Vivian Poulin

Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

*vivian.poulin@umontpellier.fr*

In collaboration with N. Schöneberg, A. Ferrari, F. Finelli, J. Lesgourgues, L. Morelli, M. Mosbech, R. Sharma, T. Simon

*SUPPORTED BY FUNDING FROM THE EUROPEAN RESEARCH COUNCIL (ERC) UNDER THE EUROPEAN UNION'S HORIZON–ERC–2022 (GRANT AGREEMENT NO. 101076865)*

*PASCOS 2026*
*Sheffield, UK*
*June, 24th 2026*

LUPM LABORATOIRE UNIVERS & PARTICULES DE MONTPELLIER
cnrs
erc European Research Council

# Status of the Hubble tension

*H0DN (Casertano et al) 2510.23823*

# Outline of my talk

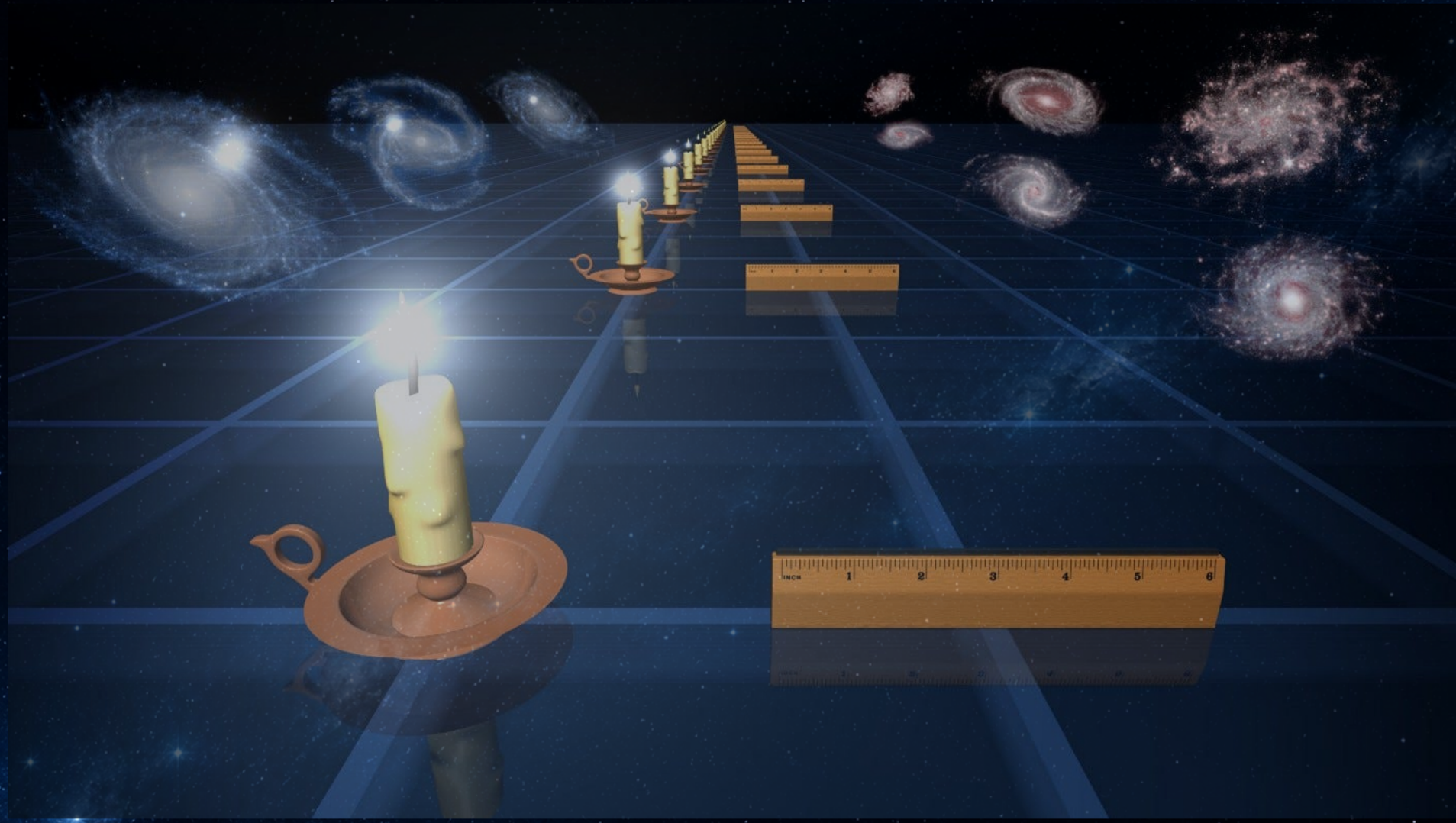
| tension $\leq 1\sigma$ *"Excellent models"* | tension $\leq 2\sigma$ *"Good models"* | tension $\leq 3\sigma$ *"Promising models"* |
|---|---|---|
| Early Dark Energy [228, 235, 240, 250] | Early Dark Energy [212, 229, 236, 263] | DE in extended parameter spaces [289] |
| Exponential Acoustic Dark Energy [259] | Rock 'n' Roll [242] | Dynamical Dark Energy [281, 309] |
| Phantom Crossing [315] | New Early Dark Energy [247] | Holographic Dark Energy [350] |
| Late Dark Energy Transition [317] | Acoustic Dark Energy [257] | Swampland Conjectures [370] |
| Metastable Dark Energy [314] | Dynamical Dark Energy [309] | MEDE [399] |
| PEDE [394] | Running vacuum model [332] | Coupled DM - Dark radiation [534] |
| Vacuum Metamorphosis [402] | Bulk viscous models [340, 341] | Decaying Ultralight Scalar [538] |
| Elaborated Vacuum Metamorphosis [401, 402] | Holographic Dark Energy [350] | BD-ΛCDM [852] |
| Sterile Neutrinos [433] | Phantom Braneworld DE [378] | Metastable Dark Energy [314] |
| Decaying Dark Matter [481] | PEDE [391, 392] | Self-Interacting Neutrinos [700] |
| Neutrino-Majoron Interactions [509] | Elaborated Vacuum Metamorphosis [401] | Dark Neutrino Interactions [716] |
| IDE [637, 639, 657, 661] | IDE [659, 670] | IDE [634–636, 653, 656, 663, 669] |
| DM - Photon Coupling [685] | Interacting Dark Radiation [517] | Scalar-tensor gravity [855, 856] |
| $f(\mathcal{T})$ gravity theory [812] | Decaying Dark Matter [471, 474] | Galileon gravity [877, 881] |
| BD-ΛCDM [851] | DM - Photon Coupling [686] | Nonlocal gravity [886] |
| Über-Gravity [59] | Self-interacting sterile neutrinos [711] | Modified recombination [986] |
| Galileon Gravity [875] | $f(\mathcal{T})$ gravity theory [817] | Effective Electron Rest Mass [989] |
| Unimodular Gravity [890] | Über-Gravity [871] | Super ΛCDM [1007] |
| Time Varying Electron Mass [990] | VCDM [893] | Axi-Higgs [991] |
| ΛCDM [995] | Primordial magnetic fields [992] | Self-Interacting Dark Matter [479] |
| Ginzburg-Landau theory [996] | Early modified gravity [859] | Primordial Black Holes [545] |
| Lorentzian Quintessential Inflation [979] | Bianchi type I spacetime [999] | *DiValentino++ 2103.01183* |
| Holographic Dark Energy [351] | $f(\mathcal{T})$ [818] | |

Can we classify "good" and "bad" models against the same datasets and tension metrics?

# The $H_0$ world cup

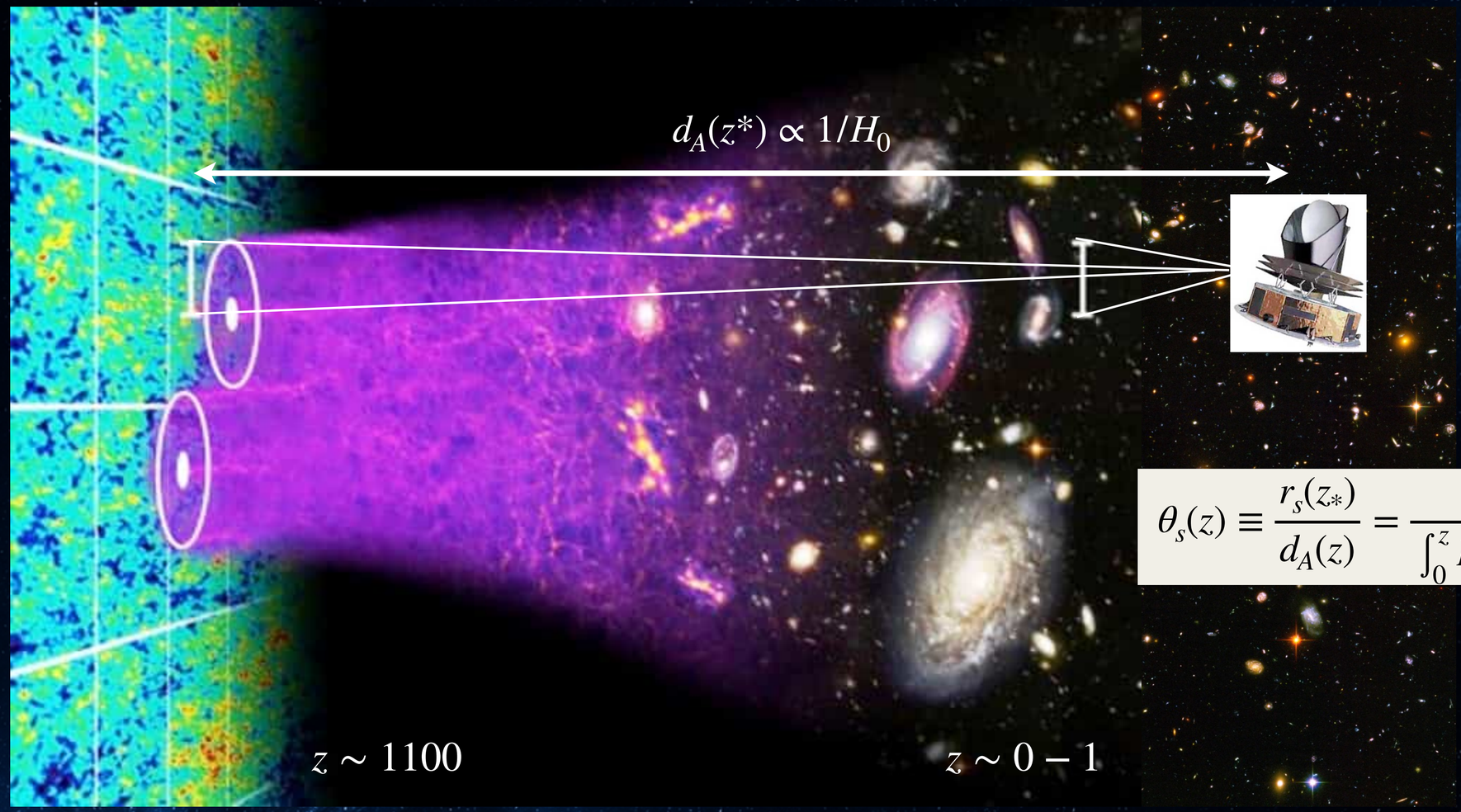
- The $H_0$ olympics: a brief recap of where we stand
- The $H_0$ world cup: qualified models, rules and results
- Lessons: the cosmic calibration tension
- Perspective: towards the string axiverse?

# Standard Candles or Standard Rulers?



- The direct and indirect calibrations of the cosmic distance ladder are in disagreement

# Calibrating the ladder: the "indirect" way

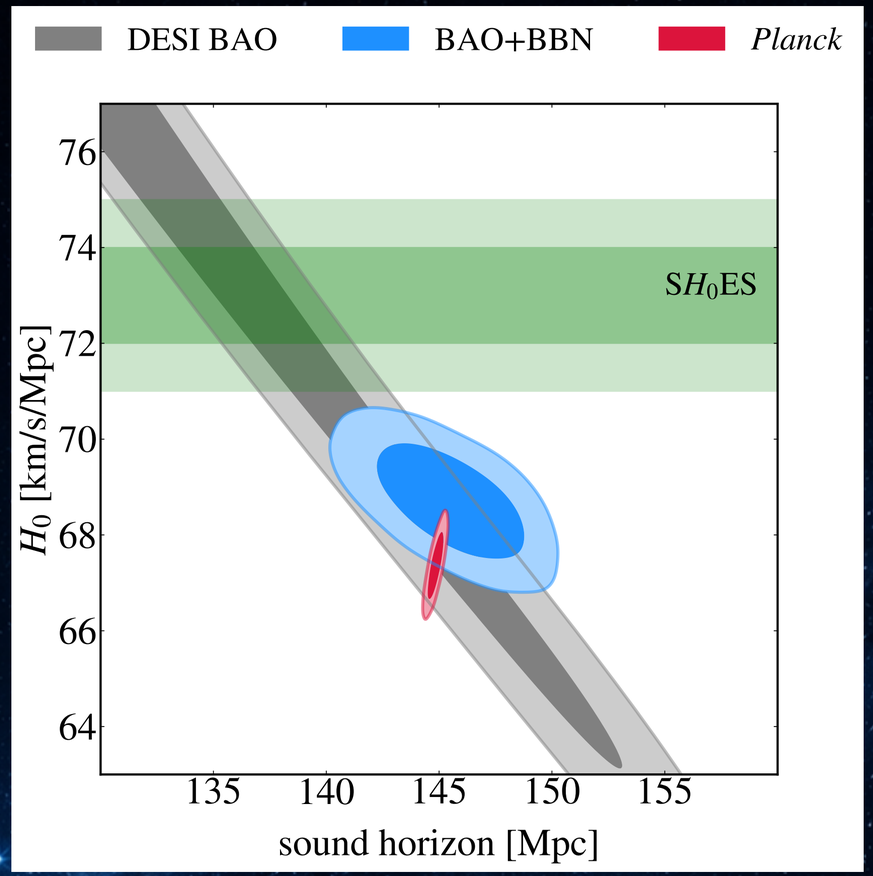


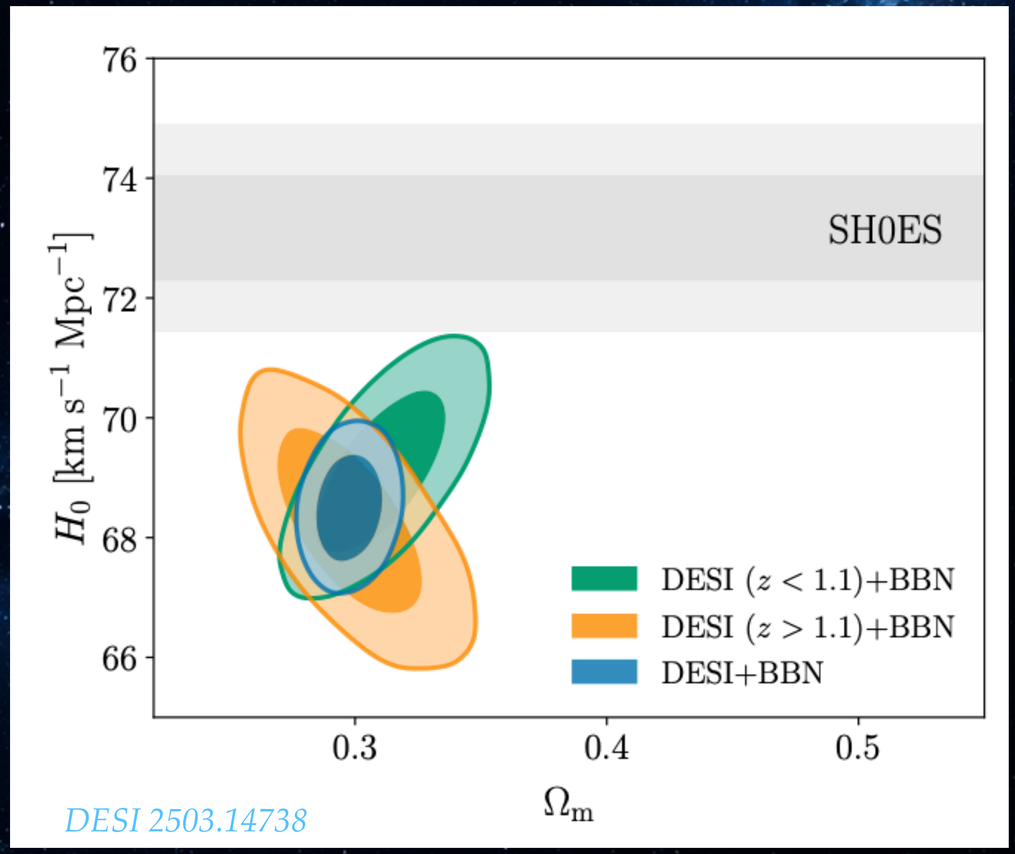

$$\theta_s(z) \equiv \frac{r_s(z_*)}{d_A(z)} = \frac{r_s H_0}{\int_0^z E^{-1}(z')dz'}$$

- *Planck* measures $\theta_s(z \sim 1000)$ at 0.04% precision / DESI measures $\theta_s$ ( $z \sim 0.1-2$) at 1%
- Measuring $H_0$ requires a model-dependent calibration of the sound horizon $r_s$

# DESI confirms the Hubble tension without CMB

- Under ΛCDM, the BAO can be combined with BBN estimates of $\omega_b$ to measure $H_0$: 4.5$\sigma$ tension



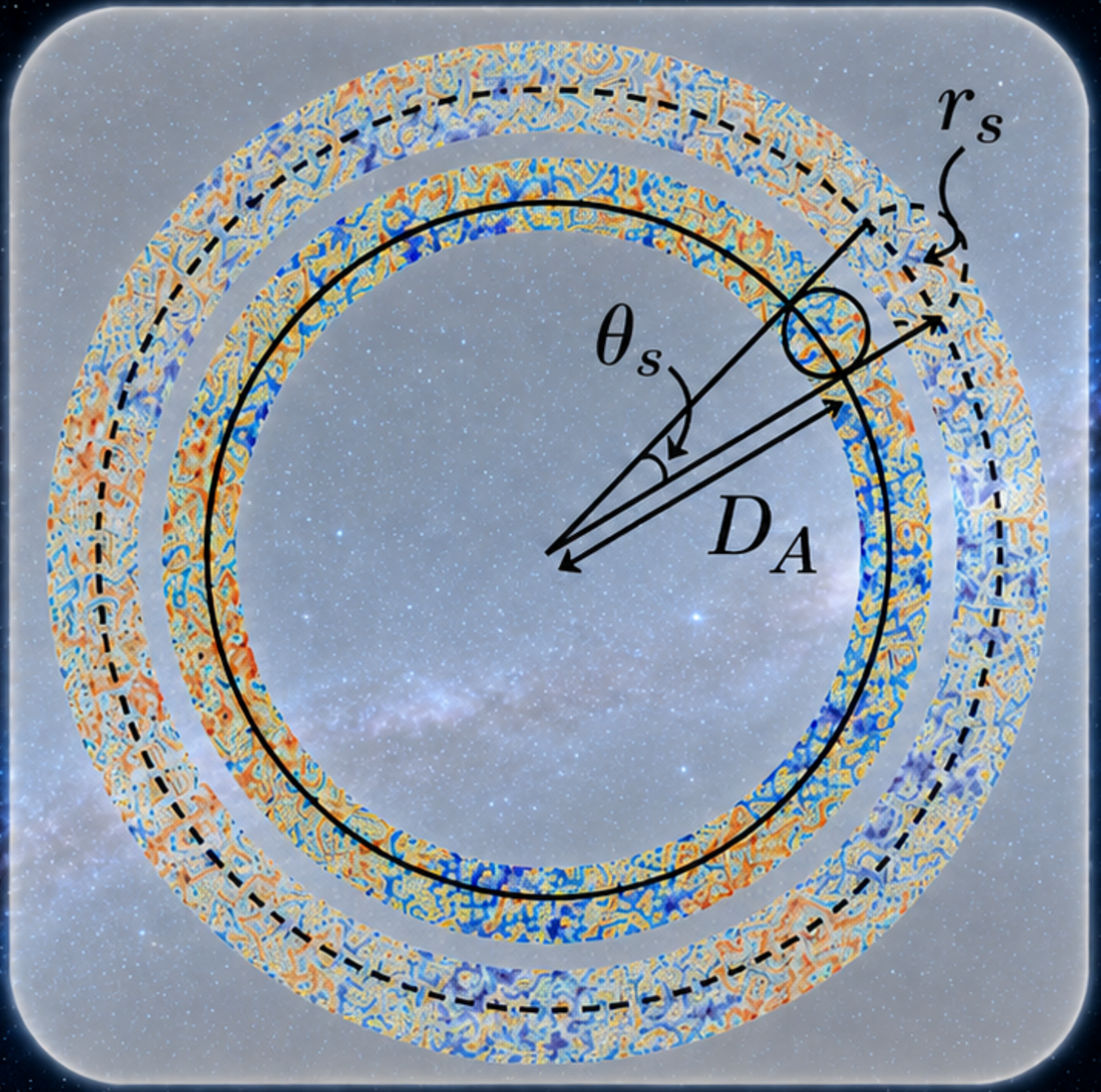




- CMB result is very robust to systematic errors, but cosmological model dependent!

# How to resolve the Hubble tension

## Late Universe models

Exploit the **geometric degeneracy**
to leave $D_A(z_*)$ invariant
$\Rightarrow$ new physics at $z \sim 0 - 1$




## Early Universe Models:

Decrease the
**size of the sound horizon** $r_s$
$\Rightarrow$ new physics at $z \sim 10^3 - 10^4$

# A “late-time” solution to the Hubble tension?

Assumed from LCDM

Measured

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)}$$

$$d_A(z) \equiv \int_0^z \frac{dz'}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + \cdots}}$$

# A “late-time” solution to the Hubble tension?

Assumed from LCDM

Measured

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)}$$

$$d_A(z) \equiv \int_0^z \frac{dz'}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + \cdots}}$$

$H_0 \uparrow \Rightarrow \Omega_X(z) \downarrow$

- ‘phantom dark energy’ $w < -1$, DE-DM interactions, decaying DM, and many more…

*[http://arxiv/insert_your_favorite_ model_here.com]*

# A “late-time” solution to the Hubble tension?

Assumed from LCDM

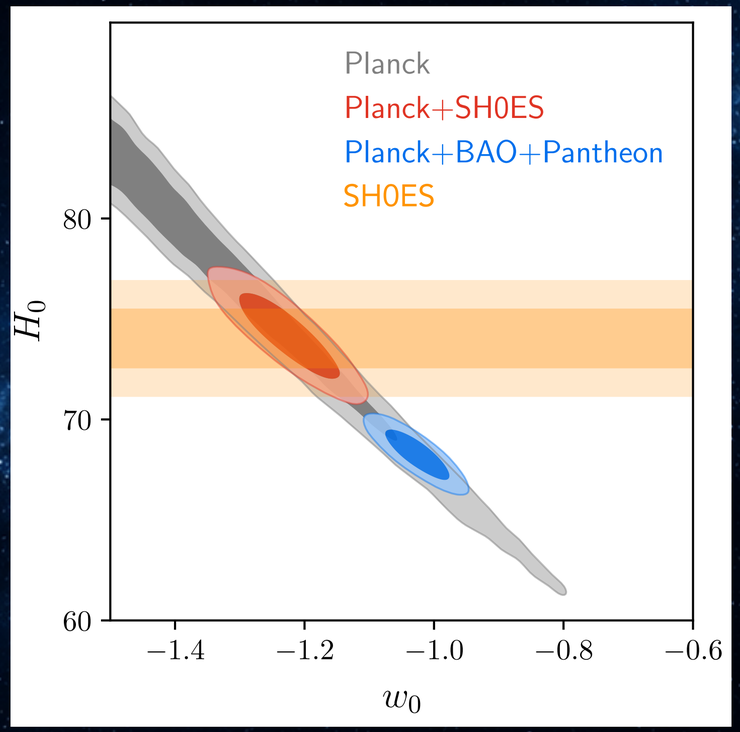
Measured

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)}$$

$$d_A(z) \equiv \int_0^z \frac{dz'}{H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + \cdots}}$$

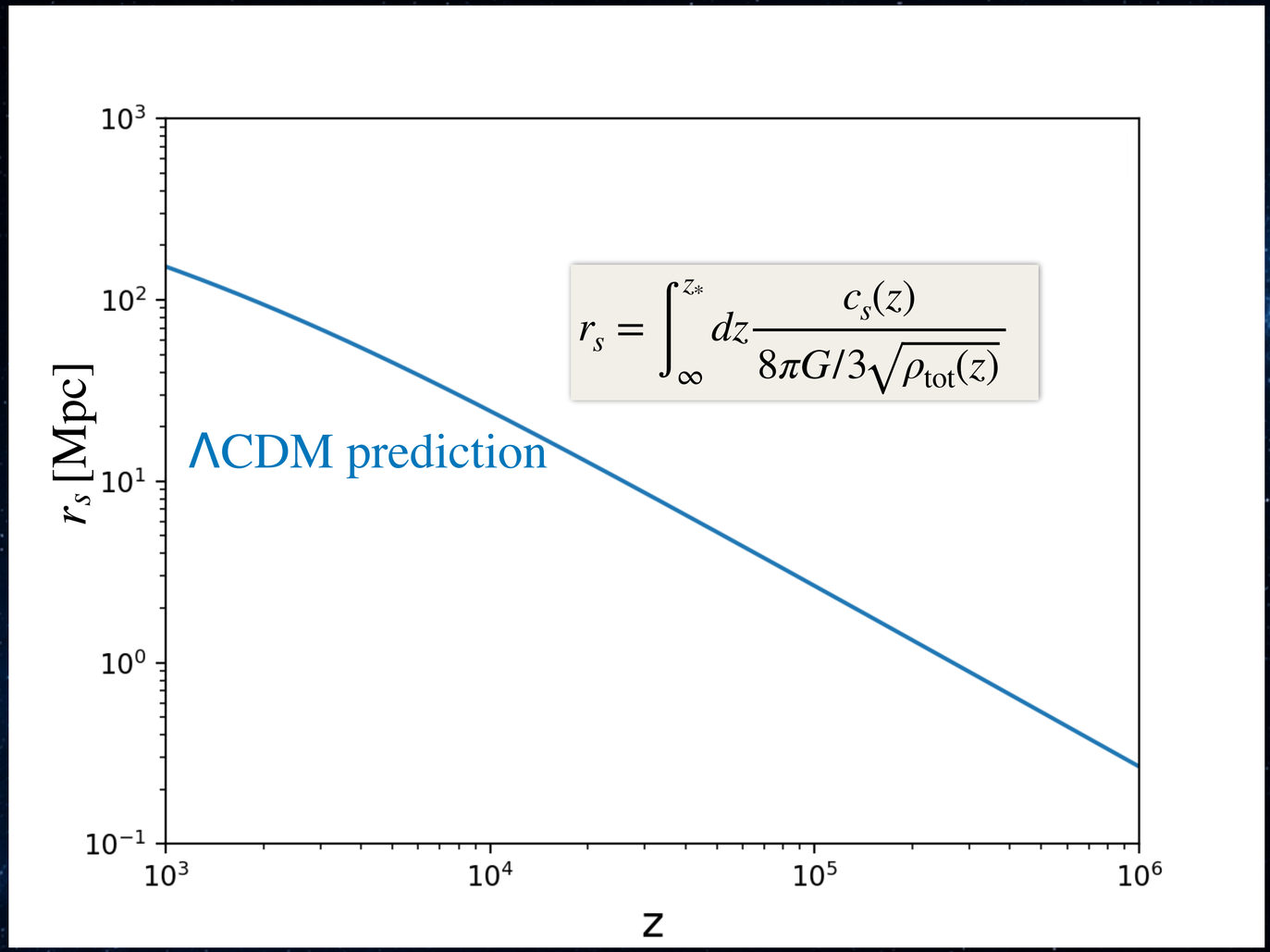
$H_0 \uparrow \Rightarrow \Omega_X(z) \downarrow$

