Cracks in LCDM

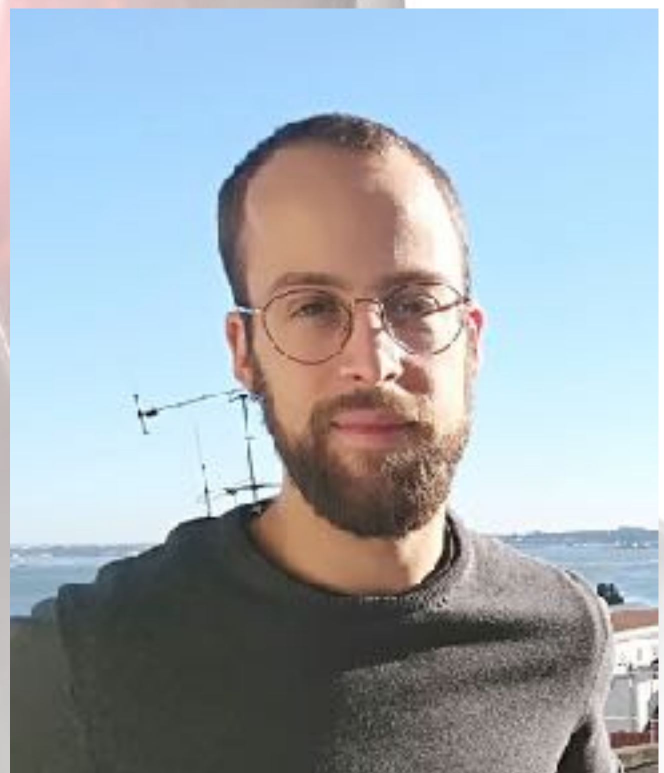
Lavinia Heisenberg

(ITP-Heidelberg)

L.Heisenberg@thphys.uni-heidelberg.de

28. June 2022, Kitzbühel Humboldt Conference, Kitzbühel/Austria

In collaboration with



Hector Villarrubia Rojo

Jann Zosso

Cosmology

Cosmology describes the Universe with 2 fundamental pillars

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GR **General Relativity**

Cosmology

Cosmology describes the Universe with 2 fundamental pillars

GR General Relativity

CP Cosmological Principle

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CP Cosmological Principle → Homogeneity & Isotropy

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$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

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$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

$$H = \frac{\dot{a}}{a}$$ expansion rate

Cosmology

Cosmology describes the Universe with 2 fundamental pillars

GR — **General Relativity**

CP — **Cosmological Principle** → **Homogeneity & Isotropy**

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

$$H = \frac{\dot{a}}{a}$$ **expansion rate**

$$H_0 = H(\text{today})$$
$$= 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$$

How can we measure H(a)?

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redshift $$a = \frac{1}{1+z}$$

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comoving distance $$d = \int_t^{t_0} \frac{dt}{a(t)} = \int_0^z \frac{dz}{H(z)}$$

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redshift $$a = \frac{1}{1+z}$$

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through distance measurements we can obtain H!

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How can we measure H(a)?

comoving distance

$$d = \int_t^{t_0} \frac{dt}{a(t)} = \int_0^z \frac{dz}{H(z)}$$

for small redshift (nearby objects)

$$d(z) = \frac{z}{H_0} + \mathcal{O}(z^2)$$

How can we measure H(a)?

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from z and d(z) we can obtain H_0

How can we measure H(a)?

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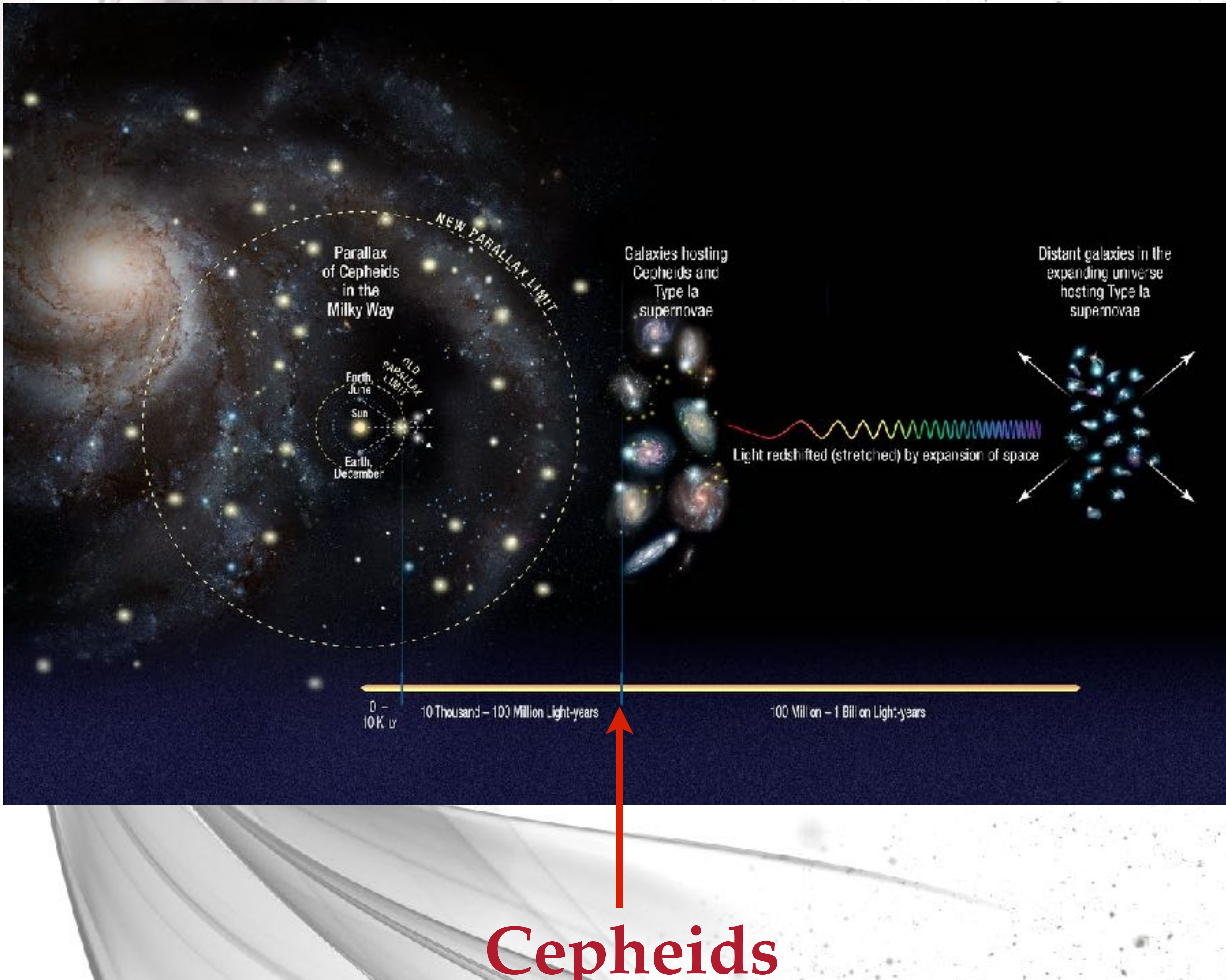
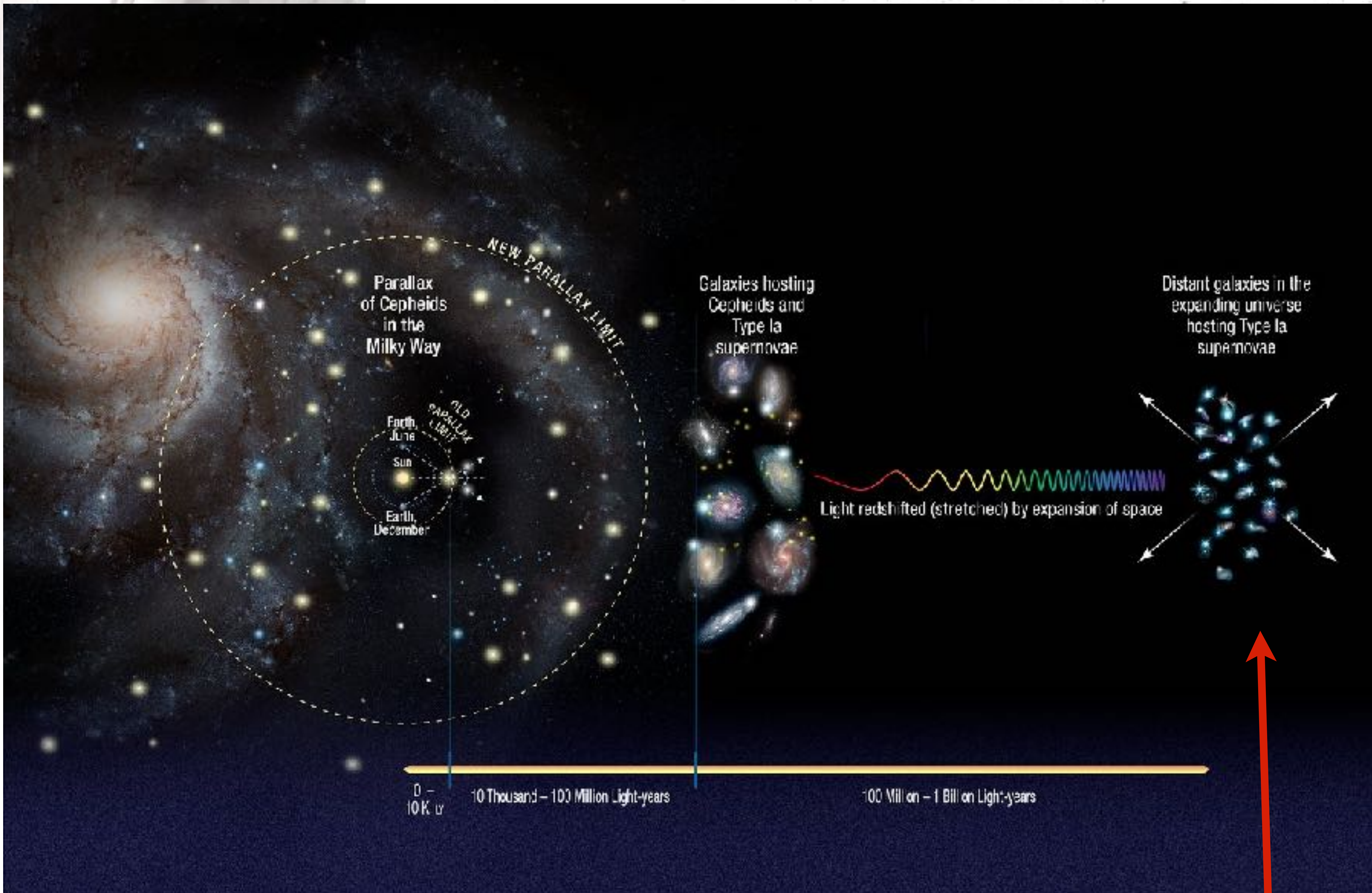
(model-independent)


NEW PARALLAX LIMIT
Parallax of Cepheids in the Milky Way
OLD PARALLAX LIMIT
Earth, June
Sun
Earth, December
Galaxies hosting Cepheids and Type Ia supernovae
Light redshifted (stretched) by expansion of space
Distant galaxies in the expanding universe hosting Type Ia supernovae
0 – 10 K ly
10 Thousand – 100 Million Light-years
100 Million – 1 Billion Light-years
Cepheids



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Supernovae

How can we measure H(a)?

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for small redshift (nearby objects)

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from z and d(z) we can obtain H_0

(model-independent)

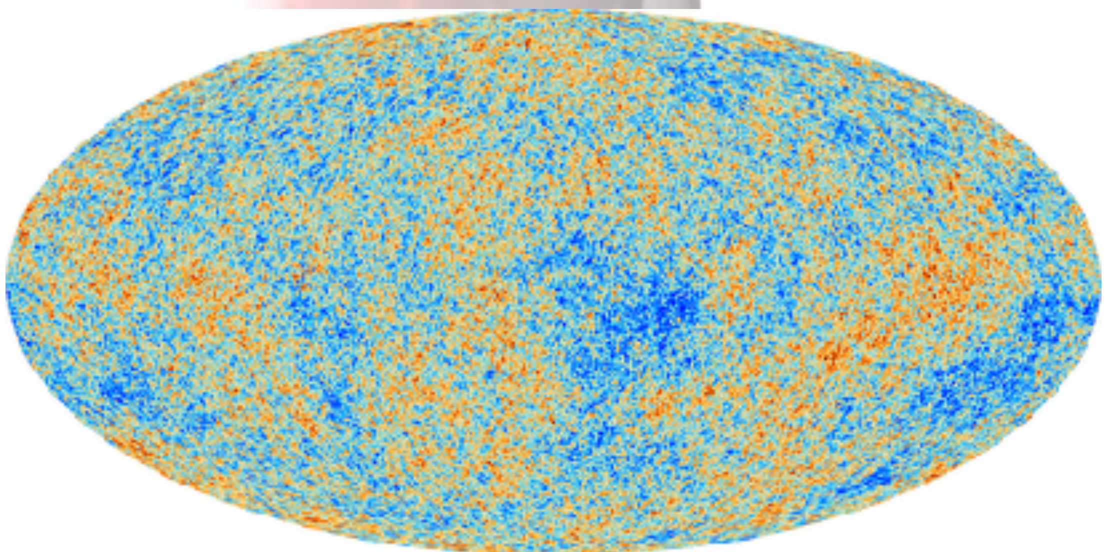
How can we measure H0 from CMB?

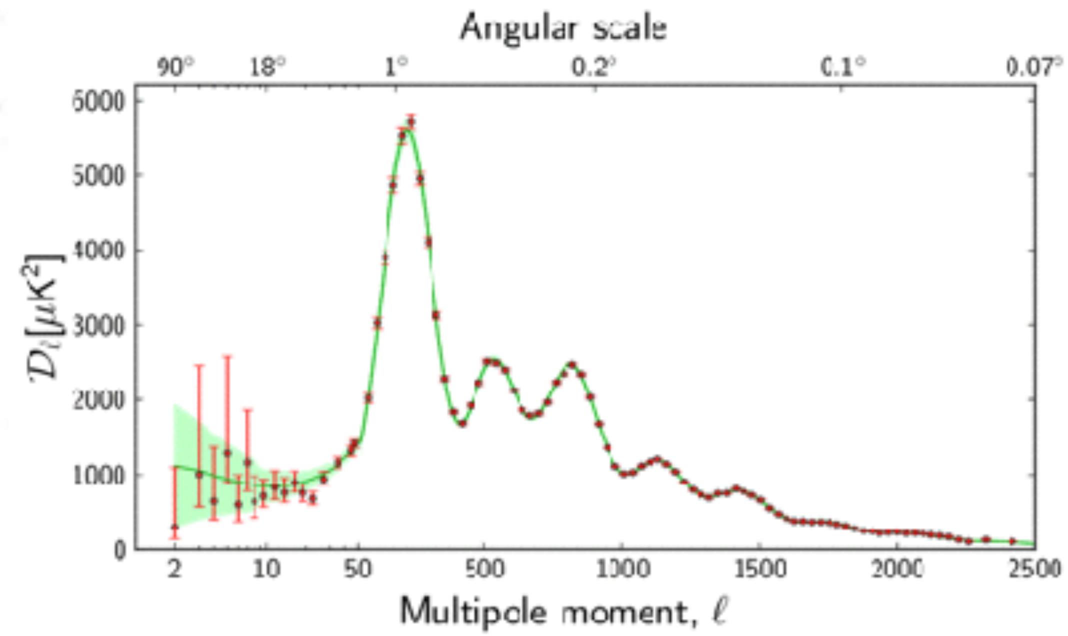
How can we measure H0 from CMB?

$$\Lambda CDM$$

$$\{H_0, \Omega_b, \Omega_m, A_s, n_s, \tau_{reio}\}$$

How can we measure H0 from CMB?



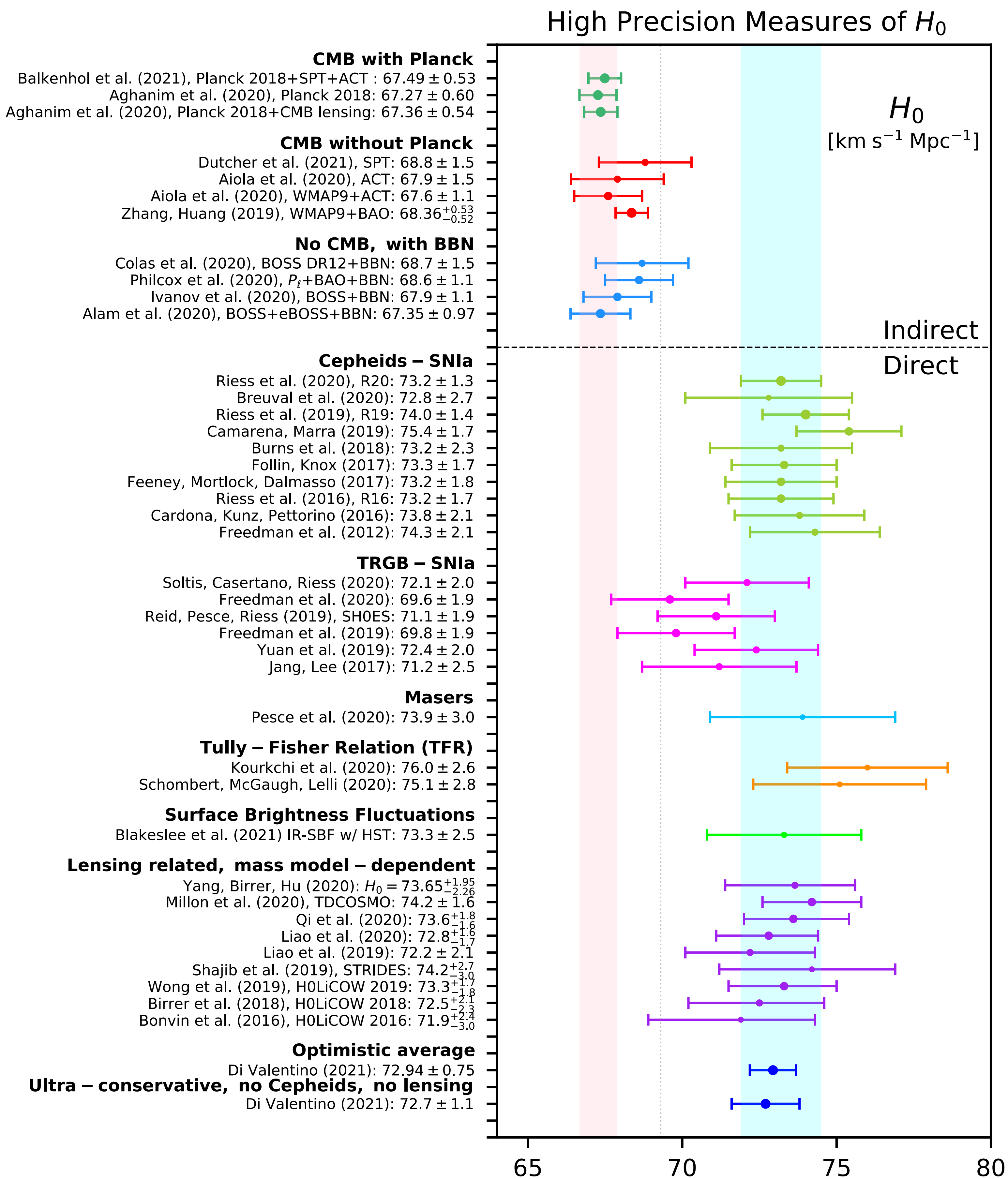


measure fluctuations **compute observables**

$$\Lambda CDM$$

$$\{H_0, \Omega_b, \Omega_m, A_s, n_s, \tau_{reio}\}$$

H0 tension



E. Di Valentino et al.
arXiv:2103.01183

See Gia Dvali's Talk:

It is hard to get de Sitter space-time from Quantum Gravity!

