# The Hubble tension (from) A Supernova perspective

**David Camarena**
PPGCosmo, UFES
**in collaboration with Valerio Marra**

16.04.2021 · PPGCosmo Seminars · UFES

# $H_0$ discrepancy

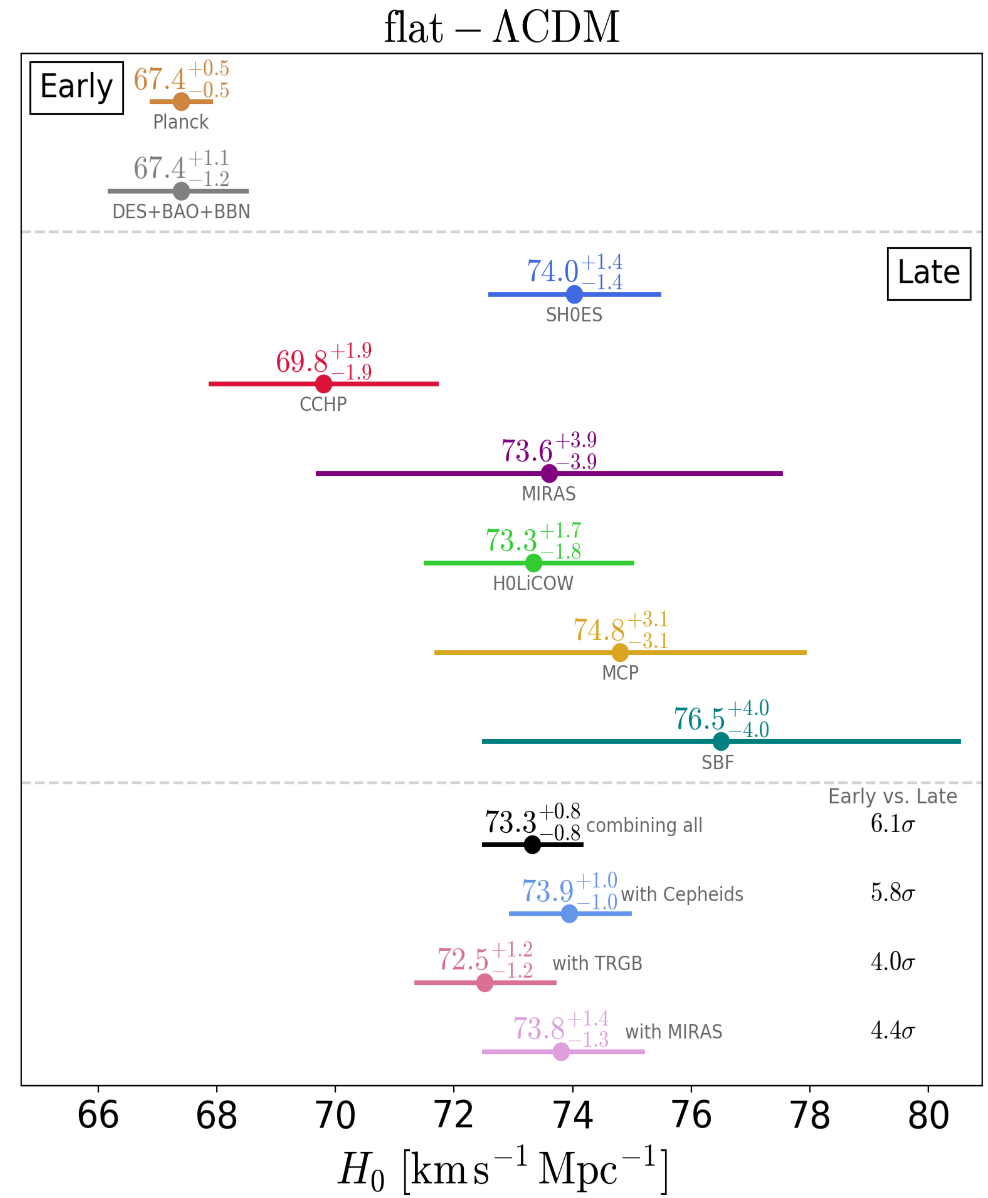
- disagreement between early and late-time
- $\Lambda$CDM model can not explain this tension
- how quantify the tension?

$$\mathcal{T} \sim \frac{|\hat{x}_1 - \hat{x}_2|}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

- statistical fluct. or real disagreement?

$2\sigma$ $\rightarrow$curiosity
$3\sigma$ $\rightarrow$tension
$4\sigma$ $\rightarrow$discrepancy
$5\sigma$ $\rightarrow$crisis

**L. Verde *et al.* arXiv:1907.10625**



# $H_0$ discrepancy

- disagreement between early and late-time
- $\Lambda$CDM model can not explain this tension
- how quantify the tension?

$$\boxed{\mathcal{T} \sim \frac{|\hat{x}_1 - \hat{x}_2|}{\sqrt{\sigma_1^2 + \sigma_2^2}}}$$

- statistical fluct. or real disagreement?