- ‘phantom dark energy’ $w < -1$, DE-DM interactions, decaying DM, and many more…
  *[http://arxiv/insert_your_favorite_ model_here.com]*
- CMB data can easily accommodate a higher $H_0$, but BAO and SN1a excludes simplest models



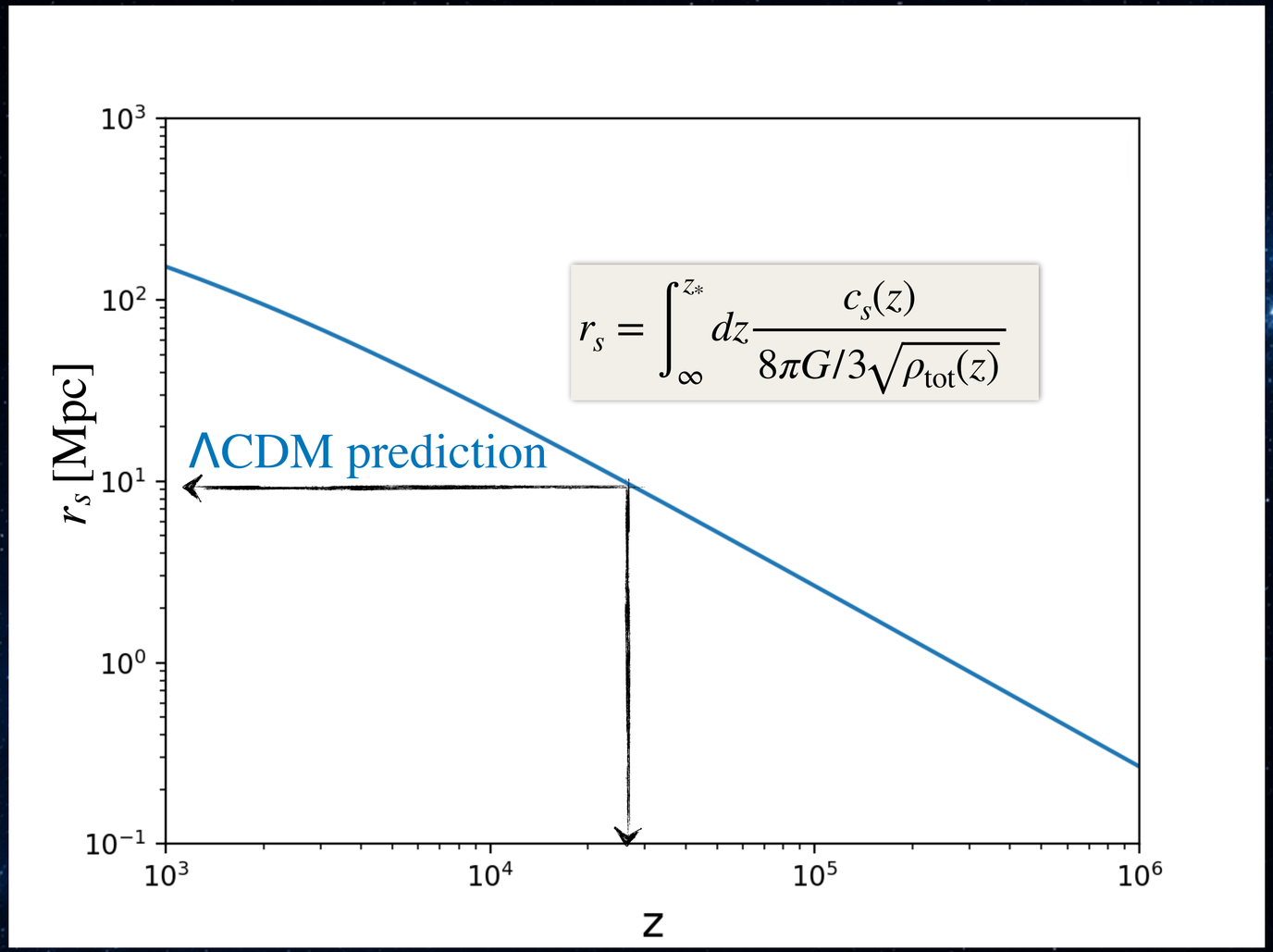
# How to decrease the sound horizon

*Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Schöneberg (VP) ++ 2107.10291*



# How to decrease the sound horizon

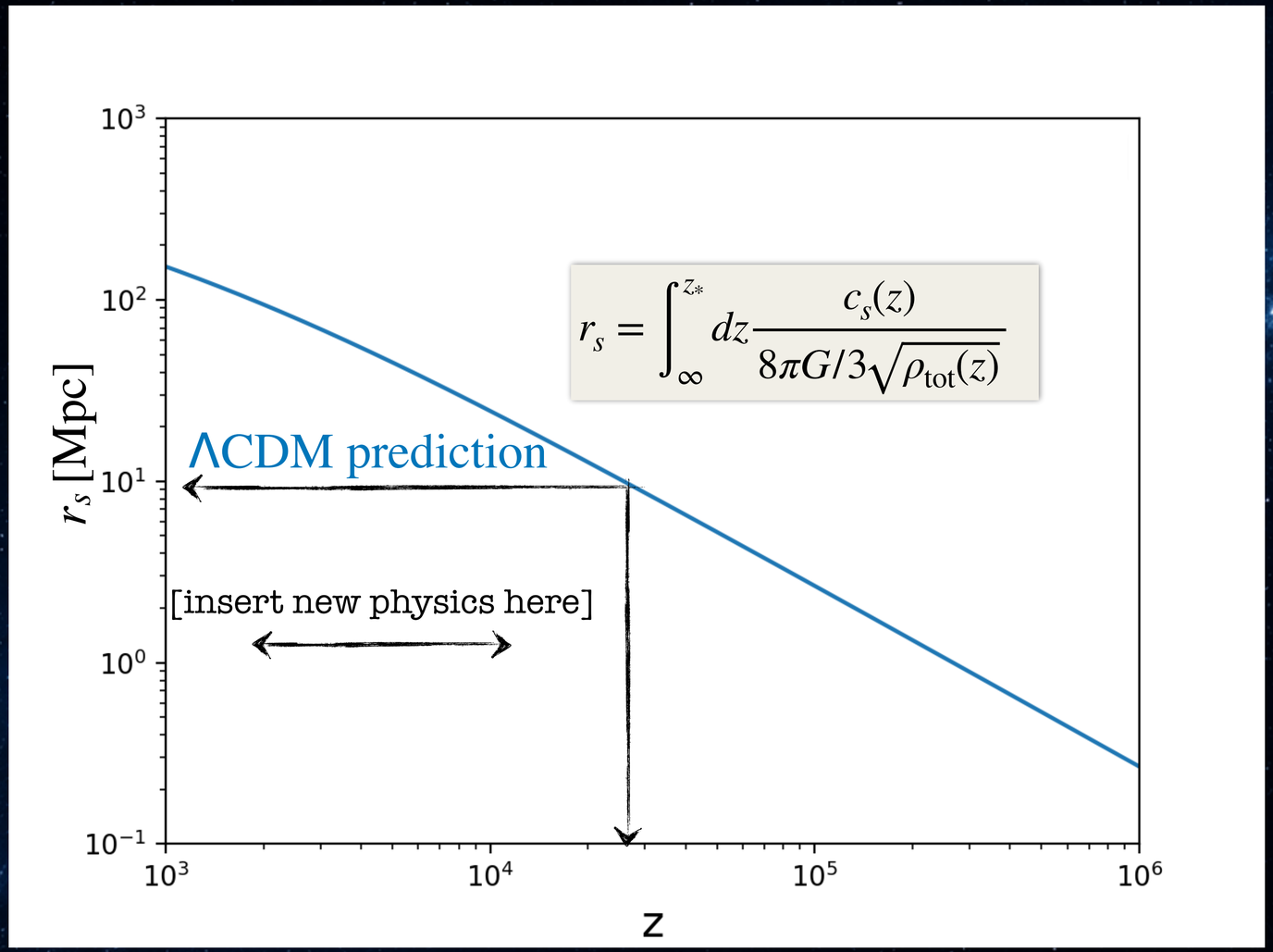
*Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Schöneberg (VP) ++ 2107.10291*




- $r_s$ reaches 10Mpc at $z \sim 25\,000$: new physics at $z \sim 10^3 - 10^4$?

# How to decrease the sound horizon

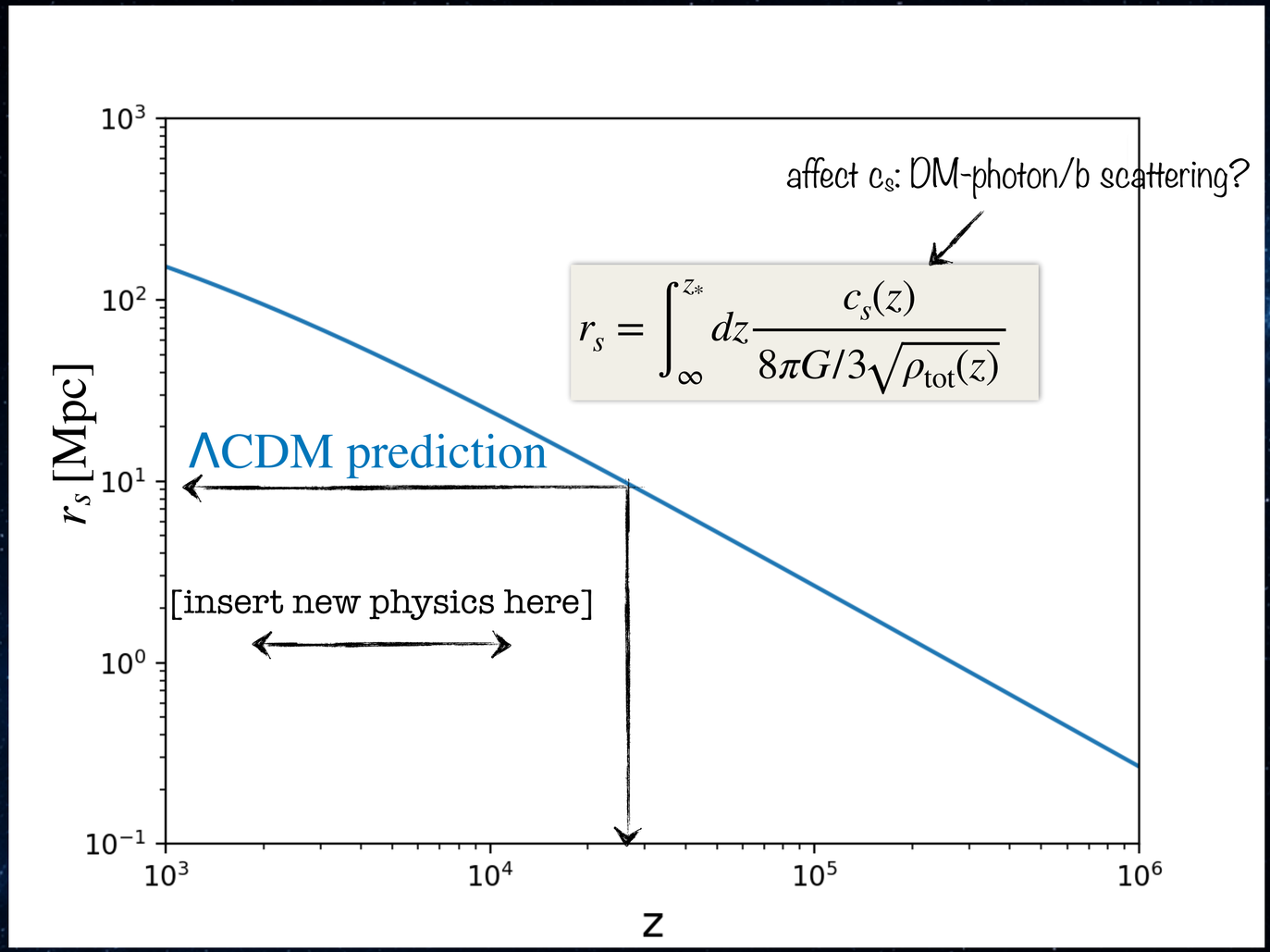
*Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Schöneberg (VP) ++ 2107.10291*




- $r_s$ reaches 10Mpc at $z \sim 25\,000$: new physics at $z \sim 10^3 - 10^4$?

# How to decrease the sound horizon

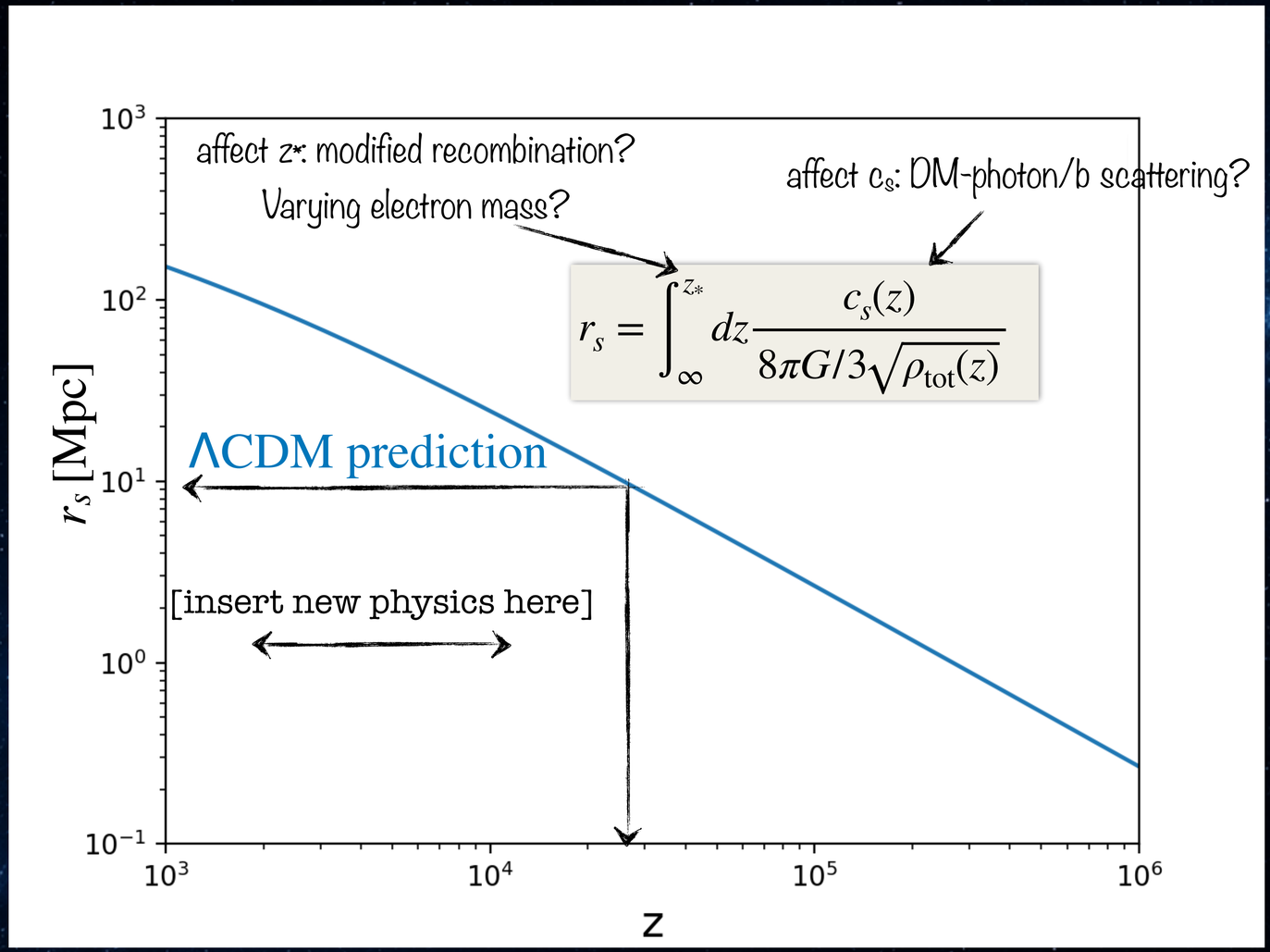
*Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Schöneberg (VP) ++ 2107.10291*




- $r_s$ reaches 10Mpc at $z \sim 25\,000$: new physics at $z \sim 10^3 - 10^4$?

# How to decrease the sound horizon

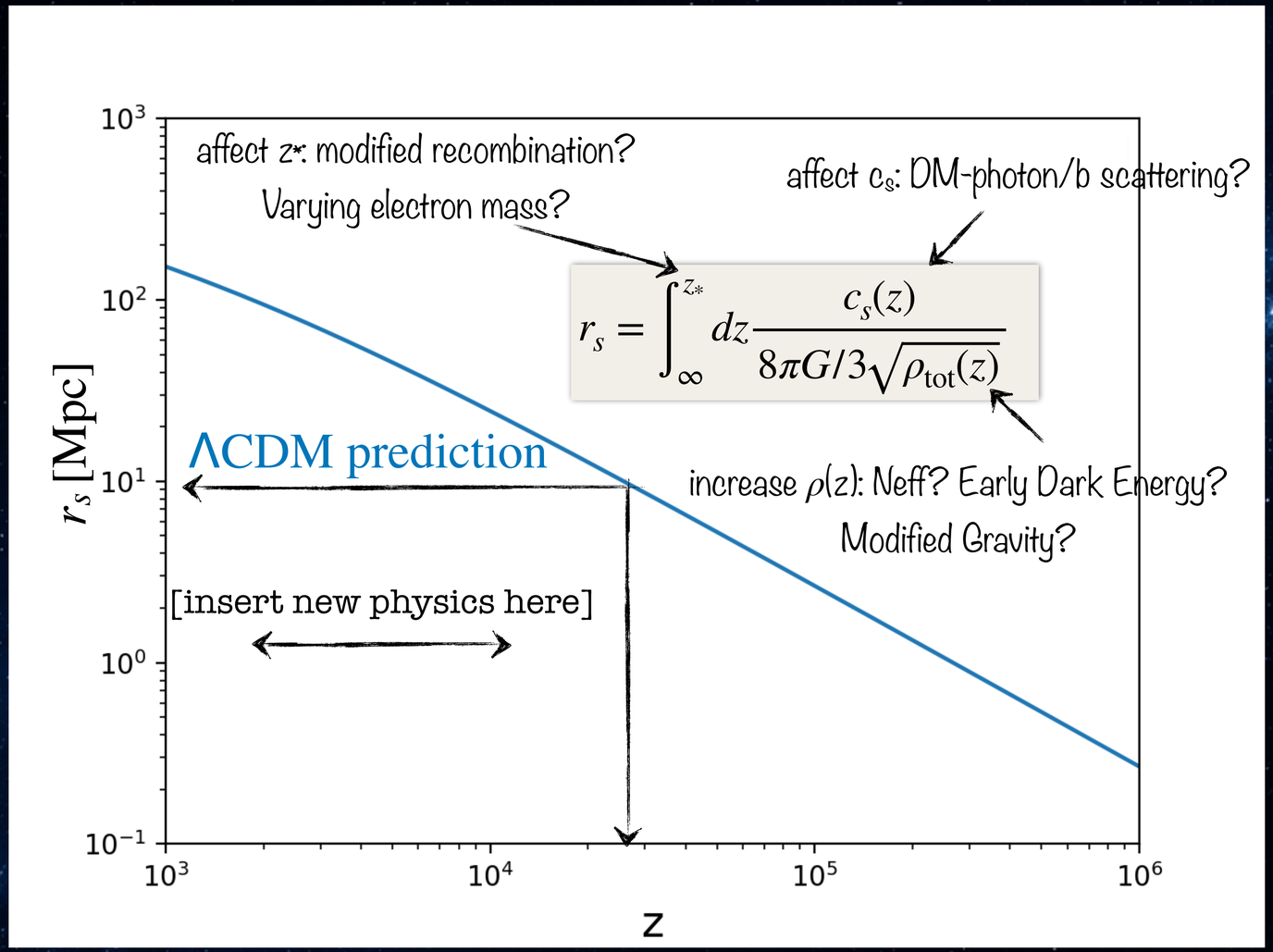
*Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Schöneberg (VP) ++ 2107.10291*




- $r_s$ reaches 10Mpc at $z \sim 25\,000$: new physics at $z \sim 10^3 - 10^4$?

# How to decrease the sound horizon

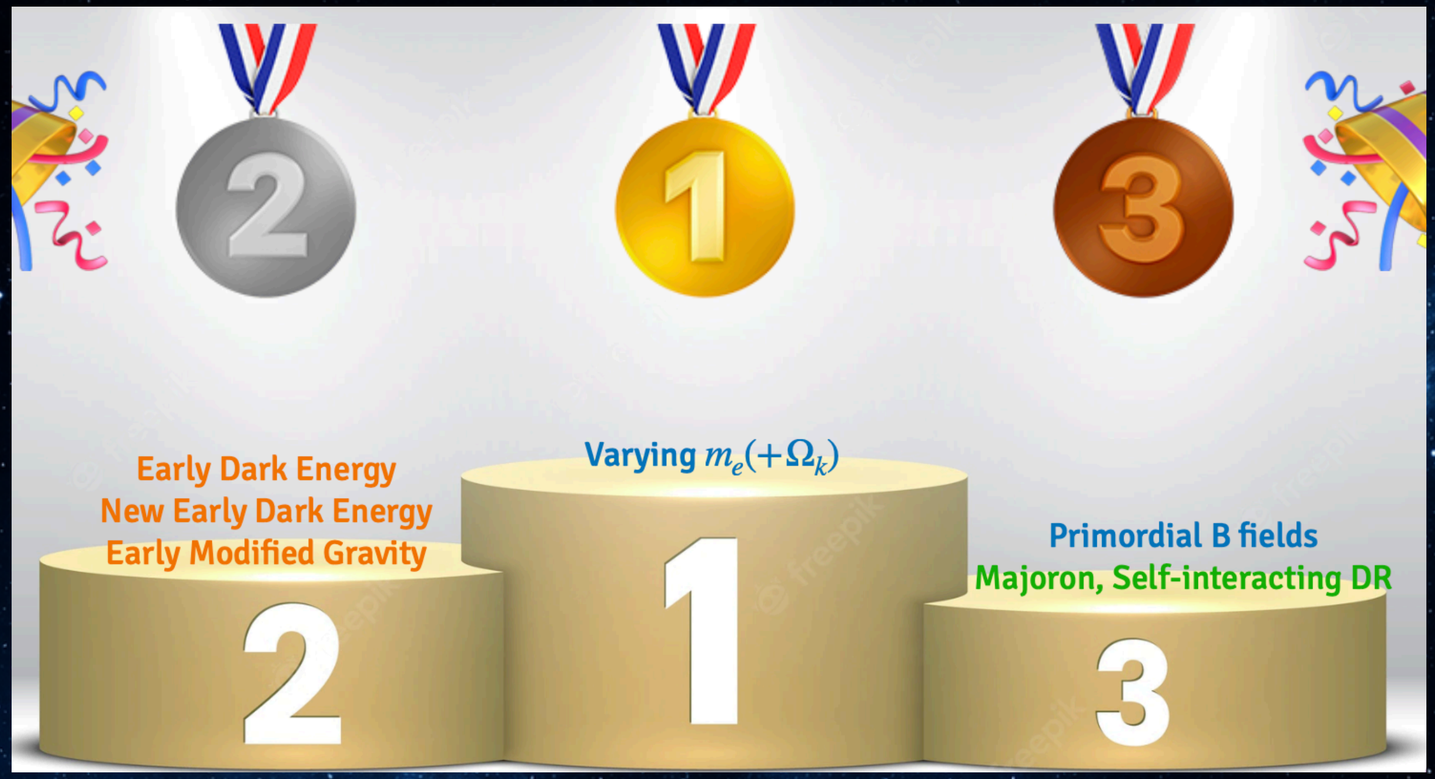
*Bernal++ 1607.05617, Raveri 1902.01366, Aylor++1811.00537 , Knox&Milllea 1908.03663, Schöneberg (VP) ++ 2107.10291*




- $r_s$ reaches 10Mpc at $z \sim 25\,000$: new physics at $z \sim 10^3 - 10^4$?

