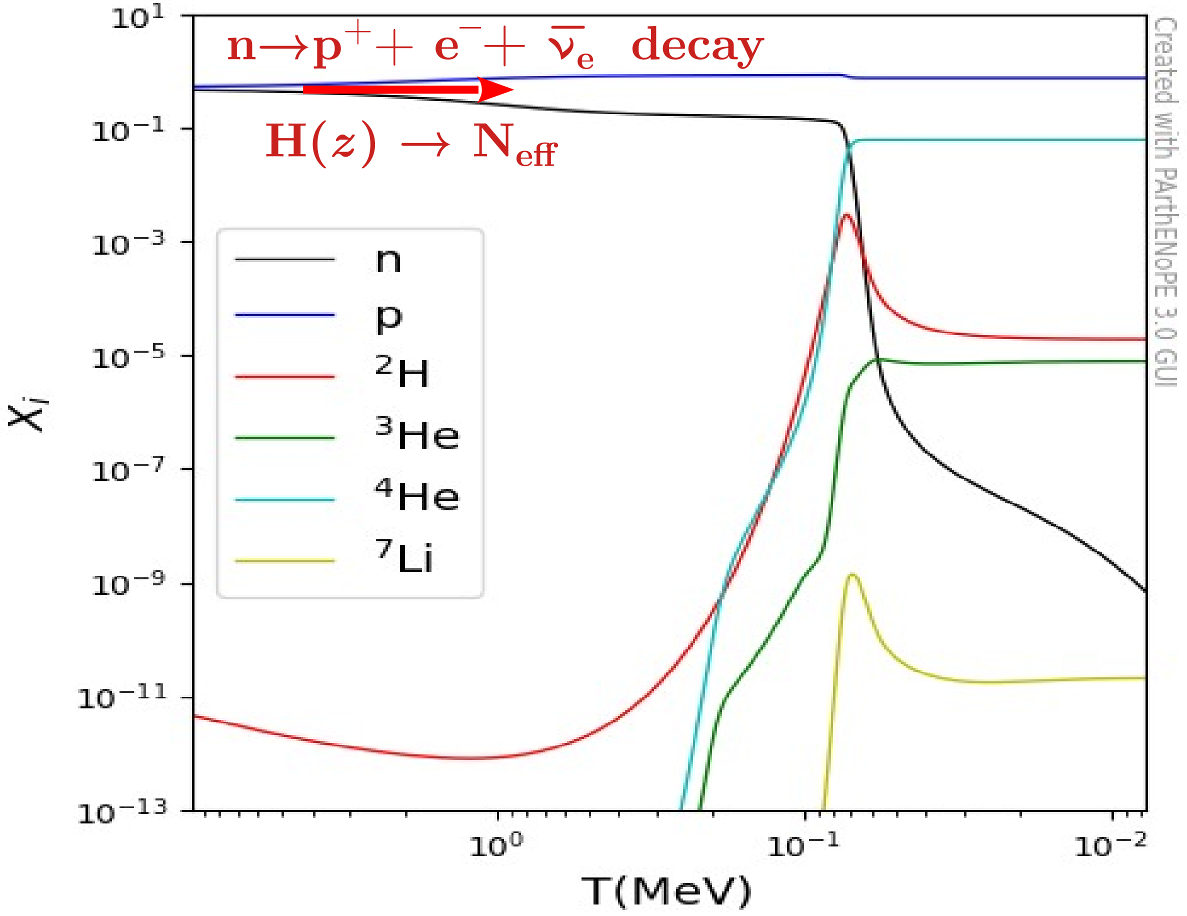
TOPICS

- Quick motivation
- The BAO principle
- The BBN principle
- Why do BAO+BBN combine so well?
- What aids this probe?
- What breaks this probe?

The BBN part


10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
X_i
n
p
^{2}H
^{3}He
^{4}He
^{7}Li
10^{0}
10^{-1}
10^{-2}
T(MeV)
Created with PArthENoPE 3.0 GUI

THE BBN PART

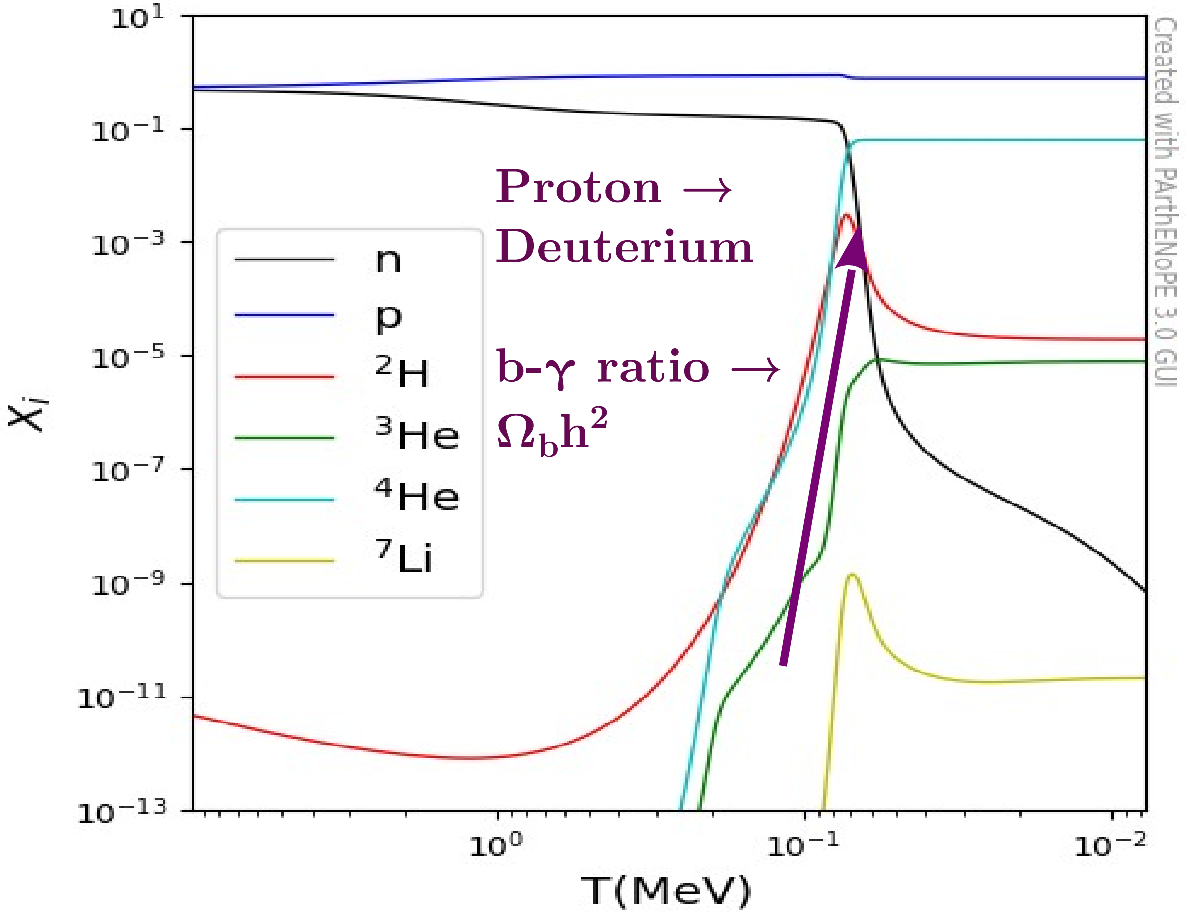


Early weak decay:

Sensitive to $\mathbf{H(z)}$, $\mathbf{N_{\rm eff}}$

Larger H(z) → less time for same ΔT → less decay → less n for He → less Helium

THE BBN PART



Proton → Deuterium

b-γ ratio → $\Omega_b h^2$

Early weak decay:

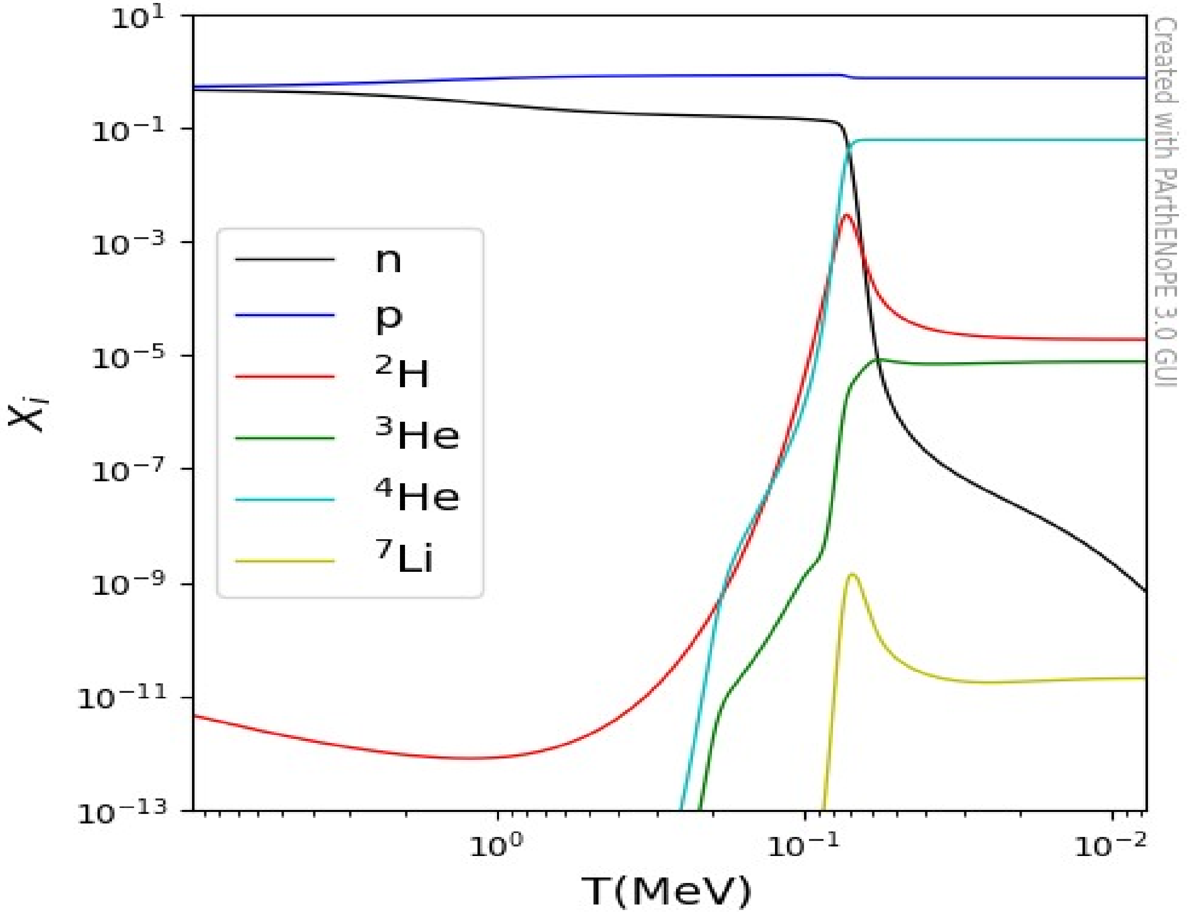
Sensitive to $\mathbf{H(z)}$, $\mathbf{N_{eff}}$

Late fusion reaction:

Sensitive to $\mathbf{\Omega_b h^2}$

More baryons → earlier decoupling → higher temperature → more deuterium burning → Less deuterium (+more Helium)

THE BBN PART



Early weak decay:

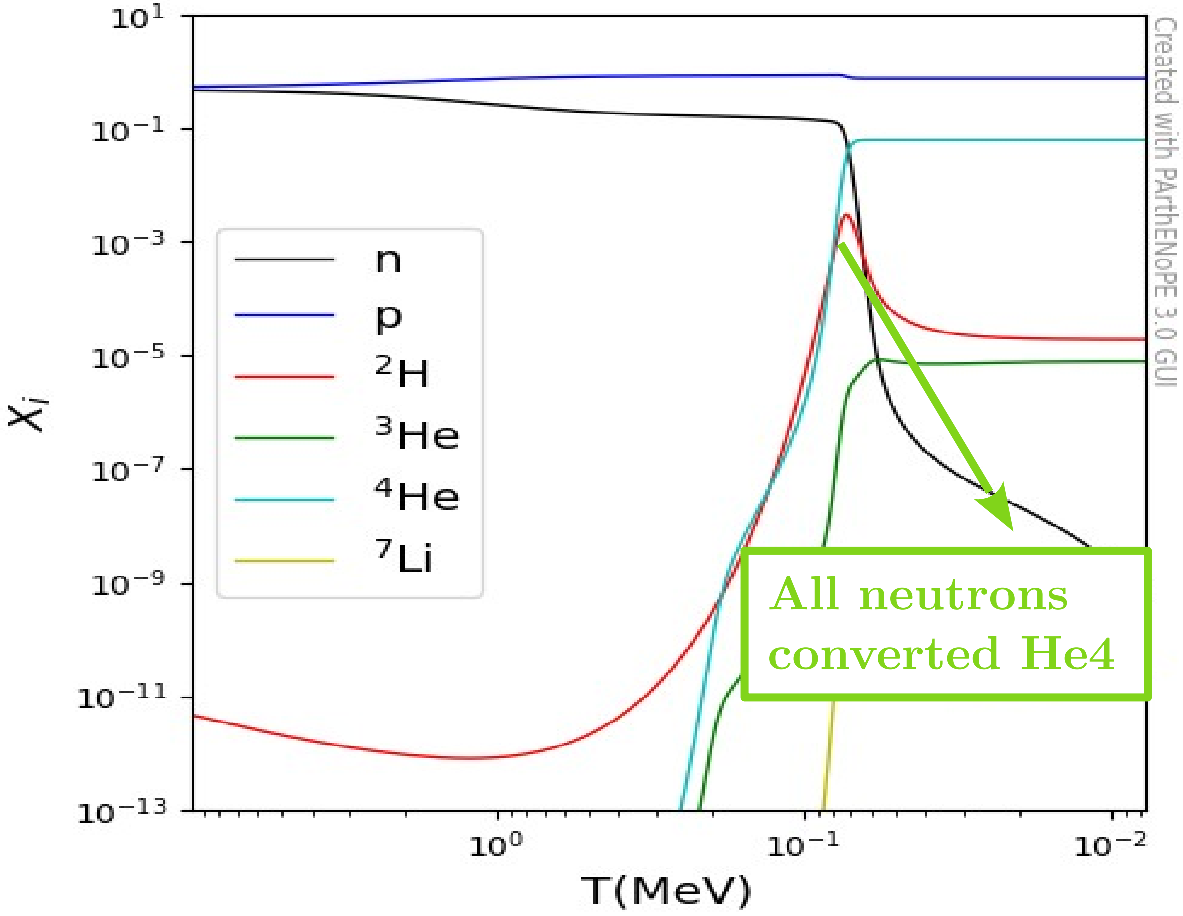
Sensitive to $\mathbf{H(z)}$, $\mathbf{N_{eff}}$

Late fusion reaction:

Sensitive to $\mathbf{\Omega_b h^2}$

Produces H2 $= D_H$

THE BBN PART



Created with PArthENoPE 3.0 GUI

All neutrons converted He4

Early weak decay:

Sensitive to $\mathbf{H(z)}$, $\mathbf{N_{eff}}$

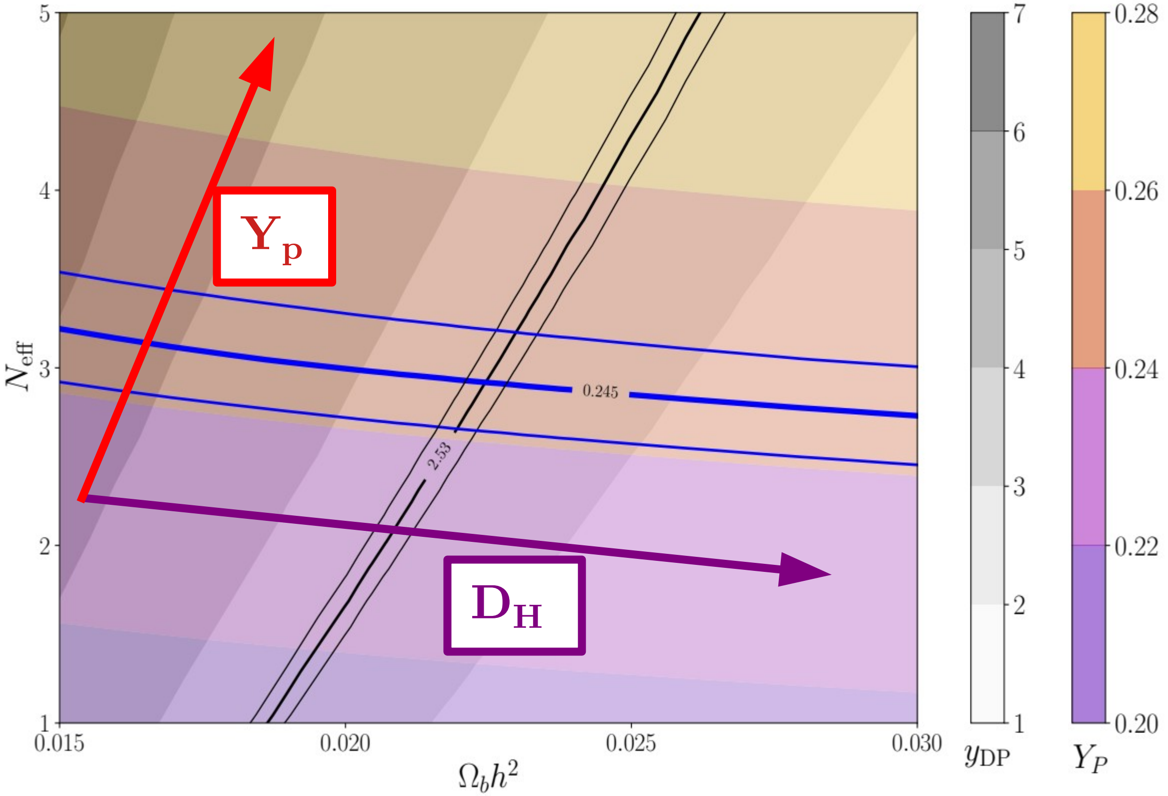
Produces He4 $= \mathrm{Y_p}$

Late fusion reaction:

Sensitive to $\mathbf{\Omega_b h^2}$

Produces H2 $= \mathrm{D_H}$

THE BBN PART



Early weak decay:

Sensitive to $\mathbf{H(z)}$, $\mathbf{N_{eff}}$

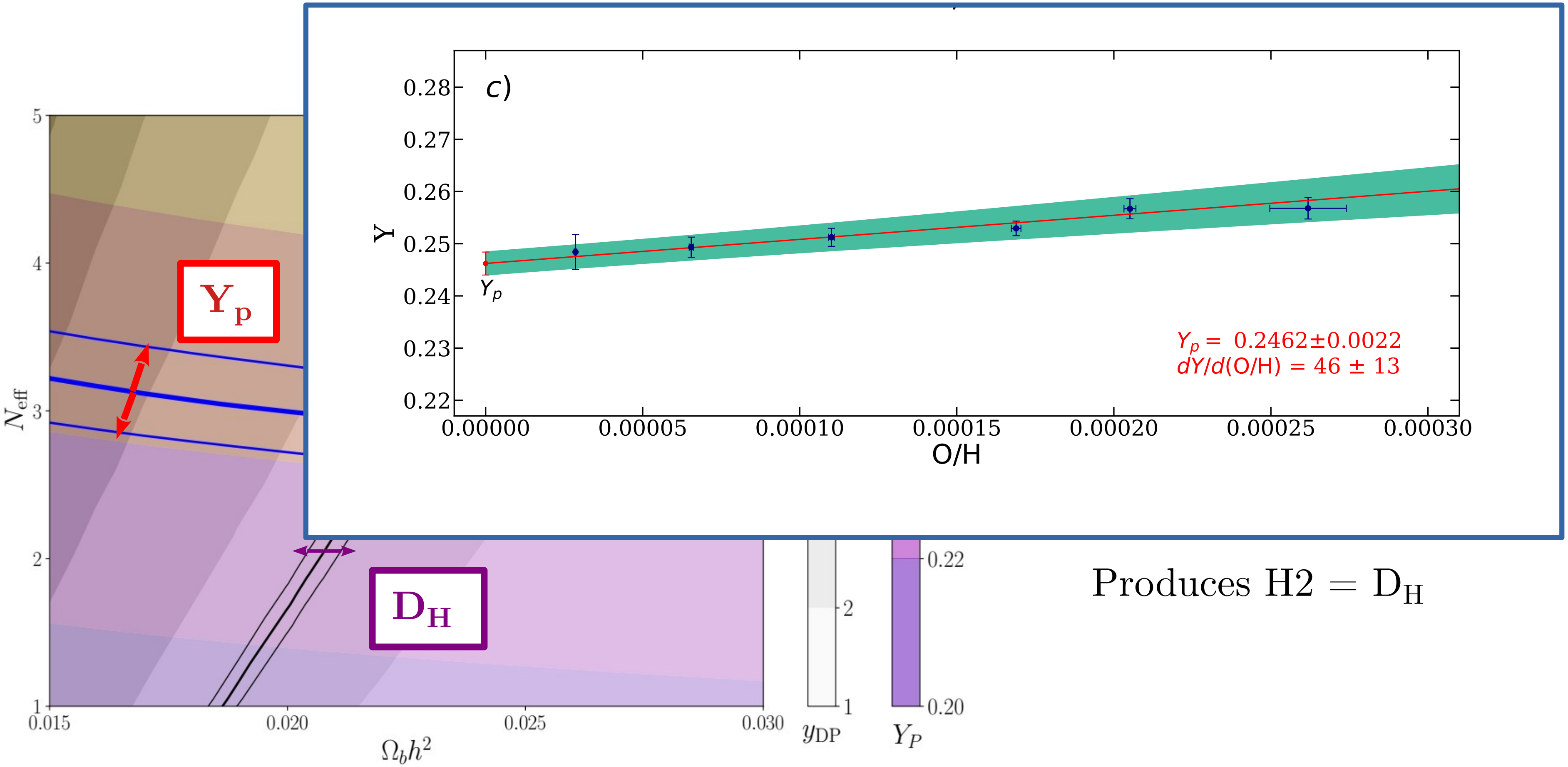
Produces He4 = Y_p

Late fusion reaction:

Sensitive to $\mathbf{\Omega_b h^2}$

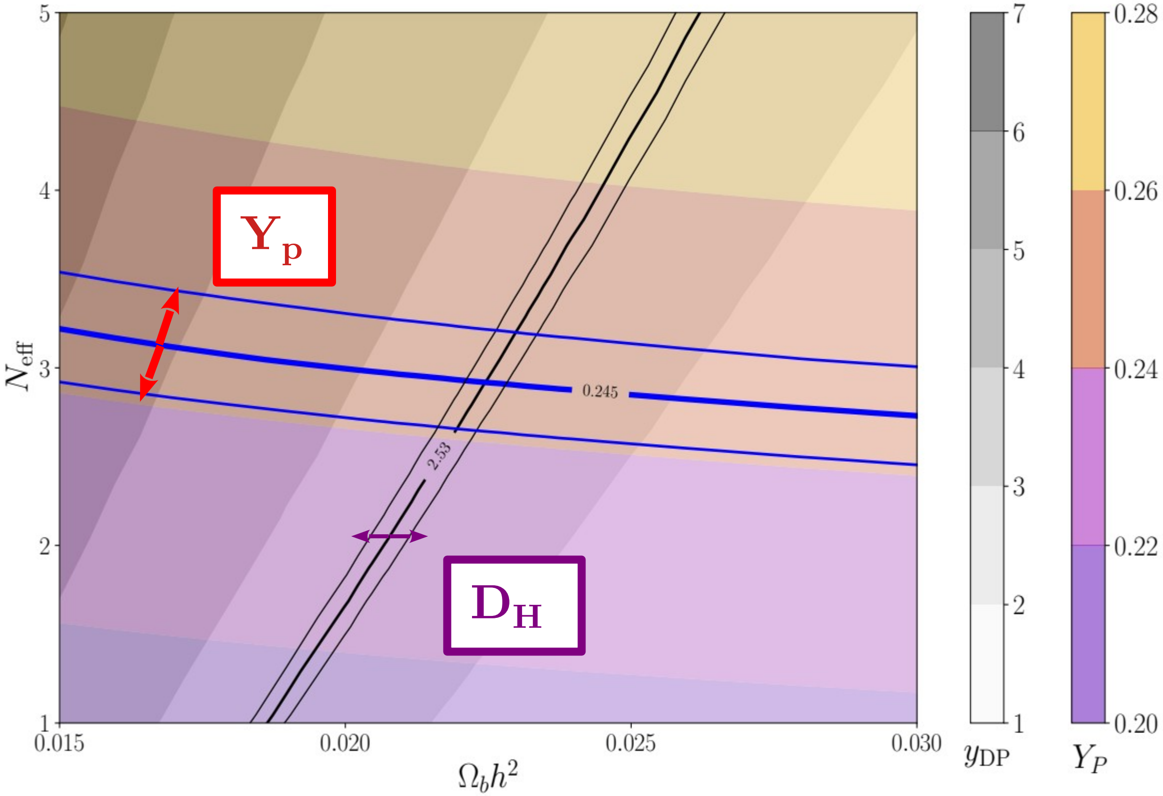
Produces H2 = D_H

The BBN part



Produces H2 = $\mathrm{D_H}$

The BBN part



Early weak decay:

Sensitive to $\mathbf{H(z), N_{eff}}$

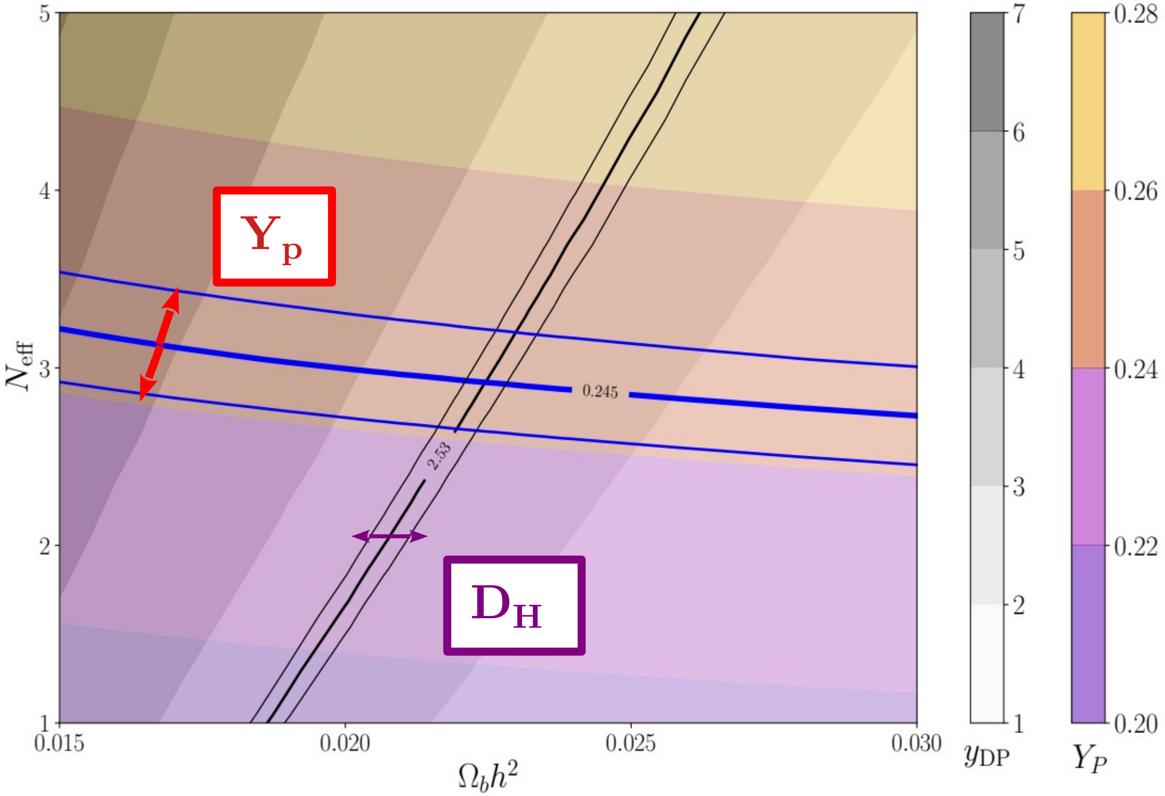
Produces He4 = $\mathbf{Y_p}$

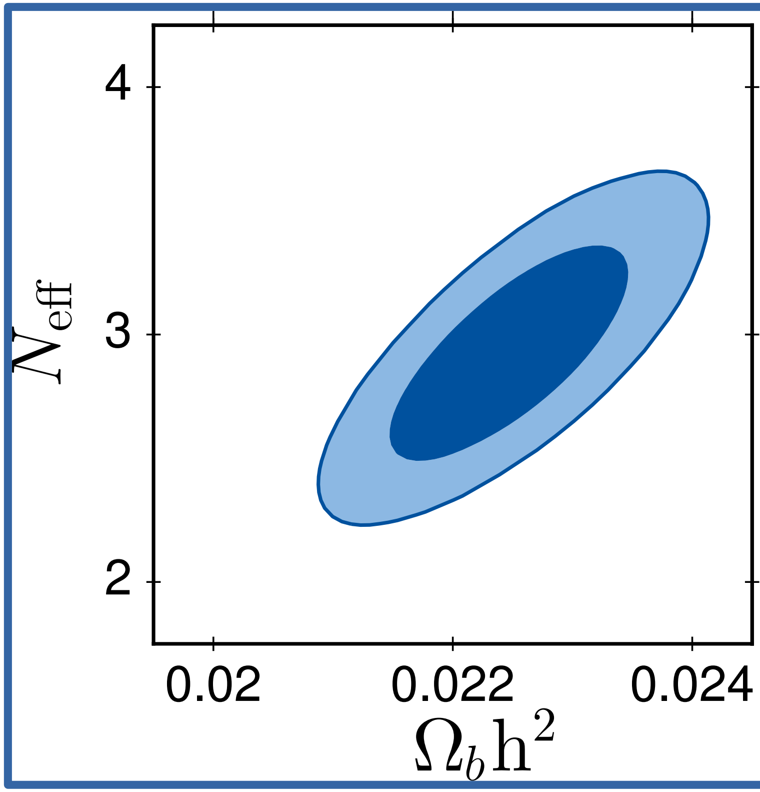
Late fusion reaction:

Sensitive to $\mathbf{\Omega_b h^2}$

Produces H2 = $\mathbf{D_H}$

THE BBN PART


5
4
3
2
1
0.015
0.020
0.025
0.030
$N_{\rm eff}$
$\Omega_b h^2$
$\mathrm{Y_p}$
$\mathrm{D_H}$
0.245
2.53
7
6
5
4
3
2
1
$y_{\rm DP}$
0.28
0.26
0.24
0.22
0.20
Y_P


4
3
2
0.02
0.022
0.024
$N_{\rm eff}$
$\Omega_b \mathrm{h}^2$

TOPICS

- Quick motivation
- The BAO principle
- The BBN principle
- Why do BAO+BBN combine so well?
- What aids this probe?
- What breaks this probe?

BAO + BBN

GENERAL IDEA:

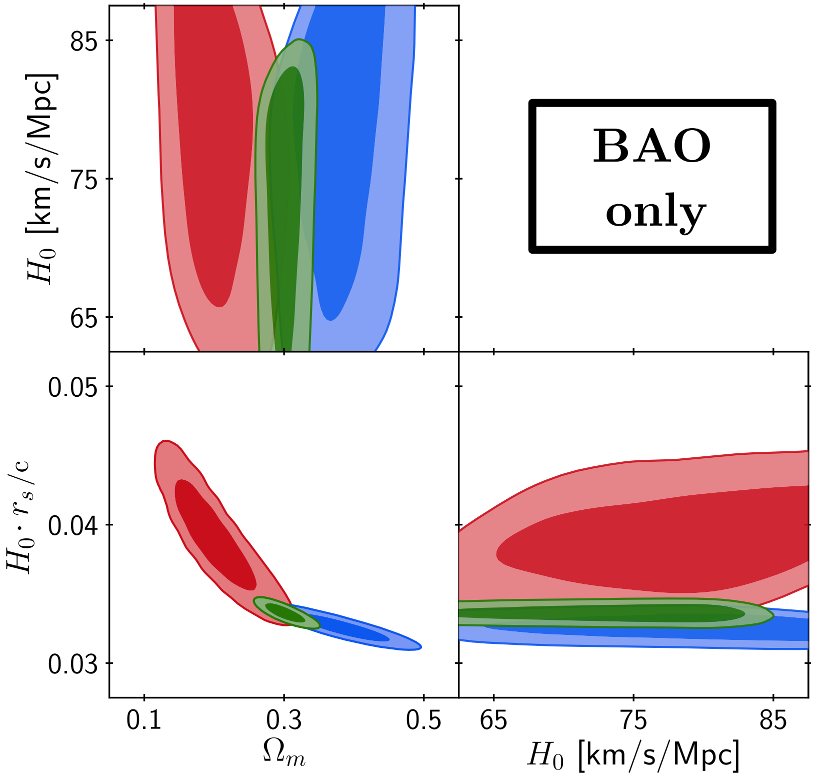
1) BAO determines Ω_m and $\mathrm{H}_0\,\mathrm{r_s}$

2) BBN determines $\Omega_\mathrm{b}\,\mathrm{h}^2$

✓ ✓
$\boxed{\mathbf{T_0\,,\ \Omega_b\,h^2}}$

$$H_0 r_s = \int_{z_\mathrm{rec}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

$\boxed{\mathbf{\Omega_m,\ \Omega_r\,h^2,\ H_0}}$
✓ ✓



BAO + BBN

GENERAL IDEA:

1) BAO determines Ω_{m} and $\mathrm{H}_0\,\mathrm{r_s}$

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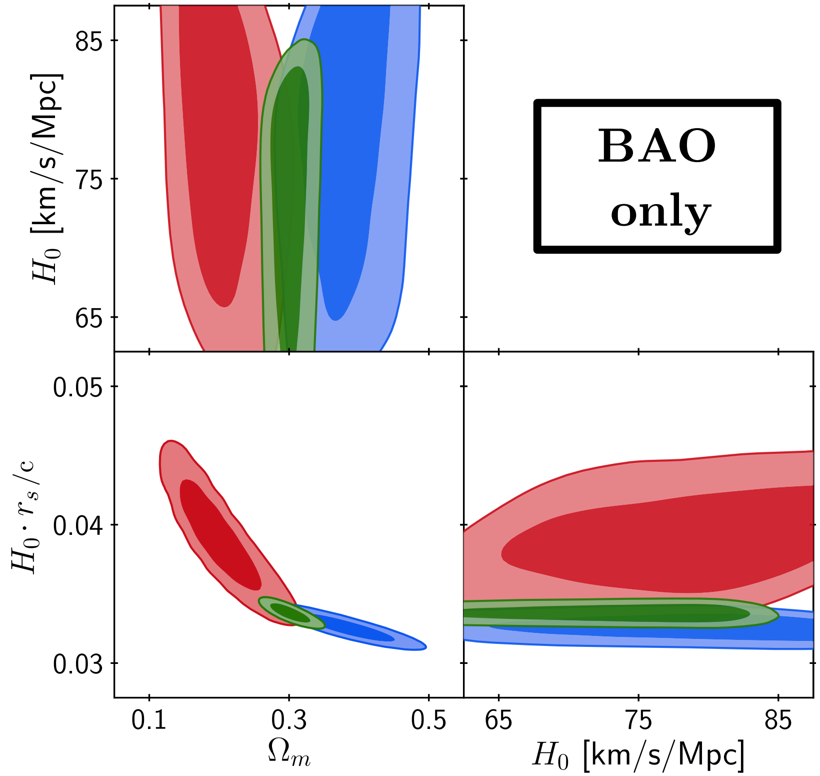
$$\boxed{\mathbf{T_0}\checkmark\,,\ \mathbf{\Omega_b\,h^2}\checkmark}$$

$$H_0 r_s = \int_{z_{\mathrm{rec}}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

$$\boxed{\mathbf{\Omega_m}\checkmark,\ \mathbf{\Omega_r\,h^2}\checkmark,\ \mathbf{H_0}}$$



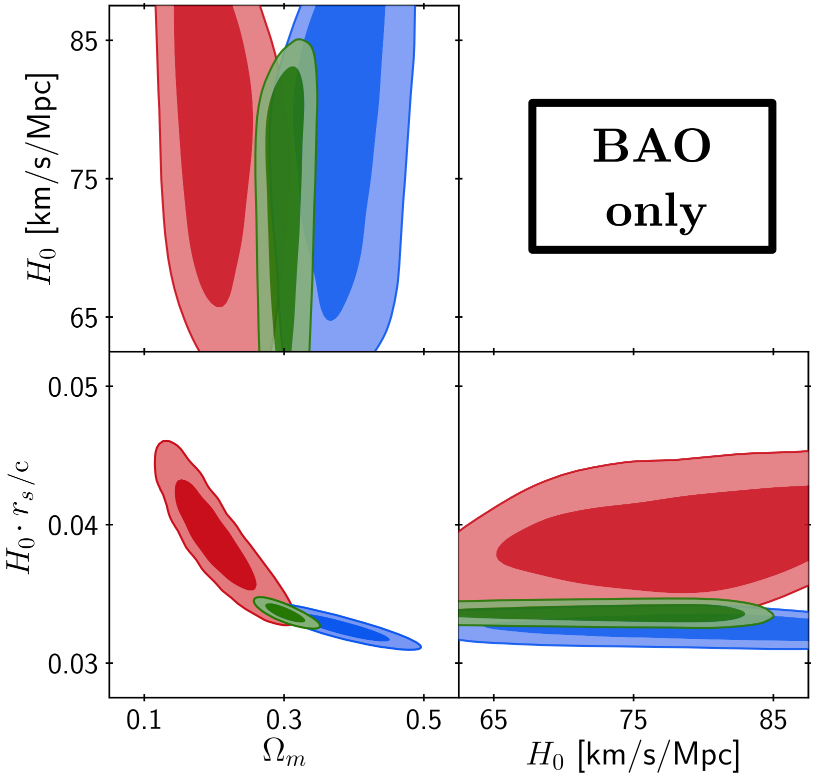
BAO + BBN

GENERAL IDEA:

1) BAO determines Ω_m and $H_0\,r_s$

2) BBN determines $\Omega_b\,h^2$

3) Their combination relates directly
$H_0\,r_s \rightarrow H_0$



BAO + BBN

GENERAL IDEA:

1) BAO determines Ω_m and $\mathrm{H}_0\,\mathrm{r}_\mathrm{s}$

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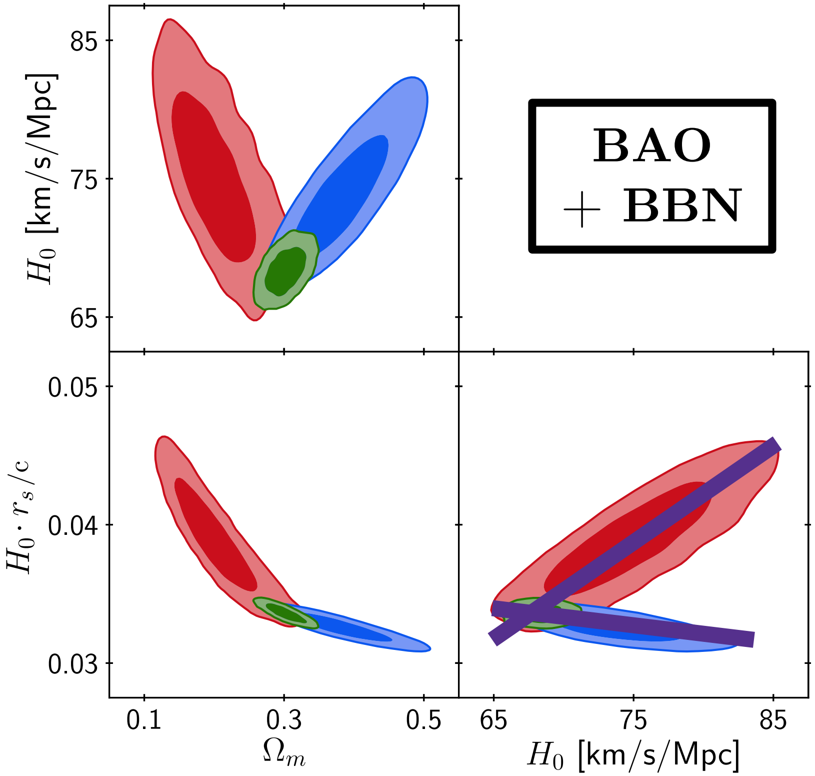

BAO + BBN

BAO + BBN

GENERAL IDEA:

1) BAO determines Ω_m and $H_0\, r_s$

2) BBN determines $\Omega_b\, h^2$

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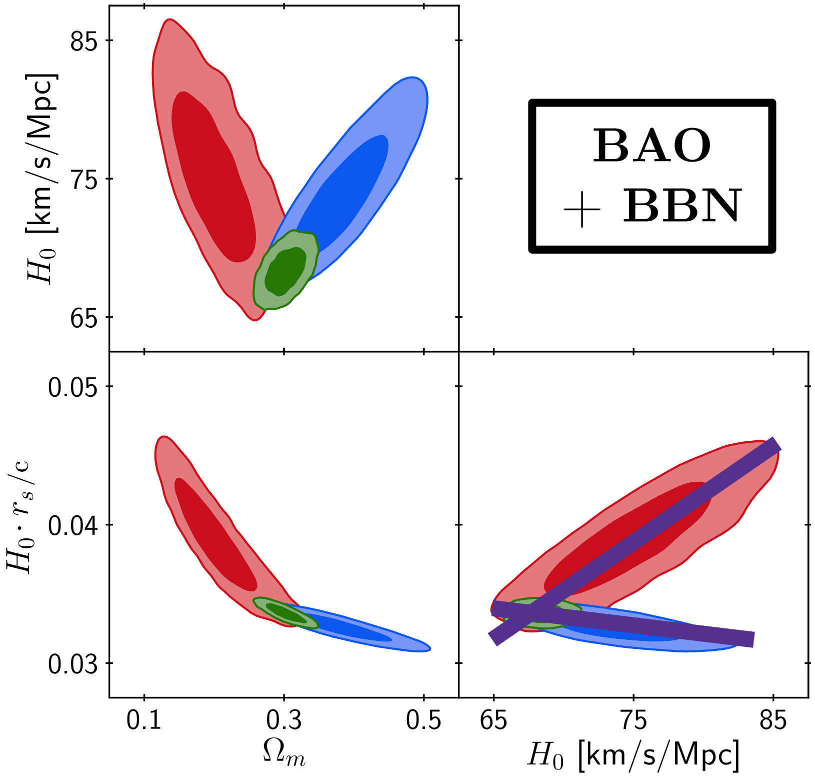
Different z → We measure H_0



BAO + BBN

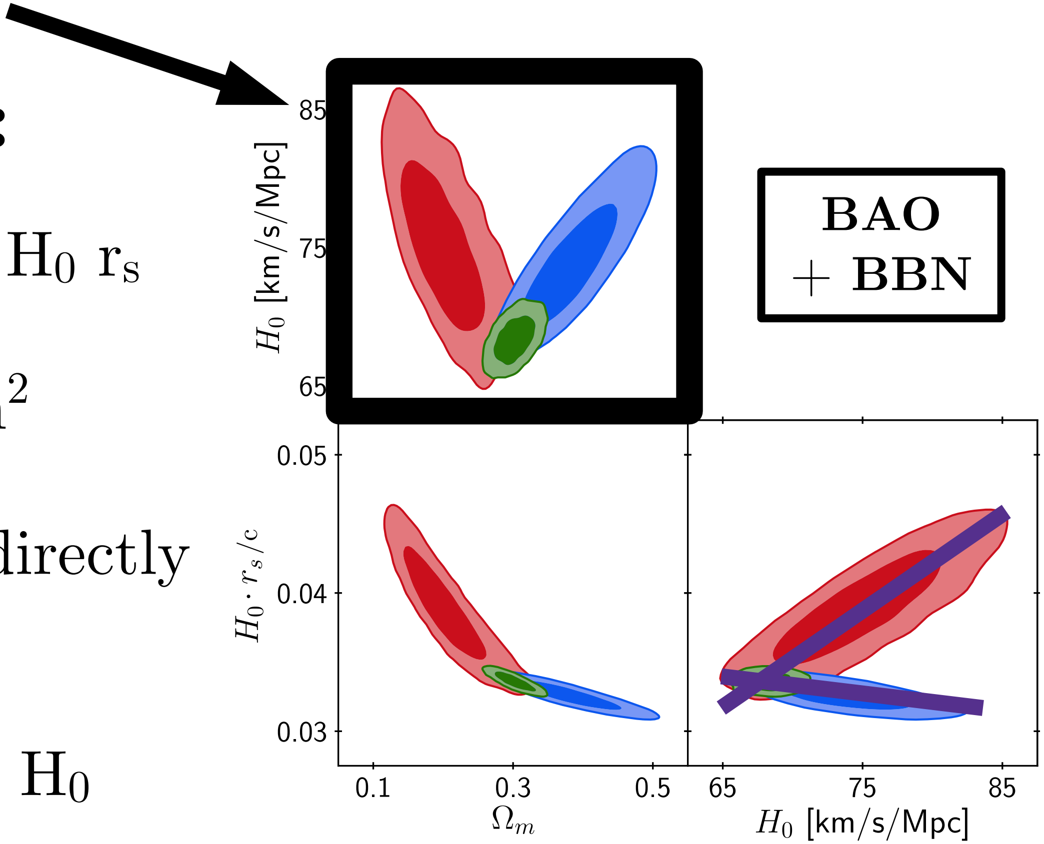
General idea:

1) BAO determines Ω_m and $\mathrm{H}_0\,\mathrm{r}_\mathrm{s}$

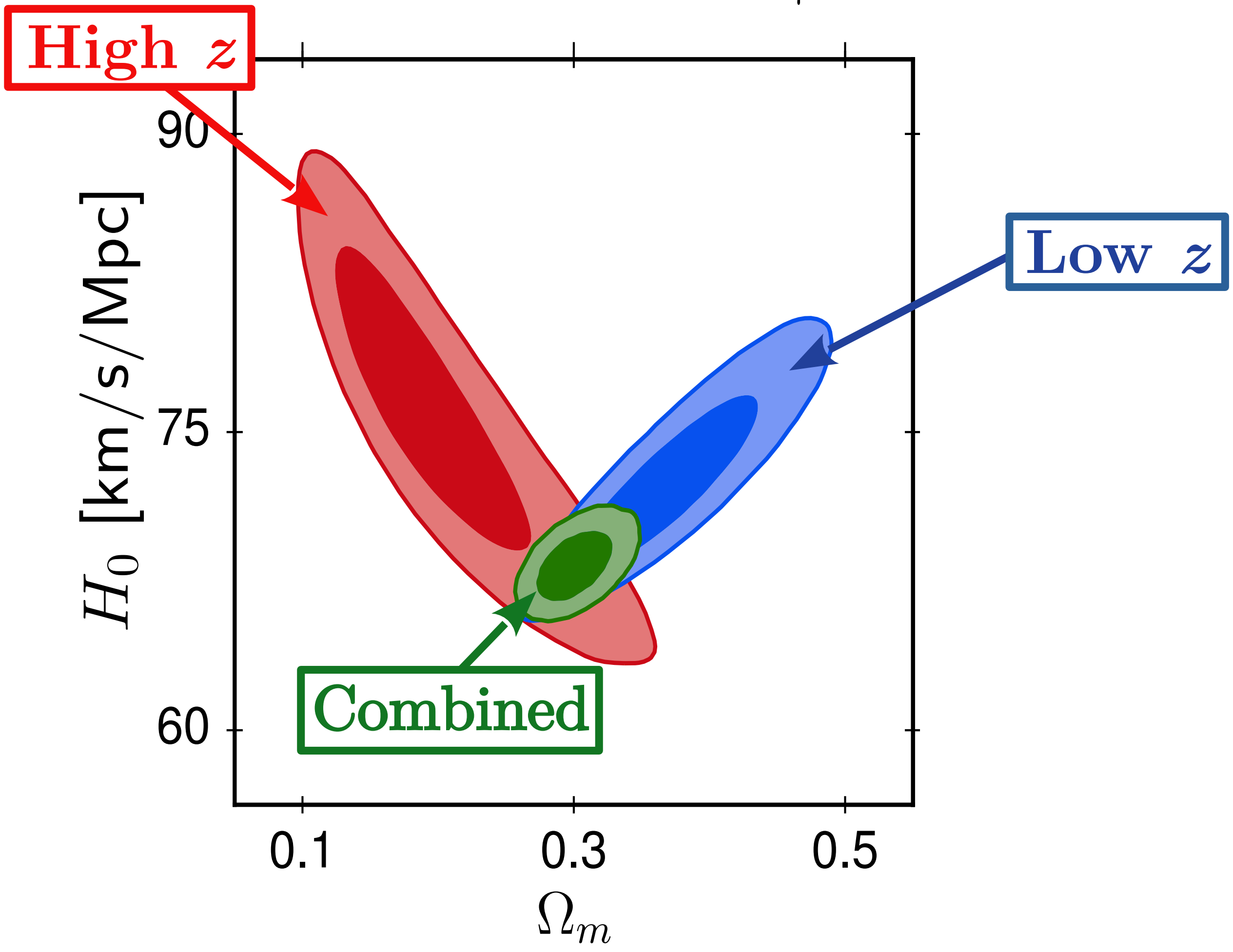
2) BBN determines $\Omega_\mathrm{b}\,\mathrm{h}^2$

3) Their combination relates directly $\mathrm{H}_0\,\mathrm{r}_\mathrm{s} \to \mathrm{H}_0$

Different z → We measure H_0

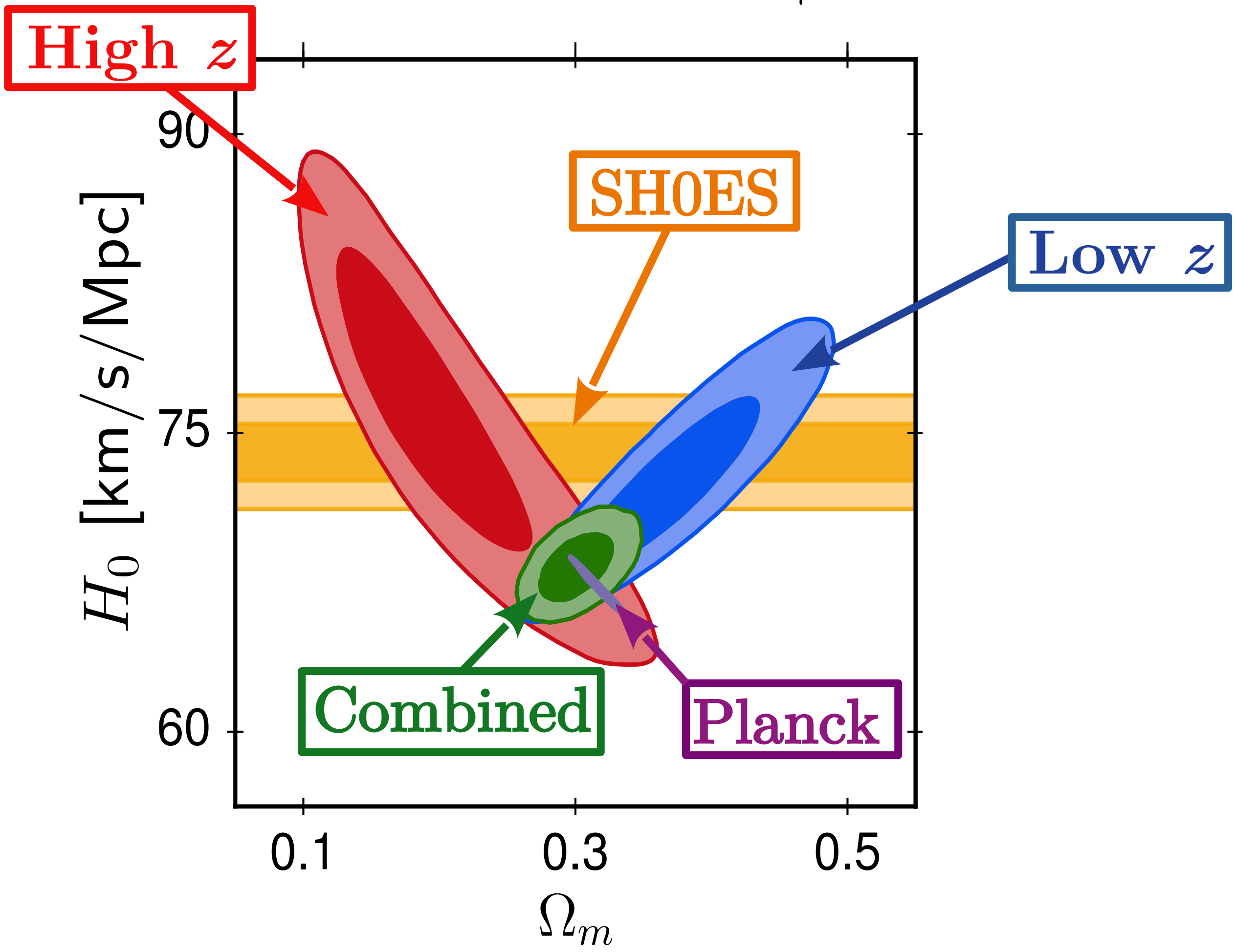


BAO + BBN



arXiv:1907.11594 → JCAP 10 (2019) 029
Nils Schöneberg, Julien Lesgourgues, Deanna C. Hooper

BAO + BBN



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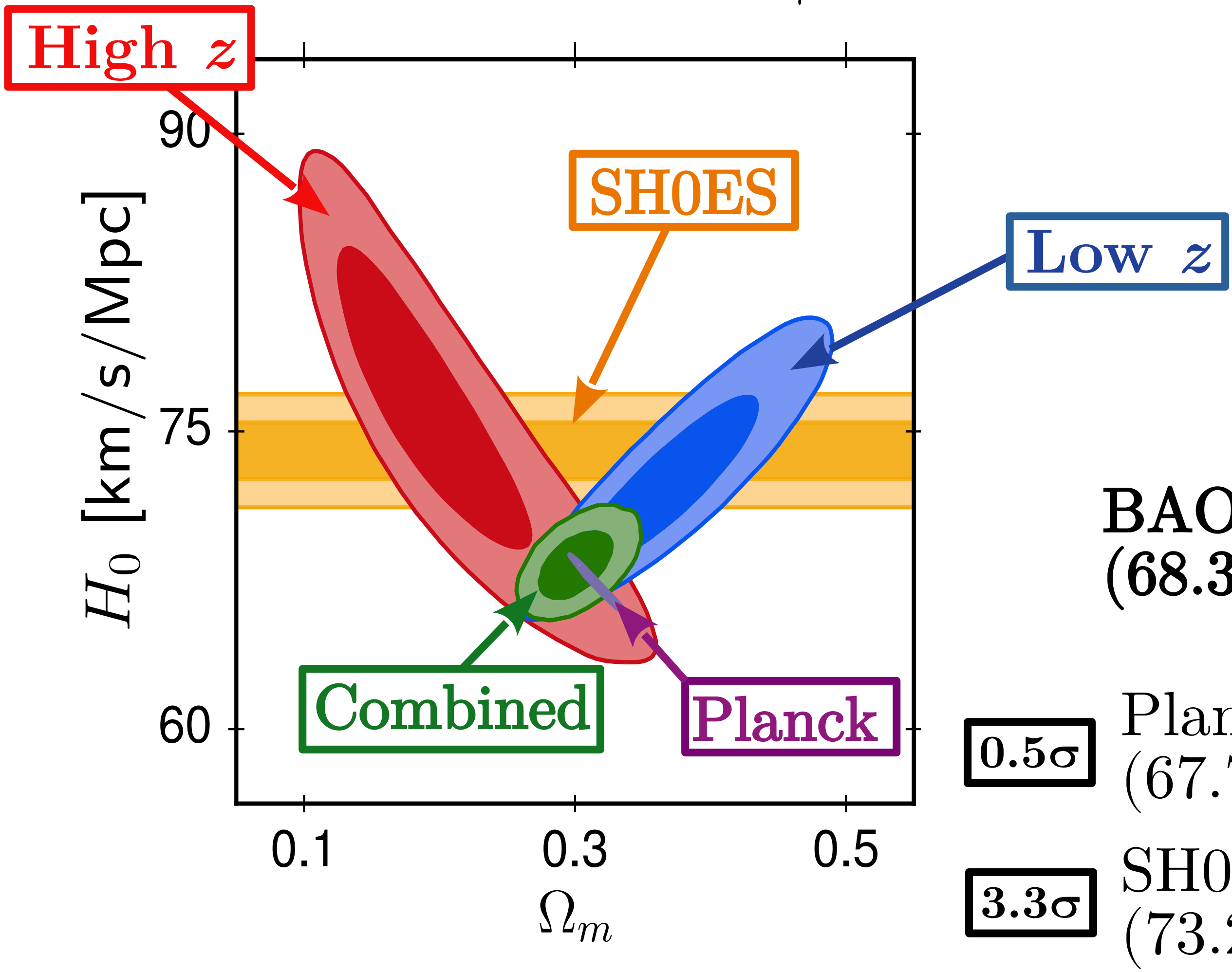

BAO+BBN
(68.3 ± 1.1) km/s/Mpc

0.5σ Planck (2018):
(67.7 ± 0.4) km/s/Mpc

3.3σ SH0ES (2022):
(73.2 ± 1.0) km/s/Mpc

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BAO + BBN

Picture from late 2019

What changed?