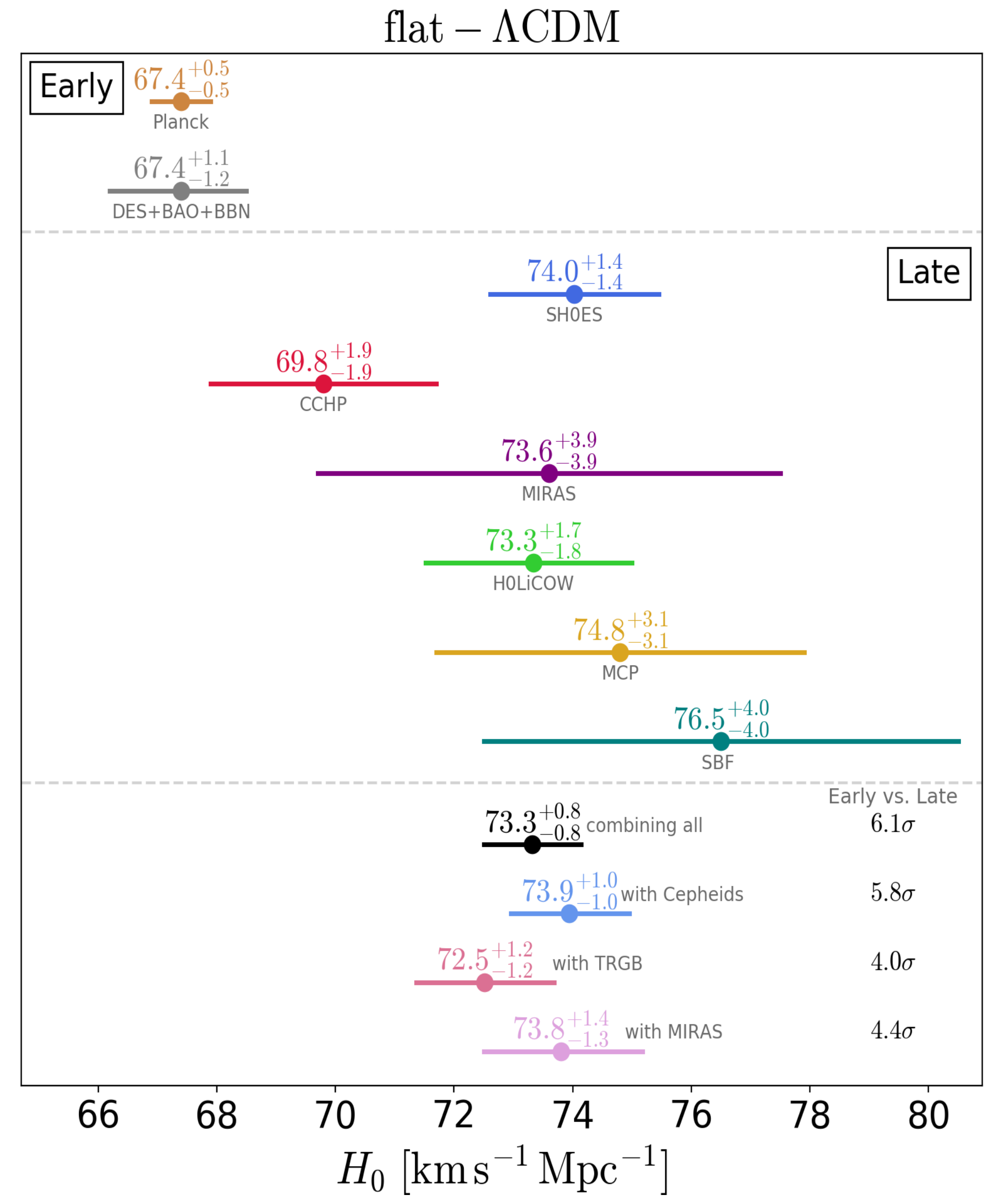
$2\sigma$ $\rightarrow$curiosity

$3\sigma$ $\rightarrow$**tension**

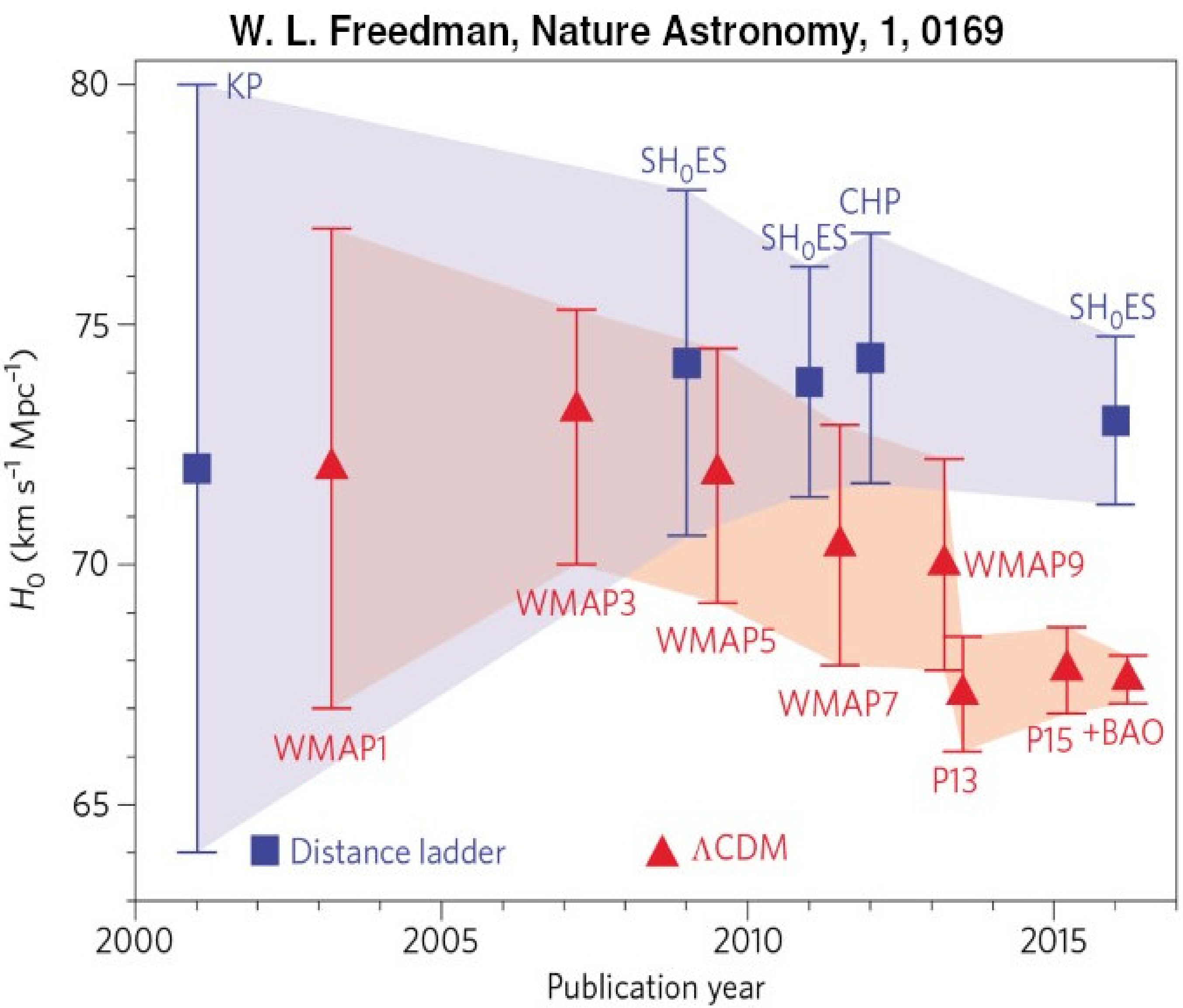
$4\sigma$ $\rightarrow$**discrepancy**

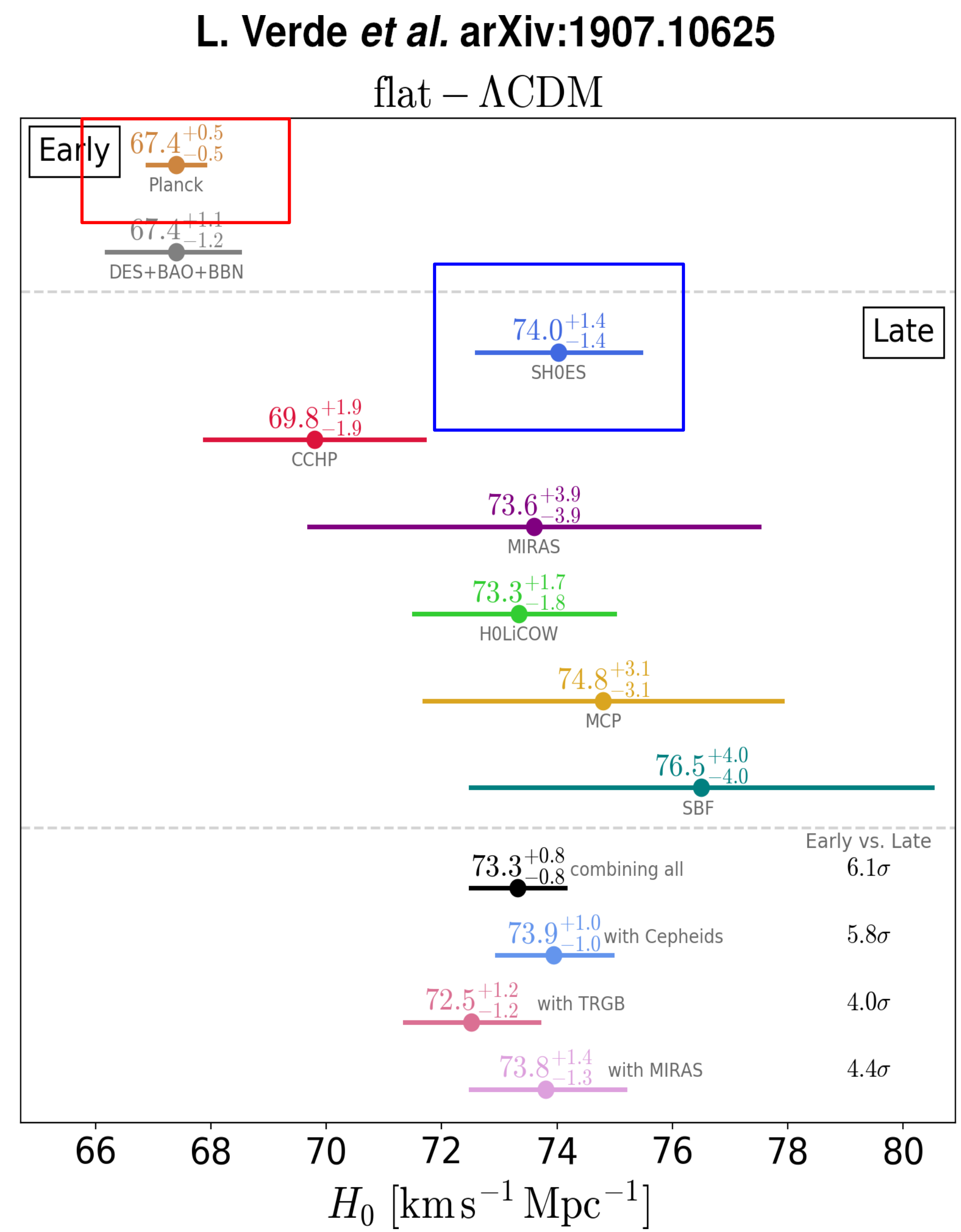
$5\sigma$ $\rightarrow$**crisis!**

**L. Verde *et al.* arXiv:1907.10625**



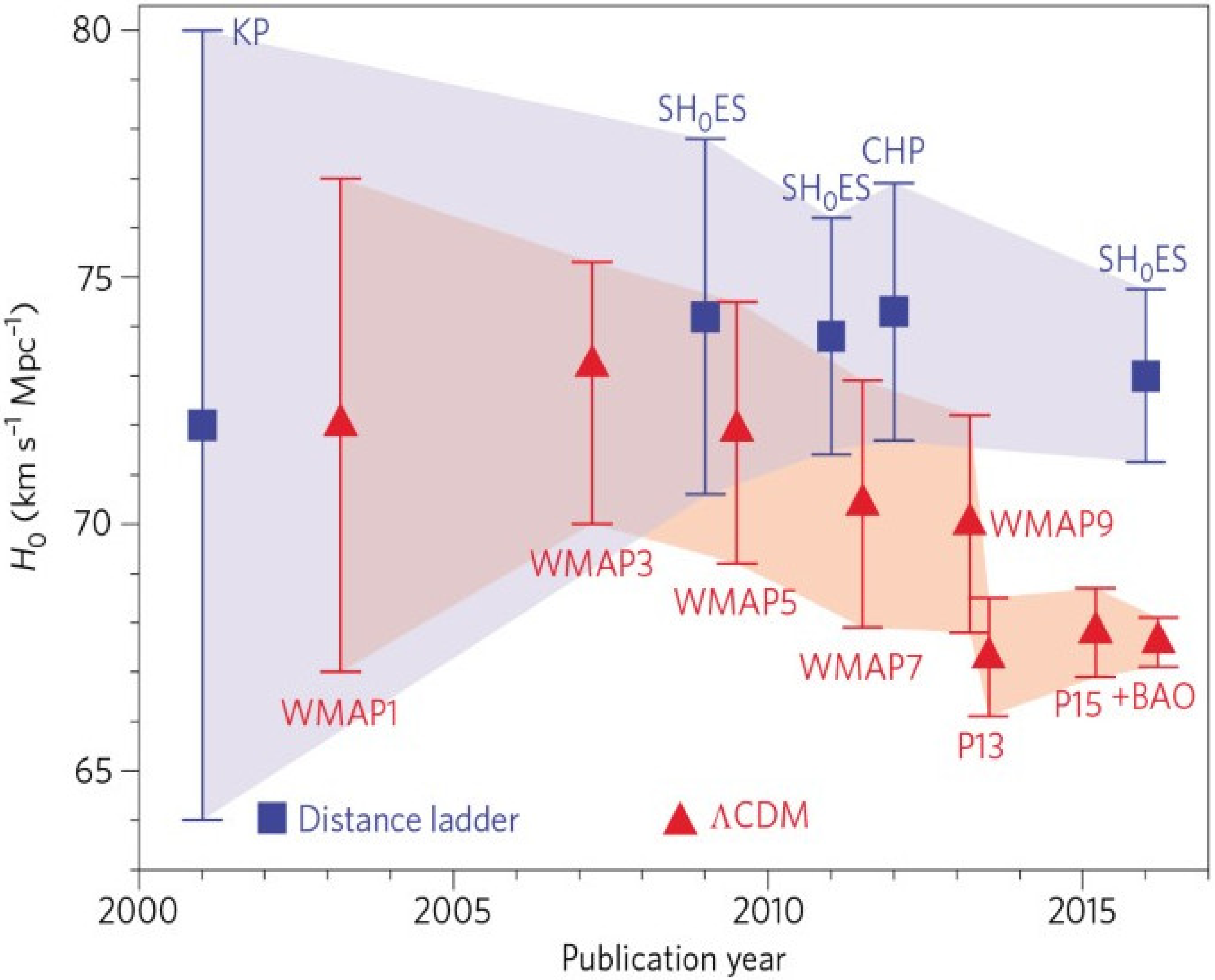
# $H_0$ discrepancy



# $H_0$ discrepancy

W. L. Freedman, Nature Astronomy, 1, 0169




Riess, A. G. et. al, arXiv:2012.08534

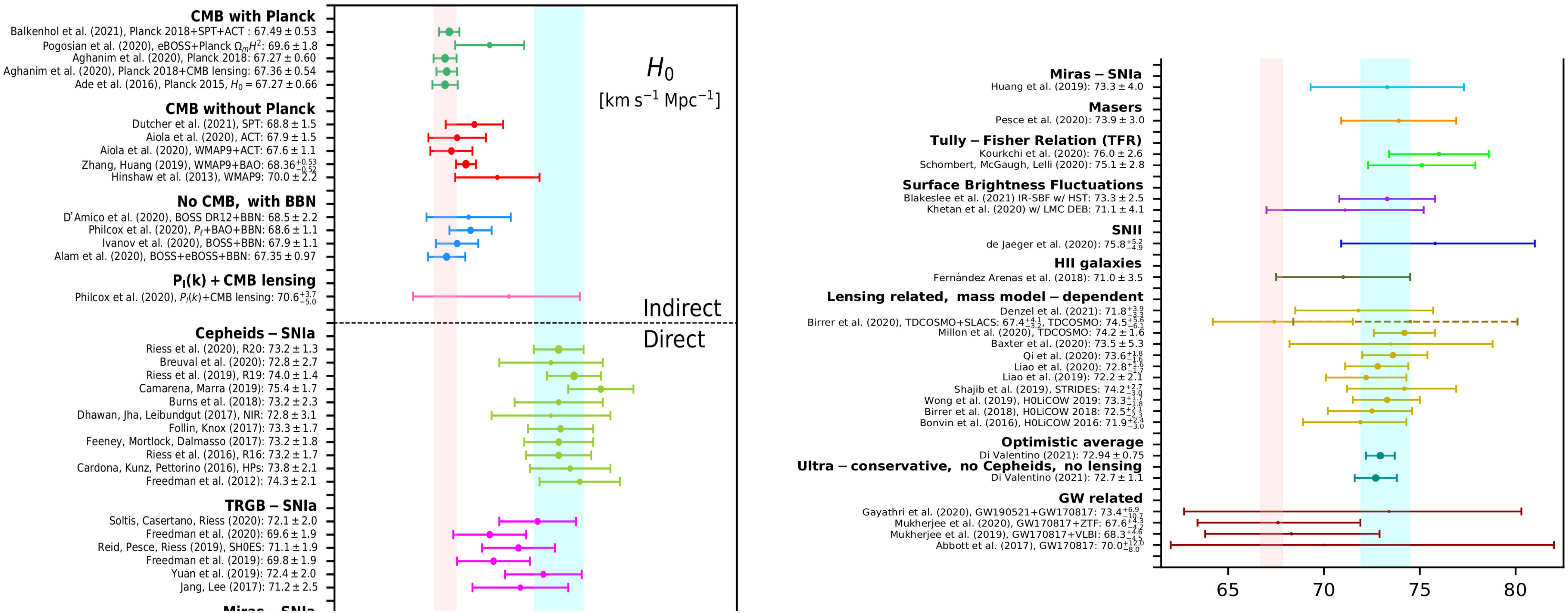
$H_0 = 73.2 \pm 1.3$

$\boxed{\sim 4\sigma}$

$H_0 = 67.49 \pm 0.53$

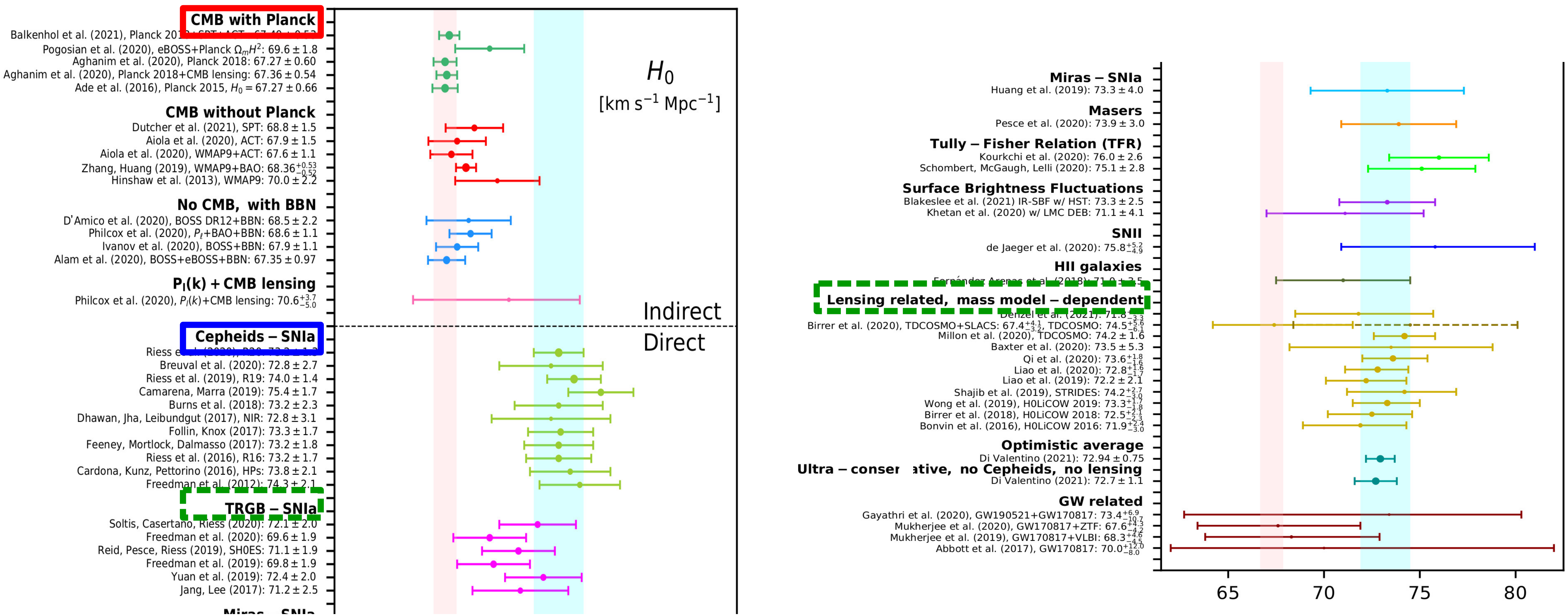
Planck Collaboration, arXiv:1807.06209

# $H_0$ discrepancy




E. Di Valentino *et al.*, arXiv:2103.01183

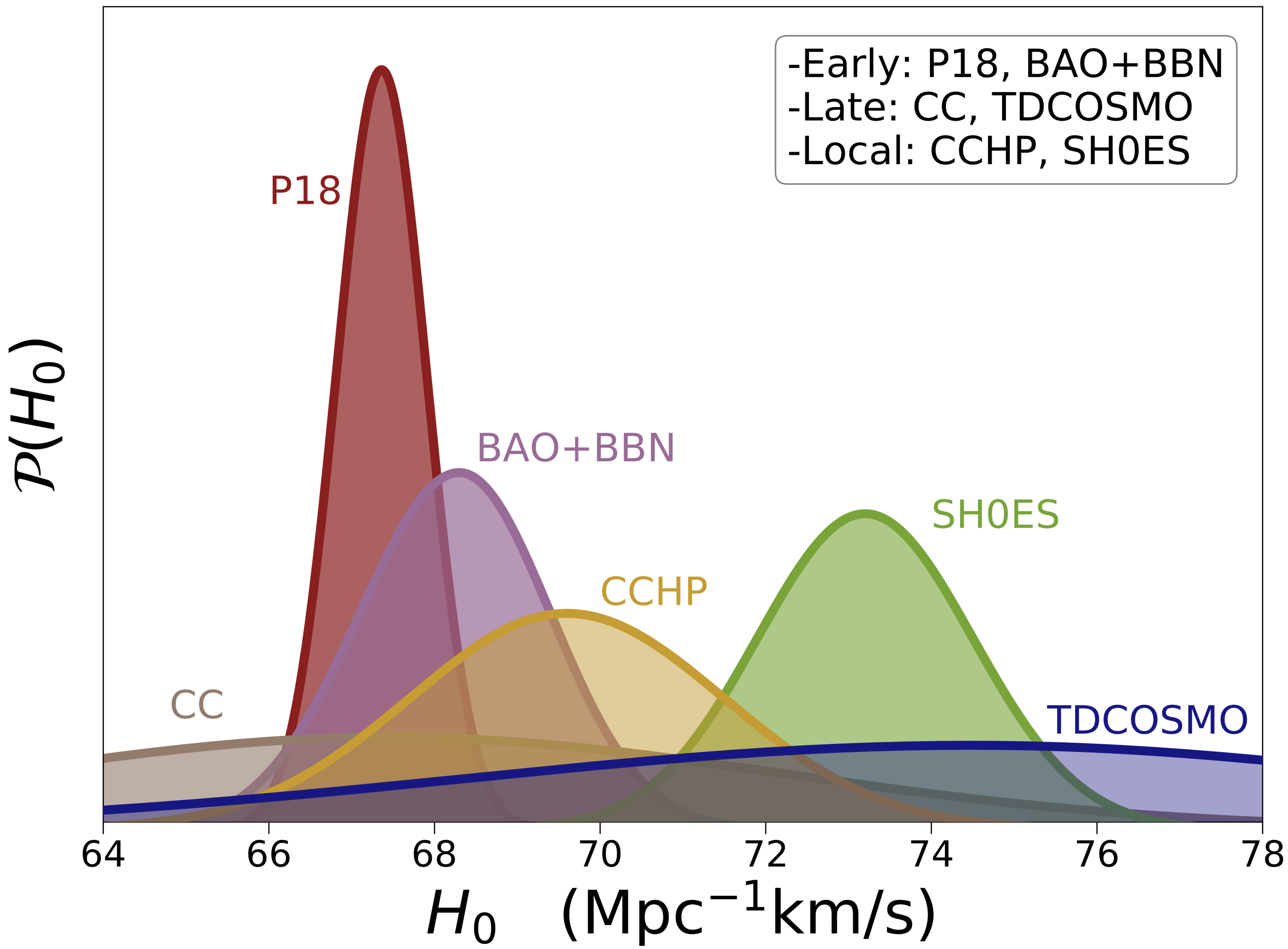
# $H_0$ discrepancy



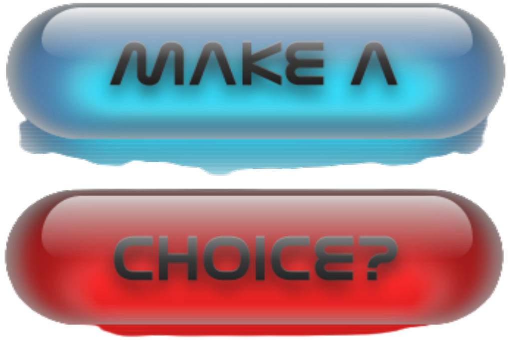

E. Di Valentino *et al.*, arXiv:2103.01183

# $H_0$ discrepancy

J. L. Bernal et. al, arXiv:2102.05066



# Systematic or new physics?




### Systematic errors

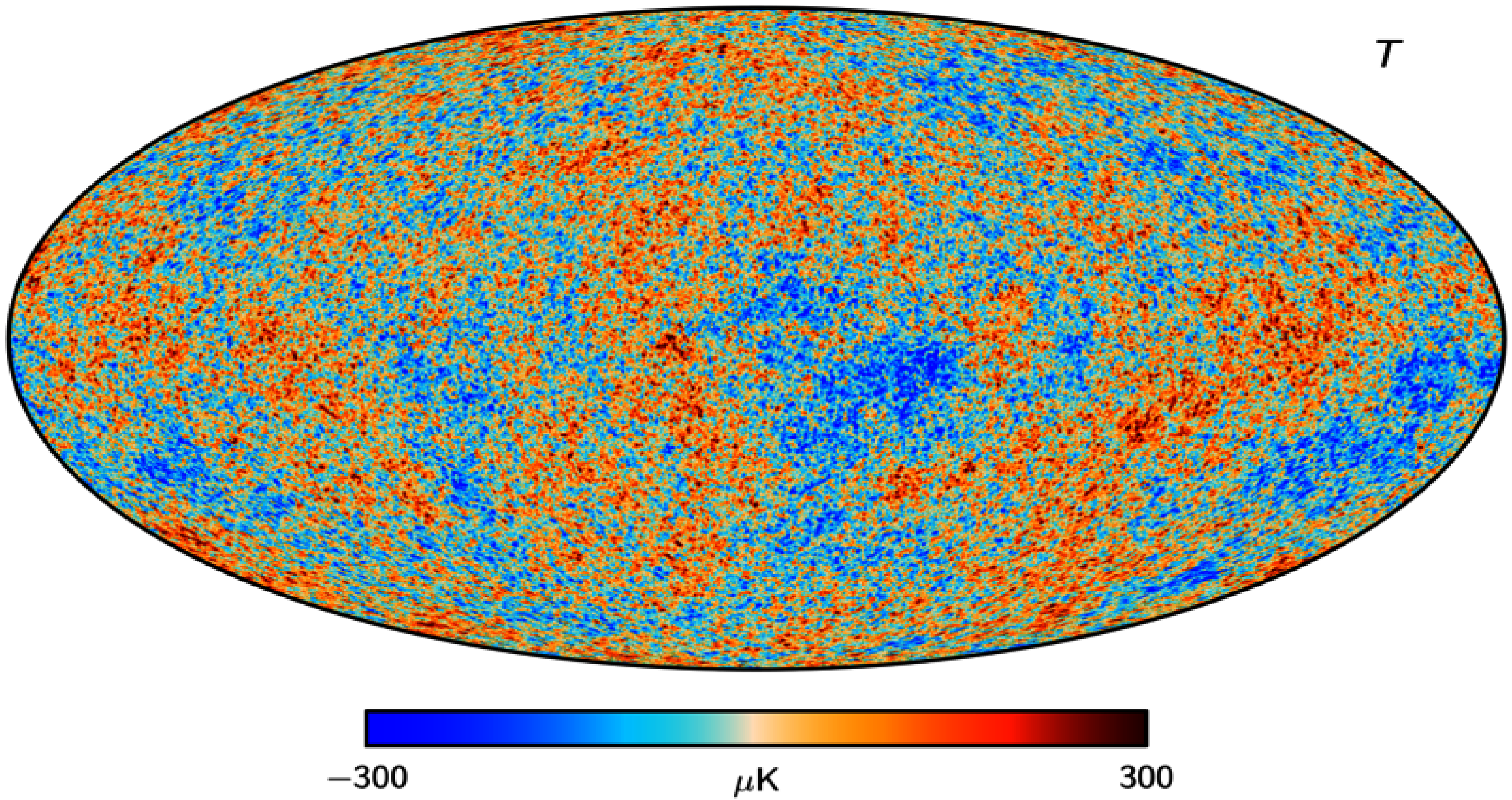
- Cosmic variance on $H_0$
- Cepheids calibration
- Excess of lens $A_L$
- Discrepancy low-$\ell$ and high-$\ell$
- ...

### New physics

- Low-$z$ transitions
- Early dark energy
- Neutrinos
- Void modelss
- Dark sector interactions
- ...

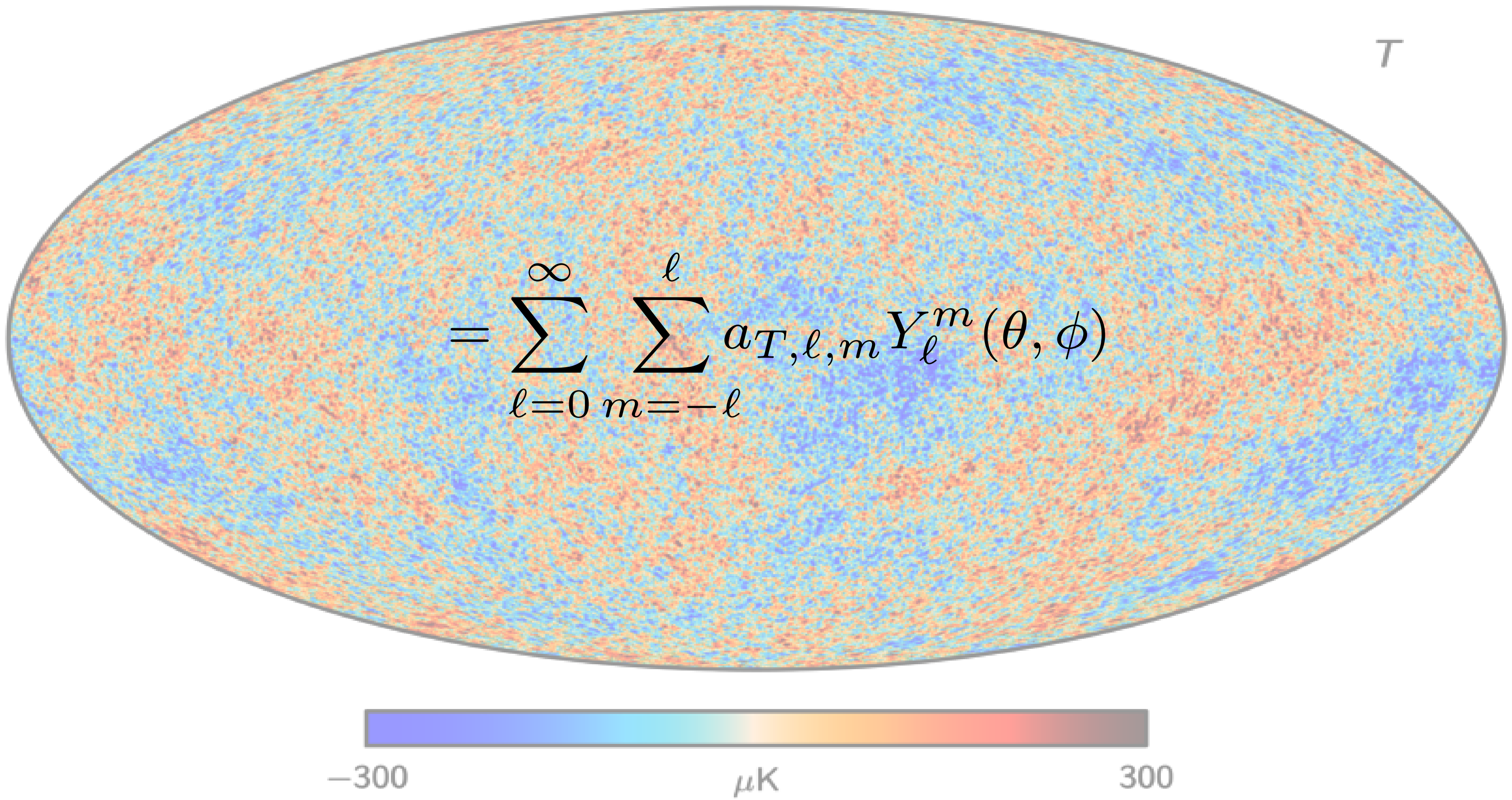
# Cosmic Microwave Background

$TT$ map



# Cosmic Microwave Background

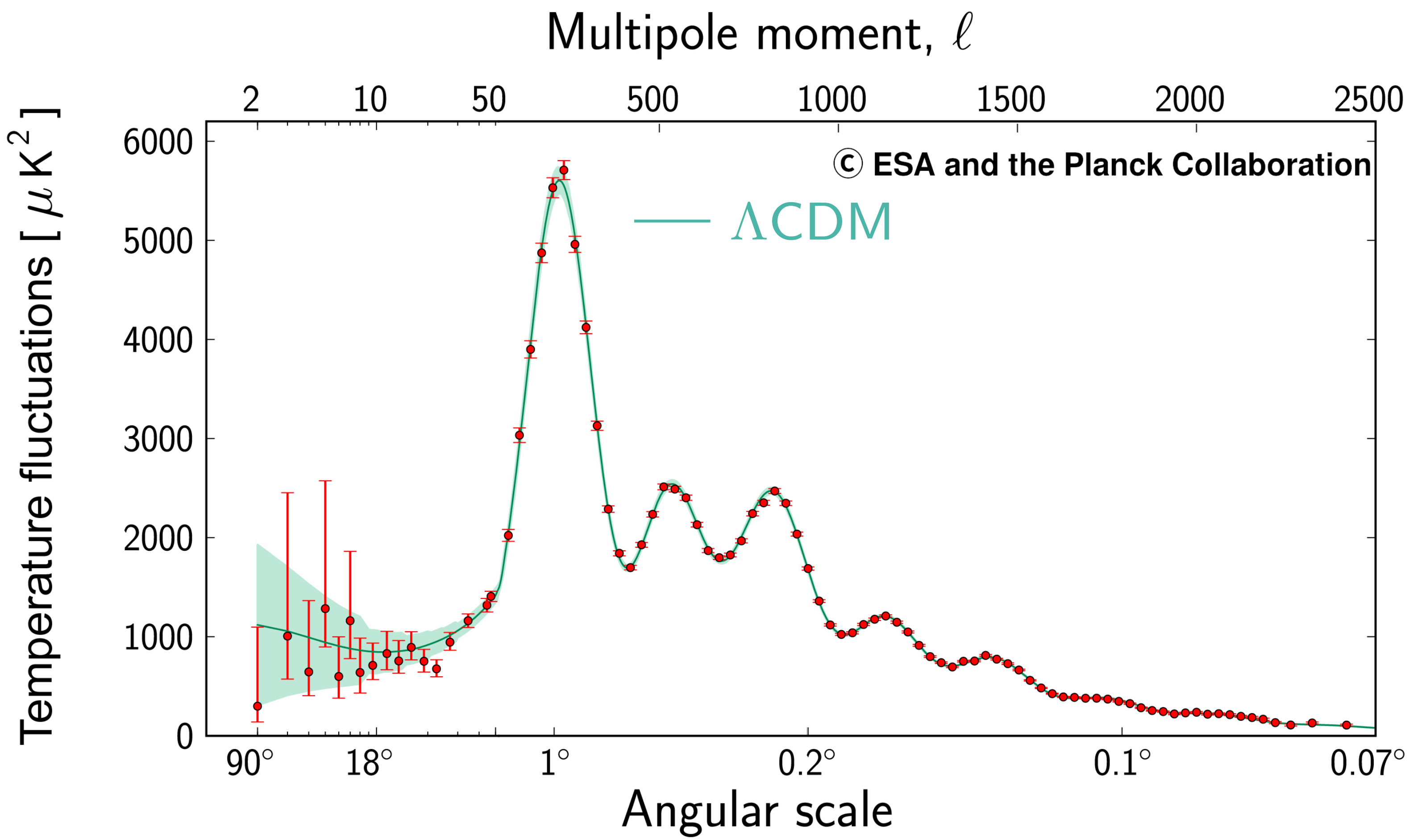
$$C_{TT,\ell} = \left\langle \left| a_{T,\ell m} \right|^2 \right\rangle$$




$$= \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{T,\ell,m} Y_{\ell}^{m}(\theta, \phi)$$

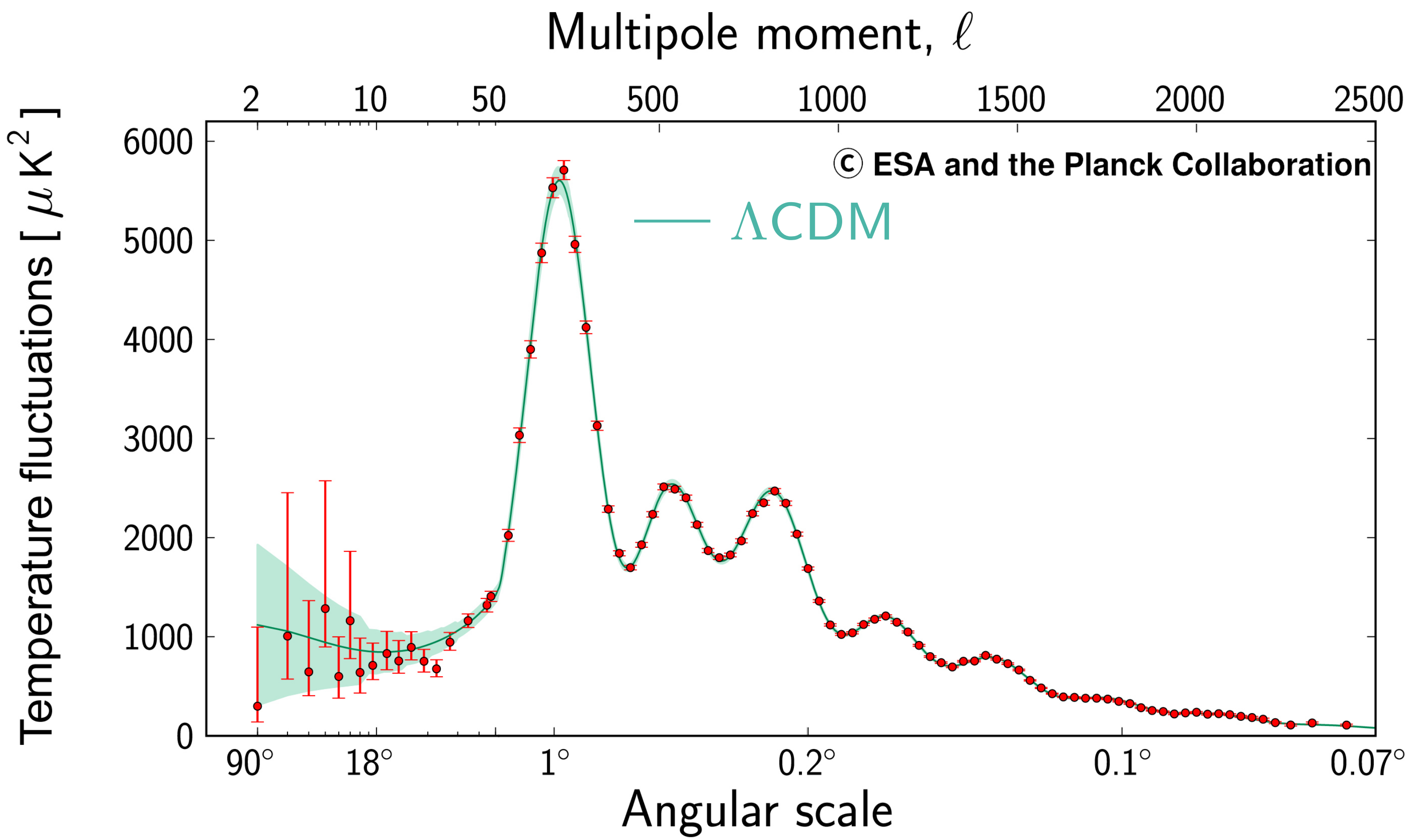
# Cosmic Microwave Background

$$C_{TT,\ell} = \left\langle \left| a_{T,\ell m} \right|^2 \right\rangle$$



# Cosmic Microwave Background

$$C_{TT,\ell} = \langle |a_{T,\ell m}|^2 \rangle$$



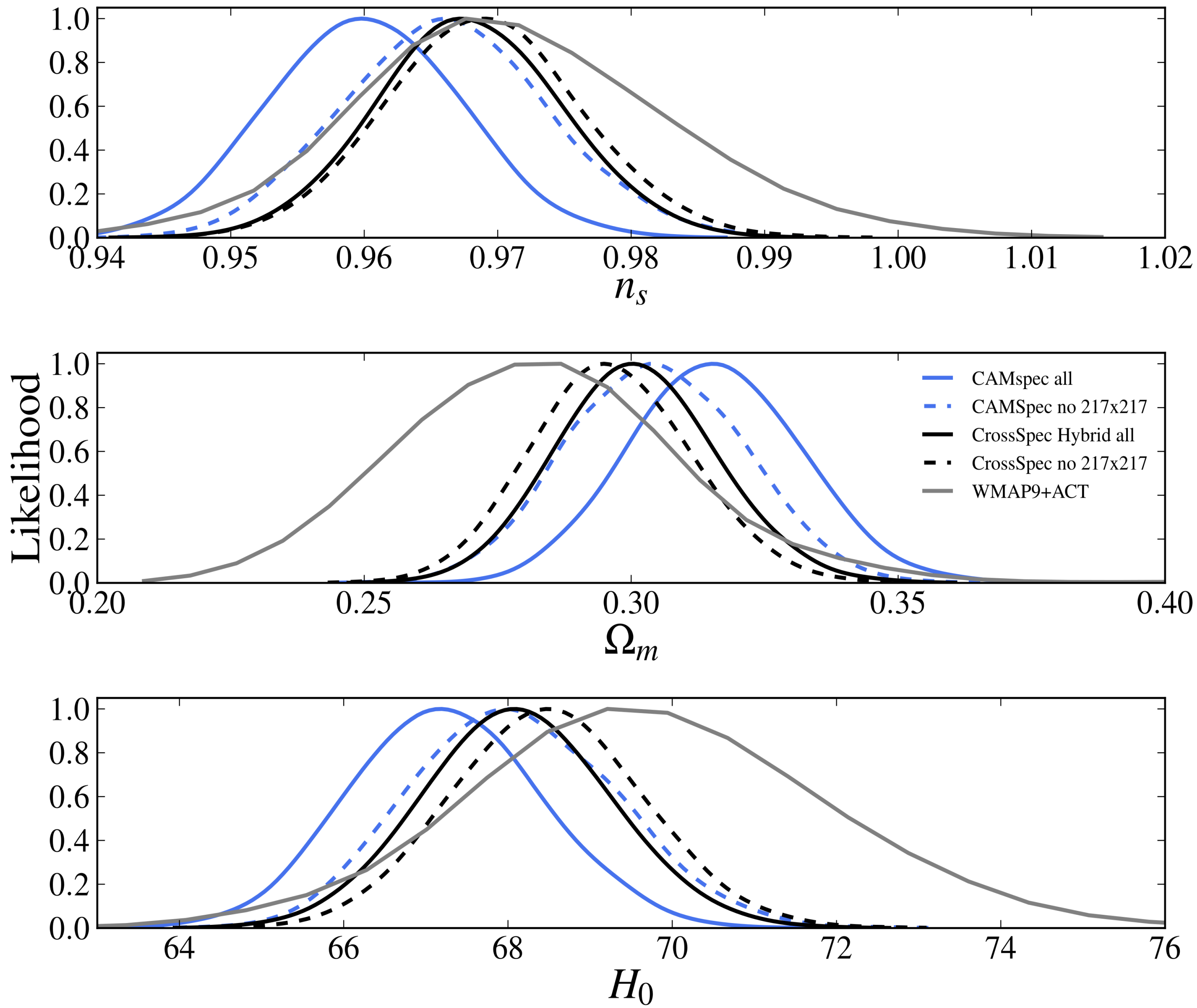

**Results from Planck18 (arXiv:1807.06209)**

| Parameter | TT,TE,EE+lowE+lensing 68% limits |
|---|---|
| $\Omega_b h^2$ . . . . . . . . . . . | $0.02237 \pm 0.00015$ |
| $\Omega_c h^2$ . . . . . . . . . . . | $0.1200 \pm 0.0012$ |
| $100\theta_{MC}$ . . . . . . . . . | $1.04092 \pm 0.00031$ |
| $\tau$ . . . . . . . . . . . . . | $0.0544 \pm 0.0073$ |
| $\ln(10^{10} A_s)$ . . . . . . . | $3.044 \pm 0.014$ |
| $n_s$ . . . . . . . . . . . . | $0.9649 \pm 0.0042$ |
| $H_0$ [km s$^{-1}$ Mpc$^{-1}$] . . | $67.36 \pm 0.54$ |

From peak structure: $r_s$ $(d_A^*)$, $\Omega_b h^2$, $\Omega_m h^2 \rightarrow H_0$

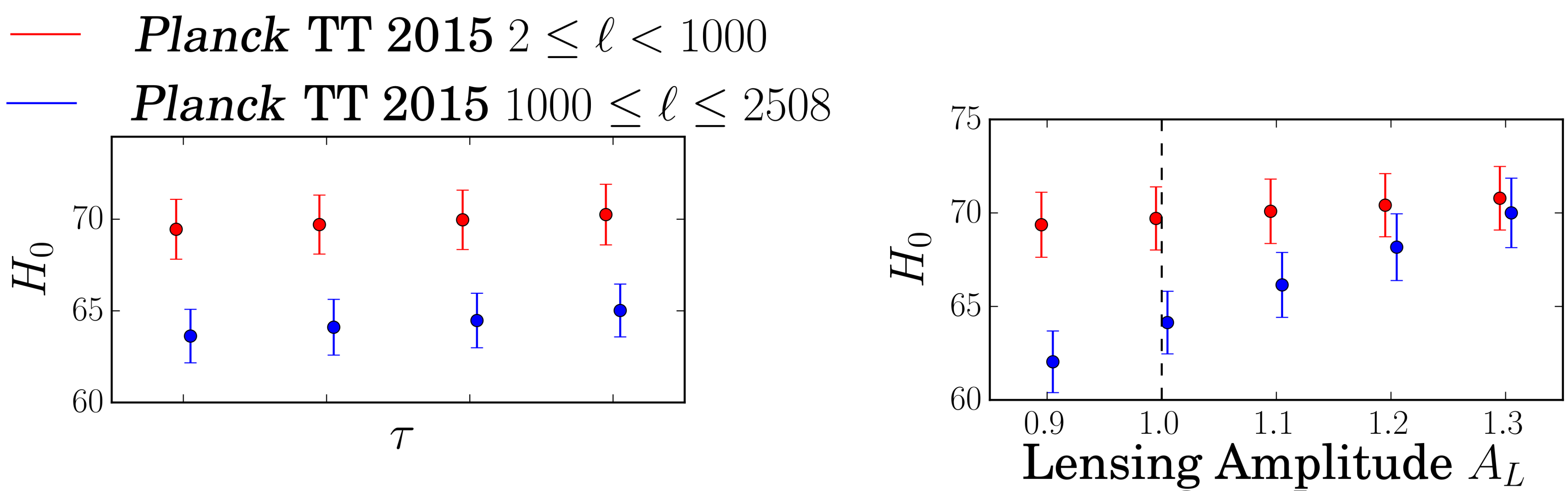
# Cosmic Microwave Background

- Internal inconsistencies in the Planck $TT$ power spectrum between frequencies (D. Spergel et al., arXiv:1312.3313)