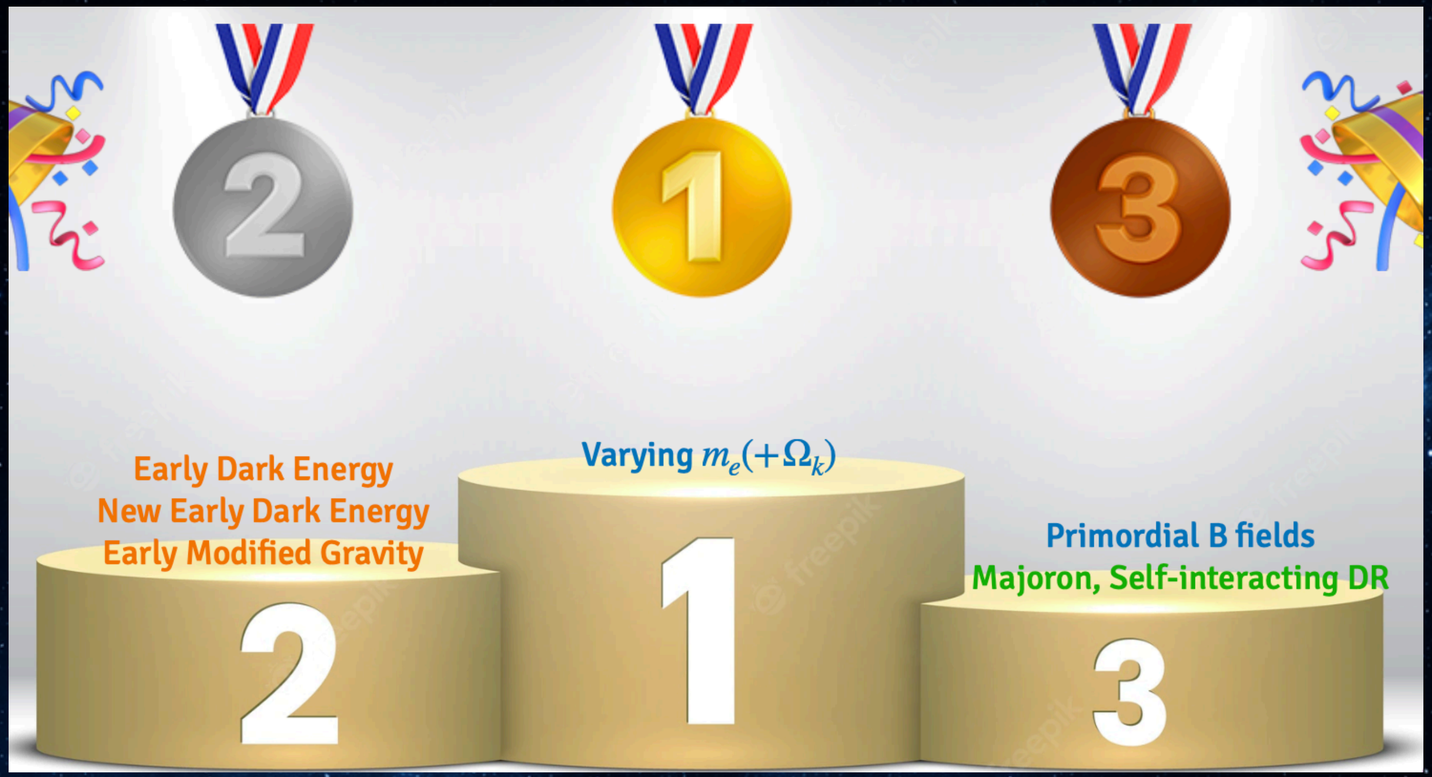
# The $H_0$ olympics: fairly ranking models

*Schöneberg, Abellan, (VP) ++ 2107.10291*



# The $H_0$ olympics: fairly ranking models

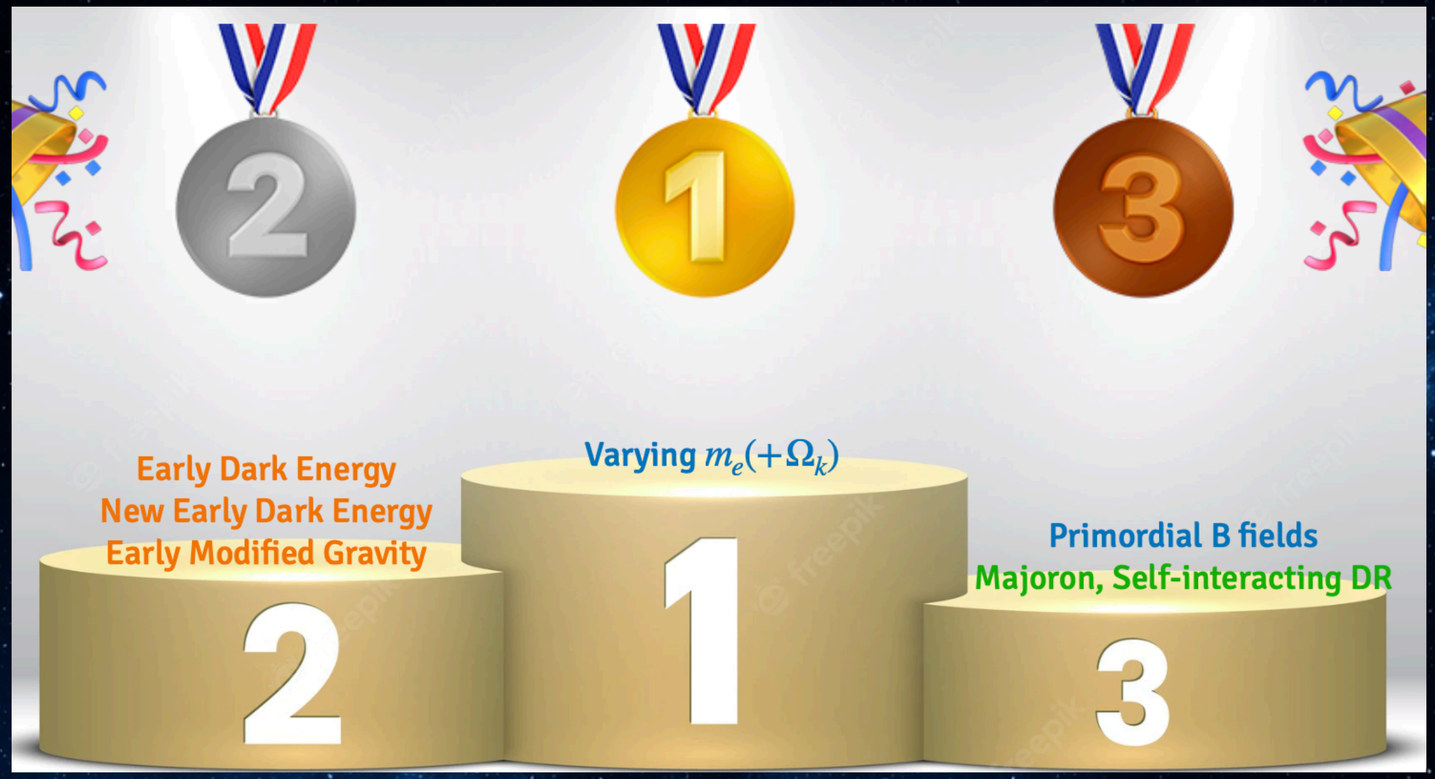
*Schöneberg, Abellan, (VP) ++ 2107.10291*




- Varying electron mass $m_e + \Omega_k$ won the contest: $< 2\sigma$ (GT and DMAP) + strongly favored over ΛCDM

# The $H_0$ olympics: fairly ranking models

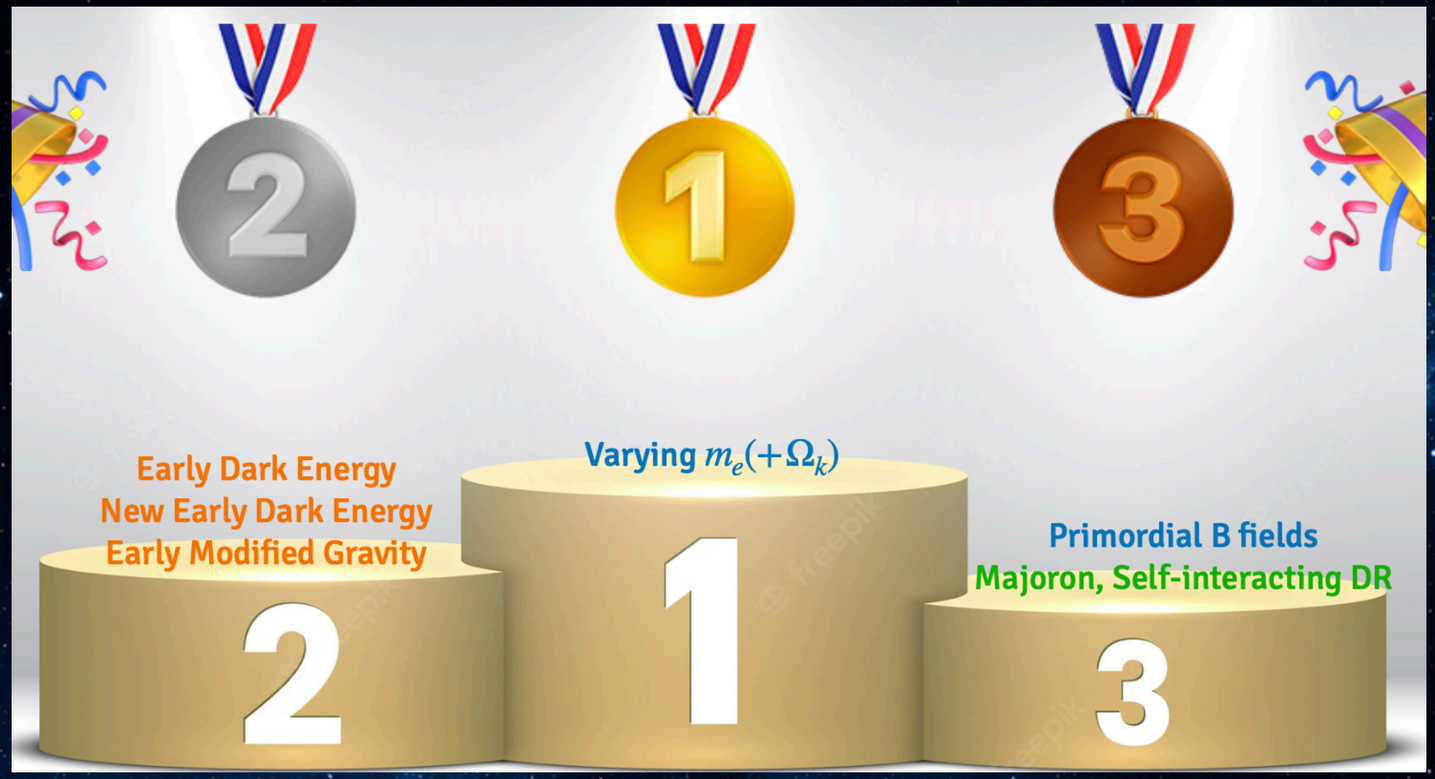
*Schöneberg, Abellan, (VP) ++ 2107.10291*




- Varying electron mass $m_e + \Omega_k$ won the contest: $< 2\sigma$ (GT and DMAP) + strongly favored over ΛCDM
- Early Dark Energy models $< 2\sigma$ DMAP and strongly favored over ΛCDM but disfavored by Gaussian metrics

# The $H_0$ olympics: fairly ranking models

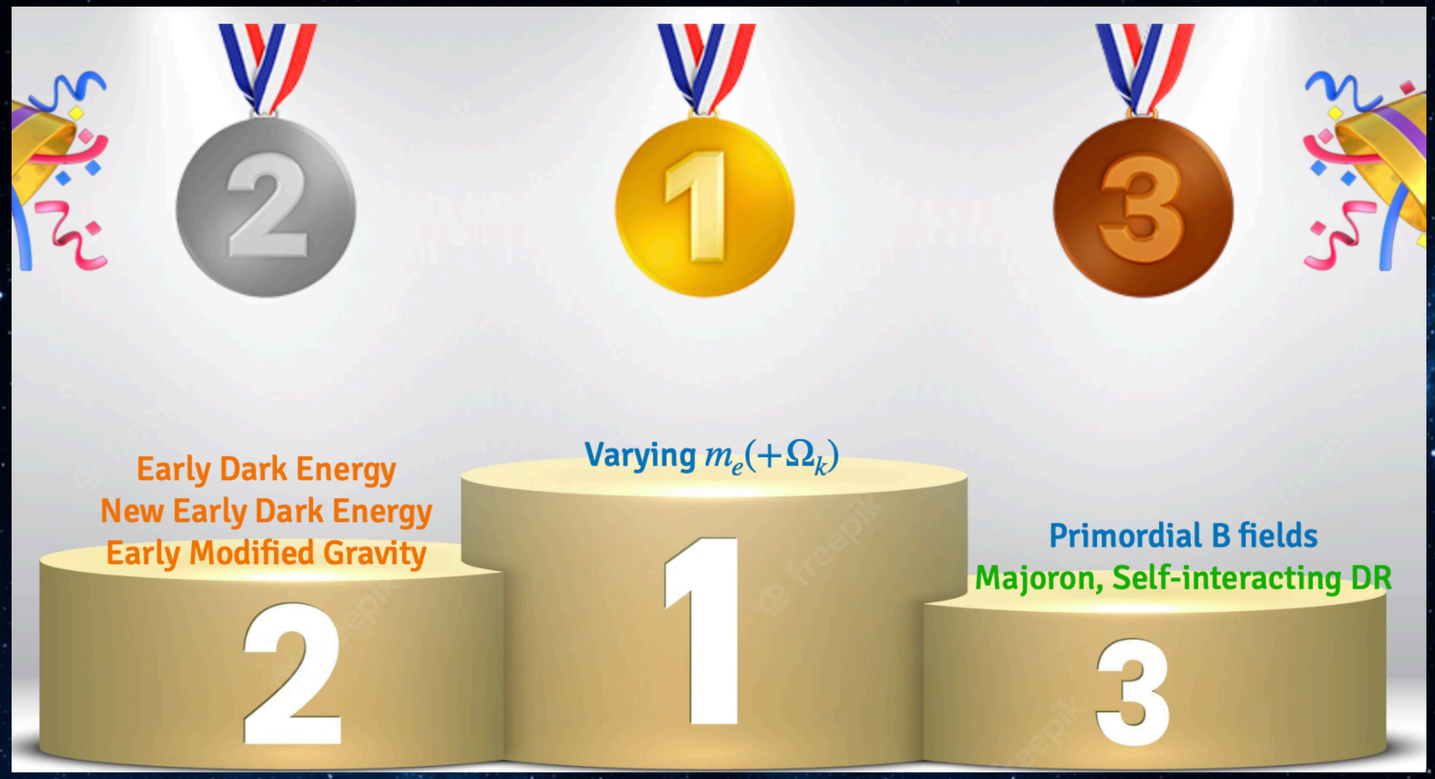
*Schöneberg, Abellan, (VP) ++ 2107.10291*




- Varying electron mass $m_e + \Omega_k$ won the contest: $< 2\sigma$ (GT and DMAP) + strongly favored over ΛCDM
- Early Dark Energy models $< 2\sigma$ DMAP and strongly favored over ΛCDM but disfavored by Gaussian metrics
- Primordial B-fields $> 3\sigma$ GT/DMAP but favored over ΛCDM

# The $H_0$ olympics: fairly ranking models

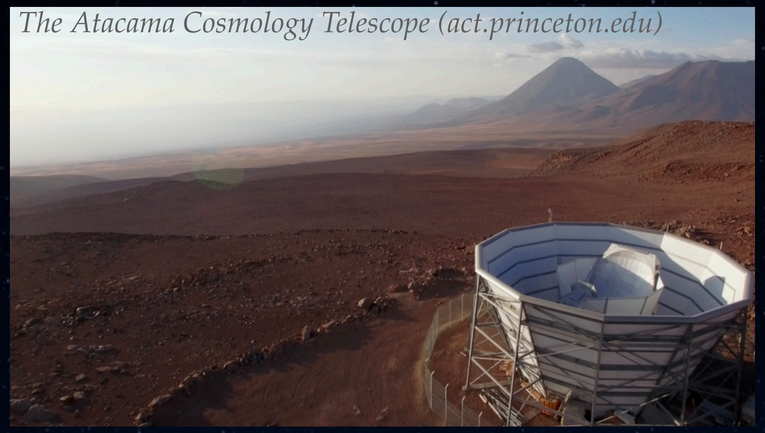
*Schöneberg, Abellan, (VP) ++ 2107.10291*

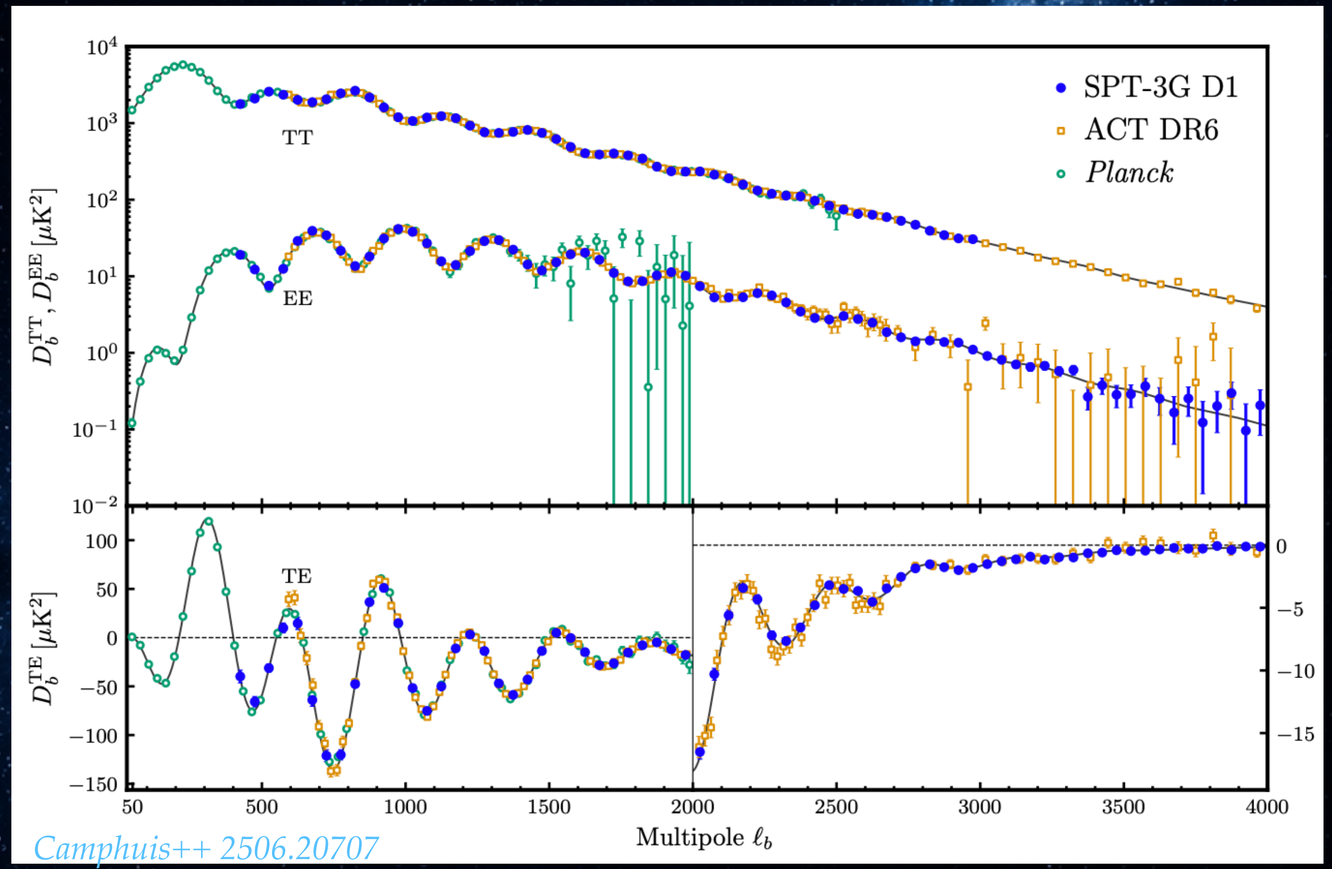



- Varying electron mass $m_e + \Omega_k$ won the contest: $< 2\sigma$ (GT and DMAP) + strongly favored over ΛCDM
- Early Dark Energy models $< 2\sigma$ DMAP and strongly favored over ΛCDM but disfavored by Gaussian metrics
- Primordial B-fields $> 3\sigma$ GT/DMAP but favored over ΛCDM
- Majoron, SIDR $\sim 3\sigma$ and barely favored over ΛCDM

# New CMB data at small scales

- ACT and SPT adds information at $\ell \sim 500 - 4000$ in TT,TE,EE.

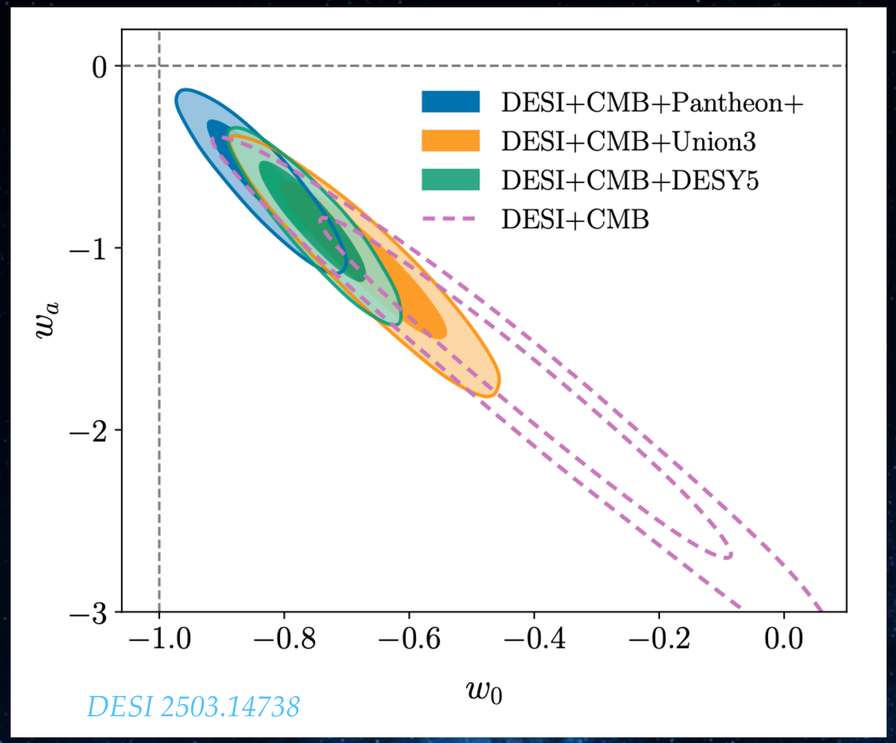




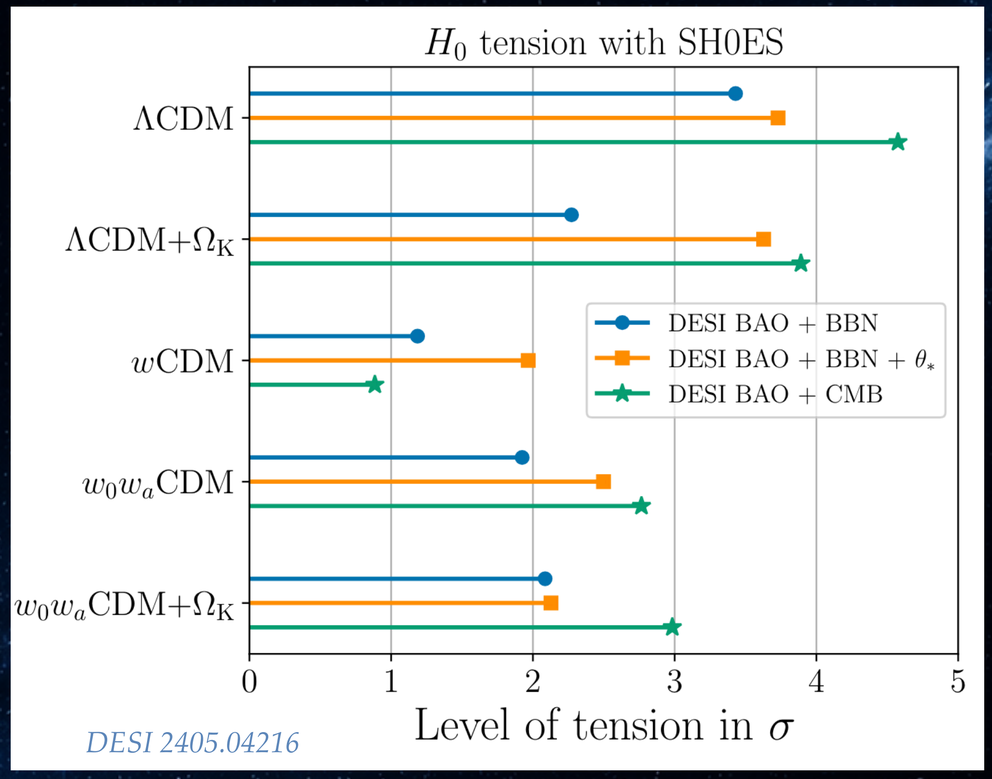
# Hints of evolving Dark Energy in DESI?

*Chevallier, Polarski 2001; Linder 2002*

$$w(a) = w_0 + w_a(1-a)$$




*DESI 2503.14738*




*DESI 2405.04216*

- $2.5-4\sigma$ preference for $w_0 > -1, w_a < 0$

*See Cortês&Liddle 2404.08056, Shlivko&Steinhardt 2405.03933, Berghaus++ 2404.14341, DESI 2405.04216, 2405.13588, Efstathiou 2408.0*

- Can this hint for phantom dark energy help resolve the Hubble tension?

