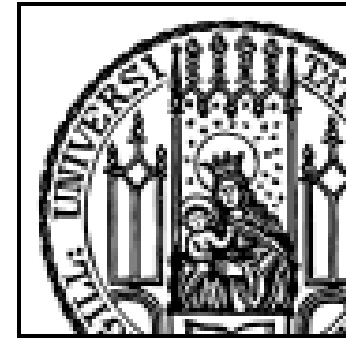
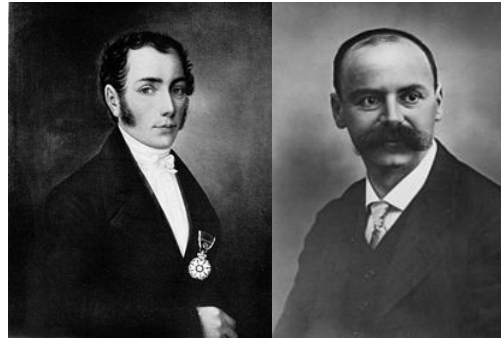
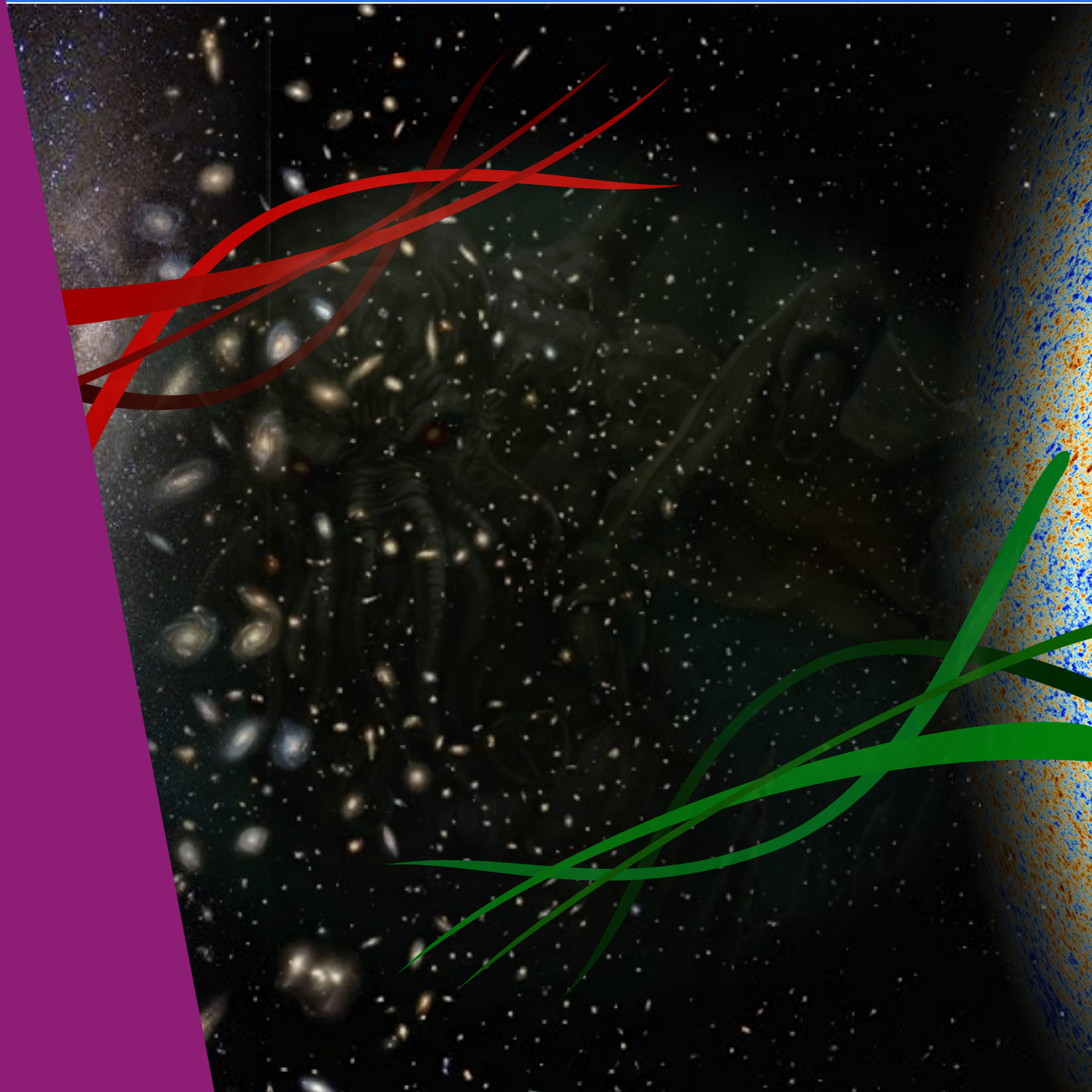




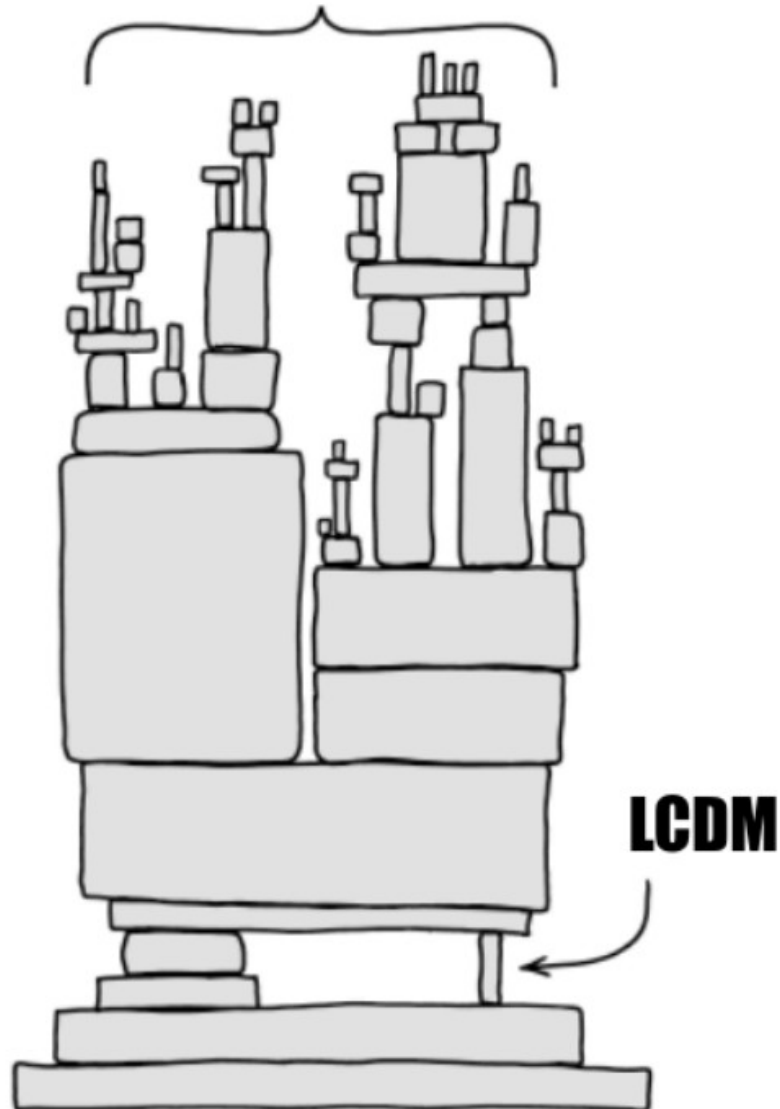
The H0 world cup

Part I

Crisis

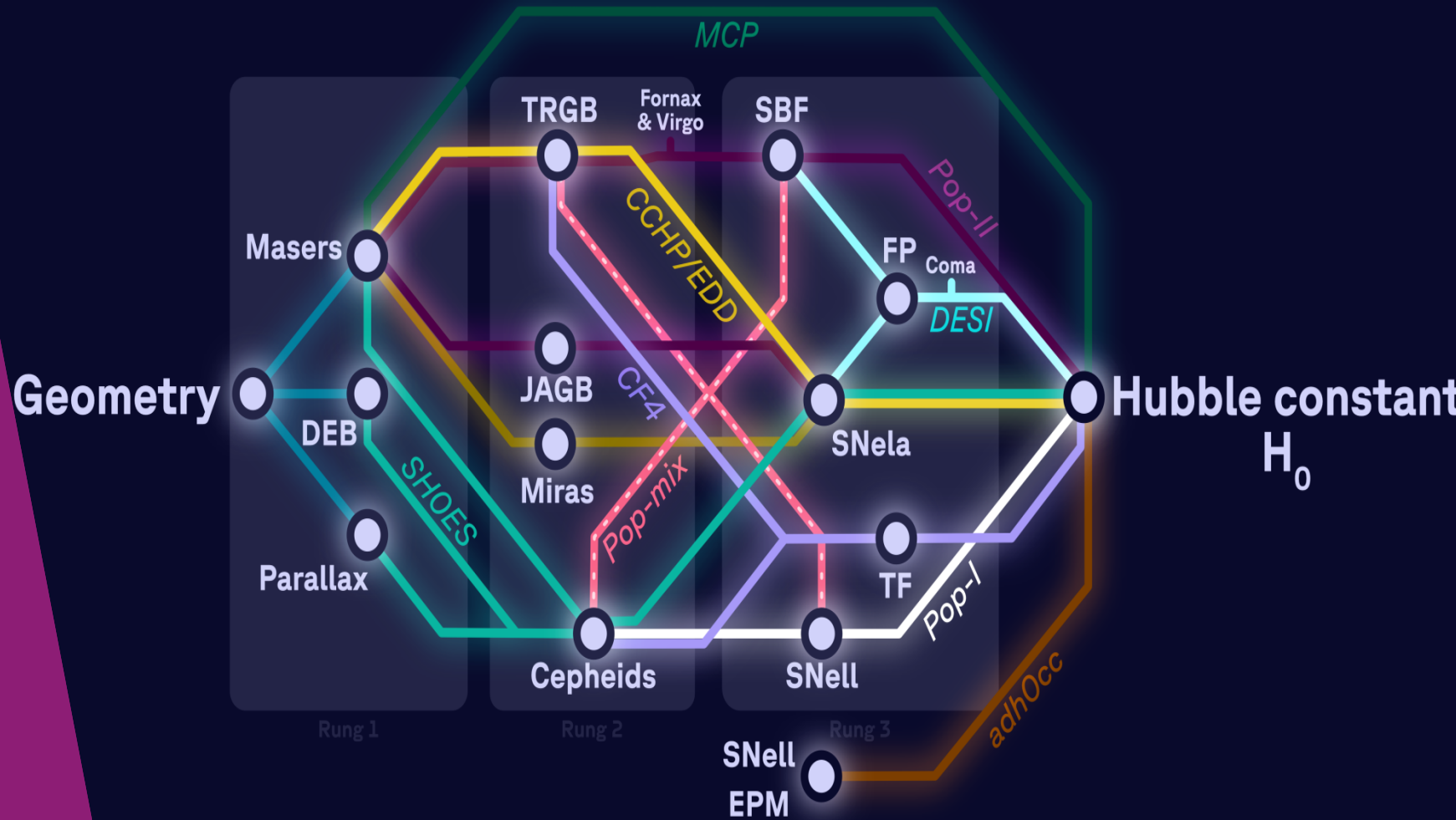


**Neutrino mass bounds, N_{eff} limits
Dark matter, Dark energy**



Crisis

$$H_0 = (73.5 \pm 0.8) \text{ km/s/Mpc}$$

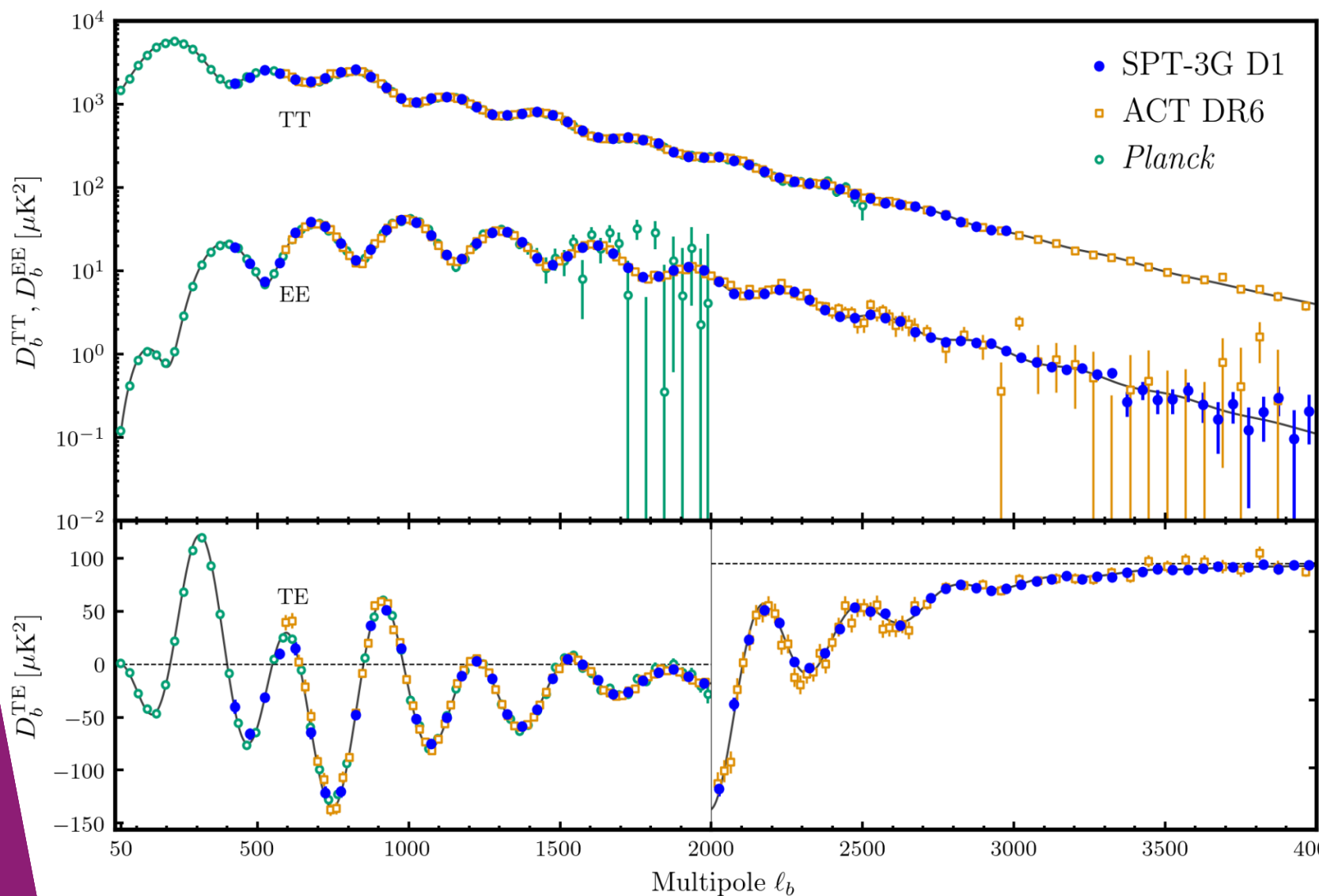


Crisis

Local Distance Network

Based on Casertano et al. (2025)
Graphic by Fabio Crameri, ISSI

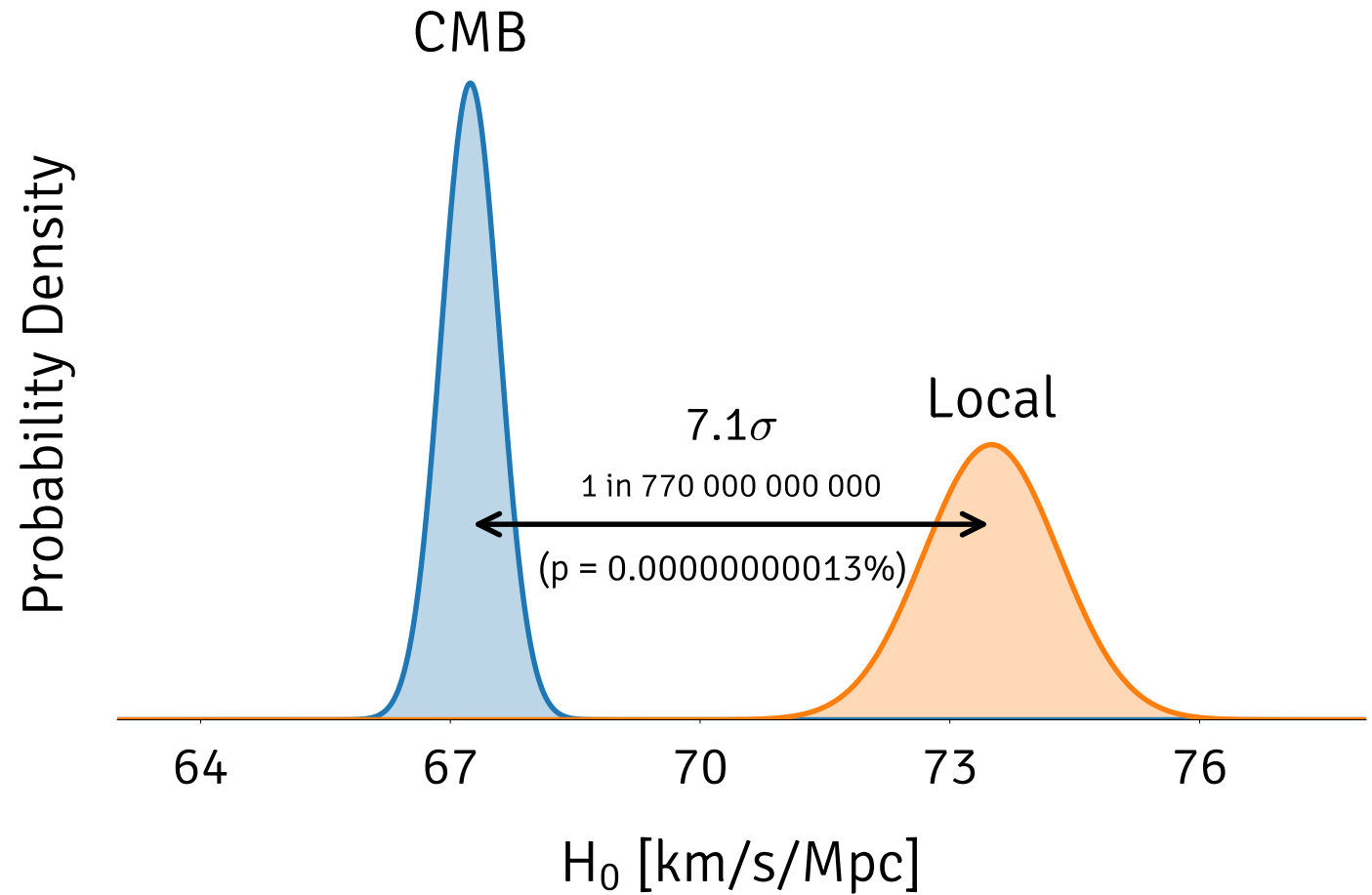
$$H_0 = (67.19 \pm 0.38) \text{ km/s/Mpc}$$



Crisis

also LSS+BBN

In Λ CDM:



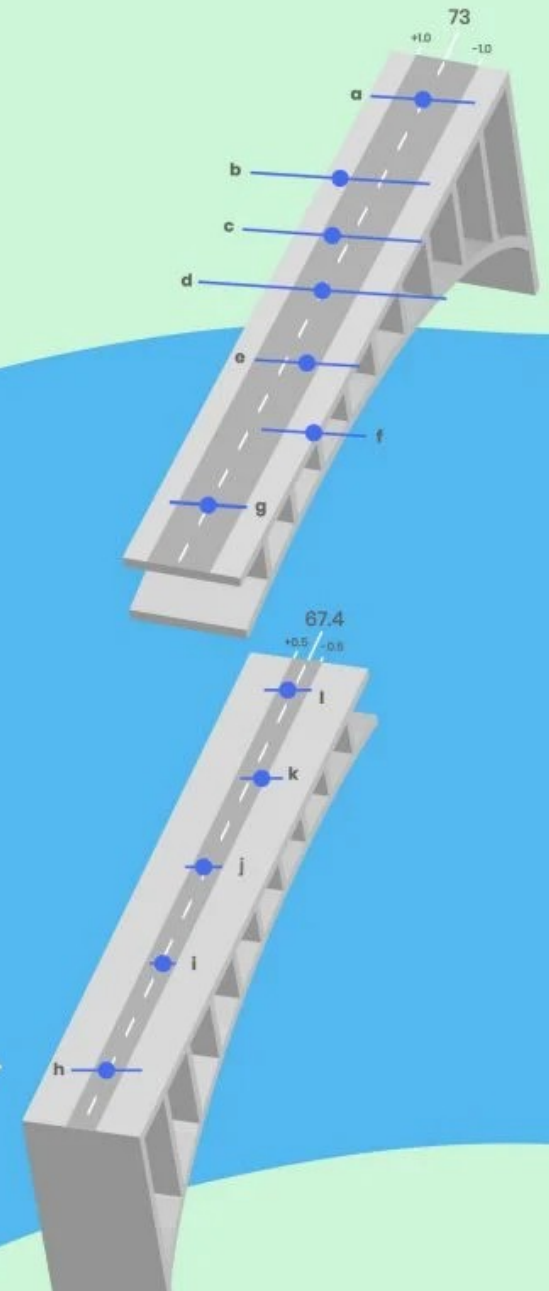
Crisis

Late Route

- a. Gravitational Lensing (H0LICOW)
- b. Surface Brightness Fluctuations in Galaxies
- c. Masers
- d. Mira variables
- e. Tip of Red Giant Branch 1
- f. Tip of Red Giant Branch 2
- g. Cepheid variables

Early Route

- h. Baryon Acoustic Fluctuation + Big Bang nucleosynthesis
- i. Cosmic Microwave Background (Planck)
- j. Wilkinson Microwave Anisotropy Probe (CMB) + Baryon Acoustic Oscillations
- k. Atacama Cosmology Telescope Polarimeter (CMB) + Baryon Acoustic Oscillations
- l. South Pole Telescope Sunyaev-Zel'dovich effect survey (CMB) + Baryon Acoustic Oscillations



Crisis

Late Route

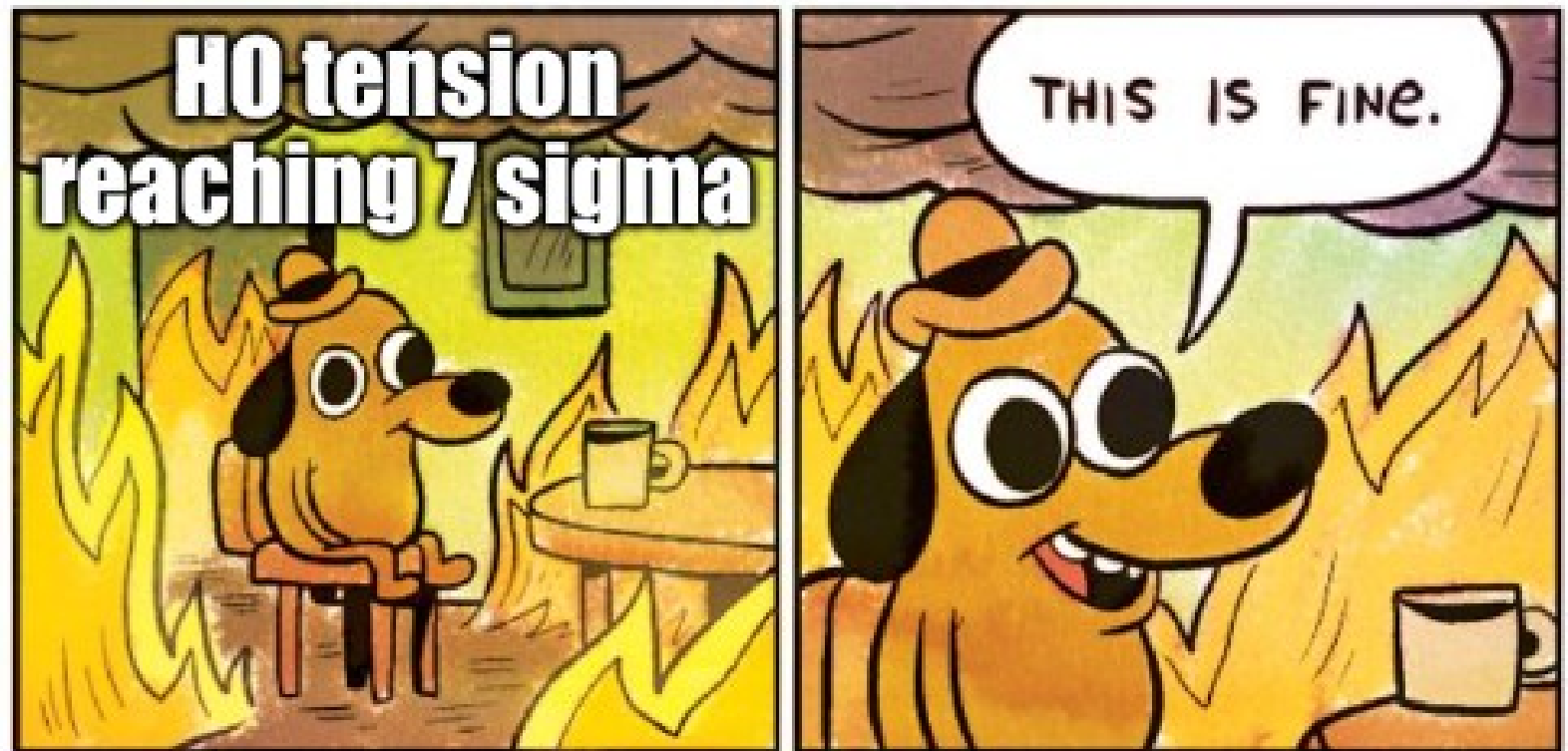
- a. Gravitational Lensing (H0LiCOW)
- b. Surface Brightness Fluctuations in Galaxies
- c. Masers
- d. Mira variables
- e. Tip of Red Giant Branch 1
- f. Tip of Red Giant Branch 2
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Early Route

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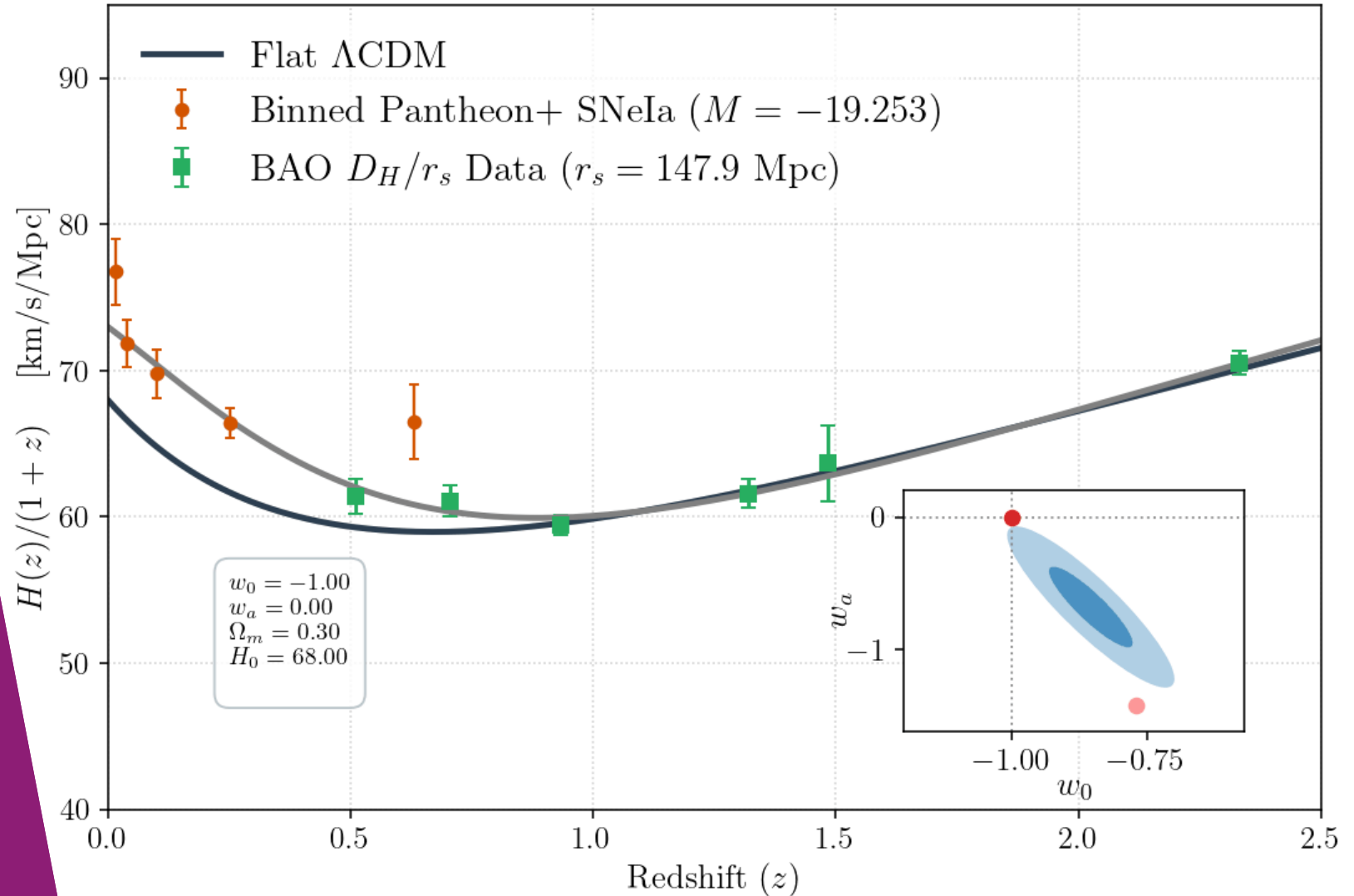


Crisis



Crisis

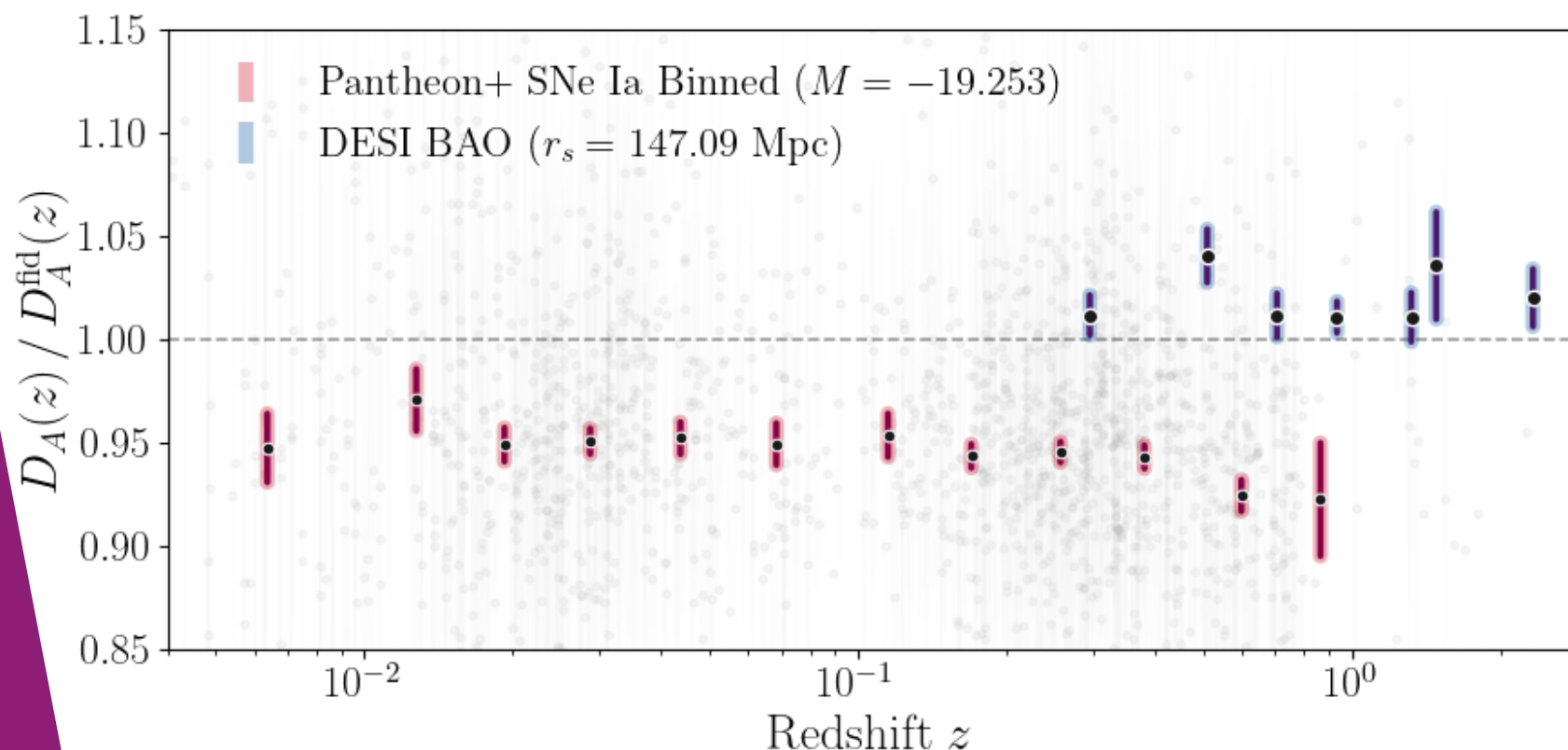
Evolution of $\frac{H(z)}{1+z}$ with w_0/w_a



Crisis

COSMIC CALIBRATOR TENSION

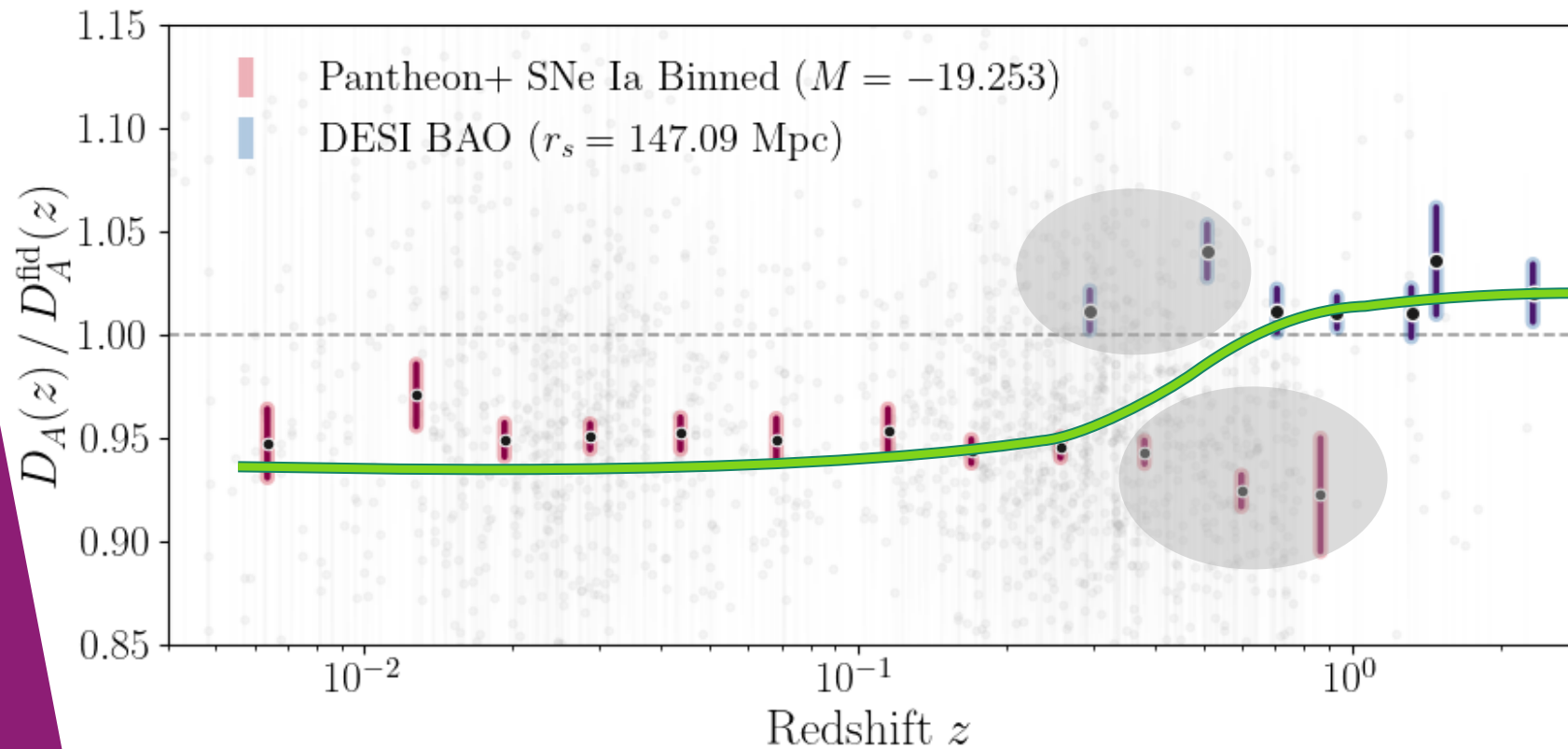
Idea by Poulin+2407.18292



Crisis

$$m - M + 25 - 10 \log_{10}(1 + z) = 5 \log_{10}(D_A[\text{Mpc}])$$

COSMIC CALIBRATOR TENSION



Crisis

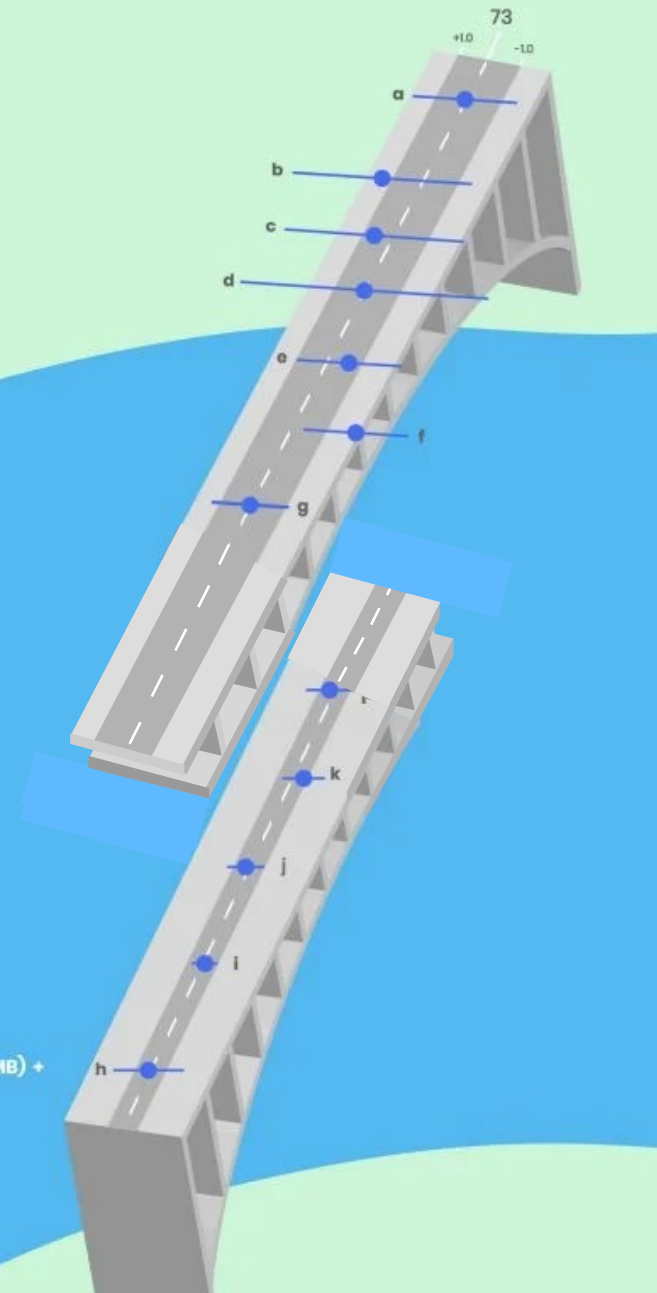
$$m - M + 25 - 10 \log_{10}(1 + z) = 5 \log_{10}(D_A[\text{Mpc}])$$

Late Route

- a. Gravitational Lensing (H0LiCOW)
- b. Surface Brightness Fluctuations in Galaxies
- c. Masers
- d. Mira variables
- e. Tip of Red Giant Branch 1
- f. Tip of Red Giant Branch 2
- g. Cepheid variables

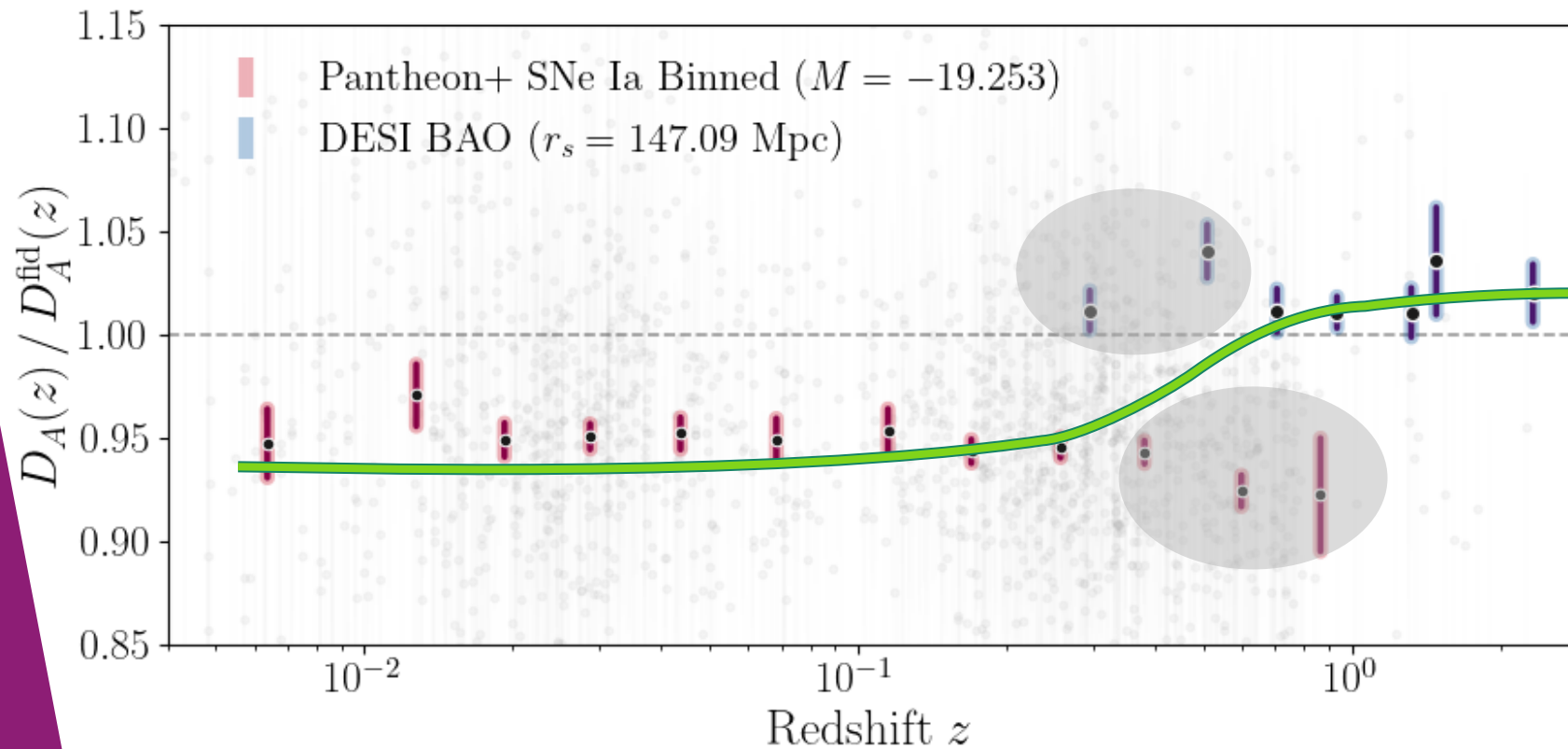
Early Route

- h. Baryon Acoustic Fluctuation + Big Bang nucleosynthesis
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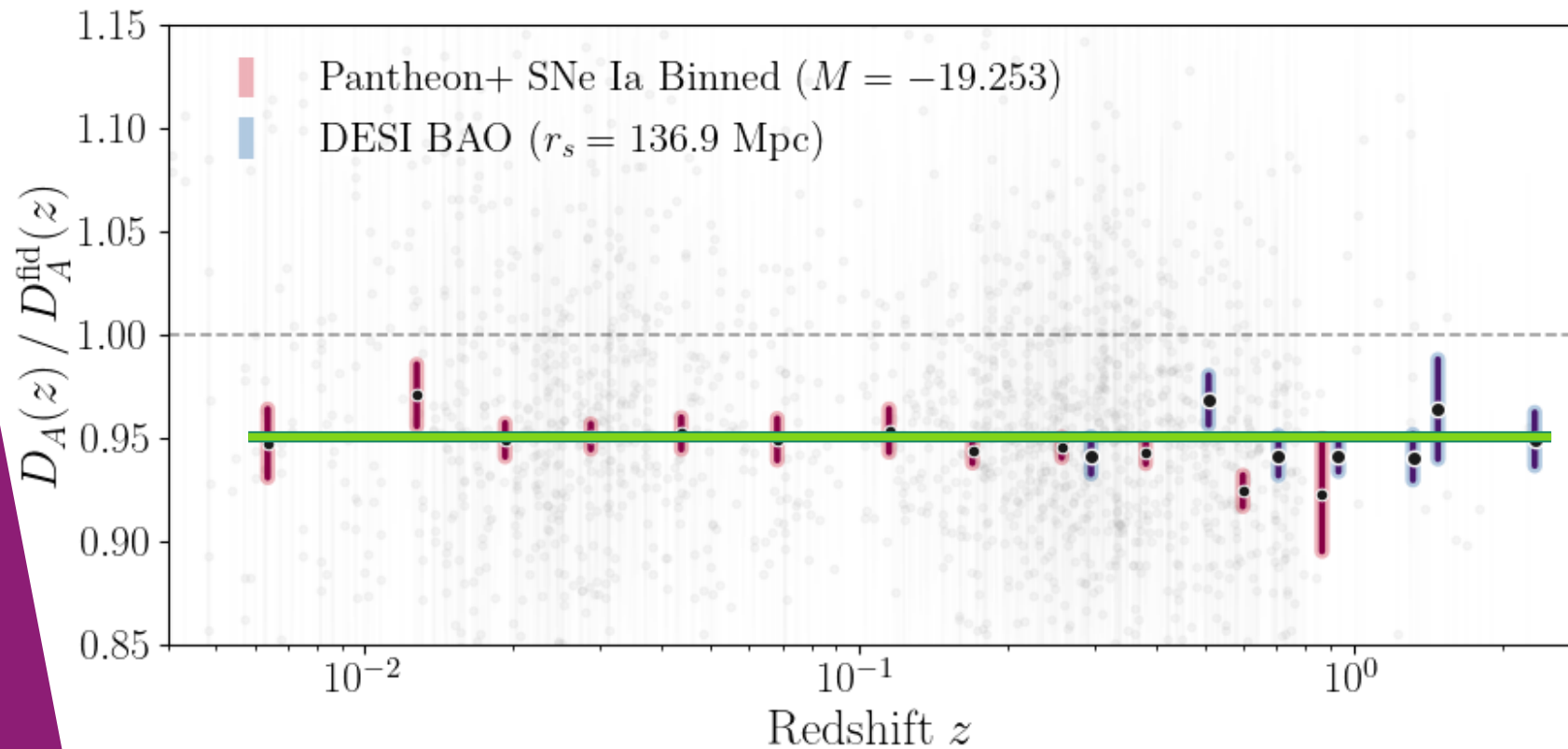
Crisis

COSMIC CALIBRATOR TENSION



Crisis

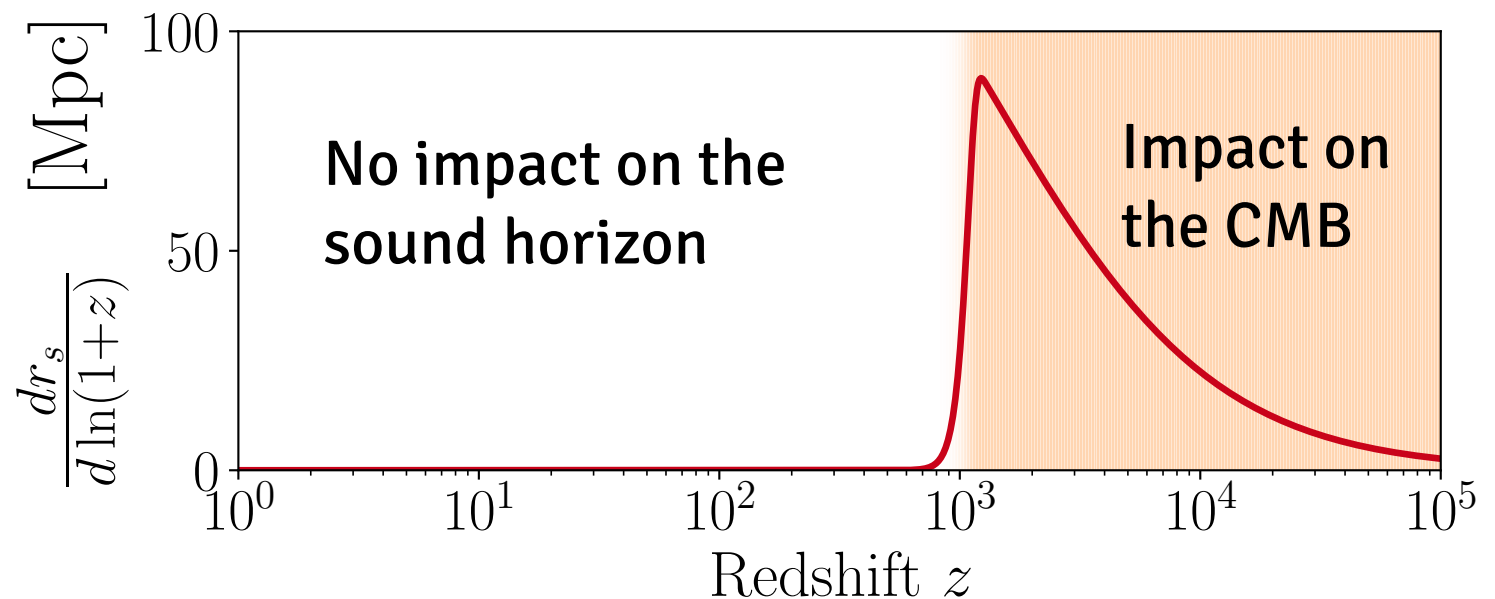
COSMIC CALIBRATOR TENSION



Crisis

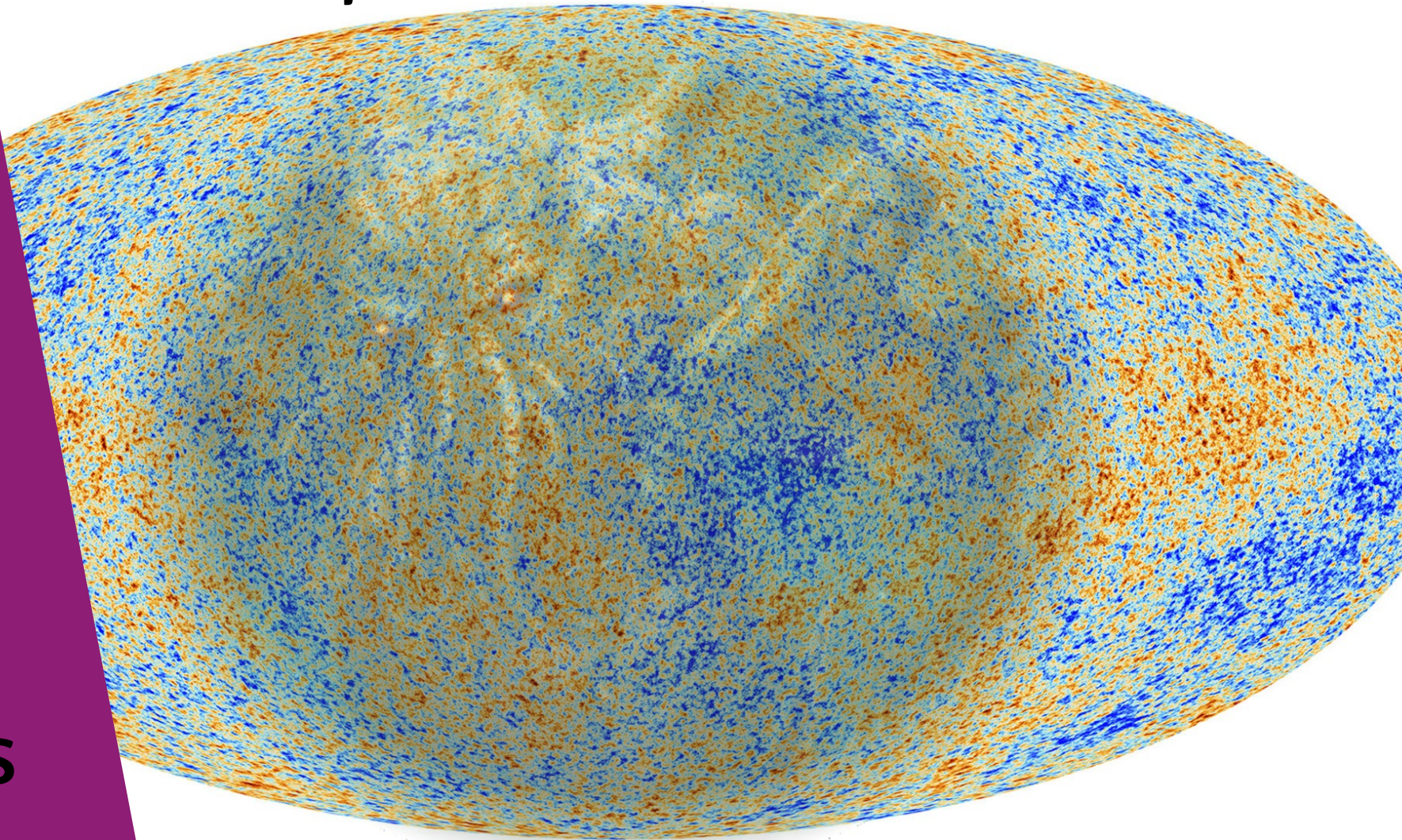
COSMIC CALIBRATOR TENSION

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z) dz}{H(z)}$$



Crisis

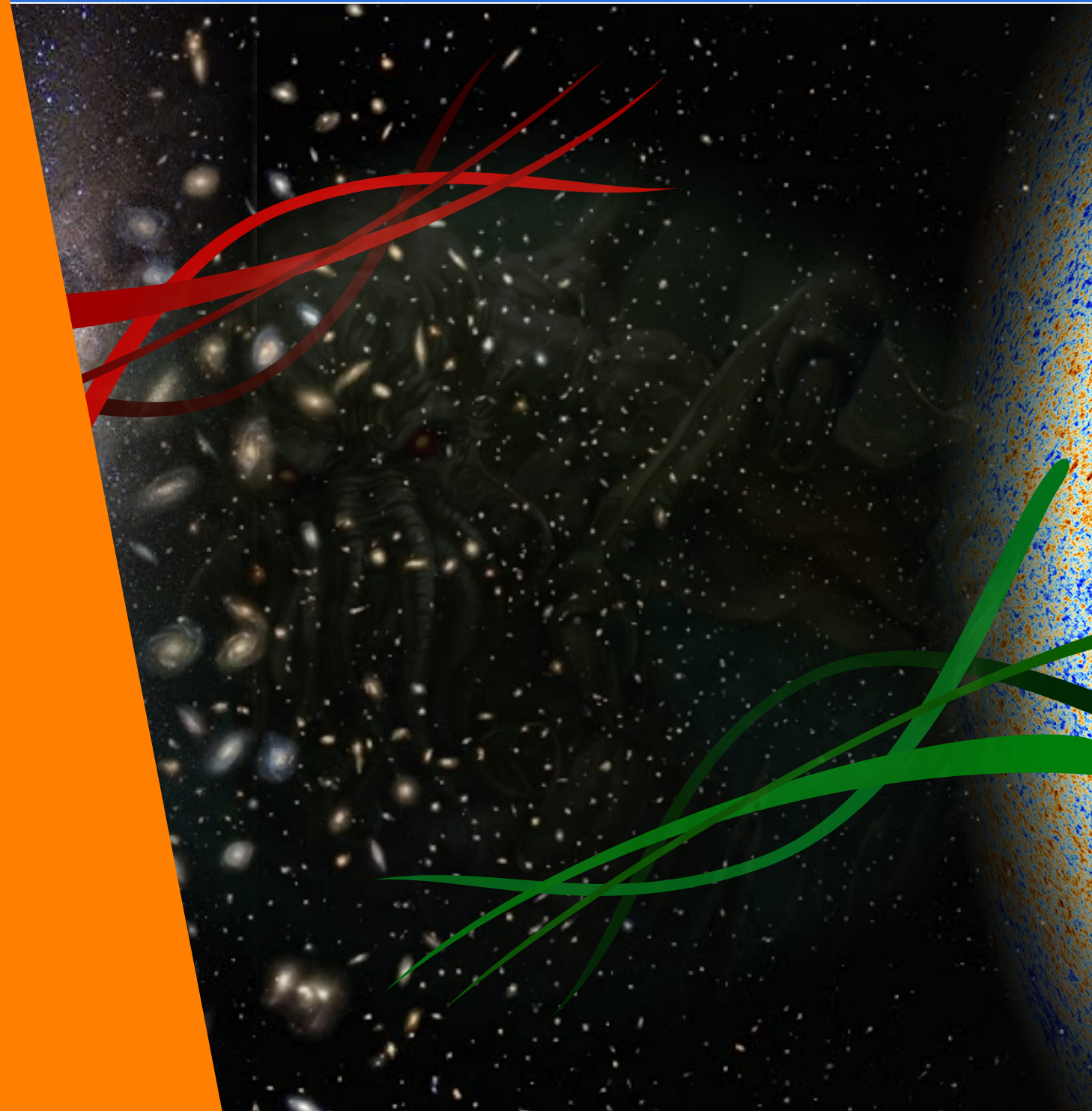
Trying to change r_s
provokes the beast !



