Title: Cosmological tensions and how to ease them

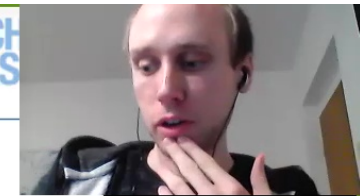
Speakers: Nils SchÃ¶neberg

Series: Cosmology & Gravitation

Date: December 15, 2020 - 11:00 AM

URL: http://pirsa.org/20120028

Abstract: Tensions between measurements in the early and the late universe could be the first hint of new physics beyond the cosmological standard model. In particular, the clustering of large scale structure and the current value of the Hubble parameter show intriguing discrepancies between measurements in the early and late universe. In this talk, I review the most common ways of easing these two tensions and focus specifically on parameter extensions and various models of dark matter, such as warm dark matter, cannibalistic dark matter, dark matter interactions, and dark radiation. To constrain these models a variety of cosmological probes, both current and future, is required at different scales and redshifts.



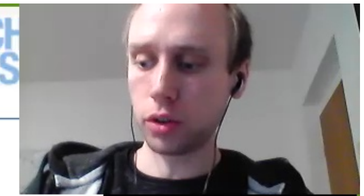
Cosmological tensions

and how to ease them

By Nils Schöneberg

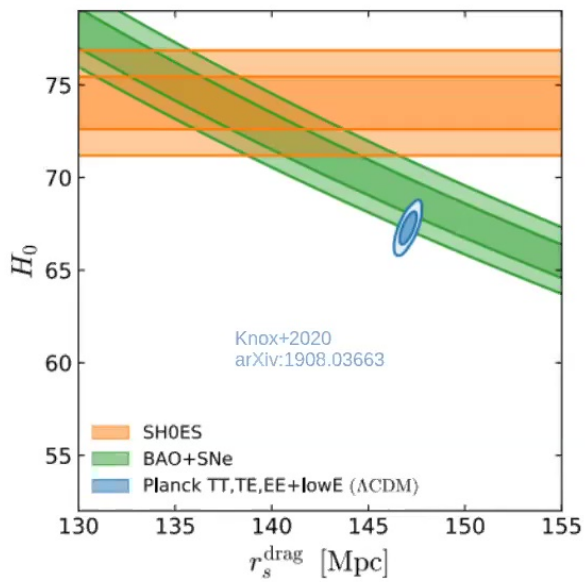
Institute for theoretical particle physics and cosmology

RWTH Aachen University

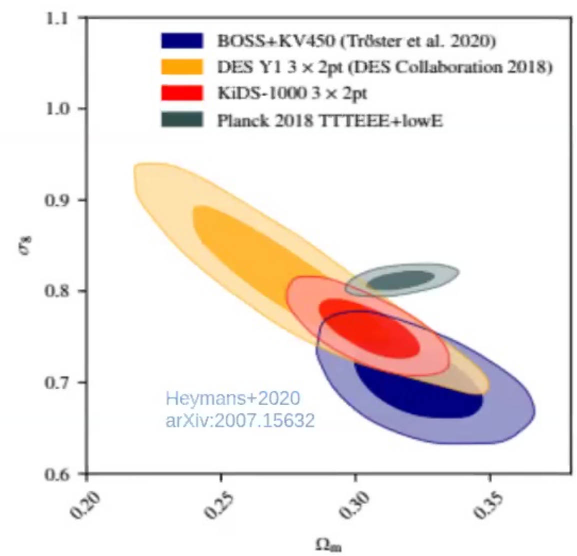


The tale of two tensions

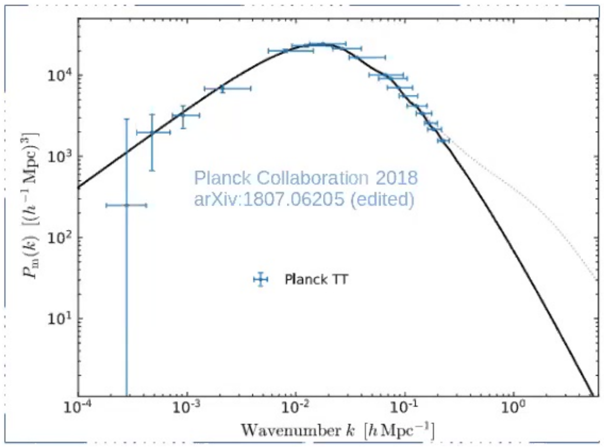
$$H_0 \leftrightarrow r_s \qquad (> 4\sigma)$$

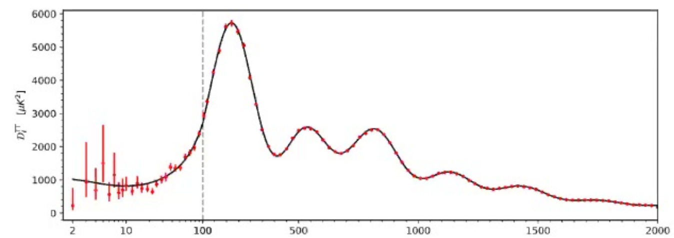


$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5} \qquad (> 2.5\sigma)$$



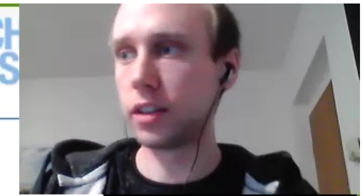
The weak lensing tension



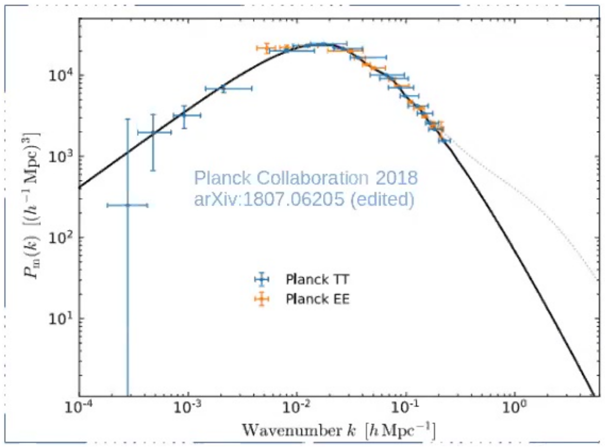


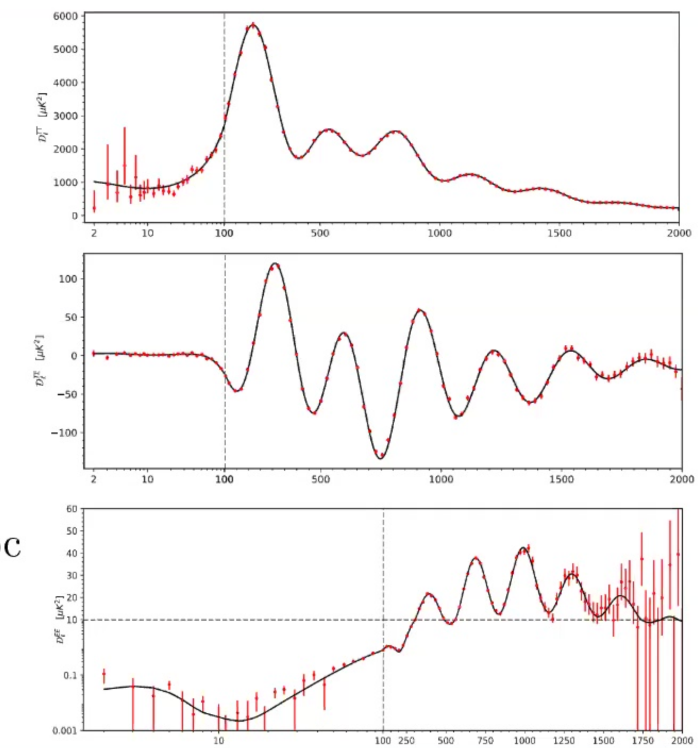
$$k_{\rm max} \approx \frac{\ell_{\rm max}}{\chi_{\rm rec}} \approx \frac{2000}{14040{\rm Mpc}} \approx 0.14/{\rm Mpc}$$

1) Data　2) Tension　3) Models　4) Conclusion



The weak lensing tension

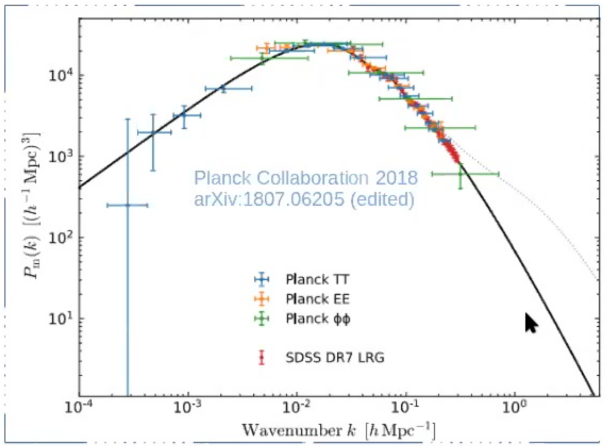




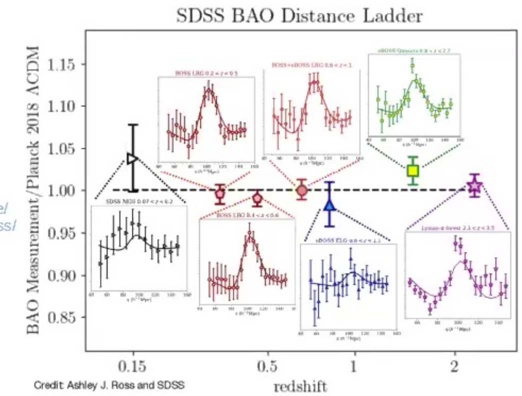
$$k_{\max} \approx \frac{\ell_{\max}}{\chi_{\rm rec}} \approx \frac{2000}{14040\mathrm{Mpc}} \approx 0.14/\mathrm{Mpc}$$

1) Data   2) Tension   3) Models   4) Conclusion

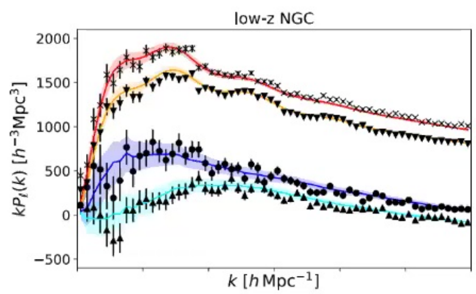
The weak lensing tension



Planck Collaboration 2018
arXiv:1807.06205 (edited)

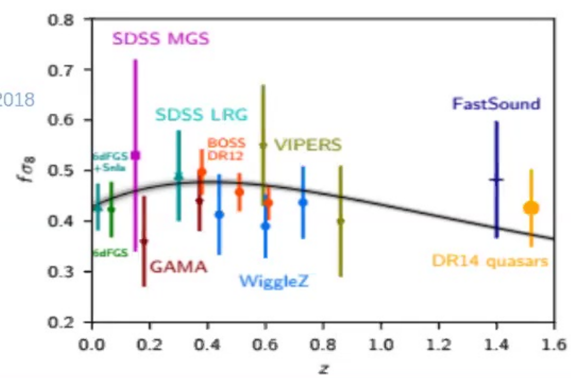


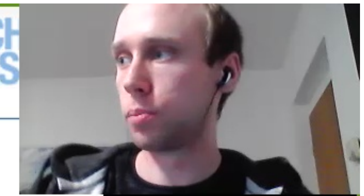
Ashley J. Ross
https://www.sdss.org/science/cosmology-results-from-eboss/



Philcox+2020
arXiv:2002.04035
(Full-shape BAO)

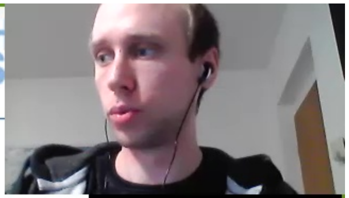
Planck Collaboration 2018
arXiv:1807.06209