# Cosmic Microwave Background

- Internal inconsistencies in the Planck $TT$ power spectrum between frequencies (D. Spergel et al., arXiv:1312.3313)
- Tension between mutipoles $\ell < 1000$ and $\ell \geq 1000$ (G. E. Addison et. al arXiv:1511.00055)

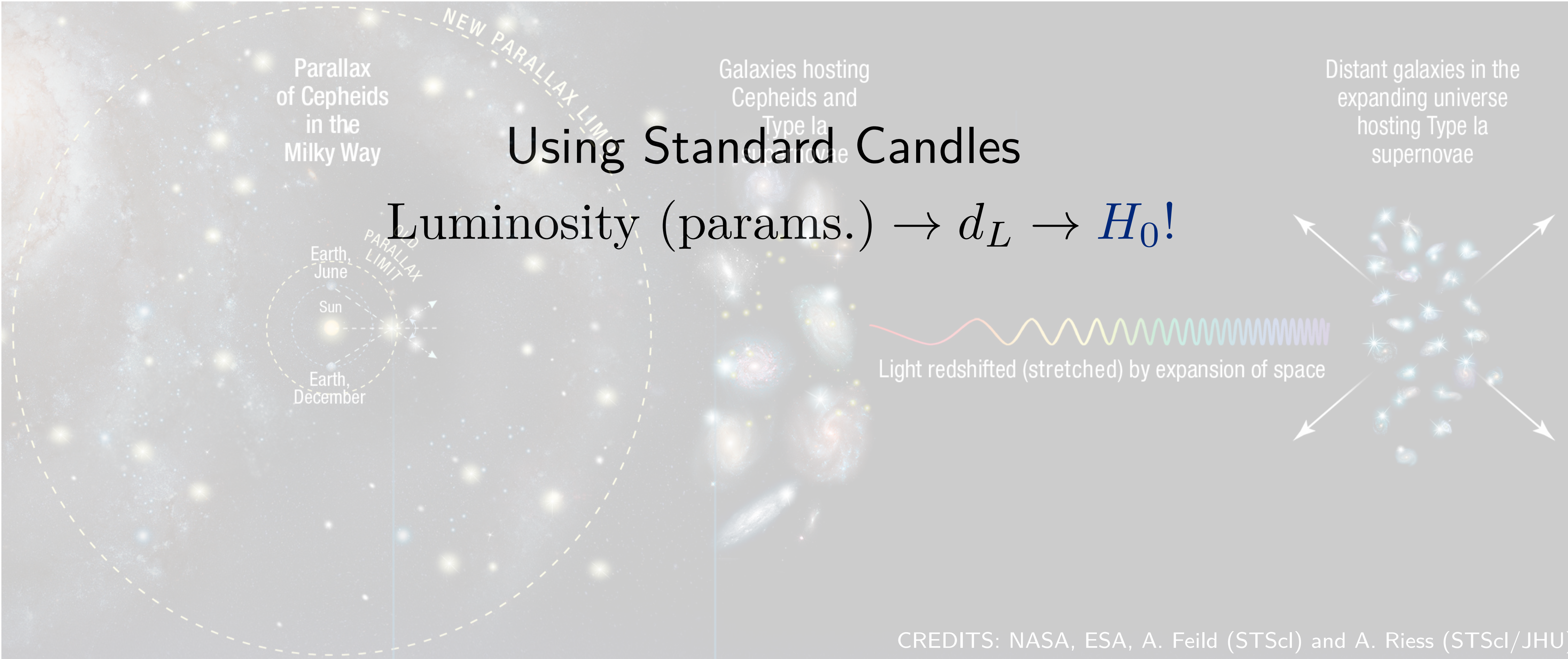


# Cosmic Microwave Background

- Internal inconsistencies in the Planck $TT$ power spectrum between frequencies (D. Spergel et al., arXiv:1312.3313)
- Tension between mutipoles $\ell < 1000$ and $\ell \geq 1000$ (G. E. Addison et. al arXiv:1511.00055)
- Planck 2018 conclusions (Planck Collaboration arXiv:1807.06209):

*“Nevertheless, **there are a number of curious “tensions“** both internal to the Planck data [...] and with some external data sets [...] **none of these**, with the exception of the discrepancy with direct measurements of $H_0$, **is significant at more than the $2-3\sigma$ level**. Such relatively modest discrepancies generate interest, inpart, because of the high precision of the Planck data set. **We could, therefore, disregard these tensions** and conclude that the $6$ parameter $\Lambda$CDM model provides an astonishingly accuratedescription of the Universe“*

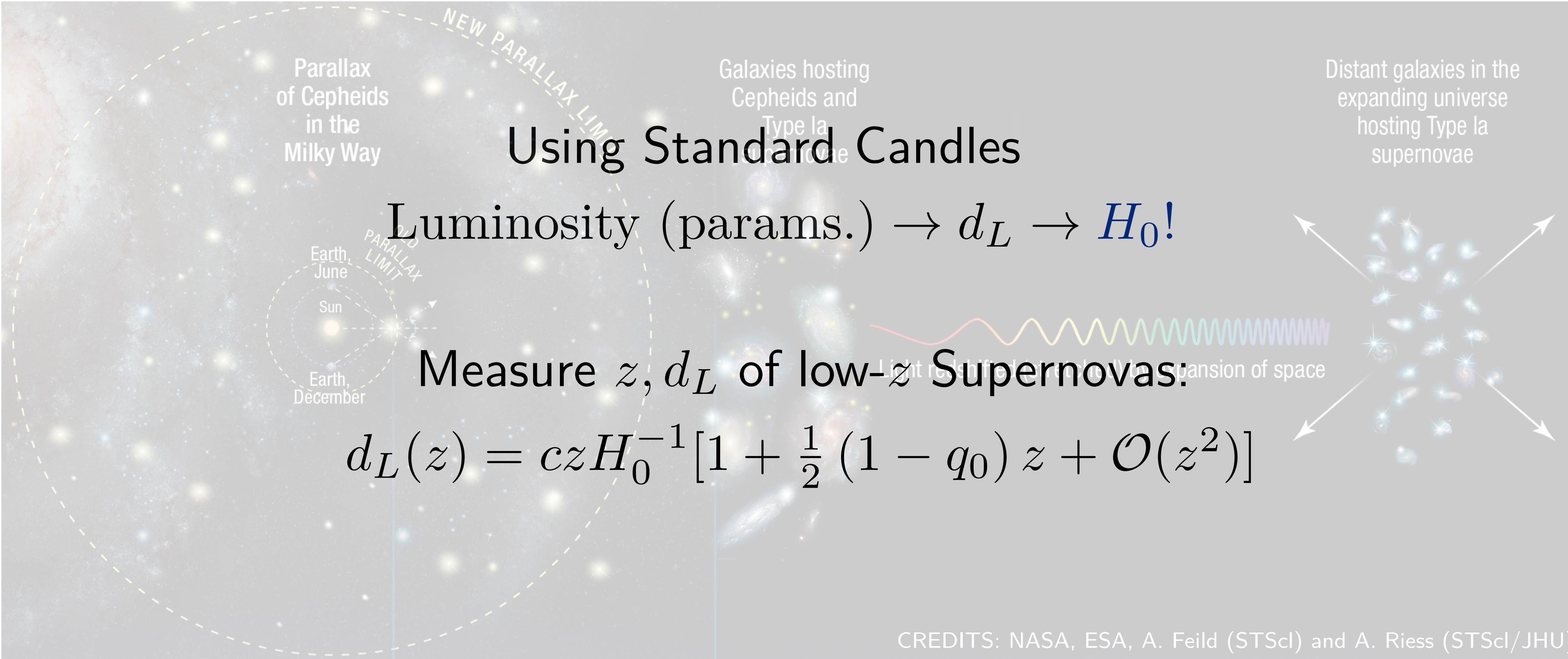
# The cosmic distance ladder




Using Standard Candles

$$\text{Luminosity (params.)} \rightarrow d_L \rightarrow H_0!$$

# The cosmic distance ladder




Using Standard Candles

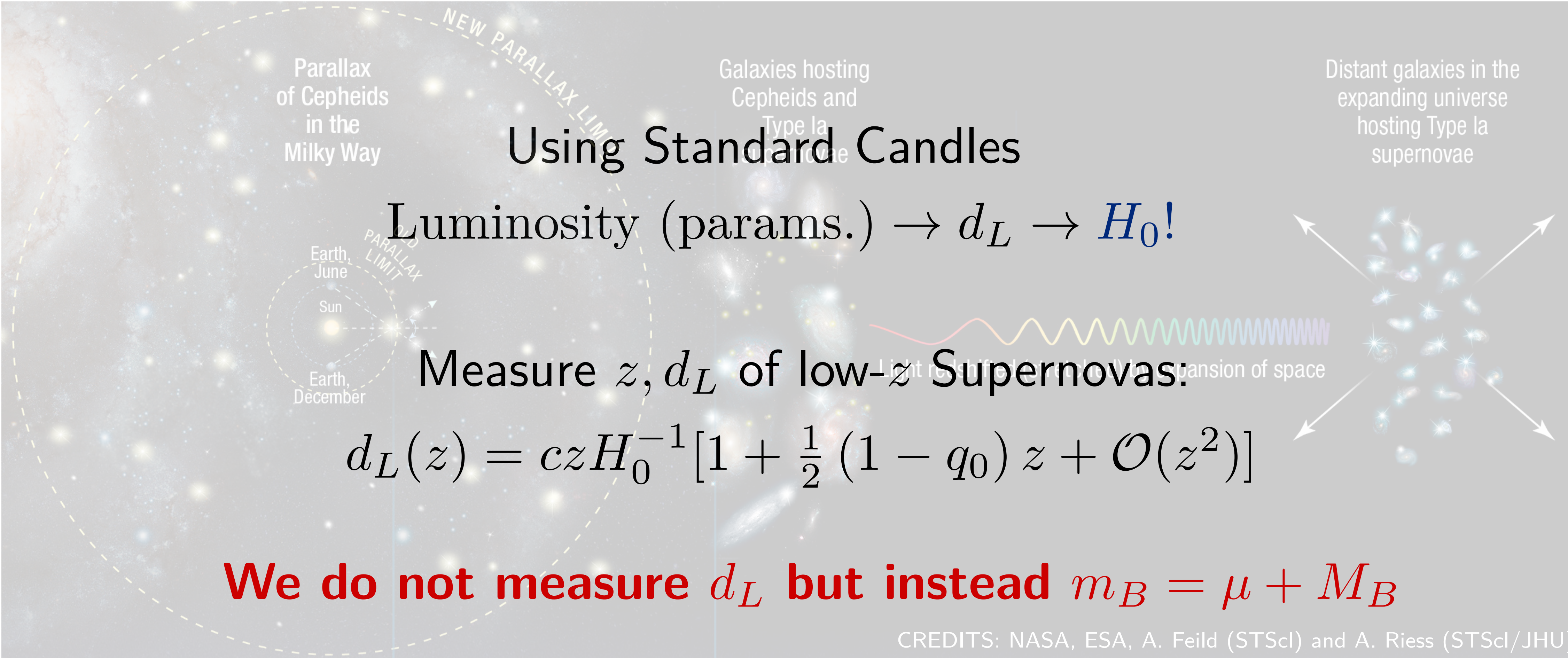
$$\text{Luminosity (params.)} \rightarrow d_L \rightarrow H_0!$$

Measure $z, d_L$ of low-$z$ Supernovas:

$$d_L(z) = czH_0^{-1}[1 + \tfrac{1}{2}(1-q_0)\,z + \mathcal{O}(z^2)]$$

CREDITS: NASA, ESA, A. Feild (STScI) and A. Riess (STScI/JHU)

# The cosmic distance ladder




Using Standard Candles

$$\text{Luminosity (params.)} \rightarrow d_L \rightarrow H_0!$$

Measure $z, d_L$ of low-$z$ Supernovas:

$$d_L(z) = czH_0^{-1}[1 + \tfrac{1}{2}(1-q_0)\,z + \mathcal{O}(z^2)]$$

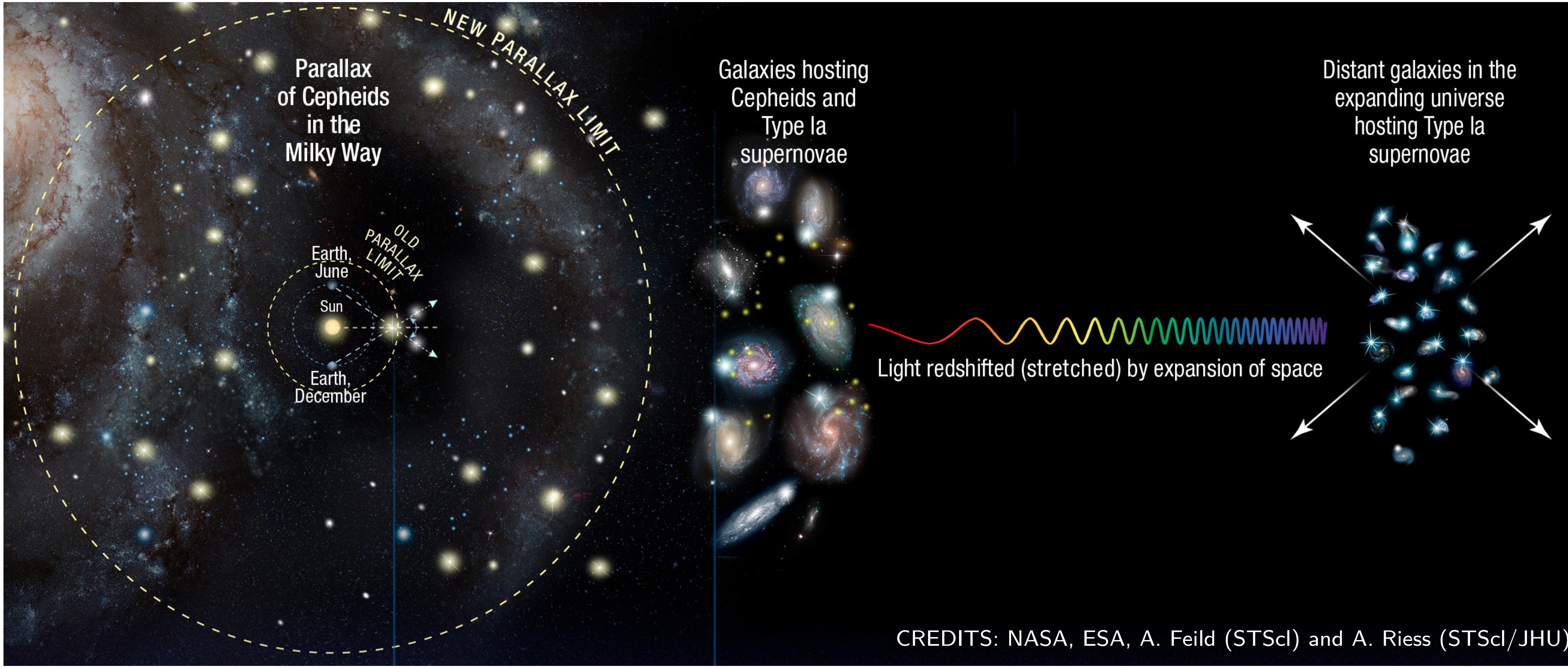
**We do not measure $d_L$ but instead $m_B = \mu + M_B$**

CREDITS: NASA, ESA, A. Feild (STScI) and A. Riess (STScI/JHU)

$$\mu(z) = 5\log_{10}\frac{d_L(z)}{10pc}$$

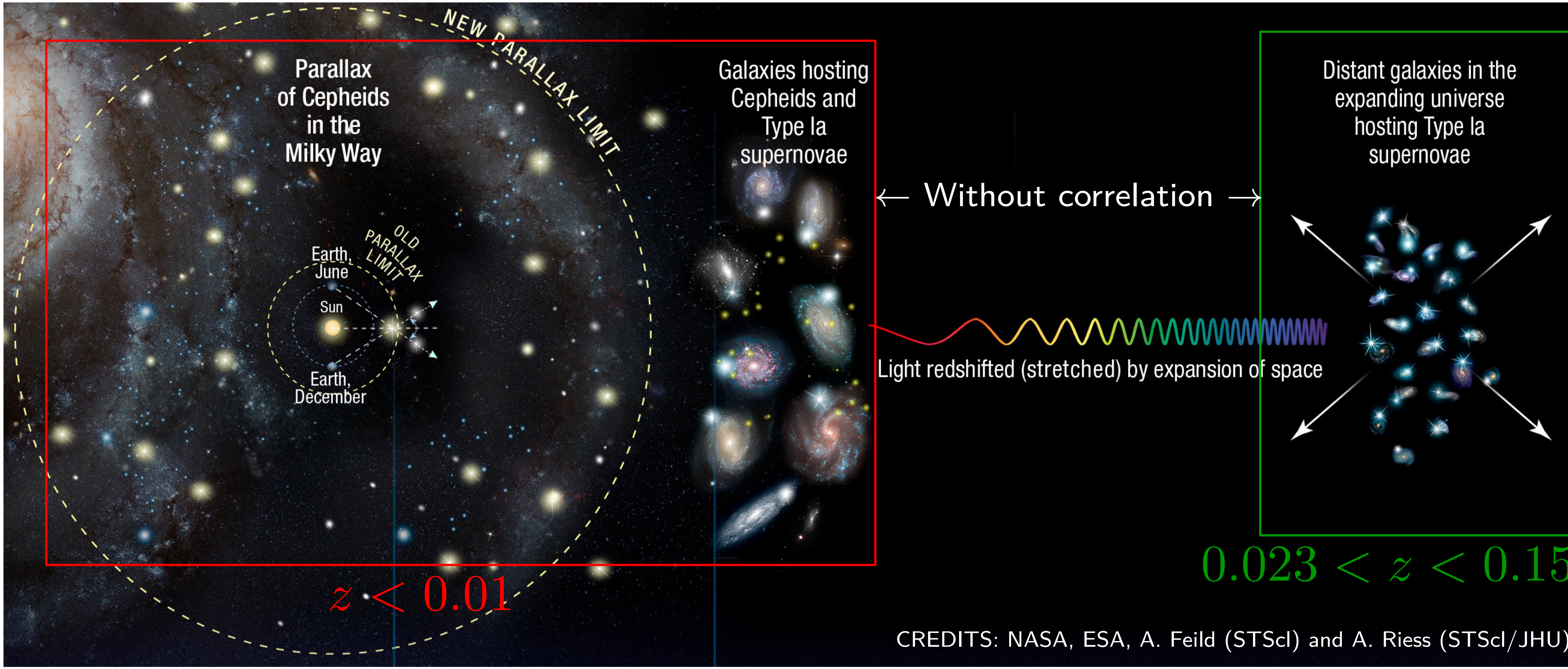
**Supernovas need to be calibrated through $M_B$!**

# The cosmic distance ladder




$$\mu = m_B - M_B + \text{nuisances}$$
$$d_L = d_L\,(m_B, M_B, \text{nui.})$$

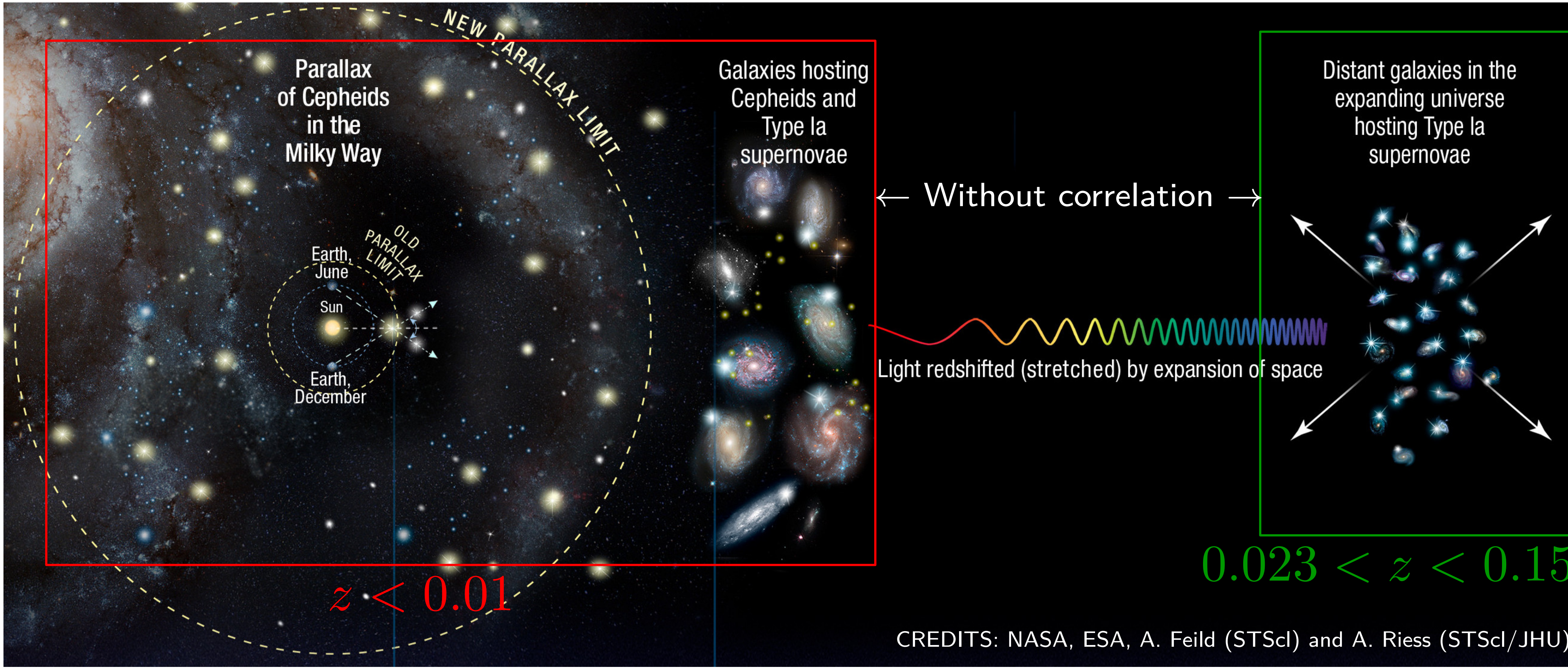
# The cosmic distance ladder




$$\mu = m_B - M_B + \text{nuisances}$$
$$d_L = d_L\left(m_B, M_B, \text{nui.}\right)$$

$$d_L(z) = czH_0^{-1}\left[1 + \tfrac{1}{2}\left(1 - q_0\right)z + \mathcal{O}(z^2)\right]$$

# The cosmic distance ladder




$$\mu = m_B - M_B + \text{nuisances}$$
$$d_L = d_L\left(m_B, M_B, \text{nui.}\right)$$

$$d_L(z) = czH_0^{-1}\left[1 + \tfrac{1}{2}\left(1 - q_0\right)z + \mathcal{O}(z^2)\right]$$

**$M_B$ is the backbone of SH0ES analysis!**

# The cosmic distance ladder

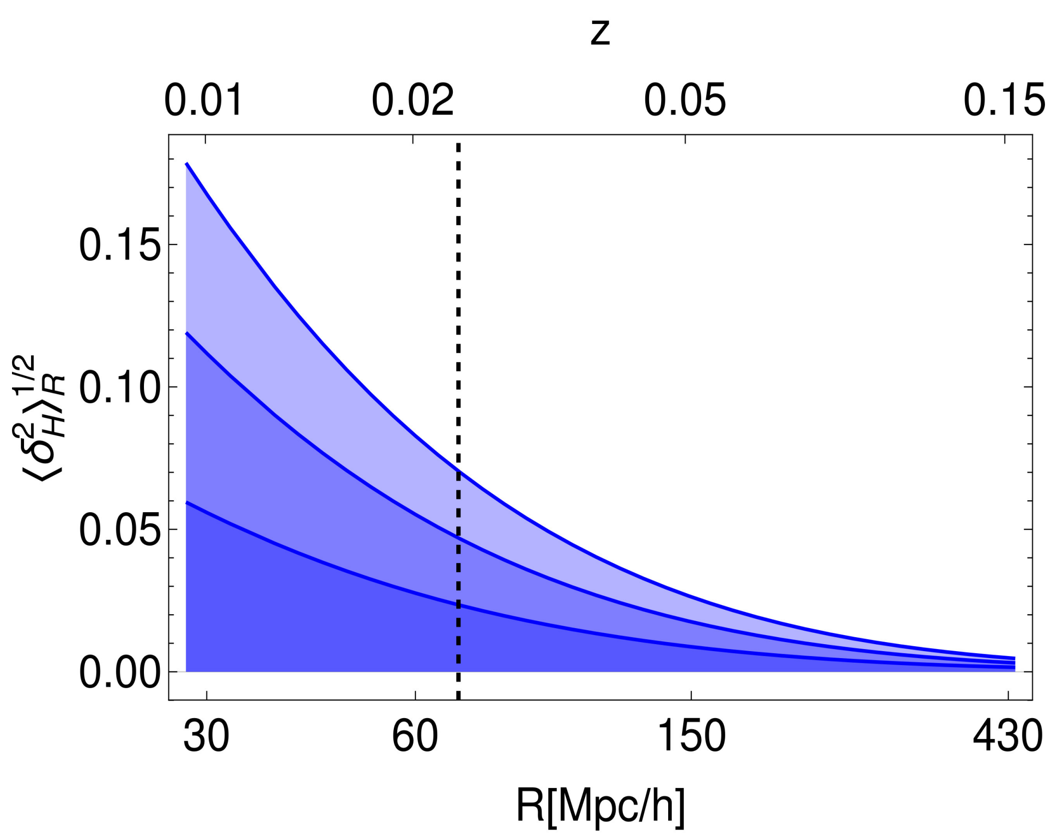
- Why Supernovas in $0.023 < z < 0.15$?

# The cosmic distance ladder

- Why Supernovas in $0.023 < z < 0.15$?