Crisis

Part II

Models



ACDM

Aghanim et al. (2020), Planck 2018

Ade et al. (2016), Planck 2015

Anharmonic Oscillations

Poulin et al. (2019), Data A+R18

Ultra – Light Axions

Hill et al. (2020), Planck 2018; Data B+R19

Ivanov et al. (2020), Data C

D'Amico et al. (2020), Data B+FS

Chudaykin et al. (2020), Data D

Smith et al. (2020), Data A+R19 (n=3)

Smith et al. (2020), Data A+R19 (n=free)

Power – Law Potential

Chudaykin et al. (2020), Data D+S₈+R19

Rock 'n' Roll

D'Amico et al. (2020), Data B

Agrawal et al. (2019), Data E+R18

Early Dark Energy

Murgia et al. (2020), Planck 2018; Data F

New Early Dark Energy

Niedermann et al. (2020), Data B+R19

Anti – de Sitter phase

Ye et al. (2020), Data B+R19

Acoustic Dark Energy

Lin et al. (2020), Data B+ACT

Yin et al. (2020), Data B+R19

Lin et al. (2019), Data A+R19

EDE in α -attractors

Braglia et al. (2020), Data B+R19

PEDE

al. (2021), Planck 2018; Data A+R19

on et al. (2020), Planck 2015; Data B

Li et al. (2019), Data C

GEDE

Li et al. (2020), Planck 2018

MEDE

m et al. (2020), Planck 2018+BAO

VM

t et al. (2020), Planck 2018; Data D

entino et al. (2018), Planck 2015

VM (+neutrinos)

al. (2021), Planck 2018; Data D

VM – VEV

al. (2020), Planck 2018; Data D

tino et al. (2018), Planck 2015

(2021), Planck 2018; Data D

DiValentino+2103.01183

THE SOLUTIONS?

wCDM

Aghanim et al. (2020), Planck 2018 (95%); Data B

CPL parametrization

Aghanim et al. (2020), Planck 2018 (95%); Data B

wCDM+ $\alpha_s + N_{\text{eff}} + \Sigma m_\nu + A_s$

Di Valentino et al. (2020), Planck 2018; Data C

JBP parametrization

Yang et al. (2021), Planck 2018; Data C

BA parametrization

Yang et al. (2021), Planck 2018; Data C

One – parameter parametrization (model i)

Yang et al. (2019), Planck 2015; Data D+JLA

One – parameter parametrization (model iv)

Yang et al. (2019), Planck 2015; Data D+JLA

Metastable dark energy

Yang et al. (2020), Planck 2018; Data C+DES+R19

Phantom Crossing

Di Valentino et al. (2020), Data C

Late Dark Energy Transition

Benevento et al. (2020), Data E+R19

Running vacuum model

Solà et al. (2021), Data B+DES+RSD+CC+H₀ prior

Solà et al. (2017), Data F+R16

Bulk viscous models

da Silva et al. (2020), Data G

Yang et al. (2019), Planck 2015+Pantheon

Holographic Dark Energy

Colgáin et al. (2021), Data B

Dai et al. (2020), Data C+R19

Guo et al. (2018), Data F+JLA+R16

Holographic Dark Energy (+neutrinos)

Guo et al. (2018), Data F+JLA+R16

Tsallis Holographic Dark Energy

da Silva et al. (2020), Data G

Swampland Conjectures

Agrawal et al. (2019), Data H+R19

Late time transitions in the quintessence field

Di Valentino et al. (2019), Planck 2015

Phantom Braneworld Dark Energy

Alam et al. (2016), Data D+Union 2.1

IVS ($Q = H\dot{\xi}\rho_{DE}$)

Di Valentino et al. (2020), Planck 2018; Data A+R19

Kumar et al. (2019), Planck 2015 TT; Data B+R16

Kumar et al. (2017), Data C+JLA

IVS ($Q = 3H\dot{\xi}\rho_{DE}$)

Yang et al. (2020), Planck 2018; Data A

Coupled Scalar Field ($Q = \beta\rho_{DM}\dot{\phi}$)

Gómez-Valent et al. (2020), Planck 2018; Data D+R19

Coupled Scalar Field ($Q = r/(1-r\phi)\rho_{DM}\dot{\phi}$)

An et al. (2019), Planck 2015

IDE with constant DE EoS ($Q = H\dot{\xi}\rho_{DE}$)

Di Valentino et al. (2020), Planck 2018; Data E+R19

IDE with constant DE EoS ($Q = \delta H\rho_{DM}$)

Di Valentino et al. (2017), Planck 2015

IDE with constant DE EoS ($Q = 3H\dot{\xi}(1+w_{DE})\rho_{DM}$)

Kumar et al. (2016), Data C+JLA

IDE with constant DE EoS ($Q = 3H\dot{\xi}(1+w_{DE})(\rho_{DM}+\rho_{DE})$)

Yang et al. (2018), Planck 2015; Data C+JLA+CC

IDE with constant DE EoS ($Q = 3H\dot{\xi}(1+w_{DE})(\rho_{DM}+\rho_{DE})$)

Yang et al. (2018), Planck 2015; Data C+JLA+CC

Non – linear IDE with constant DE EoS

Pan et al. (2020), Planck 2018; Data A+R19

Three – form IDE with constant DE EoS

Yang et al. (2020), Data A+JLA

DM – Photon Couplin

Yadav (2019), Planck 2015 +BA

Kumar et al. (2018), Data

DM – Baryon Couplin

Becker et al. (2020), Data

DE – Baryon Couplin

Jimenez et al. (2020), Data

Self – interacting neutrino

Forastieri et al. (2019), Planck 201

Lancaster et al. (2017), Planck 2015; Data

Self – interacting neutrinos (strong)

Roy Choudhury et al. (2020), Planck 2018 (95%); Data E (95%)

Das et al. (2020), Planck 2018; Data

Kreisch et al. (2020), Planck 201

Self – interacting neutrinos (moderate)

Roy Choudhury et al. (2020), Planck 2018 (95%); Data E (95%)

Das et al. (2020), Planck 2018; Data

Kreisch et al. (2020), Planck 201

Self – interacting sterile neutrino

Archidiacono et al. (2020), Planck 2018; Data

Dark Neutrino Interaction

Ghosh et al. (2019), Data

ACDM + N_{eff}

Aghanim et al. (2020), Planck 2018; Data A

Ade et al. (2016), Planck 2015

Sterile neutrinos

Carneiro et al. (2019), Data B+R16

Neutrino Asymmetries

Barenboim et al. (2017), Planck 2015+BKP

Thermal Axions

D'Eramo et al. (2018), Data C (95%)

Decaying dark matter

Blinov et al. (2020), Planck 2018+CMB lensing; Data D

Pandey et al. (2020), Planck 2015+R18

Decaying dark matter (long – lived)

Nygaard et al. (2020), Planck 2018 (95%); Data C (95%)

Xiao et al. (2020), Data E

Decaying dark matter (short – lived)

Nygaard et al. (2020), Planck 2018 (95%); Data C (95%)

Xiao et al. (2020), Data E

Self – interacting Dark Matter (long – lived)

Hryczuk et al. (2020), Data F

Self – interacting Dark Matter (short – lived)

Hryczuk et al. (2020), Data F

Two – body dark matter decays

Clark et al. (2020), Planck 2018+CMB lensing (95%)

Neutrino – DM interaction

Vattis et al. (2019), Data G+R18

Neutrino – Majoron interaction

Di Valentino et al. (2018), Planck 2015

Interacting Dark Radiation

Escudero et al. (2020), Data D

DM – Dark Radiation coupling

Becker et al. (2020), Data C

Decaying Ultralight Scalar

Archidiacono et al. (2019), Data E

Aghanim et al. (2020), Planck 2018

Ade et al. (2016), Planck 2015

Generalized Chaplygin gas model

Yang et al. (2018), Planck 2015

A new unified model

Yang et al. (2018), Planck 2015

Λ(t)CDM

tti et al. (2021), Data A+CMB lensing+JLA+BBN

tti et al. (2019), Planck 2015 TT+JLA+BBN+R19

f(R) gravity

Vang (2020), Planck 2018+CMB lensing; Data B

f(T) gravity (exponential)

Wang et al. (2020), Planck 2018

Hashim et al. (2020), BAO+Pantheon+BBN+R20

Hashim et al. (2020), Planck 2018; data C

f(T) gravity (power law)

Wang et al. (2020), Planck 2018

Nunes (2018), Planck 2015+BAO

f(T, B) gravity (power law)

Escamilla-Rivera et al. (2020), BAO+Pantheon+CC

f(T, B) gravity (mixed power law)

Escamilla-Rivera et al. (2020), BAO+Pantheon+CC

Brans–Dicke ACDM

Solà et al. (2020), Data D

Solà et al. (2019), Data E+R19

Scalar–tensor theories of gravity (IG)

Ballardini et al. (2020), Planck 2018+CMB lensing; Data F

Rossi et al. (2019), Planck 2015 TT+CMB lensing+BAO

Scalar–tensor theories of gravity (conformal coupling)

Ballardini et al. (2020), Planck 2018+CMB lensing; Data F

Rossi et al. (2019), Planck 2015 TT+CMB lensing+BAO

Scalar–tensor gravity with varied G_N

Ballesteros et al. (2020), Planck 2018+BAO

Early modified gravity

Abadi et al. (2021), Planck 2018

Braglia et al. (2021), Data A+BAO+Pantheon+FS+H0LiCOW

Über gravity

Moshafi et al. (2020), Planck 2018; Data A+CMB lensing

Khosravi et al. (2019), Planck 2015 TT+BAO+R16

Galileon gravity

Heisenberg et al. (2020), Data A+BAO+Pantheon

Zumalacarregui et al. (2020), Planck 2018+BAO

Frusciante et al. (2020), Planck 2015 TT (95%); Data G

Peirone et al. (2019), Planck 2015 TT (95%); Data G (95%)

Renk et al. (2017), Planck 2015 TT+CMB lensing+BAO

Nonlocal gravity

Belgacem et al. (2020), Planck 2018+BAO+Pantheon

Belgacem et al. (2018), Planck 2015+BAO+JLA

Unimodular gravity

Linares Cedeño et al. (2020), Data H+R19

VCDM

De Felice et al. (2020), Planck 2018+BAO+Pantheon

IVS with variable coupling (model A)

Yang et al. (2019), Planck 2015

IVS with variable coupling (model B)

Yang et al. (2019), Planck 2015

IDE with variable coupling (model A)

Yang et al. (2020), Planck 2018; Data A (95%)

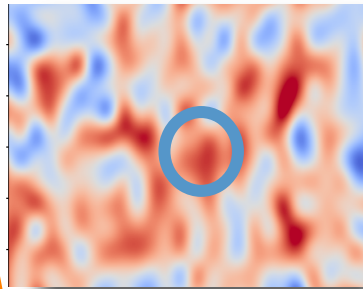
IDE with variable coupling (model B)

Yang et al. (2020), Planck 2018 (95%); Data A (95%)

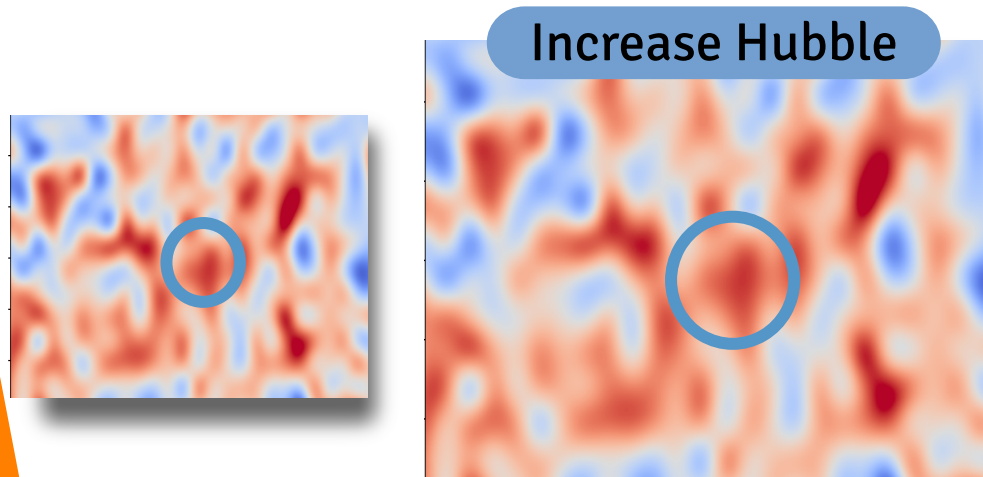
IDE with sign – changing interaction

Pan et al. (2019), Data C

Anisotropic Stress in IDE



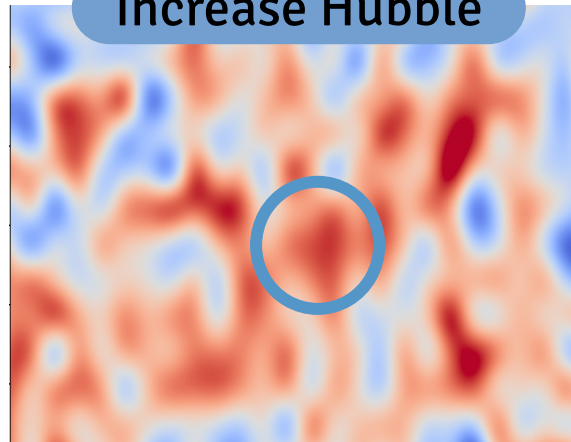
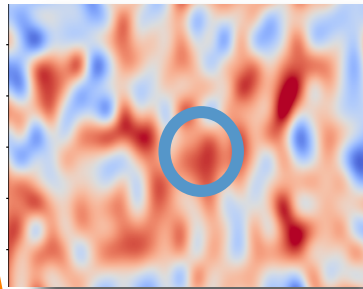
Models



$$\theta_s \propto H_0$$

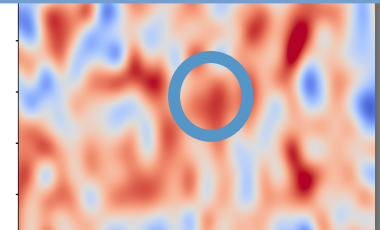
Models

Increase Hubble



$$\theta_s \propto H_0$$

Restore distance



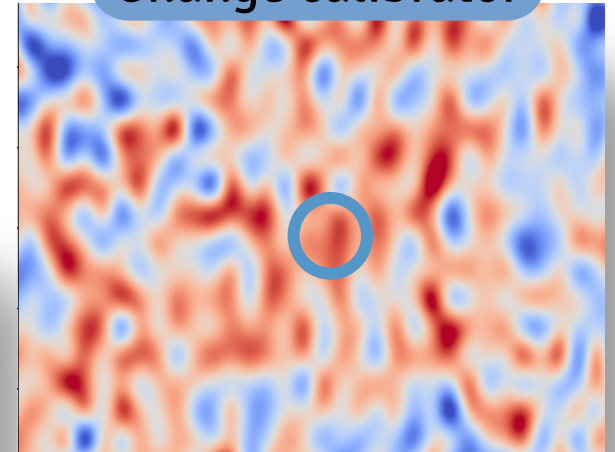
$$\theta_s \propto H_0 f(\Omega_{\text{DE}}(z))$$

Group L (unlikely)

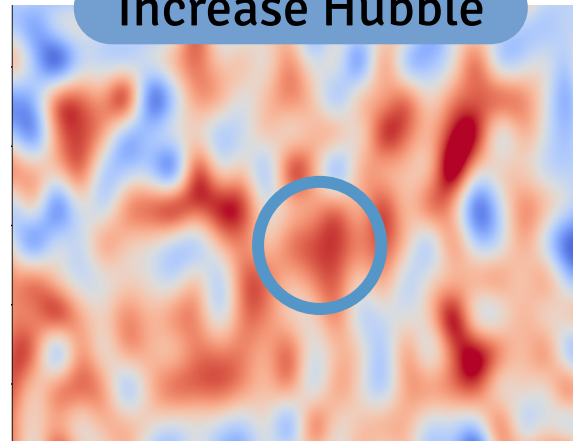
Models

$$\theta_s \propto H_0 \cdot r_s$$

Change calibrator

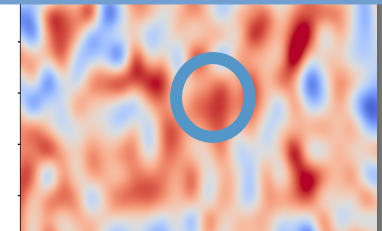


Increase Hubble



$$\theta_s \propto H_0$$

Restore distance



$$\theta_s \propto H_0 f(\Omega_{\text{DE}}(z))$$

Group L (unlikely)

Models

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z) dz}{H(z)}$$

Models

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z) dz}{H(z)}$$

Modified recombination (group M)

Models

$$r_s = \int_{z_*}^{\infty} \frac{\cancel{c_s(z)} dz}{H(z)}$$

Modified recombination (group M)

Models

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z) dz}{H(z)}$$

Modified recombination (group M)

Radiation solutions (group R)

$$H(z) \propto \sqrt{\rho_m + \rho_{\text{rad}}}$$

Models

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z) dz}{H(z)}$$

Modified recombination (group M)

Radiation solutions (group R)

Other early $H(z)$ solutions (group E)

$$H(z) \propto \sqrt{\rho_m + \rho_{\text{rad}} + \rho_{\text{early}}}$$

Models

GROUP M: MOD. RECOMBINATION

- Fundamental constants $\rightarrow m_e^{\text{early}} / m_e^{\text{late}}$

$$z_* \propto E_{\text{binding}}^{\text{Hydrogen}} = \frac{1}{2} m_e \alpha^2$$

Talk on *next Monday* about group M solutions!

Models

GROUP M: MOD. RECOMBINATION

- Fundamental constants $\rightarrow m_e^{\text{early}} / m_e^{\text{late}}$

$$z_* \propto E_{\text{binding}}^{\text{Hydrogen}} = \frac{1}{2} m_e \alpha^2$$

- Primordial magnetic fields $\rightarrow \langle n_e^2 \rangle > \langle n_e \rangle^2$

$$z_*^{\text{inhomog}} > z_*^{\text{vanilla}}$$

2307.05475

2312.11448

2404.03655

2506.16517

Models

GROUP M: MOD. RECOMBINATION

- Fundamental constants $\rightarrow m_e^{\text{early}} / m_e^{\text{late}}$

$$z_* \propto E_{\text{binding}}^{\text{Hydrogen}} = \frac{1}{2} m_e \alpha^2$$

- Primordial magnetic fields $\rightarrow \langle n_e^2 \rangle > \langle n_e \rangle^2$

$$z_*^{\text{inhomog}} > z_*^{\text{vanilla}}$$

2307.05475

2312.11448

2404.03655

2506.16517

- Free-form reconstruction

2404.05715, 2411.16678

Models

GROUP R: RADIATION

- Free-streaming

$$\Delta N_{\text{eff}}$$

Models

GROUP R: RADIATION

- Free-streaming $\rightarrow$ shear, ν drag, BBN

$$\Delta N_{\text{eff}}$$

Models

GROUP R: RADIATION

- Free-streaming $\rightarrow$ shear, ν drag, BBN

$$\Delta N_{\text{eff}}$$

- Self-interacting

$$\Delta N_{\text{eff}}^{\text{SIDR}}$$

Models

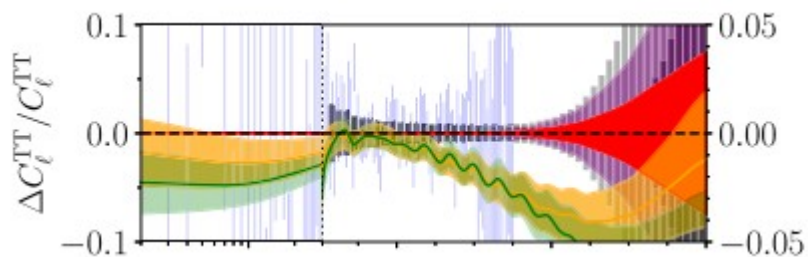
GROUP R: RADIATION

- Free-streaming $\rightarrow$ shear, ν drag, BBN

$$\Delta N_{\text{eff}}$$

- Self-interacting $\rightarrow$ large L suppress, BBN

$$\Delta N_{\text{eff}}^{\text{SIDR}}$$



Models

GROUP R: RADIATION

- Free-streaming

$$\Delta N_{\text{eff}}$$

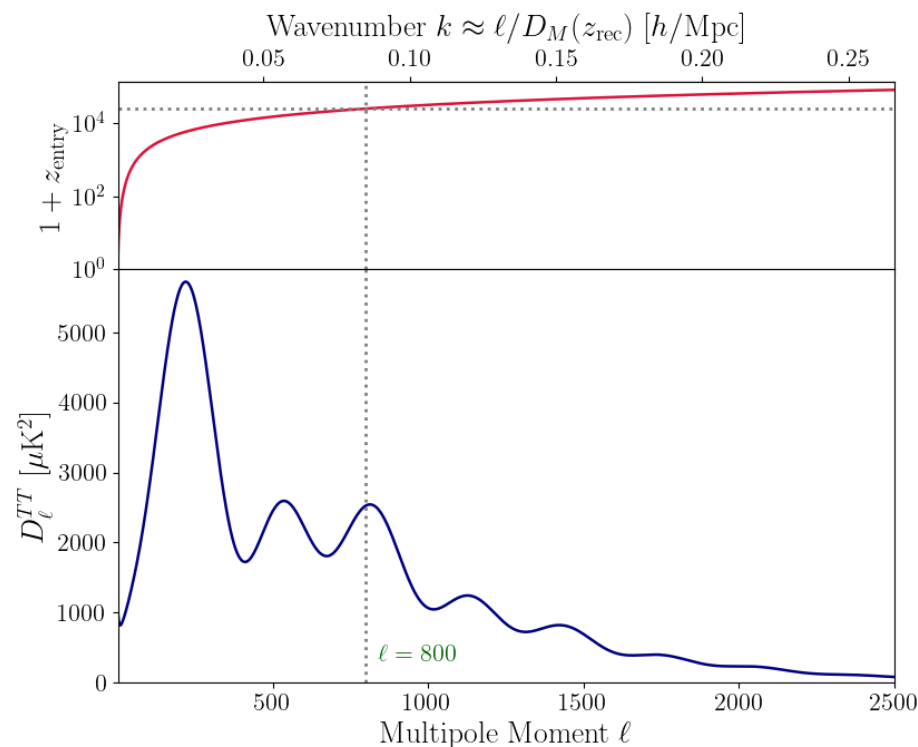
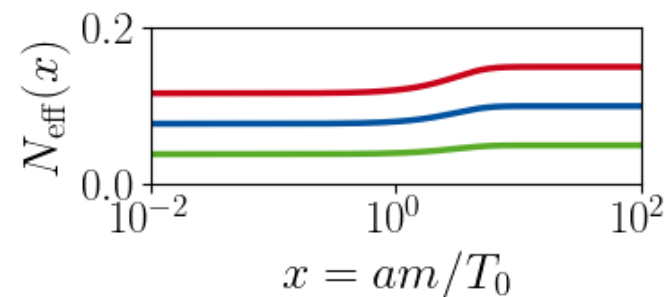
- Self-interacting

$$\Delta N_{\text{eff}}^{\text{SIDR}}$$

- Wess-Zumino

$$\Delta N_{\text{wzdr}}$$

Models



GROUP R: RADIATION

- Free-streaming $\rightarrow$ shear, ν drag, BBN

$$\Delta N_{\text{eff}}$$

- Self-interacting $\rightarrow$ large L suppress, BBN

$$\Delta N_{\text{eff}}^{\text{SIDR}}$$

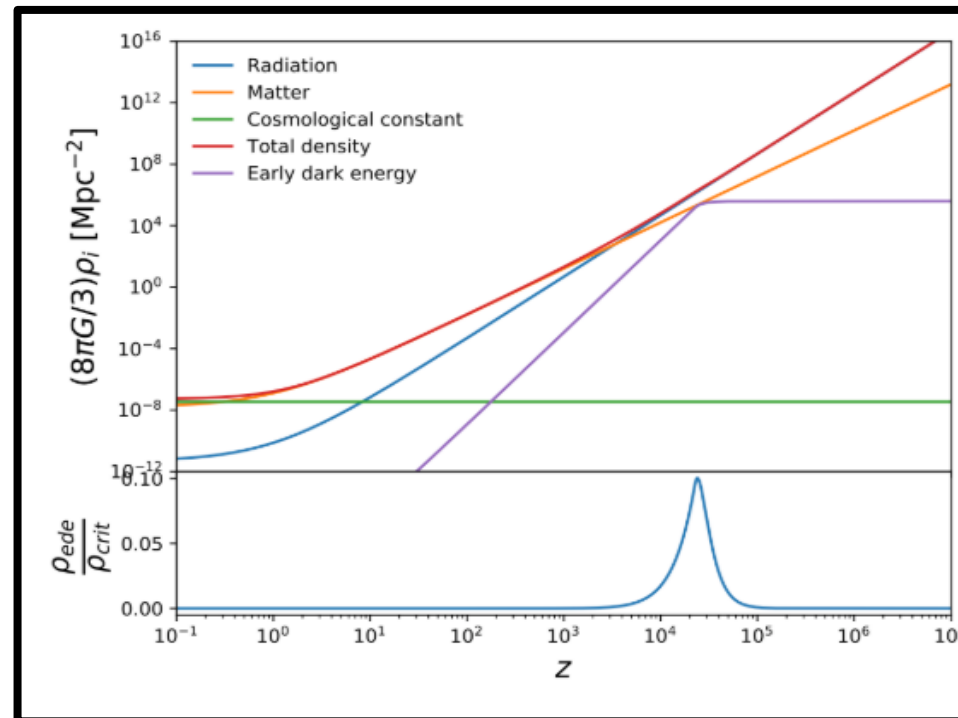
- Wess-Zumino $\rightarrow$ some large L, BBN

$$\Delta N_{\text{wzdr}}$$

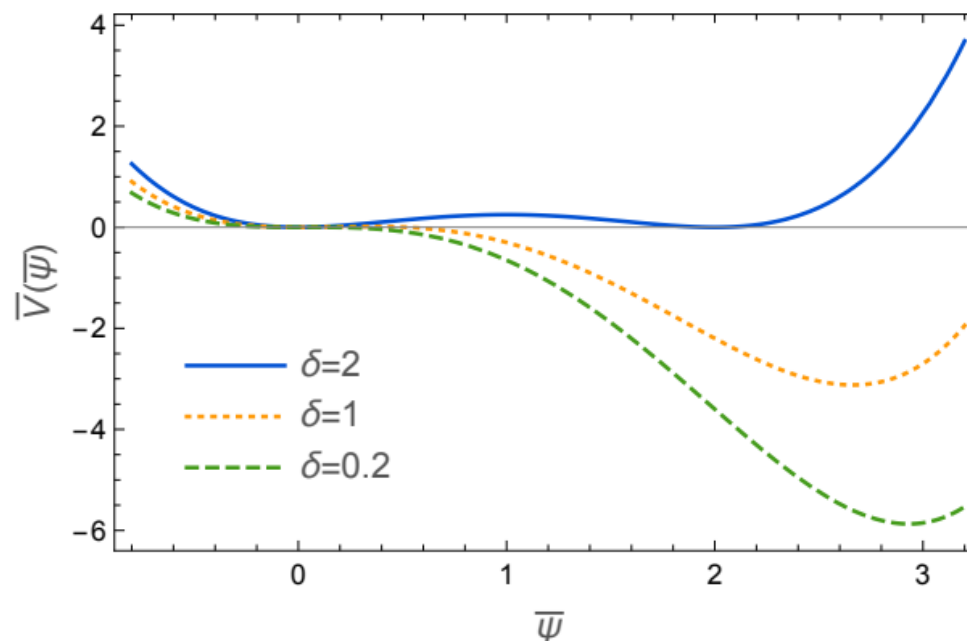
Models

GROUP E: EARLY

- Axion early dark energy → fine-tuning,
Lagrangian $V_n(\Theta) = m^2 f^2 [1 - \cos(\Theta)]^n$,



Models

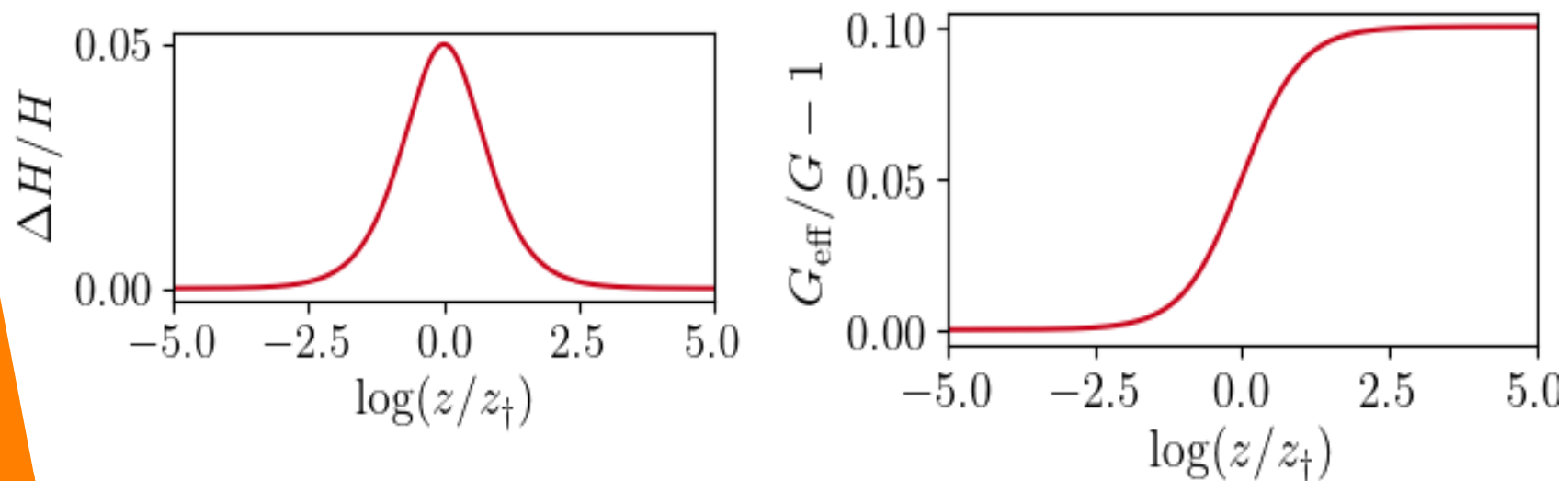


- Cold New Early Dark Energy → fine-tuning

$$V(\psi, \phi) = \frac{\lambda}{4}\psi^4 + \frac{\beta}{2}M^2\psi^2 - \frac{\alpha}{3}M\psi^3 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\tilde{\lambda}\phi^2\psi^2$$

Models

GROUP E: EARLY



- Early Modified gravity $\rightarrow$ fine-tuning
EMG (+RnR)

Models

GROUP L: LATE

- Sign-switching cosm. constant

$$\Lambda \rightarrow -\Lambda$$

- Dark Matter Dark Energy interactions

$$Q \propto \xi H \rho_{\text{de}}$$

- Removing EE reionization constraints

Allali+2503.05691

Sailer+2504.16932

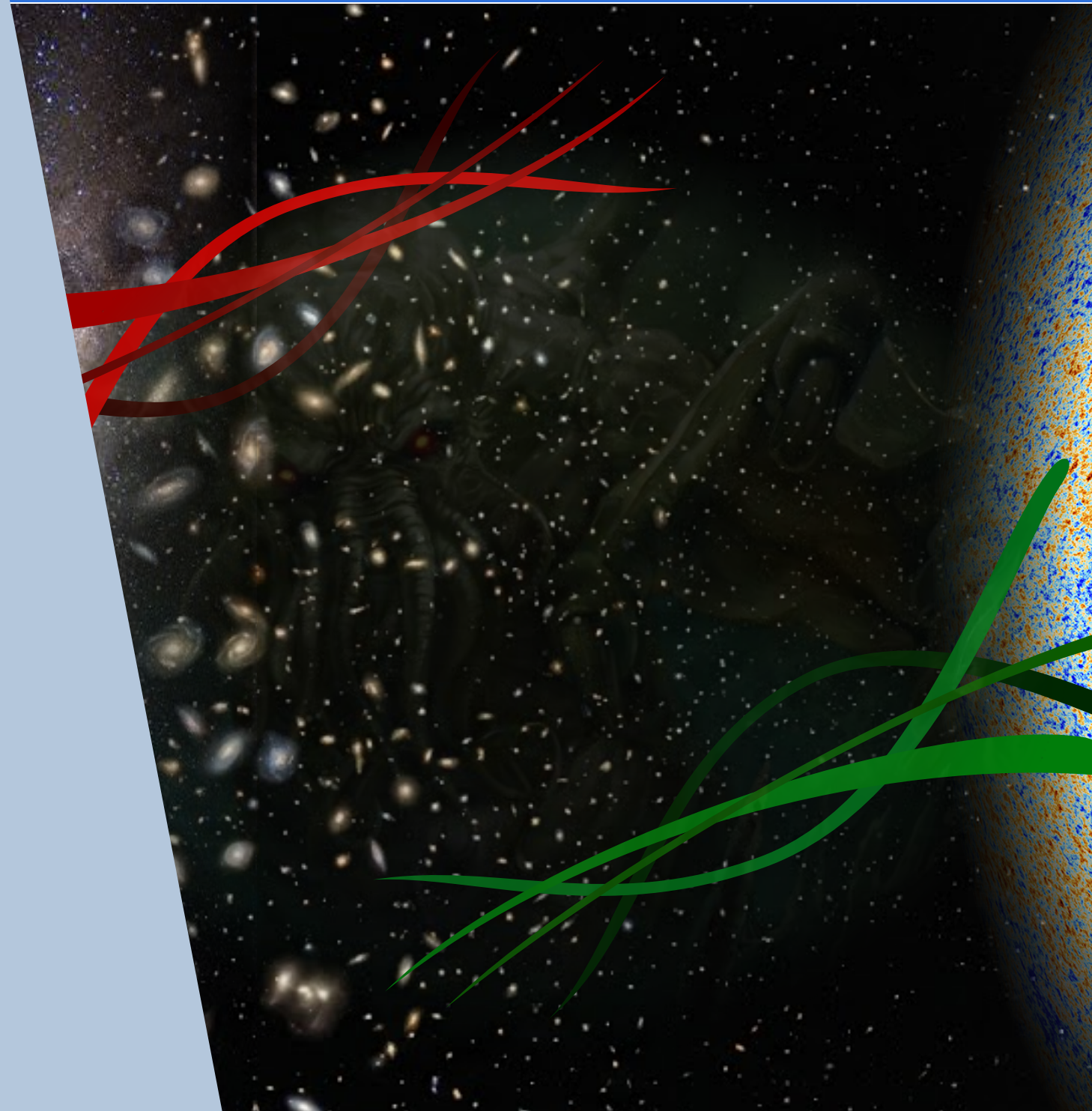
Jhaveri+2504.21813

Allali+2509.09678

Models

Part III

Results



Goodness of fit

VS

Tension reduction

Results

Goodness of fit

How well does the model
fit joint CMB + ... and SH0ES data?

VS

How well does the model
reduce the tension of CMB + ... vs SH0ES data?

Tension reduction

Results

Goodness of fit

Fits well but no tension reduction →
tension remains

VS

Reduces tension but no good fit
(e.g. $\Omega_m h^2 = 0.11$) → excluded by data

Tension reduction

Results

Goodness of fit

Frequentist: ΔAIC , Bayesian: Bayes Factor

VS

Frequentist: Δ_{DMAP} , Bayesian: Δ_{shift}

Tension reduction

Results

Old H_0 olympics (2021):

Group M + curvature



Group E
Group R (best)



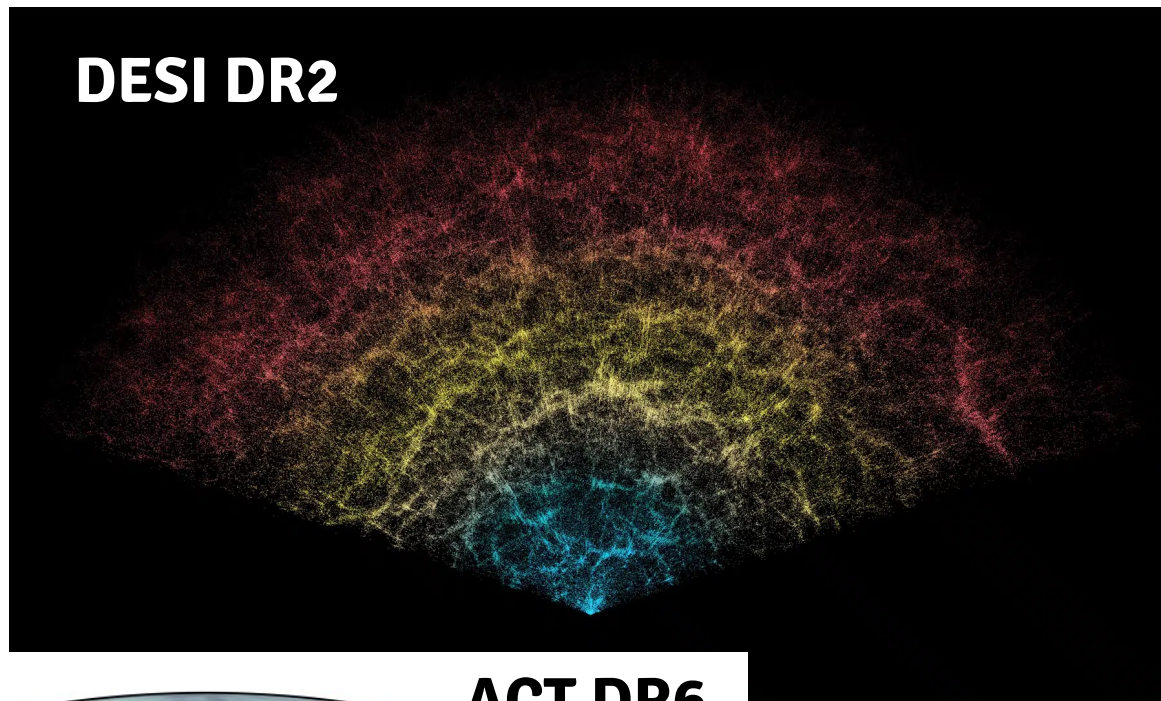
Groups M+R (rest)



Results

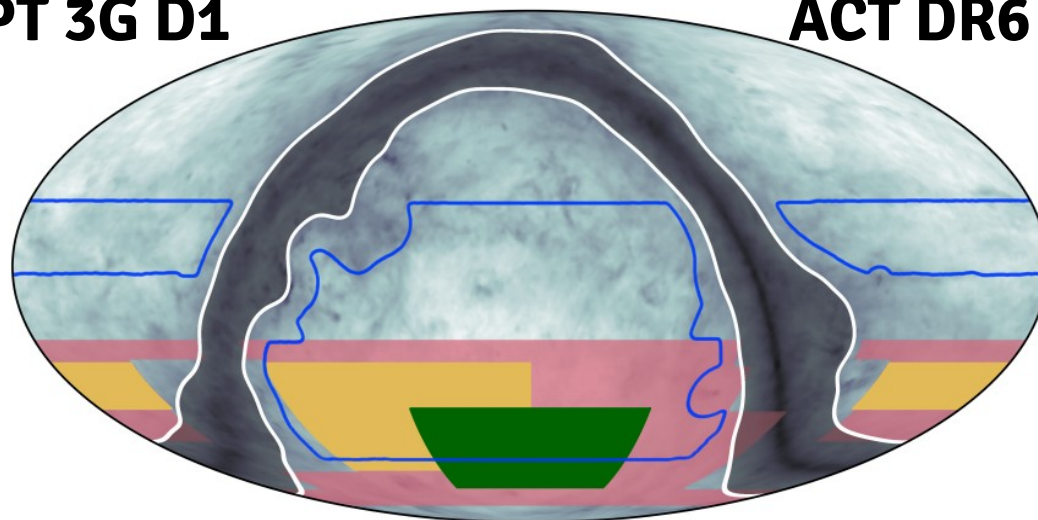
+ new
models

DESI DR2



SPT 3G D1

ACT DR6



+ new
variations

+ free Σm_ν

Results

■ SPT-3G Main (this work)
■ Planck galactic mask

■ SPT-3G Summer
— ACT DR6

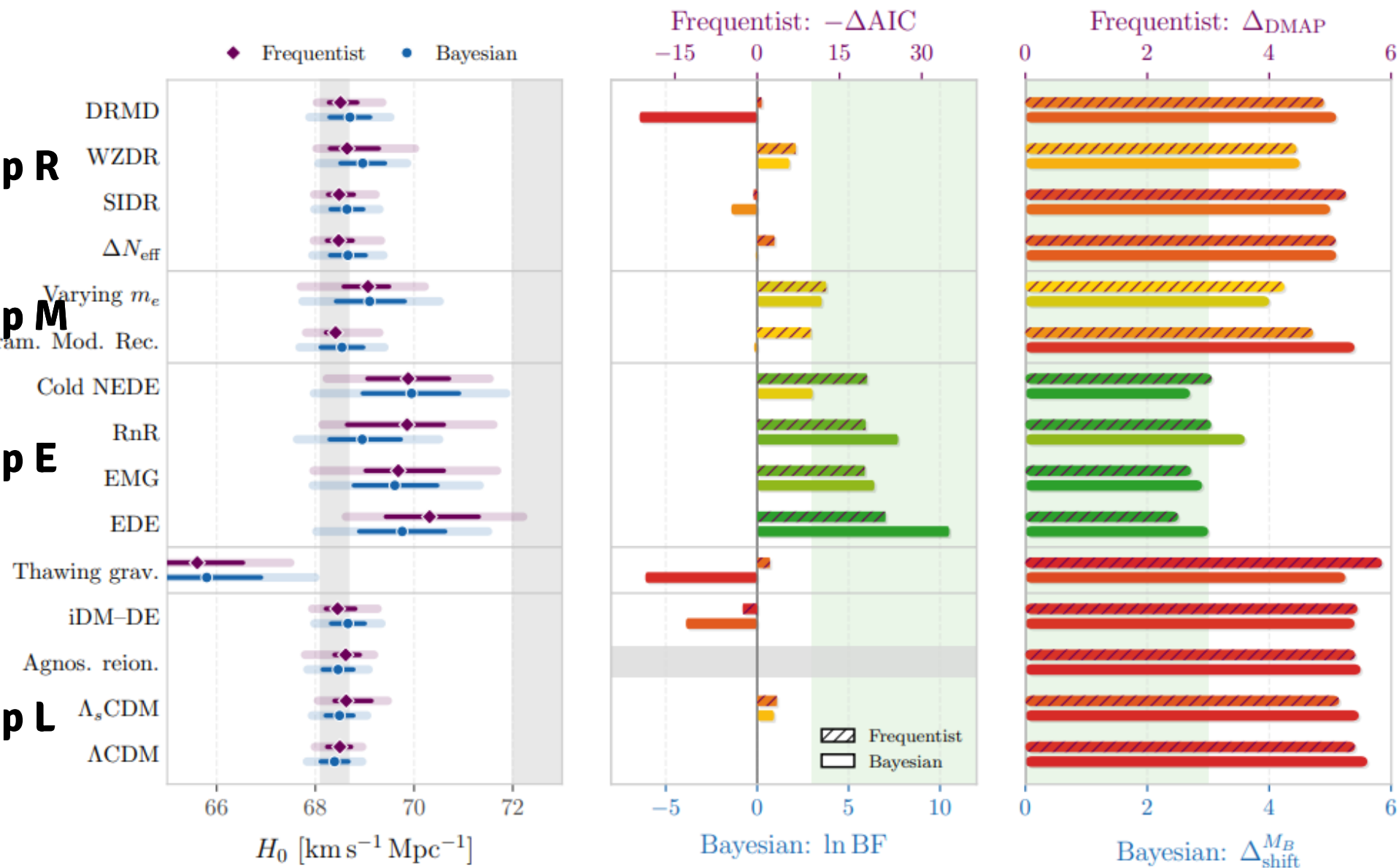
■ SPT-3G Wide

Group R

Group M

Group E

Group L



Group E



Group M

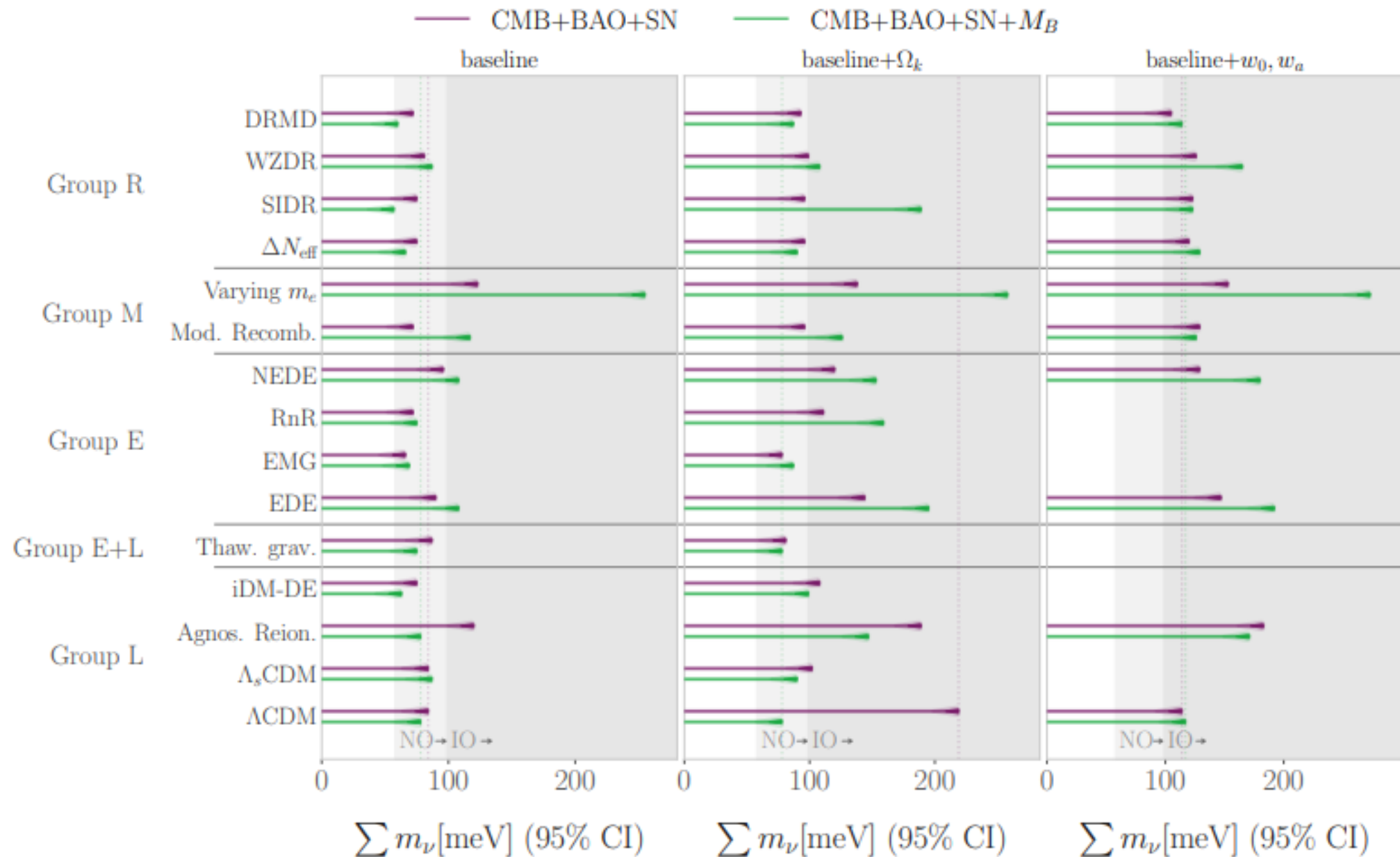


Group R (best)

Groups M+R (rest)

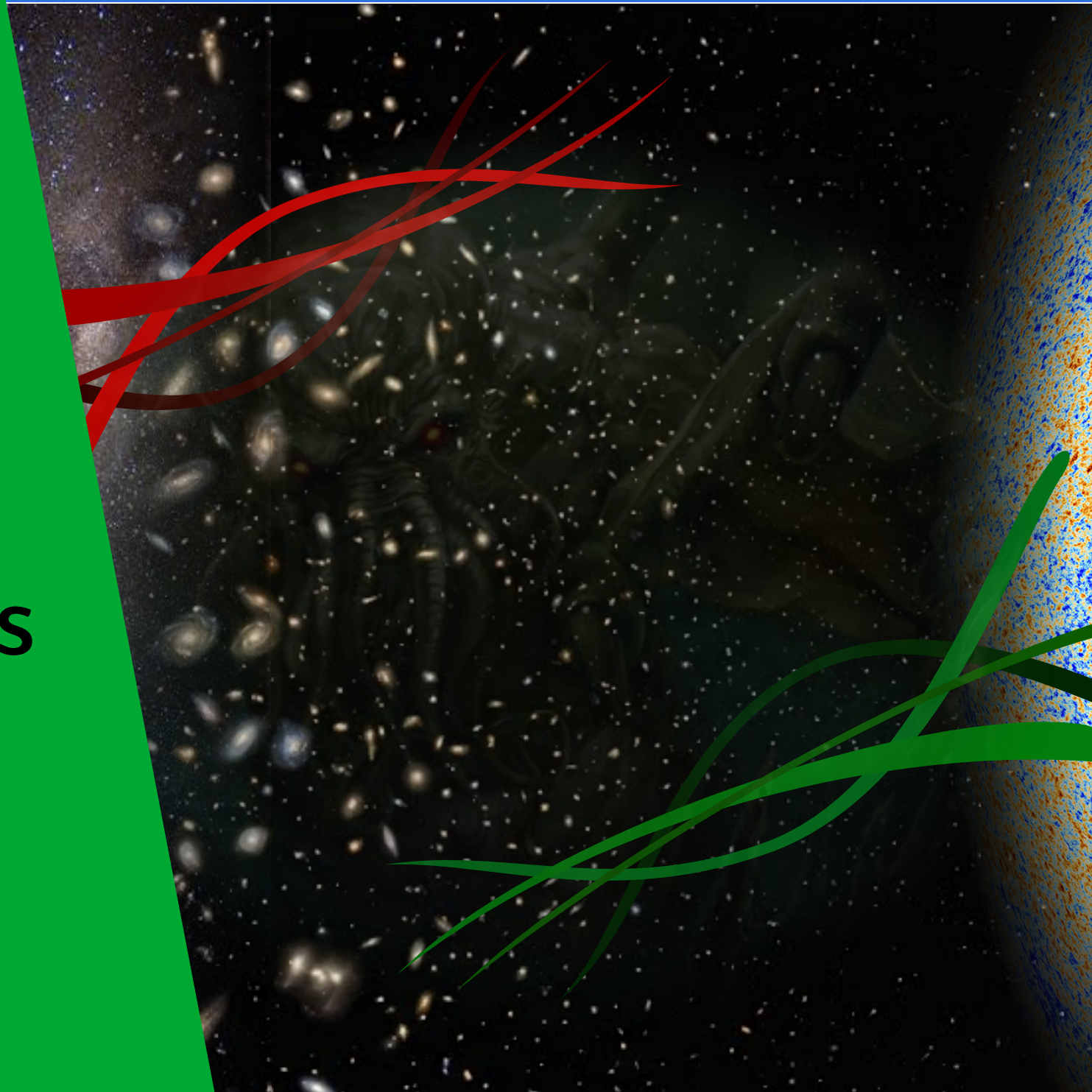


Results



Part III

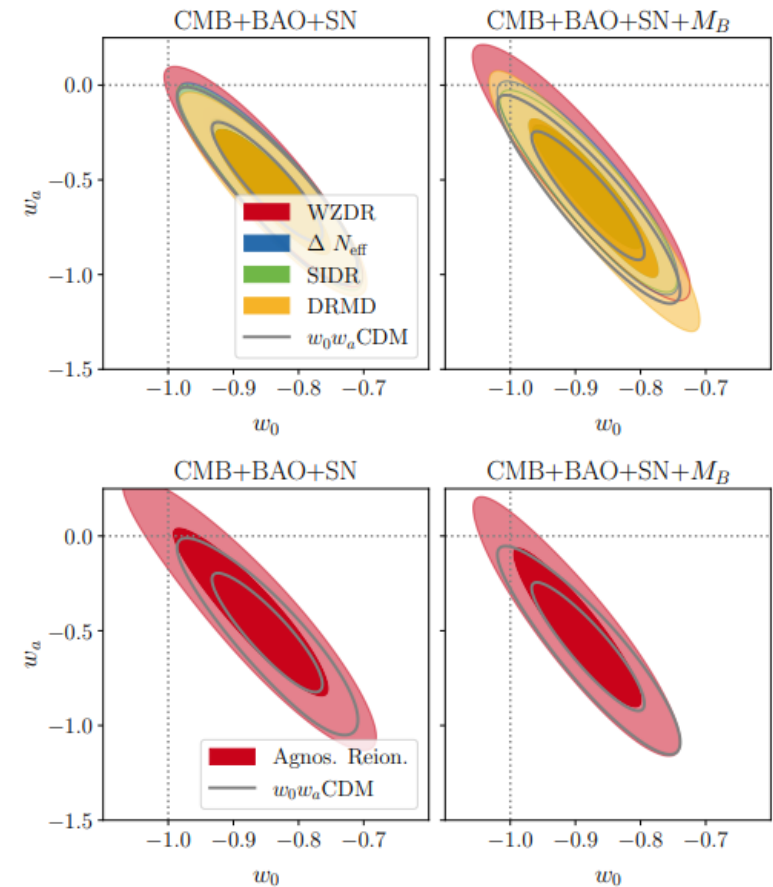
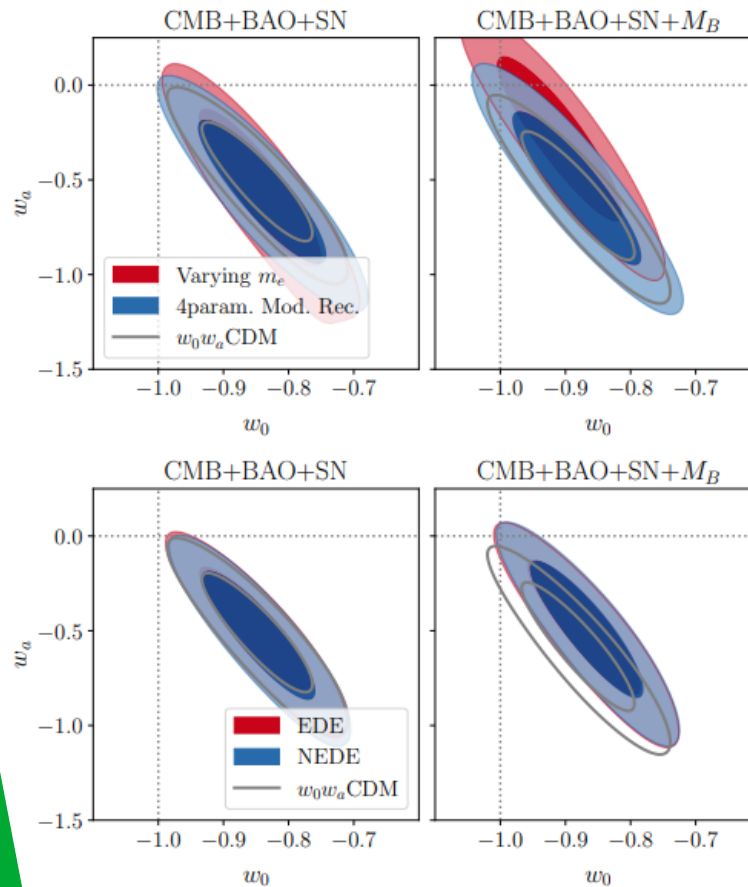
Variations



CPL DARK ENERGY

Group M

Group R



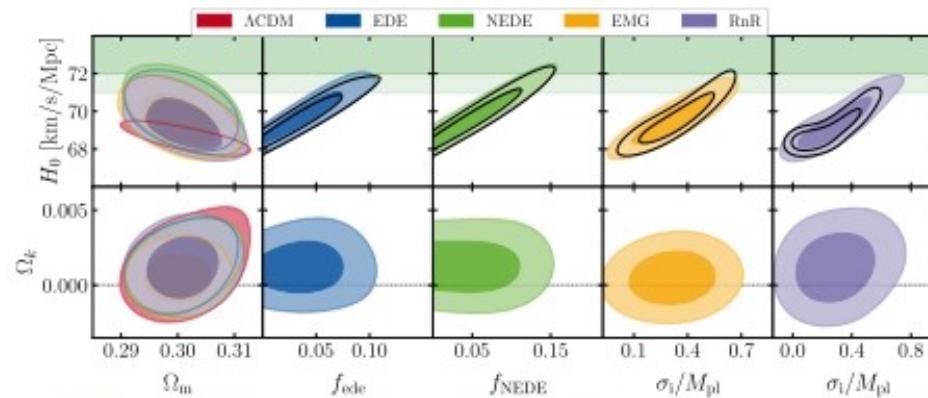
Group E

Group L

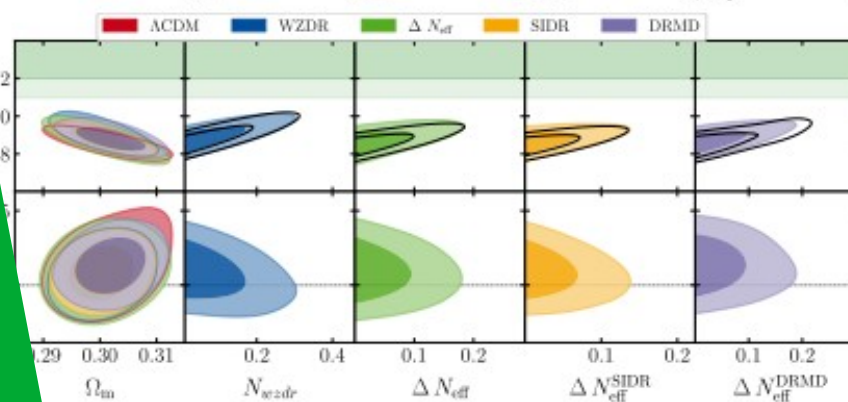
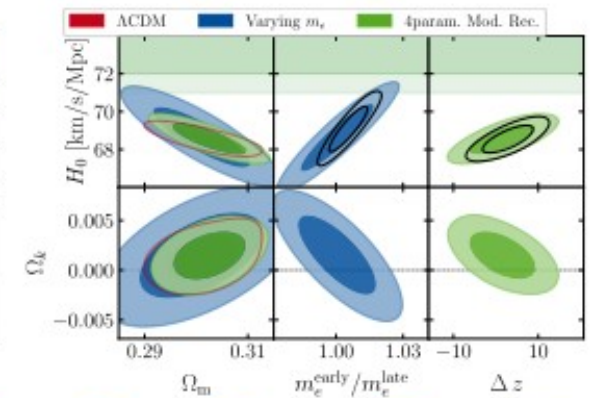
Variation

CURVATURE : IMPACT ONLY FOR M

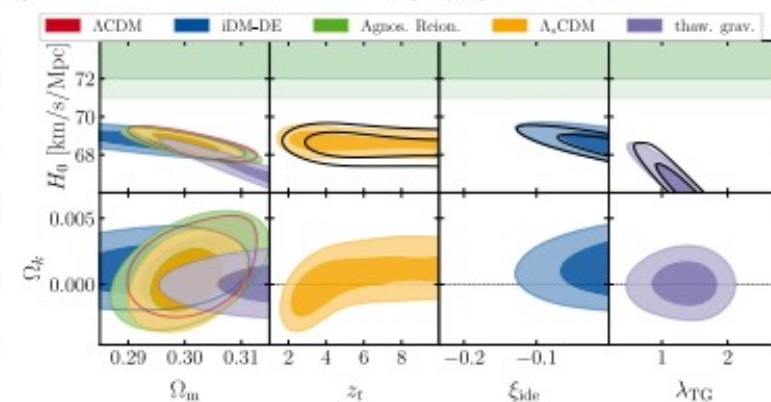
Group E



Group M



Group R

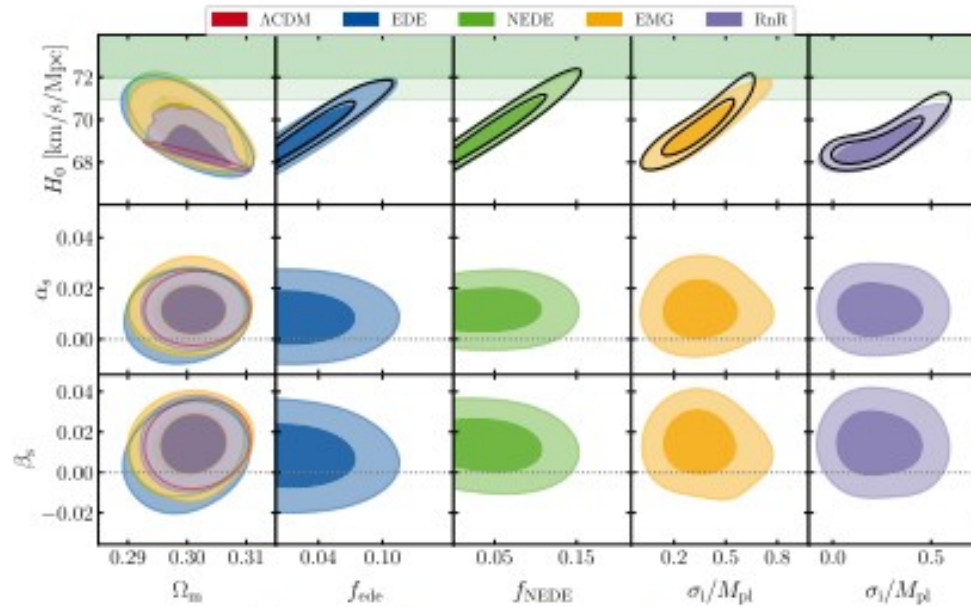


Group L

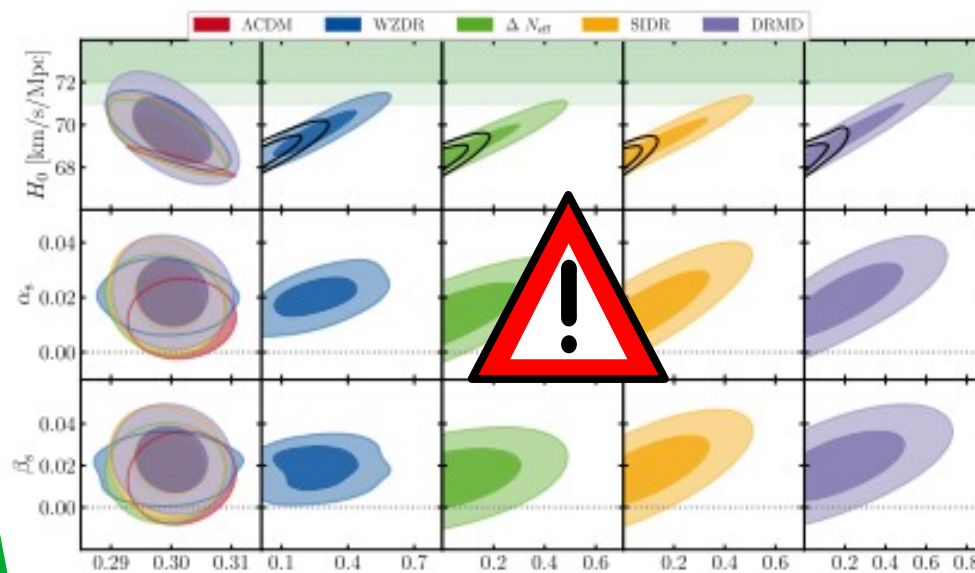
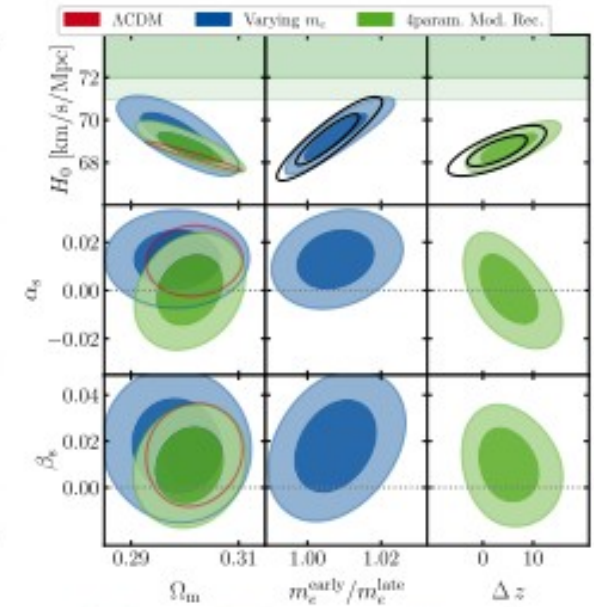
Variation