# The $H_0$ world cup: which teams qualified?

## Group L : Late-time models

- Sign-switching $\Lambda_s$CDM [2108.09239]
- Interacting iDM-DE [1704.08342]
- Free $\tau$ reionization (no lowIEE) [2504.21813]
- $w_0 w_a$
- $\Omega_k$

## Group R : Extra-Radiation

- Free-streaming $\Delta N_{\rm eff}$
- Self-interacting $\Delta N_{\rm idr}$
- Step-like $\Delta N_{\rm idr}$ WZDR [2111.00014]
- Radiation-Matter Decoupling DMDR [2508.03795]

AIM FOR $H_0$
WIN THE UNIVERSE

## Group E : Early Dark Energy

- Axion-like EDE [1811.04083]
- New EDE [1910.10739]
- Rock'n'Roll EDE [1904.01016]
- Early Modified Gravity EMG [2011.12934]

## Group M : Modified Recombination

- Varying electron mass $m_e$ [1912.03986]
- 4-parameter modified recombination [2406.10202]

# The competition

- Baseline competition includes:
  - **SPA:** Planck Camspec NPIPE at $\ell < 1000$ (TT) and $\ell < 600$ (TE, EE) ; SPT and ACT at $\ell \sim 500 - 4000$
  - **L:** Planck+ACT+SPT lensing (ACT_planck_baseline + muse SPT3G 2yr)

# The competition

- Baseline competition includes:
  - **SPA:** Planck Camspec NPIPE at $\ell < 1000$ (TT) and $\ell < 600$ (TE, EE) ; SPT and ACT at $\ell \sim 500 - 4000$
  - **L:** Planck+ACT+SPT lensing (ACT_planck_baseline + muse SPT3G 2yr)
  - **B:** DESI DR2 BAO ($\alpha_\perp, \alpha_\parallel$) over $z \sim 0.1 - 4$ (galaxies + Ly-$\alpha$)

# The competition

- Baseline competition includes:
  - **SPA:** Planck Camspec NPIPE at $\ell < 1000$ (TT) and $\ell < 600$ (TE, EE) ; SPT and ACT at $\ell \sim 500 - 4000$
  - **L:** Planck+ACT+SPT lensing (ACT_planck_baseline + muse SPT3G 2yr)
  - **B:** DESI DR2 BAO ($\alpha_\perp, \alpha_\parallel$) over $z \sim 0.1 - 4$ (galaxies + Ly-$\alpha$)
  - **S:** Pantheon+ SN1a data in the range $0.01 < z < 2.3$

# The competition

- Baseline competition includes:
  - **SPA:** Planck Camspec NPIPE at $\ell < 1000$ (TT) and $\ell < 600$ (TE, EE) ; SPT and ACT at $\ell \sim 500 - 4000$
  - **L:** Planck+ACT+SPT lensing (ACT_planck_baseline + muse SPT3G 2yr)
  - **B:** DESI DR2 BAO ($\alpha_\perp, \alpha_\parallel$) over $z \sim 0.1 - 4$ (galaxies + Ly-$\alpha$)
  - **S:** Pantheon+ SN1a data in the range $0.01 < z < 2.3$
  - **M:** SH0ES prior $M_B = -19.253 \pm 0.027$

# The competition

- Baseline competition includes:
  - **SPA:** Planck Camspec NPIPE at $\ell < 1000$ (TT) and $\ell < 600$ (TE, EE) ; SPT and ACT at $\ell \sim 500 - 4000$
  - **L:** Planck+ACT+SPT lensing (ACT_planck_baseline + muse SPT3G 2yr)
  - **B:** DESI DR2 BAO ($\alpha_\perp, \alpha_\parallel$) over $z \sim 0.1 - 4$ (galaxies + Ly-$\alpha$)
  - **S:** Pantheon+ SN1a data in the range $0.01 < z < 2.3$
  - **M:** SH0ES prior $M_B = -19.253 \pm 0.027$

$\Rightarrow$.We perform four sets of runs **SPA-L; SPA-LB; SPA-LBS; SPA-LBS-M**

# The competition

- Baseline competition includes:
  - **SPA:** Planck Camspec NPIPE at $\ell < 1000$ (TT) and $\ell < 600$ (TE, EE) ; SPT and ACT at $\ell \sim 500 - 4000$
  - **L:** Planck+ACT+SPT lensing (ACT_planck_baseline + muse SPT3G 2yr)
  - **B:** DESI DR2 BAO ($\alpha_\perp, \alpha_\parallel$) over $z \sim 0.1 - 4$ (galaxies + Ly-$\alpha$)
  - **S:** Pantheon+ SN1a data in the range $0.01 < z < 2.3$
  - **M:** SH0ES prior $M_B = -19.253 \pm 0.027$

$\Rightarrow$.We perform four sets of runs **SPA-L; SPA-LB; SPA-LBS; SPA-LBS-M**

- Today's competition includes include 4 games
  - All models against SPA-LBS and SPA-LBS-M
  - Early universe models + $w_0 w_a$
  - All models + $\Omega_k$
  - NoACT

# The competition

- Baseline competition includes:
  - **SPA:** Planck Camspec NPIPE at $\ell < 1000$ (TT) and $\ell < 600$ (TE, EE) ; SPT and ACT at $\ell \sim 500 - 4000$
  - **L:** Planck+ACT+SPT lensing (ACT_planck_baseline + muse SPT3G 2yr)
  - **B:** DESI DR2 BAO ($\alpha_\perp, \alpha_\parallel$) over $z \sim 0.1 - 4$ (galaxies + Ly-$\alpha$)
  - **S:** Pantheon+ SN1a data in the range $0.01 < z < 2.3$
  - **M:** SH0ES prior $M_B = -19.253 \pm 0.027$

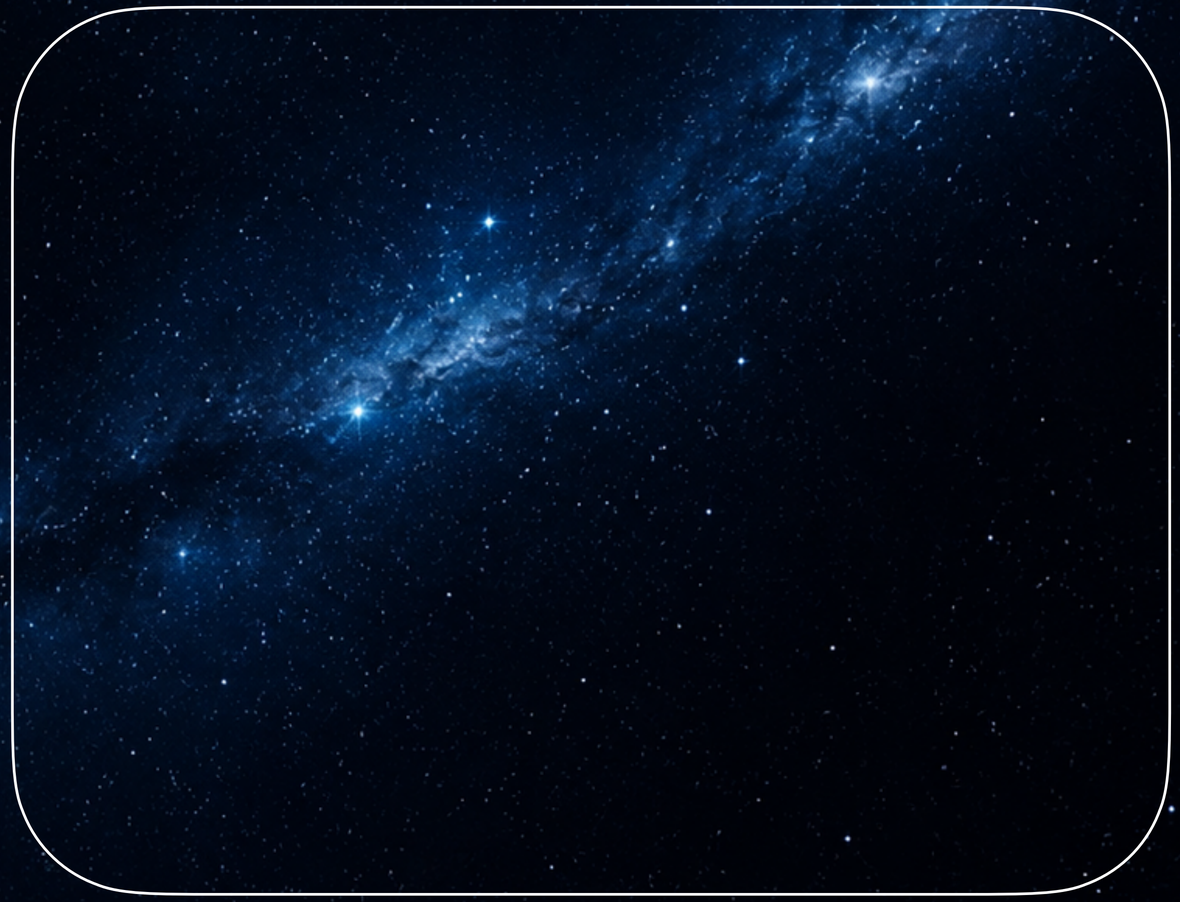
$\Rightarrow$We perform four sets of runs **SPA-L; SPA-LB; SPA-LBS; SPA-LBS-M**

- Today's competition includes include 4 games
  - All models against SPA-LBS and SPA-LBS-M
  - Early universe models + $w_0 w_a$
  - All models + $\Omega_k$
  - NoACT

1. How well does the model resolve the tension?
2. How much is the model favored over ΛCDM with SH0ES ?

# The Referees

- We perform both Bayesian and Frequentist tests: compute both bayesian posteriors and Likelihood profiles



# The Referees

- We perform both Bayesian and Frequentist tests: compute both bayesian posteriors and Likelihood profiles

**Bayesian**

- The parameter shift

$$p(\Delta\theta) = \int p_A(\theta)\, p_B(\theta - \Delta\theta)\, \mathrm{d}\theta\,,$$

$$p(\text{shift is required}) = \int_{p(\Delta\theta) > p(\Delta\theta=0)} p(\Delta\theta)\mathrm{d}\Delta\theta\ .$$

- The Bayes factor

$$\mathrm{BF} = \frac{\mathscr{E}(D\,|\,M_1)}{\mathscr{E}(D\,|\,M_2)} \qquad \mathscr{E}(D\,|\,M) = \int \mathscr{L}(D\,|\,\theta, M)\, \pi(\theta\,|\,M)\, \mathrm{d}\theta$$

# The Referees

- We perform both Bayesian and Frequentist tests: compute both bayesian posteriors and Likelihood profiles

## Bayesian

- The parameter shift

$$p(\Delta\theta) = \int p_A(\theta)\, p_B(\theta - \Delta\theta)\, \mathrm{d}\theta\,,$$

$$p(\text{shift is required}) = \int_{p(\Delta\theta) > p(\Delta\theta=0)} p(\Delta\theta)\mathrm{d}\Delta\theta\ .$$

- The Bayes factor

$$\mathrm{BF} = \frac{\mathscr{E}(D\,|\,M_1)}{\mathscr{E}(D\,|\,M_2)} \qquad \mathscr{E}(D\,|\,M) = \int \mathscr{L}(D\,|\,\theta, M)\, \pi(\theta\,|\,M)\, \mathrm{d}\theta$$

## Frequentist

- maximum a posteriori distance

$$\Delta_{\mathrm{DMAP}} = \sqrt{\chi^2_{\mathrm{min},A+B} - \chi^2_{\mathrm{min},A} - \chi^2_{\mathrm{min},B}}$$

- Akaike information criterion

$$\mathrm{AIC} = \Delta\chi^2_{\mathrm{min},A+B} + 2\,N_{\mathrm{param}}$$

# The Referees

- We perform both Bayesian and Frequentist tests: compute both bayesian posteriors and Likelihood profiles

*See Raveri&Hu 1806.04649*

**Bayesian**

- The parameter shift

$$p(\Delta\theta) = \int p_A(\theta)\, p_B(\theta - \Delta\theta)\, \mathrm{d}\theta\,,$$

$$p(\text{shift is required}) = \int_{p(\Delta\theta) > p(\Delta\theta=0)} p(\Delta\theta)\mathrm{d}\Delta\theta\ .$$

- The Bayes factor

$$\mathrm{BF} = \frac{\mathcal{E}(D\,|\,M_1)}{\mathcal{E}(D\,|\,M_2)} \qquad \mathcal{E}(D\,|\,M) = \int \mathcal{L}(D\,|\,\theta, M)\, \pi(\theta\,|\,M)\, \mathrm{d}\theta$$

**Frequentist**

- maximum a posteriori distance

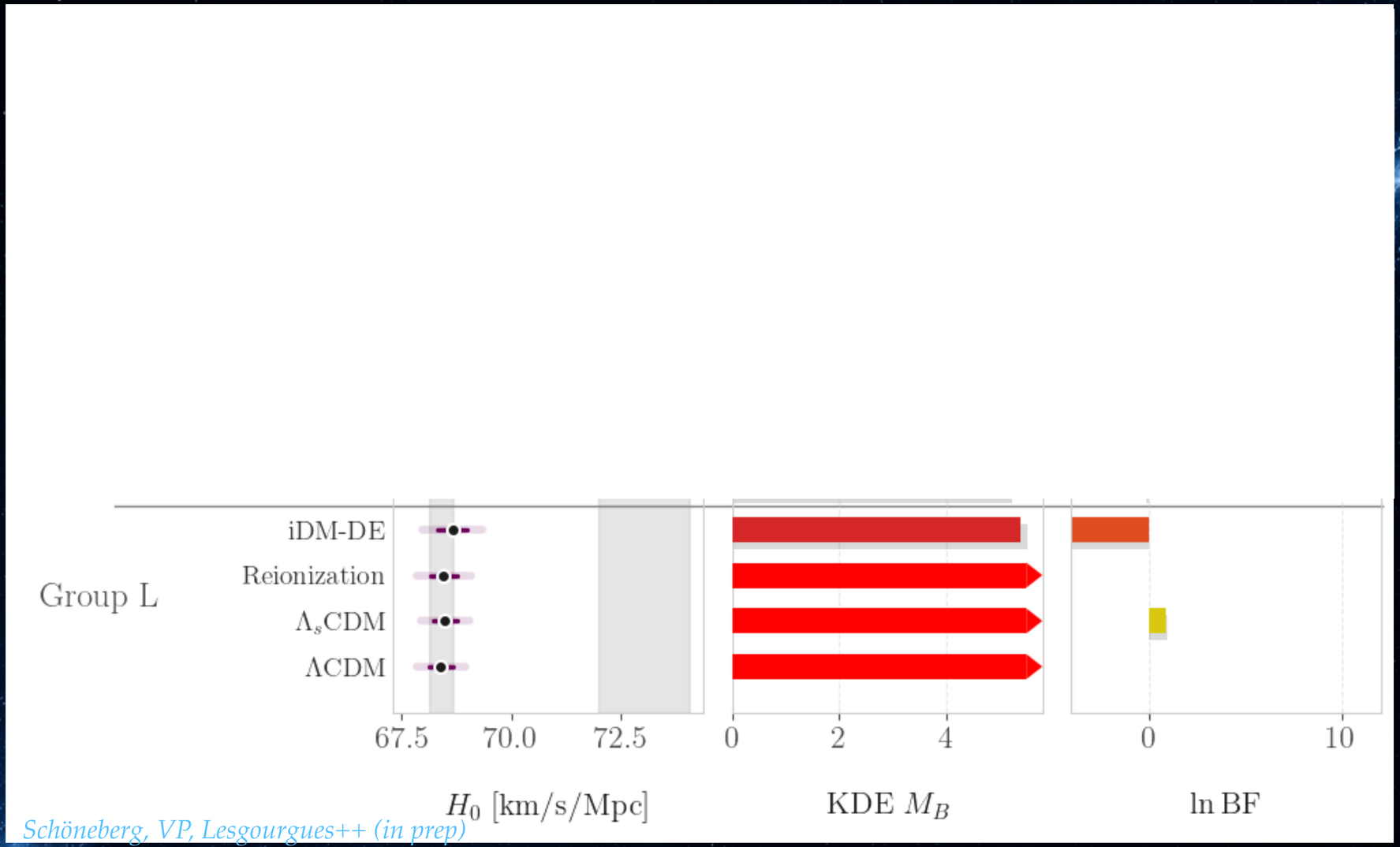
$$\Delta_{\mathrm{DMAP}} = \sqrt{\chi^2_{\mathrm{min},A+B} - \chi^2_{\mathrm{min},A} - \chi^2_{\mathrm{min},B}}$$

- Akaike information criterion

$$\mathrm{AIC} = \Delta\chi^2_{\mathrm{min},A+B} + 2\,N_{\mathrm{param}}$$

**Today I will present Bayesian results**

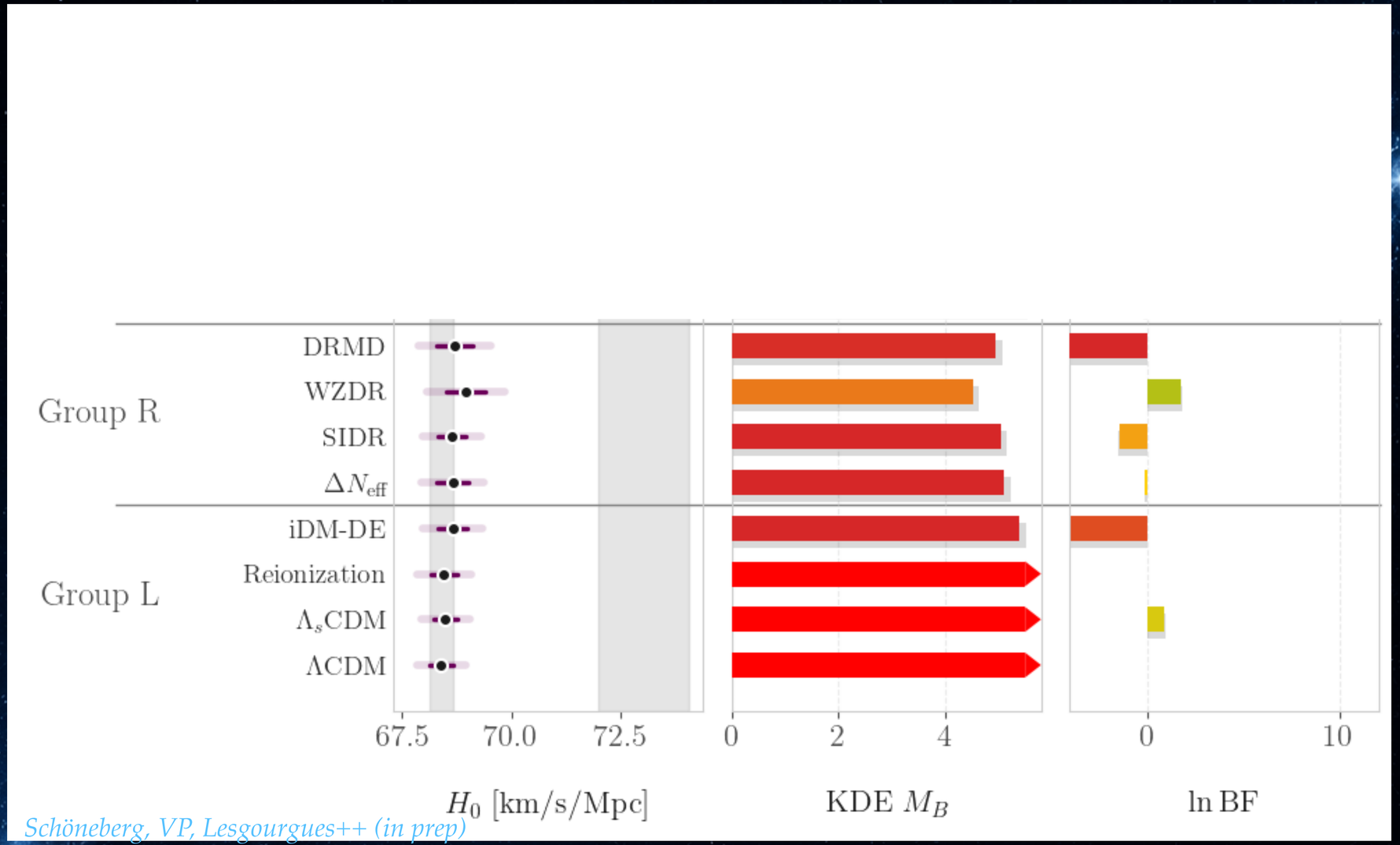
# Group stage opening game: SPA–LBS




*Schöneberg, VP, Lesgourgues++ (in prep)*

- Late-time models cannot resolve the tension: they may change $H_0$ but cannot change the magnitude calibration $M_b$

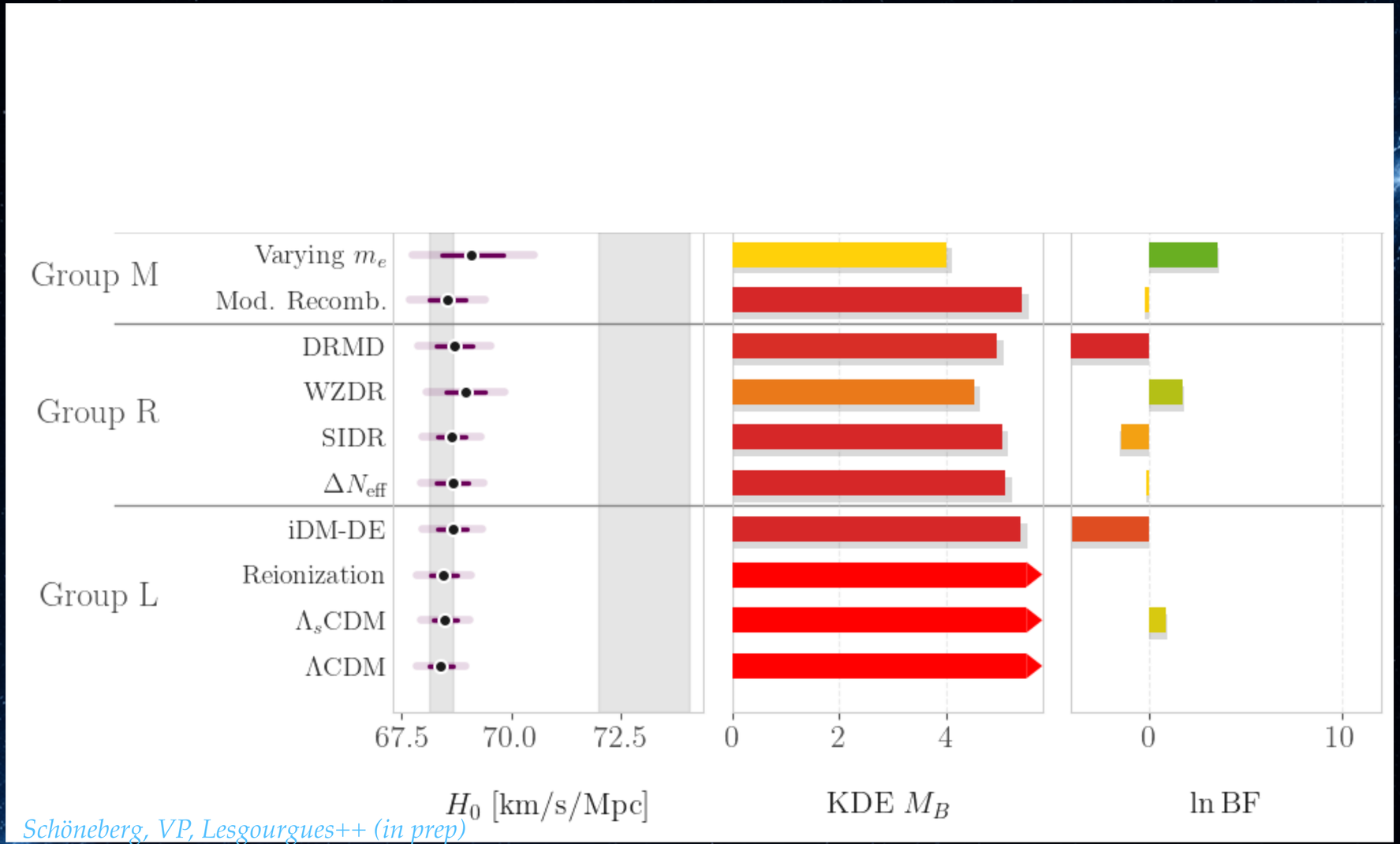
# Group stage opening game: SPA–LBS




*Schöneberg, VP, Lesgourgues++ (in prep)*

- Radiation models cannot resolve the tension: they are strongly constrained by ACT data

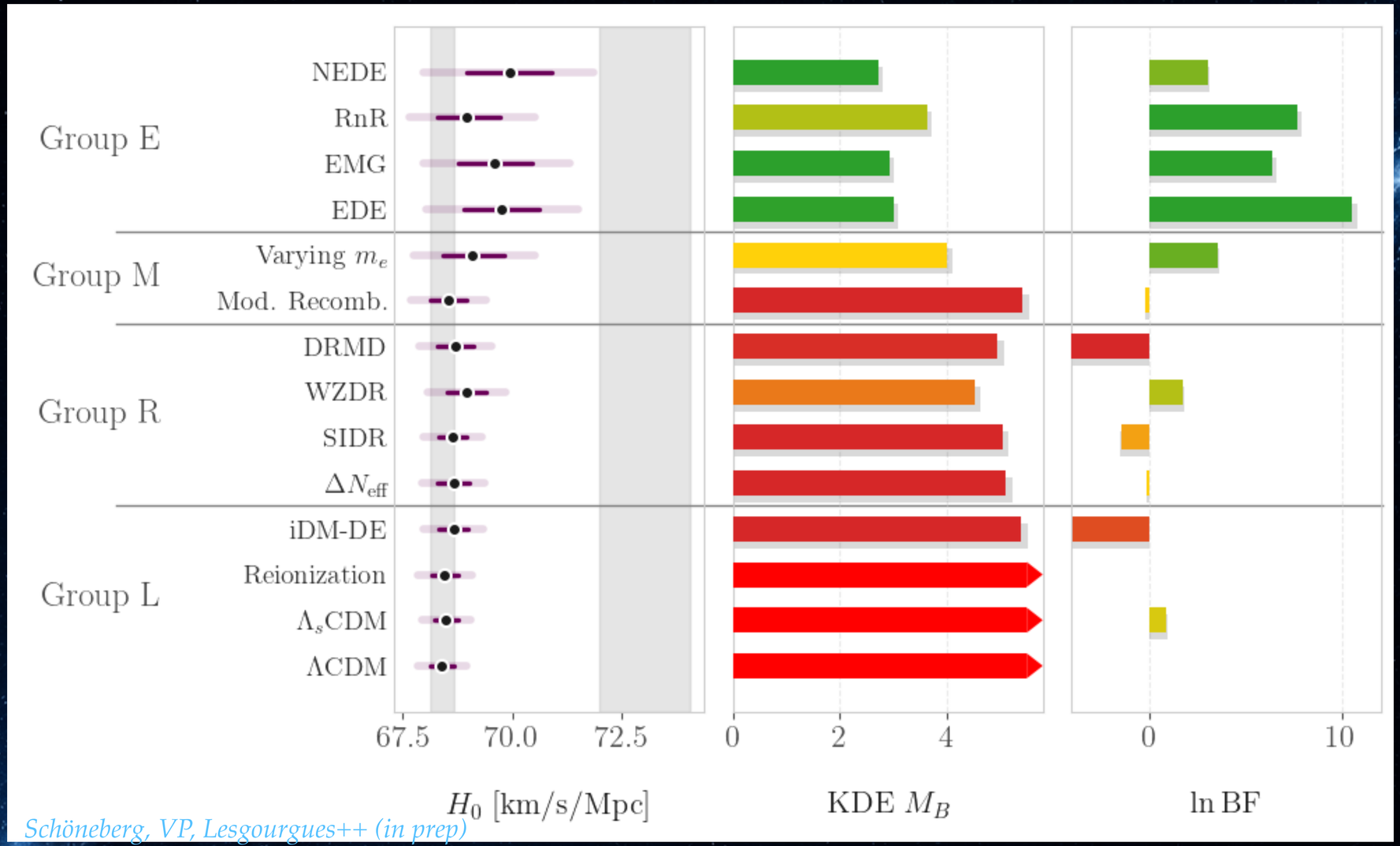
# Group stage opening game: SPA–LBS




*Schöneberg, VP, Lesgourgues++ (in prep)*

- ModRec models cannot fully resolve the tension: they are strongly constrained by ACT data