  Peculiar velocities could be non-negligible: $H_{0i} r_i = H_0 r_i + v_i^r$

  Linear perturbation theory: $\langle \delta_H^2 \rangle = \frac{f(z)^2}{2\pi R^2} \int_0^\infty dk P(k) \left[ (kR) \mathcal{L}(kR) \right]^2$




D.C and V. Marra, arXiv:1805.09900

$\Lambda$CDM ($w$ & $\gamma$ extensions) predicts:

For $0.023 < z < 0.15$:

$$\sigma_{cv} \approx 0.88 \text{ km s}^{-1} \text{ Mpc}^{-1} \ (1.2\%)$$

For $0.01 < z < 0.15$:

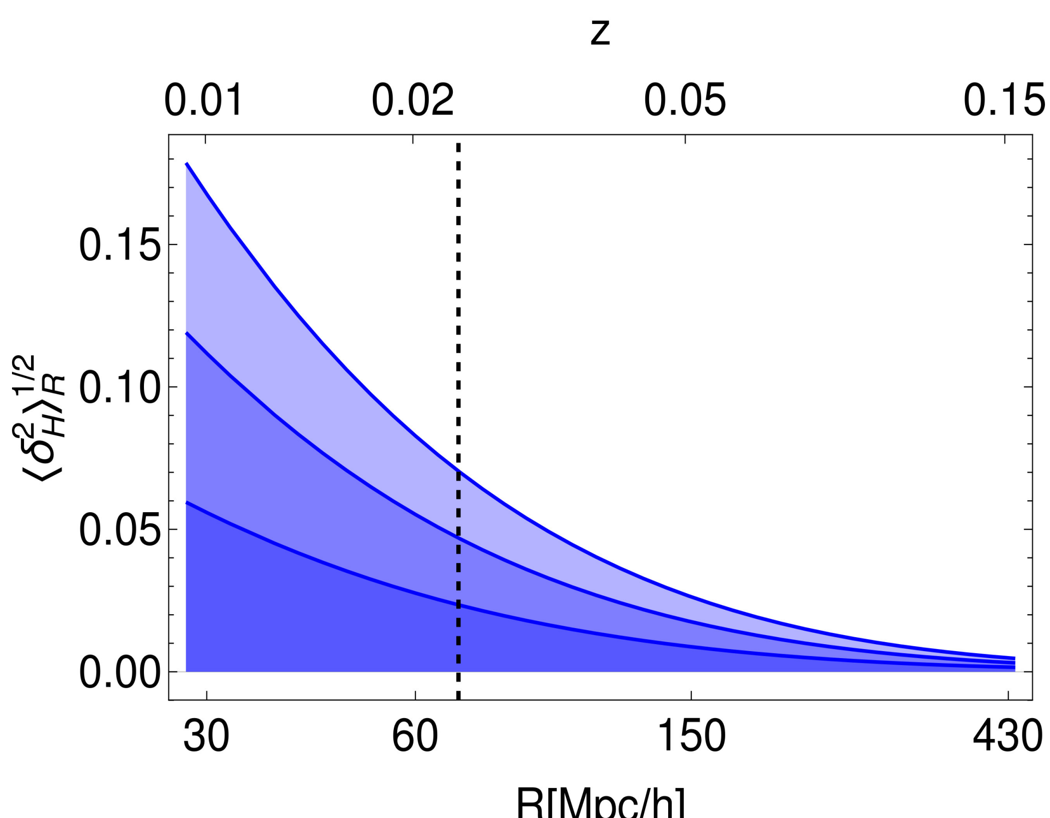
$$\sigma_{cv} \approx 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1} \ (2\%)$$

# The cosmic distance ladder

- Why Supernovas in $0.023 < z < 0.15$?

Peculiar velocities could be non-negligible: $H_{0i} r_i = H_0 r_i + v_i^r$

Linear perturbation theory: $\langle \delta_H^2 \rangle = \frac{f(z)^2}{2\pi R^2} \int_0^\infty dk P(k) \left[ (kR) \mathcal{L}(kR) \right]^2$




D.C and V. Marra, arXiv:1805.09900

$\Lambda$CDM ($w$ & $\gamma$ extensions) predicts:

For $0.023 < z < 0.15$:

$$\sigma_{cv} \approx 0.88 \text{ km s}^{-1} \text{ Mpc}^{-1} \ (1.2\%)$$

For $0.01 < z < 0.15$:

$$\sigma_{cv} \approx 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1} \ (2\%)$$

**Not enough** to explain $H_0$ tension!

# The cosmic distance ladder

- Why Supernovas in $0.023 < z < 0.15$?
  - "Cosmic variance" on $H_0$ (E. L. Turner et al., Astron. J.103, p.1427 (1992) )
  - Deviation from FLRW metric: $2.4\%$ (0.010) or $1.3\%$ (0.023) (V. Marra et al., arXiv:1303.3121)
  - $\Lambda$CDM N-body simulations: $0.8\%$ (R. Wojtak et al., arXiv:1312.0276), $1.1\%$ (I. Odderskov et al., arXiv:1407.7364)
  - Sample variance: $0.31$ km s$^{-1}$ Mpc$^{-1}$ $(0.4\%)$ (Wu and Huterer arXiv:1706.09723)
  - Local void coinstrained by supernovas: $0.6\%$ (W. D'Arcy Kenworthy et al. arXiv:1901.08681)

# The cosmic distance ladder

- Why Supernovas in $0.023 < z < 0.15$?
  - "Cosmic variance" on $H_0$ (E. L. Turner et al., Astron. J.103, p.1427 (1992) )
  - Deviation from FLRW metric: $2.4\%$ (0.010) or $1.3\%$ (0.023) (V. Marra et al., arXiv:1303.3121)
  - $\Lambda$CDM N-body simulations: $0.8\%$ (R. Wojtak et al., arXiv:1312.0276), $1.1\%$ (I. Odderskov et al., arXiv:1407.7364)
  - Sample variance: $0.31$ km s$^{-1}$ Mpc$^{-1}$ $(0.4\%)$ (Wu and Huterer arXiv:1706.09723)
  - Local void coinstrained by supernovas: $0.6\%$ (W. D'Arcy Kenworthy et al. arXiv:1901.08681)

**Consensus: local structures does not explain $4.2\sigma$ discrepancy!**

# The cosmic distance ladder

- Why Supernovas in $0.023 < z < 0.15$?

$\mathcal{L}$: likelihood
$p$: prior

$$d_L^{\rm SN}\left(m_B, M_B, \text{nui.}\right)$$

confront!

$$d_L(z) = czH_0^{-1}[1 + \frac{1}{2}\left(1 - q_0\right)z + \frac{1}{6}\left(1 - q_0 - 3q_0^2 + j_0\right)z^2 + \mathcal{O}(z^3)]$$

Bayes' theorem:

$$f(H_0|\text{SN}) = \mathcal{E}^{-1}\int dM_B\ dq_0\ dj_0\ p(q_0)p(j_0)p(M_B)\mathcal{L}(\text{params}|\text{SN})$$

# The cosmic distance ladder

- Why Supernovas in $0.023 < z < 0.15$?

$\mathcal{L}$: likelihood
$p$: prior

$$d_L^{\text{SN}}\left(m_B, M_B, \text{nui.}\right)$$

$$\updownarrow \text{ confront!}$$

$$d_L(z) = czH_0^{-1}[1 + \tfrac{1}{2}\left(1 - q_0\right)z + \tfrac{1}{6}\left(1 - q_0 - 3q_0^2 + j_0\right)z^2 + \mathcal{O}(z^3)]$$

**Higher z means higher orders:** $+s_0, \ell_0$

Bayes' theorem:

$$f(H_0|\text{SN}) = \mathcal{E}^{-1}\int dM_B\ dq_0\ dj_0\ p(q_0)p(j_0)p(M_B)\mathcal{L}(\text{params}|\text{SN})$$

**SH0ES assumes:** $q_0 = -0.55\ \&\ j_0 = 1.$

**Model-independent determination?**

# Absolute magnitude of Supernovas

Since SH0ES assumes: $q_0 = -0.55$ & $j_0 = 1$.

$$f(H_0|\mathrm{SN}) = \mathcal{E}^{-1}\int dM_B f(M_B)\mathcal{L}(\mathrm{params}|\mathrm{SN})$$

| Paralax, Cepheis, ... $M_B$ | $\Longrightarrow$ | Hubble flow Supernovas $z, m_B$ & nui. | $\Longrightarrow$ | $H_0$ |
|---|---|---|---|---|

# Absolute magnitude of Supernovas

Since SH0ES assumes: $q_0 = -0.55$ & $j_0 = 1$.

$$f(H_0|\mathrm{SN}) = \mathcal{E}^{-1} \int dM_B f(M_B) \mathcal{L}(\mathrm{params}|\mathrm{SN})$$

$$M_B \Longleftarrow \boxed{\begin{array}{c}\text{Hubble flow Supernovas}\\ z, m_B \text{ \& nui.}\end{array}} \Longleftarrow \boxed{\begin{array}{c}\text{Posterior}\\ H_0\end{array}}$$

D.C and V. Marra, arXiv:1906.11814

# Absolute magnitude of Supernovas

Since SH0ES assumes: $q_0 = -0.55$ & $j_0 = 1$.

$$f(H_0|\mathrm{SN}) = \mathcal{E}^{-1}\int dM_B f(M_B)\mathcal{L}(\mathrm{params}|\mathrm{SN})$$

$M_B \Leftarrow$ Hubble flow Supernovas $z, m_B$ & nui. $\Leftarrow$ Posterior $H_0$

D.C and V. Marra, arXiv:1906.11814

**Demarginalization:** Assuming a Gaussian dist. $\mathcal{N}(\tilde{M}_B, \sigma_M^2)$

$$\tilde{H}_0 = \frac{\ln 10}{5}\left[\tilde{M}_B + \frac{\ln 10}{5}\left(\sigma_M^2 + \frac{1}{S_0} - \frac{S_1}{S_0}\right)\right]$$

$$\sigma_H = \frac{\ln 10}{5}\sqrt{\sigma_M^2 + \frac{1}{S_0}}$$

# Absolute magnitude of Supernovas

Since SH0ES assumes: $q_0 = -0.55$ & $j_0 = 1$.

$$f(H_0|\mathrm{SN}) = \mathcal{E}^{-1} \int dM_B f(M_B) \mathcal{L}(\mathrm{params}|\mathrm{SN})$$

$$M_B \Leftarrow \boxed{\begin{array}{c}\text{Hubble flow Supernovas} \\ z, m_B \ \& \ \mathrm{nui.}\end{array}} \Leftarrow \boxed{\begin{array}{c}\text{Posterior} \\ H_0\end{array}}$$

D.C and V. Marra, arXiv:1906.11814

**Deconvolution:** $\log_{10} H_0 = 0.2 M_B + a_B + 5$

$$\tilde{H}_0 = \frac{\ln 10}{5}\left[\tilde{M}_B + 5a_B + 25\right]$$

$$\sigma_H = \frac{\ln 10}{5}\sqrt{\sigma_M^2 + 25\sigma_a^2}$$

# Absolute magnitude of Supernovas

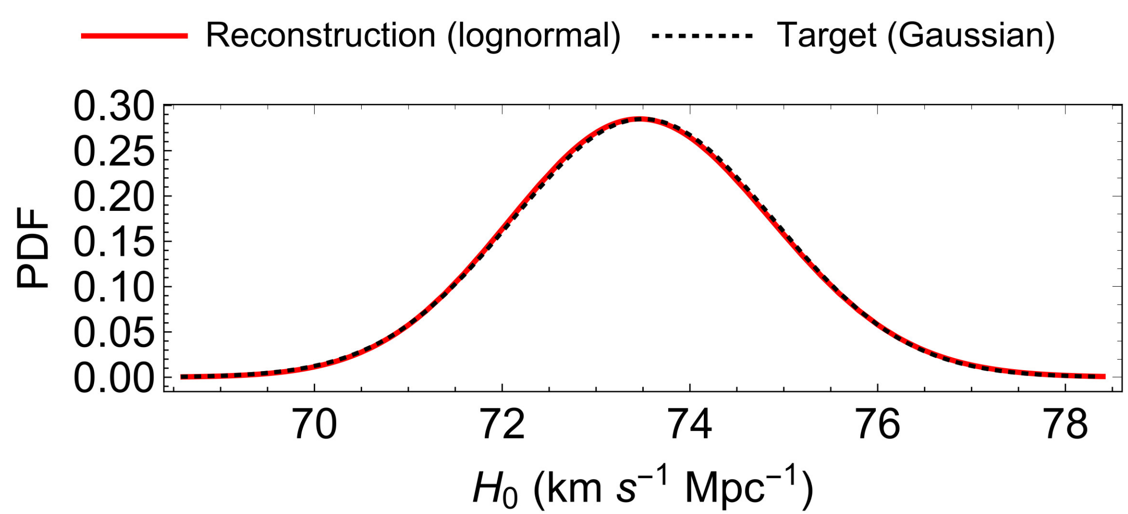
Assuming $H_0 = 73.2 \pm 1.3$ (Riess et al. arXiv:2012.08534)

Supercal, Scolnic D. M. et al. arXiv:1710.00845

| | $M_B$ | $\sigma_M$ |
|---|---|---|
| Demarginalization | −19.2421 | 0.0375 |
| Error propagation | −19.2411 | 0.0375 |
| Deconvolution | −19.2414 | 0.0375 |

Pantheon, Scolnic D. M. et al. arXiv:1710.00845

| | $M_B$ | $\sigma_M$ |
|---|---|---|
| Demarginalization | −19.2435 | 0.0373 |
| Error propagation | −19.2424 | 0.0373 |
| Deconvolution | −19.2428 | 0.0373 |



# Absolute magnitude of Supernovas

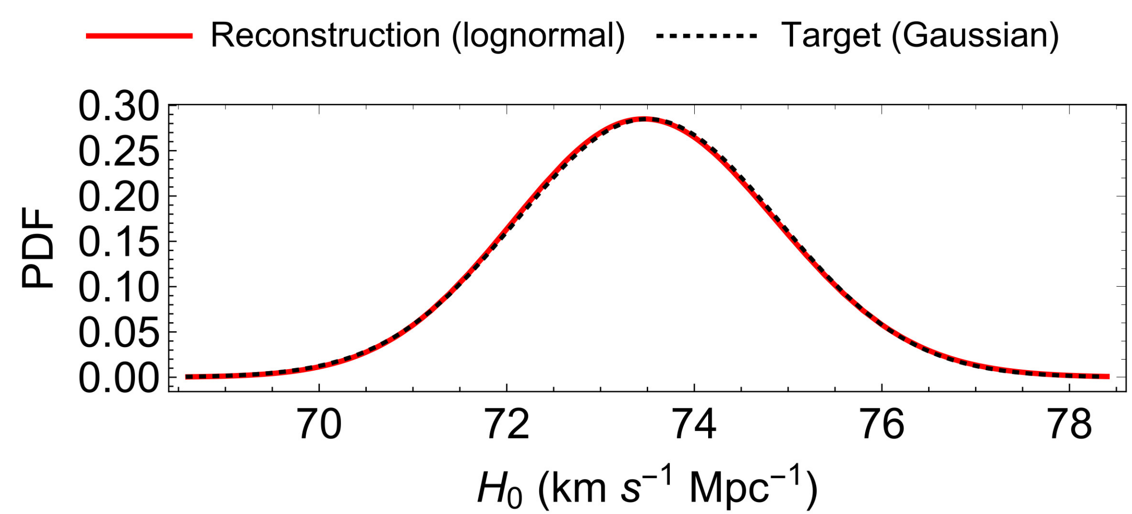
Assuming $H_0 = 73.2 \pm 1.3$ (Riess et al. arXiv:2012.08534)

Supercal, Scolnic D. M. et al. arXiv:1710.00845

| | $M_B$ | $\sigma_M$ |
|---|---|---|
| Demarginalization | -19.2421 | 0.0375 |
| Error propagation | -19.2411 | 0.0375 |
| Deconvolution | -19.2414 | 0.0375 |

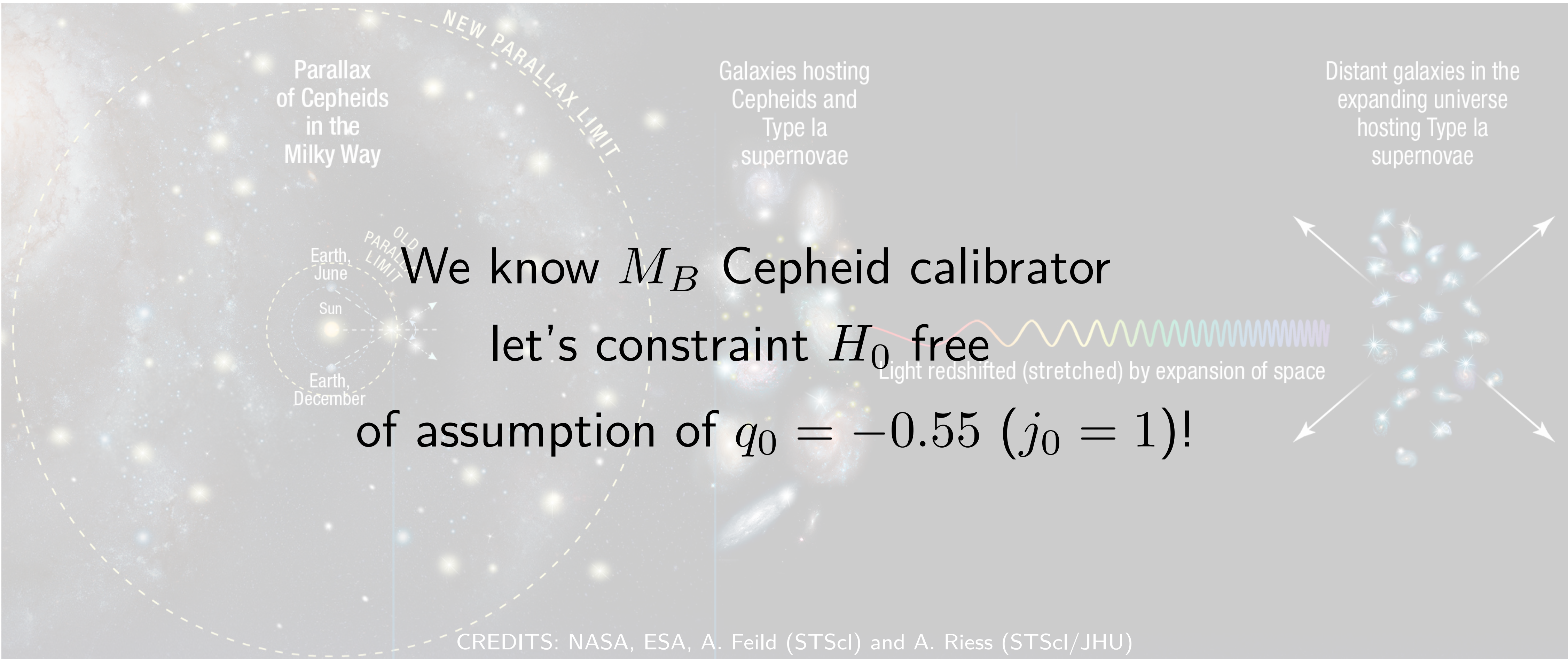
Pantheon, Scolnic D. M. et al. arXiv:1710.00845

| | $M_B$ | $\sigma_M$ |
|---|---|---|
| Demarginalization | -19.2435 | 0.0373 |
| Error propagation | -19.2424 | 0.0373 |
| Deconvolution | -19.2428 | 0.0373 |




**$H_0$ prior translated in $M_B$ prior!**

# Joint $H_0$-$q_0$ constraint




We know $M_B$ Cepheid calibrator

let's constraint $H_0$ free

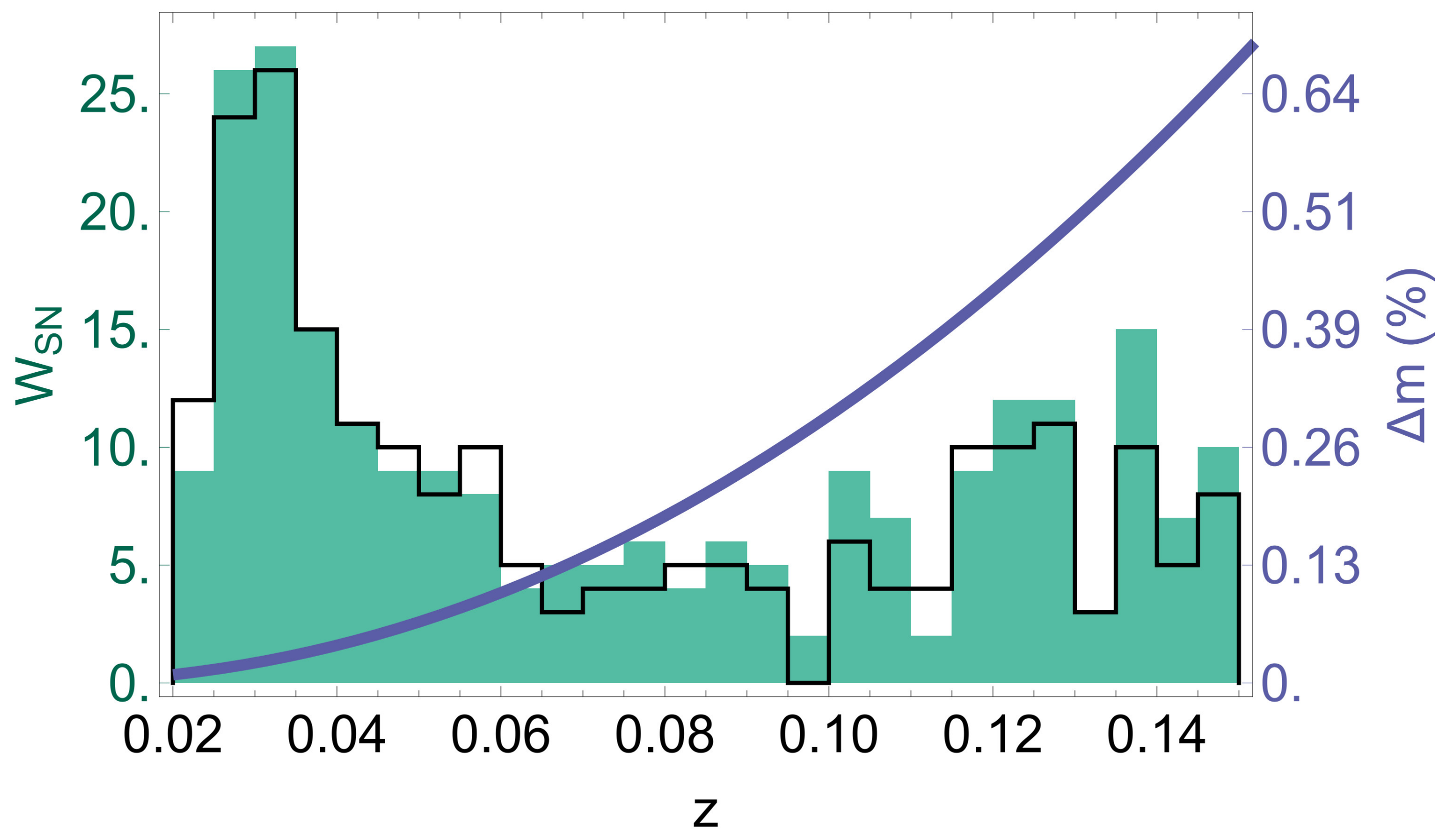
of assumption of $q_0 = -0.55$ ($j_0 = 1$)!