More on Why? → Talk next Monday

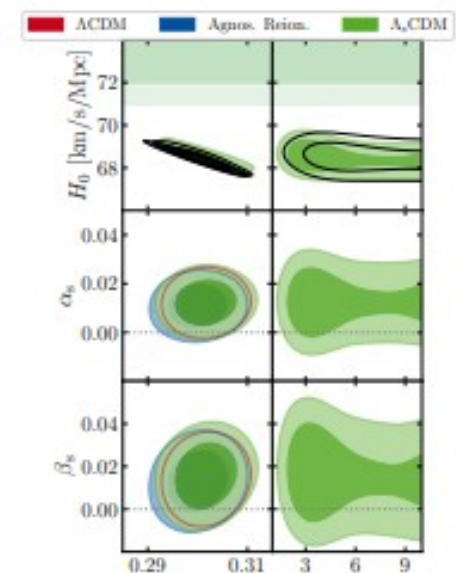
Group E RUNNING



Group M



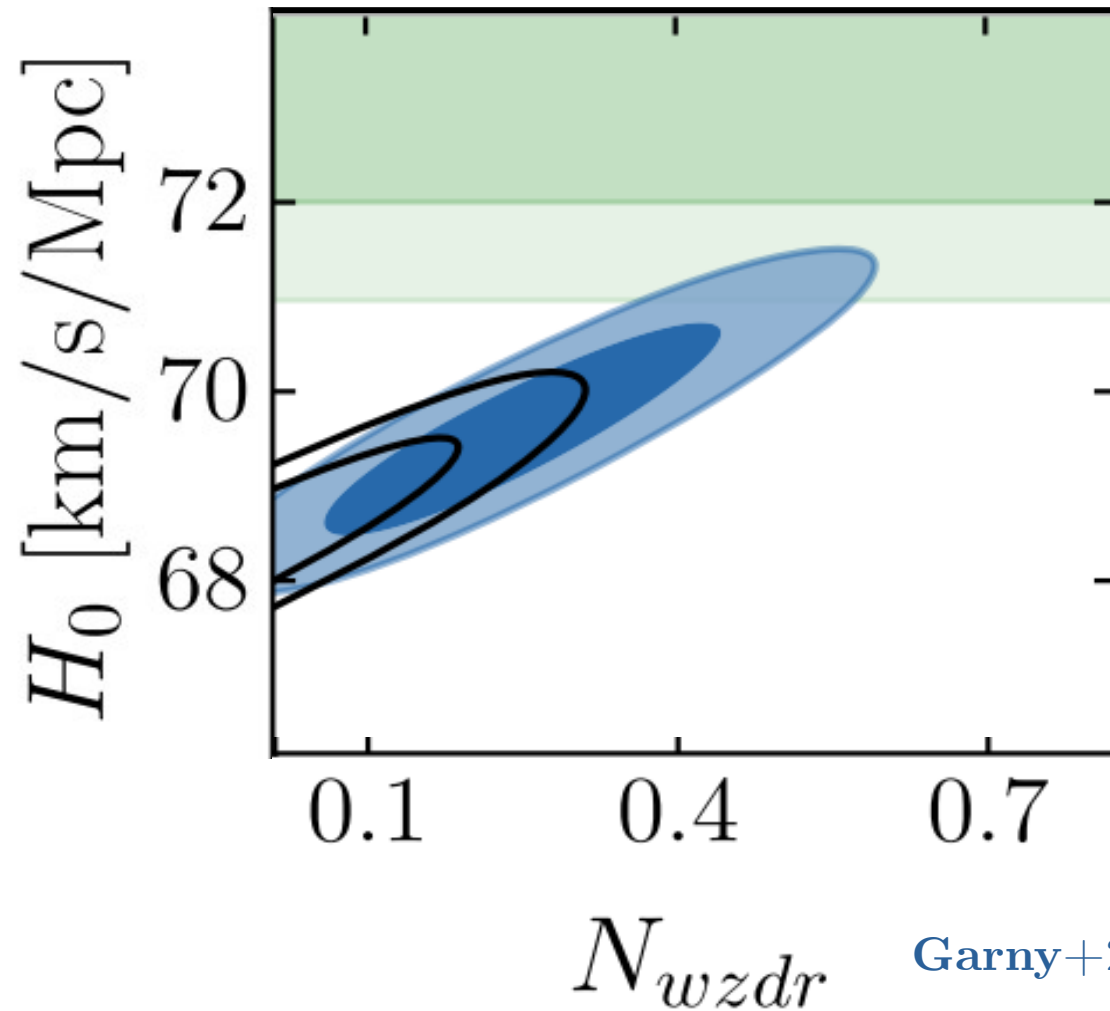
Group R



Group L

Variation

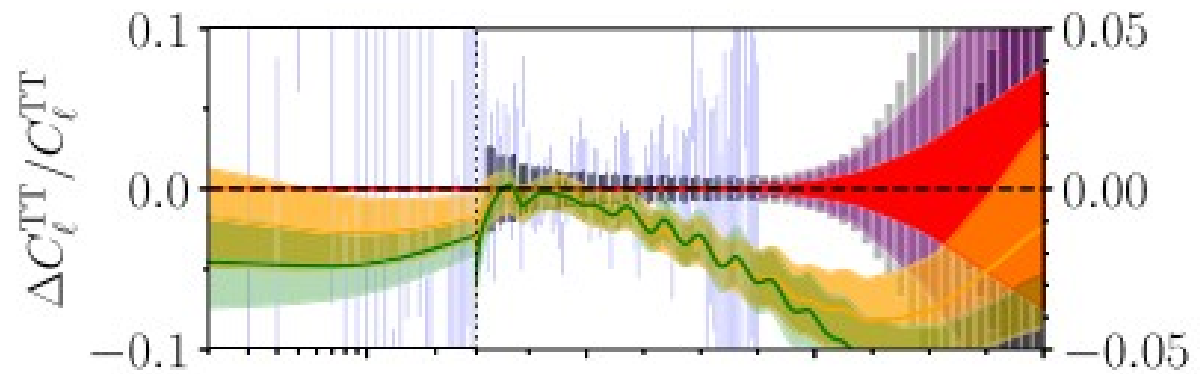
RUNNING



Garny+2604.26541

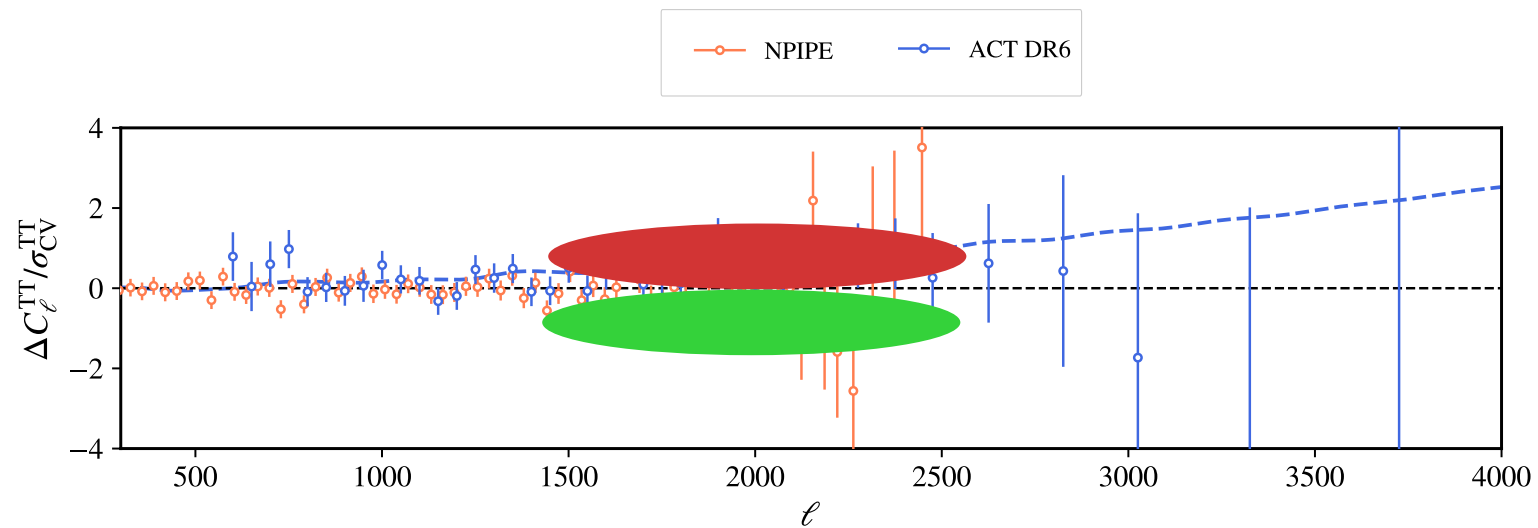
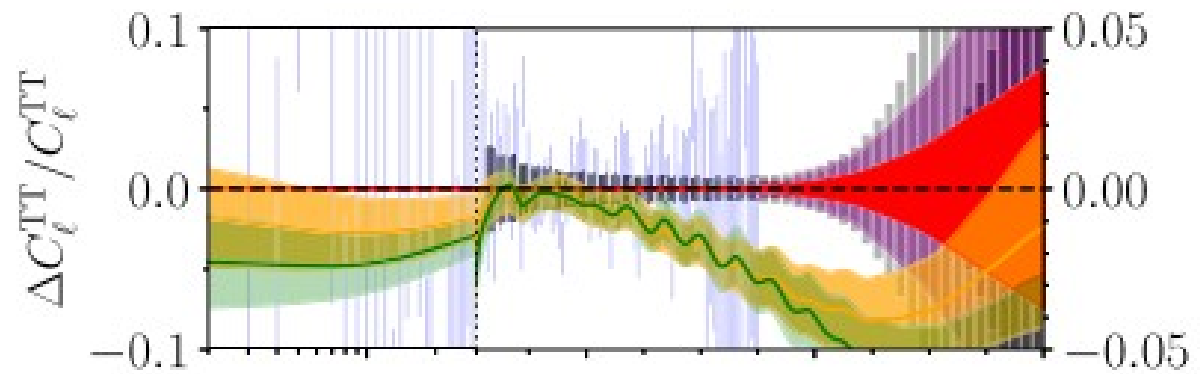
Variation

RUNNING



Variation

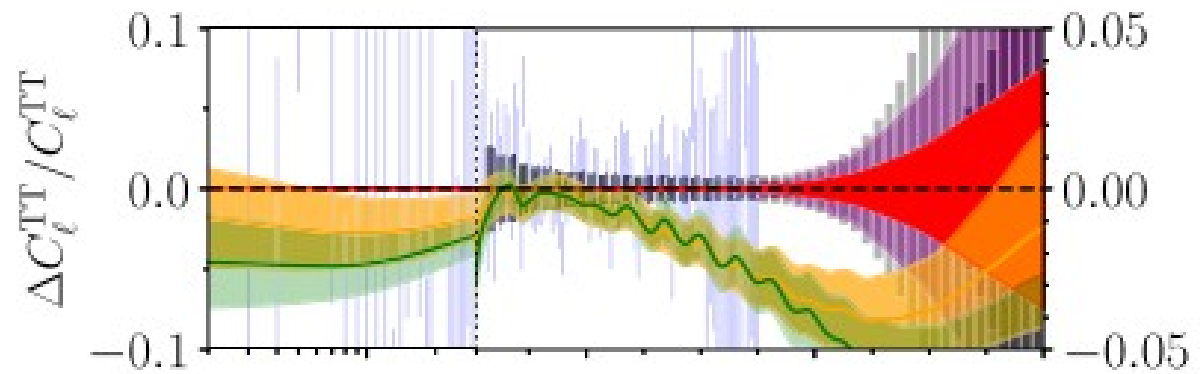
RUNNING



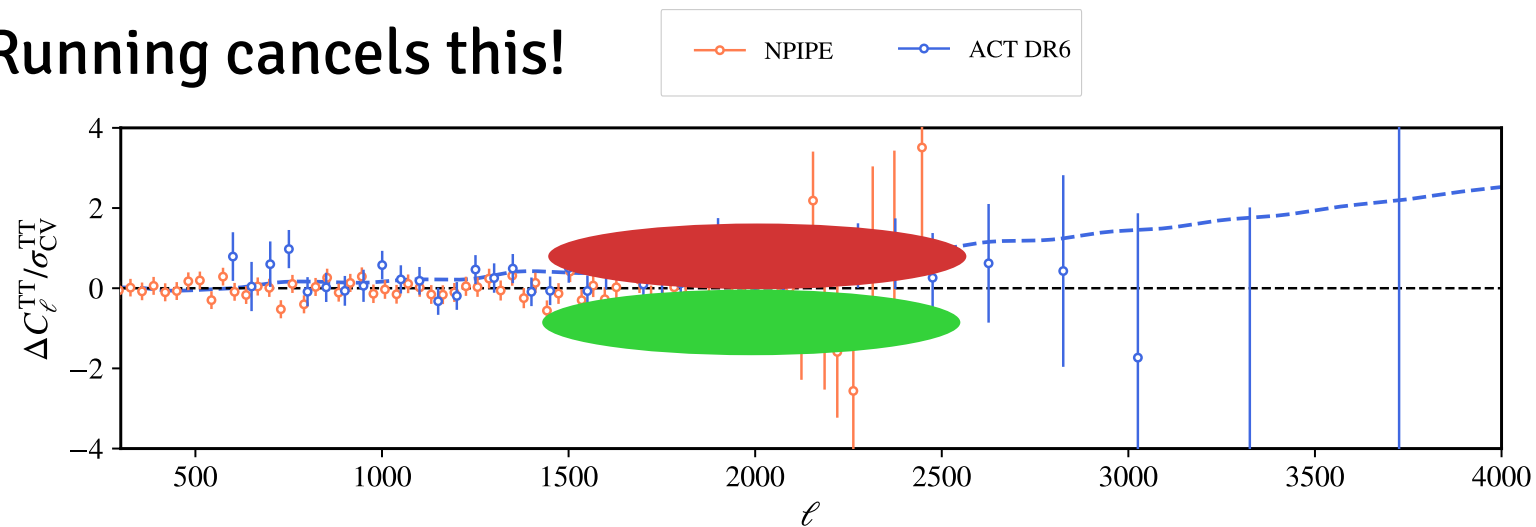
Talk by Rodrigo Calderon

Variation

RUNNING



Running cancels this!



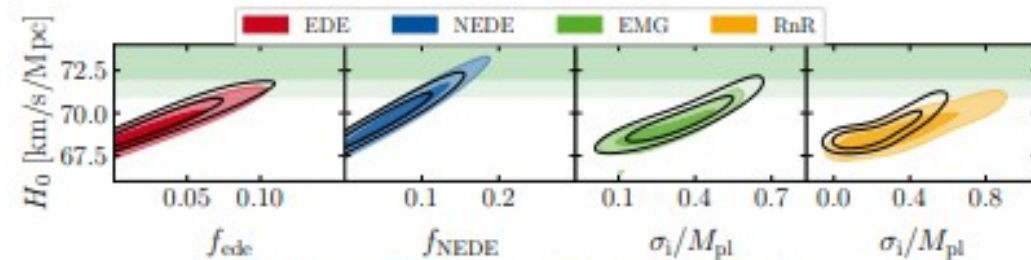
Variation

No ACT DATA

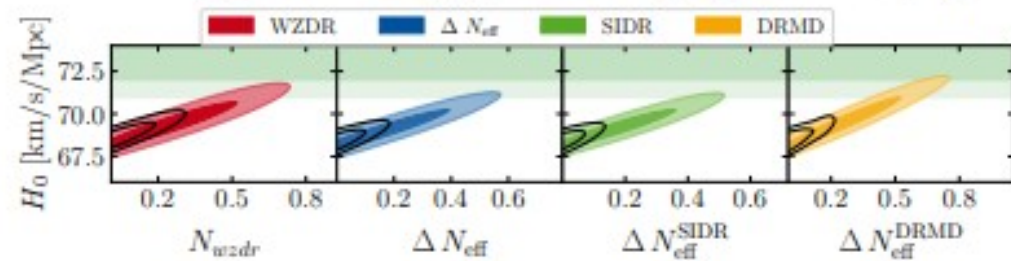
Variation

No ACT DATA

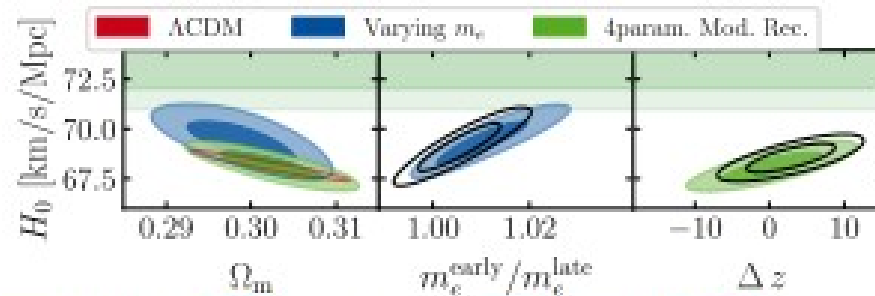
Group E



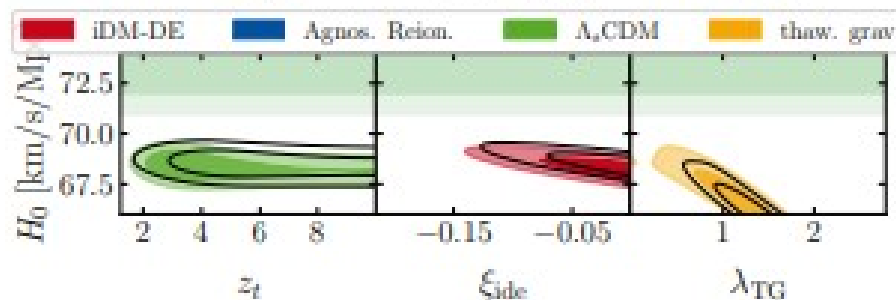
Group R



Group M

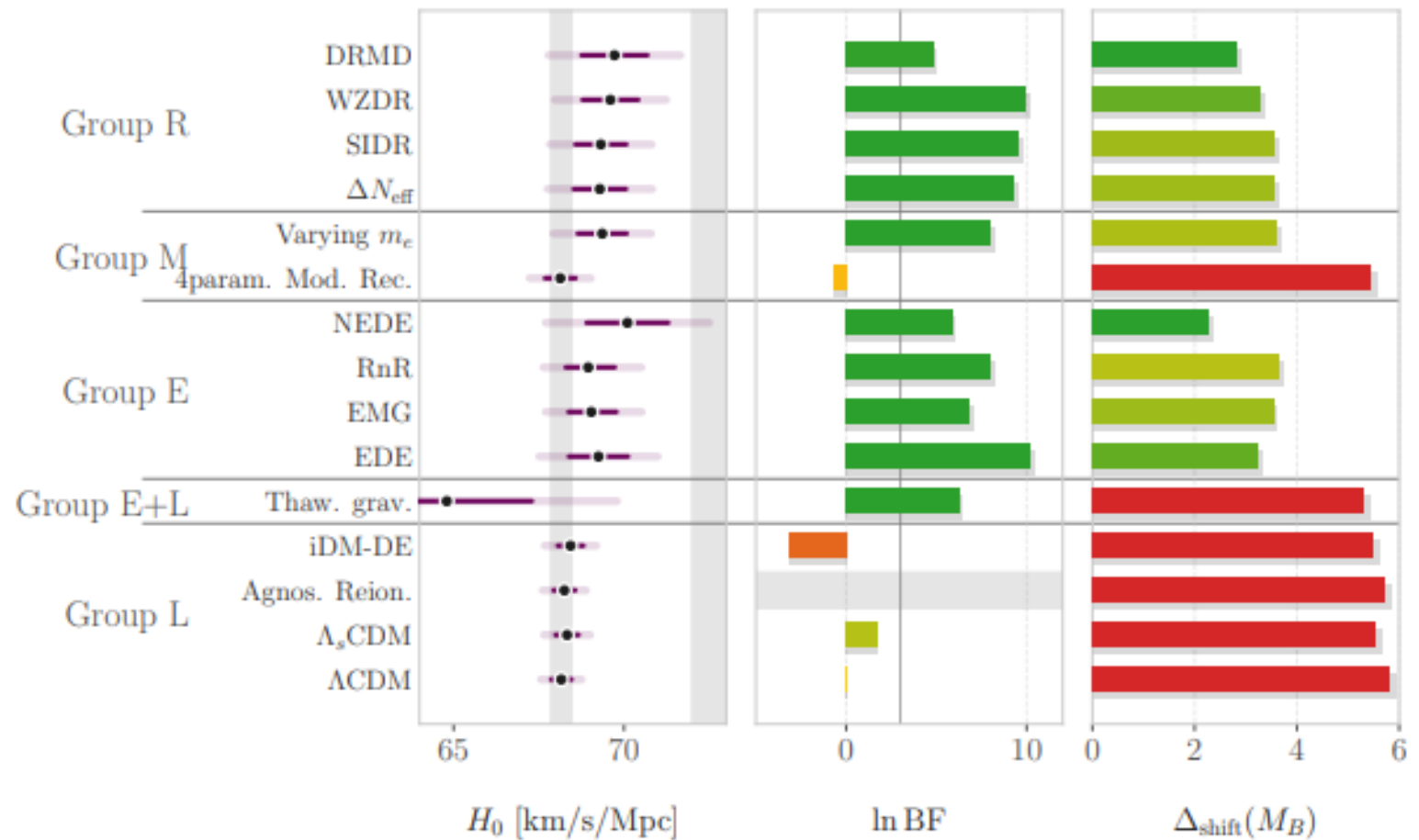


Group L



Variation

No ACT DATA



Variation

SMALL SUMMARY

Baseline: Group $E > M > R > L$

Ω_k , CPL: Not much change

Running/noACT:

R viable, M better

$\rightarrow (E \sim M \sim R) > L$

Variation

KNOCKOUT ROUND

Subselection of best models:

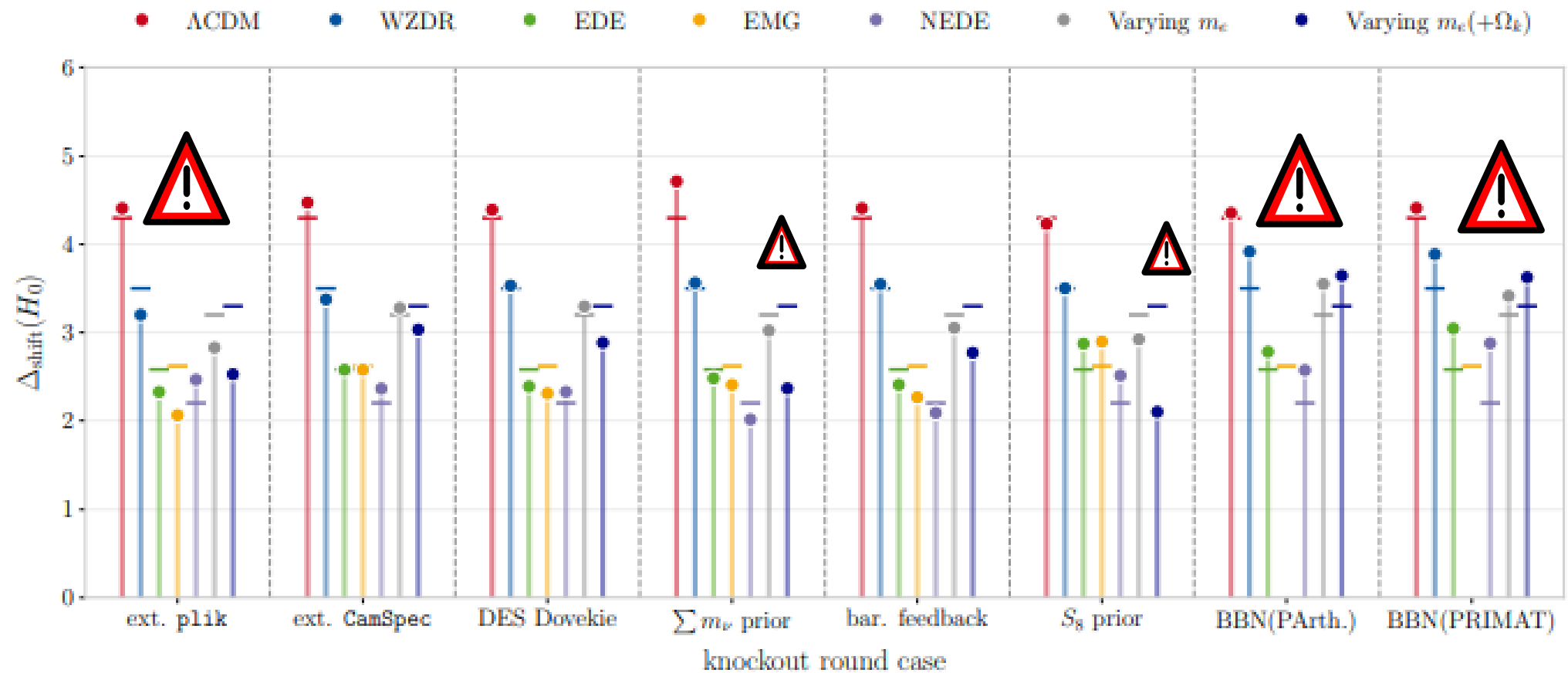
Group R: WZDR

Group M: Varying m_e

Group E: EDE, EMG

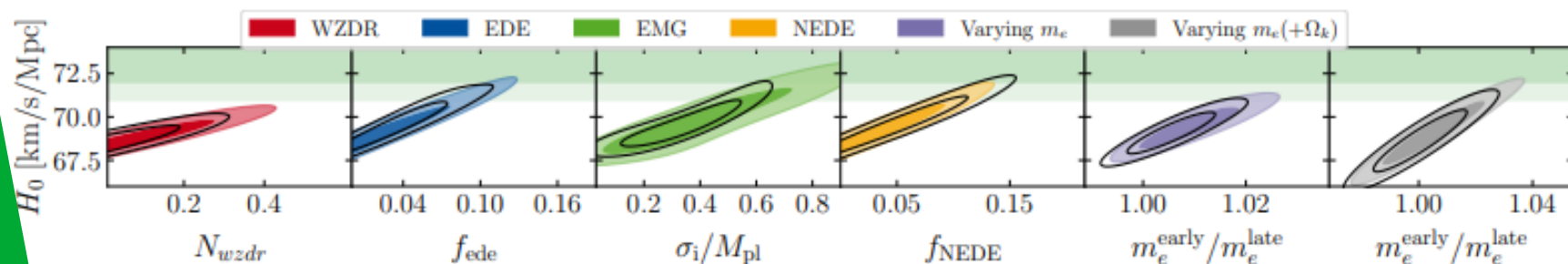
Variation

KNOCKOUT ROUND



Variation

DATA VARIATIONS



Plik data: *weaker constraint*
(like noACT, but not as strong)

CamSpec data: No change

DES Dovekie: No change

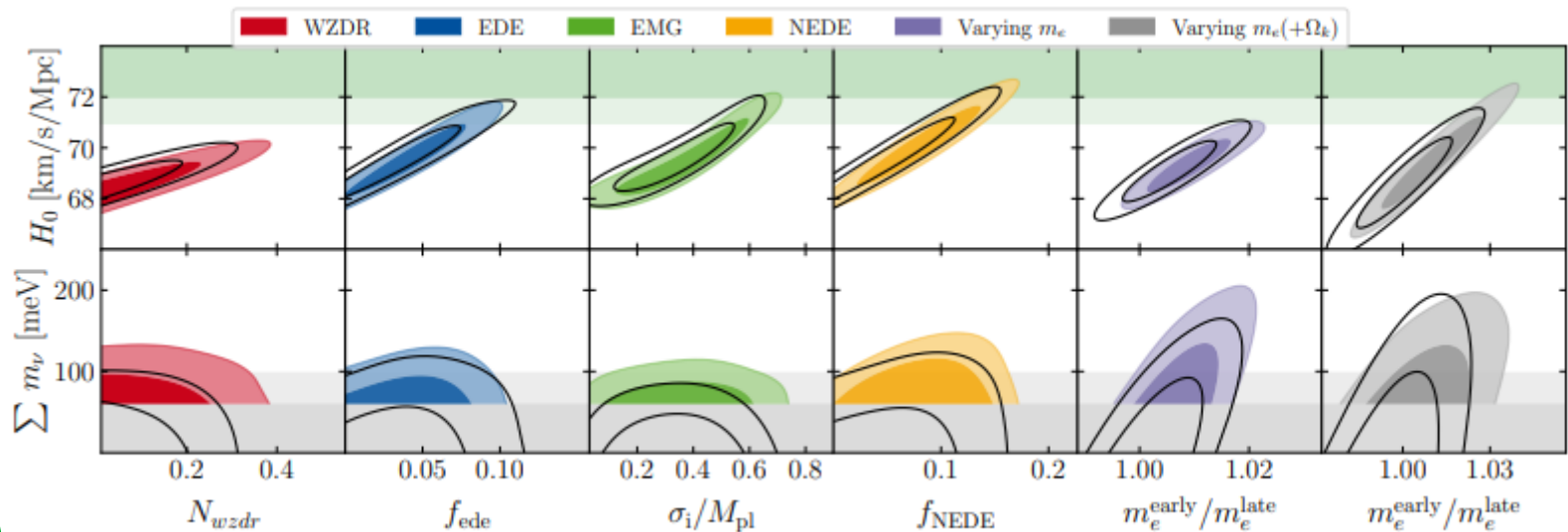
Baryonic Feedback: No change

Variation

PRIOR VARIATIONS

Σm_ν prior:

Varying electron mass $\sim E$



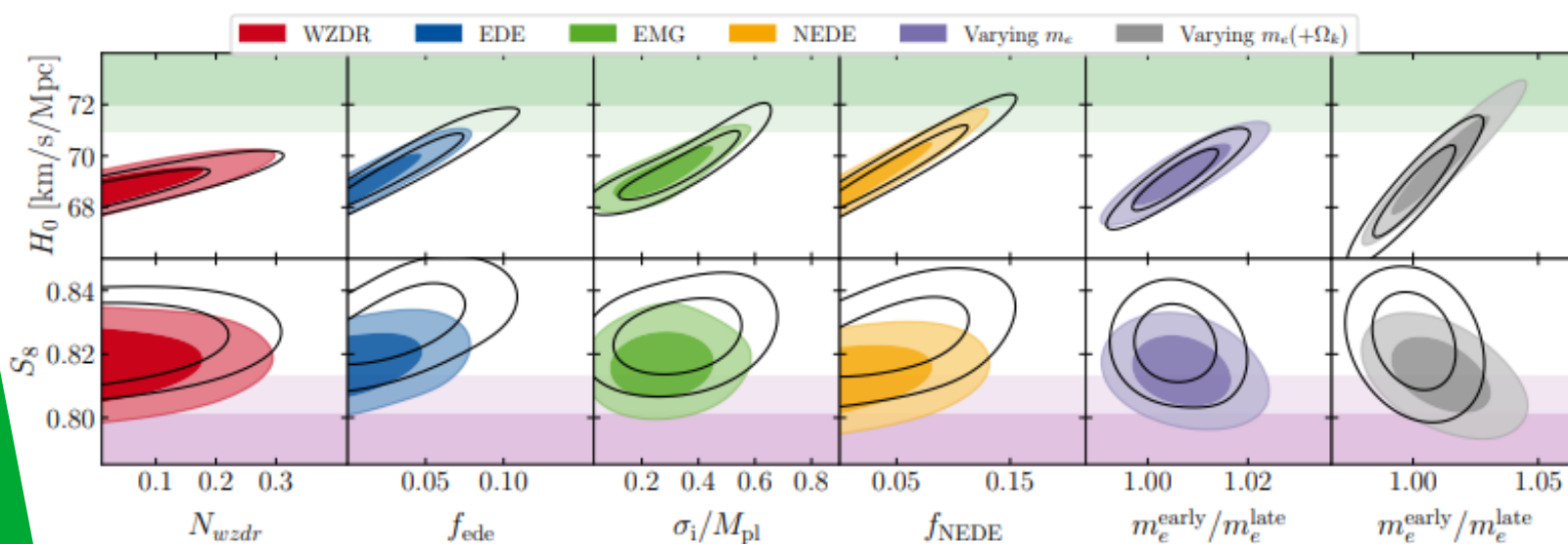
Variation

Talk on *next Monday!*

ADDITIONAL DATA (LSS)

S_8 prior (DES Y6 3x2pt):

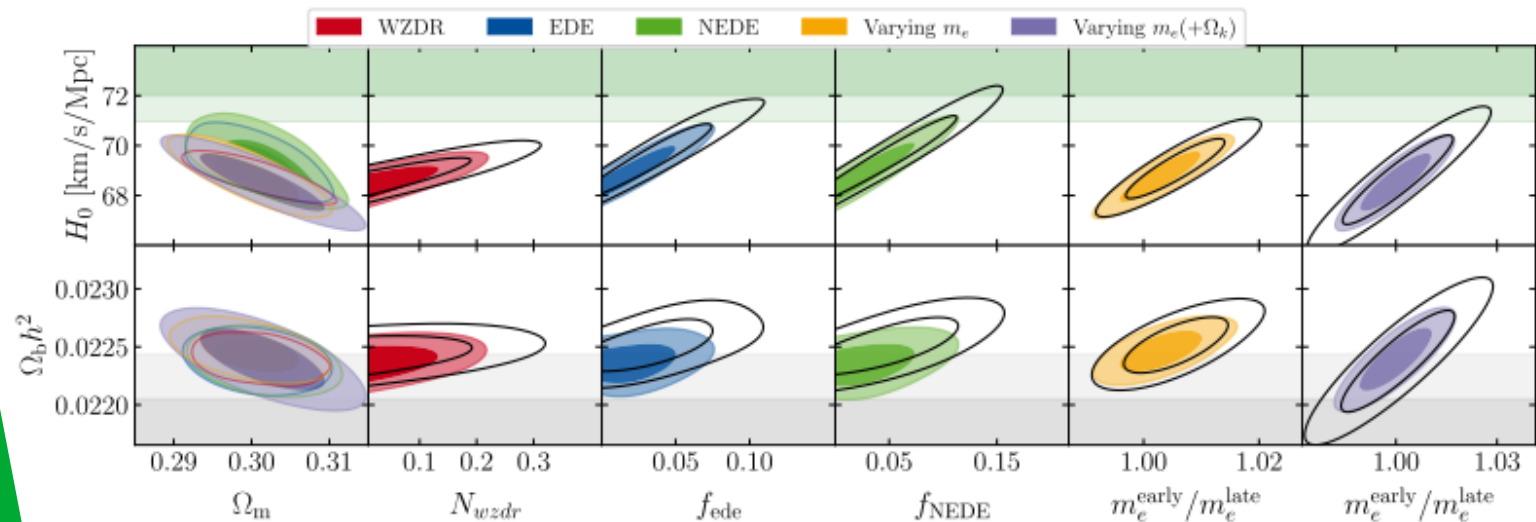
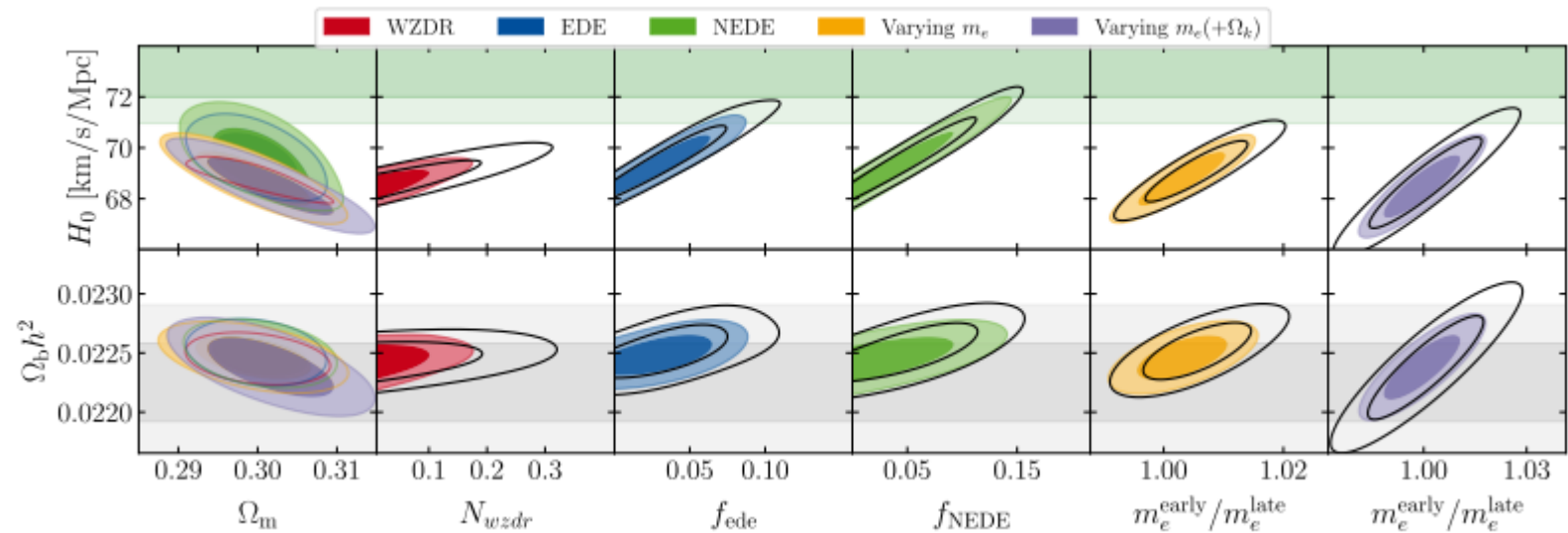
Varying electron mass overtakes all other models



Talk on *next Monday!*

Variation

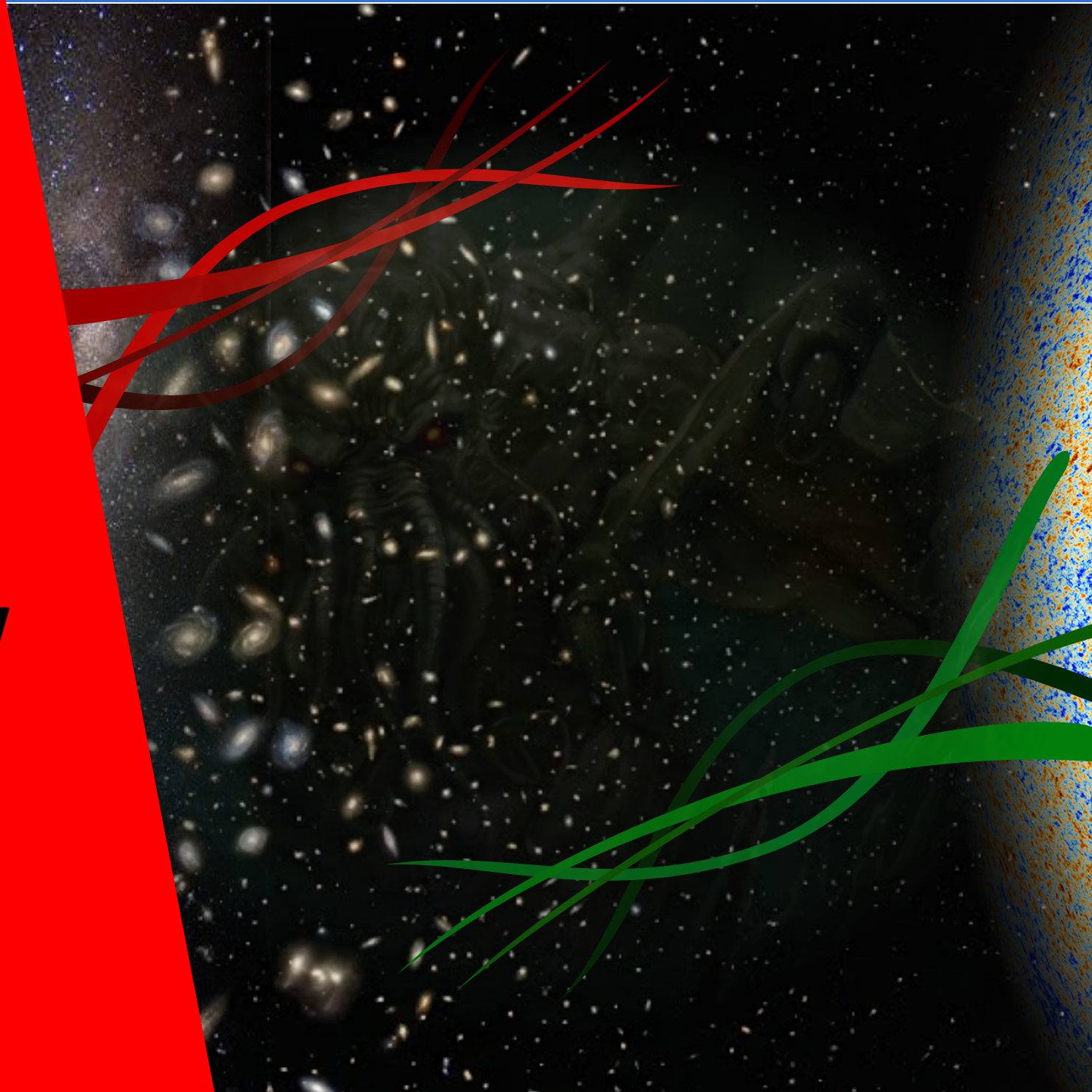
ADDITIONAL DATA (BBN)



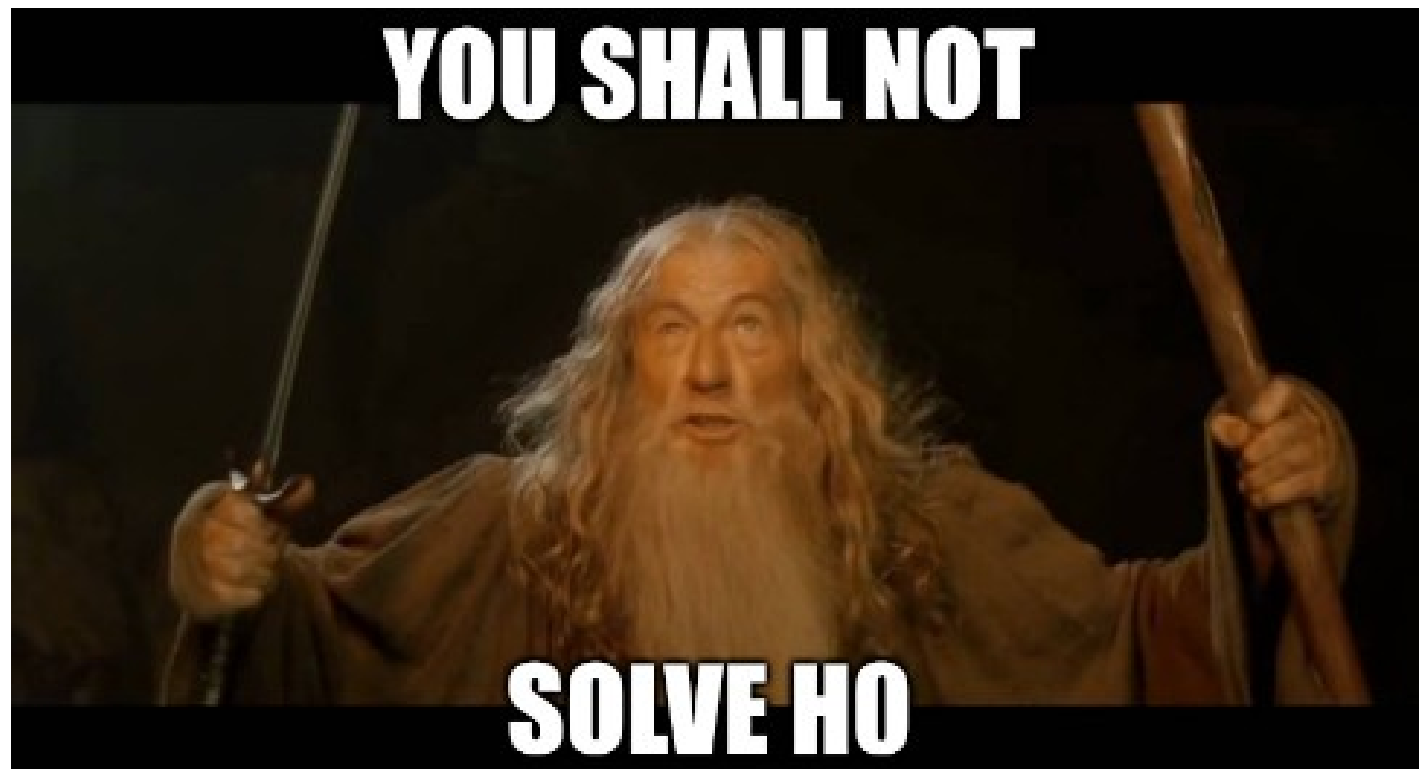
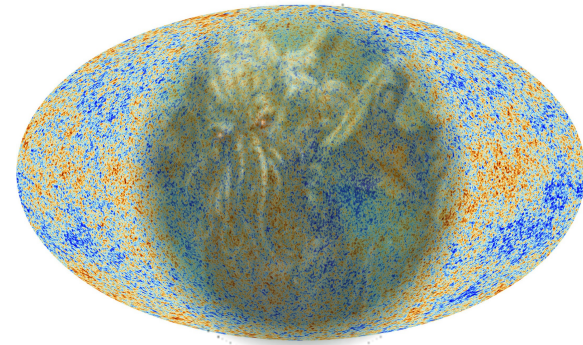
Variation

Part IV

Summary



- Cosmic calibrator tension →
We need r_d to change



Summary

- Cosmic calibrator tension →
We need r_d to change (group L is sad)

Summary

- Cosmic calibrator tension →
We need r_d to change (group L is sad)
- Ranking:
 - Early dark energy solutions 
 - Modified Recombination solutions 
 - Radiation solutions 
 - Late solutions

Summary

- Dark Energy CPL ? $\rightarrow$ No impact
- Curvature? $\rightarrow$ Only for modified Recomb.

Summary

- Dark Energy CPL ? $\rightarrow$ No impact
- Curvature? $\rightarrow$ Only for modified Recomb.
- Running $\leftrightarrow$ NoACT? $\rightarrow$ Group R becomes viable, playing field leveled

Summary

- Dark Energy CPL ? → No impact
- Curvature? → Only for modified Recomb.
- Running $\leftrightarrow$ NoACT? → Group R becomes viable, playing field leveled
- Data variations:
 - p_{lik} CMB → Slightly weaker constraints
 - S_8 or Σm_ν → Varying electron mass (Monday)
 - BBN → universally bad

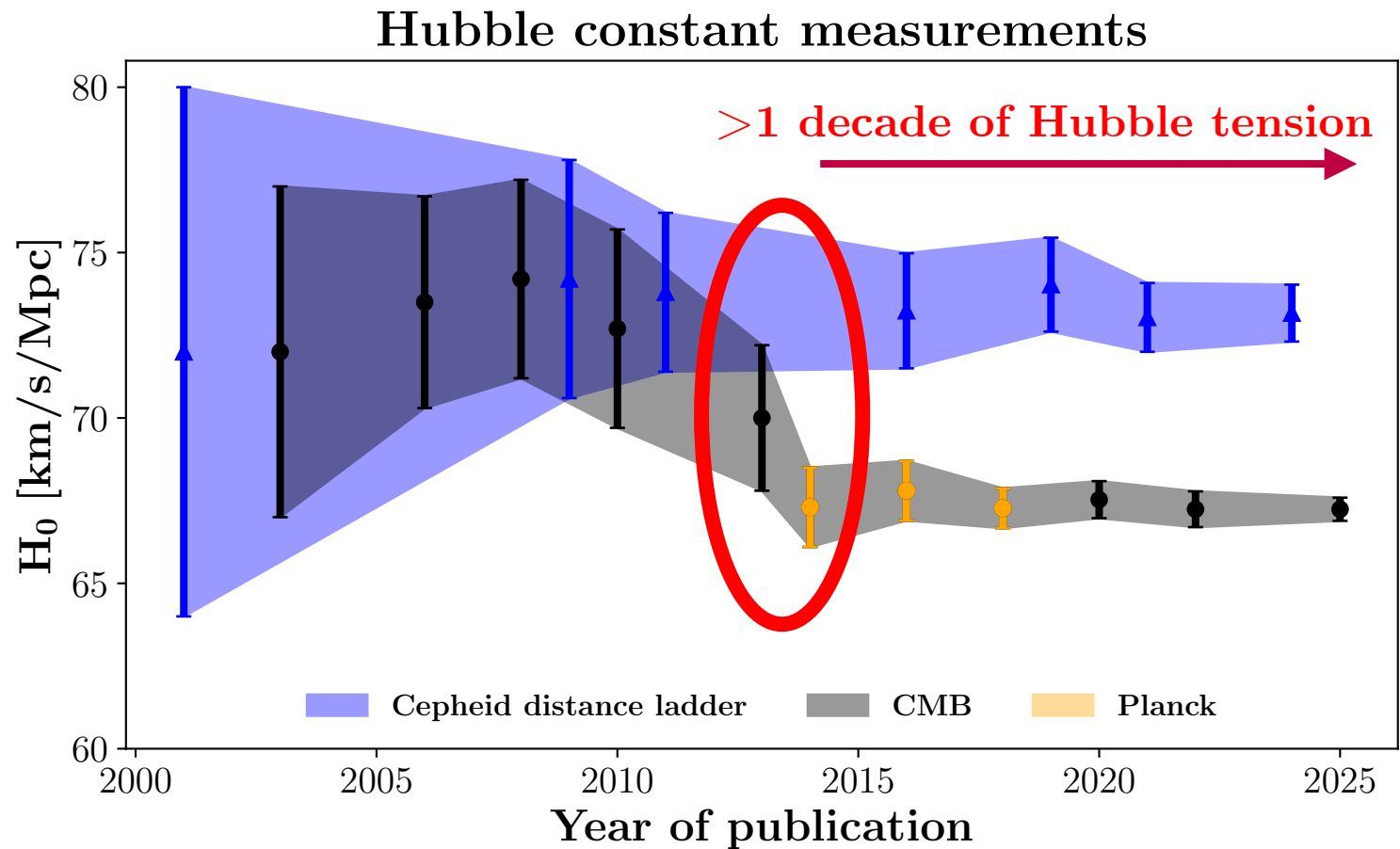
Summary

Summary



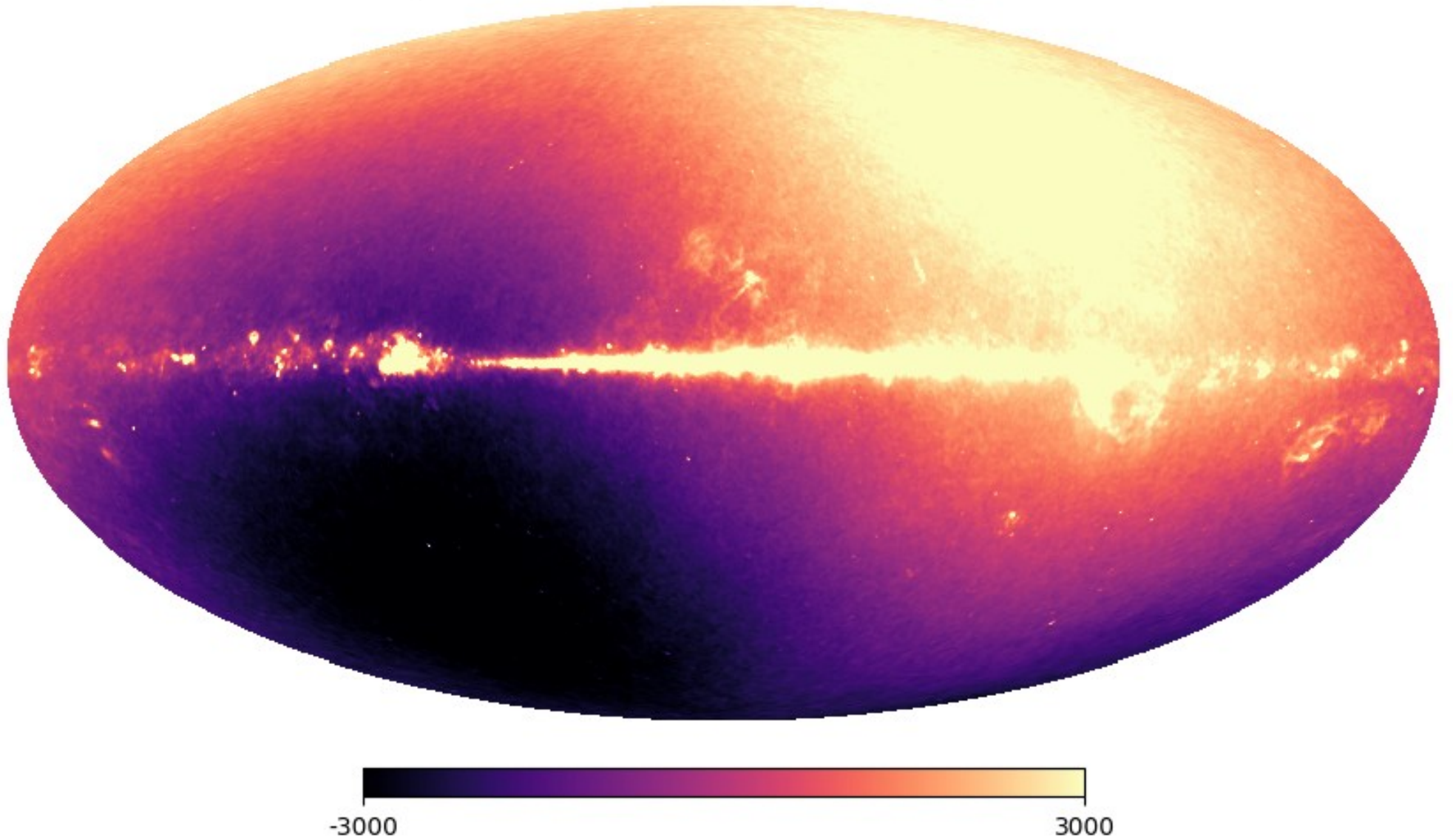
BACKUP SLIDES

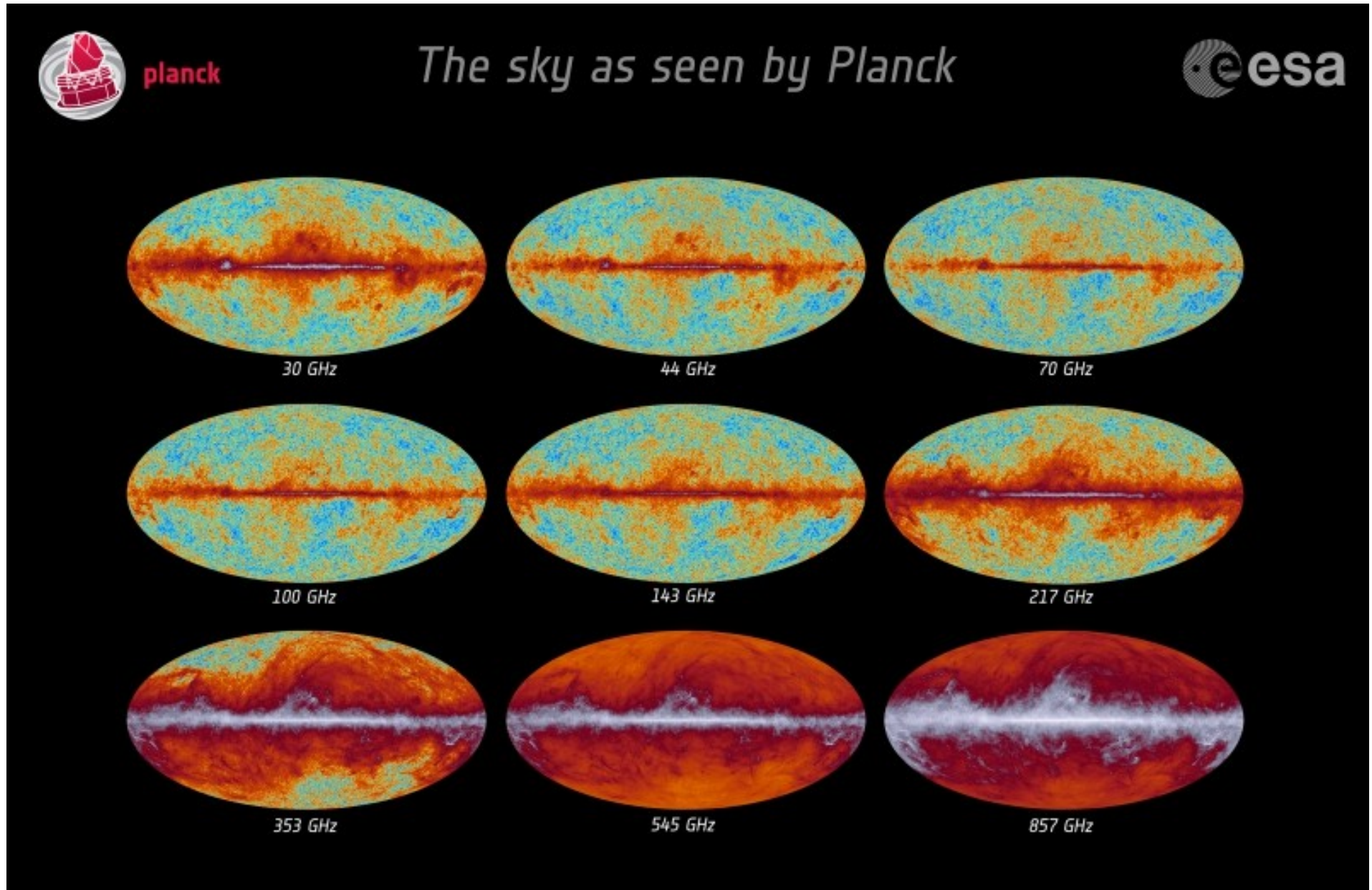
HISTORY



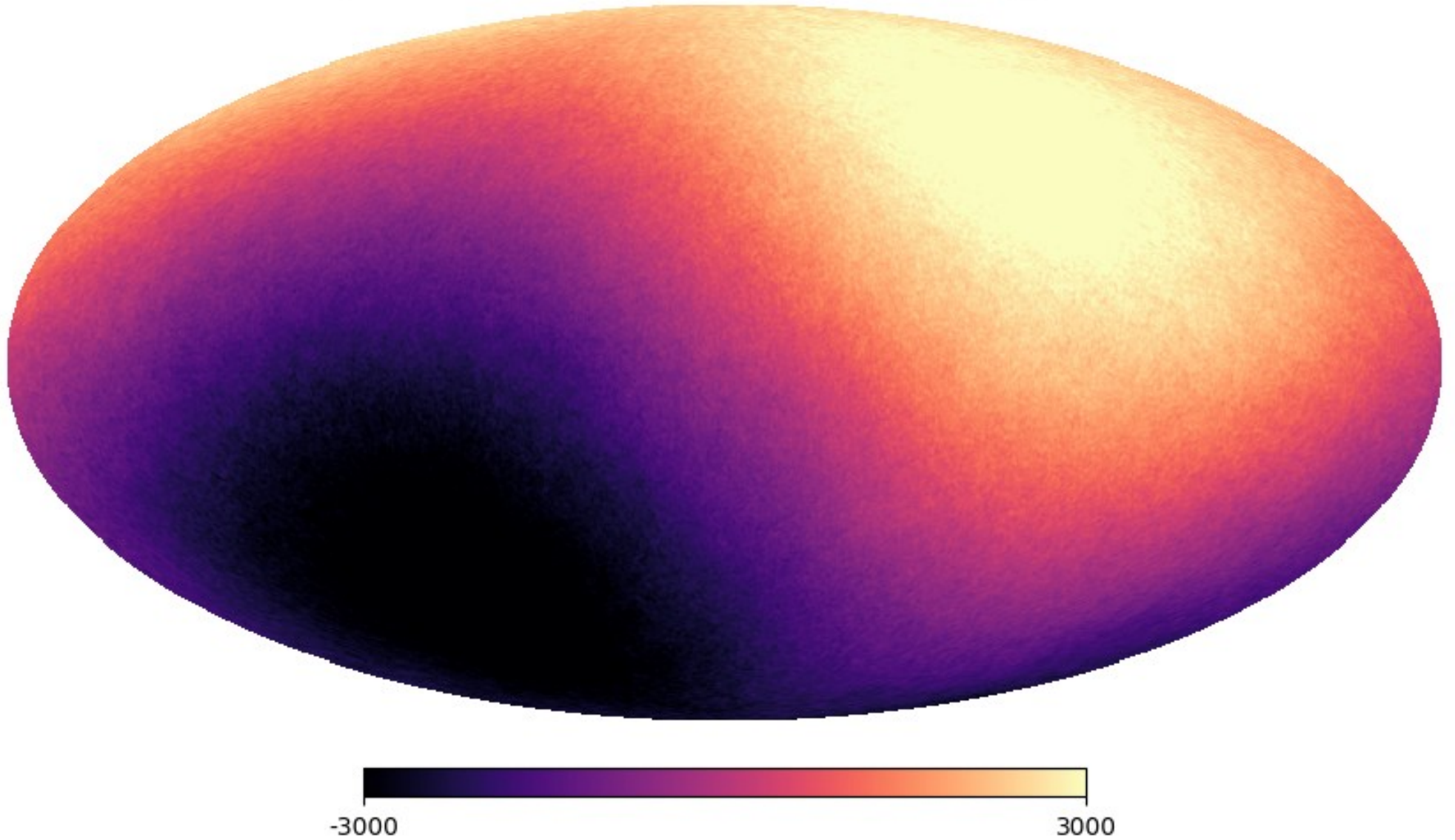
→ Obviously caused by the CMB

Beyond-Planck CMB map (uncorrected) , 30GHz

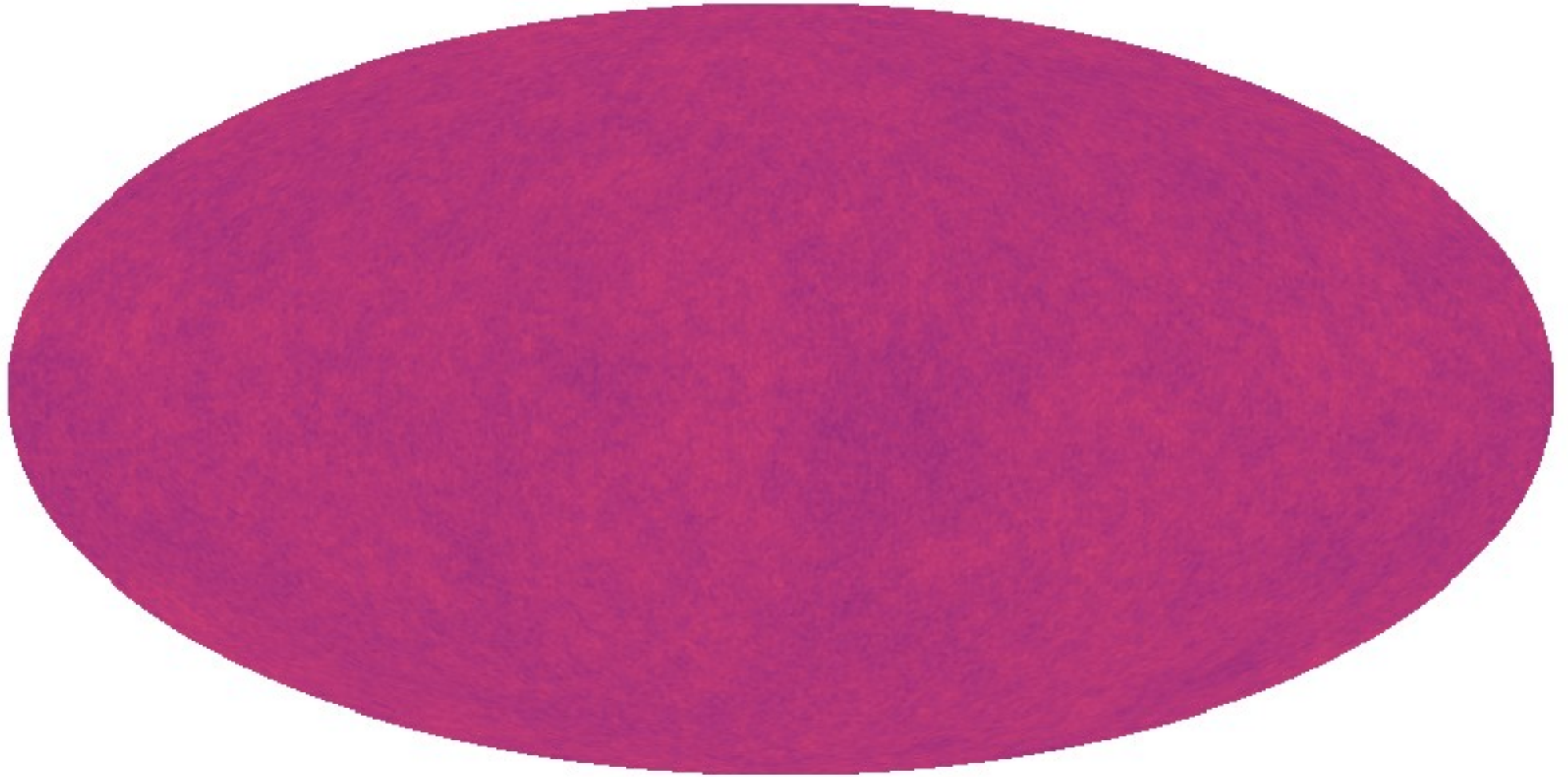




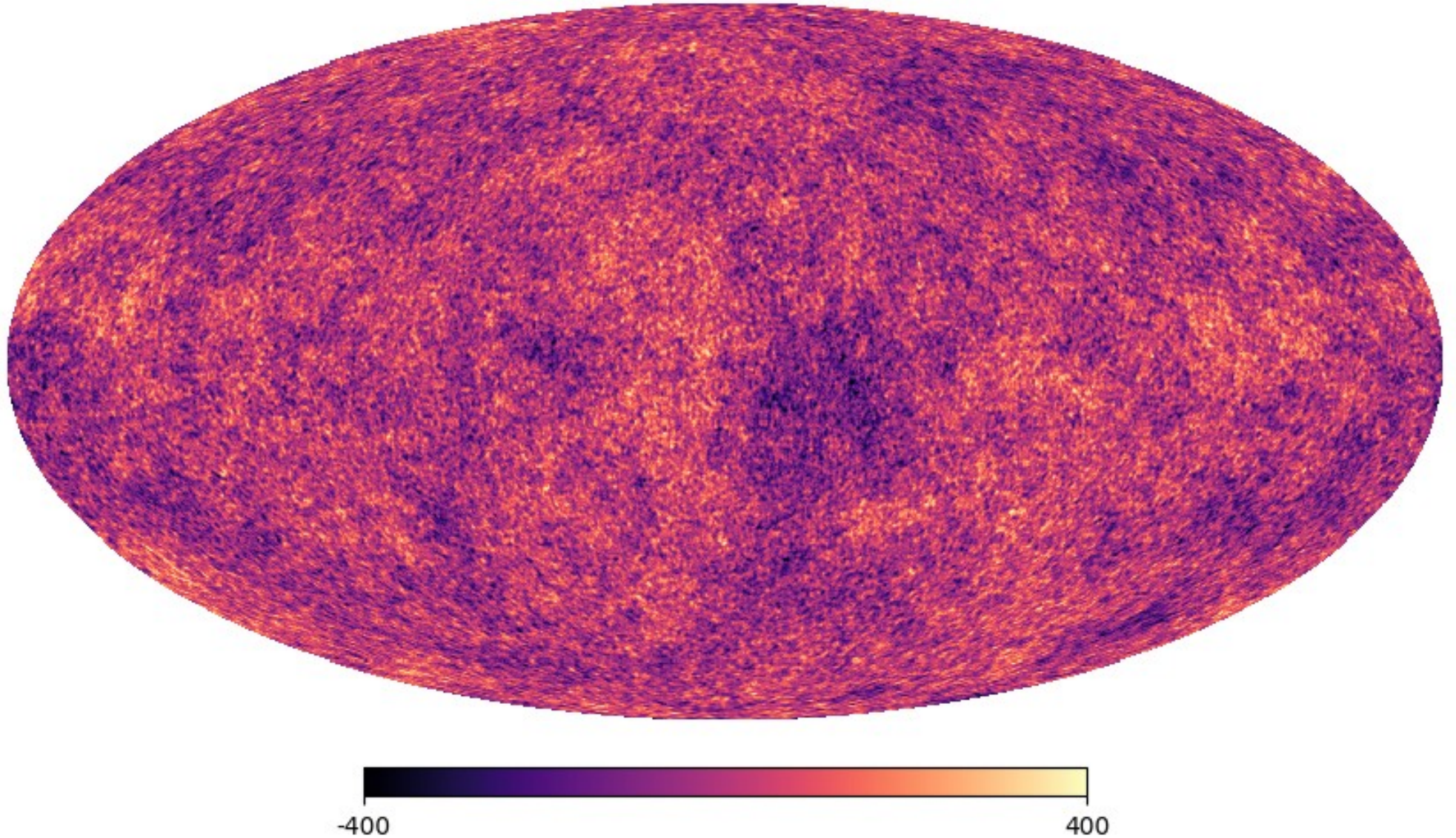
Beyond-Planck CMB map (foregrounds removed) , 30GHz