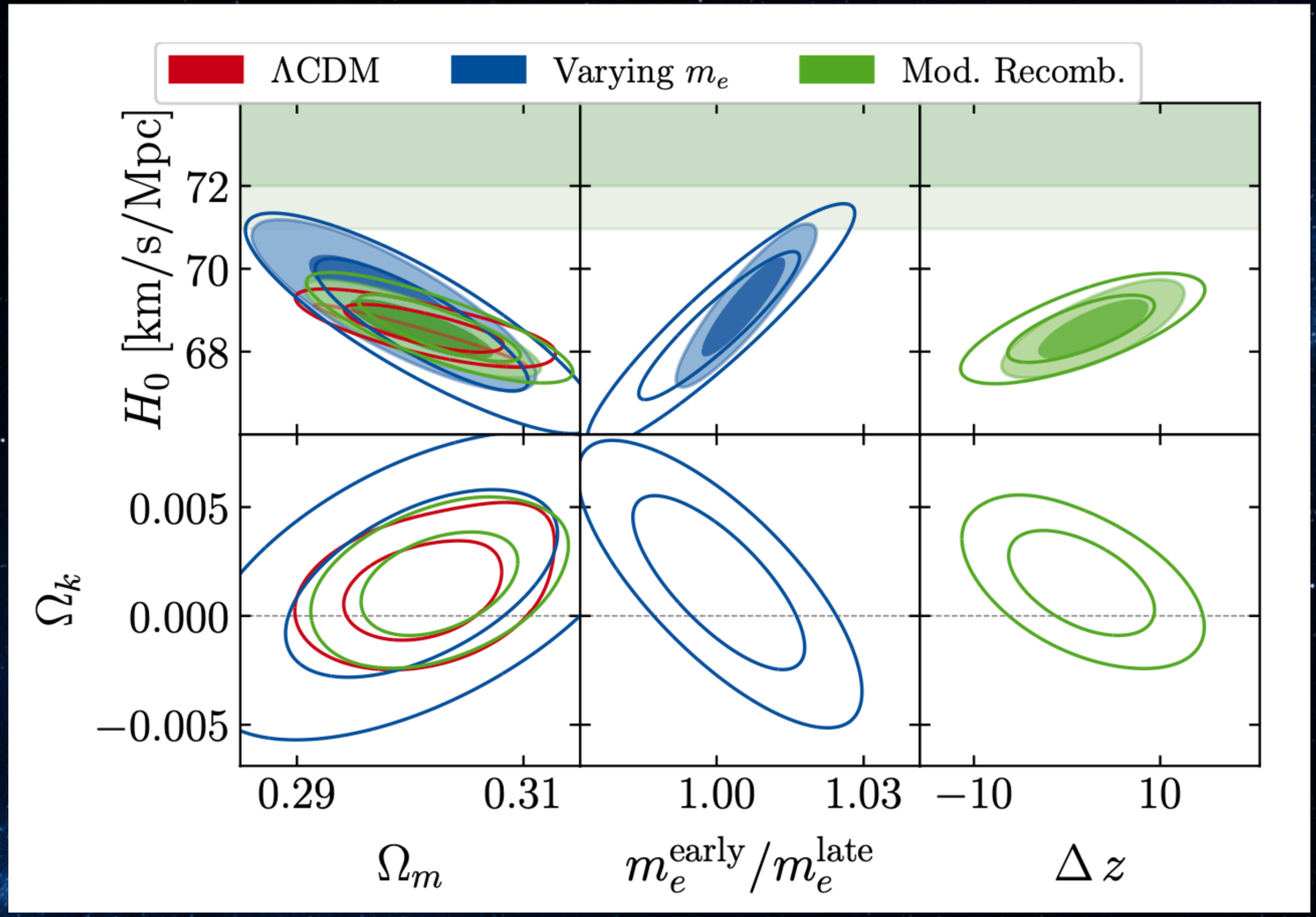
# Group stage opening game: SPA–LBS




*Schöneberg, VP, Lesgourgues++ (in prep)*

- EDE models can reduce the tension to 2.5-3$\sigma$: this is better than with NPIPE and SDSS data (~3.5-4$\sigma$) tension

# Group stage second game : curvature $\Omega_k$



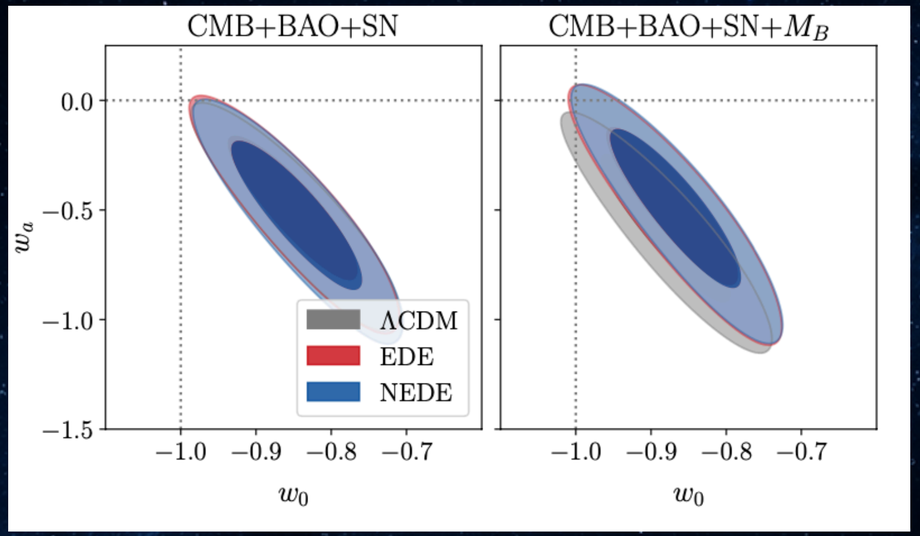

- Group M models and in particular varying electron mass benefits most from non-zero curvature

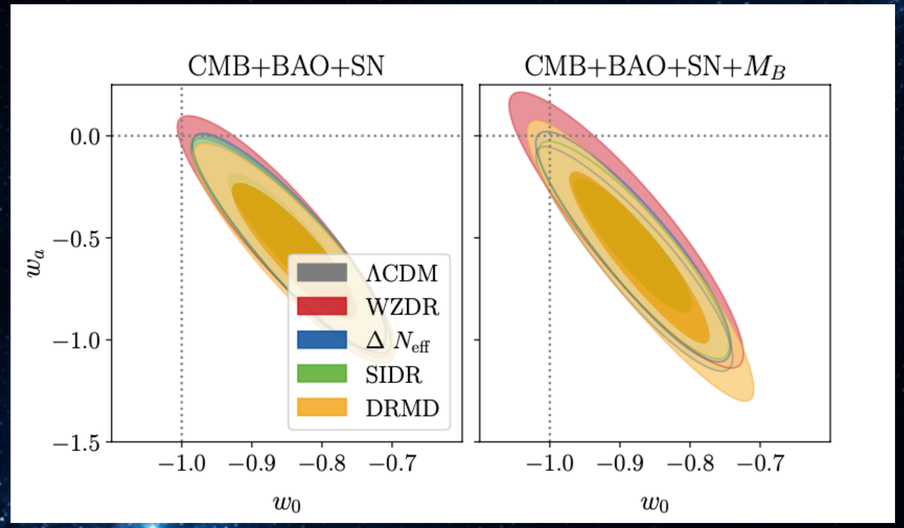
*See also Sekiguchi++2007.03381*

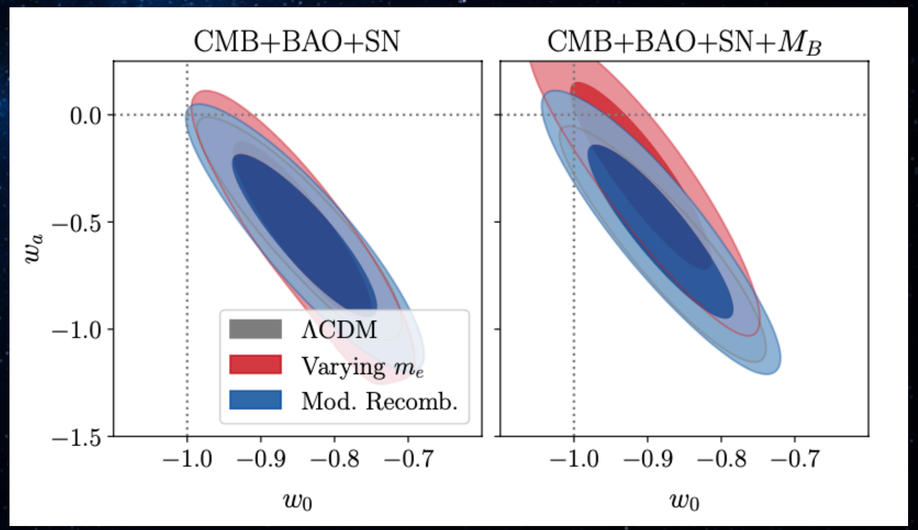
# Group stage third game: $w_0 w_a$

- CMB+DESI favors DDE: how does these models affect this?
- Electron mass / WZDR / EDE / NEDE tend to shift $w_a \to 0$
- Early universe solution + quintessence?

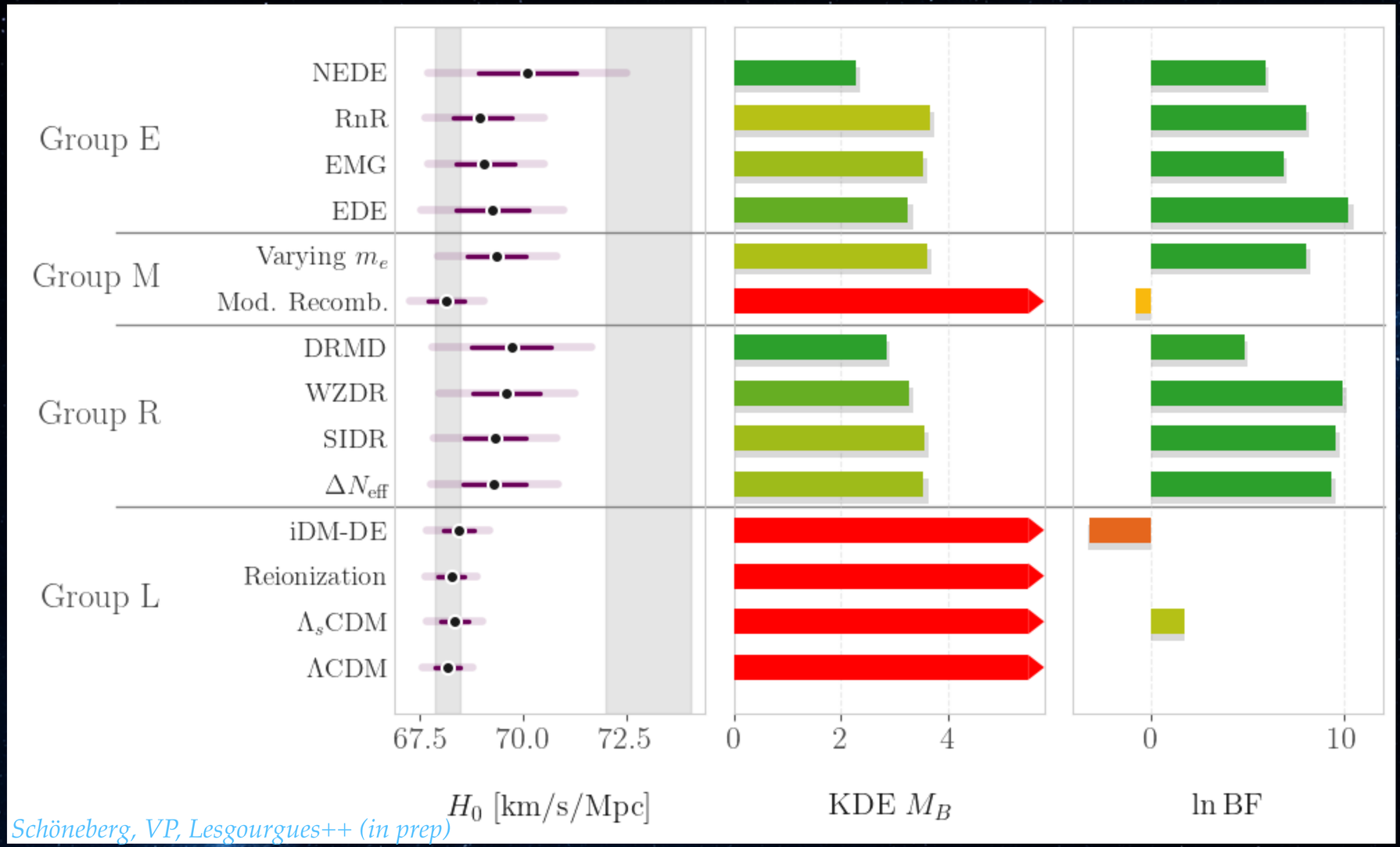
*Lynch++ 2406.10202; Chaussidon++ 2503.24343 ; Khalife ++ 2507.23355; Javeri++ 2604.08530*



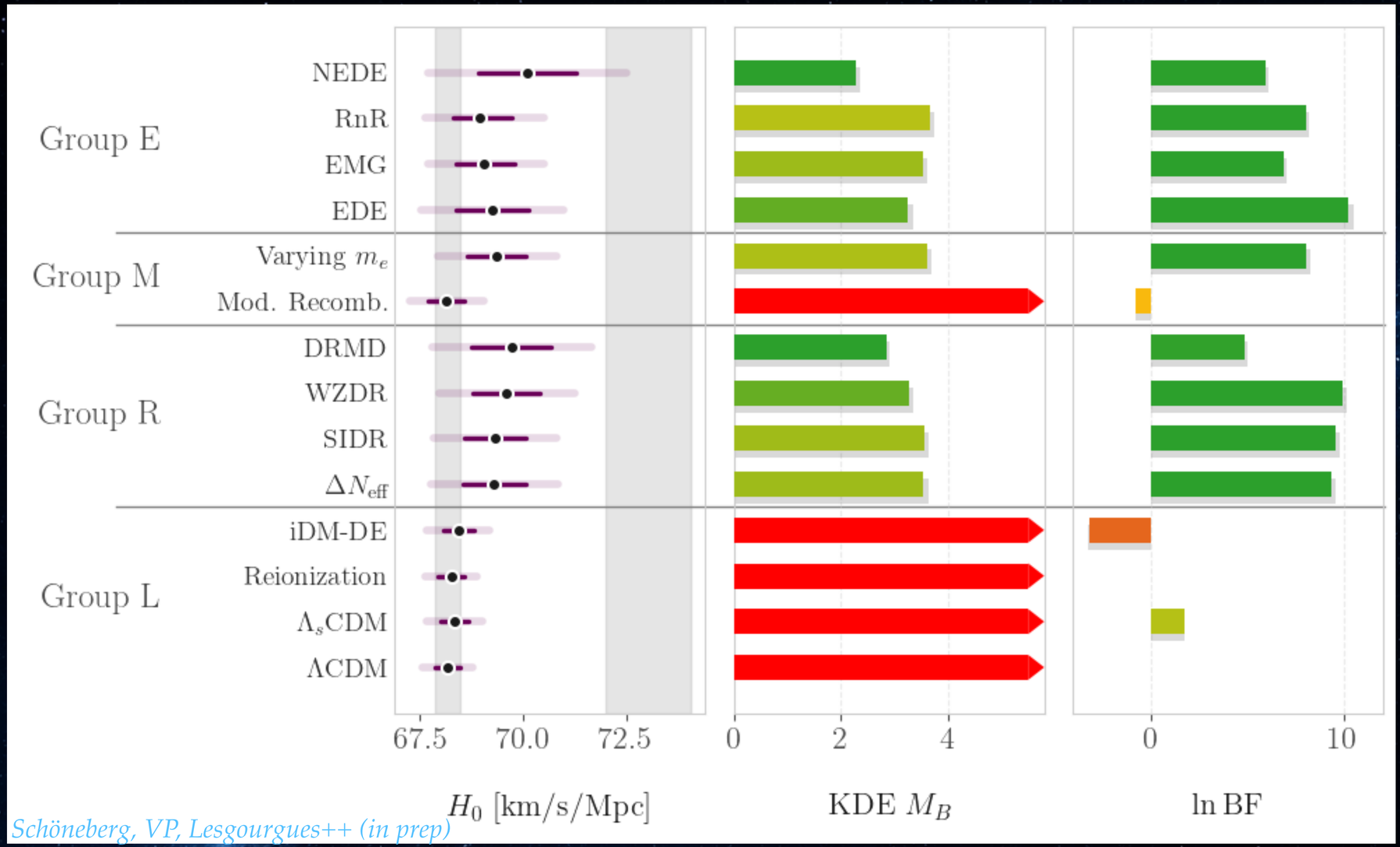
# Final chance re-draft: Removing ACT



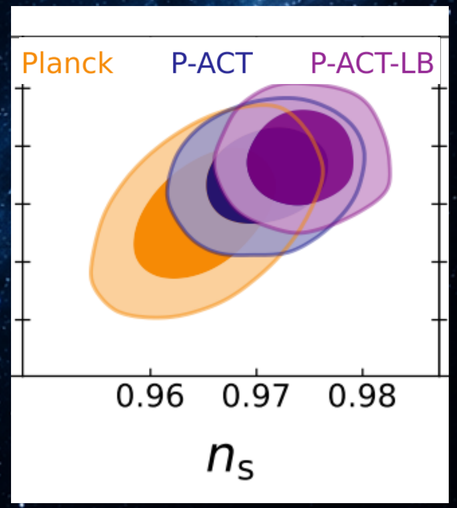

*Schöneberg, VP, Lesgourgues++ (in prep)*

- Strong impact of ACT on radiation and varying $m_e$: they perform very well without ACT

# Final chance re-draft: Removing ACT

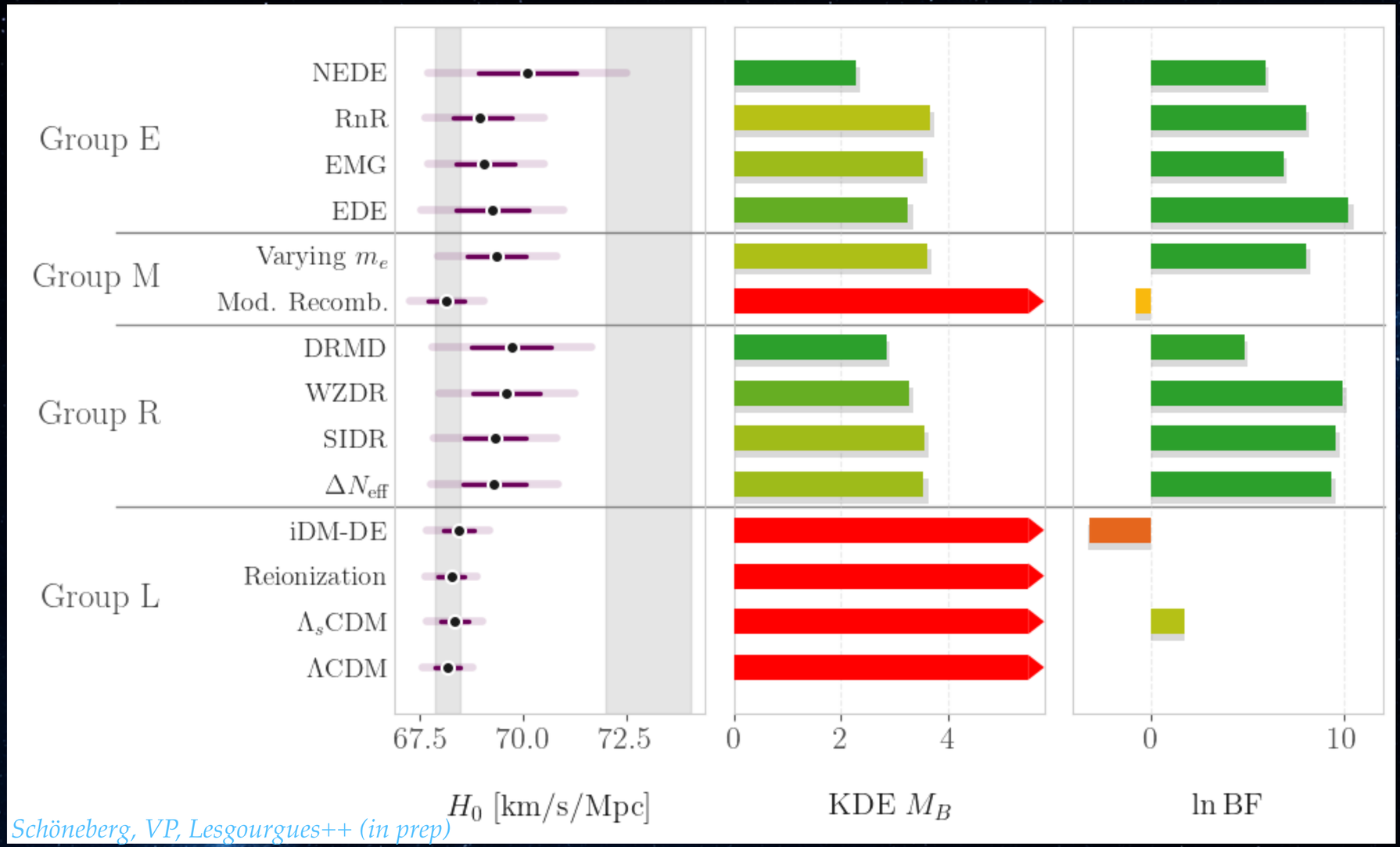



*Schöneberg, VP, Lesgourgues++ (in prep)*

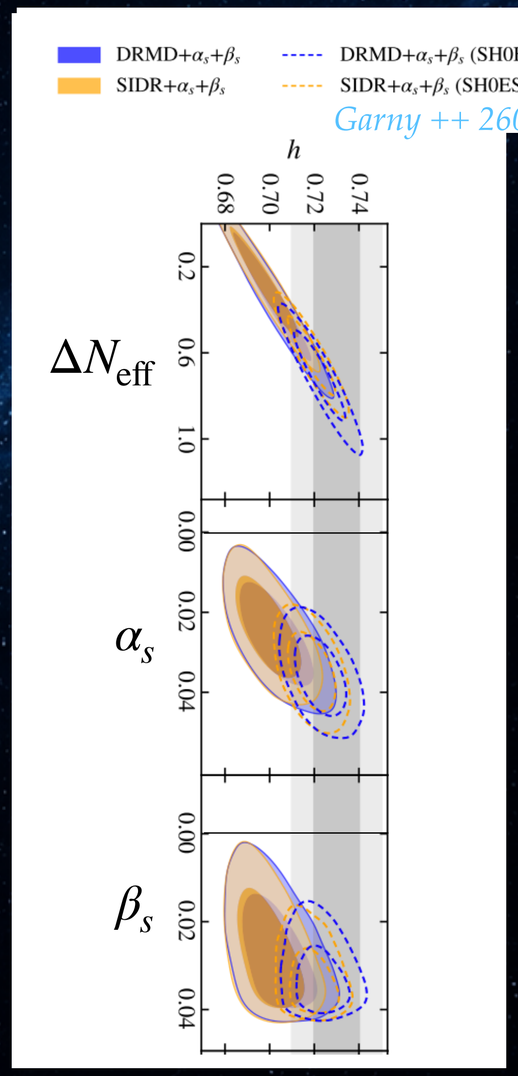



- Strong impact of ACT on radiation and varying $m_e$: they perform very well without ACT

# Final chance re-draft: Removing ACT




*Schöneberg, VP, Lesgourgues++ (in prep)*




- Strong impact of ACT on radiation and varying $m_e$: they perform very well without ACT

# The wold cup winners

- Early Dark Energy models are currently performing better than other models:
  ⇒ 2.5-3$\sigma$ residual tensions, strongly favored over ΛCDM with SH0ES

# The wold cup winners

- Early Dark Energy models are currently performing better than other models:
  ⇒ 2.5-3$\sigma$ residual tensions, strongly favored over ΛCDM with SH0ES

- Radiation and varying $m_e$ are constrained by ACT data: additional freedom ($\alpha_s, \beta_s$) helps relax constraints

# The wold cup winners

- Early Dark Energy models are currently performing better than other models:
  ⇒ 2.5-3$\sigma$ residual tensions, strongly favored over ΛCDM with SH0ES

- Radiation and varying $m_e$ are constrained by ACT data: additional freedom ($\alpha_s$, $\beta_s$) helps relax constraints

- Late-time models can explain DESI/CMB tension but cannot resolve the Hubble tension:
  ⇒ Do we need both early and late-time modifications?

