Nils Schöneberg Rome, Wednesday 14.02.2024 nils.science@gmail.com

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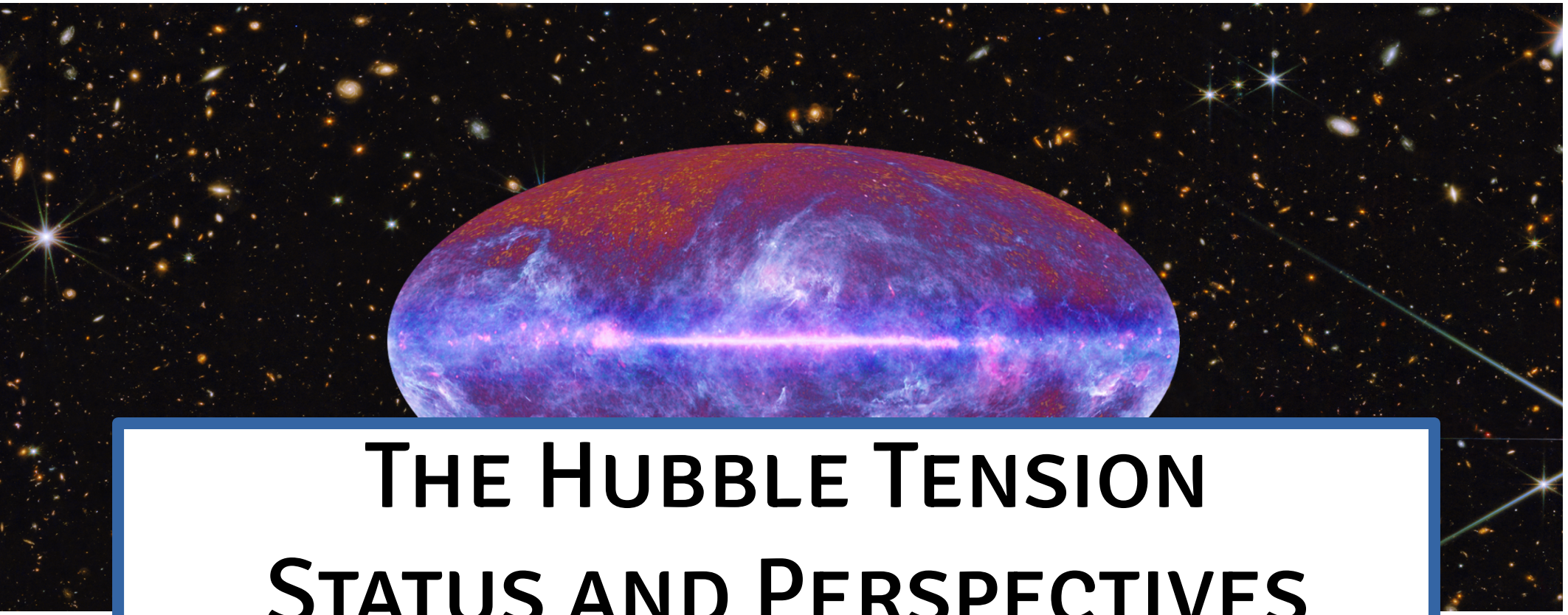
ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020-2023



The Hubble Tension
Status and Perspectives

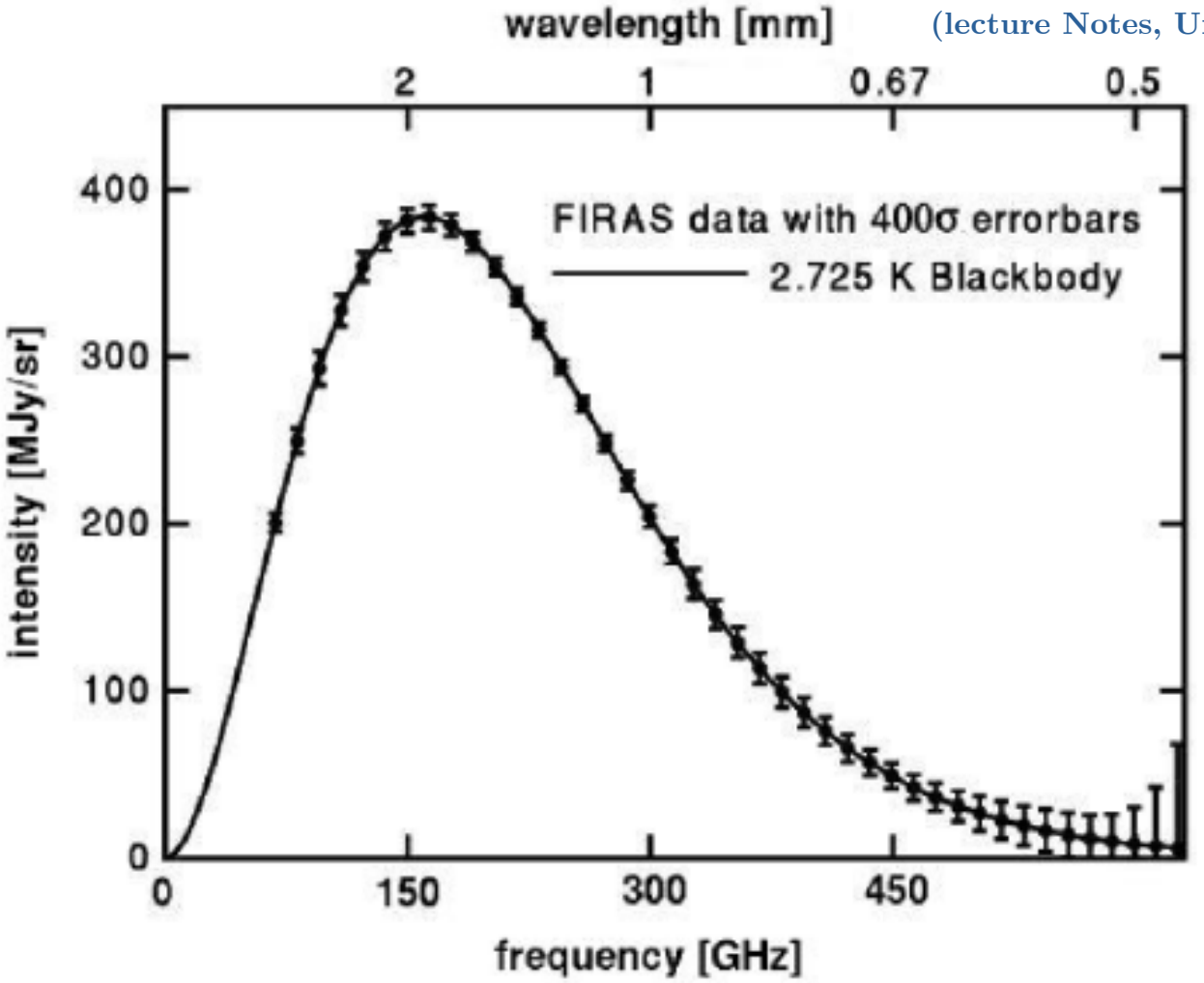
https://plancksatellite.org.uk/science/ and https://science.nasa.gov/mission/webb/multimedia/images/#first-images

IN THIS TALK:

- What is the Hubble tension?
  - The CMB side
  - Local distance ladder and standard candles
- Probes of the Hubble tension
  - BAO+BBN
  - Other probes of the expansion rates
- What can we expect in the future?

The CMB

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



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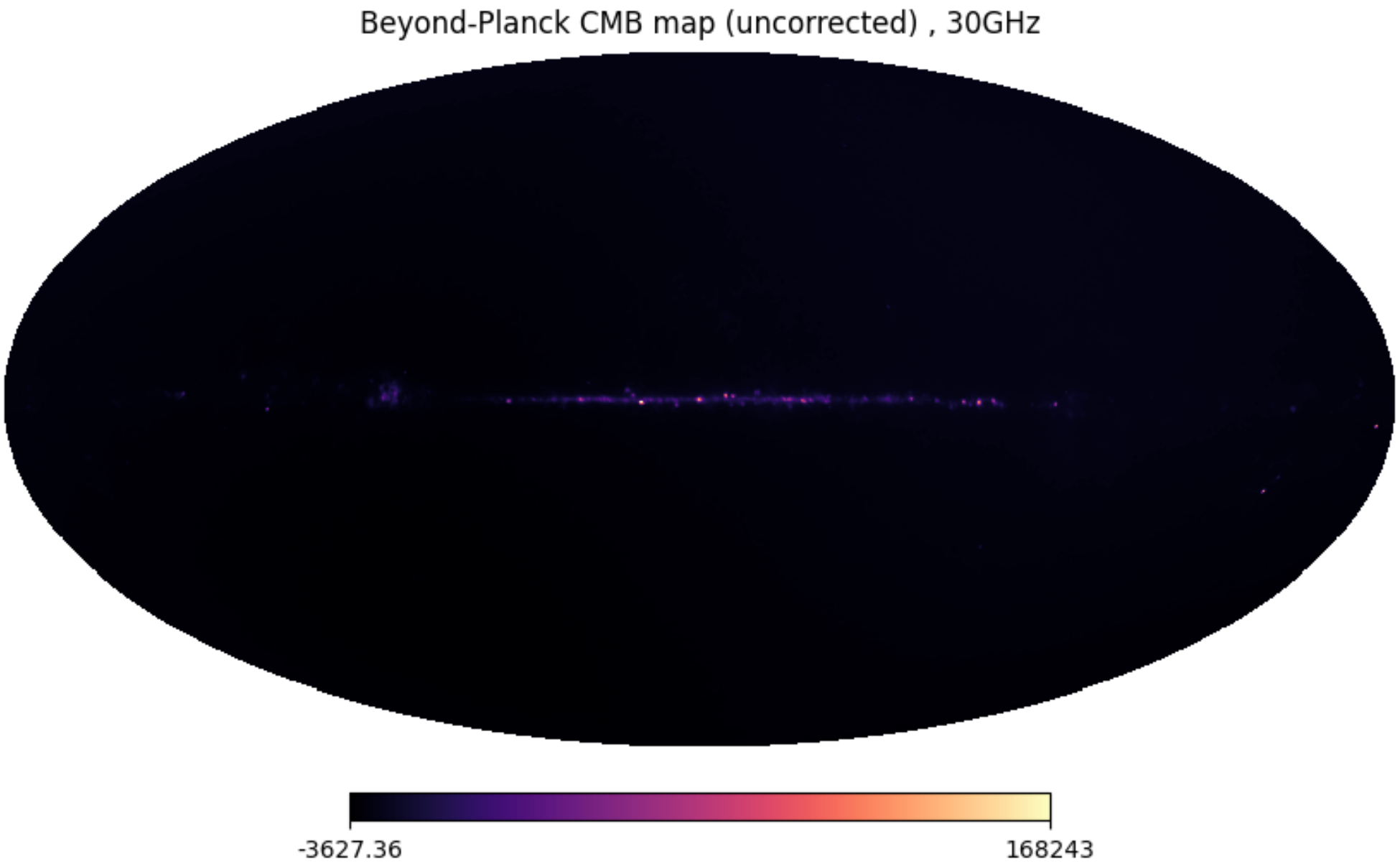

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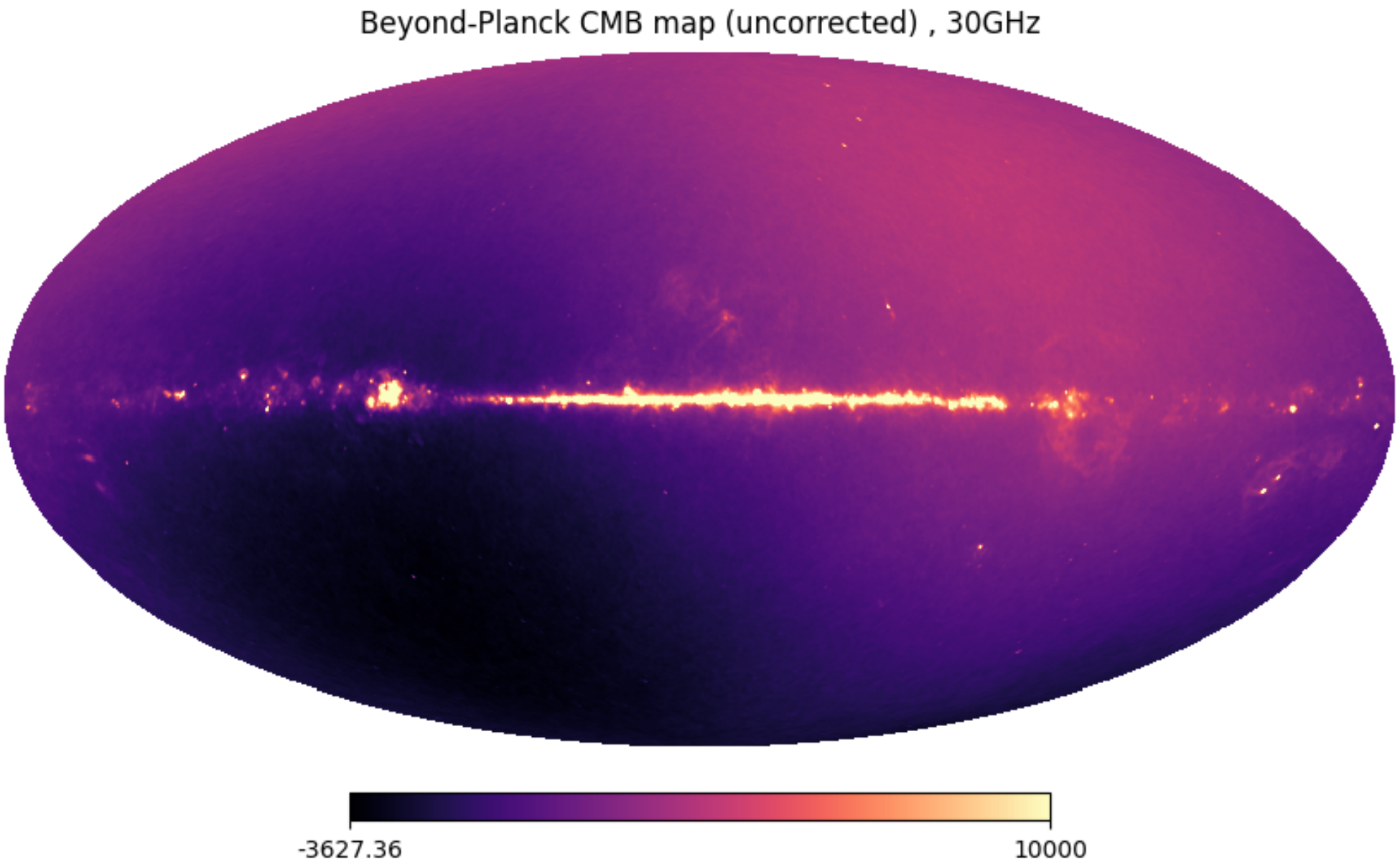

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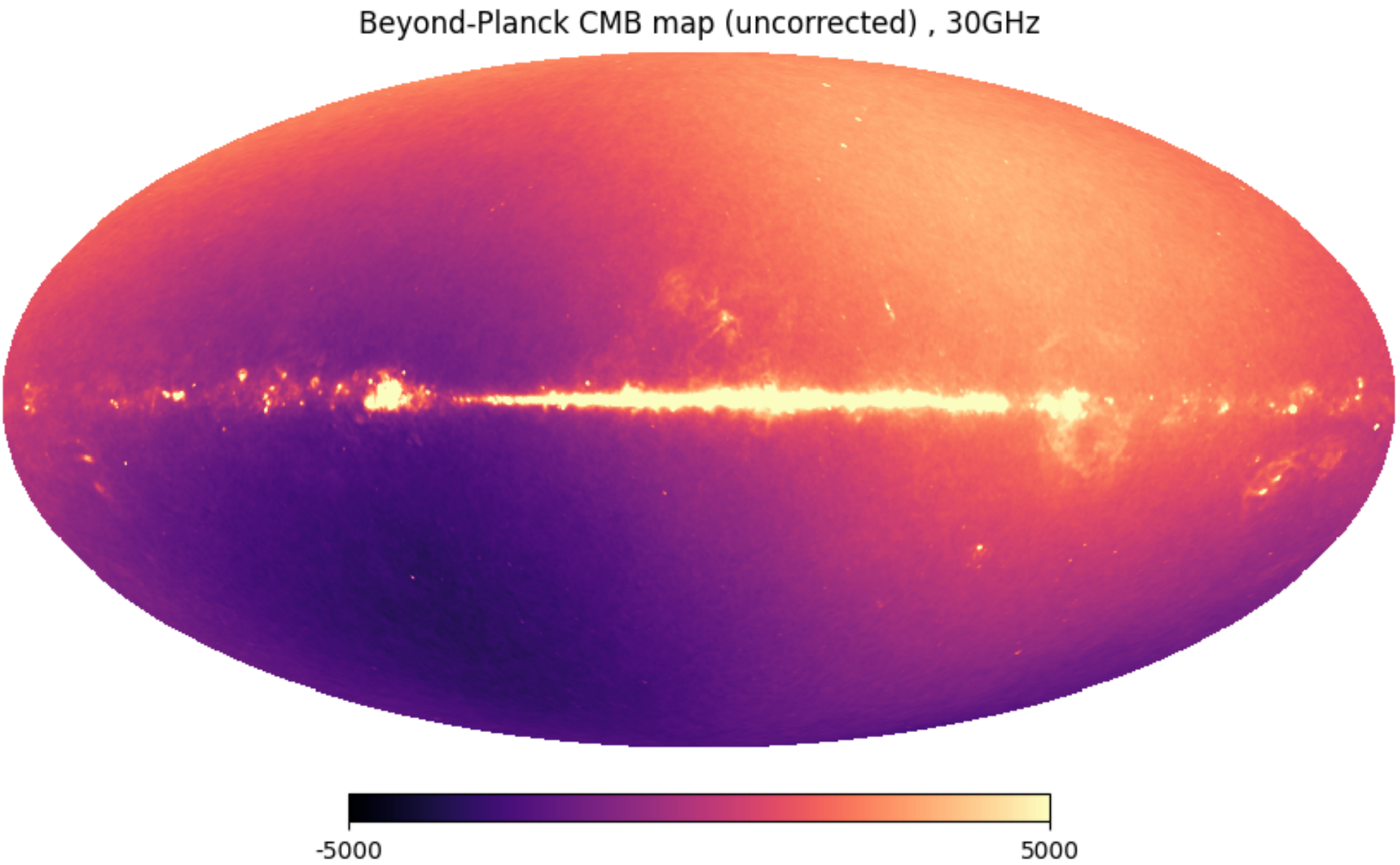

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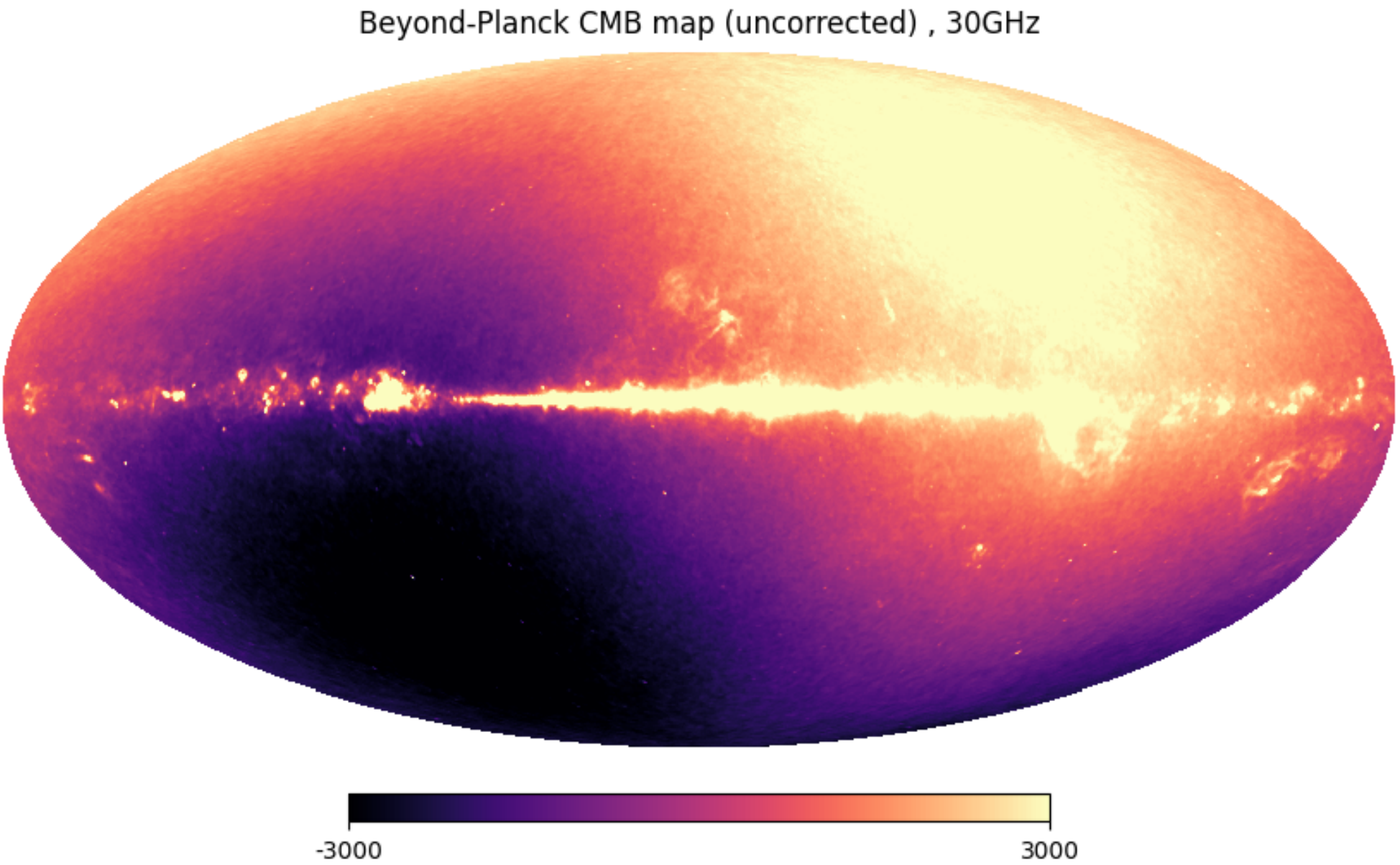

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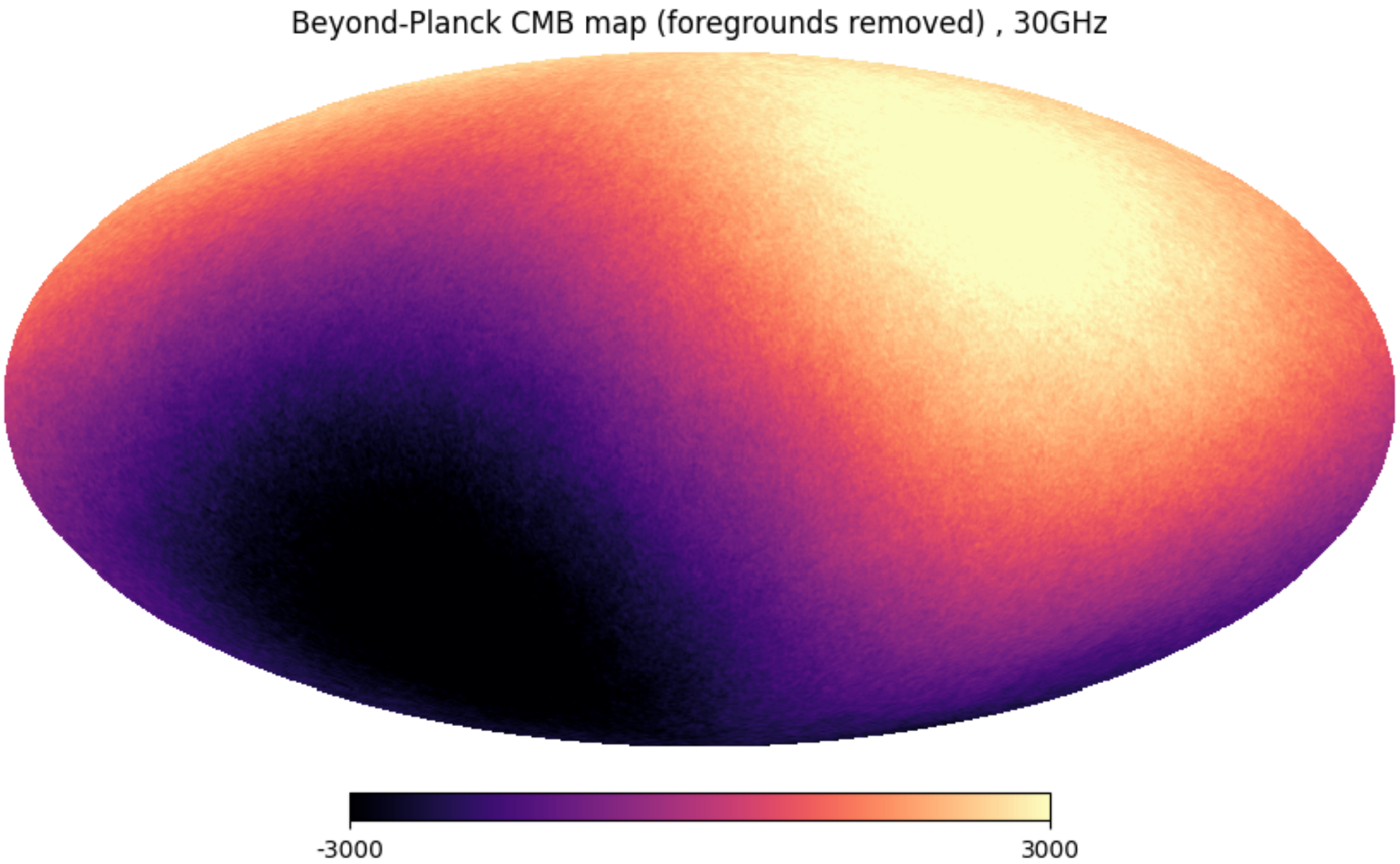

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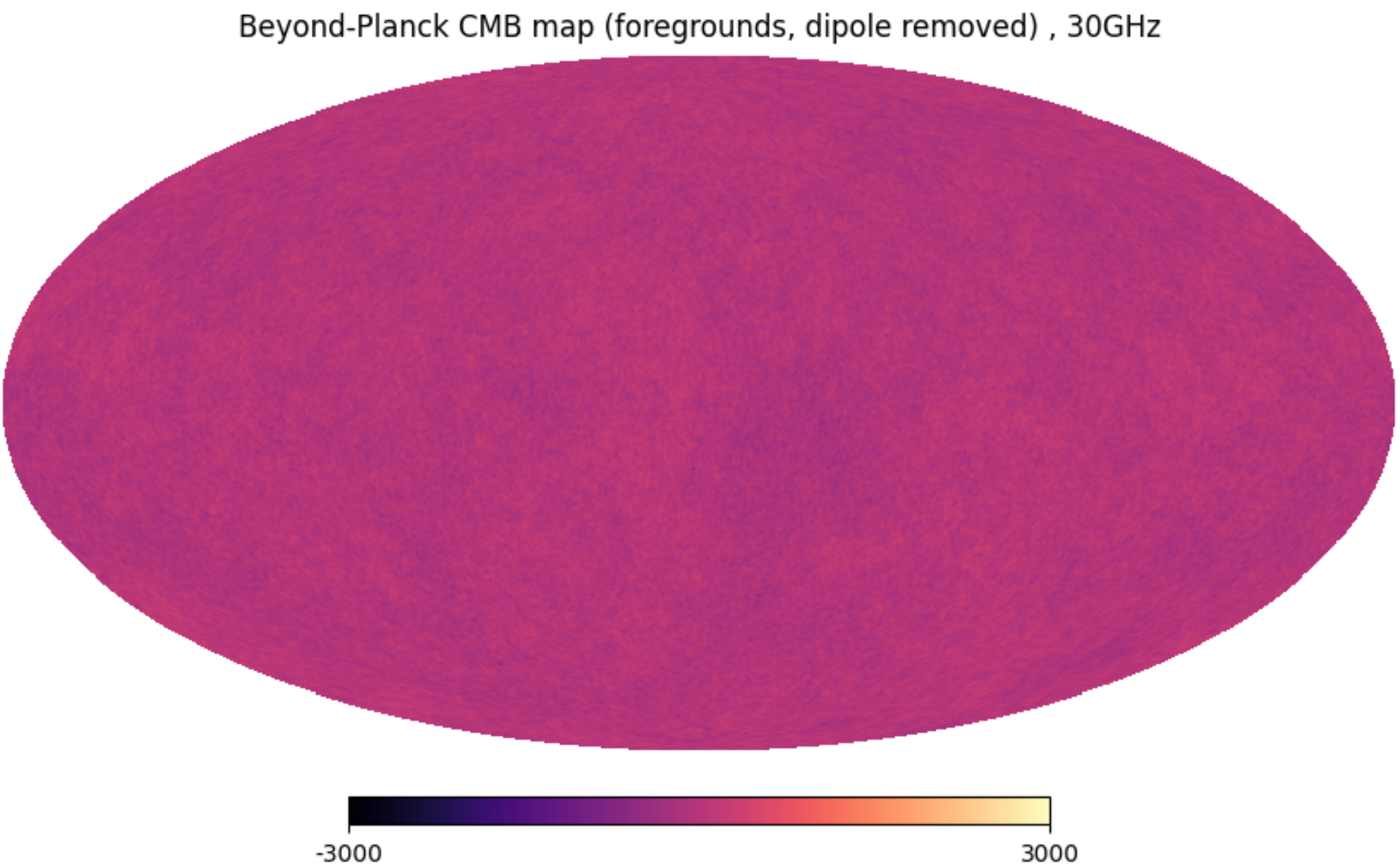

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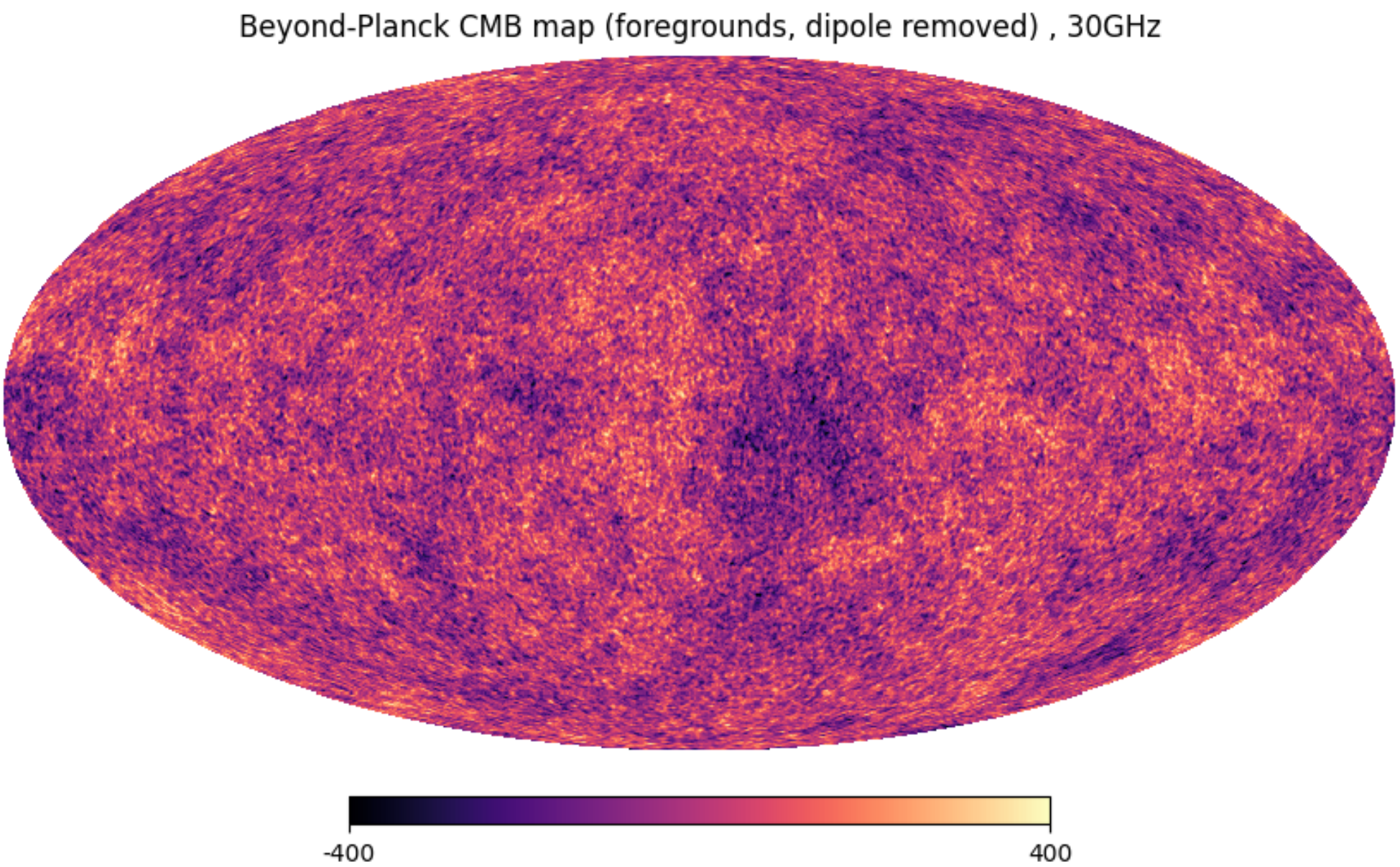

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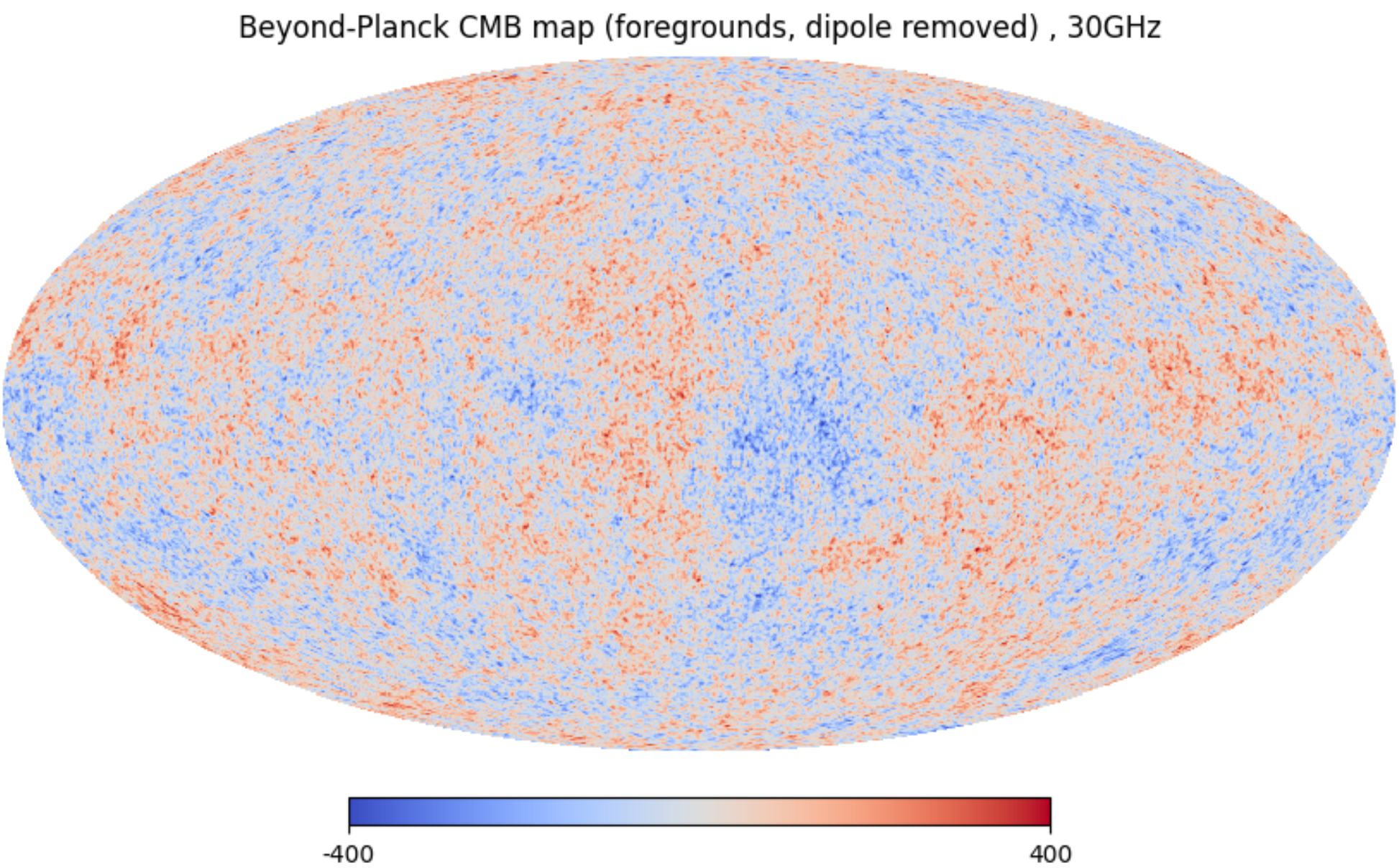

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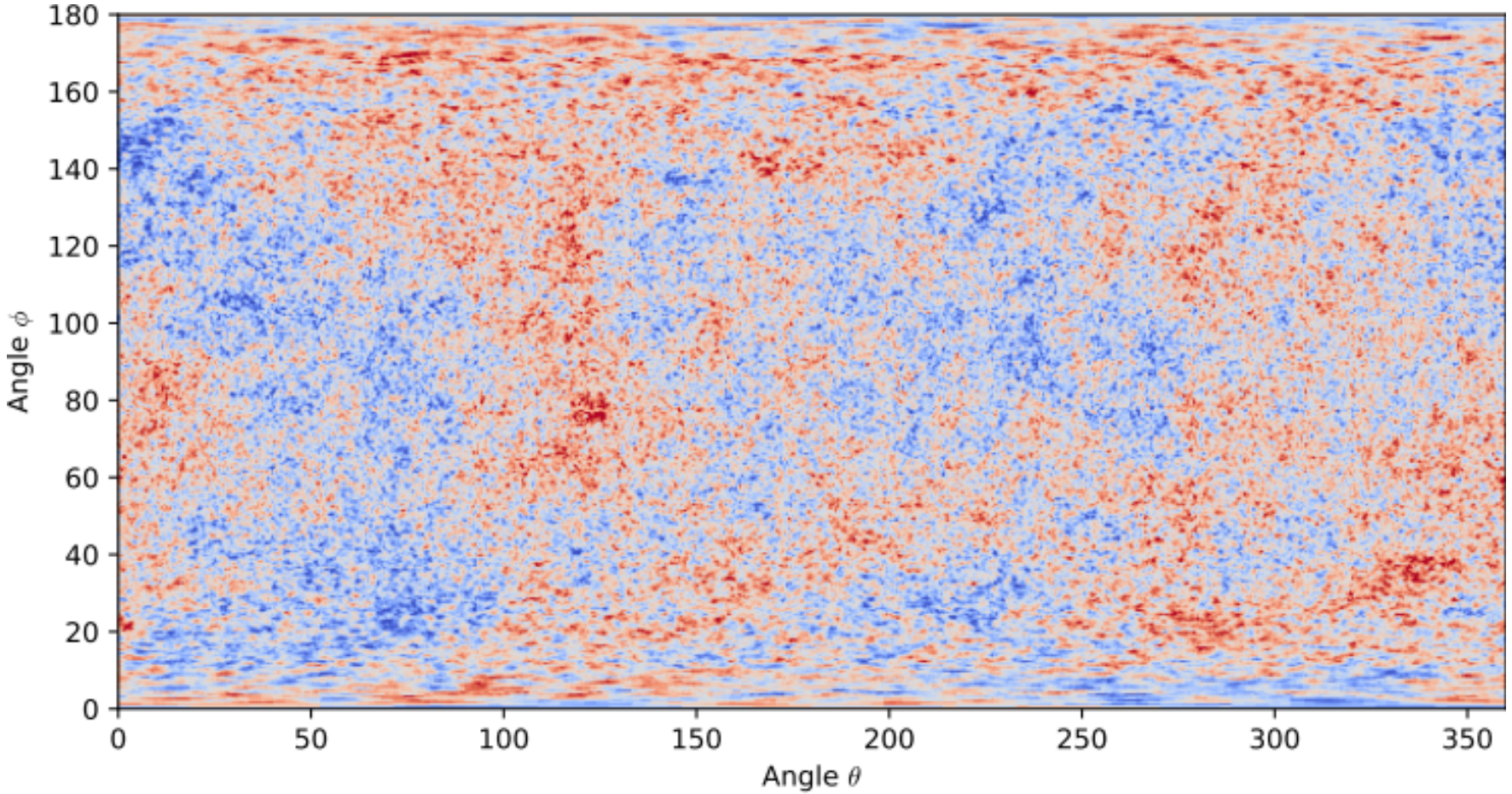
The CMB



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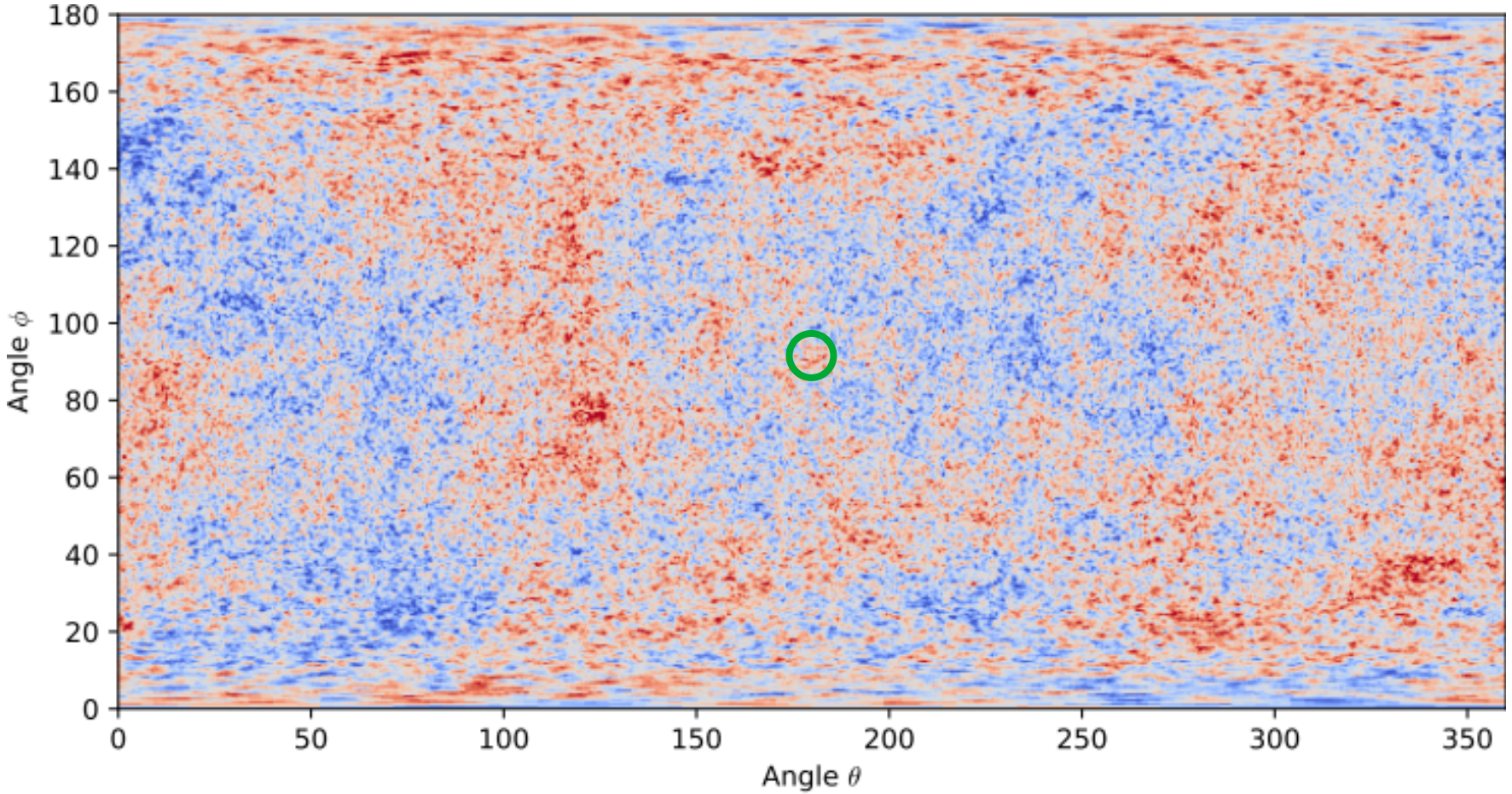
The CMB



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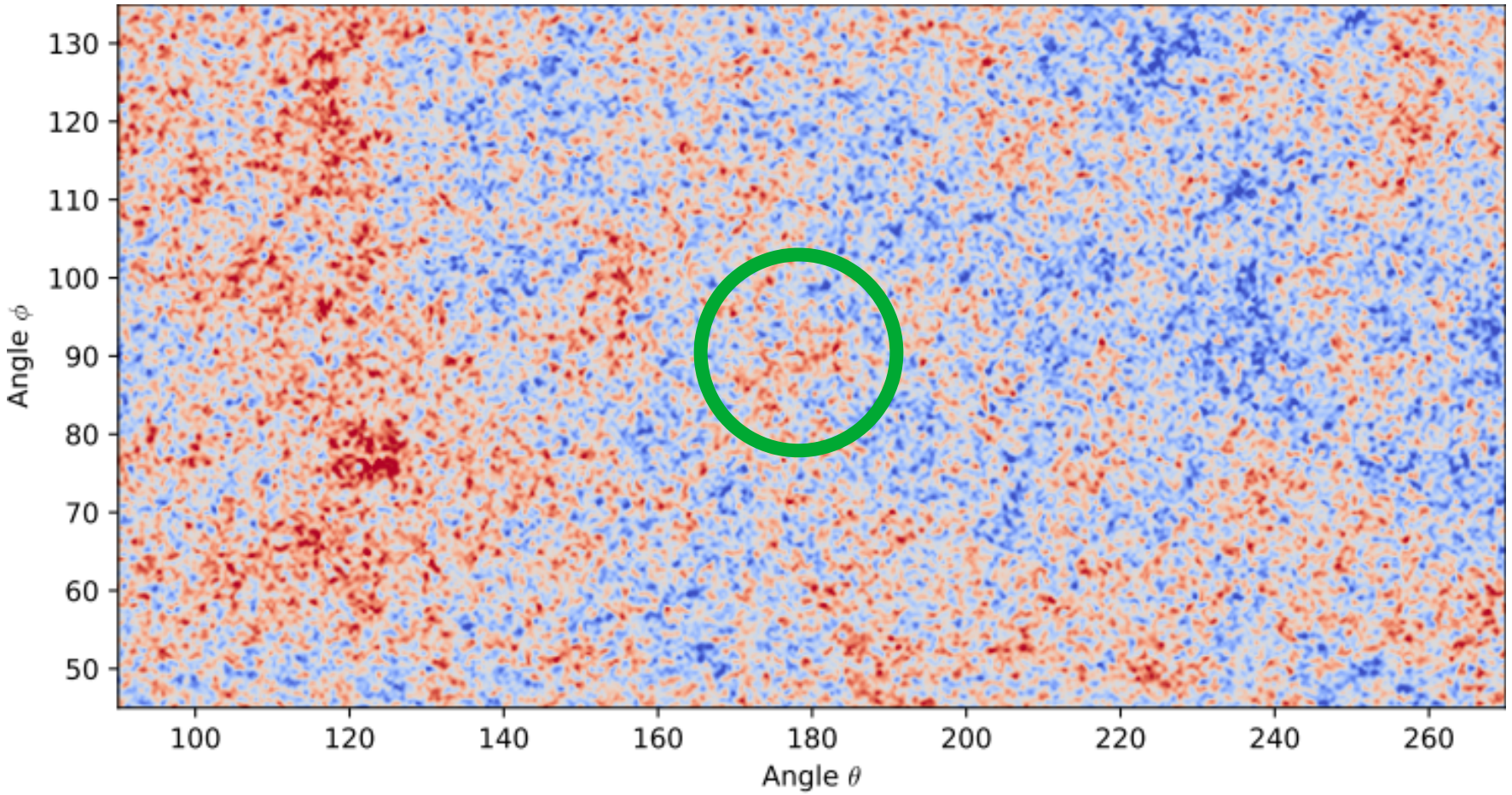
The CMB



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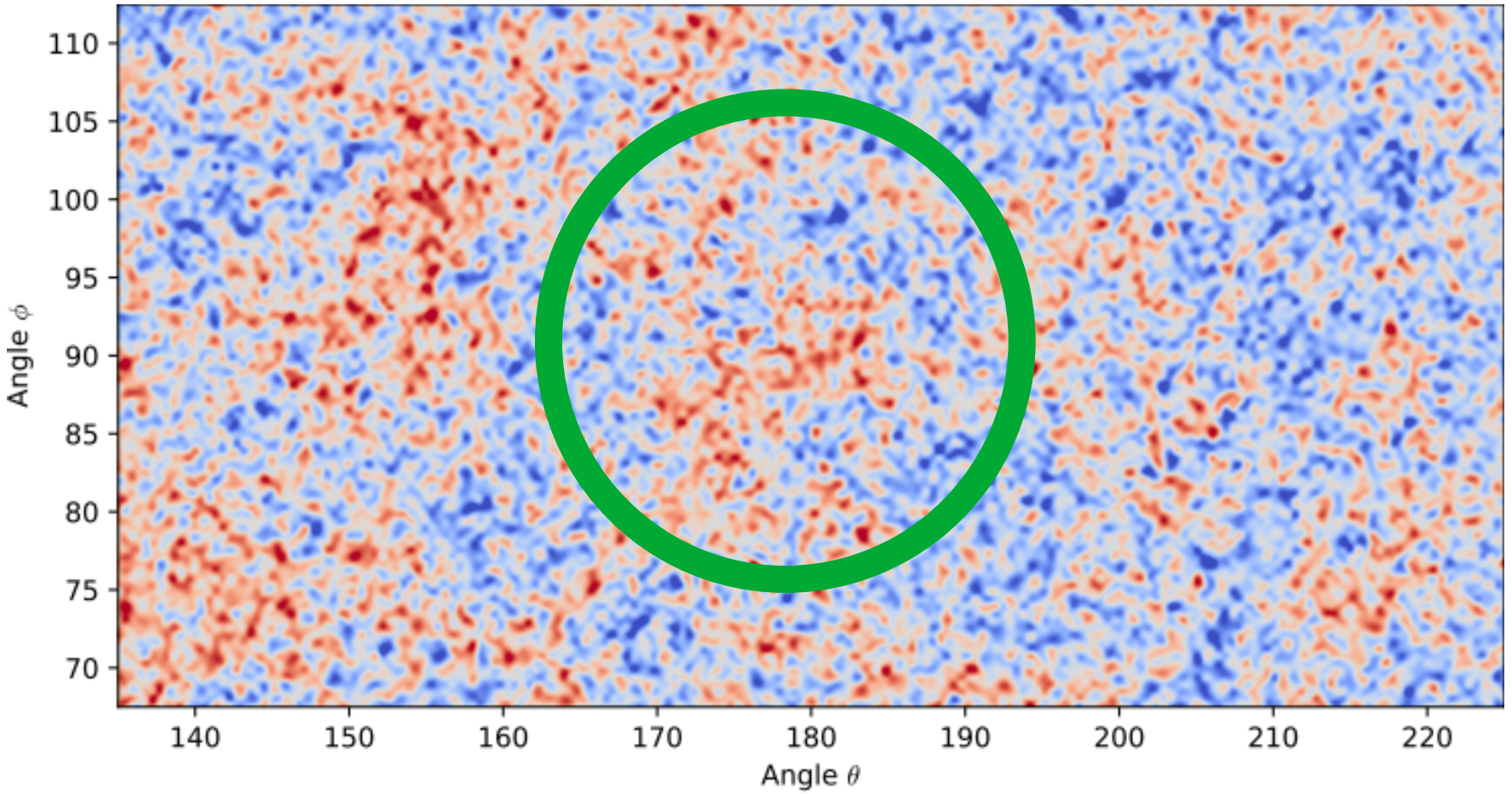
The CMB



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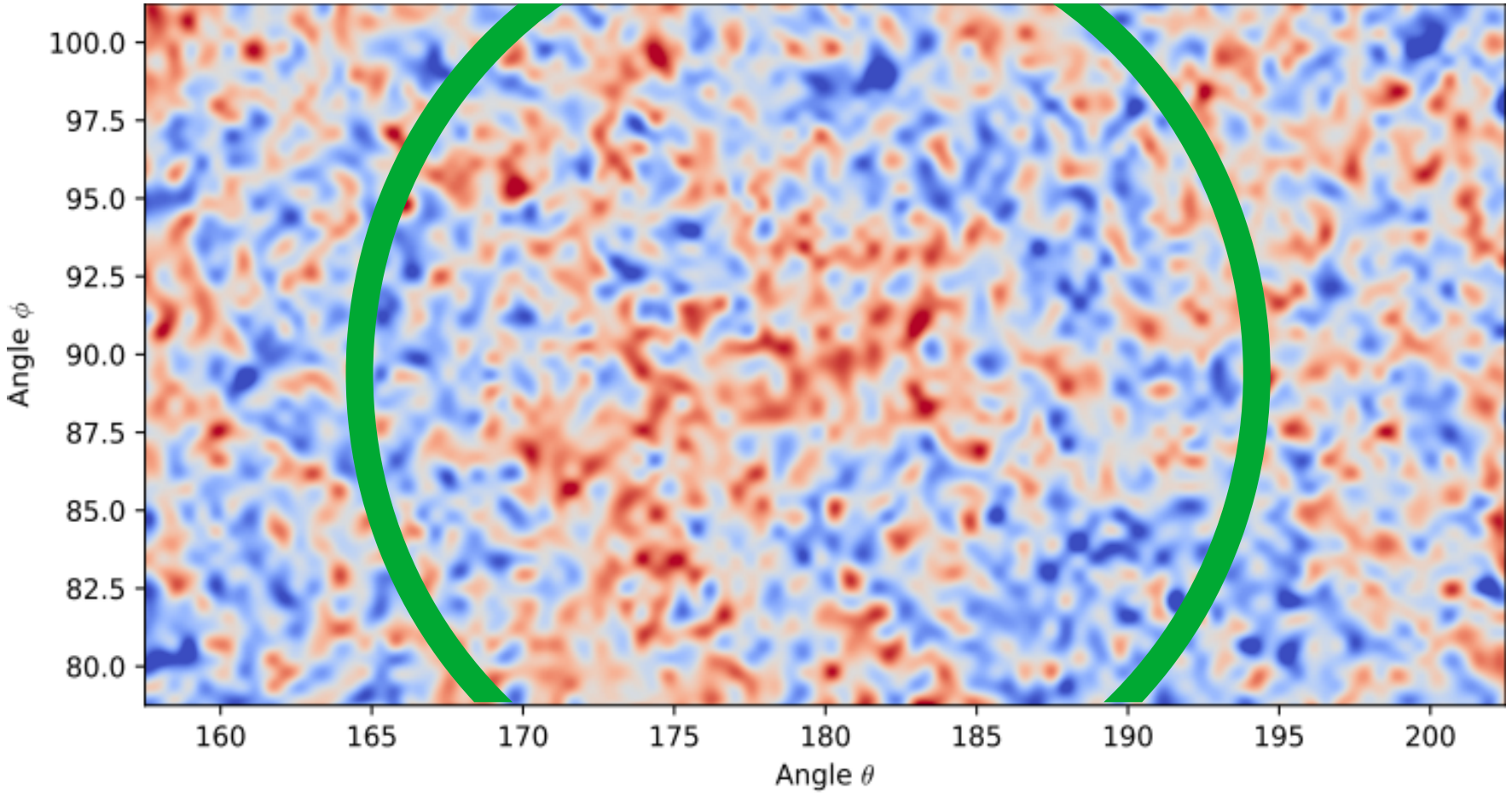
The CMB



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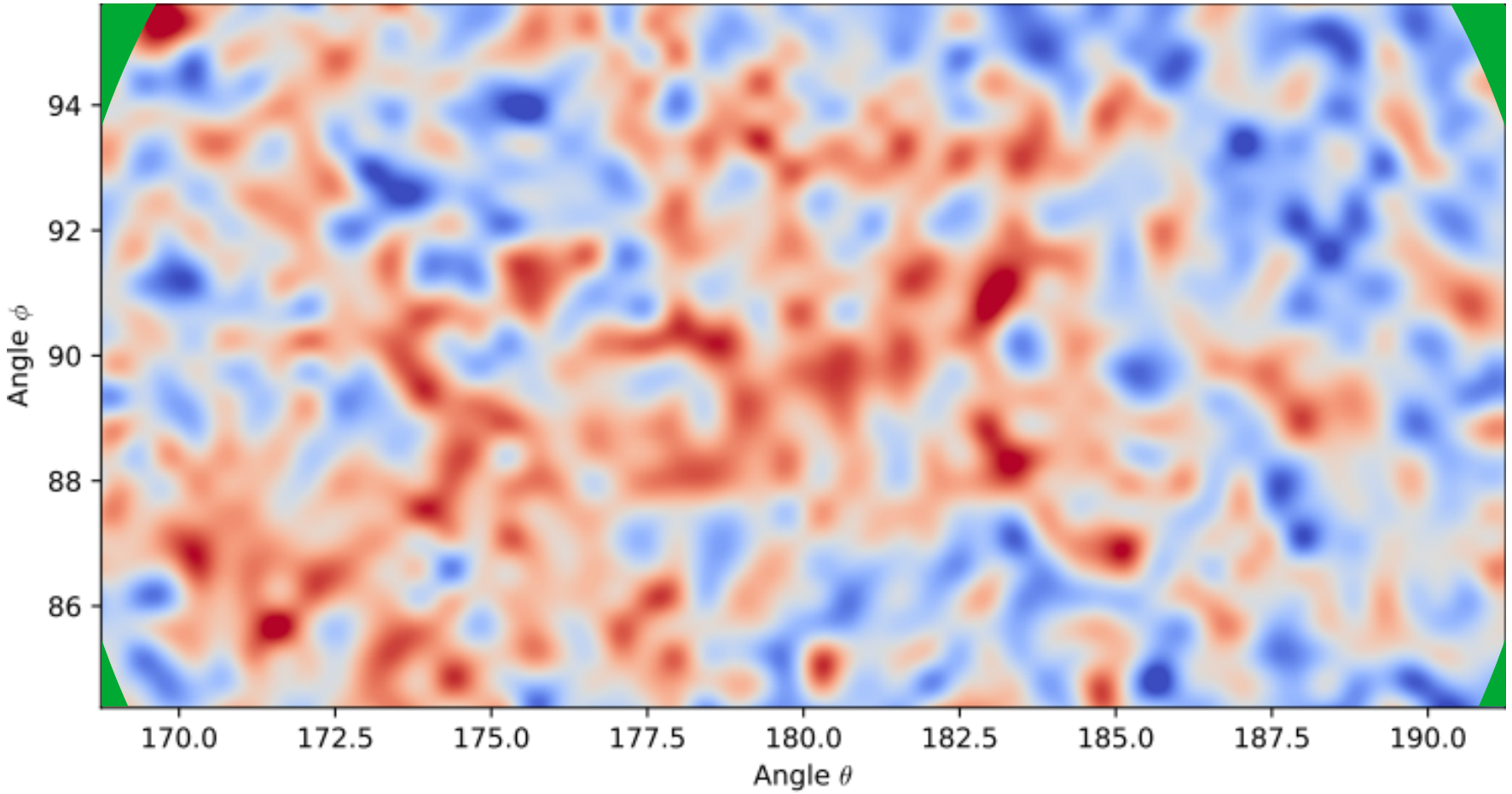
The CMB