# Joint $H_0$-$q_0$ constraint

We assume:

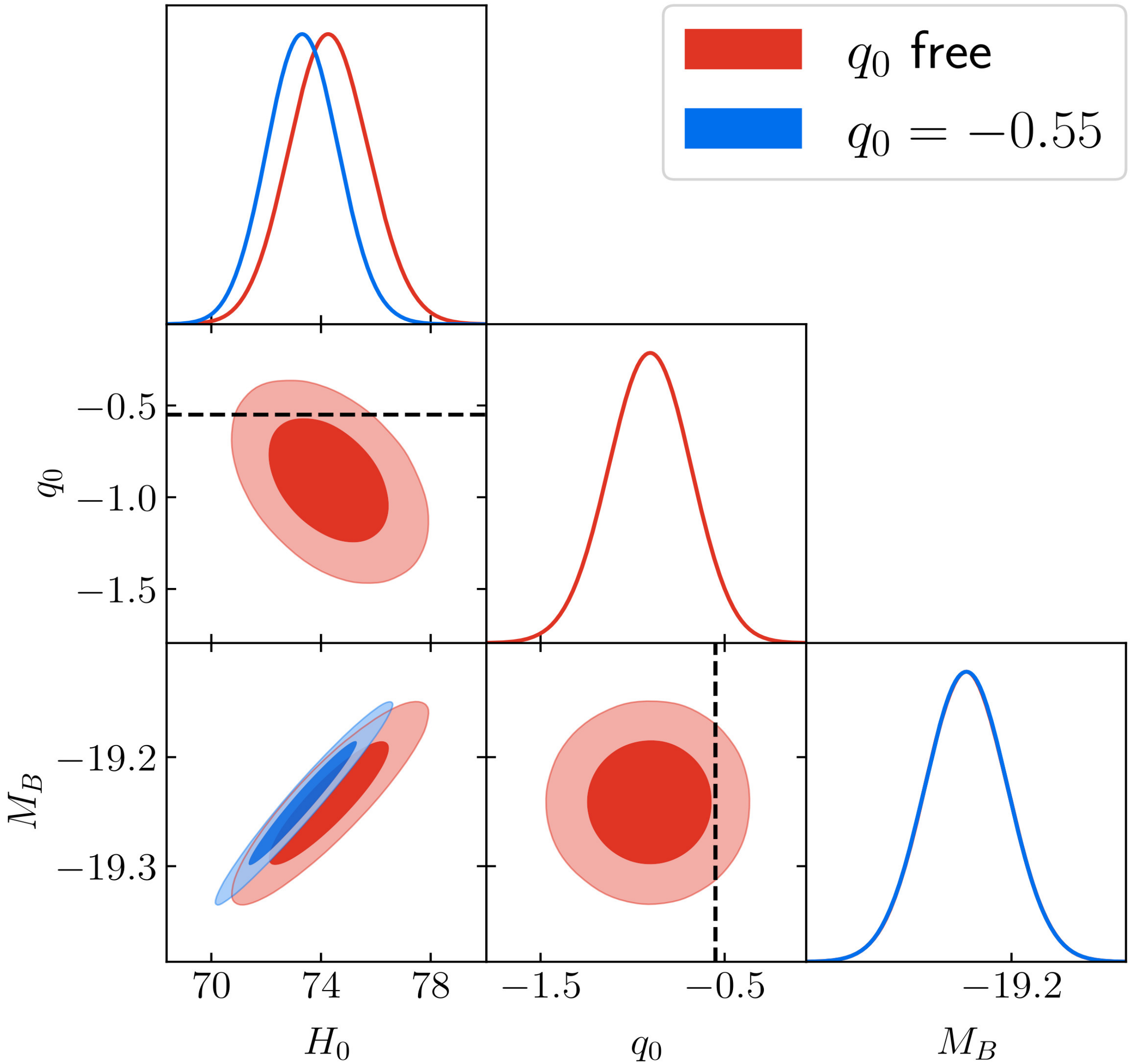
$$d_L(z) = czH_0^{-1}\left[1 + \tfrac{1}{2}\left(1 - q_0\right)z\right]$$

$$f(H_0, q_0|\mathrm{SN}) = \mathcal{E}^{-1}\int dM_B\ f(H_0)f(q_0)f(M_B)\mathcal{L}(\mathrm{params}|\mathrm{SN})$$




D.C and V. Marra, arXiv:1906.11814

# Joint $H_0$-$q_0$ constraint

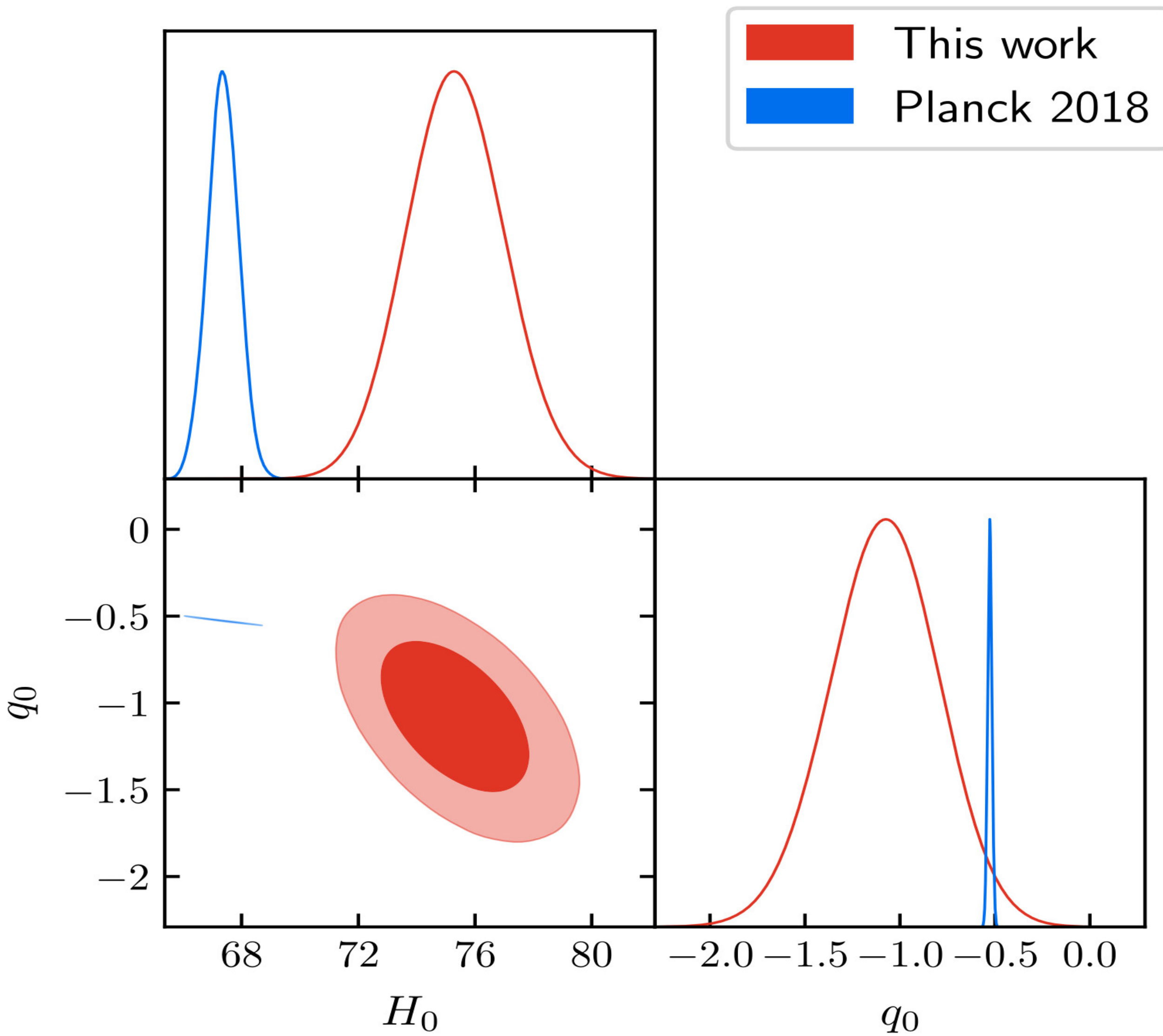



D.C and V. Marra, arXiv:2101.08641

| parameter | $\mu_i \pm \sigma_i$ | $C_{ij}$ | |
|---|---|---|---|
| $H_0$ $\left[\frac{\text{km/s}}{\text{Mpc}}\right]$ | $74.30 \pm 1.45$ | 1 | -0.41 |
| $q_0$ | $-0.91 \pm 0.22$ | -0.41 | 1 |

1.2 km $s^{-1}$ $\text{Mpc}^{-1}$ higher than SH0ES

# Joint $H_0$-$q_0$ constraint




D.C and V. Marra, arXiv:2101.08641

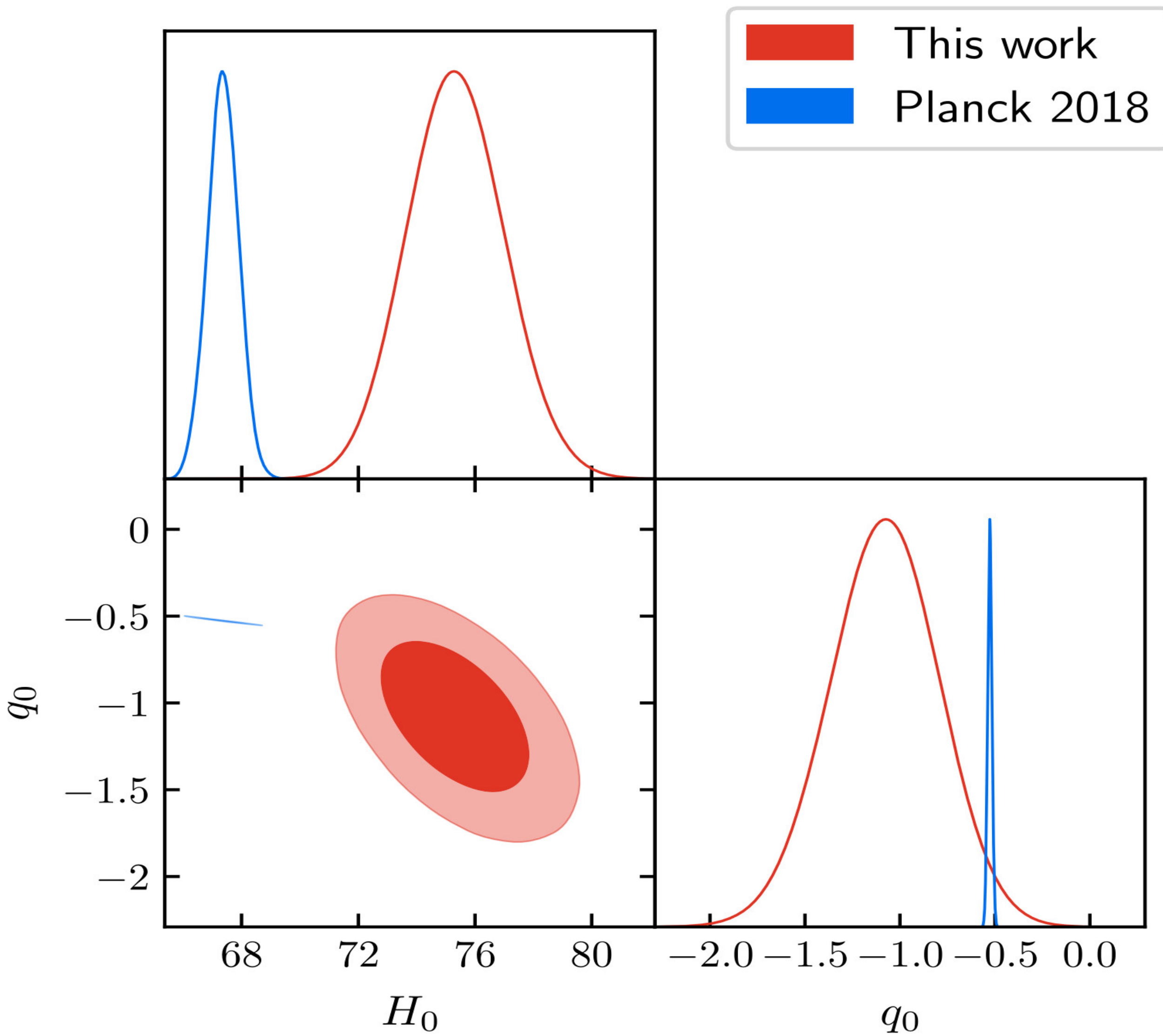
| parameter | $\mu_i \pm \sigma_i$ | $C_{ij}$ | |
|---|---|---|---|
| $H_0$ $\left[\frac{\text{km/s}}{\text{Mpc}}\right]$ | $74.30 \pm 1.45$ | 1 | -0.41 |
| $q_0$ | $-0.91 \pm 0.22$ | -0.41 | 1 |

1.2 km $s^{-1}$ $\text{Mpc}^{-1}$ higher than SH0ES

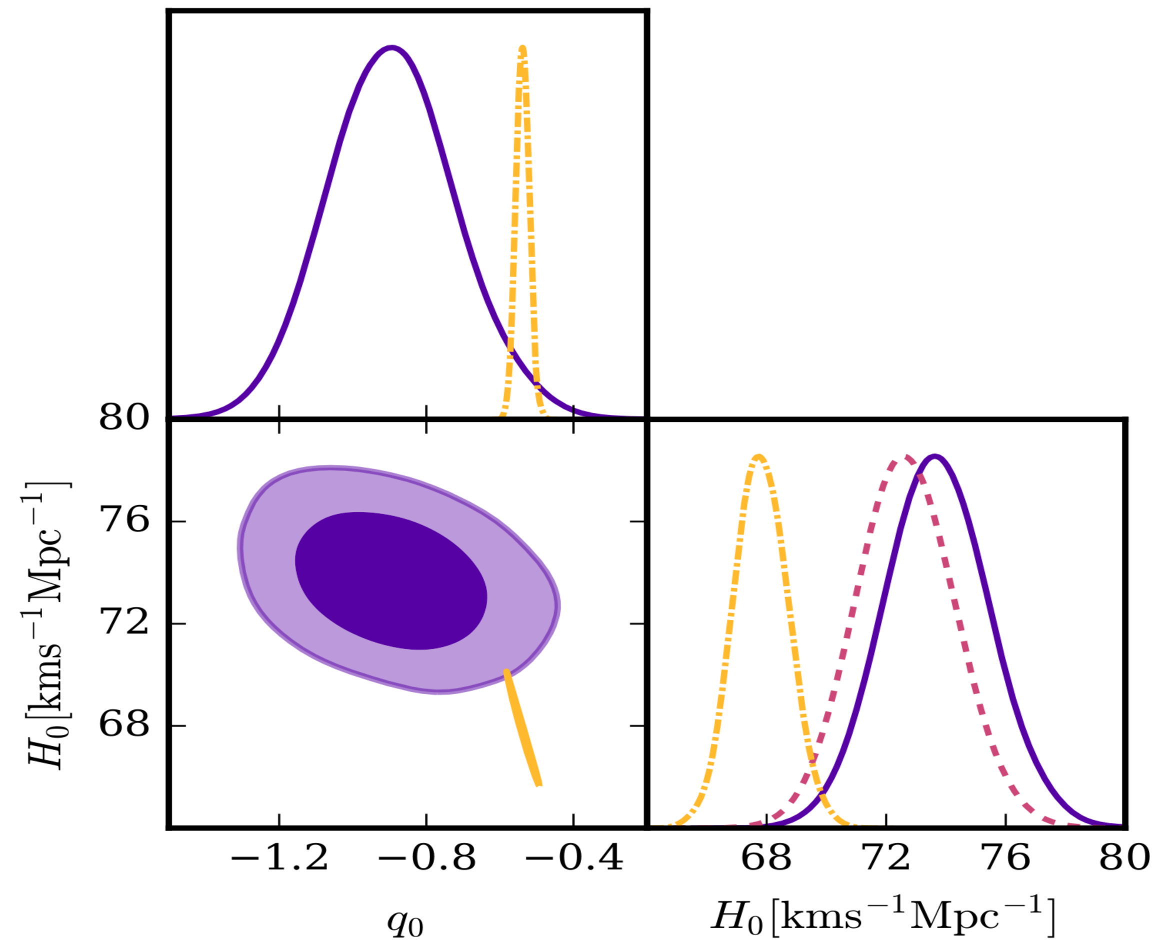
$H_0$ : $4.5\sigma$ discrepancy with CMB

$q_0$ : $\sim 2\sigma$ "curiosity" with CMB

# Joint $H_0$-$q_0$ constraint




Feeney et al. (arXiv:1707.00007)



# The cosmic distance ladder

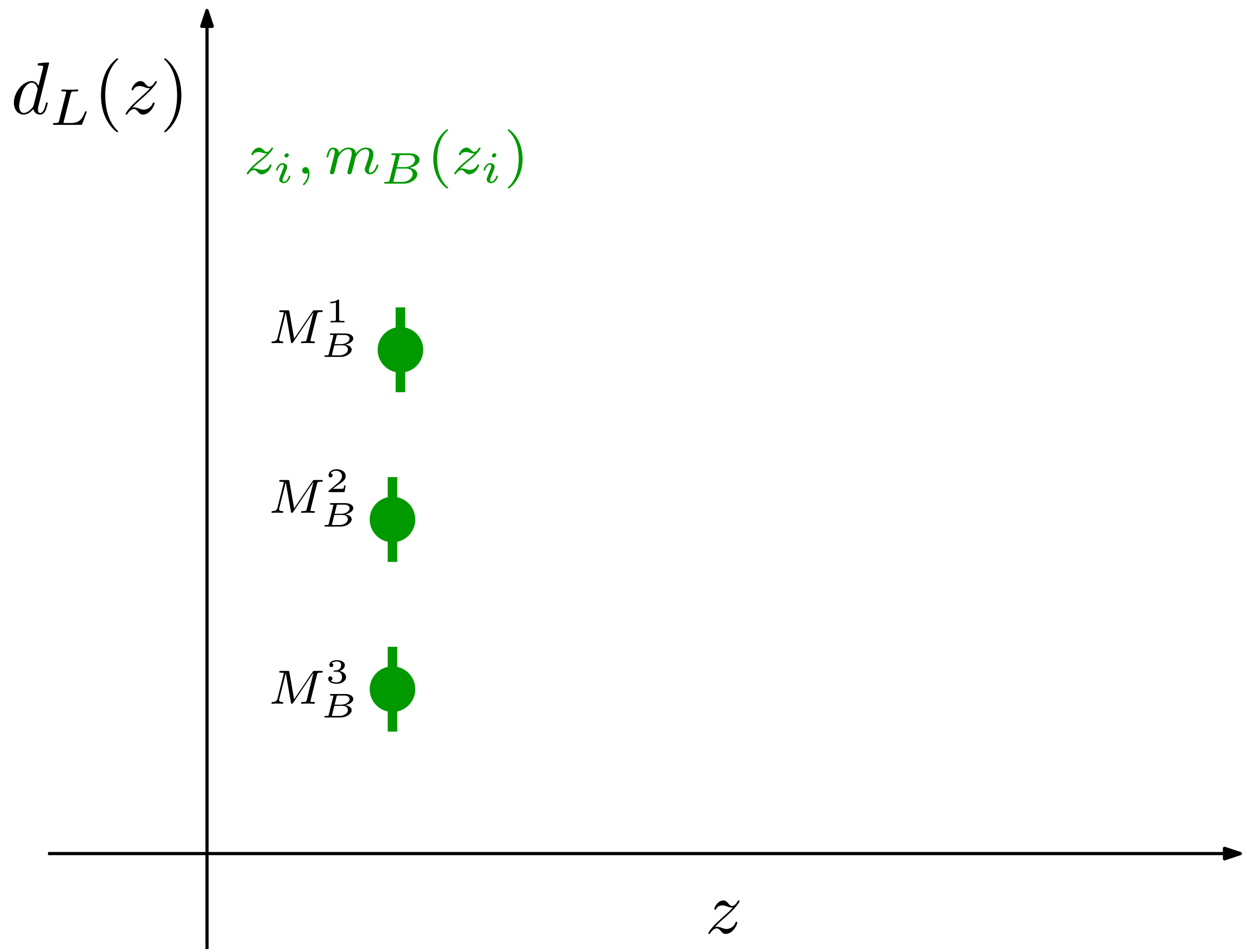
- Sub-luminous low metallicity Cepheids underestimates errors (G. Efstathiou, arXiv:1311.3461)
- Bayesian hierarchical model of the local distance ladder: join analysys leads to $H_0 = 72.72 \pm 1.67$ marginalizing over $\sim 3000$ parameters (Feeney et al., arXiv:1707.00007)
- Blind re-anlysis: in agreement with SH0ES analysis, no human bias detected (B. R. Zhang et al., arXiv:1706.07573)
- Tension among anchors (G. Efstathiou, arXiv:2007.10716)
- Local Hole $\sim 150$ h$^{-1}$ Mpc reduces $\sim 1.8\%$ the local Hubble constant. (B. R. Zhang et al., arXiv:1810.02595)
- Analysis of simulated data $(0.01 < z < 2.3)$ shows that the assumption on the DE model produces $\Delta H_0 = 0.47$. (S. Dhawan et al., arXiv:2001.09260)