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BAO + BBN

Picture from late 2019

What changed?

→ New BBN results from LUNA experiment

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BAO + BBN

Picture from late 2019

What changed?

→ New BBN results from LUNA experiment

→ New BAO from DR16

arXiv:1907.11594 → JCAP 10 (2019) 029
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BAO + BBN

Picture from late 2019

What changed?

→ New BBN results from LUNA experiment

→ New BAO from DR16

20% tighter constraints now!

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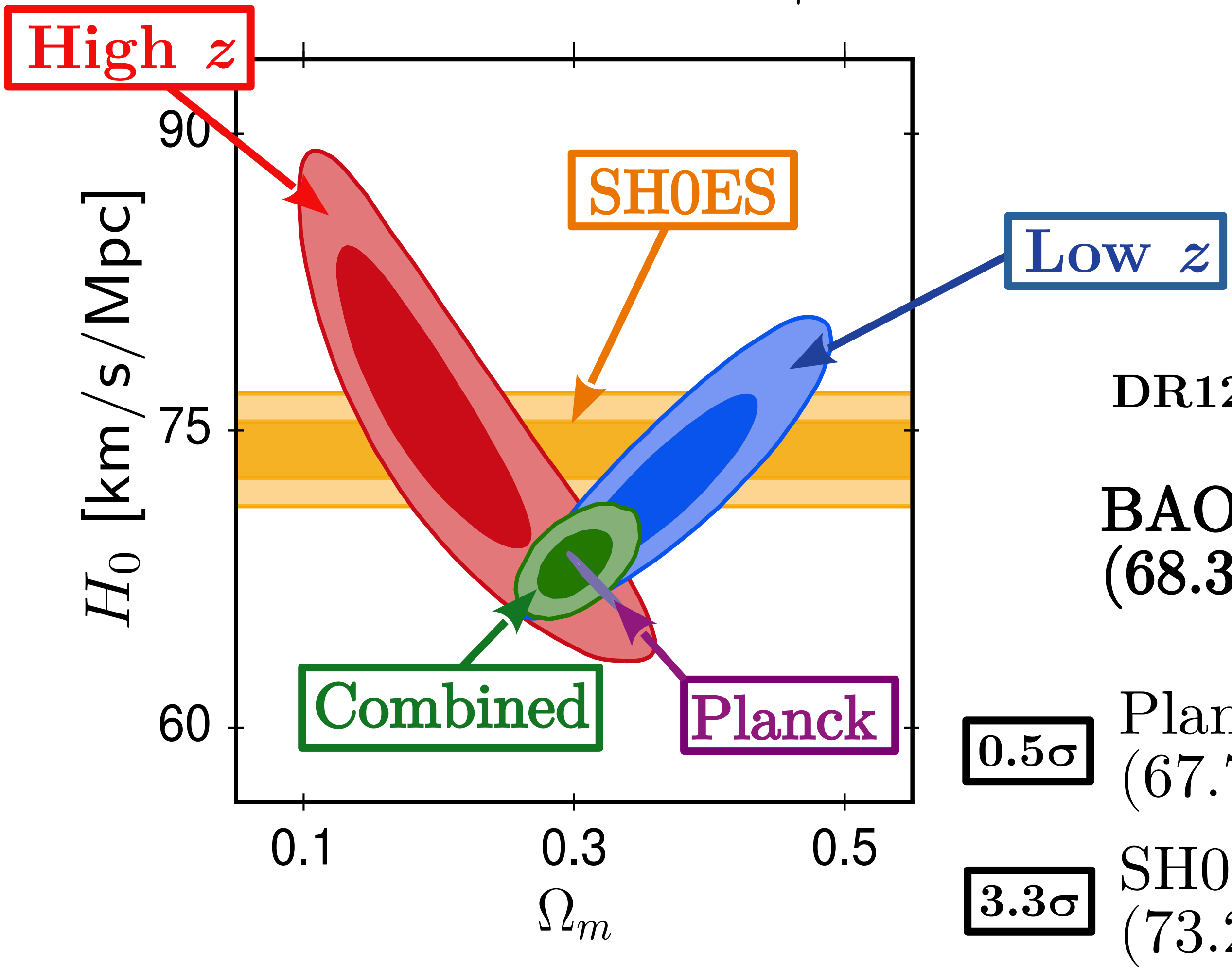
BAO + BBN



DR12 + no LUNA

BAO+BBN
(68.3 ± 1.1) km/s/Mpc

0.5σ Planck (2018):
(67.7 ± 0.4) km/s/Mpc

3.3σ SH0ES (2022):
(73.2 ± 1.0) km/s/Mpc

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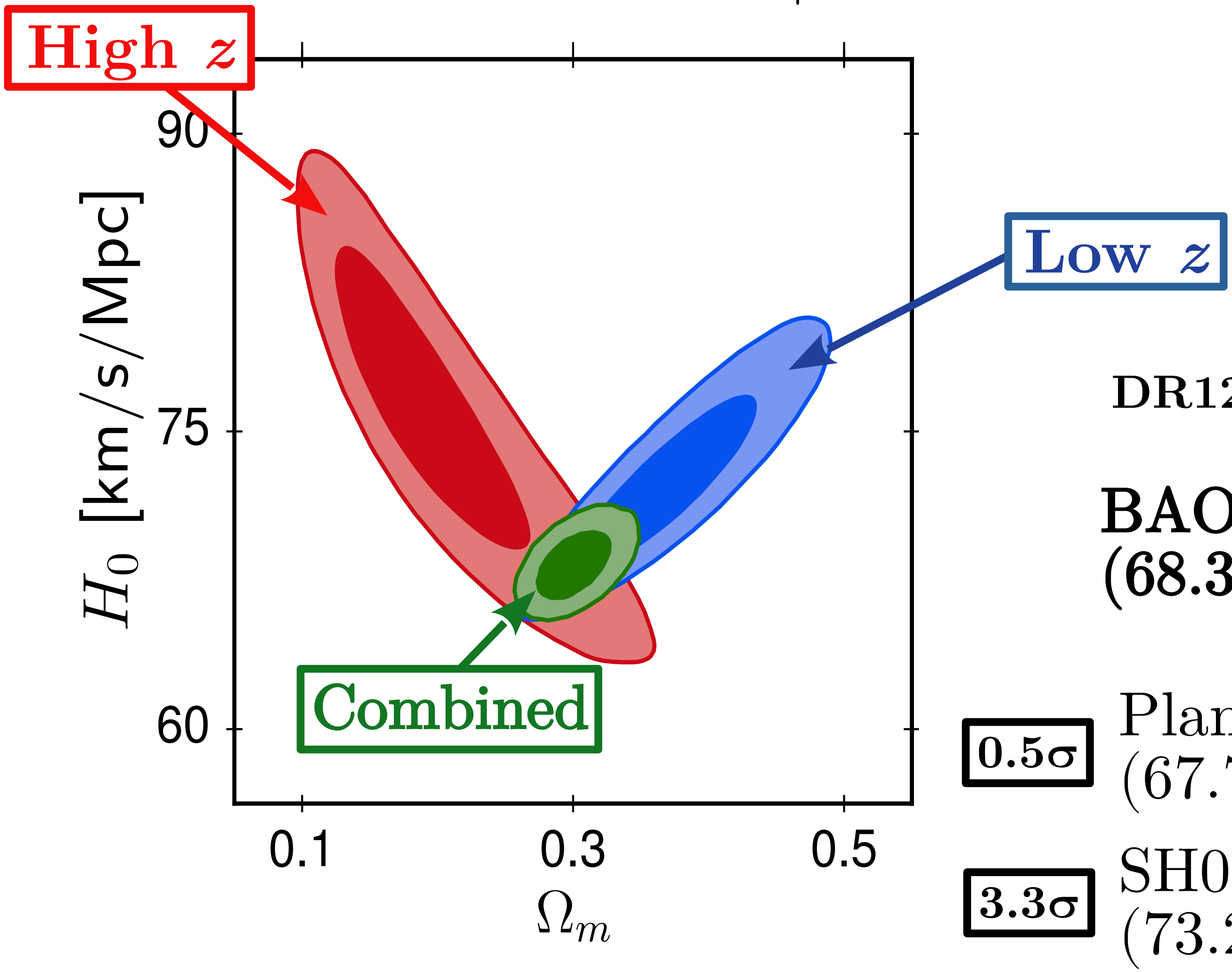
BAO + BBN



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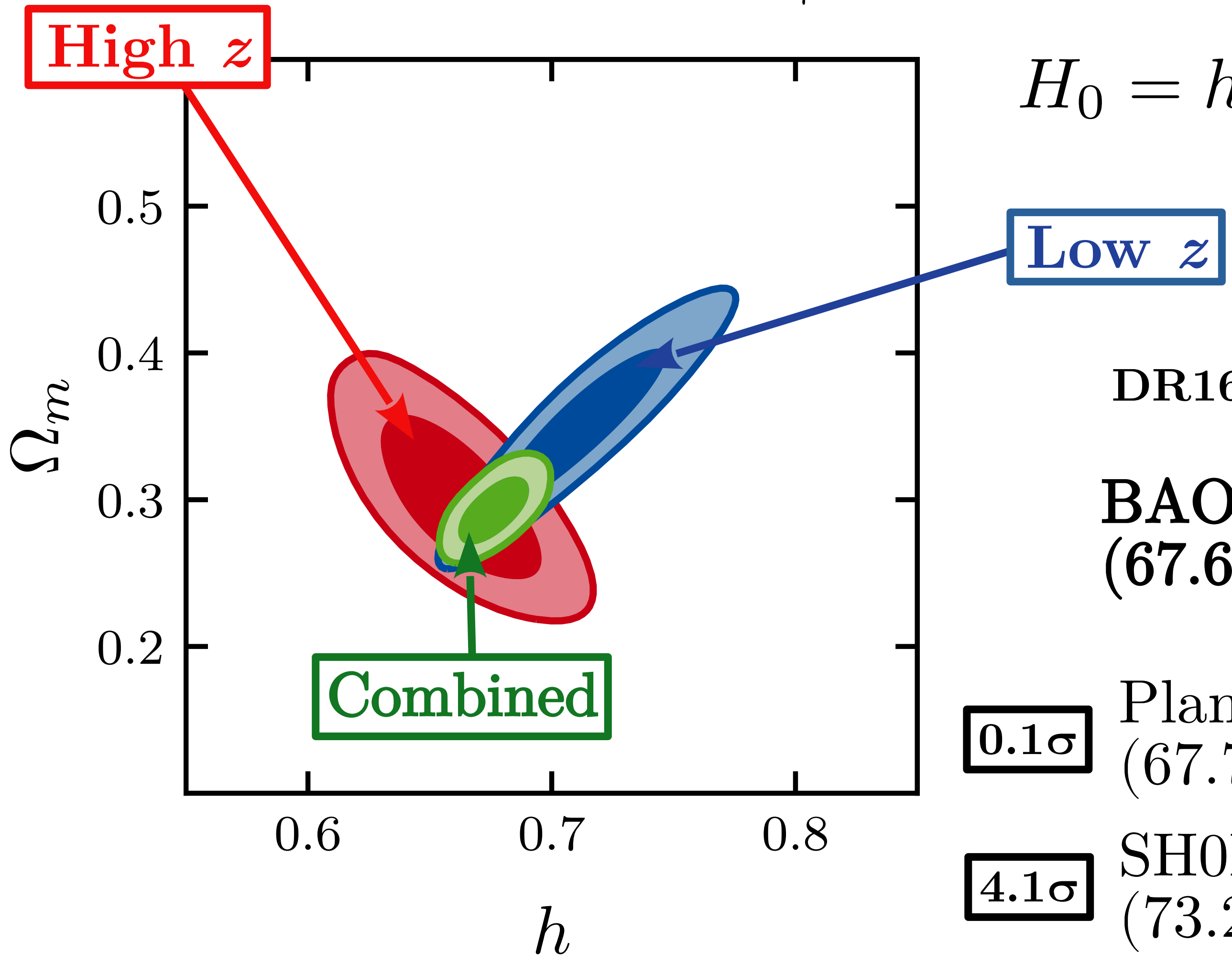
BAO + BBN



$H_0 = h \cdot 100\text{km/s/Mpc}$

DR16 + LUNA

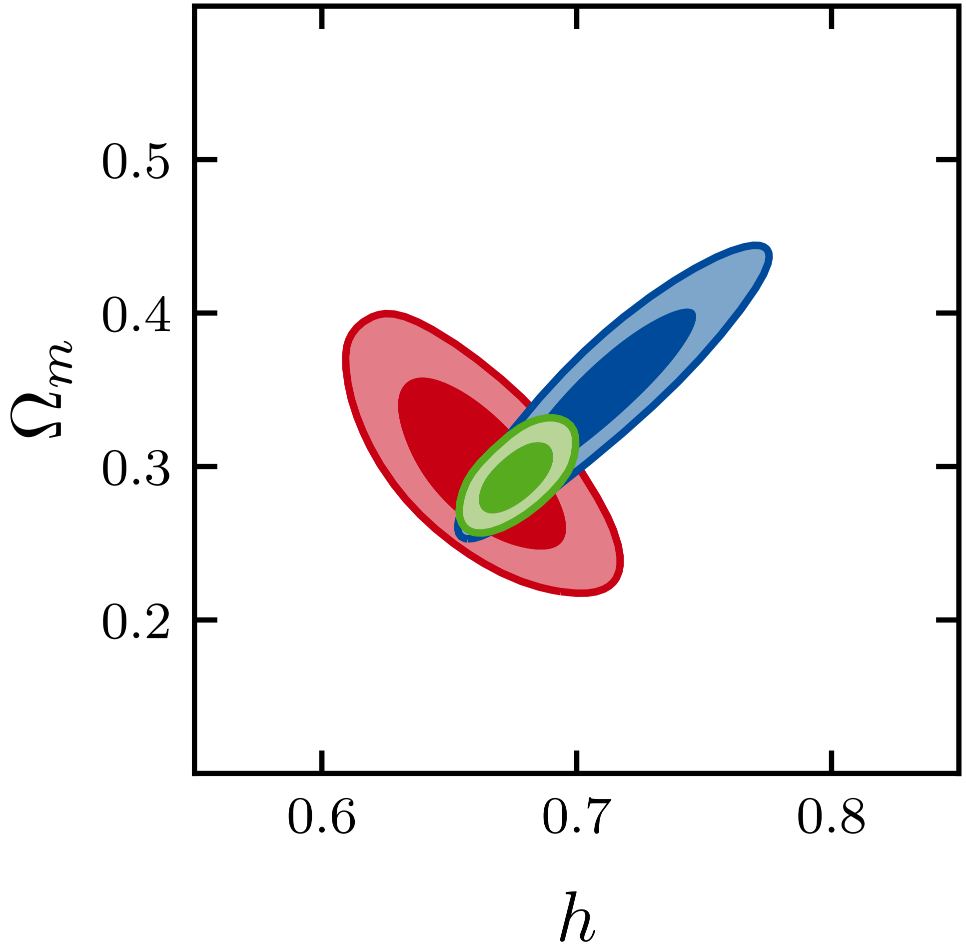
BAO+BBN (new)
(67.6 ± 1.0) km/s/Mpc

0.1σ Planck (2018):
(67.7 ± 0.4) km/s/Mpc

4.1σ SH0ES (2022):
(73.2 ± 1.0) km/s/Mpc

arXiv:2209.14330 → Accepted in JCAP
Nils Schöneberg, Licia Verde, Hector Gil-Marín, Samuel Brieden

BAO + BBN



DR16 + LUNA

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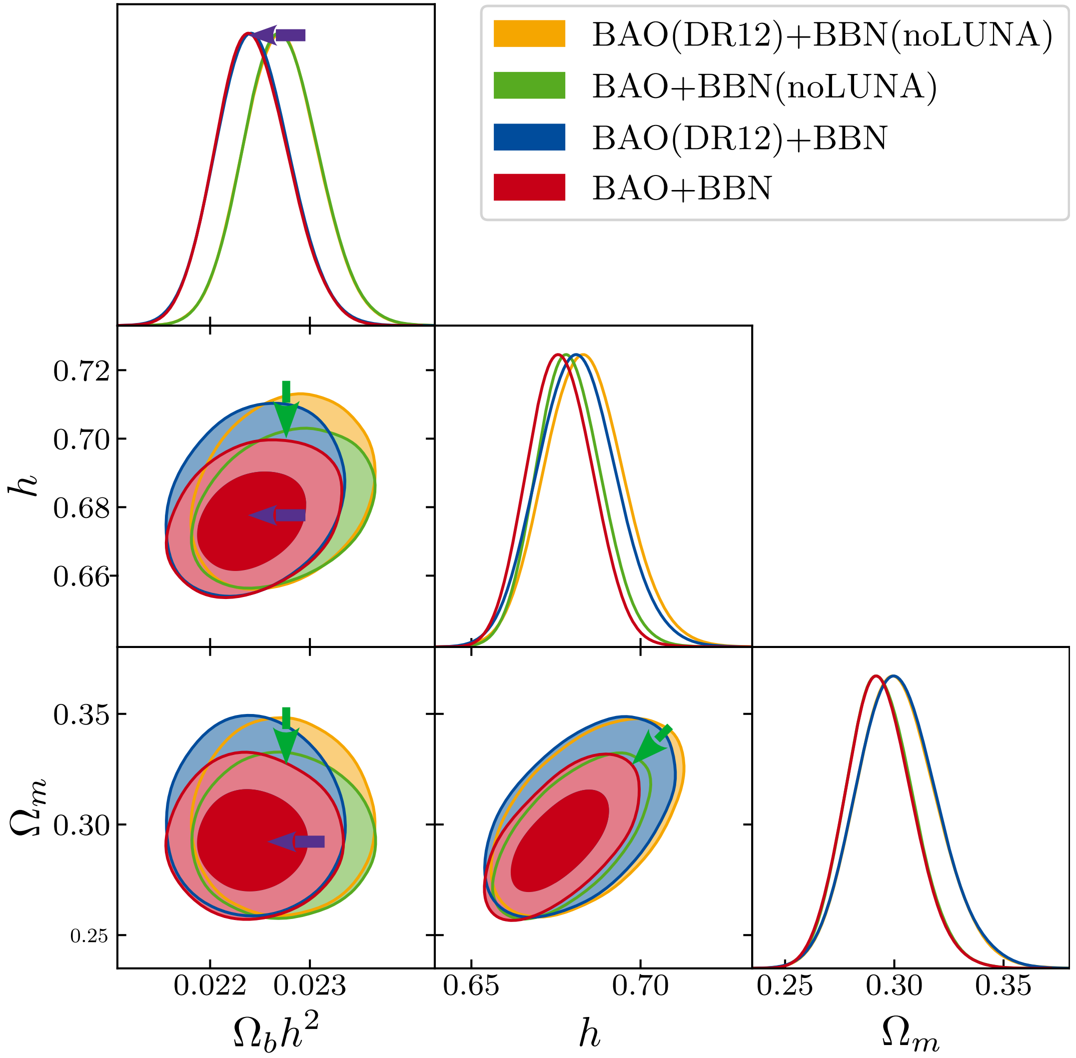
Nils Schöneberg, Licia Verde, Hector Gil-Marín, Samuel Brieden

POSSIBLE QUESTIONS

- Why did constraint increase? BBN or BAO?