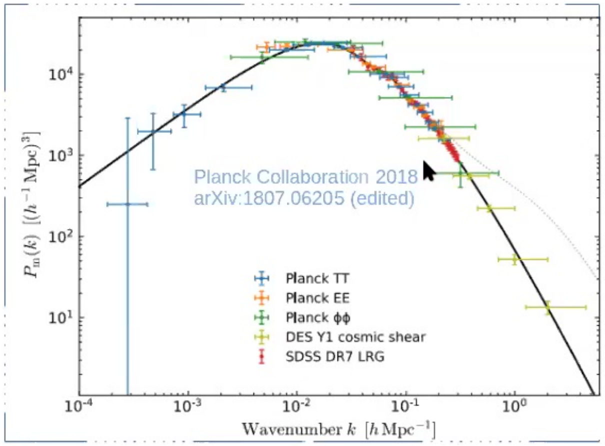


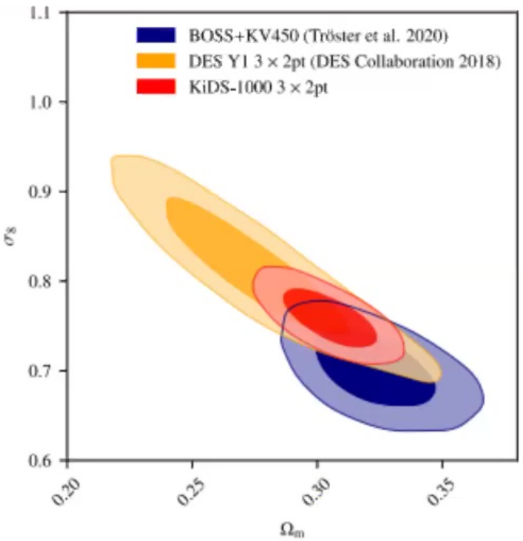
1) Data 2) Tension 3) Models 4) Conclusion

Institute for Theoretical Particle Physics and Cosmology
RWTH AACH UNIVERS

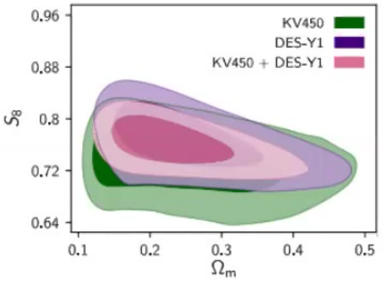


The weak lensing tension



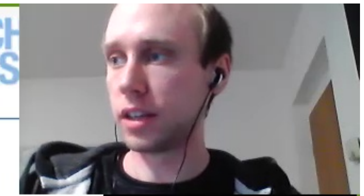


Joudaki+2020
arXiv:1906.09262v2
(edited)

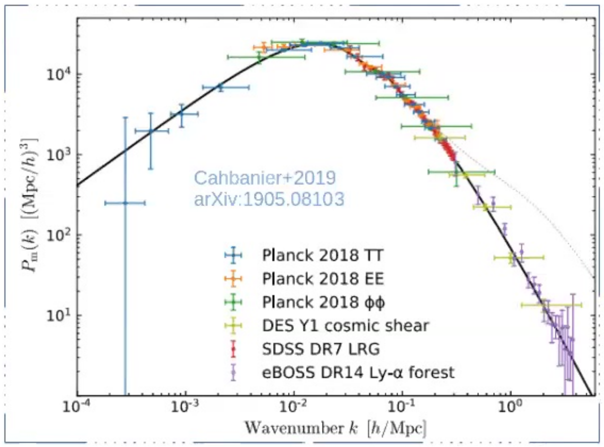


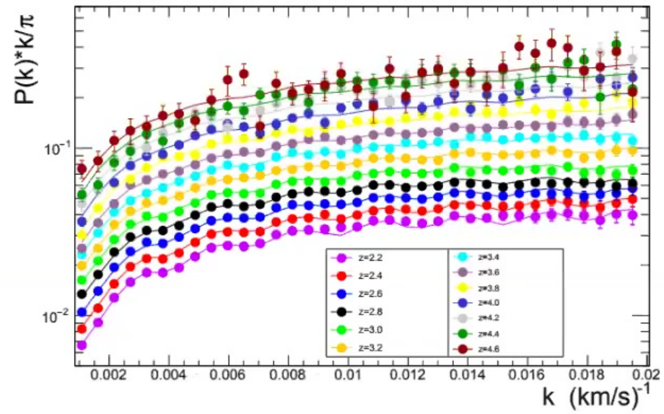
Heymans+2020
arXiv:2007.15632
(edited)

1) Data 2) Tension 3) Models 4) Conclusion



The weak lensing tension

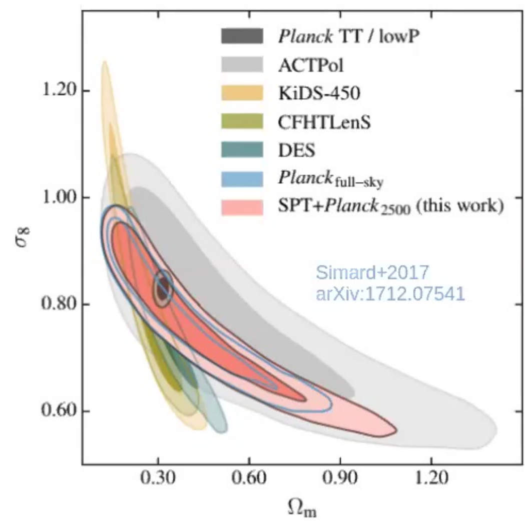


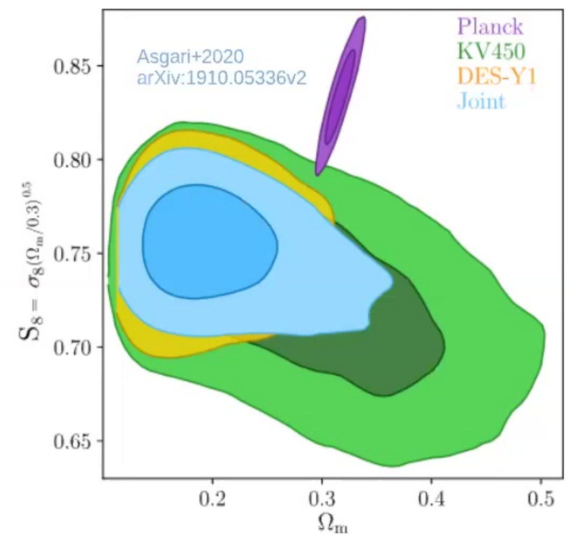


Palanque-Delabrouille+2019
arXiv:1911.09073

1) Data 2) Tension 3) Models 4) Conclusion

The weak lensing tension

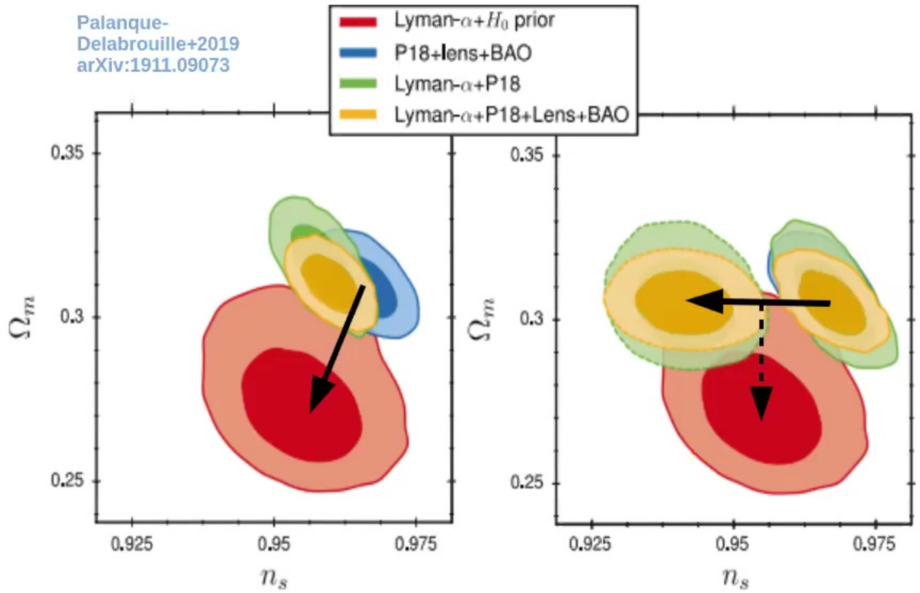




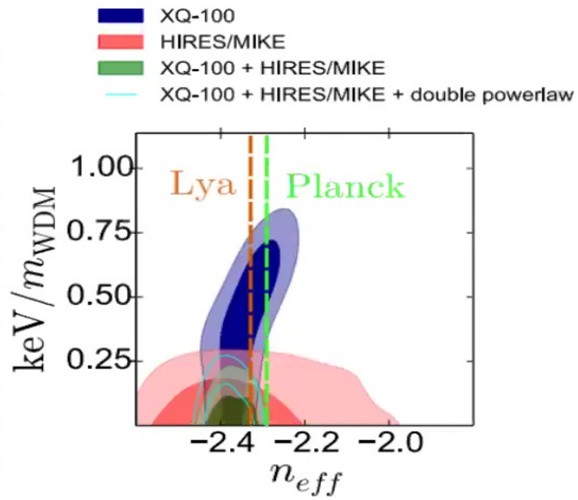
1) Data 2) Tension 3) Models 4) Conclusion

A side note about Lyman-α

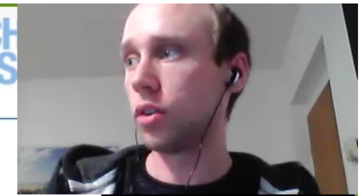
Palanque-Delabrouille+2019
arXiv:1911.09073



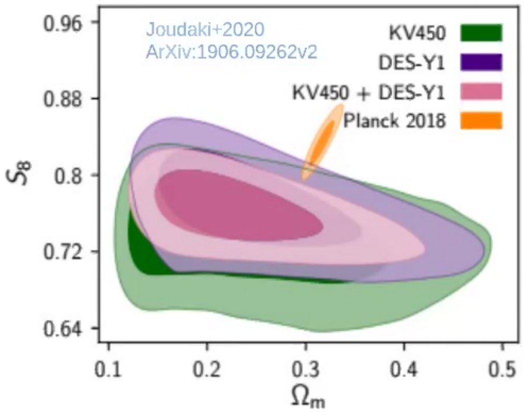
Anomalous Ω_m (or n_s)