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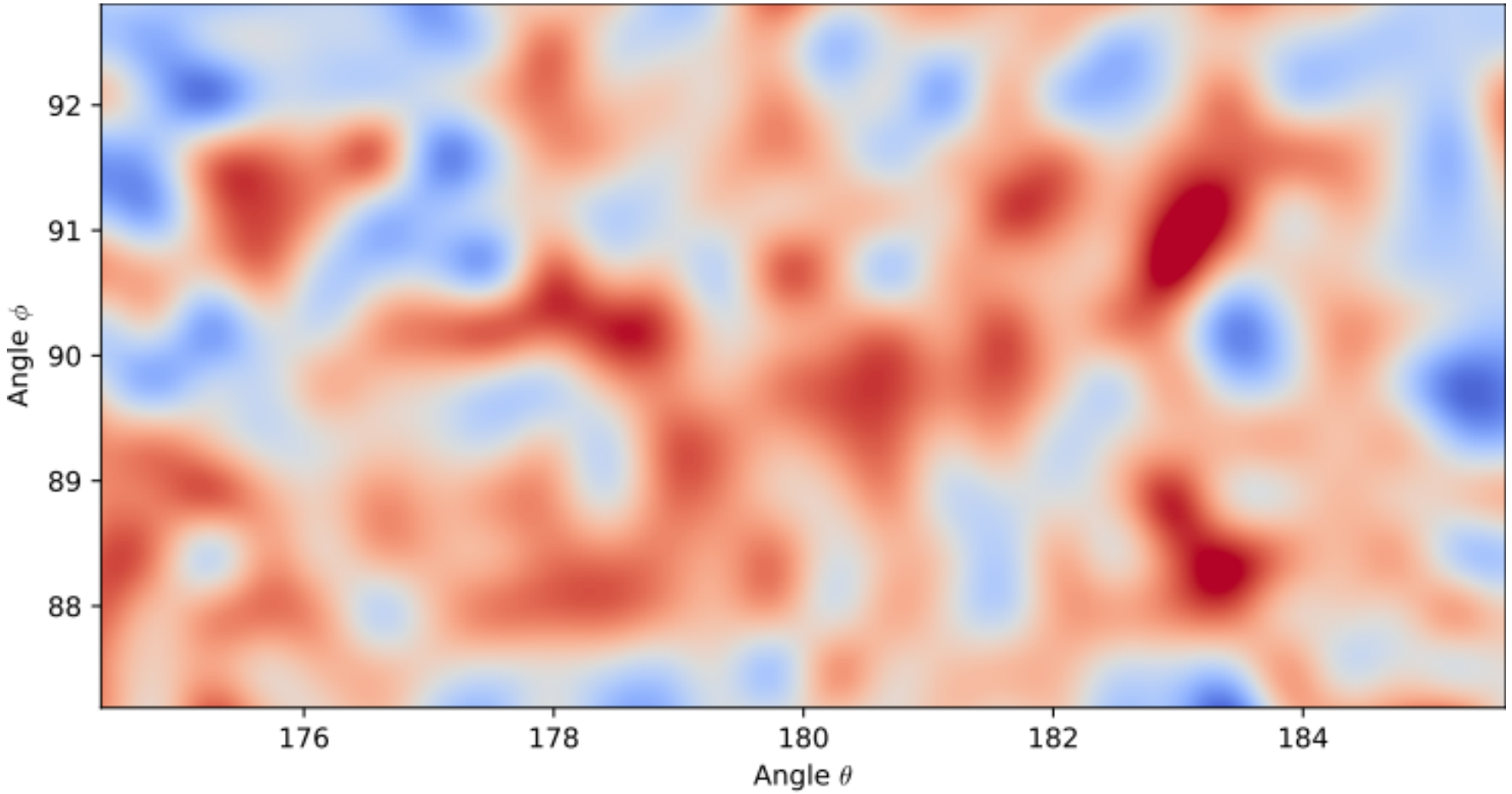
The CMB



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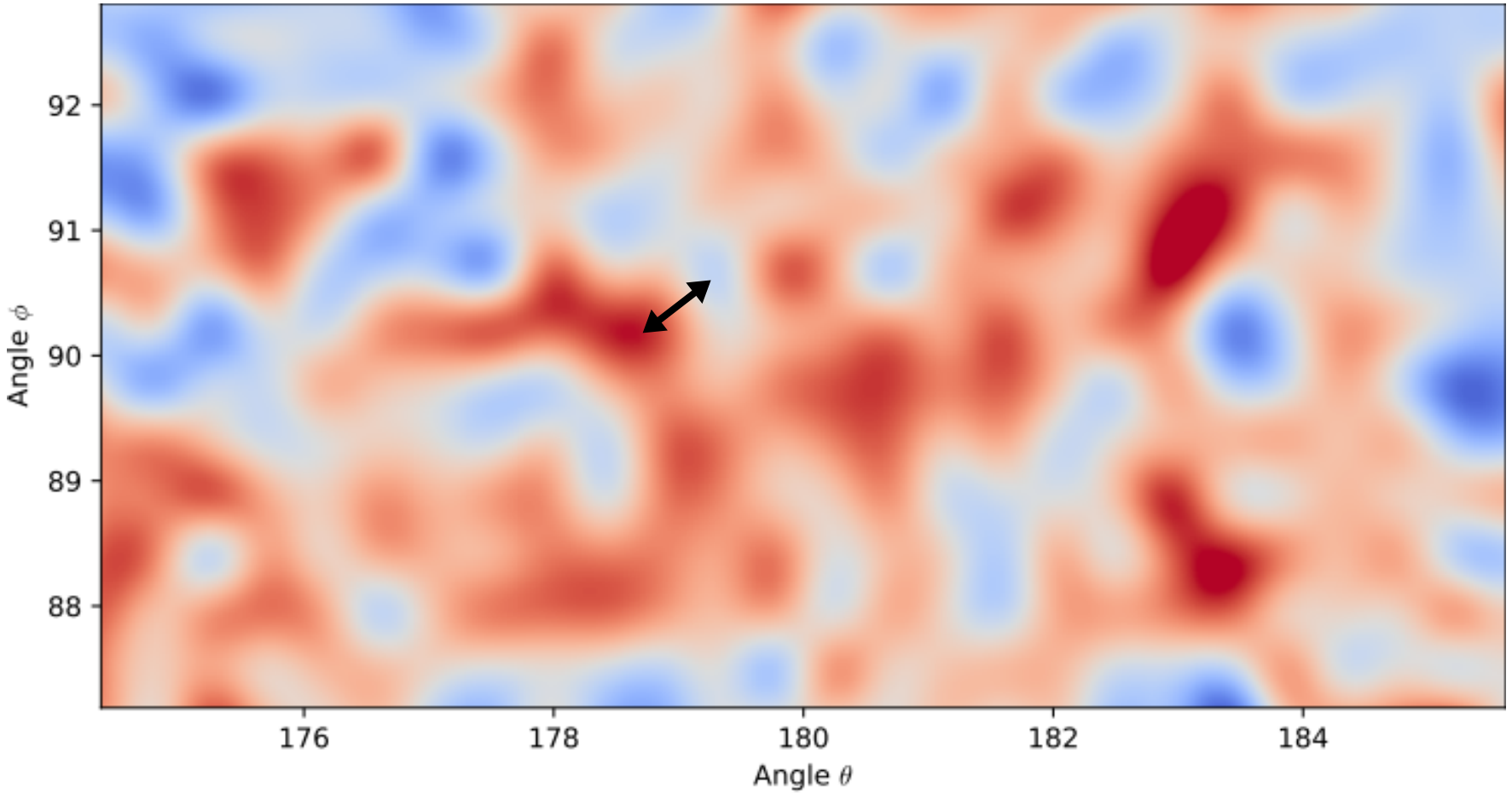

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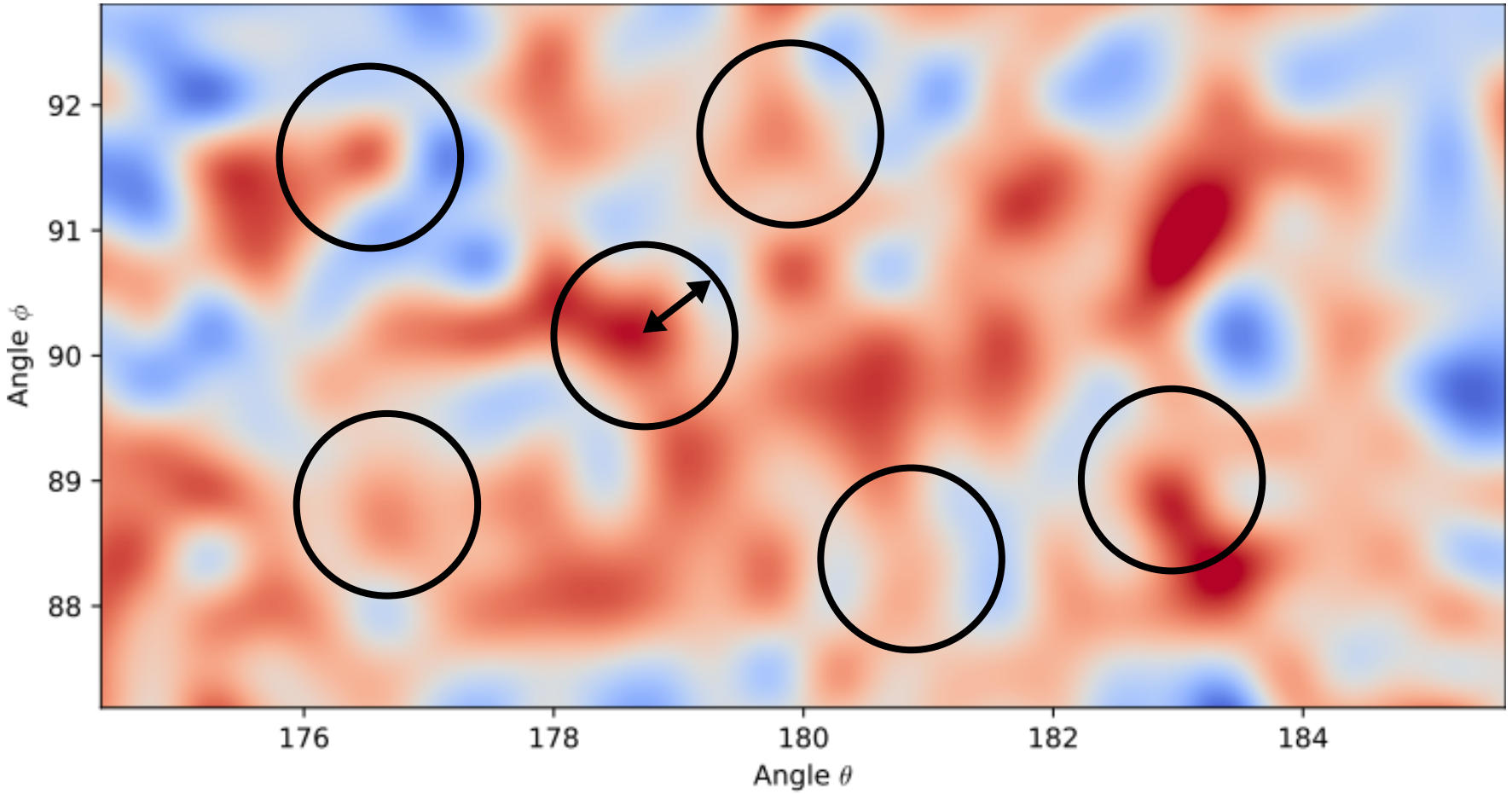
The CMB



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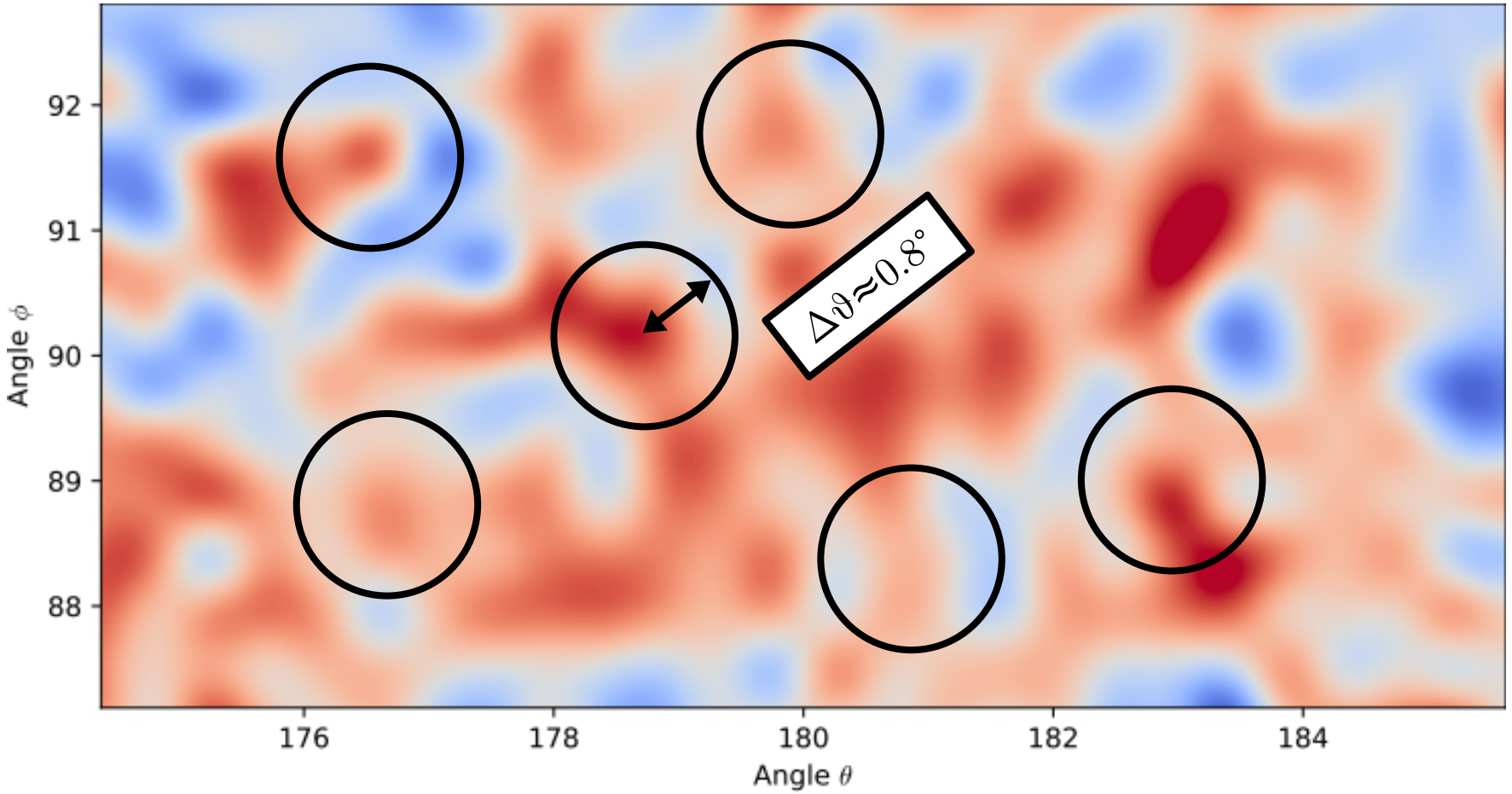
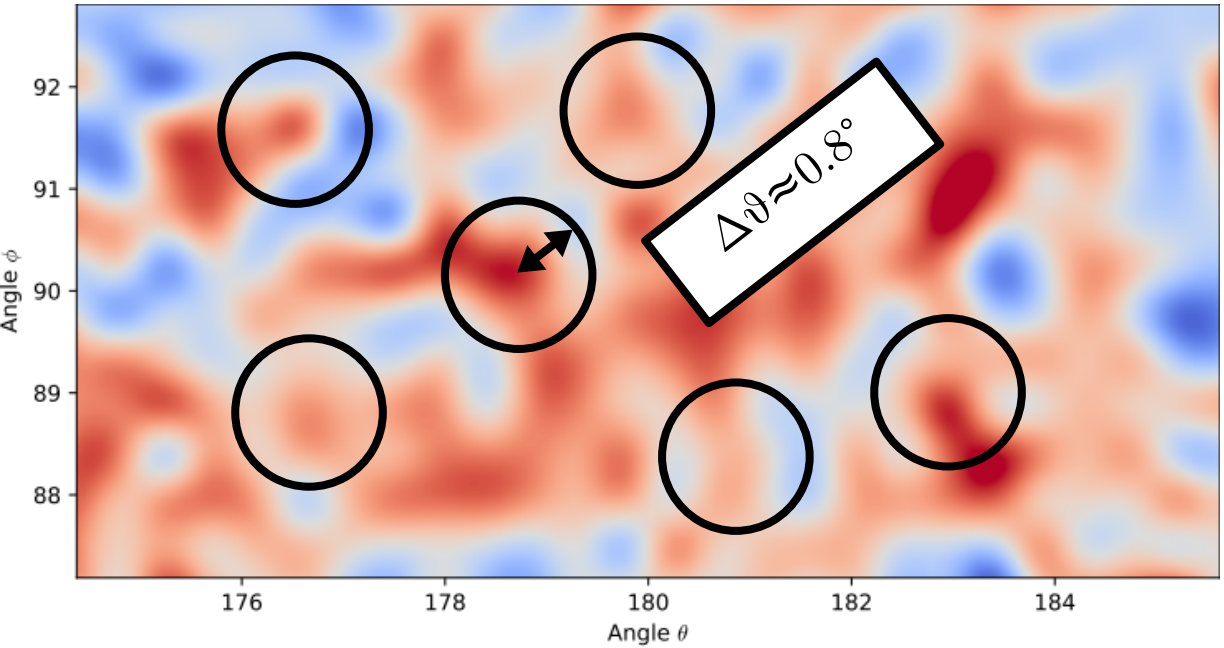
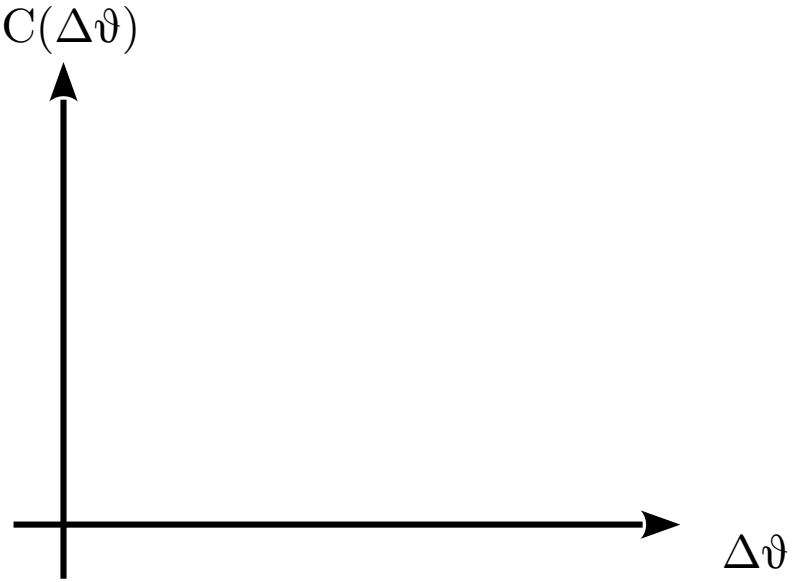
The CMB

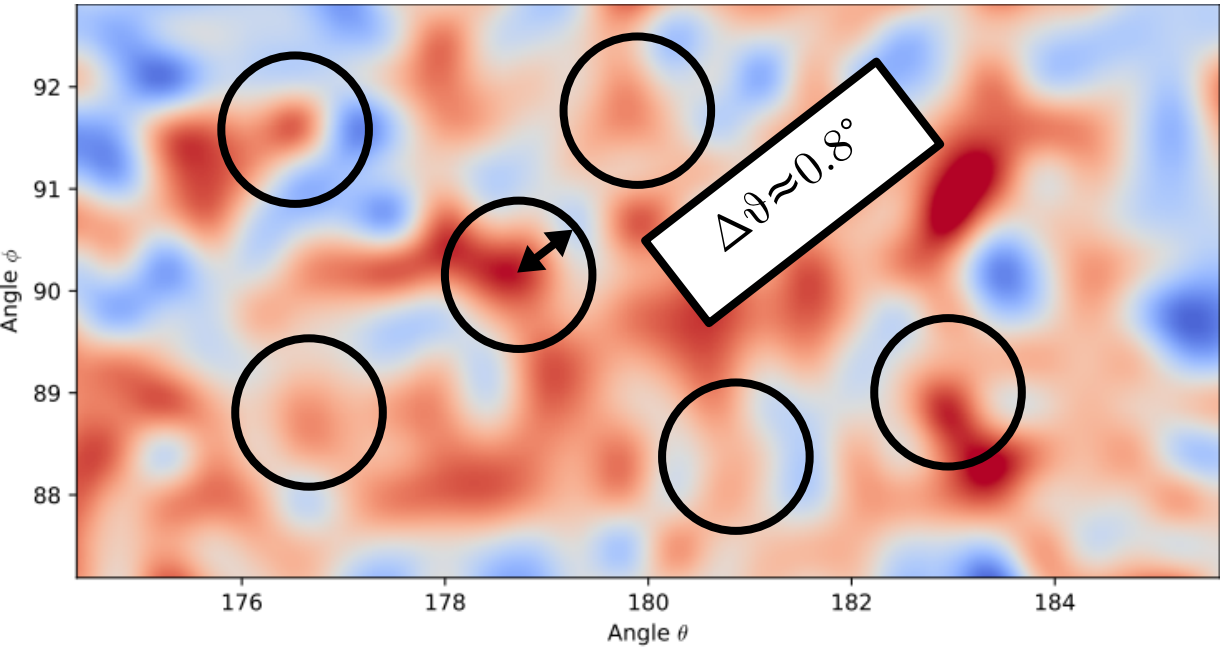


The CMB


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


$C(\Delta\vartheta)$
$\Delta\vartheta$

The CMB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91
90
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Angle ϕ
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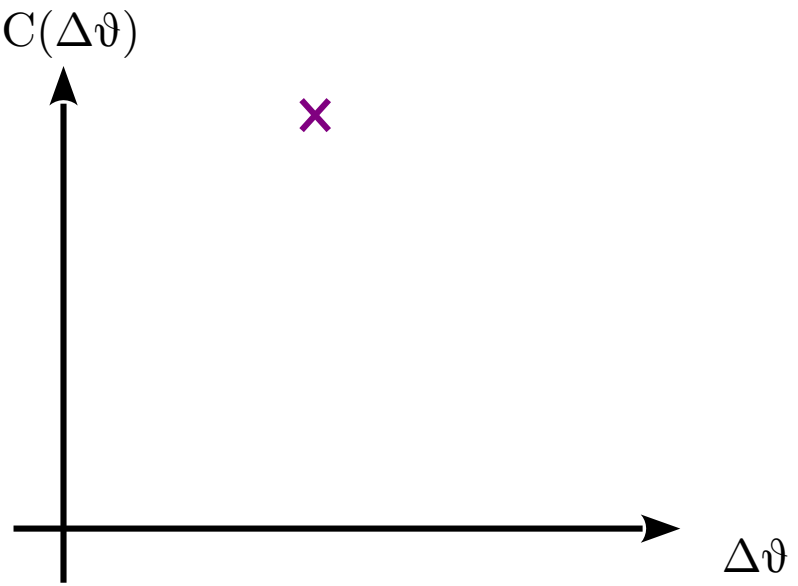
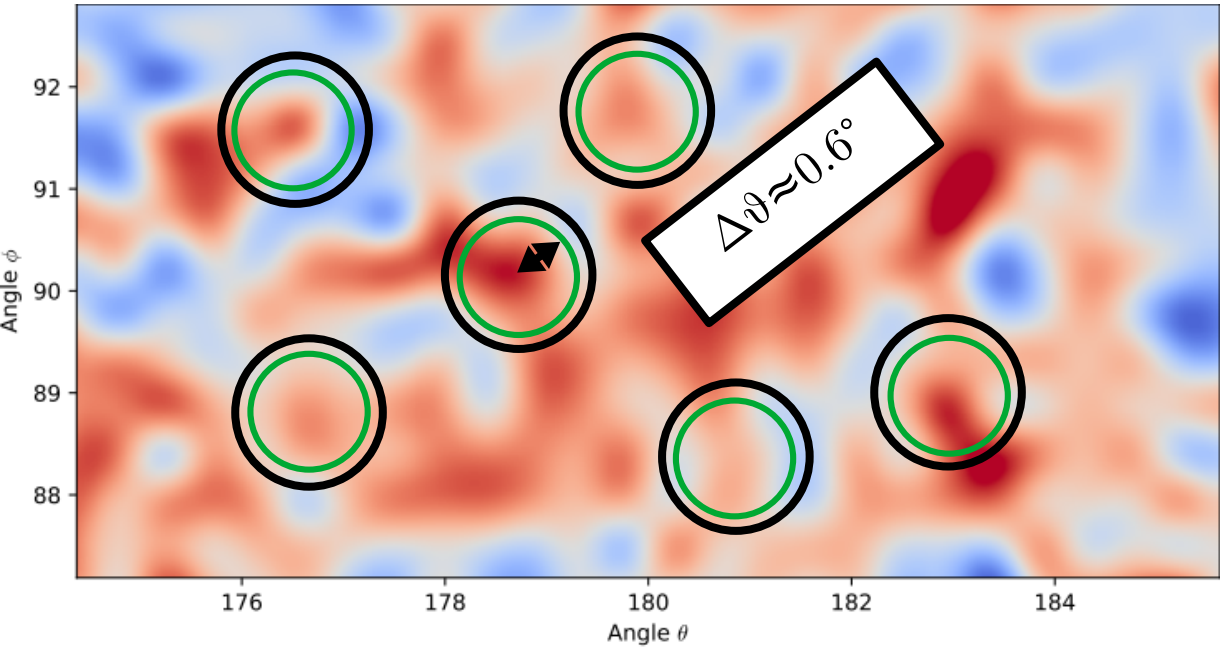
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.8^\circ$


$C(\Delta\vartheta)$
$\Delta\vartheta$

The CMB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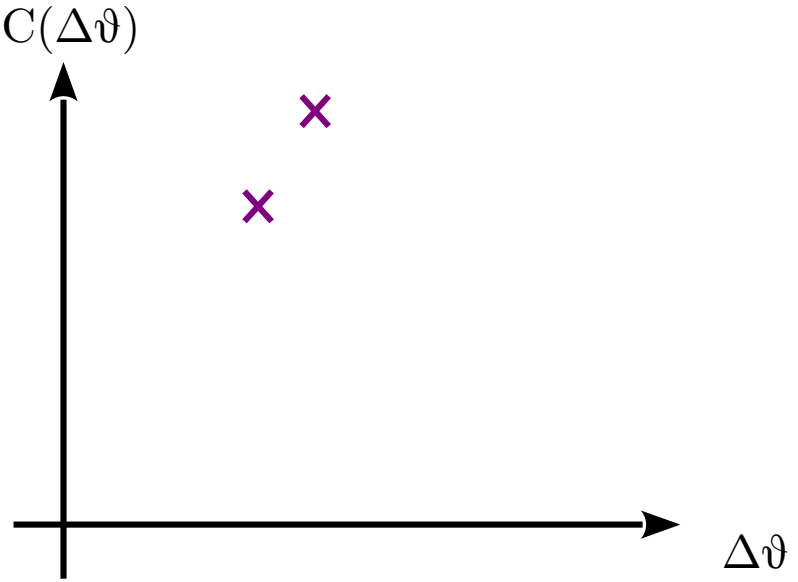
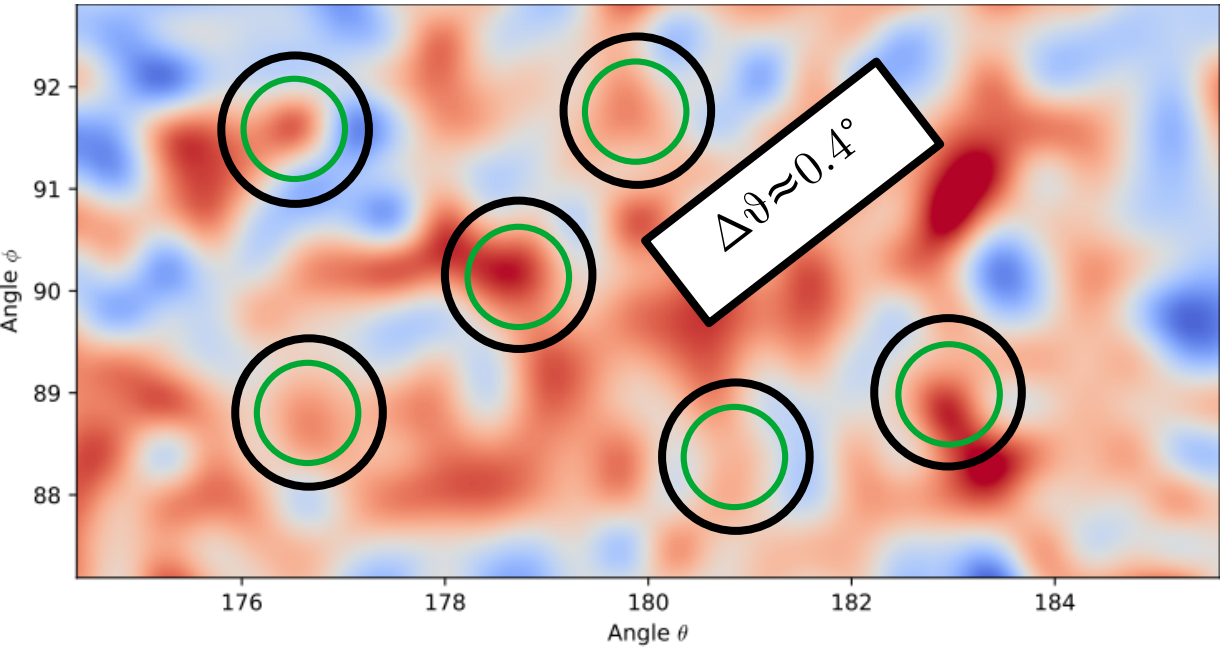
91
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.6^\circ$


$C(\Delta\vartheta)$
$\Delta\vartheta$

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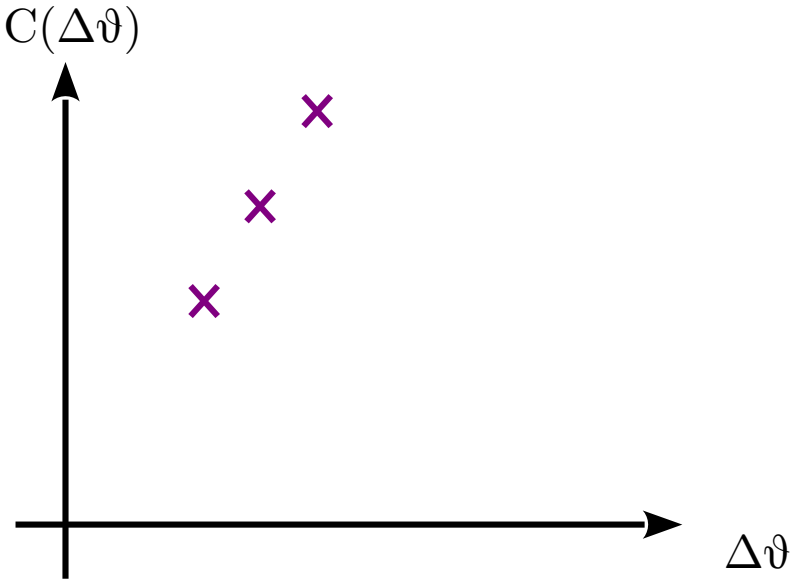
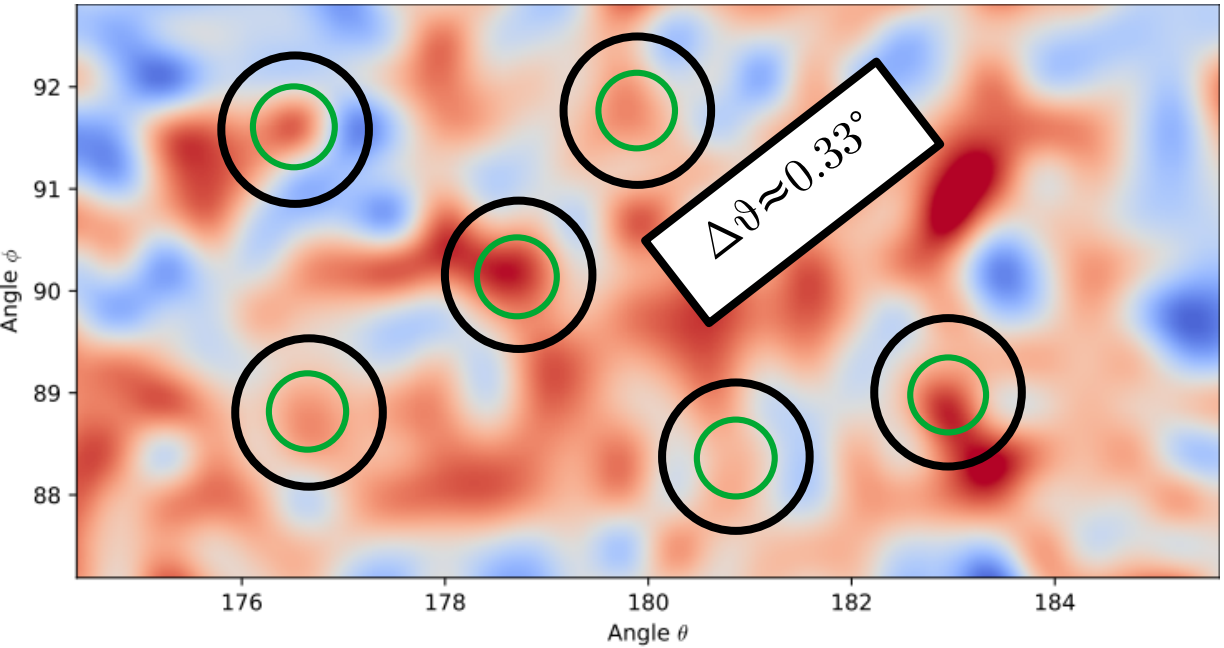
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.4°$


$C(\Delta\vartheta)$
$\Delta\vartheta$

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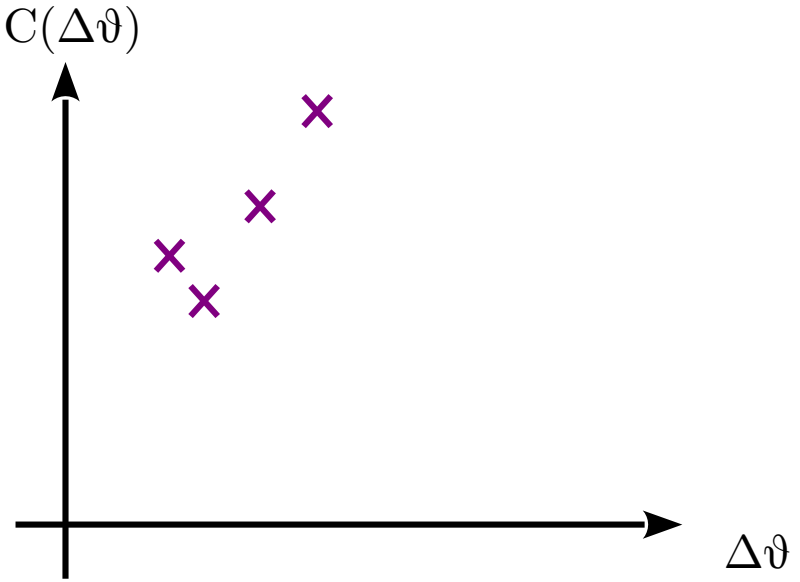
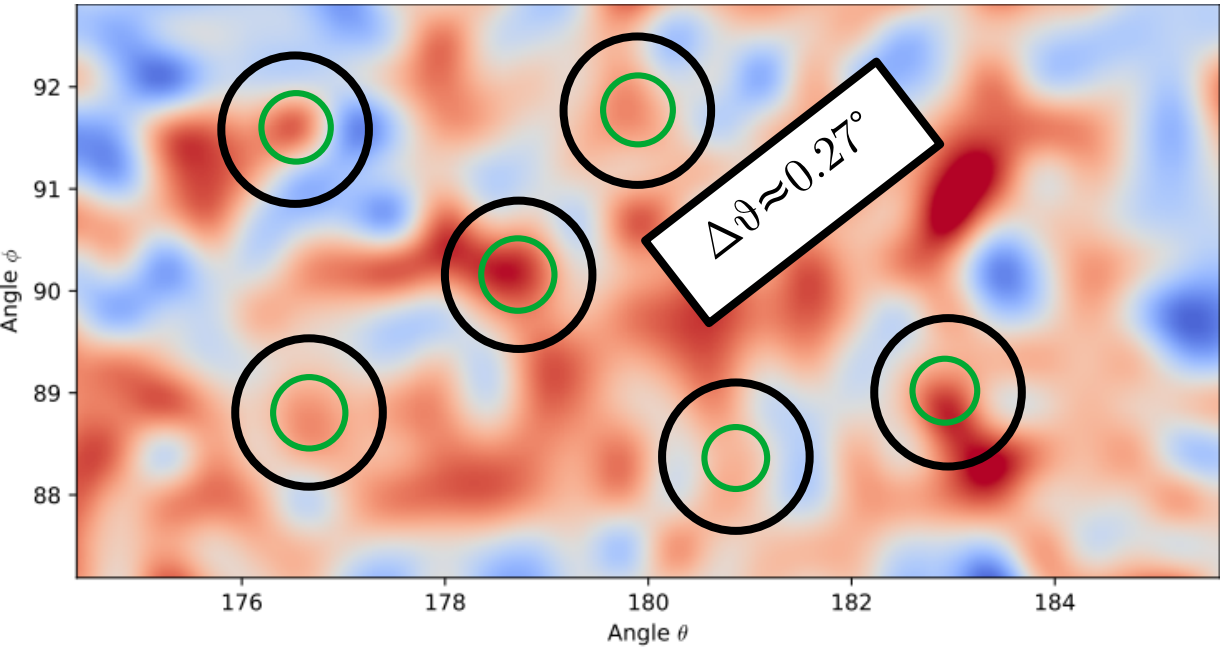
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.33°$


$C(\Delta\vartheta)$
$\Delta\vartheta$

The CMB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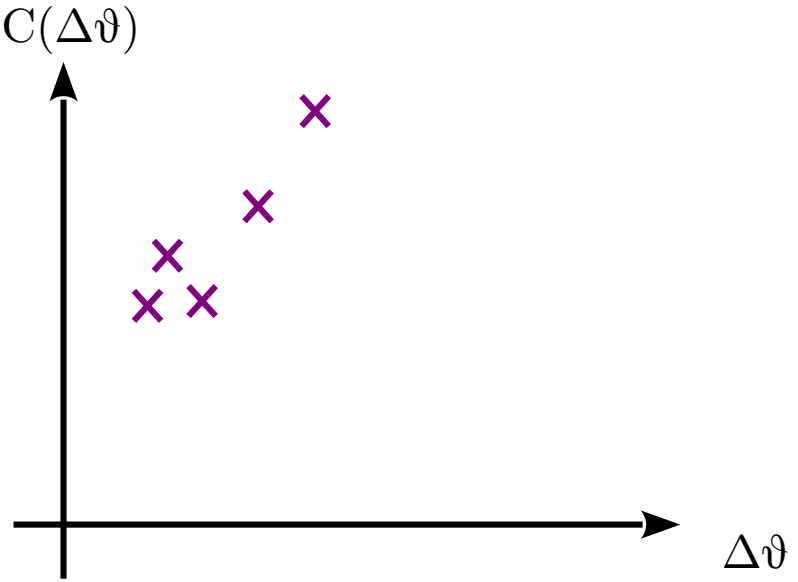
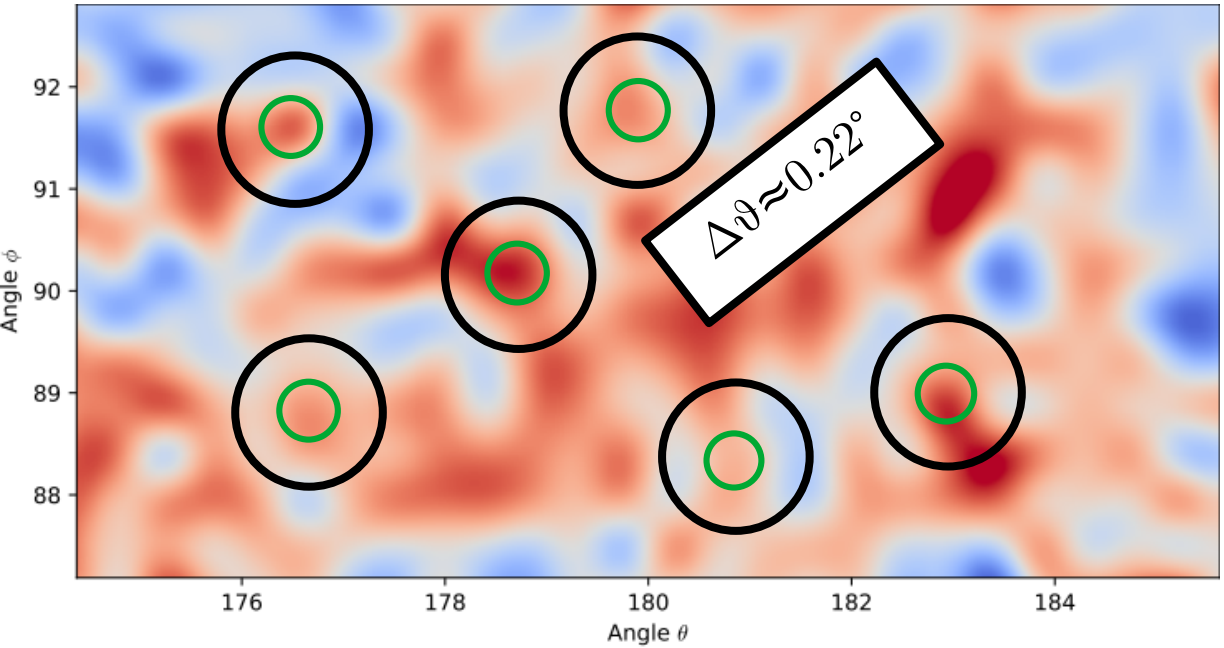
90
89
88
Angle ϕ
176
178
180
182
184
Angle θ
$\Delta\vartheta \approx 0.27°$


$C(\Delta\vartheta)$
$\Delta\vartheta$

The CMB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Angle ϕ
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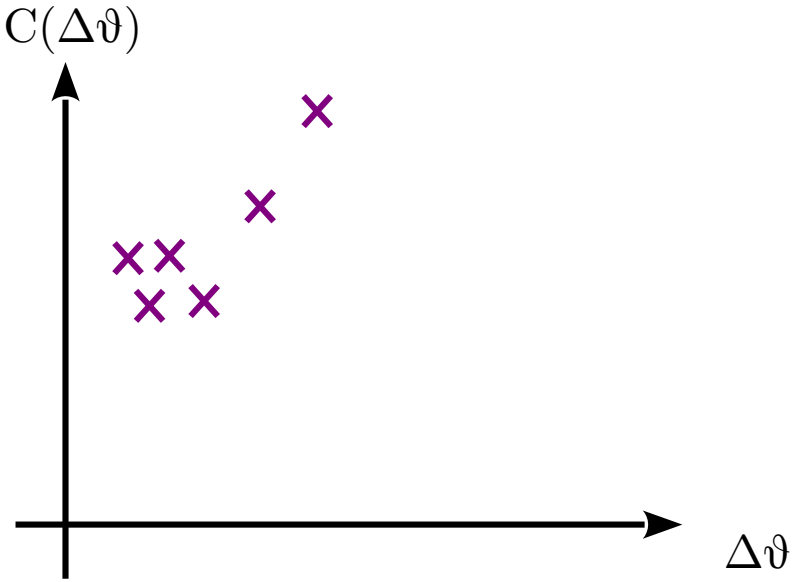
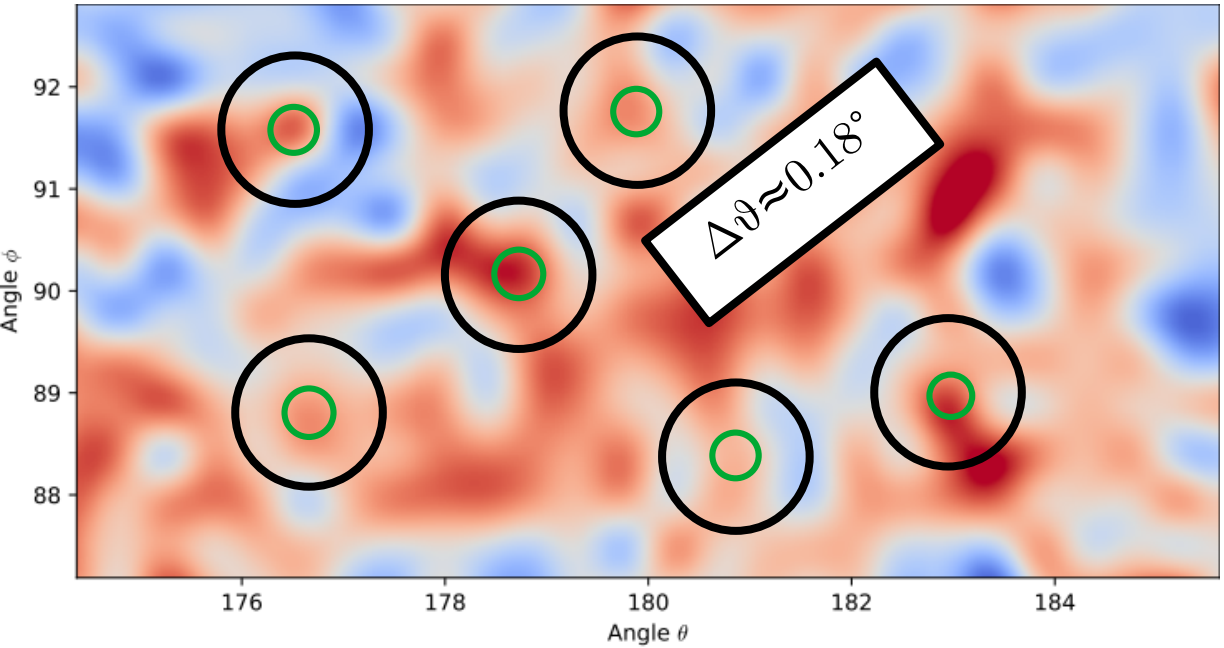
182
184
Angle θ
$\Delta\vartheta \approx 0.22°$


$C(\Delta\vartheta)$
$\Delta\vartheta$

The CMB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Angle ϕ
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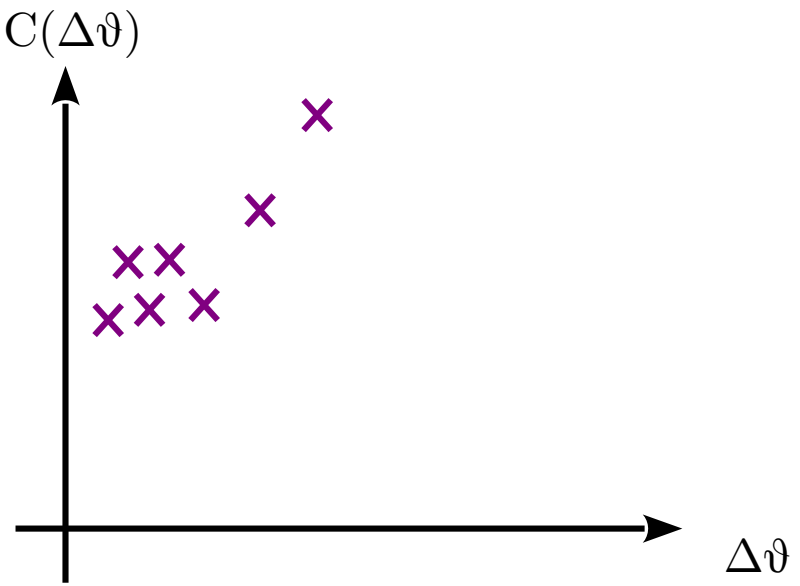
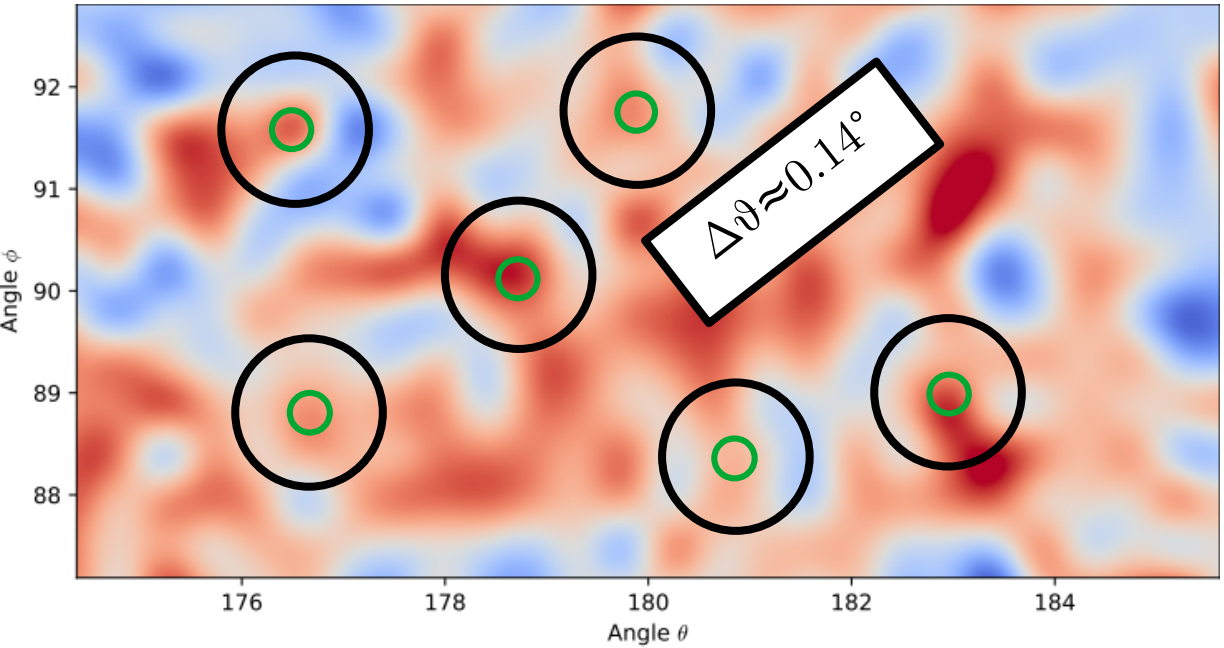
Angle θ
$\Delta\vartheta \approx 0.18°$


$C(\Delta\vartheta)$
$\Delta\vartheta$

The CMB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Angle ϕ
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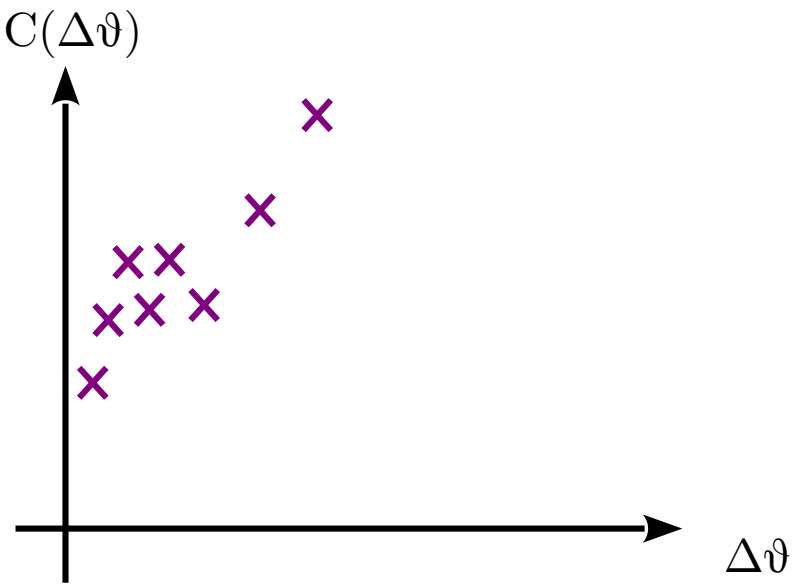
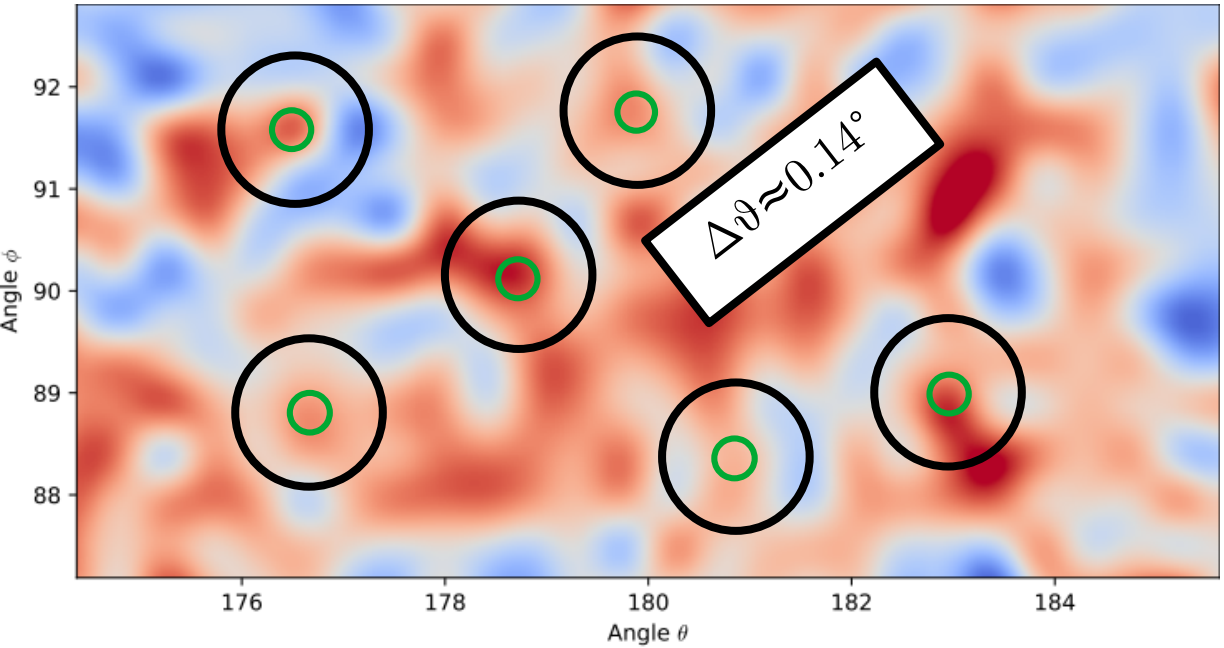
Angle θ
$\Delta\vartheta \approx 0.14°$


$C(\Delta\vartheta)$
$\Delta\vartheta$

The CMB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Angle ϕ
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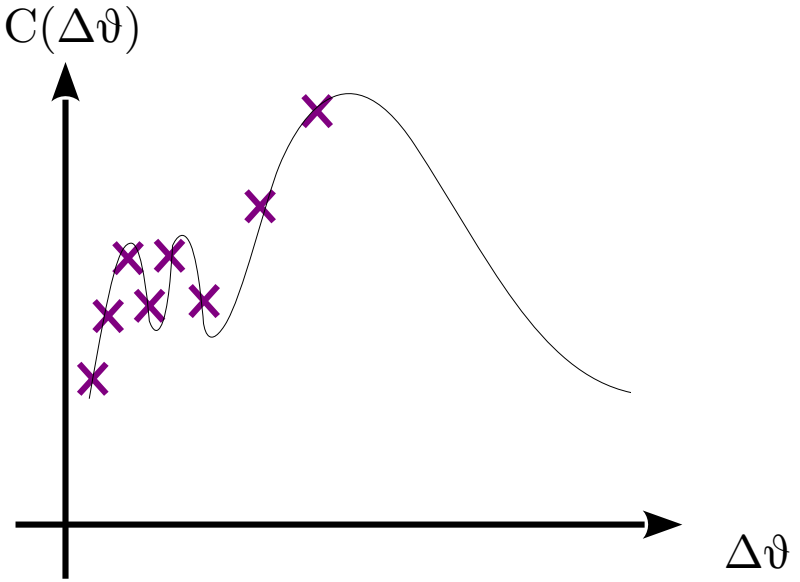
184
Angle θ
$\Delta\vartheta \approx 0.14°$