# The wold cup winners

- Early Dark Energy models are currently performing better than other models:
  ⇒ 2.5-3$\sigma$ residual tensions, strongly favored over ΛCDM with SH0ES

- Radiation and varying $m_e$ are constrained by ACT data: additional freedom ($\alpha_s, \beta_s$) helps relax constraints

- Late-time models can explain DESI/CMB tension but cannot resolve the Hubble tension:
  ⇒ Do we need both early and late-time modifications?

**Can we understand why late-time models are excluded and EDE models are favored?**
**What are consequences beyond $H_0$?**
**Can we do better than what current EDE models do ?**

# Lesson 1: the role of the distance-duality relation

$$\text{BAO: } \theta_d(z) = \frac{r_s(z_{\rm drag})}{D_A(z)}$$

$$\text{SN1a: } 5\log_{10}\left(D_L(z)/10\text{pc}\right) = m(z) - M_b$$

- GR + photon conservation imposes the "distance-duality relation": $D_A(z) = D_L(z)/(1+z)^2$

# Lesson 1: the role of the distance-duality relation

Planck

$$\text{BAO: } \theta_d(z) = \frac{r_s(z_{\rm drag})}{D_A(z)}$$

SHOES

$$\text{SN1a: } 5\log_{10}\left(D_L(z)/10\text{pc}\right) = m(z) + M_b$$

- GR + photon conservation imposes the "distance-duality relation": $D_A(z) = D_L(z)/(1+z)^2$

# Lesson 1: the role of the distance-duality relation

Planck

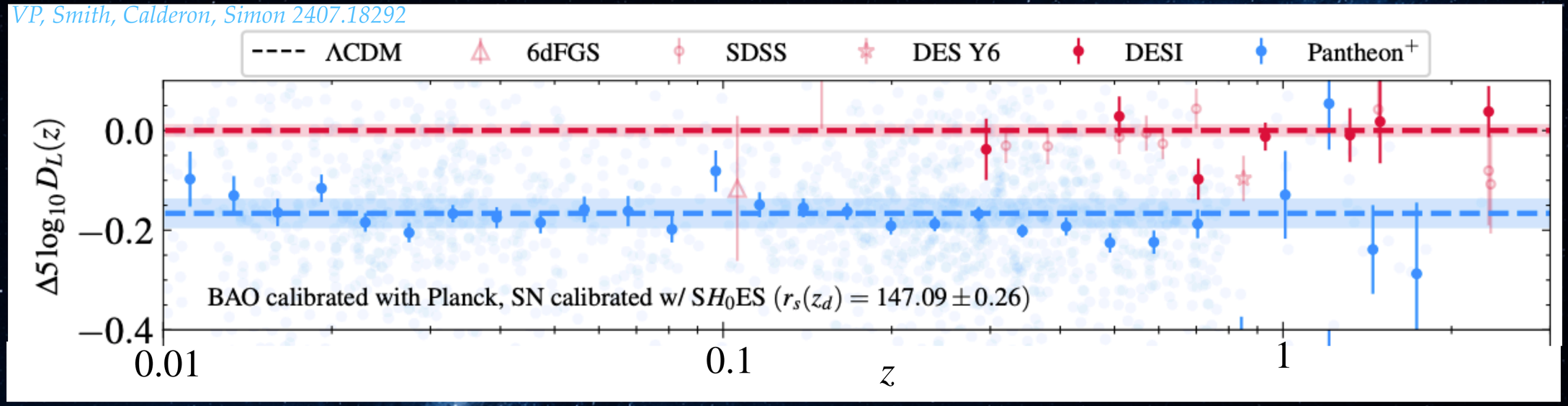
$$\text{BAO: } \theta_d(z) = \frac{r_s(z_{\rm drag})}{D_A(z)}$$

SHOES

$$\text{SN1a: } 5\log_{10}\left(D_L(z)/10\text{pc}\right) = m(z) + M_b$$

- GR + photon conservation imposes the "distance-duality relation": $D_A(z) = D_L(z)/(1+z)^2$

*VP, Smith, Calderon, Simon 2407.18292*




- Assuming $r_s \sim 147$ Mpc and $M_b \sim -19.25$, $D_A(z)$ and $D_L(z)$ are incompatible! Still true with DESI

*Camarena&Marra 2101.08641, Efstathiou 2103.08723, Raveri*

# Lesson 1: the role of the distance-duality relation

Planck

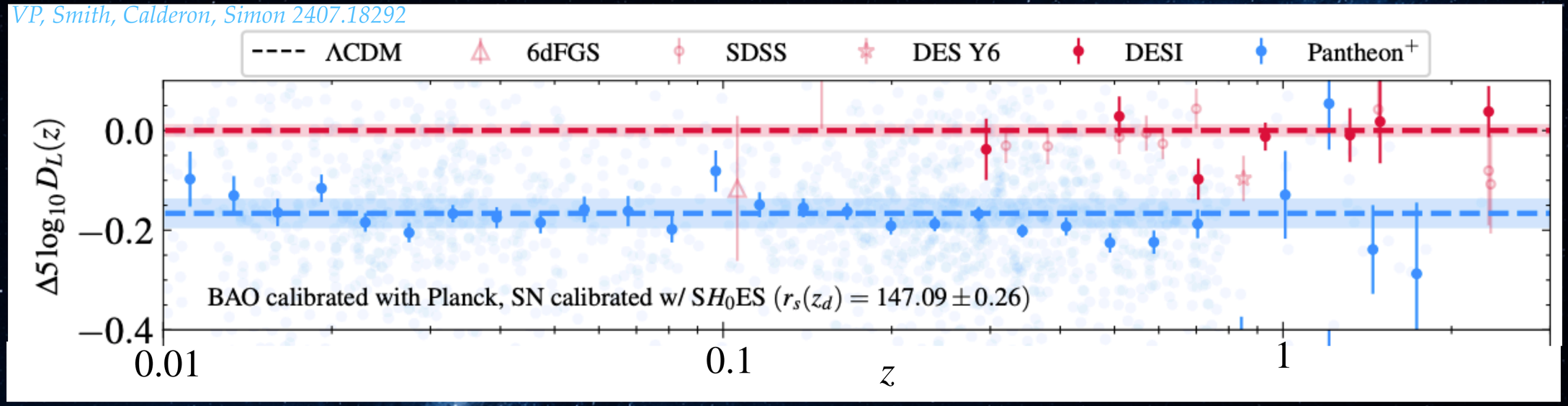
$$\text{BAO: } \theta_d(z) = \frac{r_s(z_{\rm drag})}{D_A(z)}$$

SHOES

$$\text{SN1a: } 5\log_{10}\left(D_L(z)/10\text{pc}\right) = m(z) + M_b$$

- GR + photon conservation imposes the "distance-duality relation": $D_A(z) = D_L(z)/(1+z)^2$

*VP, Smith, Calderon, Simon 2407.18292*




- Assuming $r_s \sim 147$ Mpc and $M_b \sim -19.25$, $D_A(z)$ and $D_L(z)$ are incompatible! Still true with DESI

*Camarena&Marra 2101.08641, Efstathiou 2103.08723, Raveri*

**Solving the tension require to either change calibrators or break the DDR relation**

*Aylor++ 1811.00537, Tutusaus++ 2311.16862, Teixeira (VP)++ 2504.10464*

# Lesson 1: the role of the distance-duality relation

Planck

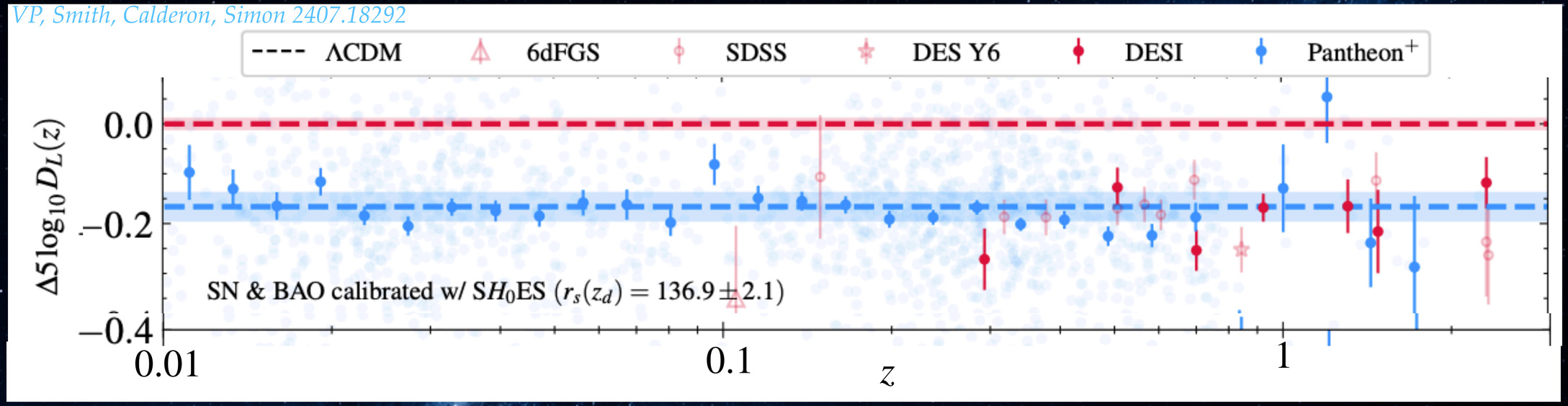
$$\text{BAO: } \theta_d(z) = \frac{r_s(z_{\rm drag})}{D_A(z)}$$

SHOES

$$\text{SN1a: } 5\log_{10}\left(D_L(z)/10\text{pc}\right) = m(z) + M_b$$

- GR + photon conservation imposes the "distance-duality relation": $D_A(z) = D_L(z)/(1+z)^2$

*VP, Smith, Calderon, Simon 2407.18292*




- Assuming $r_s \sim 147$ Mpc and $M_b \sim -19.25$, $D_A(z)$ and $D_L(z)$ are incompatible! Still true with DESI

*Camarena&Marra 2101.08641, Efstathiou 2103.08723, Raveri*

**Solving the tension require to either change calibrators or break the DDR relation**

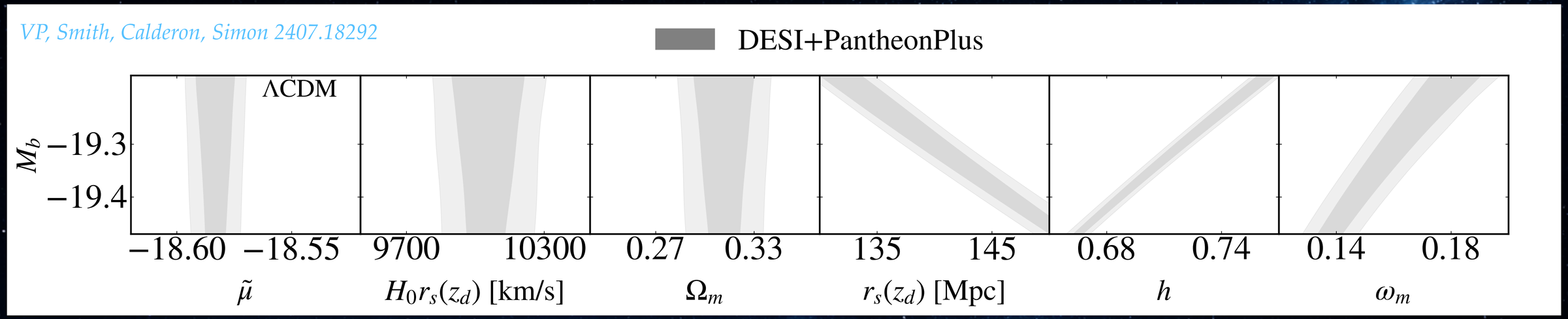
*Aylor++ 1811.00537, Tutusaus++ 2311.16862, Teixeira (VP)++ 2504.10464*

# Lesson 2: The cosmic calibration tension beyond $H_0$

- What is the impact of calibrating the BAO+SN1a Hubble diagram with either Planck or SH0ES?

# Lesson 2: The cosmic calibration tension beyond $H_0$

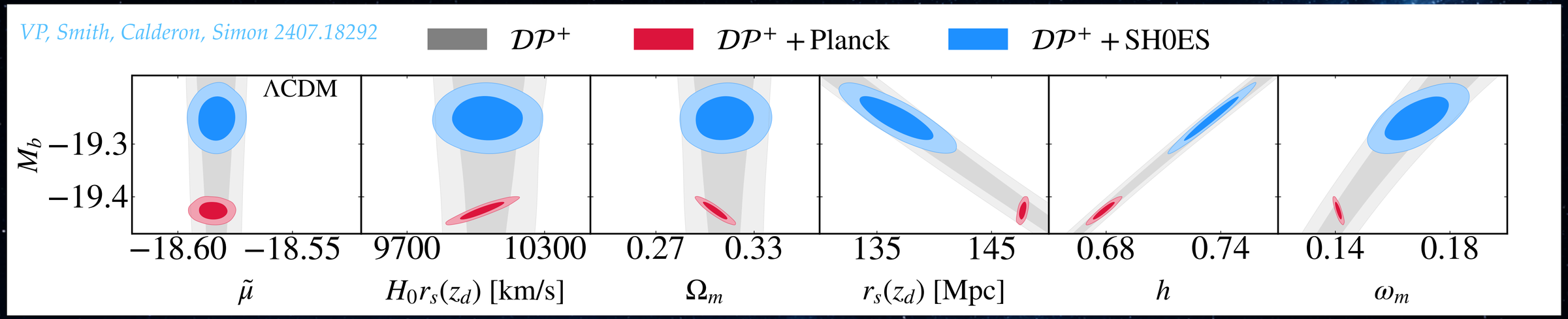
- What is the impact of calibrating the BAO+SN1a Hubble diagram with either Planck or SH0ES?




- Under ΛCDM, BAO and SN1a provide tight constraints to $\tilde{\mu} \equiv M - 5\log_{10}(h)$; $H_0 r_d$; $\Omega_m$

# Lesson 2: The cosmic calibration tension beyond $H_0$

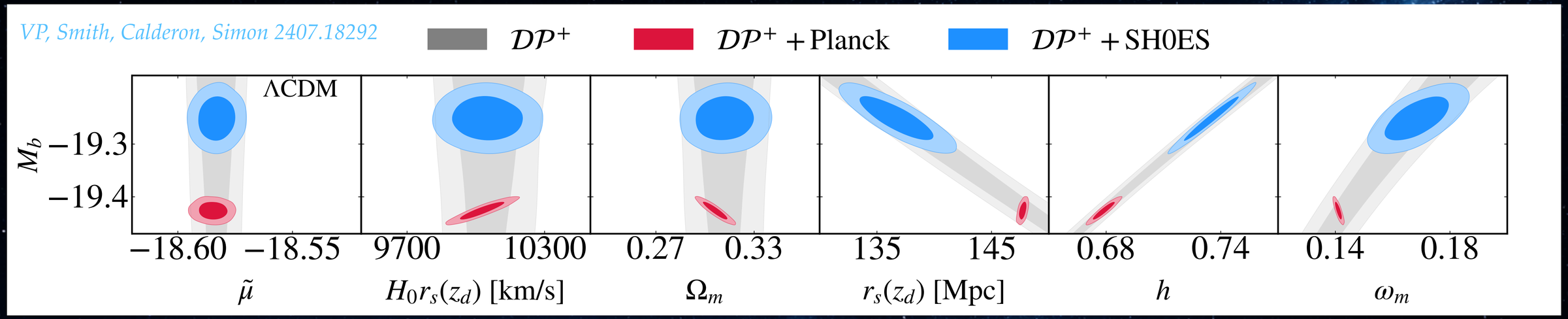
- What is the impact of calibrating the BAO+SN1a Hubble diagram with either Planck or SH0ES?




- Under ΛCDM, BAO and SN1a provide tight constraints to $\tilde{\mu} \equiv M - 5\log_{10}(h)$; $H_0 r_d$; $\Omega_m$
- Calibrating the BAO and SN1a leads to measurement of $H_0$ and $\omega_m = \Omega_m h^2$

# Lesson 2: The cosmic calibration tension beyond $H_0$

- What is the impact of calibrating the BAO+SN1a Hubble diagram with either Planck or SH0ES?

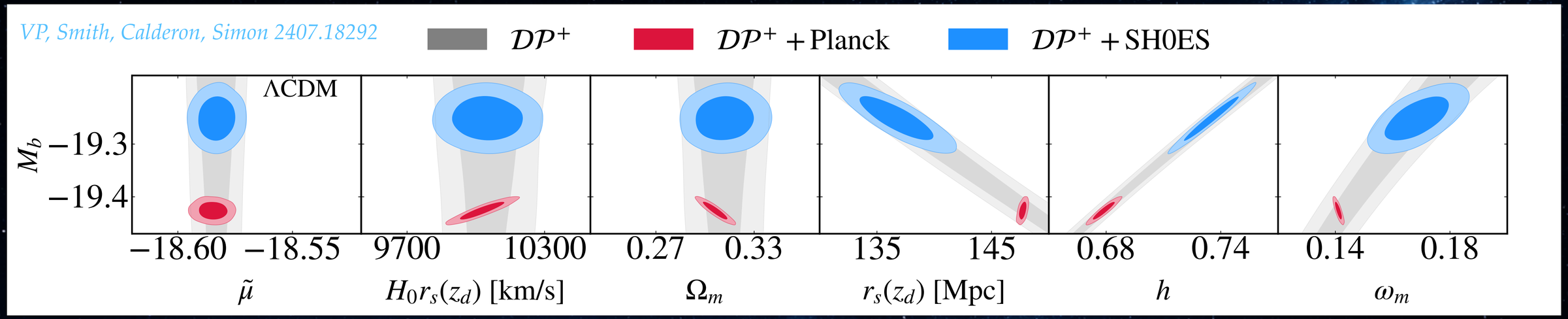



- Under ΛCDM, BAO and SN1a provide tight constraints to $\tilde{\mu} \equiv M - 5\log_{10}(h)$; $H_0 r_d$; $\Omega_m$
- Calibrating the BAO and SN1a leads to measurement of $H_0$ and $\omega_m = \Omega_m h^2$
- Challenge for new physics: Reduce the sound horizon and compensate the larger $\omega_m$ on the CMB

*See also Jedamzik++ 2010.04158, Blanchard++ 2205.05017, Pedrotti++ 2408.04530*

# Lesson 2: The cosmic calibration tension beyond $H_0$

- What is the impact of calibrating the BAO+SN1a Hubble diagram with either Planck or SH0ES?



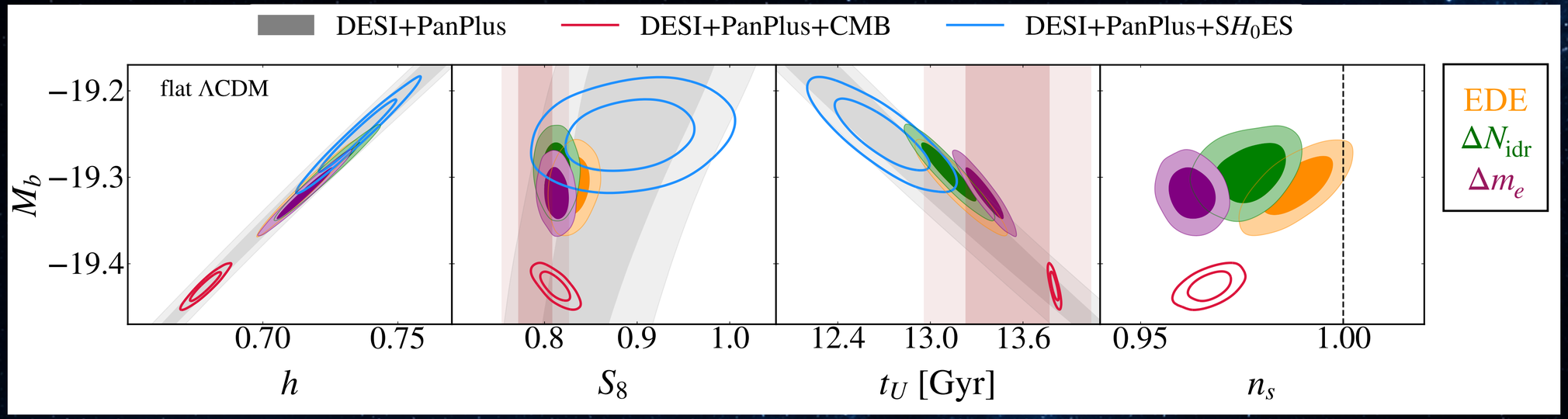

- Under ΛCDM, BAO and SN1a provide tight constraints to $\tilde{\mu} \equiv M - 5\log_{10}(h)$; $H_0 r_d$; $\Omega_m$
- Calibrating the BAO and SN1a leads to measurement of $H_0$ and $\omega_m = \Omega_m h^2$
- Challenge for new physics: Reduce the sound horizon and compensate the larger $\omega_m$ on the CMB

*See also Jedamzik++ 2010.04158, Blanchard++ 2205.05017, Pedrotti++ 2408.04530*

**This is why pre-recombination expansion history changes (EDE, radiation) are favored!**

# Lesson 3: Model-dependent predictions beyond $H_0$

*VP, Smith, Calderon, Simon 2407.18292*




- Slight increase in $S_8$ but no tension with KiDS Legacy and $\lesssim 2\sigma$ with DESY3+KiDS combined

*Hill++ 2003.07355; Ivanov++ 2006.11235, D'Amico 2006.12420, Simon (VP) ++ 2208.05930*

- Age of the universe $\sim$ 0.7 Gyr younger: problem with old objects?

*Bernal++ 2102.05066, Boylan-Kolchin 2103.15824, Vagnozzi 2105.10425*

- $n_s$ increases, compatible with 1? Helps with JWST UV luminosity functions?

*Gen Ye++ 2103.09729, 2205.02478, Goldstein++ 2303.00746 Shen++ 2509.19427*

# Inflation, Dark Energy ... and Early Dark Energy?

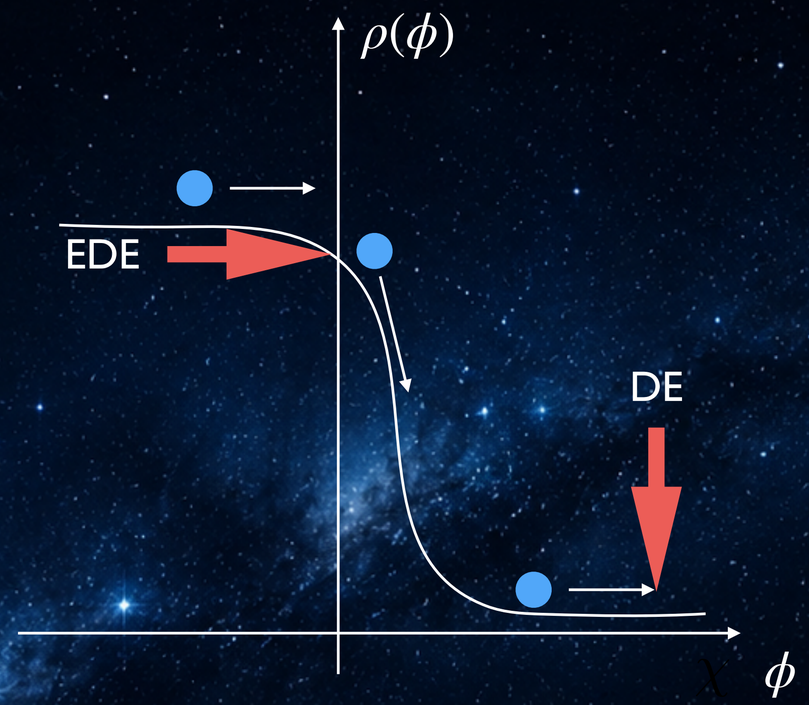
- The idea that DE altered the early universe is not new: explains the DE coincidence problem

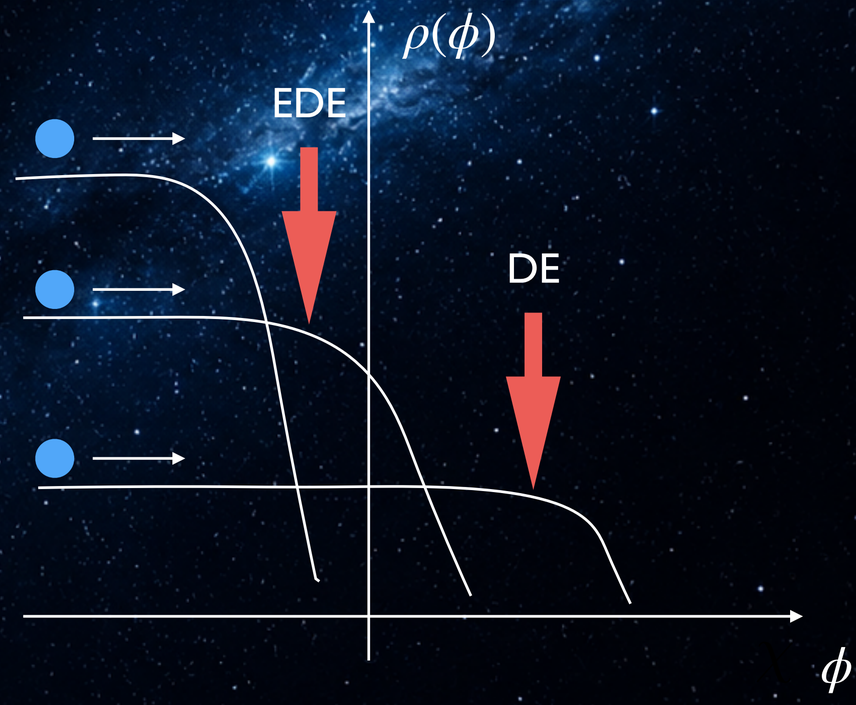
*e.g. Dodelson++astro-ph/0002360, Griest astro-ph/0202052, Bielefeld (Caldwell)++ 1305.2209, Kamionkowski++1409.0549*

- Is their one field with a complicated potential or many fields with simple potentials? String axiverse?