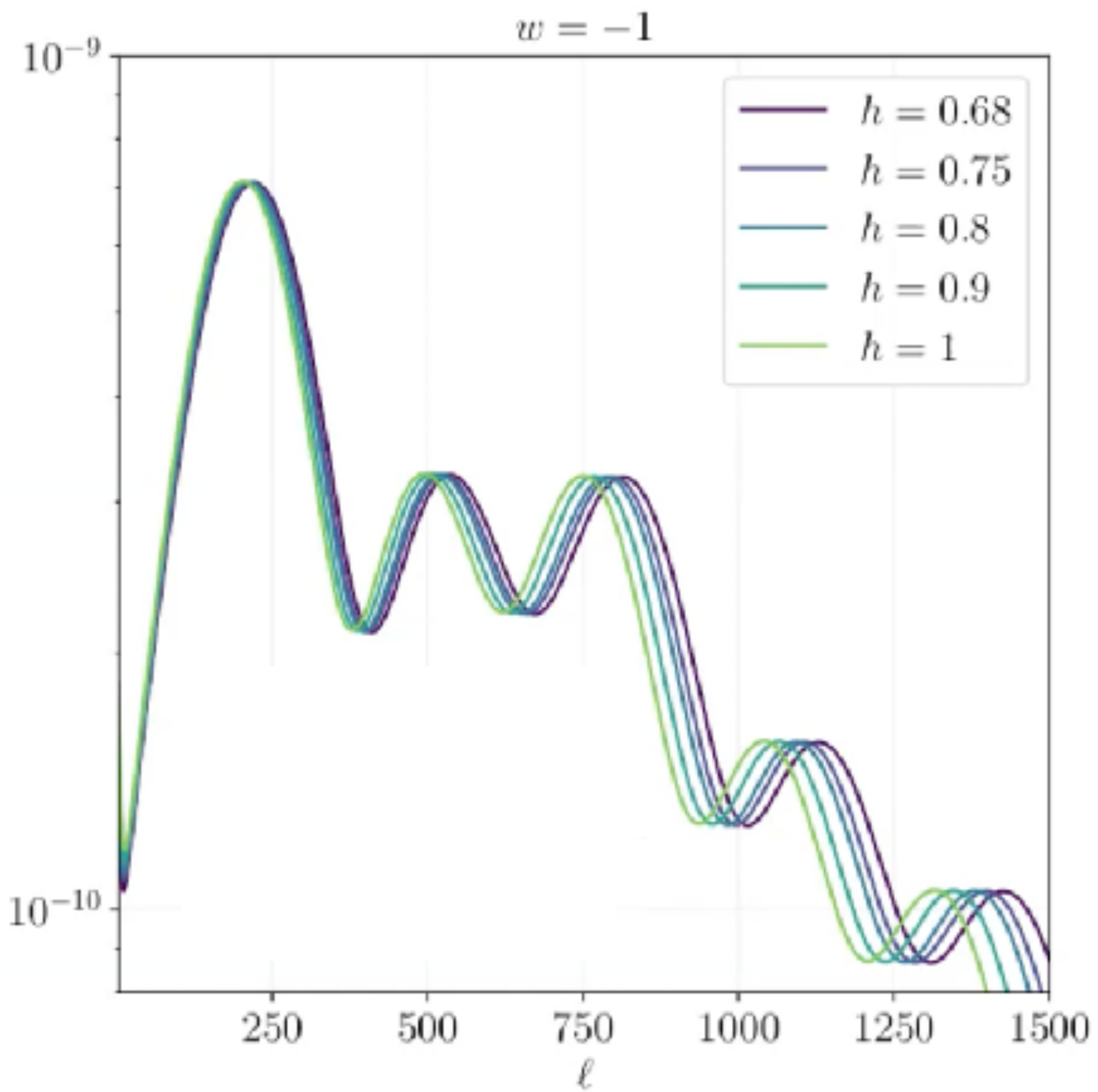
Early versus late-time solutions

We want $H_0 \uparrow$

We want $H_0 \uparrow$ **(or h$\uparrow$)**

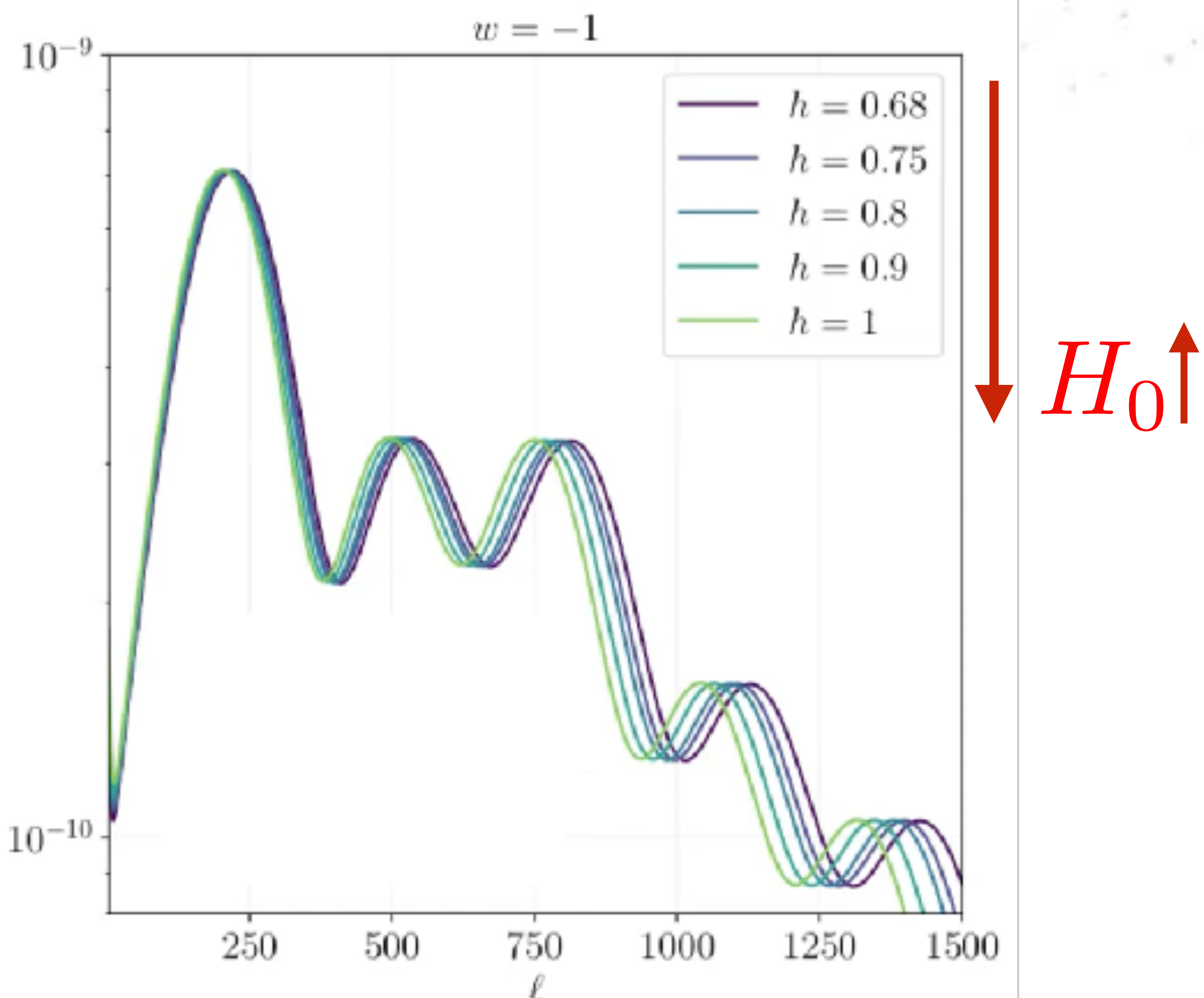
$$H_0 = H(\text{today}) = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Early versus late-time solutions



L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Early versus late-time solutions



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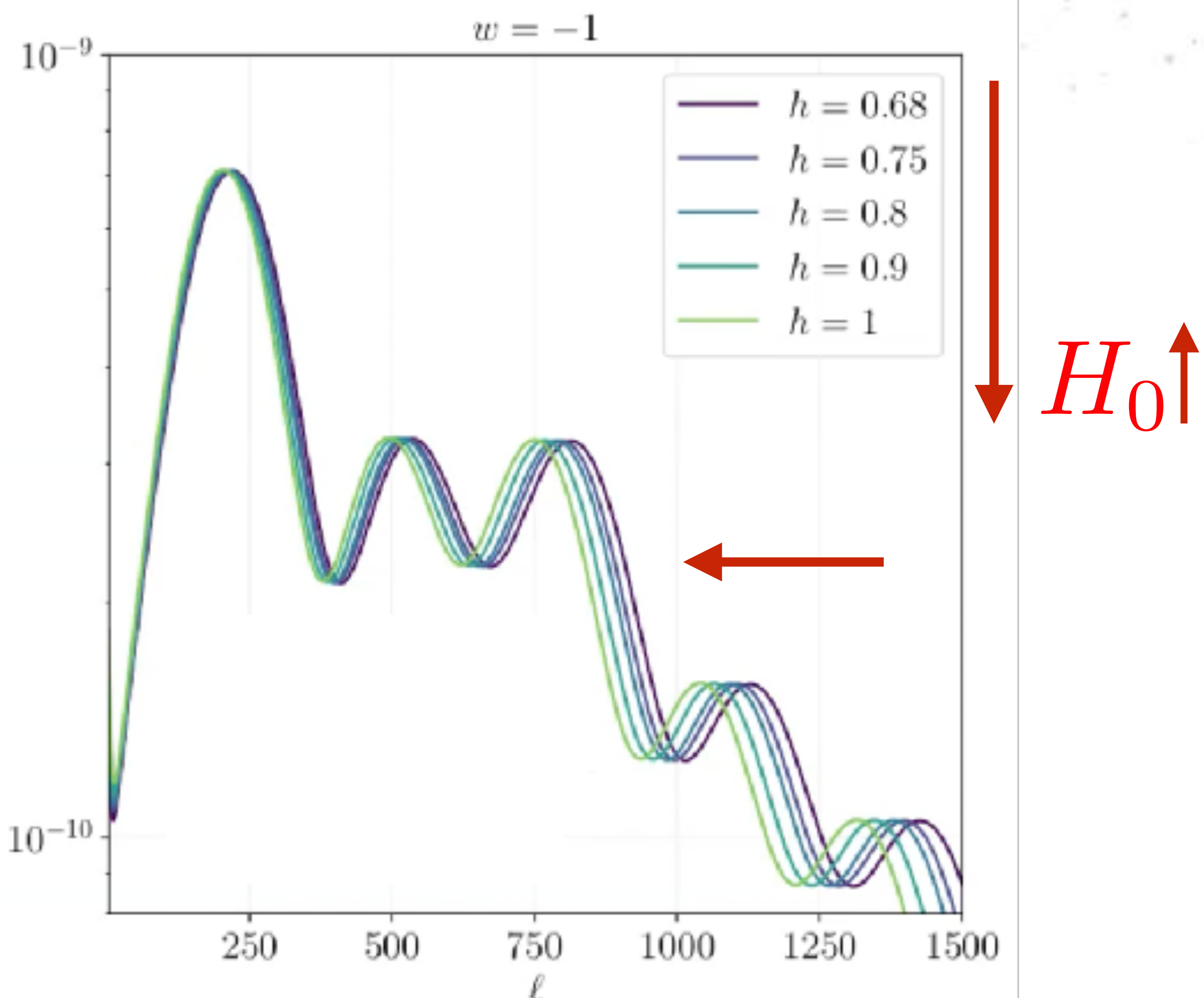

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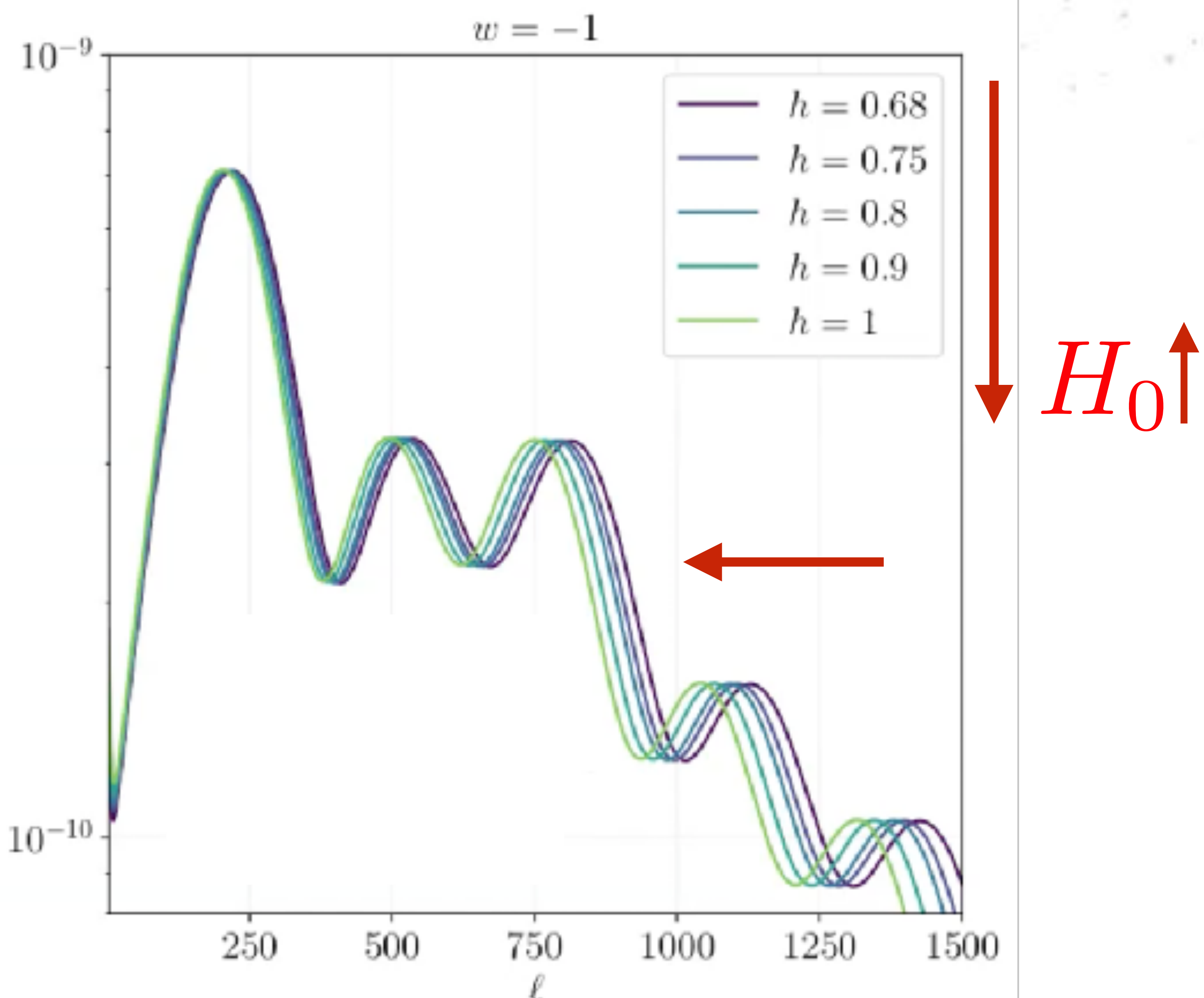
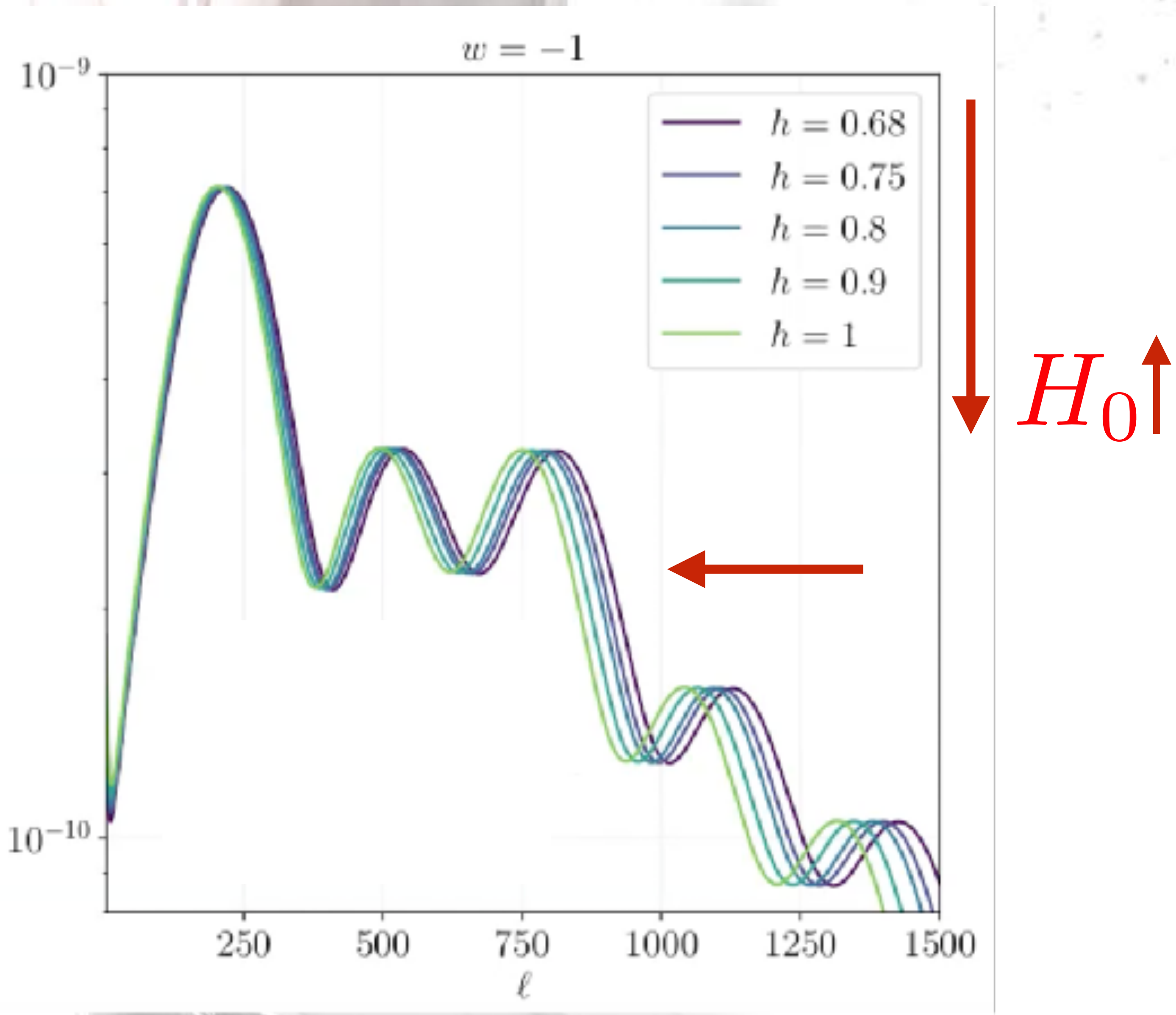


acoustic scale: overall position of the peaks

$$\theta_\star = \frac{r_s(z_\star)}{d_A(z_\star)}$$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Early versus late-time solutions



acoustic scale: overall position of the peaks

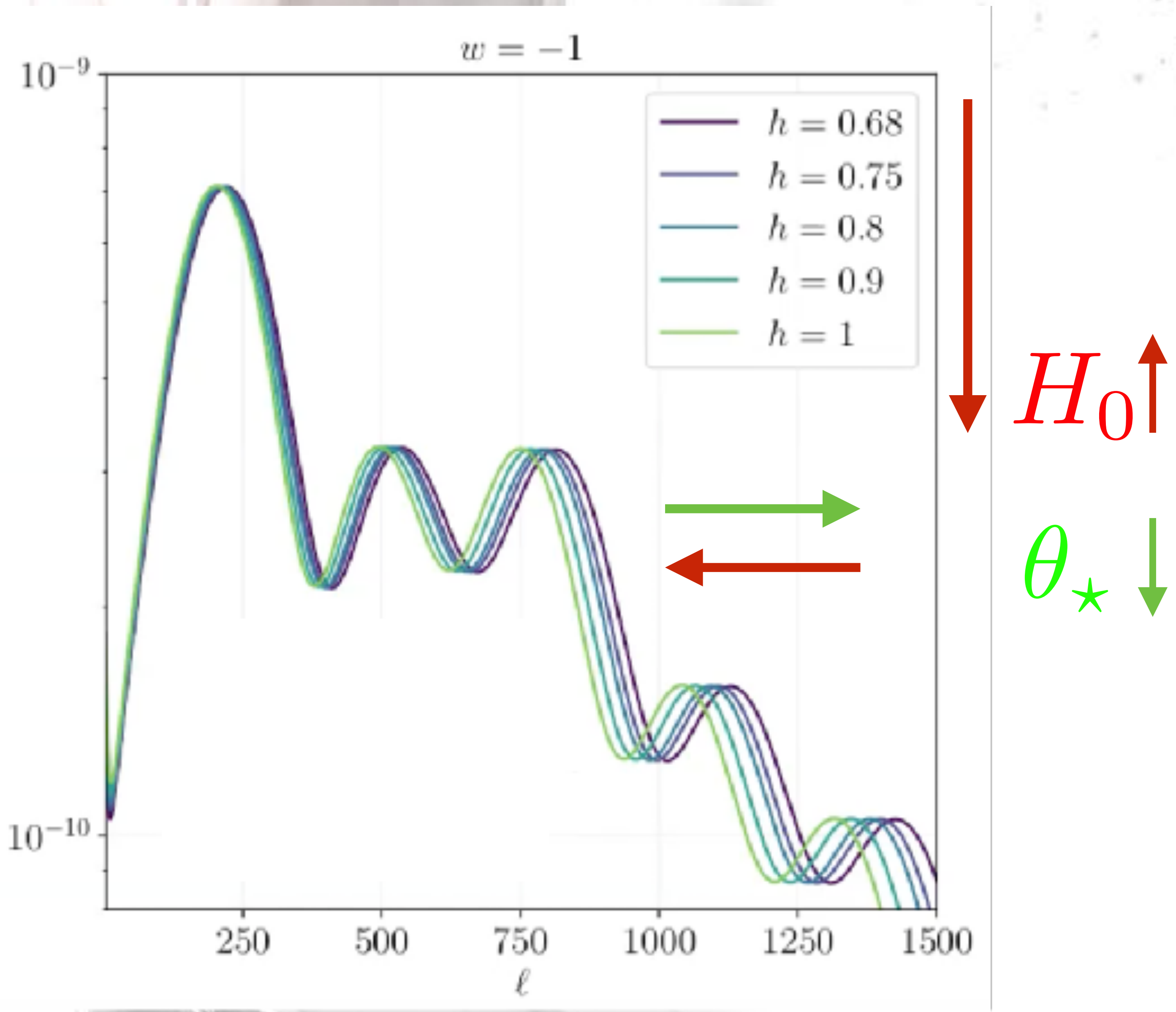
sound horizon

$$\theta_\star = \frac{r_s(z_\star)}{d_A(z_\star)}$$

angular diameter distance

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Early versus late-time solutions