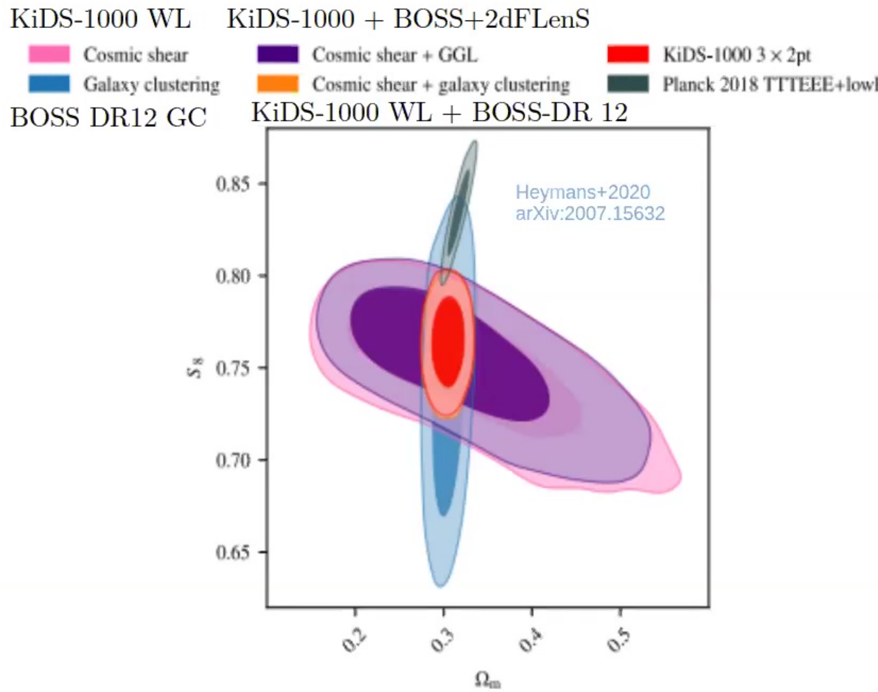


Irsic+2017
arXiv:1702.01764

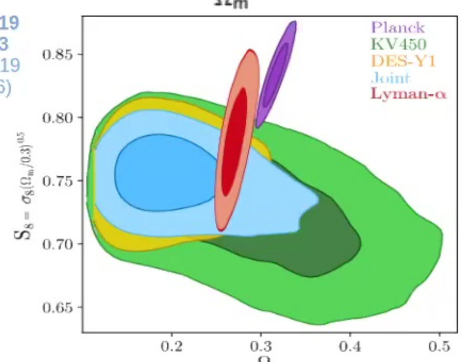


The weak lensing tension



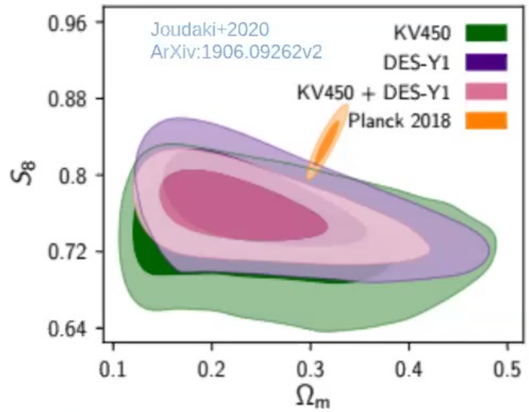


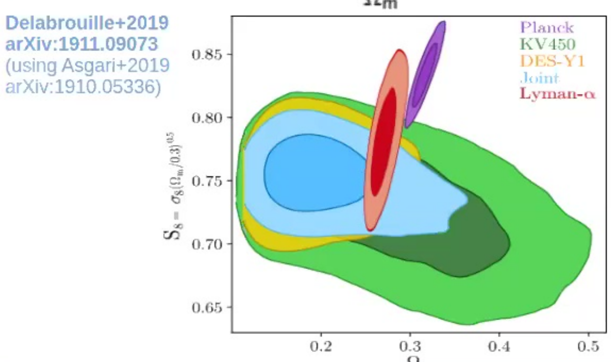
Delabrouille+2019
arXiv:1911.09073
(using Asgari+2019
arXiv:1910.05336)

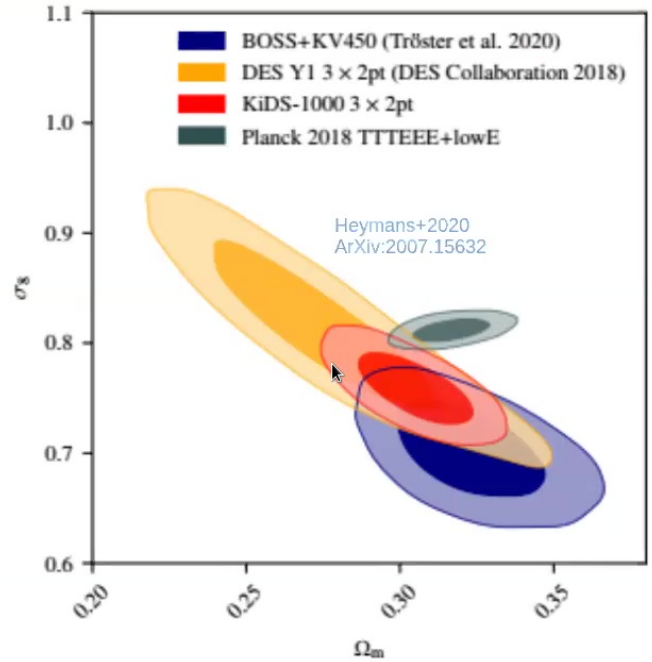


1) Data | 2) Tension | 3) Models | 4) Conclusion

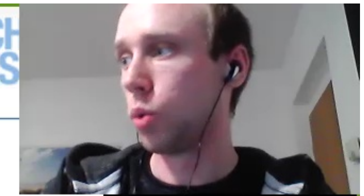
The weak lensing tension





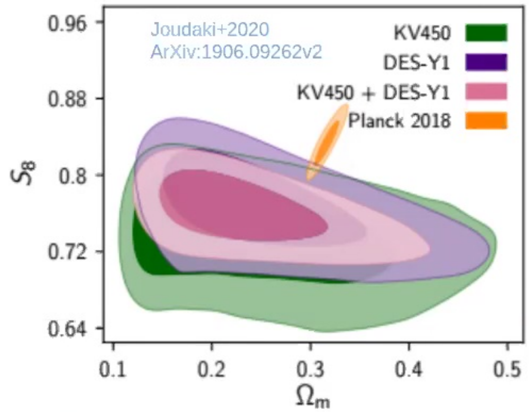


Institute for Theoretical Particle Physics and Cosmology

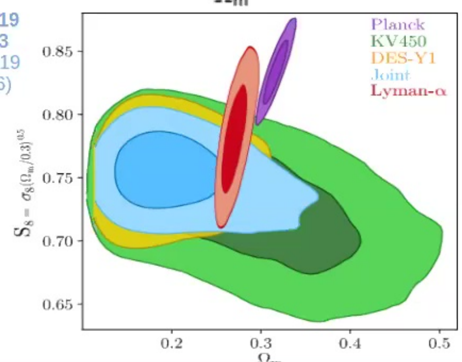


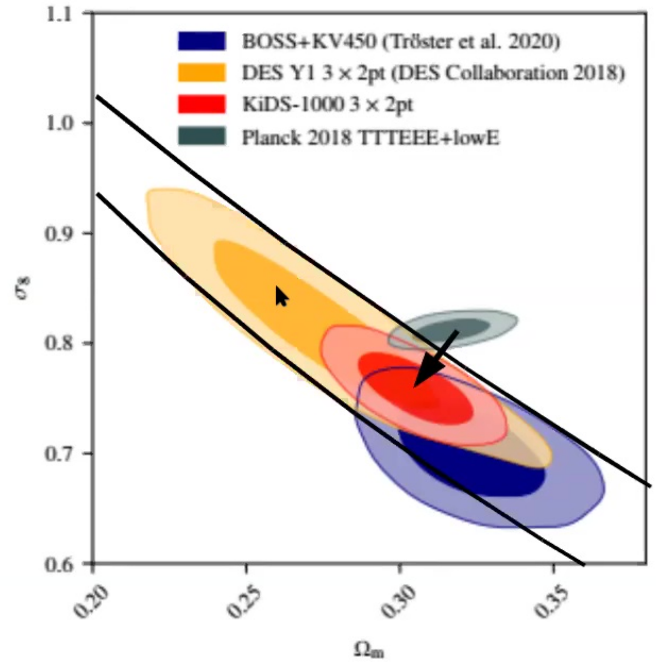
1) Data 2) Tension 3) Models 4) Conclusion

The weak lensing tension

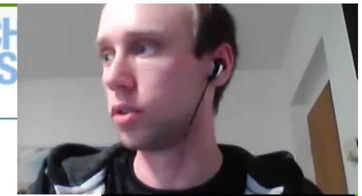


Delabrouille+2019
arXiv:1911.09073
(using Asgari+2019
arXiv:1910.05336)





1) Data | 2) Tension | 3) Models | 4) Conclusion



The weak lensing tension

Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

$$\frac{\mathrm{d}^2\delta}{\mathrm{d}\ln a^2} + \left[\frac{\mathrm{d}\ln a\mathcal{H}}{\mathrm{d}\ln a} + (1-3w)\right]\frac{\mathrm{d}\delta}{\mathrm{d}\ln a} + \frac{3}{2}(1+w)\left[\frac{k^2}{k_s^2} - 1\right]\delta = 0$$

$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{\boxed{c_s}} \qquad c_s^2 = \frac{\delta P}{\delta \rho}$$

Critical

1) Data 2) Tension 3) Models 4) Conclusion

The weak lensing tension

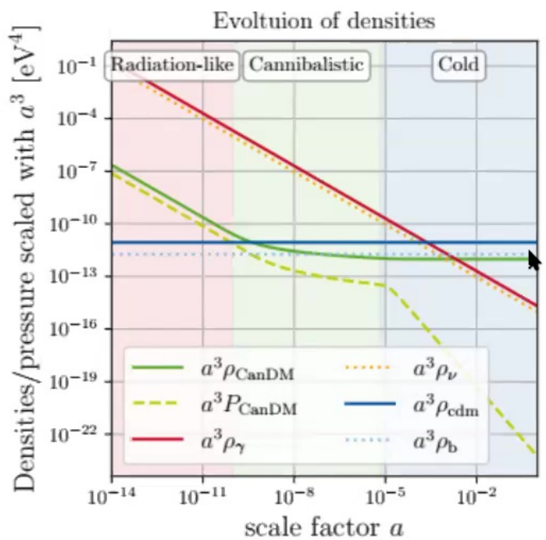
Option 1)

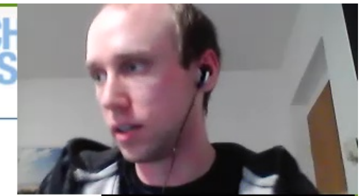
Give Dark Matter some sound scale
Suppresses clustering below k_s

$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486

Example : CanDM





1) Data 2) Tension 3) Models 4) Conclusion

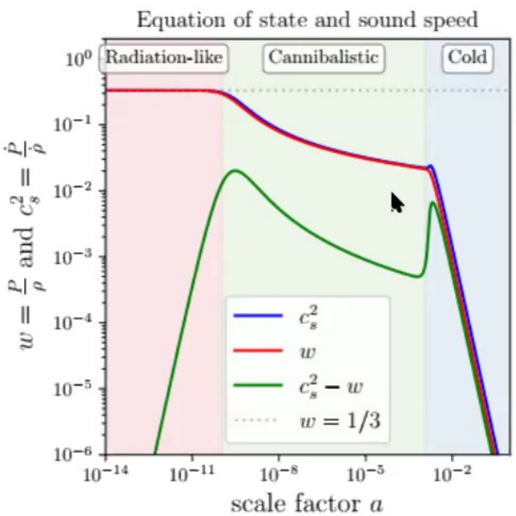
The weak lensing tension

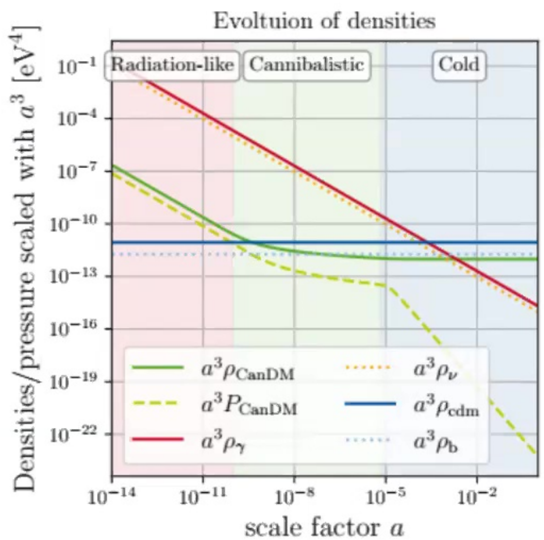
Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486