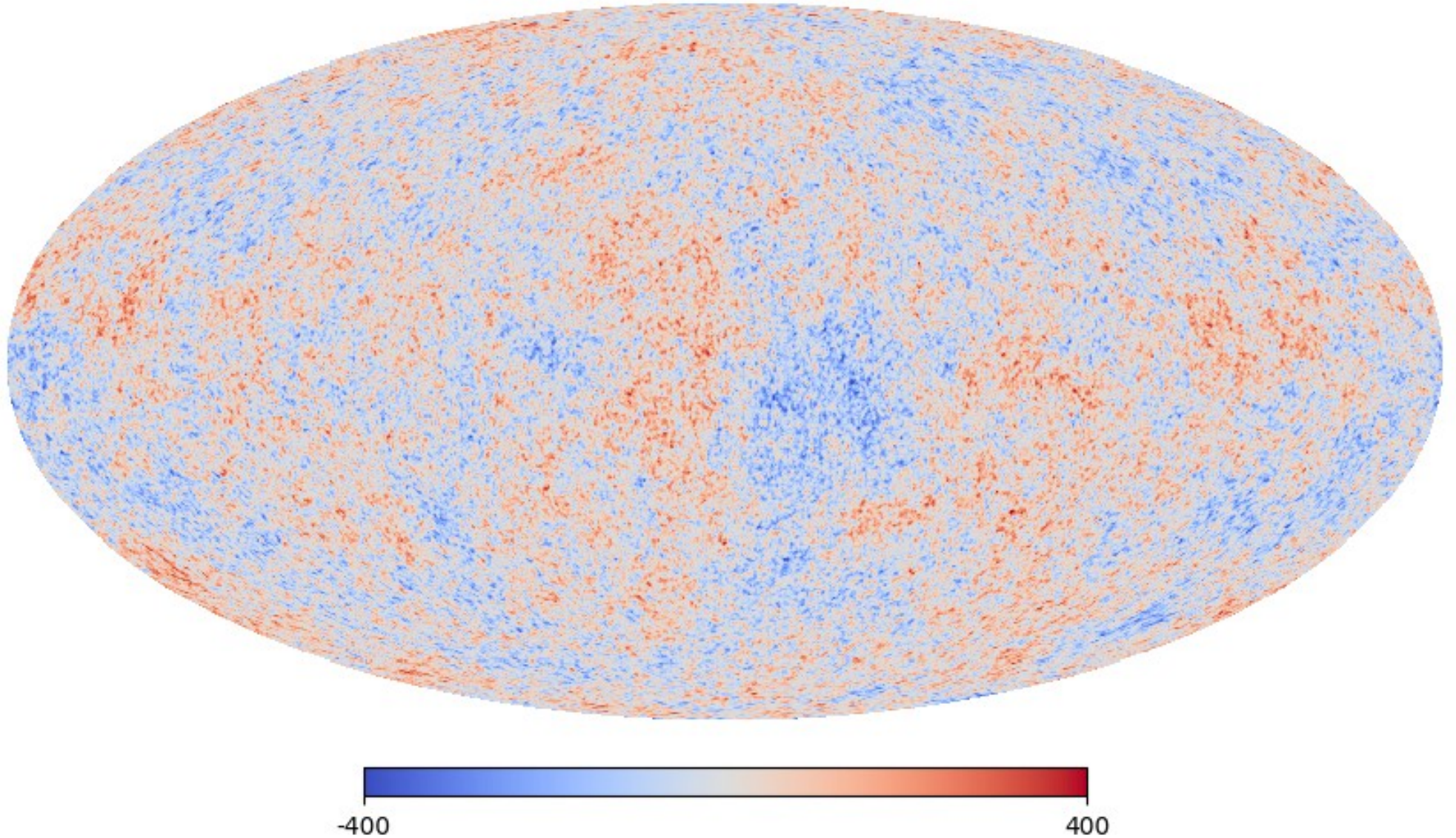
Beyond-Planck CMB map (foregrounds, dipole removed) , 30GHz



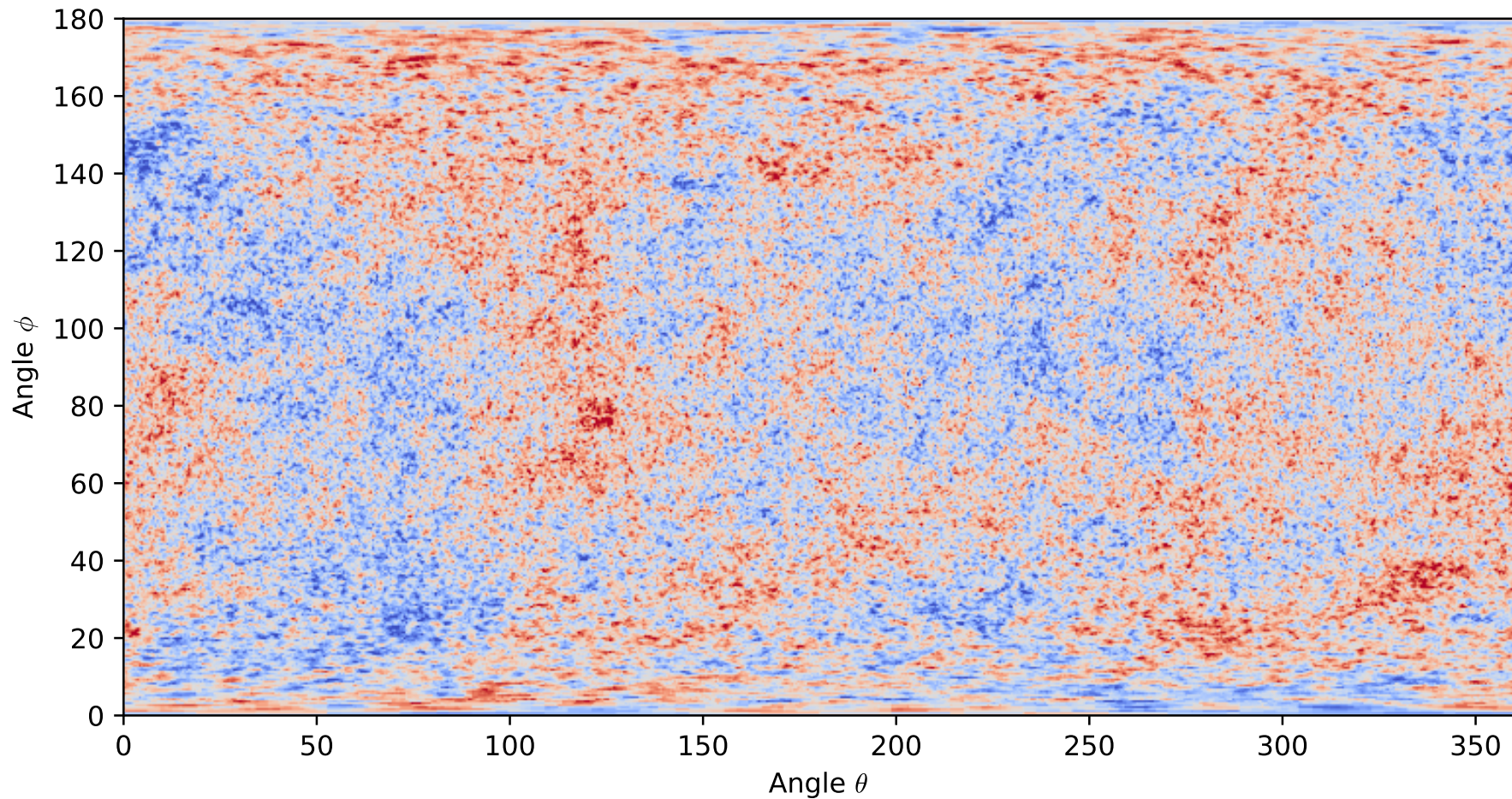
Beyond-Planck CMB map (foregrounds, dipole removed) , 30GHz



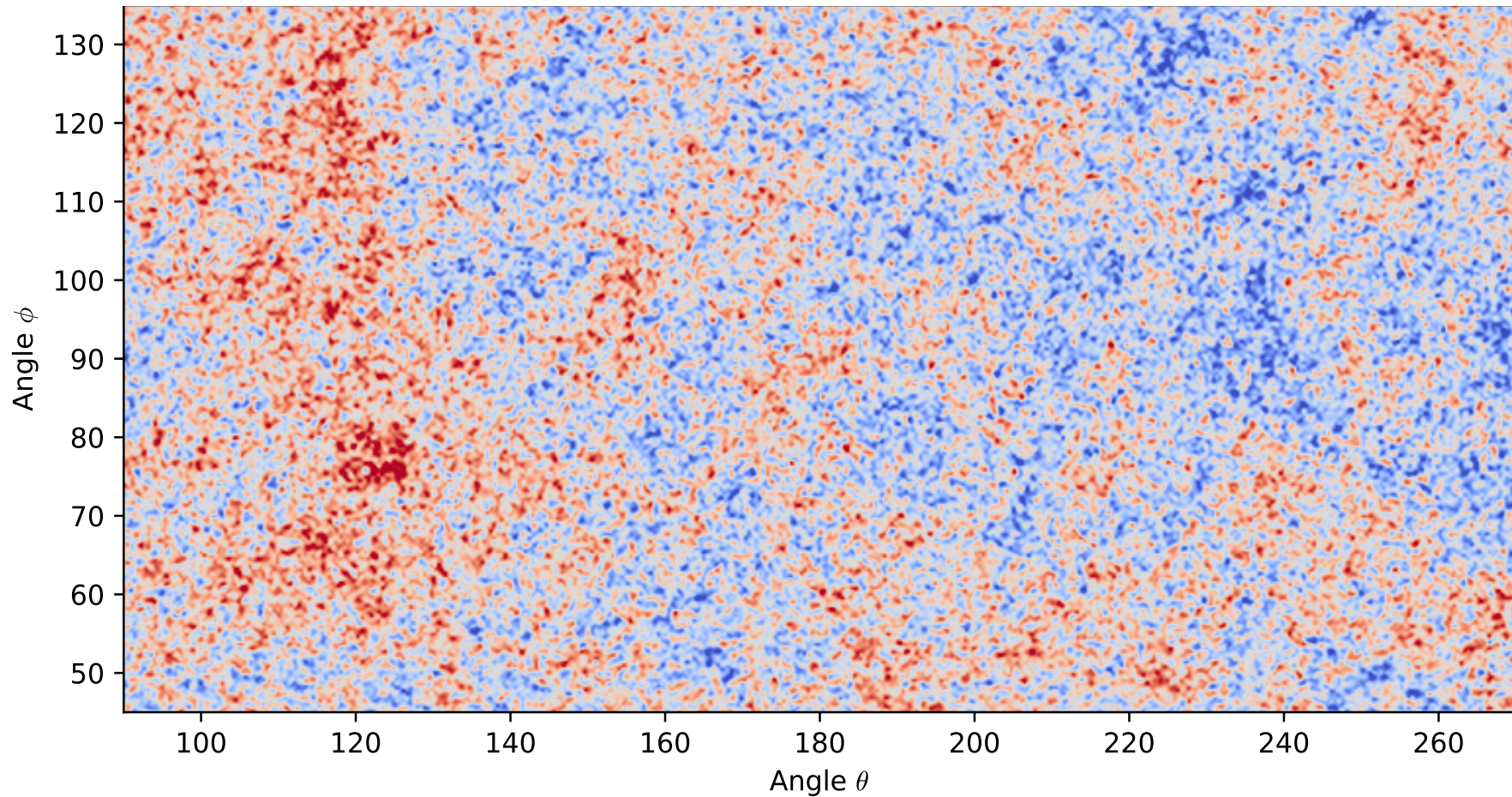
Beyond-Planck CMB map (foregrounds, dipole removed) , 30GHz



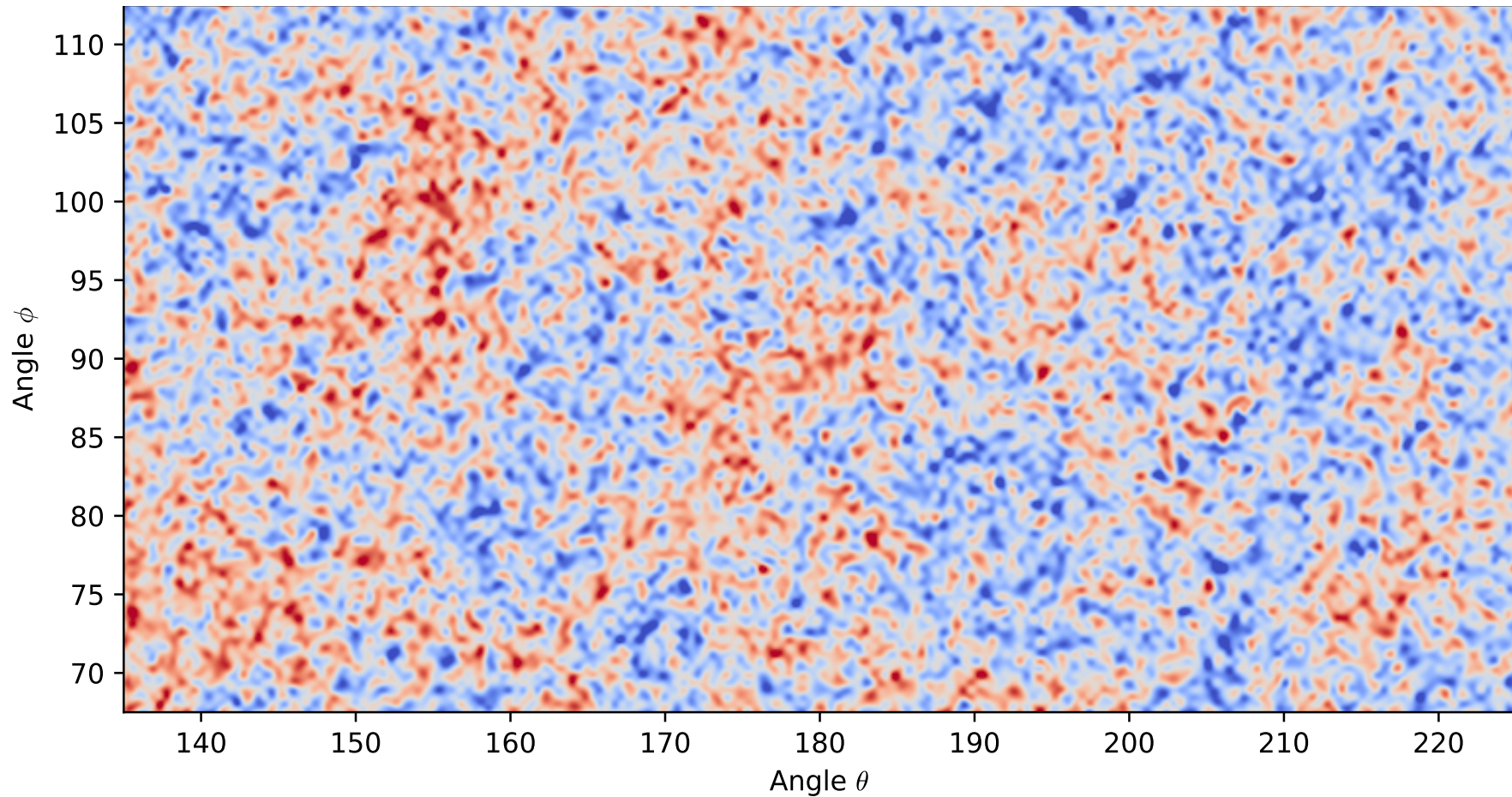
THE CMB ANISOTROPIES



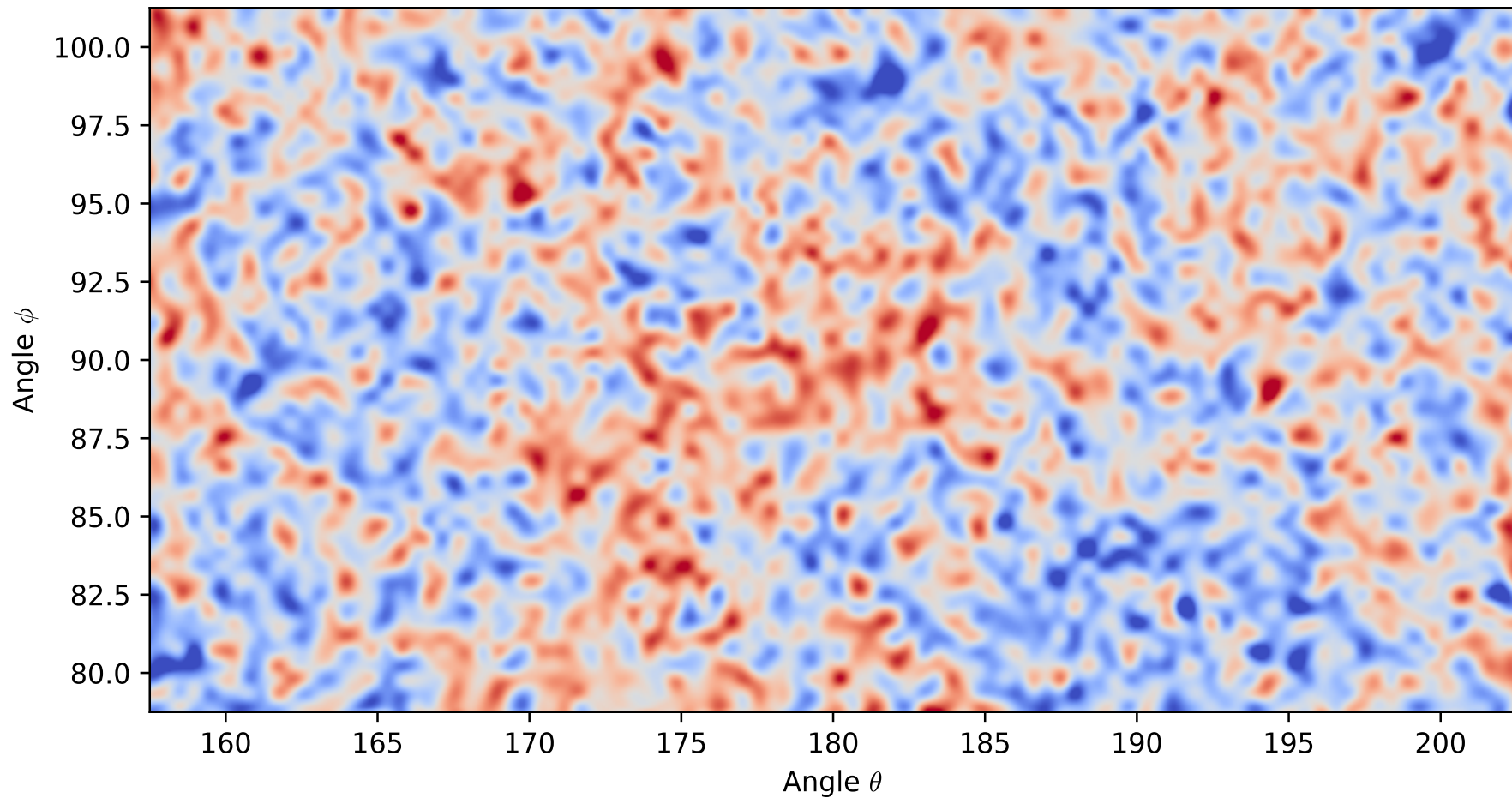
THE CMB ANISOTROPIES



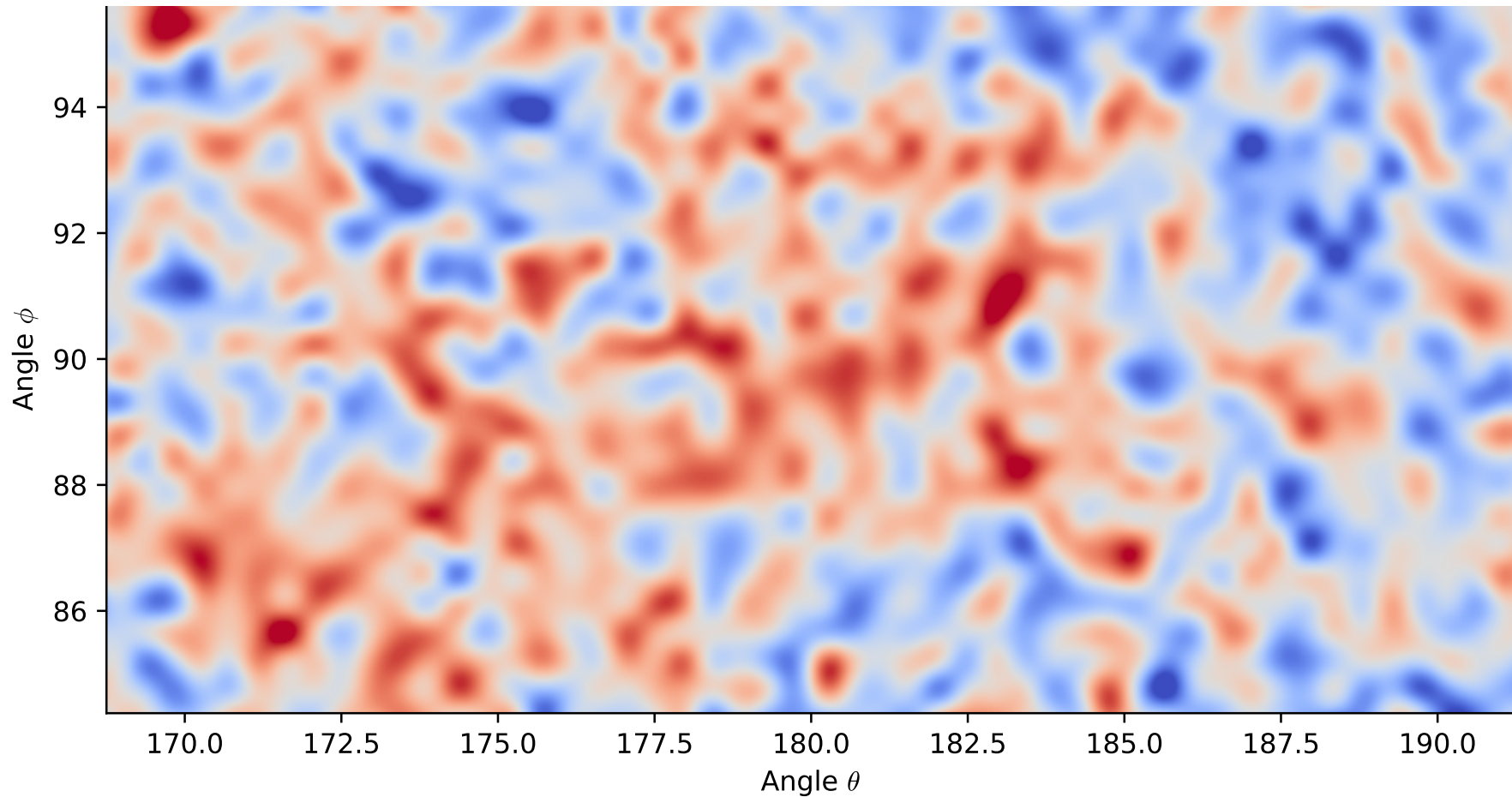
THE CMB ANISOTROPIES



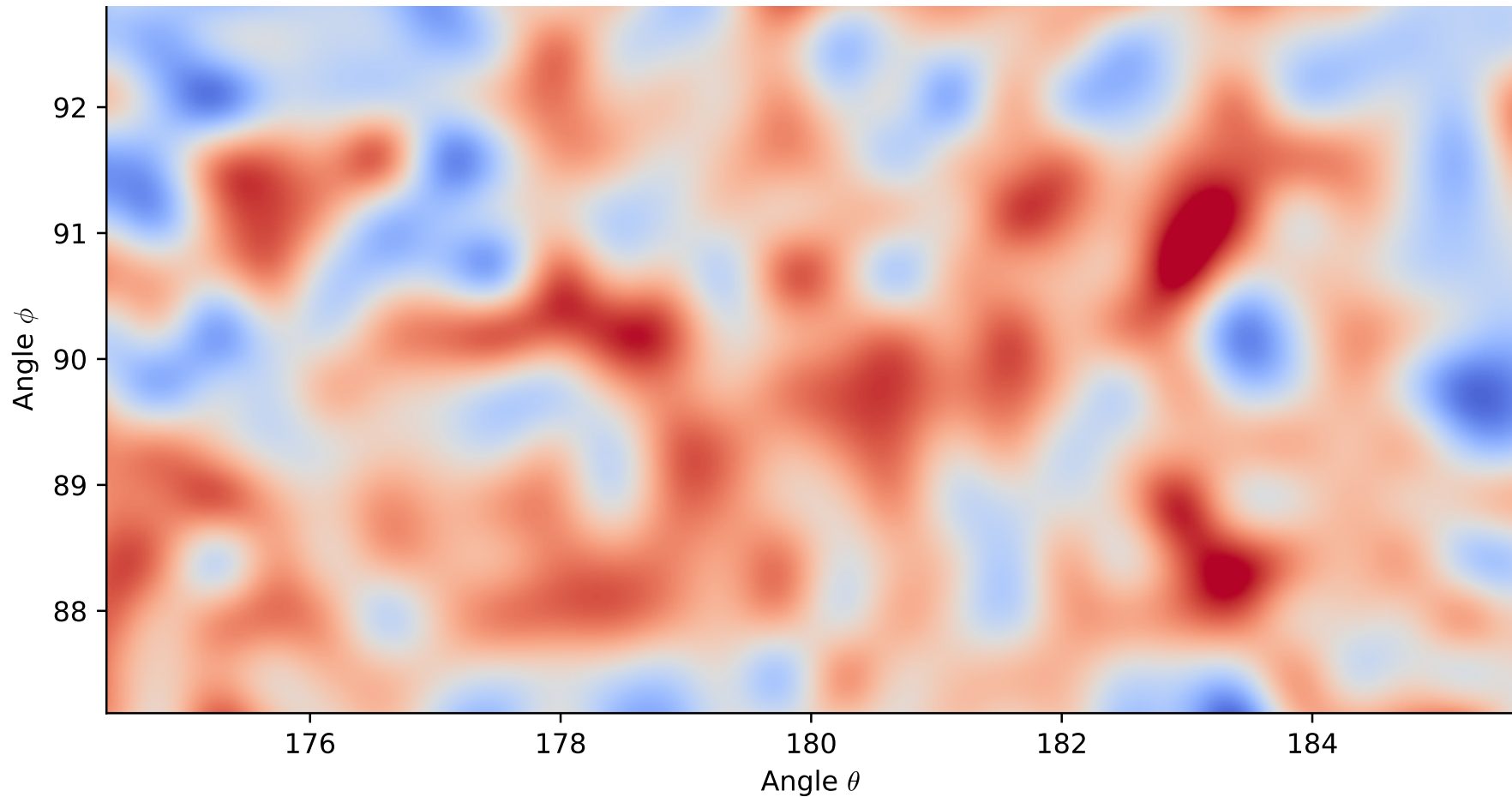
THE CMB ANISOTROPIES



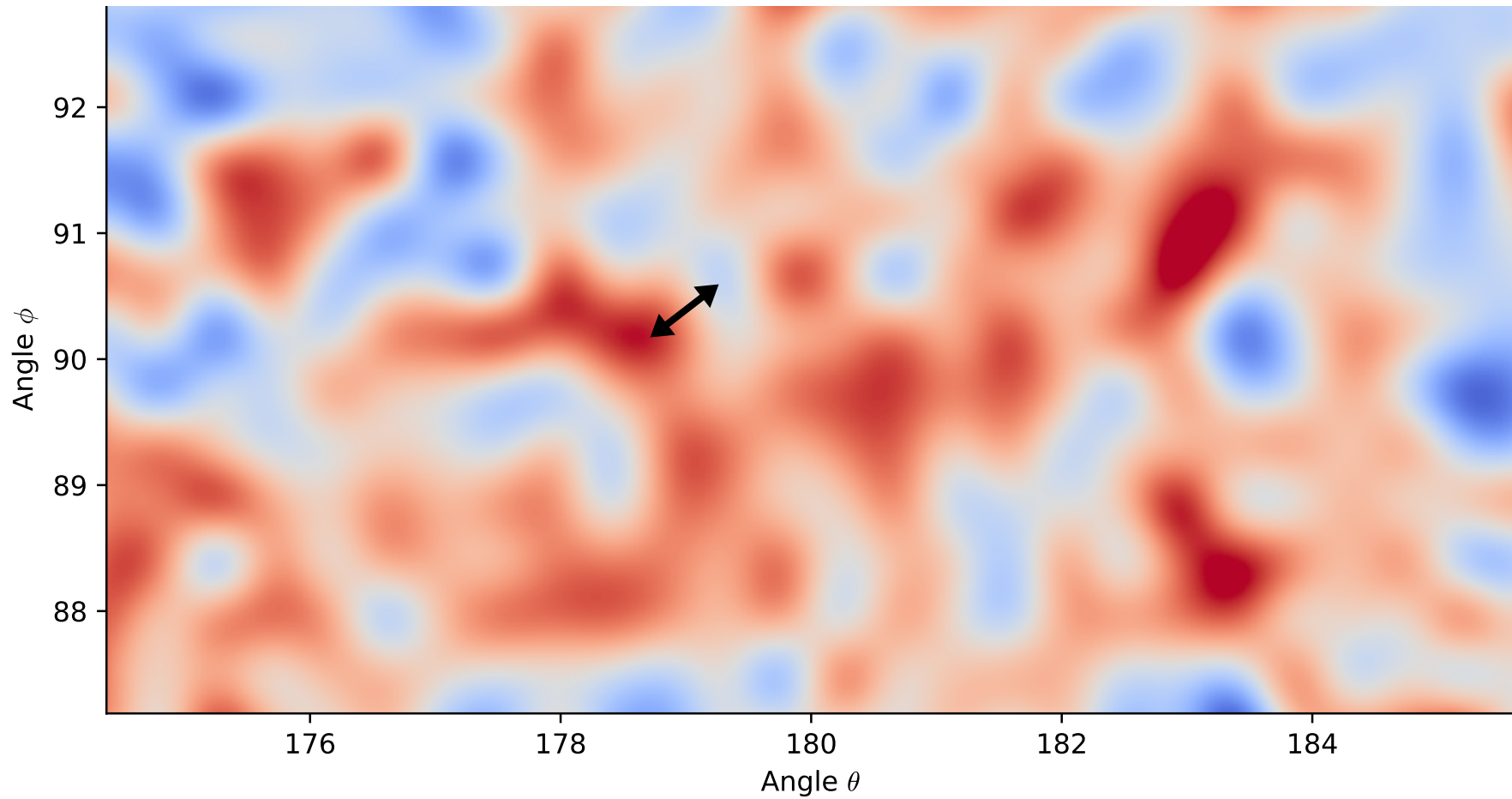
THE CMB ANISOTROPIES



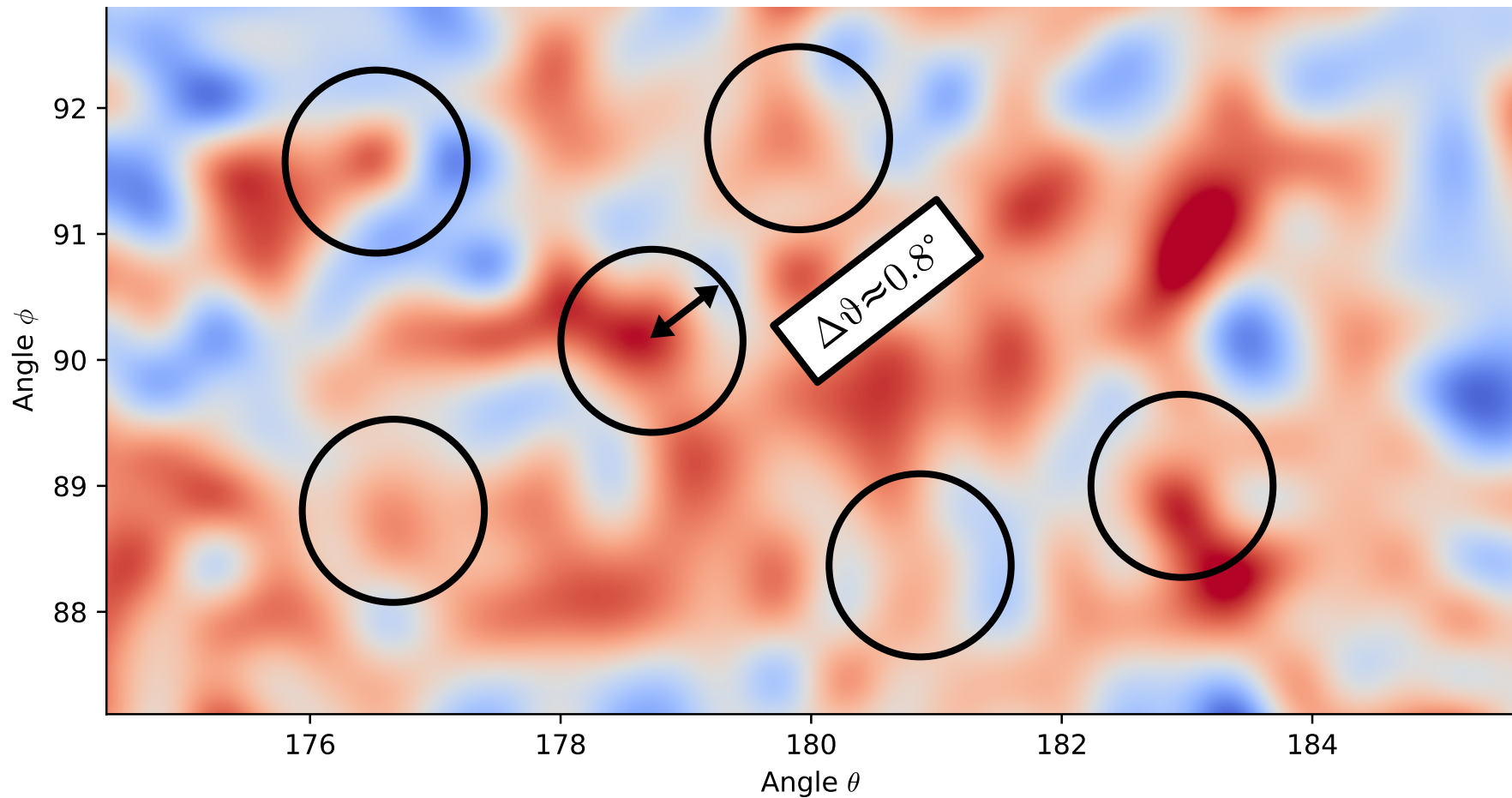
THE CMB ANISOTROPIES



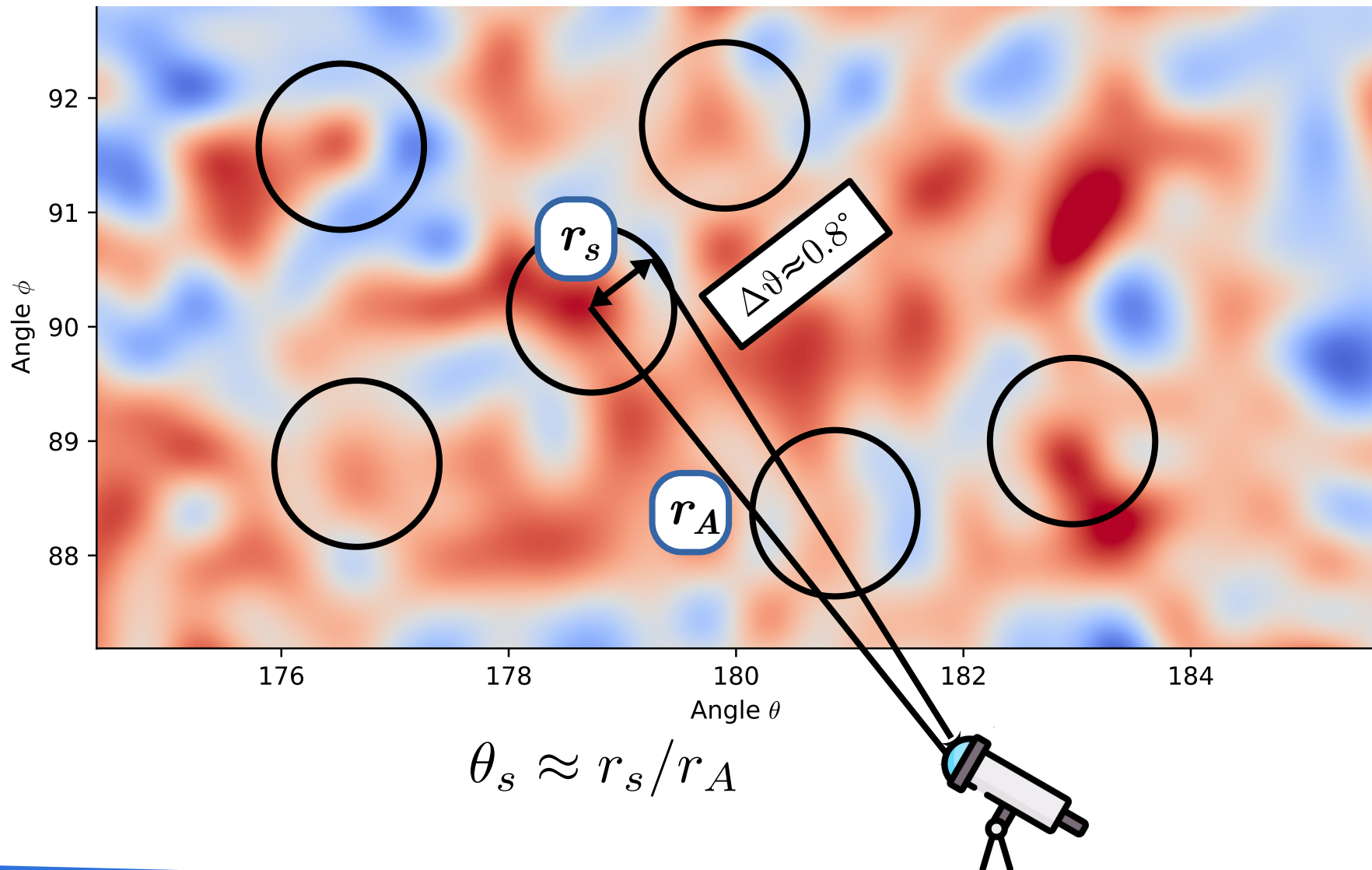
THE CMB ANISOTROPIES



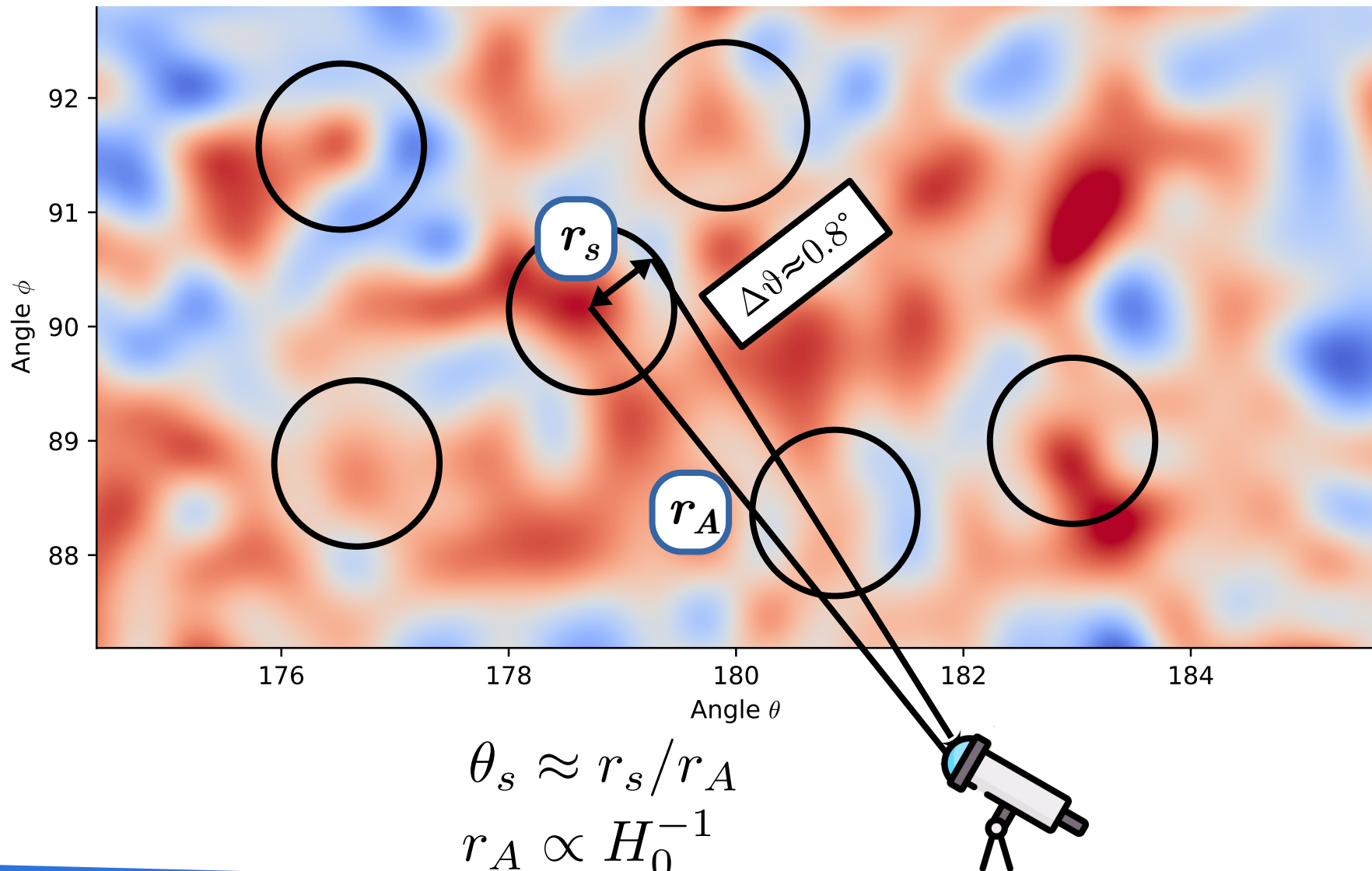
THE CMB ANISOTROPIES



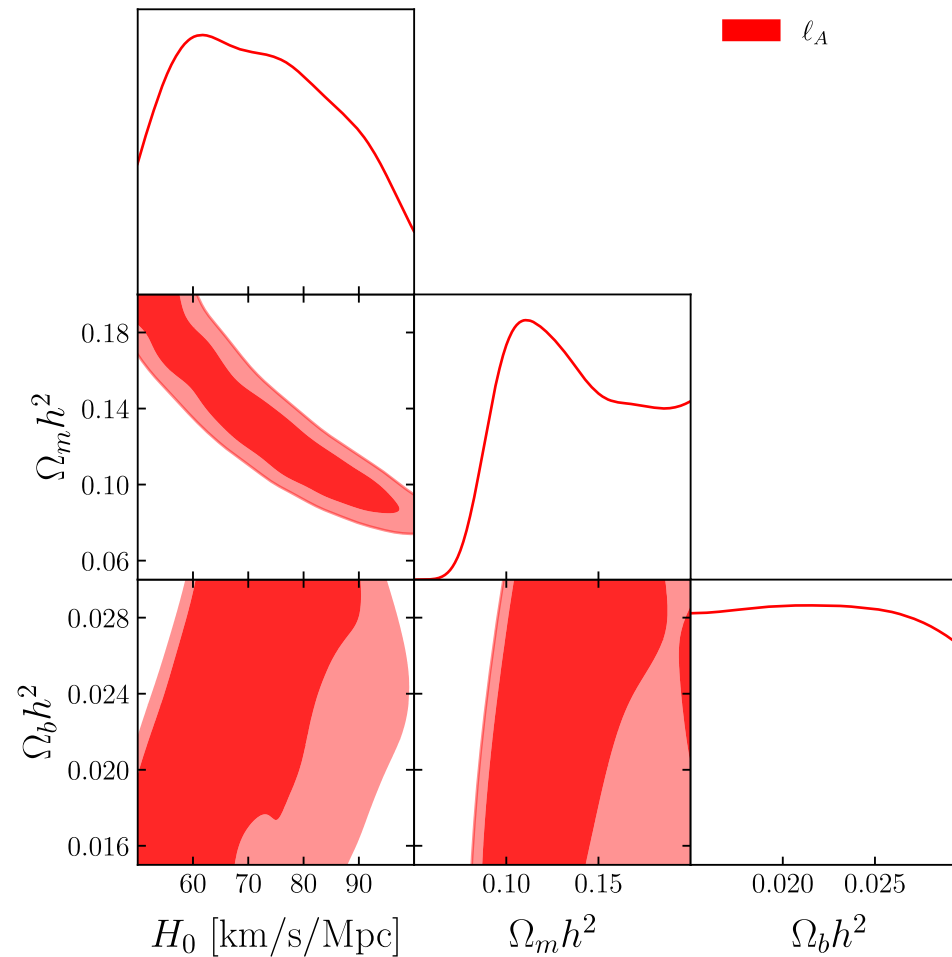
THE CMB ANISOTROPIES



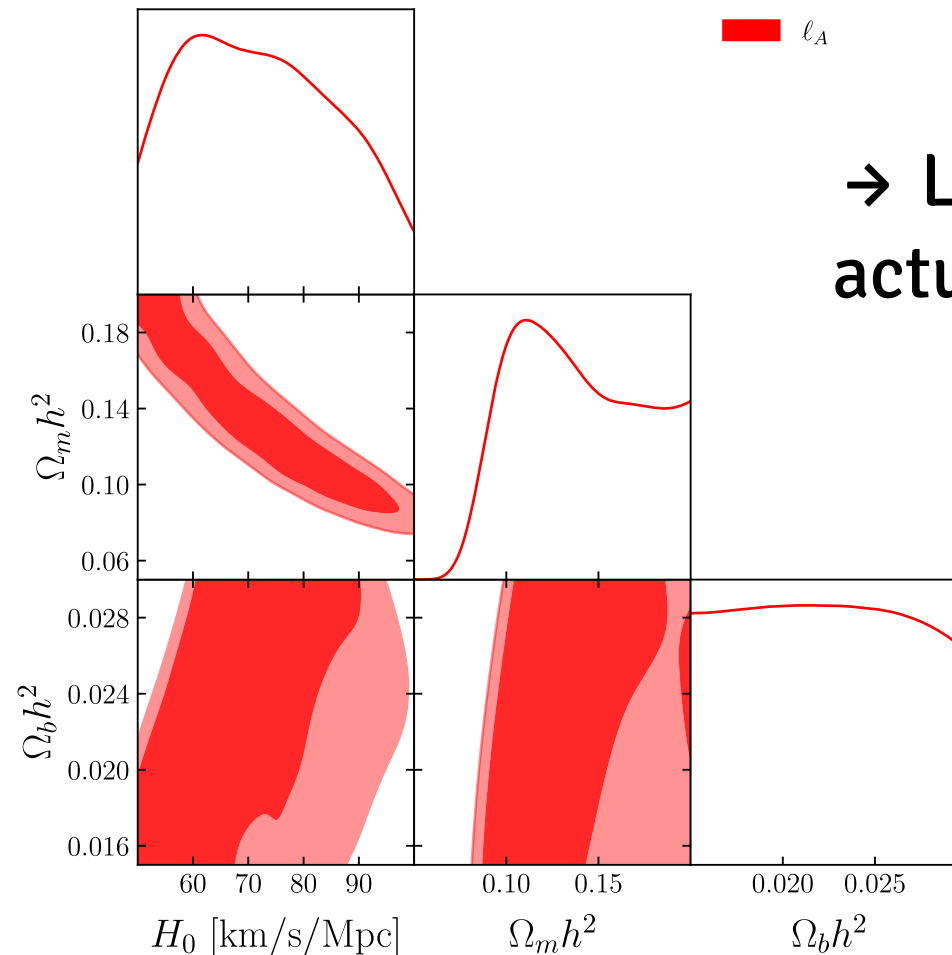
THE CMB ANISOTROPIES



IF YOU ONLY HAD THAT SCALE...

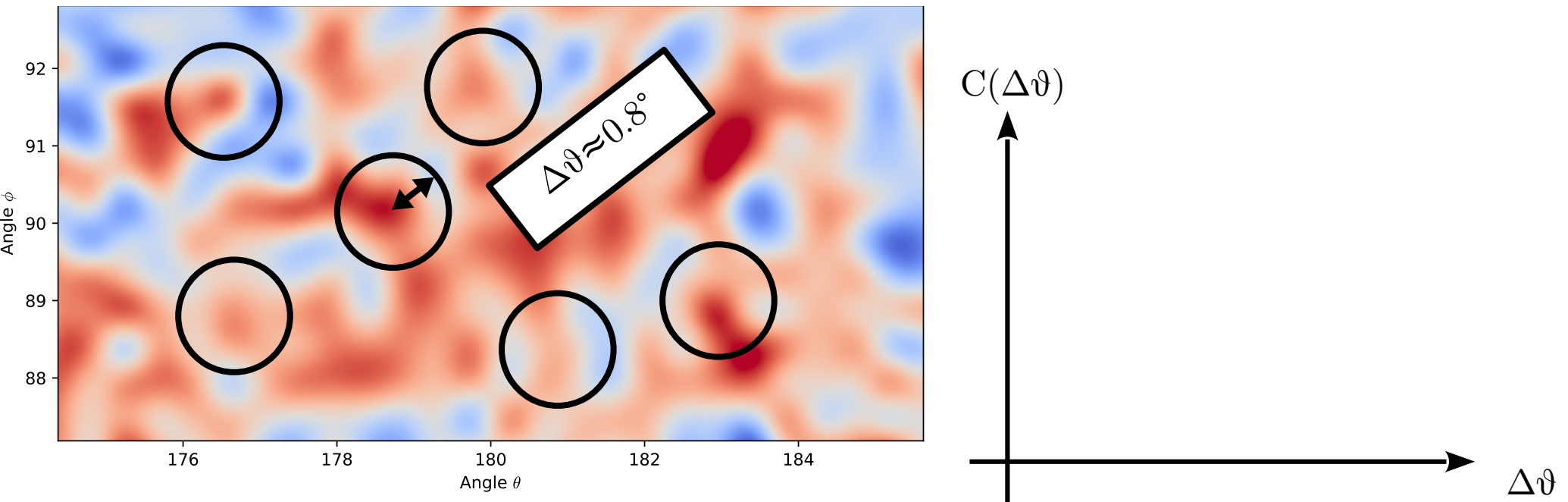


IF YOU ONLY HAD THAT SCALE...

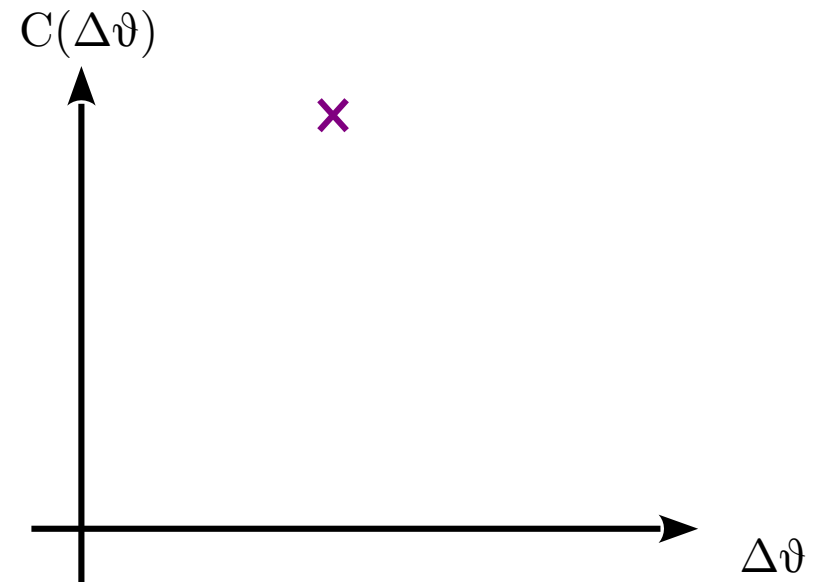
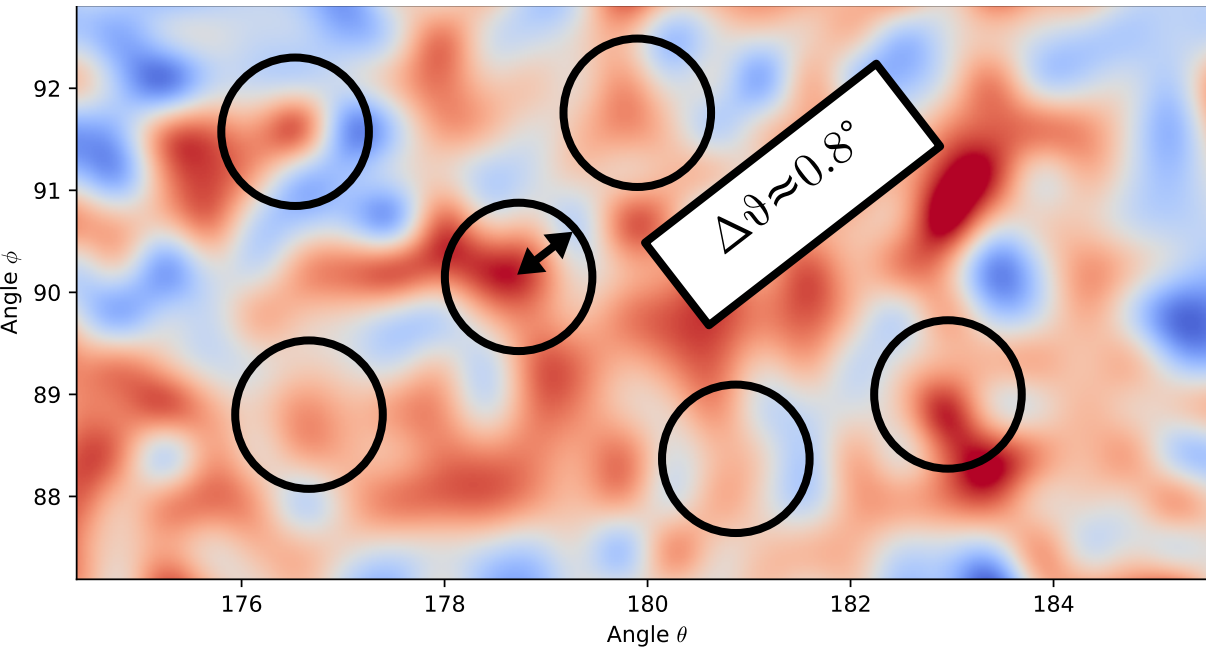


→ Let's see how it's actually done!