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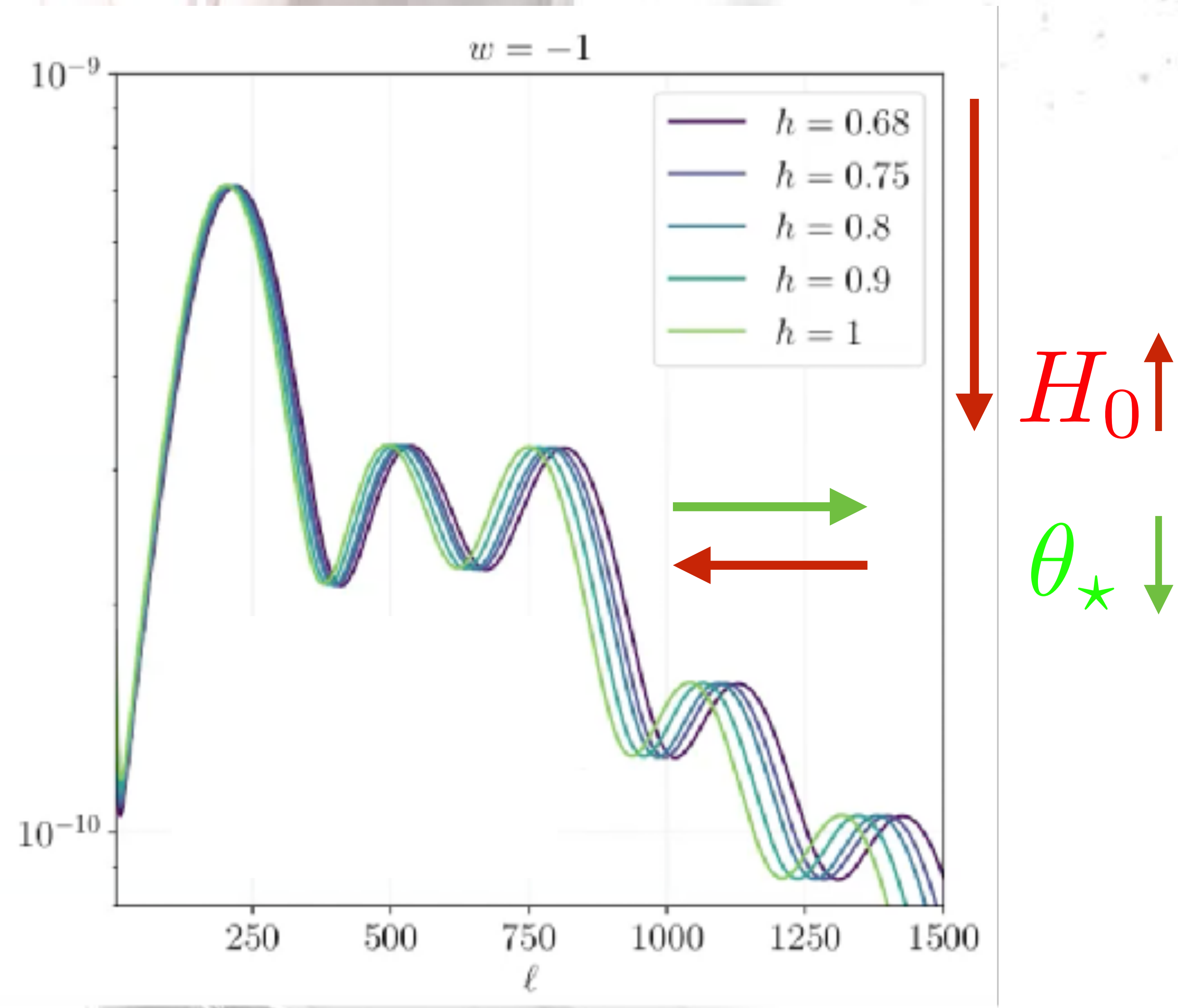


acoustic scale: overall position of the peaks

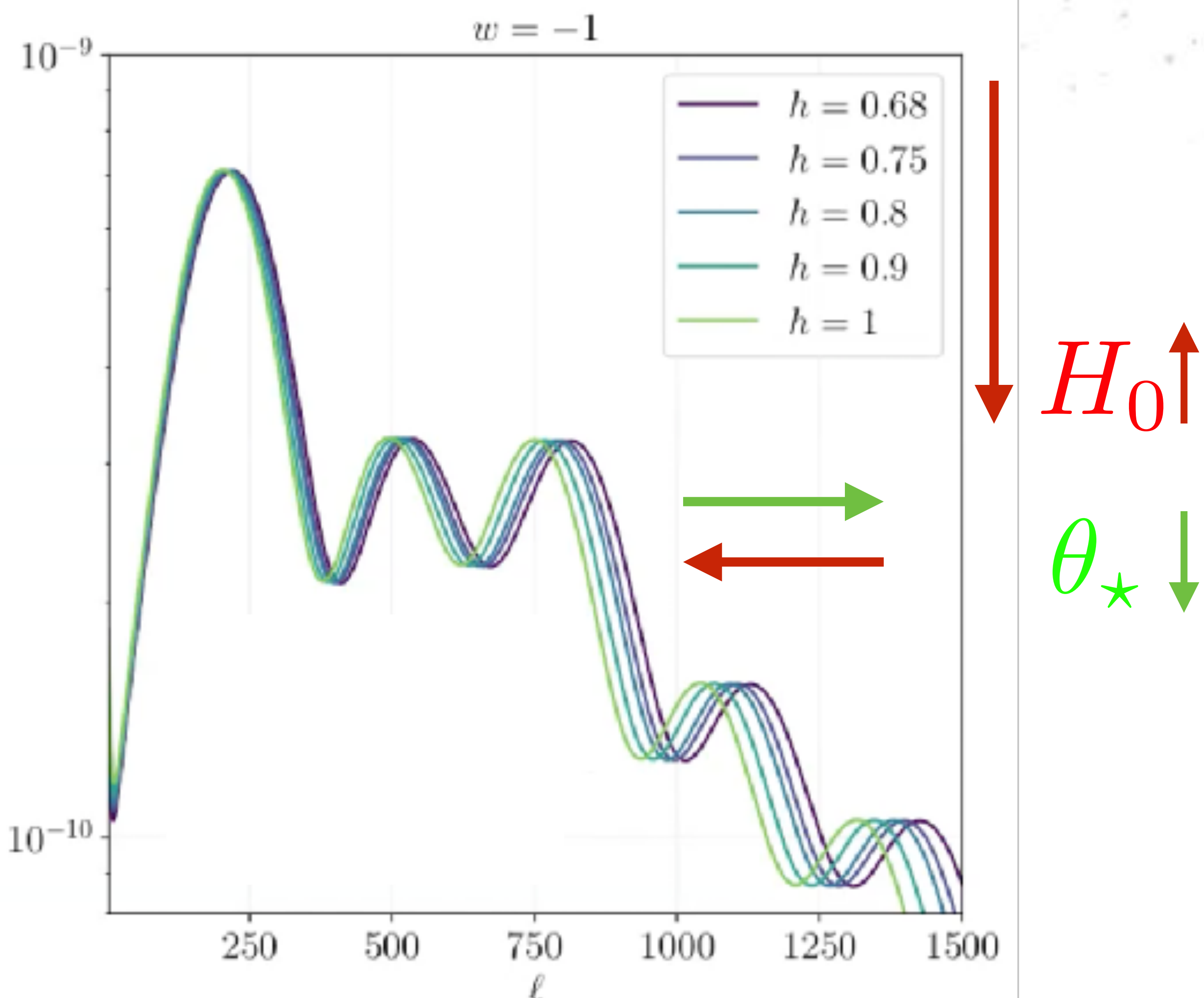
$$\theta_\star = \frac{r_s(z_\star)}{d_A(z_\star)}$$

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

Early H(z)

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Early versus late-time solutions



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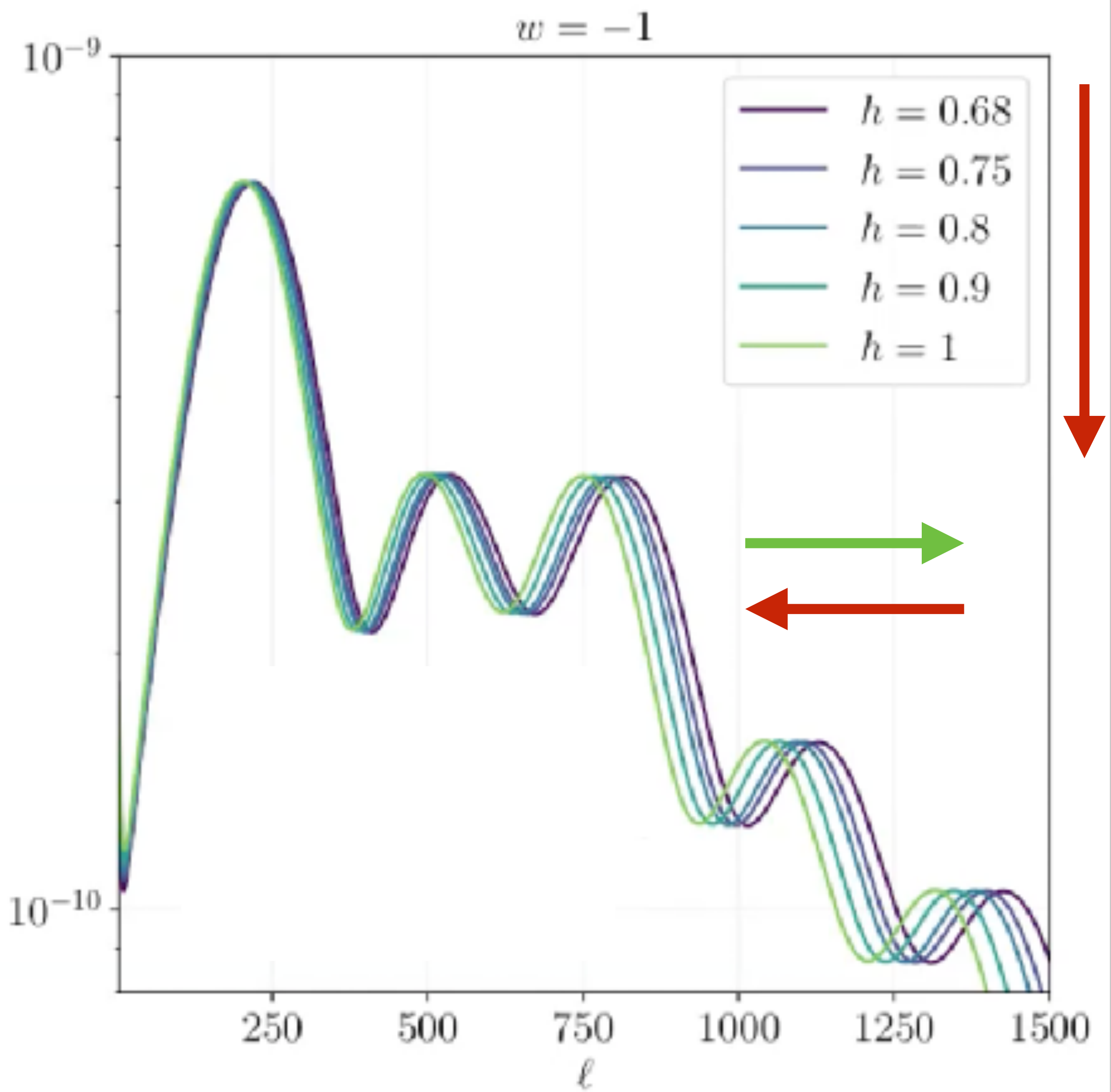
Late H(z)

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Early versus late-time solutions



$H_0 \uparrow$

$\theta_\star \downarrow$

acoustic scale: overall position of the peaks

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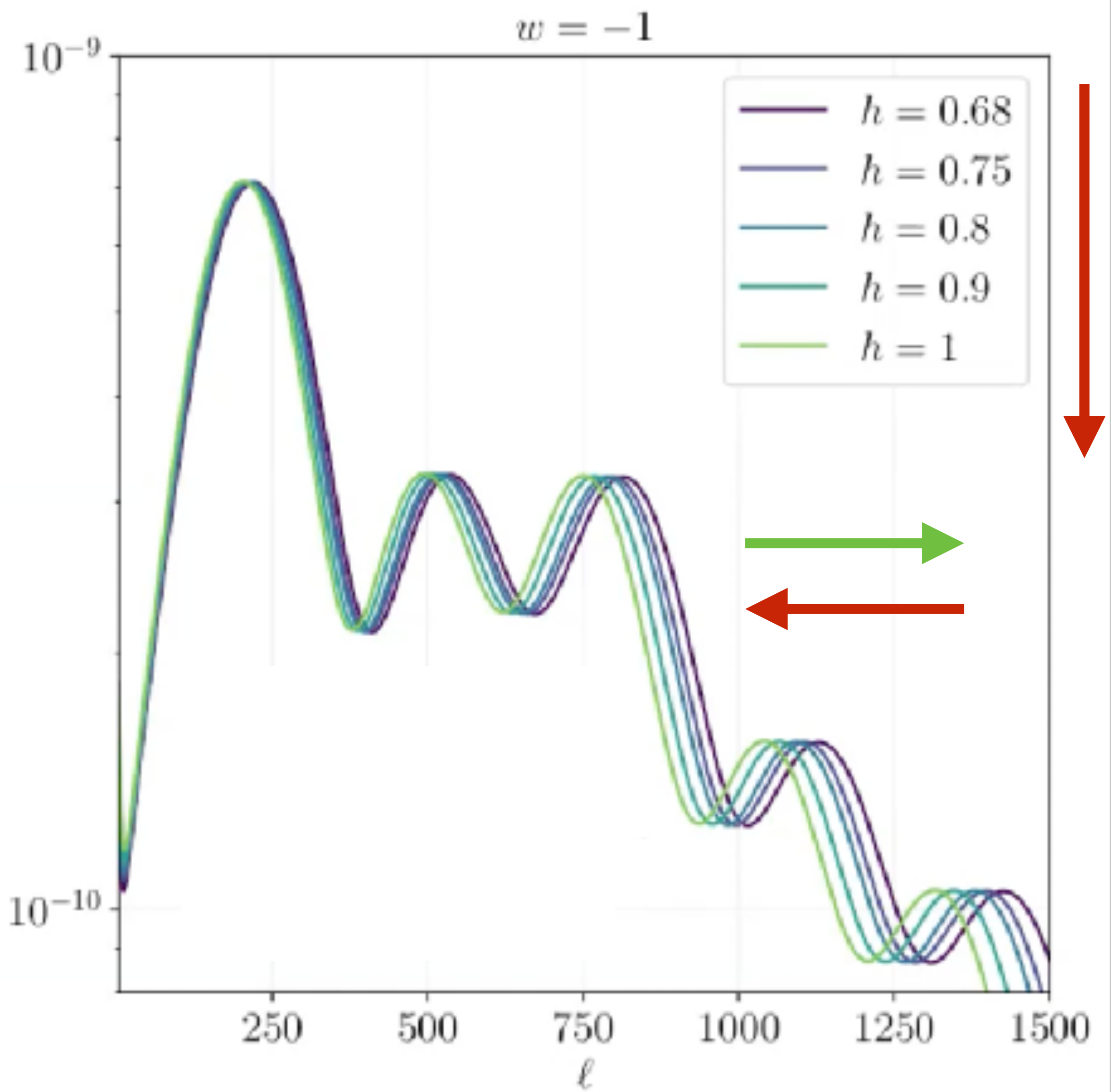
Early — **Early-time solutions** $r_s(z_\star) \downarrow$

Late — **Late-time solutions** $d_A(z_\star) \uparrow$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Early versus late-time solutions



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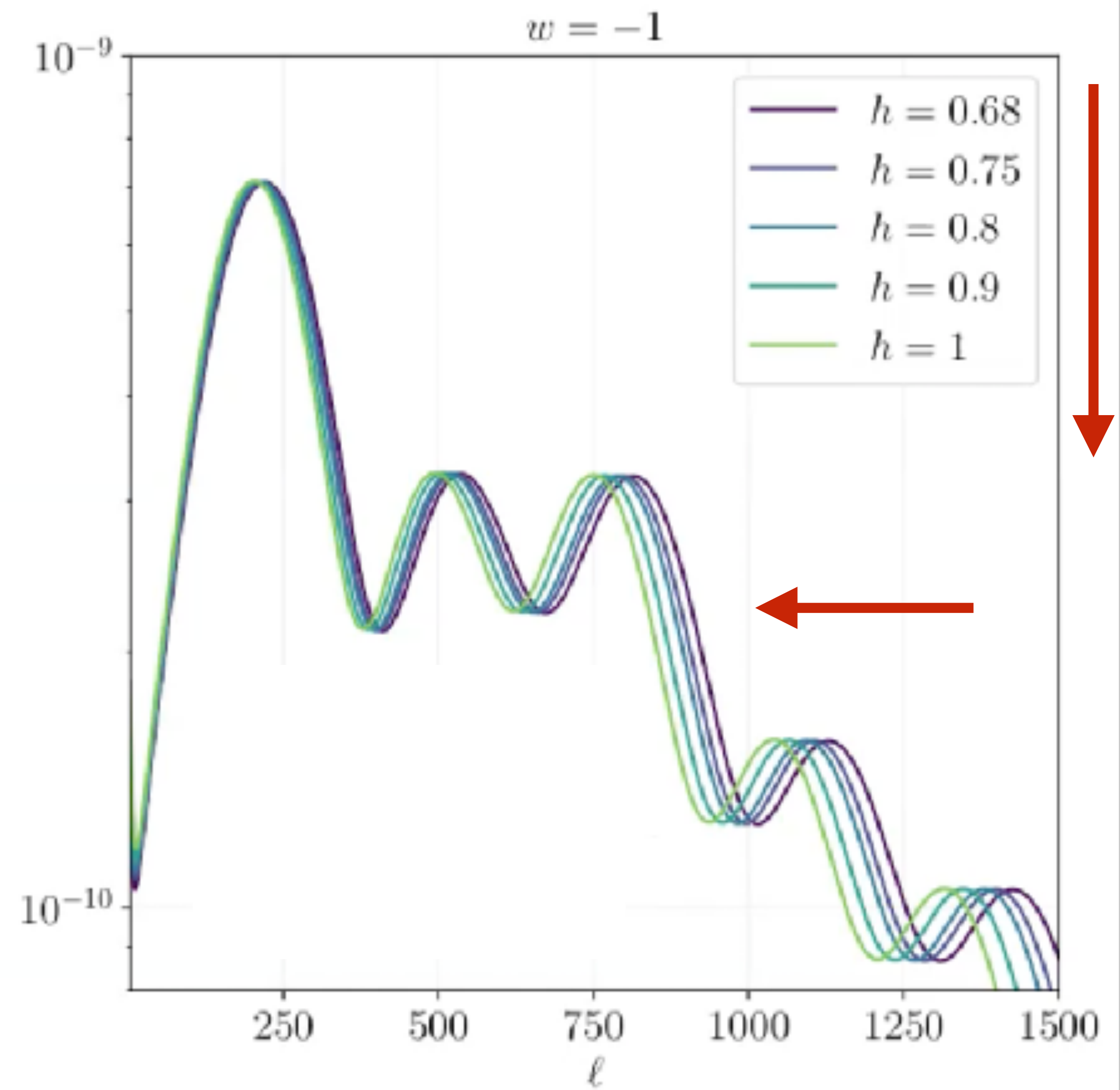
L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Late-time solutions

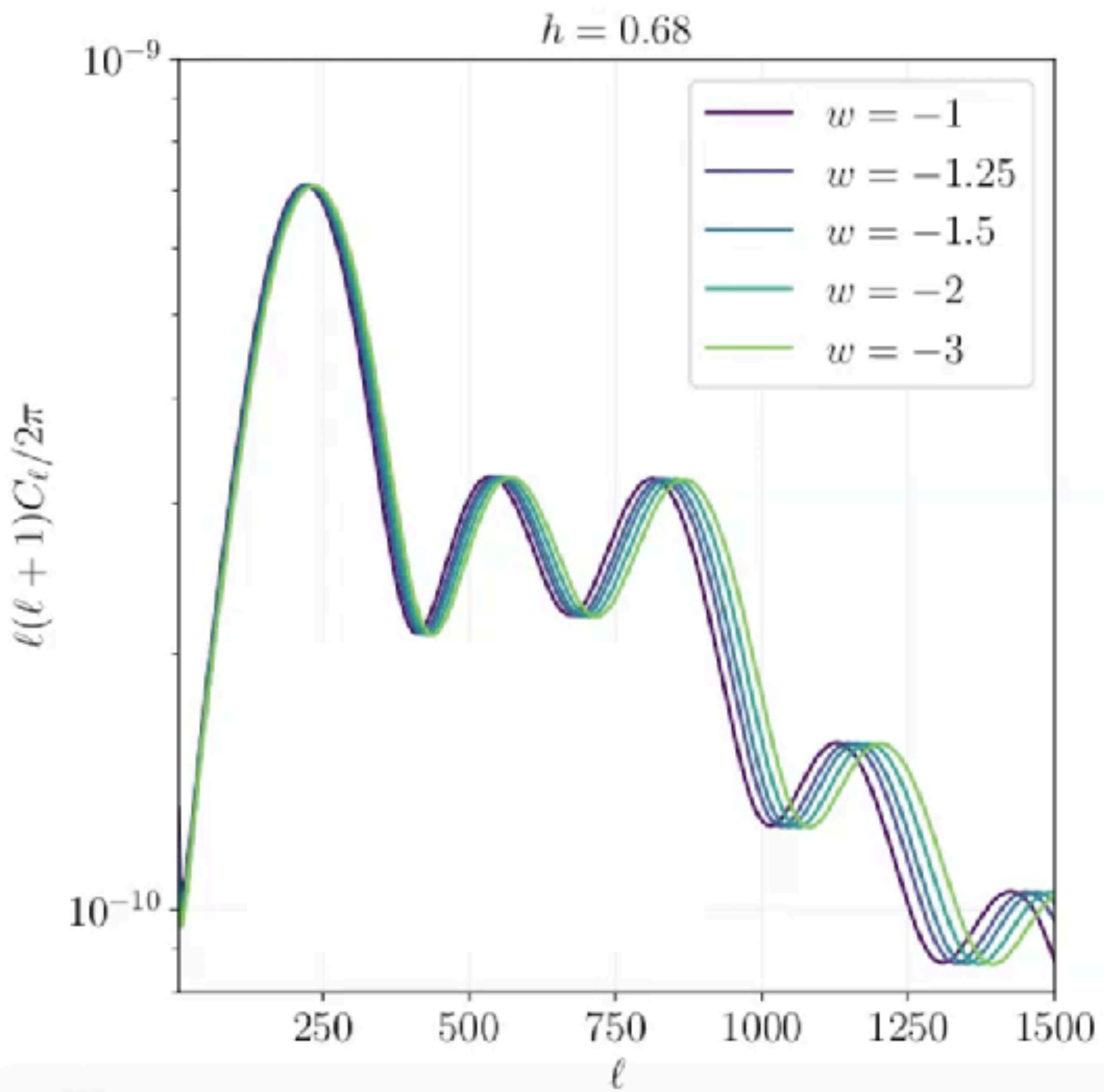
Late-time solutions



$H_0 \uparrow$

Late | Late-time solutions $d_A(z_\star) \uparrow$

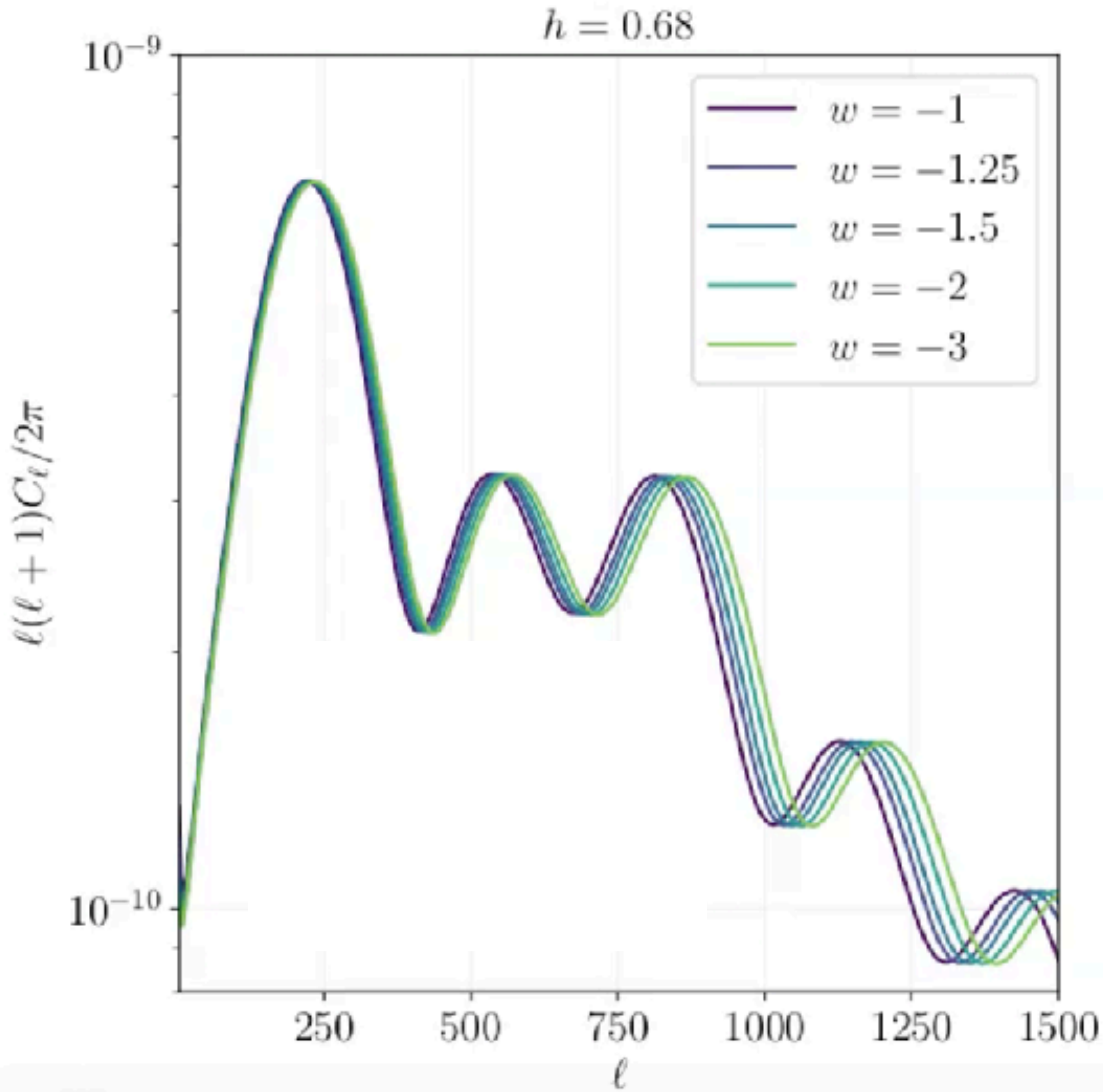
L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623