# Inverse distance ladder

**CMB** and **BAO**(and others probes to calibrate **Supernovas**)

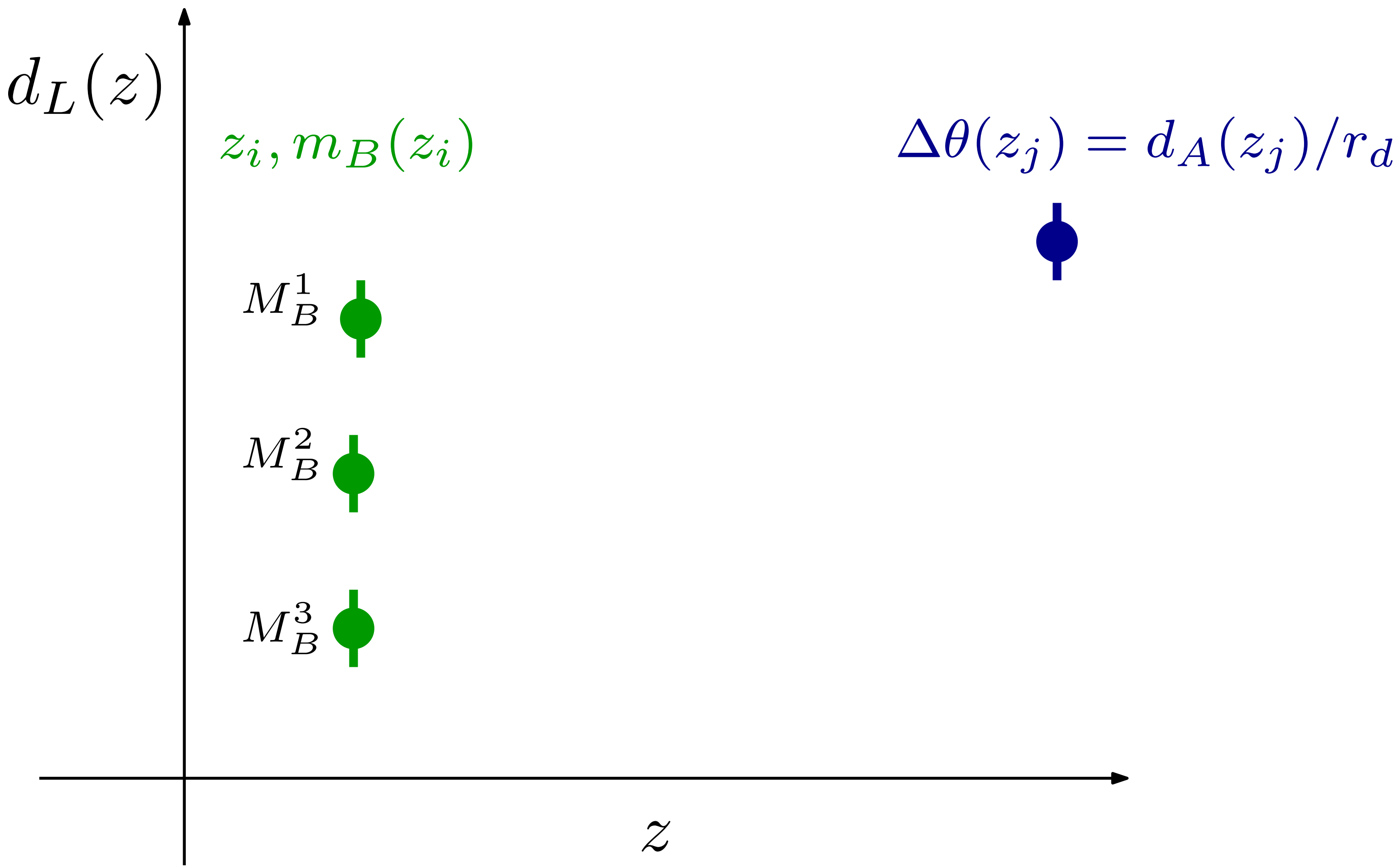
# Inverse distance ladder

**CMB** and **BAO**(and others probes to calibrate **Supernovas**)



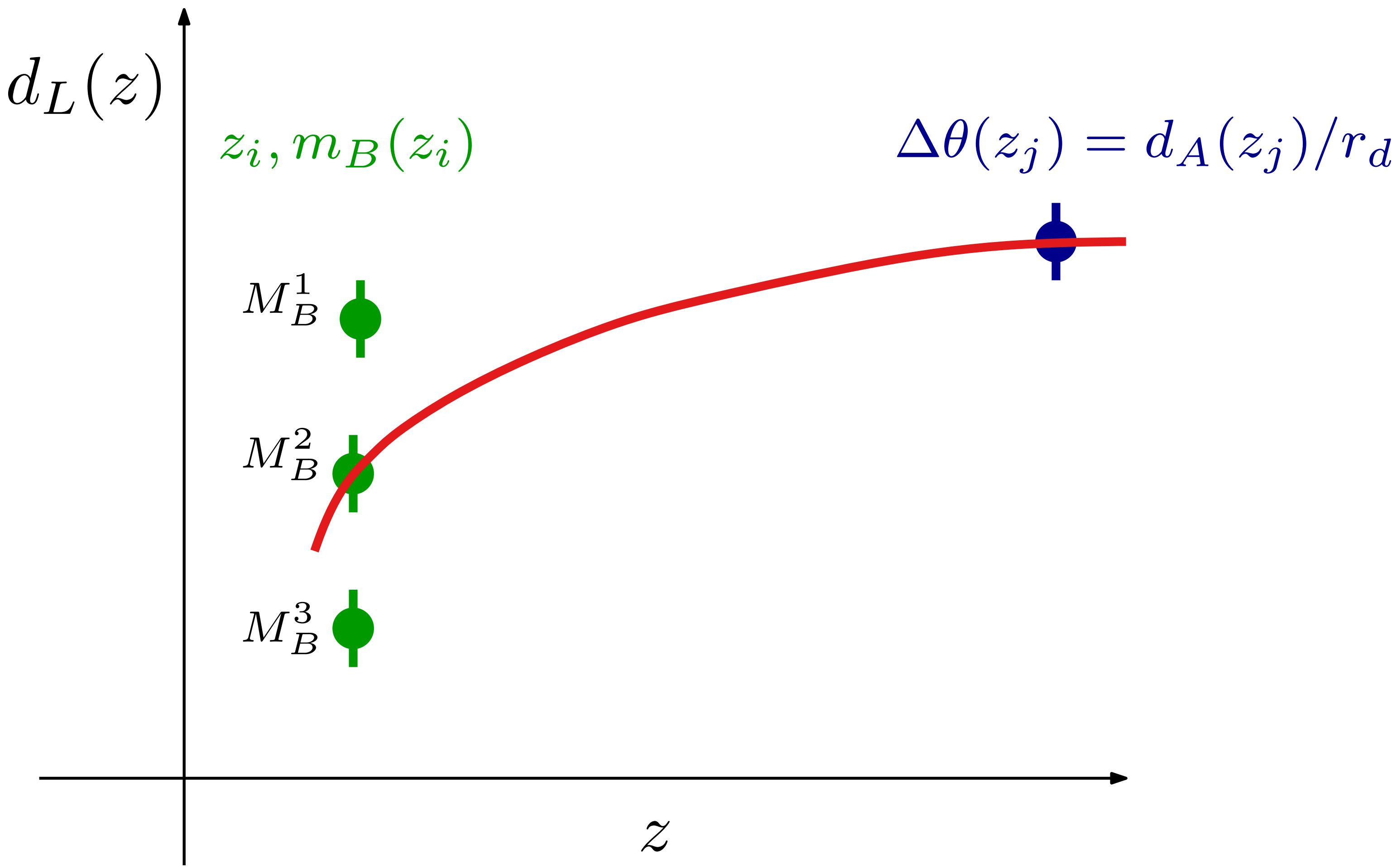
# Inverse distance ladder

**CMB** and **BAO**(and others probes to calibrate **Supernovas**)



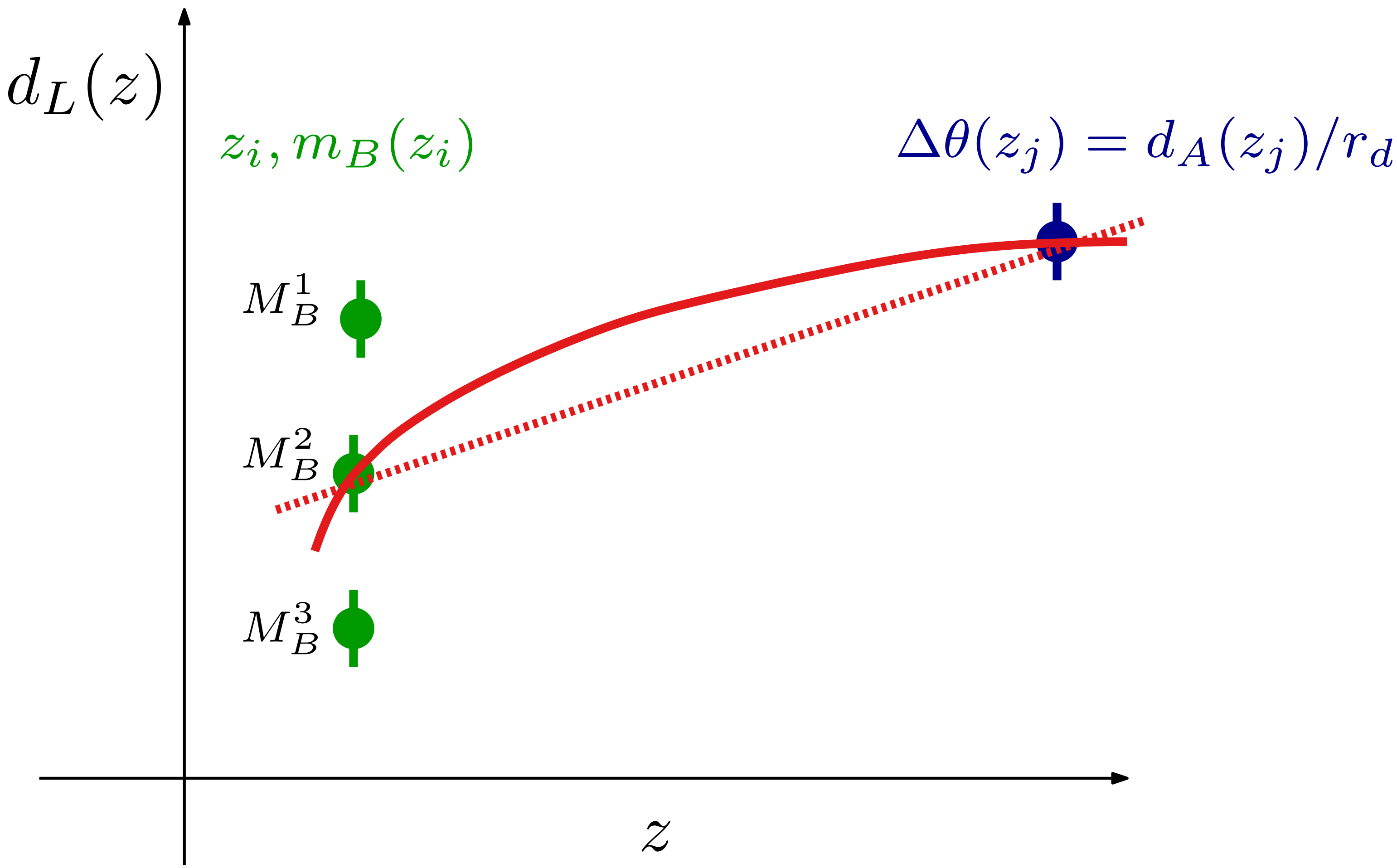
# Inverse distance ladder

**CMB** and **BAO**(and others probes to calibrate **Supernovas**)



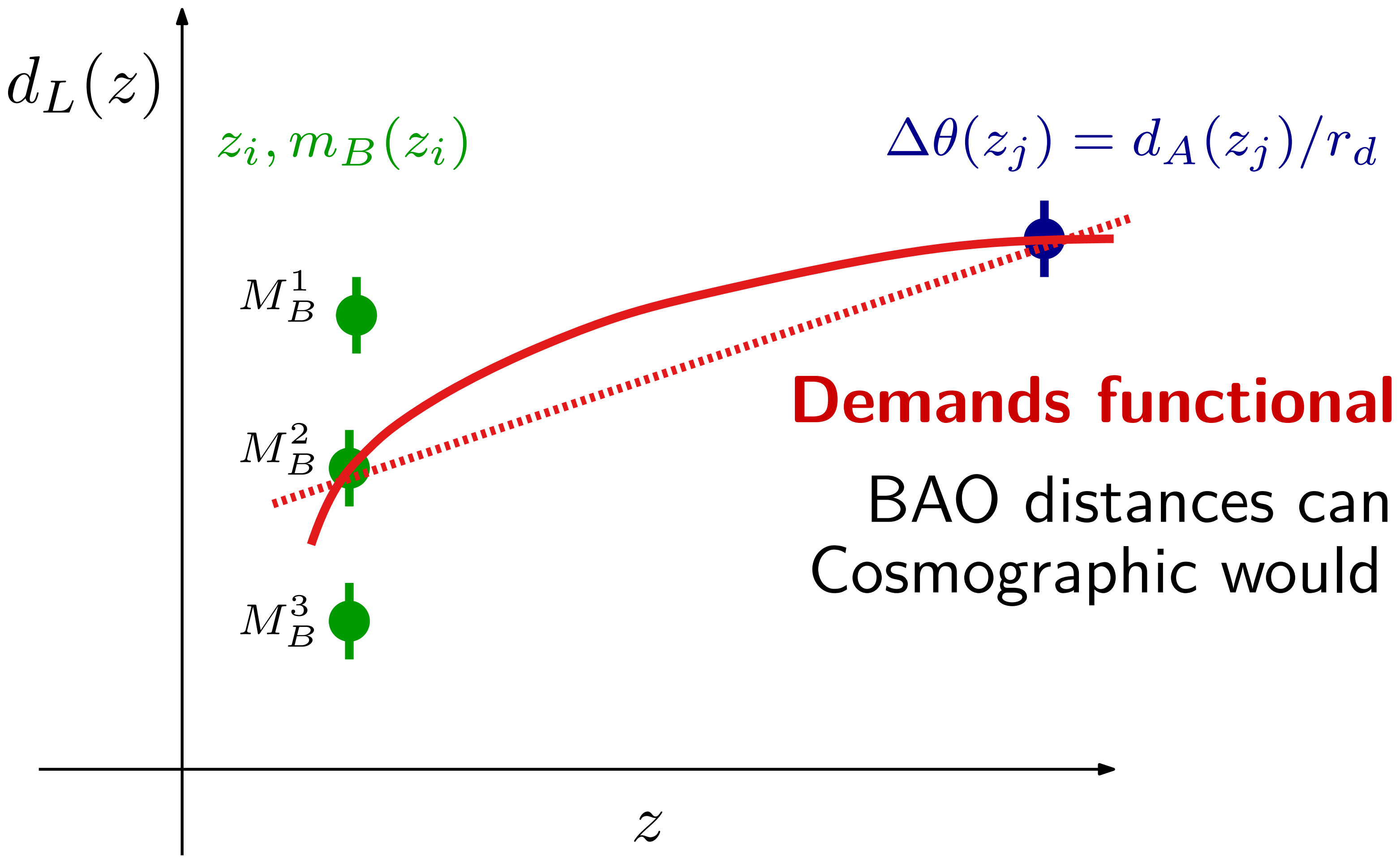
# Inverse distance ladder

**CMB** and **BAO**(and others probes to calibrate **Supernovas**)



# Inverse distance ladder

**CMB** and **BAO**(and others probes to calibrate **Supernovas**)



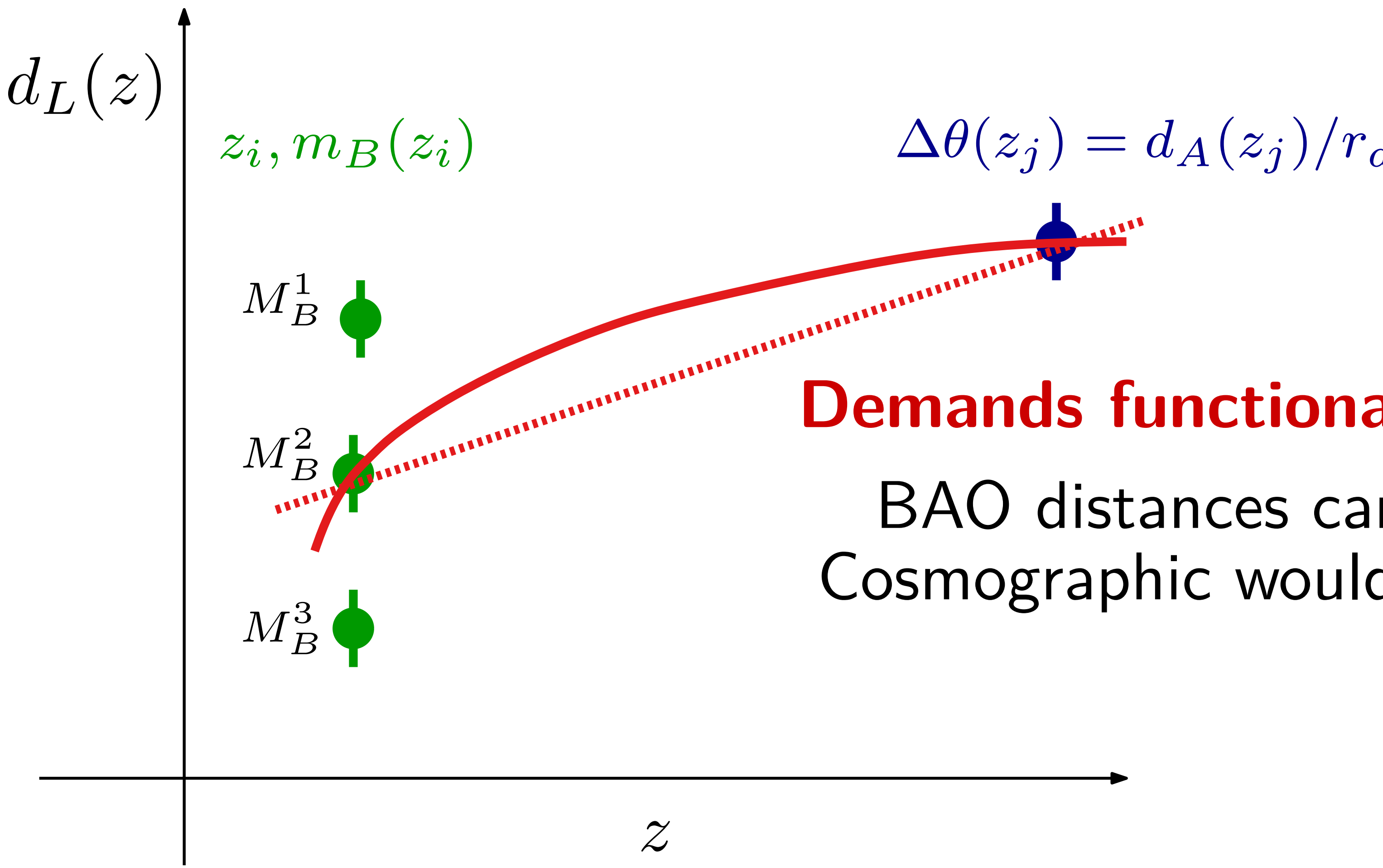

**Demands functional form of $d_L$!**

BAO distances can reach $1 < z$

Cosmographic would need $s_0$, $\ell_0$, ...

# Inverse distance ladder

**CMB** and **BAO**(and others probes to calibrate **Supernovas**)



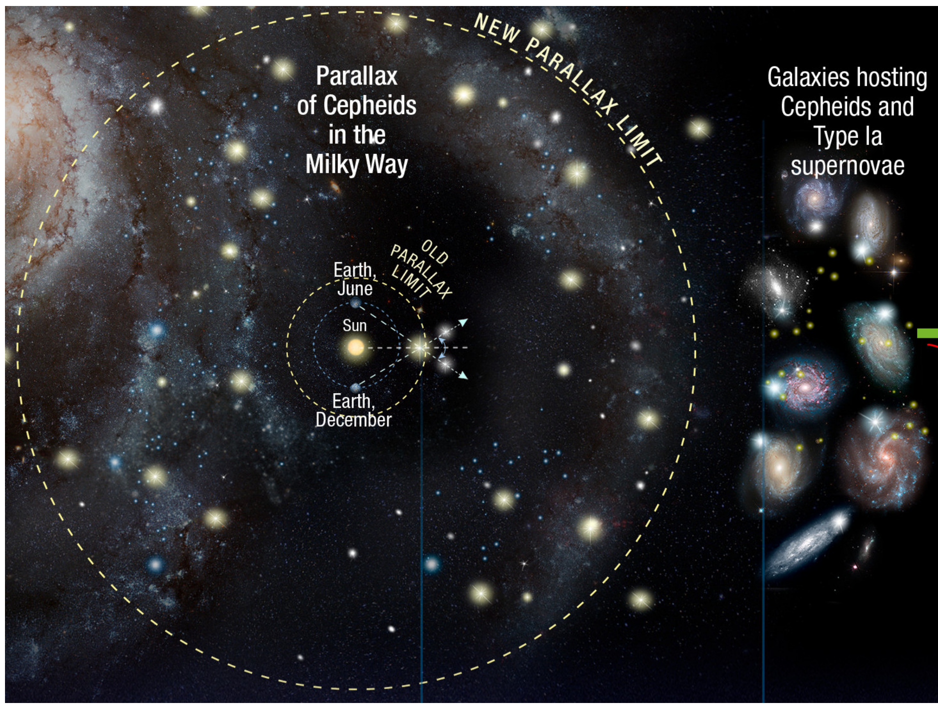

**Demands functional form of $d_L$!**

BAO distances can reach $1 < z$
Cosmographic would need $s_0$, $\ell_0$, ...

**(not local) constraint on $H_0$ depends on $d_L$ assumption**

# Inverse distance ladder

**CMB** and **BAO**(and others probes to calibrate **Supernovas**)

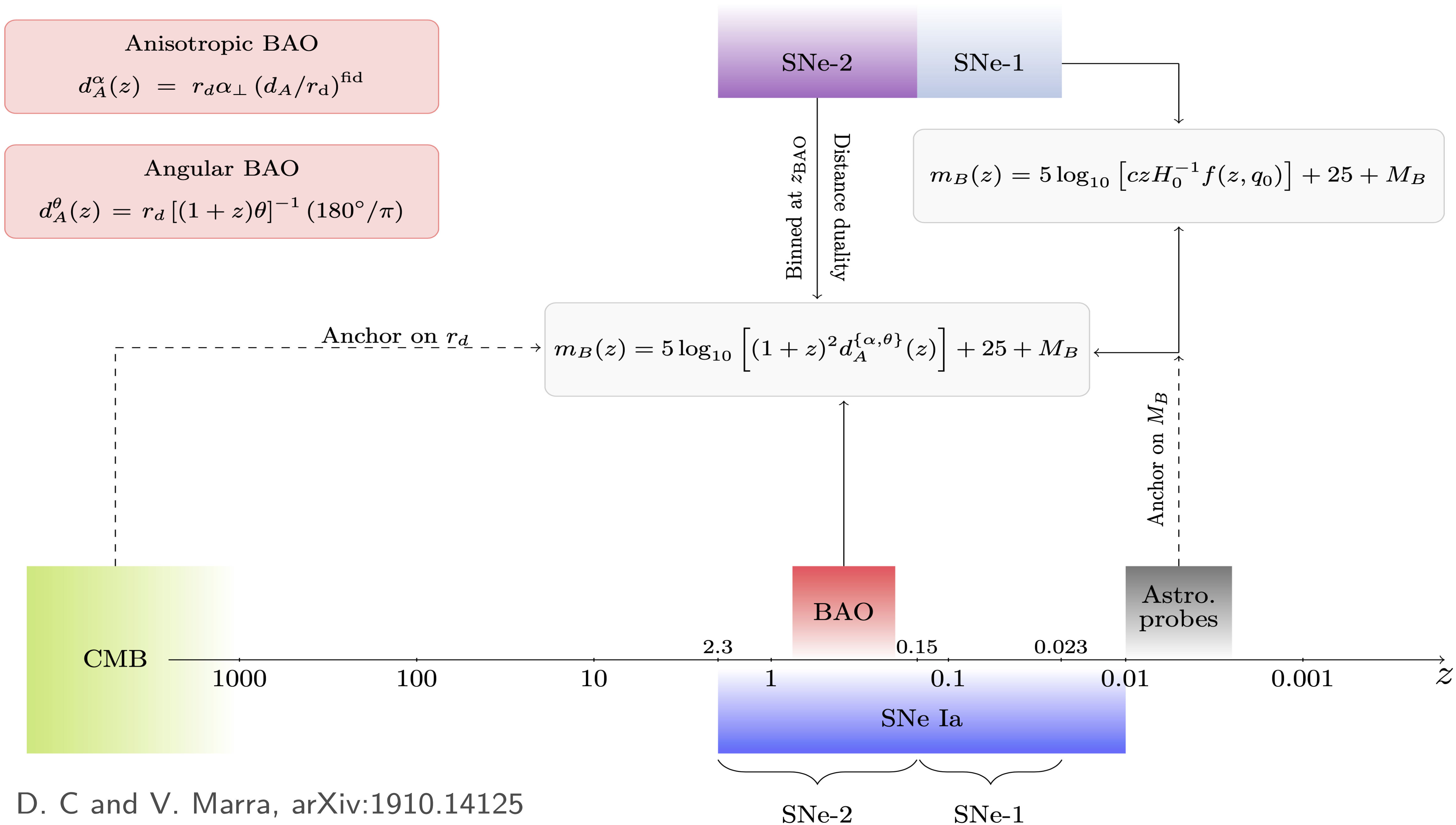



Don't care about $d_L$ beyond $z = 0.15$

Cepheids & Supernovas
at same redshift

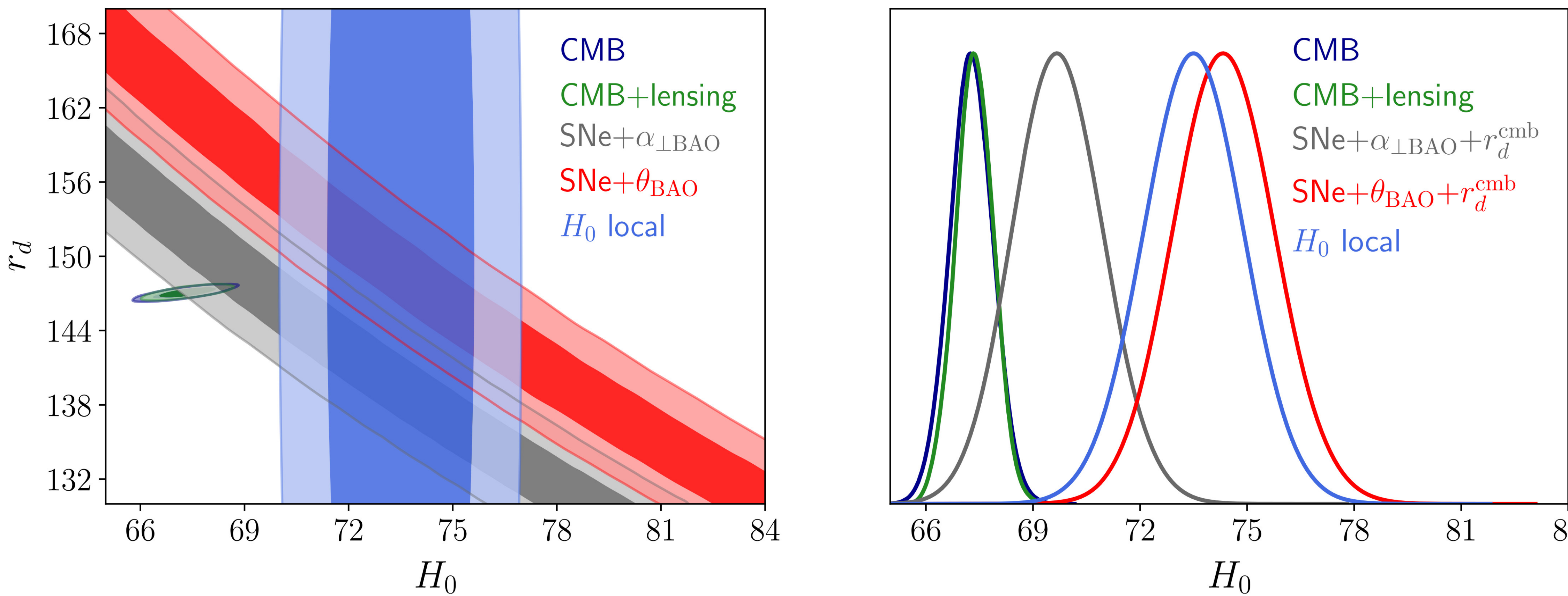
$$M_B = m_B - 5\log_{10}\frac{d_L}{10pc}$$

# Inverse distance ladder



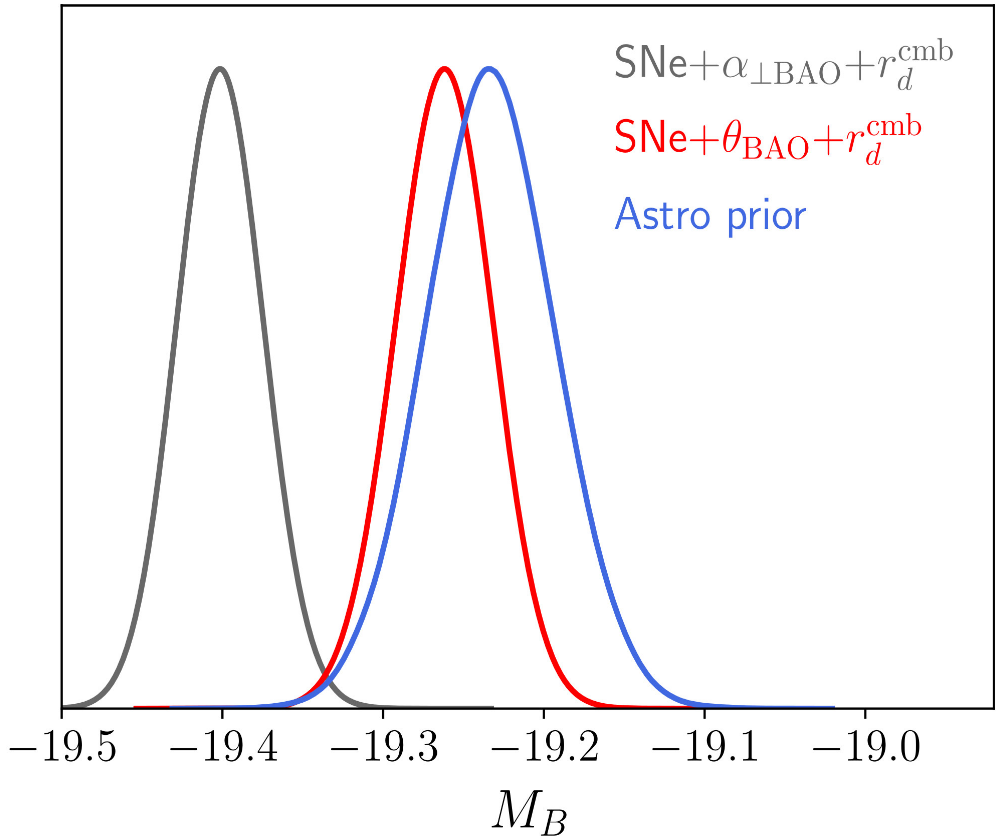

D. C and V. Marra, arXiv:1910.14125

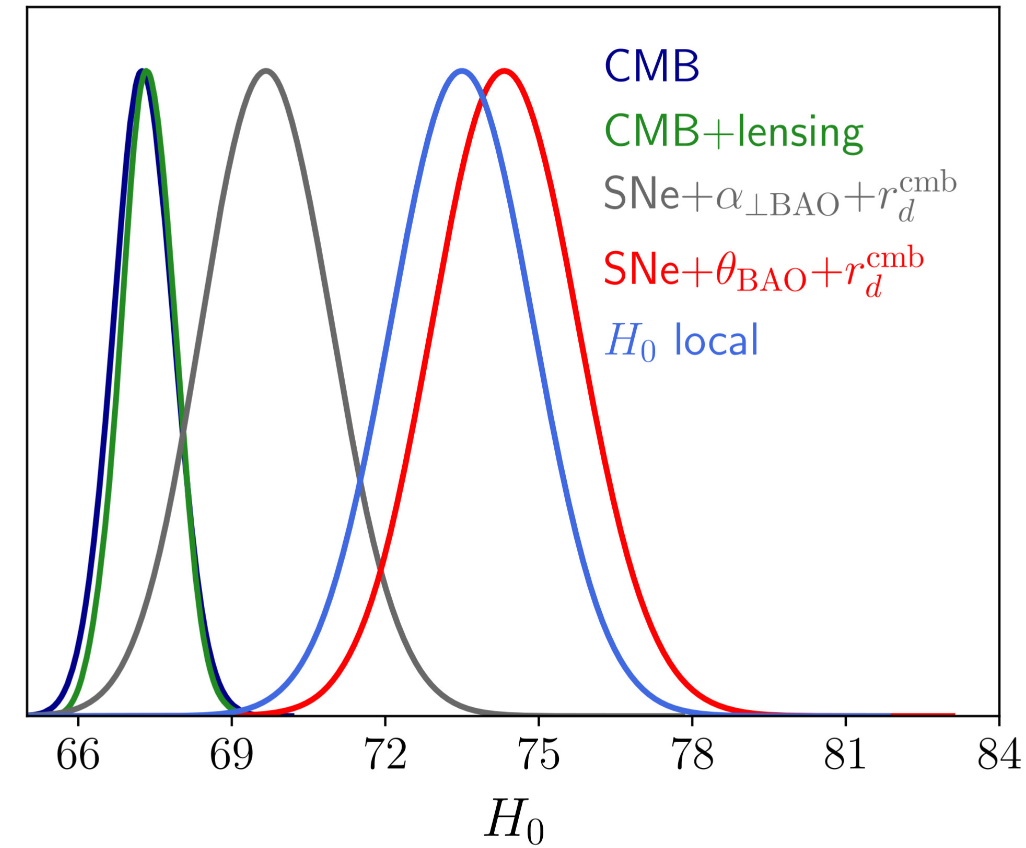
# Inverse distance ladder



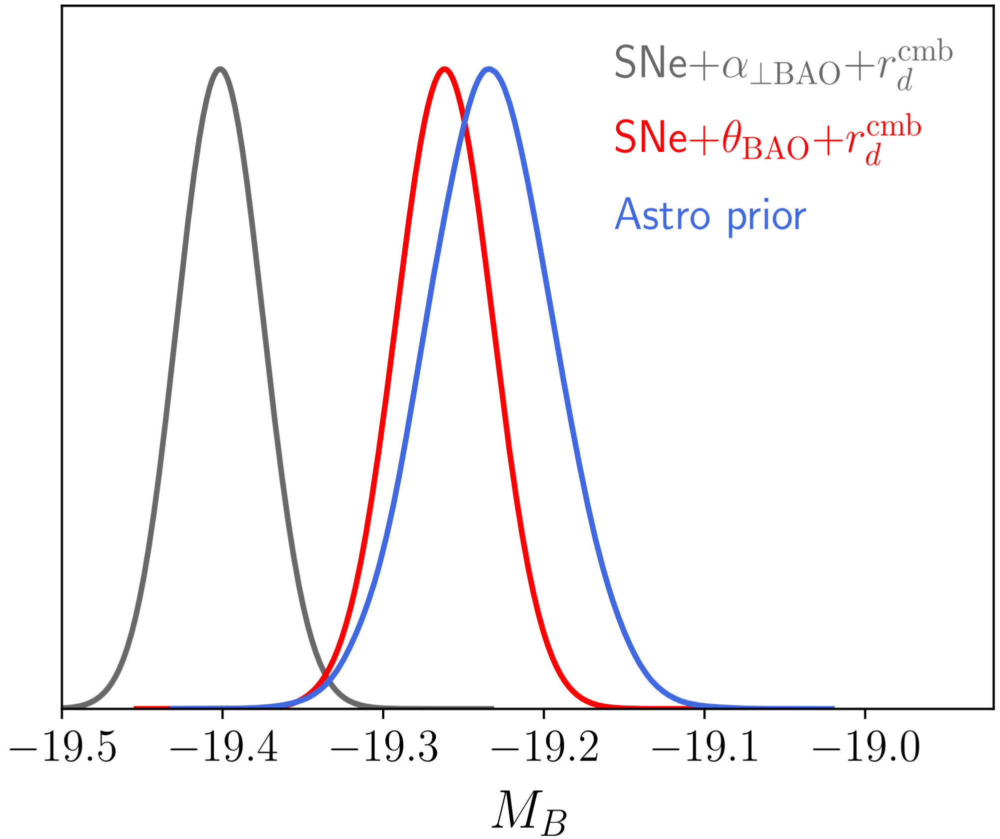

$\alpha_{\perp\mathrm{BAO}}$ : Power spectrum reconstruction and full-shape analyses (BOSS collaboration)
$\theta_{\mathrm{BAO}}$ : parametric fit to the angular 2-point correlation function $\omega(\theta)$