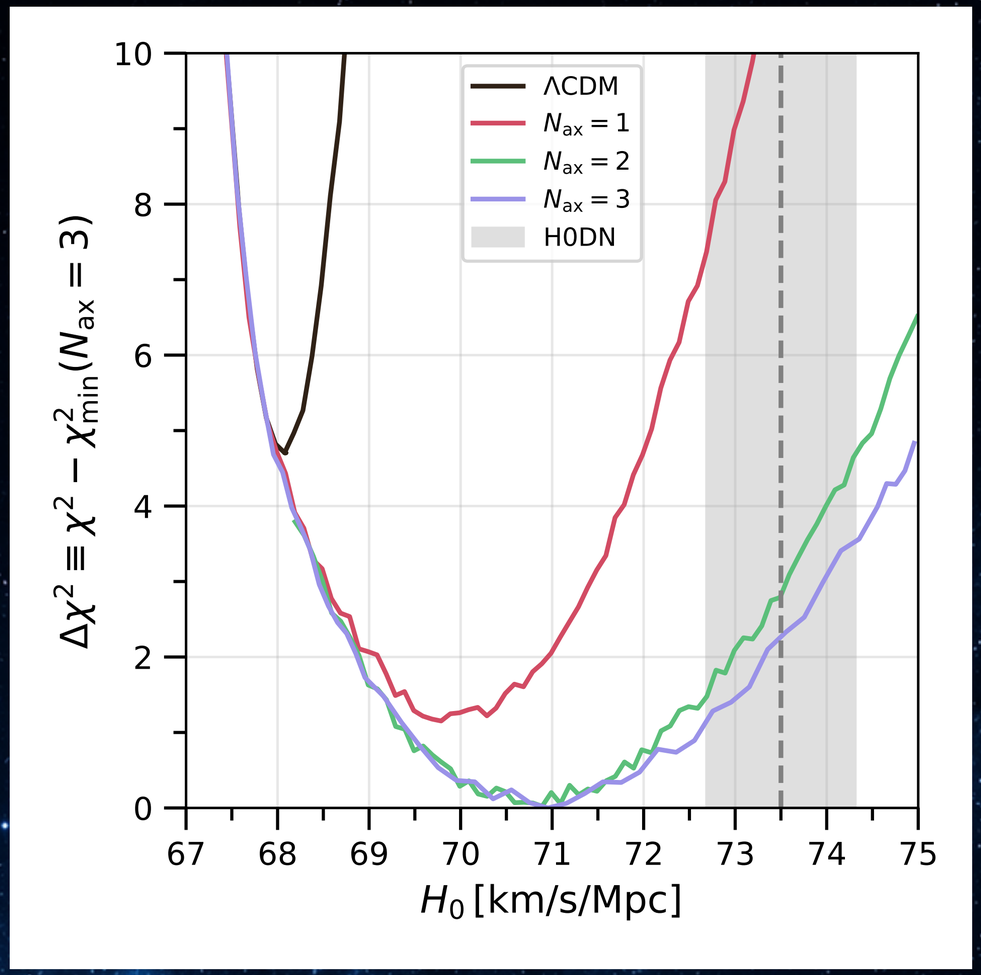
*Arvinataki++ 0905.4720; Kamionkowski ++ 1409.0549; Karwal++ 1608.01309*

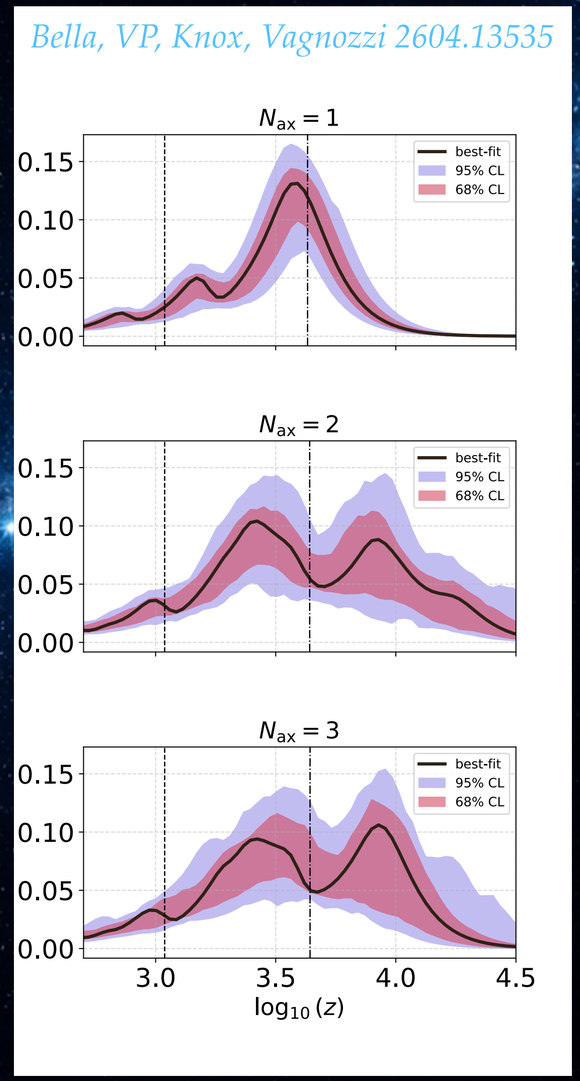
- We know of Inflation, late-time Dark Energy: could there be more of such era to be discovered?



# A multi-field model performs significantly better



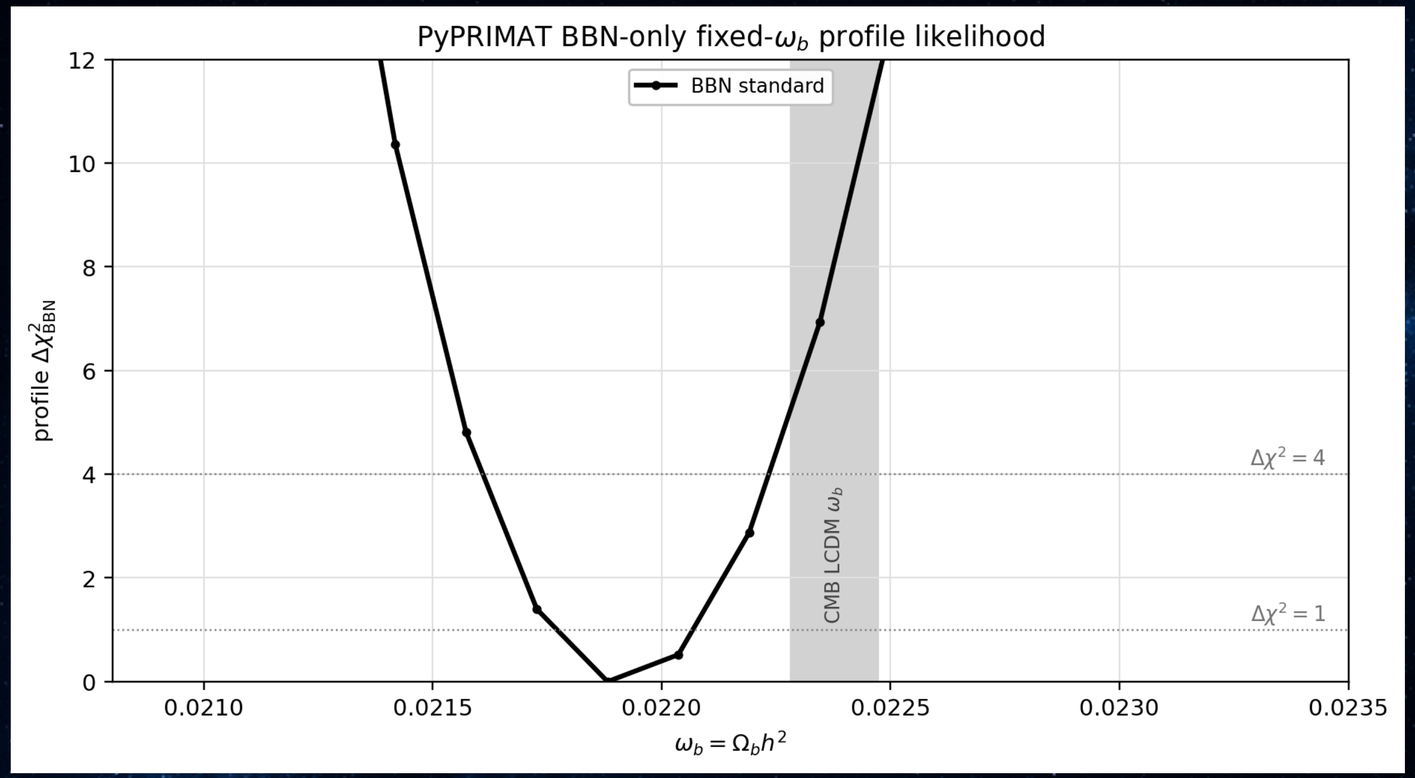




- A model with 2-fields yields < 1.5 $\sigma$ tension even with NPIPE!
- Smoother / more extended energy injection performs better

# Hint of Very Early Dark Energy at BBN?

- $2\sigma$ tension between $\omega_b^{\rm BBN}$ and $\omega_b^{\rm LCDM/Planck}$ => $3\sigma$ with $\omega_b^{\rm EDE/Planck}$

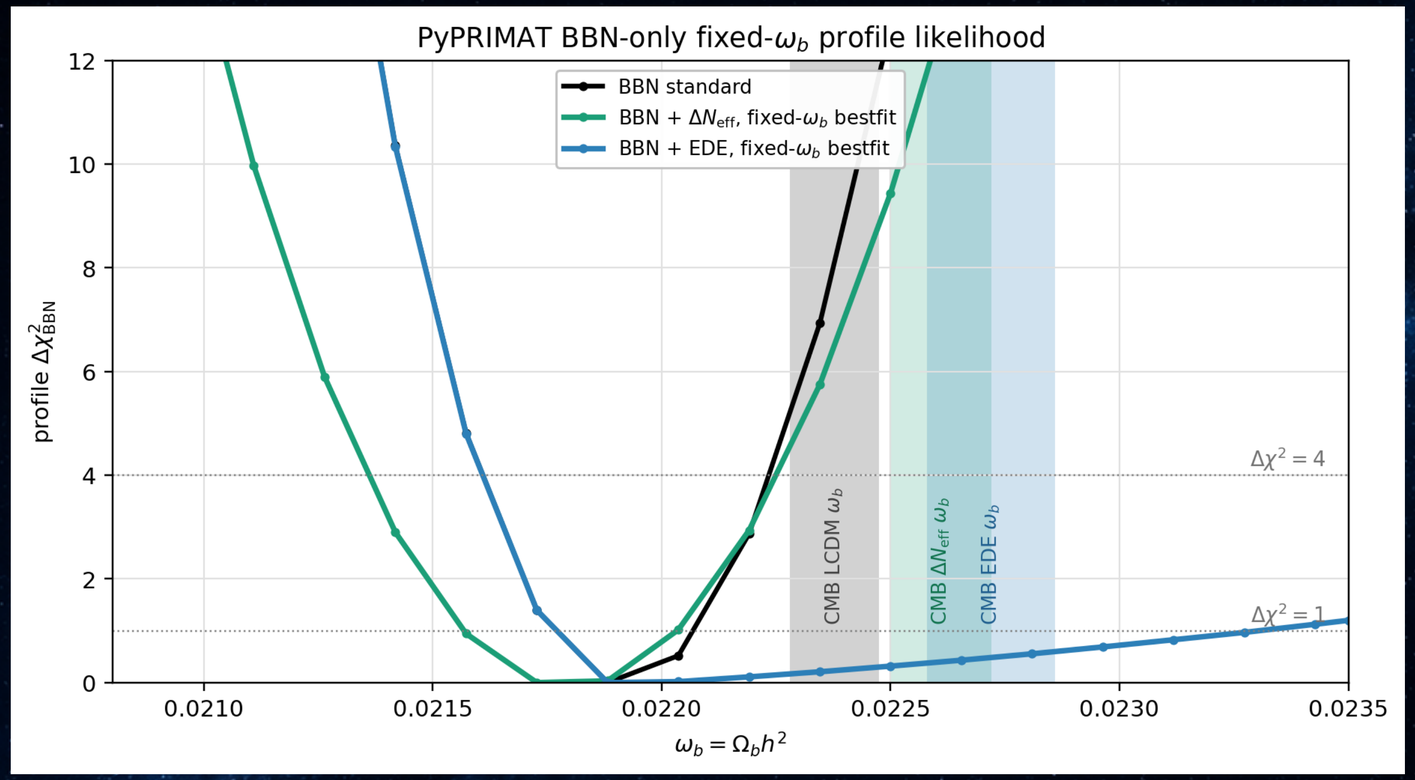
*Giovanetti 2604.05095*

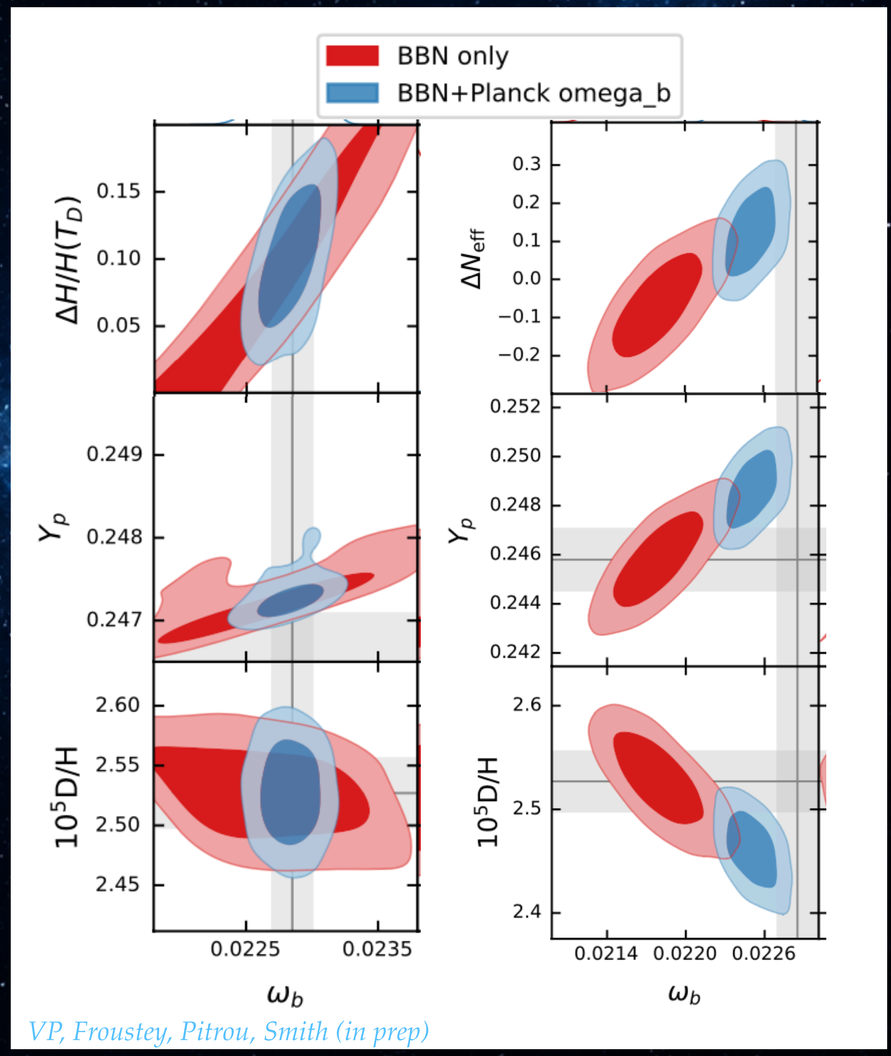


# Hint of Very Early Dark Energy at BBN?

- $2\sigma$ tension between $\omega_b^{\rm BBN}$ and $\omega_b^{\rm LCDM/Planck}$ => $3\sigma$ with $\omega_b^{\rm EDE/Planck}$
- $\Delta H/H \sim 10\,\%$ at $T_{\rm D} \simeq 3\times10^8$ K $\Leftrightarrow$ $z \simeq 10^8$
- Increase in $N_{\rm eff}$ fails; localized EDE injection works
  $\Rightarrow$predicts small increase in $Y_p$

*Giovanetti 2604.05095*

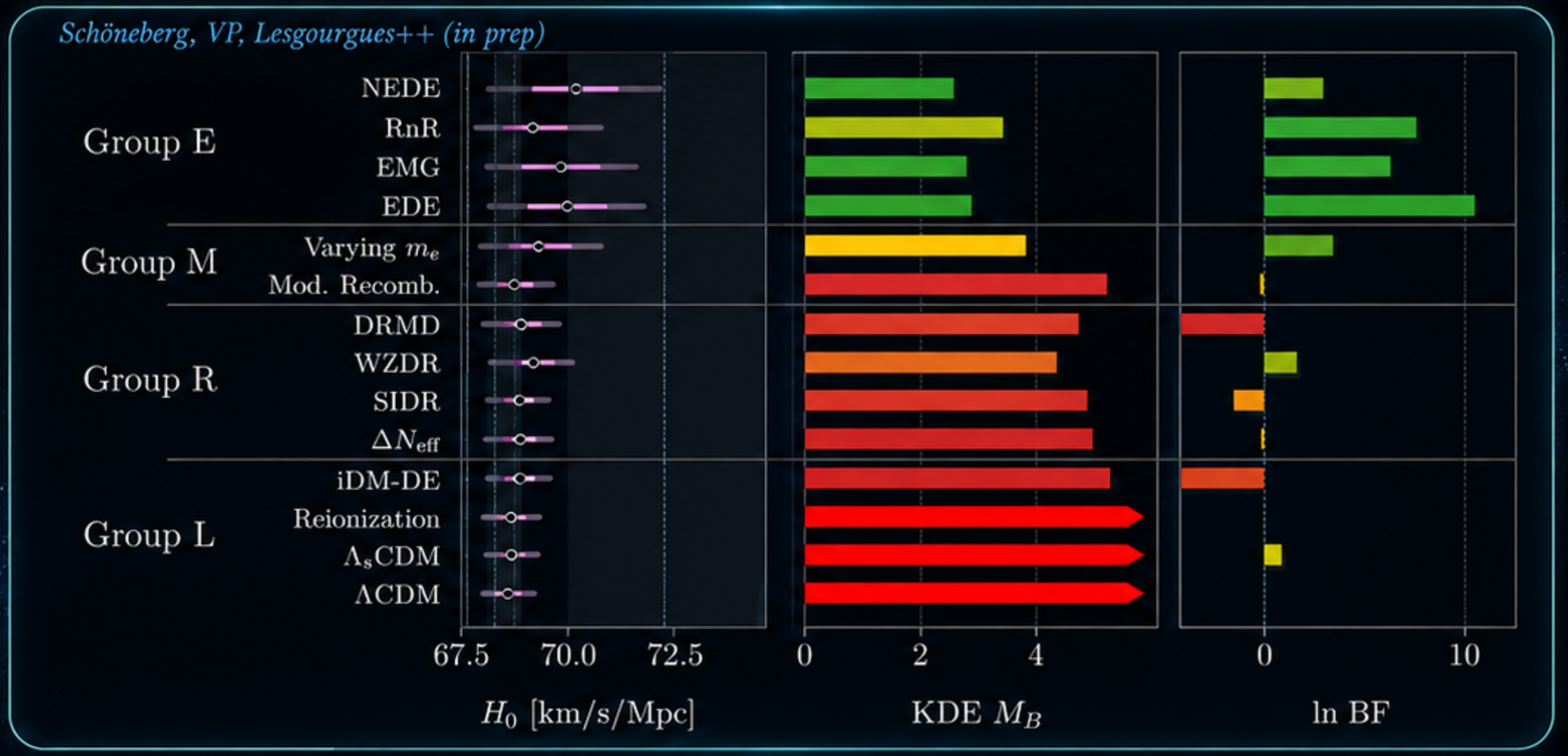



*VP, Froustey, Pitrou, Smith (in prep)*

# The Hubble tension: is $H_0$ coming home?

- The "$H_0$ tension" is at its core an issue with the standard ruler calibration of the distance ladder
- Calibrating the ladder has implications beyond the value of $H_0$: smaller $t_V$, larger $\omega_m$ and $s_8$




- Several EDE models lead to $2.5 - 3\sigma$ tension, not favored by CMB alone but DESI helps!
- No fully successful solution yet, but models are predictive and on the verge of falsification

# How to model Early Dark Energy

- Initially slowly-rolling field (due to Hubble friction) that later dilutes faster than matter

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0 \qquad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi),\ P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

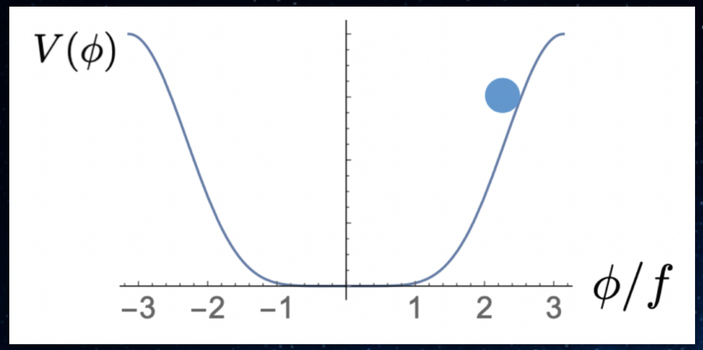
# How to model Early Dark Energy

- Initially slowly-rolling field (due to Hubble friction) that later dilutes faster than matter

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0 \qquad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi),\ P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

- Oscillating potential: $V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$

*Karwal& Kamionkowski 1608.01309; VP++ 1806.10608 & 1811.04083; Smith++ 1908.06995*

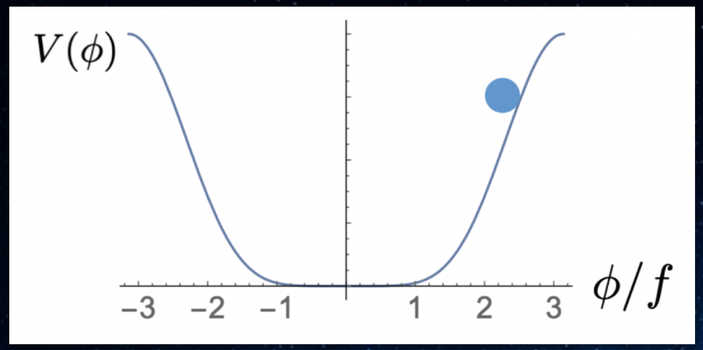


# How to model Early Dark Energy

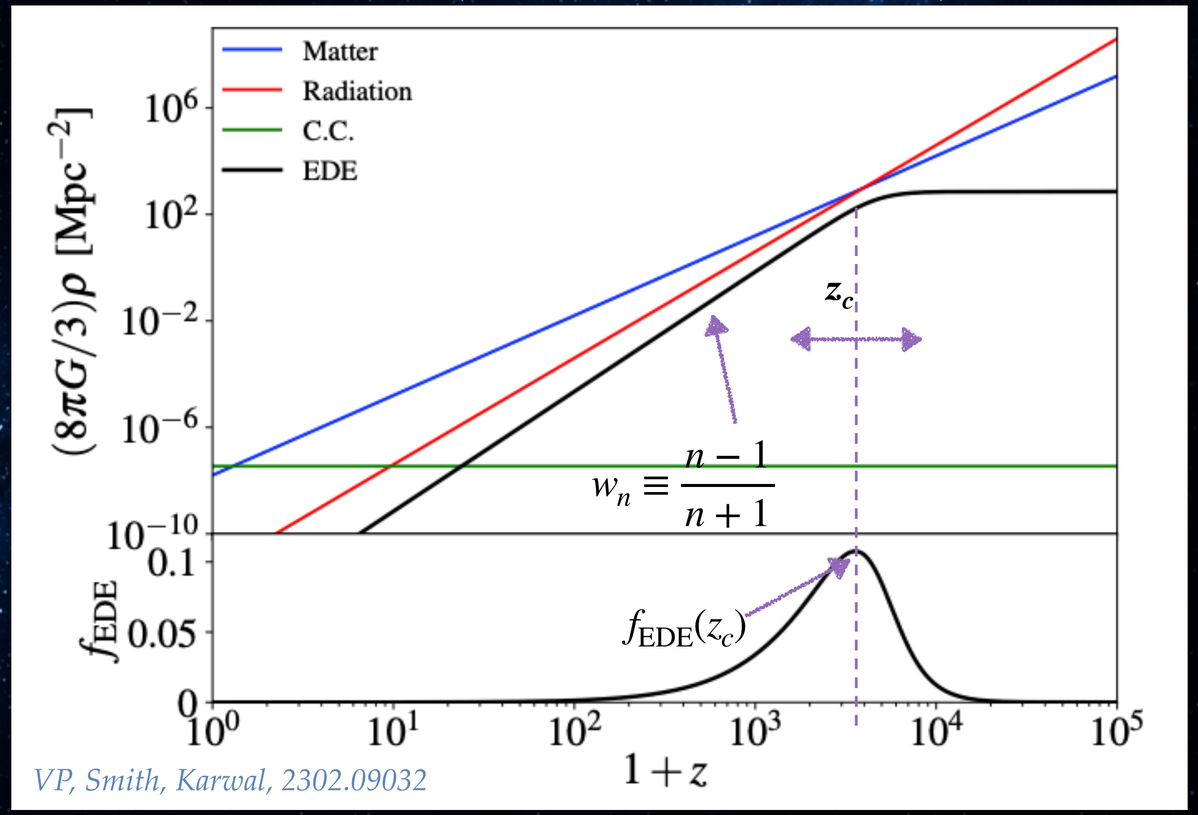
- Initially slowly-rolling field (due to Hubble friction) that later dilutes faster than matter

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0 \qquad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi),\ P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

- Oscillating potential: $V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$




*Karwal& Kamionkowski 1608.01309; VP++ 1806.10608 & 1811.04083; Smith++ 1908.06995*