$C(\Delta\vartheta)$
$\Delta\vartheta$

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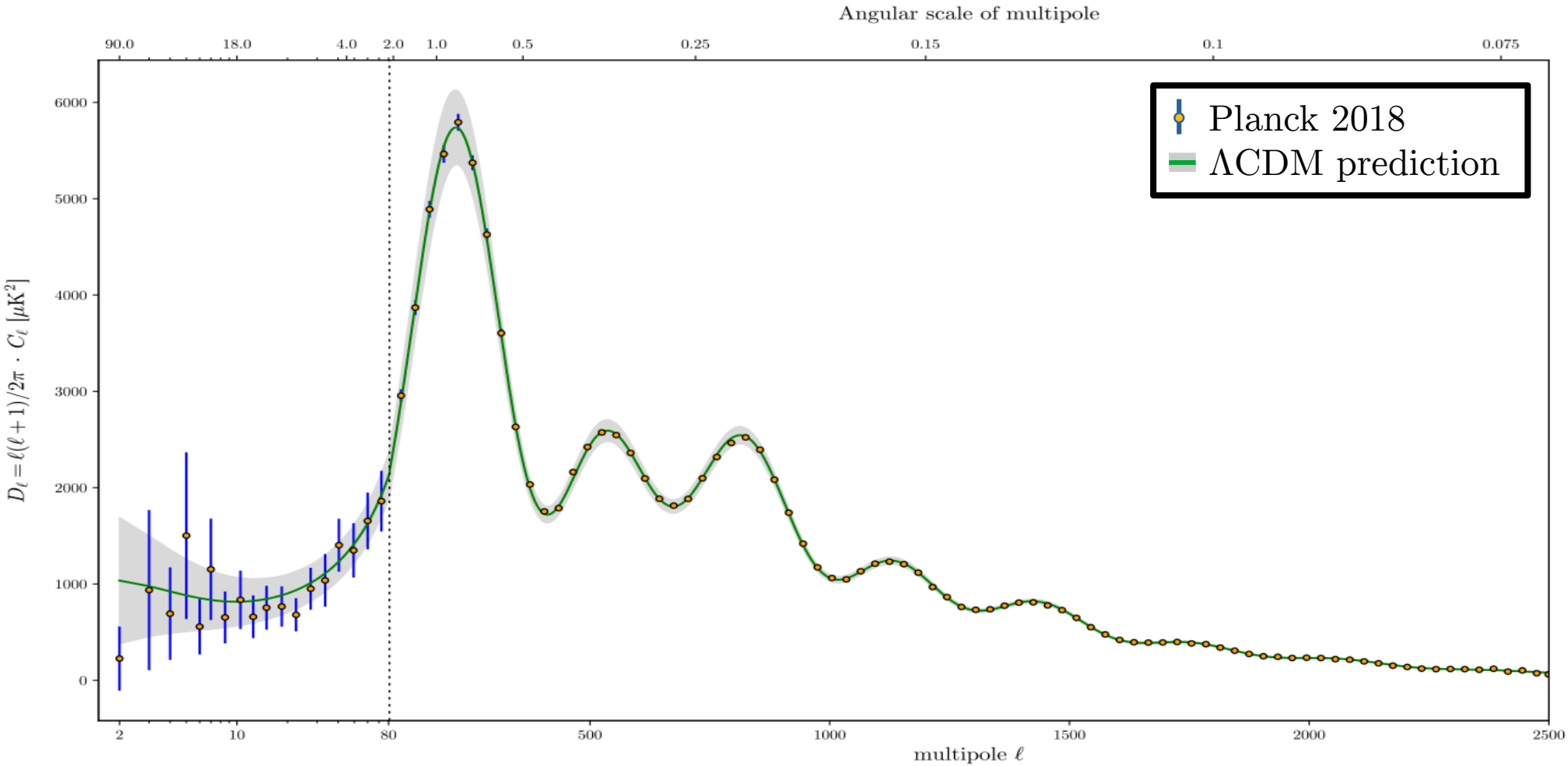
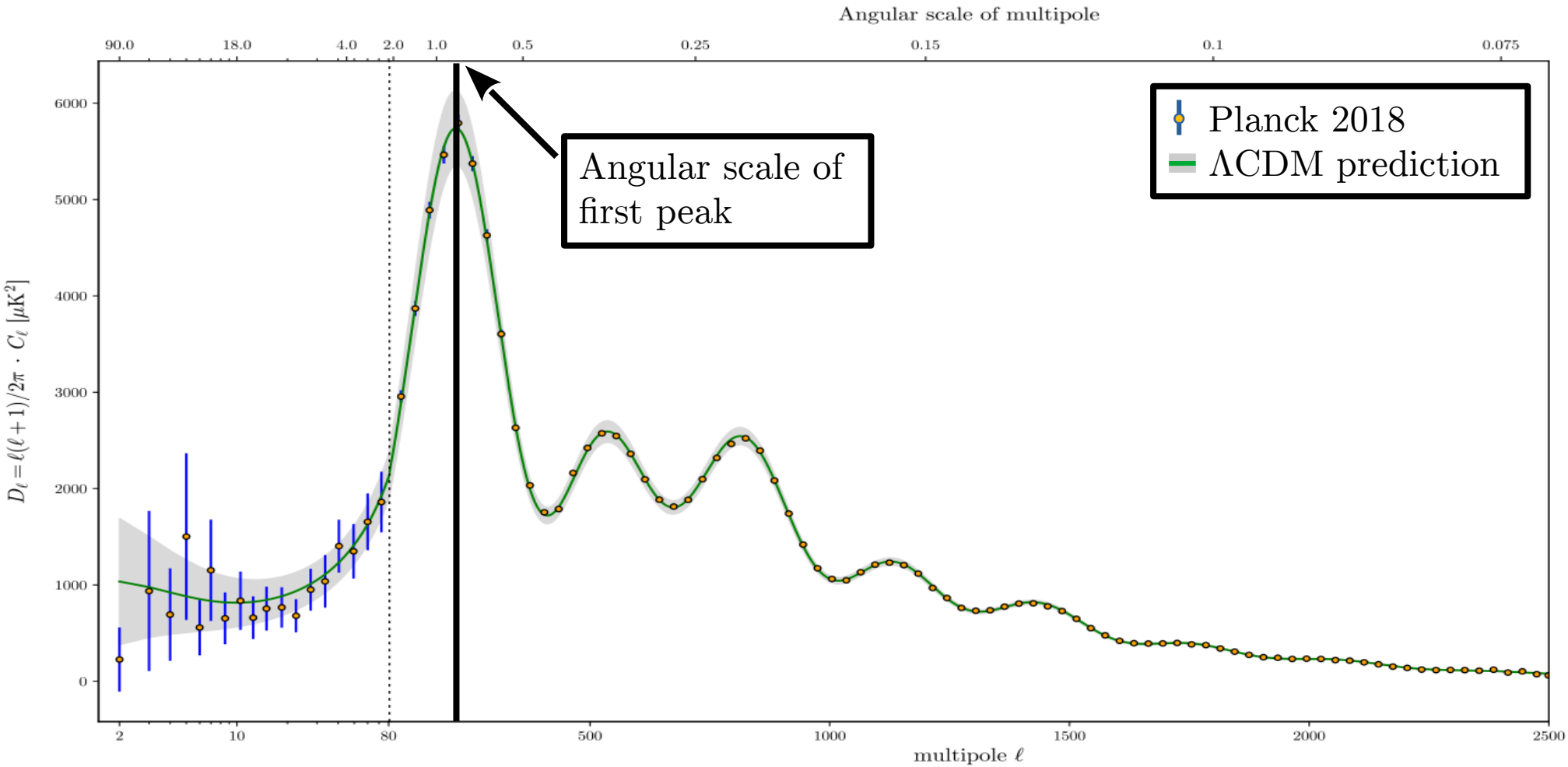
The CMB



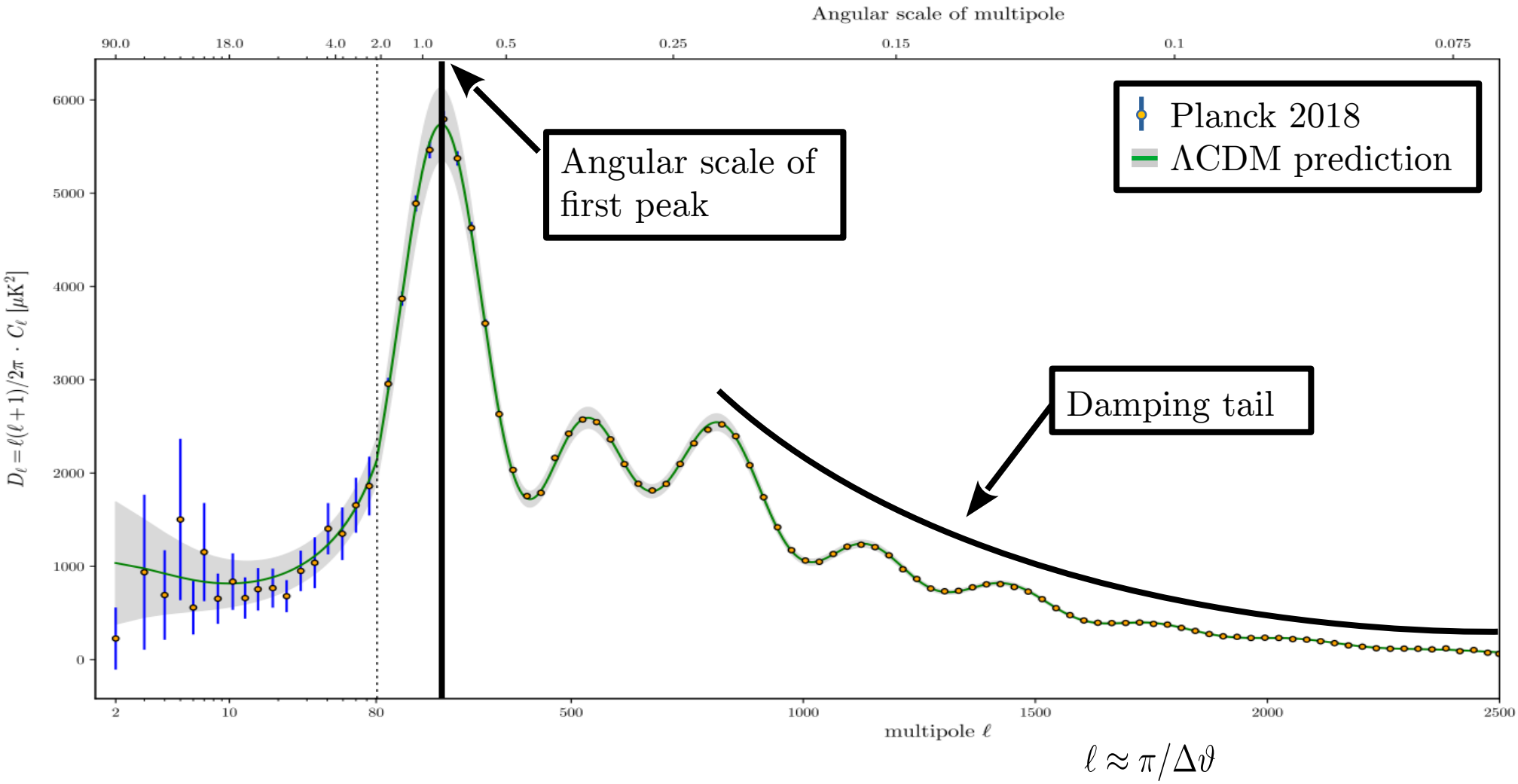
$$\ell \approx \pi/\Delta\vartheta$$

The CMB



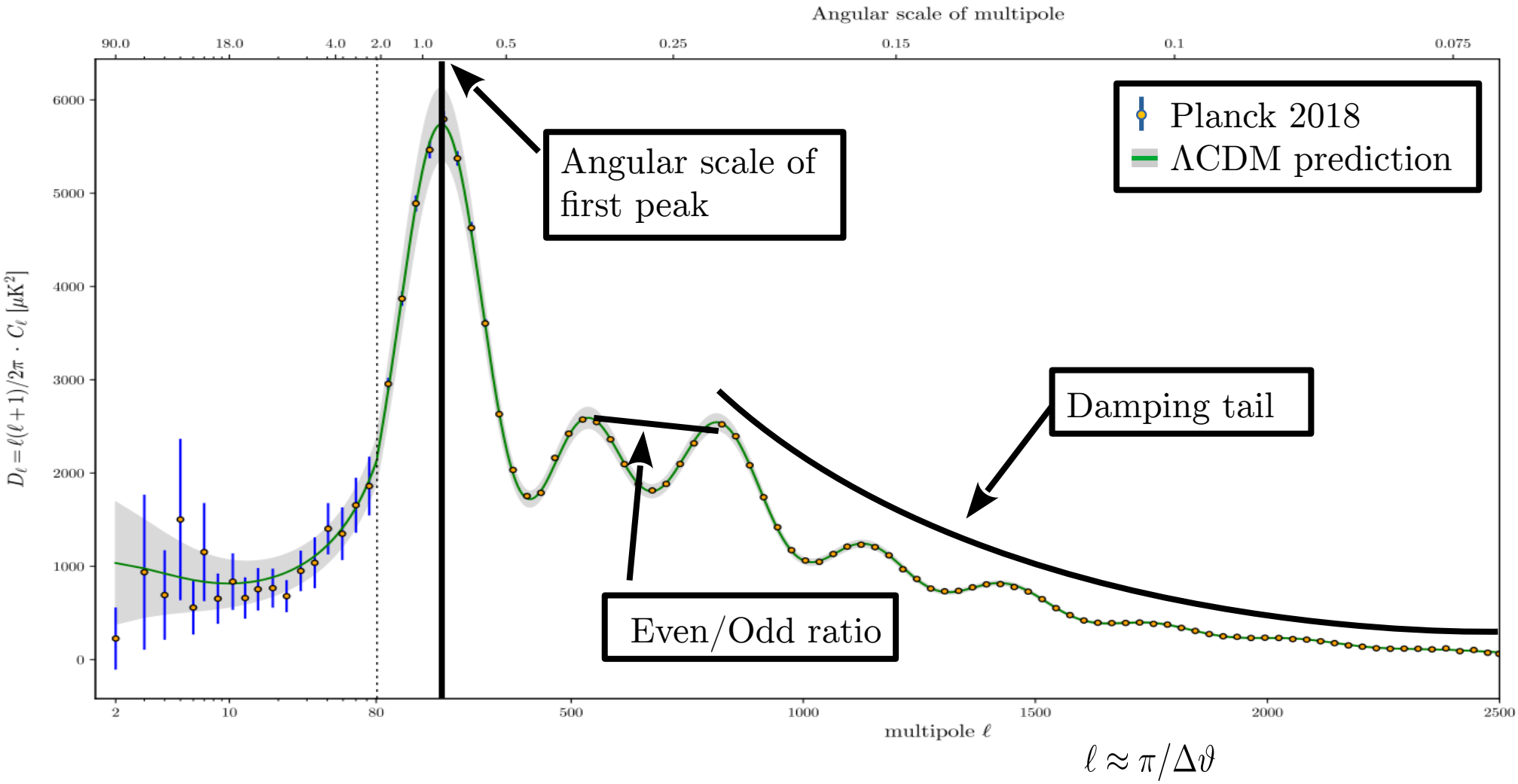
$$\ell \approx \pi/\Delta\vartheta$$

The CMB



$$\ell \approx \pi/\Delta\vartheta$$

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
Angular scale of first peak
Damping tail
Even/Odd ratio
$D_\ell = \ell(\ell+1)/2\pi \cdot C_\ell\ [\mu\mathrm{K}^2]$
multipole ℓ
$\ell \approx \pi/\Delta\vartheta$

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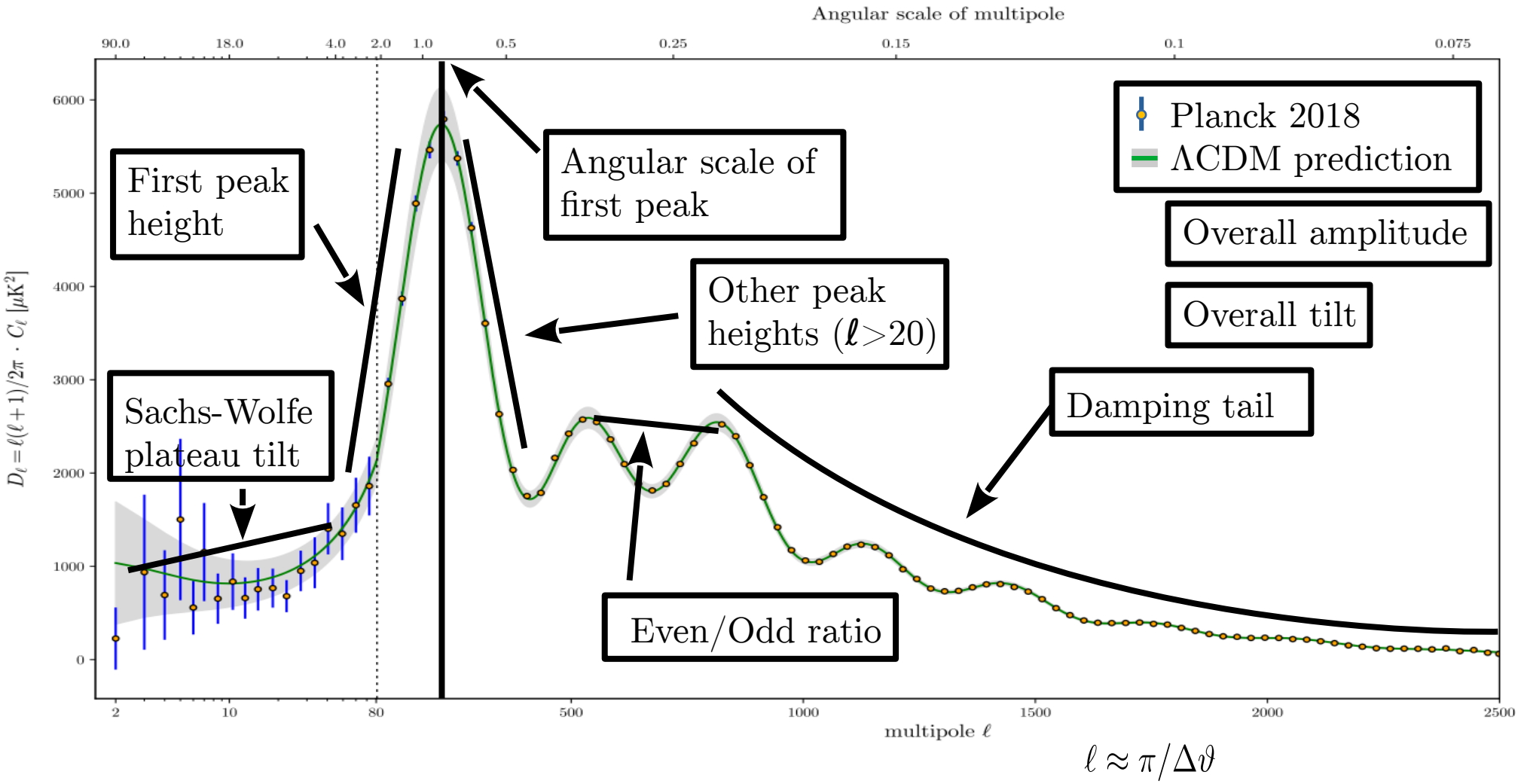
The CMB



$$\ell \approx \pi/\Delta\vartheta$$

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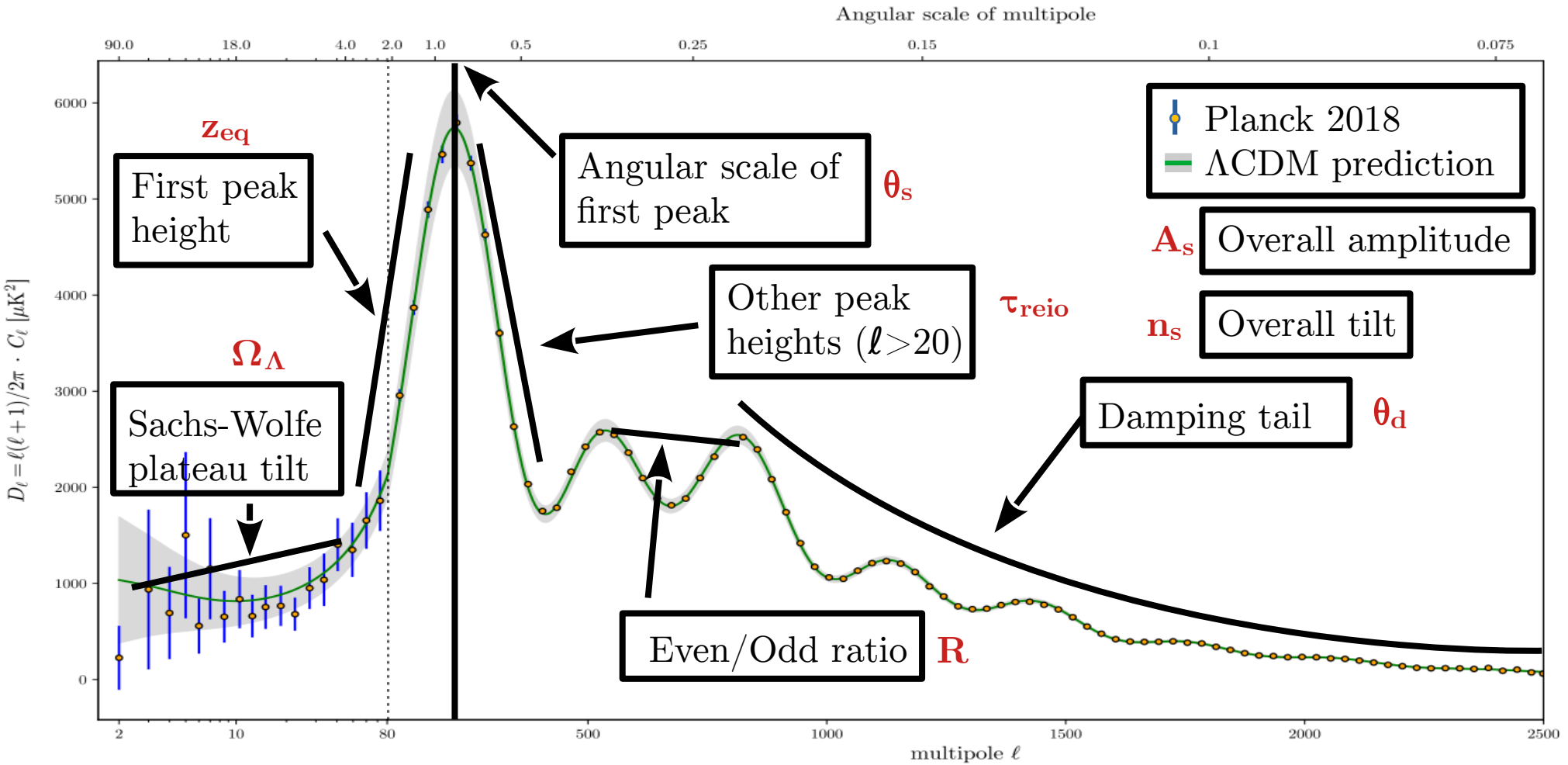
The CMB



$$\ell \approx \pi/\Delta\vartheta$$

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The CMB

z_{eq}

θ_s

A_s

τ_{reio}

n_s

Ω_Λ

θ_d

R

The CMB

z_{eq}

Ω_Λ

θ_s

R

θ_d

A_s

n_s

τ_{reio}

The CMB

z_{eq}

Ω_Λ

θ_s

R

θ_d

A_s

n_s

τ_{reio}

Primordial information
+ Reionization

The CMB

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

$\mathbf{\Omega_\Lambda}$ → $\Omega_\Lambda \to \Omega_m$

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

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

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

$\mathbf{A_s}$, $\mathbf{n_s}$, $\mathbf{\tau_{reio}}$ | Primordial information + Reionization

The CMB

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

$\mathbf{\Omega_\Lambda}$ → $\Omega_\Lambda \to \Omega_m$

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

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

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

$\mathbf{A_s}$, $\mathbf{n_s}$, $\mathbf{\tau_{reio}}$ | Primordial information + Reionization

The CMB

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

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

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

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

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

$\mathbf{A_s}$, $\mathbf{n_s}$, $\mathbf{\tau_{reio}}$ | Primordial information + Reionization

The CMB

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

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

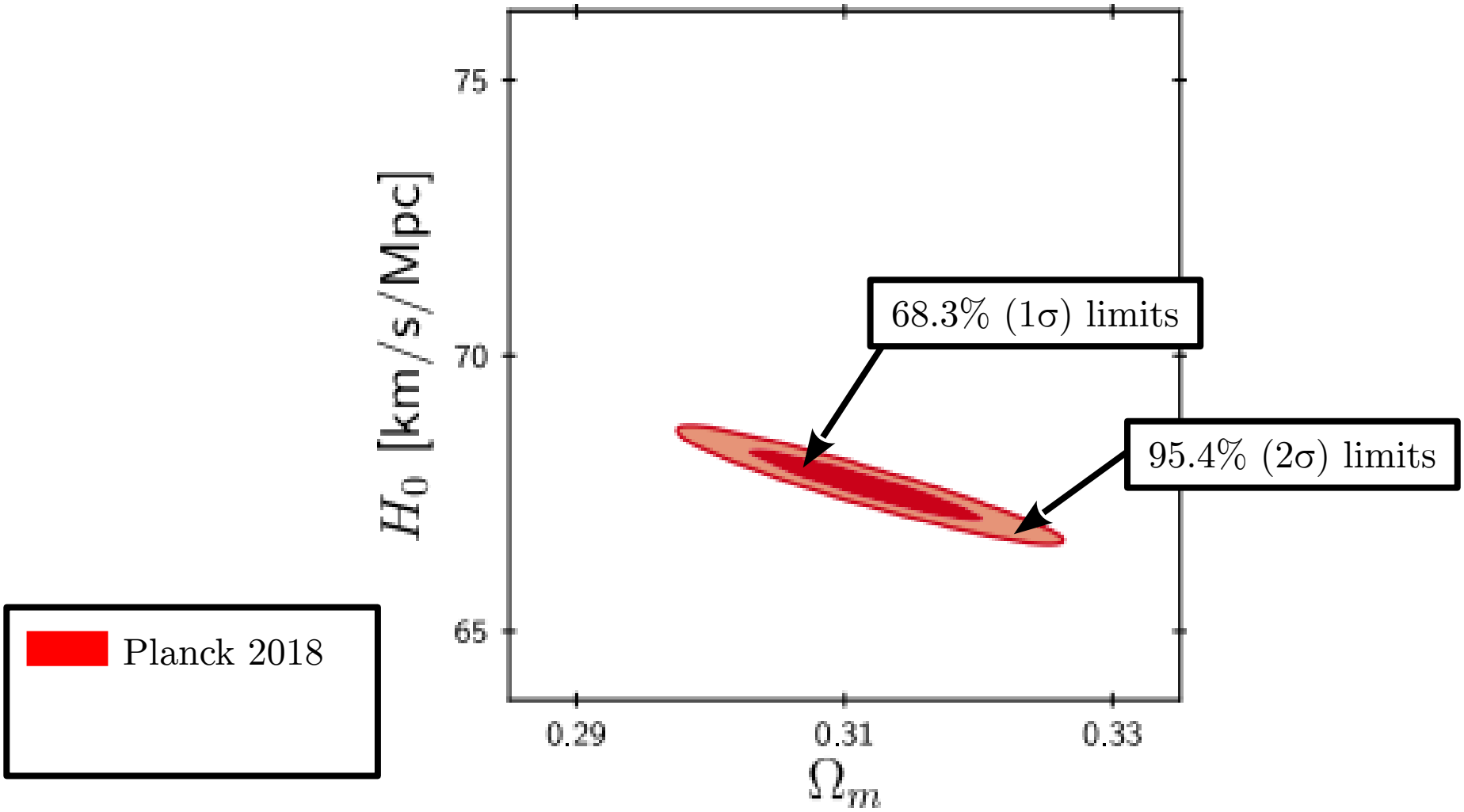
θ_s → $r_s/D_A(z_*) \to \boxed{\Omega_m h^3}, \Omega_b h^2$ [0.03% precision]

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

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

A_s, n_s, τ_{reio} | Primordial information + Reionization

The Hubble Tension



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Standard Candle

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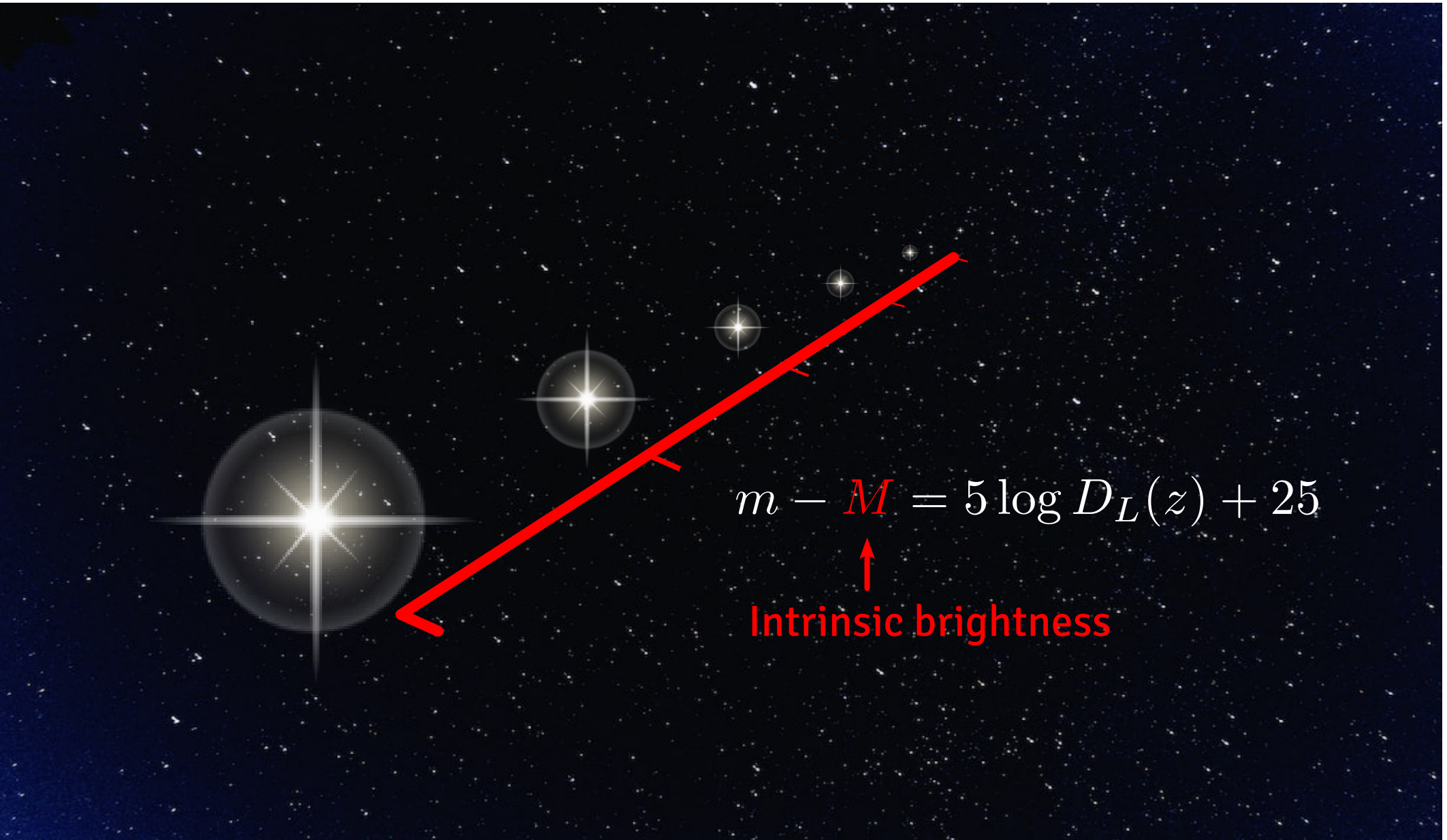

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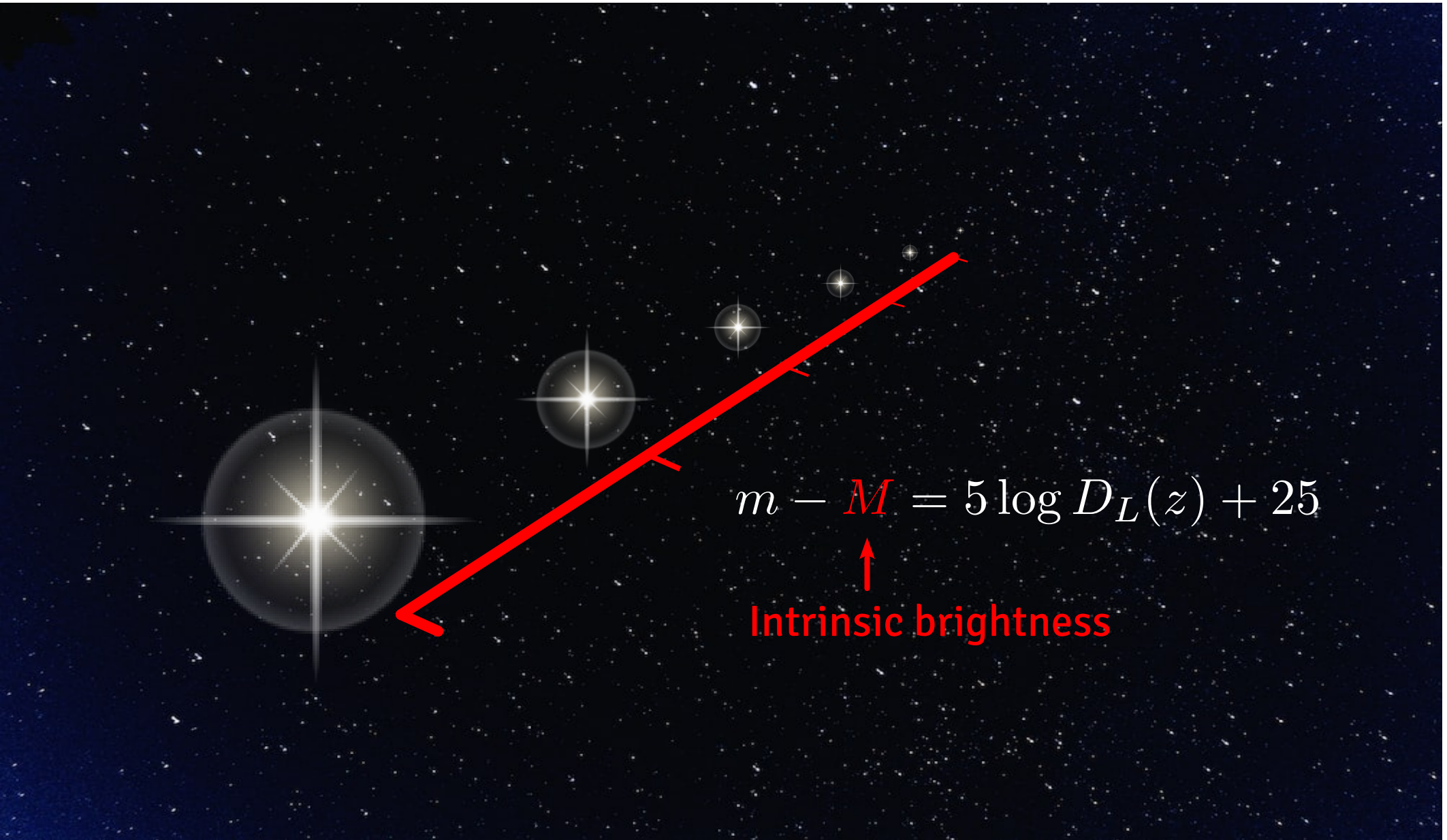

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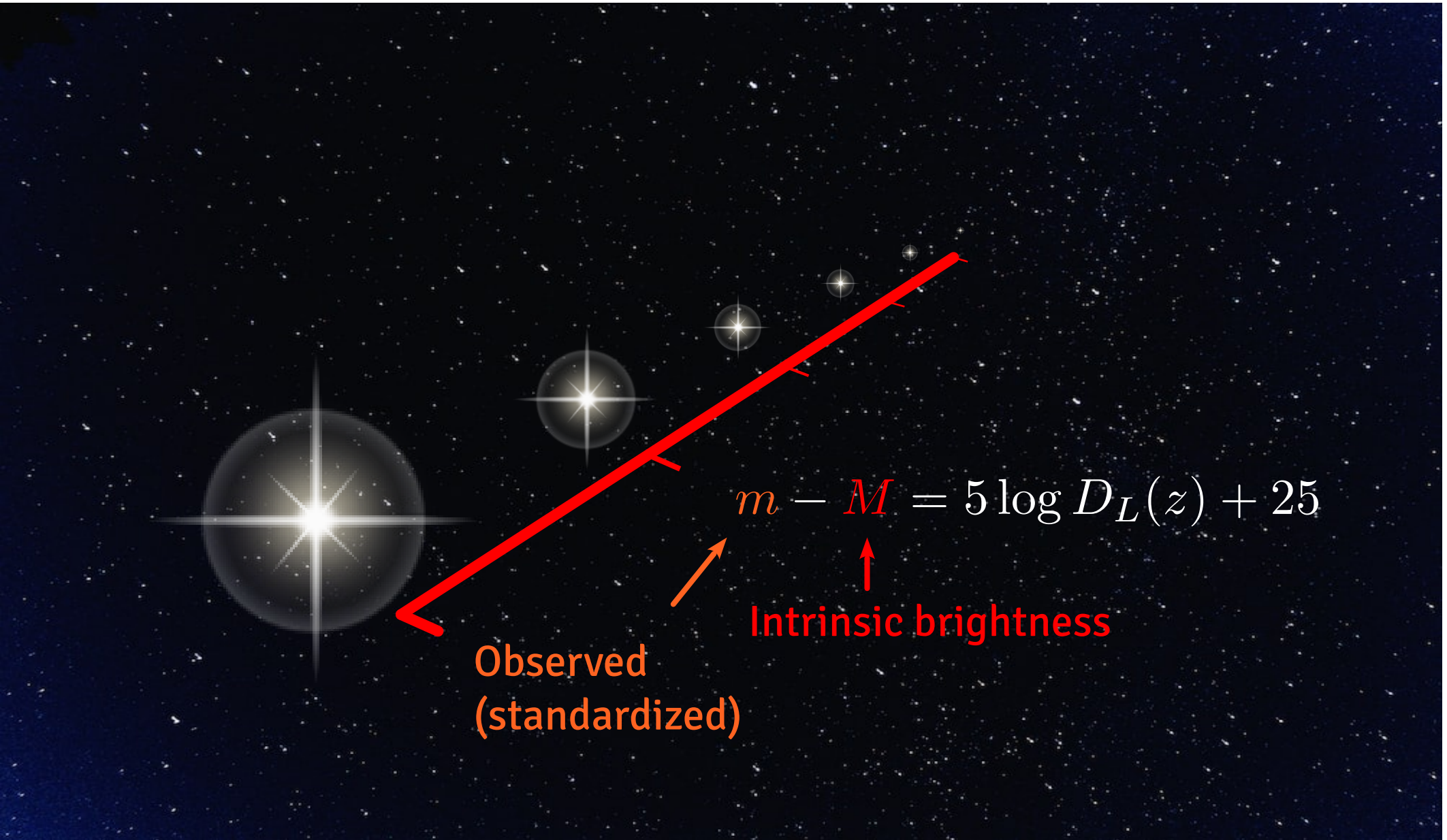

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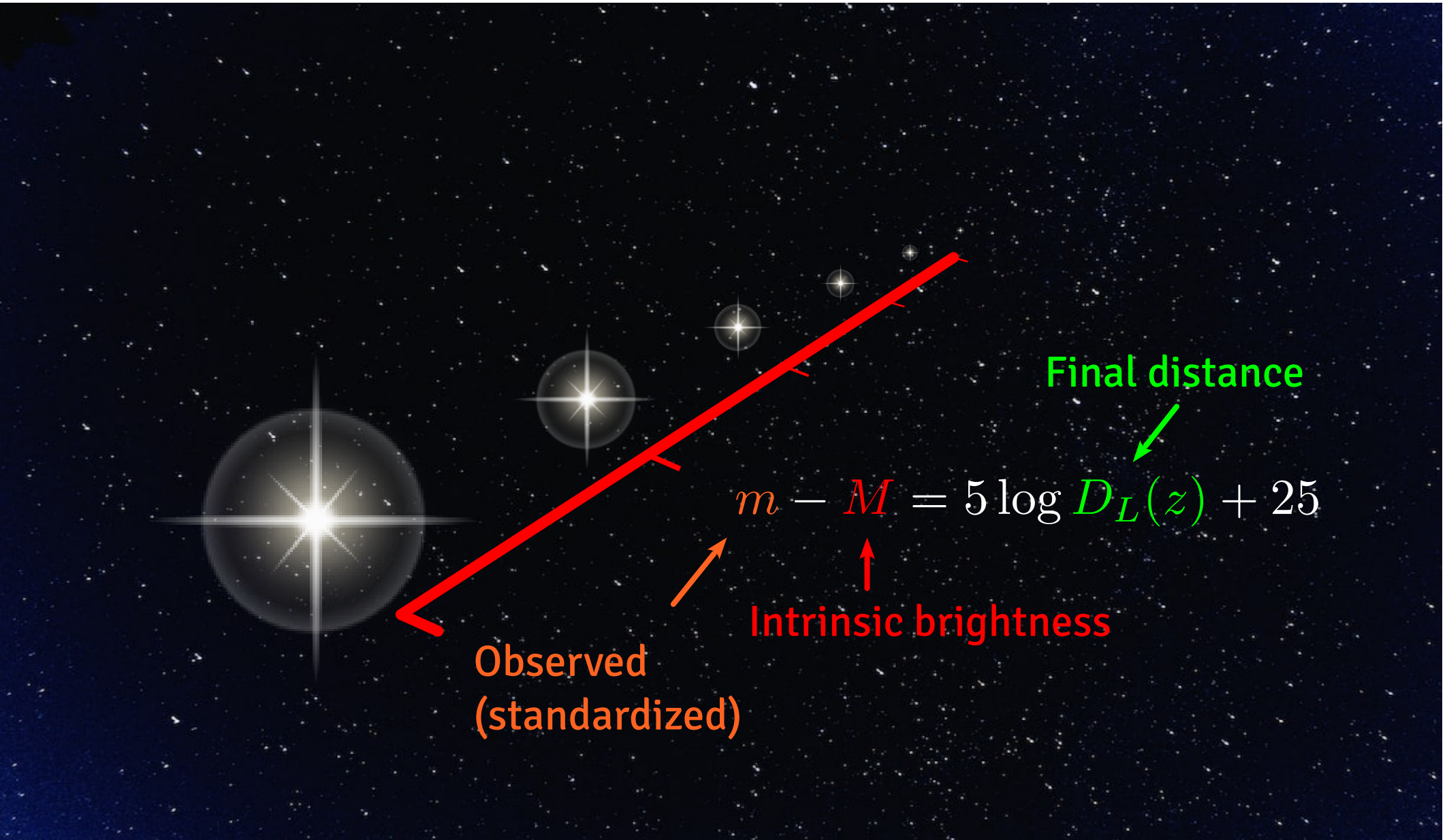

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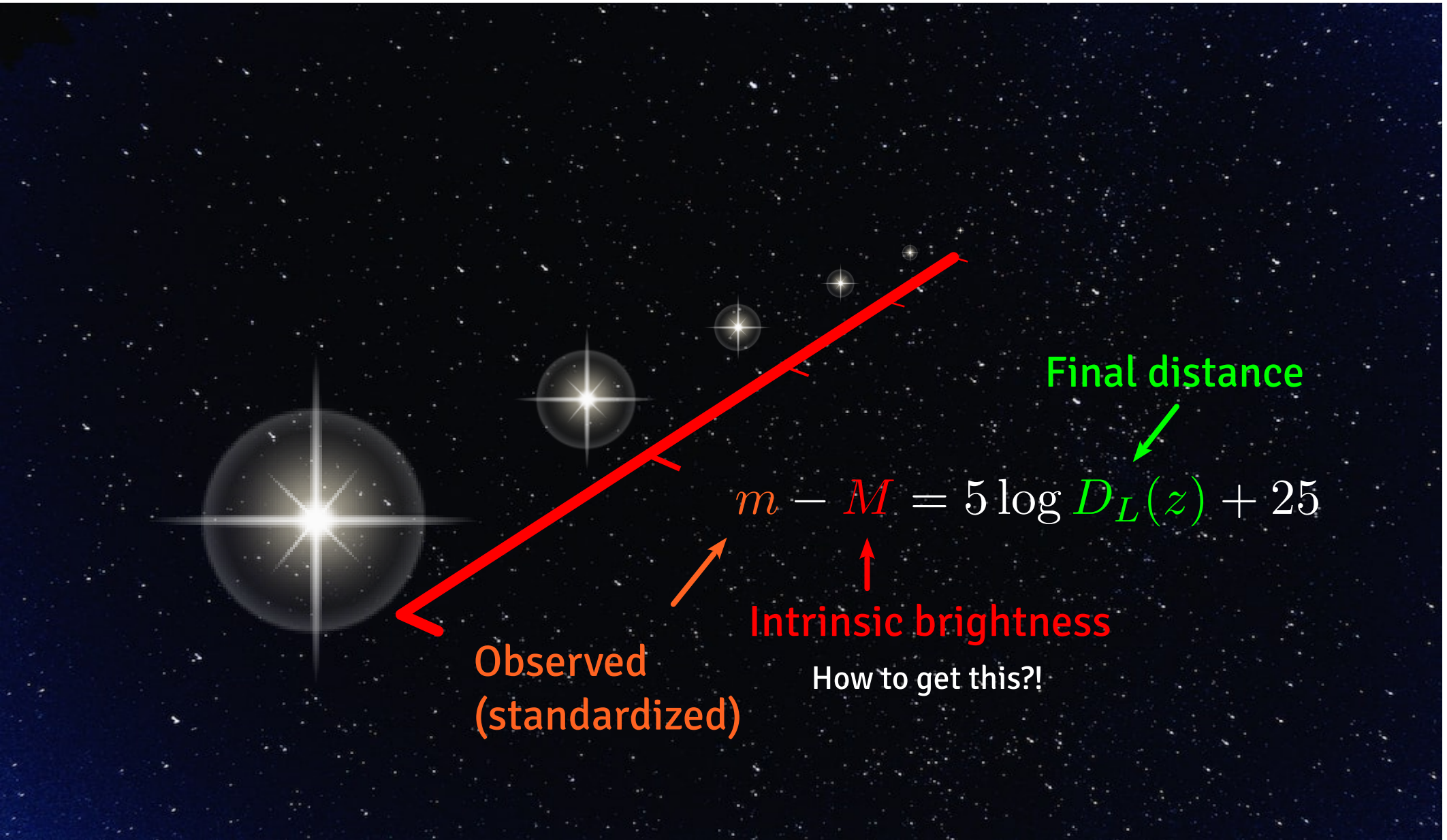

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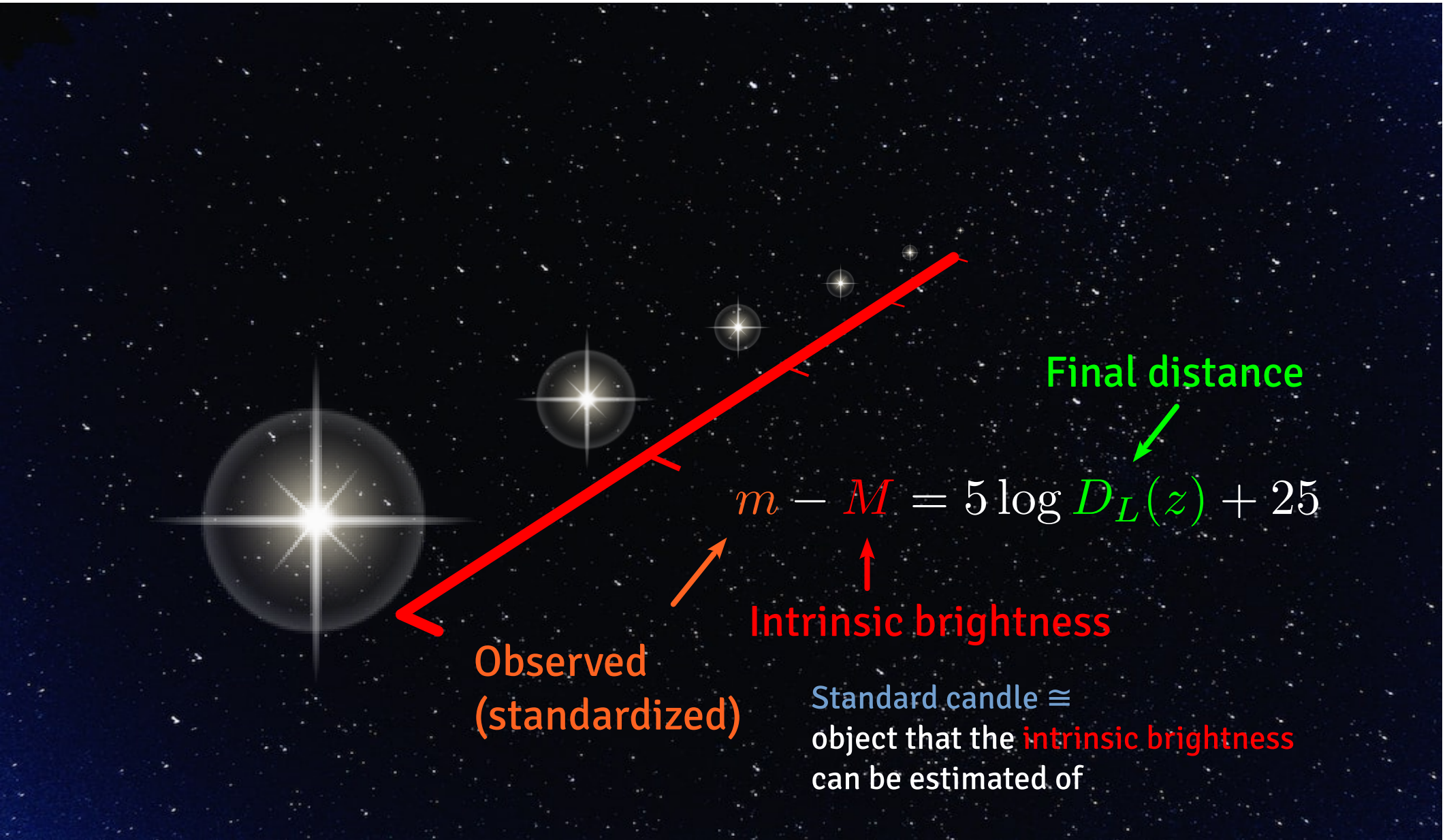

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Galaxy spectral lines → redshift

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- => To get H(z), we need distance and redshift
- Often not a problem… **but sometimes it is!**

Standard Candles

Sadly, this is *not* where the issues stop

Even when we find objects with good intrinsic properties that allow for estimation of the intrinsic magnitude and also give their redshift, there is still *one more hurdle*!

Issues of Standard Candles

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- Nearby objects are faint at large distance
- Faraway bright objects are uncommon in the local universe

Issues of Standard Candles

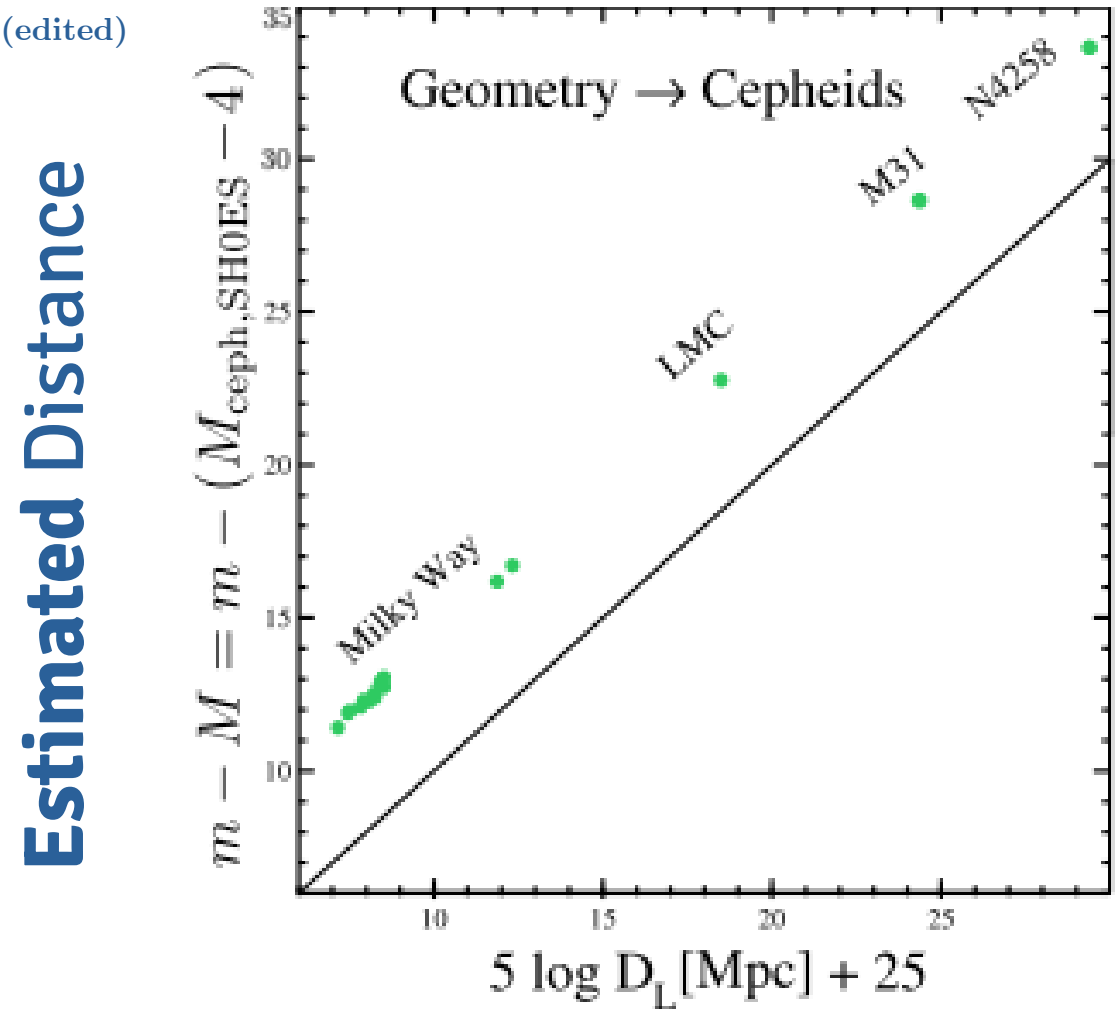
- Calibration of M requires nearby objects of known dista
- Mea n the Hub
- Nea
- Fara l universe

The solution:

Build a ladder!