Late

Late-time solutions $d_A(z_\star)\uparrow$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623



$w \downarrow$

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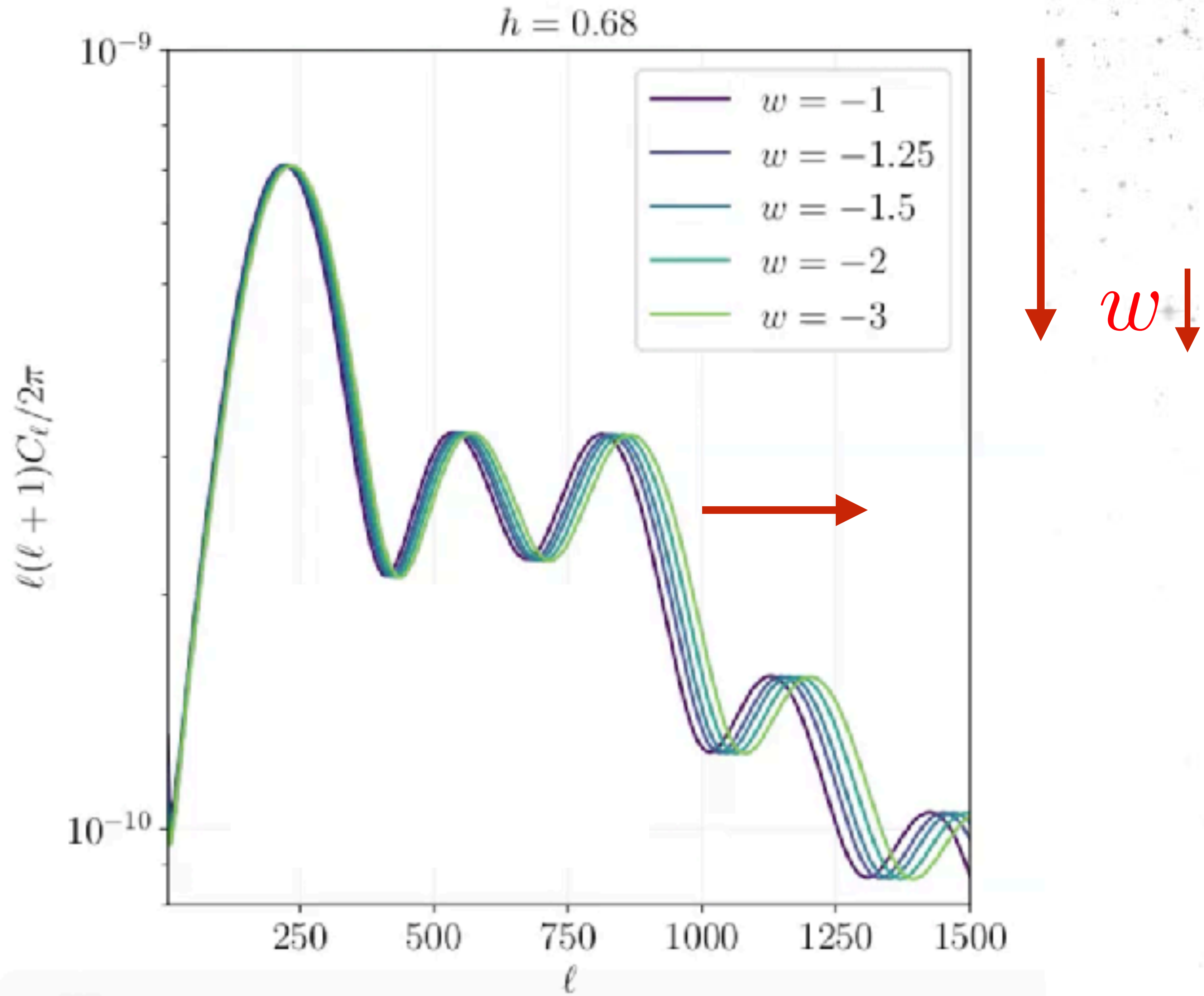
Late-time solutions $d_A(z_\star) \uparrow$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623



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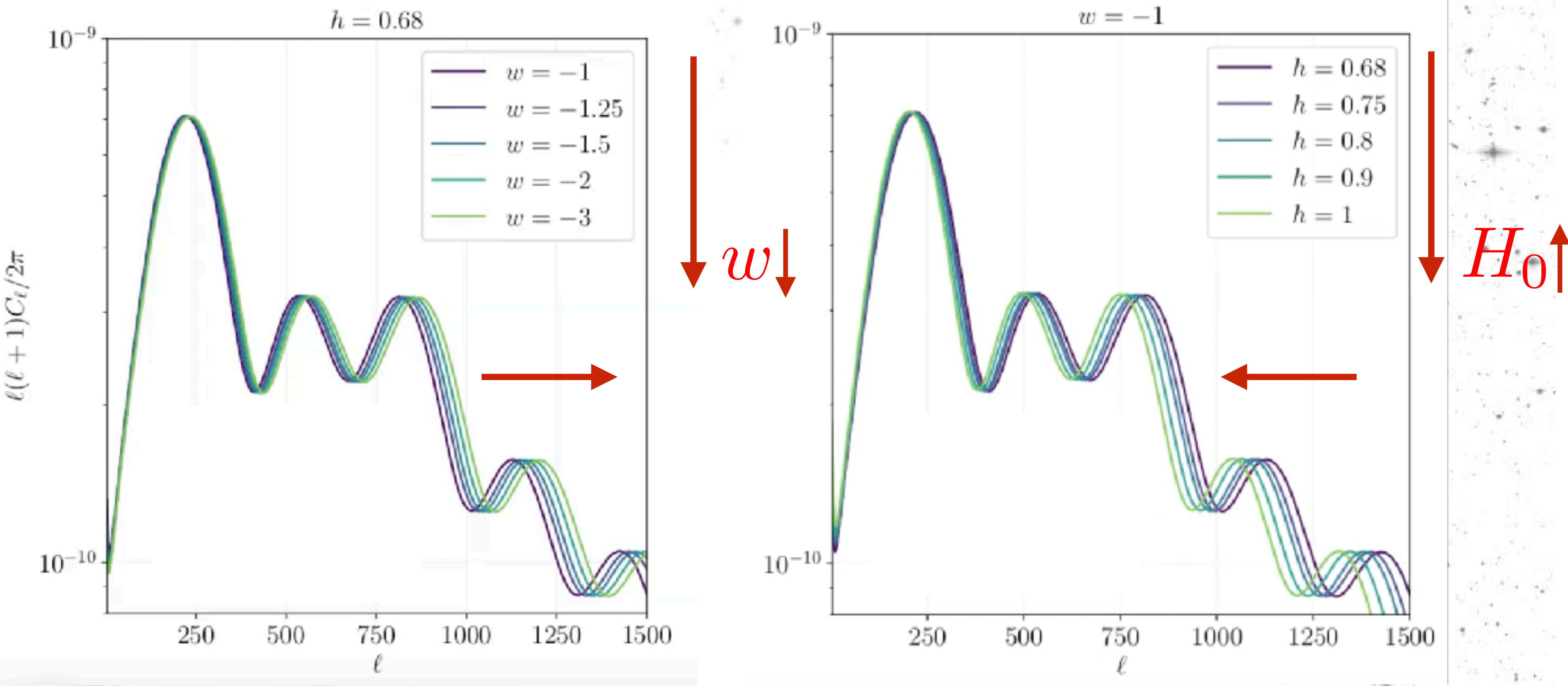
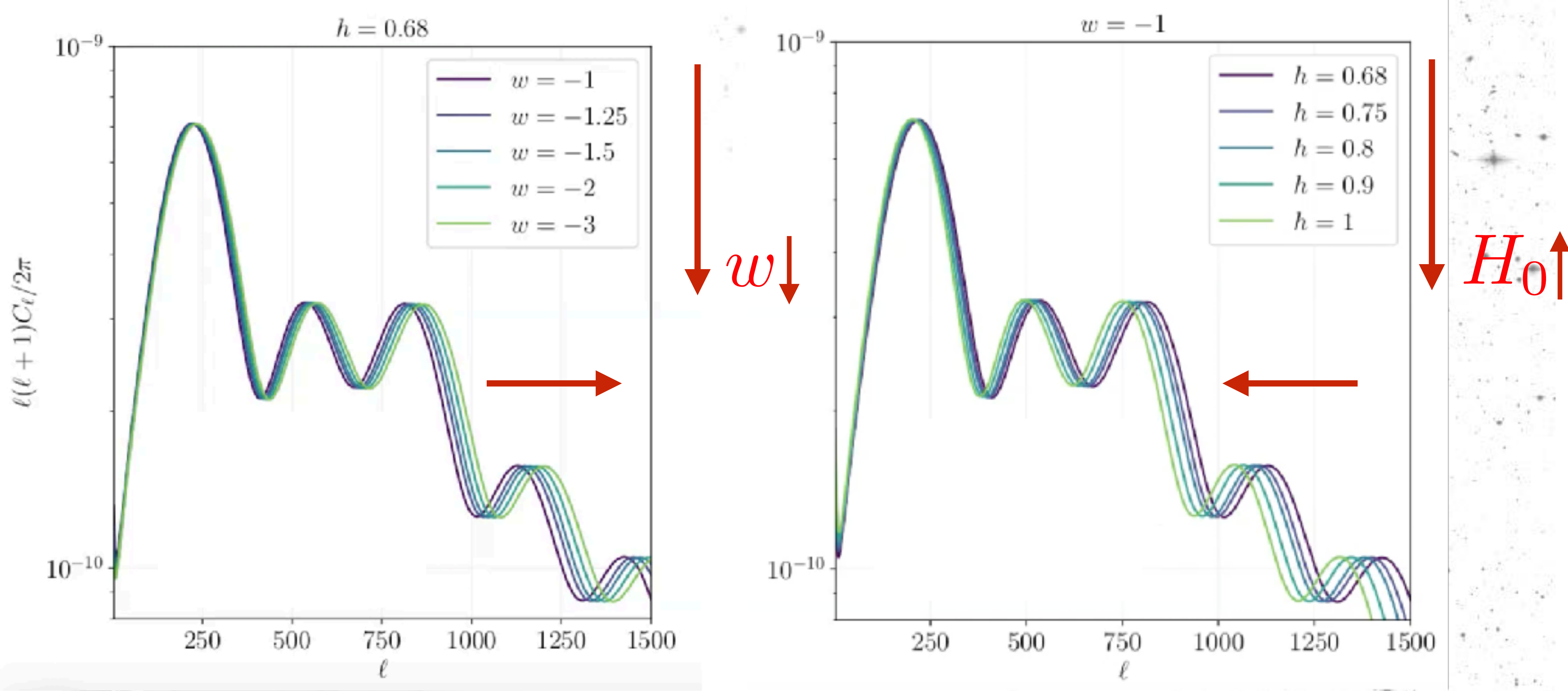
L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623



Late

Late-time solutions $d_A(z_\star)\uparrow$

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623



You need phantom DE! $w < -1$

Late

Late-time solutions $d_A(z_\star)\uparrow$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

A concrete example of a successful covariant theory

A_μ

Vector Field (Generalized Proca)

A_μ

Vector Field (Generalized Proca)

- second order equations of motion
- Lorentz invariant and local
- 3 propagating degrees of freedom

A_μ

Vector Field (Generalized Proca)

L. H., JCAP 1405, 015 (2014), arXiv:1402.7026
G.Tasinato JHEP 1404 (2014)067 arXiv:1402.6450
Allys, Peter, Rodriguez, JCAP 1602 (2016) 02, 004

L.H & J.Beltran, Phys.Lett.B757 (2016) 405-411, arXiv:1602.03410

- second order equations of motion
- Lorentz invariant and local
- 3 propagating degrees of freedom

$$\mathcal{L}_2 = f_2(A_\mu, F_{\mu\nu}, \tilde{F}_{\mu\nu})$$

$$\mathcal{L}_3 = f_3(A^2)\ \ \partial \cdot A$$

$$\mathcal{L}_4 = f_4(A^2)\ \ \left[(\partial \cdot A)^2 - \partial_\rho A_\sigma \partial^\sigma A^\rho\right]$$

$$\mathcal{L}_5 = f_5(A^2)\ \ \left[(\partial \cdot A)^3 - 3(\partial \cdot A)\partial_\rho A_\sigma \partial^\sigma A^\rho + 2\partial_\rho A_\sigma \partial^\gamma A^\rho \partial^\sigma A_\gamma\right] + \tilde{f}_5(A^2)\tilde{F}^{\alpha\mu}\tilde{F}^\beta{}_\mu \partial_\alpha A_\beta$$

$$\mathcal{L}_6 = f_6(A^2)\tilde{F}^{\alpha\beta}\tilde{F}^{\mu\nu}\partial_\alpha A_\mu \partial_\beta A_\nu$$

A_μ

Vector Field (Generalized Proca)

It was believed that a single vector field is in tension with

A_μ

Vector Field (Generalized Proca)

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CP Cosmological Principle → Homogeneity & Isotropy

A_μ Vector Field (Generalized Proca)

It was believed that a single vector field is in tension with

CP Cosmological Principle → Homogeneity & Isotropy

and therefore not appropriate for dark energy applications.

Vector Field (Generalized Proca)

- Generalized Proca iniated a radiacal change of view!

Vector Field (Generalized Proca)

→ **Generalized Proca iniated a radiacal change of view!**

$$A_\mu = (A_0(t), 0, 0, 0)$$

Vector Field (Generalized Proca)

→ **Generalized Proca iniated a radiacal change of view!**

GR + $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(-\frac{1}{2}A_\mu A^\mu) + G_3(-\frac{1}{2}A_\mu A^\mu)\nabla_\alpha A^\alpha$

Vector Field (Generalized Proca)

→ **Generalized Proca iniated a radiacal change of view!**

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G.Tasinato JHEP 1404 (2014)067
arXiv:1402.6450

L.H. & de Felice,Kase,Mukohyama,
Tsujikawa,Zhang, JCAP
1606,2016,06,048, arXiv:1603.05806

- Dark Energy fixed point

Vector Field (Generalized Proca)

GR +

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(-\frac{1}{2}A_\mu A^\mu) + G_3(-\frac{1}{2}A_\mu A^\mu)\nabla_\alpha A^\alpha$$

Vector Field (Generalized Proca)

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- **Reduces the H_0 tension and delivers a better fit to data**

L.H. & de Felice,Tsujikawa, PRD95 (2017)12, 123540, arXiv:1703.09573

Vector Field (Generalized Proca)

GR + $$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(-\frac{1}{2}A_\mu A^\mu) + G_3(-\frac{1}{2}A_\mu A^\mu)\nabla_\alpha A^\alpha$$

Linear perturbations

L.H & H. Villarrubia Rojo
arxiv:2010.00513

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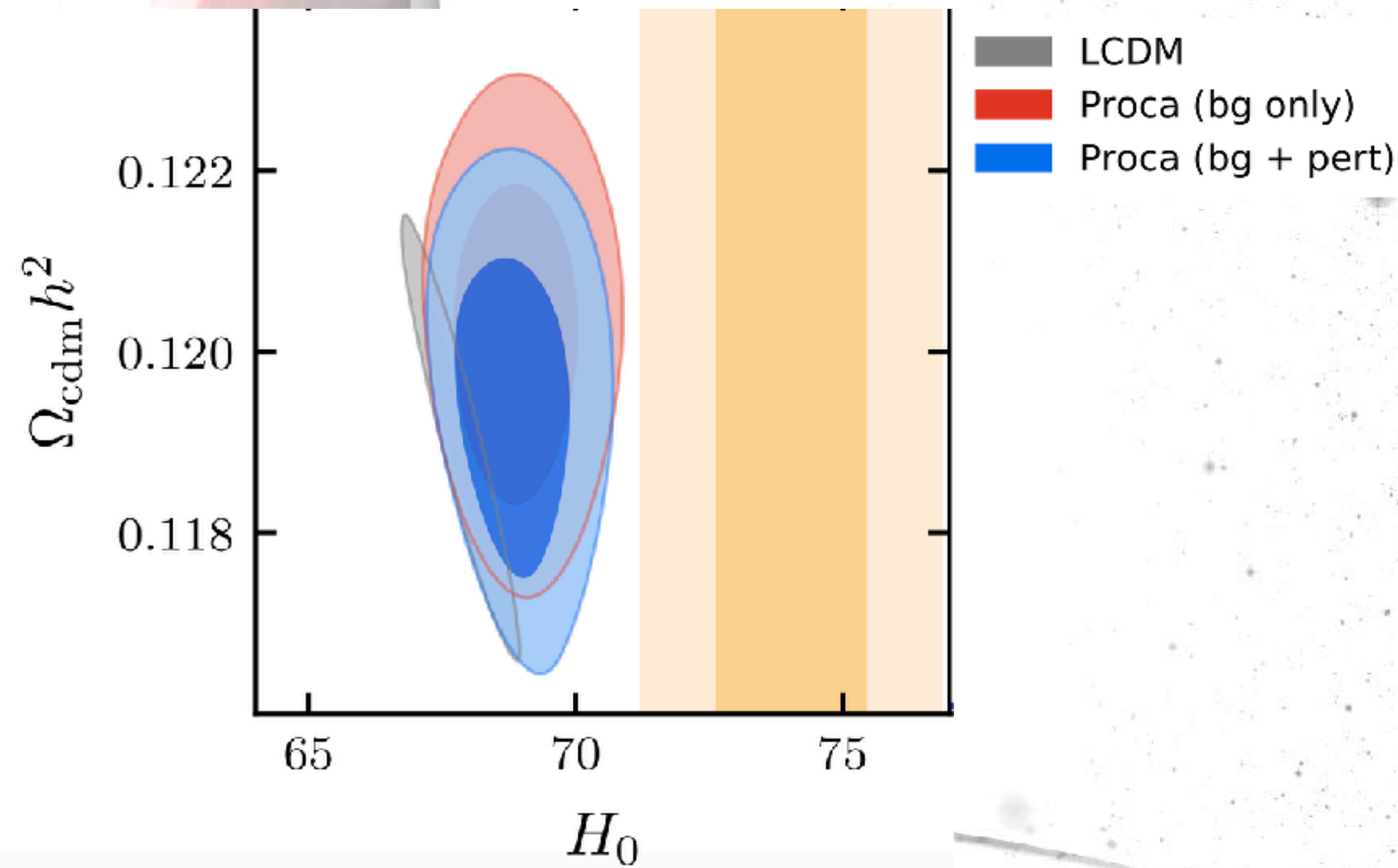
Linear perturbations → **Embedding into a Boltzman code**

L.H & H. Villarrubia Rojo
arxiv:2010.00513

Vector Field (Generalized Proca)



L.H & H. Villarrubia Rojo
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Linear perturbations → **Embedding into a Boltzman code**

At the background level, it gives phantom DE $w < -1$

At the perturbation level, non-trivial contribution from additional dof.

L.H & H. Villarrubia Rojo
arxiv:2010.00513

σ_8

How can we measure

$$\sigma_8$$

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GR General Relativity

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Cosmology describes the Universe with 2 fundamental pillars

GR General Relativity

CP Cosmological Principle → ~~Homogeneity & Isotropy~~

+ small perturbations

How can we measure sigma8?

How can we measure sigma8?

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

↑

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$$ **perturbations**

$$T_{\mu\nu} = \bar{T}_{\mu\nu} + \delta T_{\mu\nu} \rightarrow \{\delta\rho, \delta\vec{P}\}$$

How can we measure sigma8?