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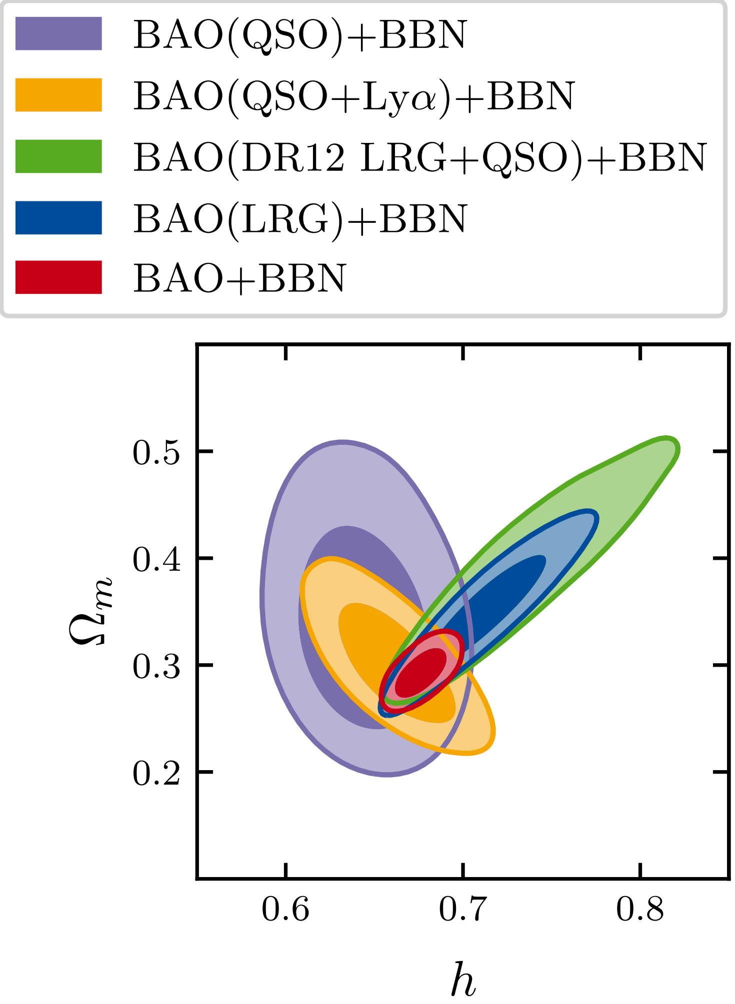
POSSIBLE QUESTIONS

- Why did constraint increase? BBN or BAO?
- Why better agreement of contours?



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TOPICS

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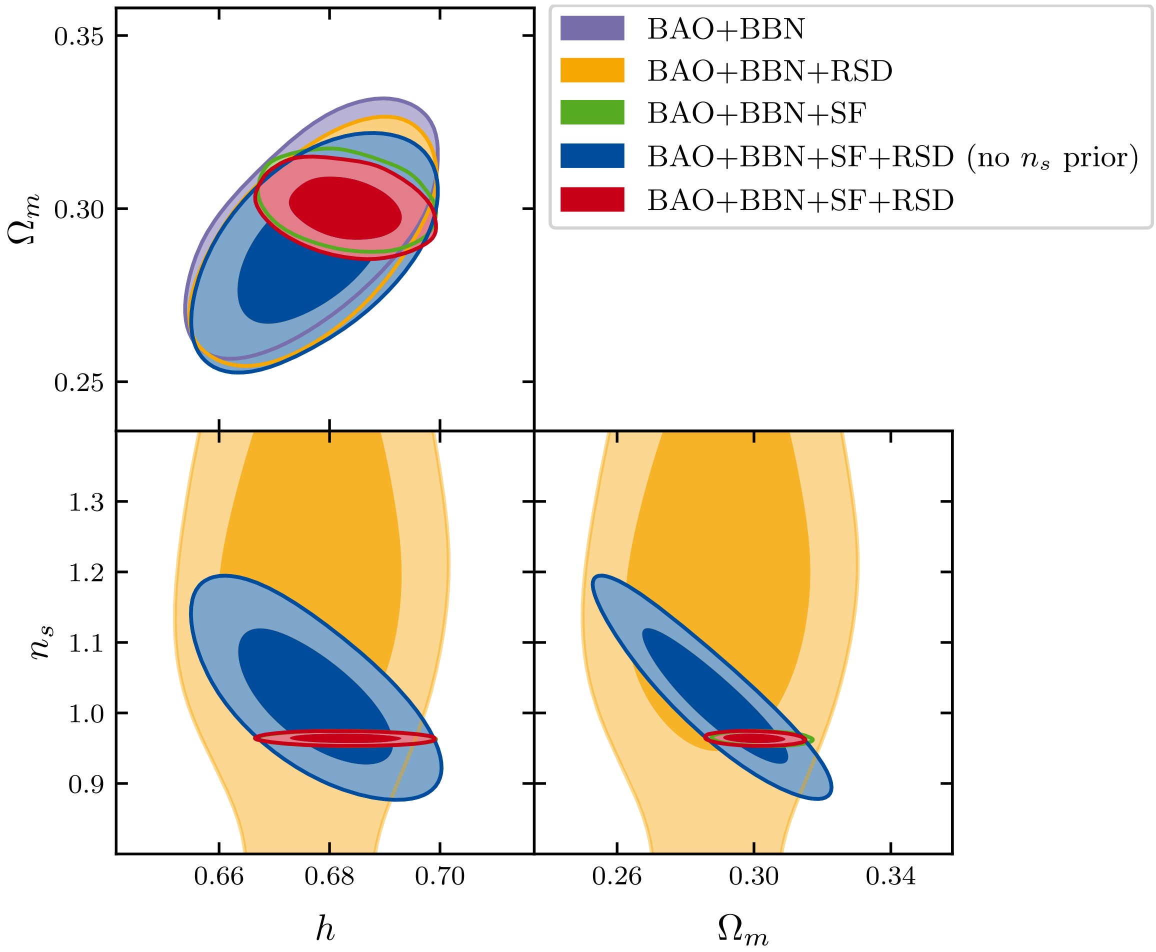
COMBINING BAO+BBN



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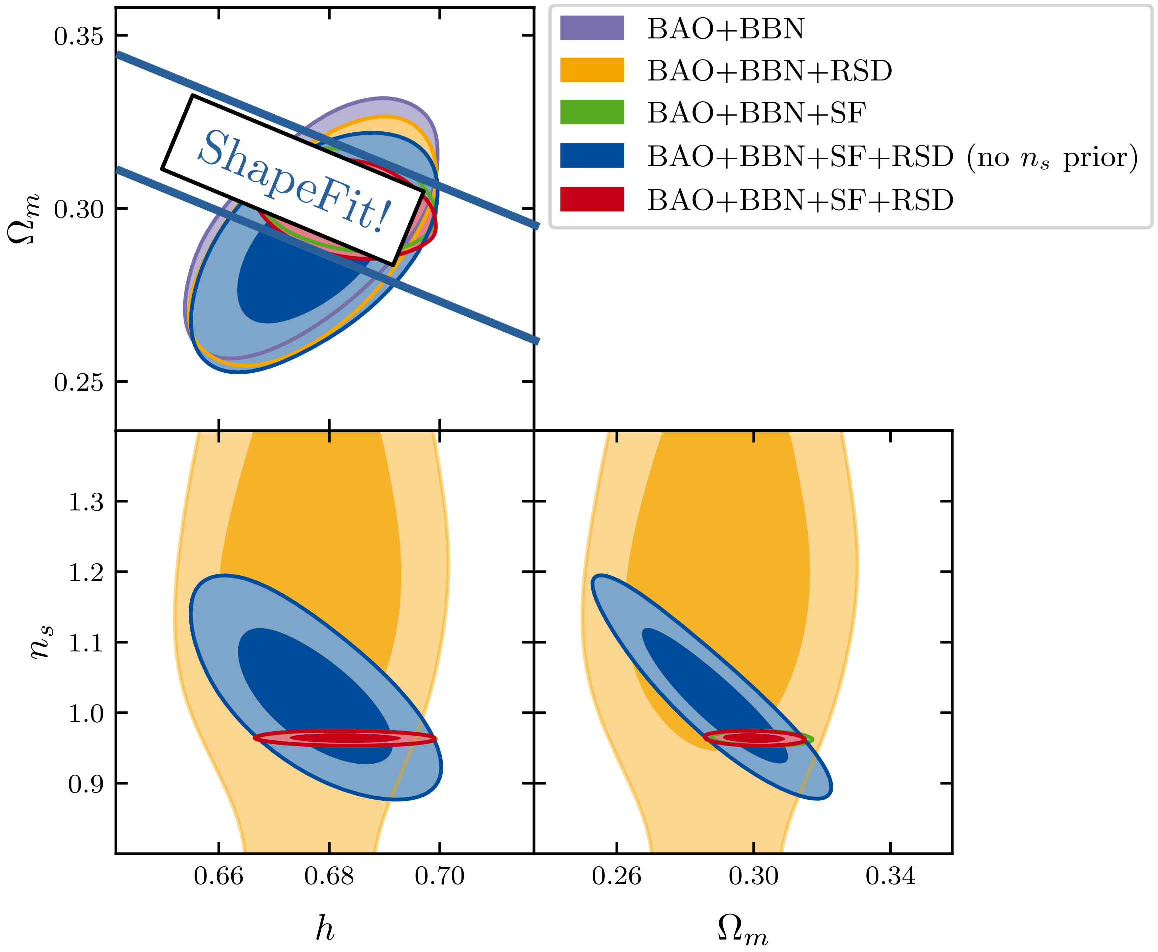
Nils Schöneberg, Licia Verde, Hector Gil-Marín, Samuel Brieden

COMBINING BAO+BBN



arXiv:2209.14330 → Accepted in JCAP
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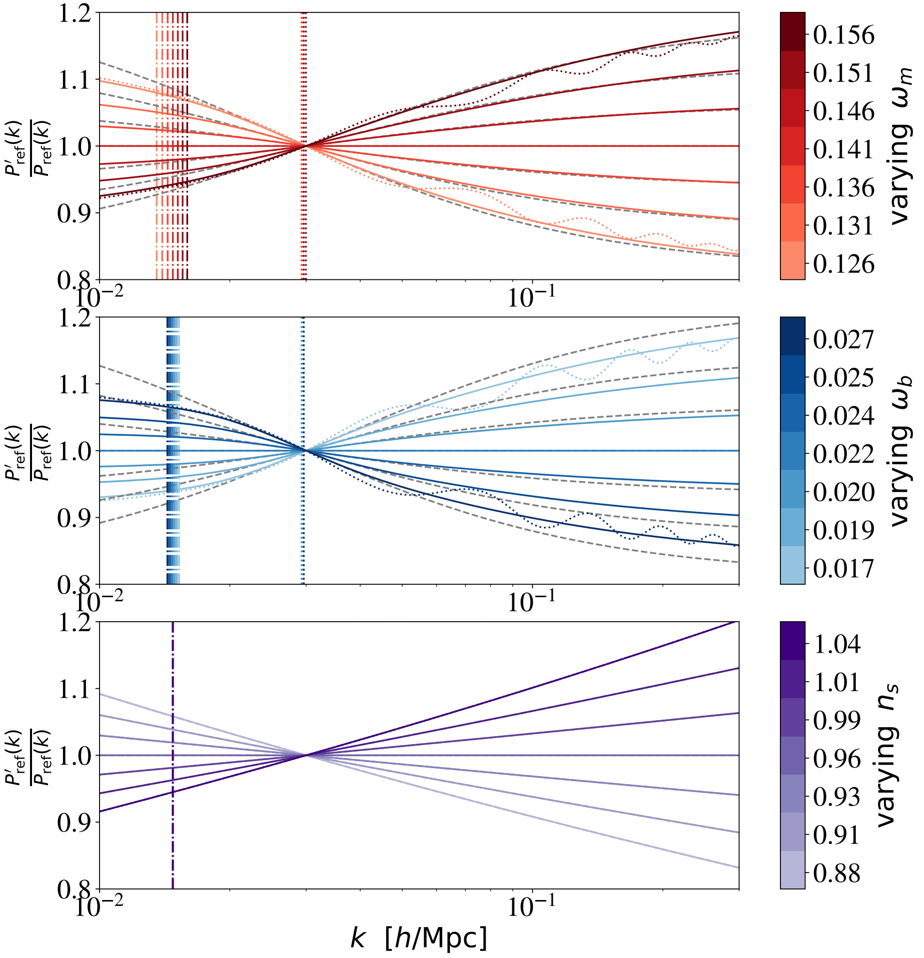


Slope at k=0.03h/Mpc

Effects:

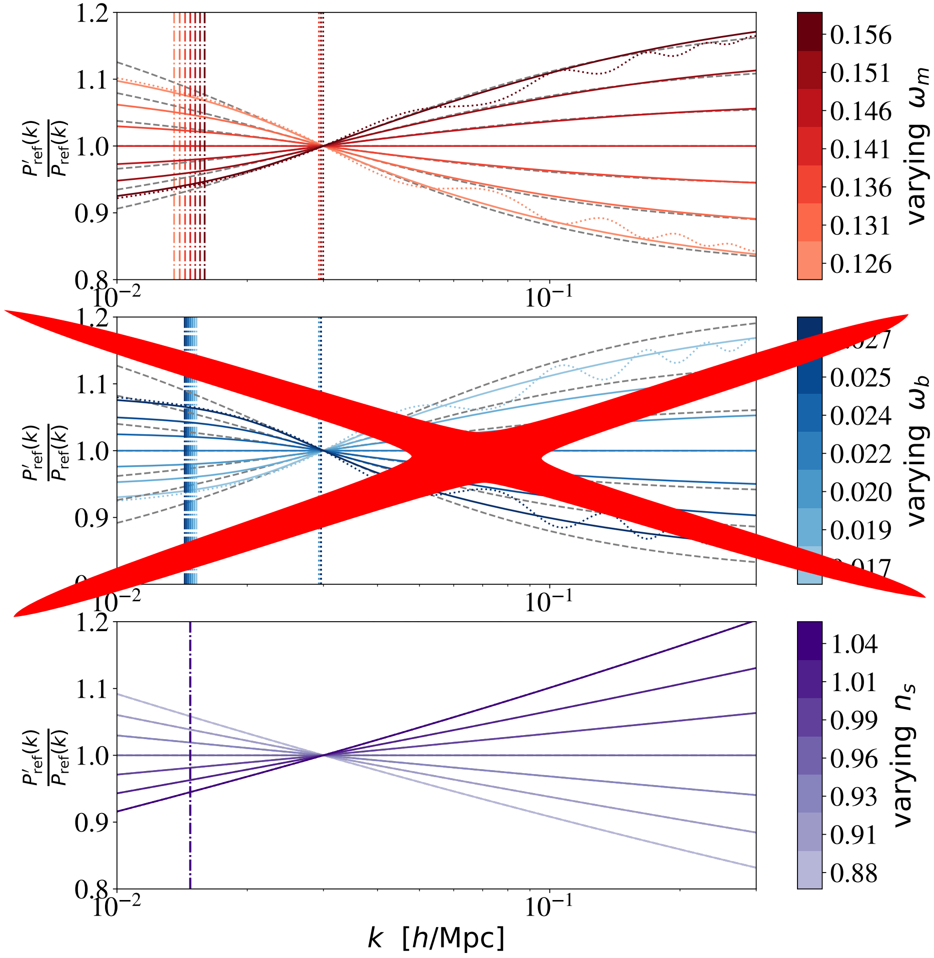
- Radiation-Matter equality
  $\Omega_{\rm m}{\rm h}^2 \rightarrow z_{\rm eq} \rightarrow k_{\rm eq} \rightarrow$ P(k) turn

- Baryon suppression
  $\Omega_{\rm b}{\rm h}^2/\Omega_{\rm m}{\rm h}^2 \rightarrow f_b \rightarrow$ P(k) dip

- Overall slope
  $n_s \rightarrow$ P(k) tilt

arXiv:2106.07641 → JCAP 12 (2021) 12, 054
Samuel Brieden, Héctor Gil-Marín, Licia Verde