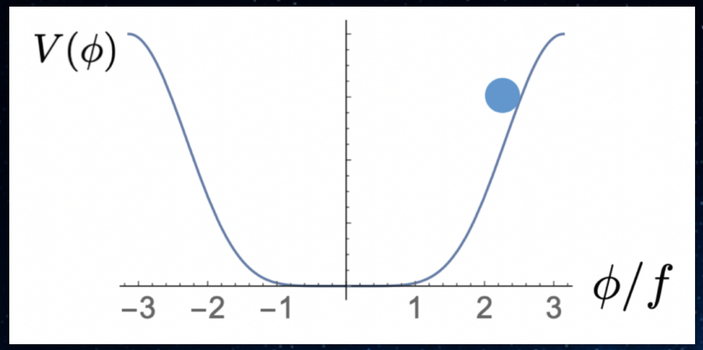

*VP, Smith, Karwal, 2302.09032*

# How to model Early Dark Energy

- Initially slowly-rolling field (due to Hubble friction) that later dilutes faster than matter

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0 \qquad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi),\ P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

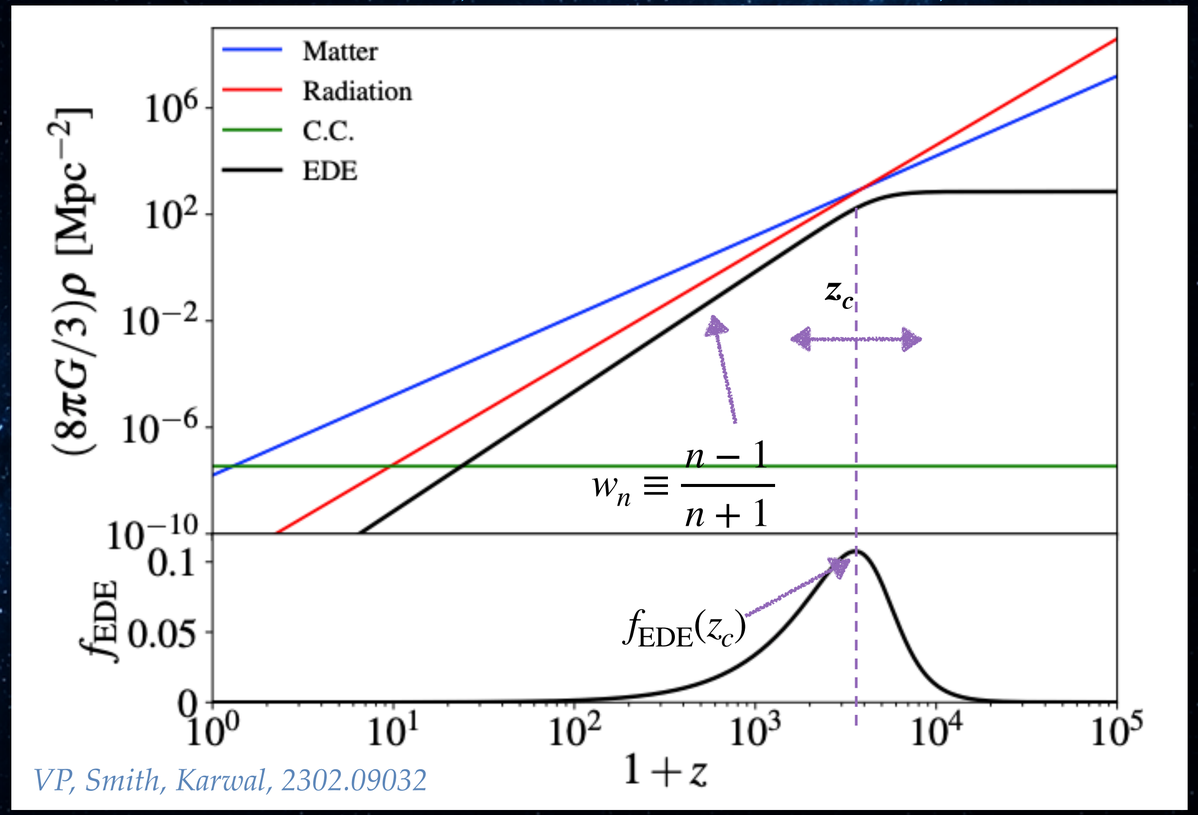
- Oscillating potential: $V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)^n$




- Perturbations controlled by

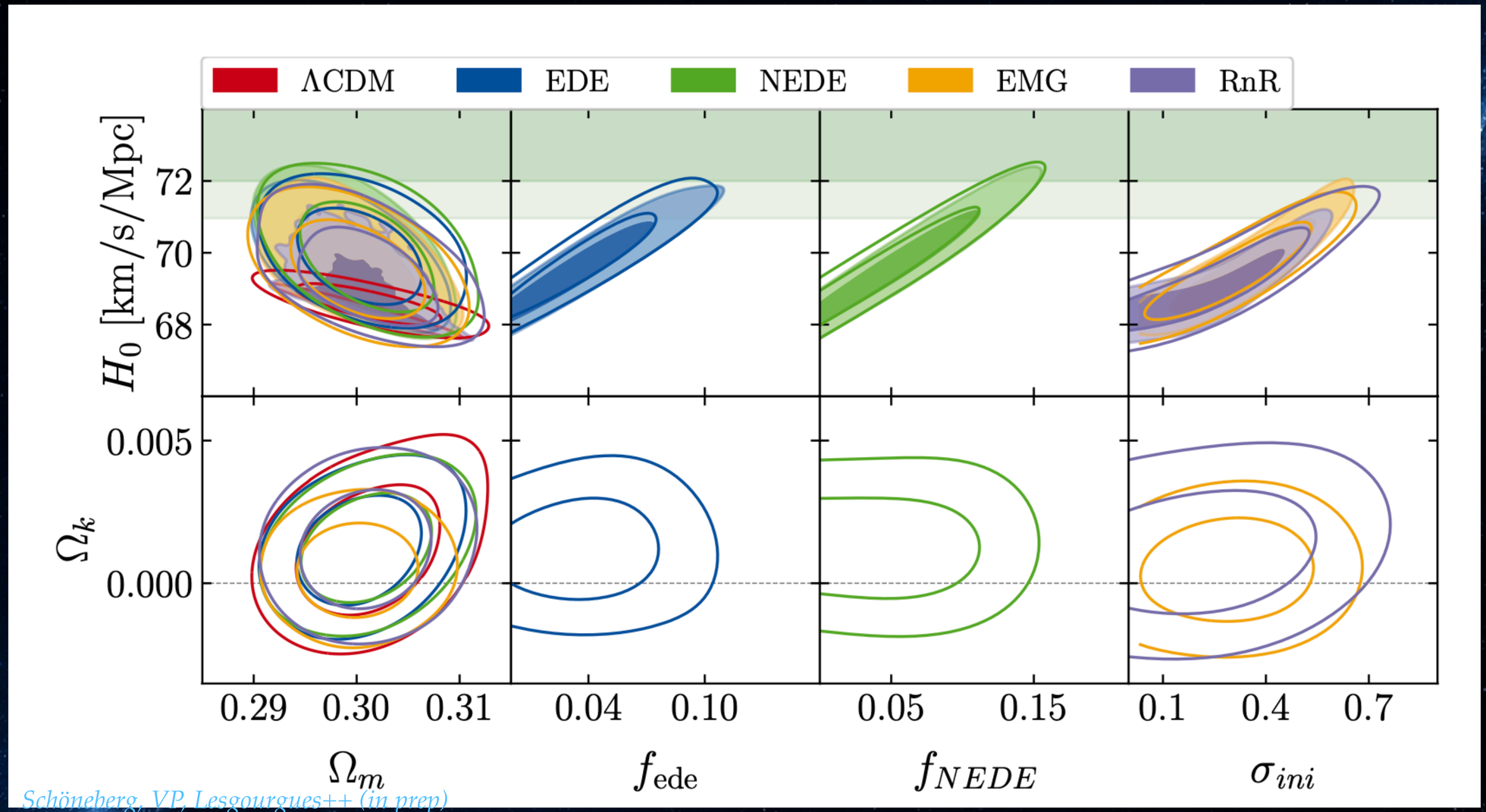
$$c_s^2 = \frac{2a^2(n-1)\varpi^2(a) + k^2}{2a^2(n+1)\varpi^2(a) + k^2}$$

*Karwal& Kamionkowski 1608.01309; VP++ 1806.10608 & 1811.04083; Smith++ 1908.06995*




*VP, Smith, Karwal, 2302.09032*

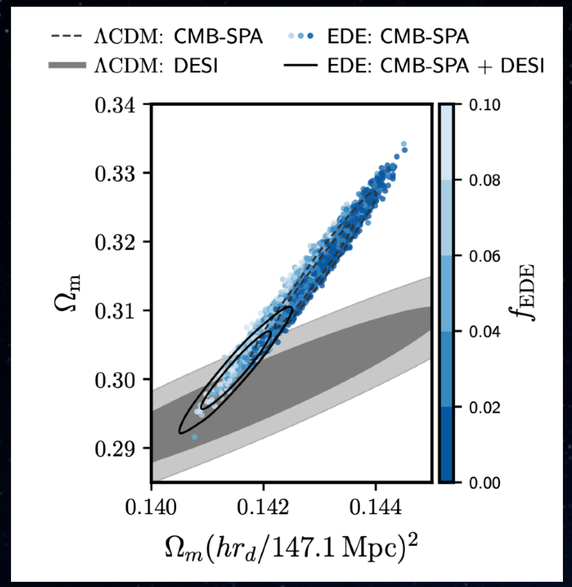
# Group stage second game : curvature $\Omega_k$

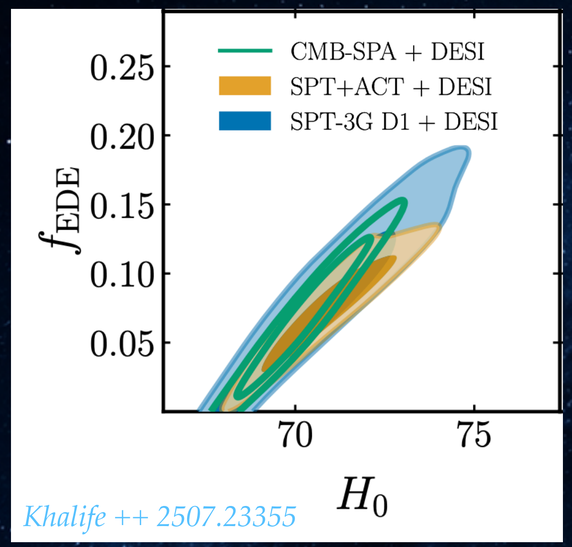



*Schöneberg, VP, Lesgourgues++ (in prep)*

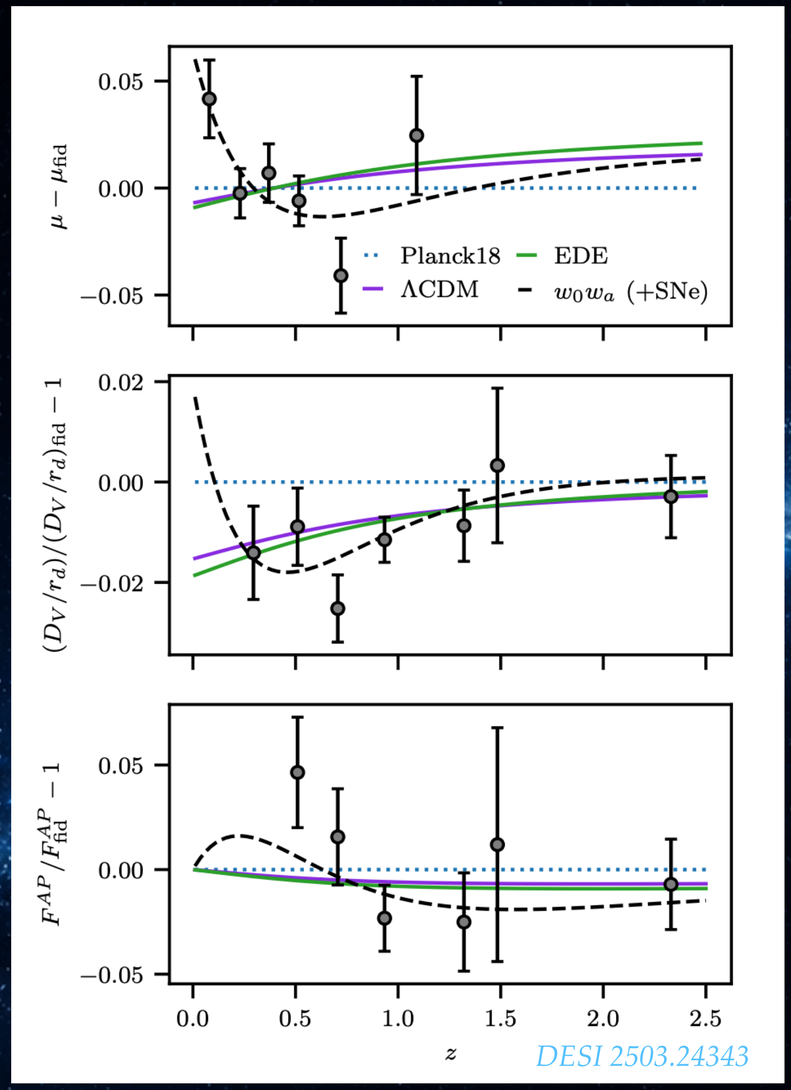
- Group E: not much impact from curvature

# Early Dark Energy reduces the CMB/DESI tension




*Khalife ++ 2507.23355*

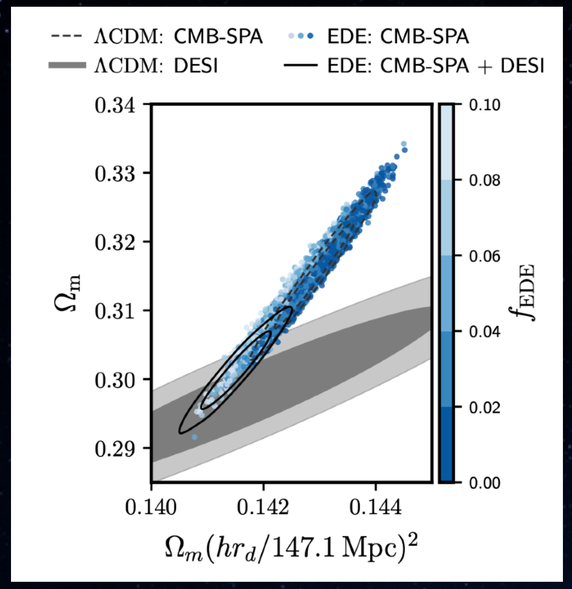


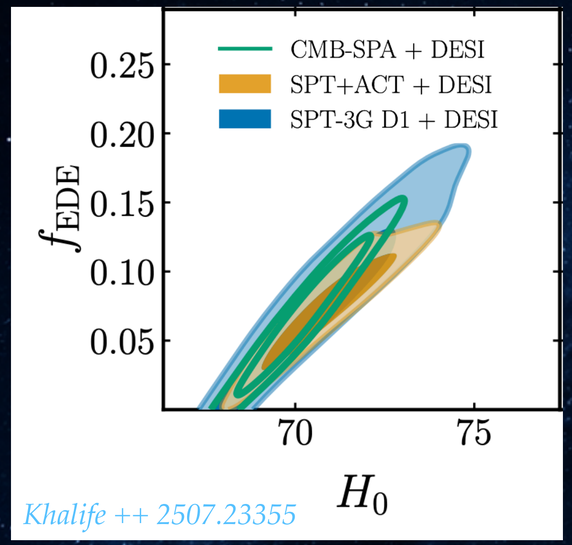

*DESI 2503.24343*

| Data | ΛCDM - EDE | ΛCDM - $w_0w_a$ |
|---|---|---|
| CMB+BAO | 7.4 | 13 |
| +SNe | 7.5 | 19 |

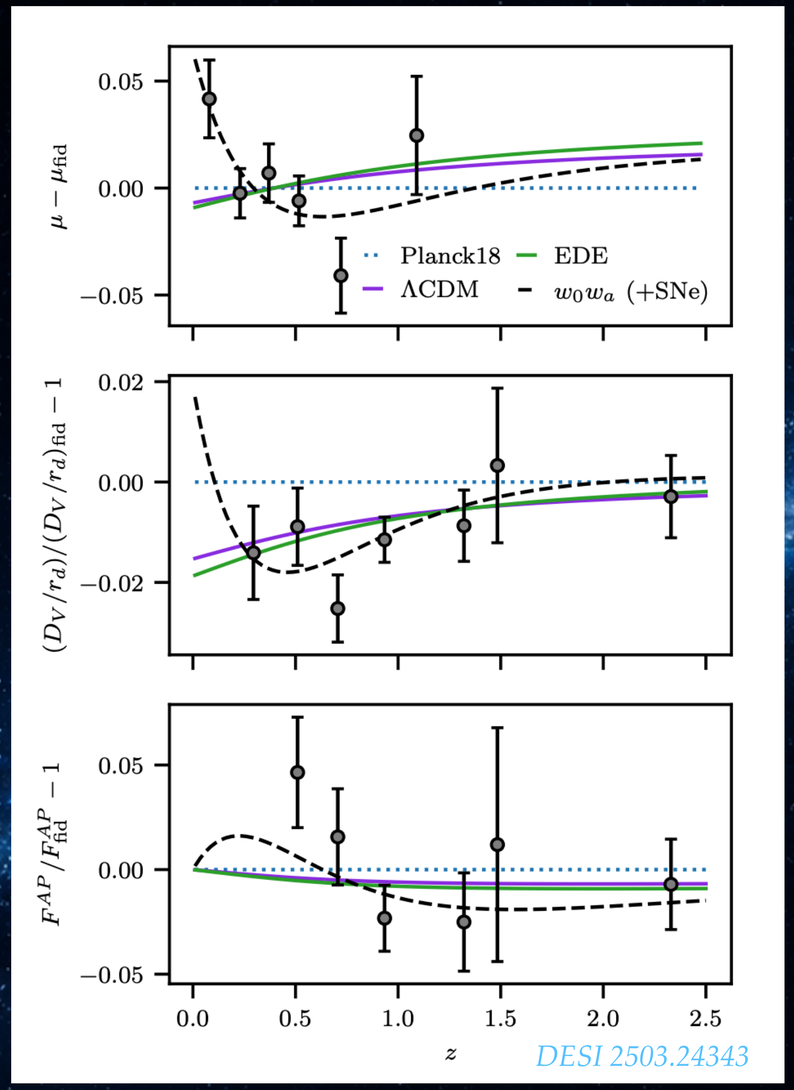
- Early-universe modifications as an alternative explanation to DESI+H0 results?

# Early Dark Energy reduces the CMB/DESI tension




*Khalife ++ 2507.23355*

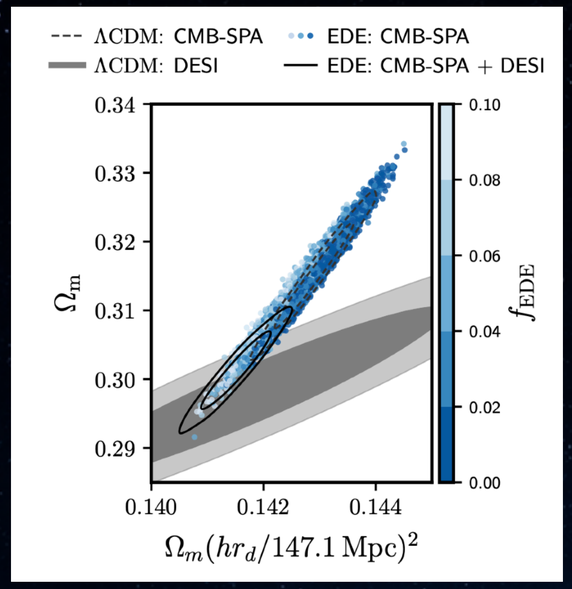


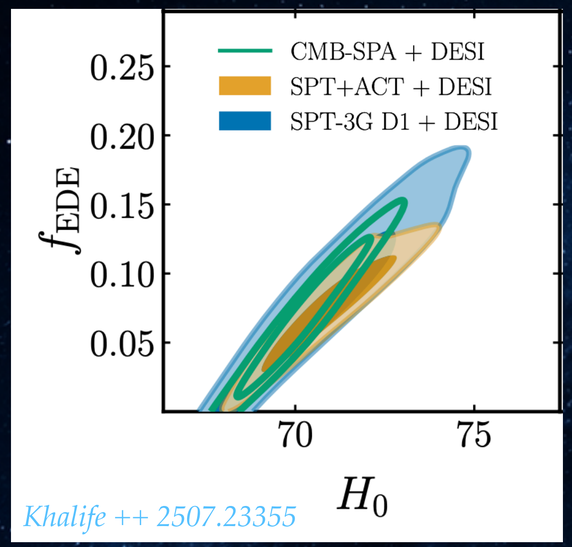

*DESI 2503.24343*

| Data | ΛCDM - EDE | ΛCDM - $w_0w_a$ |
|---|---|---|
| CMB+BAO | 7.4 | 13 |
| +SNe | 7.5 | 19 |
| +SNe+CCHP | 8.7 | 14 |
| +SNe+SH0ES | 26 | -4.6 |

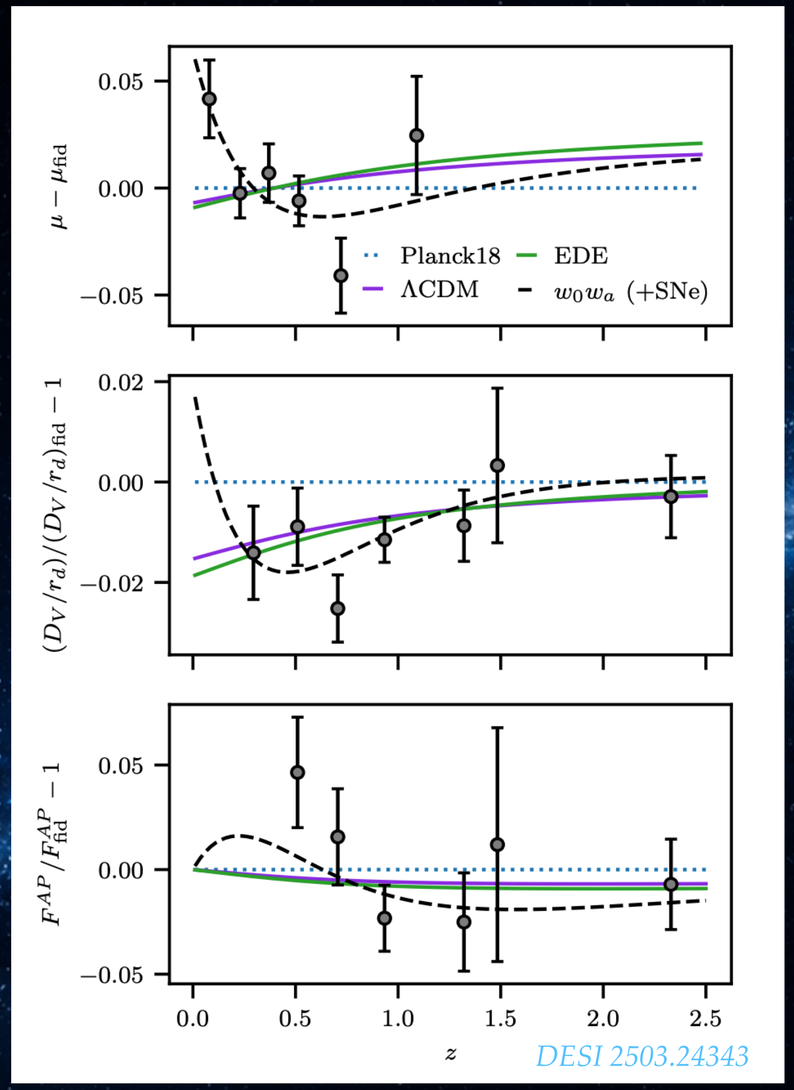
- Early-universe modifications as an alternative explanation to DESI+H0 results?

# Early Dark Energy reduces the CMB/DESI tension




*Khalife ++ 2507.23355*

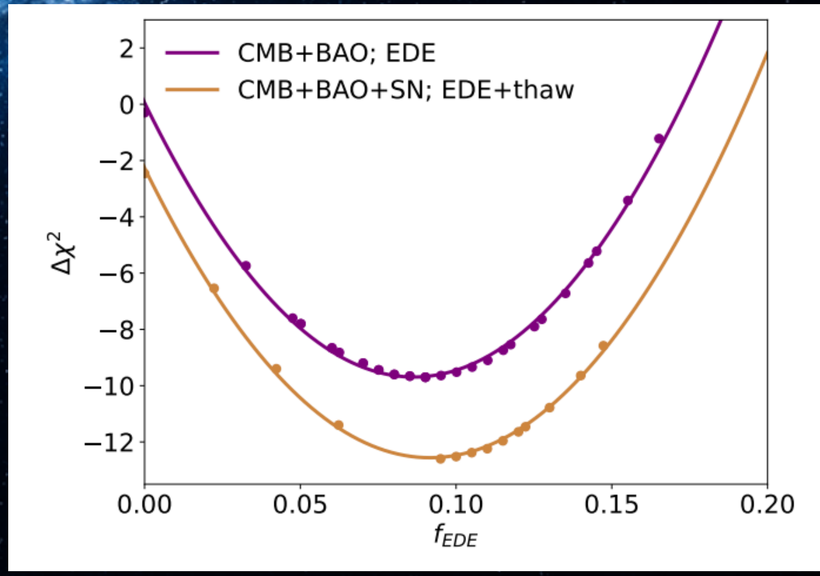



*DESI 2503.24343*

| Data | ΛCDM - EDE | ΛCDM - $w_0w_a$ |
|---|---|---|
| CMB+BAO | 7.4 | 13 |
| +SNe | 7.5 | 19 |
| +SNe+CCHP | 8.7 | 14 |
| +SNe+SH0ES | 26 | -4.6 |

| CMB + BAO + SN | |
|---|---|
| EDE+thaw | -12.6 |
| $w_0w_a$ | -15.8 |

*Jhaveri++ 2604.08530*




- Early-universe modifications as an alternative explanation to DESI+H0 results?