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$$

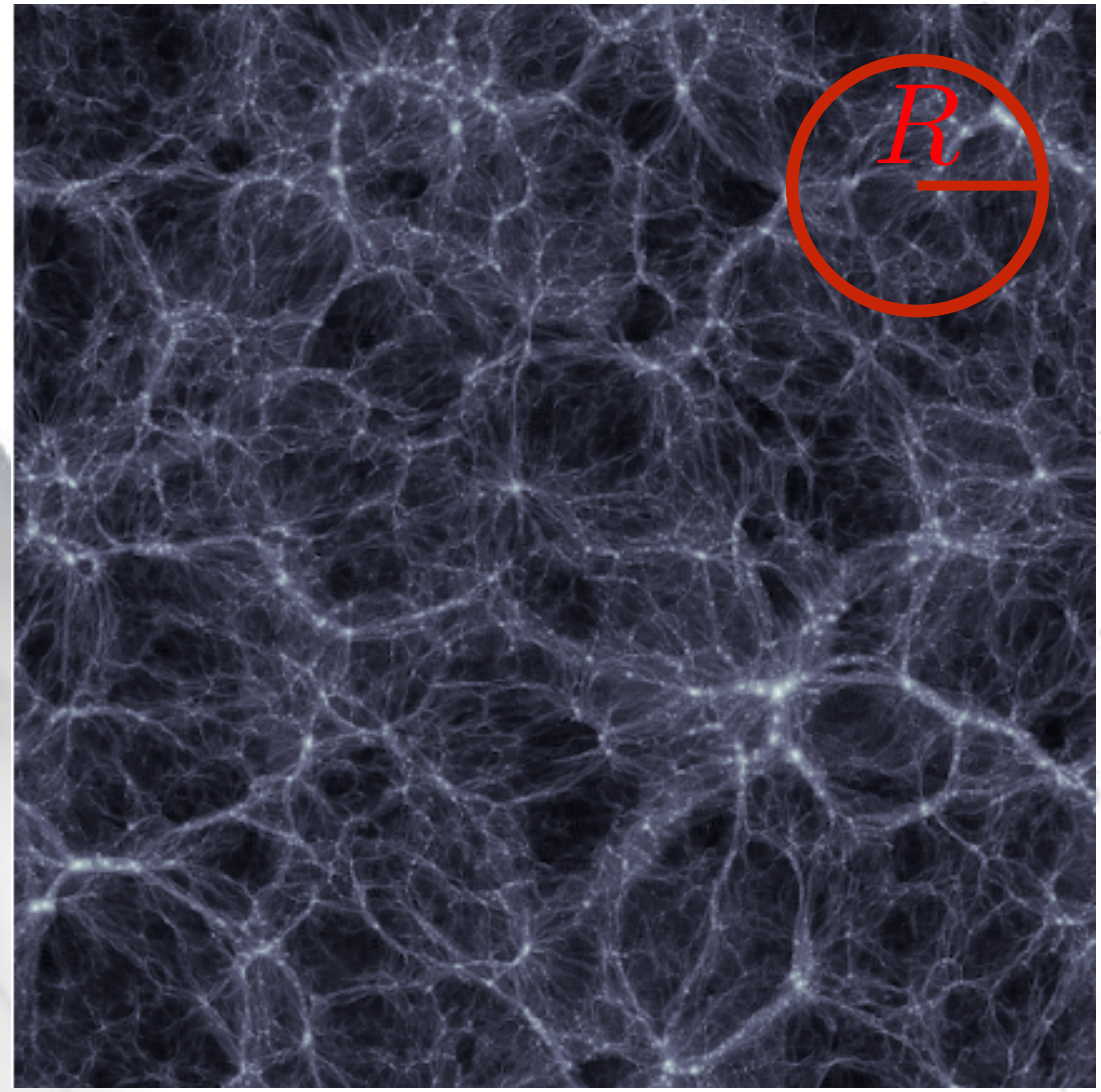
perturbations

$$T_{\mu\nu} = \bar{T}_{\mu\nu} + \delta T_{\mu\nu} \rightarrow \{\delta\rho, \delta\vec{P}\}$$

Matter overdensity

$$\delta_m = \frac{\delta\rho_m - \bar{\rho}_m}{\bar{\rho}_m}$$

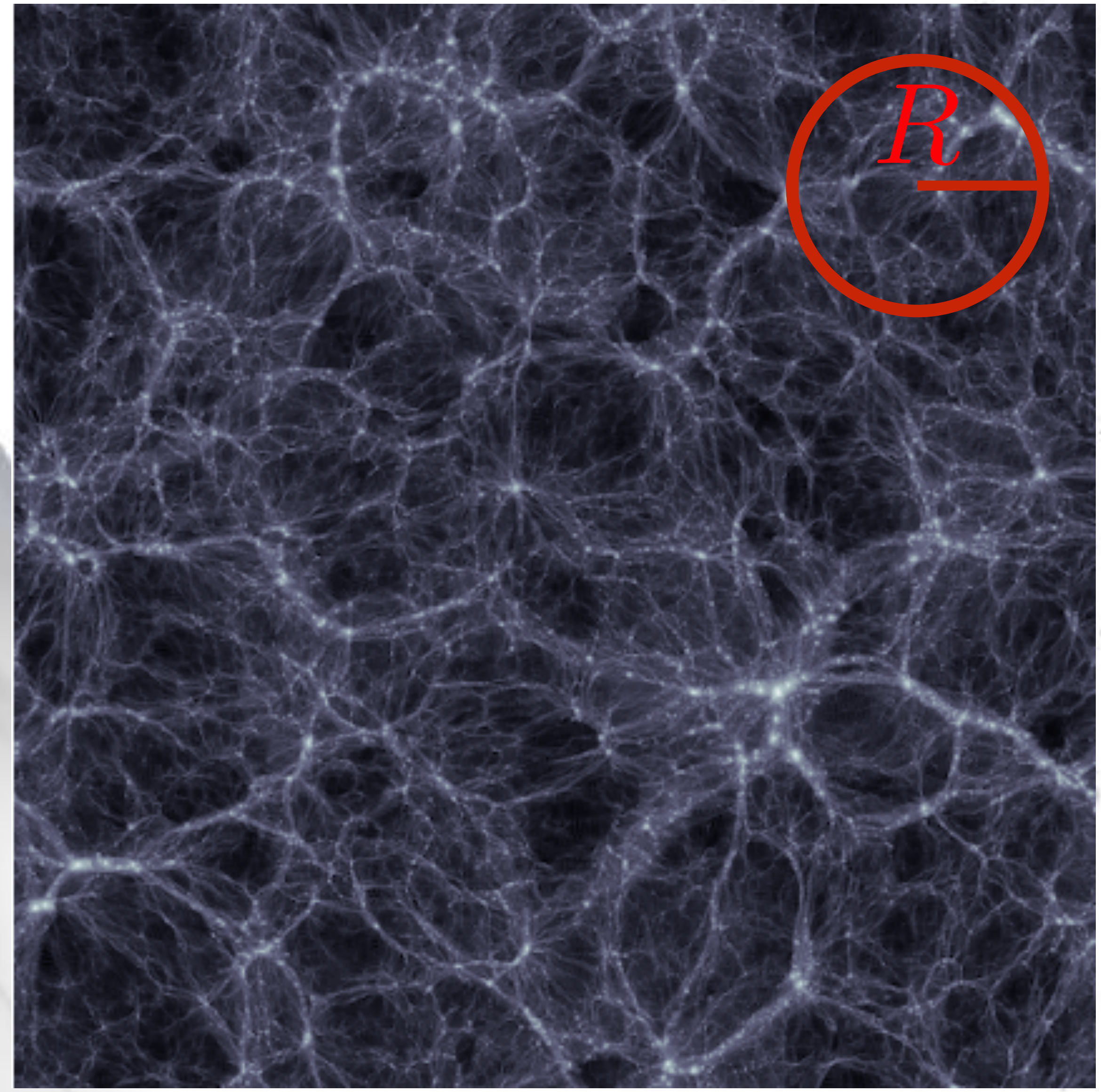
How can we measure sigma8?



Matter overdensity

$$\delta_m = \frac{\delta\rho_m - \bar{\rho}_m}{\bar{\rho}_m} \qquad \delta_R =$$

How can we measure sigma8?

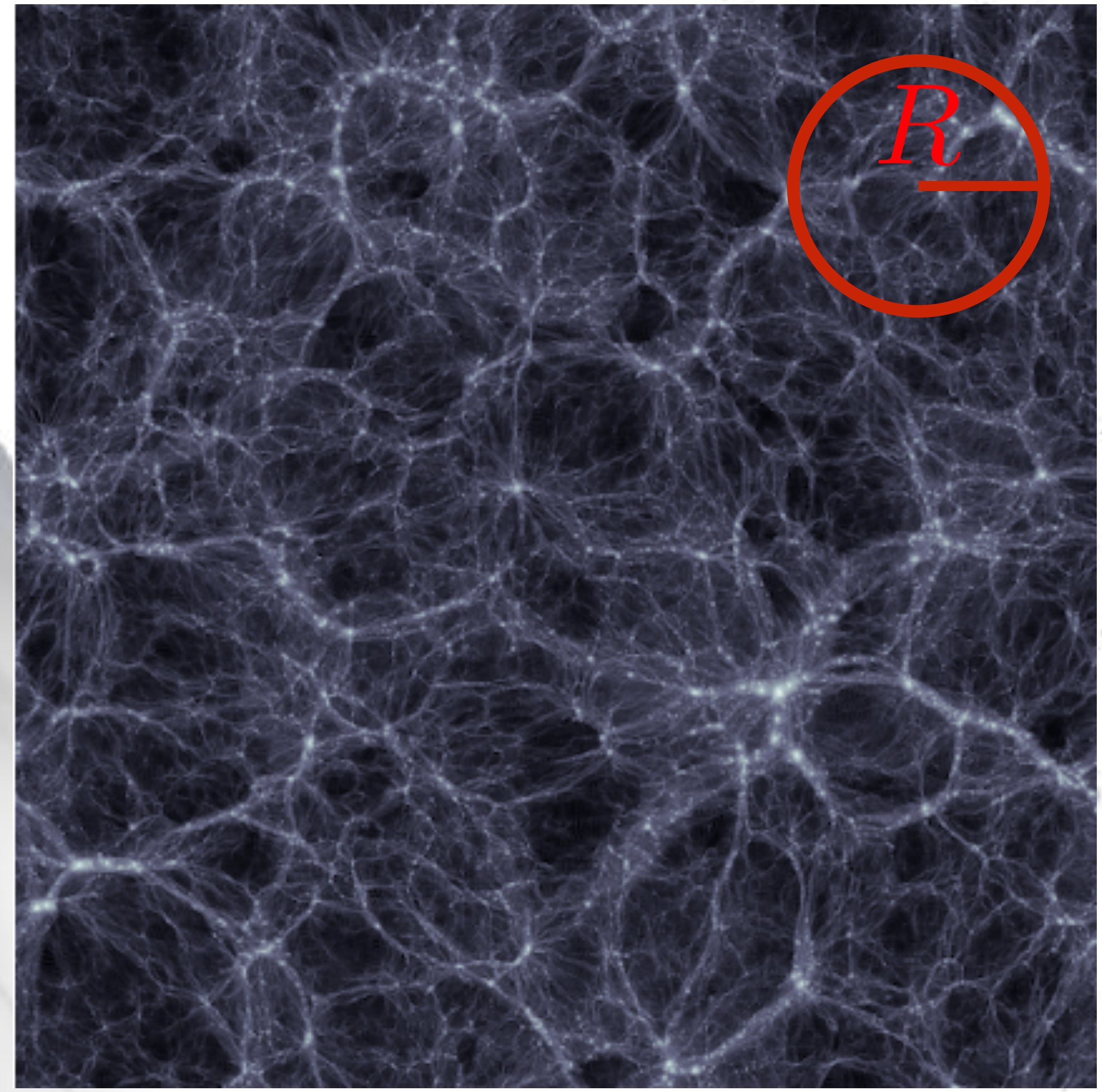


Matter overdensity

$$\delta_m = \frac{\delta\rho_m - \bar{\rho}_m}{\bar{\rho}_m}$$

$$\delta_R = \int_{x<R} \frac{d^3x}{V}\delta_m$$

How can we measure sigma8?

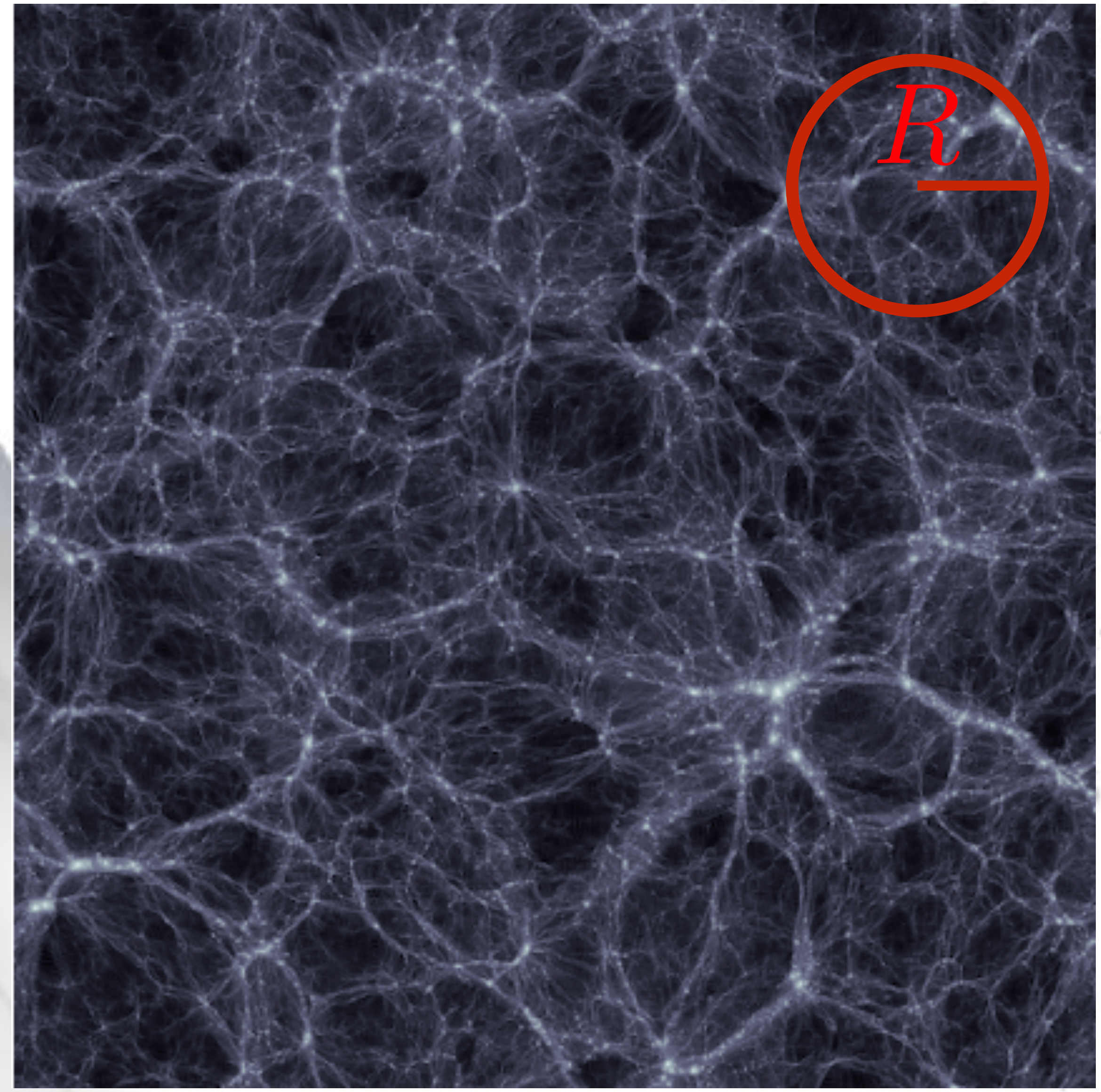


Statistics

$$\langle \delta_R^2(x) \rangle = \sigma_R^2$$

$$\delta_R = \int_{x<R} \frac{d^3x}{V} \delta_m$$

How can we measure sigma8?



Statistics

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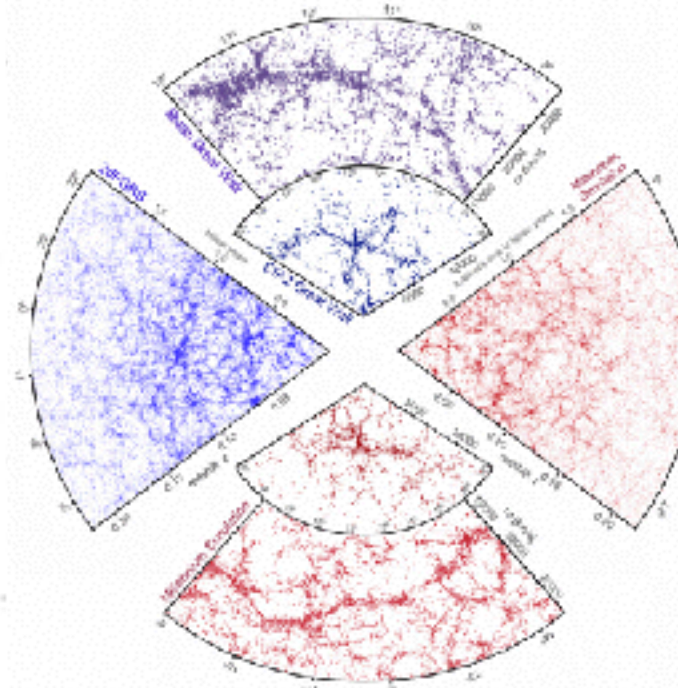
$$\delta_R = \int_{x<R} \frac{d^3x}{V} \delta_m$$

$$R = 8 \text{ Mpc } h^{-1} \rightarrow \sigma_8$$

How can we measure sigma8?

- **galaxy surveys**



Statistics

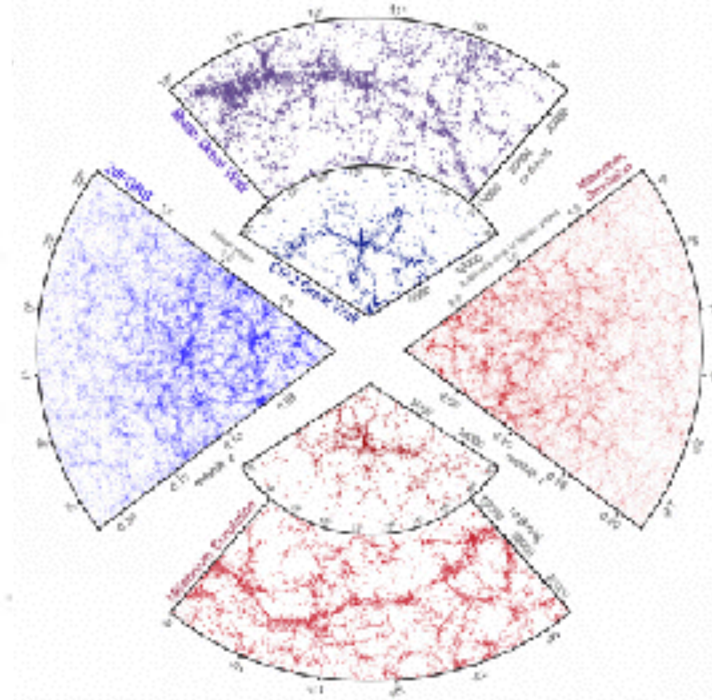
$$\langle \delta_R^2(x) \rangle = \sigma_R^2$$

$$\delta_R = \int_{x<R} \frac{d^3x}{V} \delta_m$$

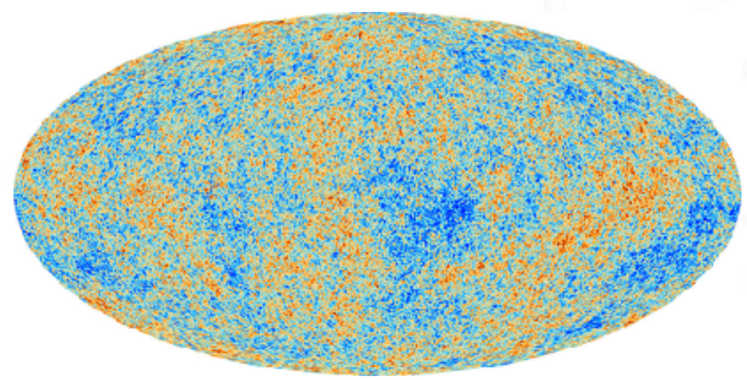
$$R = 8 \text{ Mpc } h^{-1} \rightarrow \sigma_8$$

How can we measure sigma8?