1) Data 2) Tension 3) Models 4) Conclusion

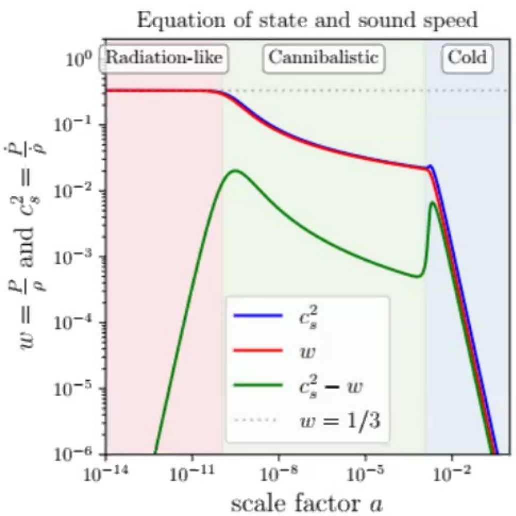
The weak lensing tension

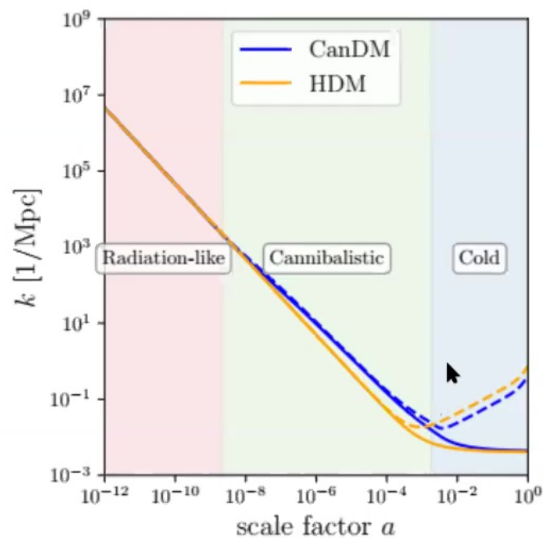
Option 1)

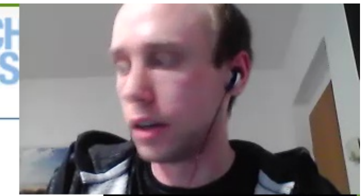
Give Dark Matter some sound scale
Suppresses clustering below k_s

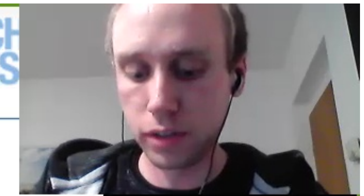
$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486









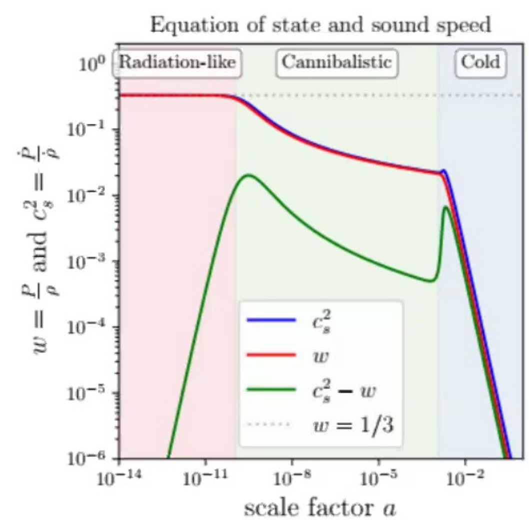
The weak lensing tension

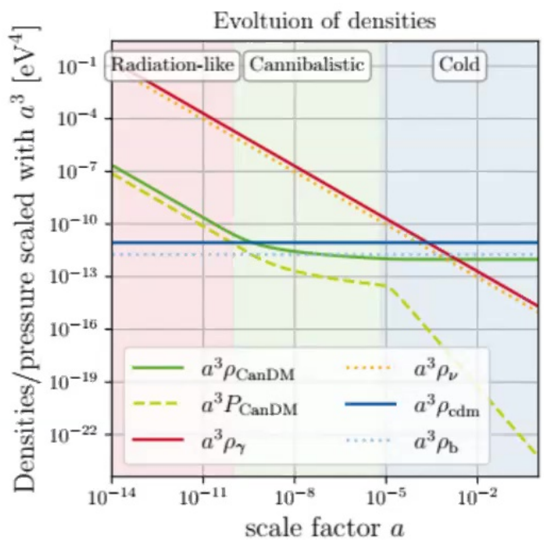
Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486





1) Data 2) Tension 3) Models 4) Conclusion

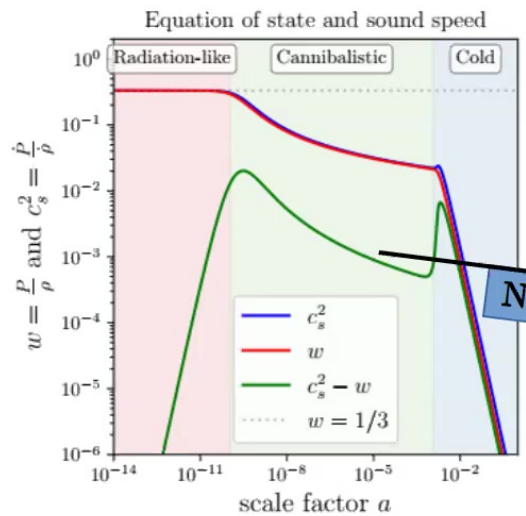
The weak lensing tension

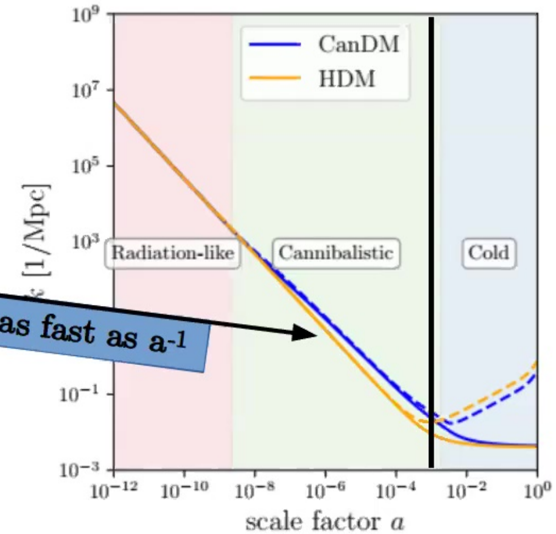
Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486





1) Data 2) Tension 3) Models 4) Conclusion

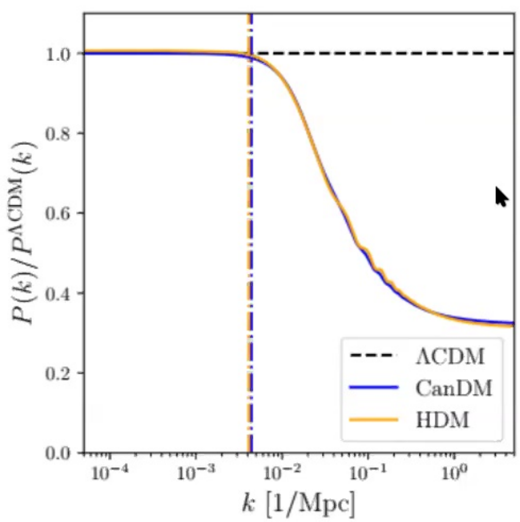
The weak lensing tension

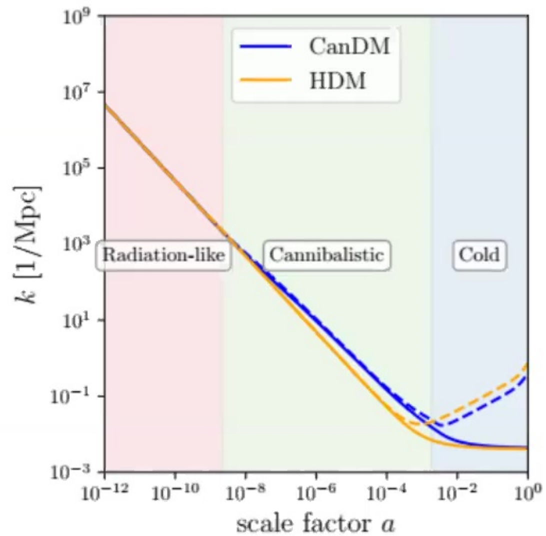
Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

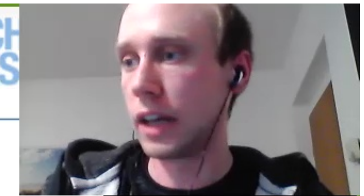
$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486





1) Data 2) Tension 3) Models 4) Conclusion



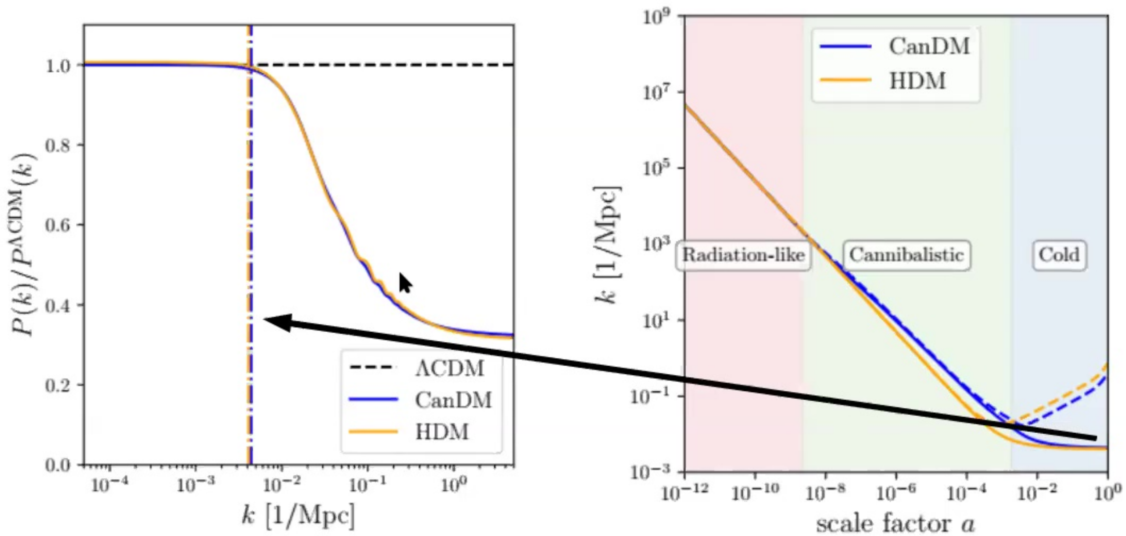
The weak lensing tension

Option 1)

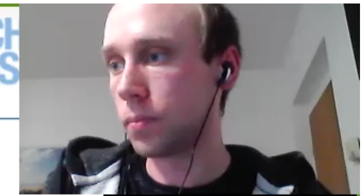
Give Dark Matter some sound scale
Suppresses clustering below k_s