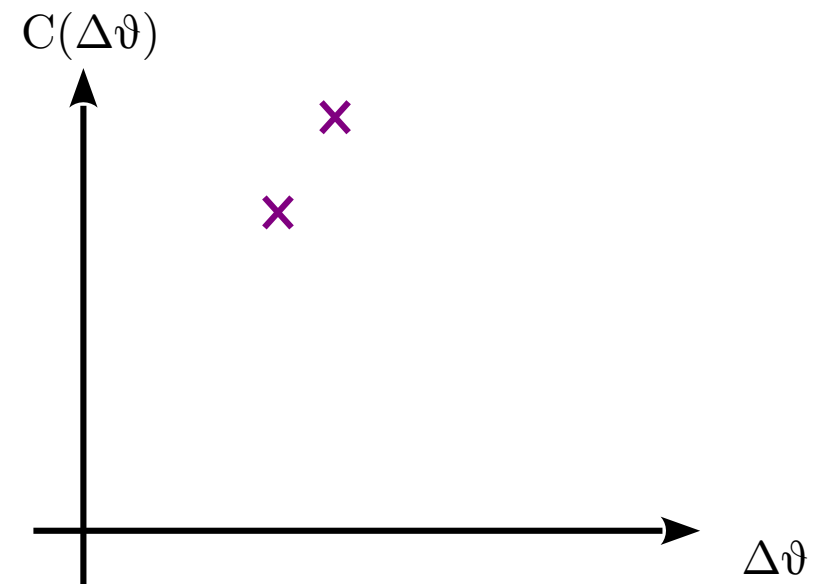
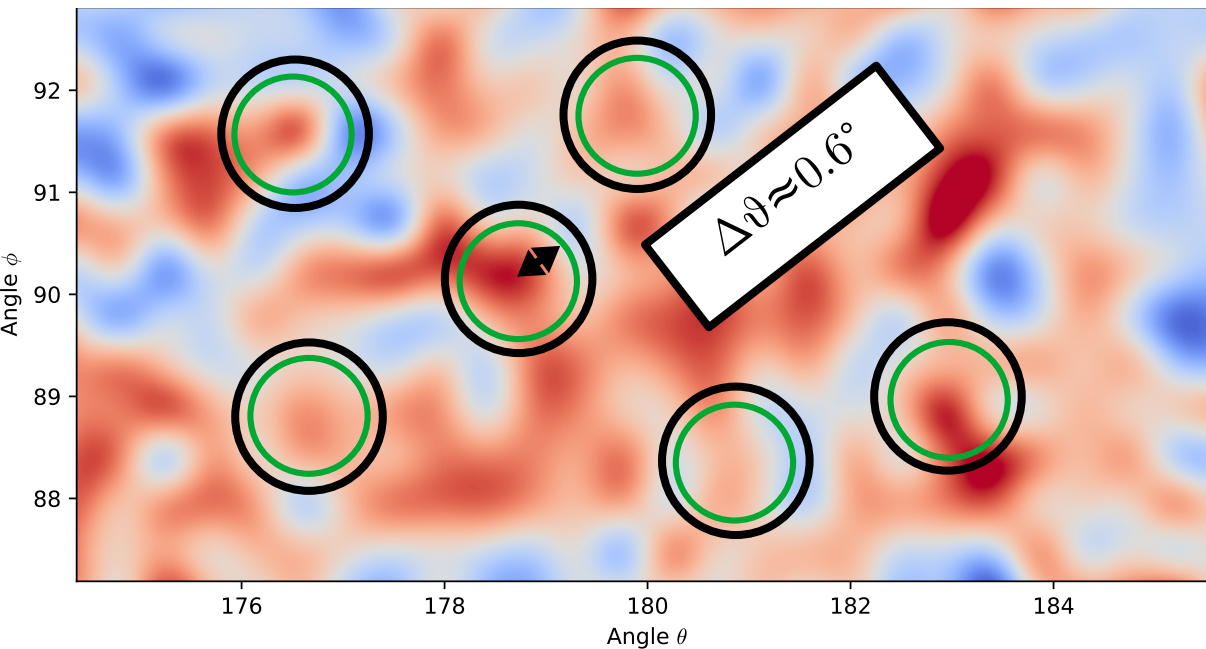
THE CMB ANISOTROPIES



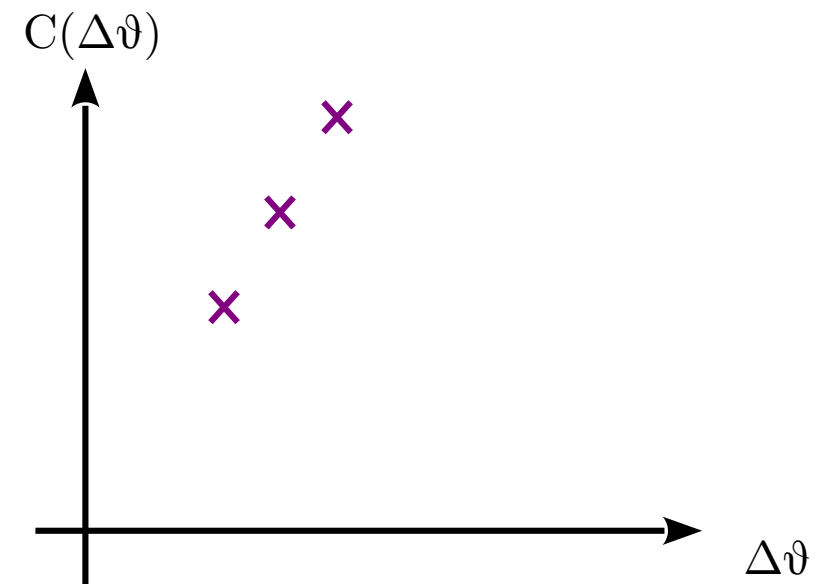
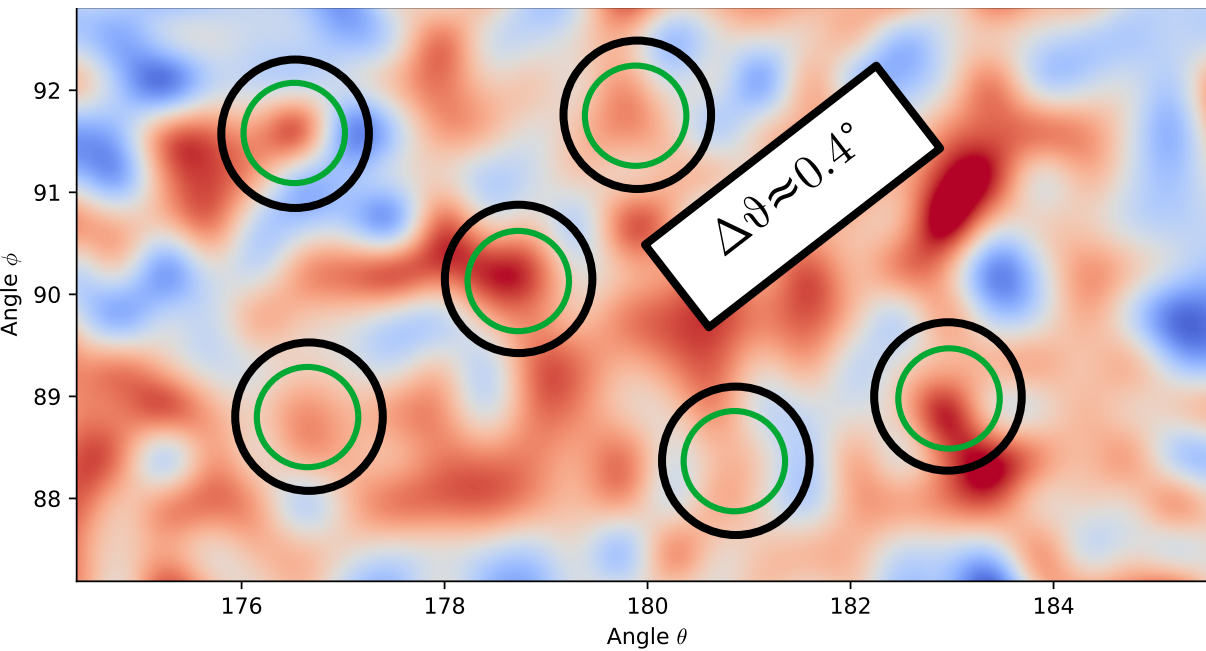
THE CMB ANISOTROPIES



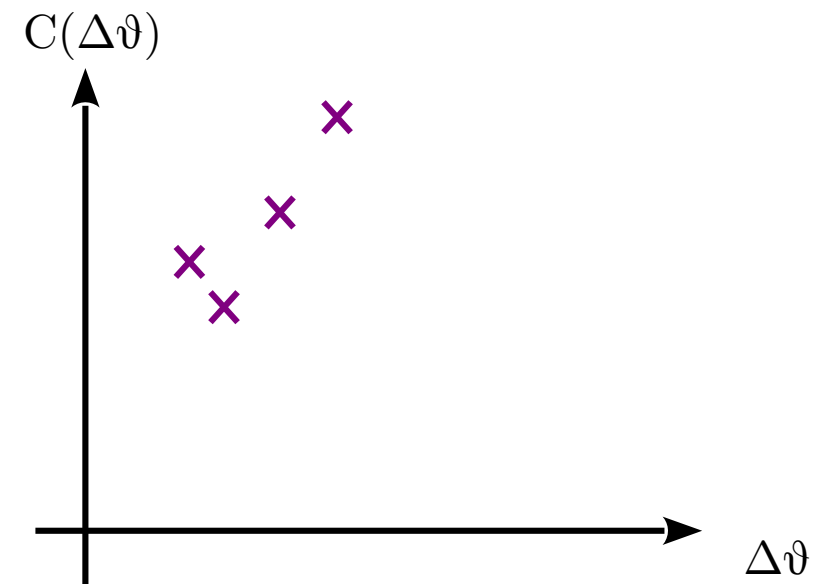
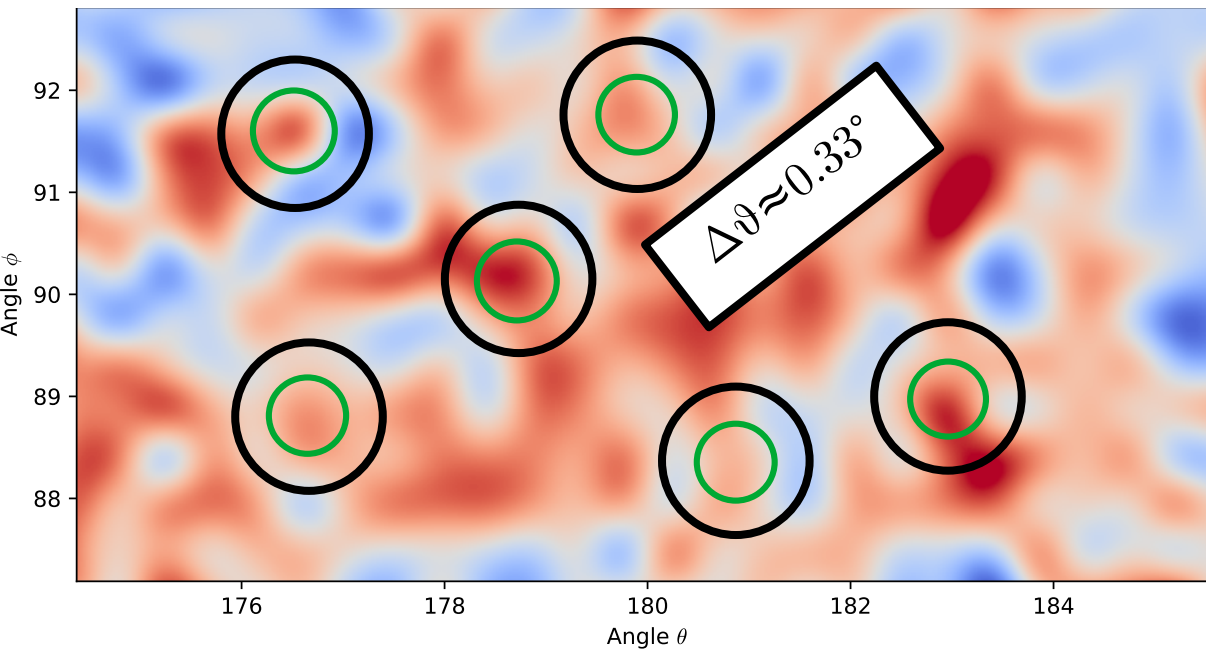
THE CMB ANISOTROPIES



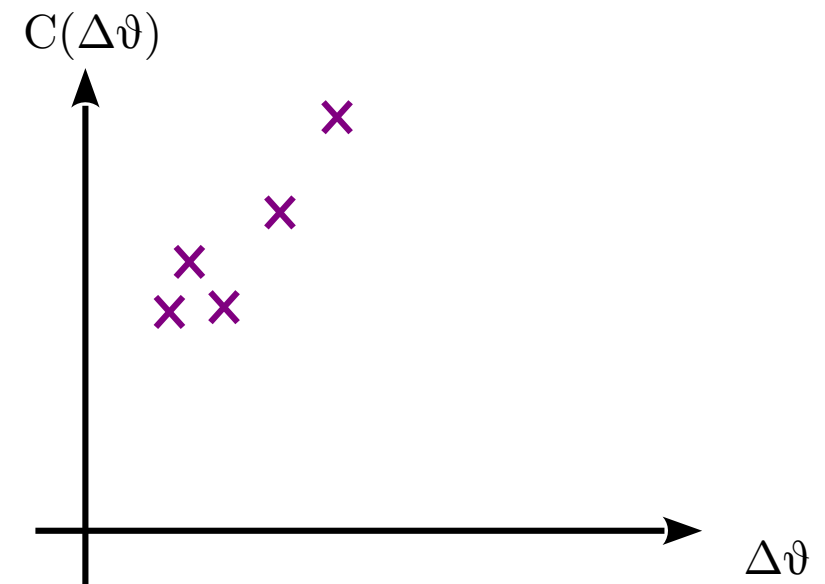
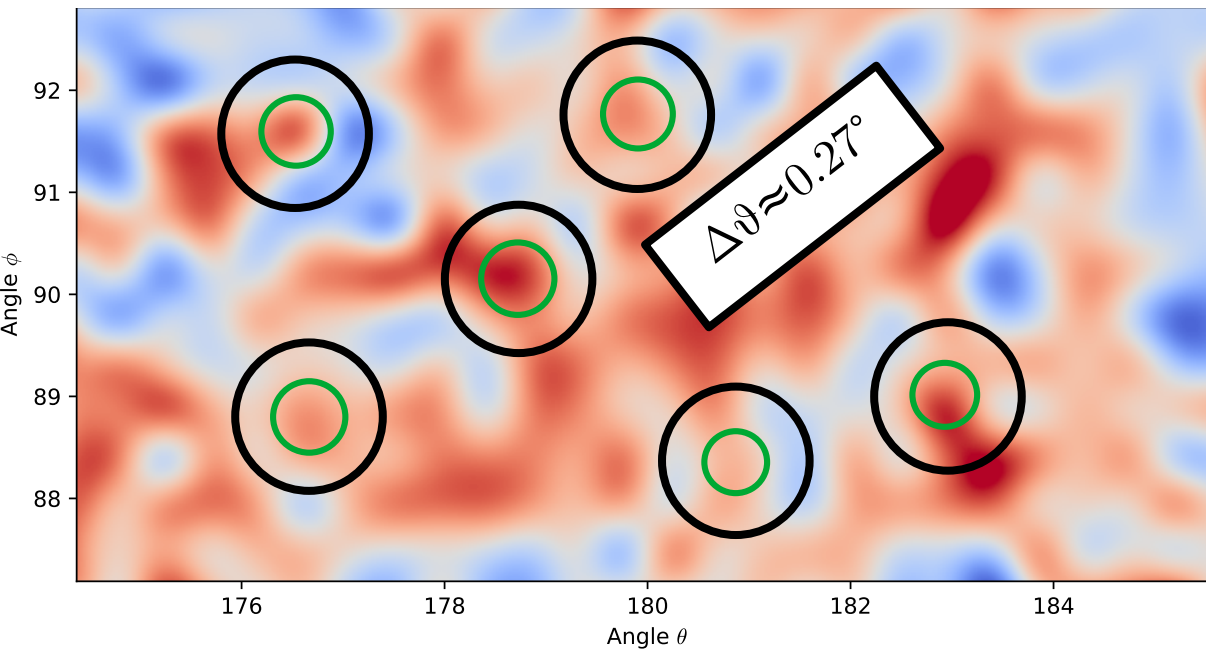
THE CMB ANISOTROPIES



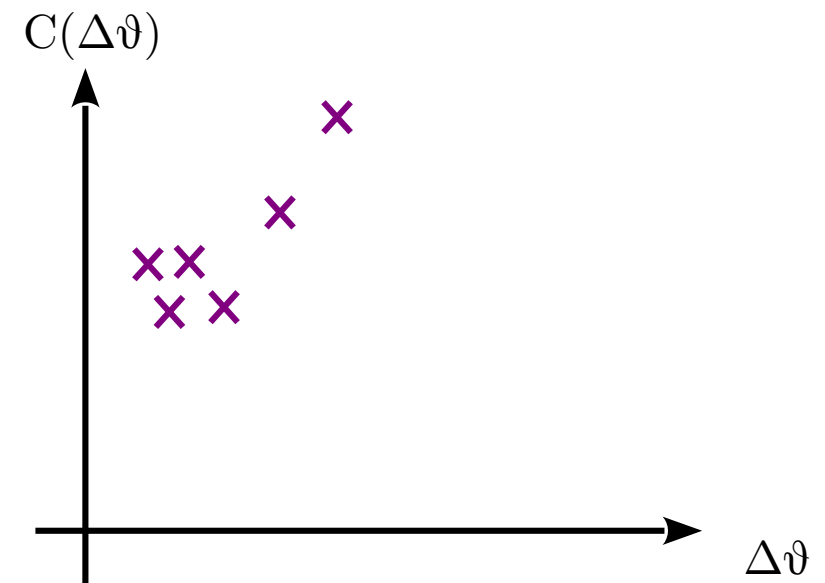
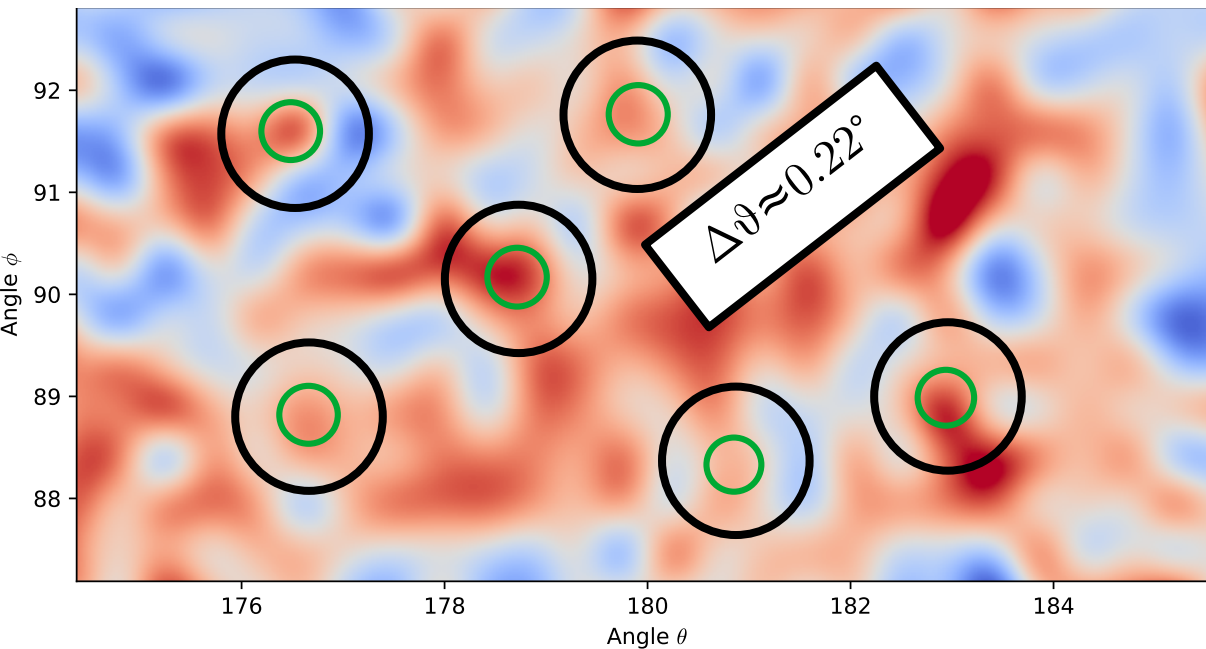
THE CMB ANISOTROPIES



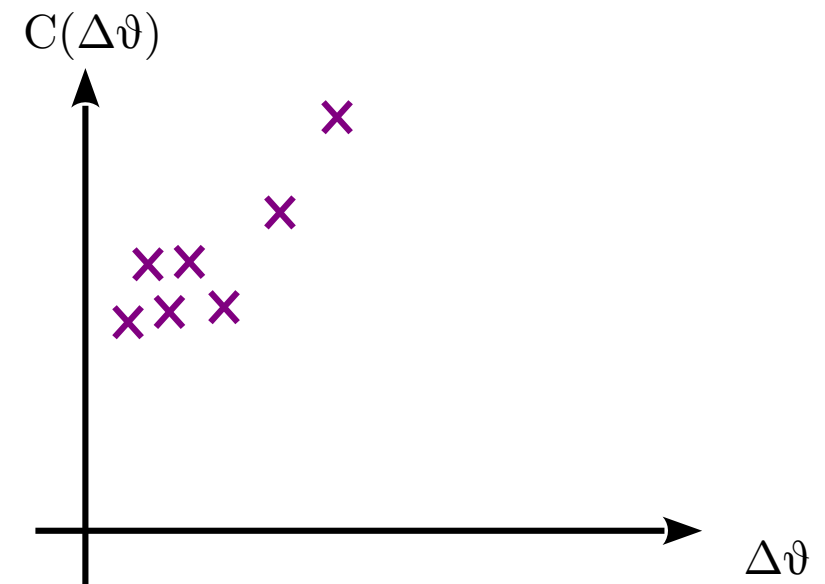
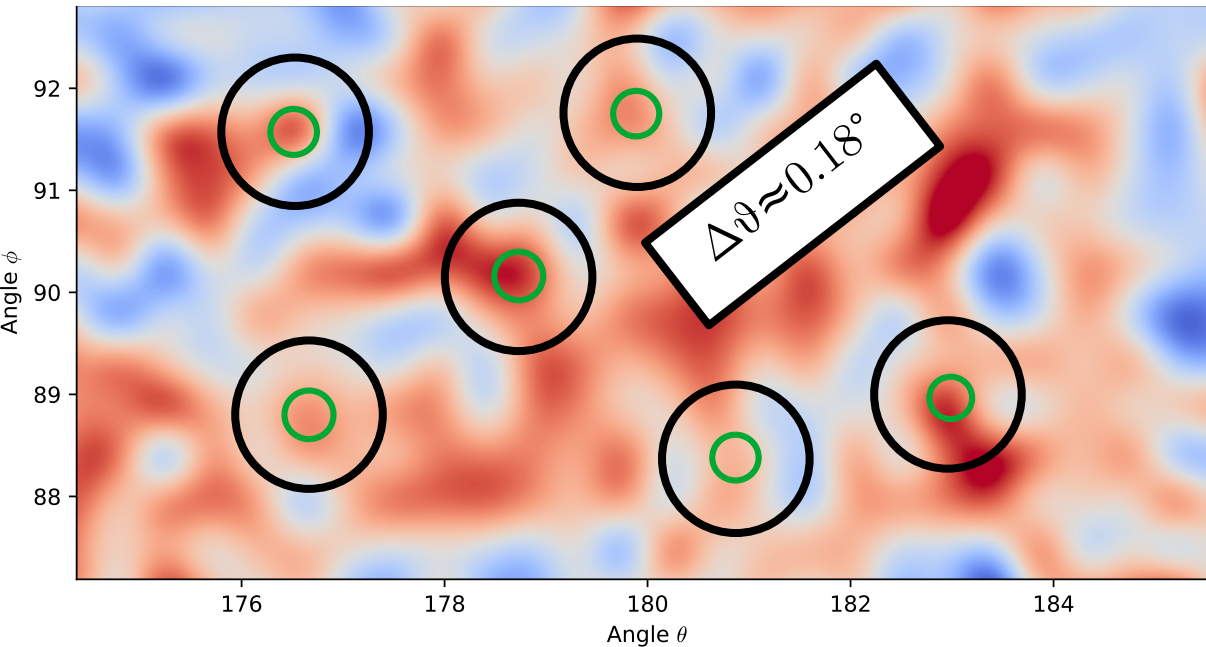
THE CMB ANISOTROPIES



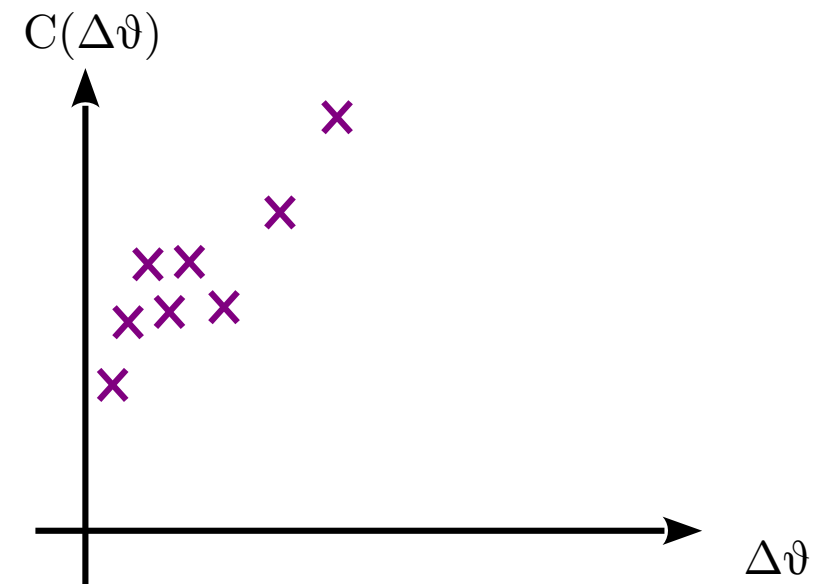
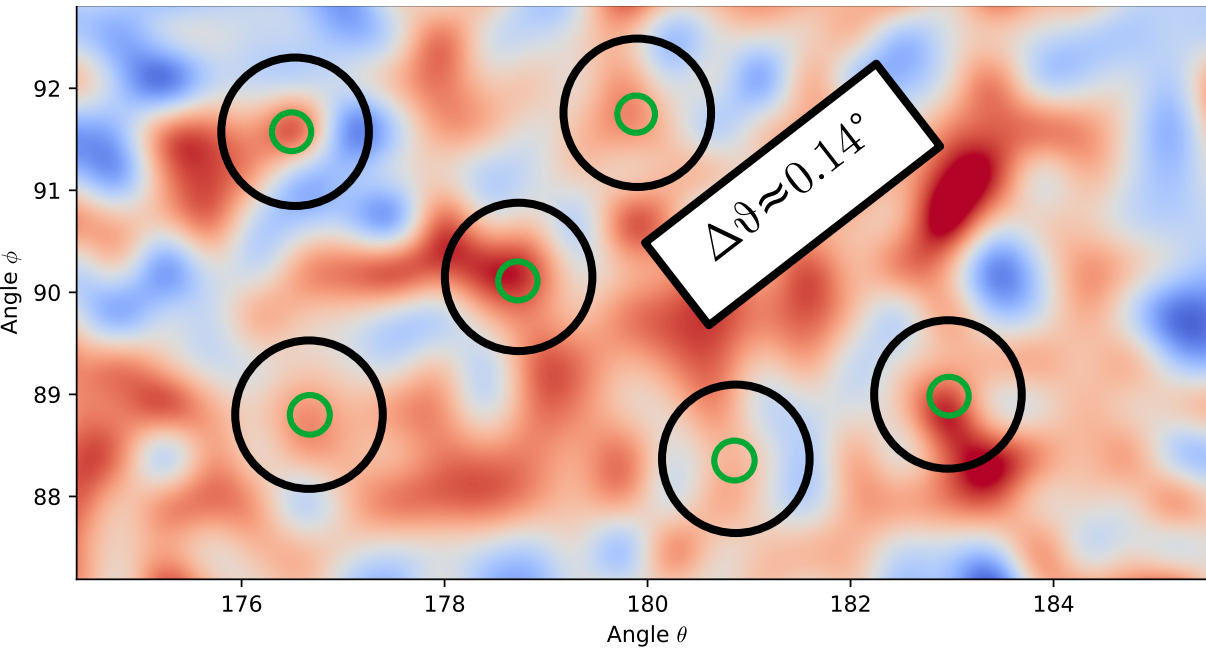
THE CMB ANISOTROPIES



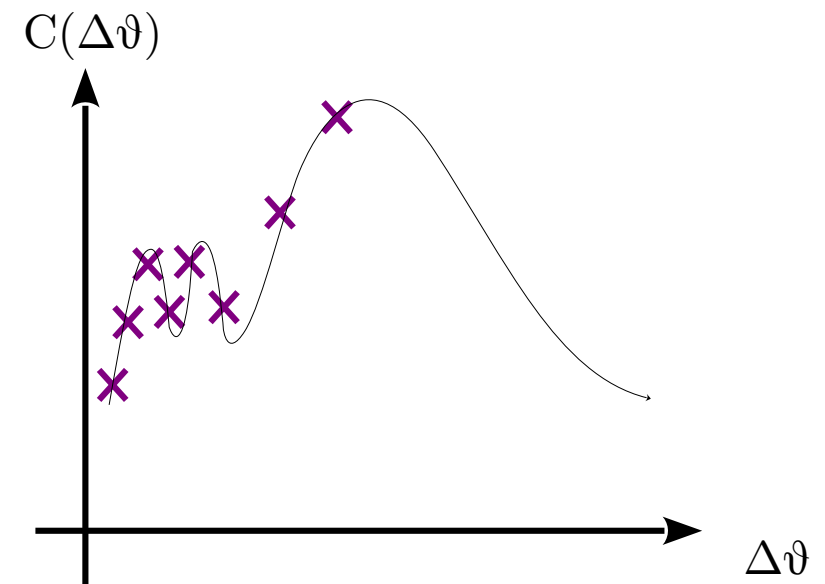
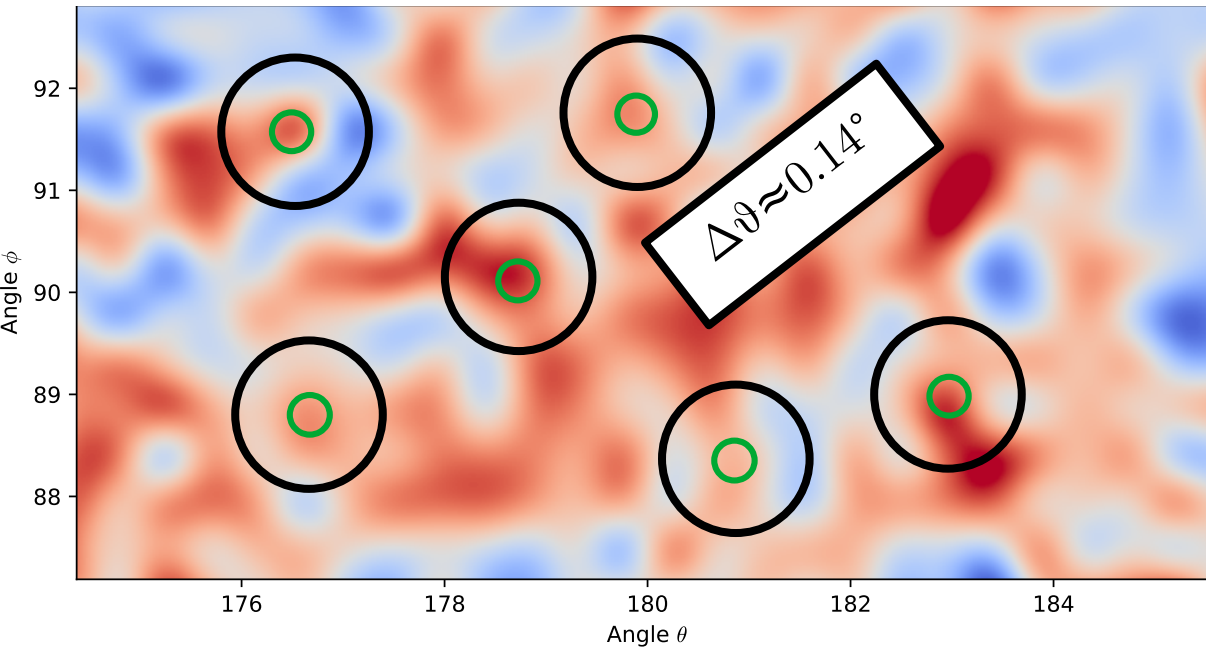
THE CMB ANISOTROPIES



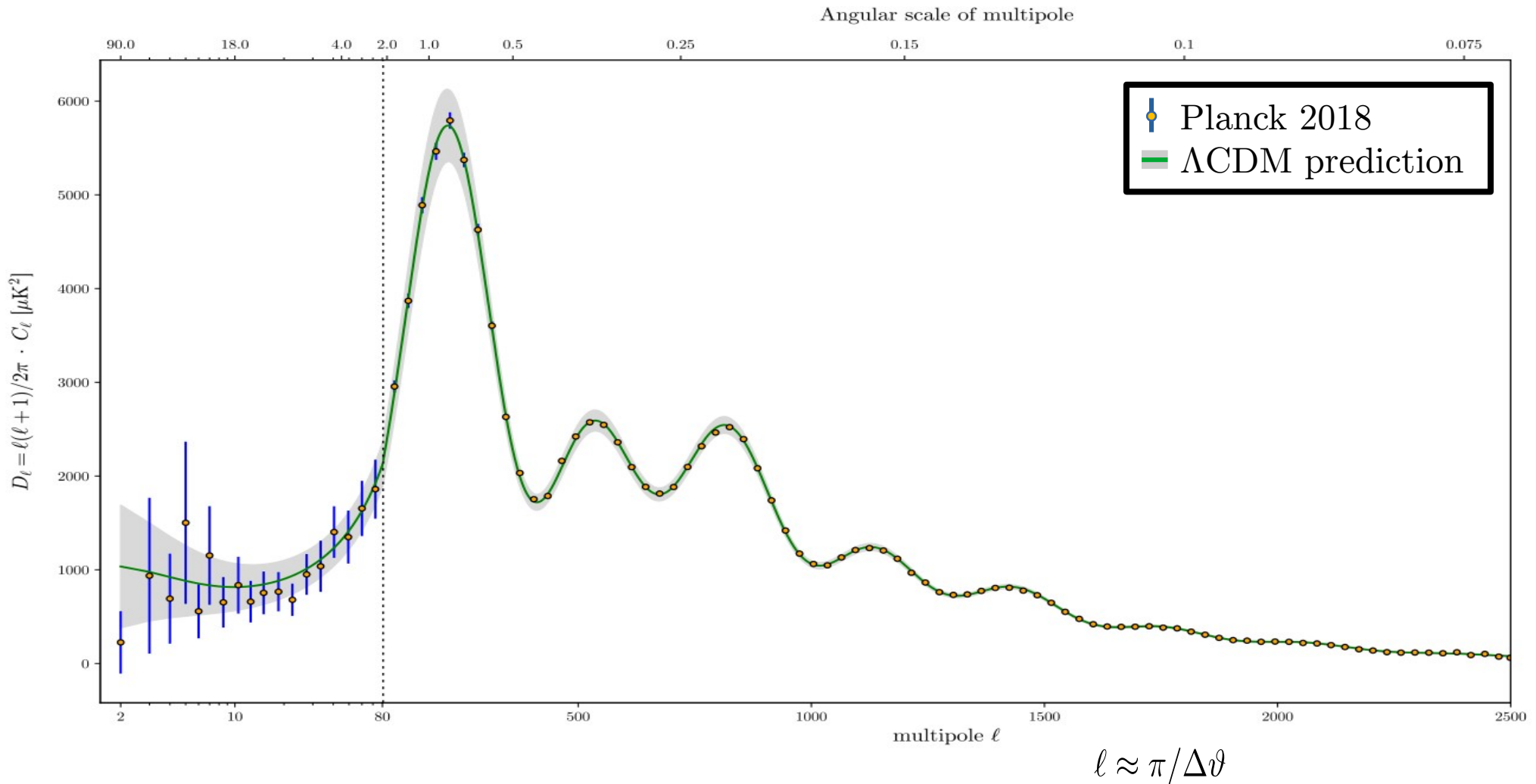
THE CMB ANISOTROPIES



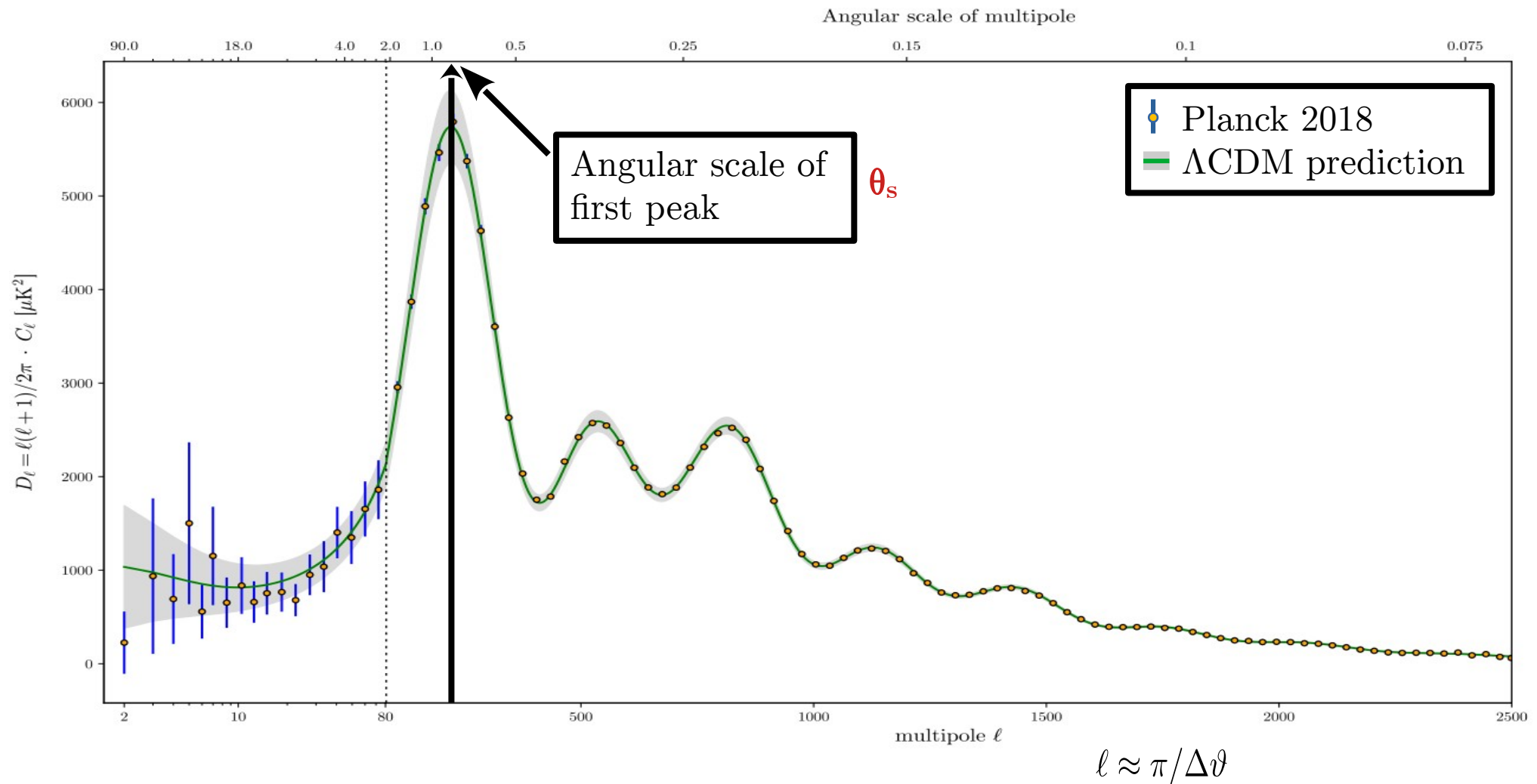
THE CMB ANISOTROPIES



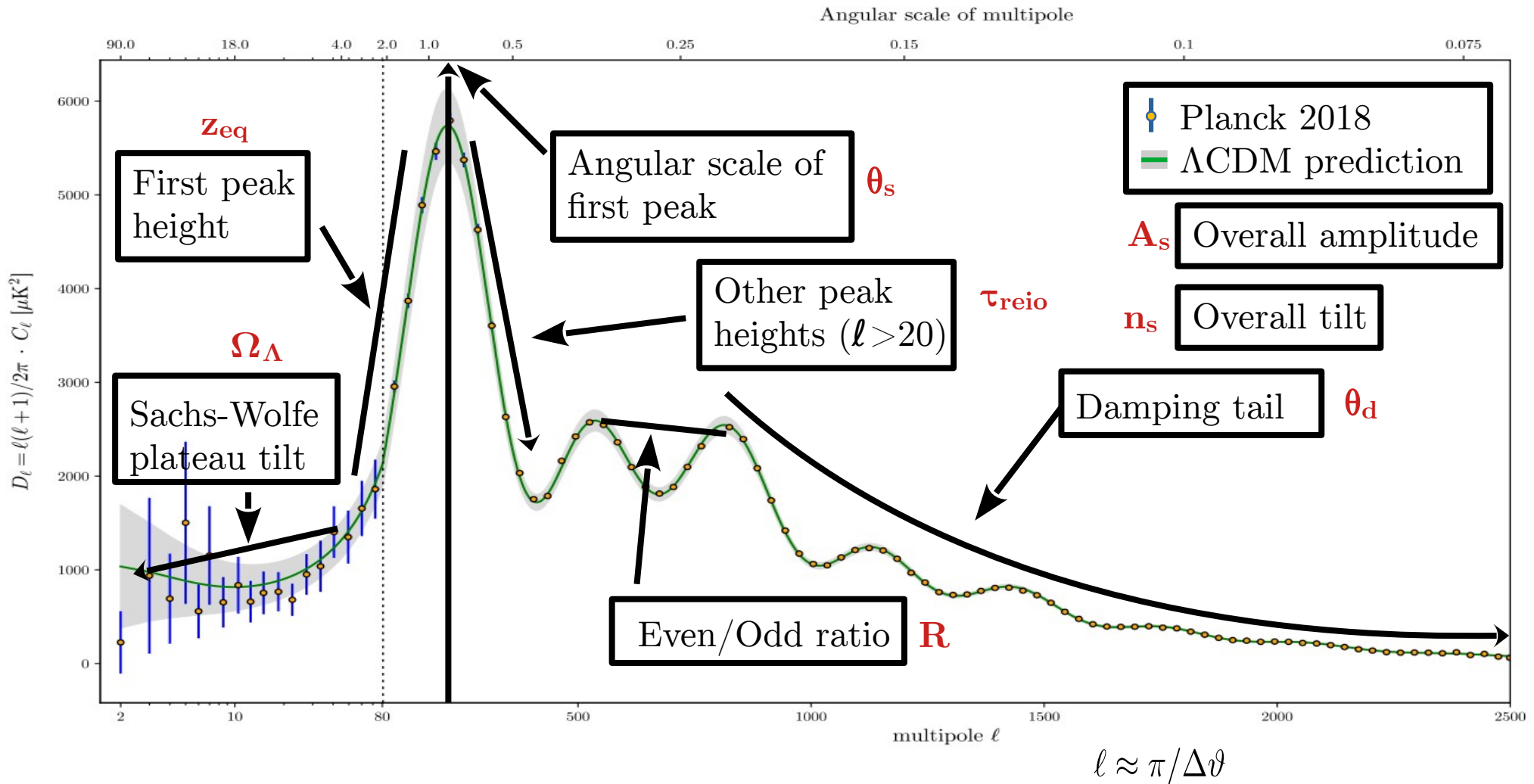
THE CMB



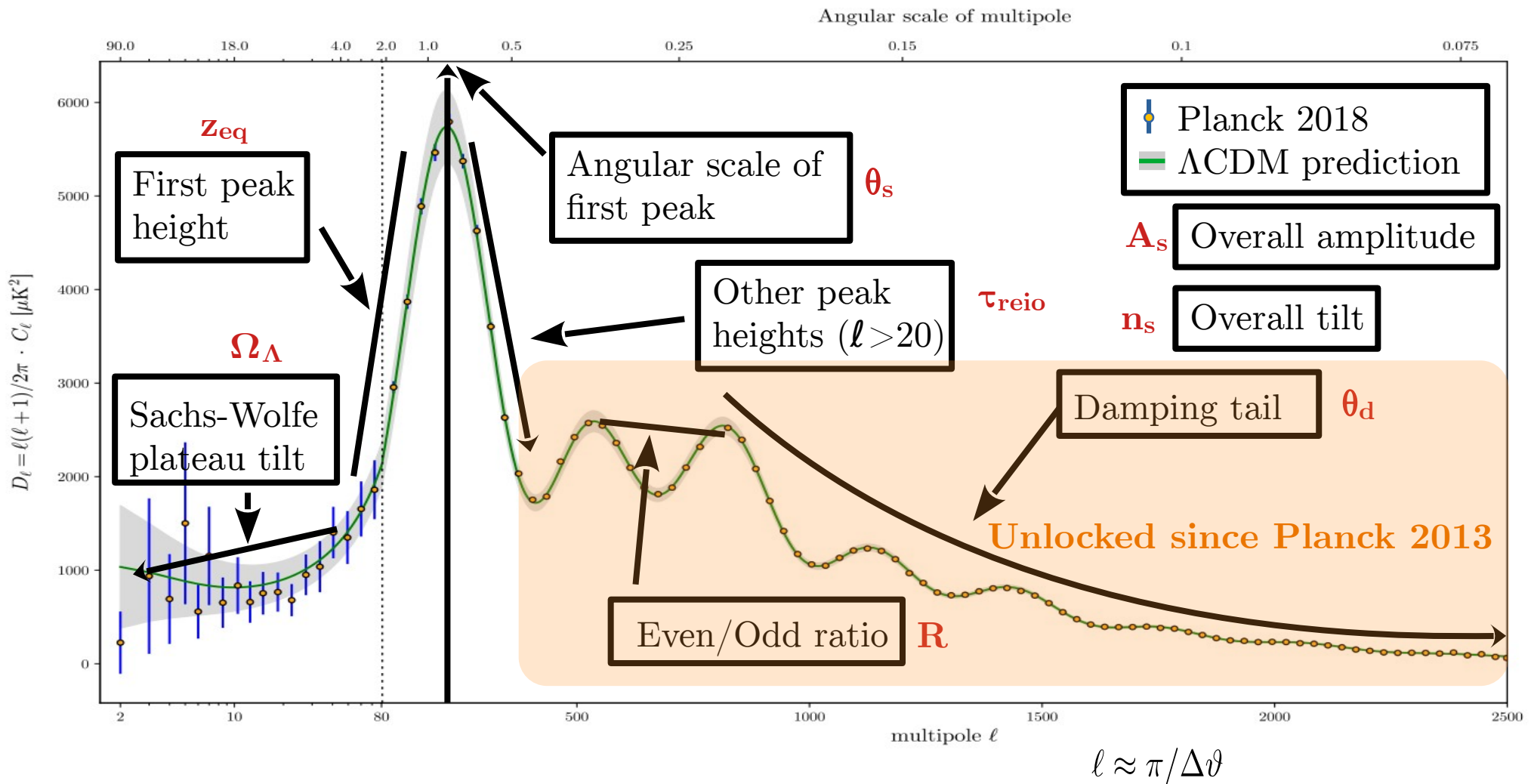
THE CMB



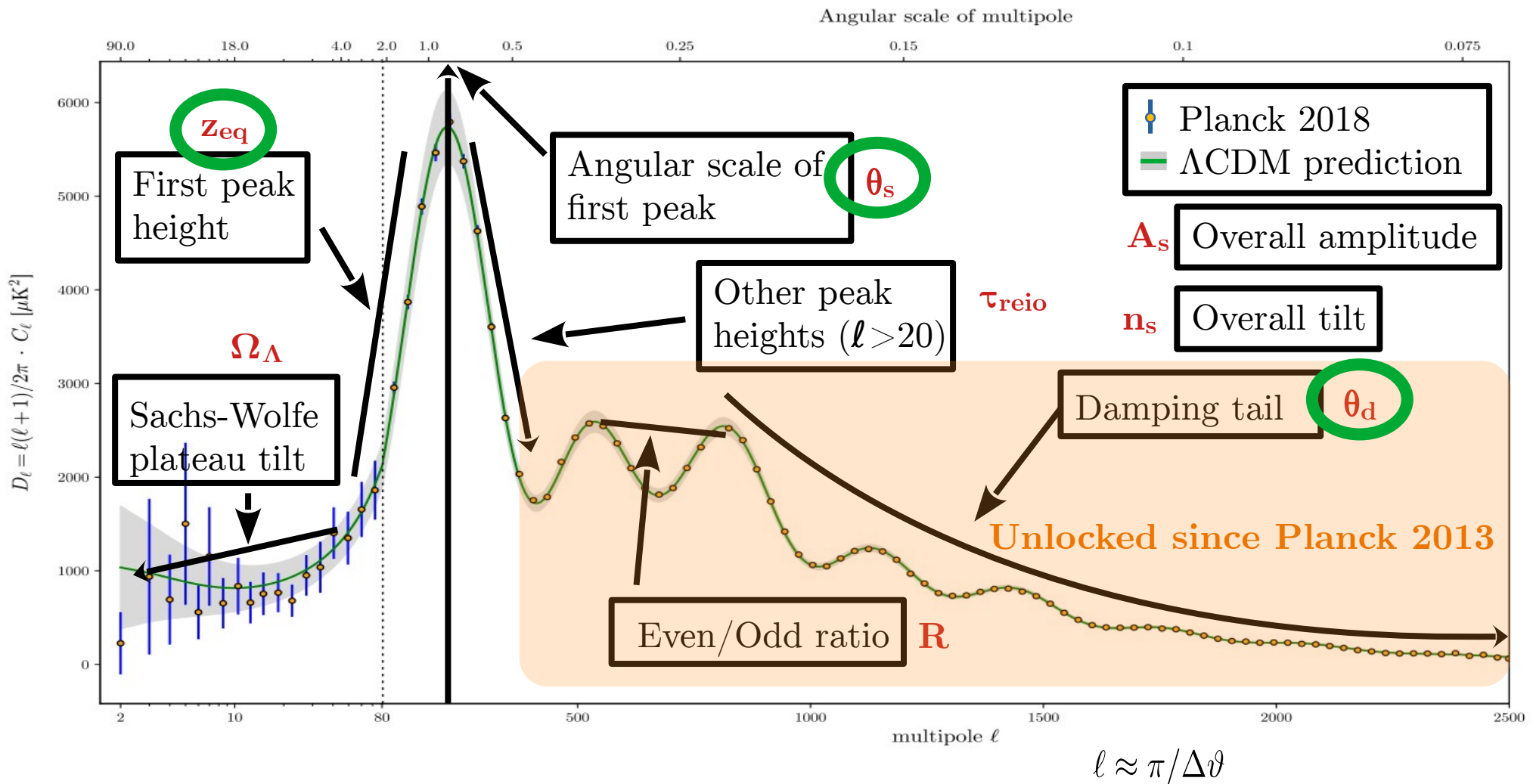
THE CMB



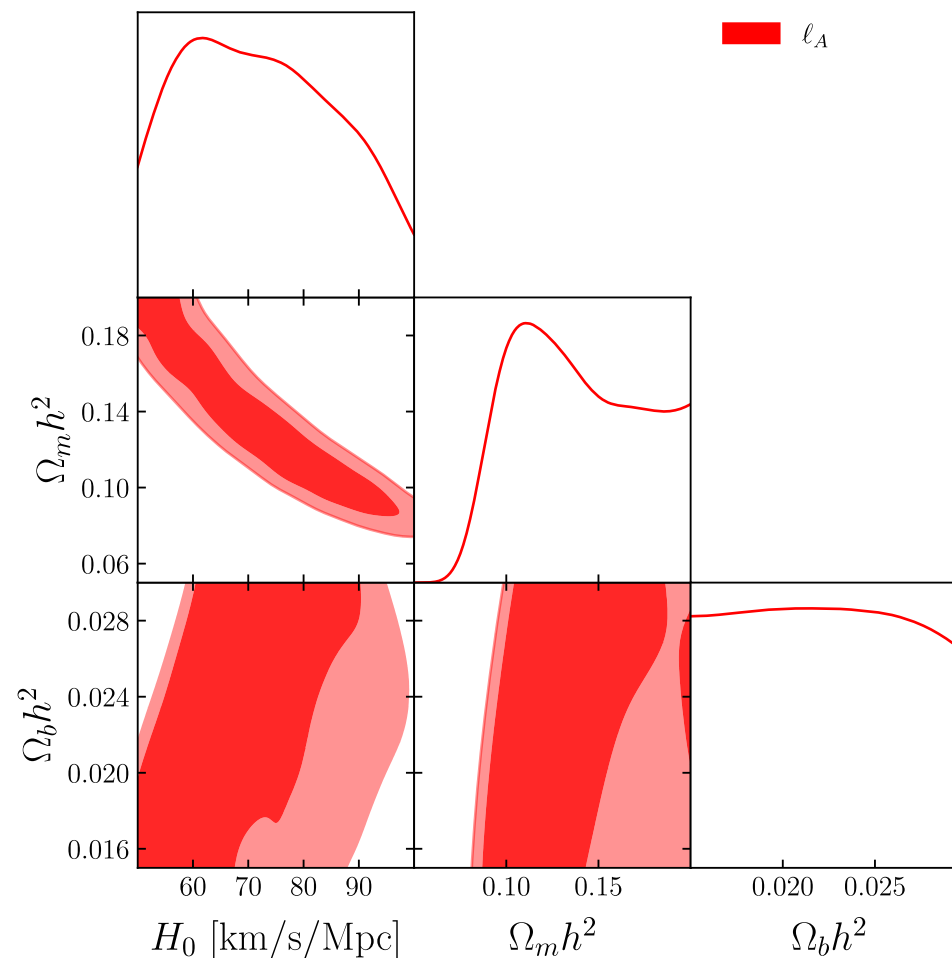
THE CMB



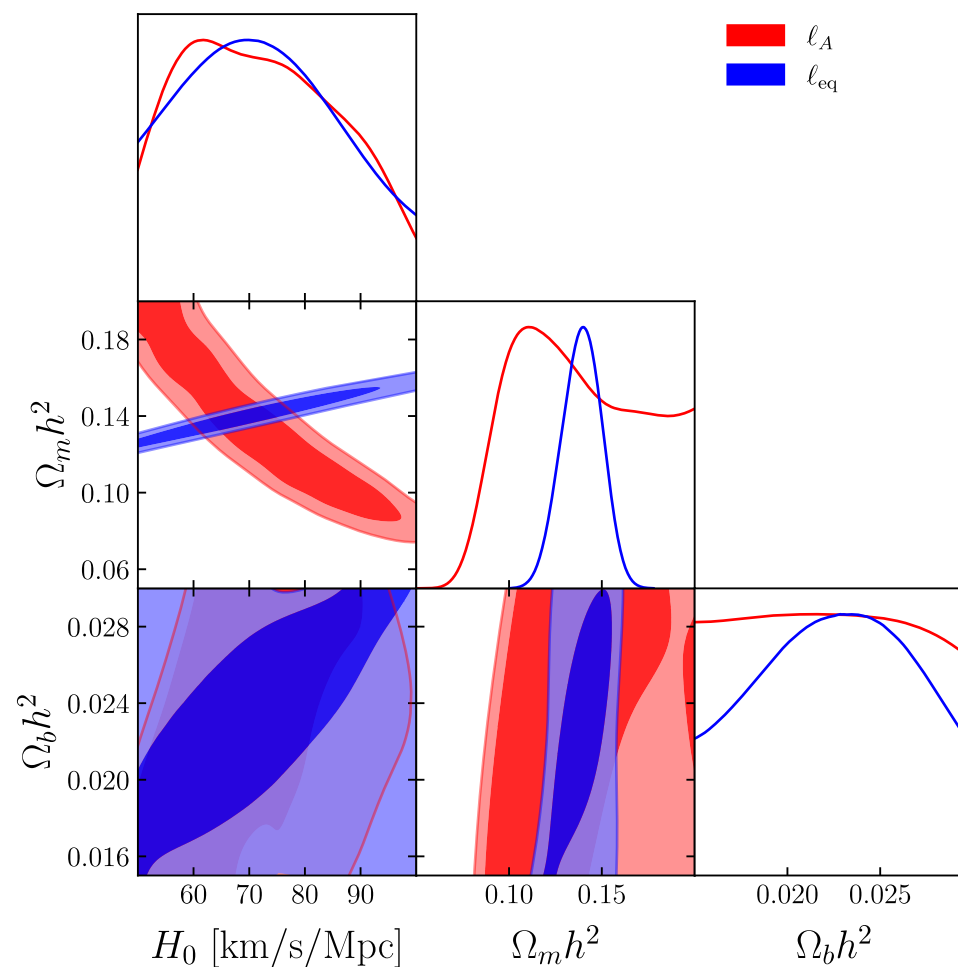
THE CMB



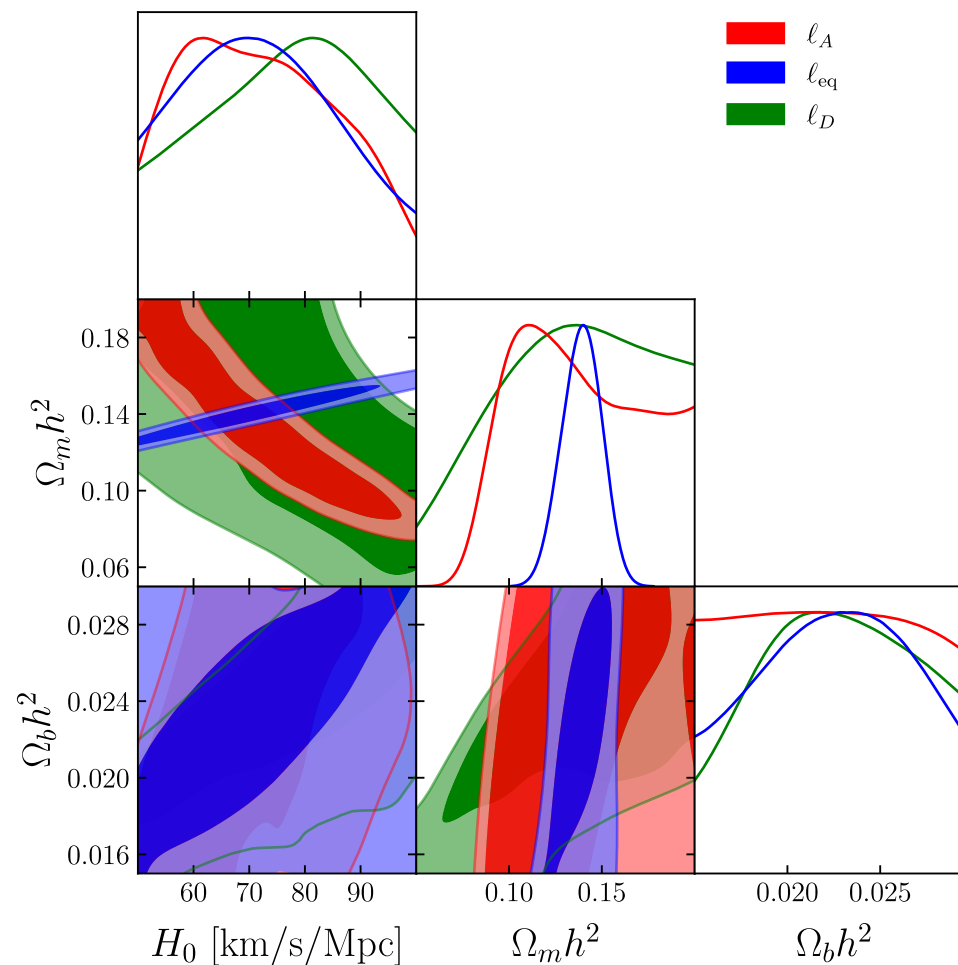
IF YOU ONLY HAD THOSE SCALES...



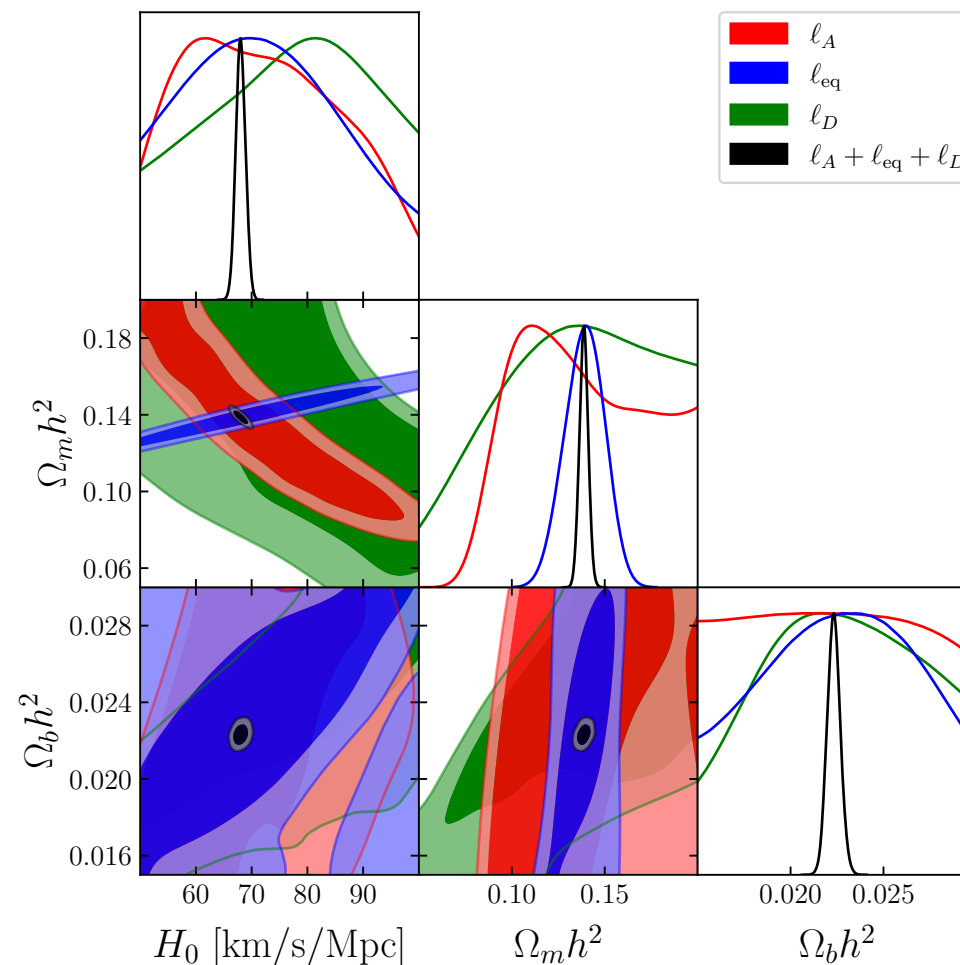
IF YOU ONLY HAD THOSE SCALES...