- galaxy surveys



- CMB



$$\Lambda CDM$$

$$\{H_0, \Omega_b, \Omega_m, A_s, n_s, \tau_{reio}\}$$

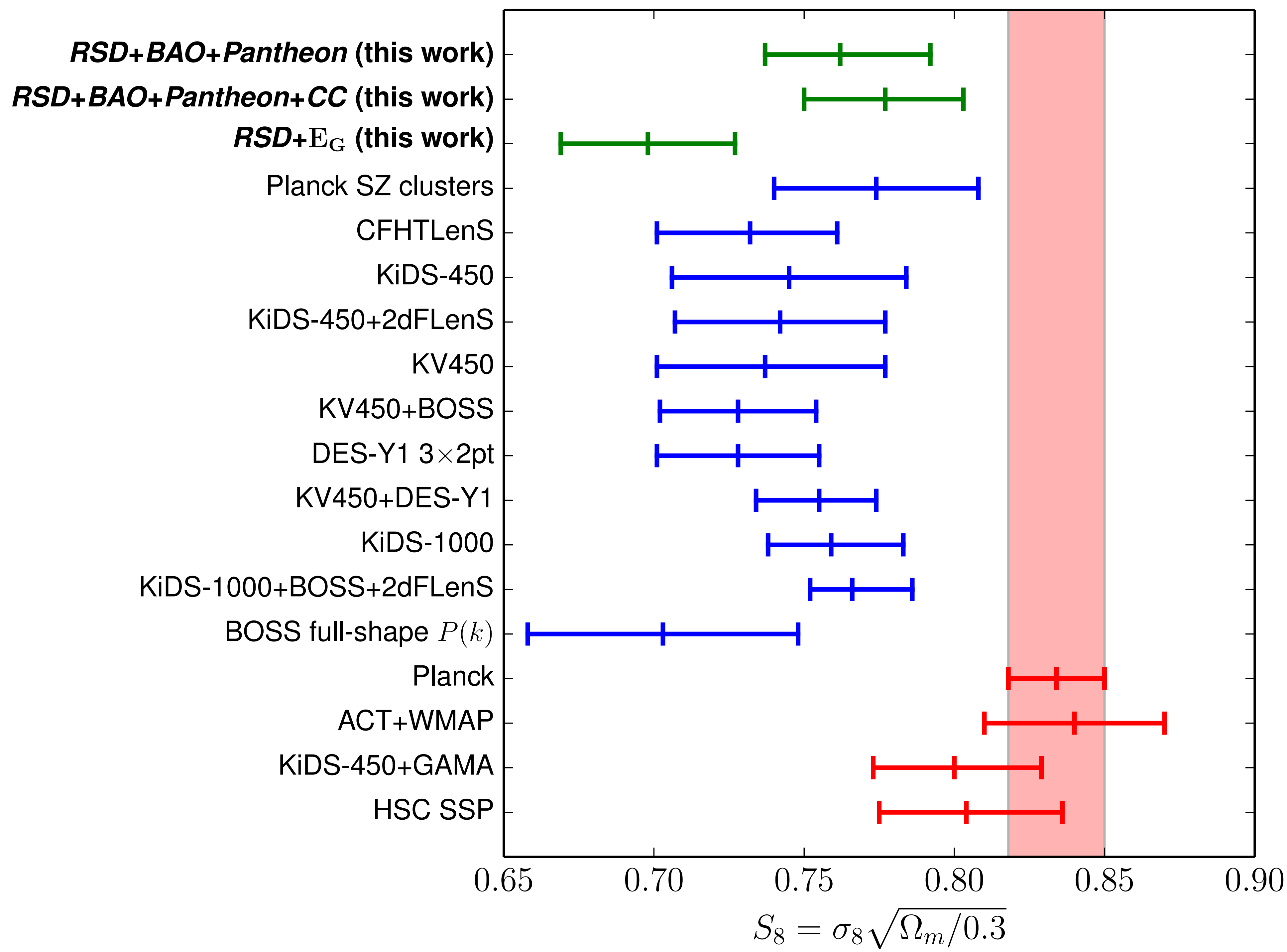
Statistics

$$\langle \delta_R^2(x) \rangle = \sigma_R^2$$

$$\delta_R = \int_{x<R} \frac{d^3x}{V} \delta_m$$

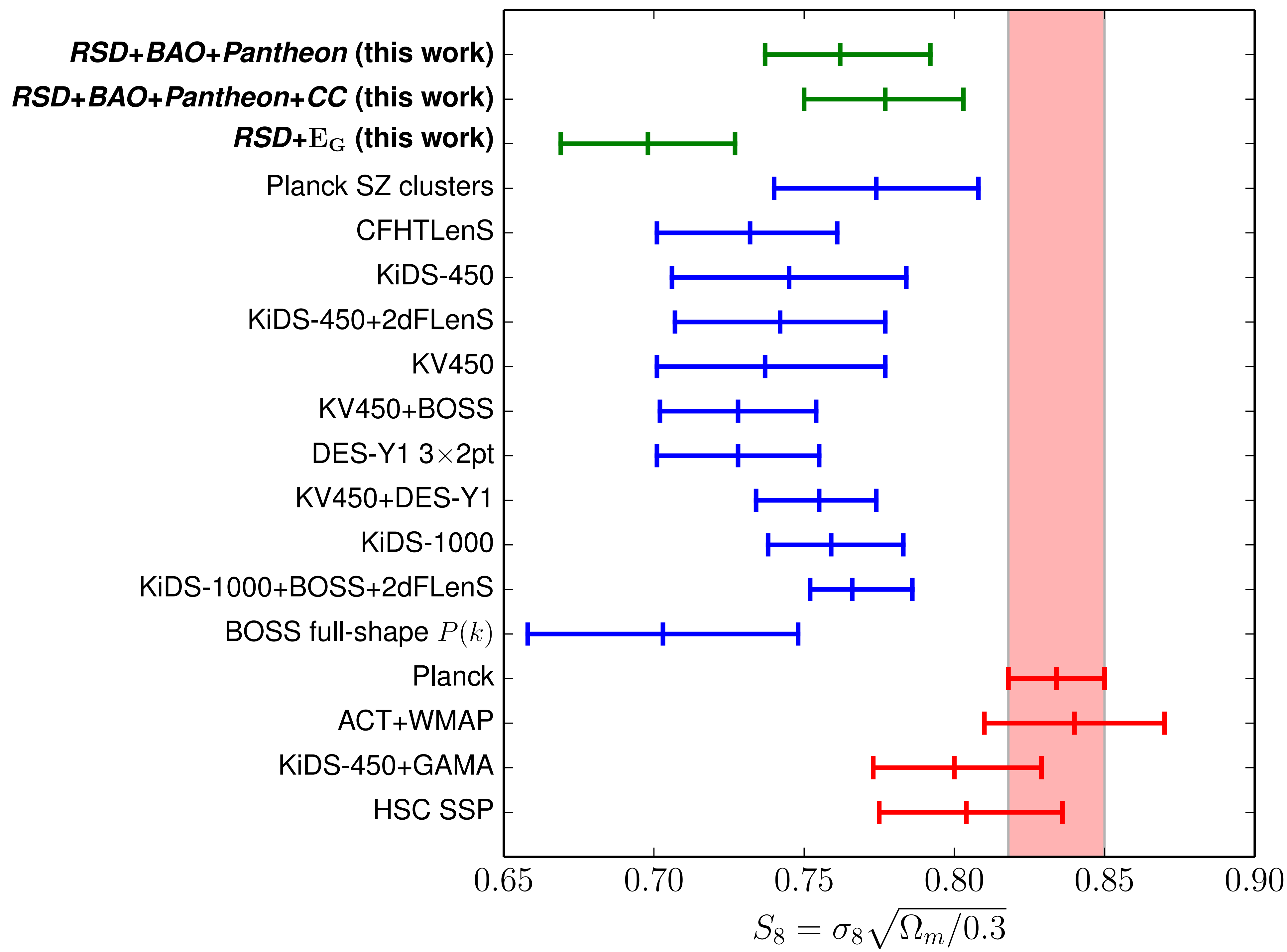
$$R = 8 \text{ Mpc } h^{-1} \rightarrow \sigma_8$$

sigma8 tension



Nunes, Vagnozzi
arXiv:2106.01208

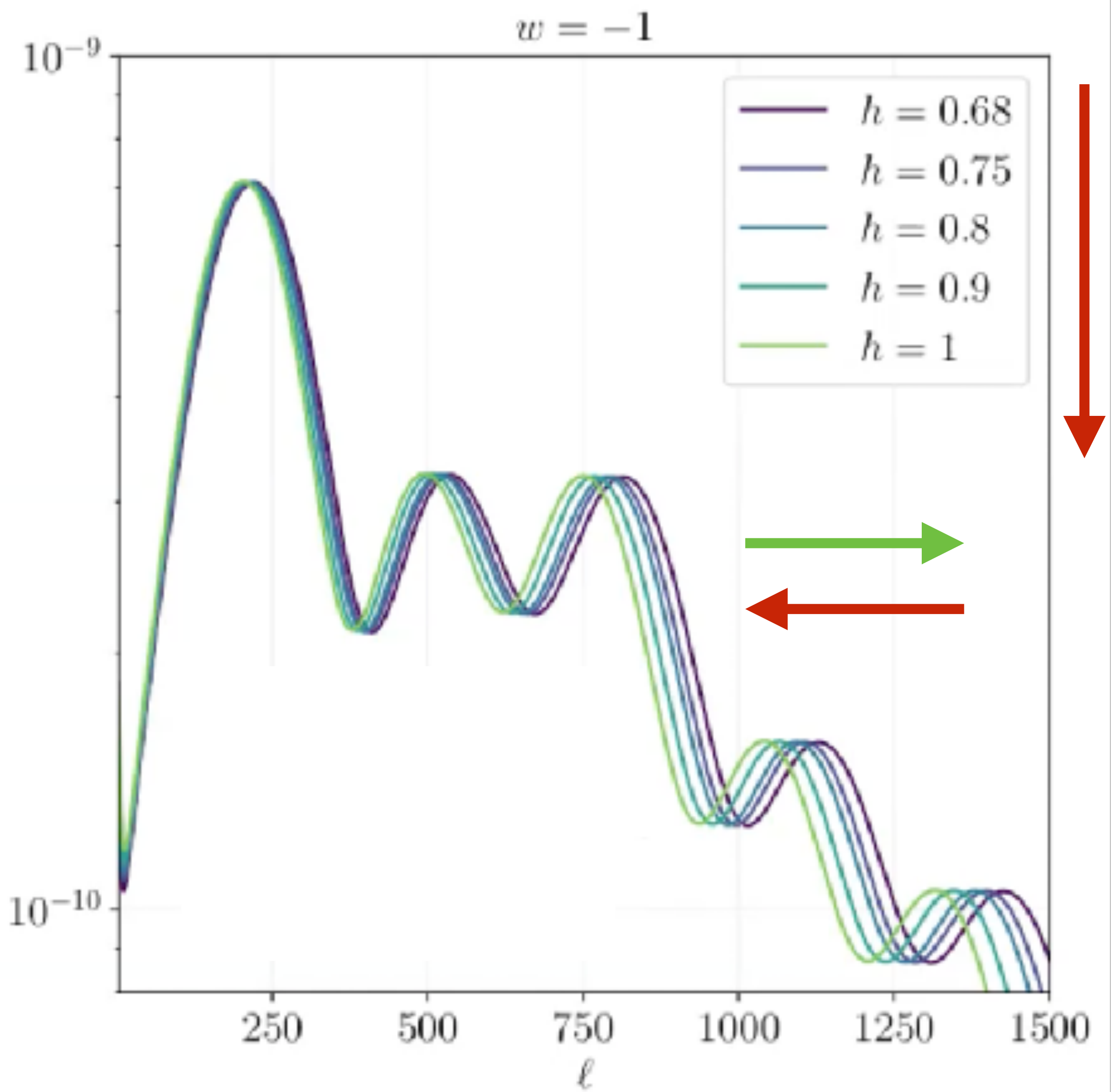
sigma8 tension



CMB not only yields a lower H0 but also a higher sigma8

Nunes, Vagnozzi arXiv:2106.01208

Early versus late-time solutions



$H_0 \uparrow$

$\theta_\star \downarrow$

acoustic scale: overall position of the peaks

$$\theta_\star = \frac{r_s(z_\star)}{d_A(z_\star)}$$

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

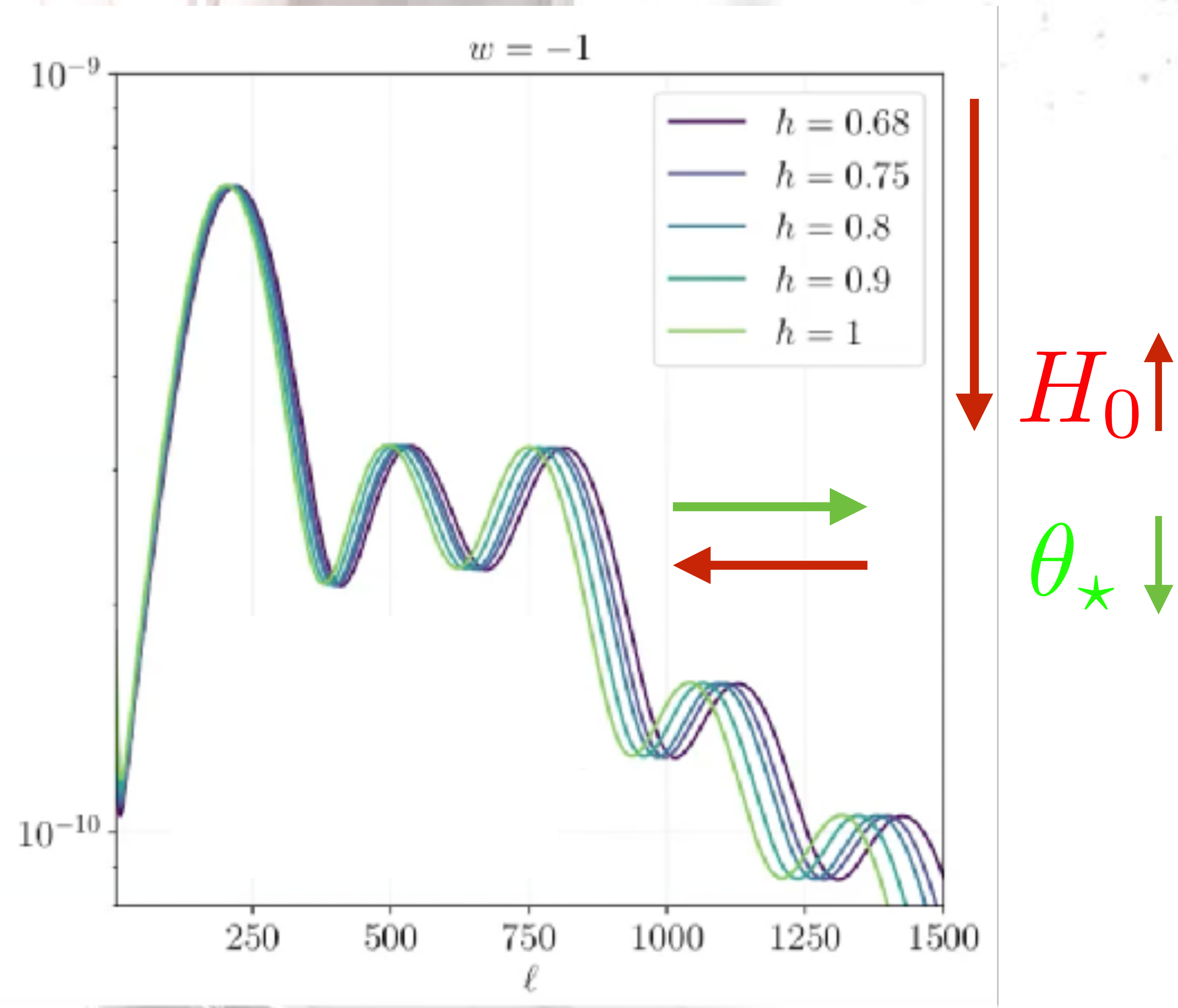
$$d_A(z_\star) = \int_0^{z_\star} \frac{dz}{H}$$

Early — **Early-time solutions** $r_s(z_\star) \downarrow$

Late — **Late-time solutions** $d_A(z_\star) \uparrow$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Early versus late-time solutions



acoustic scale: overall position of the peaks

$$\theta_\star = \frac{r_s(z_\star)}{d_A(z_\star)}$$

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

$$d_A(z_\star) = \int_0^{z_\star} \frac{dz}{H}$$

→ **sigma8 tension usually worsen!**

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Vector Field (Generalized Proca)

GR $+$ $$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(-\frac{1}{2}A_\mu A^\mu) + G_3(-\frac{1}{2}A_\mu A^\mu)\nabla_\alpha A^\alpha$$

Linear perturbations → **Embedding into a Boltzman code**

At the background level, it gives phantom DE $w < -1$

At the perturbation level, non-trivial contribution from additional dof.

L.H & H. Villarrubia Rojo
arxiv:2010.00513

Vector Field (Generalized Proca)

GR $+$ $$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + G_2(-\frac{1}{2}A_\mu A^\mu) + G_3(-\frac{1}{2}A_\mu A^\mu)\nabla_\alpha A^\alpha$$

Linear perturbations → Embedding into a Boltzman code

At the background level, it gives phantom DE $w < -1$

It does not help with the sigma8 tension but at least it does not worsen it.

L.H & H. Villarrubia Rojo
arxiv:2010.00513

Could late-time DE models solve H0 and sigma 8 simultaneously ?

Solving H0 and sigma8 simultaneously

Goal

Solve both tensions simultaneously!

Solve them without assuming any model nor any parametrization

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Goal

Solve both tensions simultaneously!

Solve them without assuming any model nor any parametrization

$

Embedding into a Boltzman code is very expensive!

Fully analytically

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Assume:

Small deviations from a given cosmological background (for example $\Lambda\mathrm{CDM}$)

$\Lambda\mathrm{CDM}$

$$\{H_0, \Omega_b, \Omega_m, A_s, n_s, \tau_{reio}\}$$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Assume:

Small deviations from a given cosmological background (for example ΛCDM)

ΛCDM

$$\{H_0, \Omega_b, \Omega_m, A_s, n_s, \tau_{reio}\}$$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Assume: **Small deviations from a given cosmological background (for example ΛCDM)**

ΛCDM

$$\{H_0, \Omega_b, \Omega_m, A_s, n_s, \tau_{reio}\}$$

at the background level

$$H = H_{\Lambda\mathrm{CDM}}(z)$$

$$G_{\mathrm{eff}} = G$$

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Assume: **Small deviations from a given cosmological background (for example $\Lambda\mathrm{CDM}$)**

$$\{H_0, \Omega_b, \Omega_m, A_s, n_s, \tau_{\rm reio} \; .....\}$$

at the background level

$$H = H_{\Lambda\mathrm{CDM}}(z) + \delta H(z)$$

$$G_{\rm eff} = G + \delta G(z)$$

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Assume: Small deviations from a given cosmological background (for example ΛCDM)

ΛCDM

$$\{H_0 + \Delta H_0 \,, \Omega_b + \Delta \Omega_b \,, \Omega_m + \Delta \Omega_m \ldots$$

at the background level

$$H = H_{\Lambda \mathrm{CDM}}(z) + \delta H(z)$$

$$G_{\mathrm{eff}} = G + \delta G(z)$$

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Consider: **a general deviation from** $\Lambda\mathrm{CDM}$

$$\{H_0 + \Delta H_0\,, \Omega_m + \Delta\Omega_m, H(z) + \delta H(z) \quad .....\}$$

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Consider: a general deviation from $\Lambda\mathrm{CDM}$

$$\{H_0 + \Delta H_0\,, \Omega_m + \Delta\Omega_m, H(z) + \delta H(z) \quad \ldots\ldots\}$$

Compute: the variations to first order in the observables

$$\Delta\theta_\star,\ \Delta\sigma_8, \ldots$$

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

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Relate: the deviations of the parameters $\Delta H_0,\ \Delta\Omega_m, \ldots$

with $\delta H(z)$ using CMB priors

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Consider: a general deviation from ΛCDM

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Relate: the deviations of the parameters $\Delta H_0,\ \Delta\Omega_m, \ldots$ with $\delta H(z)$ using CMB priors

Generate: response functions

$$\frac{\Delta\sigma_8(z)}{\sigma_8(z)} = \int_0^\infty \frac{dx_z}{1+x_z} \mathcal{R}_{\sigma_8}(x_z, z) \frac{\delta H(x_z)}{H(x_z)}$$

L.H & H. Villarrubia Rojo,
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arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Consider: a general deviation from $\Lambda\mathrm{CDM}$

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L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

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Solving H0 and sigma8 simultaneously

The variation of the Hubble parameter

$$\frac{\Delta H(z)}{H(z)} = \frac{H_0^2}{H^2}\frac{\delta h}{h} + \frac{\delta H(z)}{H(z)}$$

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Solving H0 and sigma8 simultaneously

The variation of the Hubble parameter

$$\frac{\Delta H(z)}{H(z)} = \frac{H_0^2}{H^2}\frac{\delta h}{h} + \frac{\delta H(z)}{H(z)}$$

Observable: the comoving distance

$$d = \int_0^z \frac{dz}{H(z)}$$

L.H & H. Villarrubia Rojo,
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Solving H0 and sigma8 simultaneously

The variation of the Hubble parameter

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Observable: the comoving distance

$$d = \int_0^z \frac{dz}{H(z)}$$

The change in the comoving distance

$$\frac{\Delta d(z)}{d(z)} = -\frac{1}{d(z)}\int_0^z d_z \frac{\Delta H(z)}{H(z)^2}$$

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Solving H0 and sigma8 simultaneously

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Solving H0 and sigma8 simultaneously

The variation of the Hubble parameter

$$\frac{\Delta H(z)}{H(z)} = \frac{H_0^2}{H^2}\frac{\delta h}{h} + \frac{\delta H(z)}{H(z)}$$

The change in any observable

$$\frac{\Delta \mathcal{O}(z)}{\mathcal{O}(z)} = I_{\mathcal{O}}(z)\frac{\delta h}{h} + \int_0^\infty \frac{dx_z}{1+x_z} R_{\mathcal{O}}(x_z, z)\frac{\delta H(x_z)}{H(x_z)}$$

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Solving H0 and sigma8 simultaneously

The variation of the Hubble parameter

$$\frac{\Delta H(z)}{H(z)} = \frac{H_0^2}{H^2}\frac{\delta h}{h} + \frac{\delta H(z)}{H(z)}$$

We need to relate δh with $\delta H(z)$

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Solving H0 and sigma8 simultaneously

The variation of the Hubble parameter

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We need to relate δh with $\delta H(z)$

CMB priors! $$\theta_\star = \frac{r_s(z_\star)}{d_A(z_\star)}$$

In order to agree with CMB observations the acoustic scale needs to remain unchanged!