Calibrate bright faraway objects
using faint nearby ones

Riess+1604.01424 (edited)



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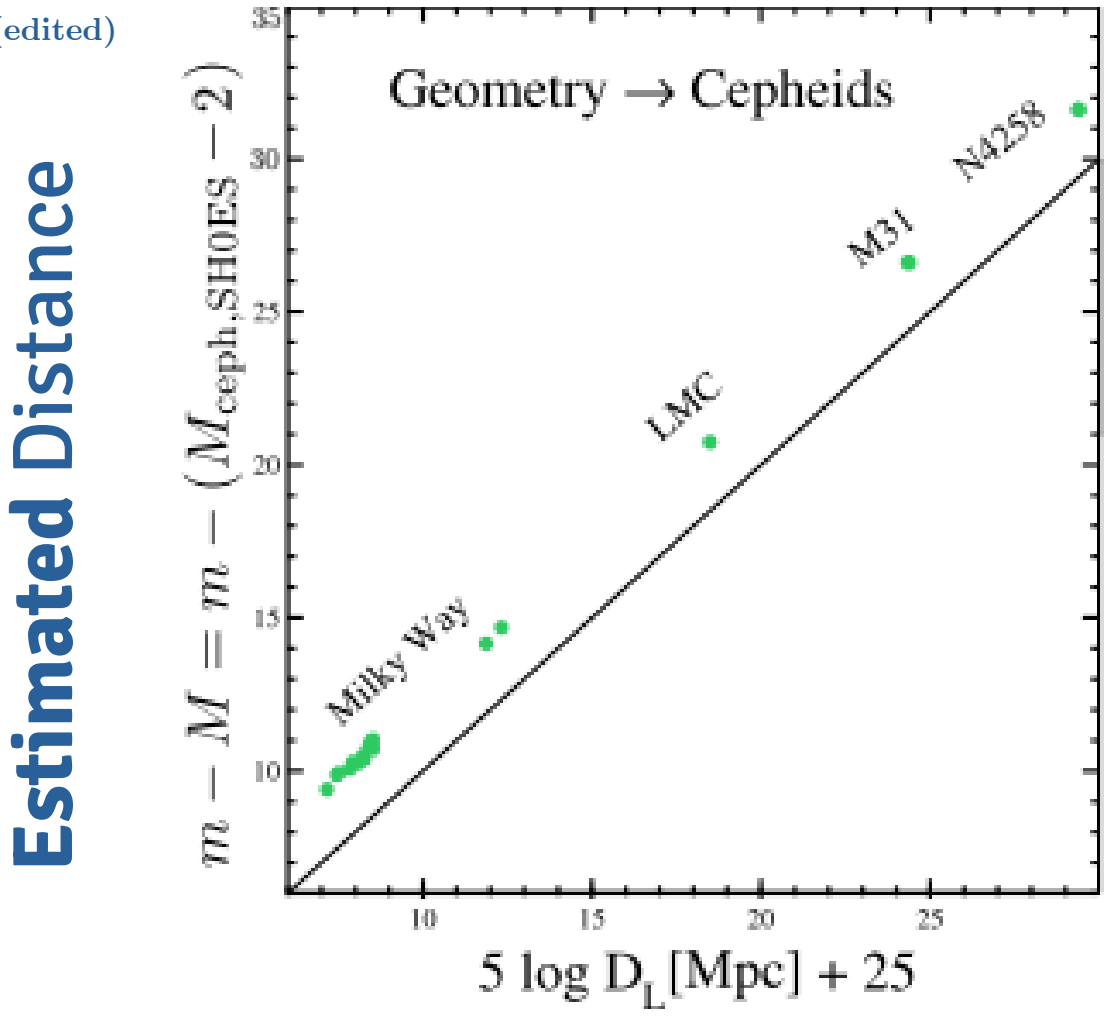

Estimated Distance

Measured Distance

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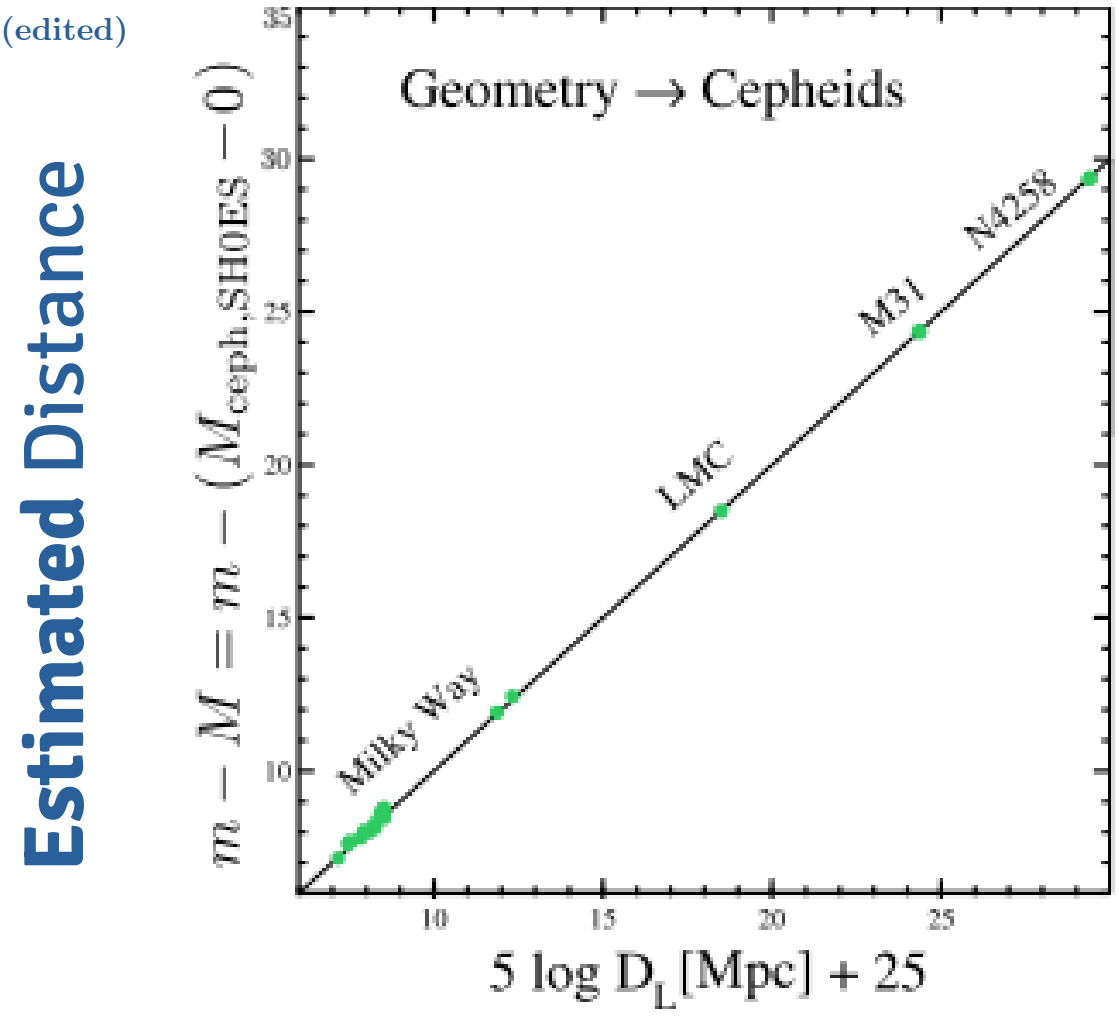

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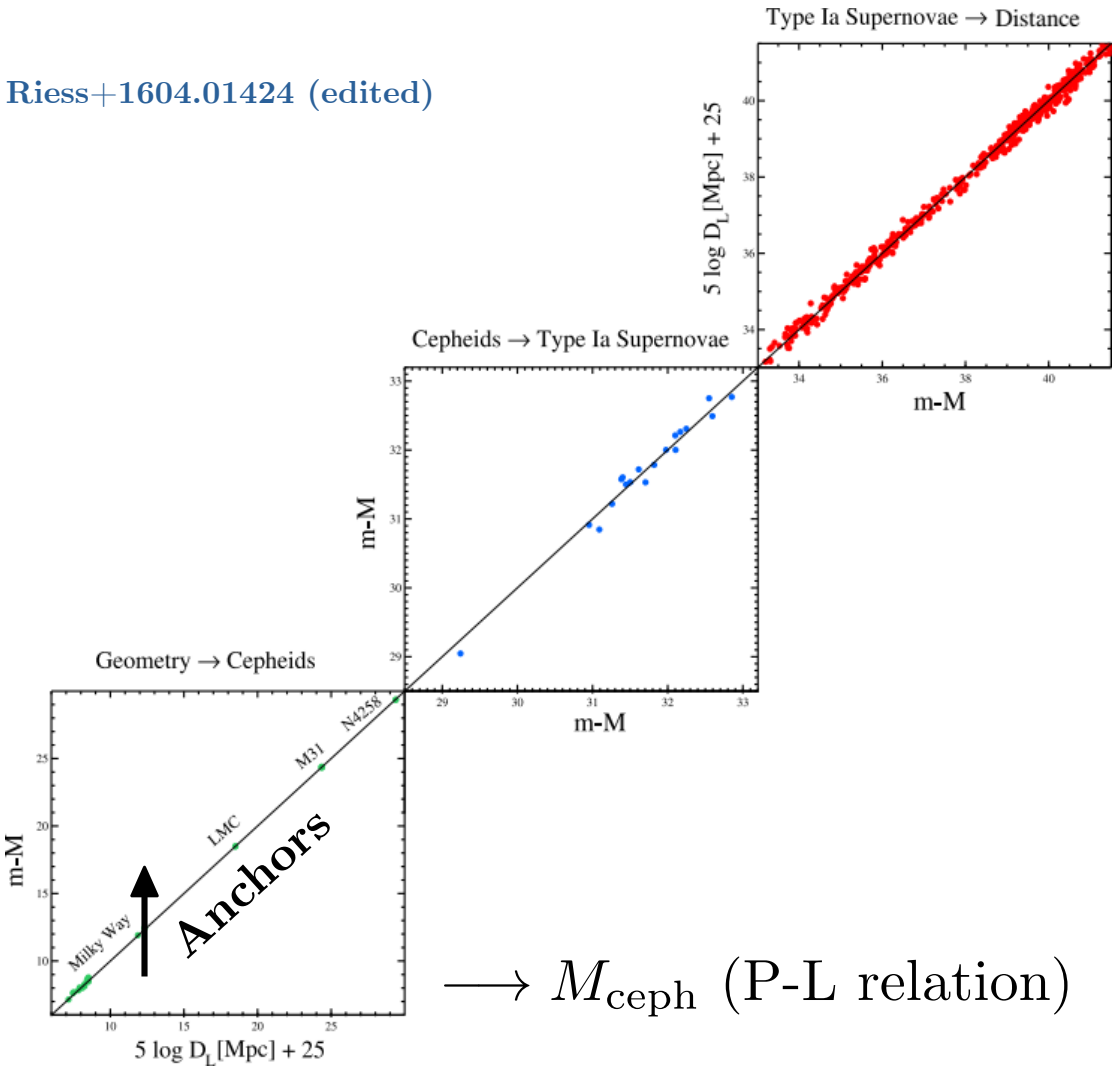

$\longrightarrow M_{\mathrm{ceph}}$ (P-L relation)

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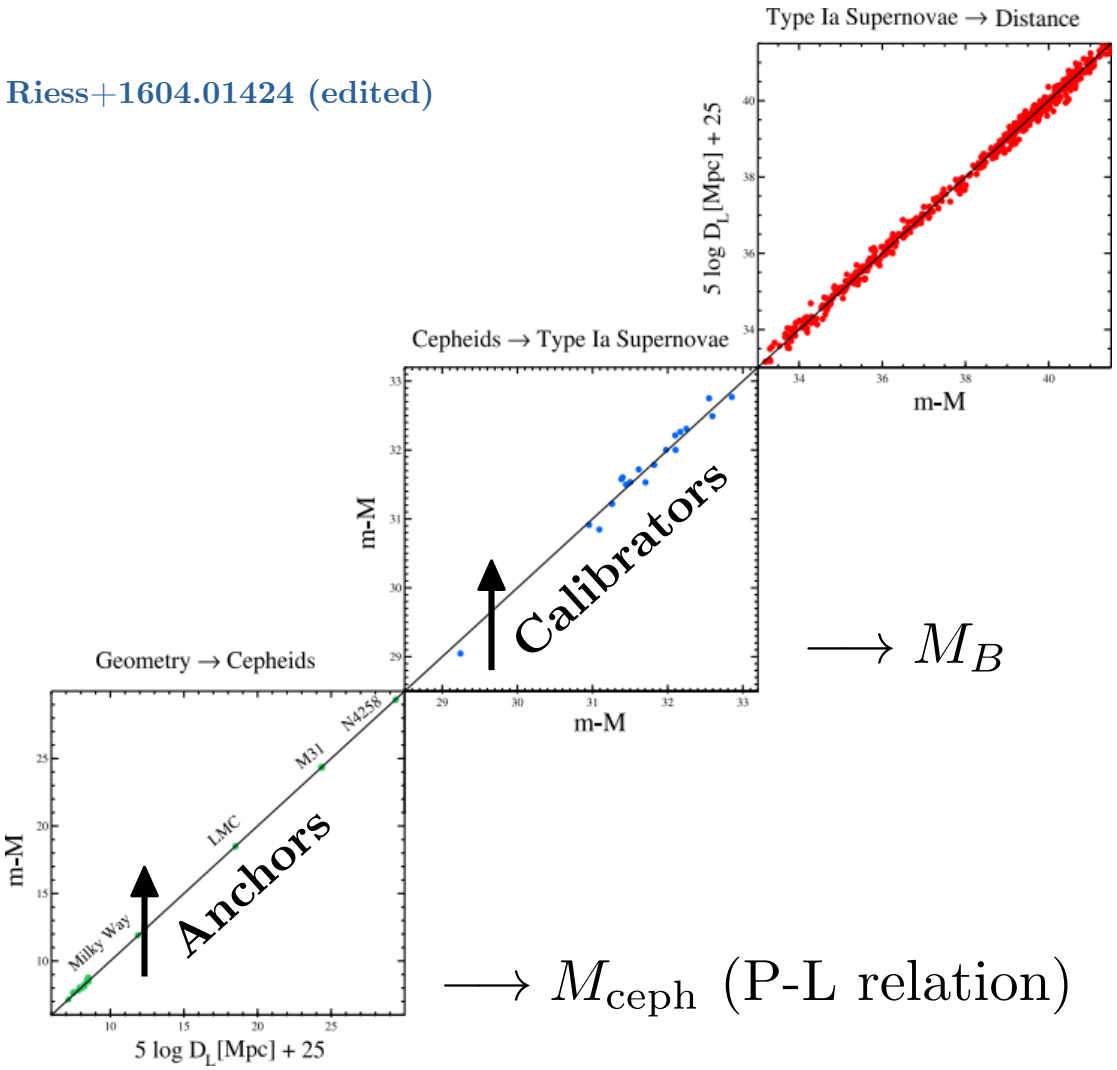

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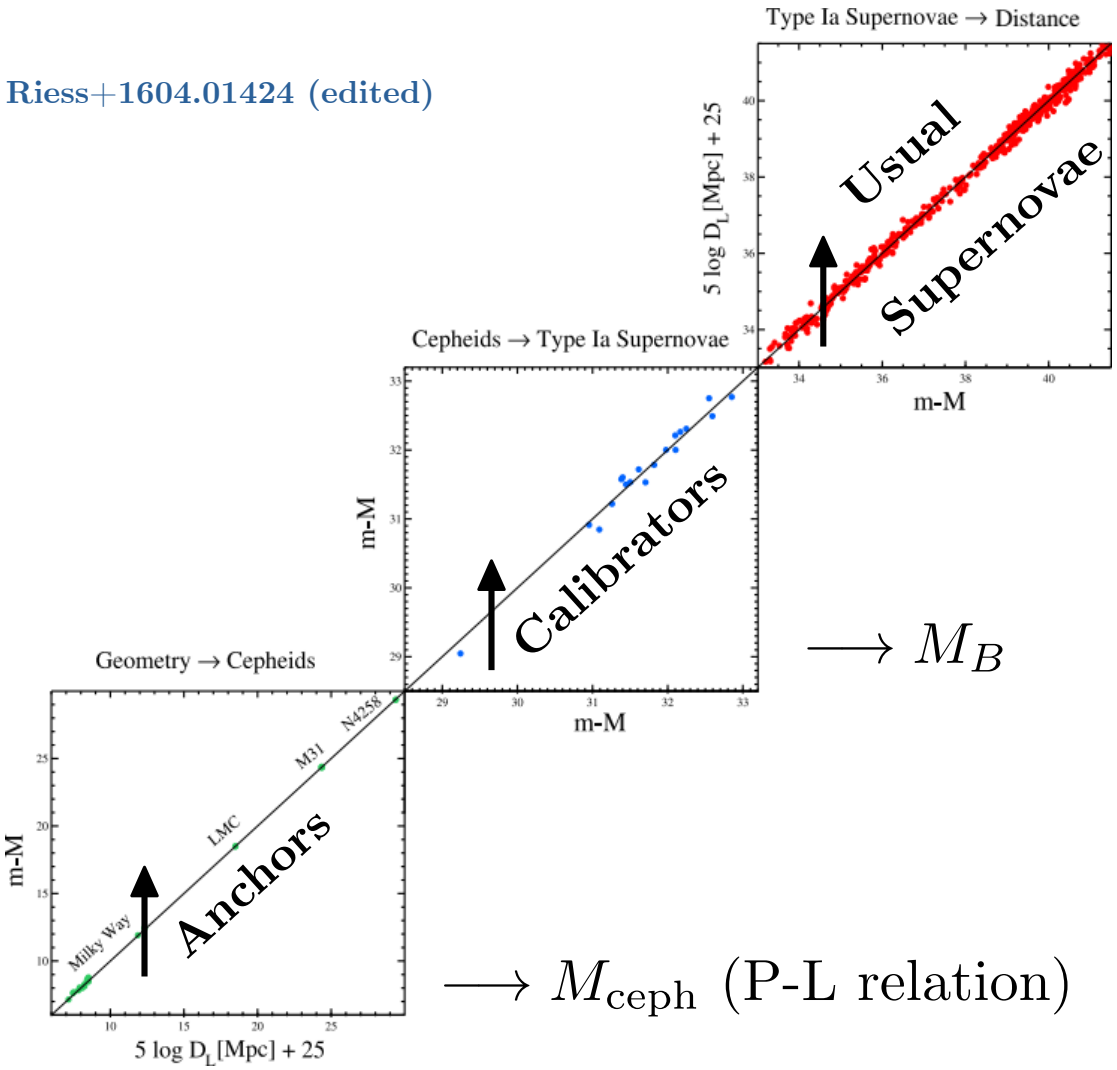

$\longrightarrow D_L$

$+$ (measured) z $\longrightarrow H_0$

$\longrightarrow M_B$

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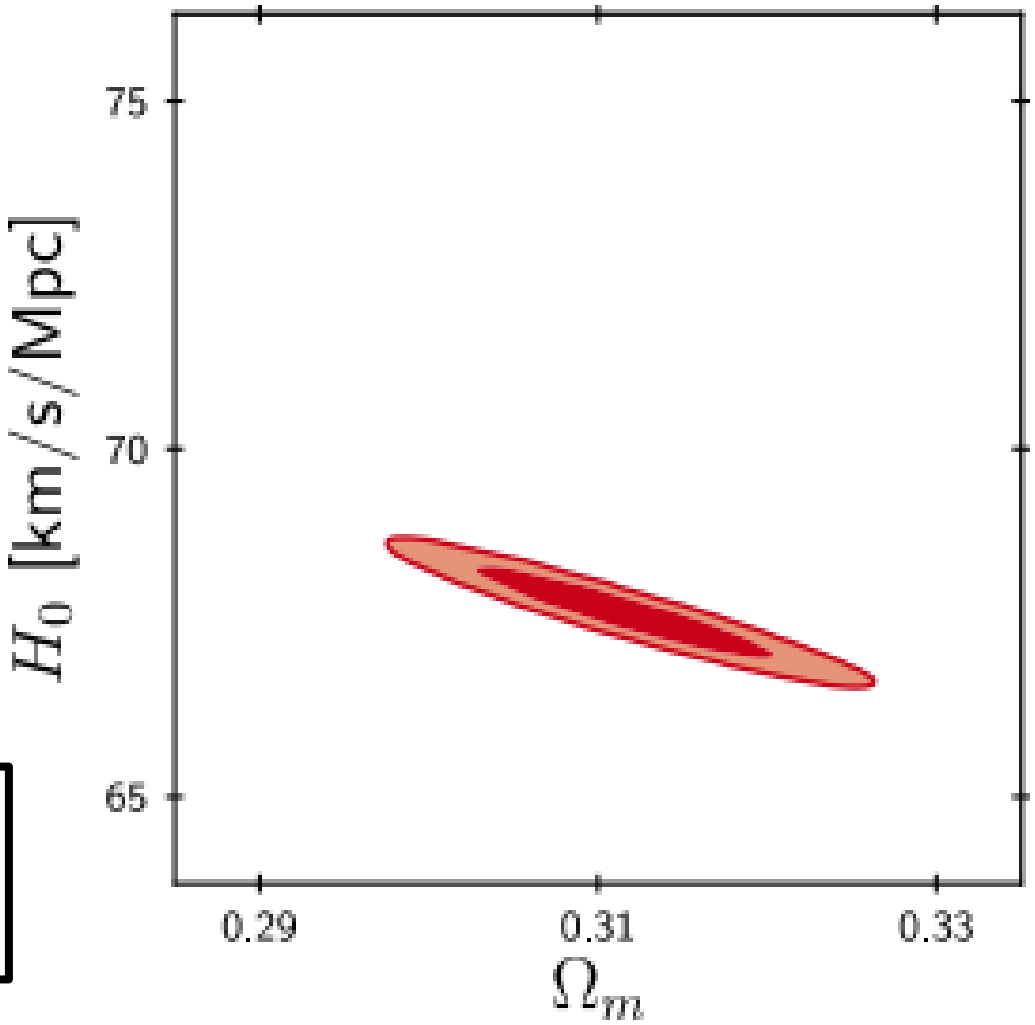
The Hubble Tension



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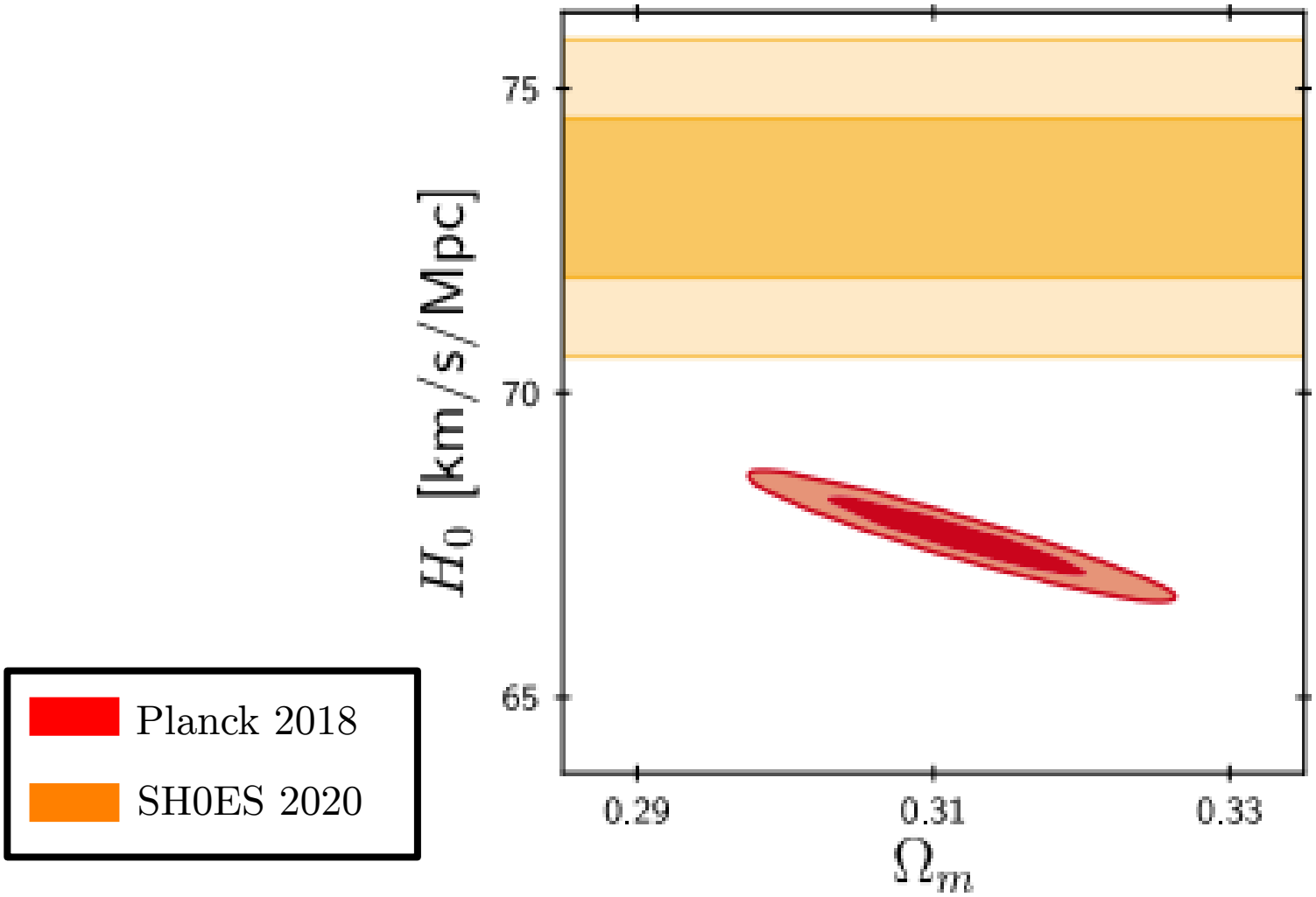

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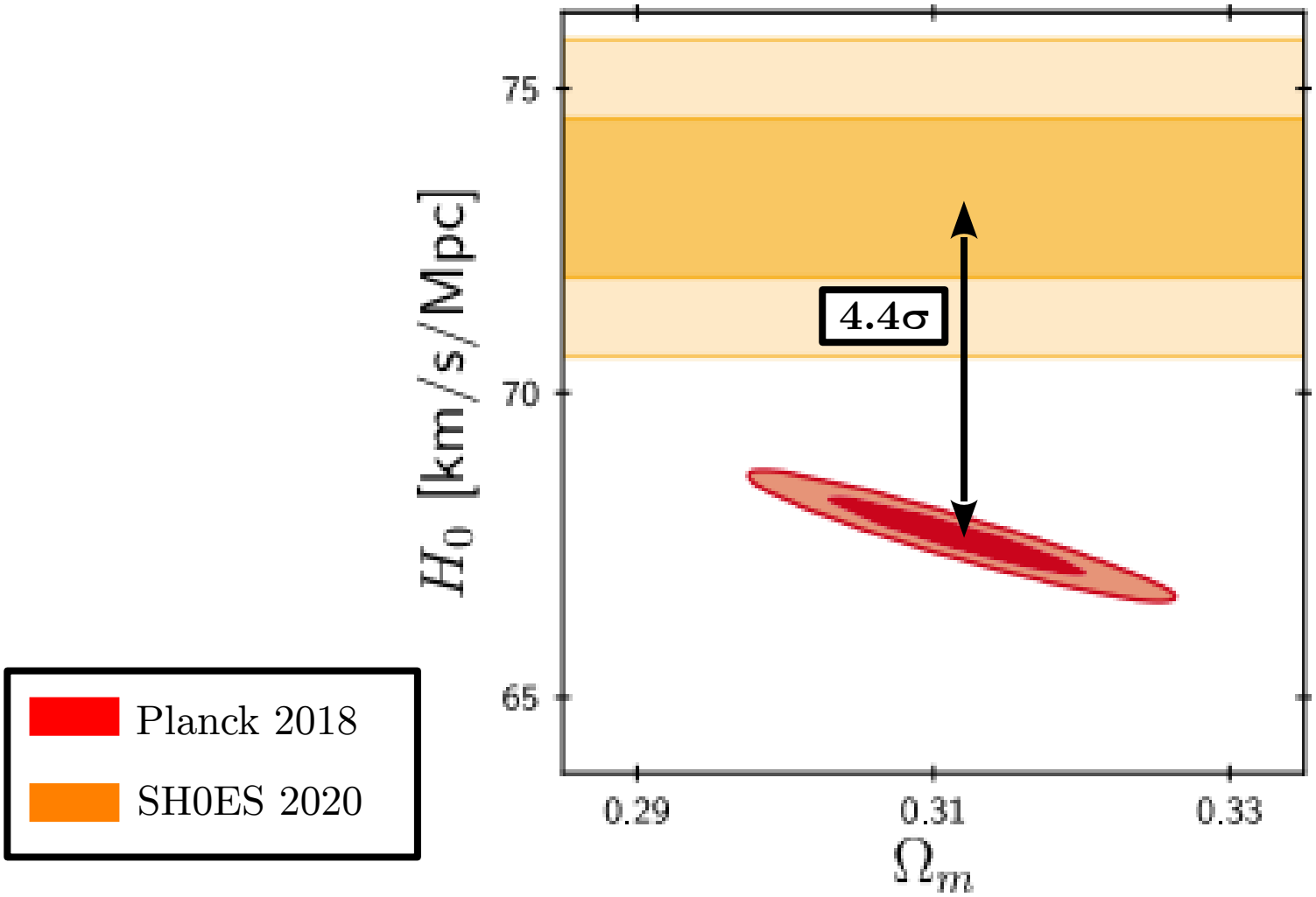

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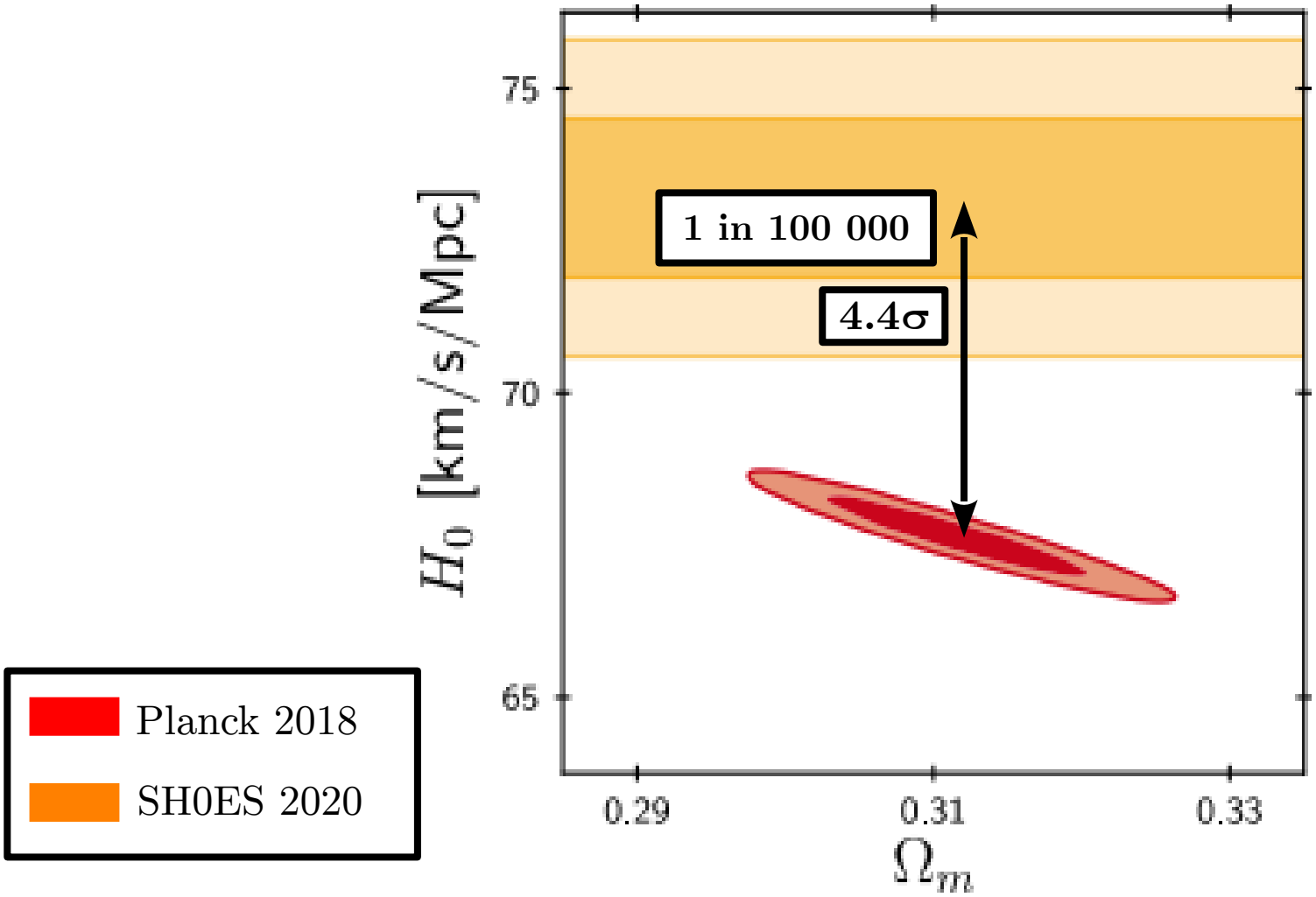

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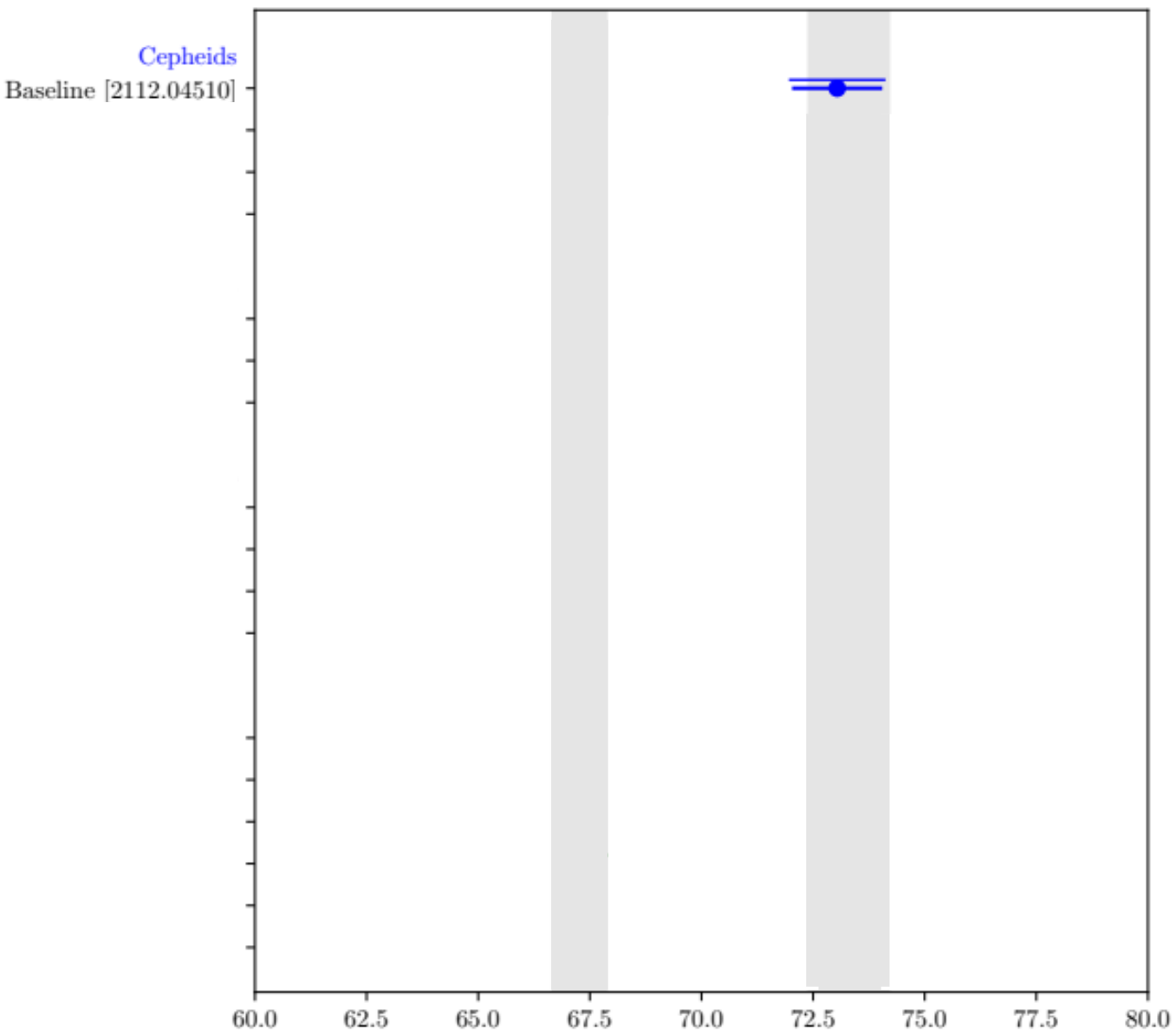

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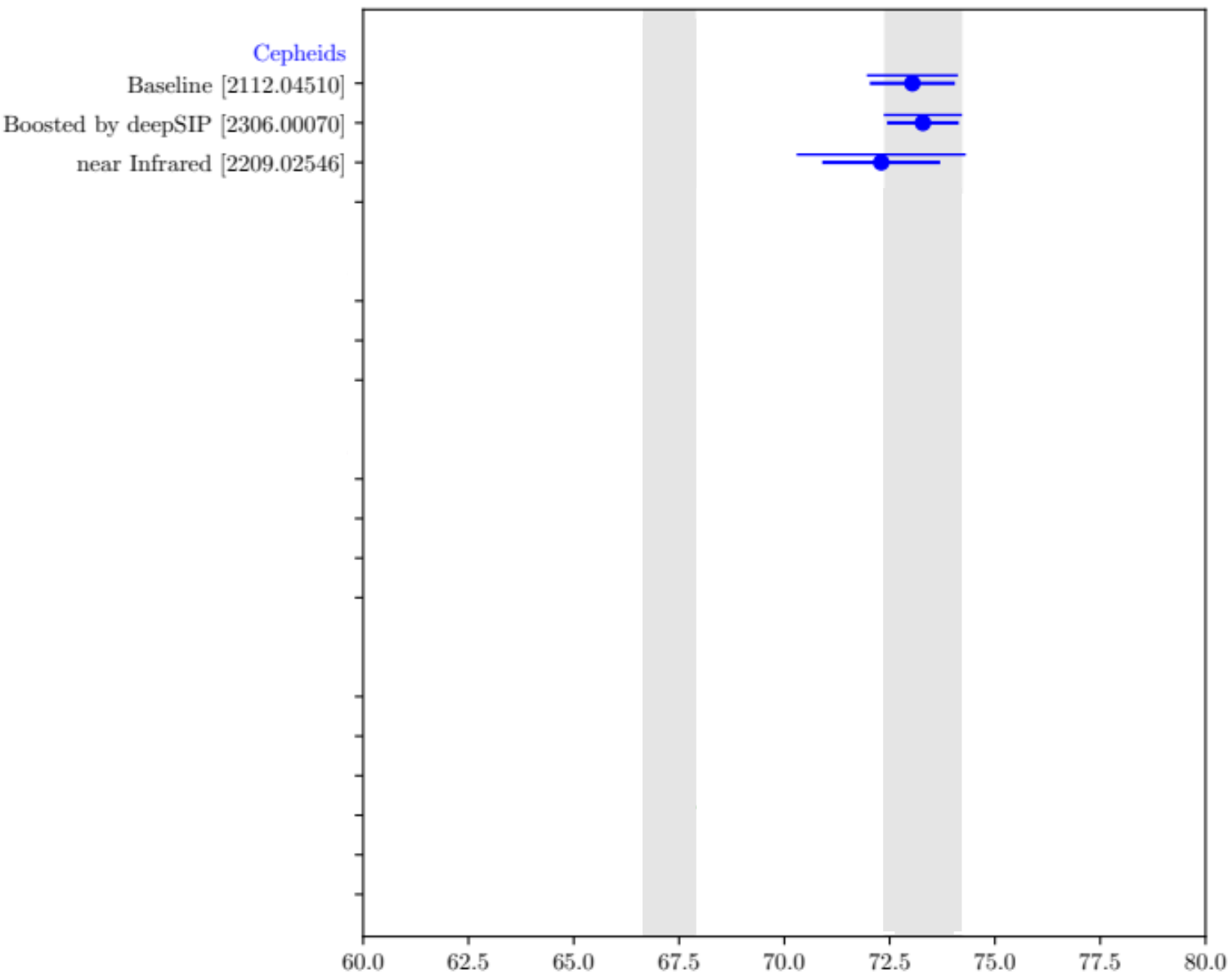

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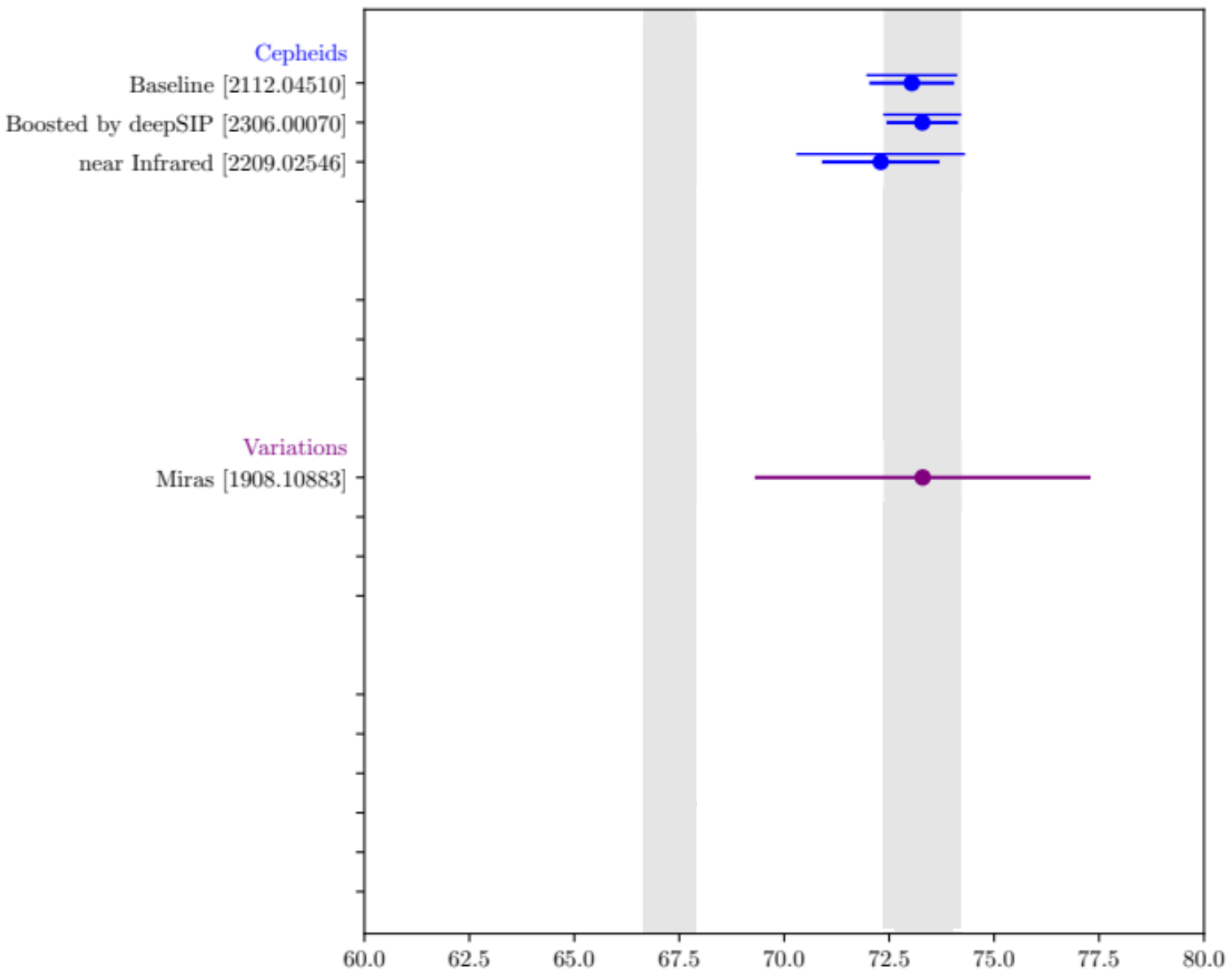

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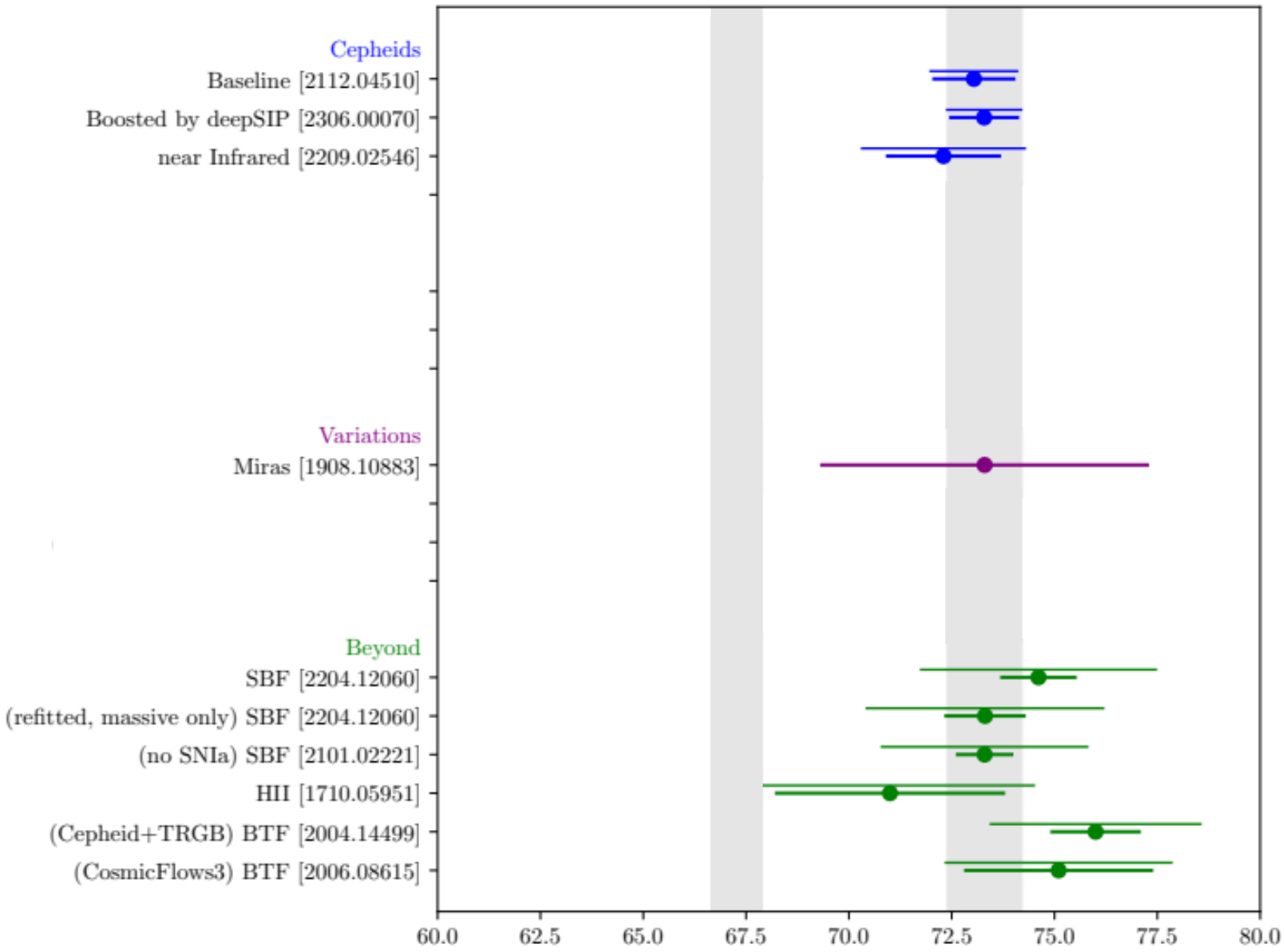

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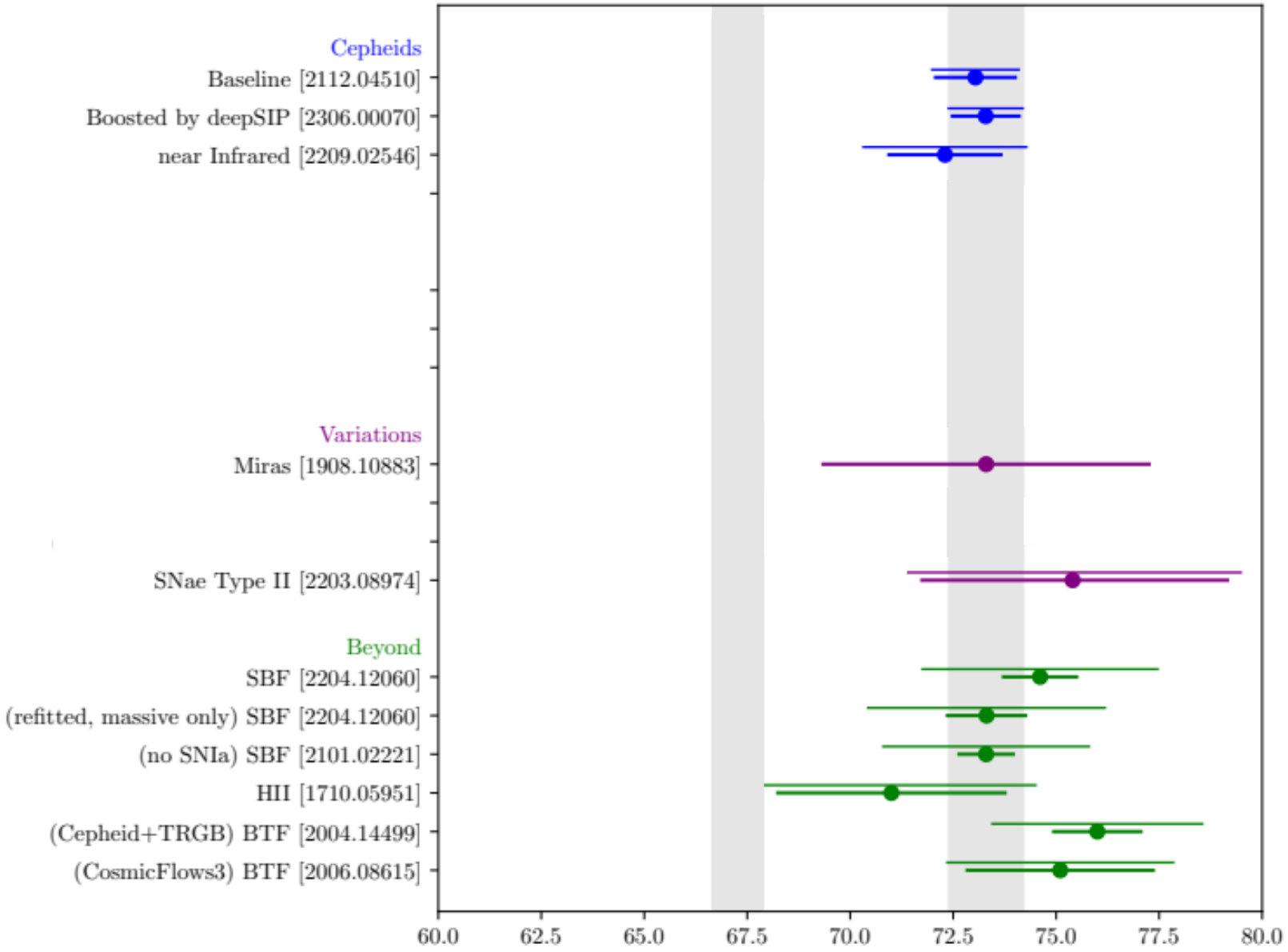

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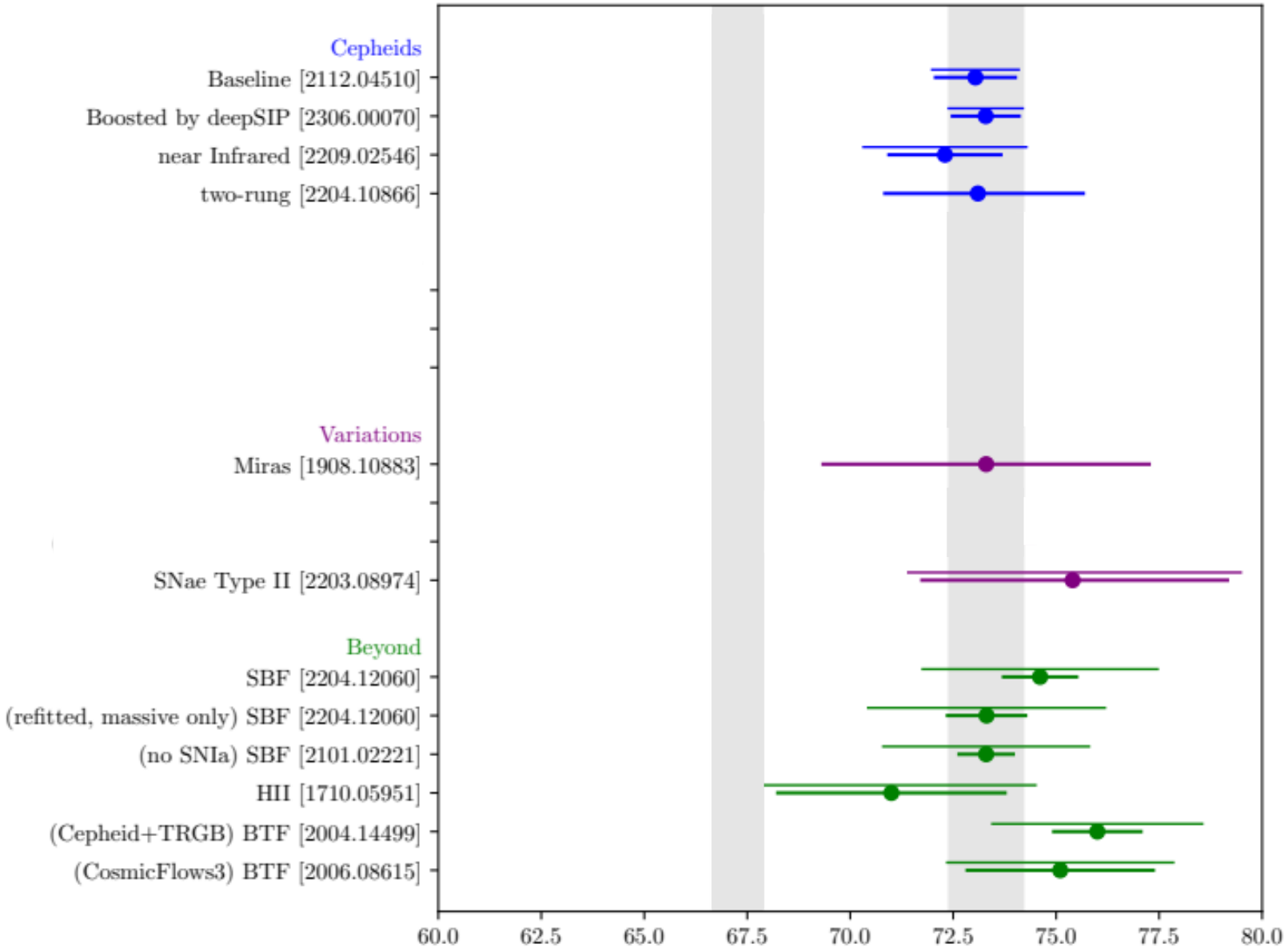

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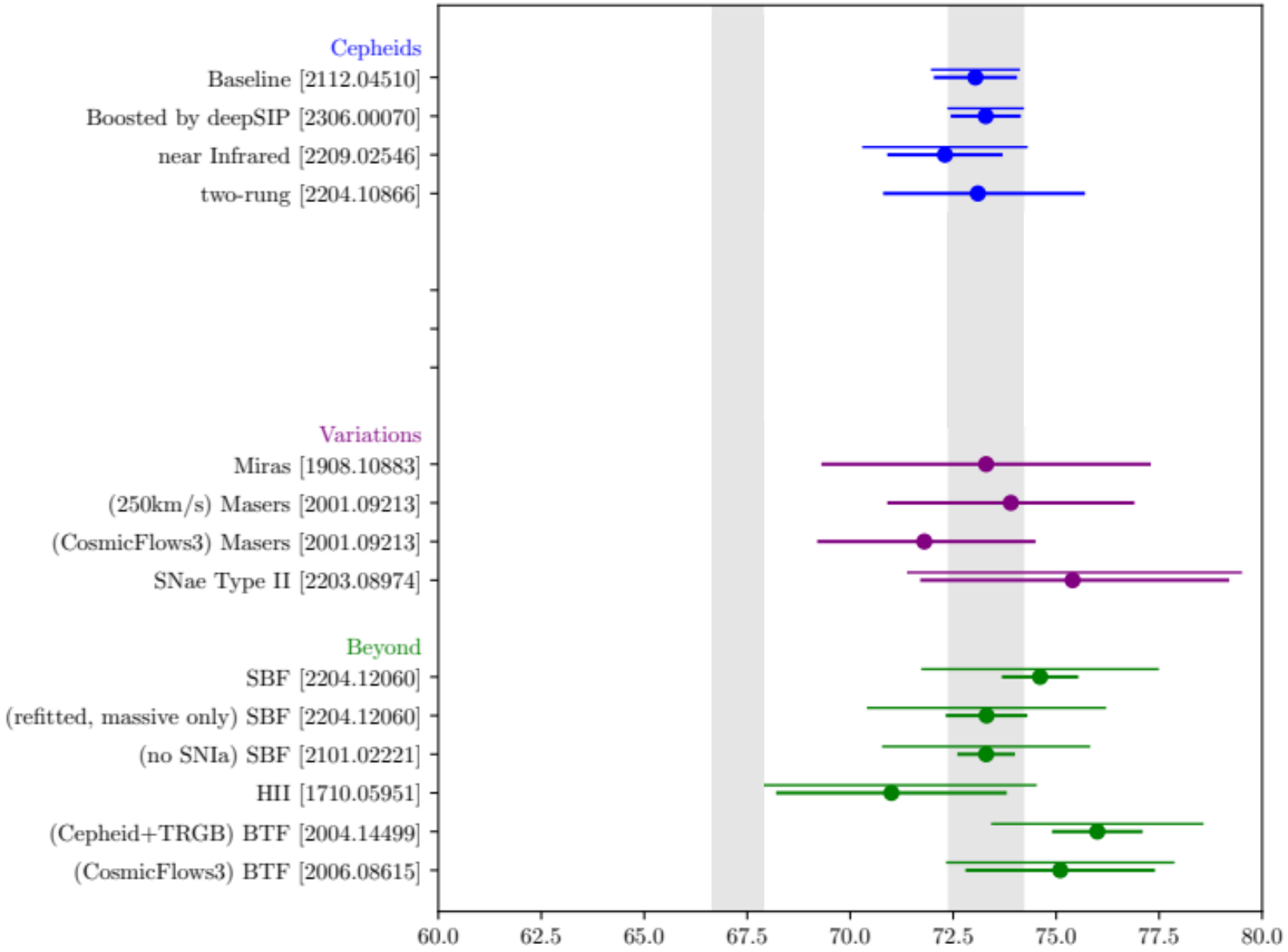
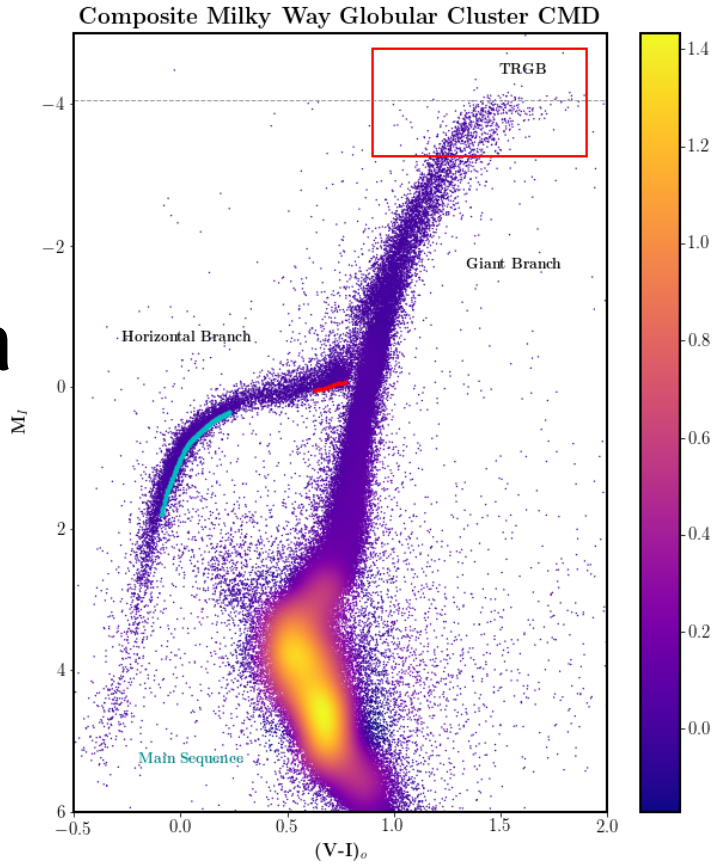


Short Interlude: What about the TRGB?

- TRGB = tip of red giant brach

- Red giants accumulate Helium in their cores

→ Helium flash and carbon burn



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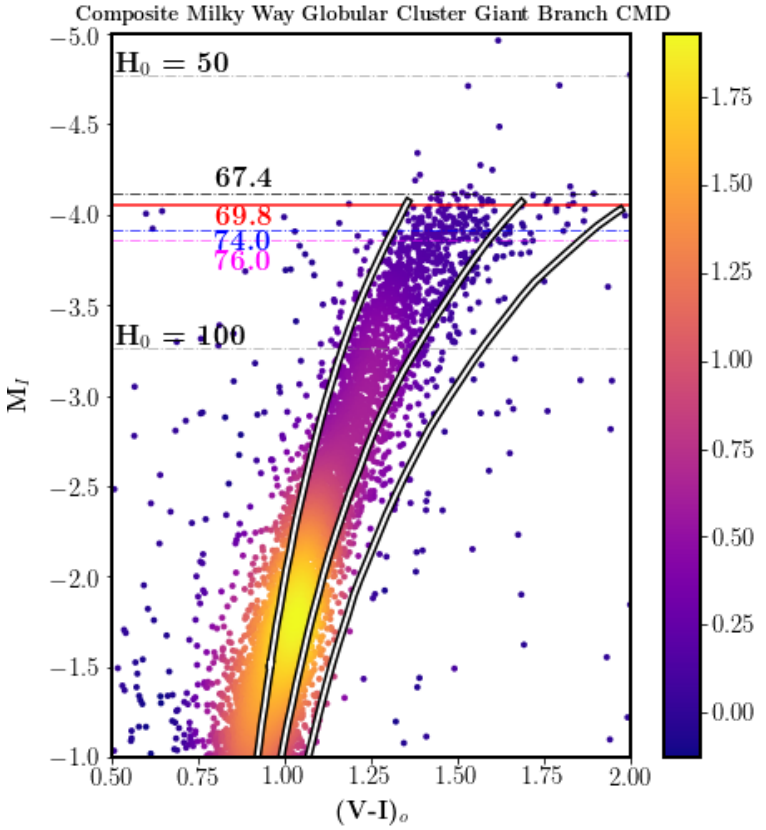
Estimate the intrinsic magnitude from where population of stars abruptly ends



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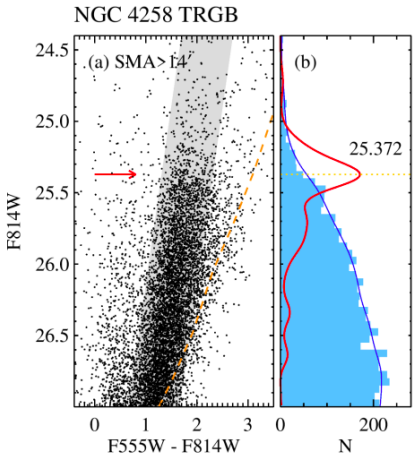
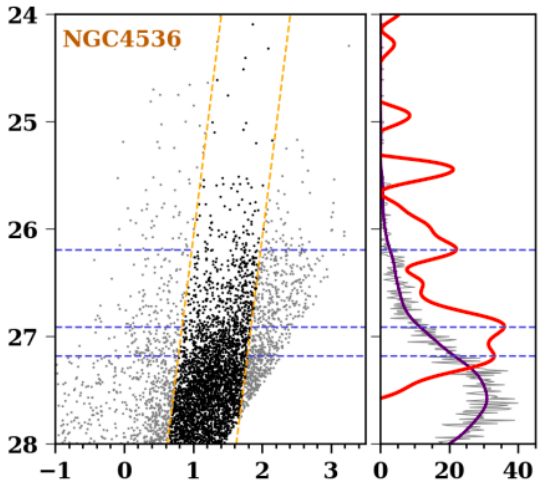
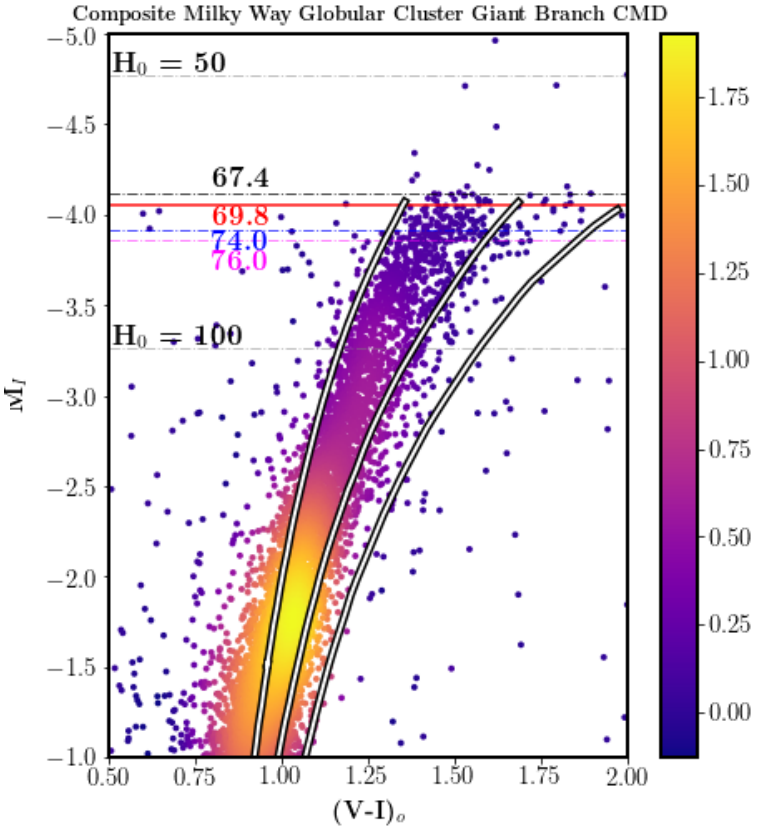
Issue:
What is *abruptly*?