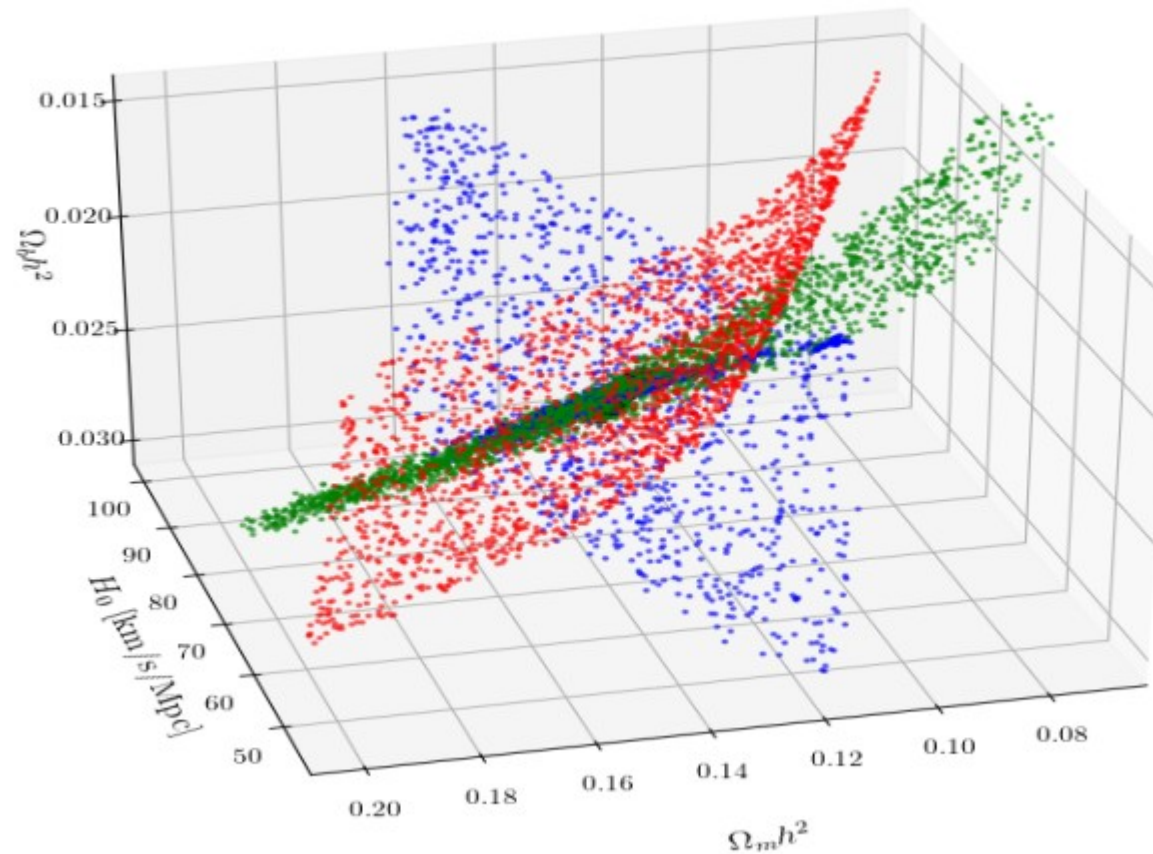
IF YOU ONLY HAD THOSE SCALES...



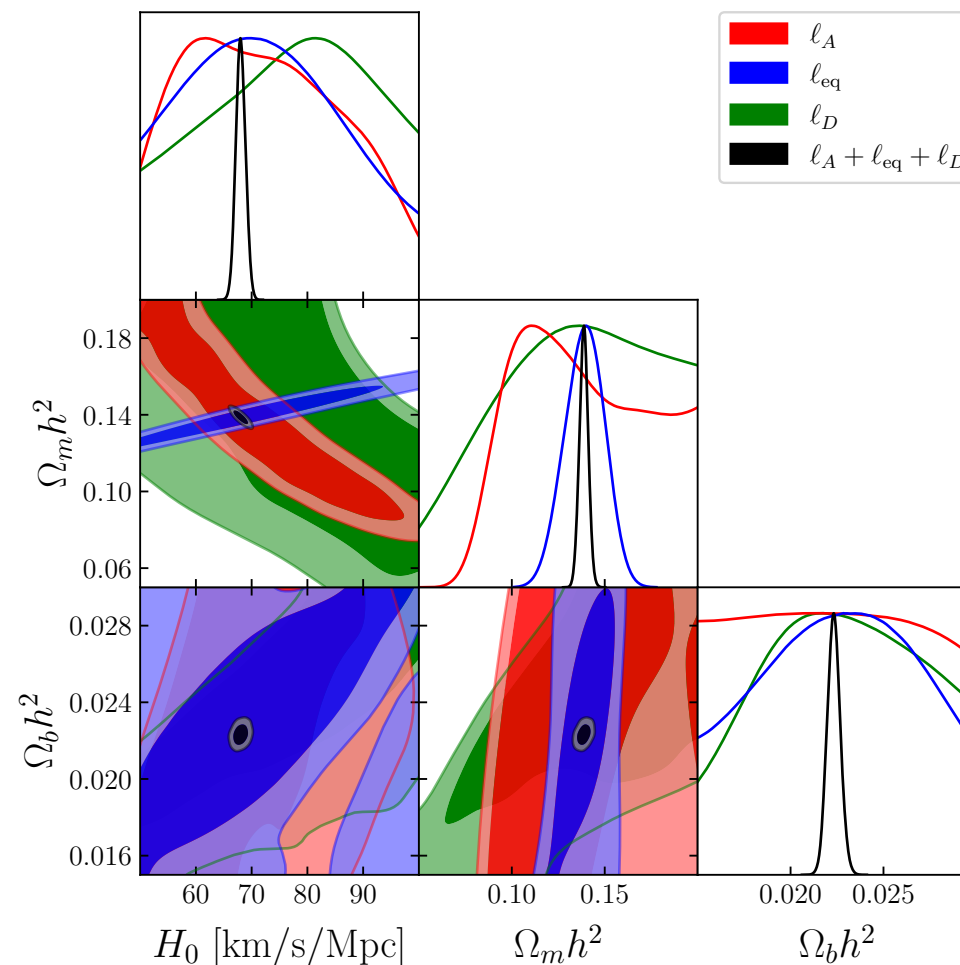
IF YOU ONLY HAD THOSE SCALES...



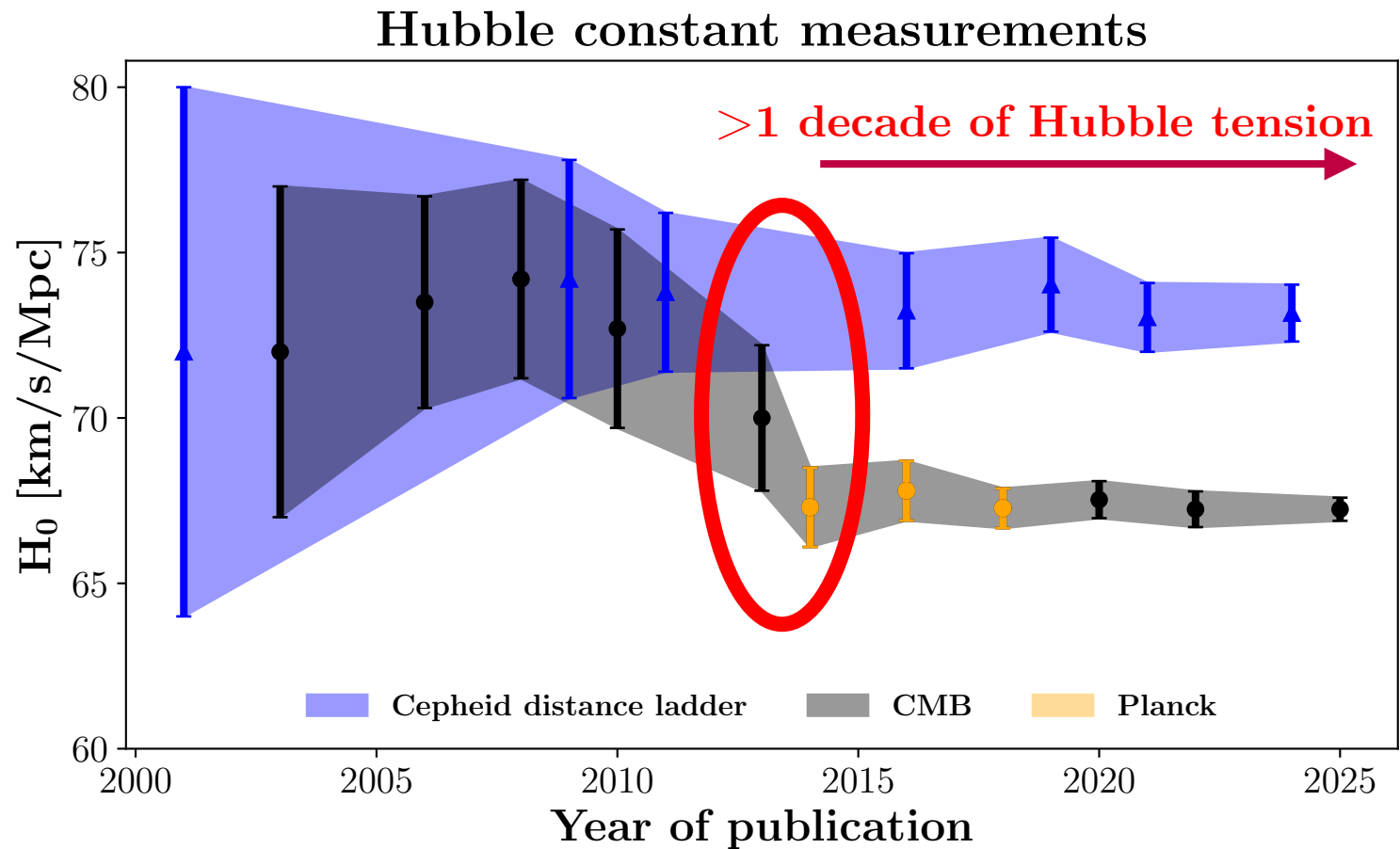
IF YOU ONLY HAD THOSE SCALES...

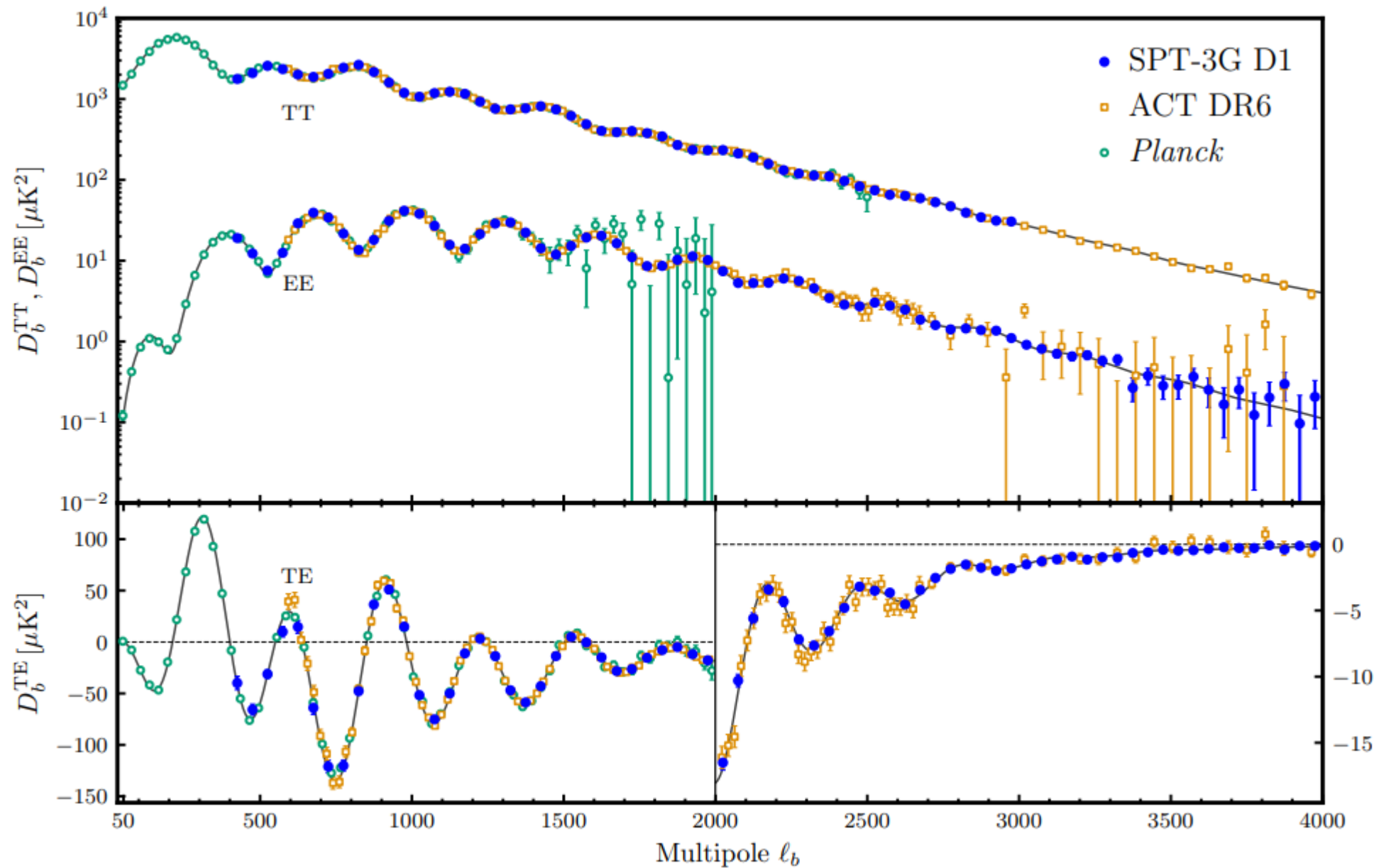


IF YOU ONLY HAD THOSE SCALES...

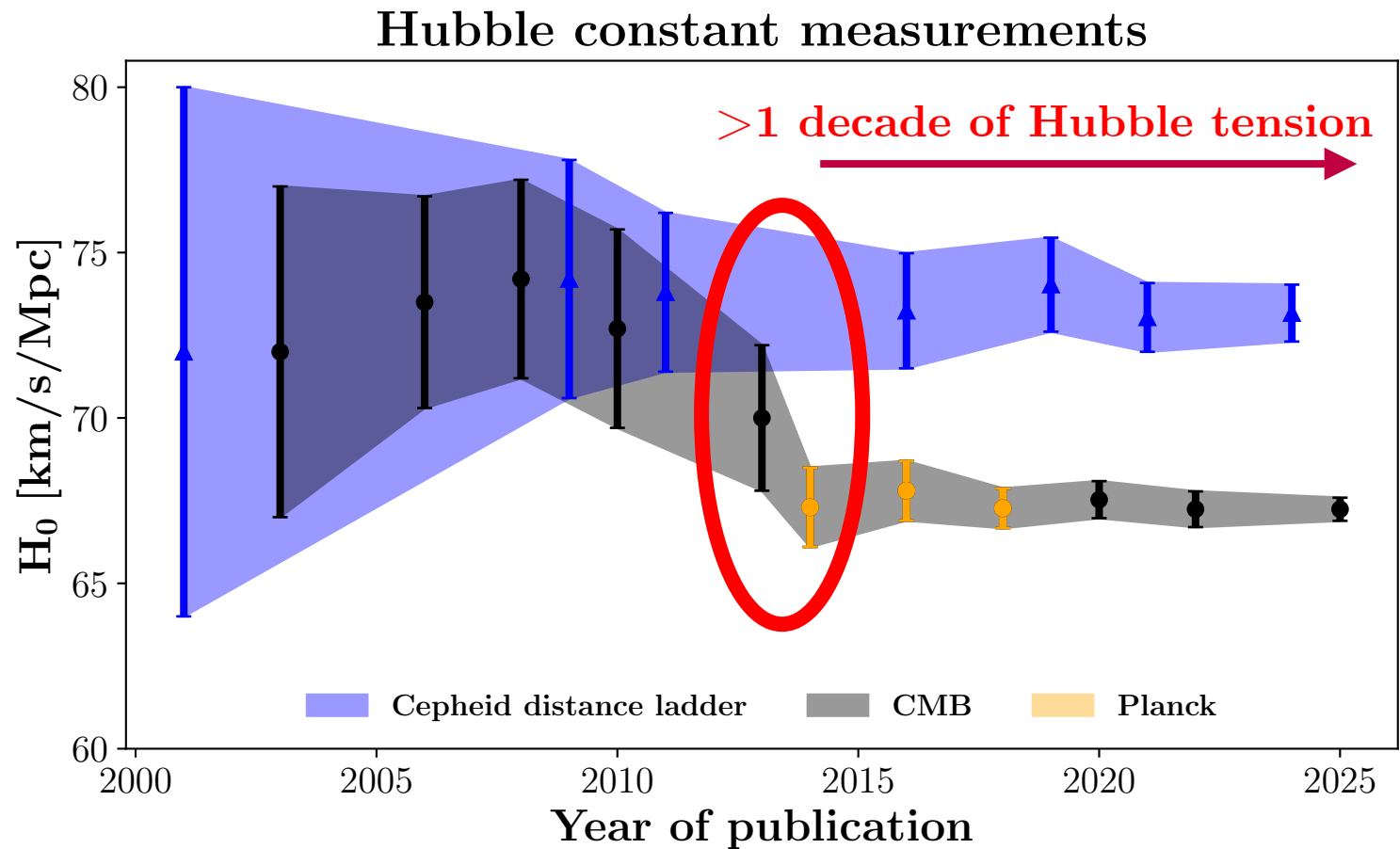


HISTORY

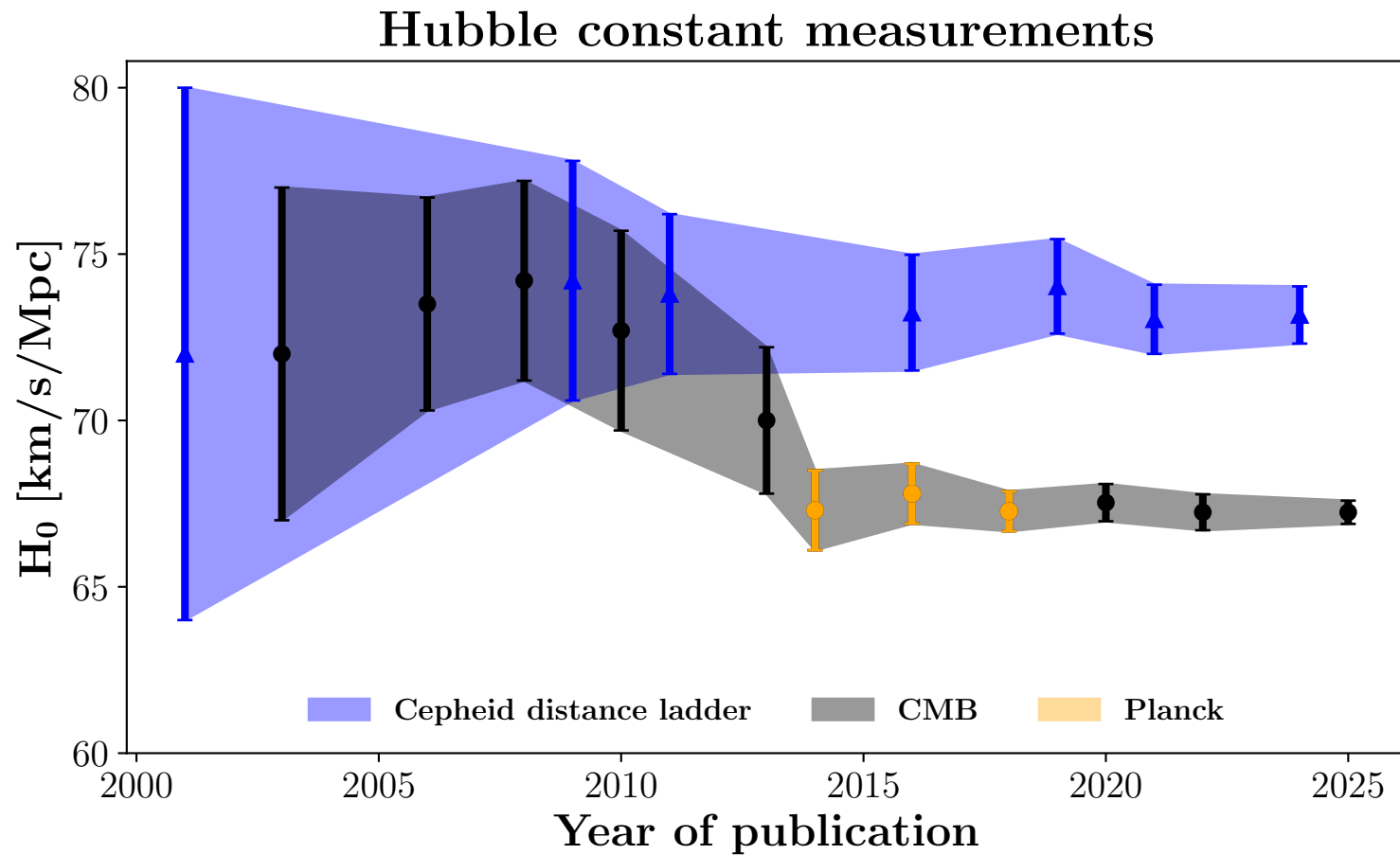




HISTORY



HISTORY

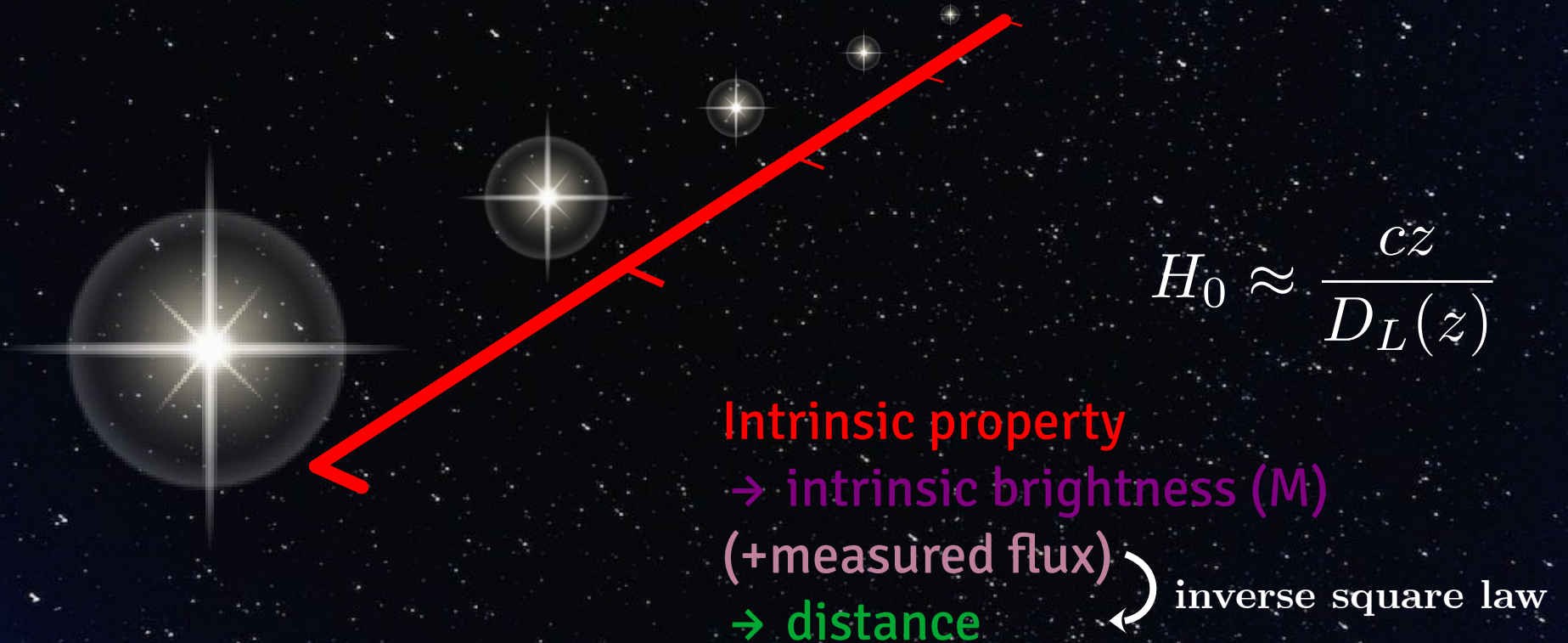


STANDARD CANDLE



$$H_0 \approx \frac{cz}{D_L(z)}$$

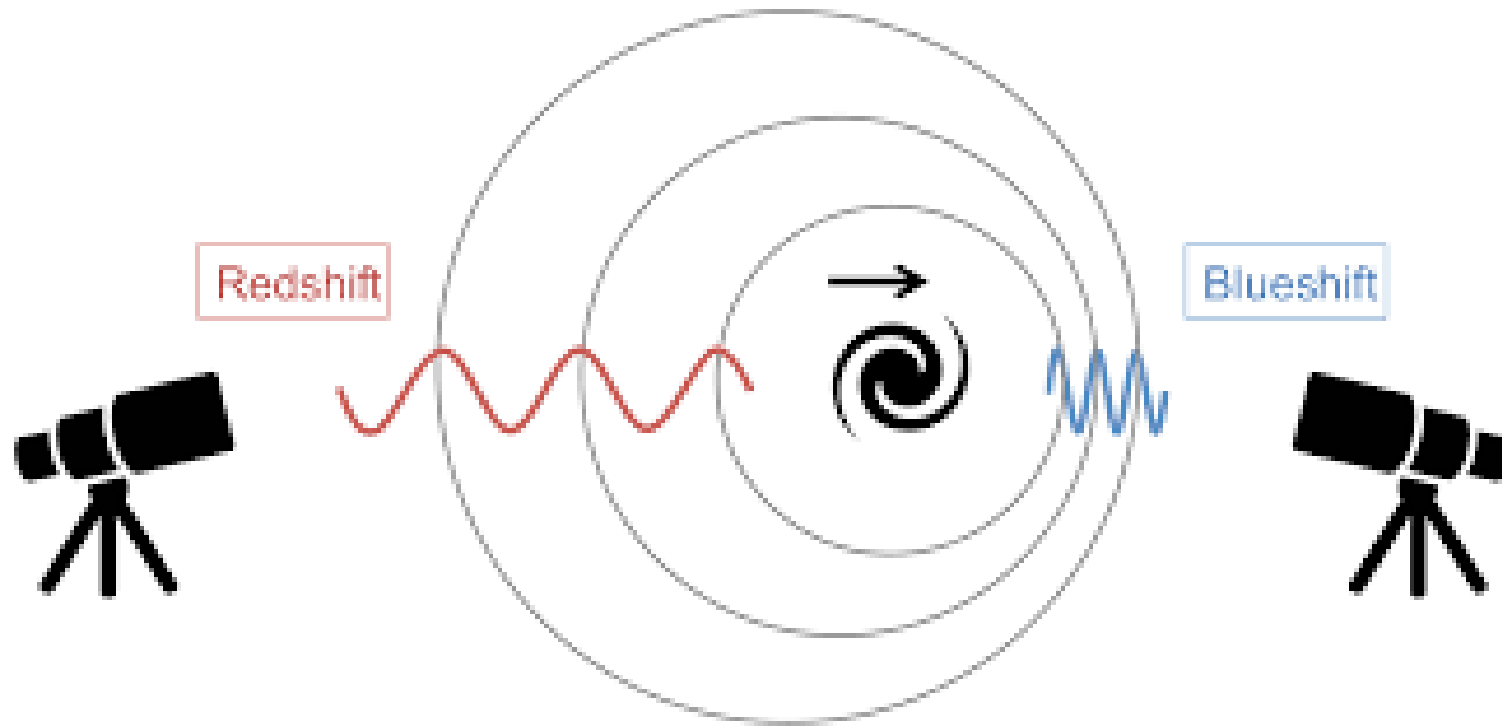
STANDARD CANDLE



ISSUES OF STANDARD CANDLES

- Calibration of M requires nearby objects of known distance

STANDARD CANDLE



$$z^{\text{obs}} \approx z + \frac{v_p}{c}$$

Hard to predict
(especially at low redshift)

ISSUES OF STANDARD CANDLES

- **Calibration** of M requires **nearby objects** of known distance
- **Measurement** of z requires **faraway objects** (in the Hubble flow, no peculiar velocities)

ISSUES OF STANDARD CANDLES

- **Calibration** of M requires **nearby objects** of known distance
- **Measurement** of z requires **faraway objects** (in the Hubble flow, no peculiar velocities)
- **Nearby objects are faint** at large distance

ISSUES OF STANDARD CANDLES

- **Calibration** of M requires **nearby objects** of known distance
- **Measurement** of z requires **faraway objects** (in the Hubble flow, no peculiar velocities)
- **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 distances

- Measuring the distances (in

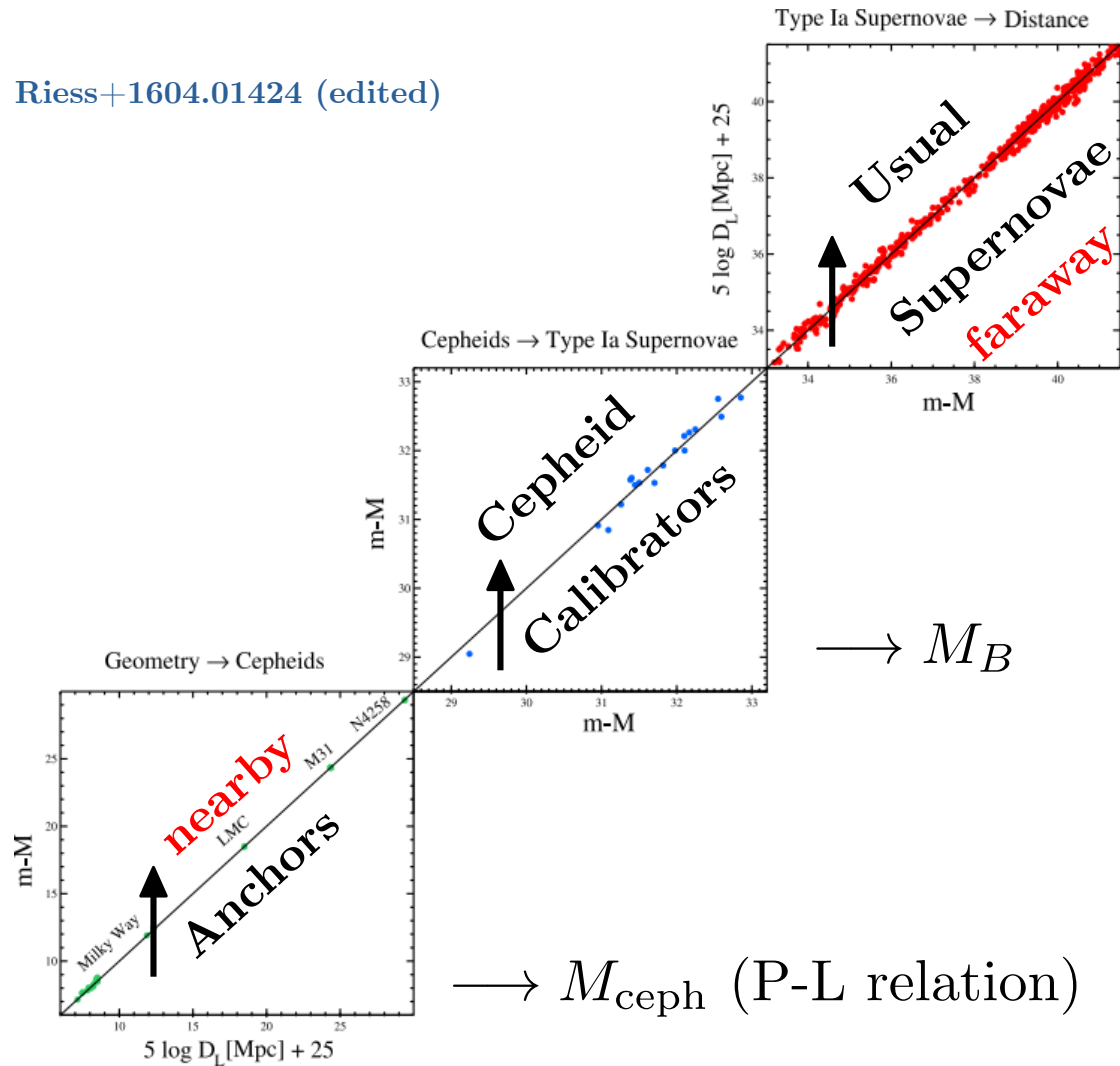
The solution:

Build a ladder!

Calibrate bright faraway objects
using faint nearby ones

- Nearby objects
- Faraway objects in the local universe

Riess+1604.01424 (edited)



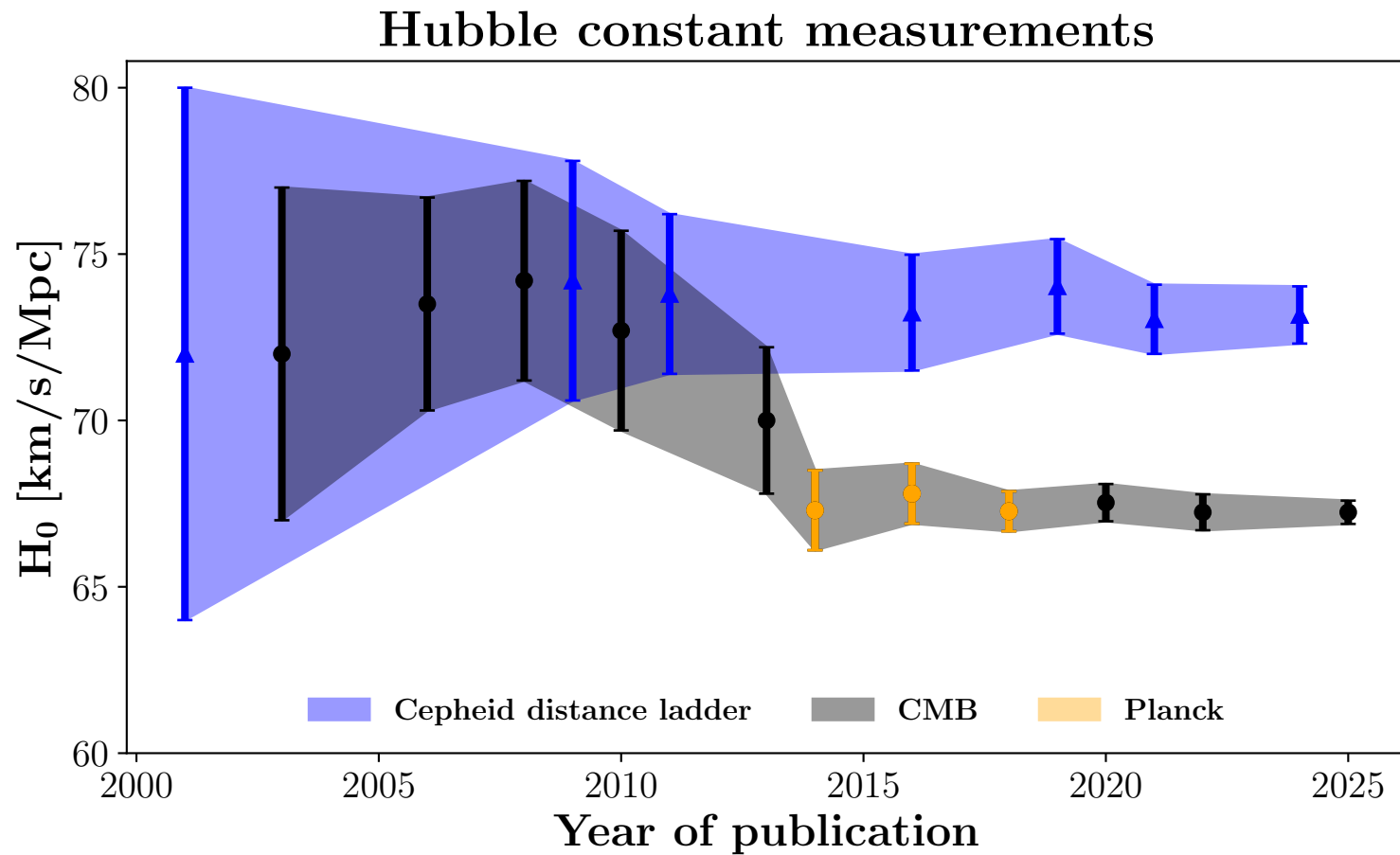
→ D_L

+ (measured) z → H_0

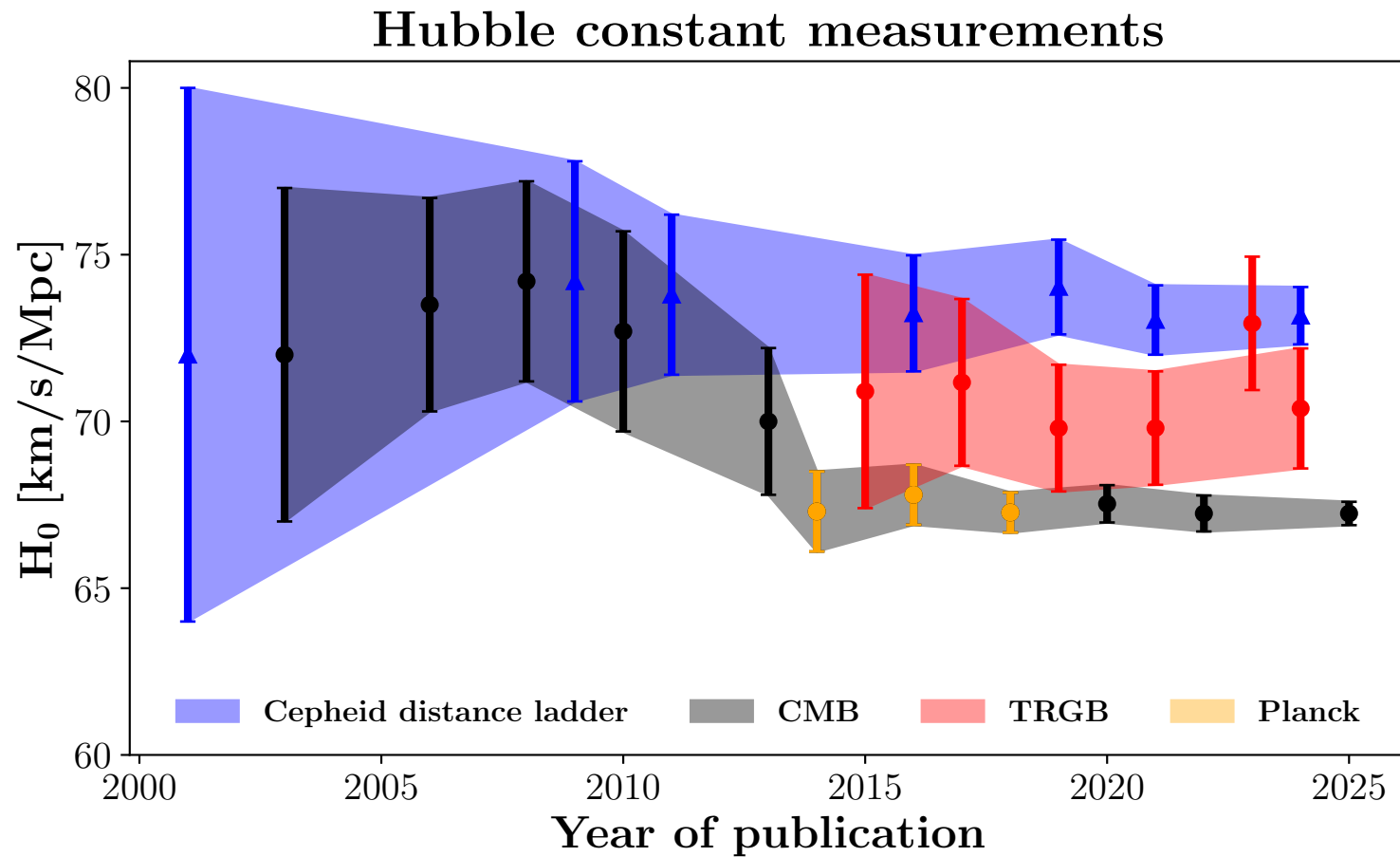
→ M_B

→ M_{ceph} (P-L relation)

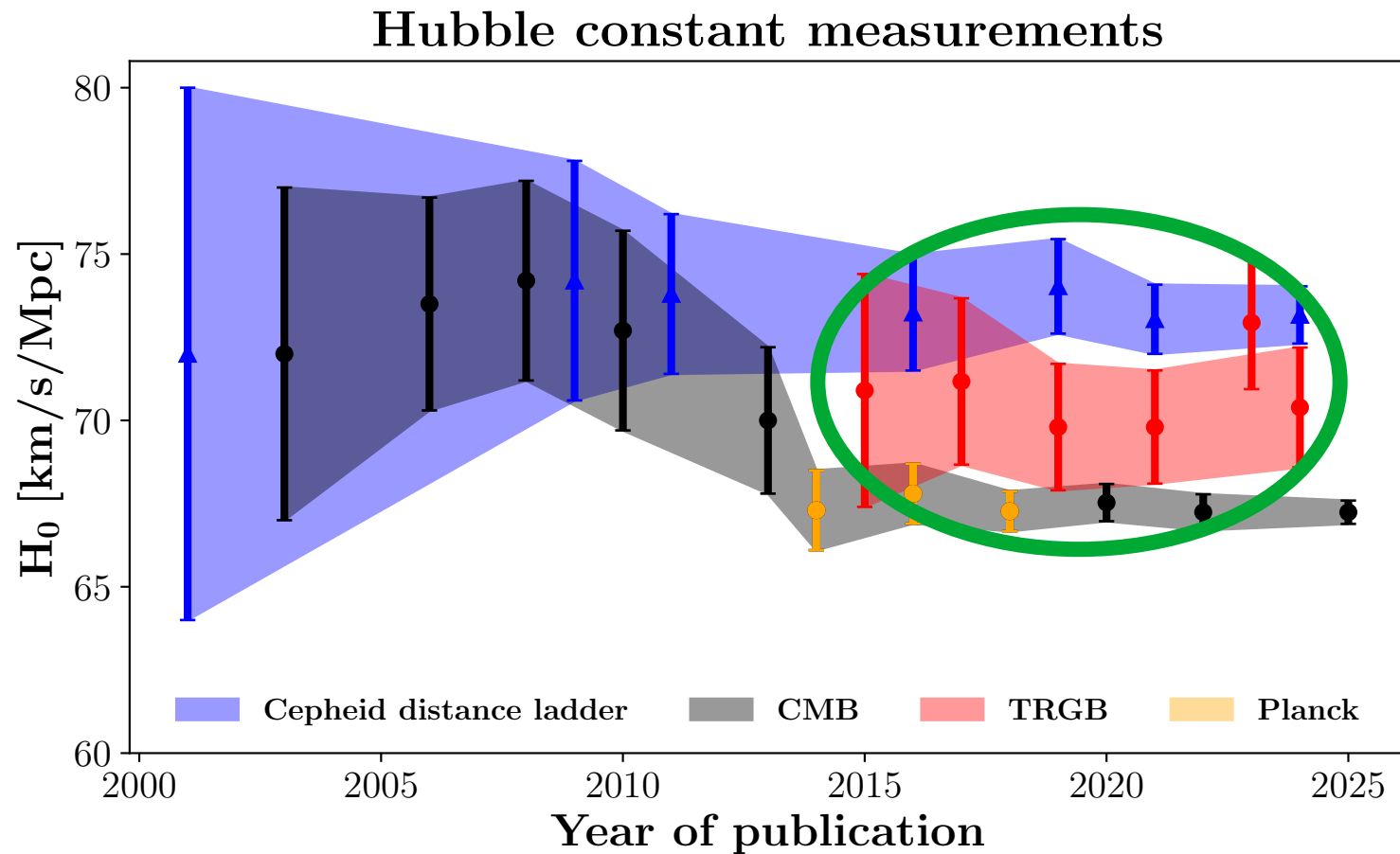
HISTORY



HISTORY

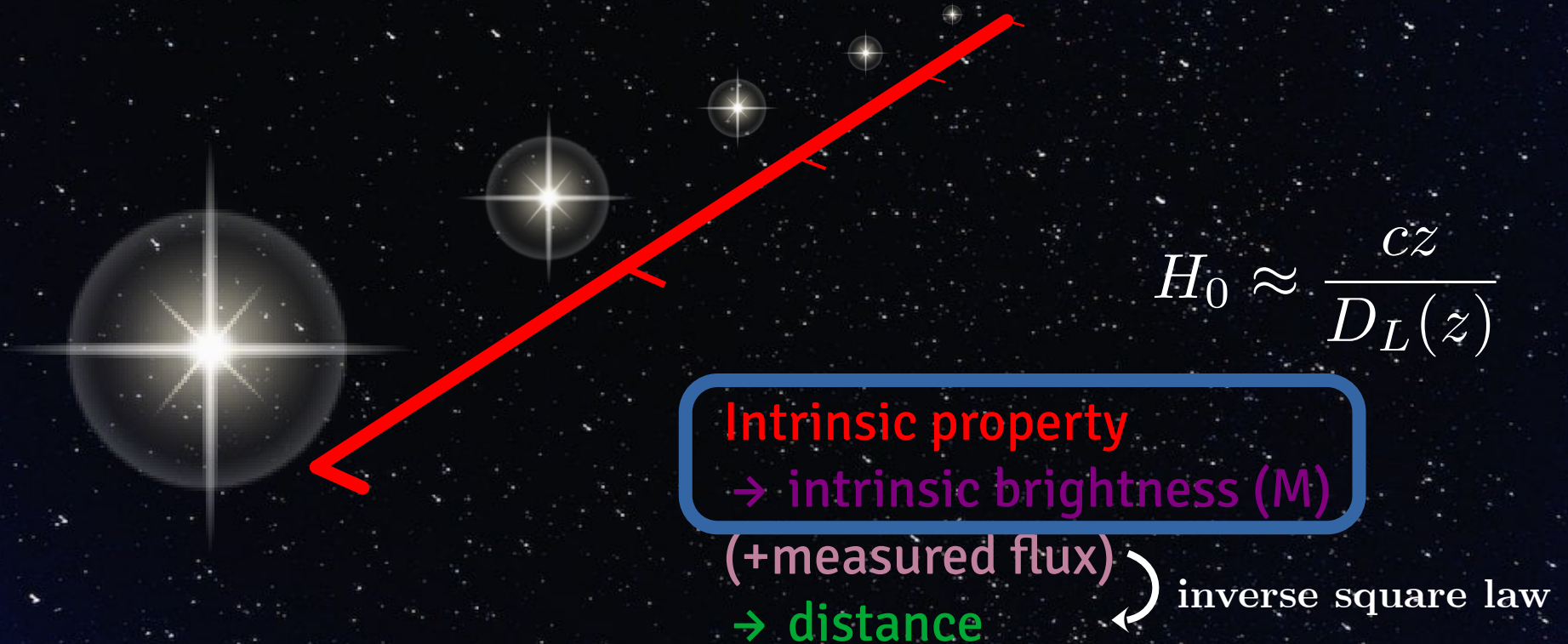


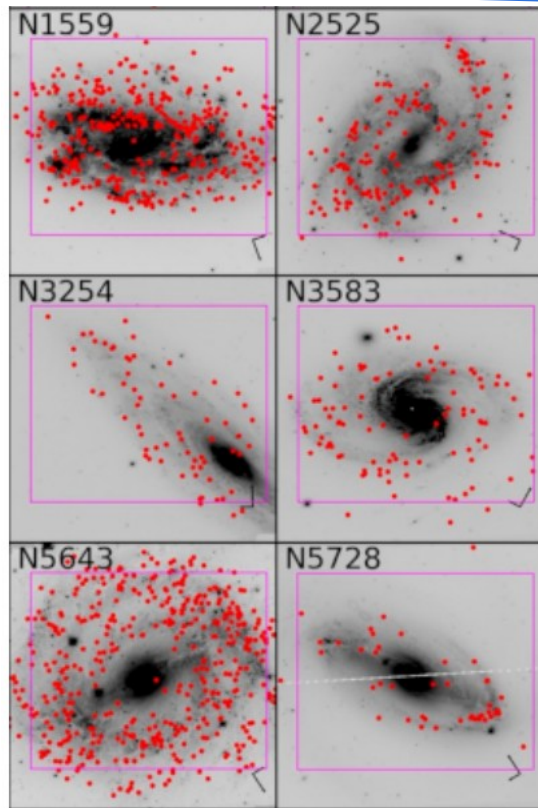
HISTORY



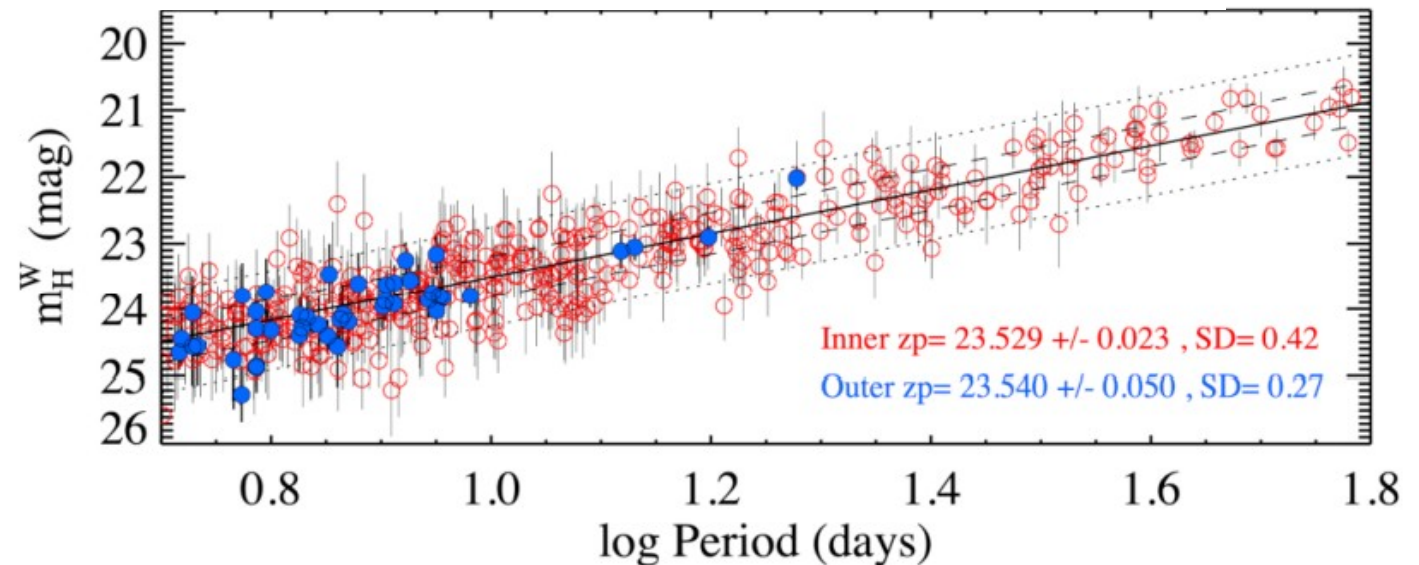
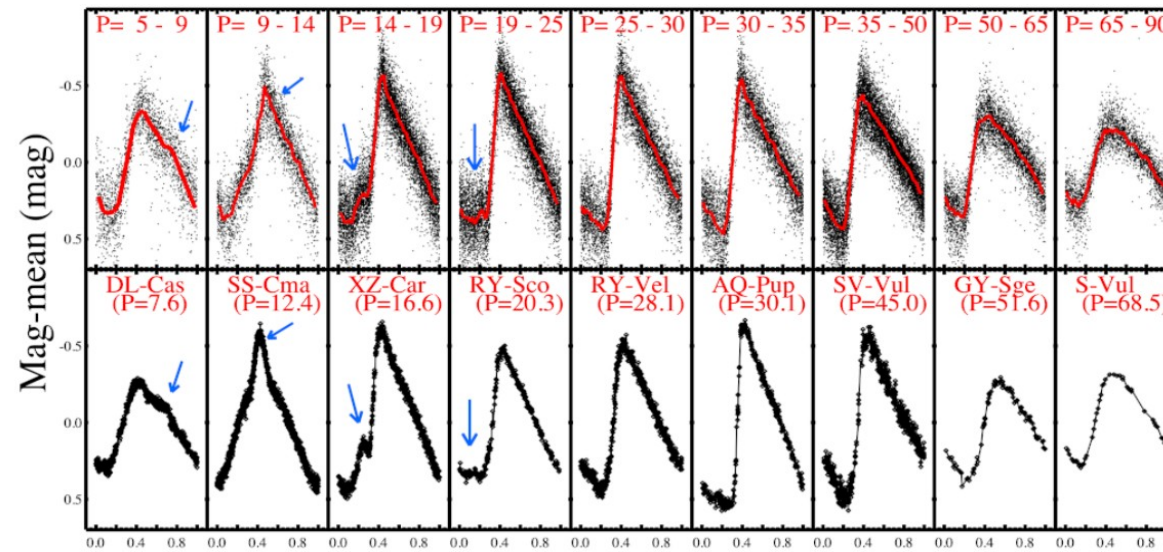
→ Obviously caused by the LDL