$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486



1) Data 2) Tension 3) Models 4) Conclusion



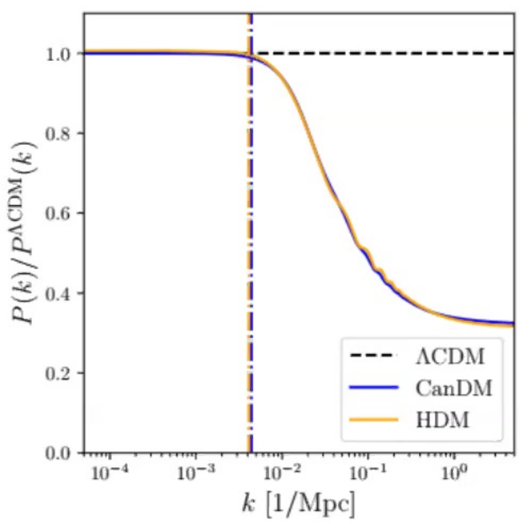
The weak lensing tension

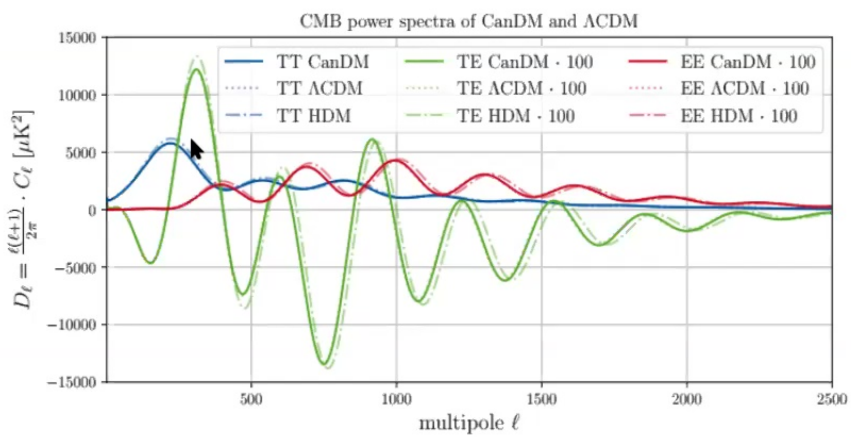
Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486





1) Data 2) Tension 3) Models 4) Conclusion

The weak lensing tension

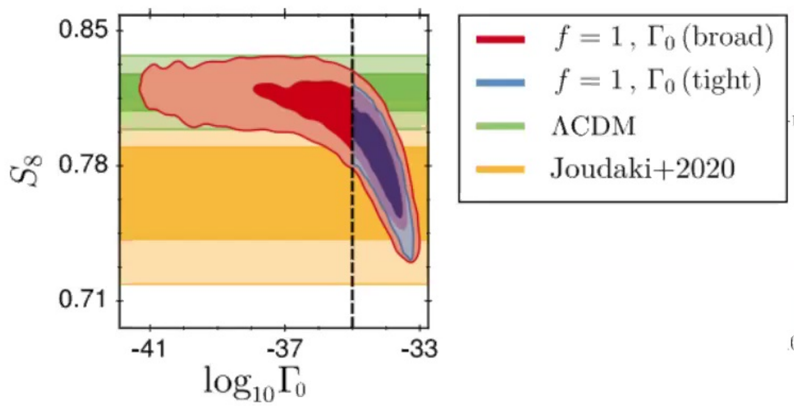
Option 1)

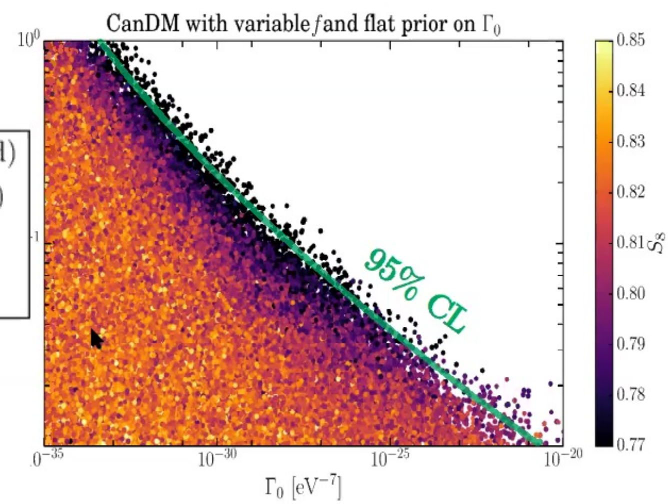
Give Dark Matter some sound scale
Suppresses clustering below k_s

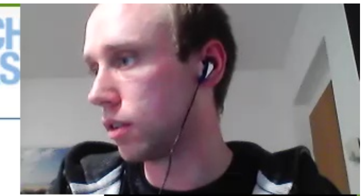
$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Heimersheim+2020
arXiv:2008.08486

Example : CanDM







1) Data 2) Tension 3) Models 4) Conclusion

The weak lensing tension

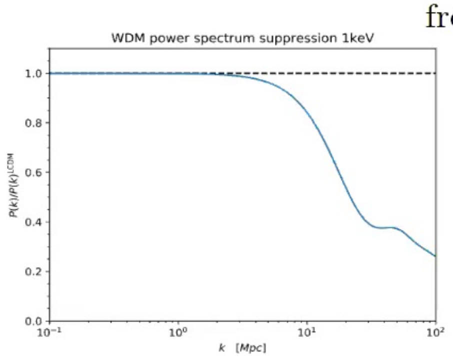
Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

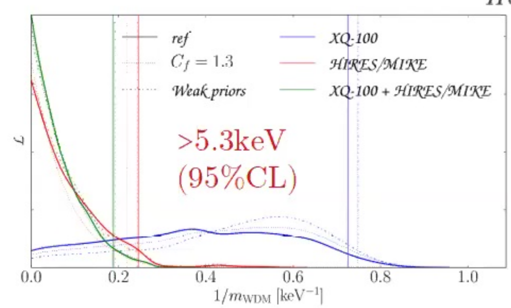
$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Example : WDM

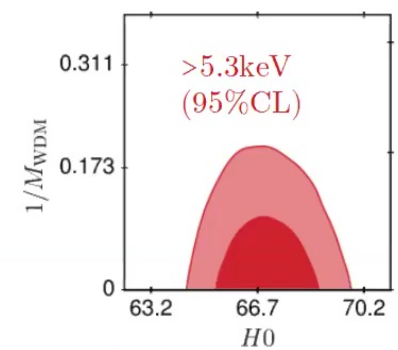
Generates c_s through free-streaming

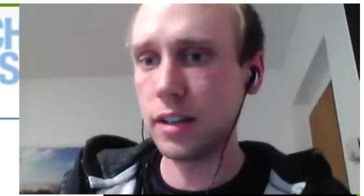


Irsic+2017
arXiv:1702.01[illegible]64

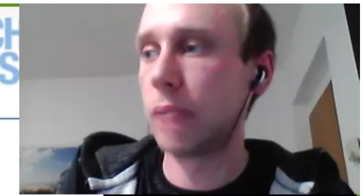


Delabrouille+2019
arXiv:1911.09073





1) Data 2) Tension 3) Models 4) Conclusion



The weak lensing tension

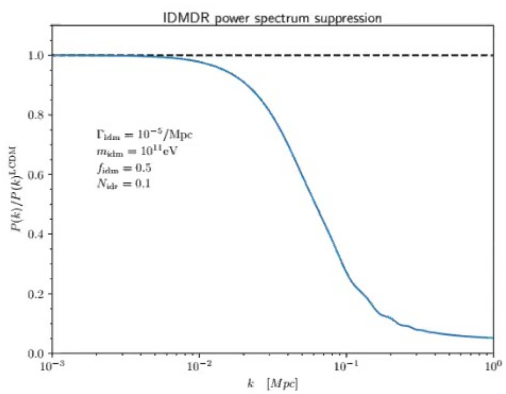
Option 1)

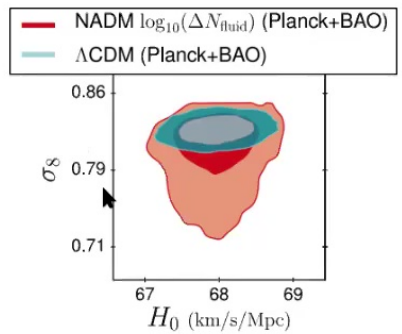
Give Dark Matter some sound scale
Suppresses clustering below k_s

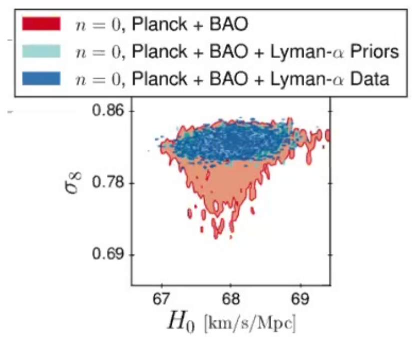
$$k_s = \sqrt{\frac{3}{2}(1+w)}\frac{\mathcal{H}}{c_s}$$

Archidiacono+2019
arXiv:1907.01496

Example : Dark Radiation interaction (ETHOS)







1) Data 2) Tension 3) Models 4) Conclusion

The weak lensing tension

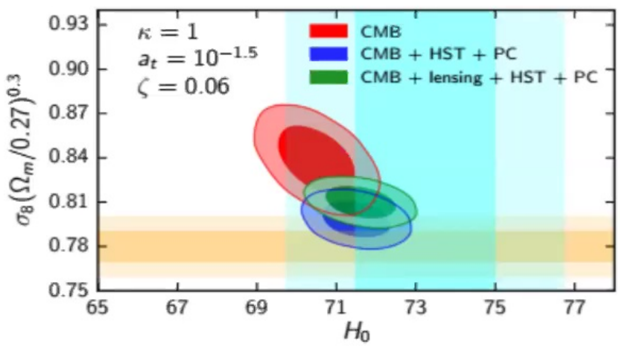
Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

Option 2)

Generate a free-streaming component
Suppresses clustering below k_s

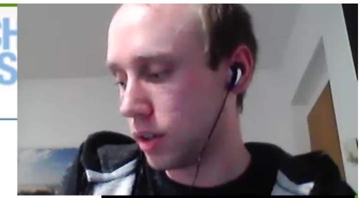
Bringmann+2018
arXiv:1803.03644



Seems promising, but
perturbations

1) Data 2) Tension 3) Models 4) Conclusion

Institute for Theoretical Particle Physics and Cosmology



The weak lensing tension

Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

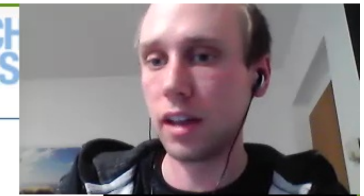
Option 2)

Generate a free-streaming component
Suppresses clustering below k_s

Option 3)

Use parameter degeneracies to shift
S_8 from CMB $\rightarrow$ Requires larger H_0

1) Data   2) Tension $\boxed{\text{3) Models}}$ 4) Conclusion



The weak lensing tension

Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

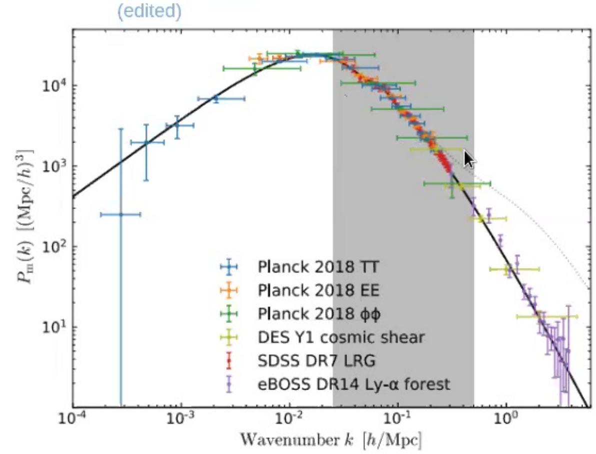
Option 2)

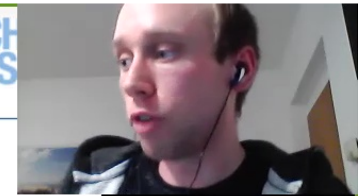
Generate a free-streaming component
Suppresses clustering below k_s

Option 3)

Use parameter degeneracies to shift
S_8 from CMB $\rightarrow$ Requires larger H_0

Cahbanier+2019
ArXiv:1905.08103
(edited)