Sung Jang+2020 (2008.04181) Scolnic+2023 (2304.06693)

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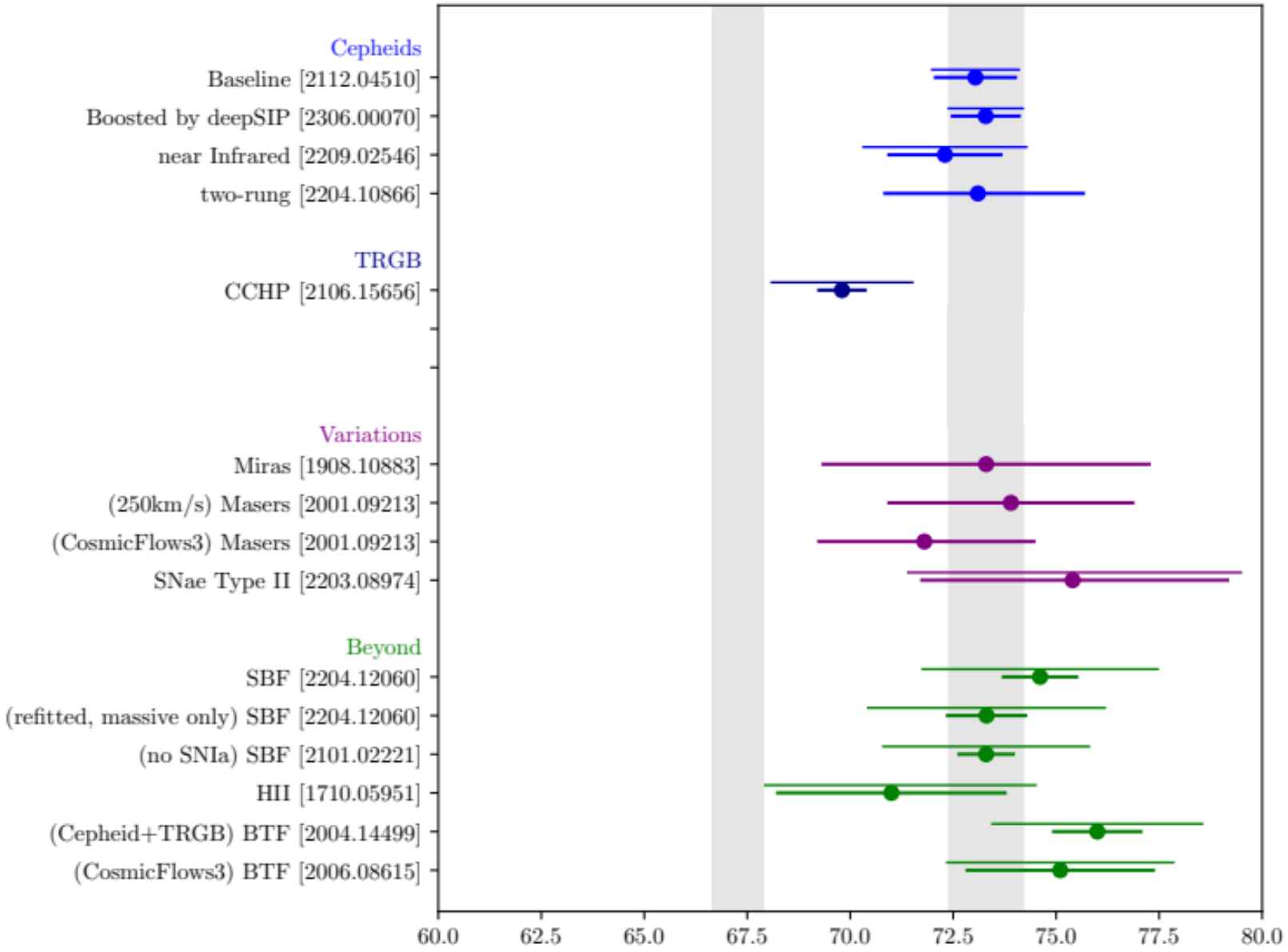

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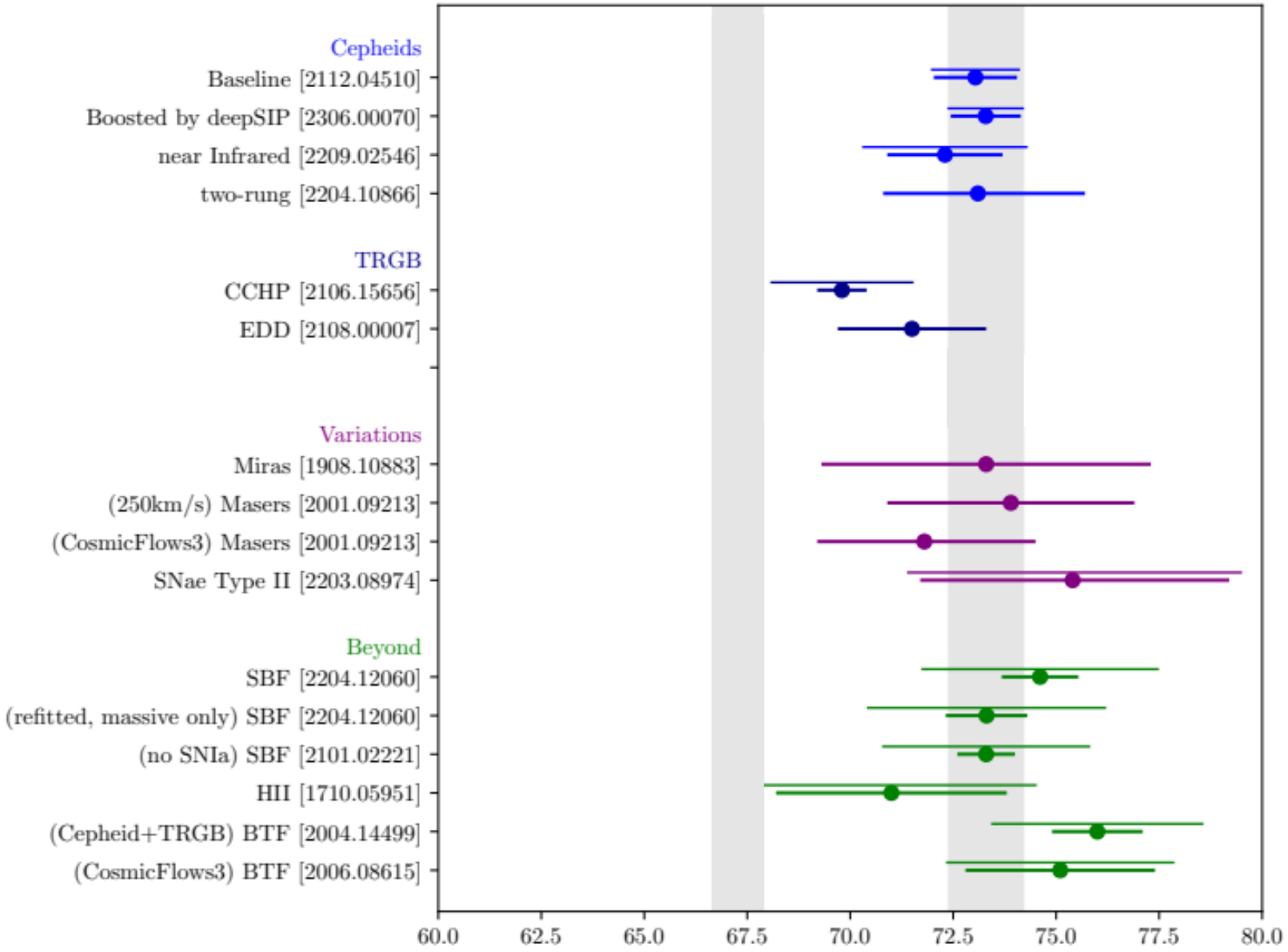

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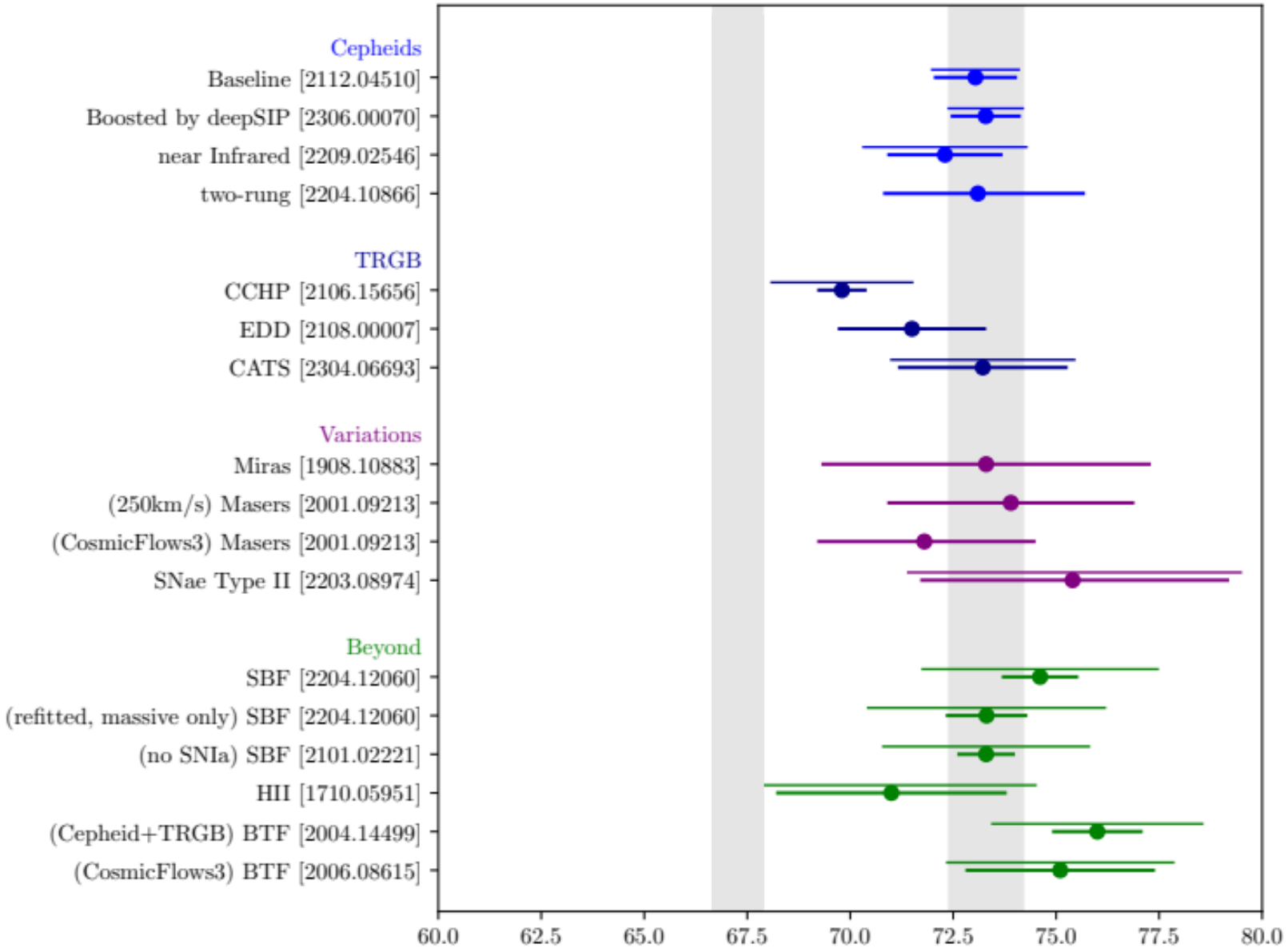

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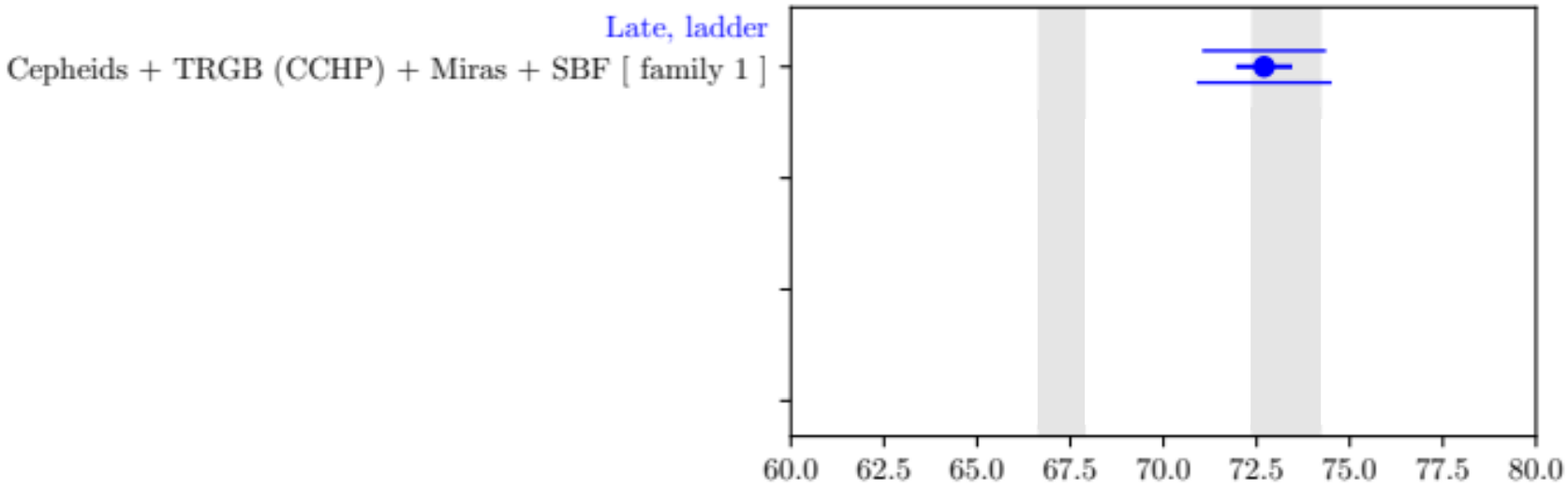

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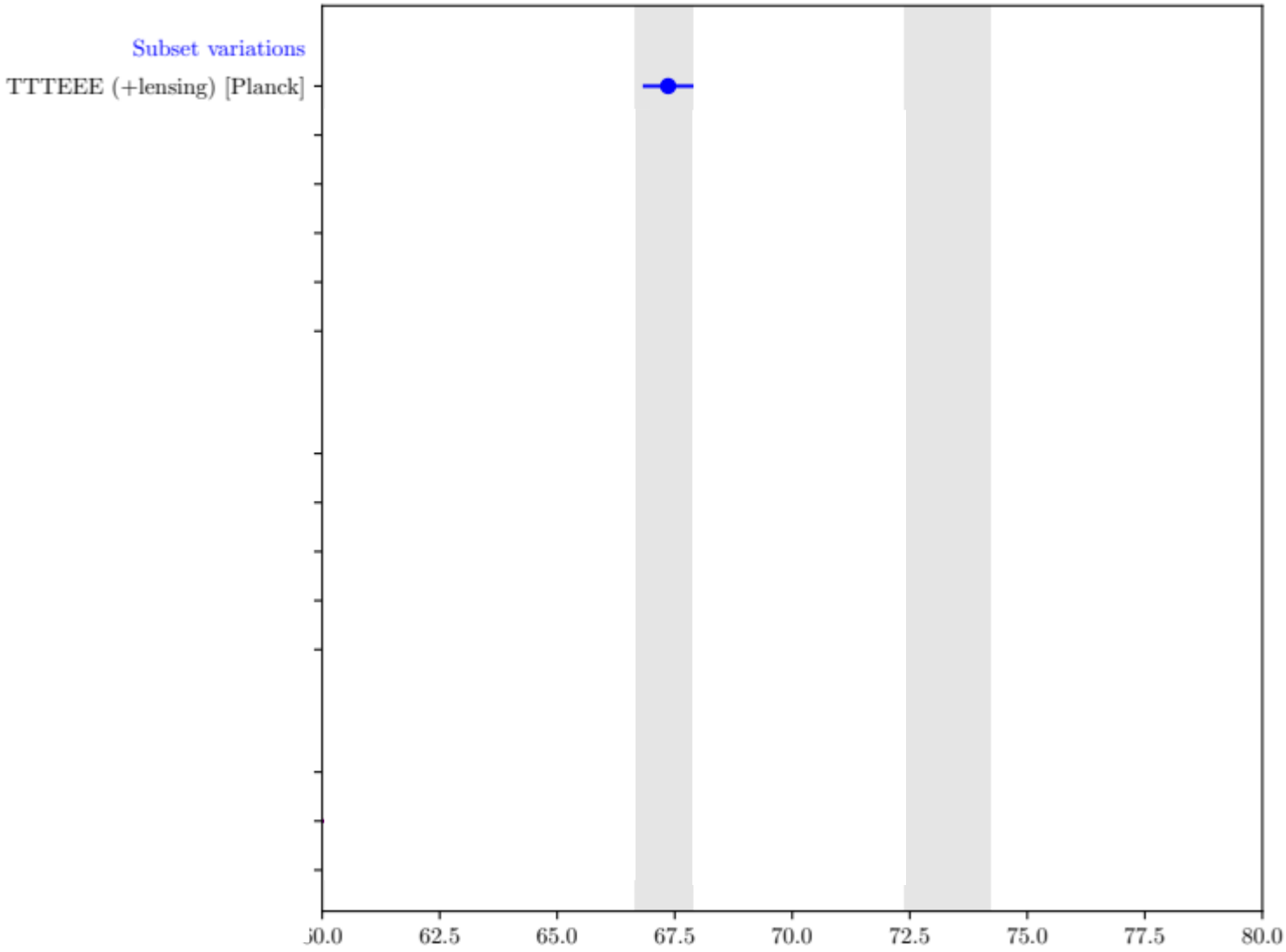

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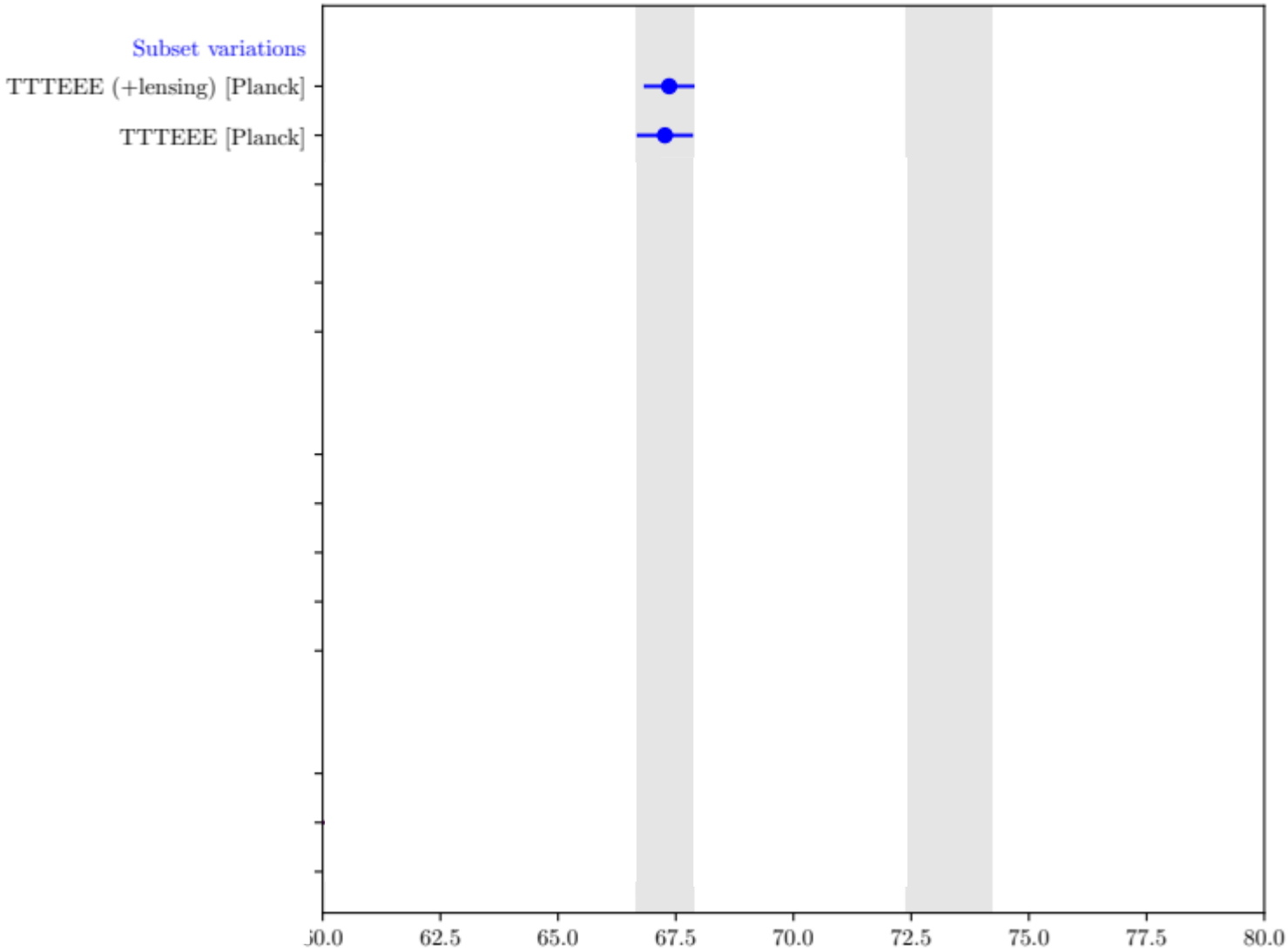

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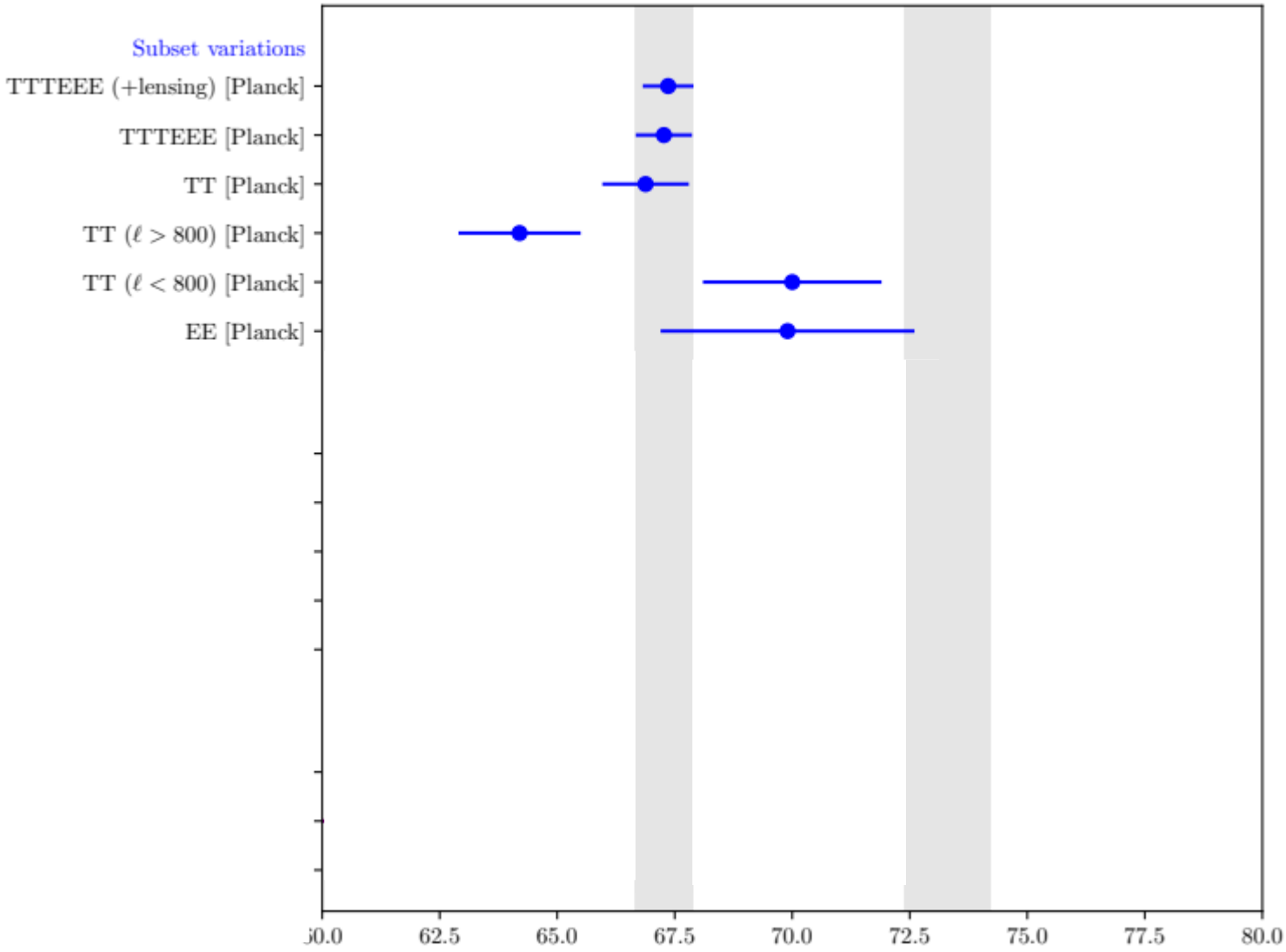

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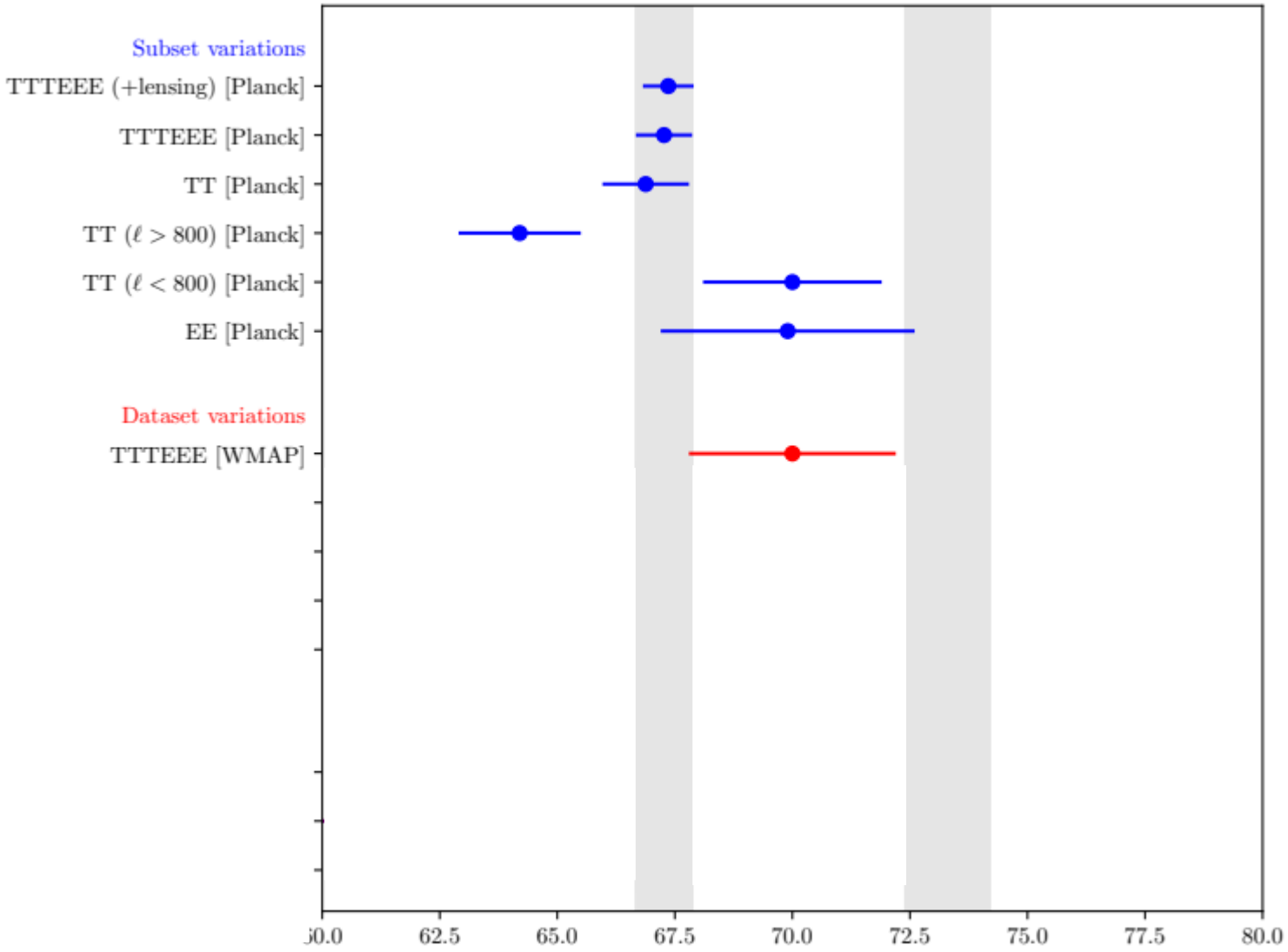

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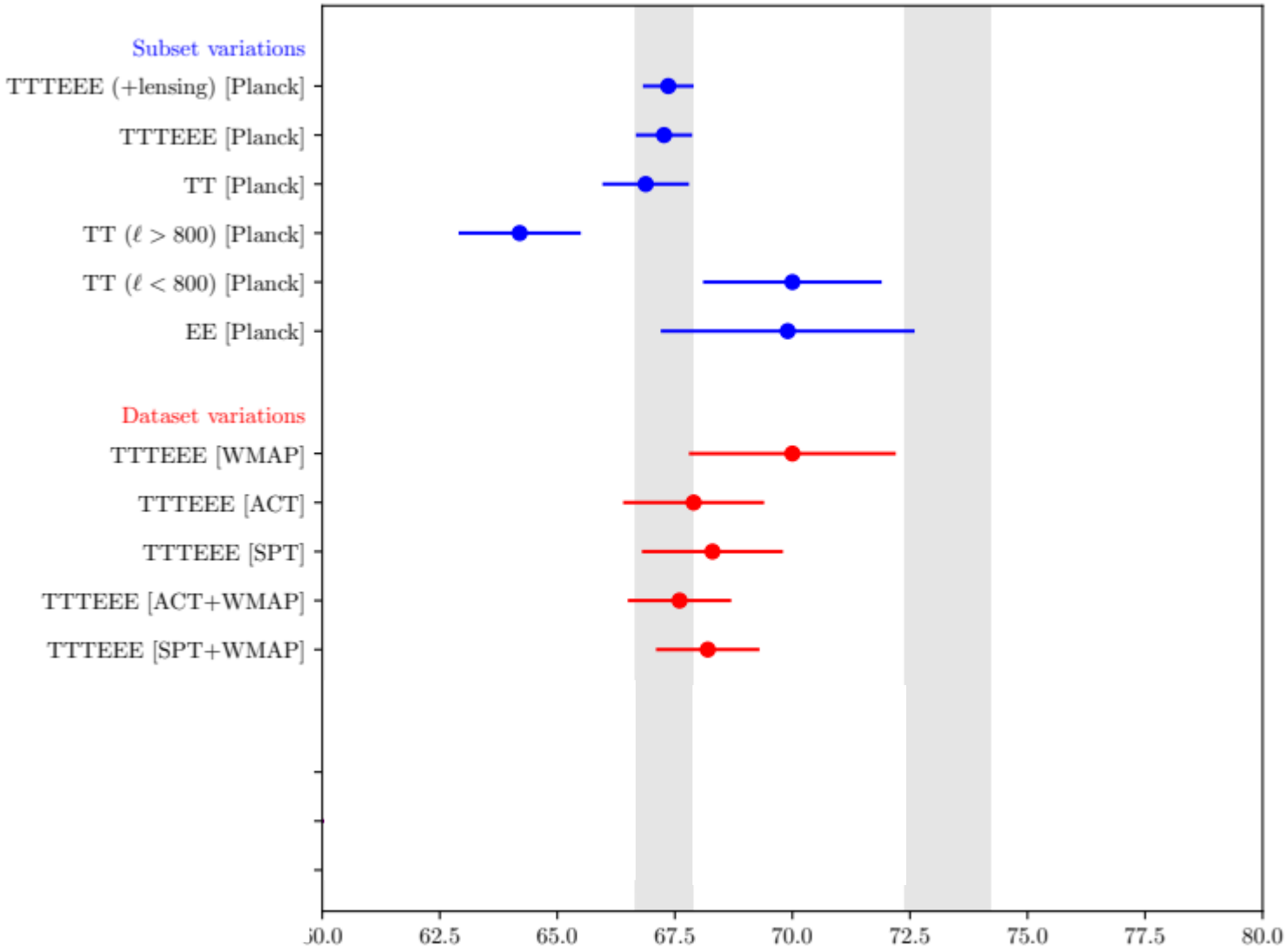

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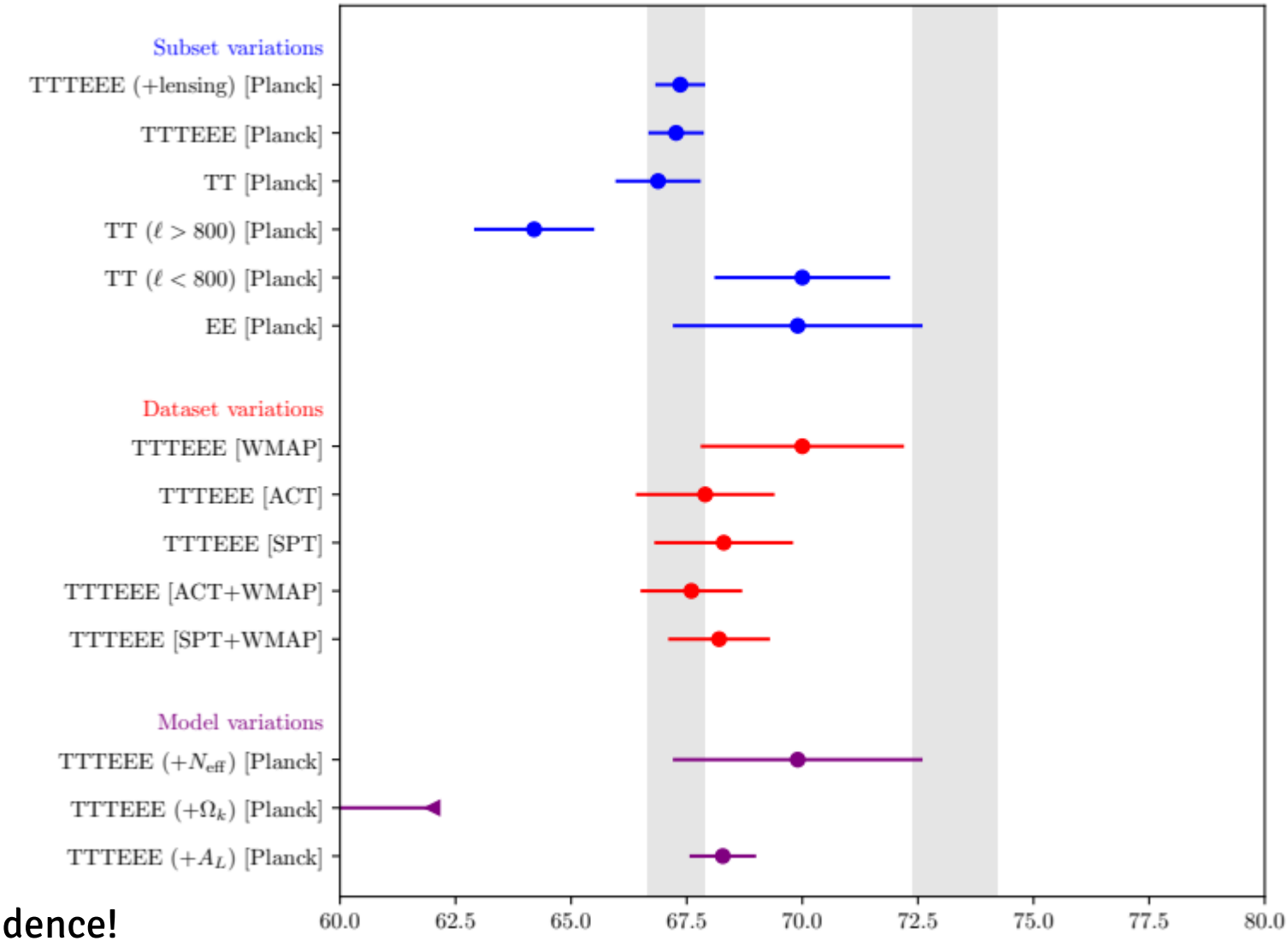


Model-dependence!

What to do?

Given that the CMB appears to be

- model dependent
- only inferring H_0 very indirectly

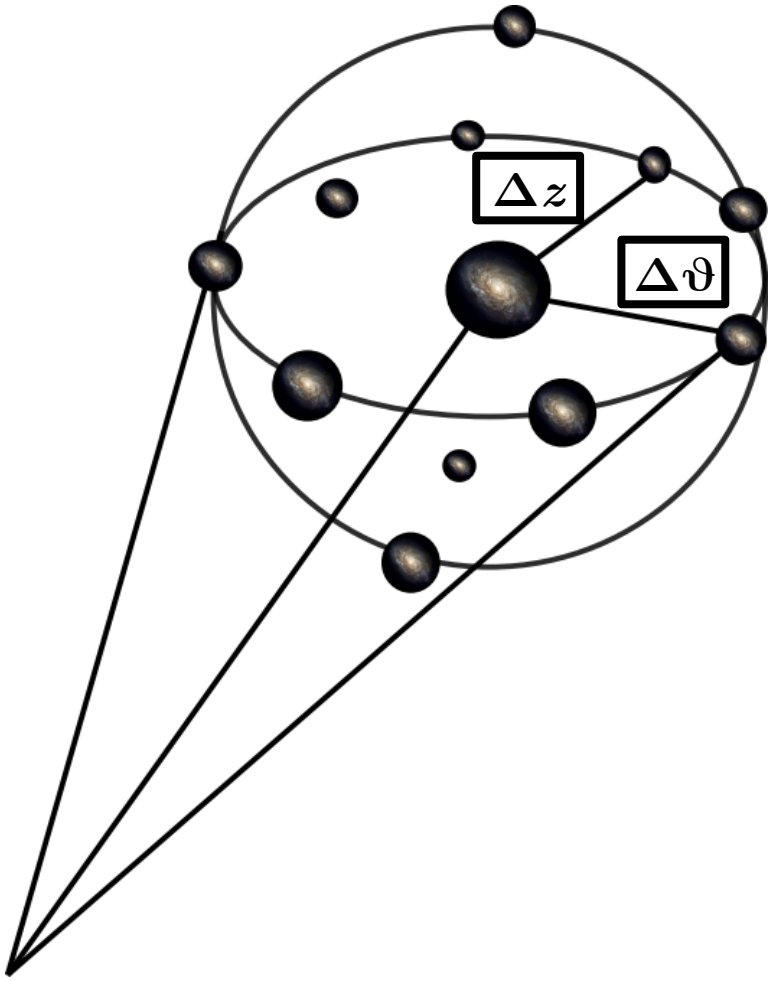
we might use independent confirmation!

BAO+BBN – A CLOSER LOOK

BAO AND THE SOUND HORIZON

GENERAL IDEA:

1) BAO determines Ω_{m} and H_0 r_{s}



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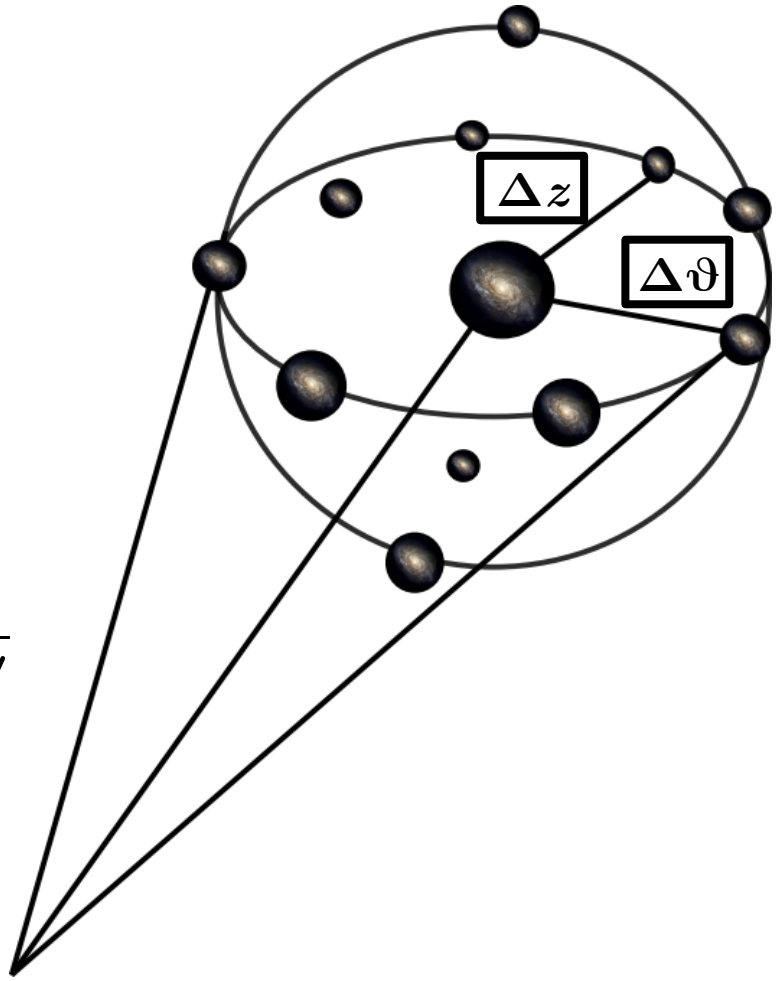
$$\Delta z \approx \frac{h r_s}{1/(H(z)/h)} \qquad \Delta\vartheta \approx \frac{h r_s}{\int_0^z H(z')/h \mathrm{d}z'}$$



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GENERAL IDEA:

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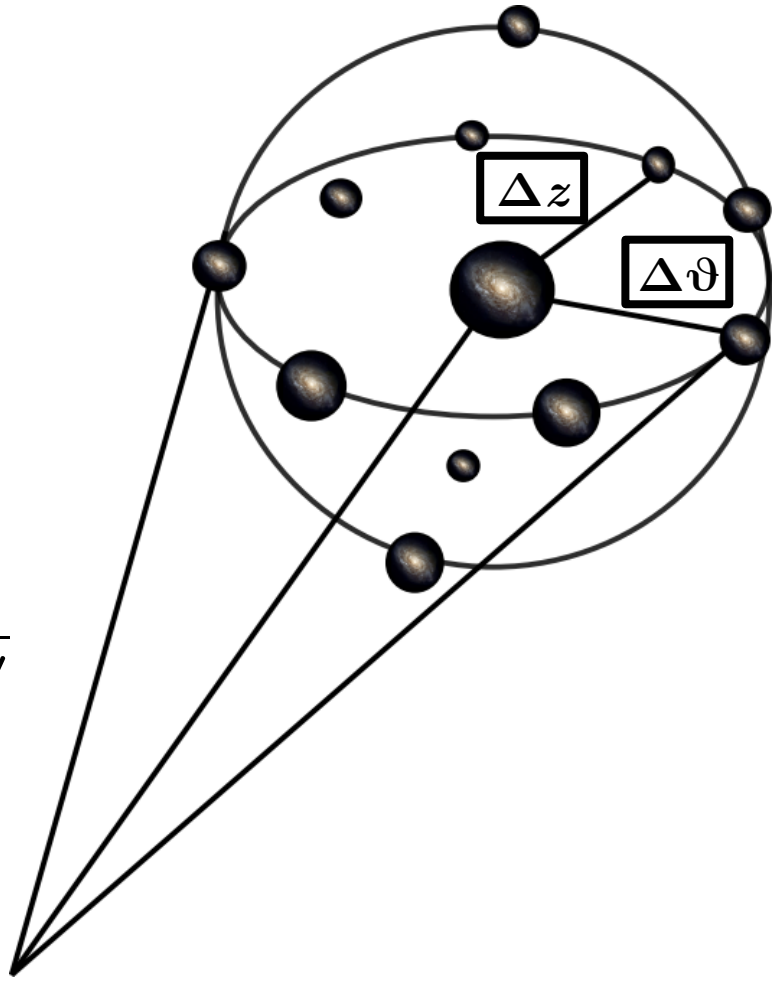

$$\Delta z \approx \frac{hr_s}{1/(H(z)/h)} \qquad \Delta\vartheta \approx \frac{hr_s}{\int_0^z H(z')/h\mathrm{d}z'}$$

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

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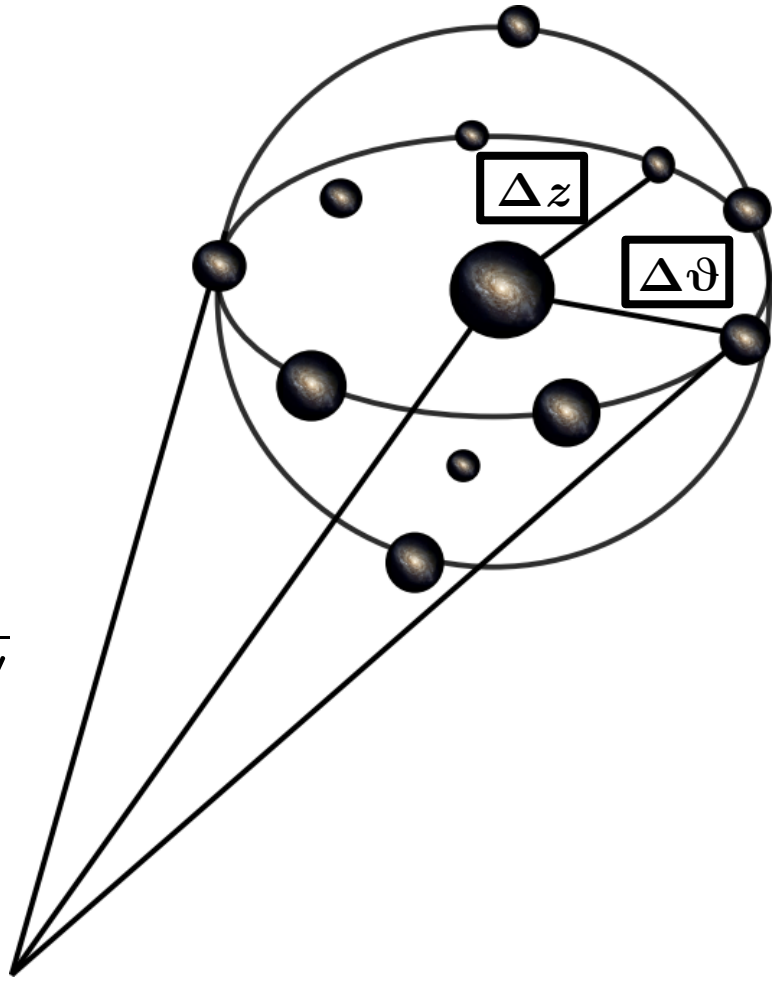
BAO AND THE SOUND HORIZON

GENERAL IDEA:

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



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

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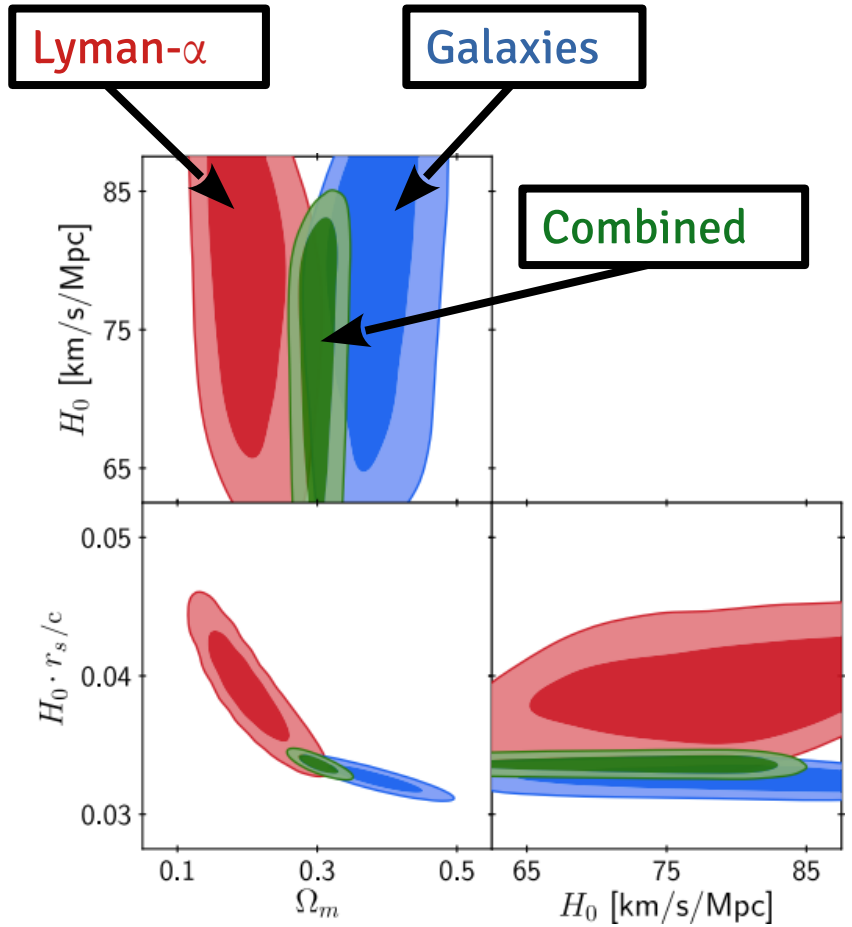
BAO + BBN

General idea:

1) BAO determines $\Omega_{\rm m}$ and H_0 $r_{\rm s}$



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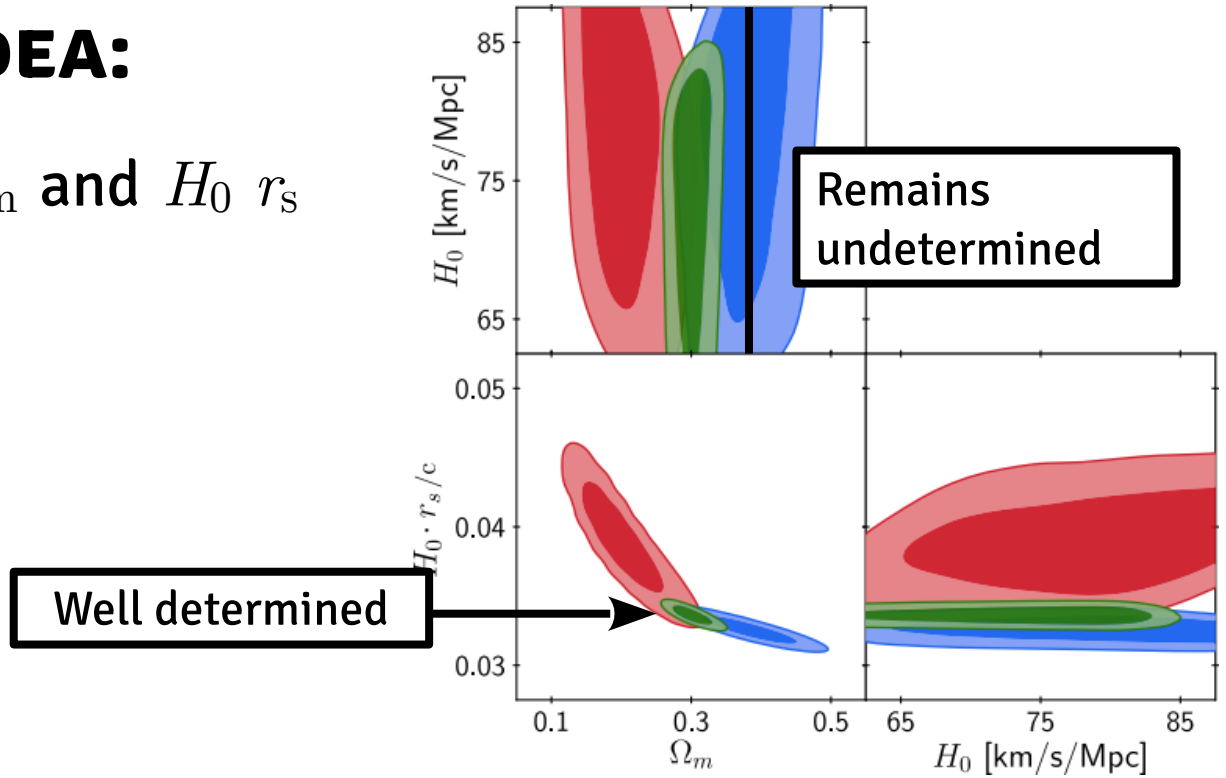

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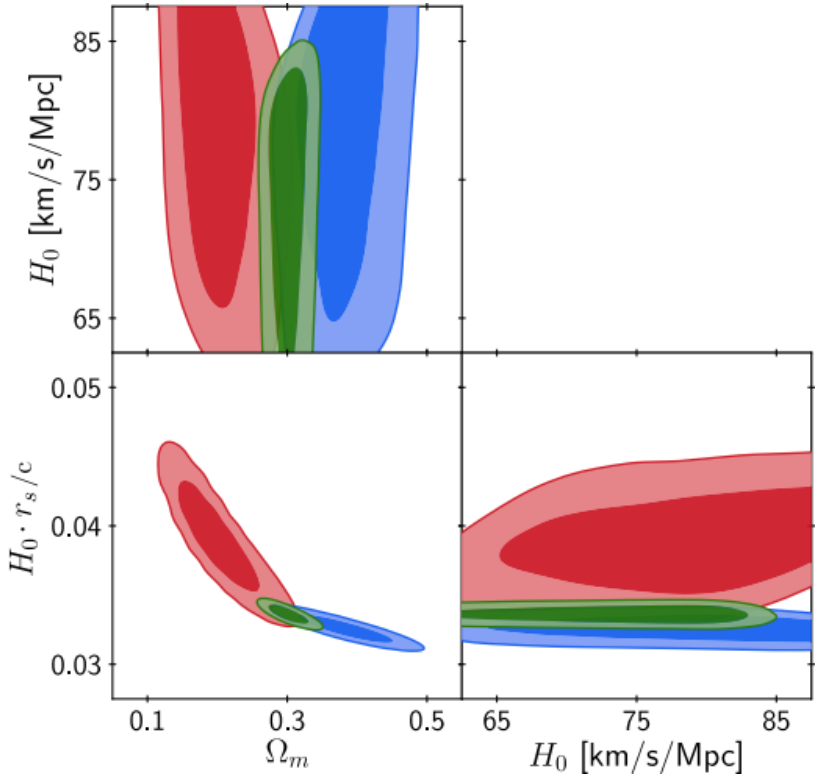
$$H_0 r_s = \int_{z_{\rm rec}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

T_0 , $\Omega_b h^2$

Ω_m , $\Omega_r h^2$, H_0



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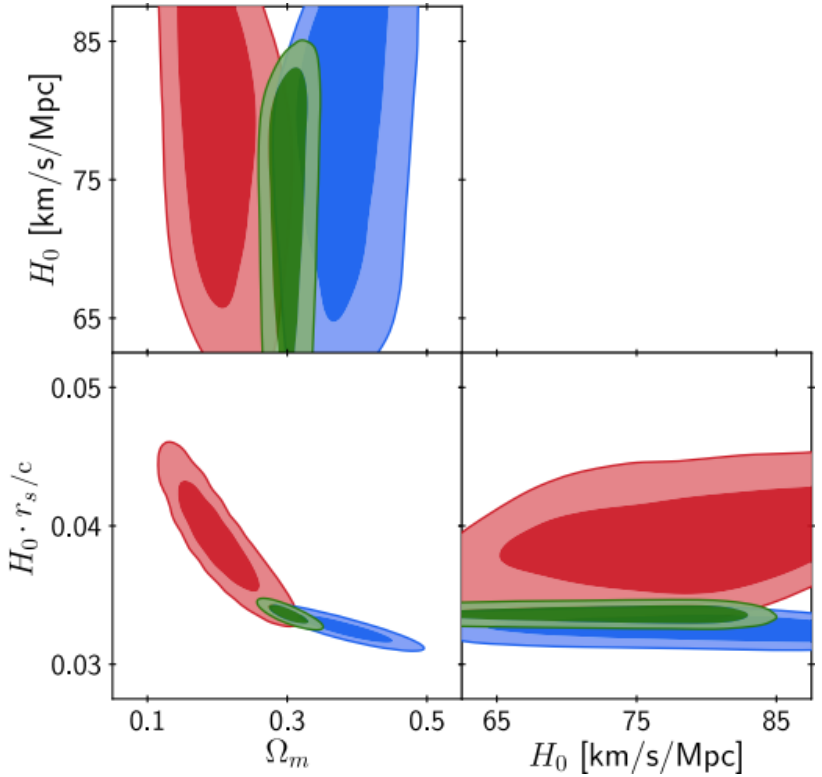