STANDARD CANDLE





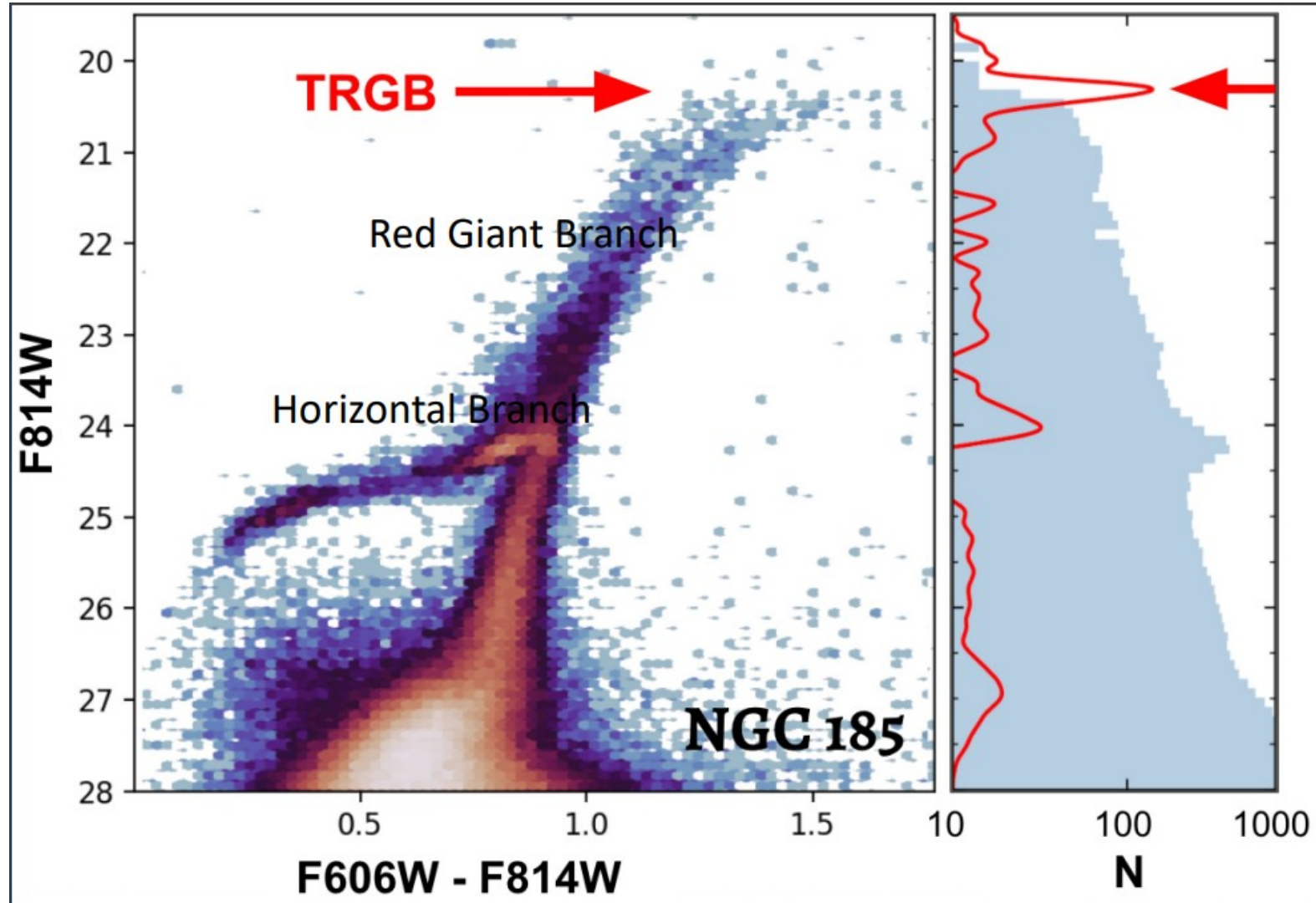
CEPHEID VS TRGB



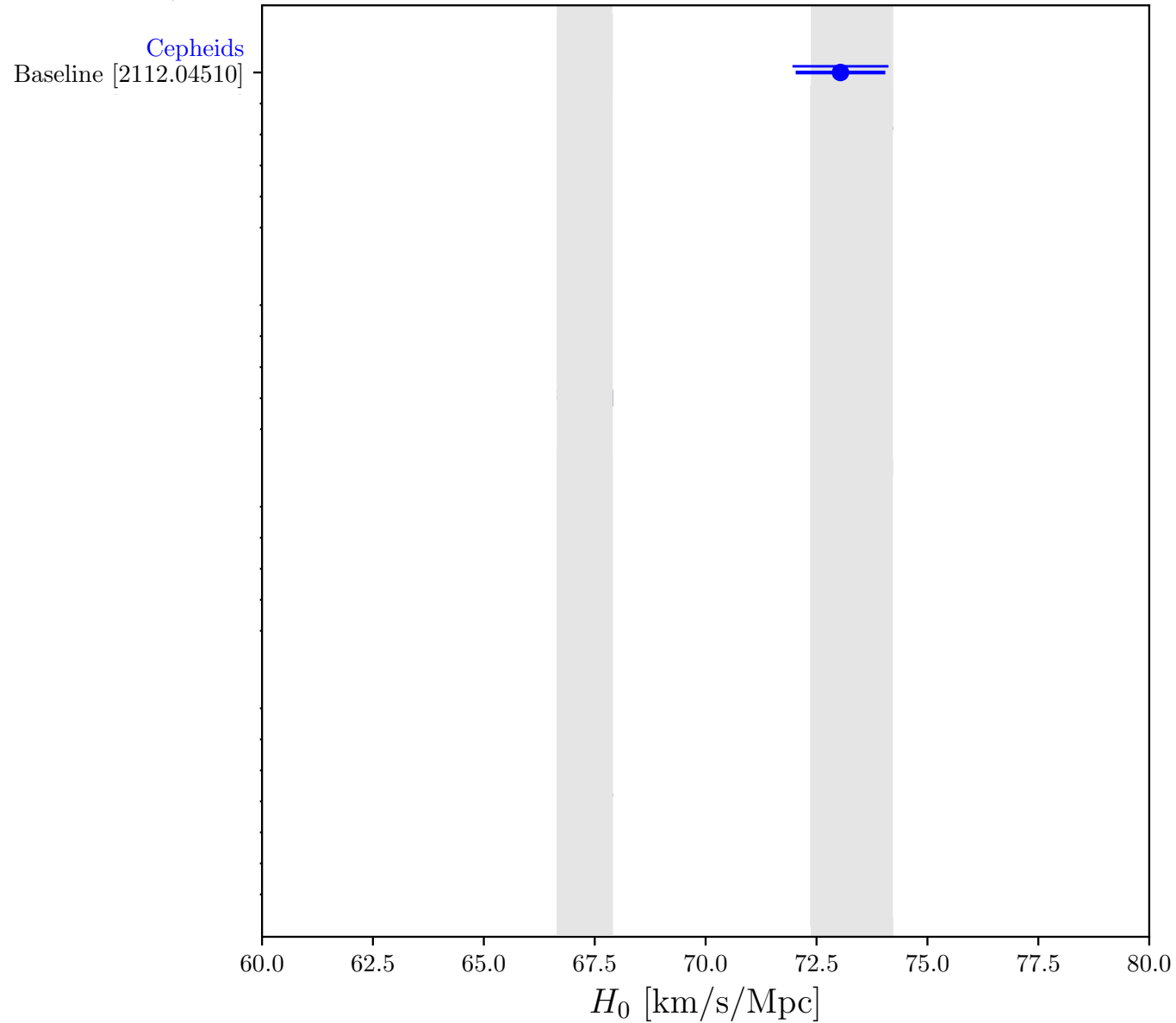
Data courtesy M. Geha,

Plot by I. Jang

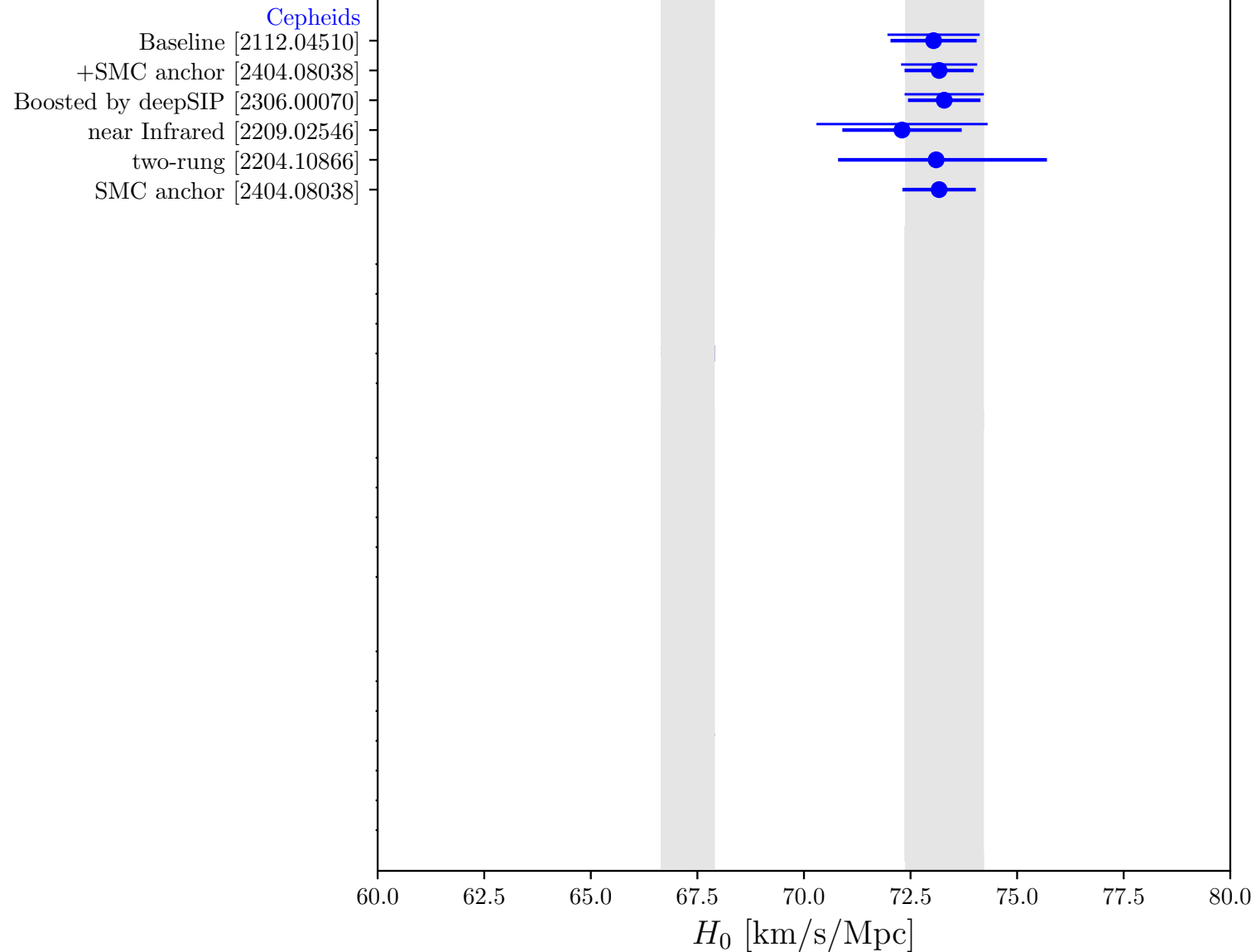
CEPHEID VS TRGB



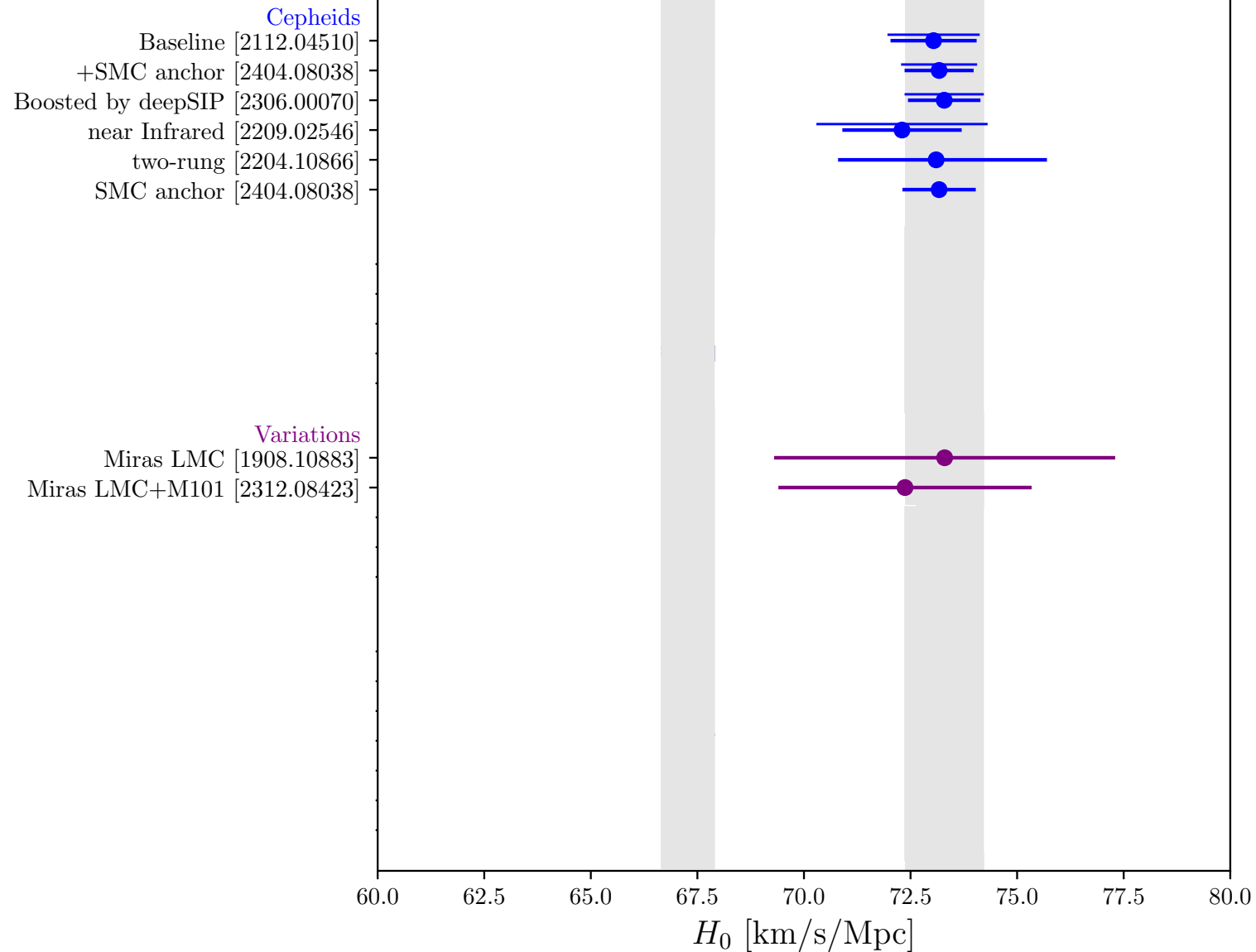
2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)



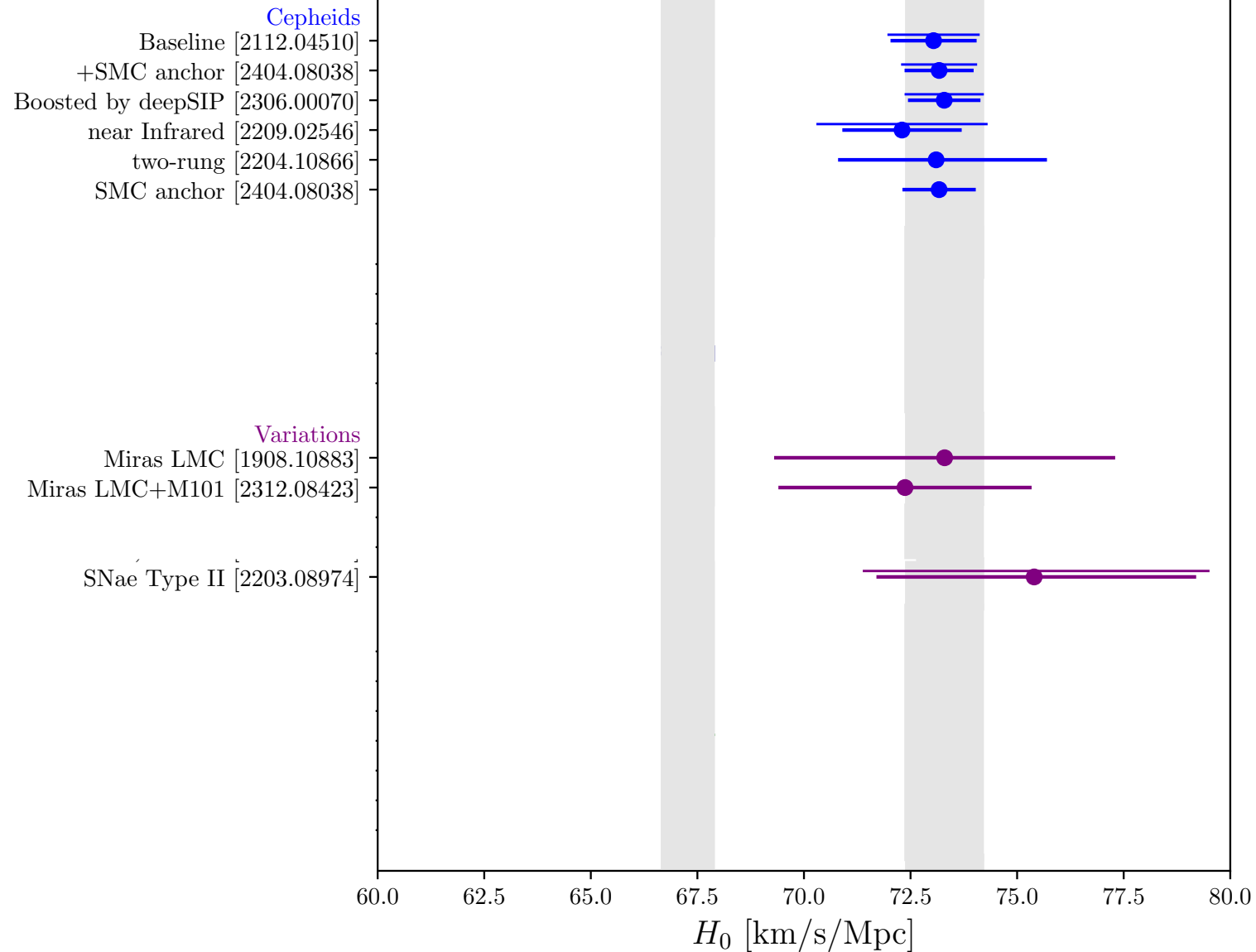
2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)



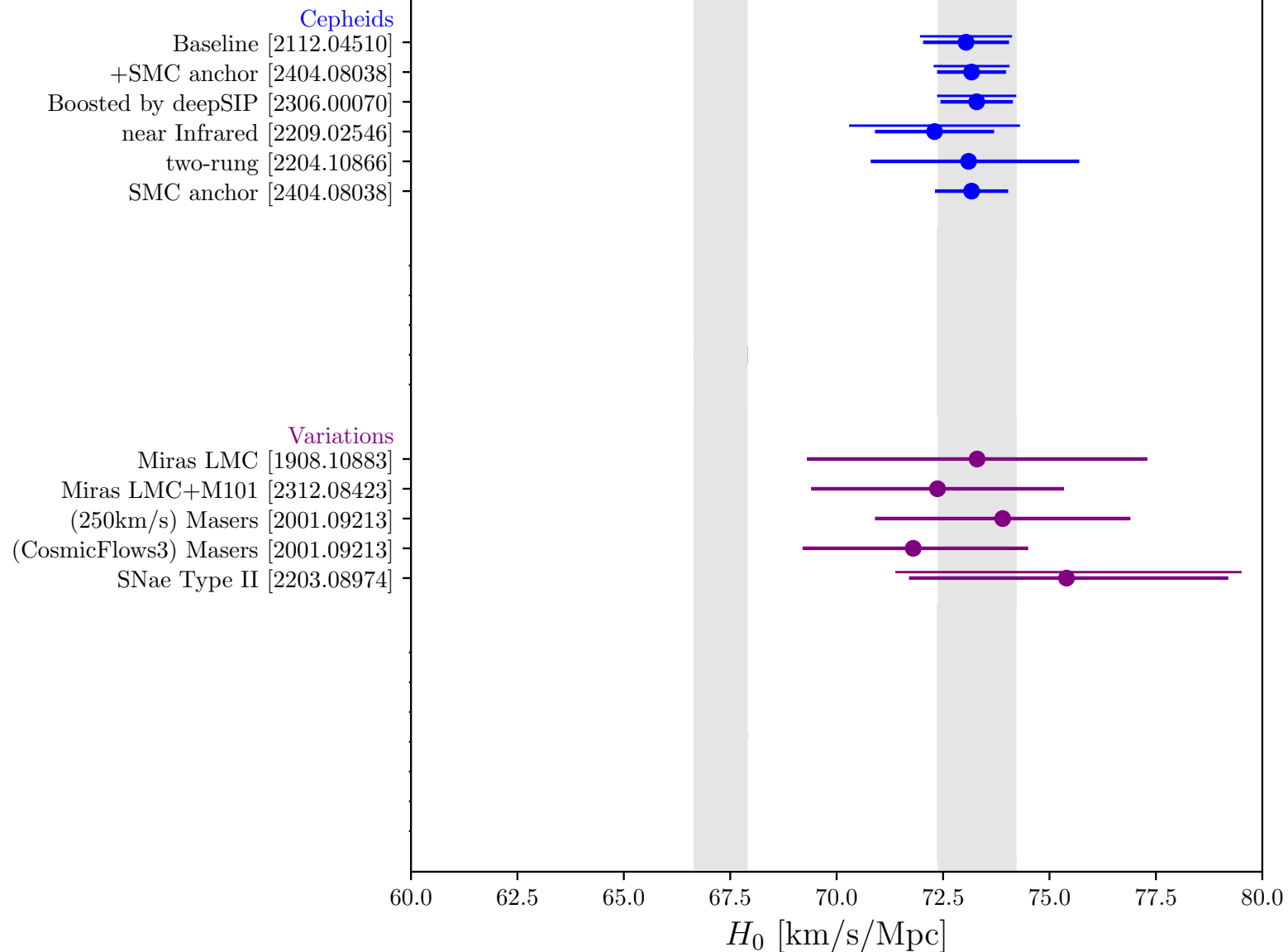
2311.13305 – A tale of many H_0
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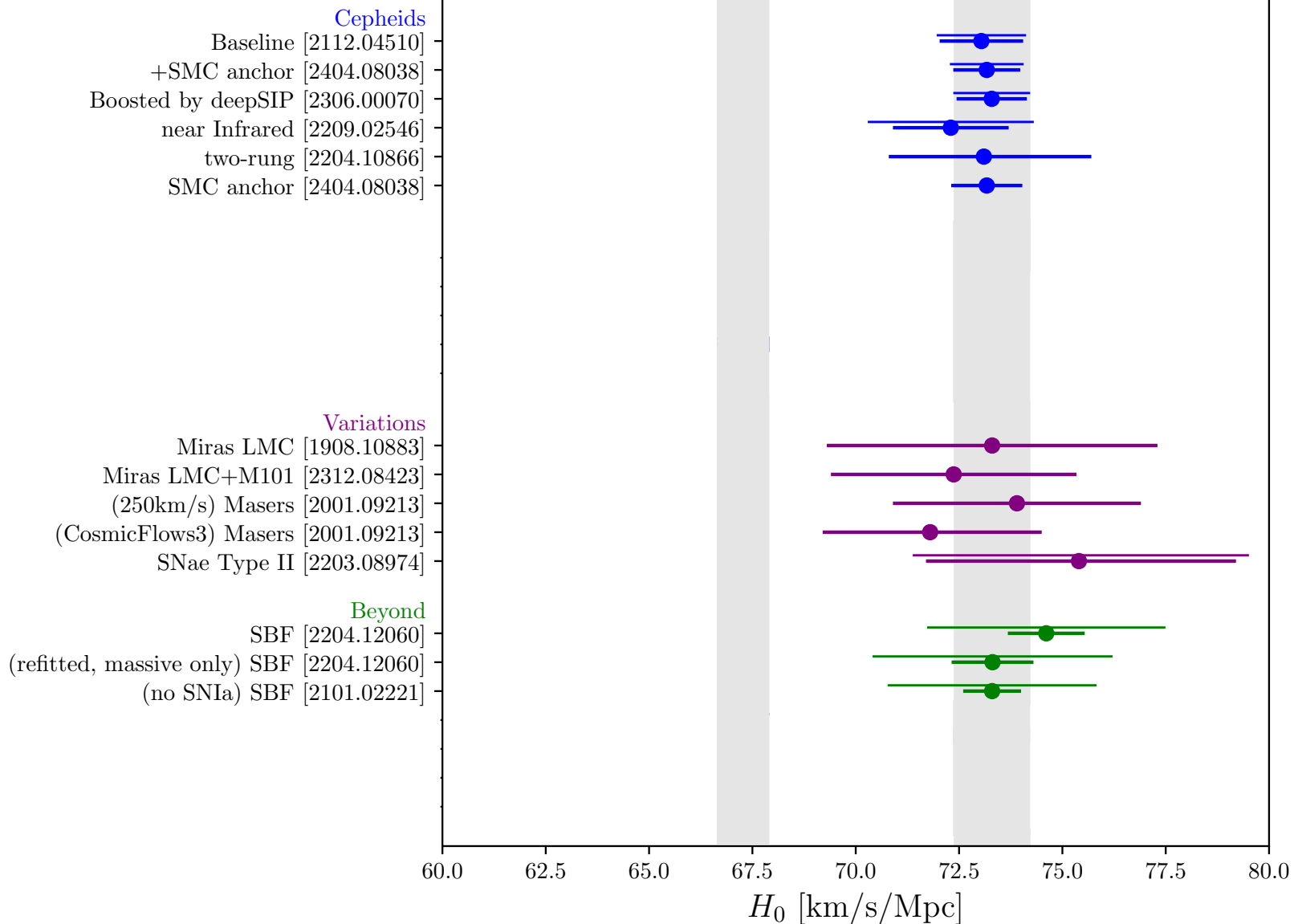
2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)



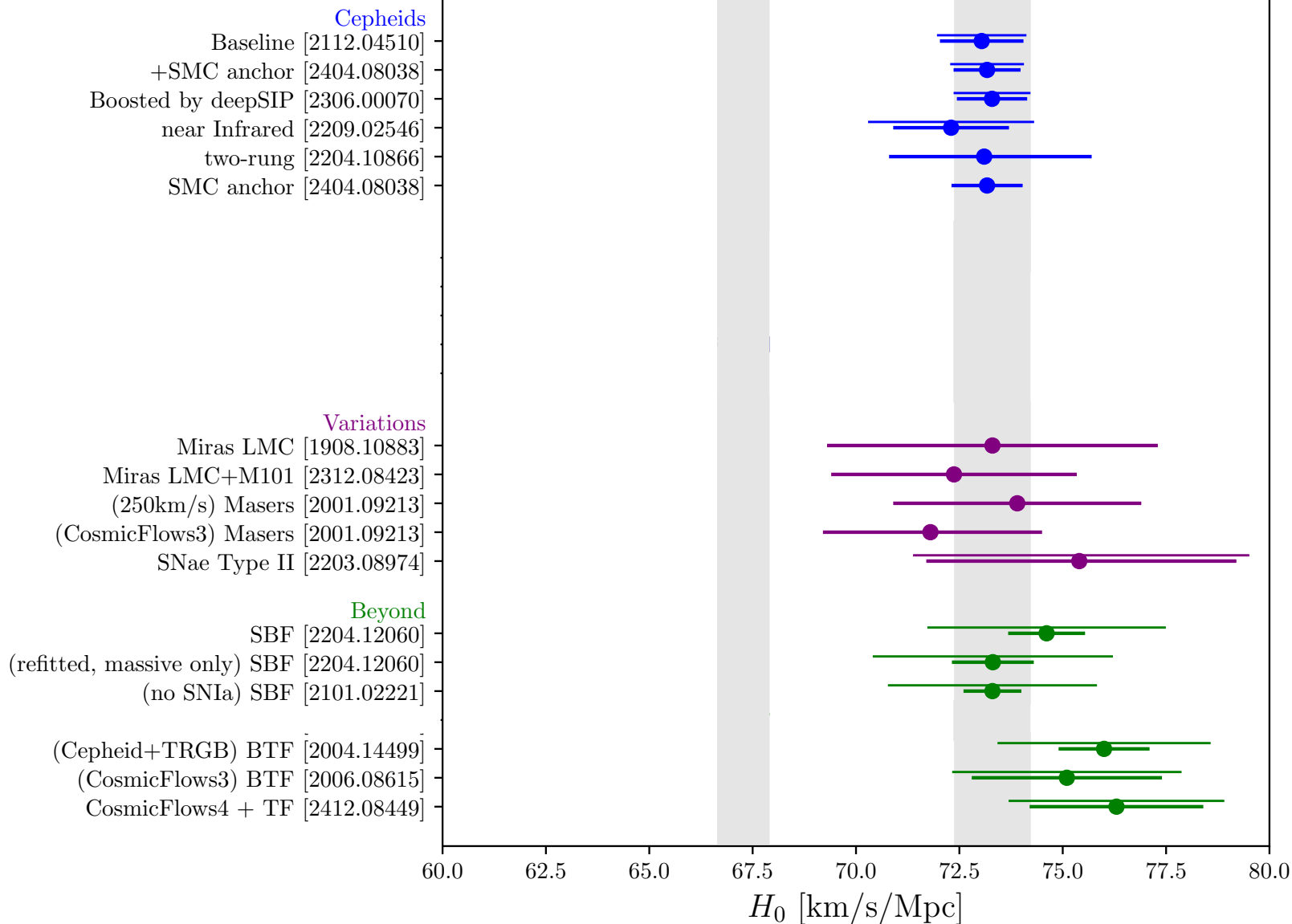
2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)



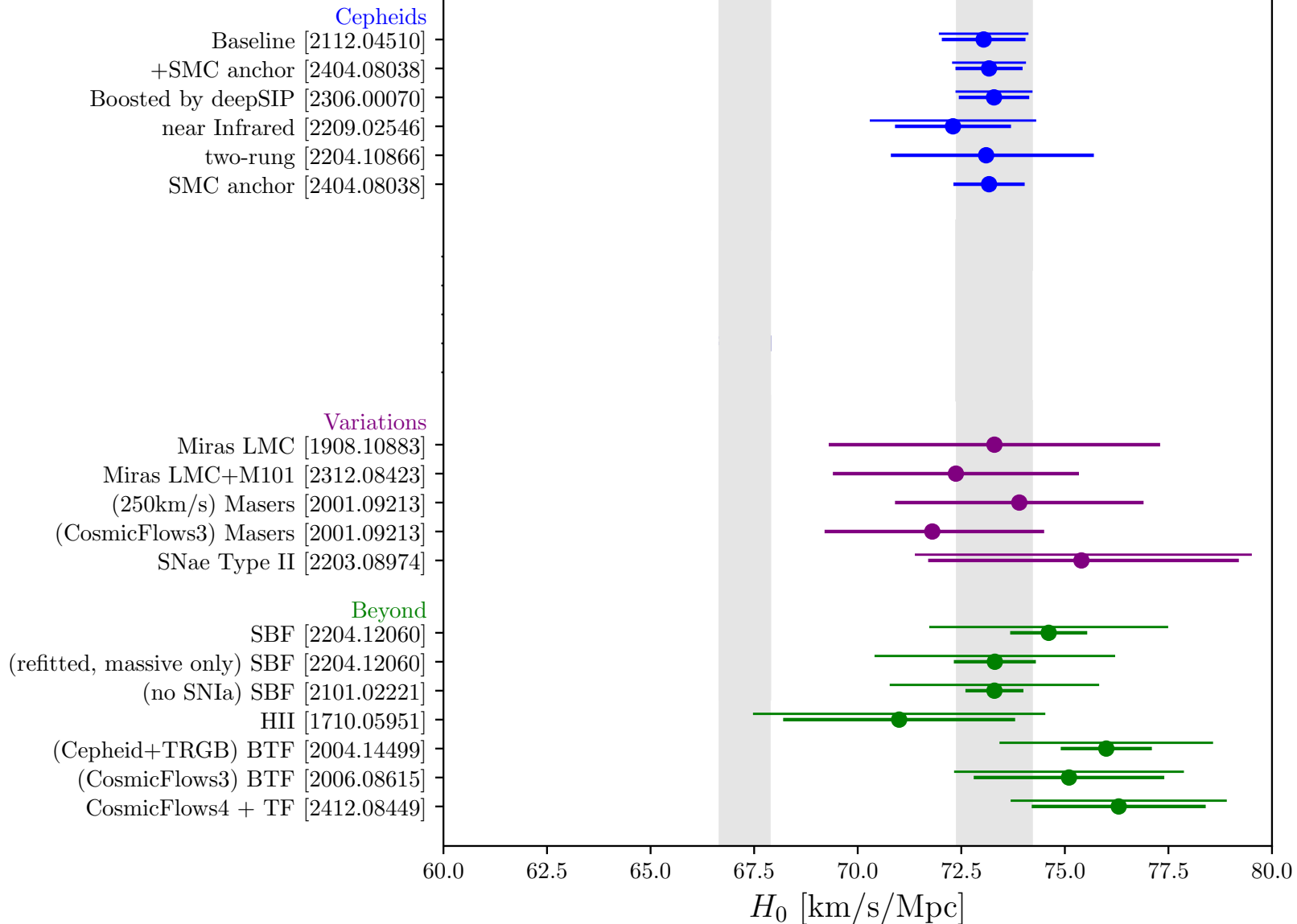
2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)



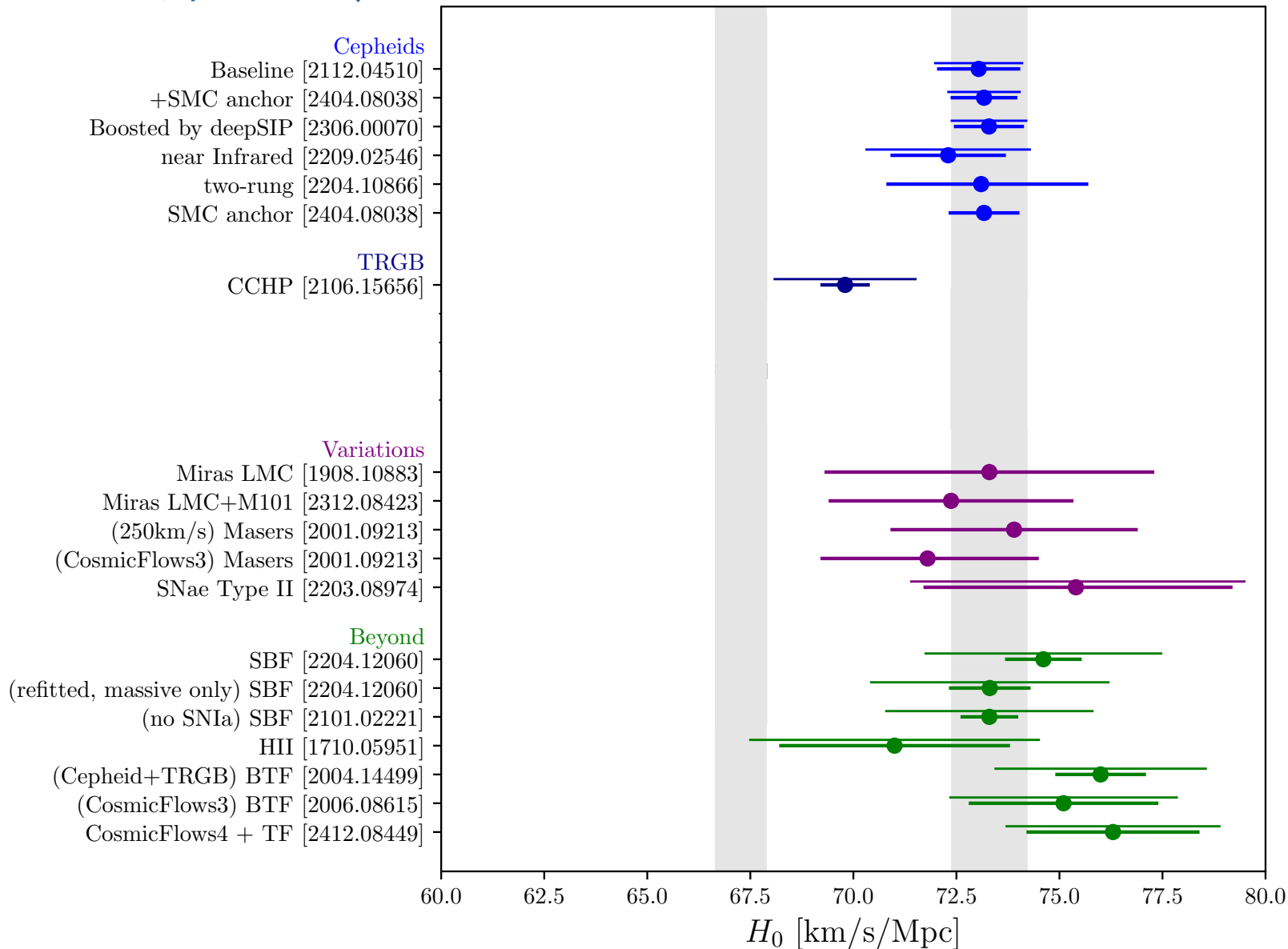
2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)



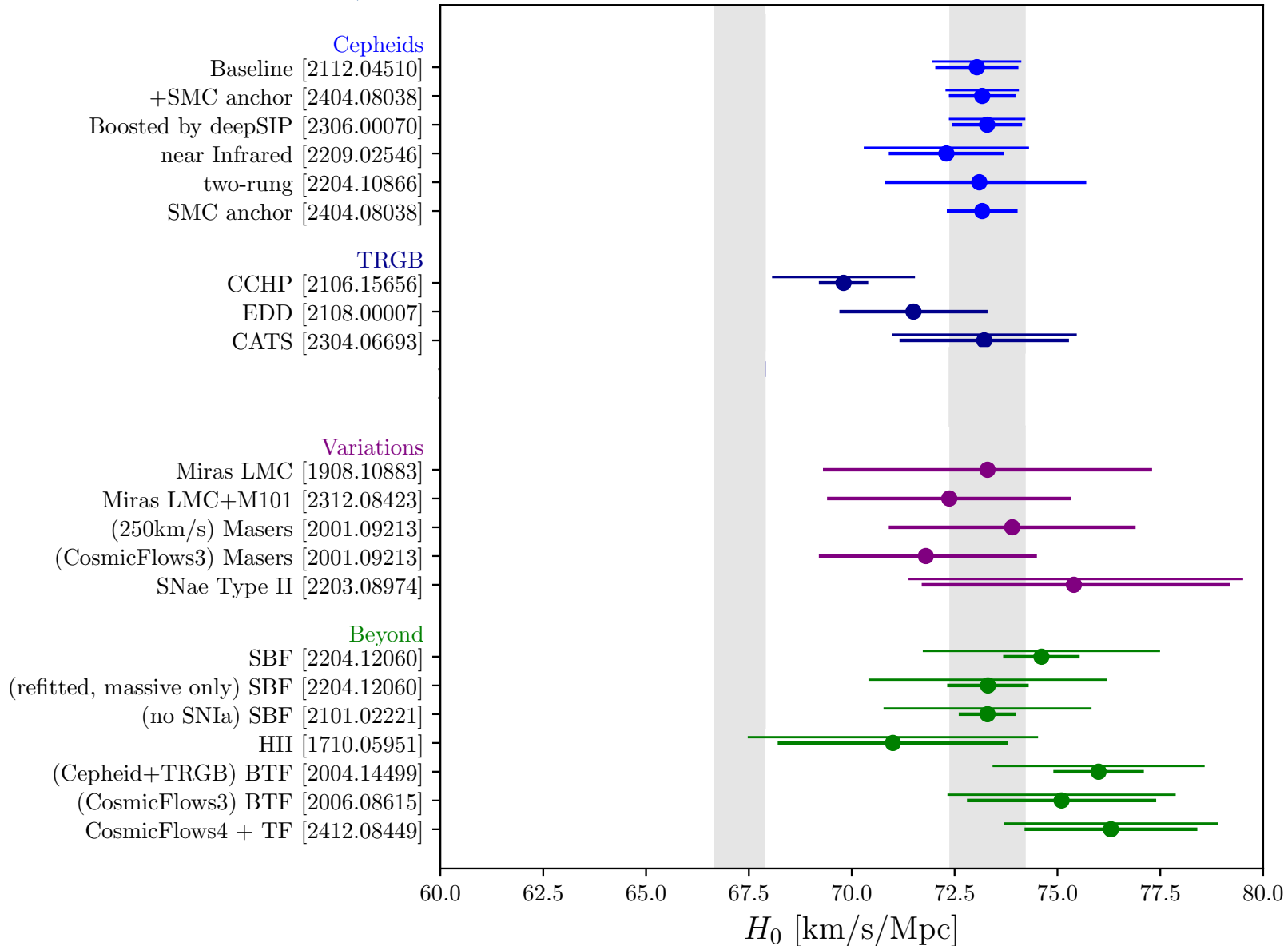
2311.13305 – A tale of many H_0
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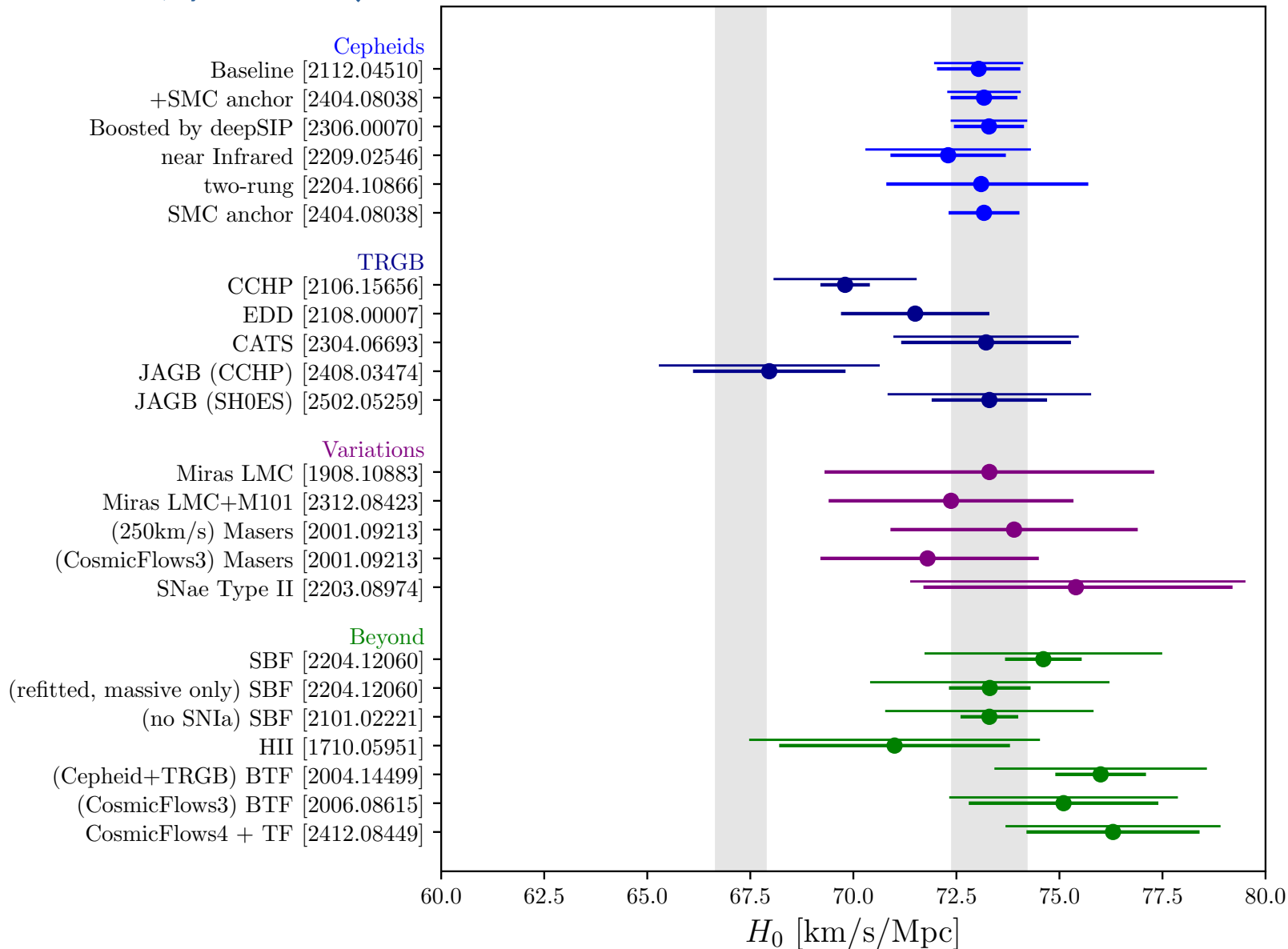
2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)

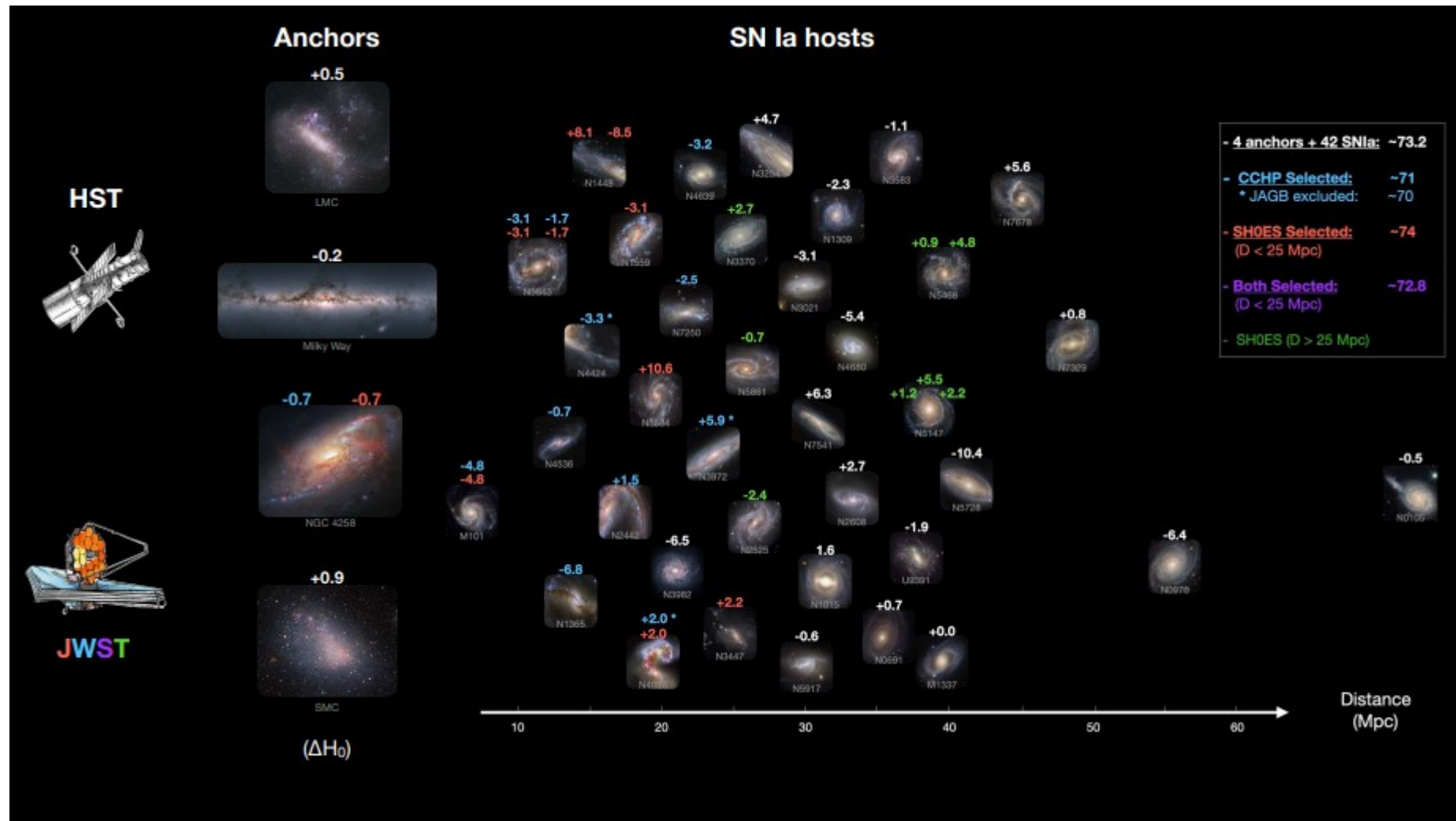


2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)



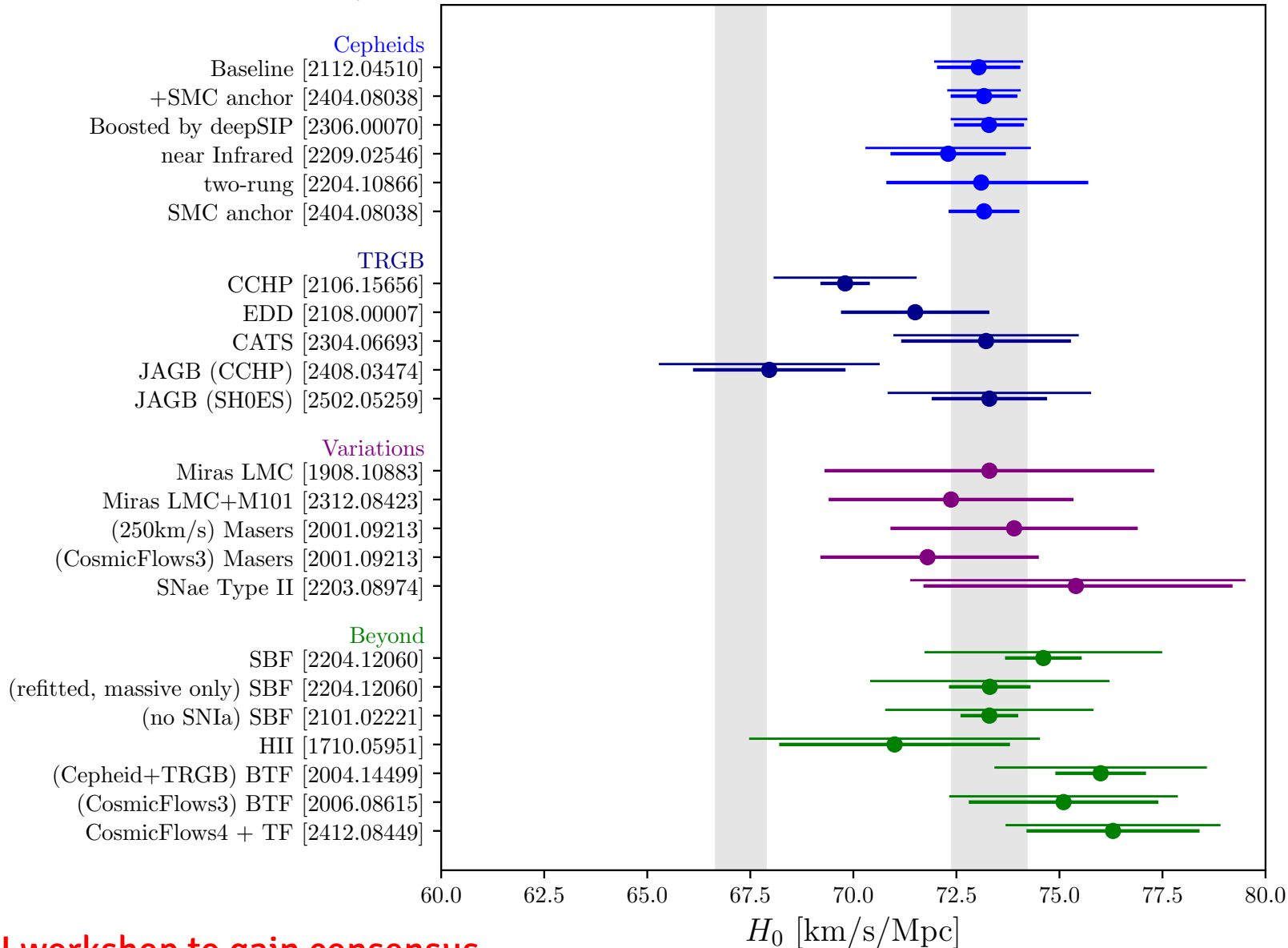
2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)





Selection of data (which hosts, which supernovae)

2311.13305 – A tale of many H_0
(review in ARAA, updated to 2025)



→ ISSI workshop to gain consensus

**The Local Distance Network: a community consensus report on
the measurement of the Hubble constant at $\sim 1\%$ precision**

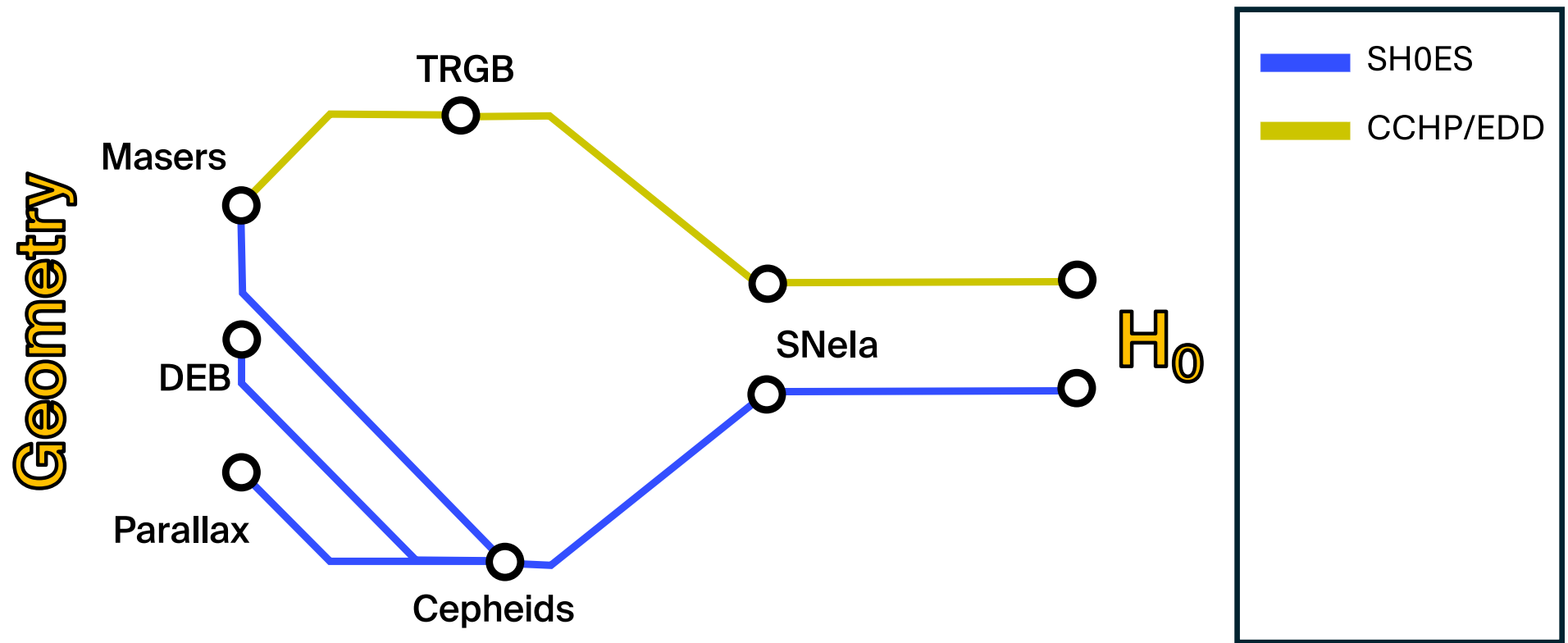
H0DN-ISSI CONSENSUS REPORT

STEFANO CASERTANO,¹ GAGANDEEP ANAND ¹, RICHARD I. ANDERSON ², REACHEL BEATON ¹,
ANUPAM BHARDWAJ ³, JOHN BLAKESLEE ⁴, PAULA BOUBEL ⁵, LOUISE BREUVAL ⁶, DILLON BROUT ⁷,
MICHELE CANTIello ⁸, MAURICIO CRUZ REYES ², GEZA CSÖRNYEI ⁹, THOMAS DE JAEGER ¹⁰, SUHAIL DHAWAN ¹¹,
ELEONORA DI VALENTINO ¹², LLUÍS GALBANY ^{13,14}, HÉCTOR GIL-MARÍN ^{15,16,14}, DARIUSZ GRACZYK ¹⁷,
CAROLINE HUANG ¹⁸, JOSEPH B. JENSEN ¹⁹, PIERRE KERVELLA ^{20,21}, BRUNO LEIBUNDGUT ²², BASTIAN LENGEN ²,
SIYANG LI ²³, LUCAS MACRI ²⁴, EMRE ÖZÜLKER ¹², DOMINIC W. PESCE ^{18,25}, ADAM RIESS ¹,
MARTINO ROMANIELLO ²², KHALED SAID ²⁶, NILS SCHÖNEBERG ^{27,28}, DAN SCOLNIC ²⁹, TERESA SICIGNANO ^{22,30,31},
DOROTA M. SKOWRON ³², SYED A. UDDIN ^{33,34}, LICIA VERDE ^{35,15}, MARIA VINCENZI ³⁶
AND ANTONELLA NOTA ³⁷

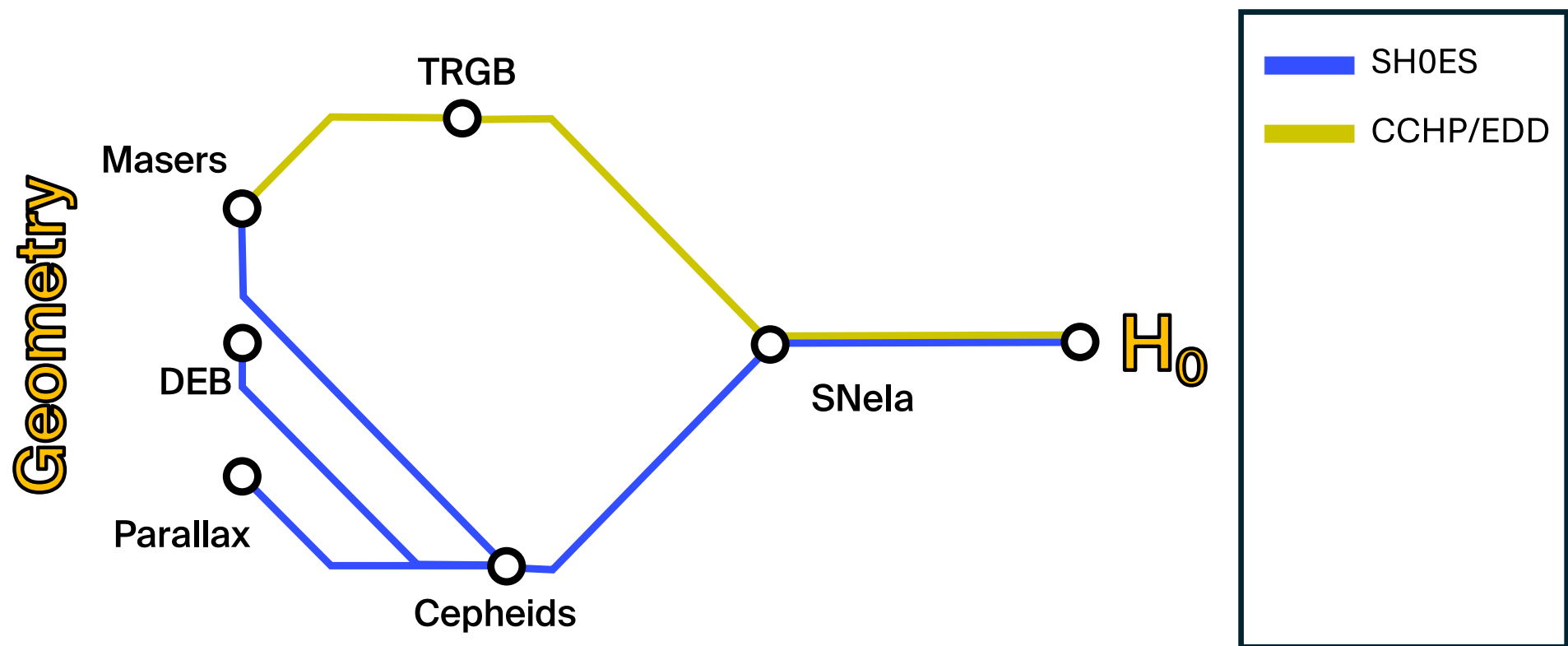


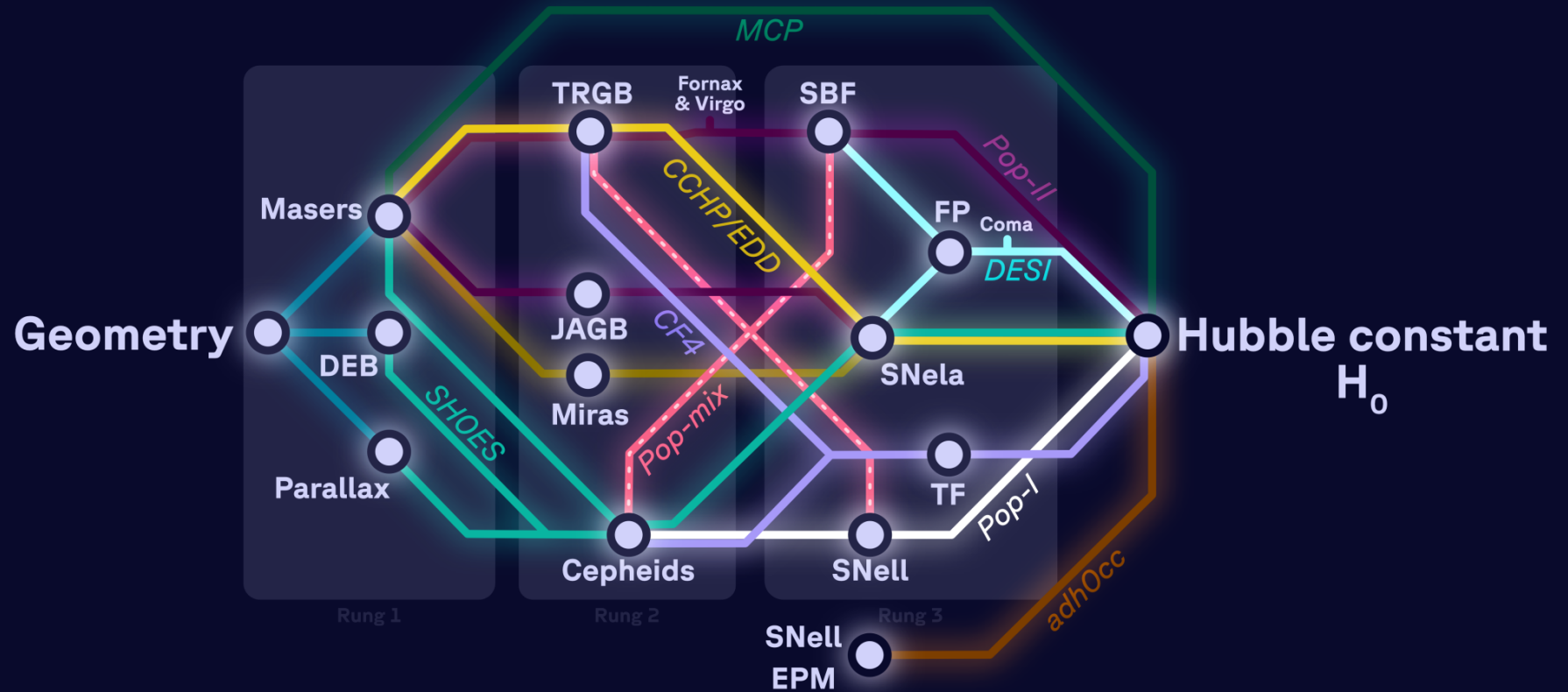
→ ISSI workshop to gain consensus

The Local Distance Network to H_0



The Local Distance Network to H_0





Local Distance Network

Based on Casertano et al. (2025)
Graphic by Fabio Crameri, ISSI

ADVANTAGES

- 1) Consistent treatment of combining different probes

HOW IT WORKS

- Gaussian linear model

$$\begin{aligned}
 \mathbf{X} &= \begin{bmatrix} \mu_1 & \cdots & \cdots & \mu_\gamma & \mu_{g,1} & \mu_{g,2} & M_{Ia} & M_{II} & M_{TF}^{\text{off}} & M_{SBF}^{\text{off}} & \log_{10} H_0 & \mu_C \end{bmatrix} \\
 \mathbf{A} &= \begin{array}{c} \begin{array}{cccccc|cccc|cc} \text{Host Distances} & & & & \text{Groups} & & \text{---Absolute magnitudes---} & & & & H_0 & \mu_{\text{coma}} \\ \hline 1 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \cdots & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline 1 & \cdots & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \cdots & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline 1 & \cdots & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & 1 & \vdots & 0 & \vdots & \vdots \\ 0 & \cdots & 0 & 1 & 0 & 0 & 0 & \vdots & 1 & \vdots & 0 & 0 \\ 0 & \cdots & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ \hline 0 & \cdots & 0 & 0 & 0 & 0 & -0.2 & 0 & 0 & 0 & 1 & 0 \\ 0 & \cdots & 0 & 0 & 0 & 0 & 0 & -0.2 & 0 & 0 & 1 & 0 \\ 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & -0.2 & 0 & 1 & 0 \\ 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.2 & 1 & 0 \\ \hline 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ \hline 0 & \cdots & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & 0 & \vdots & \vdots \\ 0 & \cdots & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ \hline 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.2 \end{array} \\ \text{Hosts} & & & & \text{Groups} & & & & \text{Calibrators} & & & \\ & & & & & & & & H_0, M_{\text{Calib}} & & & \\ & & & & & & & & \text{MM/EPM} & & & \\ & & & & & & & & \text{Coma SN} & & & \\ & & & & & & & & C_{\text{SBF}} & & & \\ & & & & & & & & H_{0,C} & & & \end{array} \begin{array}{c} \mu_{\text{host},1} \\ \vdots \\ \mu_{\text{host},n-1} \\ \mu_{\text{host},n} \\ \hline 0 \\ \vdots \\ 0 \\ 0 \\ \hline m_{0B,1} \\ \vdots \\ m_{0B,k-1} \\ m_{0B,k} \\ \hline \alpha_{Ia} + 5 \\ \alpha_{II} + 5 \\ \alpha_{TF} + 5 \\ \alpha_{SBF} + 5 \\ \hline \log_{10}(H_0)_{\text{MM},1} \\ \vdots \\ \log_{10}(H_0)_{\text{EPM},m} \\ \hline m_{0,\text{Coma},1} \\ \vdots \\ m_{0,\text{Coma},p} \\ \hline \mu_{\text{ComaSBF}} \\ \hline \log_{10}(H_0)_C + 0.2\mu_C \end{array} \end{array} = \mathbf{Y}
 \end{aligned}$$

$$\chi^2 = (\mathbf{Y} - \mathbf{A}\mathbf{X})^T \mathbf{C}^{-1} (\mathbf{Y} - \mathbf{A}\mathbf{X})$$

HOW IT WORKS

- Gaussian linear mode
- Literature recovery hard enough with Gaussian uncertainties

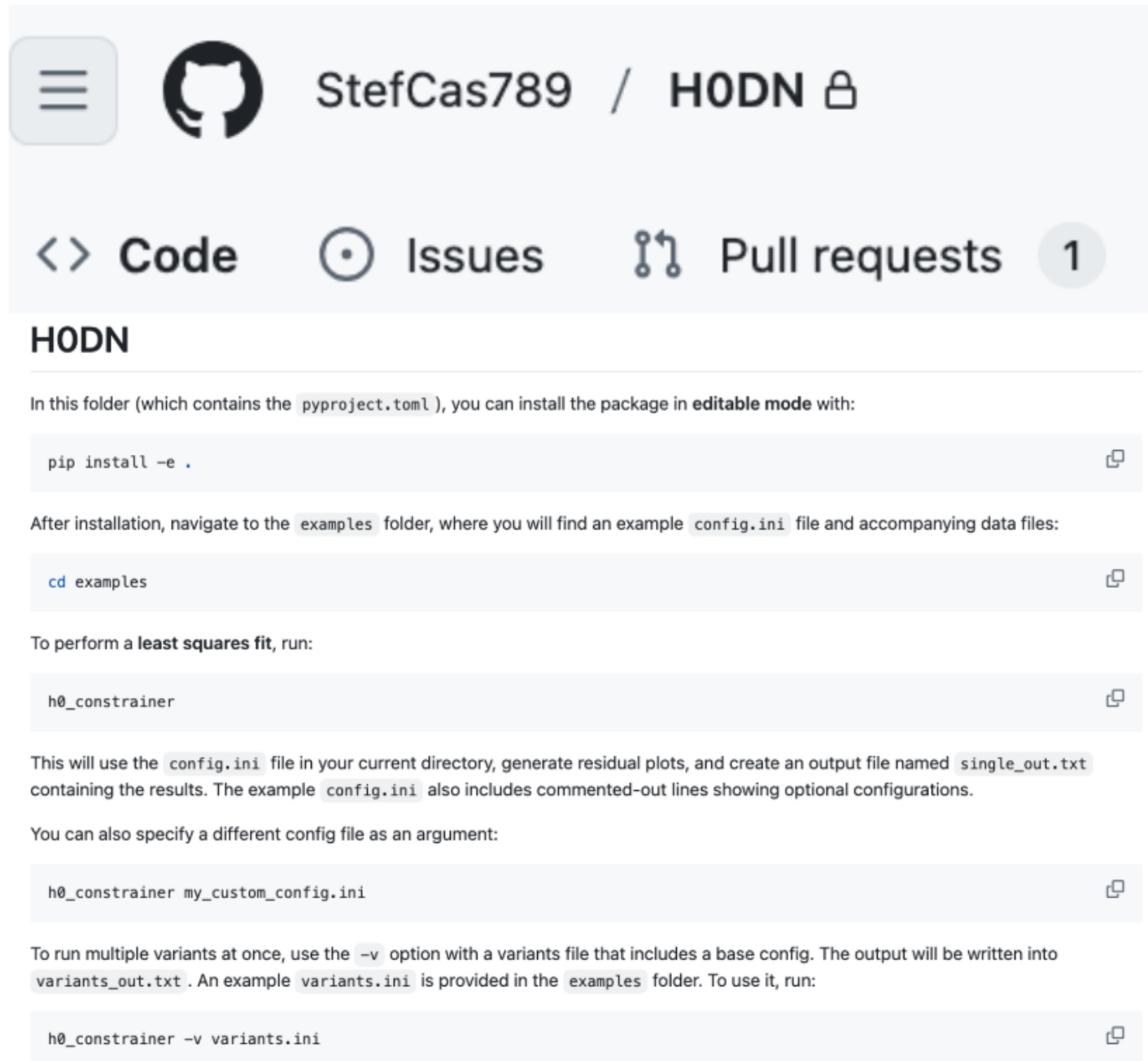
 $C =$

Hosts			Groups			Calibrators			Intercepts			MM/EPM			Coma SN			C _{SBF}	H _{0,C}
$\sigma_{\text{tot},1}^2$	...	σ_{HMAS}^2	0	...	0	0	...	0	0	0	0	0	...	0	0	...	0	0	0
⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
σ_{HMAS}^2	...	$\sigma_{\text{tot},n}^2$	0	...	0	0	...	0	0	0	0	0	...	0	0	...	0	0	0
0	...	0	$\sigma_{g,1}^2$	...	0	0	...	0	0	0	0	0	...	0	0	...	0	0	0
⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
0	...	0	0	...	$\sigma_{g,2}^2$	0	...	0	0	0	0	0	...	0	0	...	0	0	0
0	...	0	0	...	0	σ_1^2	...	0	0	0	0	0	...	0	0	...	0	0	0
⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
0	...	0	0	...	0	0	...	σ_k^2	0	0	0	0	...	0	0	...	0	0	0
0	...	0	0	...	0	0	...	0	$\sigma_{\alpha_{\text{Ia}}}^2$	0	0	0	...	0	0	...	0	0	0
0	...	0	0	...	0	0	...	0	0	$\sigma_{\alpha_{\text{II}}}^2$	0	0	...	0	0	...	0	0	0
0	...	0	0	...	0	0	...	0	0	0	$\sigma_{\alpha_{\text{TF}}}^2$	0	0	...	0	0	...	0	0
0	...	0	0	...	0	0	...	0	0	0	0	$\sigma_{\alpha_{\text{SBF}_i}}^2$	0	...	0	0	...	0	0
0	...	0	0	...	0	0	...	0	0	0	0	σ_1^2	...	0	0	...	0	0	0
⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
0	...	0	0	...	0	0	...	0	0	0	0	0	...	σ_m^2	0	...	0	0	0
0	...	0	0	...	0	0	...	0	0	0	0	0	...	0	σ_1^2	...	0	0	0
⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
0	...	0	0	...	0	0	...	0	0	0	0	0	...	0	0	...	σ_p^2	0	0
0	...	0	0	...	0	0	...	0	0	0	0	0	...	0	0	...	0	$\sigma_{C_s}^2$	0
0	...	0	0	...	0	0	...	0	0	0	0	0	...	0	0	...	0	0	σ_C^2

$$\chi^2 = (Y - AX)^T C^{-1} (Y - AX)$$

ADVANTAGES

- 1) Consistent treatment of combining different probes
- 2) Open code + open data



StefCas789 / HODN

Code Issues Pull requests 1

HODN

In this folder (which contains the `pyproject.toml`), you can install the package in **editable mode** with:

```
pip install -e .
```

After installation, navigate to the `examples` folder, where you will find an example `config.ini` file and accompanying data files:

```
cd examples
```

To perform a **least squares fit**, run:

```
h0_constrainer
```

This will use the `config.ini` file in your current directory, generate residual plots, and create an output file named `single_out.txt` containing the results. The example `config.ini` also includes commented-out lines showing optional configurations.