The weak lensing tension

Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

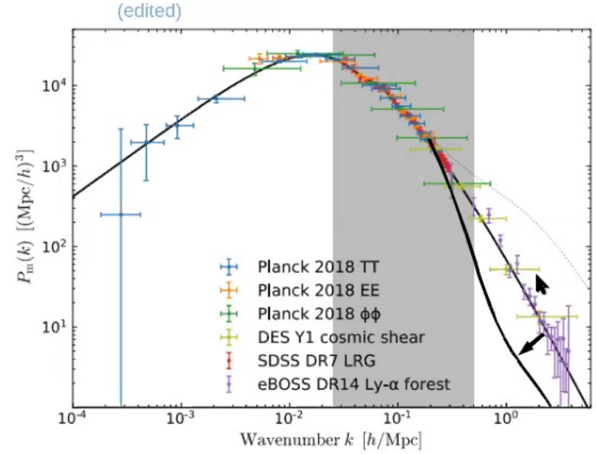
Option 2)

Generate a free-streaming component
Suppresses clustering below k_s

Option 3)

Use parameter degeneracies to shift S_8 from CMB $\rightarrow$ Requires larger H_0

Cahbanier+2019
ArXiv:1905.08103
(edited)



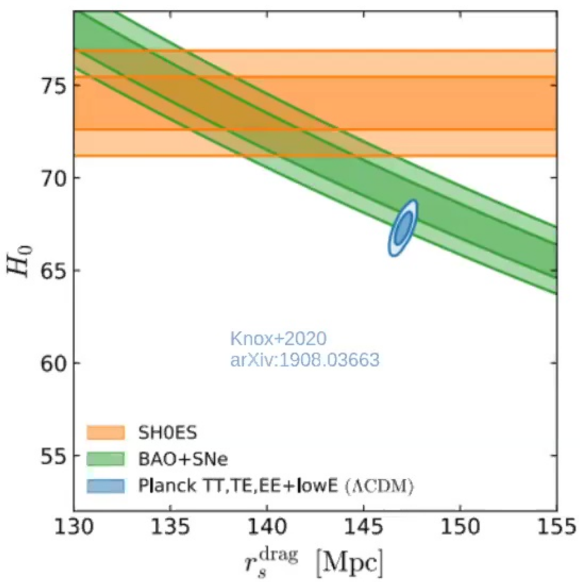
Suppressing S8 in a "sharp" way almost always influences Lyman-α data

$\rightarrow$ Shallow suppressions or dips (or modify Ω_m or Lyman-α)

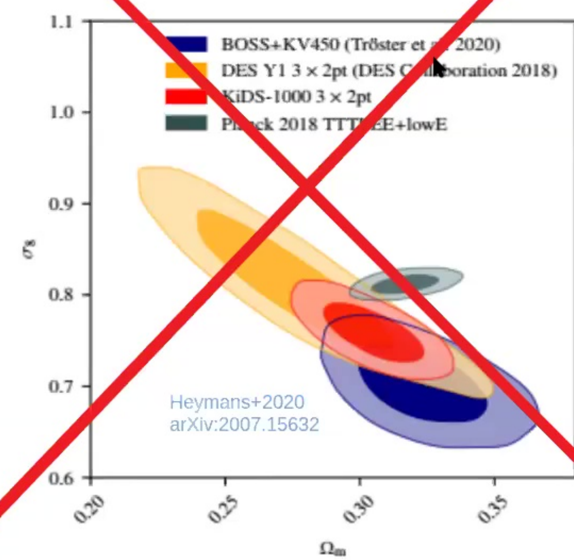
1) Data 2) Tension 3) Models 4) Conclusion

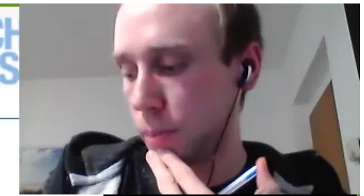
The tale of two tensions

$$H_0 \leftrightarrow r_s \qquad (> 4\sigma)$$

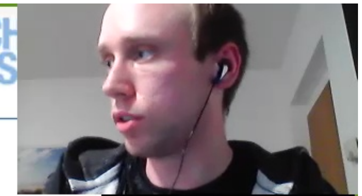


$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5} \qquad (> 2.5\sigma)$$





1) Data 2) Tension 3) Models 4) Conclusion



The weak lensing tension

Option 1)

Give Dark Matter some sound scale
Suppresses clustering below k_s

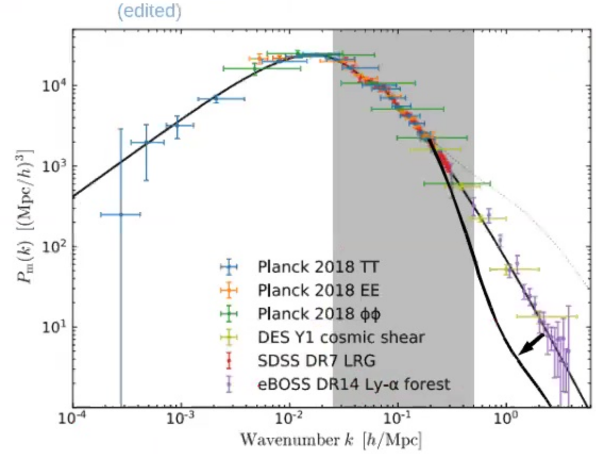
Option 2)

Generate a free-streaming component
Suppresses clustering below k_s

Option 3)

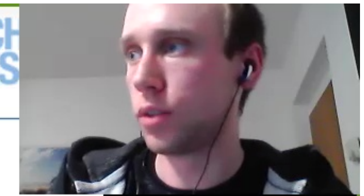
Use parameter degeneracies to shift S_8 from CMB $\rightarrow$ Requires larger H_0

Cahbanier+2019
ArXiv:1905.08103
(edited)

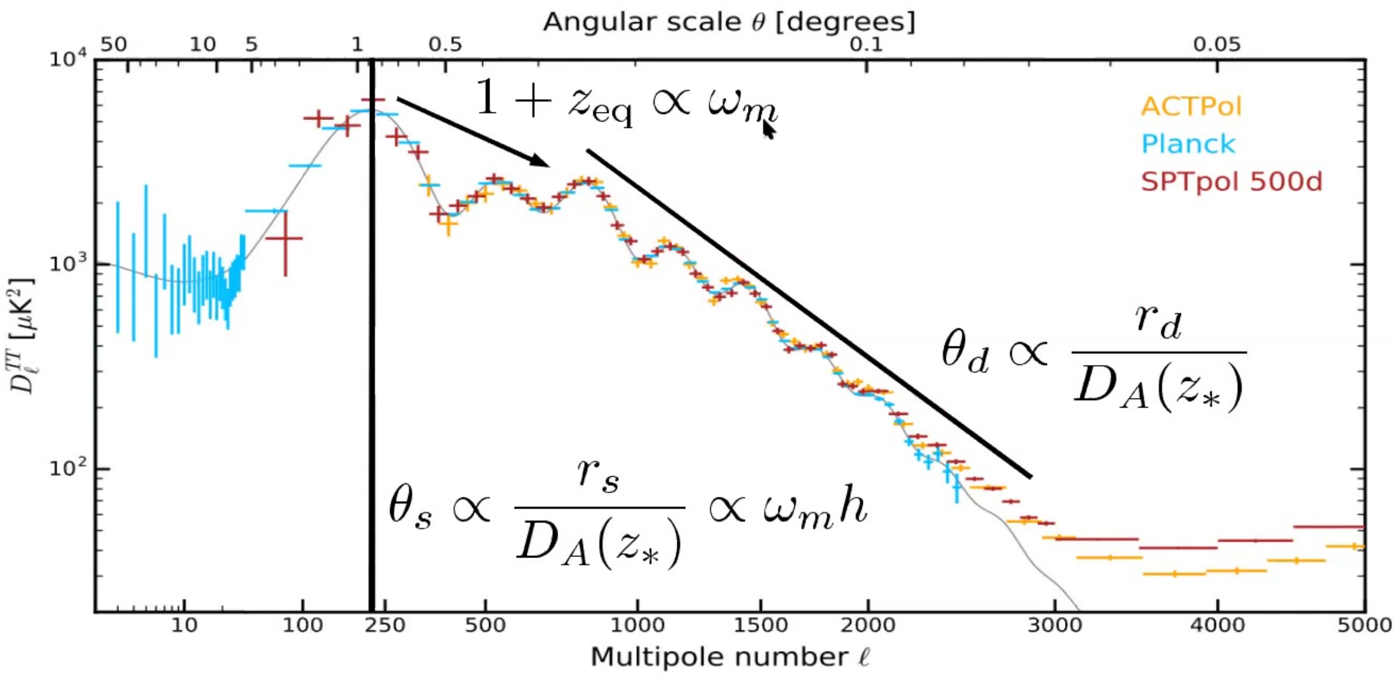


Suppressing S8 in a "sharp" way almost always influences Lyman-α data

$\rightarrow$ Shallow suppressions or dips (or modify Ω_m or Lyman-α)