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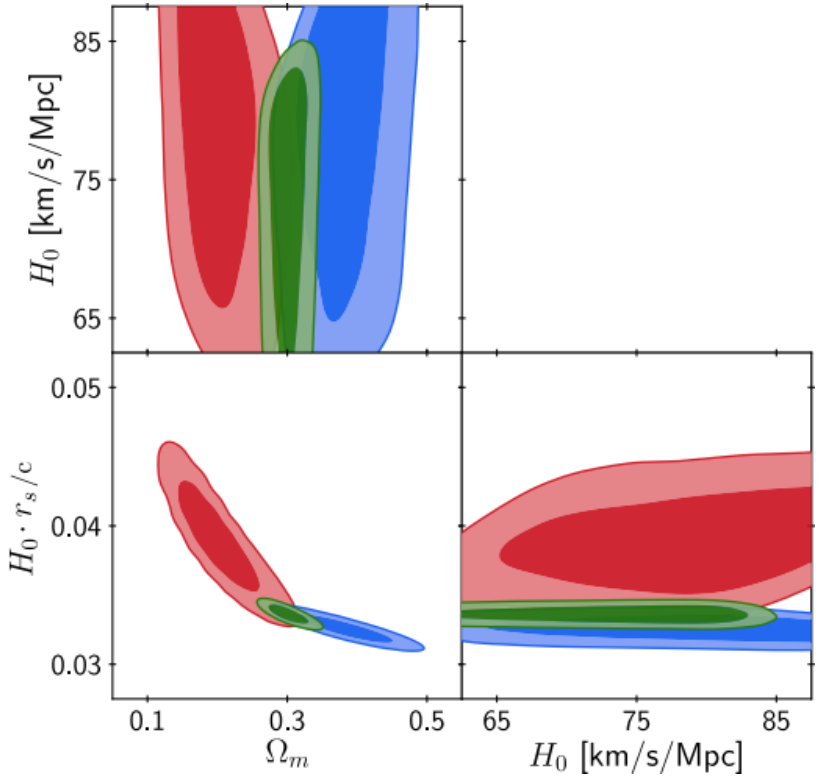

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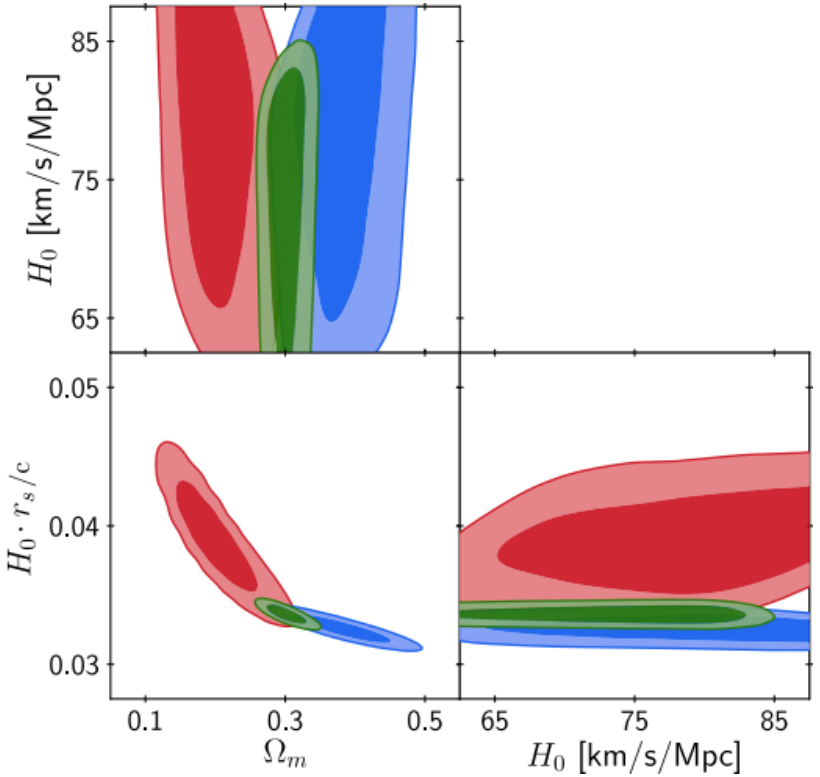

BBN

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Ω_m, $\Omega_r h^2$, H_0

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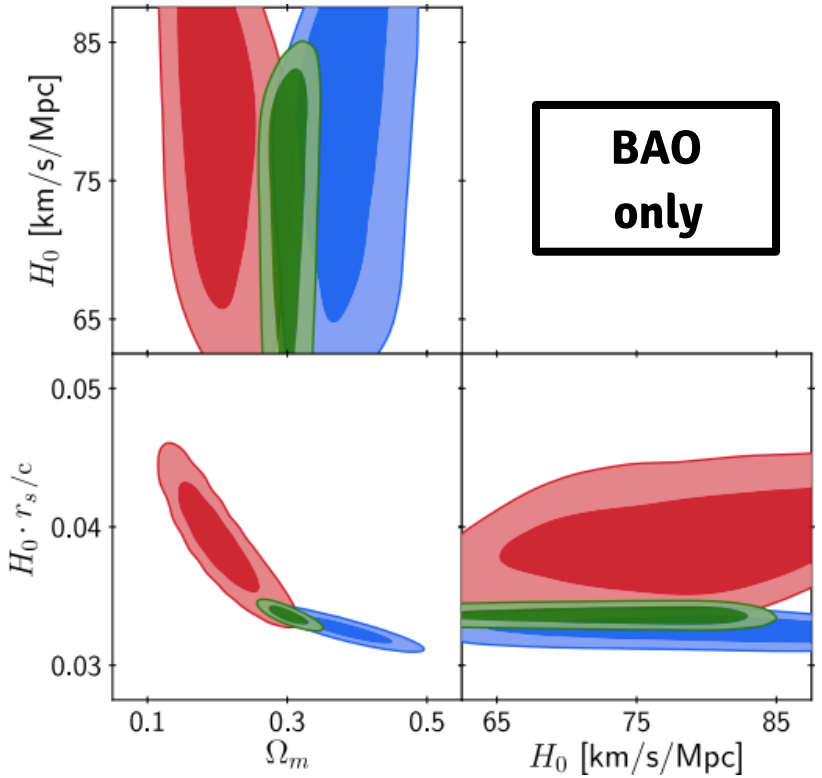

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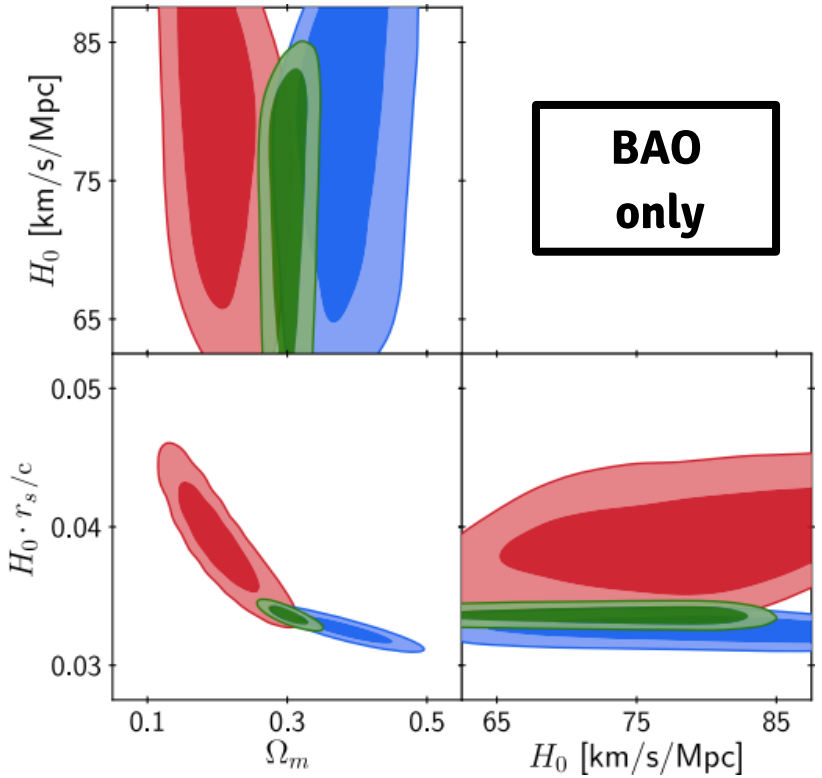

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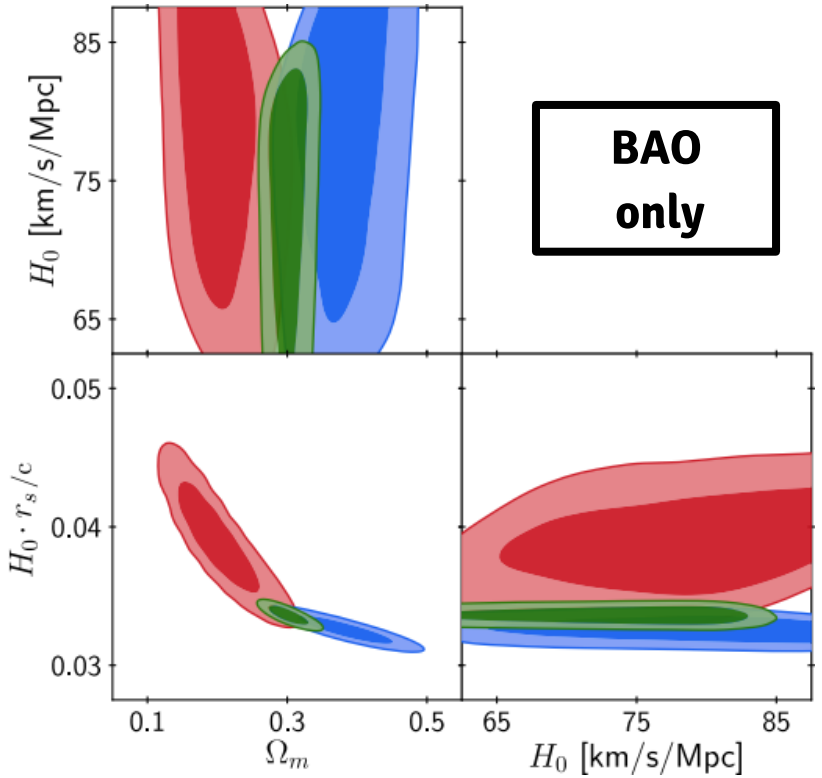
3) Their combination directly relates $H_0\ r_{\rm s} \rightarrow H_0$



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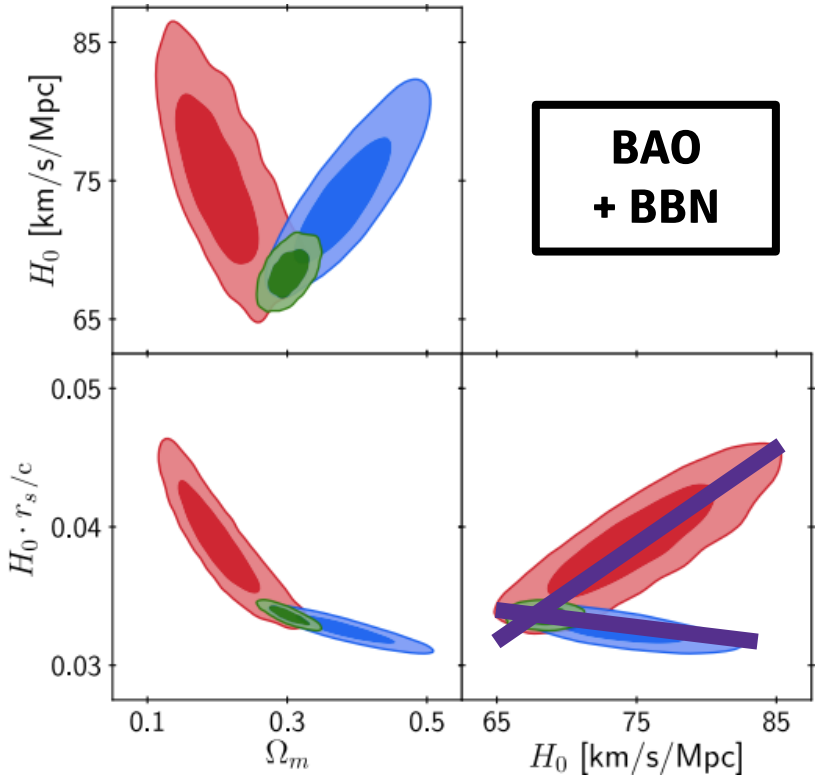

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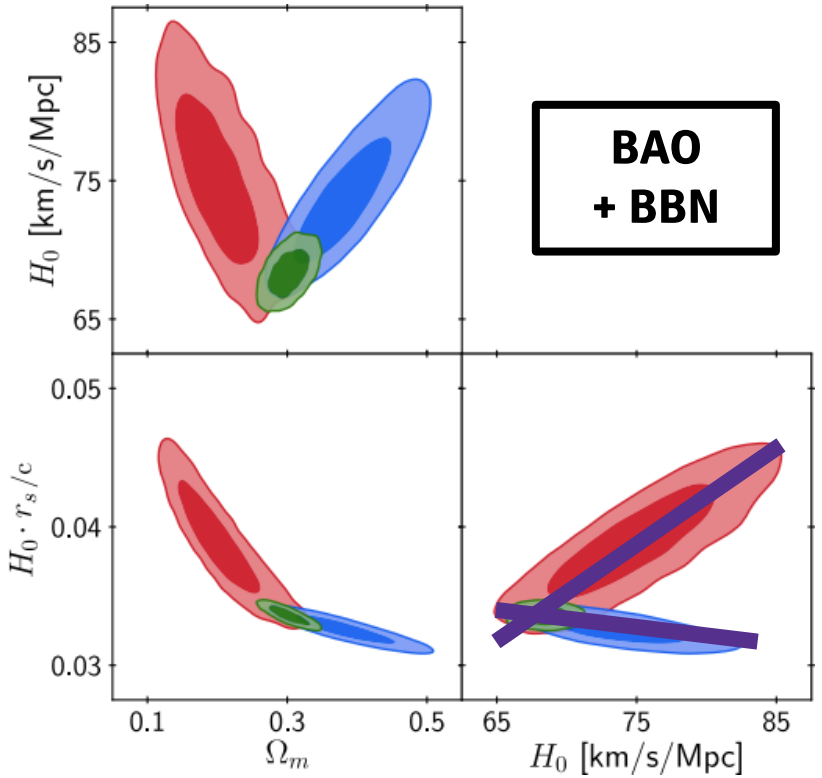

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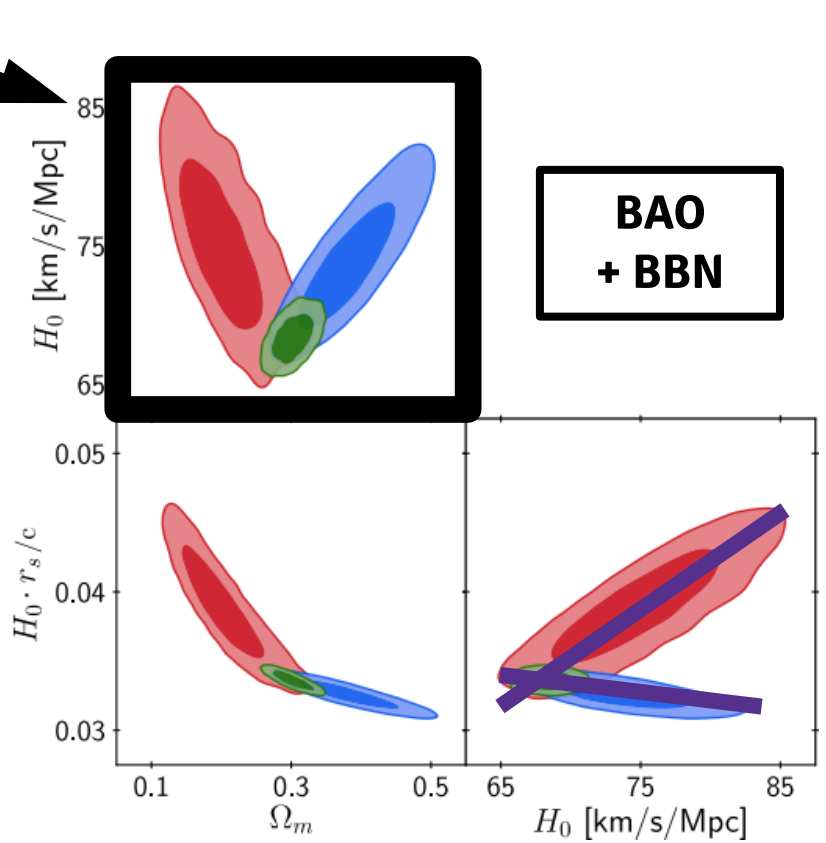

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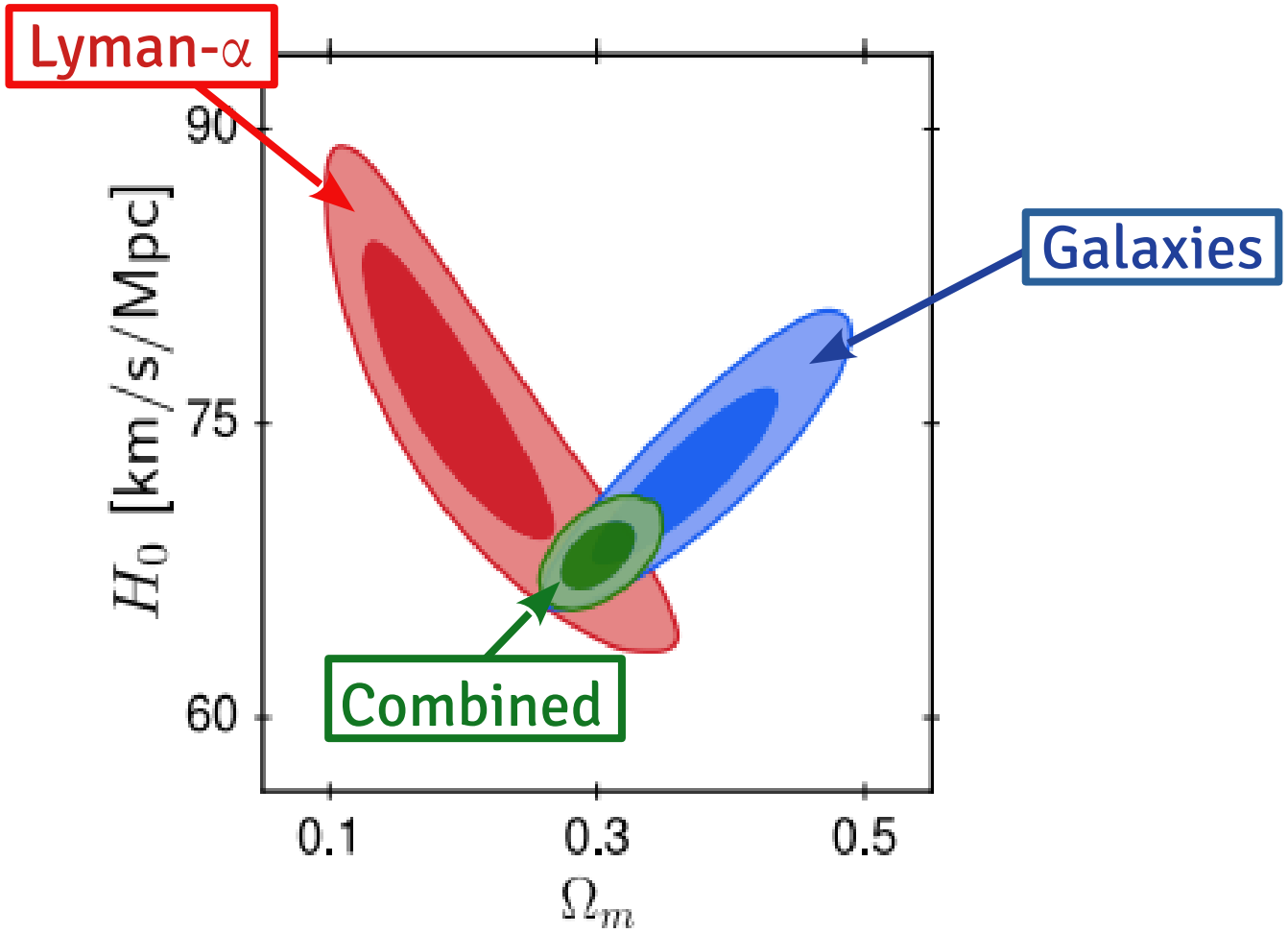

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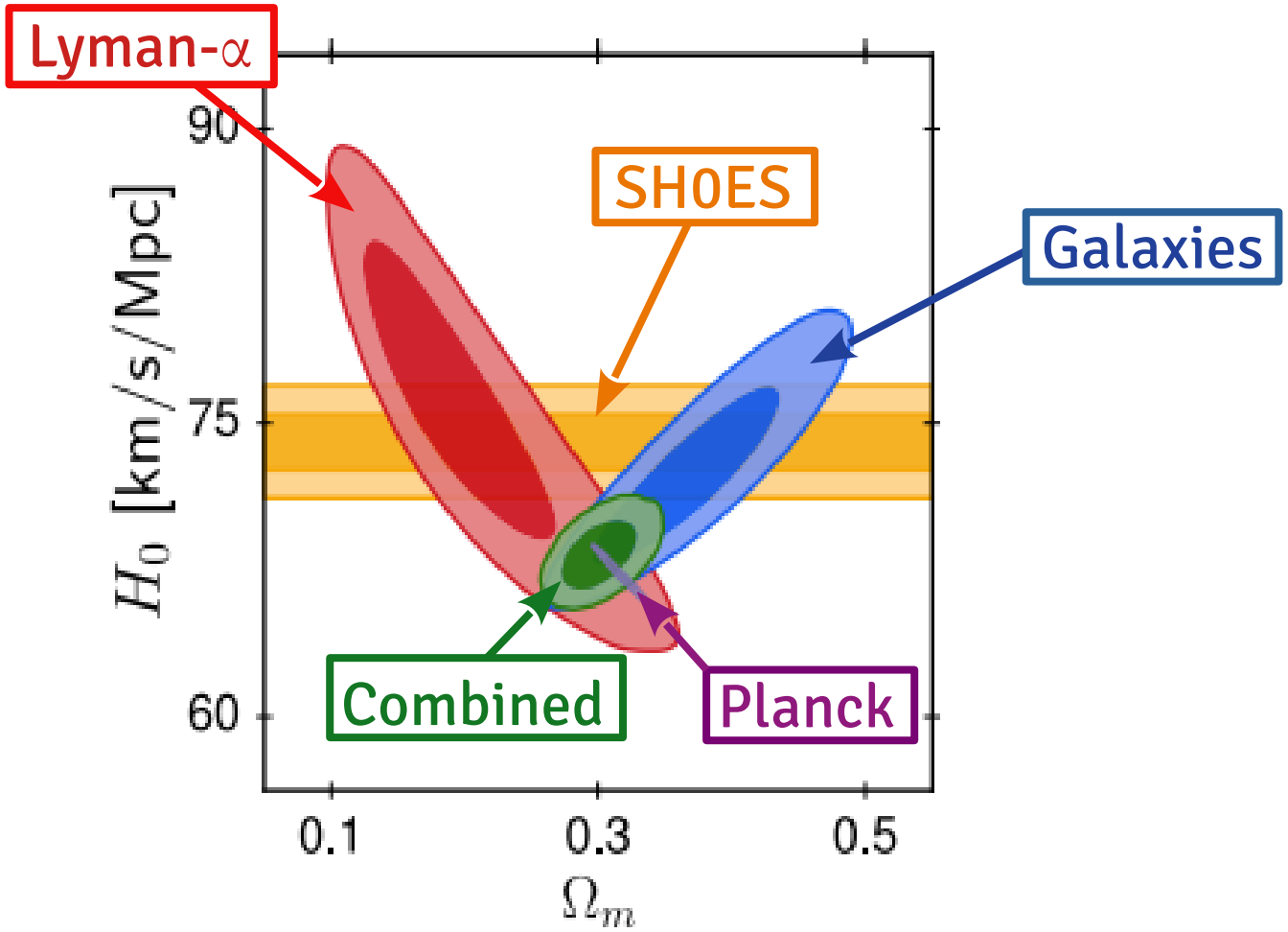

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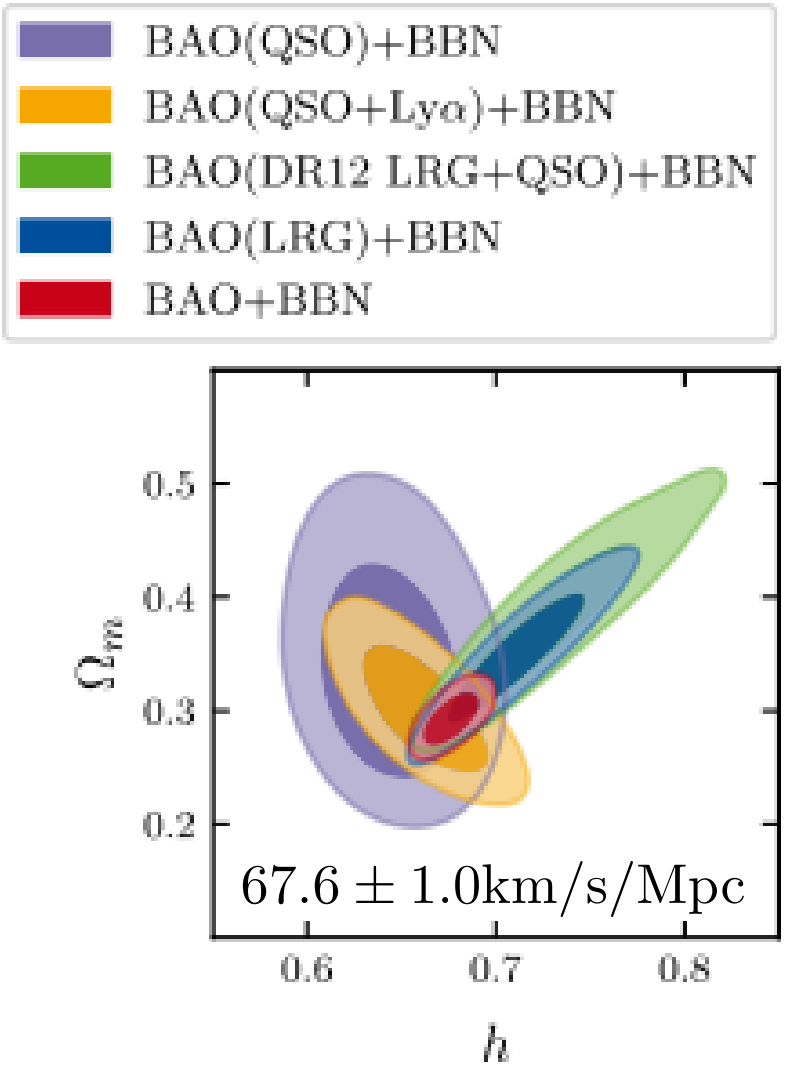

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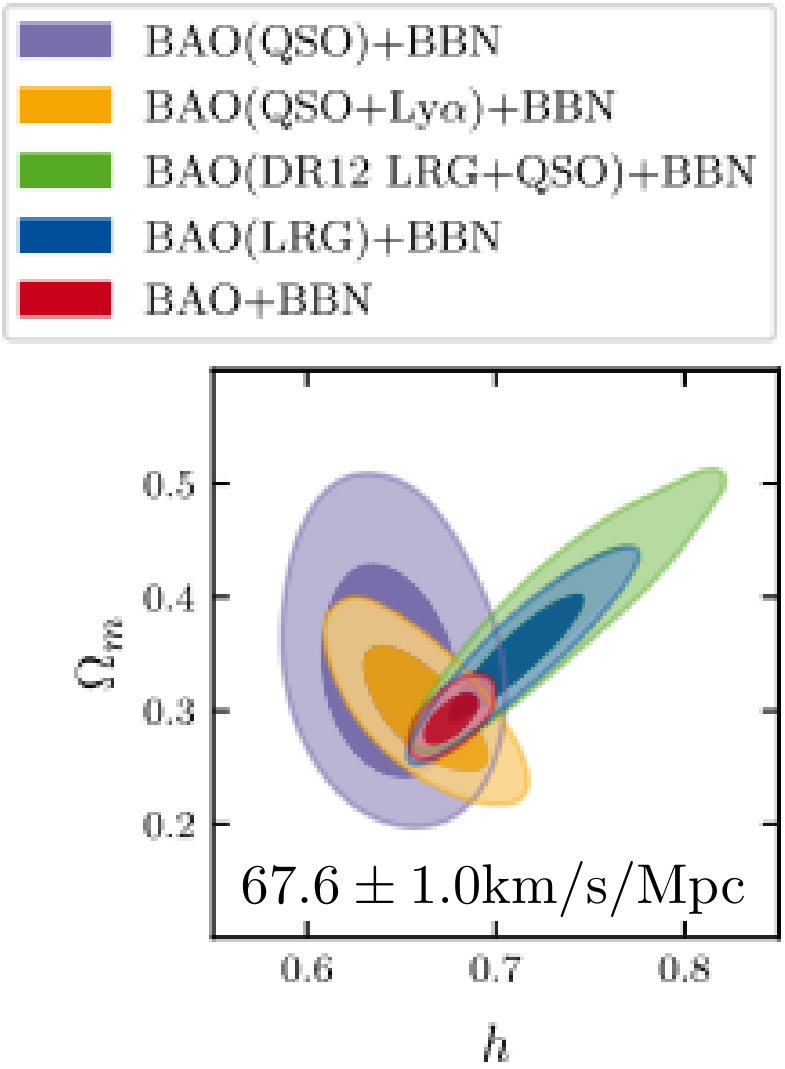

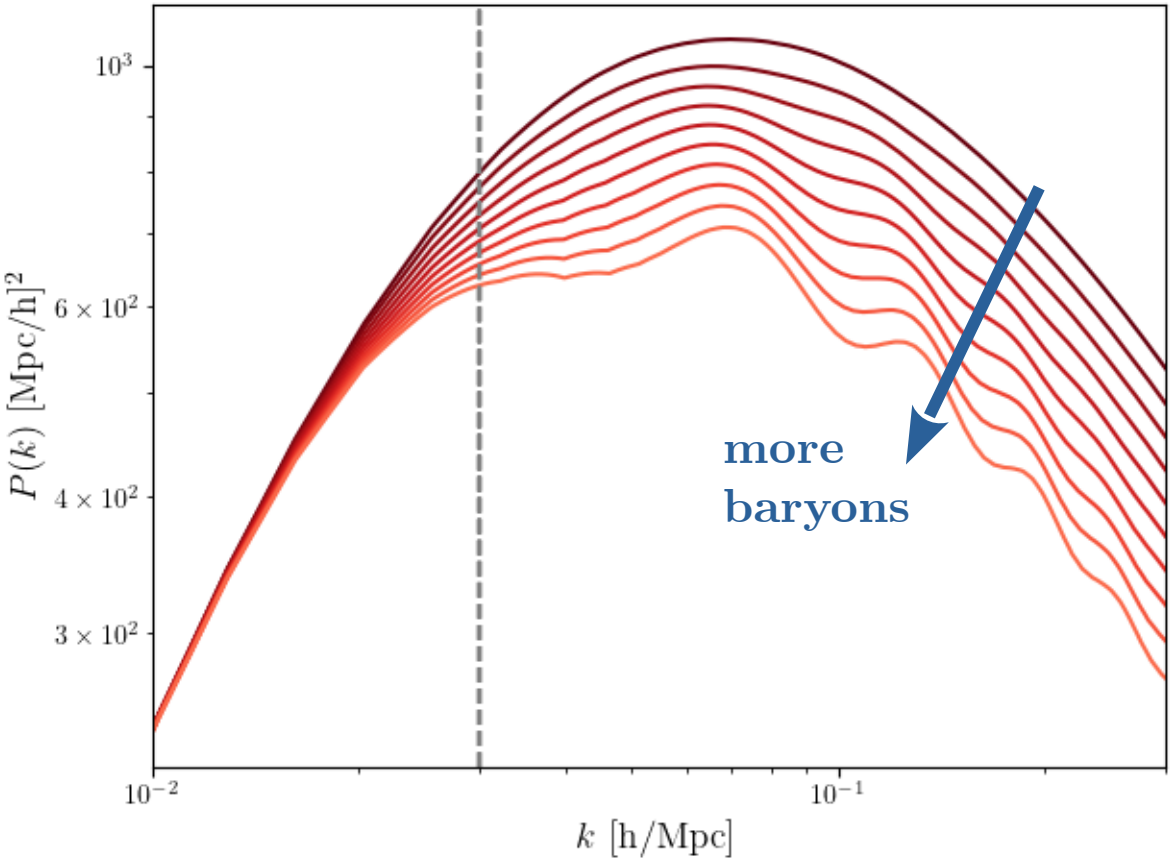

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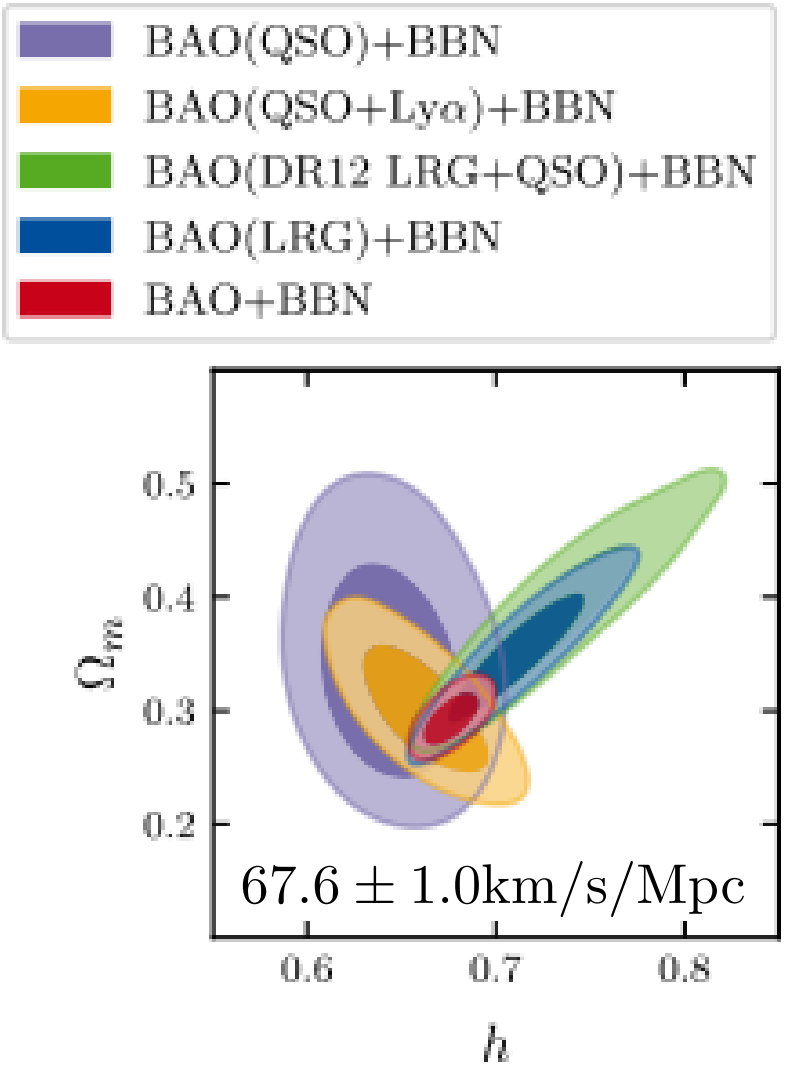

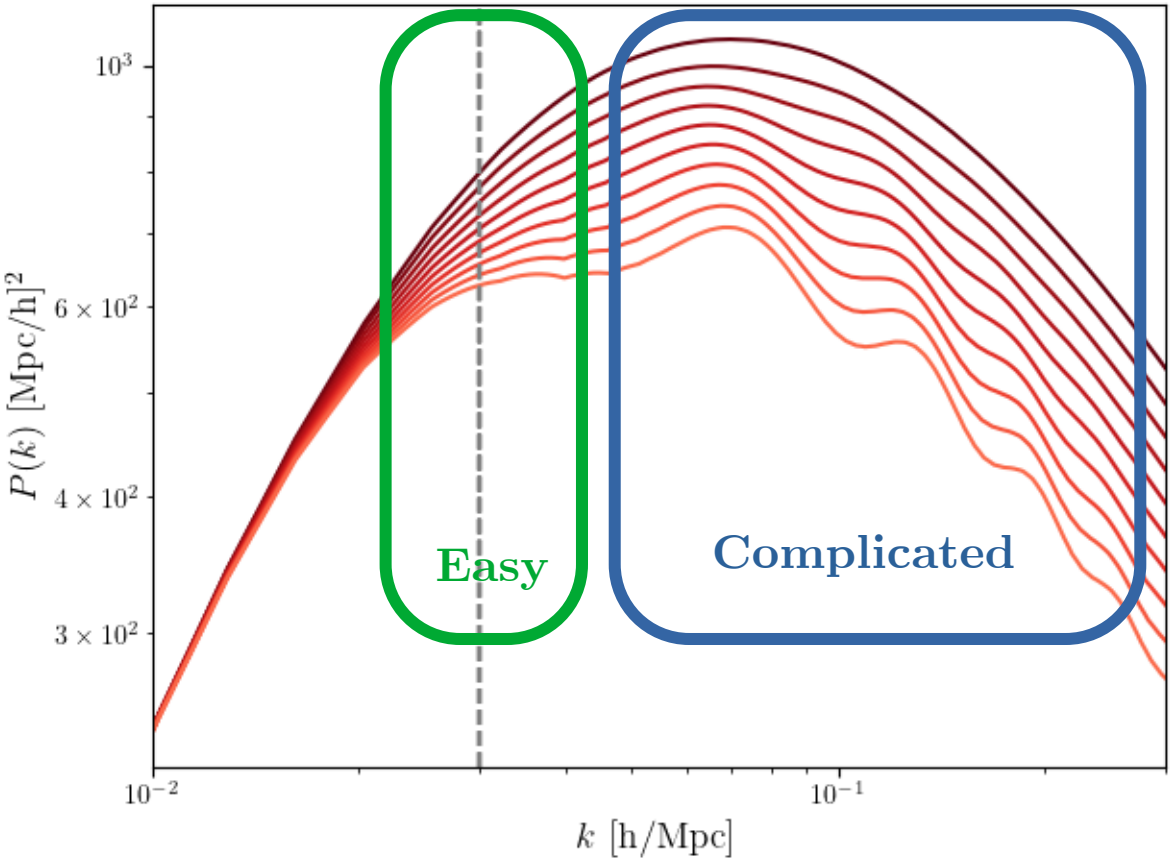

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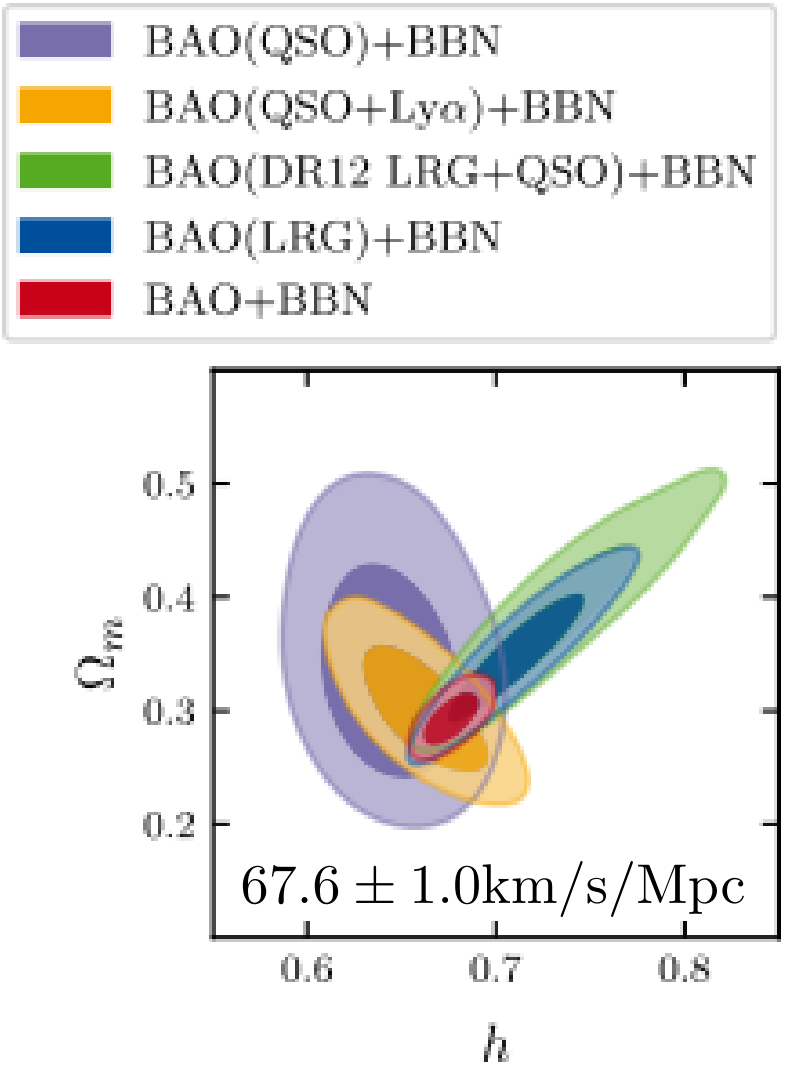
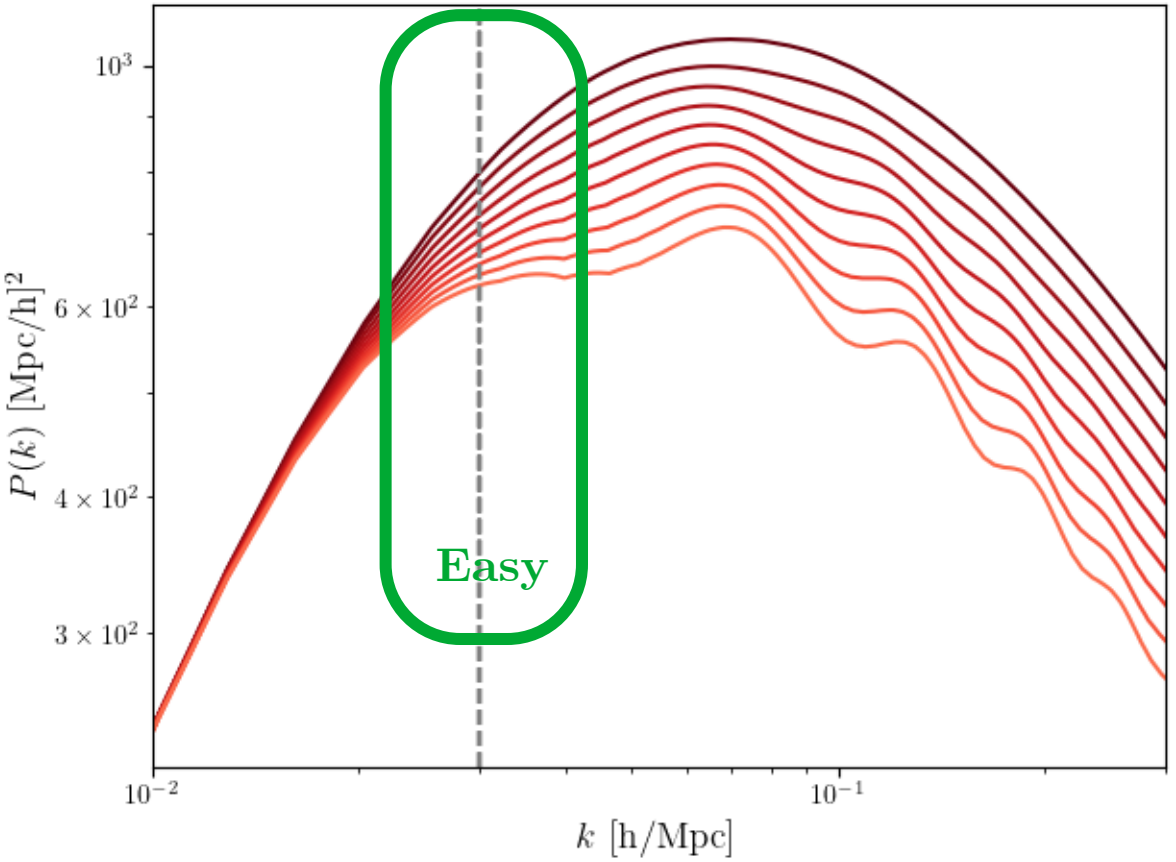
Sensitive to $\Omega_b h^2, \Omega_m h^2$





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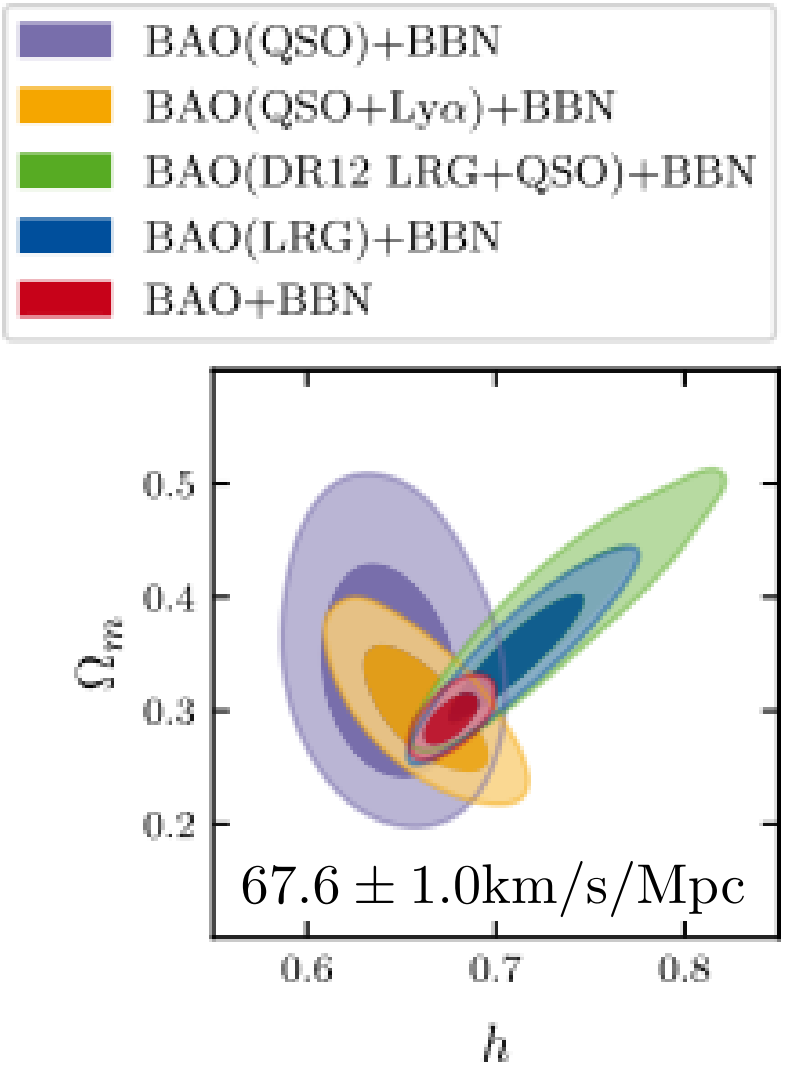
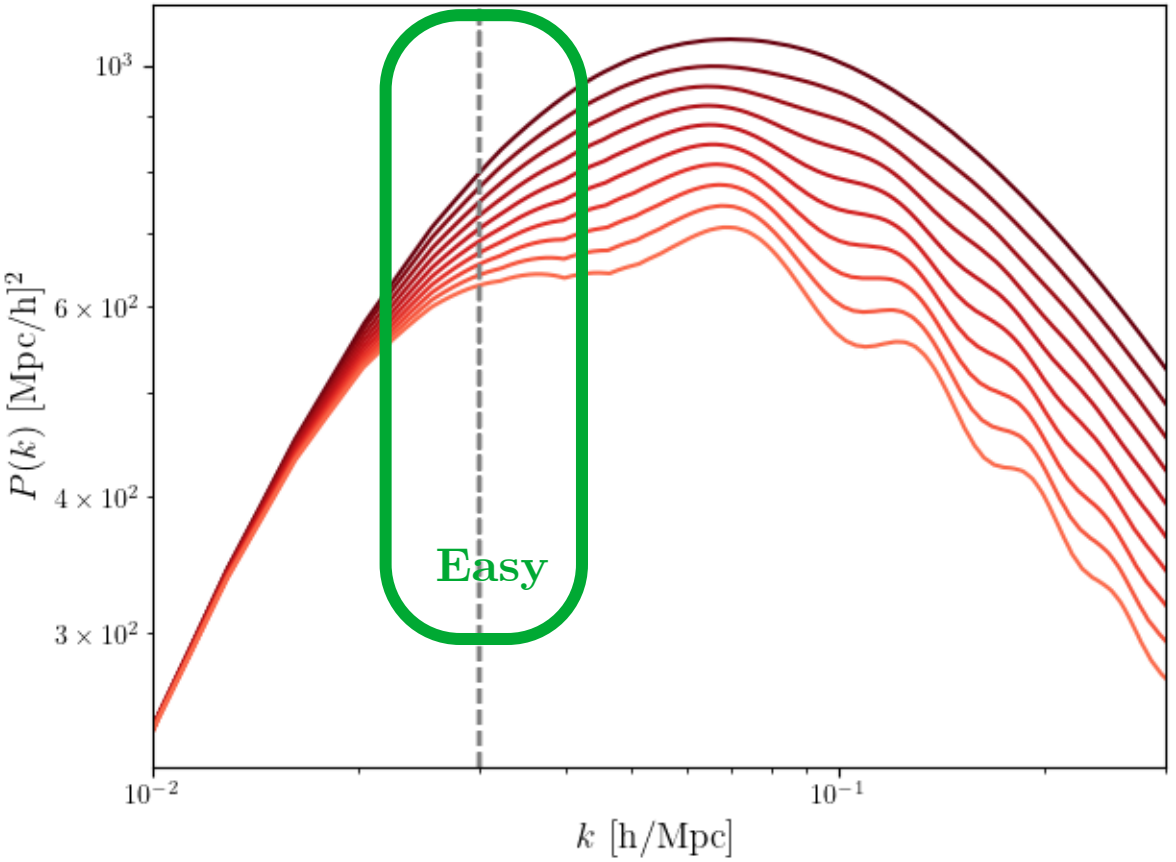
Sensitive to $\Omega_b h^2, \Omega_m h^2$





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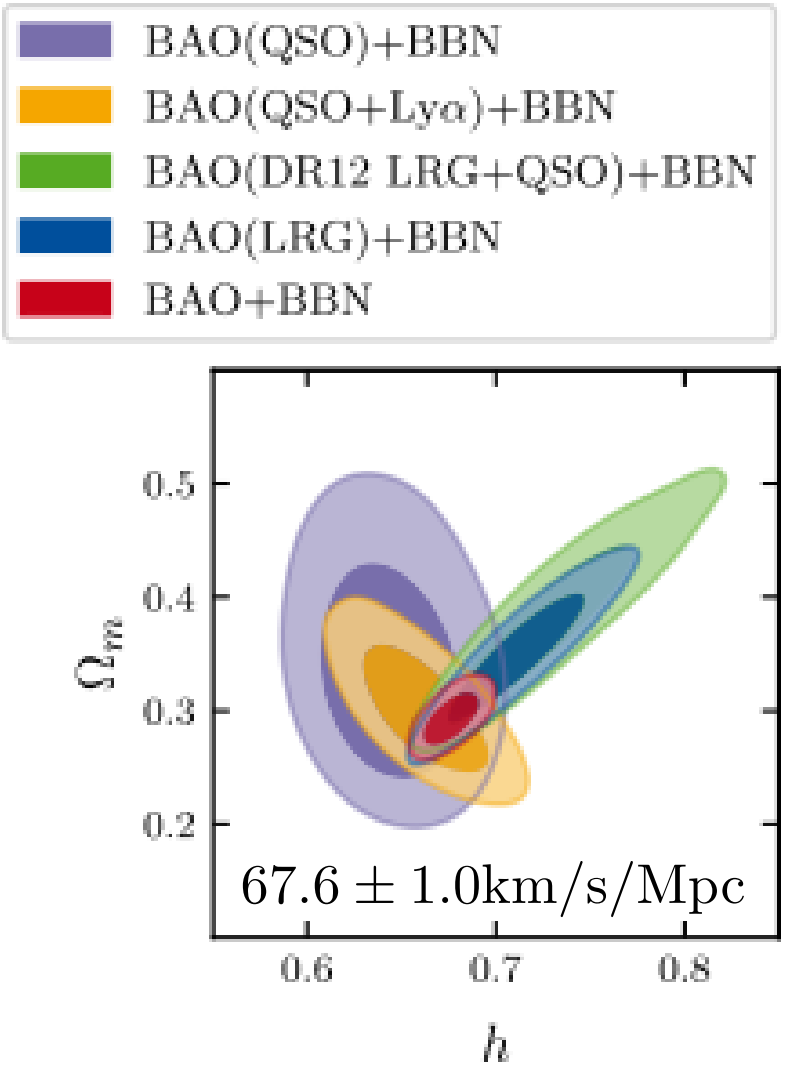
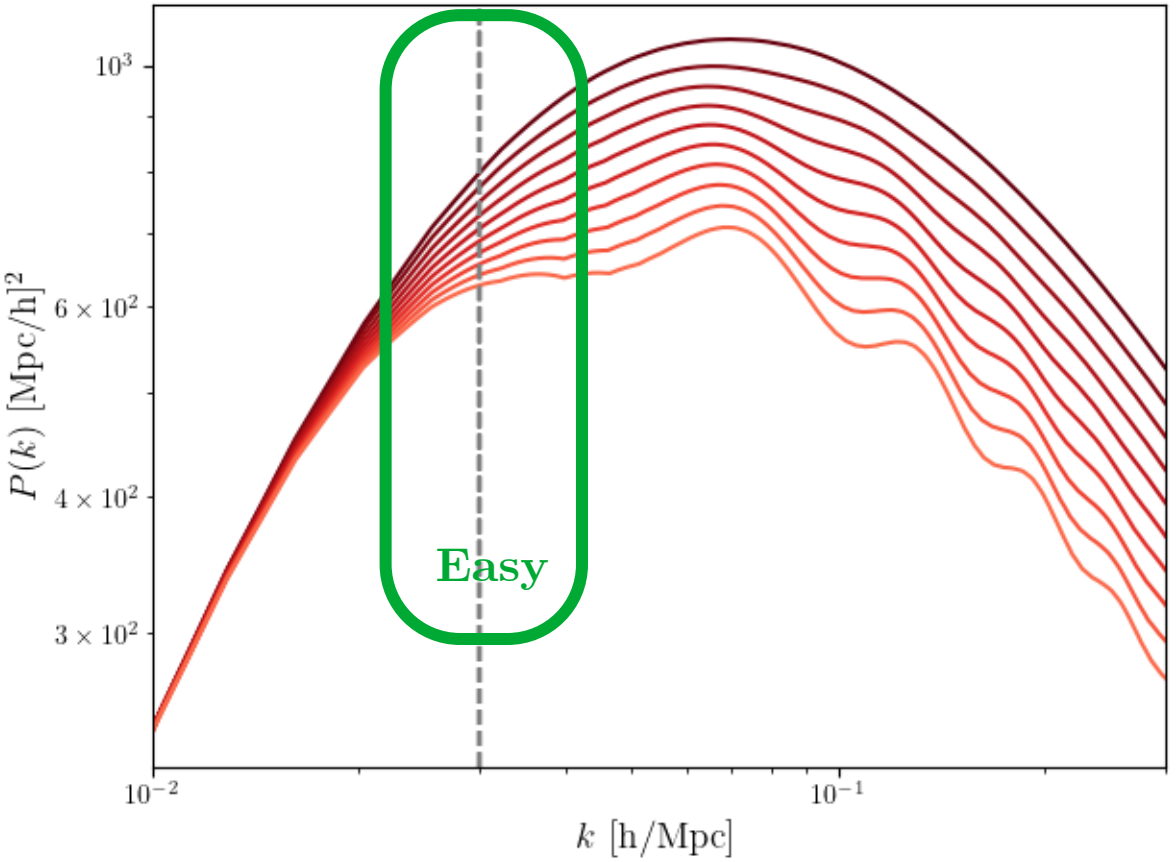


Sensitive to ~~$\Omega_b h^2$~~, $\Omega_m h^2$

BBN



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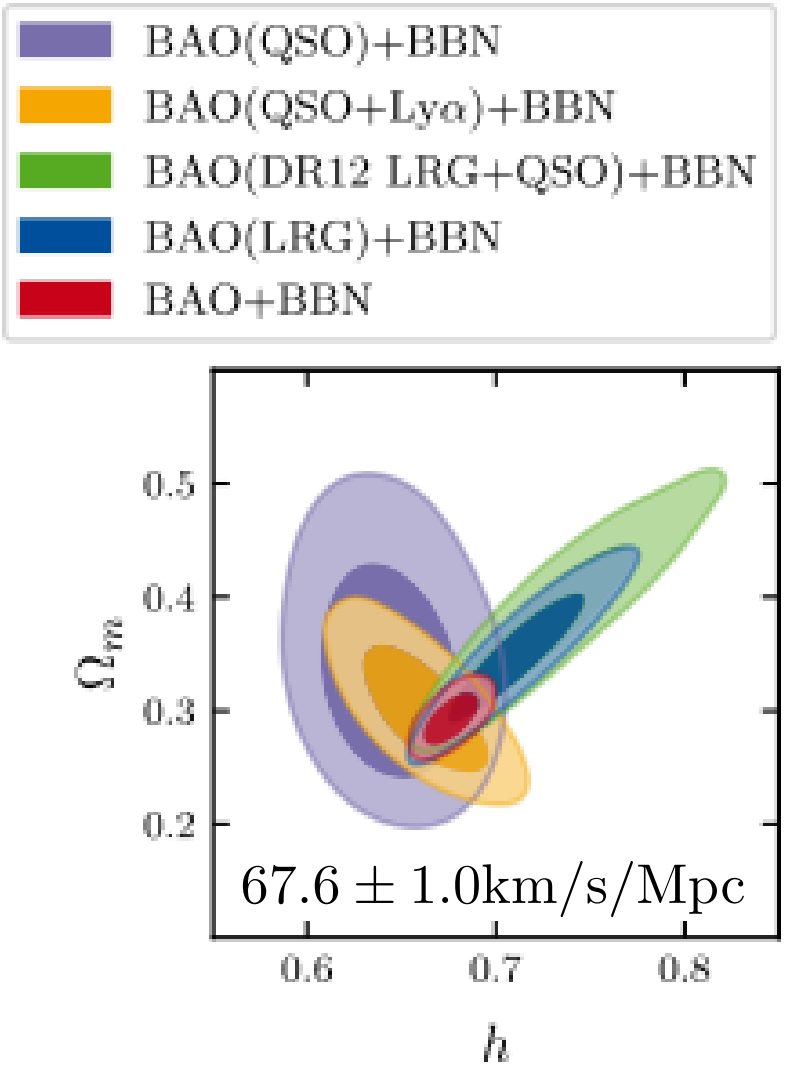