You can also specify a different config file as an argument:

```
h0_constrainer my_custom_config.ini
```

To run multiple variants at once, use the `-v` option with a variants file that includes a base config. The output will be written into `variants_out.txt`. An example `variants.ini` is provided in the `examples` folder. To use it, run:

```
h0_constrainer -v variants.ini
```

ADVANTAGES

- 1) Consistent treatment of combining different probes
- 2) Open code + open data
- 3) A deeper look at consistency/systematics

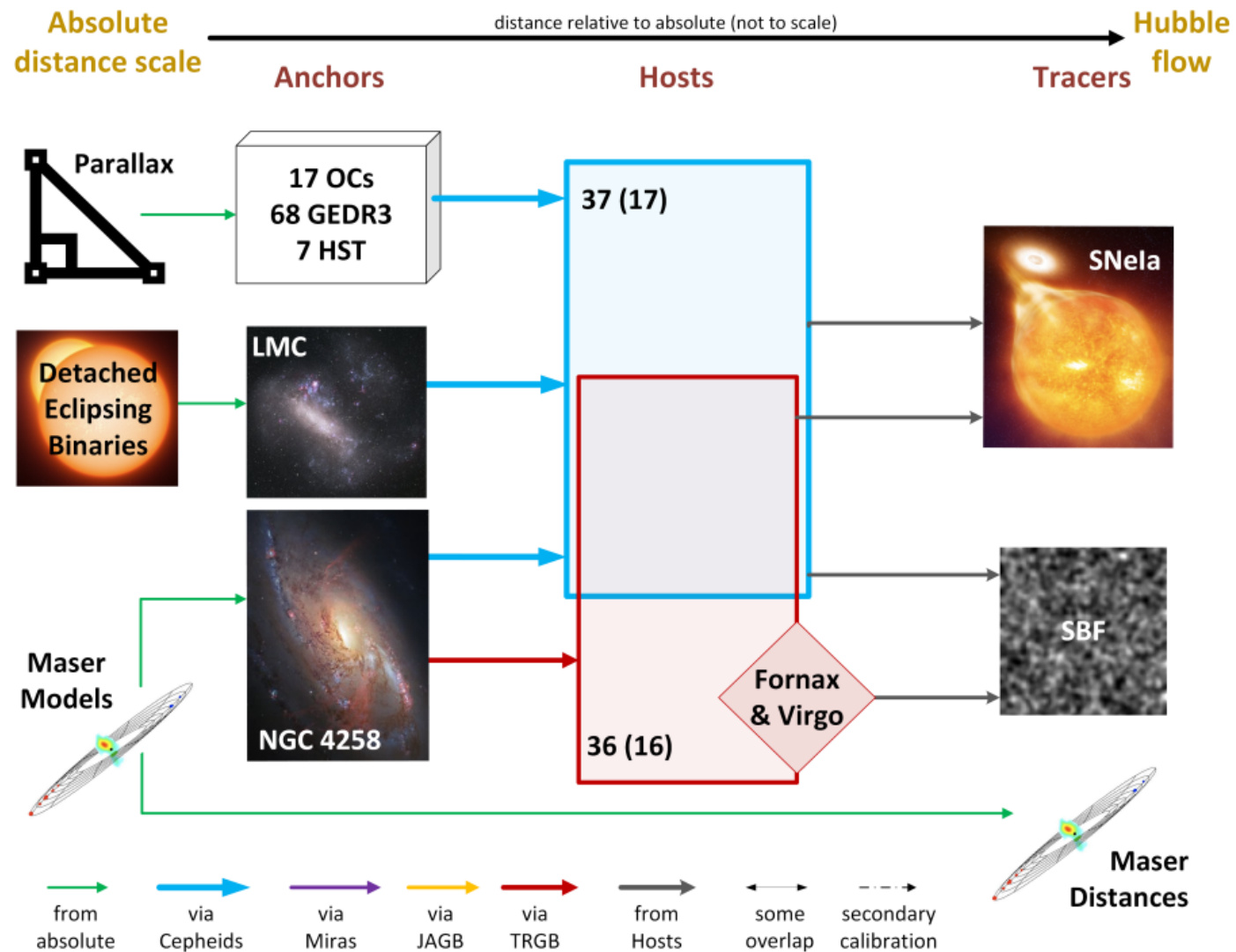
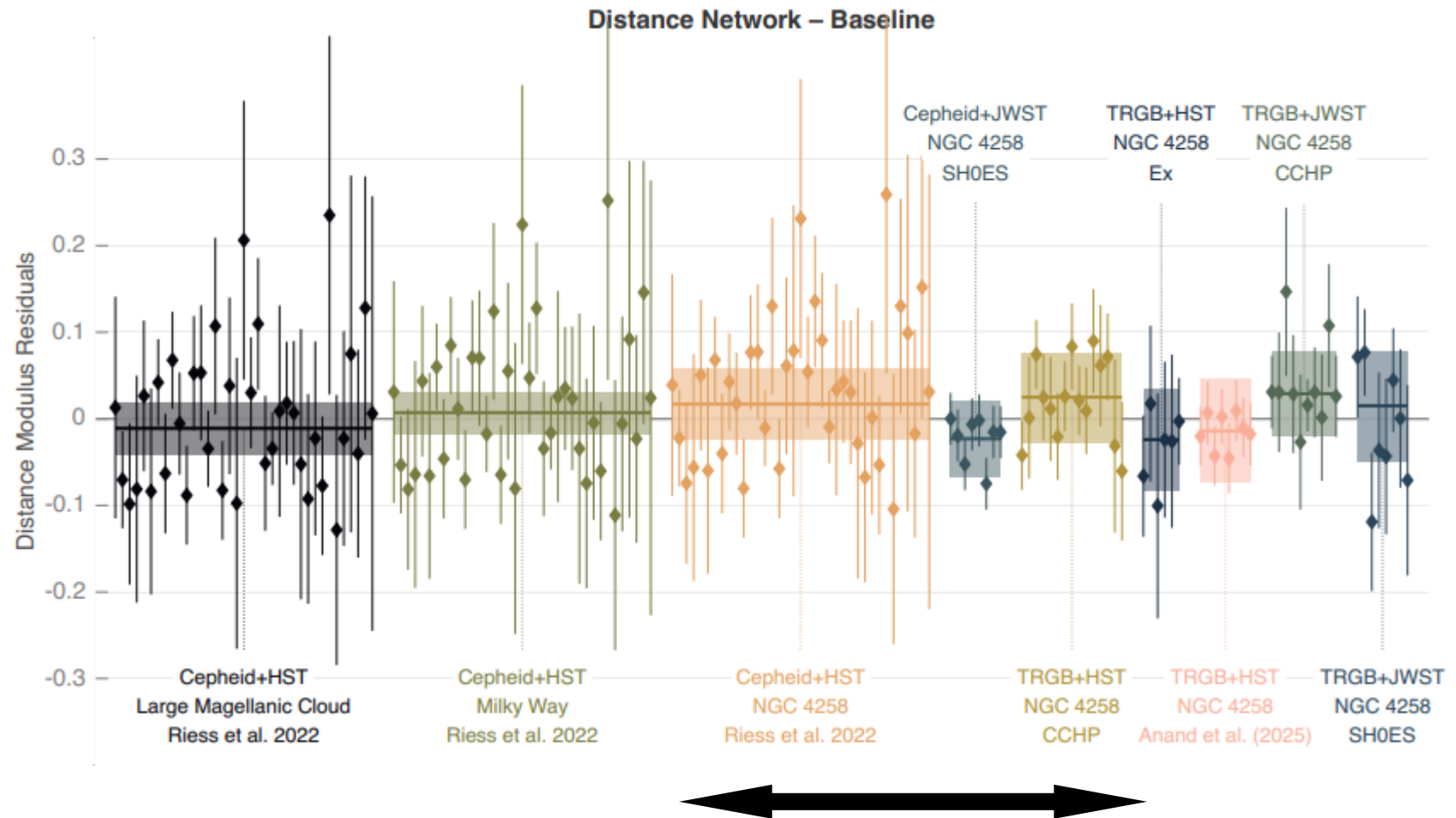
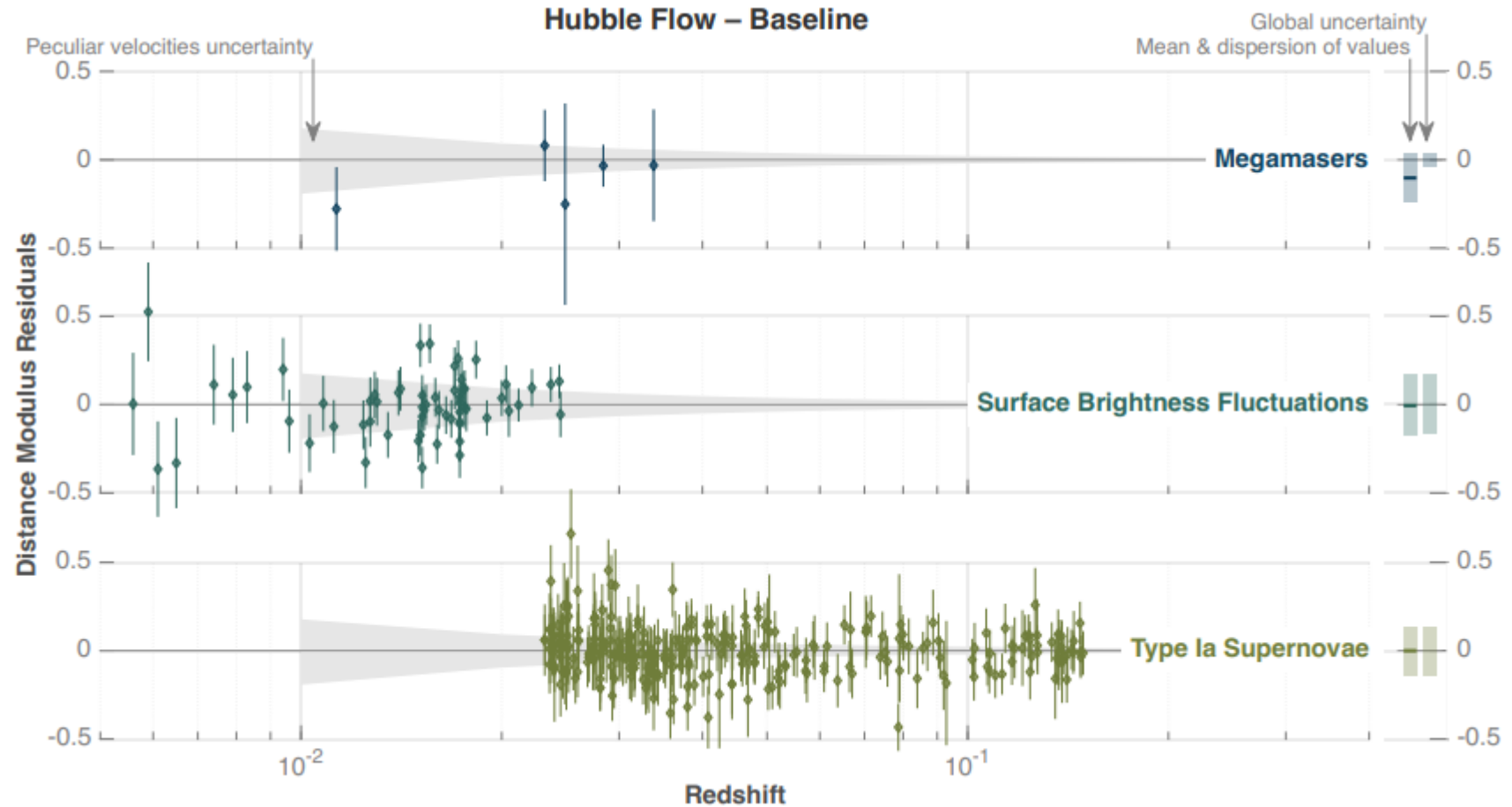


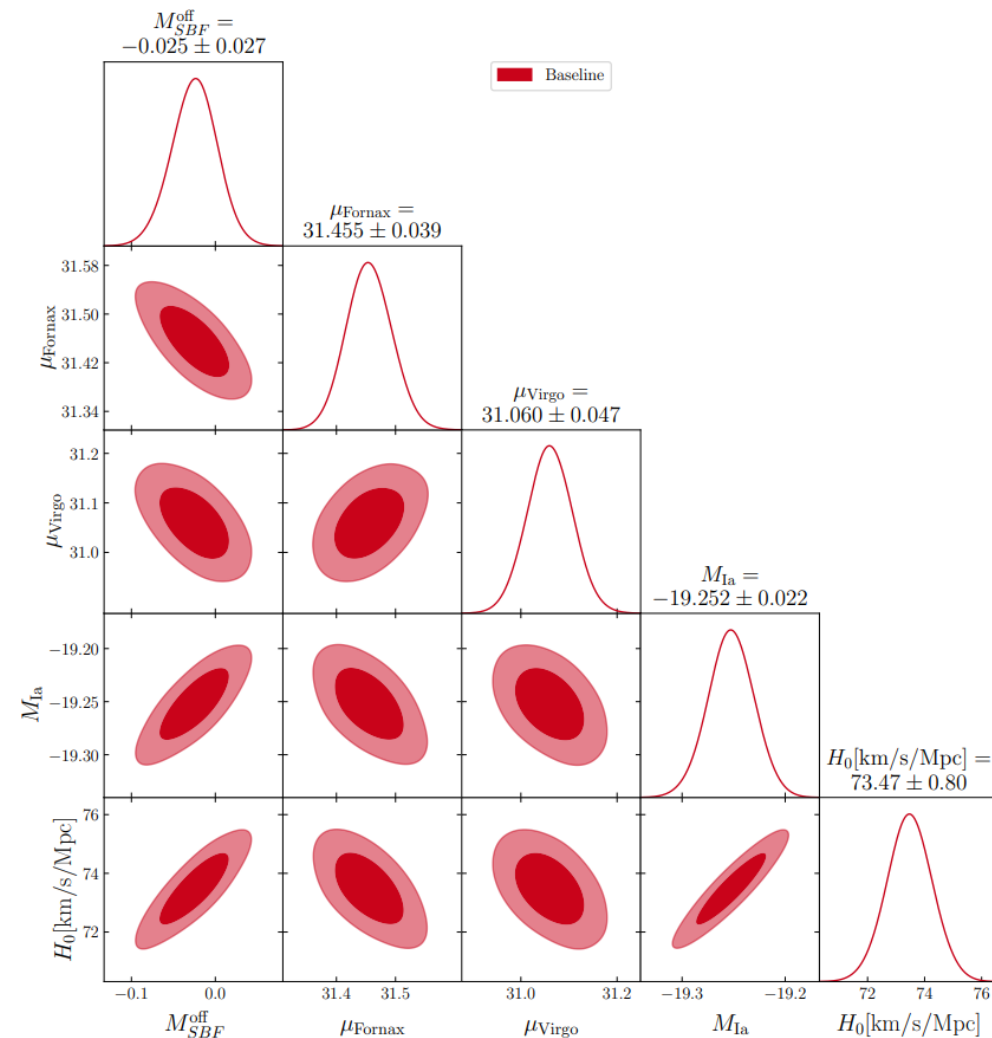
Figure 3. The Baseline Distance Network, illustrated analogously to Fig. 2



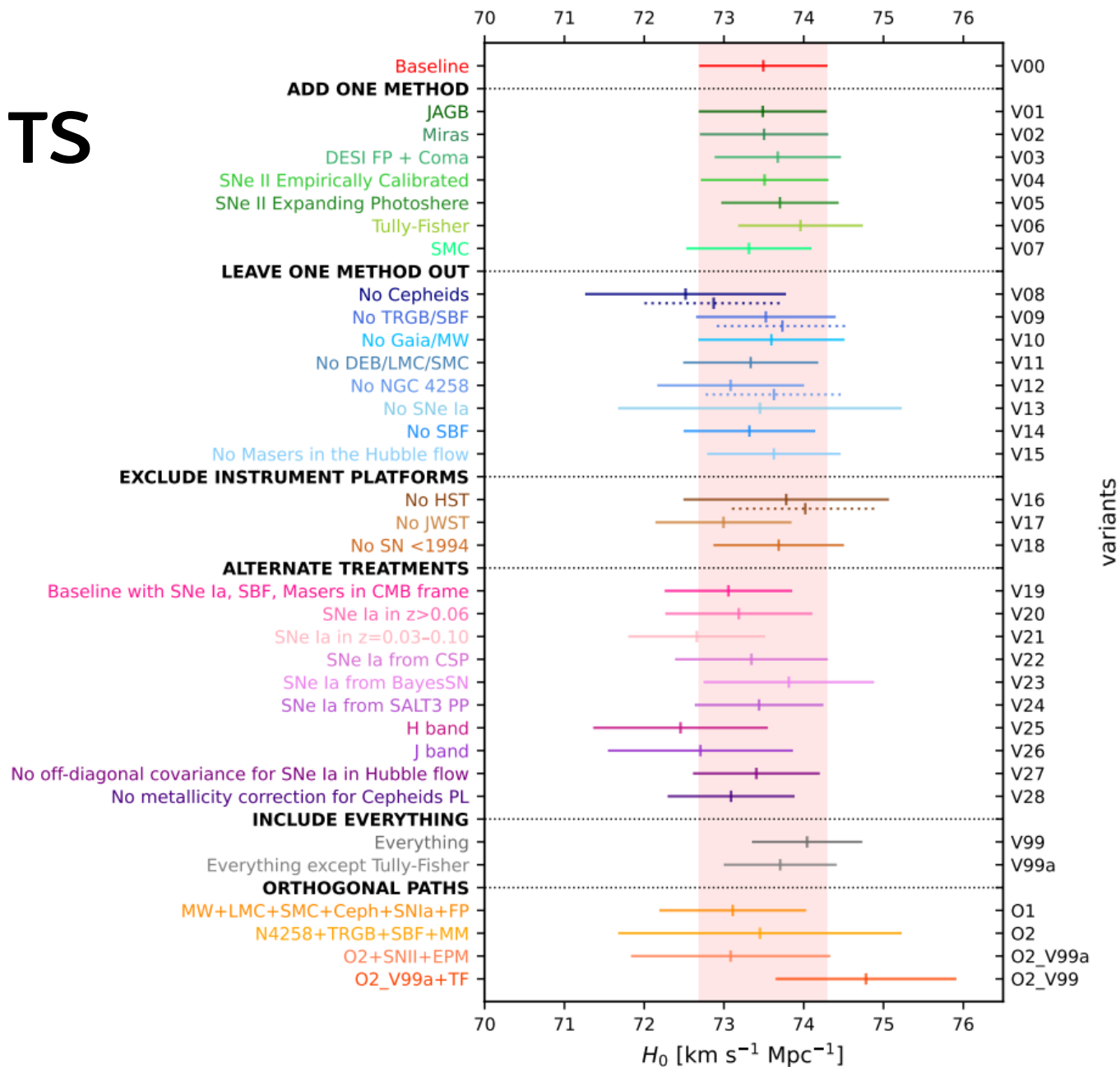
Marginal difference Cepheid vs. TRGB



RELATIVE IMPORTANCE OF DATASETS (CORRELATION WITH H_0)

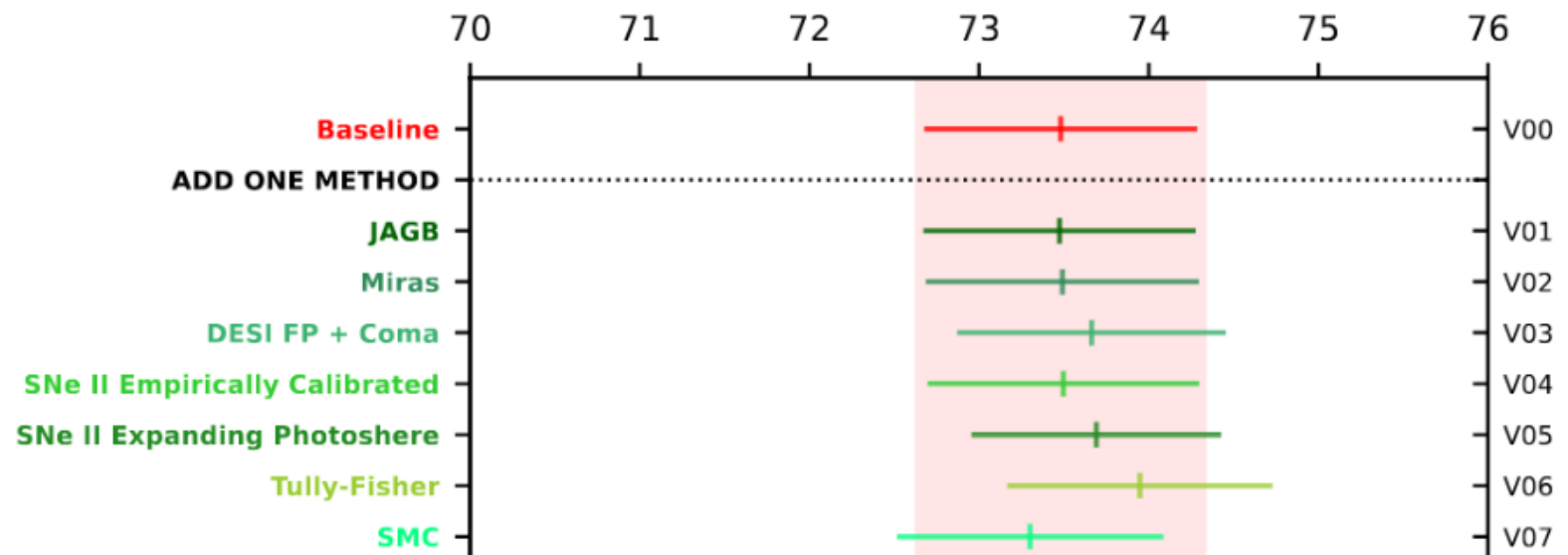


VARIANTS



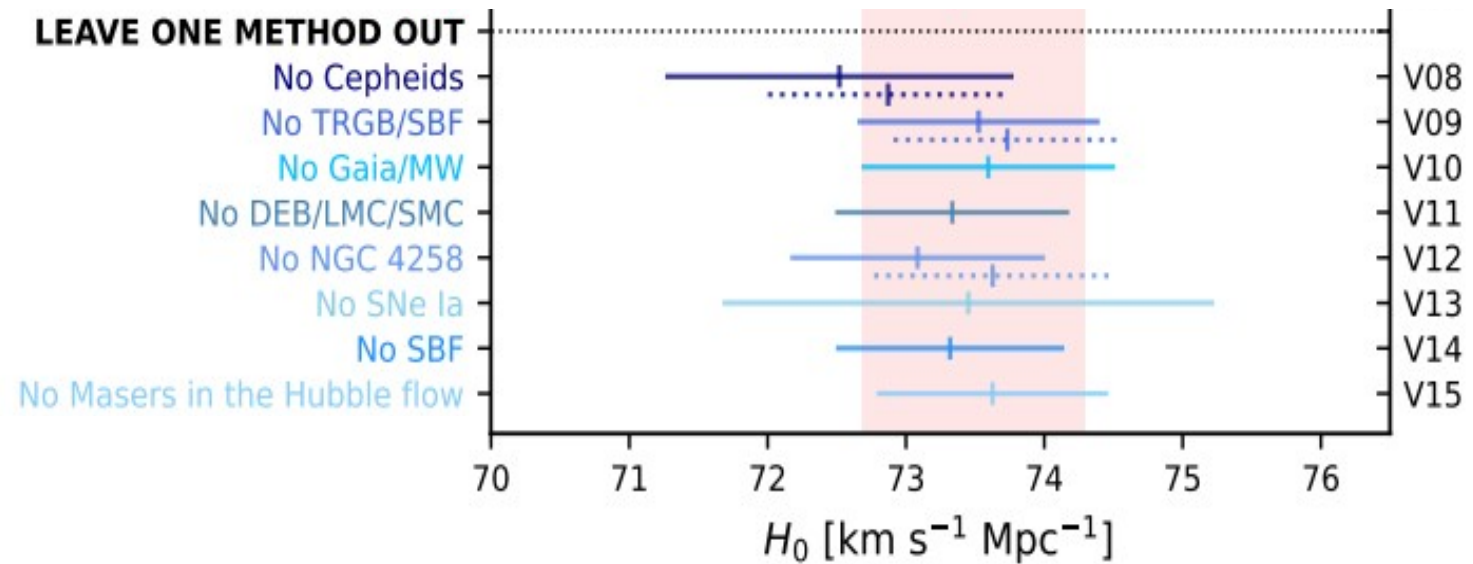
Planck+SPT+ACT (67.2)

Variants - Add one in (stuff that didn't make the first rank cut)



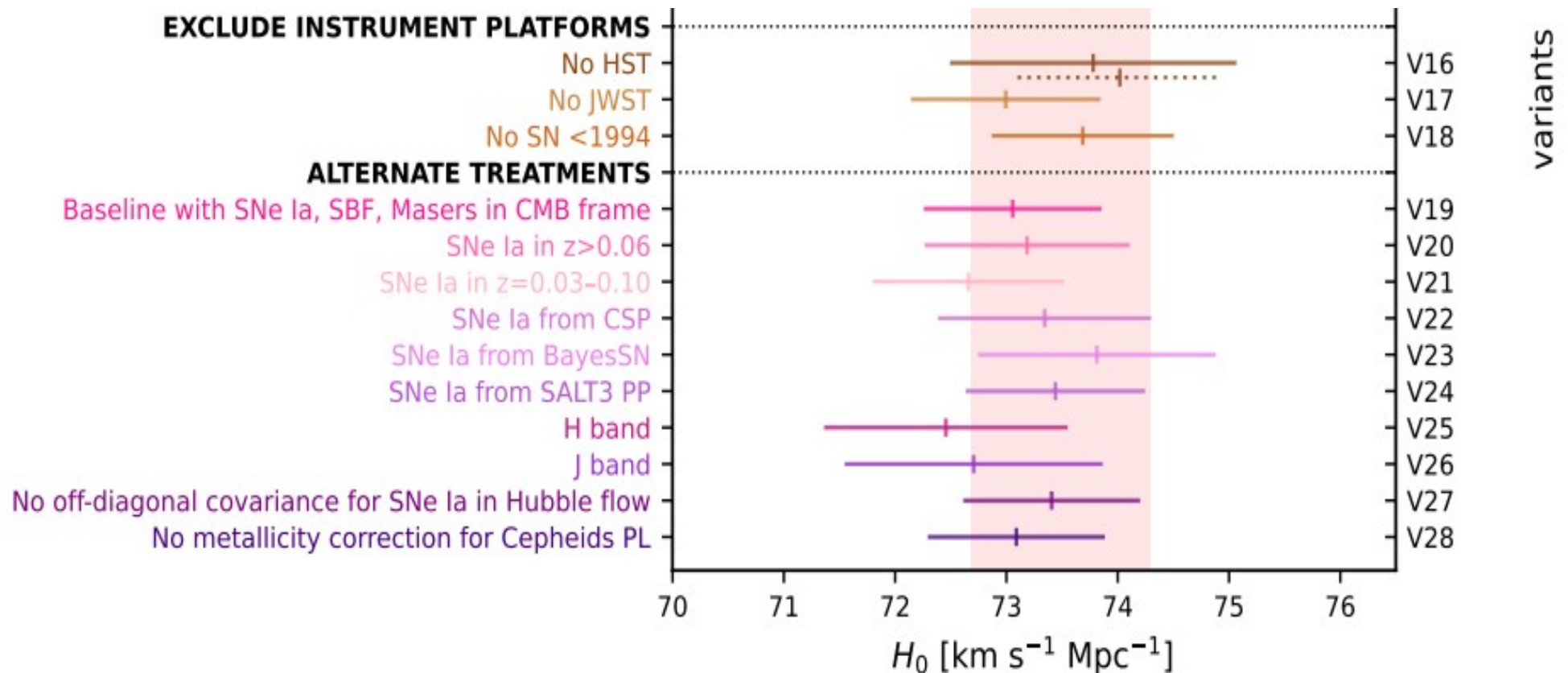
VARIANTS

No significant change in mean value or uncertainty



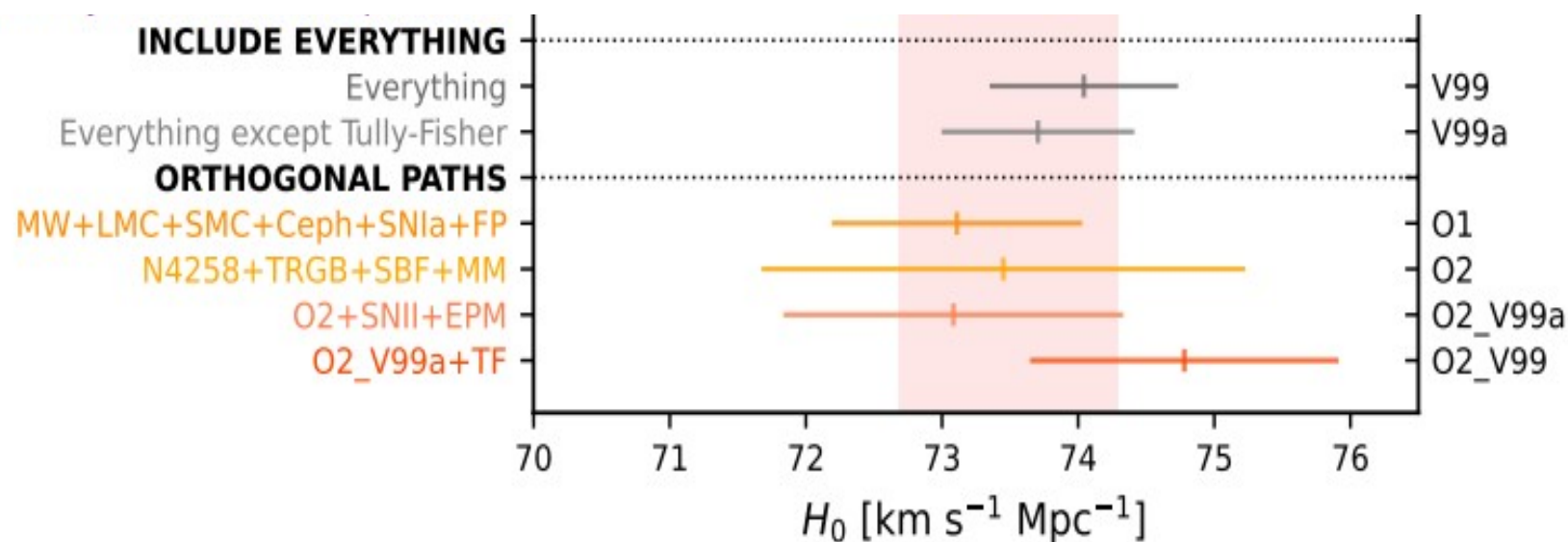
VARIANTS

No significant change in mean value or uncertainty



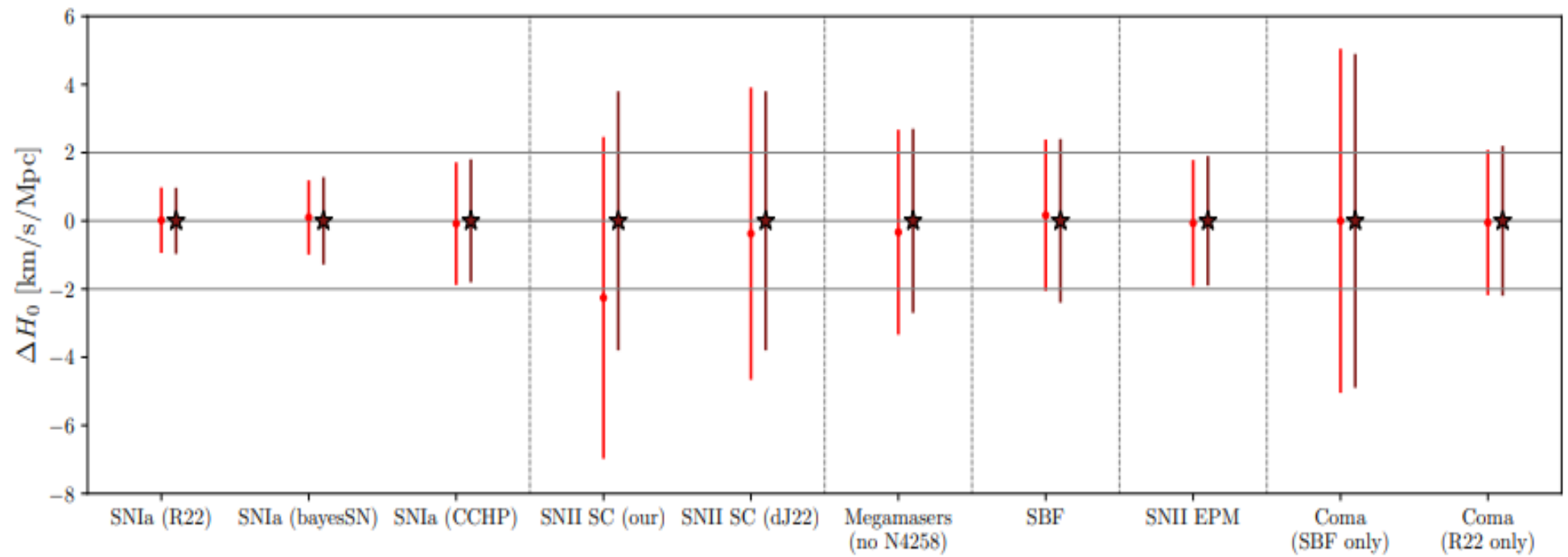
VARIANTS

Different paths through network compatible
(except TF)

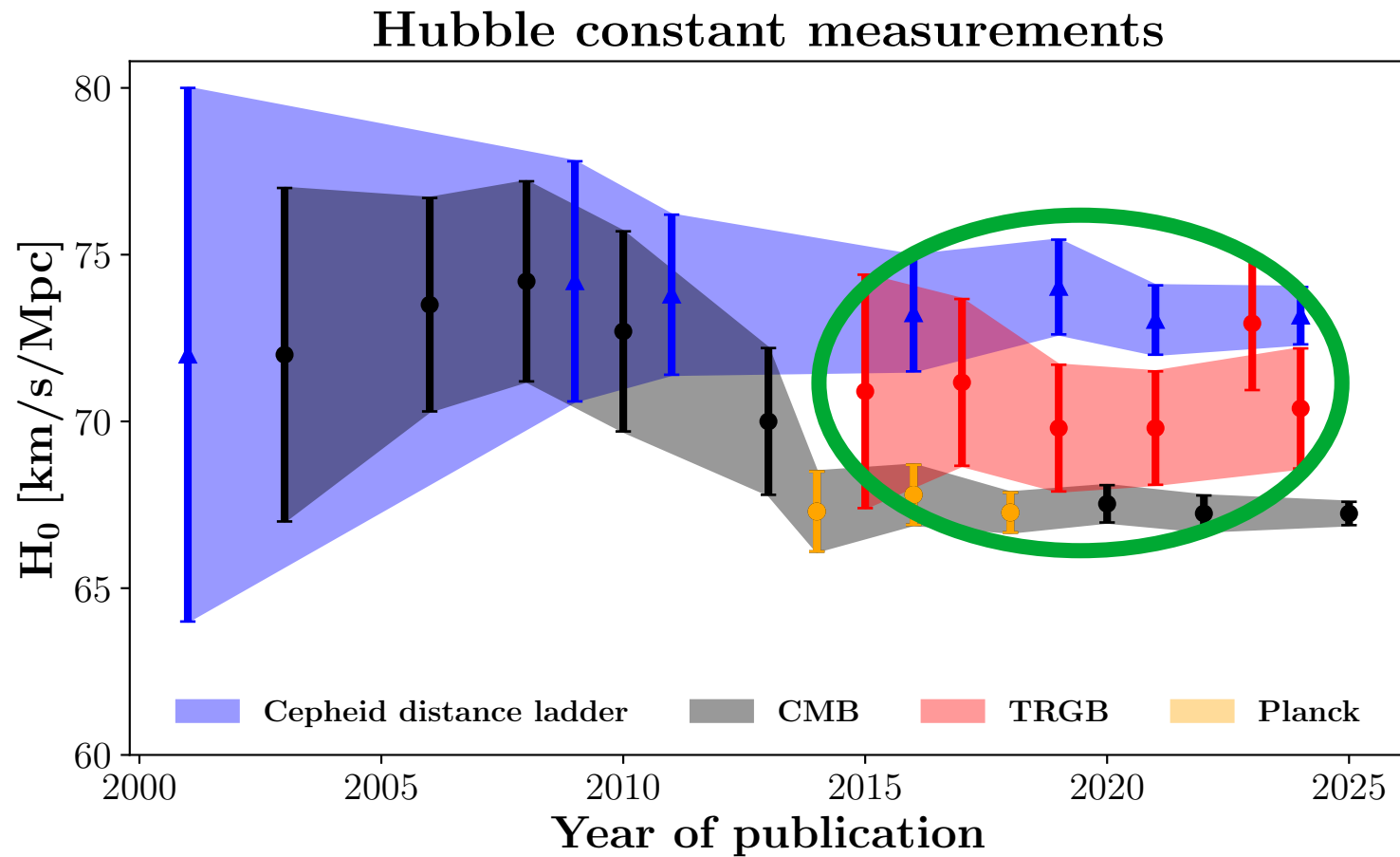


ADVANTAGES

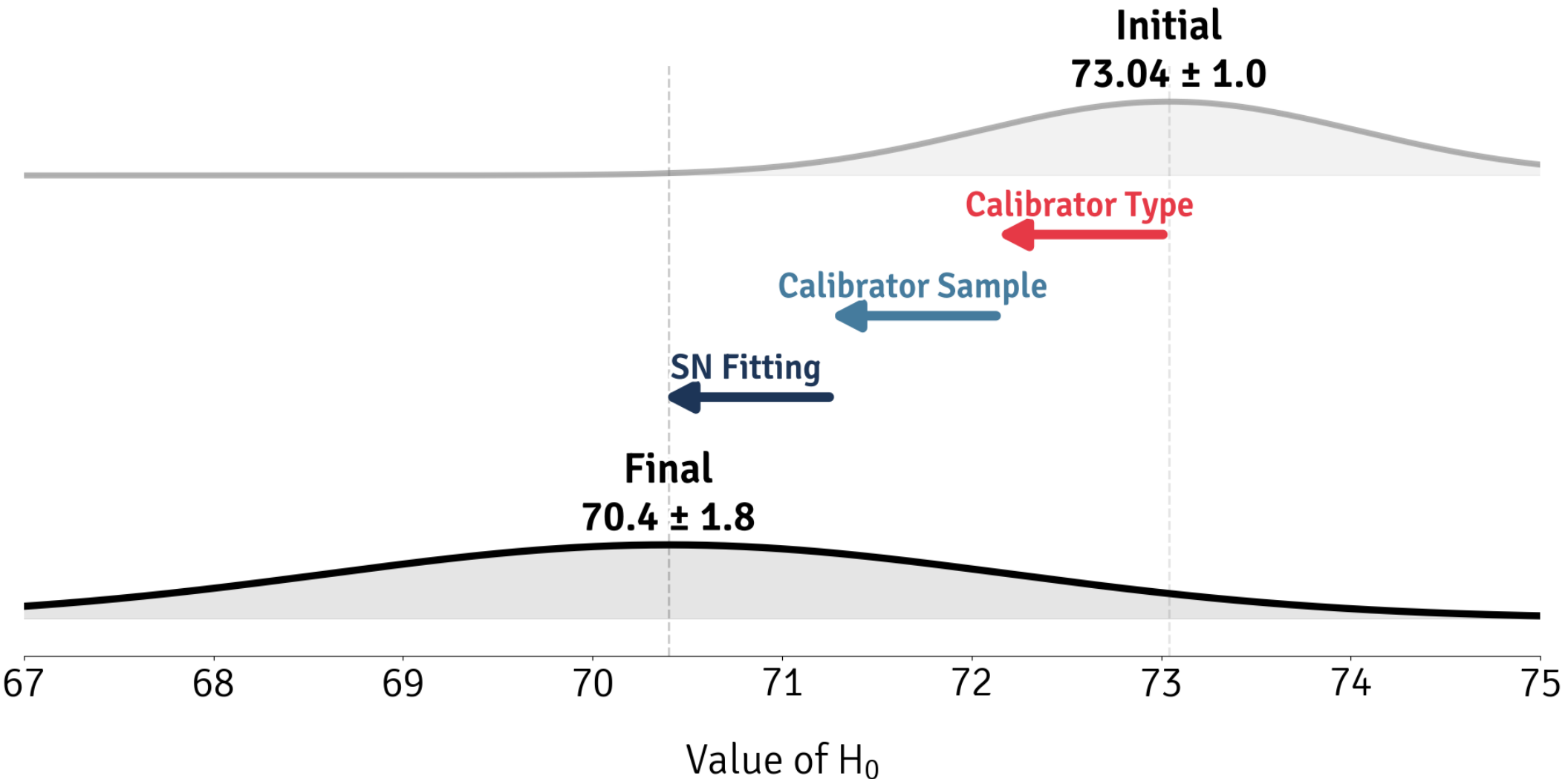
- 1) Consistent treatment of combining different probes
- 2) Open code + open data
- 3) A deeper look at consistency/systematics
- 4) A deeper look at literature differences

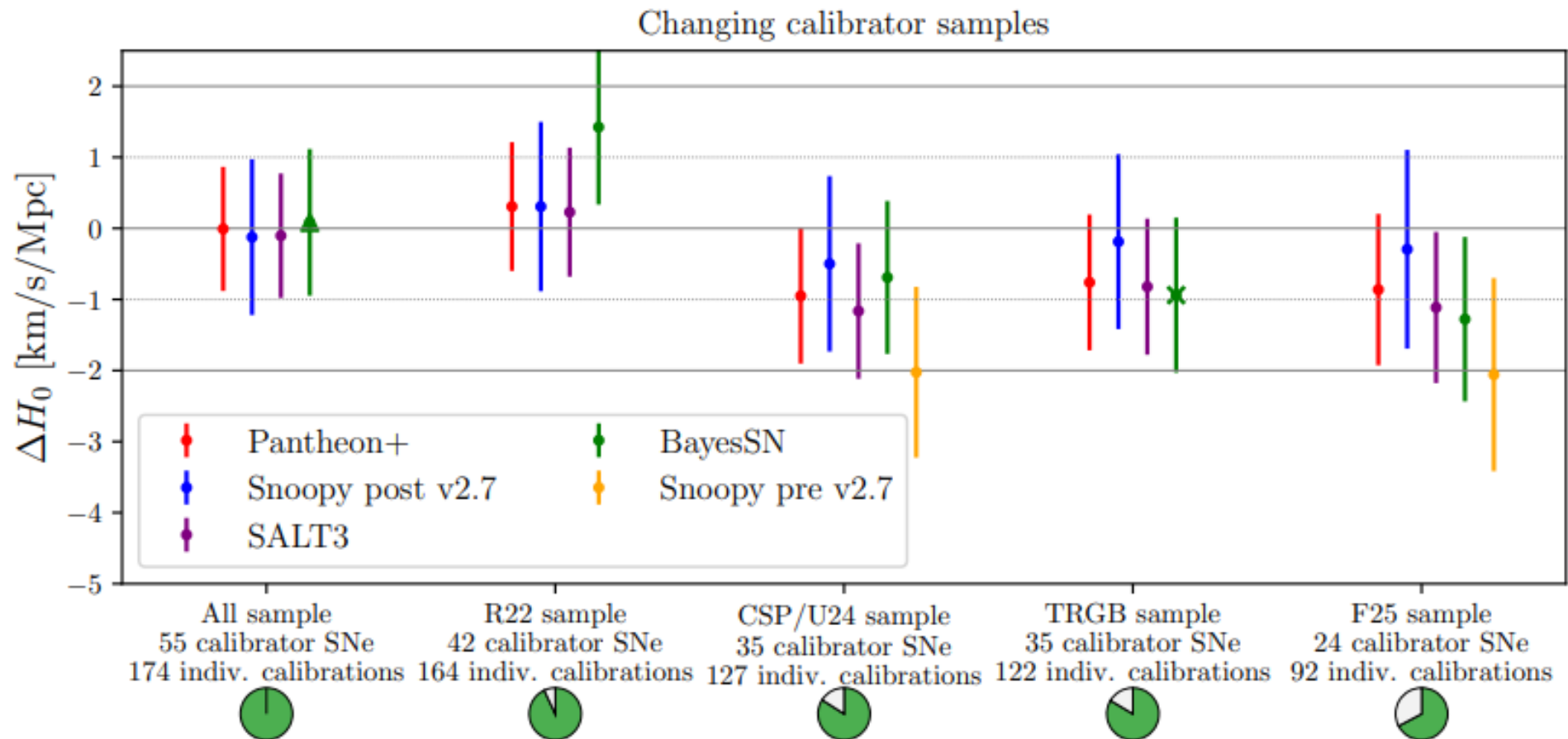


HISTORY



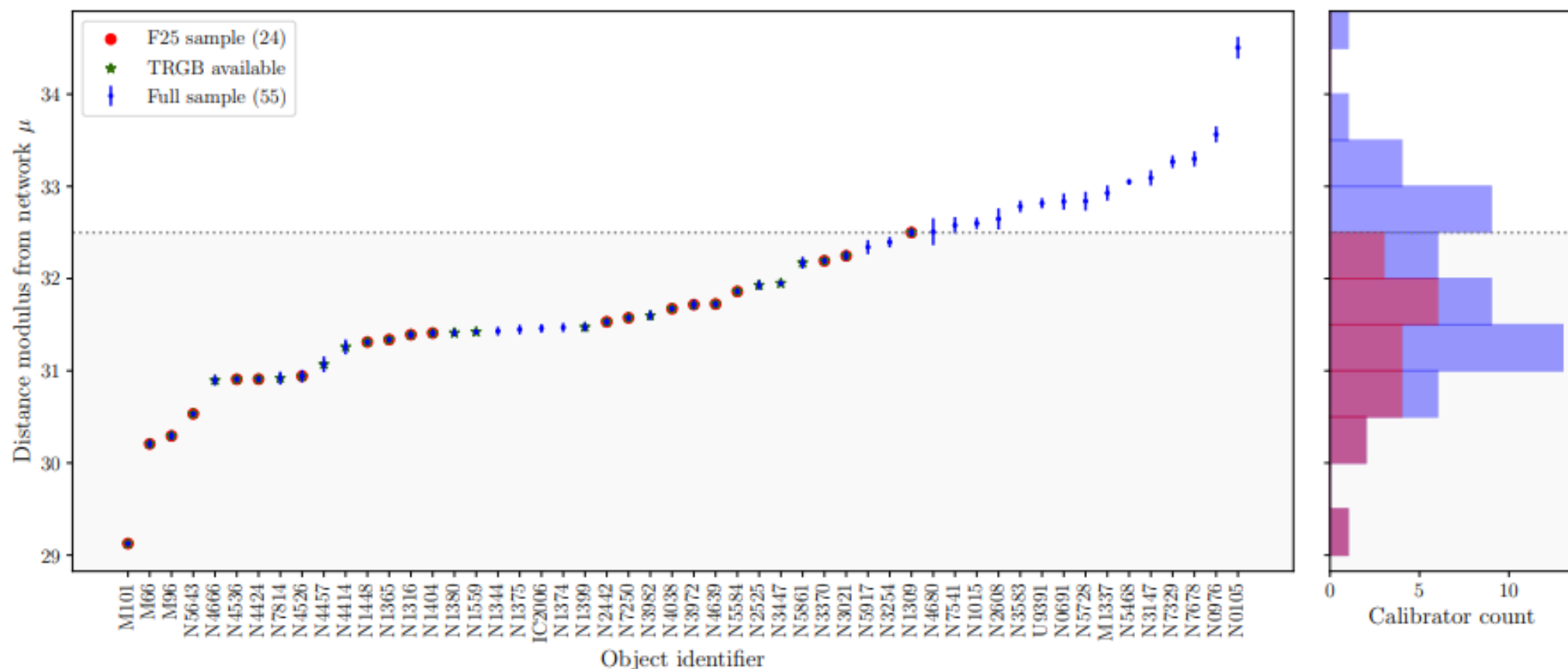
TRGB vs CEPHEIDS





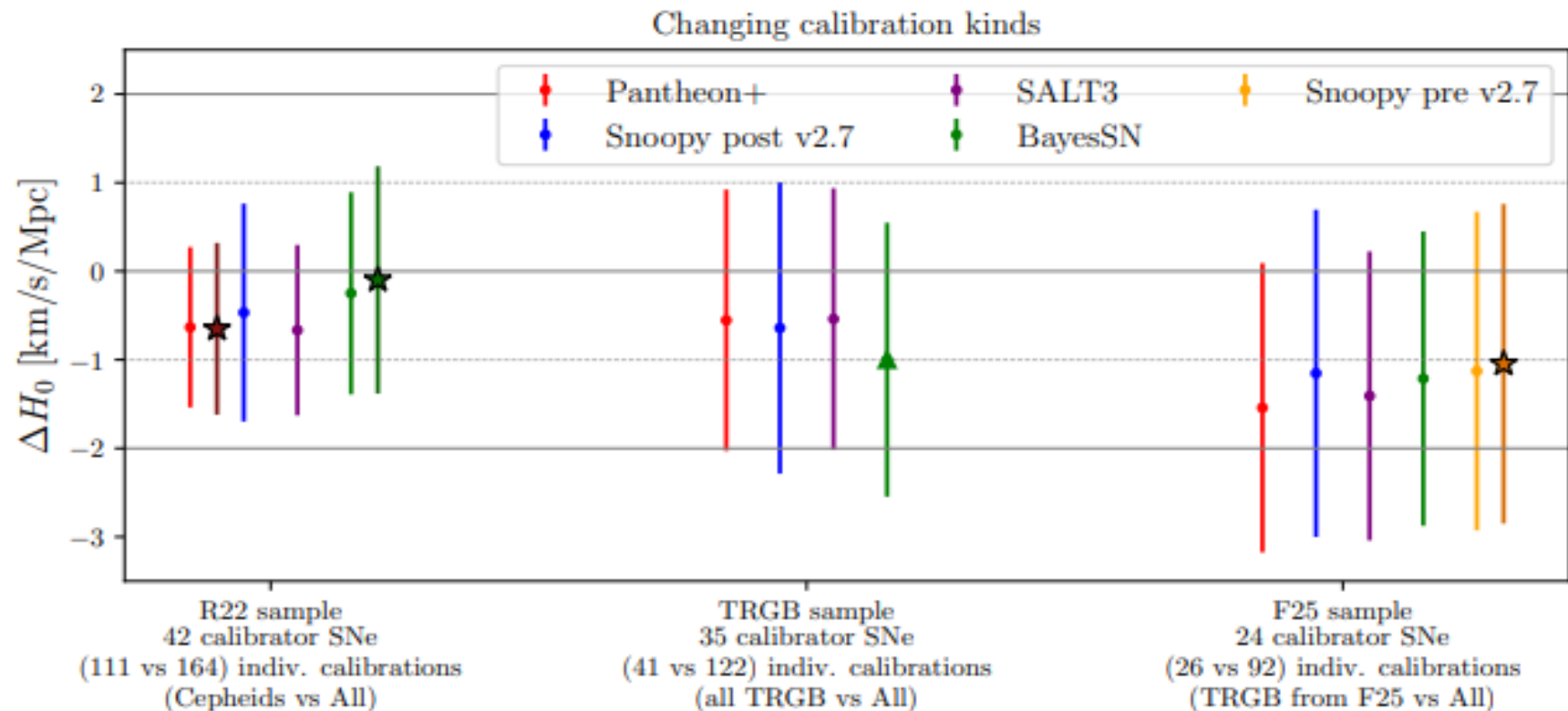
$$\Delta H_0 \simeq 1 \text{ km/s/Mpc}$$

from host sample selection effects



$$\Delta H_0 \simeq 1 \text{ km/s/Mpc}$$

from host sample selection effects



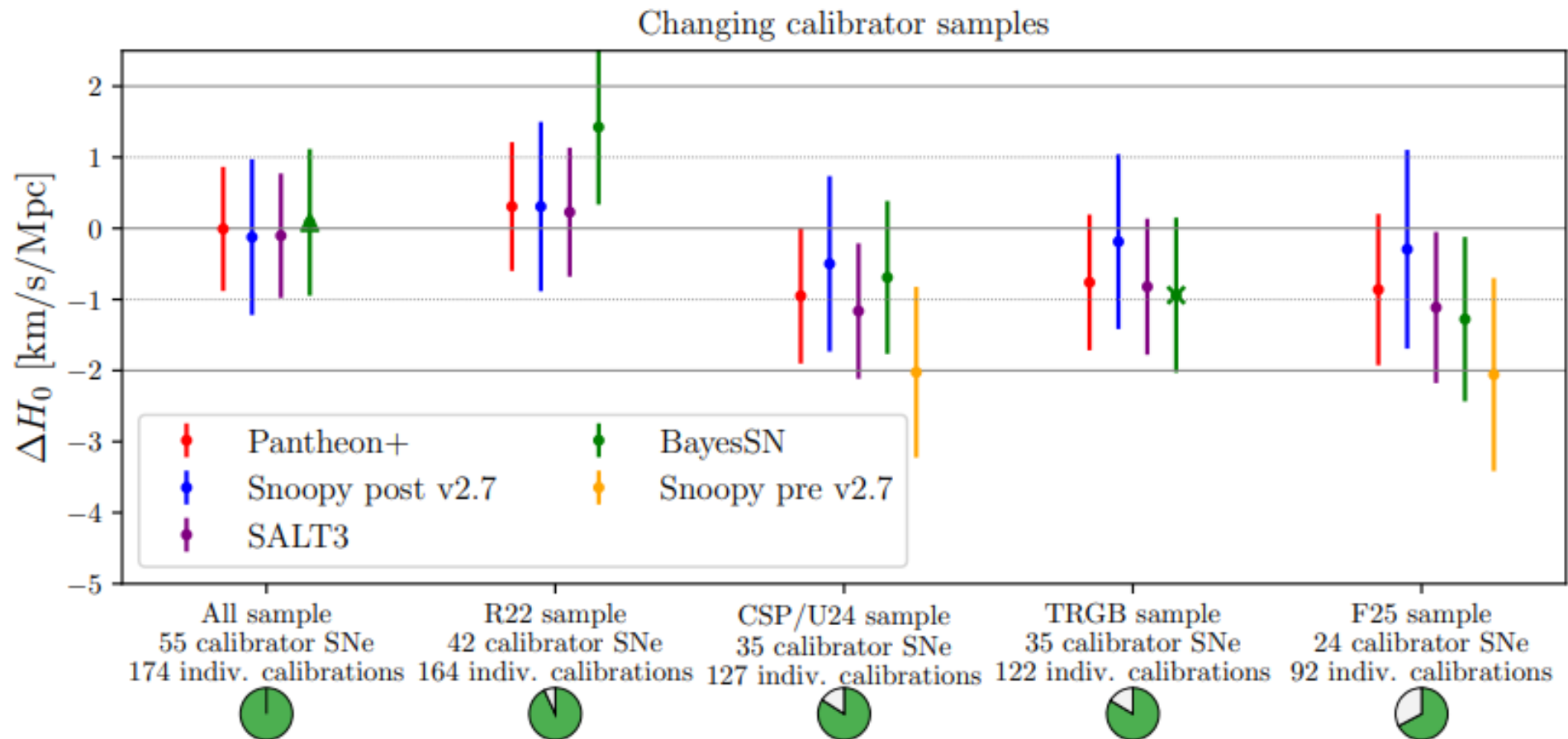
$$\Delta H_0 \simeq 1 \text{ km/s/Mpc}$$

from calibration types (e.g. TRGB vs ALL)

Result/difference	H_0	Notes
F25 (SNooPy pre v2.7, F25 sample)	70.39 ± 1.80 ($N = 24$)	F25 as published (without additional SN calibration error)
↳ No change to SNooPy version or sample	70.31 ± 1.80 ($N = 24$)	Reproduced within our network
↳ SNooPy post v2.7, F25 sample	72.05 ± 1.85 ($N = 24$)	New SNooPy raises H_0

$$\Delta H_0 \lesssim 1.5 \text{ km/s/Mpc}$$

from supernovae light curve fitting



$$\Delta H_0 \simeq 1 \text{ km/s/Mpc}$$

from supernovae light curve fitting

DIFFERENCES SHoES AND CCHP

- 1 km/s/Mpc from choice of hosts
 - 1km/s/Mpc from lightcurve fitter
 - 1km/s/Mpc from which types of calibrators
- => 3km/s/Mpc accounted for