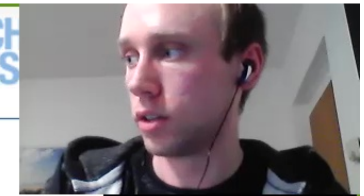


The Hubble tension

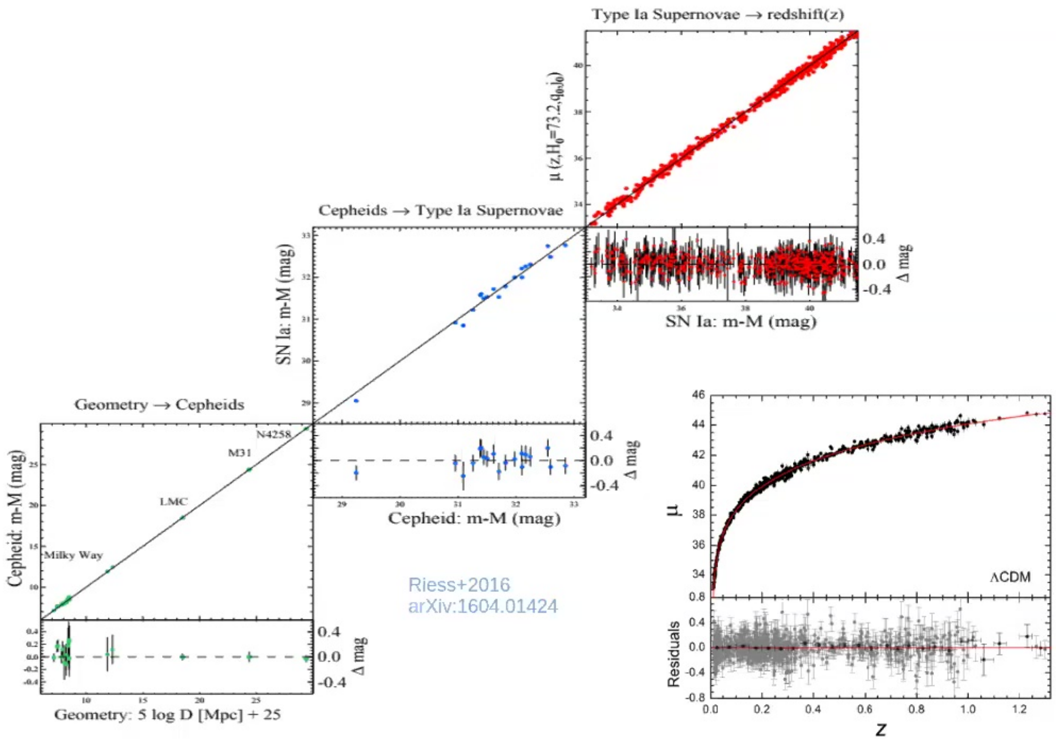


SPT Collaboration
arXiv:1910.07157

$\boxed{\text{1) Data}}$ 2) Tension 3) Models 4) Conclusion



The Hubble tension



Riess+2016
arXiv:1604.01424

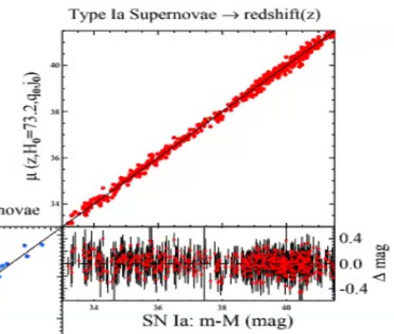
Joint Lightcurve Analysis

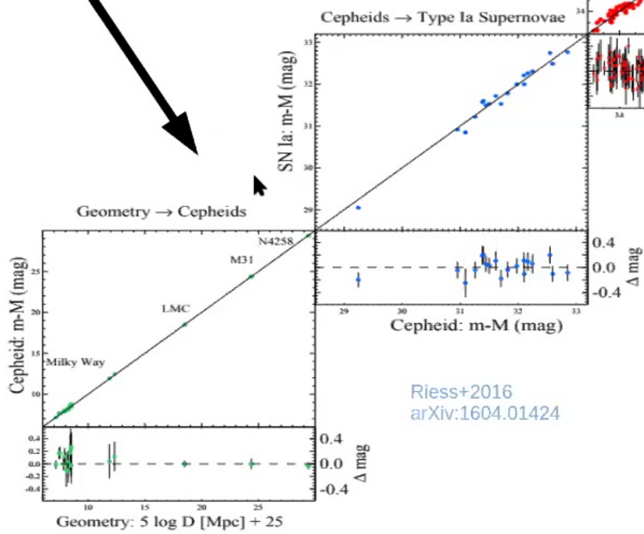
- Supernovae Legacy Survey = SNLS
- Sloan Digital Sky Survey = SDSS
- Hubble space telescope = HST
- Various low-z SNe

Melia+2018
arXiv:1809.05094

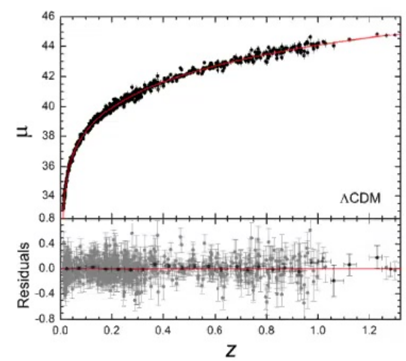
The Hubble tension

This is replacable through
other standard candles





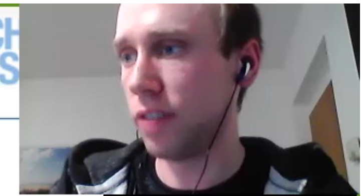
Riess+2016
arXiv:1604.01424



Joint Lightcurve Analysis

- Supernovae Legacy Survey = SNLS
- Sloan Digital Sky Survey = SDSS
- Hubble space telescope = HST
- Various low-z SNe

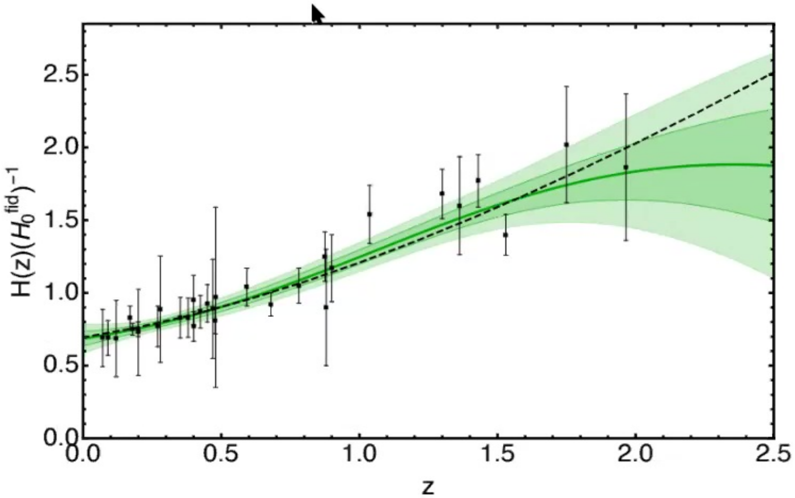
Melia+2018
arXiv:1809.05094



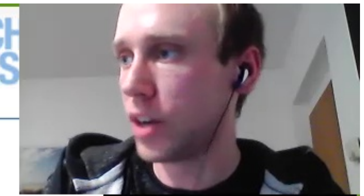
1) Data 2) Tension 3) Models 4) Conclusion

The Hubble tension

$$\frac{\mathrm{d}t}{\mathrm{d}z} = -\frac{H(z)}{1+z}$$

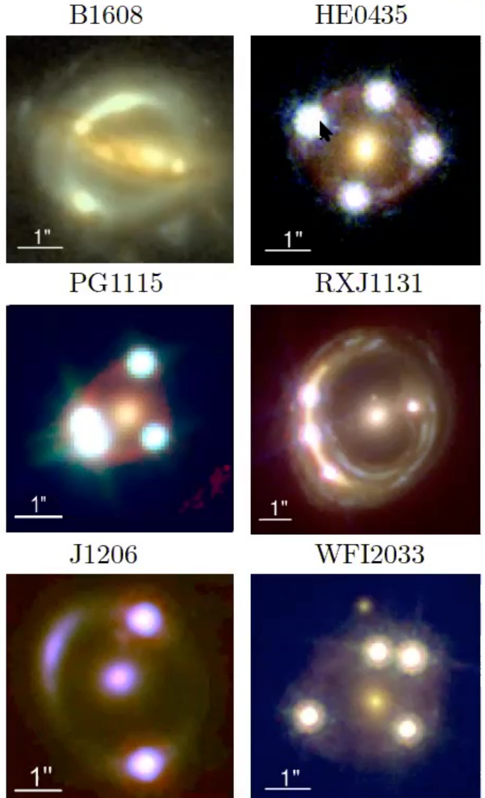


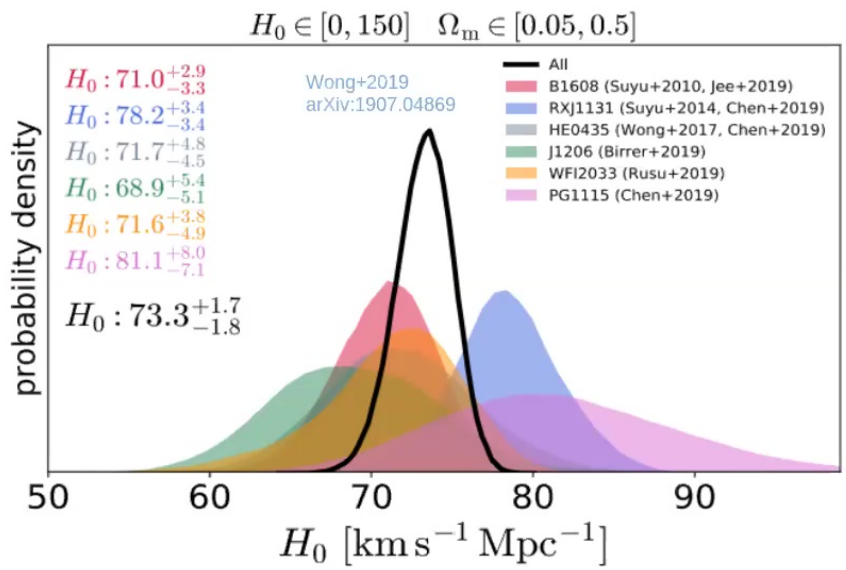
Haridasu+2018
arXiv:1805.03595



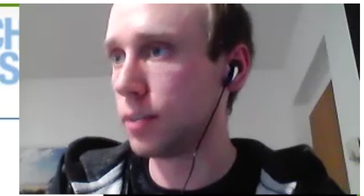
1) Data 2) Tension 3) Models 4) Conclusion

The Hubble tension

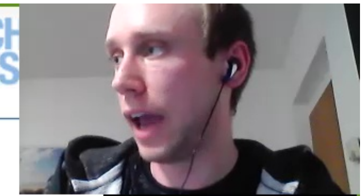




$$D_{\Delta t} = (1 + z_L)\frac{D_L D_S}{D_{LS}} \propto \frac{1}{H_0}$$



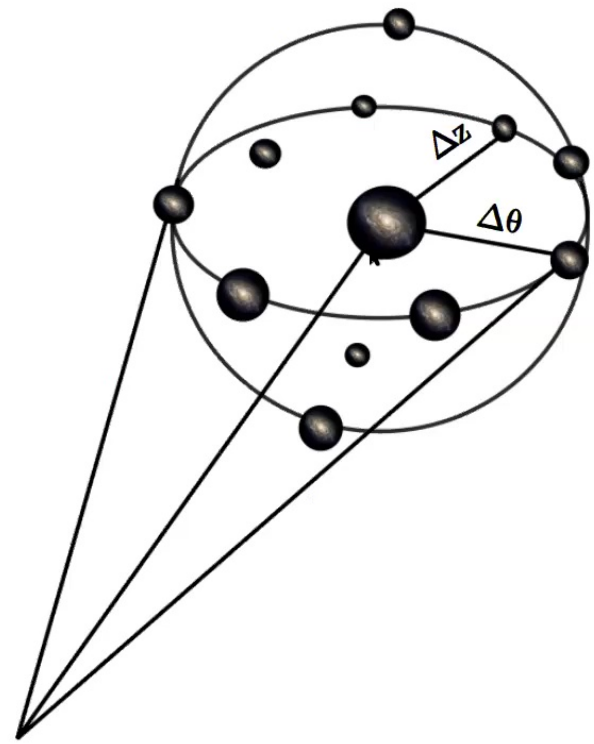
1) Data | 2) Tension | 3) Models | 4) Conclusion



The BAO+BBN path

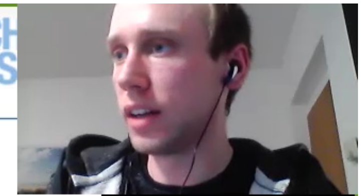
$$\Delta\theta = \Delta\chi / D_A = r_s / D_A$$

$$\Delta z = H \Delta\chi = H r_s$$



Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY



The BAO+BBN path

- Low z (z=0.38)

$$H \propto H_0 \Omega_m^{0.14}$$

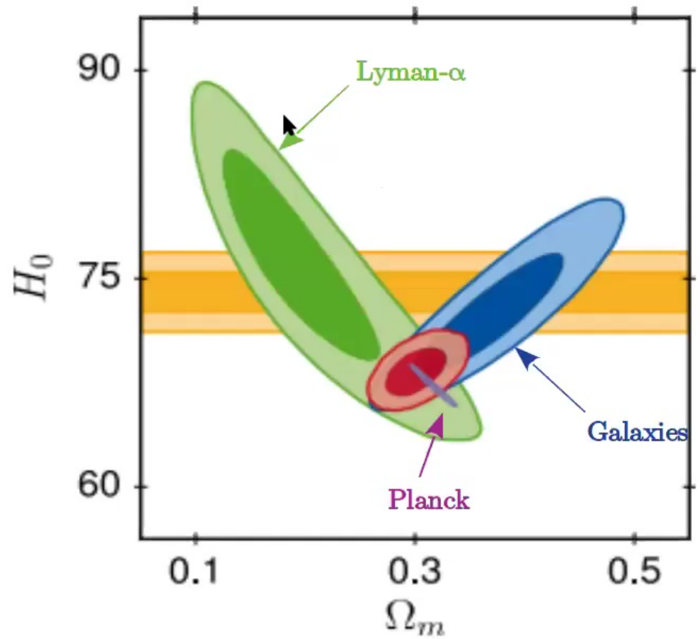
$$1/D_A \propto H_0 \Omega_m^{0.067}$$

- High z (z=2.35)