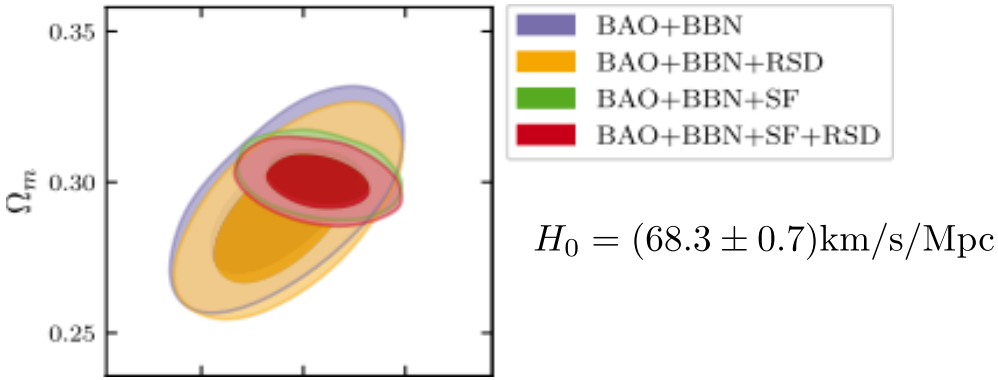

$H_0 = (68.3 \pm 0.7)$km/s/Mpc

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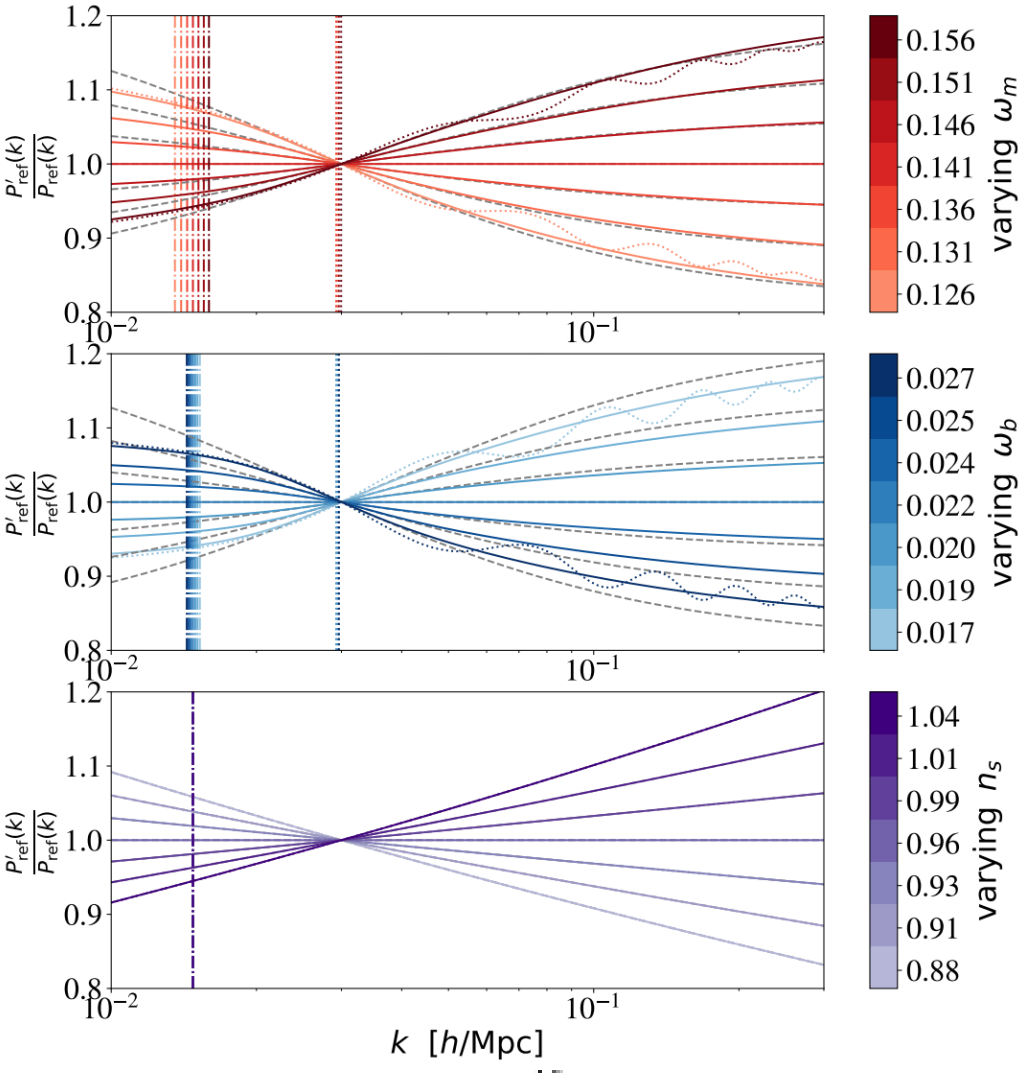

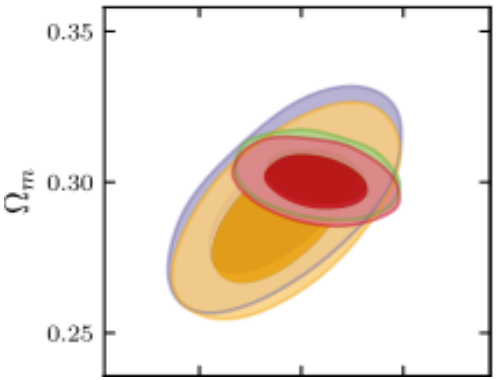

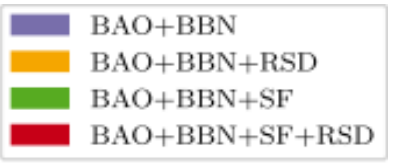

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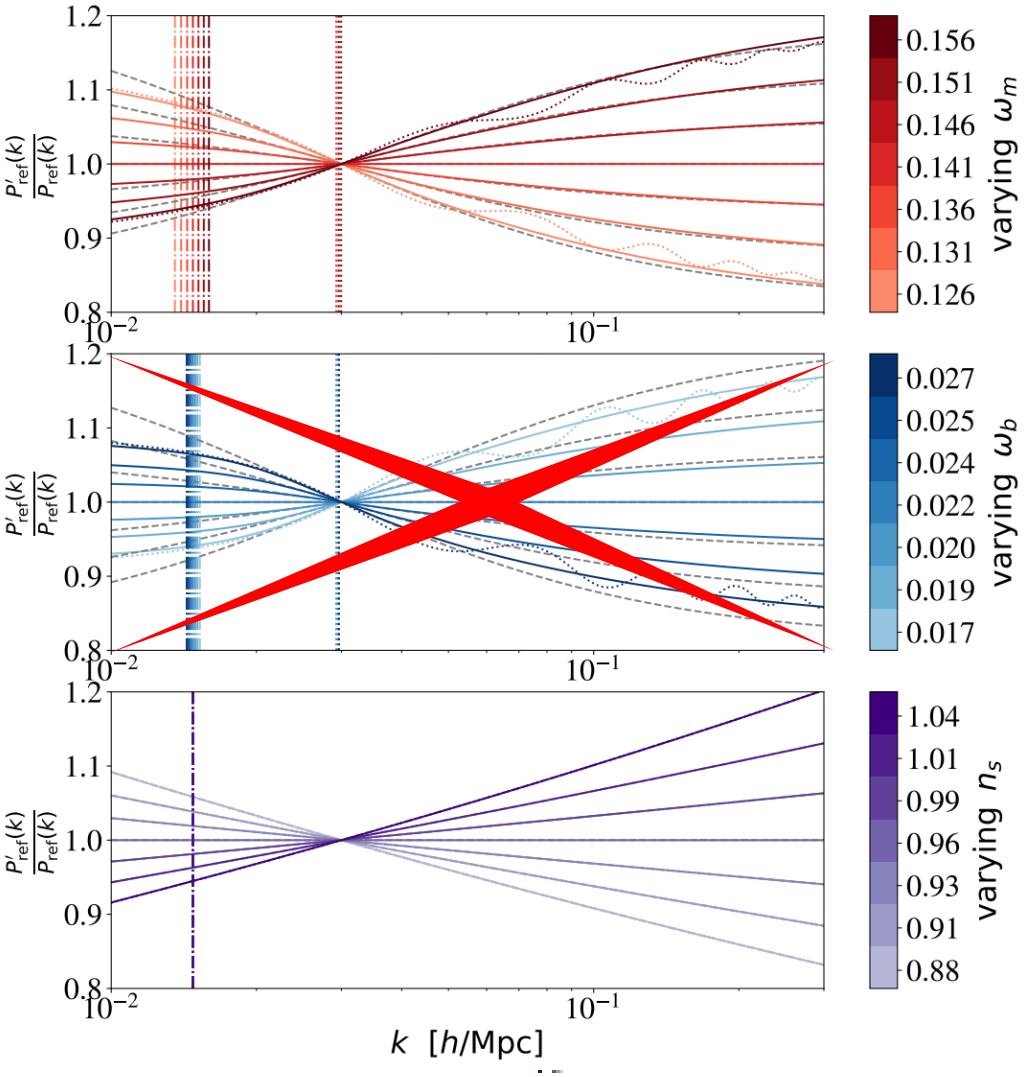

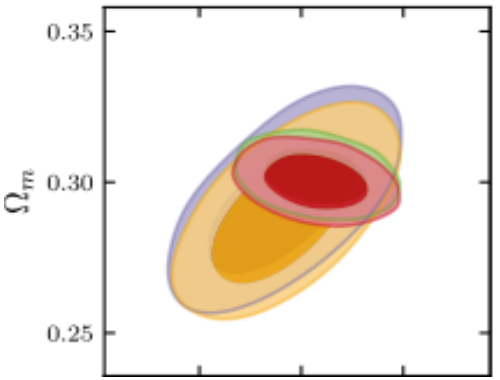

BAO+BBN
BAO+BBN+RSD
BAO+BBN+SF
BAO+BBN+SF+RSD

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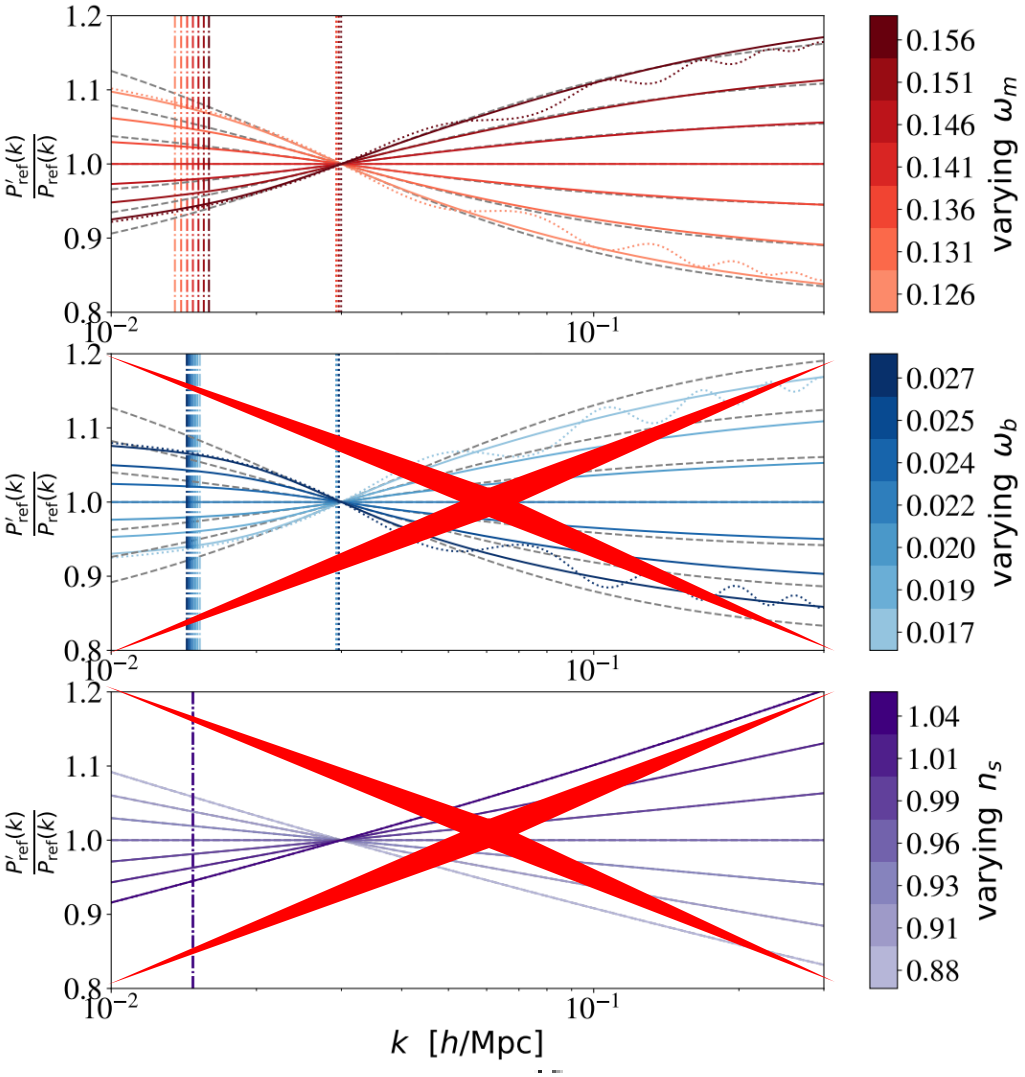

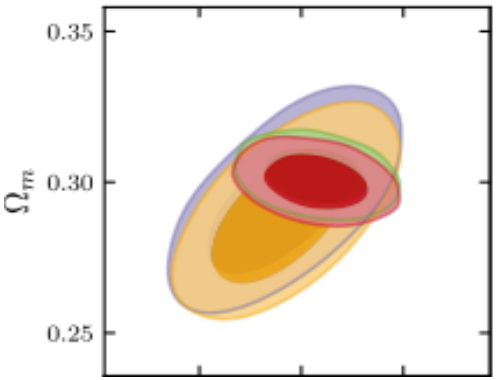

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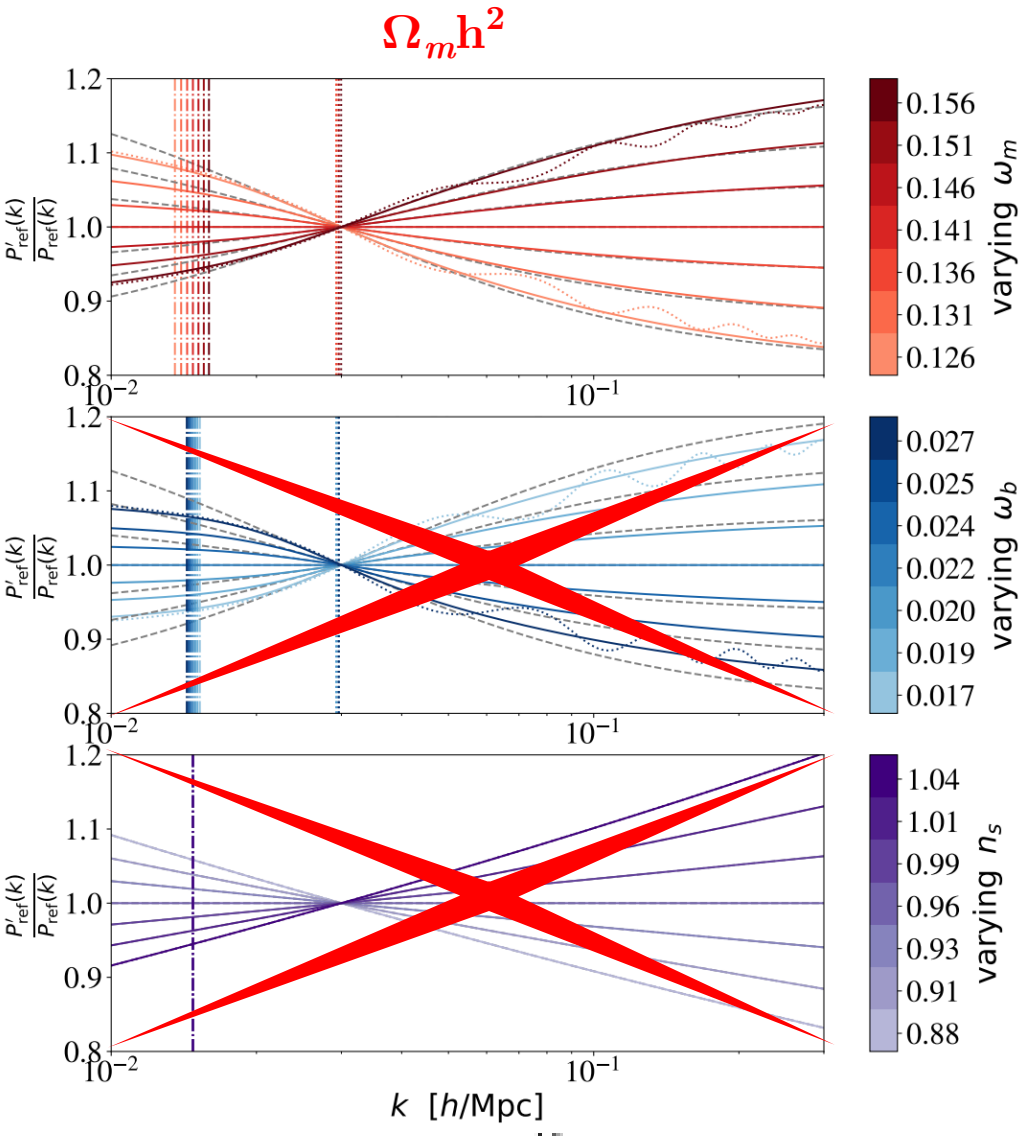

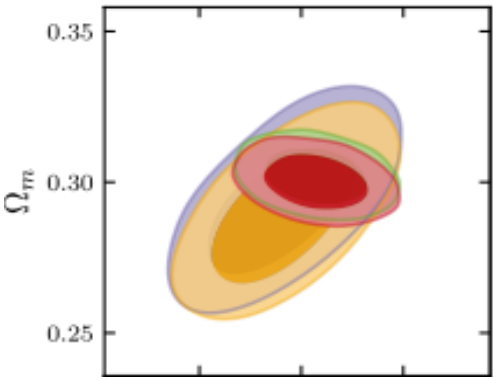

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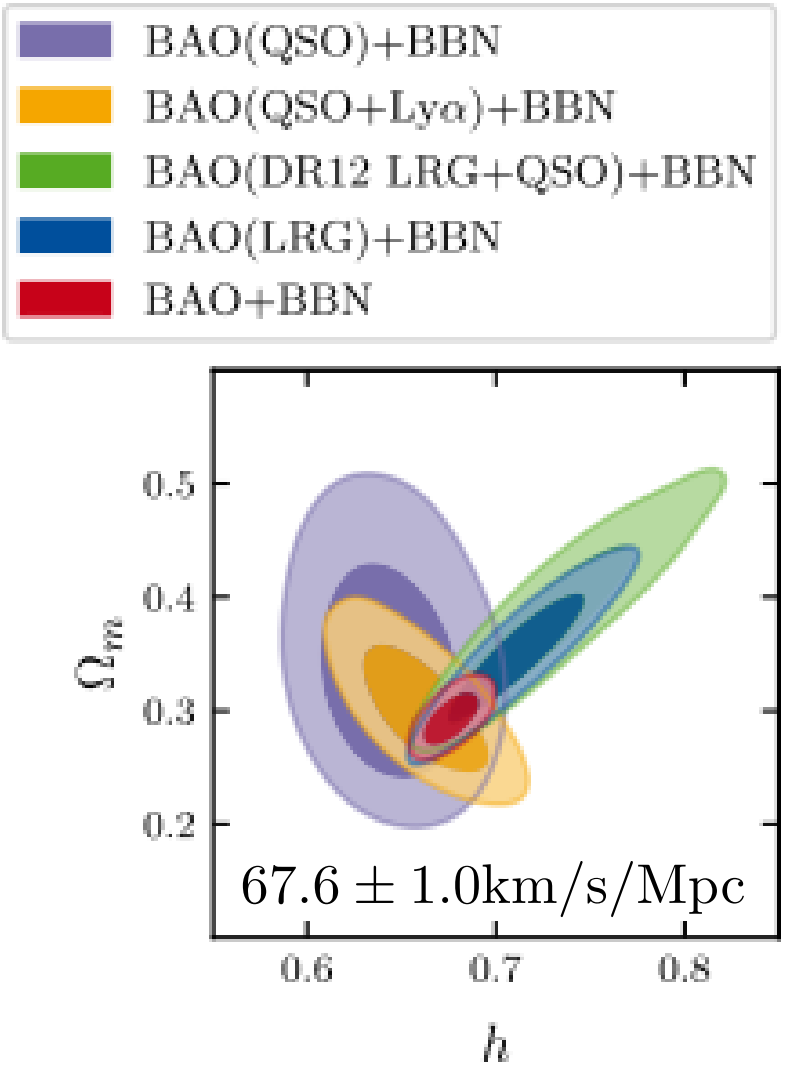

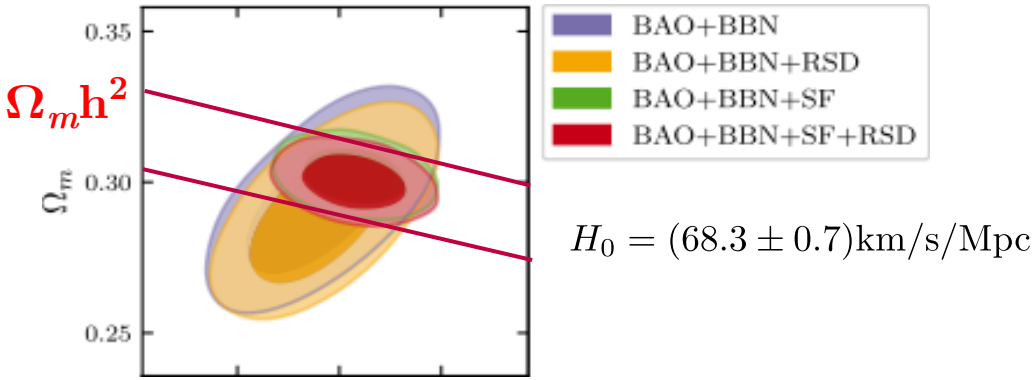

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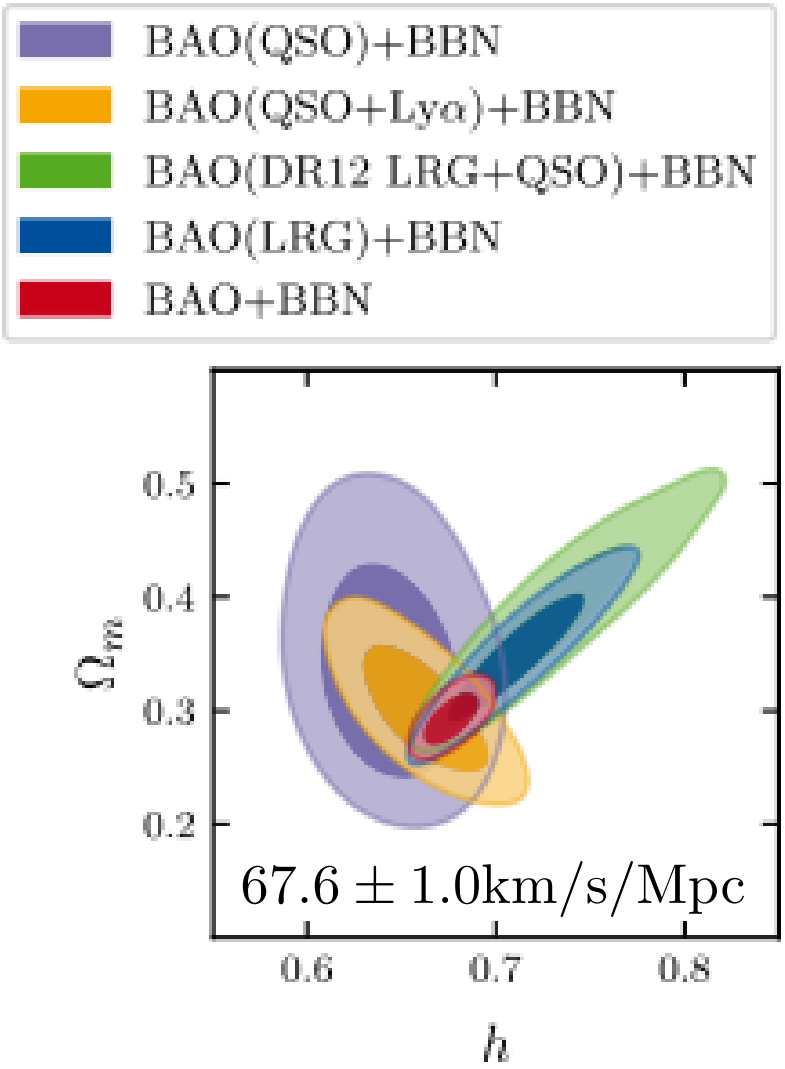
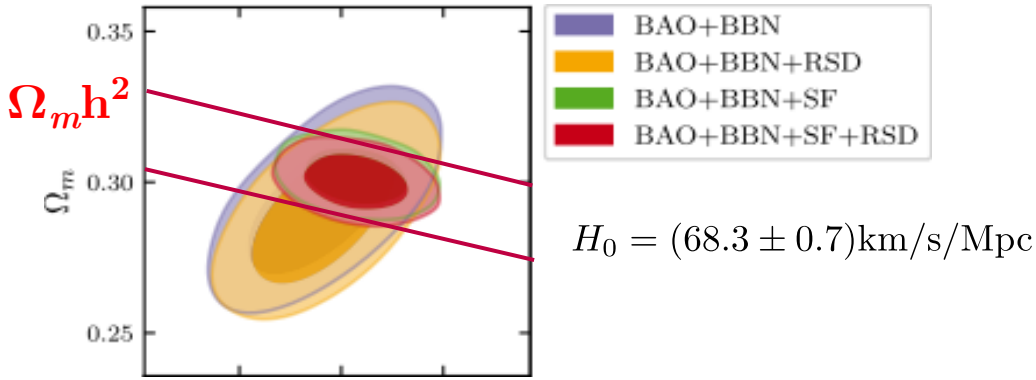


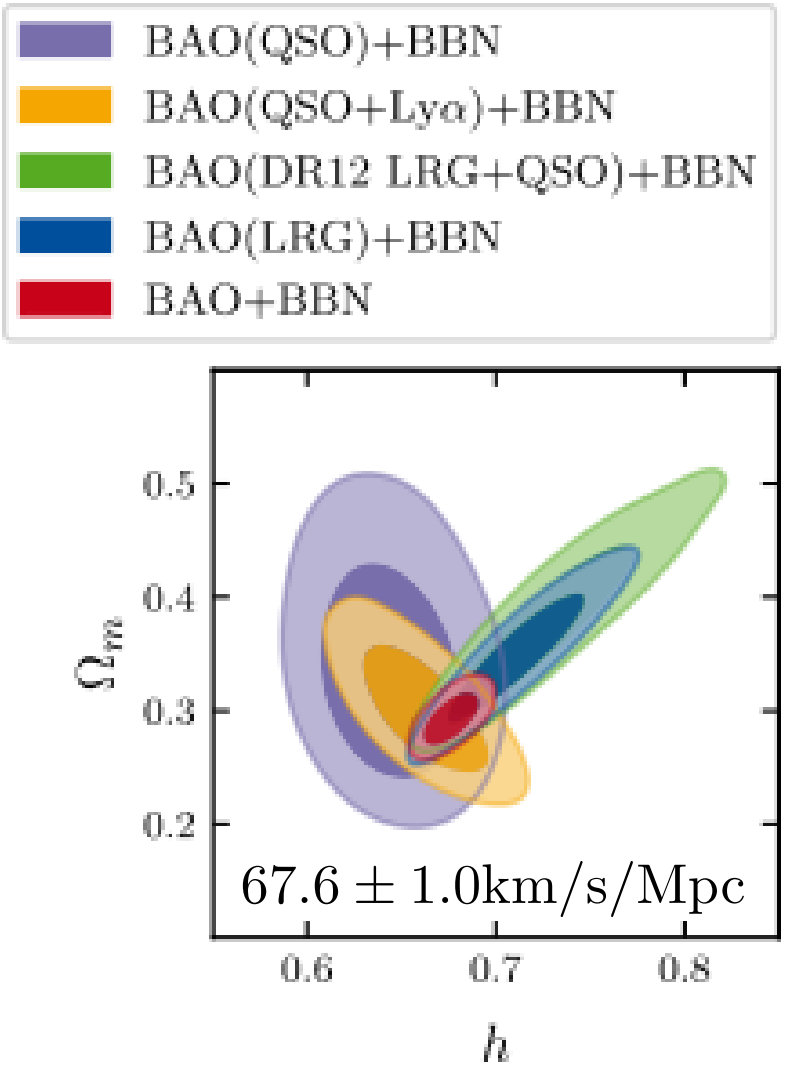


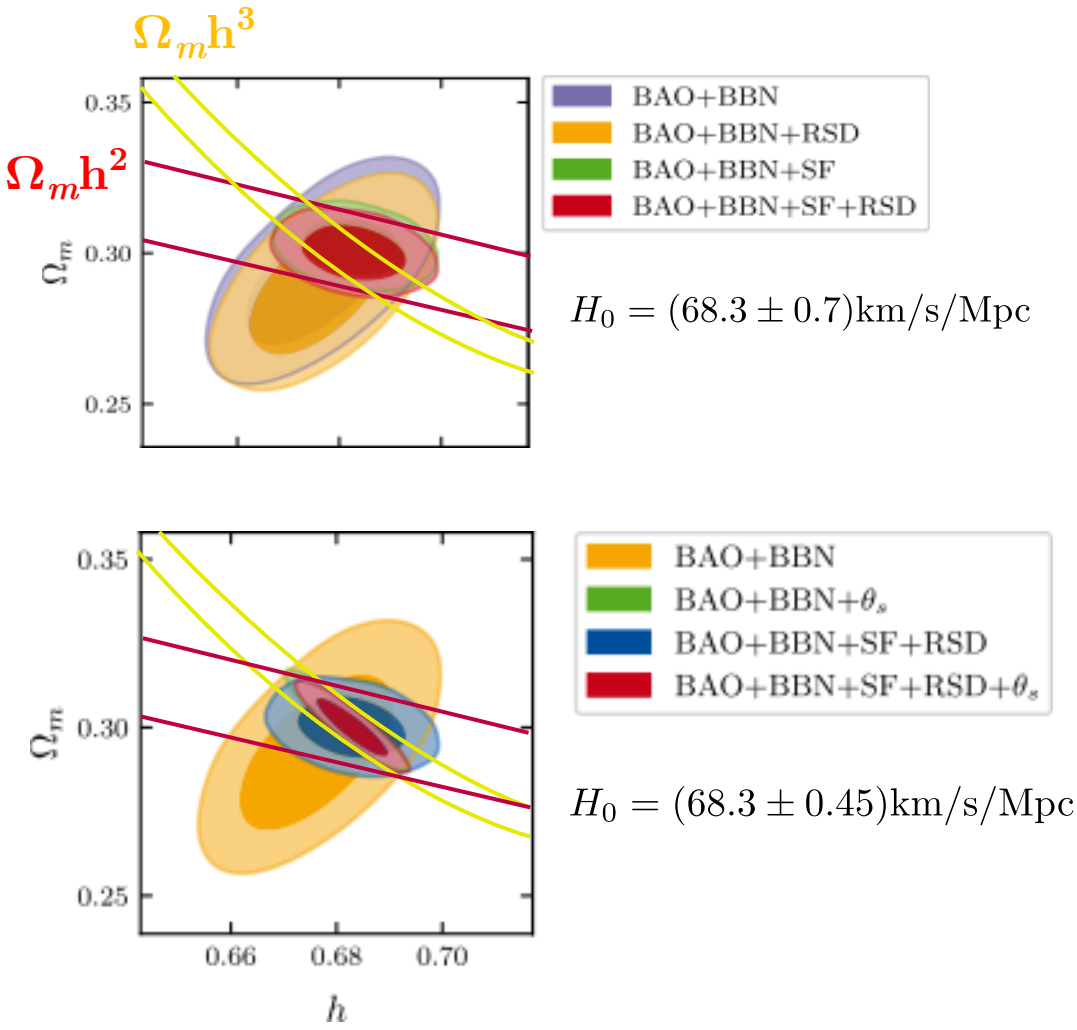
$H_0 = (68.3 \pm 0.7)$km/s/Mpc

Constraints equivalent to full LSS modeling, but more robust

→ Possible extensions in the future

arXiv:2209.14330 → JCAP 11 (2022) 039
Nils Schöneberg, Licia Verde, Héctor Gil-Marín, Samuel Brieden





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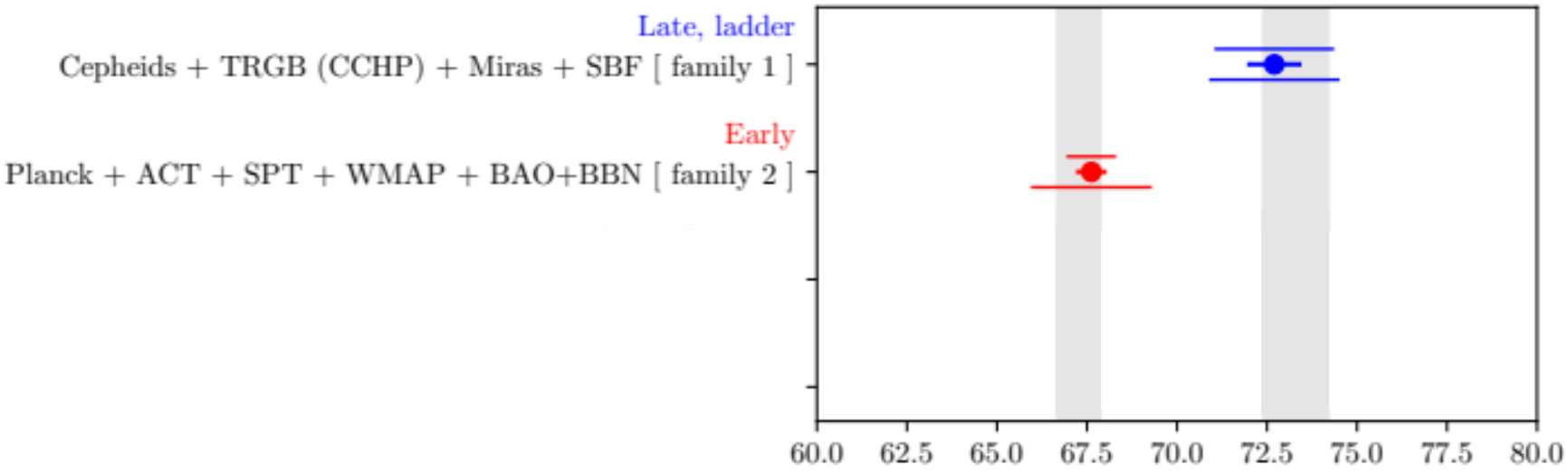
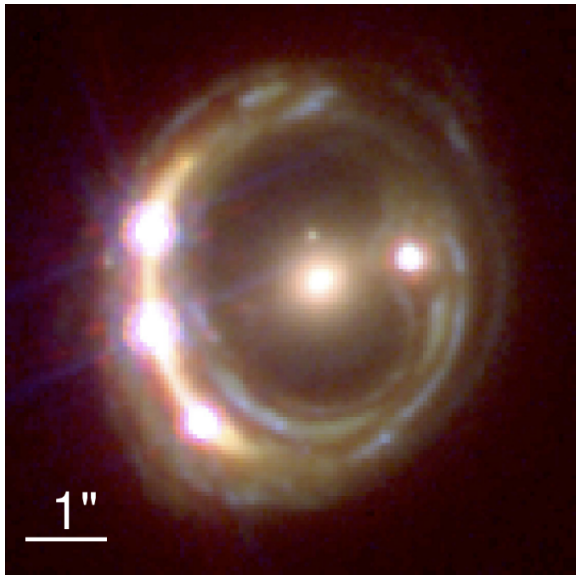


The third family

Standard candles which aren't candles

Nils Schöneberg

nils.science@gmail.com



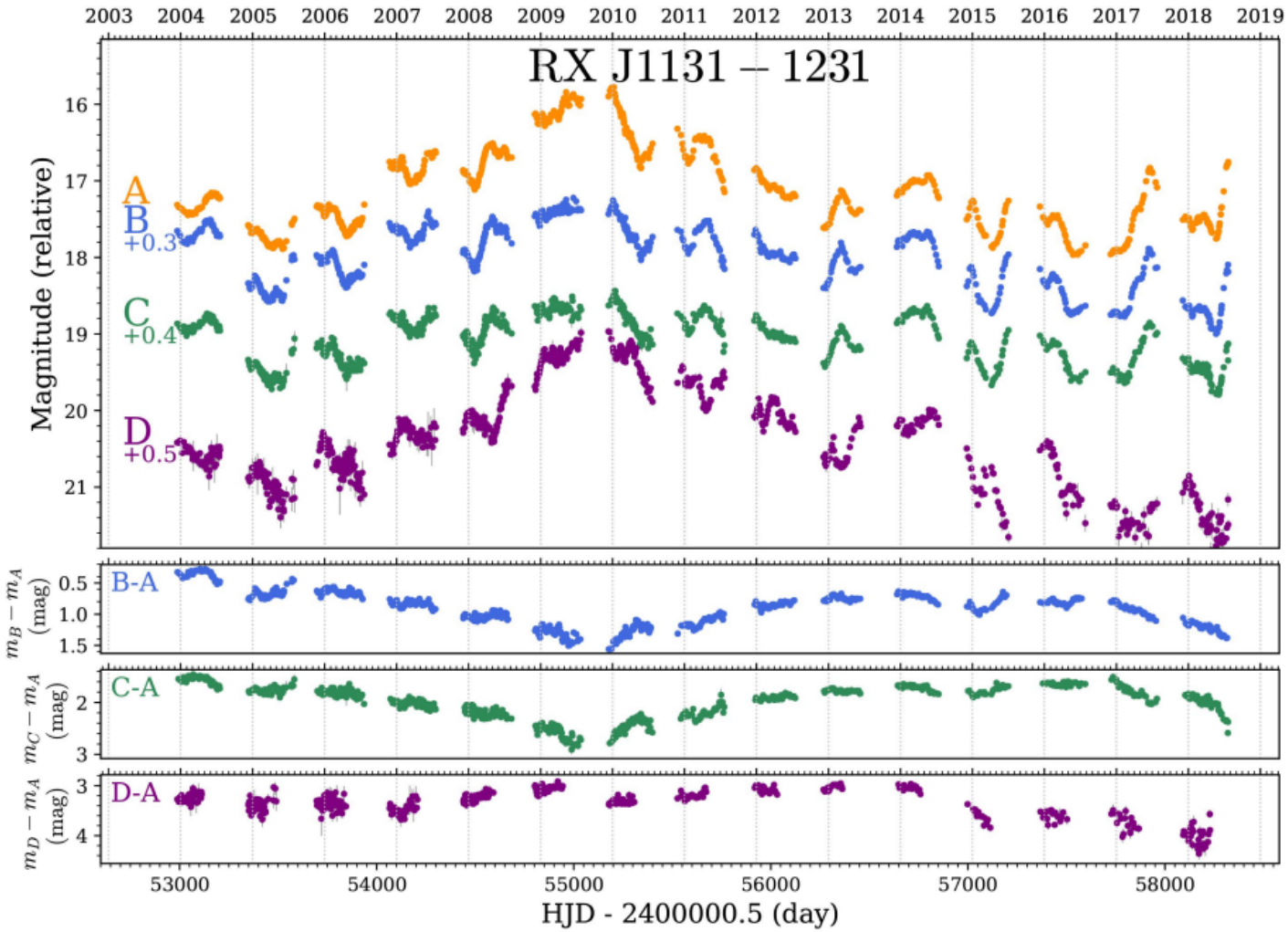
RXJ1131

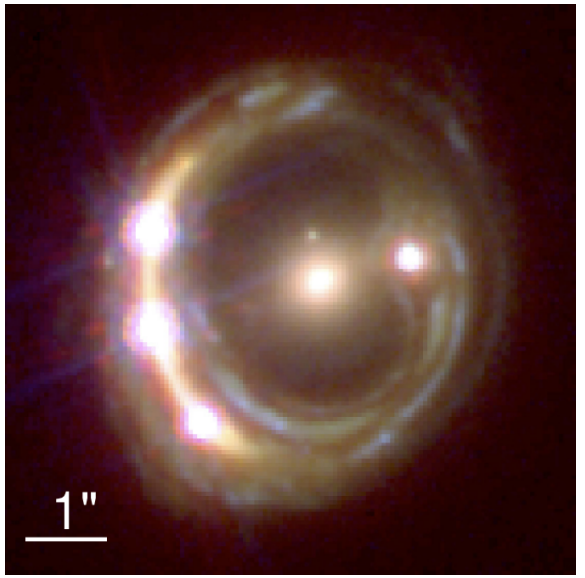
Strong Lensing

- Strong lensing gives the distance to the lens
- Redshift of lens and source typically known from spectral features
- Together this gives H_0

Nils Schöneberg nils.science@gmail.com

$$\Delta t = \frac{D_{\Delta t}}{c} \cdot \Delta\phi_{\text{Fermat}} \qquad D_{\Delta t} \propto \frac{D_L D_S}{D_{LS}} \propto \frac{1}{H_0}$$





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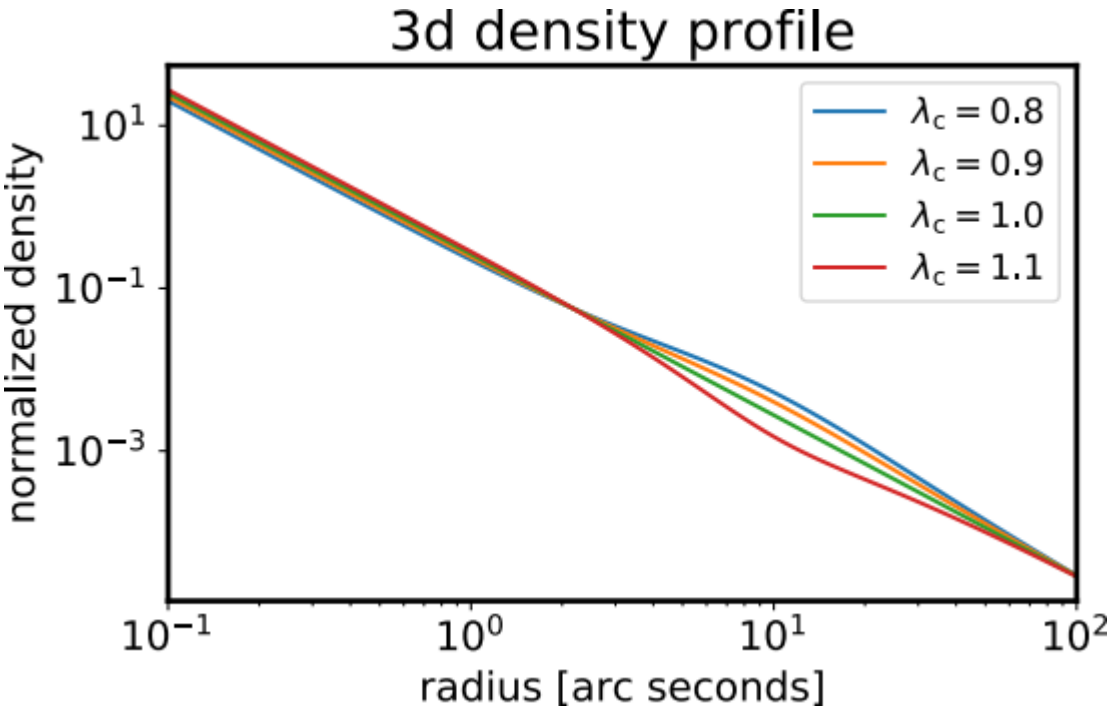
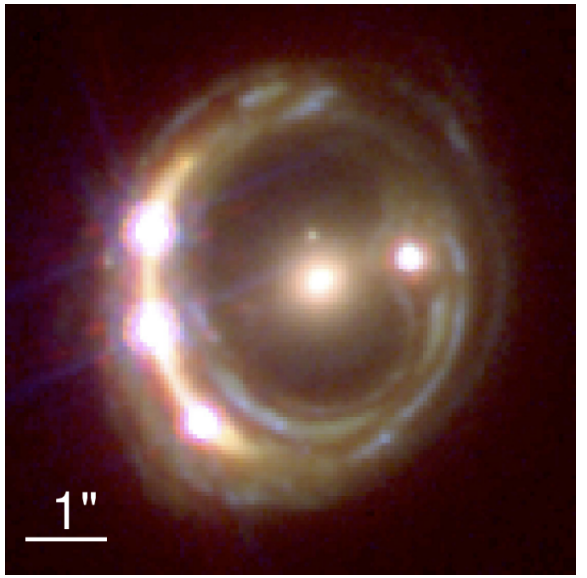
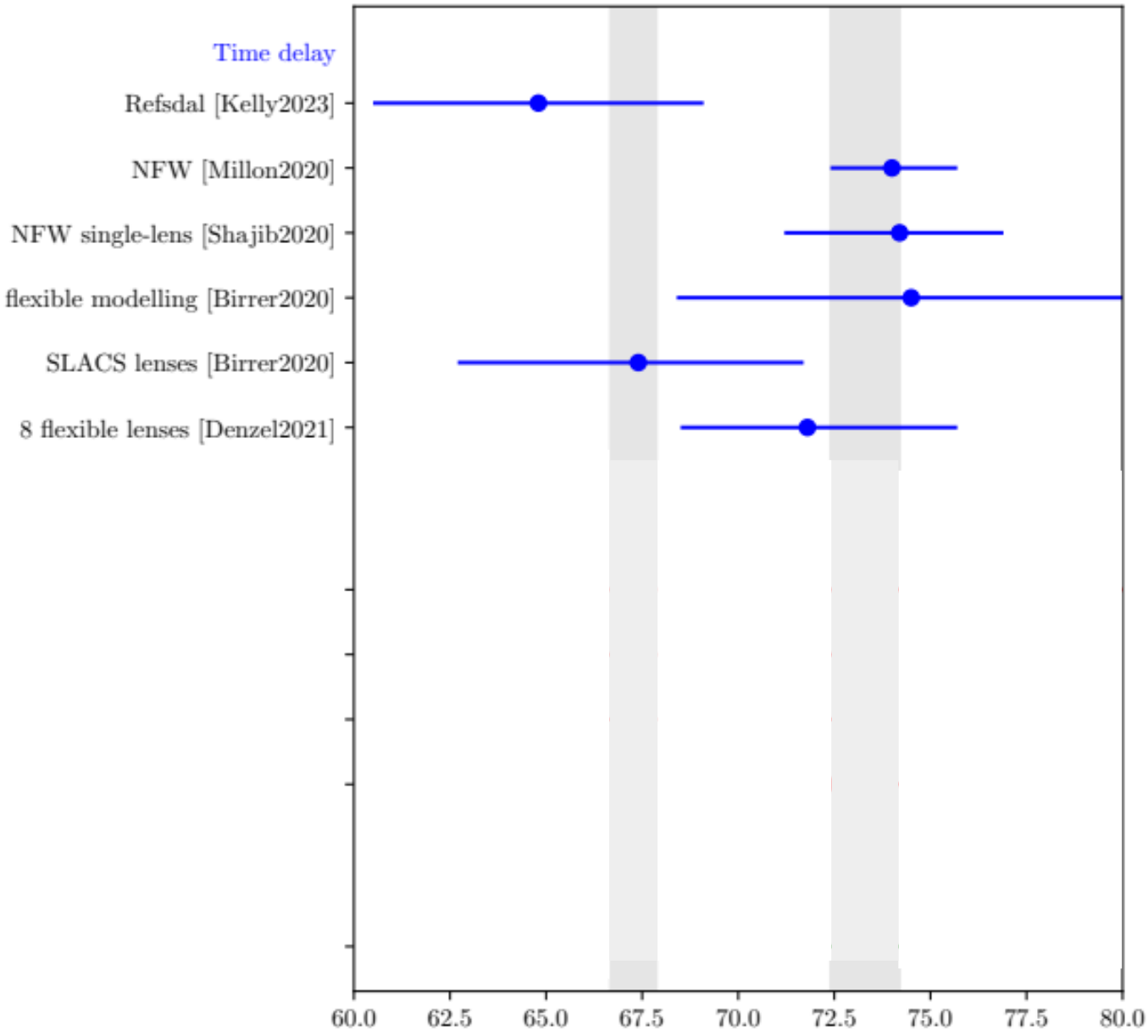




RXJ1131

$$\Delta\phi_{\mathrm{Fermat}} \to (1-\lambda)\Delta\phi_{\mathrm{Fermat}}$$

Verde,Schöneberg,Gil-Marin (upcoming review in ARAA)



Standard Sirens

- Idea: Use GW to measure distance

$$h_\times(f_z) = \sqrt{\frac{5}{96}} \frac{G^{5/6} \mathcal{M}_z^2 (f_z \mathcal{M}_z)^{-7/6}}{c^{3/2} \pi^{2/3} d_L} \cos(i)$$

Mukherjee+2019 (arxiv:1909.08627)

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constants
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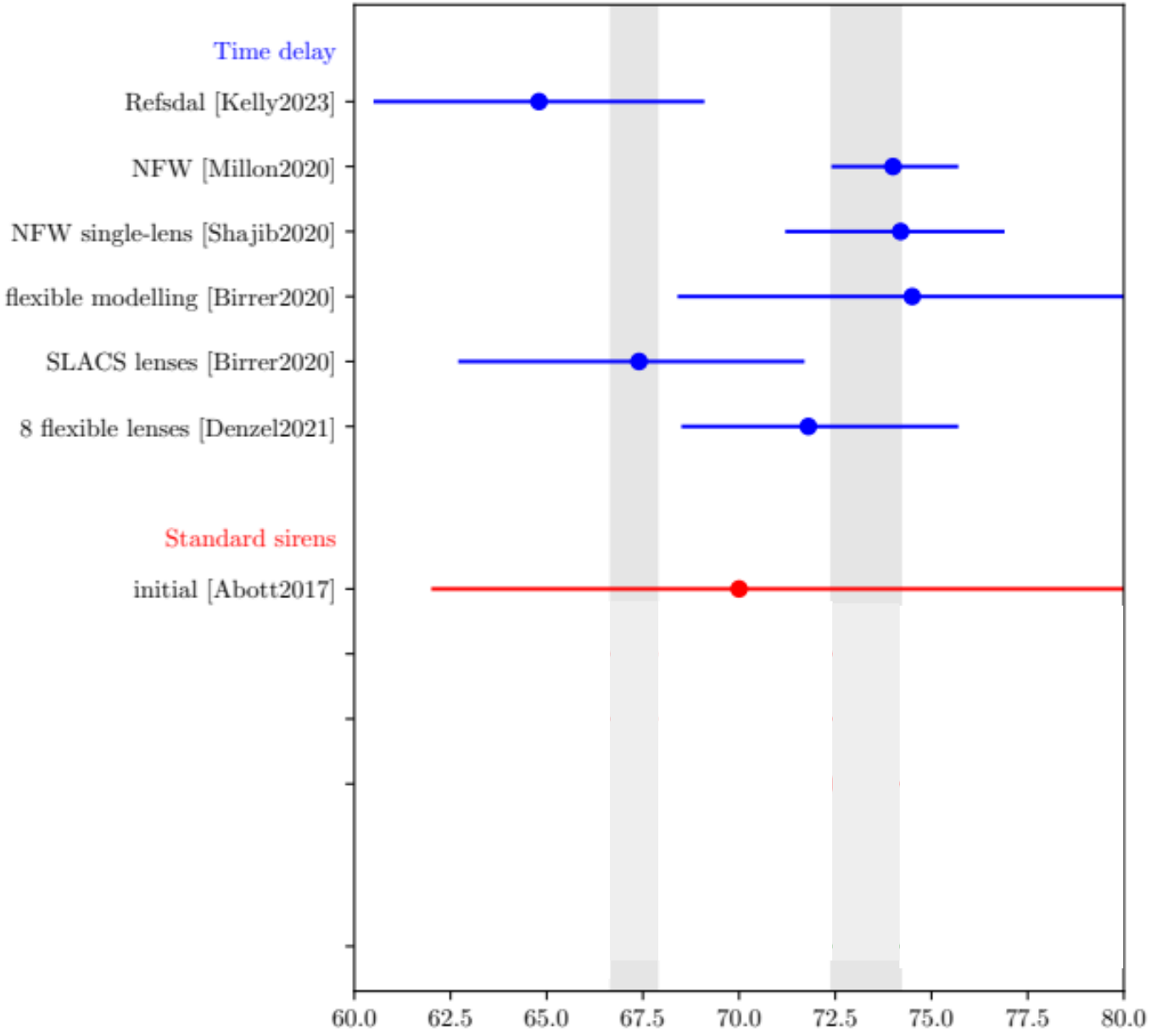
electromagnetic counterpart → z

Verde,Schöneberg,Gil-Marin (upcoming review in ARAA)

GW170817



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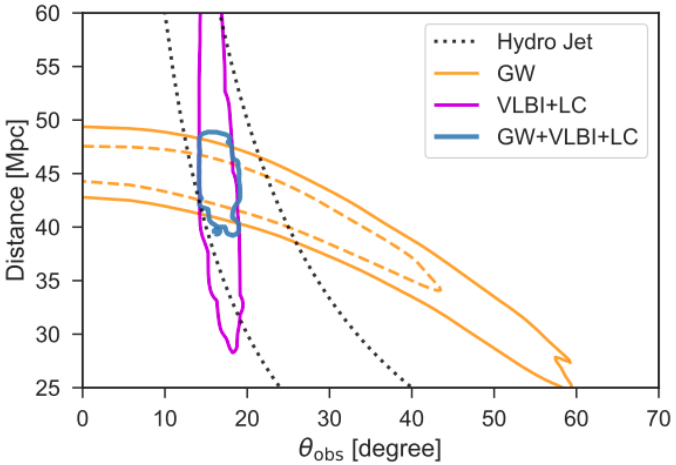

Hotokezaka+2019 (1806.10596)

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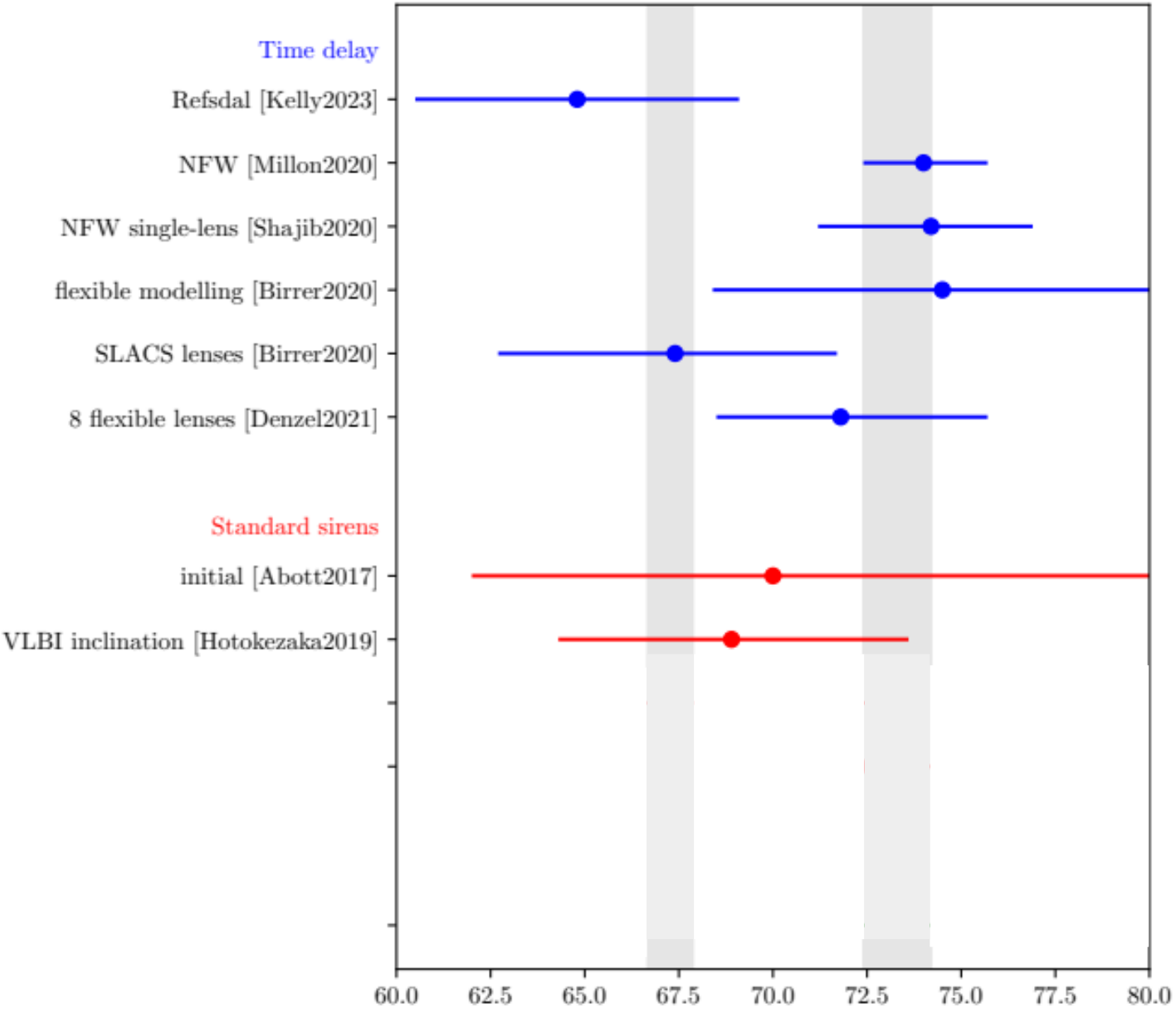
Verde,Schöneberg,Gil-Marin (upcoming review in ARAA)



Quick Reminder

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+ high redshift = more Hubble flow compared to peculiar velocities