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Solving H0 and sigma8 simultaneously

The variation of the Hubble parameter

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CMB priors! $\theta_\star = \frac{r_s(z_\star)}{d_A(z_\star)}$

In order to agree with CMB observations the acoustic scale needs to remain unchanged!

$$\frac{\Delta\theta_\star}{\theta_\star} = \frac{\Delta r_s(z_\star)}{r_s(z_\star)} - \frac{\Delta d_A(z_\star)}{d_A(z_\star)} = 0$$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Solving H0 and sigma8 simultaneously

The variation of the Hubble parameter

$$\frac{\Delta H(z)}{H(z)} = \frac{H_0^2}{H^2}\frac{\delta h}{h} + \frac{\delta H(z)}{H(z)}$$

response function relating δh with $\delta H(z)$

$$\frac{\delta h}{h} = \int_0^\infty \frac{dz}{1+z} R_h(z) \frac{\delta H(z)}{H(z)}$$

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Solving H0 and sigma8 simultaneously

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Solving H0 and sigma8 simultaneously

Remember, the variation of any observable

$$\frac{\Delta\mathcal{O}(z)}{\mathcal{O}(z)} = I_{\mathcal{O}}(z)\frac{\delta h}{h} + \int_0^\infty \frac{dx_z}{1+x_z} R_{\mathcal{O}}(x_z, z)\frac{\delta H(x_z)}{H(x_z)}$$

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Solving H0 and sigma8 simultaneously

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$$\frac{\delta h}{h} = \int_0^\infty \frac{dz}{1+z} R_h(z) \frac{\delta H(z)}{H(z)}$$

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J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Remember, the variation of any observable

$$\frac{\Delta\mathcal{O}(z)}{\mathcal{O}(z)} = I_{\mathcal{O}}(z)\frac{\delta h}{h} + \int_0^\infty \frac{dx_z}{1+x_z} R_{\mathcal{O}}(x_z, z)\frac{\delta H(x_z)}{H(x_z)}$$

$$\frac{\delta h}{h} = \int_0^\infty \frac{dz}{1+z}\, R_h(z)\, \frac{\delta H(z)}{H(z)}$$

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} = \int_0^\infty \frac{dz}{1+z} R_{\mathcal{O}}(z)\frac{\delta H(z)}{H(z)}$$

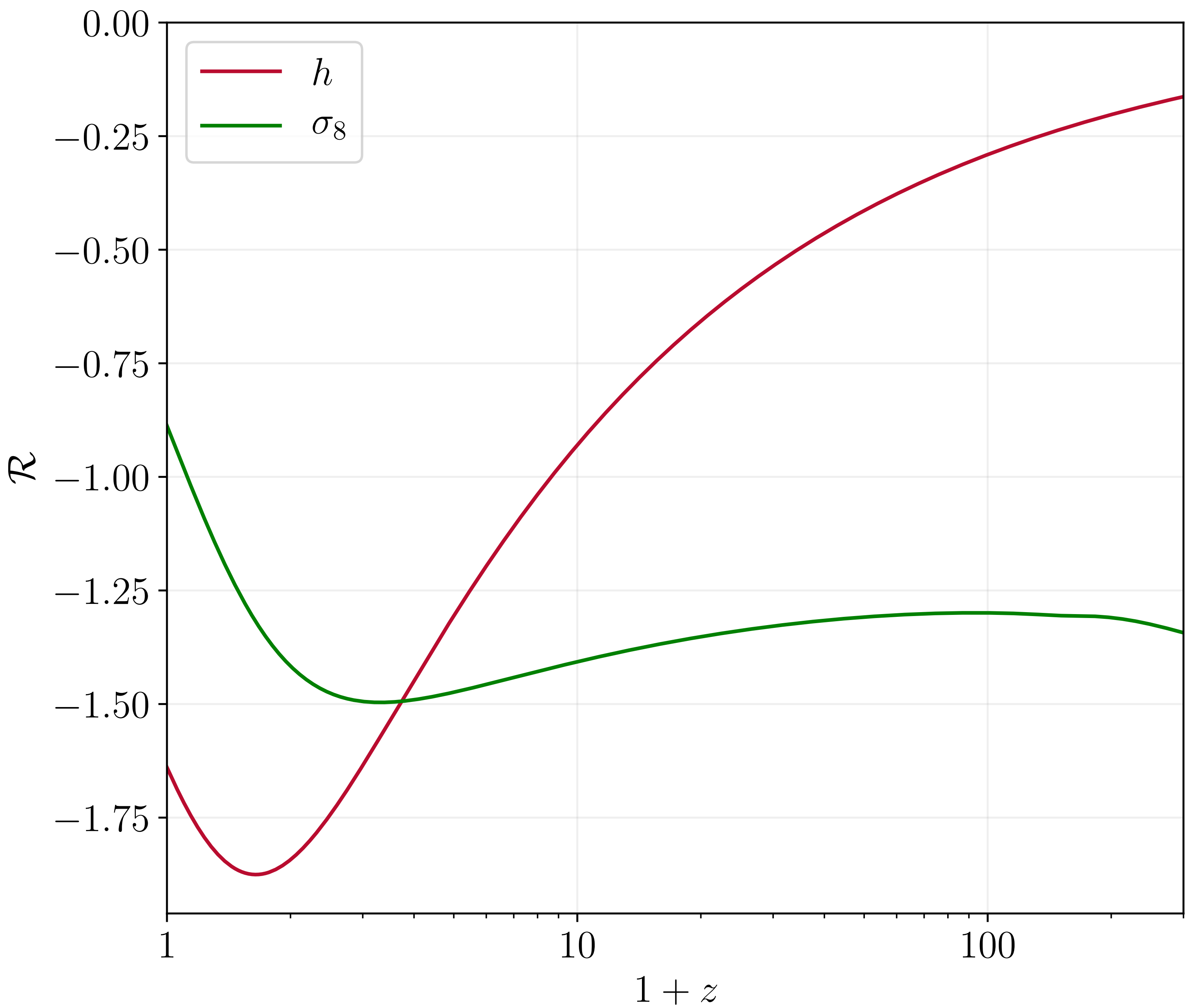
L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

Example: the variation of sigma8

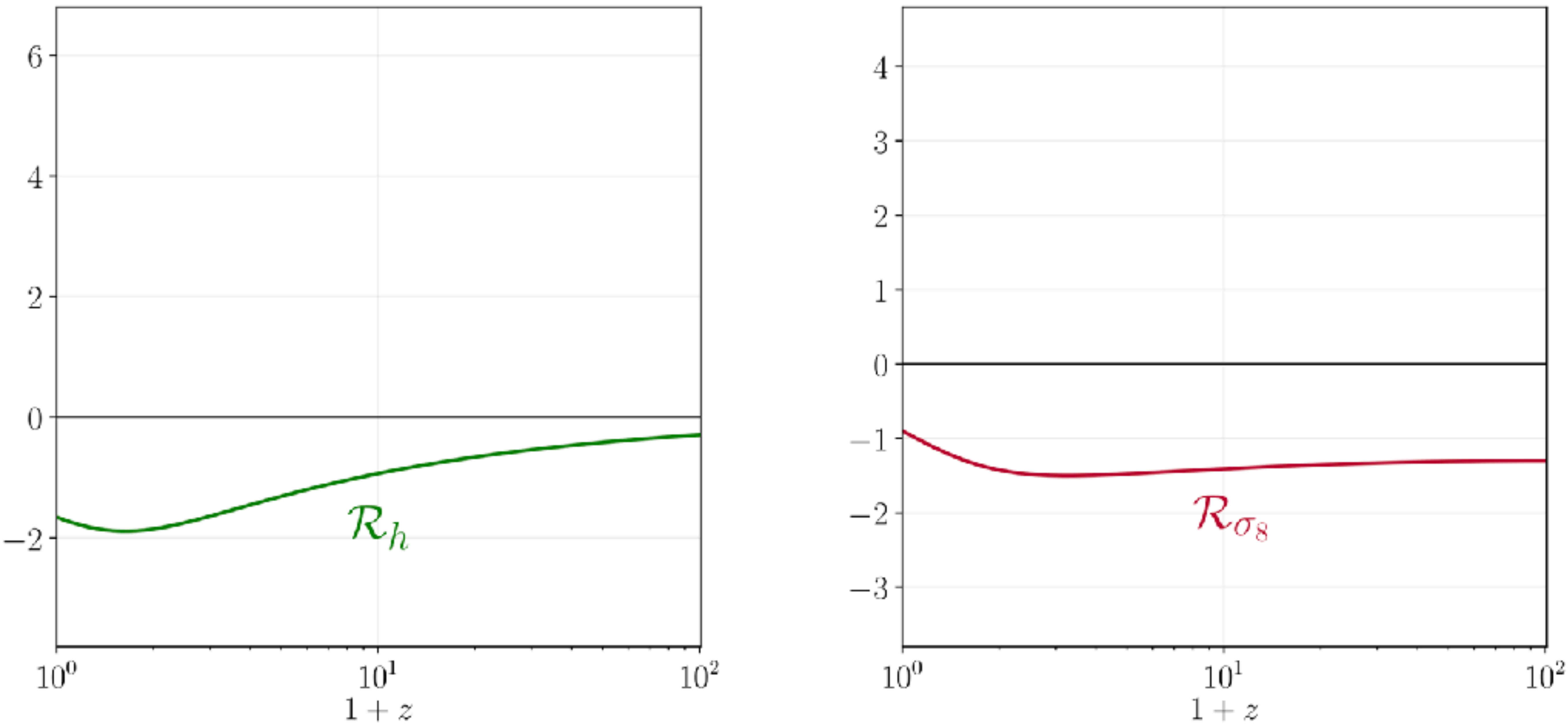
$$\frac{\delta h}{h} = \int_0^\infty \frac{dz}{1+z} R_h(z) \frac{\delta H(z)}{H(z)}$$

$$\frac{\Delta \sigma_8}{\sigma_8} = \int_0^\infty \frac{dz}{1+z} R_{\sigma_8}(z) \frac{\delta H(z)}{H(z)}$$



L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Solving H0 and sigma8 simultaneously



$R_h(z)$

$R_{\sigma_8}(z)$

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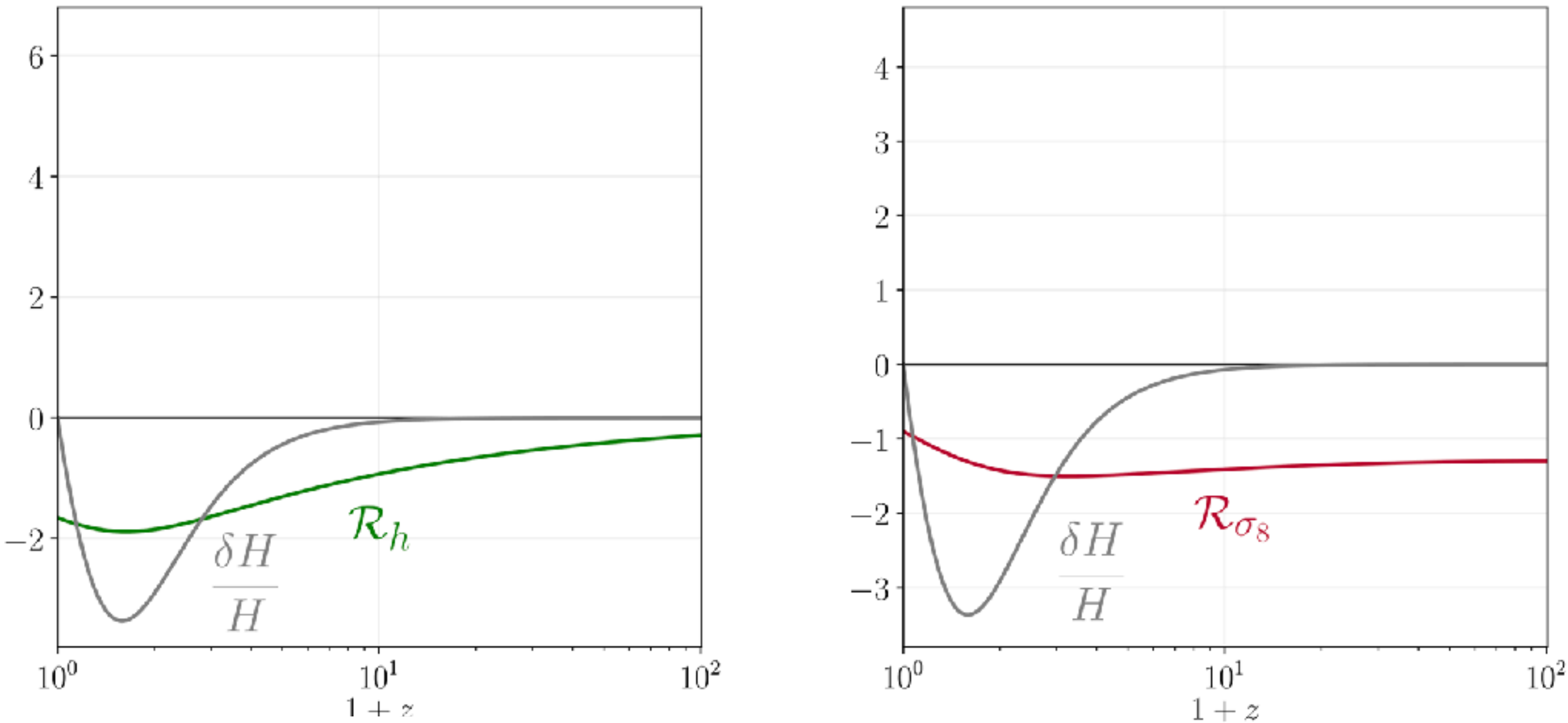
J. Zosso,

arxiv:2201.11623

Solving H0 and sigma8 simultaneously

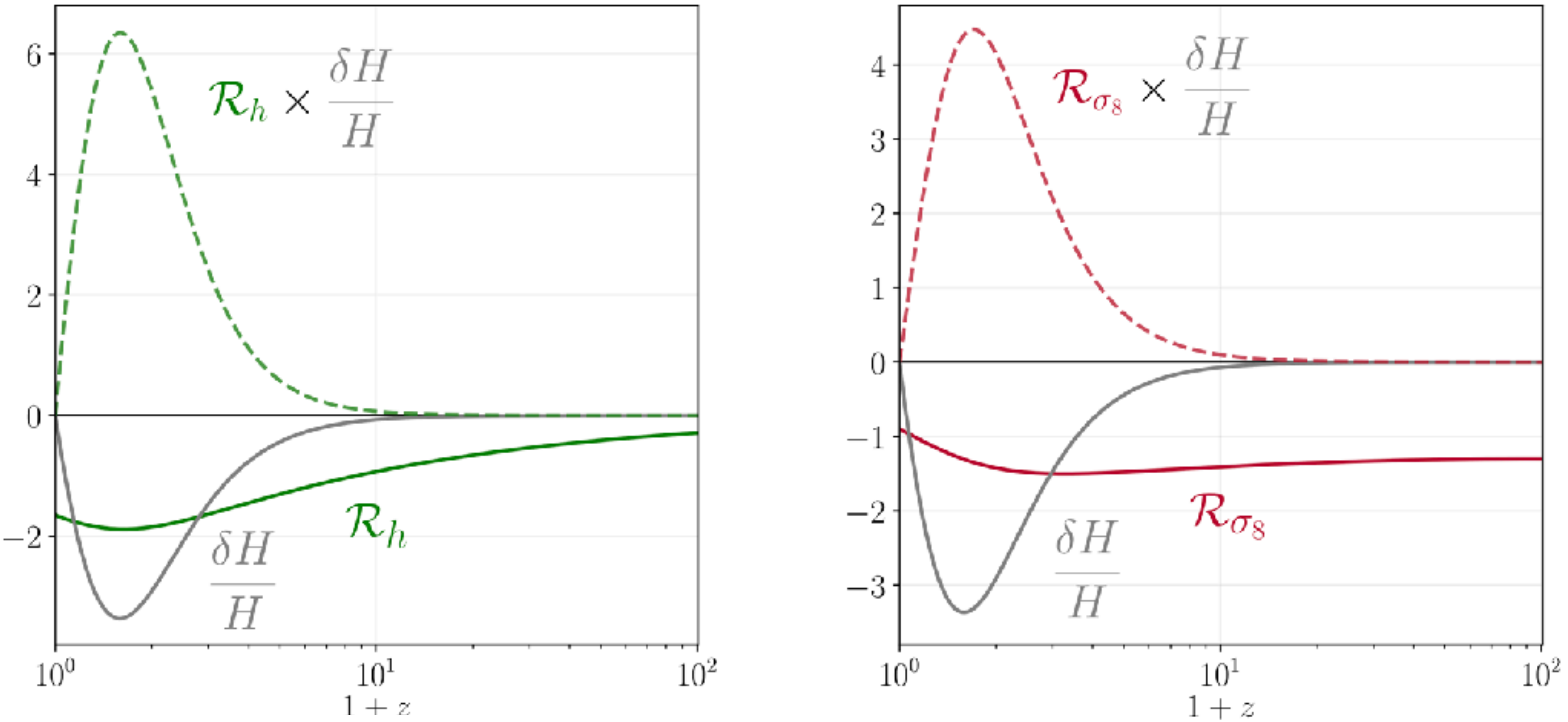


$$R_h(z)\,\frac{\delta H(z)}{H(z)}$$

$$R_{\sigma_8}(z)\,\frac{\delta H(z)}{H(z)}$$

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously



$$R_h(z)\,\frac{\delta H(z)}{H(z)}$$

$$R_{\sigma_8}(z)\,\frac{\delta H(z)}{H(z)}$$

L.H & H. Villarrubia Rojo,
J. Zosso,

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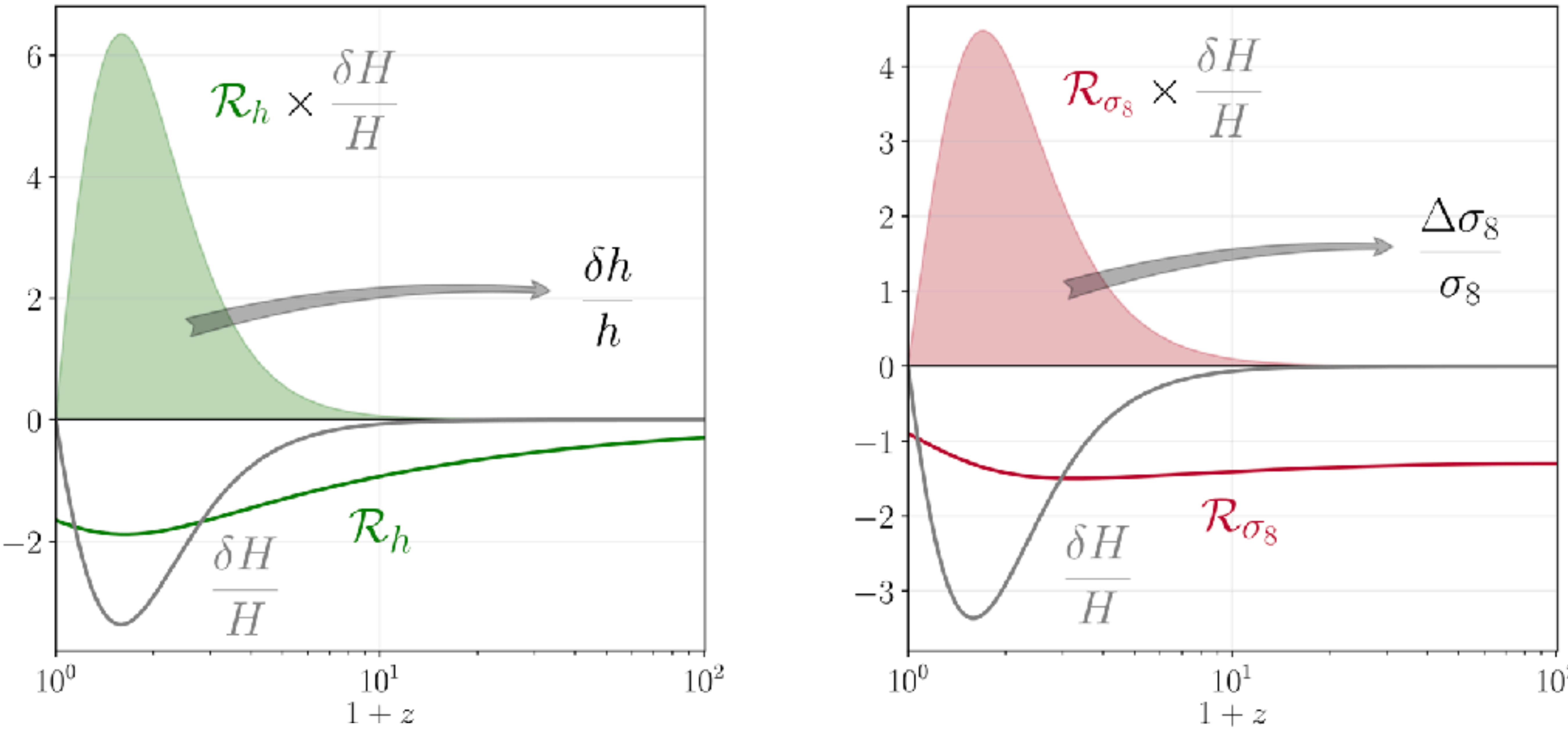
Solving H0 and sigma8 simultaneously

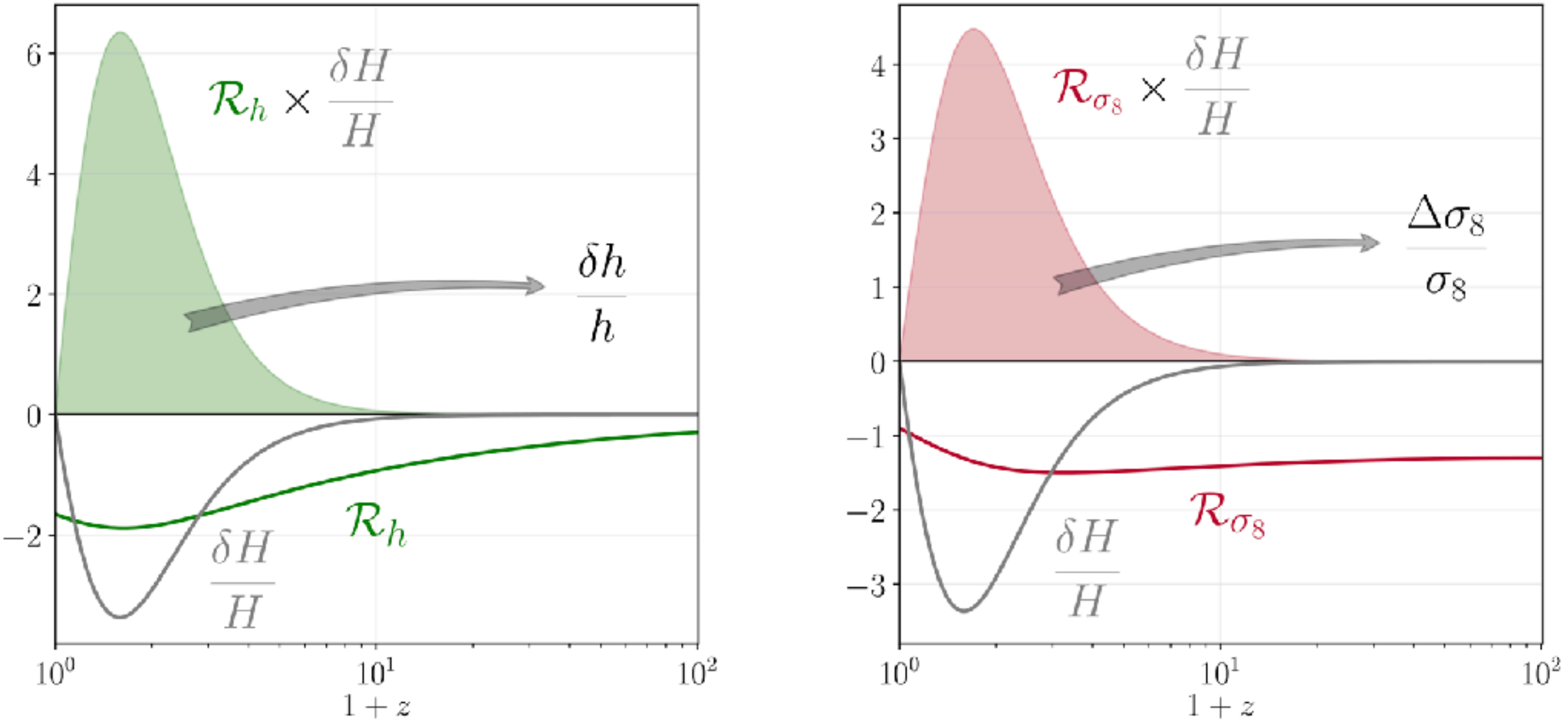


$$\frac{\delta h}{h} = \int_0^\infty \frac{dz}{1+z} R_h(z) \frac{\delta H(z)}{H(z)}$$

$$\frac{\Delta\sigma_8}{\sigma_8} = \int_0^\infty \frac{dz}{1+z} R_{\sigma_8}(z) \frac{\delta H(z)}{H(z)}$$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