# Inverse distance ladder



# Inverse distance ladder




**Tension on $M_B$!**
**(assuming $\alpha_{\perp BAO}$ and CMB)**

**Tension between $\alpha_{\perp BAO}$ and $\theta_{BAO}$**

Local deceleration parameter $< -1$

| Type of analysis | Constraint on $q_0$ |
|---|---|
| SNe+$\alpha_{\perp\mathrm{BAO}}$ | $q_0 = -1.08^{+0.29}_{-0.29}$ |
| SNe+$\theta_{\mathrm{BAO}}$ | $q_0 = -1.11^{+0.29}_{-0.29}$ |
| SNe+$\alpha_{\perp\mathrm{BAO}} + r_d^{\mathrm{cmb}}$ | $q_0 = -1.09^{+0.29}_{-0.29}$ |
| SNe+$\theta_{\mathrm{BAO}} + r_d^{\mathrm{cmb}}$ | $q_0 = -1.11^{+0.29}_{-0.29}$ |
| SNe+$\alpha_{\perp\mathrm{BAO}} + M_B$ | $q_0 = -1.08^{+0.29}_{-0.29}$ |
| SNe+$\theta_{\mathrm{BAO}} + M_B$ | $q_0 = -1.11^{+0.29}_{-0.29}$ |

Cosmic distance ladder: $q_0^{\mathrm{loc}} = -1.08 \pm 0.29.$

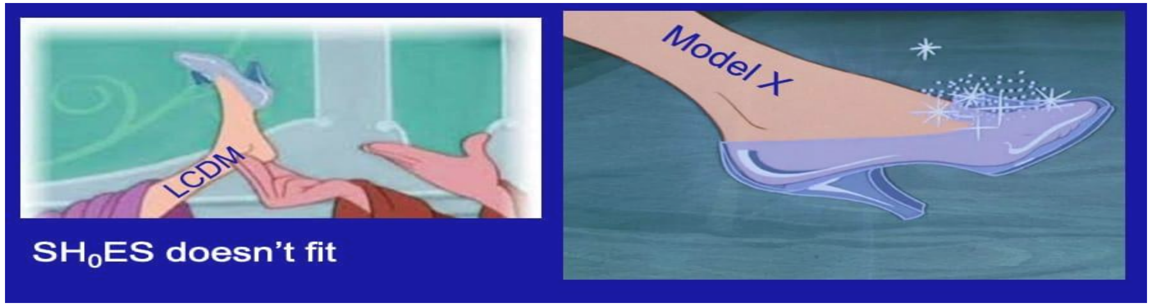
$q_0 : \sim 2\sigma$ "curiosity" with CMB

In agreement with analysis from P. Lemos et al., arXiv:1806.06781

# $M_B$ and physics beyond $\Lambda$CDM

- Discrepancy on $H_0$ between CMB and cosmic distance ladder.
- Discrepancy on $M_B$ calibration from CMB+BAO and Cepheids.
- $M_B$ is the backbone of SH0ES analysis.

Credits: Renan Alves de Oliveira



# $M_B$ and physics beyond $\Lambda$CDM

- Discrepancy on $H_0$ between CMB and cosmic distance ladder.
- Discrepancy on $M_B$ calibration from CMB+BAO and Cepheids.
- $M_B$ is the backbone of SH0ES analysis.

Credits: Renan Alves de Oliveira


Time to incluse $M_B$ on cosmological analysis?

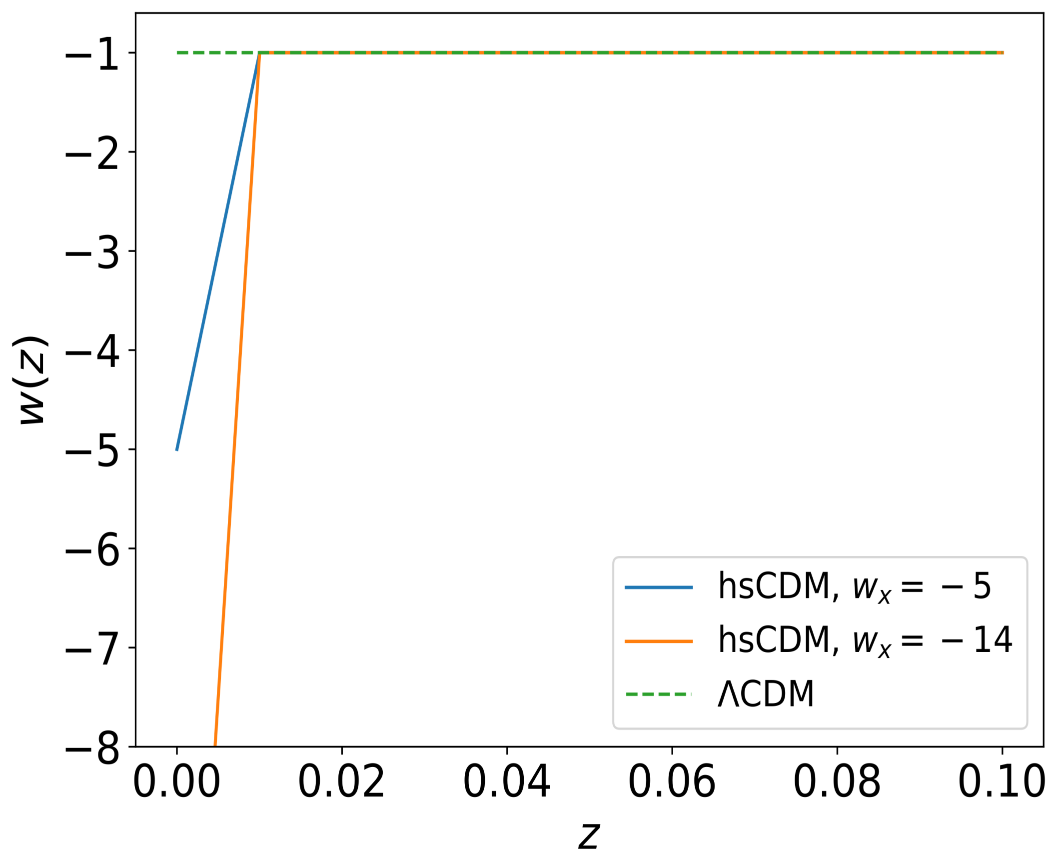
Are we trying to fit the right high hell on the left foot?

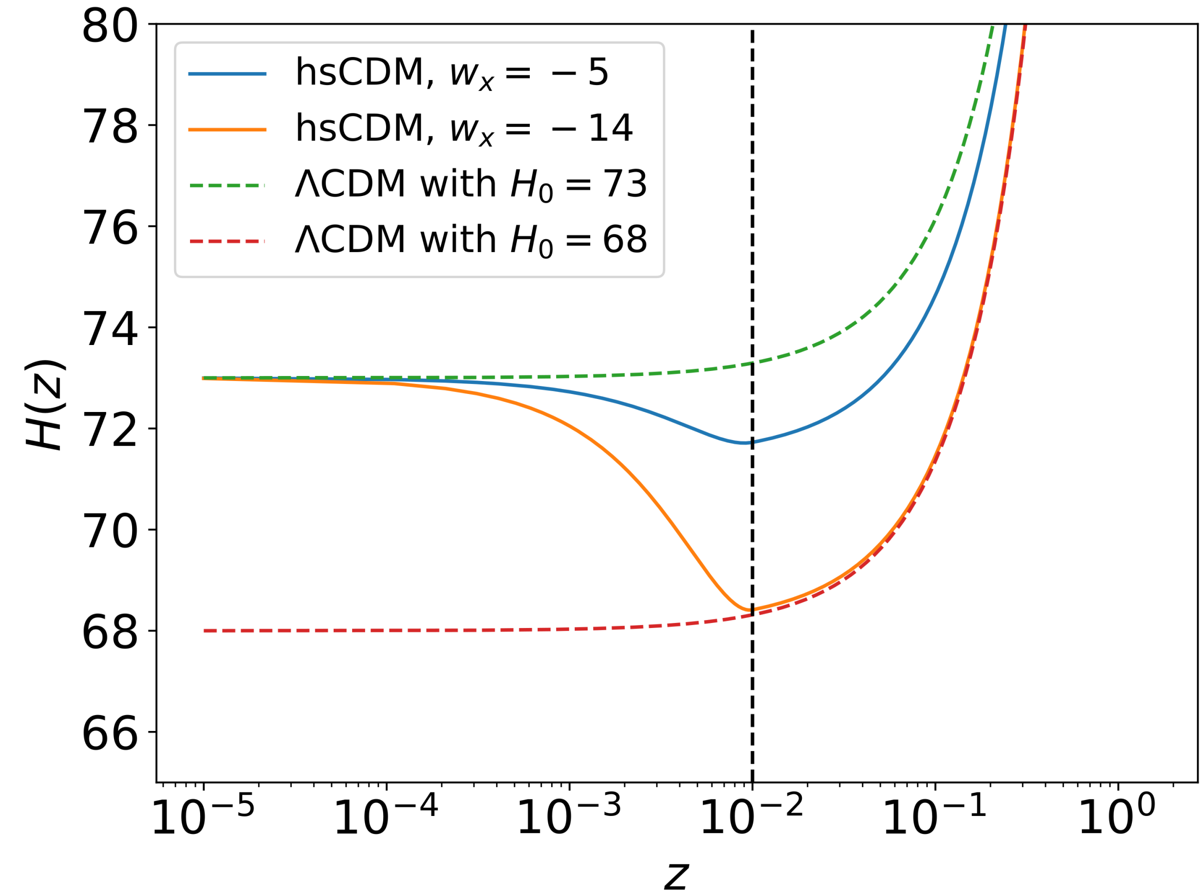
# $M_B$ vs $H_0$: hockey stick model

$$\frac{H^2(z)}{H_0^2} = \Omega_{M0}(1+z)^3 + \Omega_{R0}(1+z)^4 + \Omega_{\Lambda 0}(1+z)^{3g(z)}$$

$$w = \begin{cases} w_x - (1+w_x)\, z/z_t & \text{if } z \le z_t \text{ (the blade)} \\ -1 & \text{if } z > z_t \text{ (the shaft)} \end{cases}$$

$$g(z) = \frac{1+w_x}{z_t \ln(1+z)} \times \begin{cases} (1+z_t)\ln(1+z) - z & \text{if } z \le z_t \\ (1+z_t)\ln(1+z_t) - z_t & \text{if } z > z_t \end{cases}$$



# $M_B$ vs $H_0$: hockey stick model

$$\theta = \{H_0, \Omega_{m0}, \Omega_{b0}, w_x, z_t, M_B, n_s\}$$

$$\chi^2_{\mathrm{tot},H_0}(\theta) = \chi^2_{\mathrm{cmb}} + \chi^2_{\mathrm{bao}} + \chi^2_{\mathrm{sne}} + \chi^2_{H_0} \qquad \chi^2_{\mathrm{tot},M_B}(\theta) = \chi^2_{\mathrm{cmb}} + \chi^2_{\mathrm{bao}} + \chi^2_{\mathrm{sne}} + \chi^2_{M_B}$$

- CMB: gaussian prior on $\left(R, l_a, \Omega_{b0}, h^2, n_s\right)$
- BAO: 6dFGS, SDSS-MGS and BOSS-DR12 $(d_V(z), d_A(z)$ and $H(z))$
- Supernovas: Pantheon supernovas $(0.01 < z < 2.3)$

# $M_B$ vs $H_0$: hockey stick model

$$\theta = \{H_0, \Omega_{m0}, \Omega_{b0}, w_x, z_t, M_B, n_s\}$$

$$\chi^2_{\text{tot},H_0}(\theta) = \chi^2_{\text{cmb}} + \chi^2_{\text{bao}} + \chi^2_{\text{sne}} + \chi^2_{H_0} \qquad \chi^2_{\text{tot},M_B}(\theta) = \chi^2_{\text{cmb}} + \chi^2_{\text{bao}} + \chi^2_{\text{sne}} + \chi^2_{M_B}$$

| Analysis with prior on $H_0$ | $\hat{\chi}^2_{\text{tot}}$ | $\Delta\hat{\chi}^2$ | best-fit vector $\{H_0, \Omega_{M0}, w_x, z_t, M_B, \Omega_{B0}, n_s\}$ | distance from $H_0^{\text{R21}}$ | distance from $M_B^{\text{R21}}$ |
|---|---|---|---|---|---|
| $w$CDM | 1045.8 | 0 | {69.6, 0.29, -1.08, ——, -19.39, 0.046, 0.97} | 2.8 | 3.8 |
| $hs$CDM | 1035.1 | -10.7 | {72.5, 0.26, -14.4, 0.010, -19.42, 0.043, 0.97} | 0.5 | 4.9 |

| Analysis with prior on $M_B$ | $\hat{\chi}^2_{\text{tot}}$ | $\Delta\hat{\chi}^2$ | best-fit vector $\{H_0, \Omega_{M0}, w_x, z_t, M_B, \Omega_{B0}, n_s\}$ | distance from $H_0^{\text{R21}}$ | distance from $M_B^{\text{R21}}$ |
|---|---|---|---|---|---|
| $w$CDM | 1051.9 | 0 | {69.4, 0.29, -1.07, ——, -19.39, 0.047, 0.97} | 2.9 | 3.8 |
| $hs$CDM | 1055.4 | 3.5 | {69.3, 0.29, -1.73, 0.055, -19.41, 0.047, 0.97} | 3.0 | 4.4 |

# $M_B$ vs $H_0$: hockey stick model

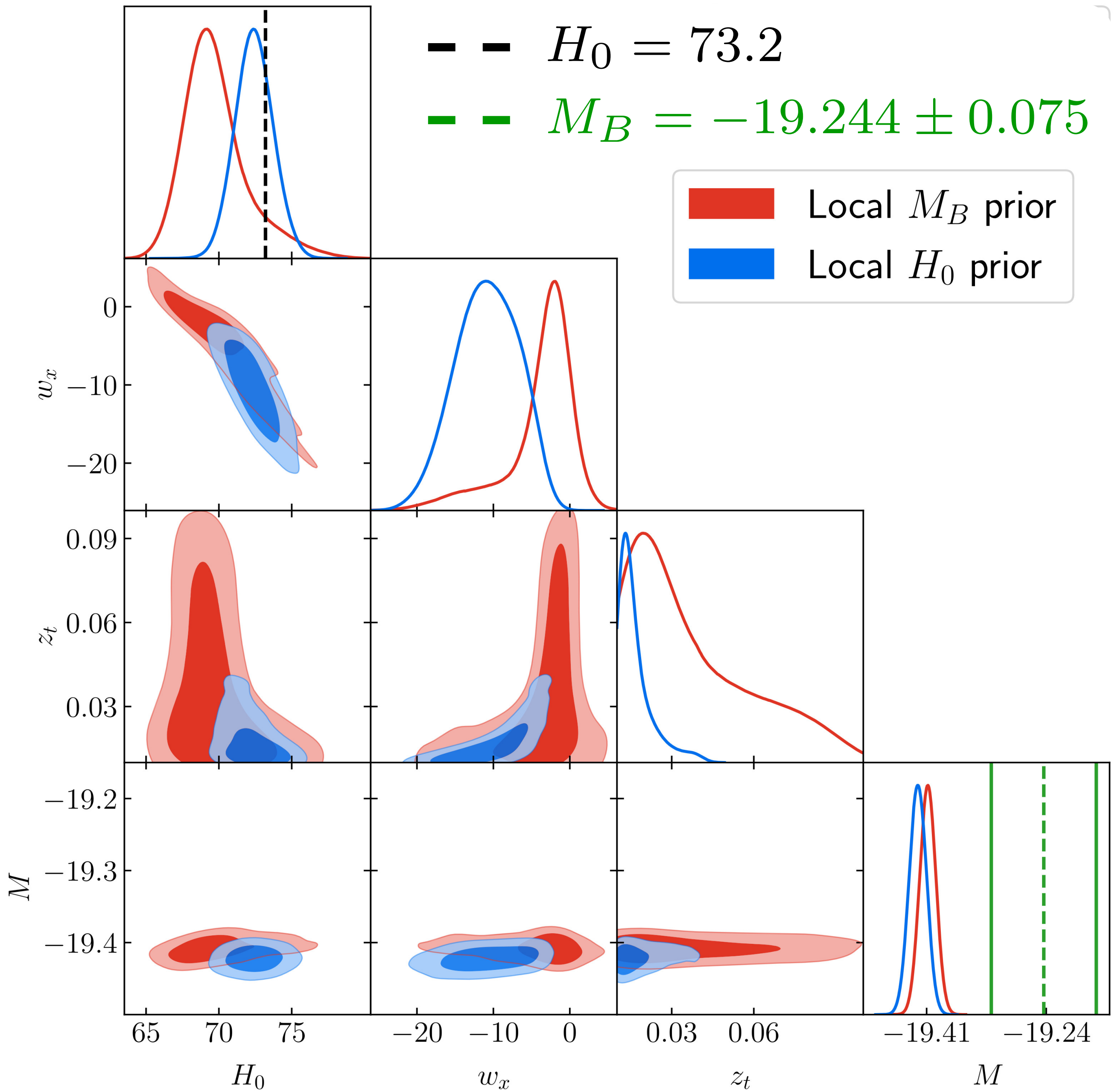
$$\theta = \{\underline{H_0}, \Omega_{m0}, \Omega_{b0}, \underline{w_x}, \underline{z_t}, M_B, n_s\}$$

$$\chi^2_{\text{tot},H_0}(\theta) = \chi^2_{\text{cmb}} + \chi^2_{\text{bao}} + \chi^2_{\text{sne}} + \chi^2_{H_0} \qquad \chi^2_{\text{tot},M_B}(\theta) = \chi^2_{\text{cmb}} + \chi^2_{\text{bao}} + \chi^2_{\text{sne}} + \chi^2_{M_B}$$

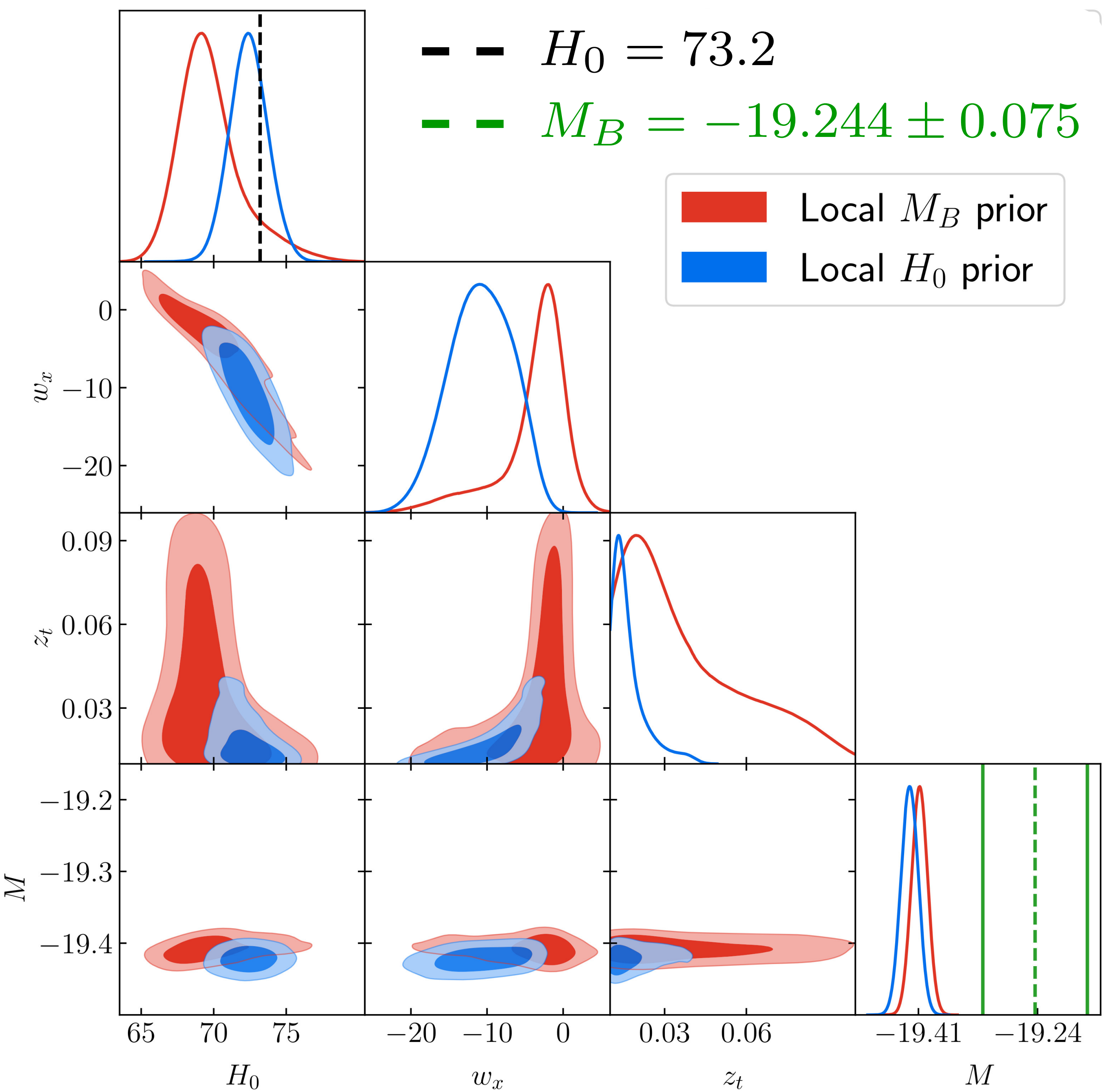
| Analysis with prior on $H_0$ | $\hat{\chi}^2_{\text{tot}}$ | $\Delta\hat{\chi}^2$ | best-fit vector $\{H_0, \Omega_{M0}, w_x, z_t, M_B, \Omega_{B0}, n_s\}$ | distance from $H_0^{\text{R21}}$ | distance from $M_B^{\text{R21}}$ |
|---|---|---|---|---|---|
| $w$CDM | 1045.8 | 0 | {69.6, 0.29, -1.08, —, -19.39, 0.046, 0.97} | 2.8 | 3.8 |
| $hs$CDM | 1035.1 | -10.7 | {72.5, 0.26, -14.4, 0.010, -19.42, 0.043, 0.97} | 0.5 | 4.9 |

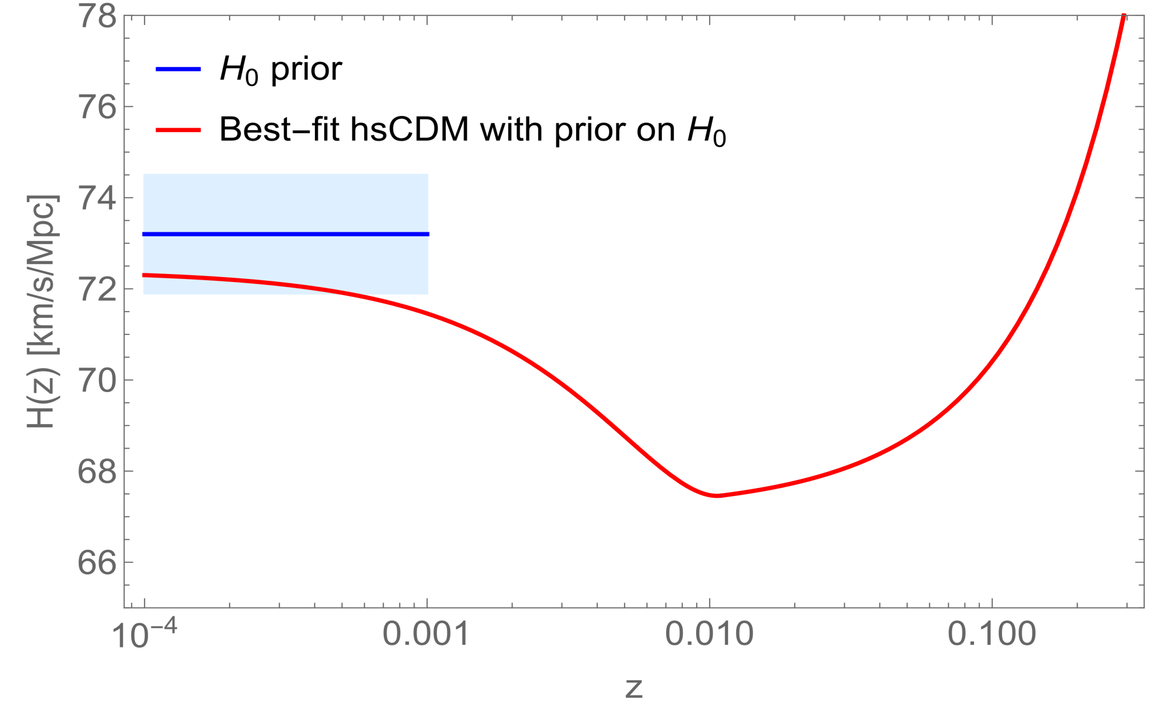
| Analysis with prior on $M_B$ | $\hat{\chi}^2_{\text{tot}}$ | $\Delta\hat{\chi}^2$ | best-fit vector $\{H_0, \Omega_{M0}, w_x, z_t, M_B, \Omega_{B0}, n_s\}$ | distance from $H_0^{\text{R21}}$ | distance from $M_B^{\text{R21}}$ |
|---|---|---|---|---|---|
| $w$CDM | 1051.9 | 0 | {69.4, 0.29, -1.07, —, -19.39, 0.047, 0.97} | 2.9 | 3.8 |
| $hs$CDM | 1055.4 | 3.5 | {69.3, 0.29, -1.73, 0.055, -19.41, 0.047, 0.97} | 3.0 | 4.4 |