Redshift of supernovae Ia: 0.15 – 2.0
Redshift of GW170817: 0.01

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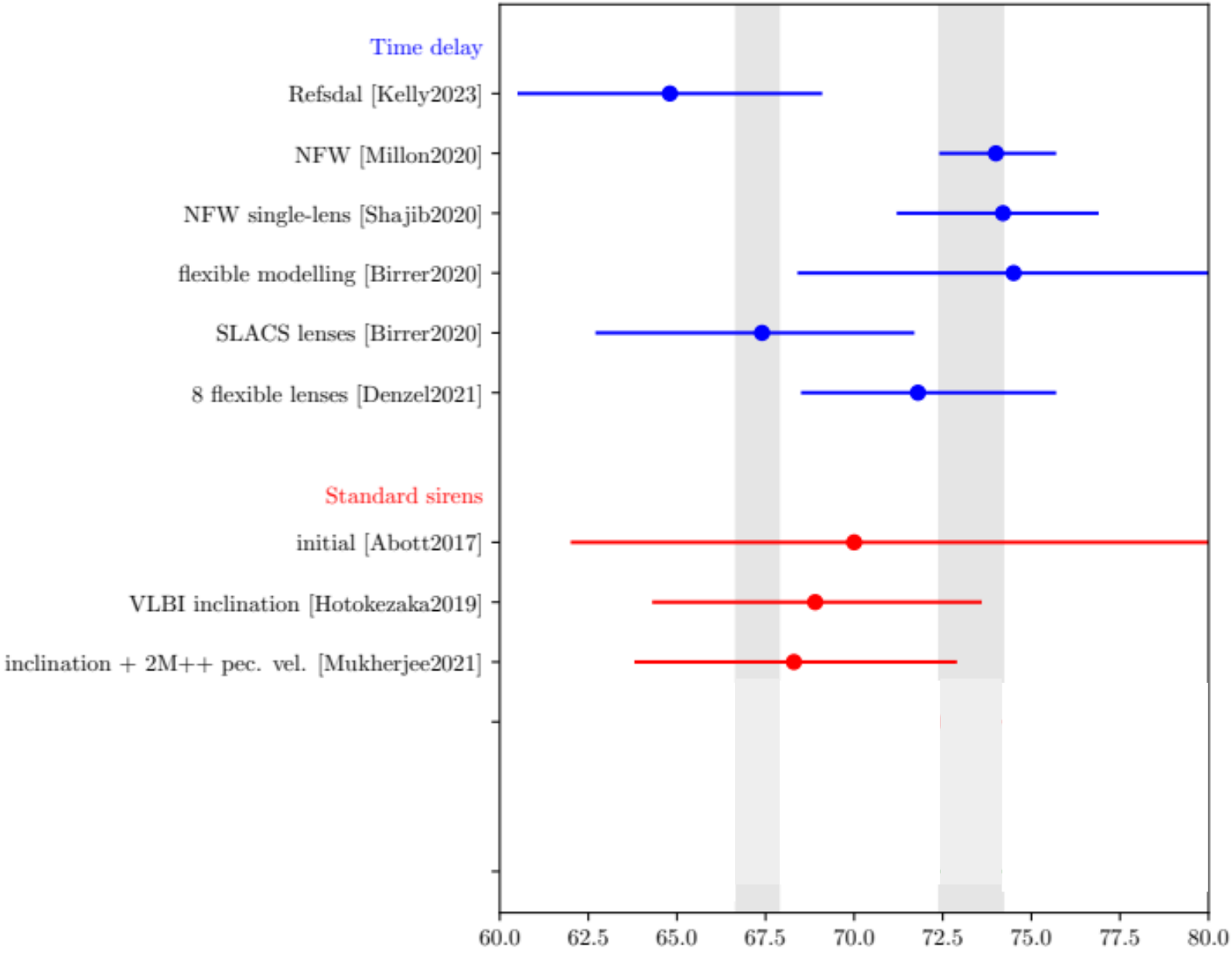
- Each individual object in Hubble flow is subject to peculiar velocities
- If we have many object, we can hope velocities average out/treat them as scatter
- If we have only one object, this is a source of uncertainty
- However, we can estimate it (from surrounding structure)

Verde,Schöneberg,Gil-Marin (upcoming review in ARAA)



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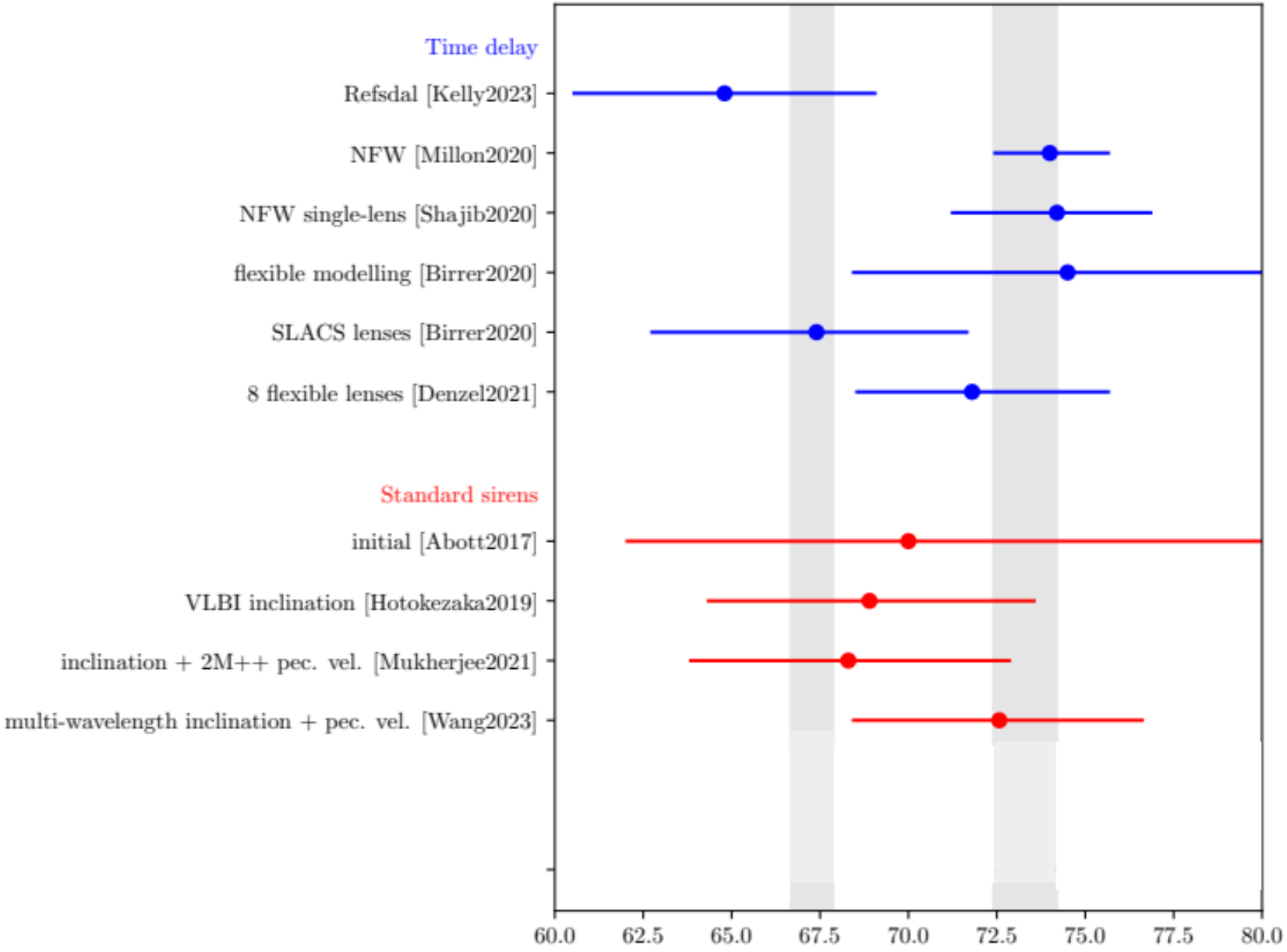
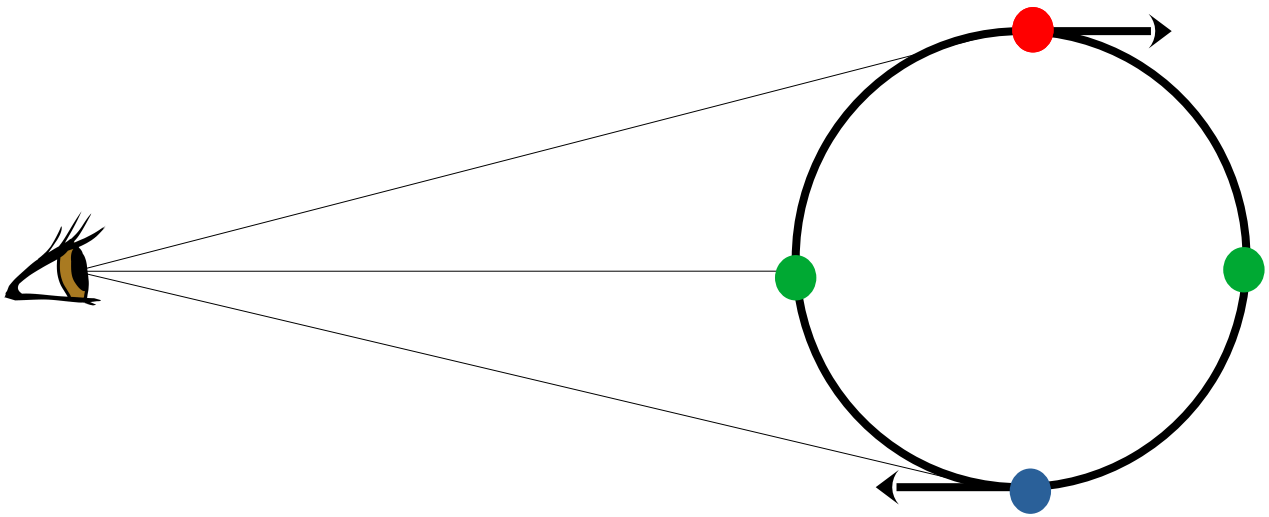


Masers – Distances from Acceleration

- Masers are an important tool to get distances



Blueshift/redshift = orbital velocity

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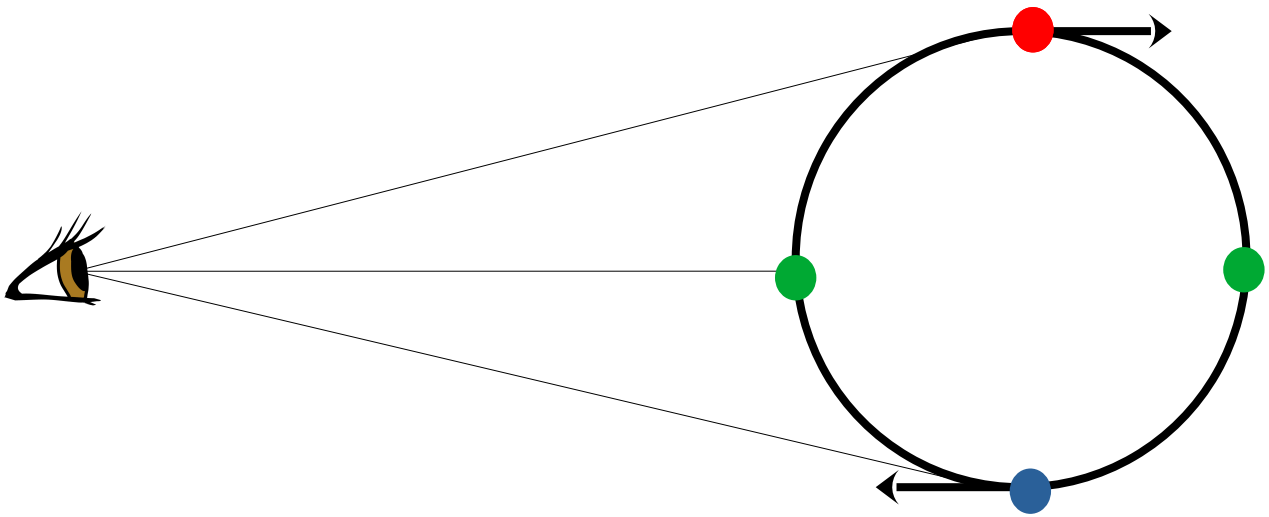

Blueshift/redshift = orbital velocity

Velocity drift = orbital acceleration

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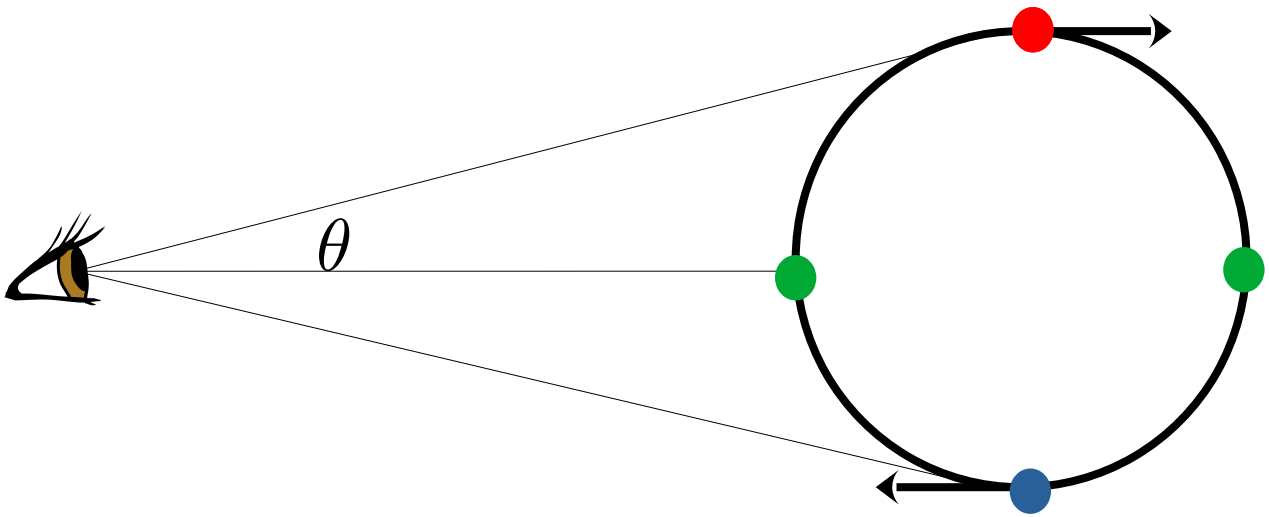
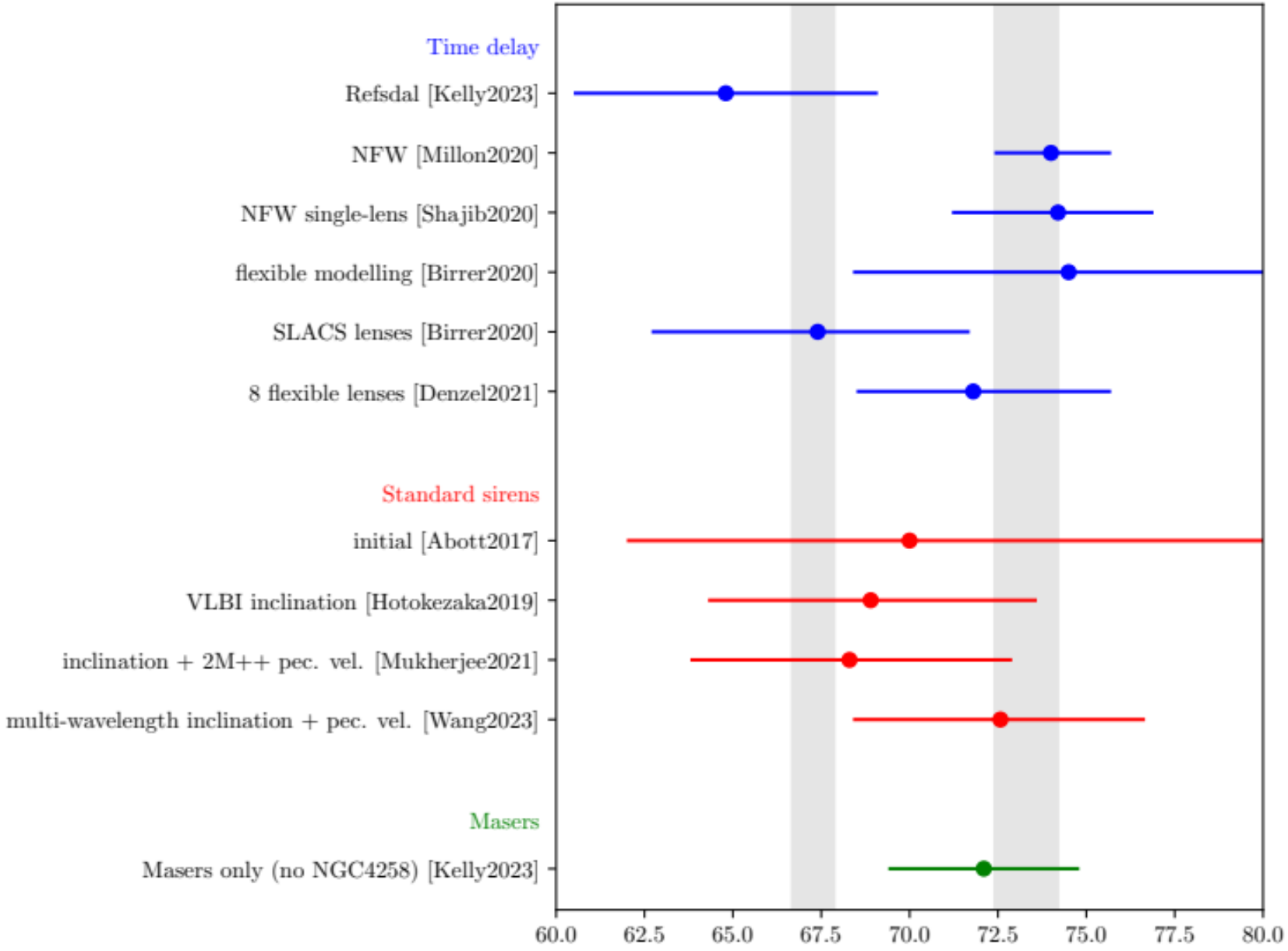
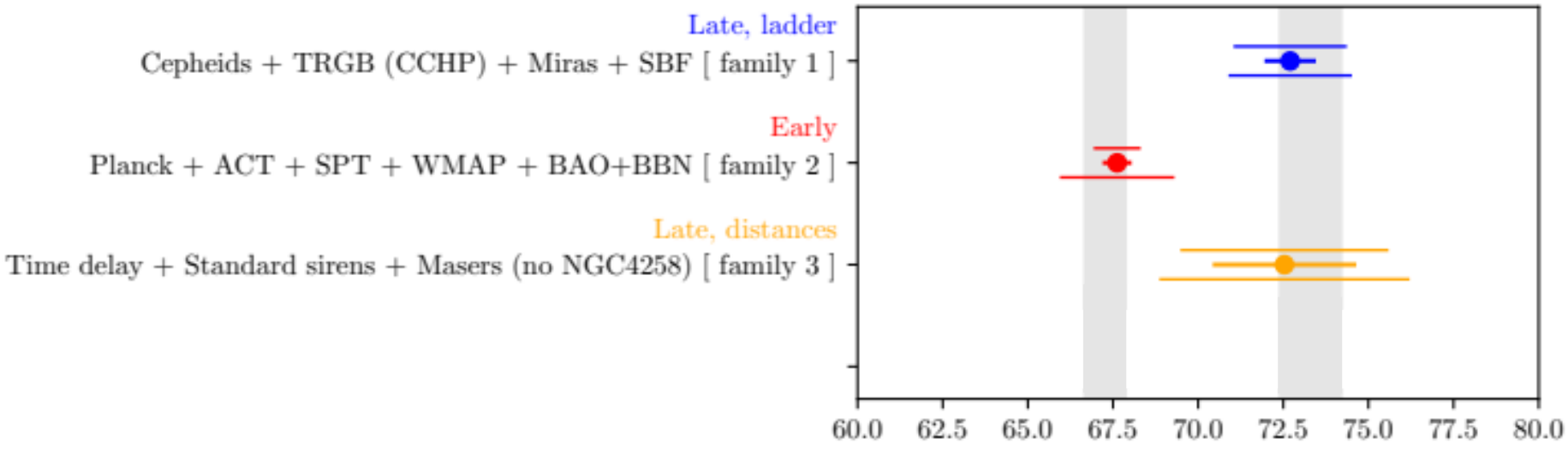


Blueshift/redshift = orbital velocity $r = v^2/a$

Velocity drift = orbital acceleration $d = r/\tan\theta$

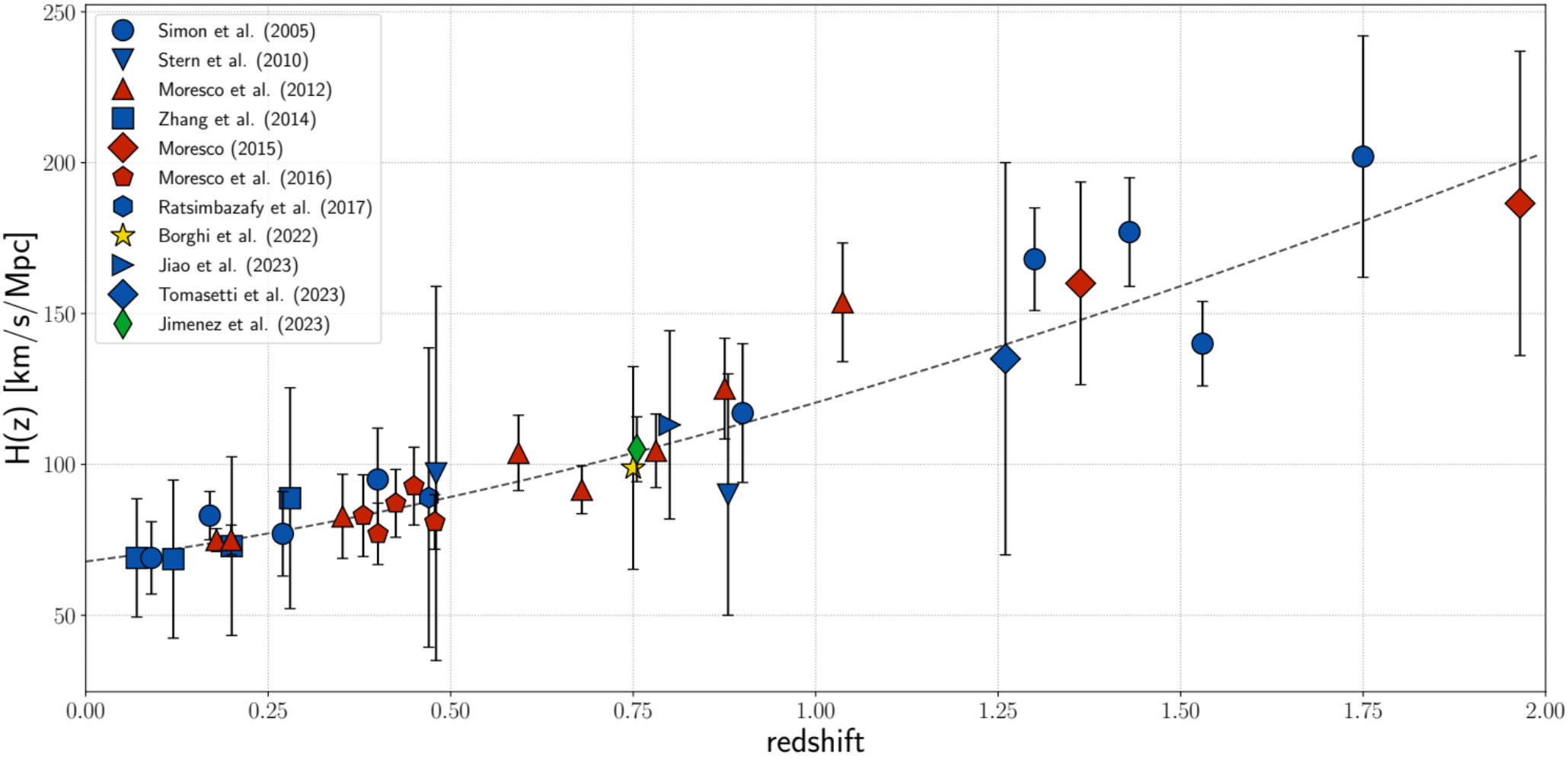
Verde,Schöneberg,Gil-Marin (upcoming review in ARAA)




Late, ladder
Cepheids + TRGB (CCHP) + Miras + SBF [family 1]
Early
Planck + ACT + SPT + WMAP + BAO+BBN [family 2]
Late, distances
Time delay + Standard sirens + Masers (no NGC4258) [family 3]
60.0
62.5
65.0
67.5
70.0
72.5
75.0
77.5
80.0

Nils Schöneberg

nils.science@gmail.com



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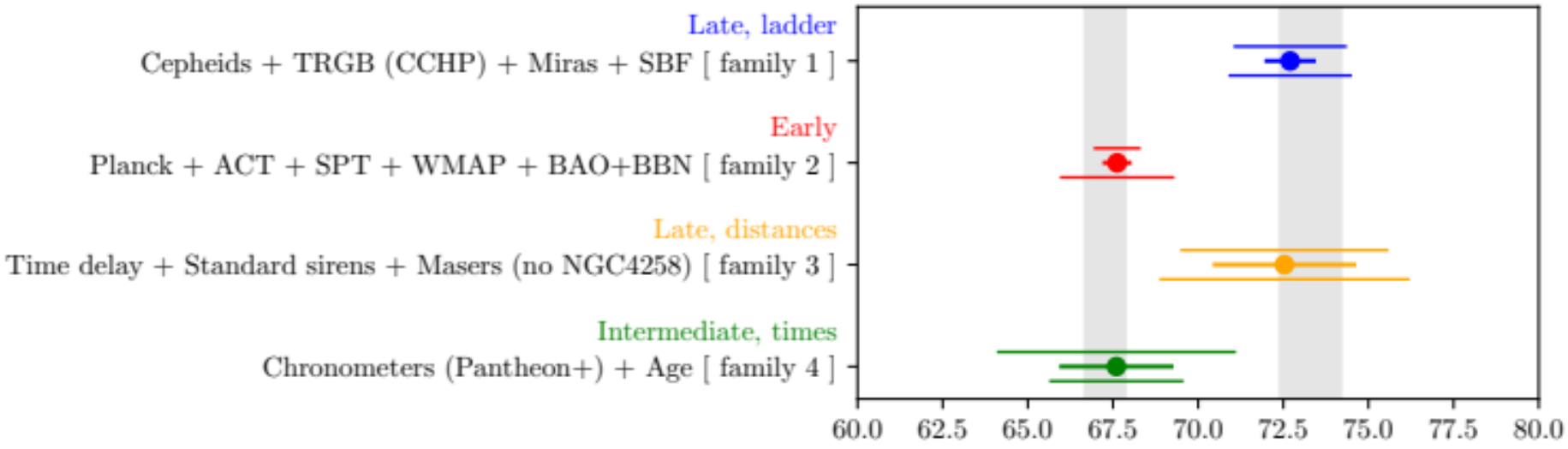

Dark Sirens

- Electromagnetic counterpart → Standard siren
- No EW → No Hubble?

Dark Sirens

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Dark Sirens

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- We might not get *individual* distances, but we can estimate stochastic distances

Dark Sirens

- Use electromagnetic observations (light) from galaxies to estimate their distribution
- This is assuming binary coalesences are associated to objects in galaxies and assuming we know the rate of merges in galaxies

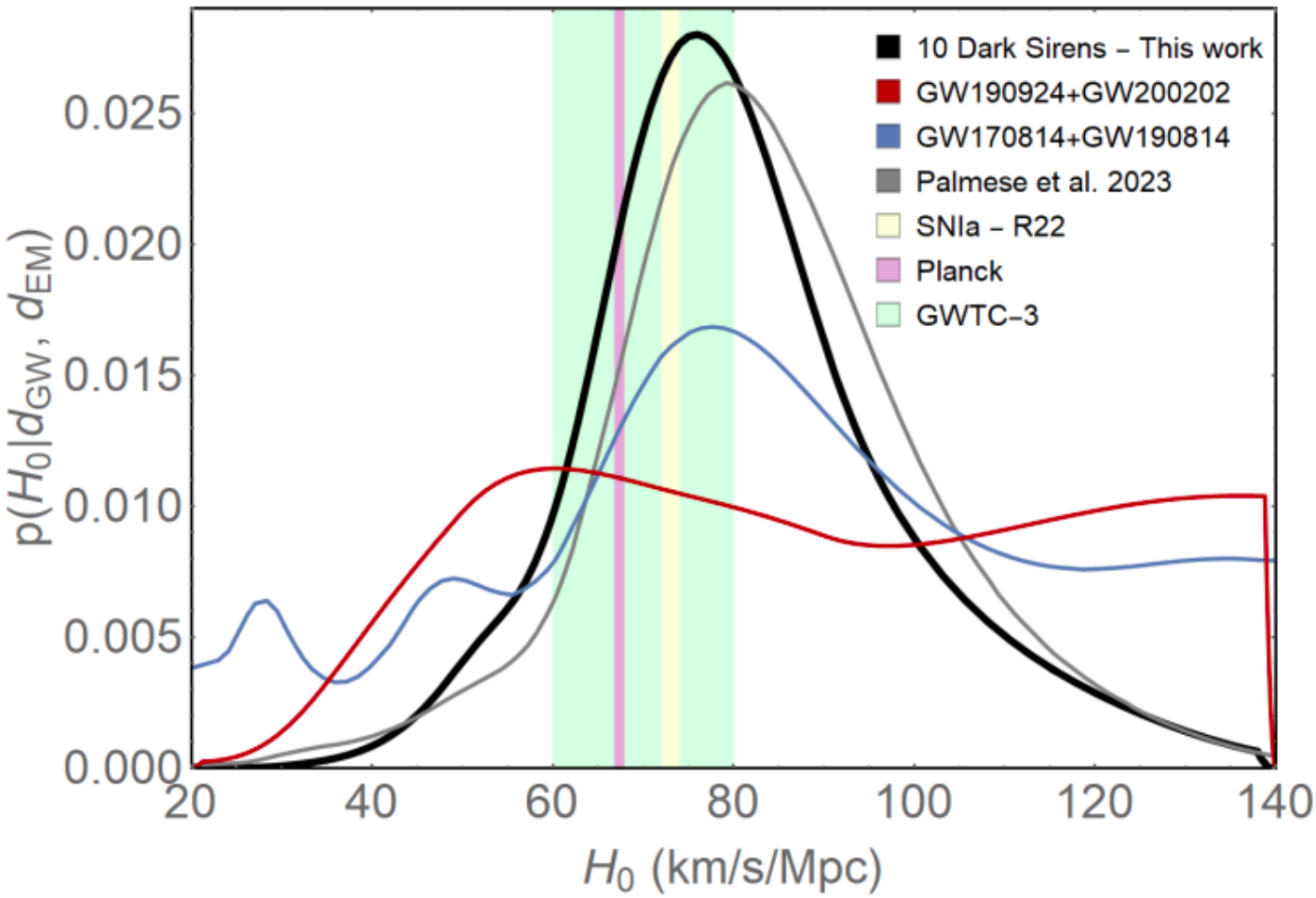
  (and that the galaxy catalogue contains the merger event source)
  (e.g. 2212.08694, 2310.13695)

Dark Sirens

Not yet competitive, but with O(1000s) events it might become

Talk by Simone

Alfradique+2023 (2310.13695)



Future Expectations

- If I could see the future, I would not be a physicist!

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- More CMB data (ACT DR6)

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- JWST local distance ladder (+TRGB discussions)
- Alternative methods reaching decent precision

  (FRB, GRB, QSOs, time delay, chronometers)
- Will GW cosmology be a part of that?

Takeaways:

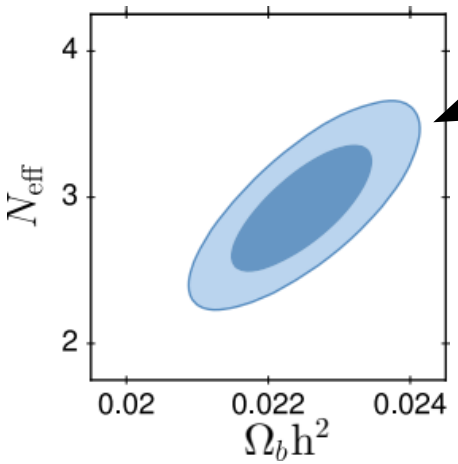
- CMB determination of H0 is model-dependent
- BAO+BBN excellent alternative (calibrated r_{s})
- Standard candle ≅ object of which intrinsic magnitude can be estimated
- Many alternate measurements
- GW could be a part of the search for an answer!

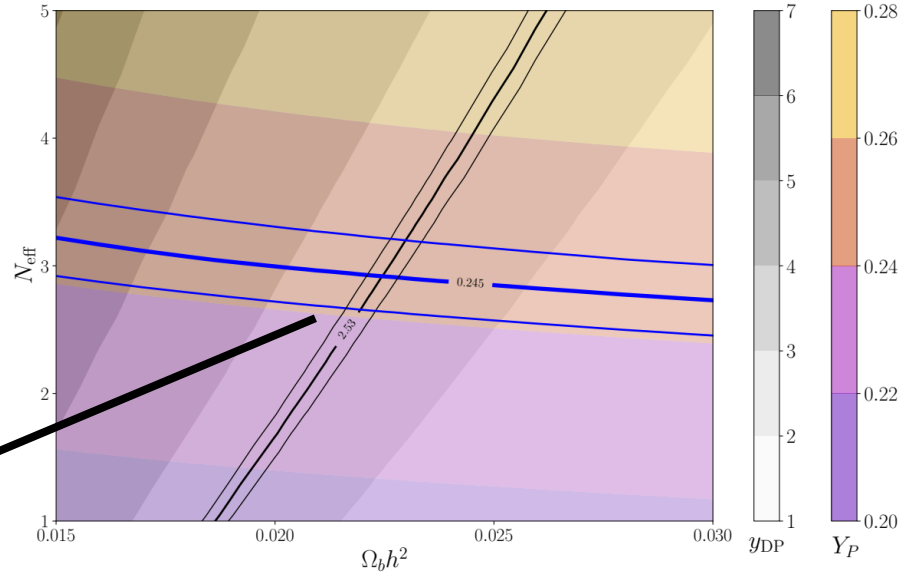
Backup Slides

BBN AND THE BARYONS

General idea:

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





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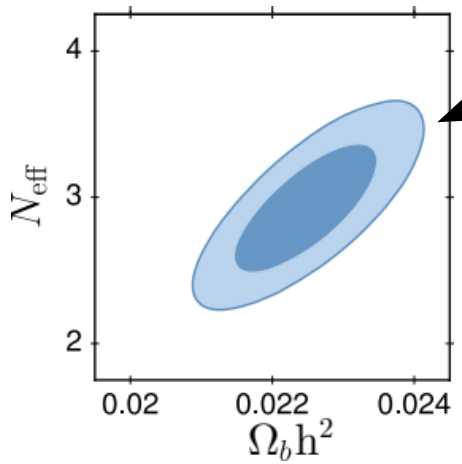
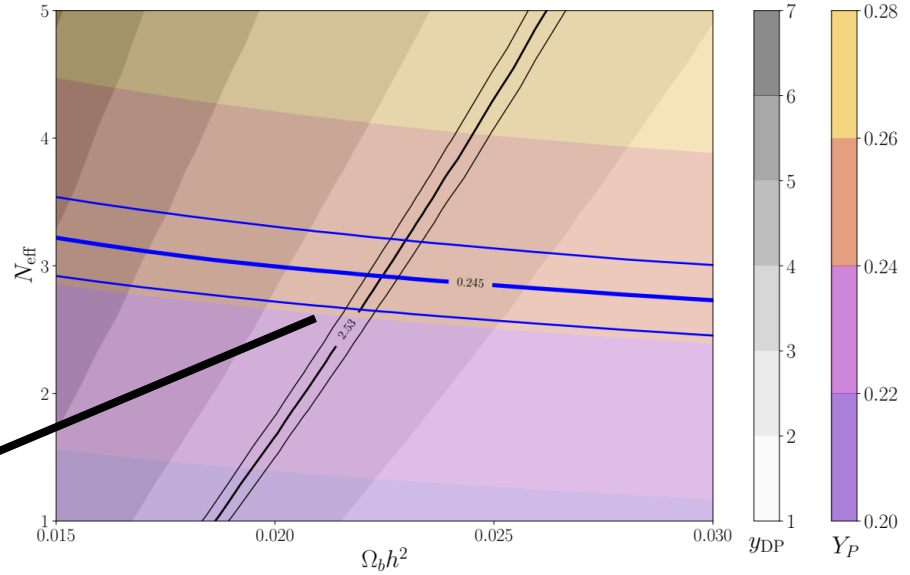




$$\Omega_b h^2 \rightarrow n_b \propto \Omega_b h^2 \rightarrow \eta_b = n_b/n_\gamma \propto \Omega_b h^2 T^{-3}$$

$\Omega_b h^2$ determines time of decoupling from photons
$\rightarrow$ Strong influence on Deuterium

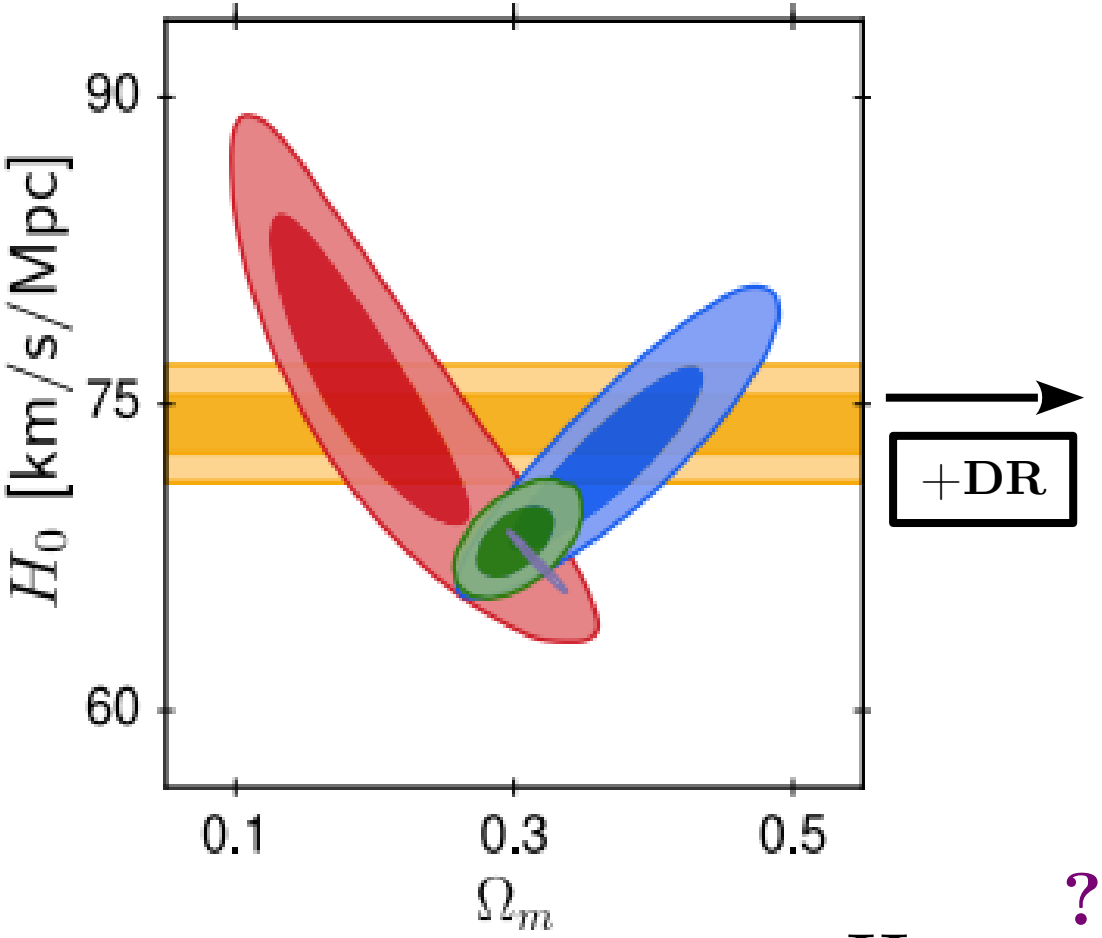
More baryons $\rightarrow$ earlier decoupling $\rightarrow$ higher temperature $\rightarrow$ more efficient deuterium burning $\rightarrow$ Less deuterium, slightly more Helium

BAO + BBN

IT WORKS!

$\rightarrow$ Is it a robust result?

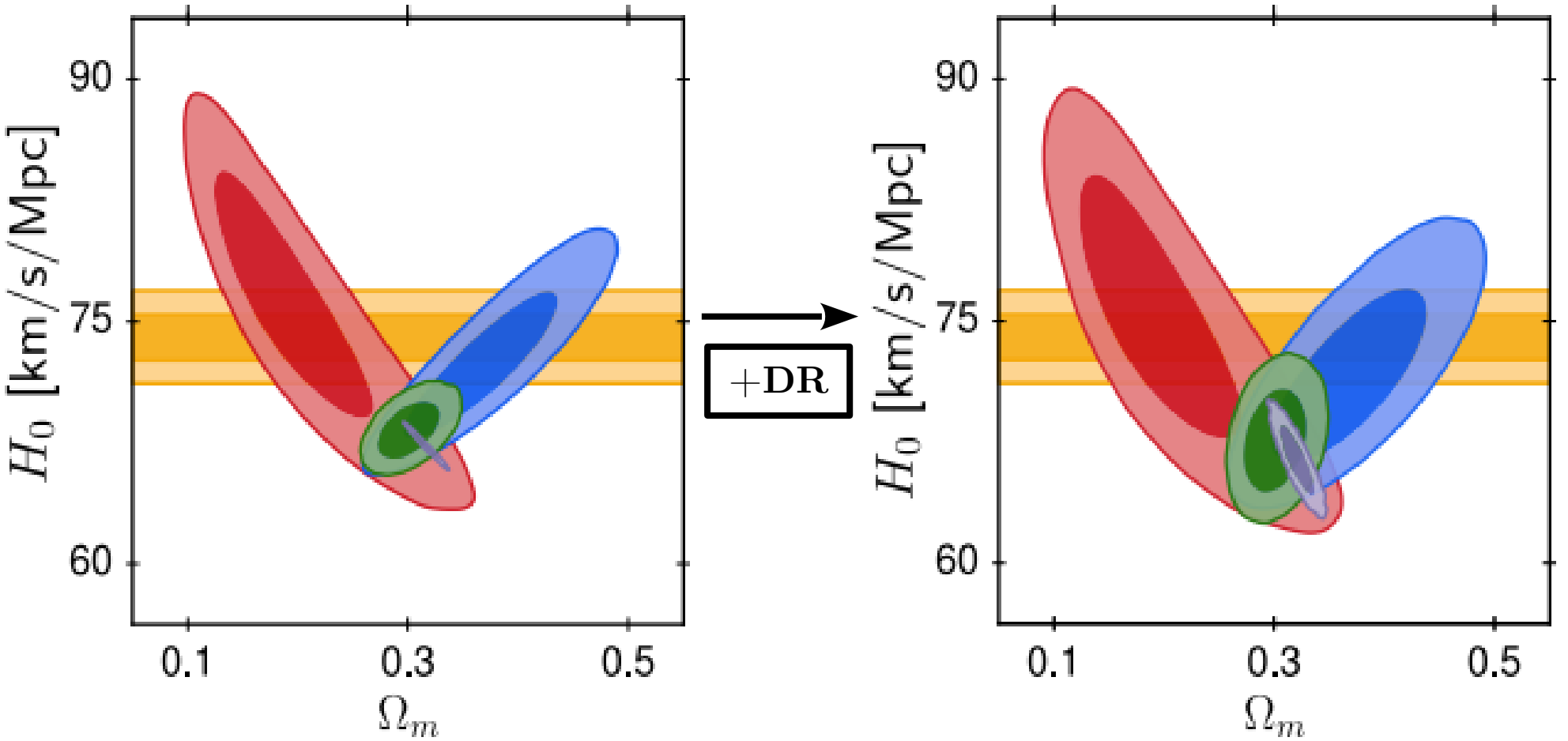
BAO + BBN



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

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

BAO + BBN



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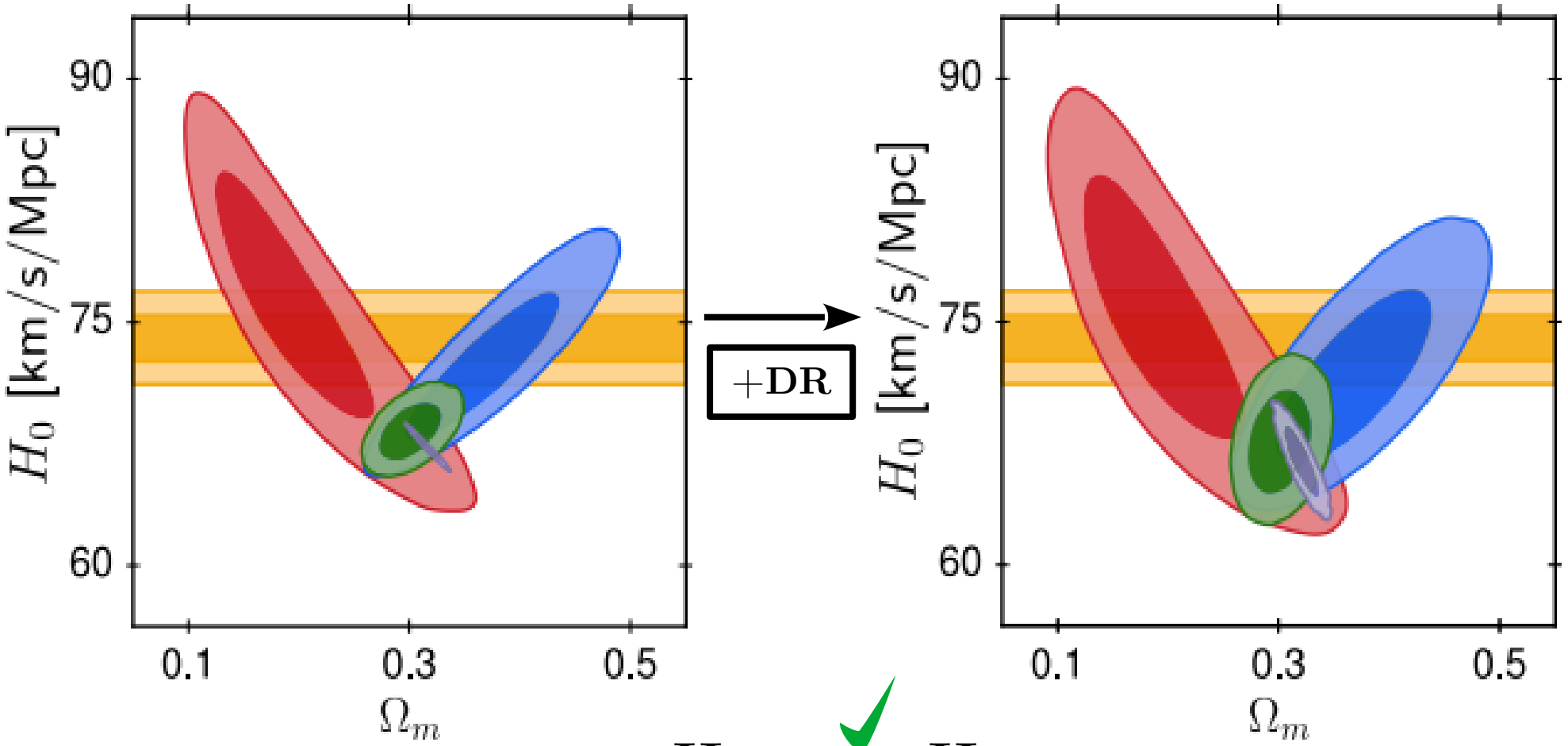

$$\mathrm{H_0\ r_s} \xrightarrow{\checkmark} \mathrm{H_0}$$

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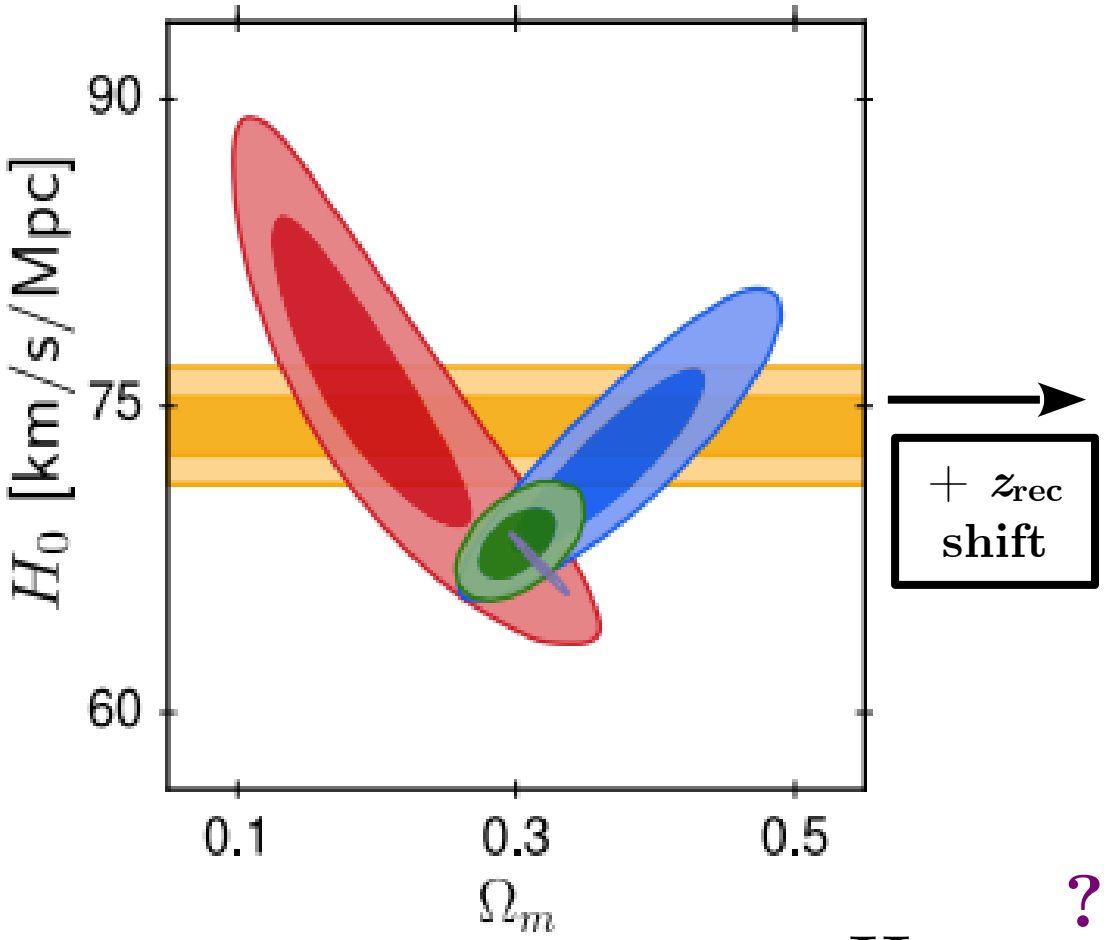
BAO + BBN



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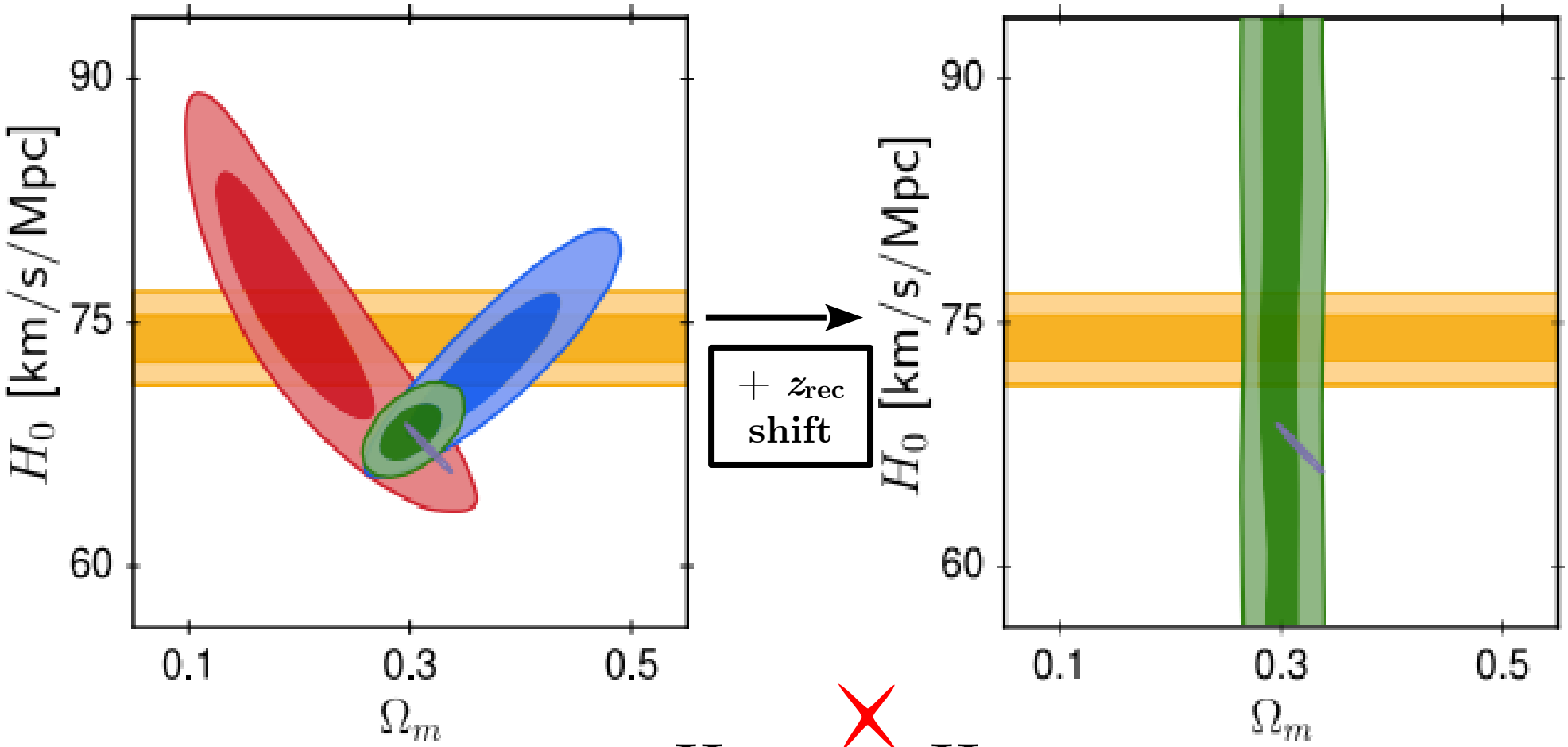

$$\mathrm{H_0\ r_s} \not\rightarrow \mathrm{H_0}$$

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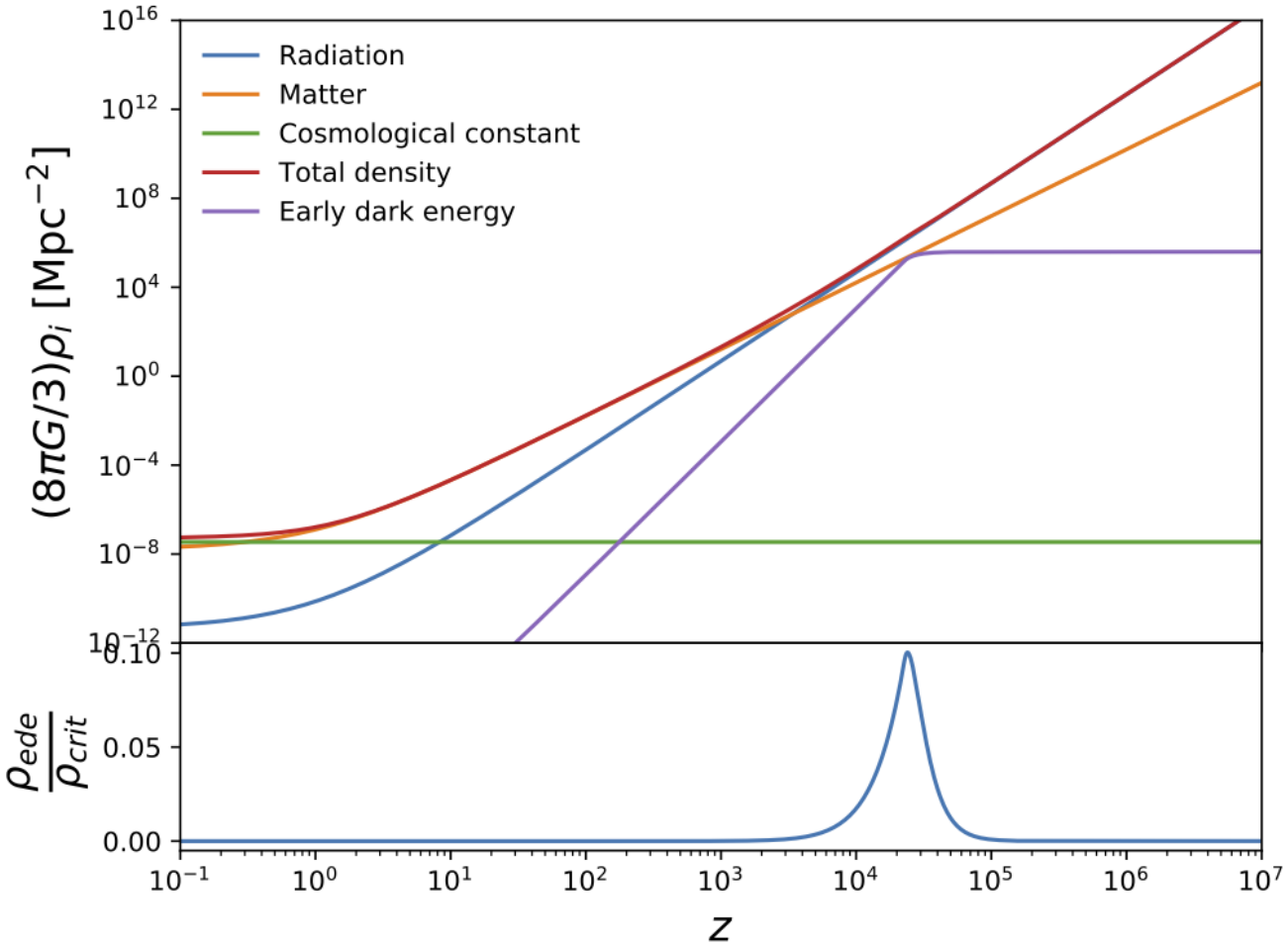
Early Dark Energy



Early Dark Energy