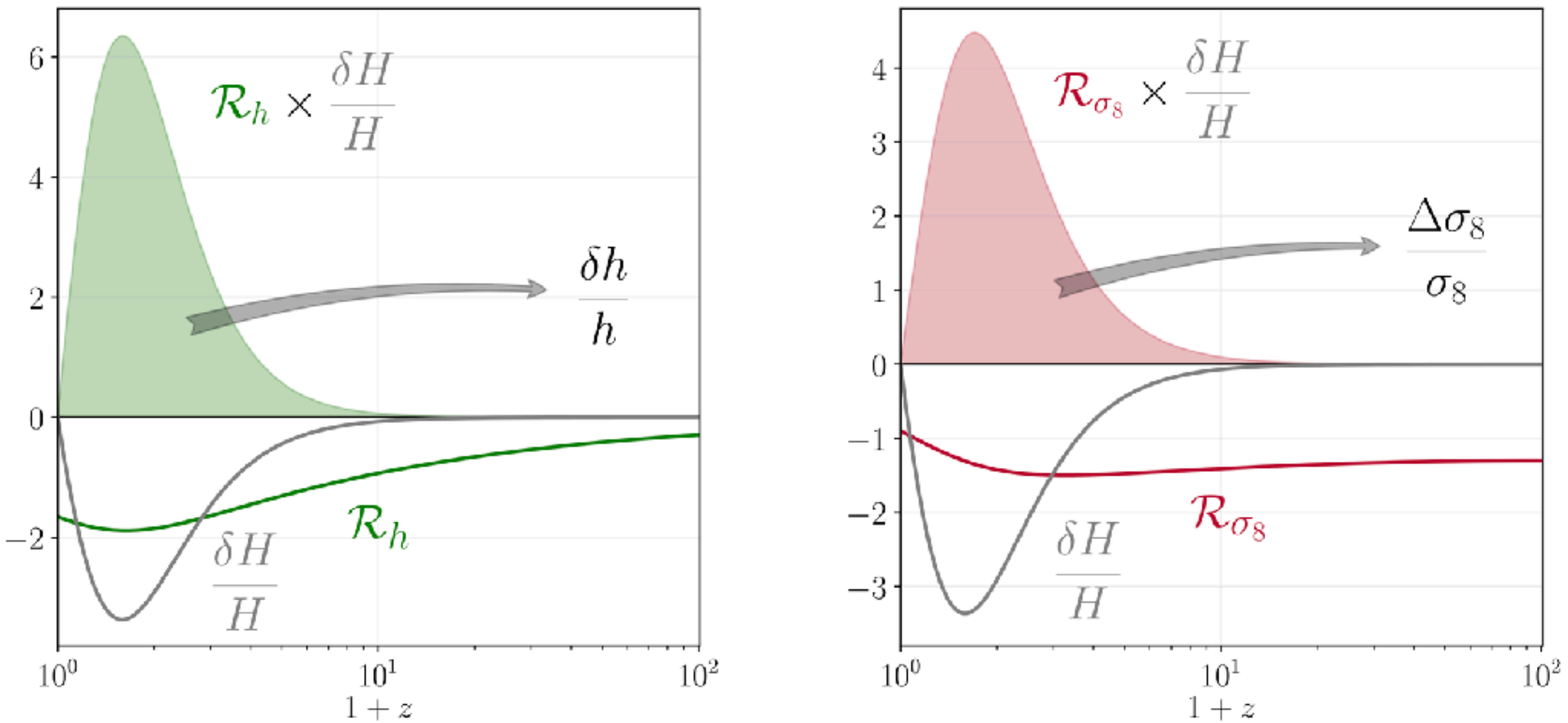
Solving H0 and sigma8 simultaneously



Solving H0 tension requires

$\delta h > 0$

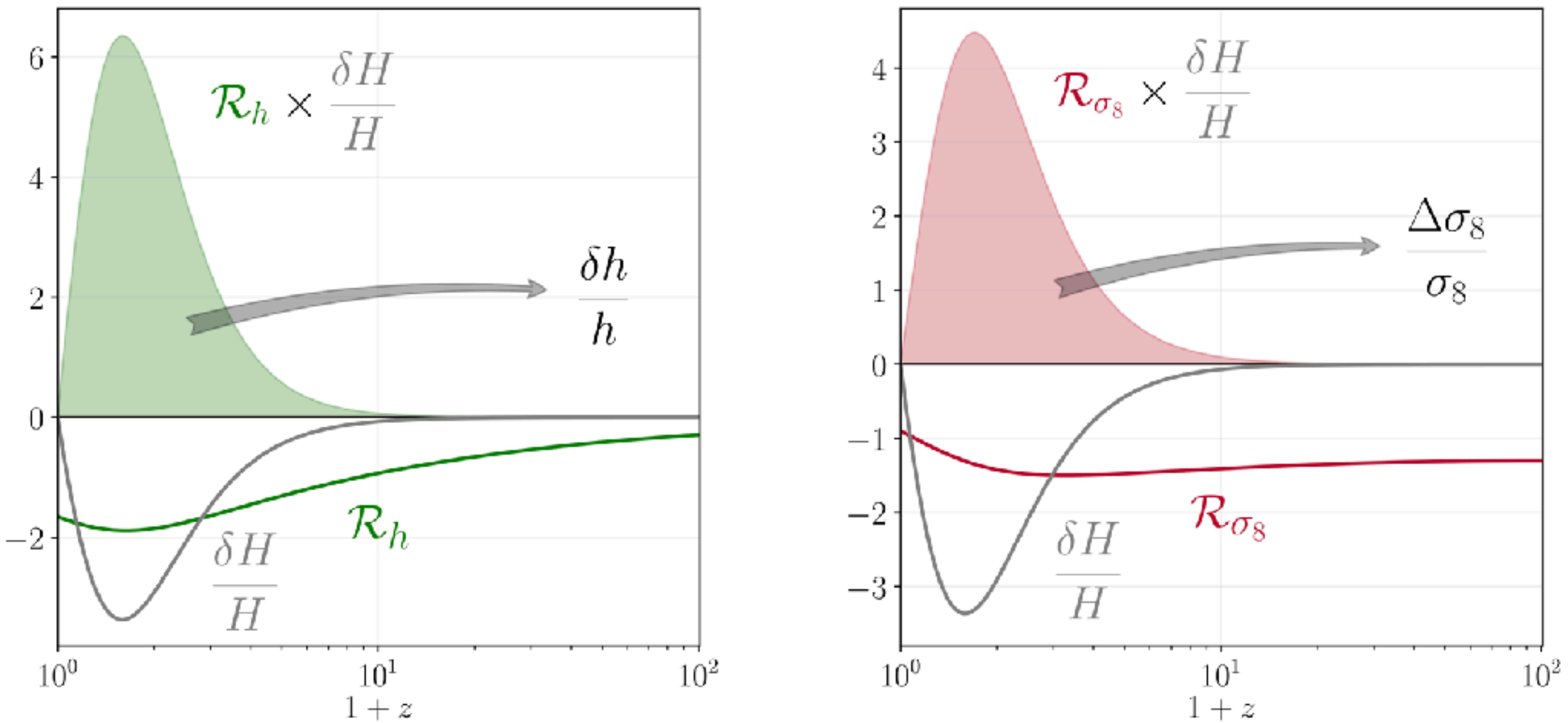
Solving H0 and sigma8 simultaneously



Solving H0 tension requires

$$\delta h > 0 \rightarrow \exists z | \delta H(z) < 0$$

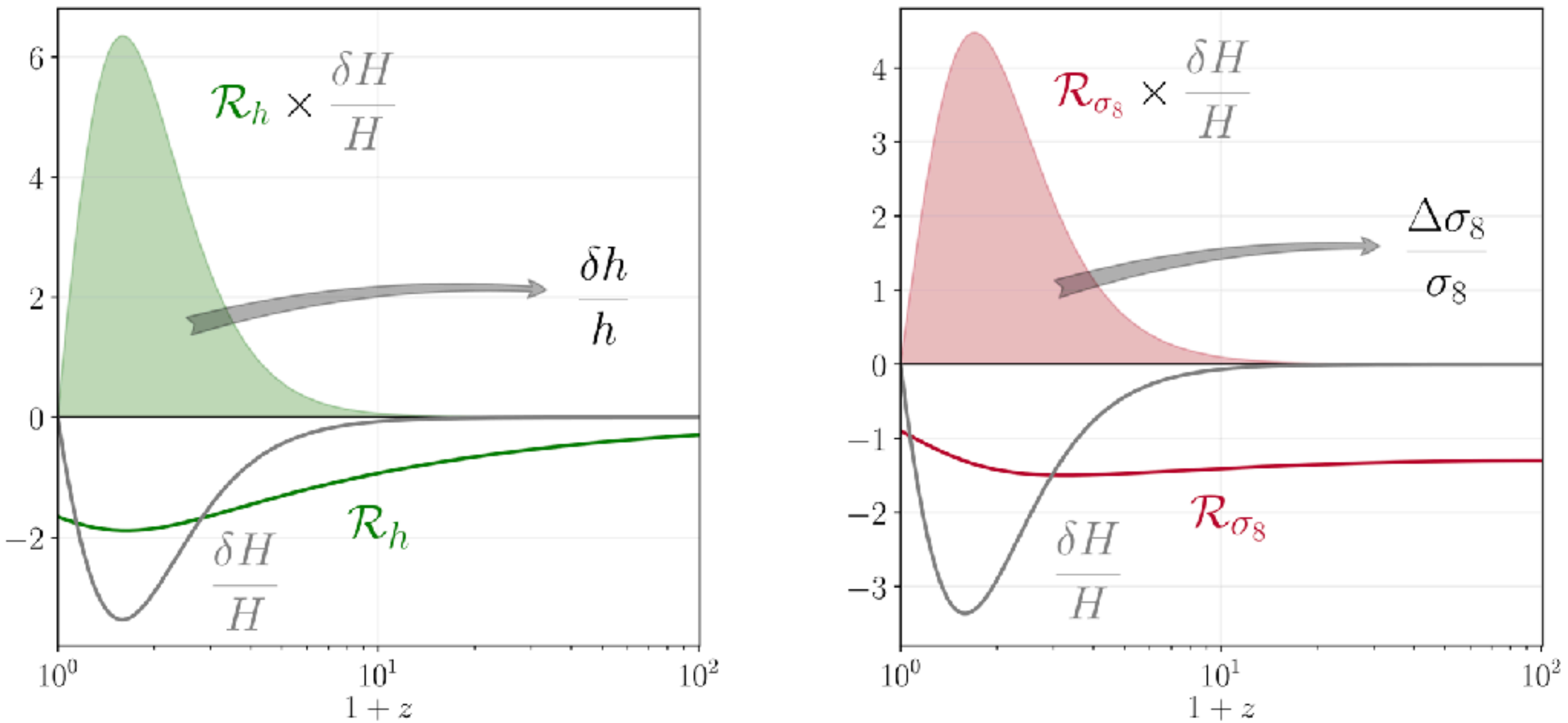
Solving H0 and sigma8 simultaneously



- **Solving H0 tension requires**

$$\delta h > 0 \rightarrow \exists z | \delta H(z) < 0$$
$$\rightarrow \exists z | w(z) < -1$$

Solving H0 and sigma8 simultaneously

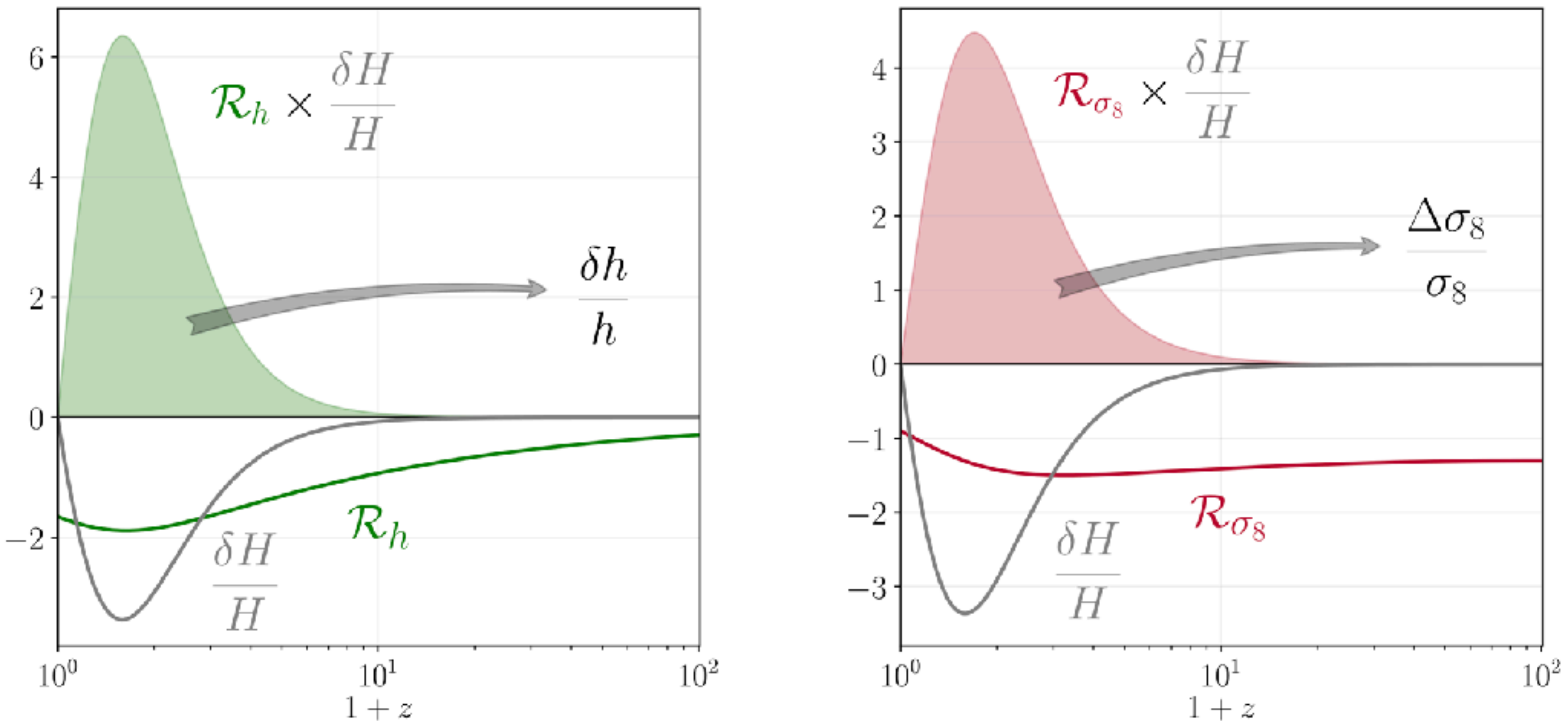


- **Solving both tensions requires** $(G_{\rm eff} = G)$

$$\delta h > 0$$

$$\Delta\sigma_8 < 0$$

Solving H0 and sigma8 simultaneously



- **Solving both tensions requires** $(G_{\rm eff} = G)$

$\delta h > 0$ → $\delta H(z)$ changes sign

$\Delta\sigma_8 < 0$ → $w(z)$ crosses -1

Solving H0 and sigma8 simultaneously

- **Solving both tensions requires** $(G_{\rm eff} \neq G)$

$$H = H_{\Lambda\rm CDM}(z) + \delta H(z)$$

L.H & H. Villarrubia Rojo,
J. Zosso,
arxiv:2201.11623

Solving H0 and sigma8 simultaneously

- **Solving both tensions requires** $(G_{\rm eff} \neq G)$

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L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

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$$H = H_{\Lambda\rm CDM}(z) + \delta H(z)$$

$$G_{\rm eff} = G + \delta G(z)$$

→ $$\delta_m(z,k) \sim \Big(D(z) + (\Delta D)|_{\delta G} \Big) T(k)$$

L.H & H. Villarrubia Rojo, J. Zosso, arxiv:2201.11623

Solving H0 and sigma8 simultaneously

- **Solving both tensions requires** $(G_{\rm eff} \neq G)$

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→ $$\delta_m(z,k) \sim \Big(D(z) + (\Delta D)|_{\delta G}\Big) T(k)$$

$$\frac{\Delta\sigma_8}{\sigma_8} = \int_0^\infty \frac{dz}{1+z} \boxed{R_{\sigma_8}(z)} \frac{\delta H(z)}{H(z)} + \int_0^\infty \frac{dz}{1+z} \boxed{\mathcal{G}_{\sigma_8}(z)} \frac{\delta G}{G}$$

L.H & H. Villarrubia Rojo,
J. Zosso,
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Solving H0 and sigma8 simultaneously

- **Solving both tensions requires** $(G_{\rm eff} \neq G)$

$$H = H_{\Lambda\rm CDM}(z) + \delta H(z)$$

$$G_{\rm eff} = G + \delta G(z)$$

$$\delta_m(z,k) \sim \Big(D(z) + (\Delta D)|_{\delta G}\Big)T(k)$$

$$\frac{\Delta\sigma_8}{\sigma_8} = \int_0^\infty \frac{dz}{1+z} R_{\sigma_8}(z) \frac{\delta H(z)}{H(z)} + \int_0^\infty \frac{dz}{1+z} \mathcal{G}_{\sigma_8}(z) \frac{\delta G}{G}$$

$\sigma_8 \uparrow$

If $\delta h > 0$ **and** $\delta H(z) < 0$

Solving H0 and sigma8 simultaneously

- **Solving both tensions requires** $(G_{\text{eff}} \neq G)$

$$H = H_{\Lambda\text{CDM}}(z) + \delta H(z)$$

$$G_{\text{eff}} = G + \delta G(z)$$

$$\delta_m(z,k) \sim \Big(D(z) + (\Delta D)|_{\delta G}\Big) T(k)$$

$$\frac{\Delta\sigma_8}{\sigma_8} = \int_0^\infty \frac{dz}{1+z} R_{\sigma_8}(z) \frac{\delta H(z)}{H(z)} + \int_0^\infty \frac{dz}{1+z} \mathcal{G}_{\sigma_8}(z) \frac{\delta G}{G}$$

$\sigma_8 \uparrow$ $\qquad$ $\sigma_8 \downarrow\downarrow\downarrow$

If $\delta h > 0$ **and** $\delta H(z) < 0$

$$\frac{\delta G(z)}{G} < \alpha(z) \frac{\delta H(z)}{H(z)} < 0$$

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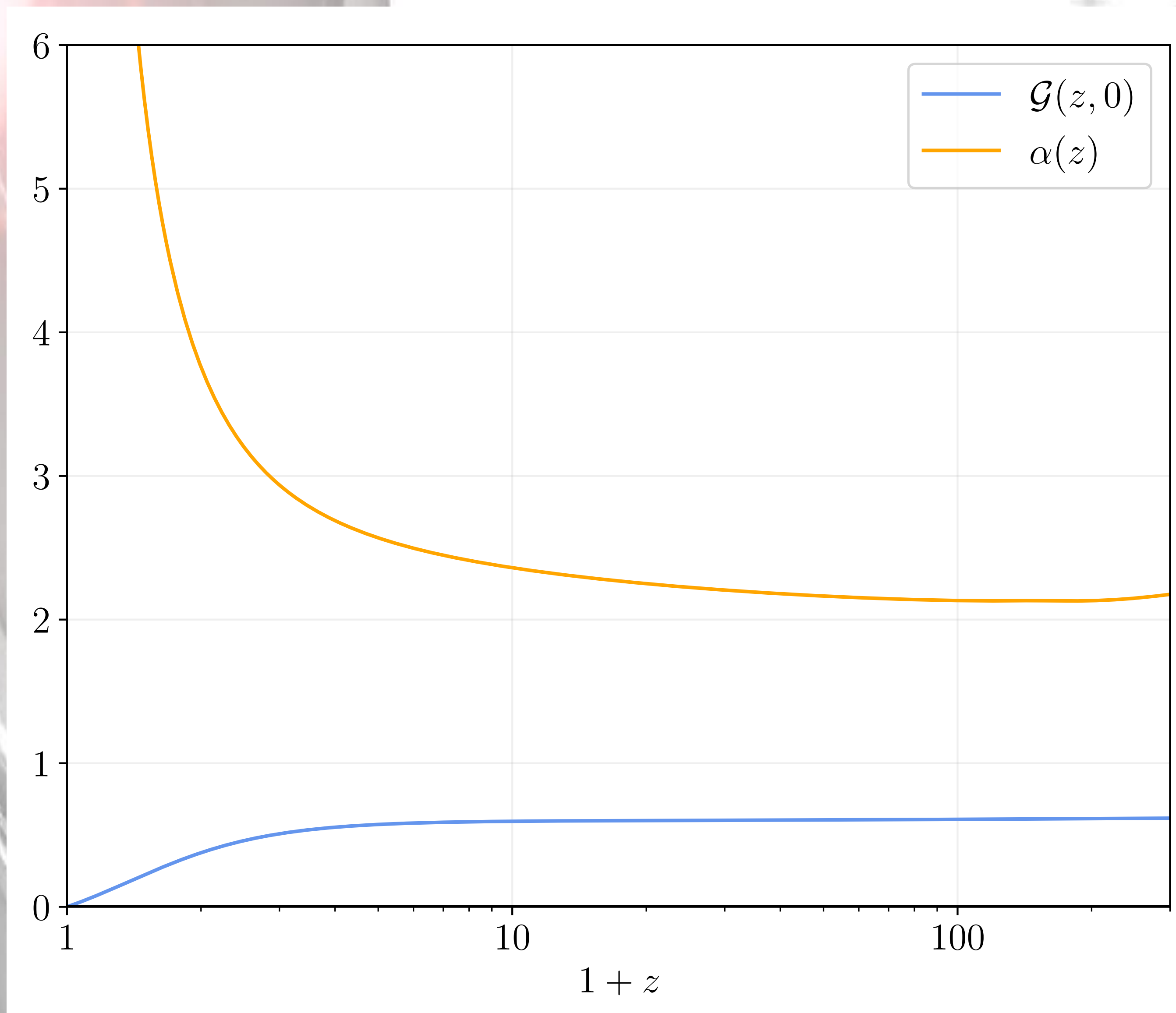

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Summary

- **Solving H0 tension**

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$$\delta h > 0 \;\Rightarrow\; \begin{array}{l} \exists z | \delta H(z) < 0 \\ \exists z | w(z) < -1 \end{array}$$

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$$\delta H(z) < 0$$

$$\rightarrow\; \frac{\delta G(z)}{G} < \alpha(z) \frac{\delta H(z)}{H(z)} < 0$$