Combining BAO+BBN



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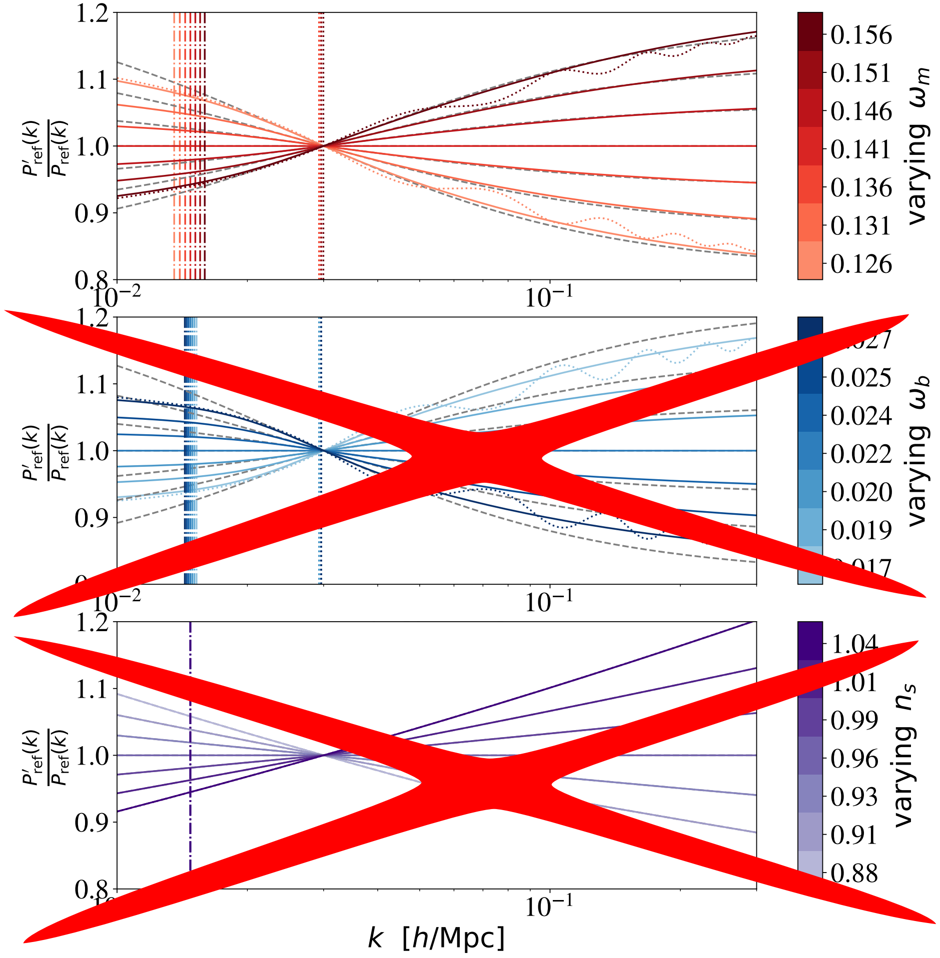

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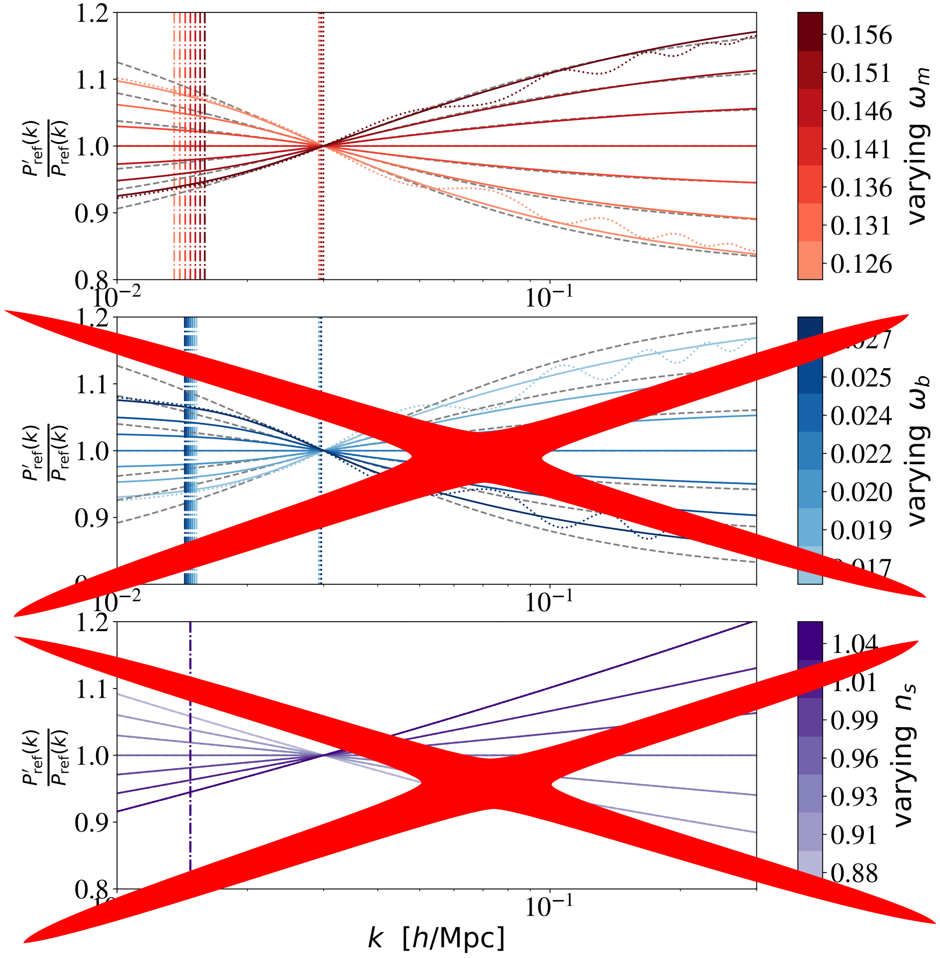

ShapeFit measures $\Omega_{\rm m}h^2$

Slope at k=0.03h/Mpc

Effects:

- Radiation-Matter equality
$\boxed{\Omega_{\rm m}h^2} \rightarrow z_{\rm eq} \rightarrow k_{\rm eq} \rightarrow$ P(k) turn

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$\cancel{\Omega_{\rm b}h^2}/\boxed{\Omega_{\rm m}h^2} \rightarrow f_b \rightarrow$ P(k) dip

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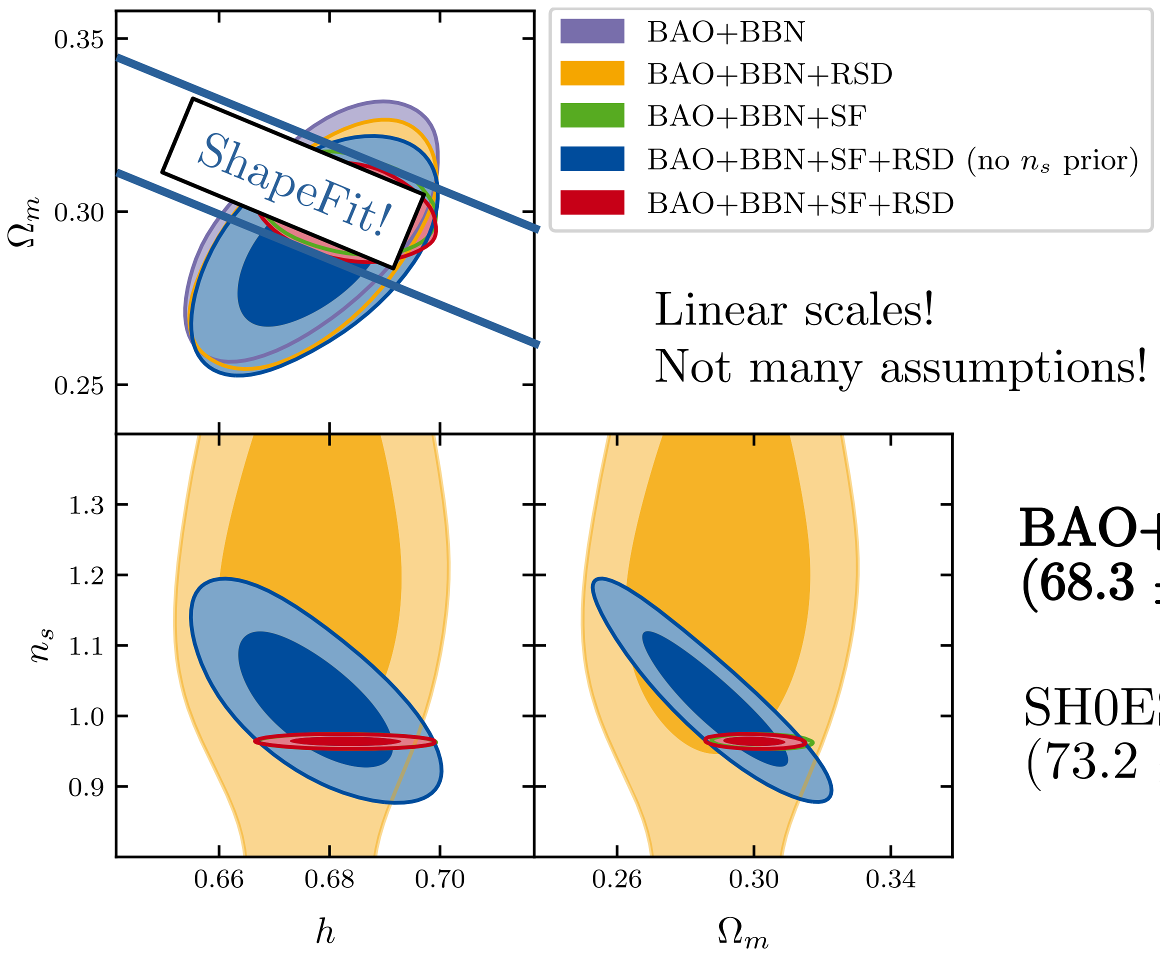

Linear scales!
Not many assumptions!

BAO+BBN (SF)
(68.3 ± 0.7) km/s/Mpc

SH0ES (2022): $\boxed{4.0\sigma}$
(73.2 ± 1.0) km/s/Mpc

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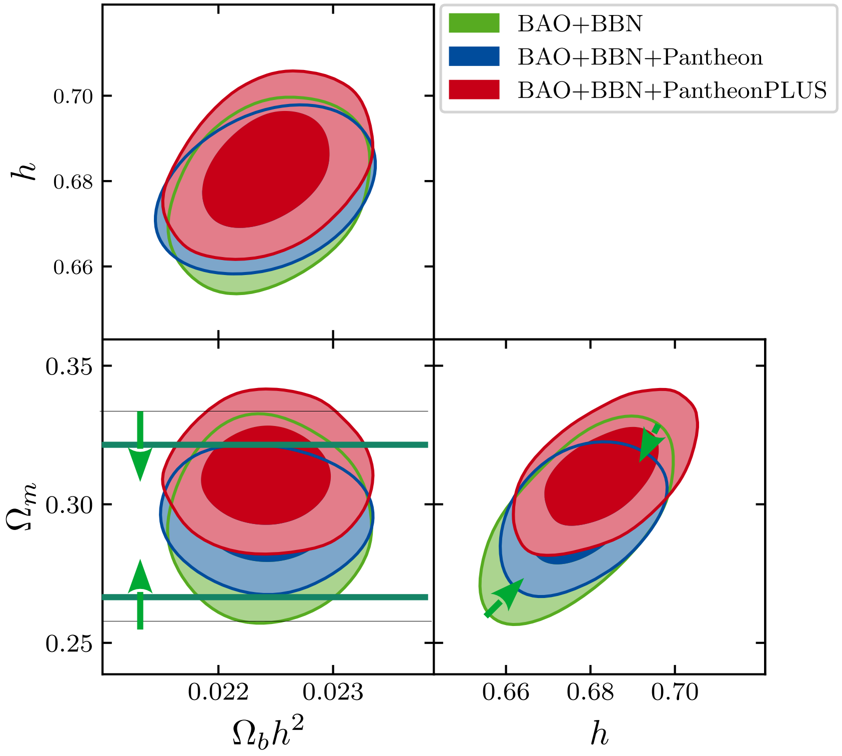
Combining BAO+BBN



Uncalibrated supernovae
Measure

$$H_0 D_L(z) = (1+z)\int_0^z \frac{dx}{\sqrt{\Omega_m[(1+x)^3-1]+1}}$$

$\rightarrow \Omega_\mathrm{m}$

BAO+BBN (Pantheon)
(67.8 ± 0.7) km/s/Mpc

SH0ES (2022): $\boxed{4.4\sigma}$
(73.2 ± 1.0) km/s/Mpc

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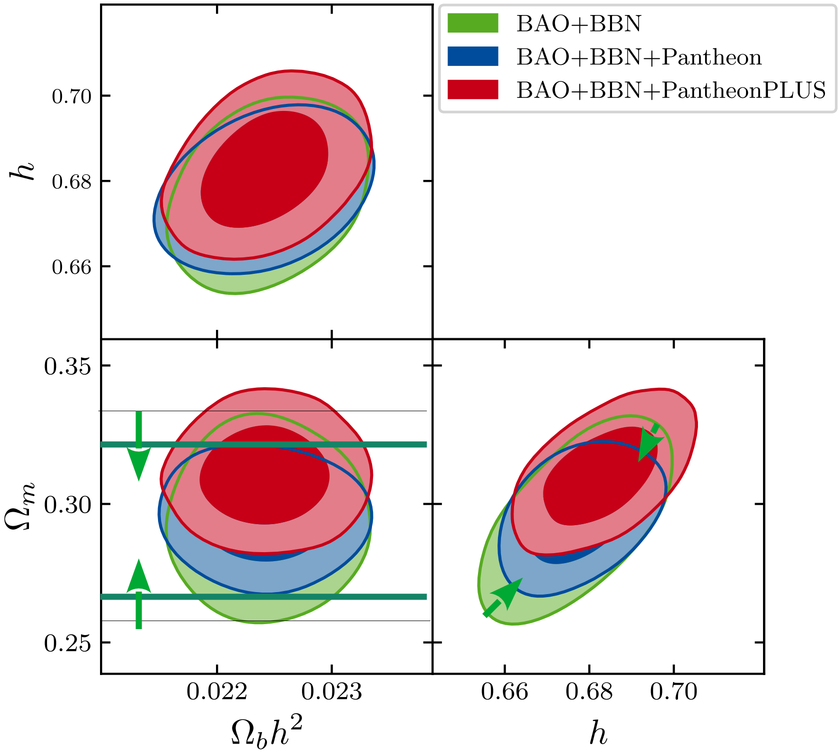
COMBINING BAO+BBN



Uncalibrated supernovae

Measure

$$H_0 D_L(z) = (1+z)\int_0^z \frac{dx}{\sqrt{\Omega_m[(1+x)^3-1]+1}}$$

$\rightarrow \Omega_\mathrm{m}$

BAO+BBN (PantheonPLUS)
(68.3 ± 0.9) km/s/Mpc

SH0ES (2022): $\boxed{\mathbf{3.6\sigma}}$
(73.2 ± 1.0) km/s/Mpc

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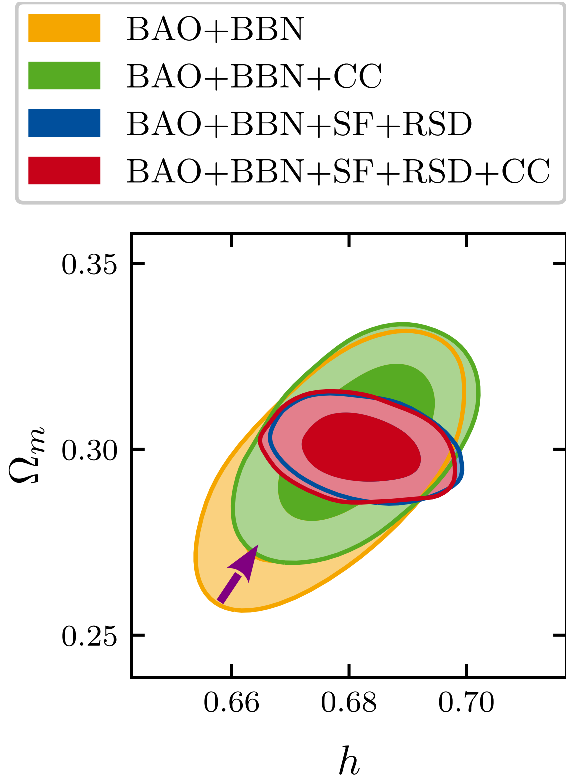
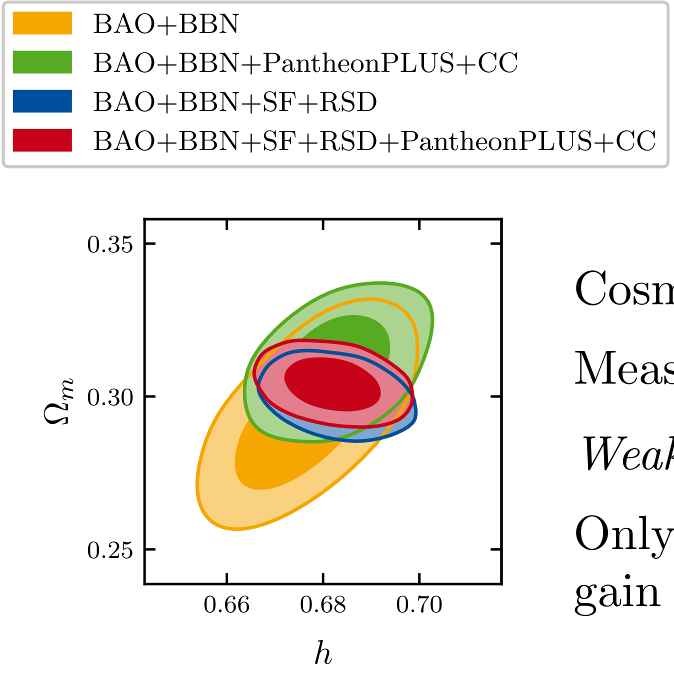
COMBINING BAO+BBN





Cosmic Chronometers

Measure H(z) → Ω_{m} , h

Weak measurement

Only when no SF we gain constraining power

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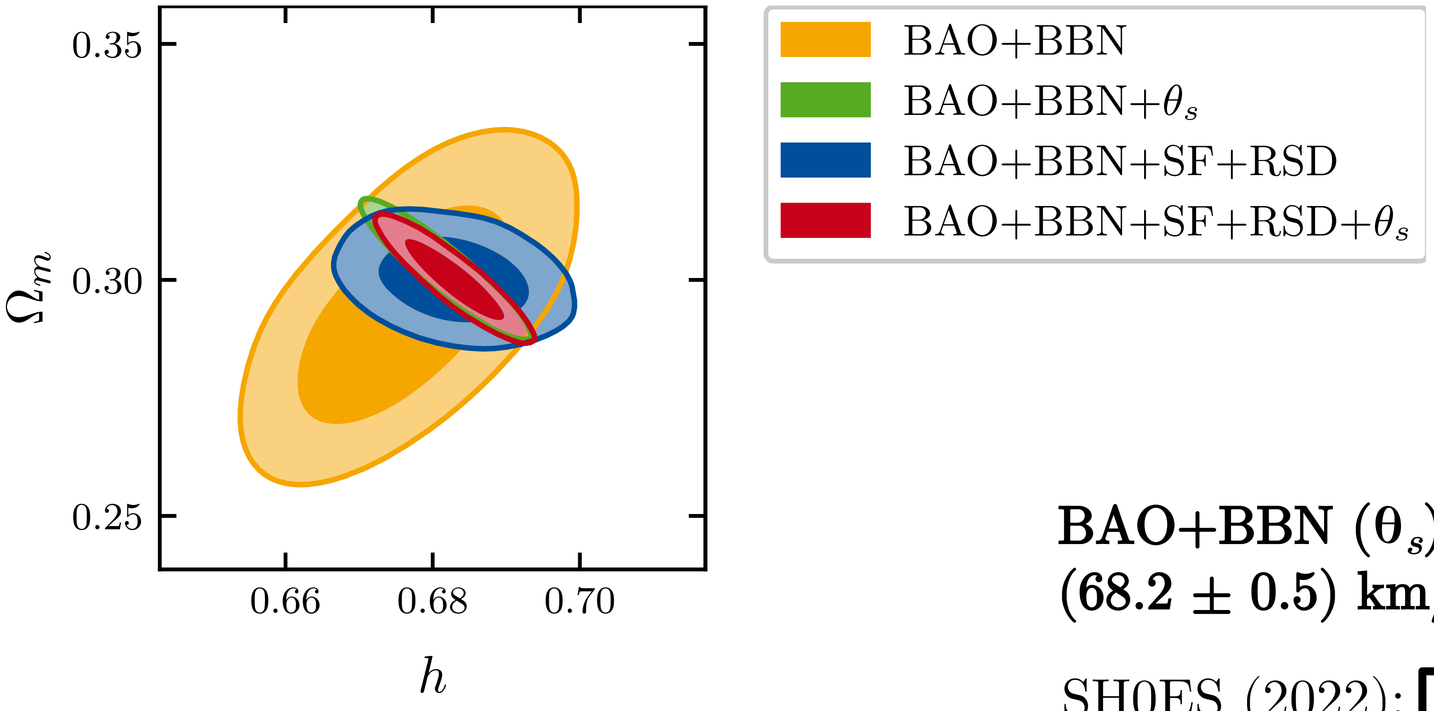
COMBINING BAO+BBN