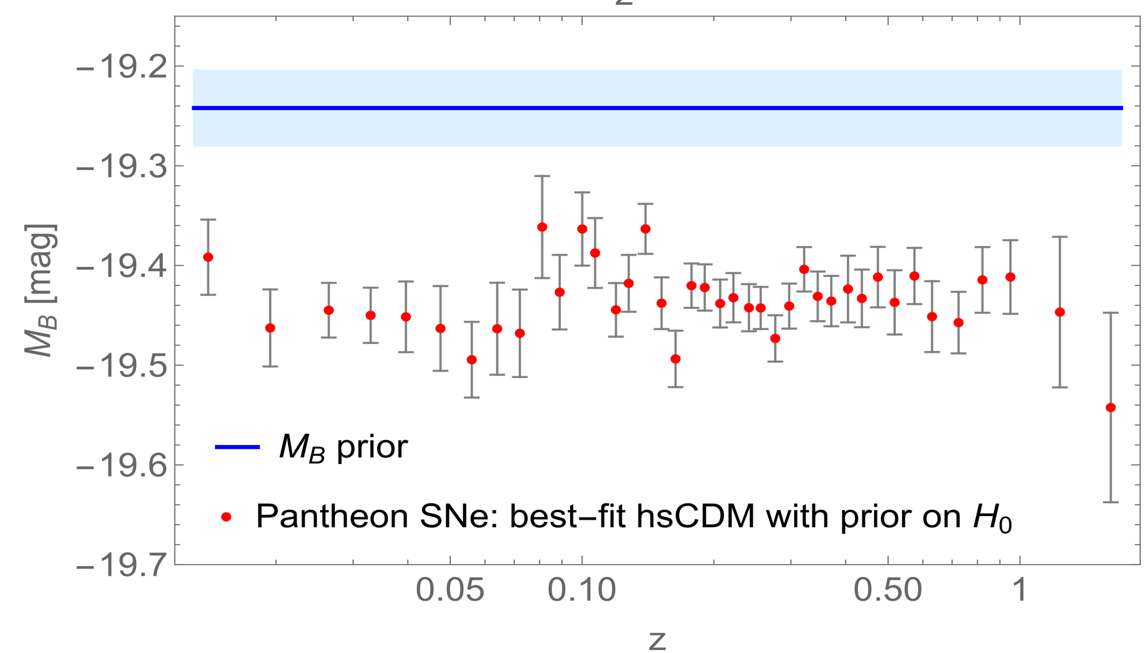
# $M_B$ vs $H_0$: hockey stick model



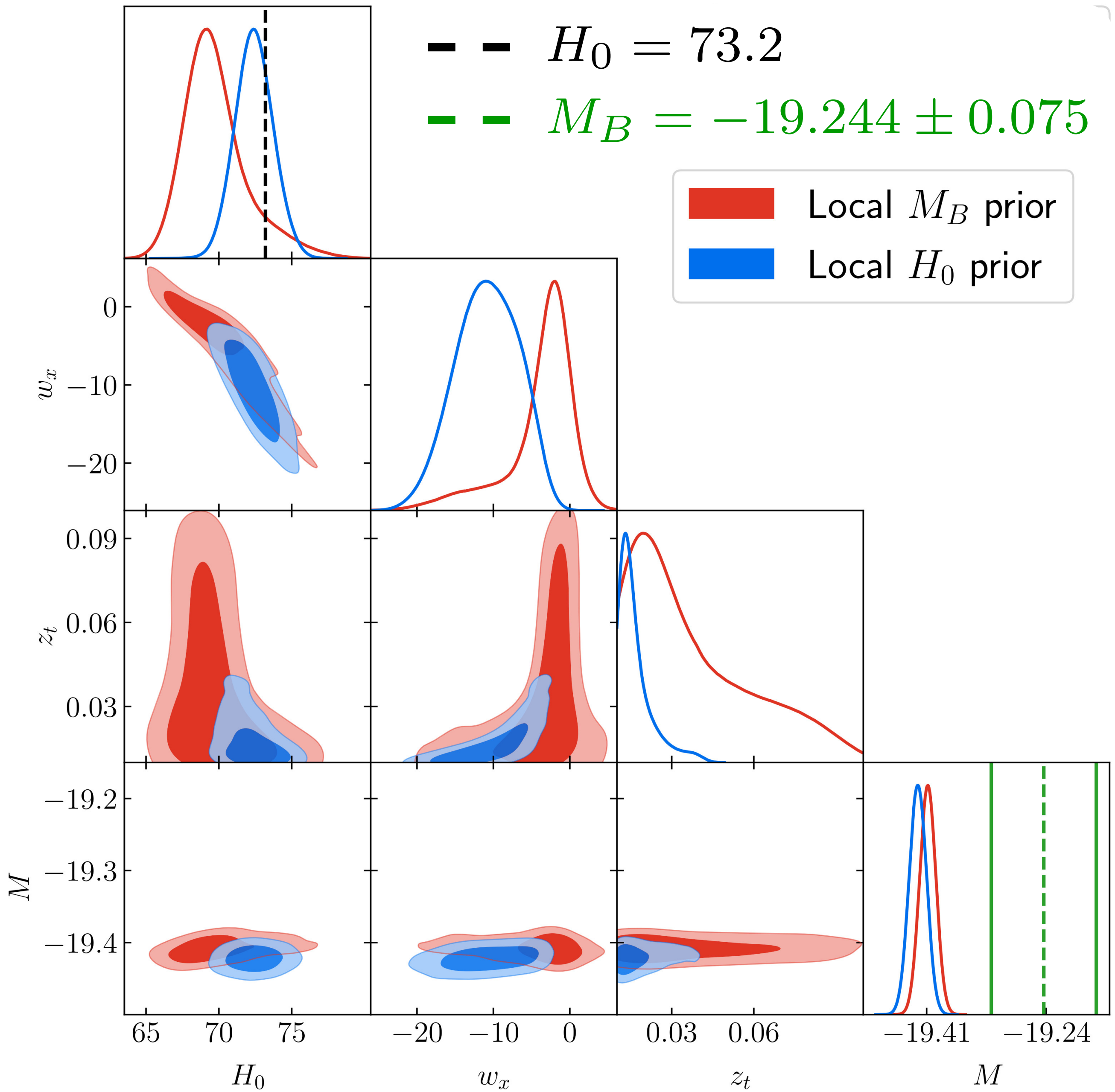
# $M_B$ vs $H_0$: hockey stick model

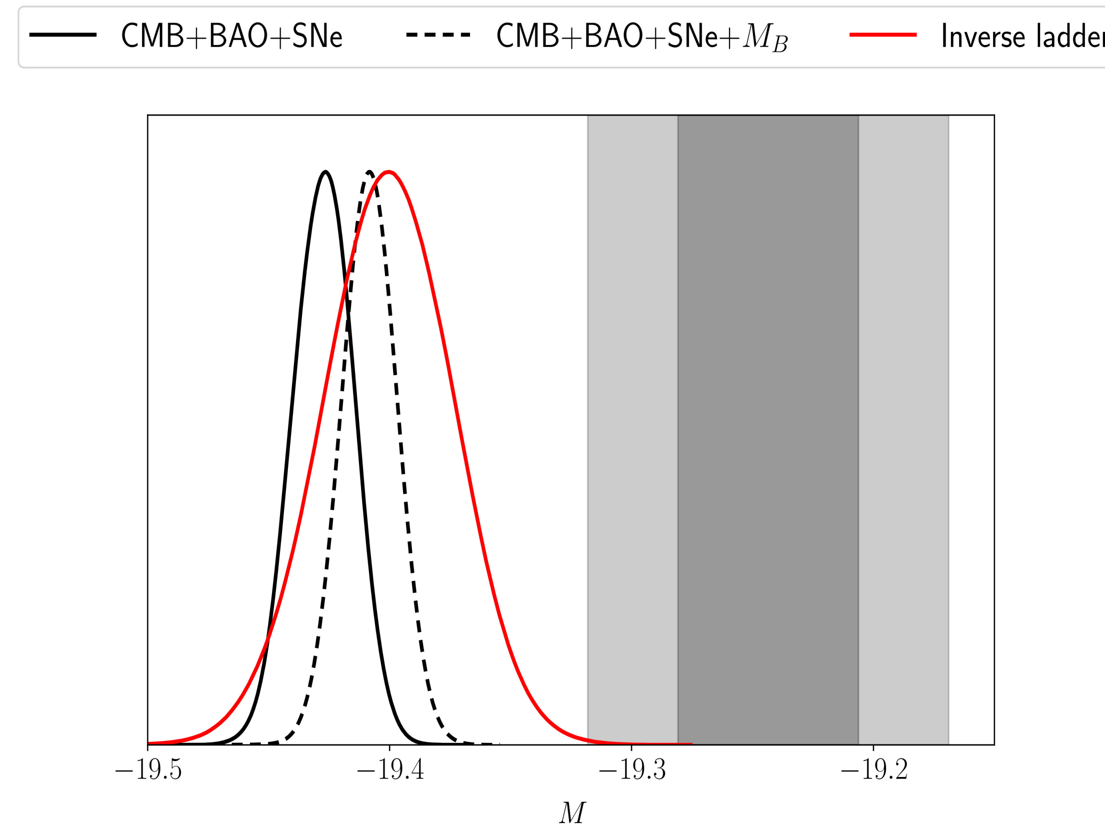


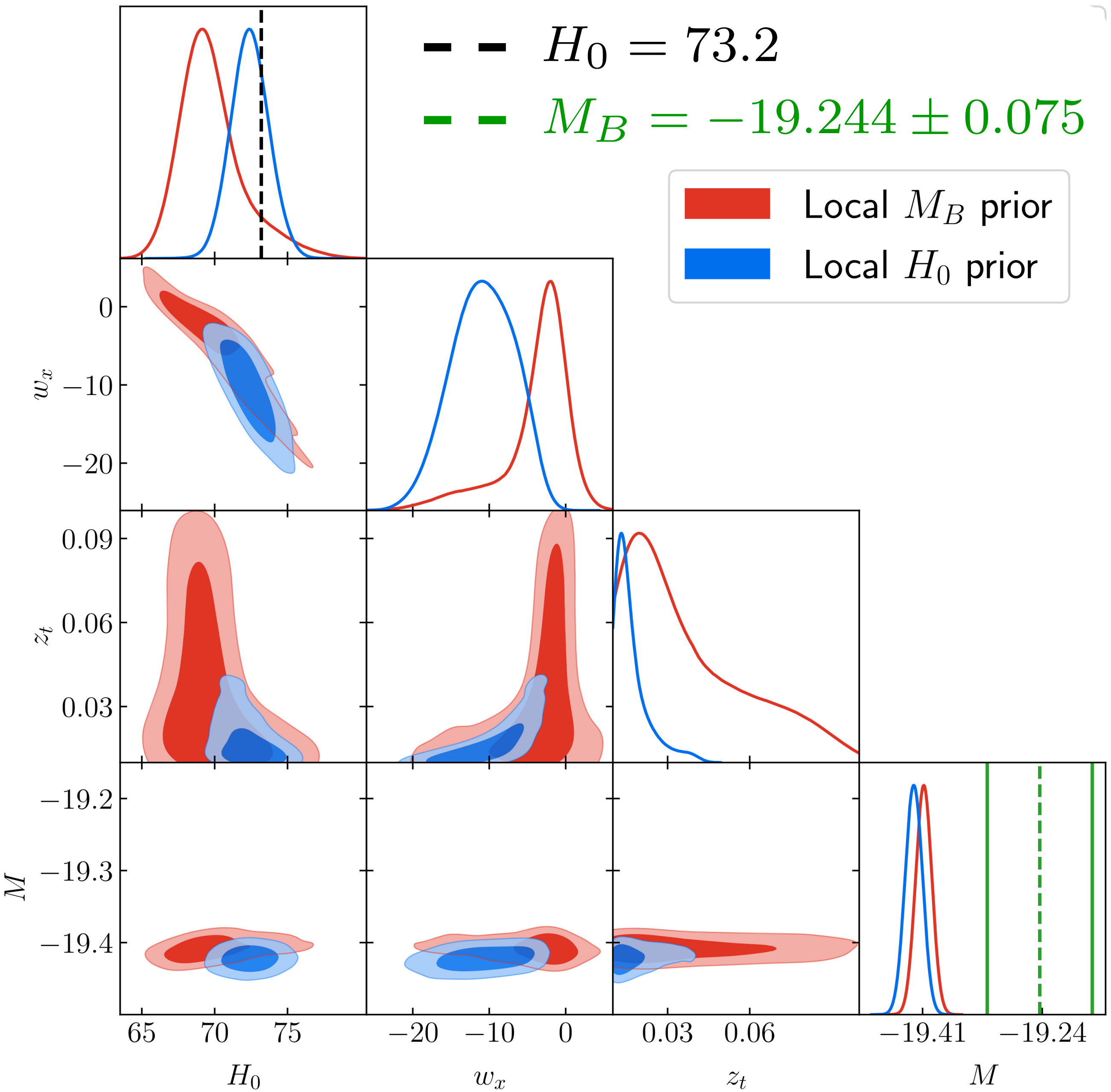



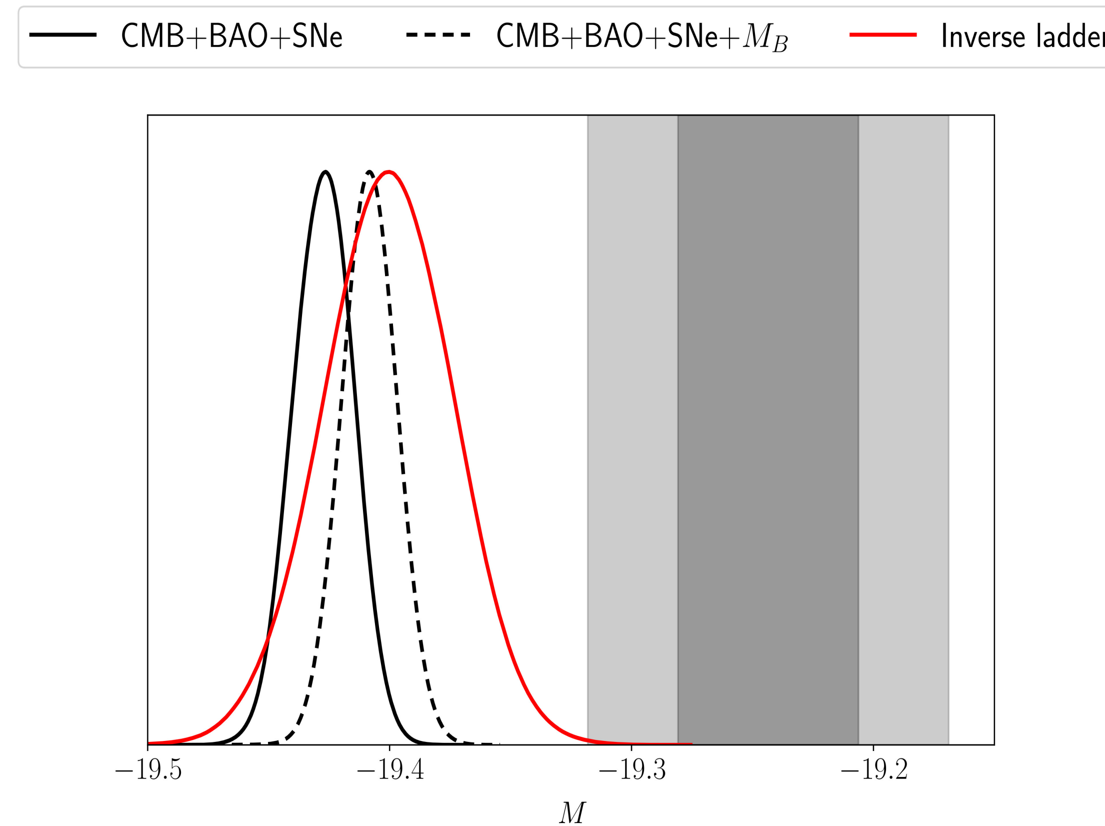
# $M_B$ vs $H_0$: hockey stick model



# $M_B$ vs $H_0$: hockey stick model



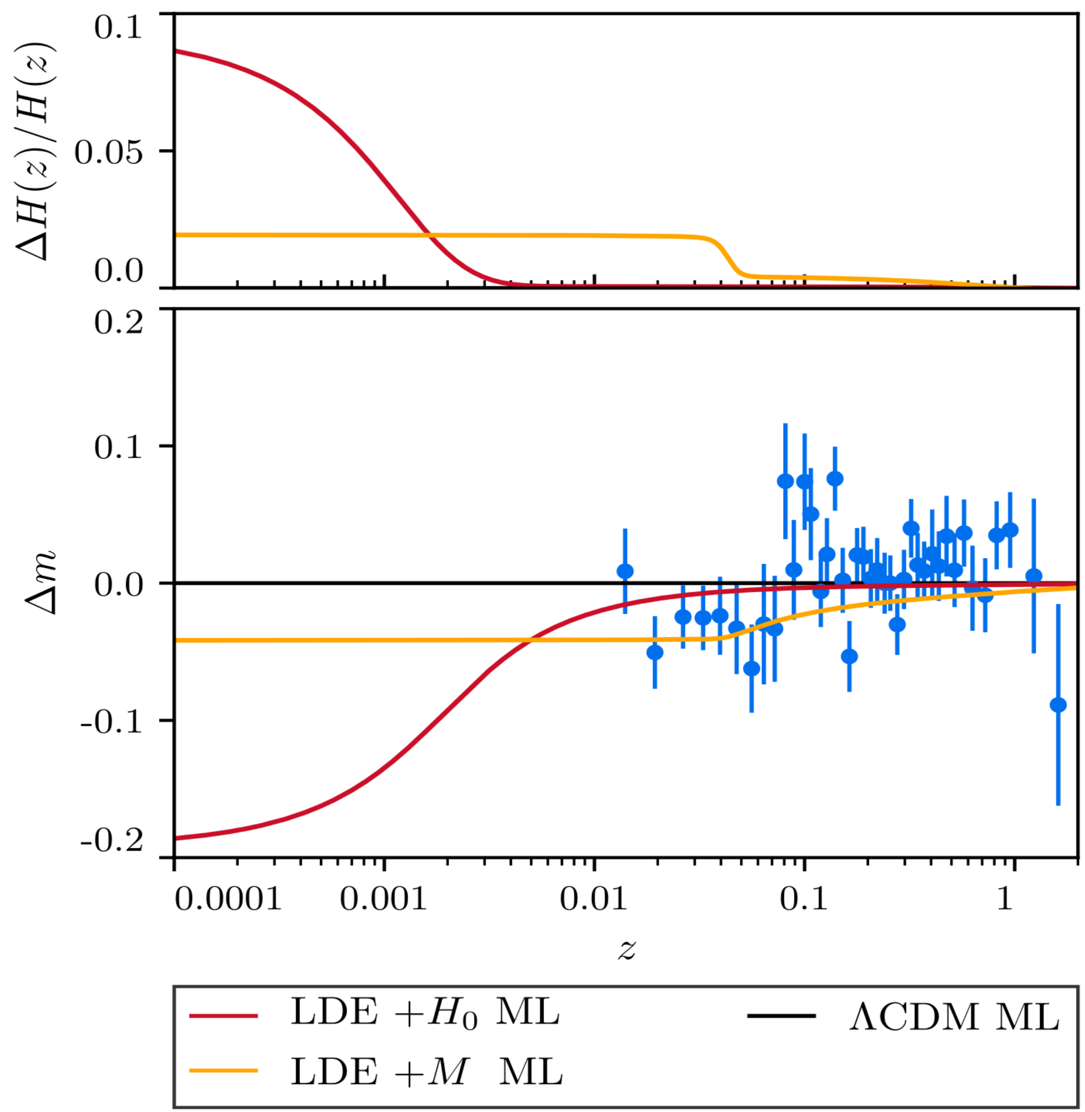

**$\sim 4.3\sigma$ tension on $M_B$!**

CMB+BAO+SN: $-19.401 \pm 0.027$

Local constraint: $-19.244 \pm 0.037$

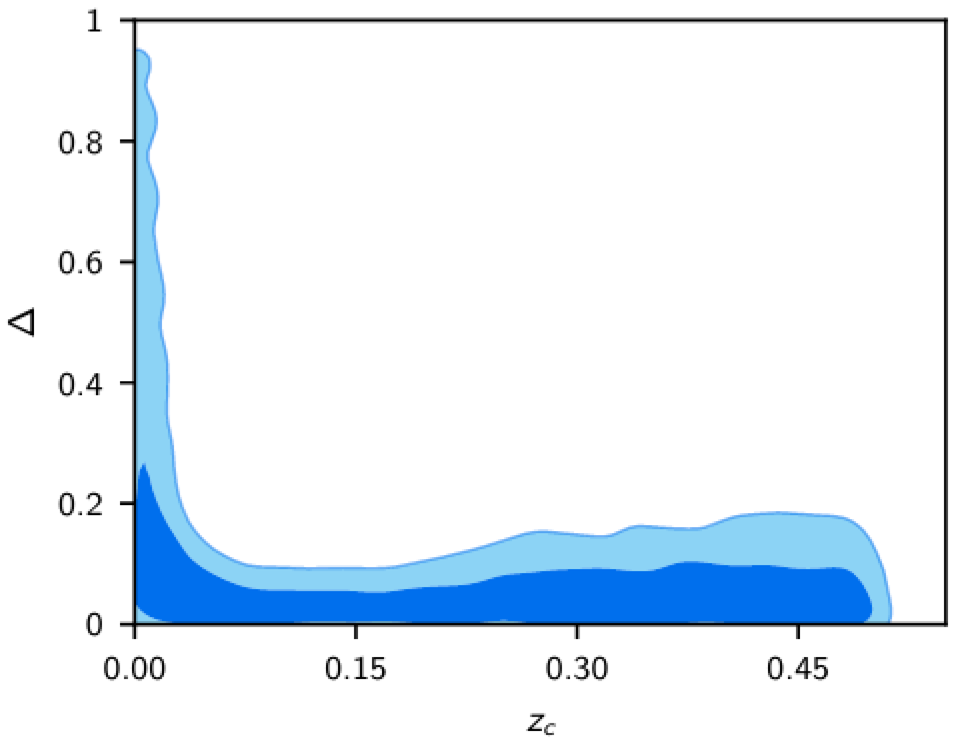
# $M_B$ and physics beyond $\Lambda$CDM

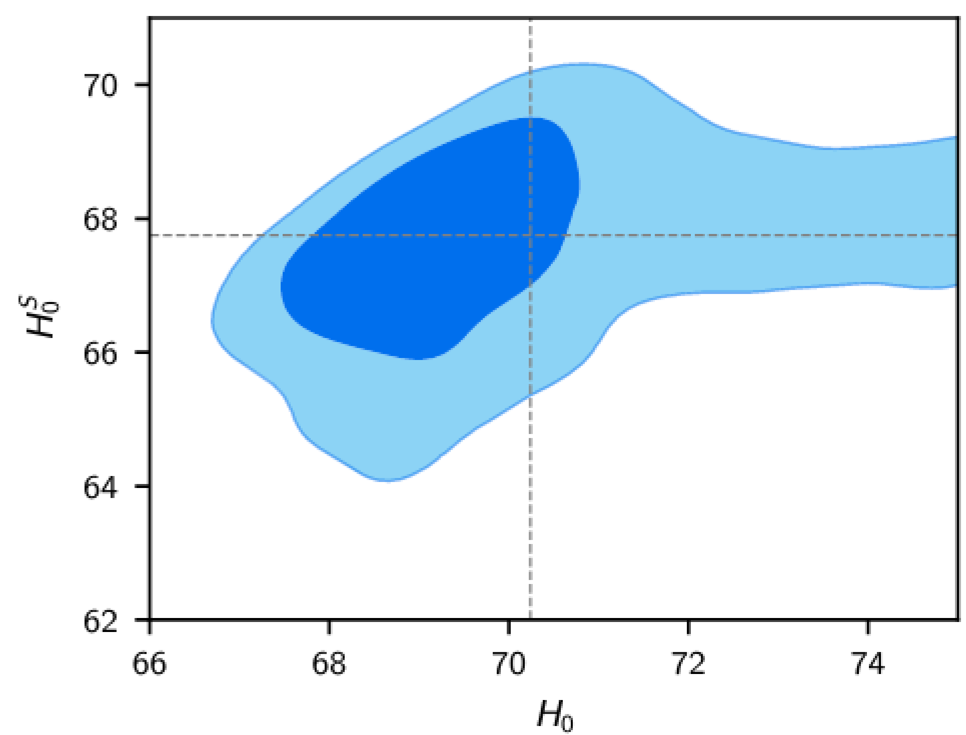
- Late dark energy fails to raise the Hubble constant (G. Benevento et al. arXiv:2002.11707)



# $M_B$ and physics beyond $\Lambda$CDM

- Late dark energy fails to raise the Hubble constant (G. Benevento et al. arXiv:2002.11707)
- Supernova data are insensitive to late time changes in the dark energy (G. Efstathiou et al. arXiv:2103.08723)



# Conclusions

- **No strong evidence systematics** error (that can solve the tension).
- **Other measurements** would be **crucial** to **confirm (or ruled out) new physics/systematics**
- **Local constraint** on $q_0$ shows a "curious" **tension** $2\sigma$ **with** $\Lambda$**CDM**
- There is a **tension between** $\alpha$ and $\theta$ BAO data set.
- **Inverse distance ladder does not agree** with the **Cepheid** calibration $M_B$ (if $r_d$ CMB and $\alpha_{\rm BAO}$ are assumed)
- Use a $M_B$ **prior** instead of a $H_0$ **prior**: avoid SN double-counting, pure astrophysical and account for the tension with Cepheids.
- **late-time modifications to** $\Lambda$**CDM do not solve the Hubble discrepancy!**

# Obrigado!