BAO+BBN (θ_s)
(68.2 ± 0.5) km/s/Mpc

SH0ES (2022): $\boxed{\mathbf{4.5\sigma}}$
(73.2 ± 1.0) km/s/Mpc

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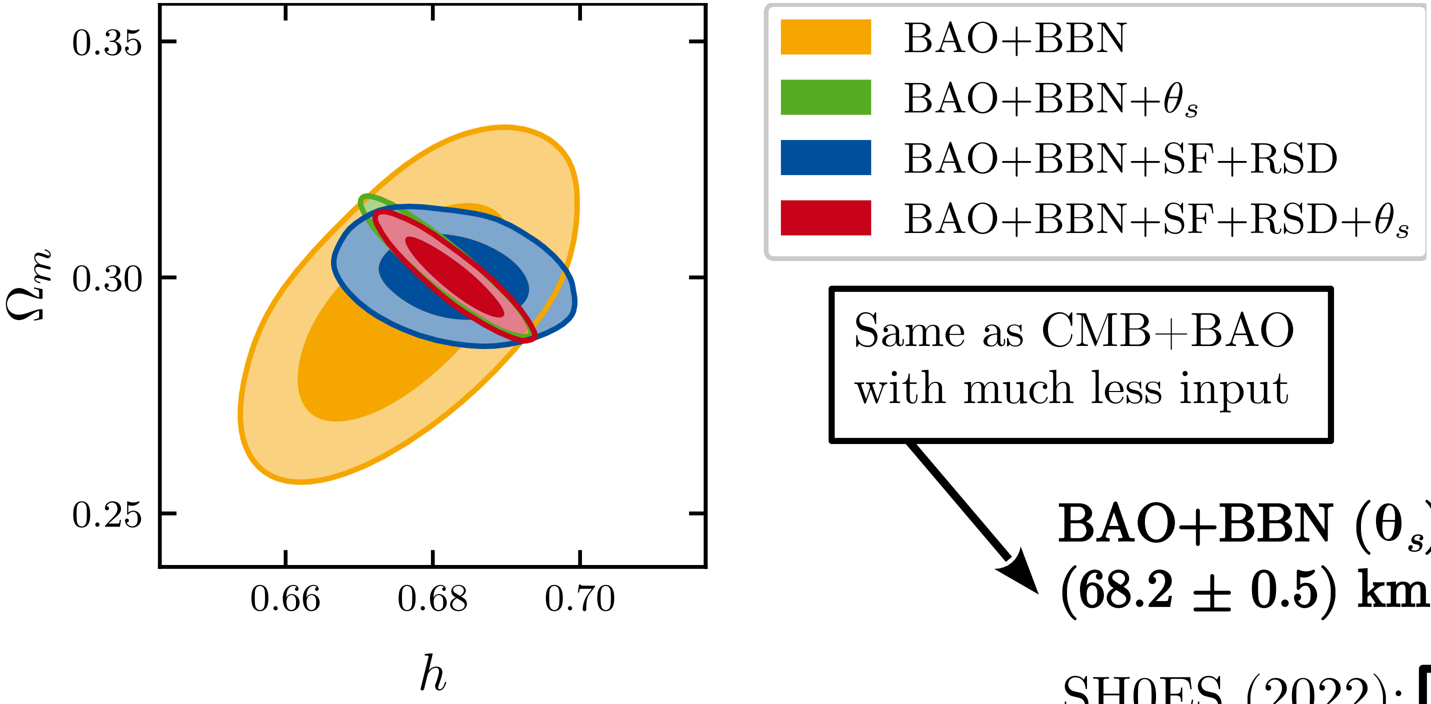
COMBINING BAO+BBN



Same as CMB+BAO
with much less input

BAO+BBN (θ_s)
(68.2 ± 0.5) km/s/Mpc

SH0ES (2022): **$\boxed{4.5\sigma}$**
(73.2 ± 1.0) km/s/Mpc

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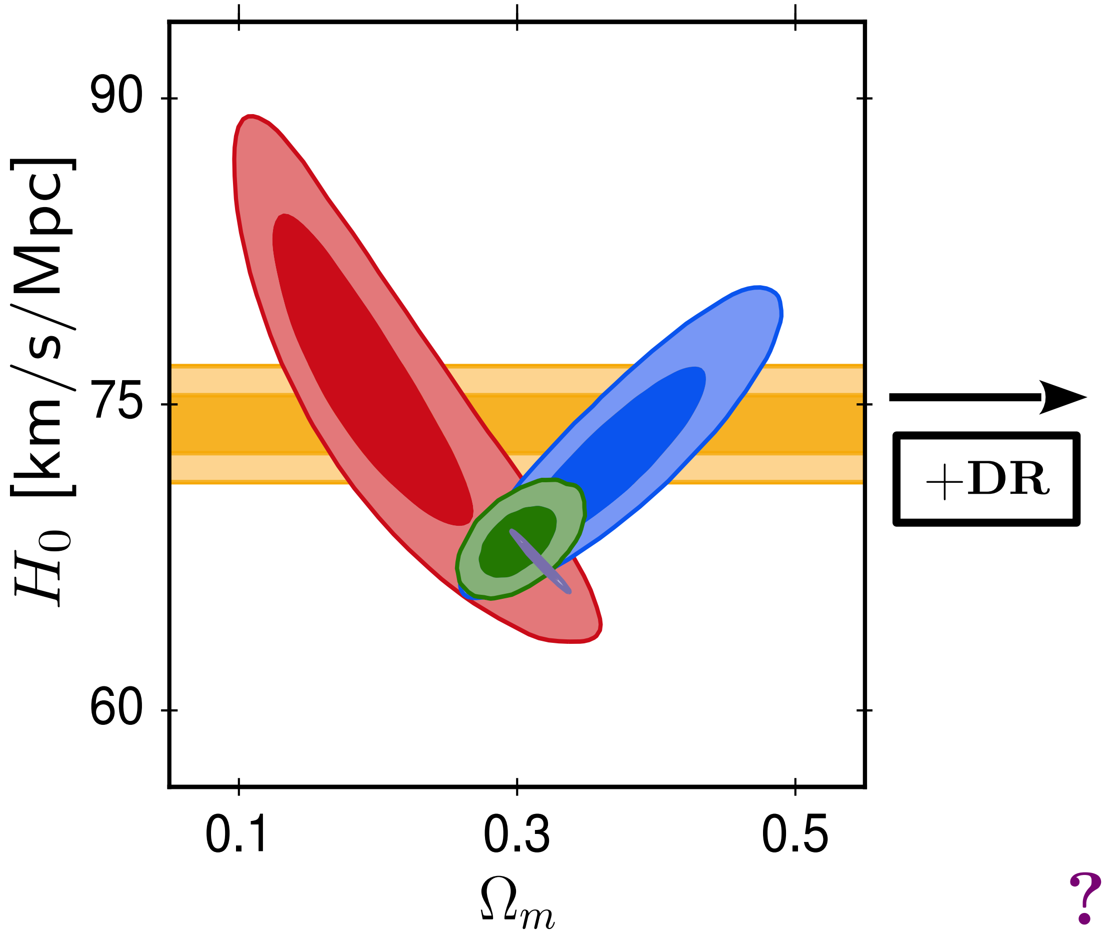
TOPICS

- Quick motivation
- The BAO principle
- The BBN principle
- Why do BAO+BBN combine so well?
- What aids this probe?
- What breaks this probe?

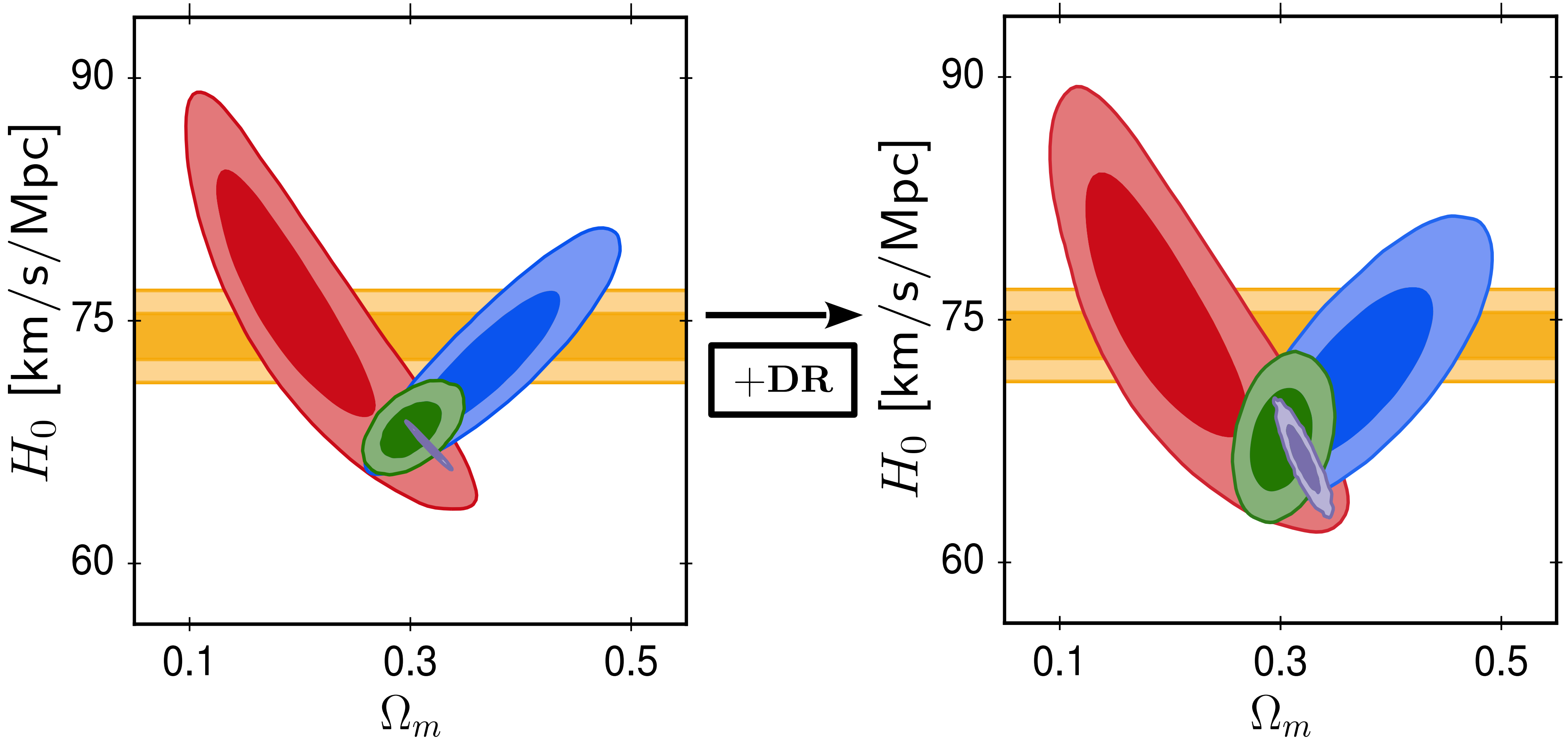
BAO + BBN



$$H_0\ r_s \overset{?}{\rightarrow} H_0$$

arXiv:1907.11594 → JCAP 10 (2019) 029
Nils Schöneberg, Julien Lesgourgues, Deanna C. Hooper

BAO + BBN



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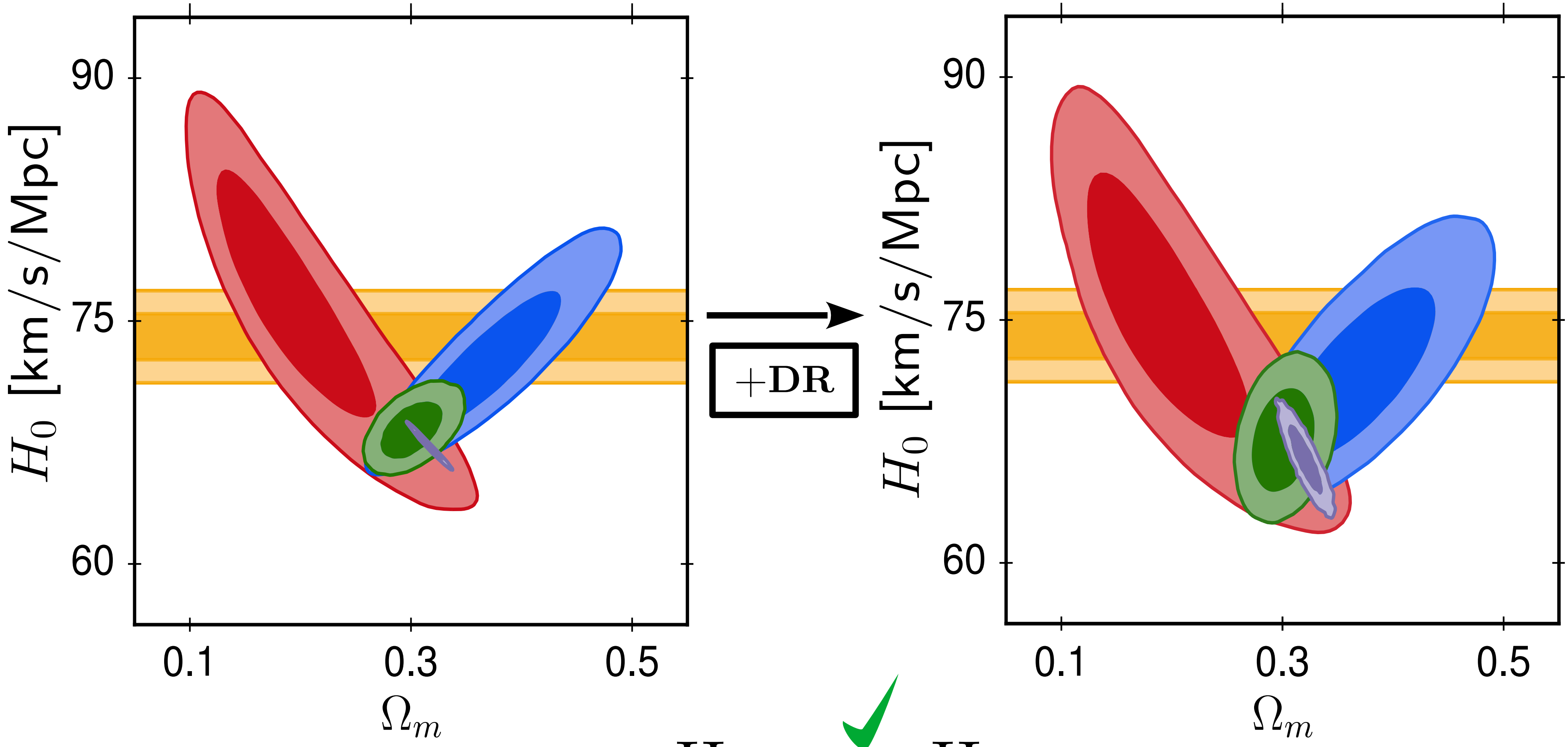
BAO + BBN



$$H_0\ r_s \overset{\checkmark}{\rightarrow} H_0$$

arXiv:1907.11594 → JCAP 10 (2019) 029
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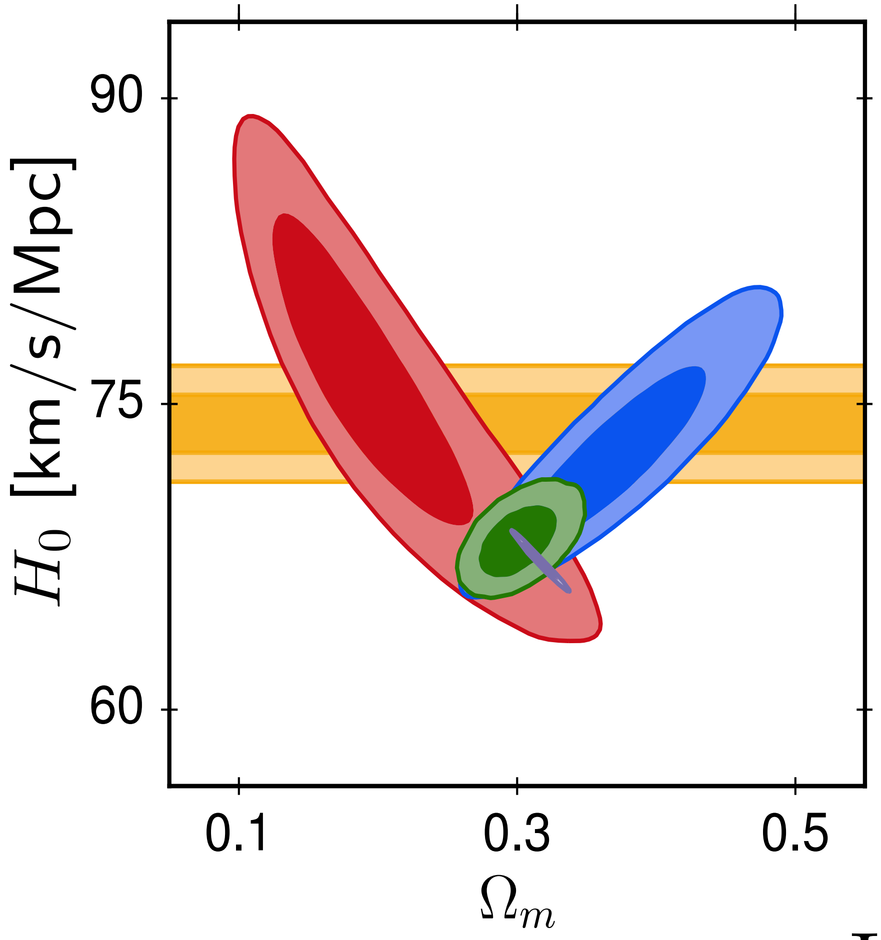
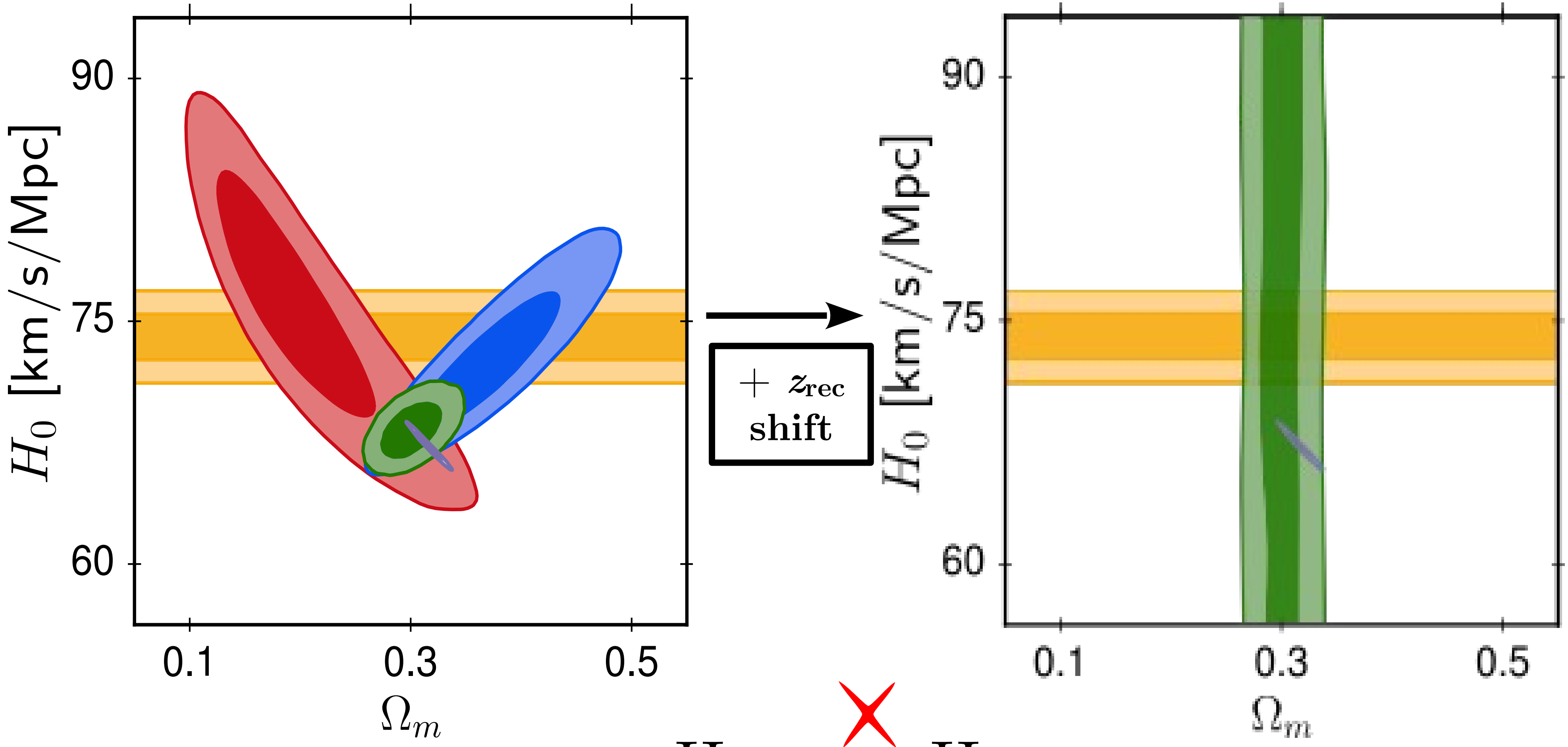
BAO + BBN



+ z_{rec}
shift

$$\mathrm{H}_0\ \mathrm{r}_\mathrm{s} \overset{?}{\rightarrow} \mathrm{H}_0$$

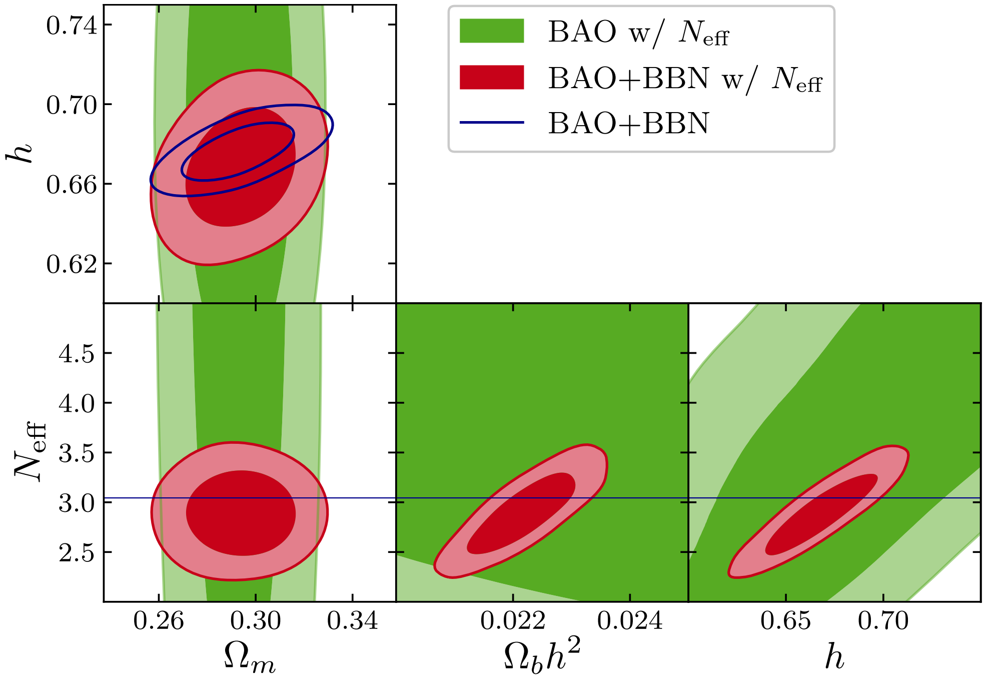
BAO + BBN



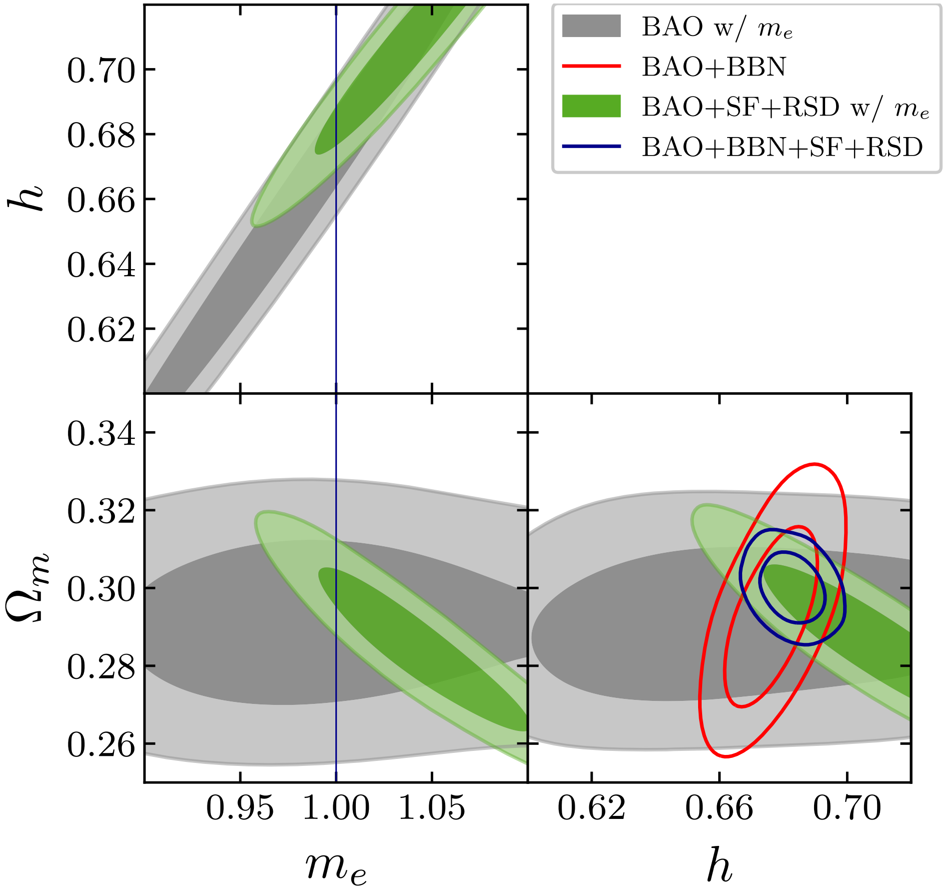
$+\ z_{\mathrm{rec}}$ **shift**

$$\mathrm{H}_0\ \mathrm{r}_\mathrm{s} \overset{\times}{\rightarrow} \mathrm{H}_0$$

BAO+BBN

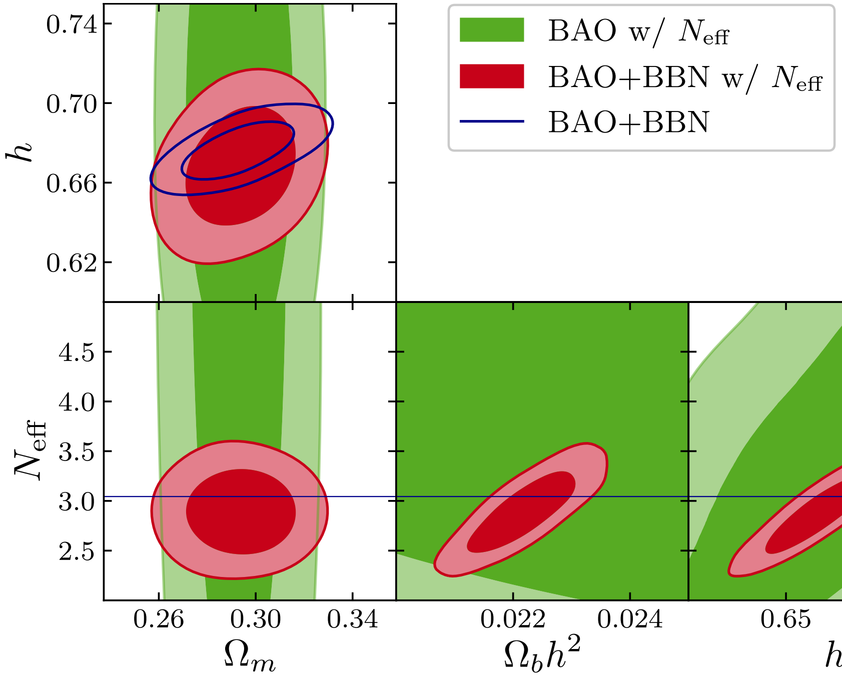


$\mathbf{N_{eff}}$

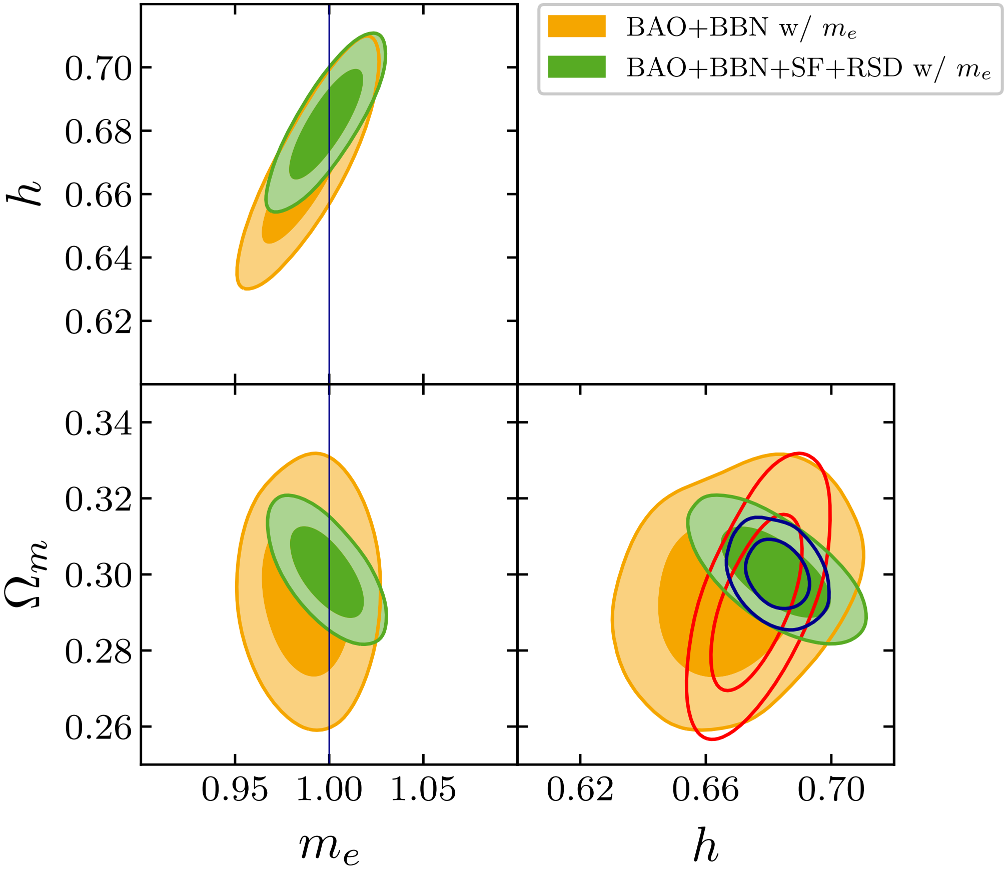


$\boldsymbol{m_e}$

BAO+BBN

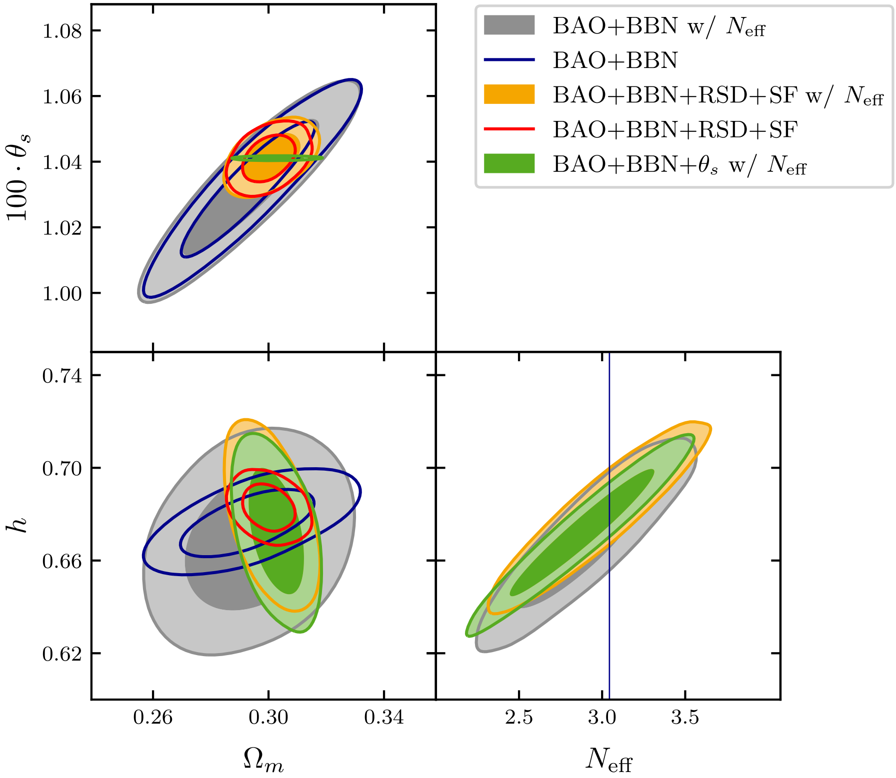


$N_{\rm eff}$

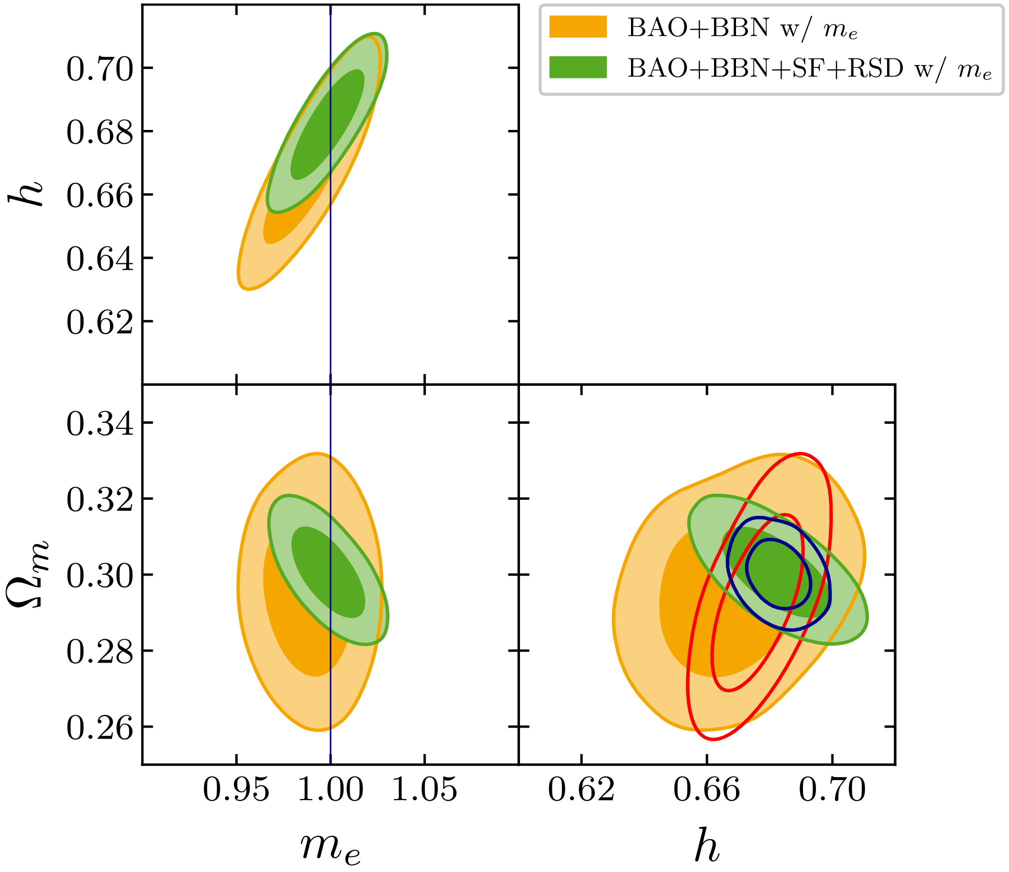


m_e

BAO+BBN



$N_{\rm eff}$



m_e

CONCLUSIONS

- BAO+BBN most precise non-CMB probe

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- Model dependence if r_s modified without BBN