$$H \propto H_0 \Omega_m^{0.44}$$

$$1/D_A \propto H_0 \Omega_m^{0.251}$$

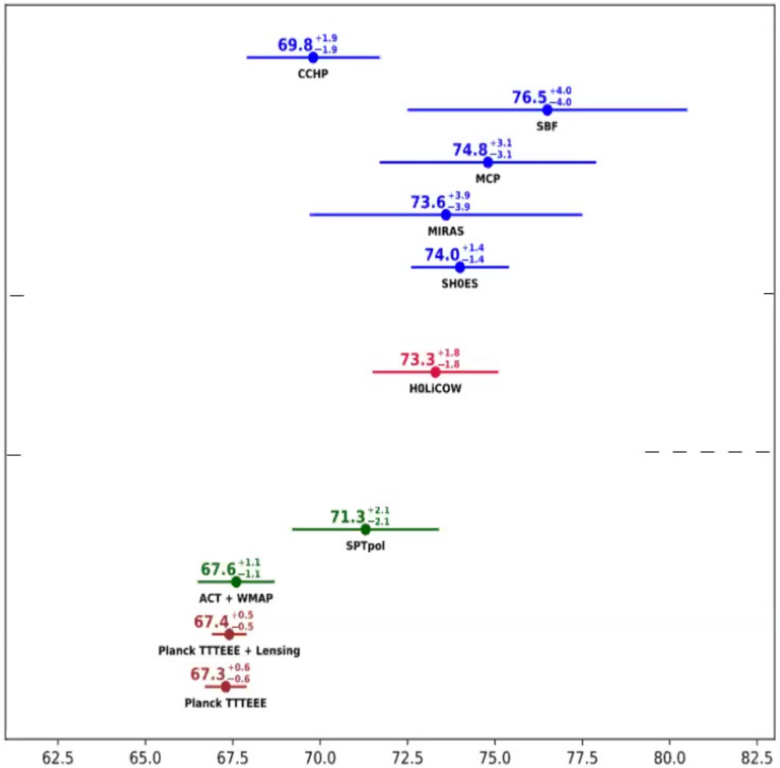
The BAO+BBN path



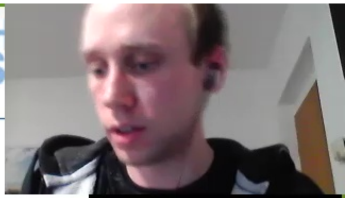
Schöneberg+2019
arXiv:1907.11594
(based on Cuceo+2019)

1) Data 2) Tension 3) Models 4) Conclusion

The Hubble tension

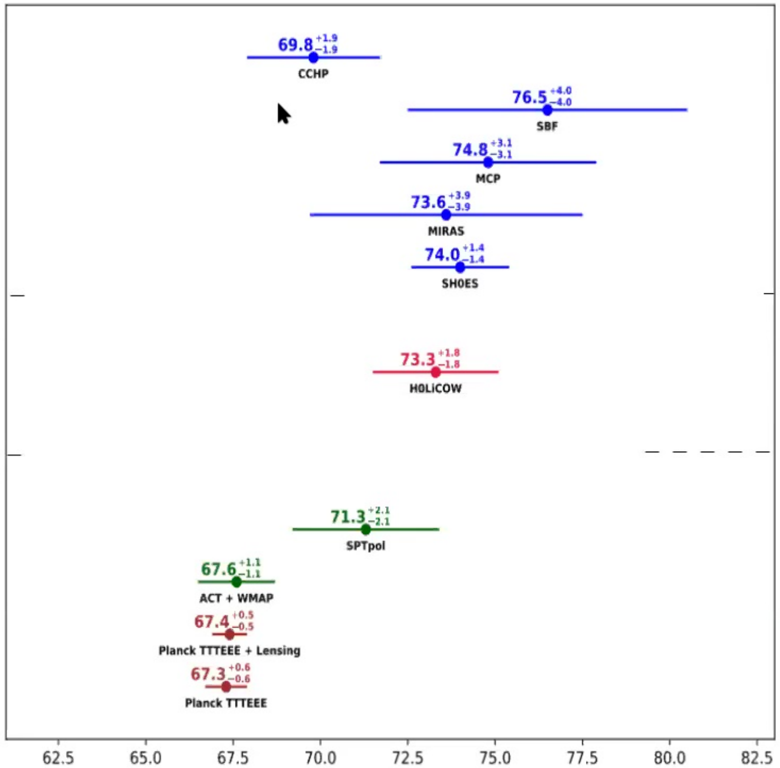


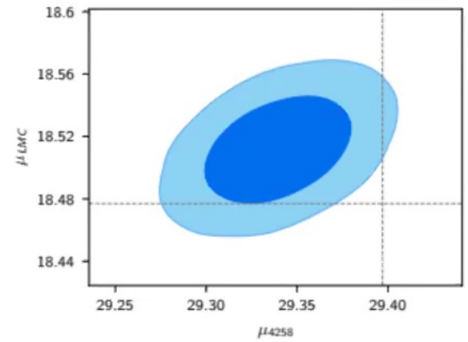
1) Data 2) Tension 3) Models 4) Conclusion

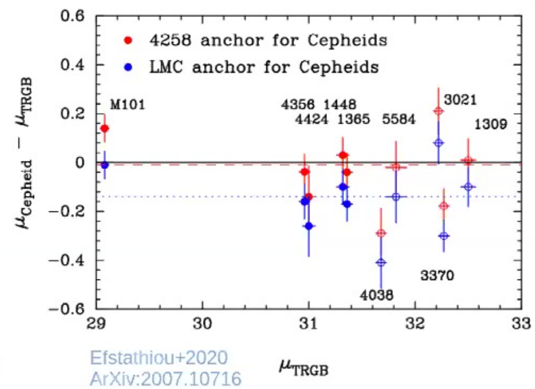


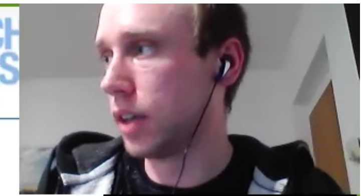
Institute for Theoretical Particle Physics and Cosmology

The Hubble tension



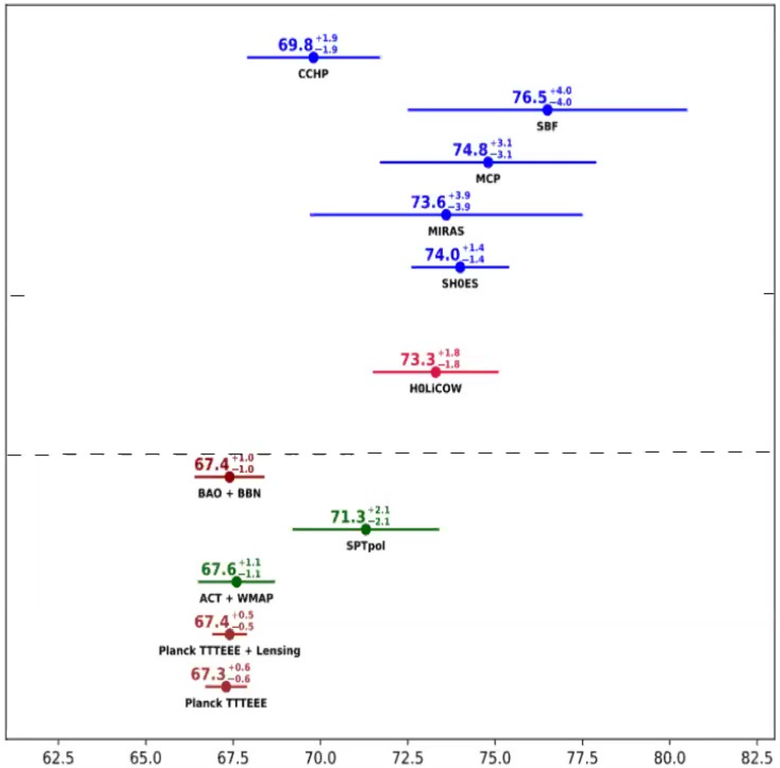






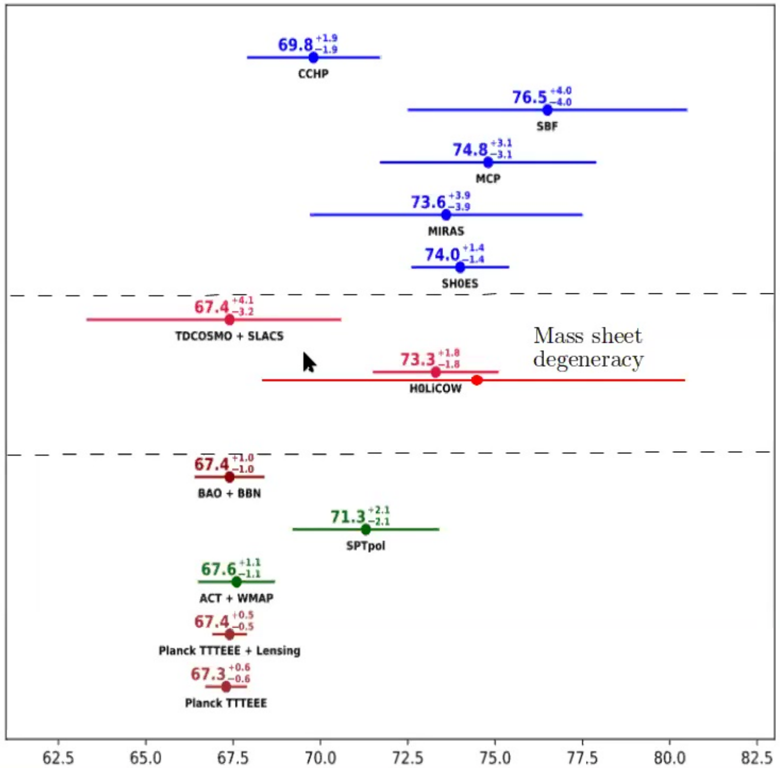
1) Data 2) Tension 3) Models 4) Conclusion

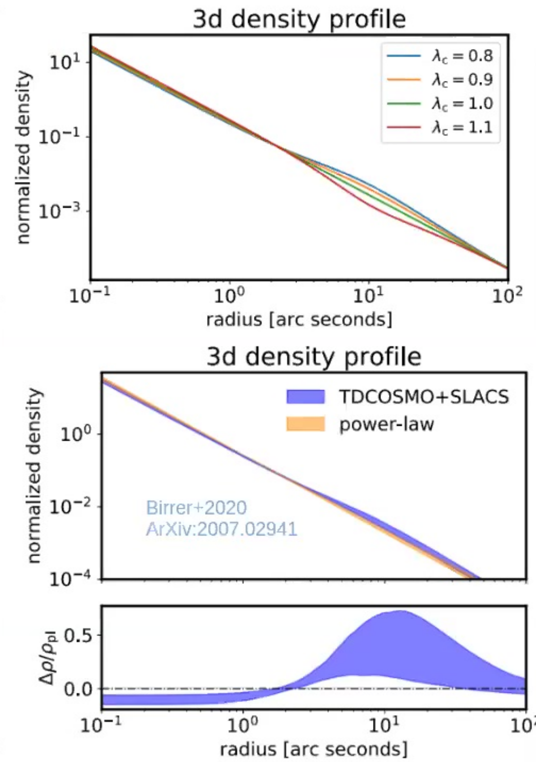
The Hubble tension

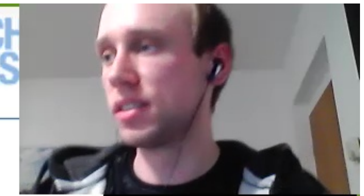


Institute for Theoretical Particle Physics and Cosmology

The Hubble tension

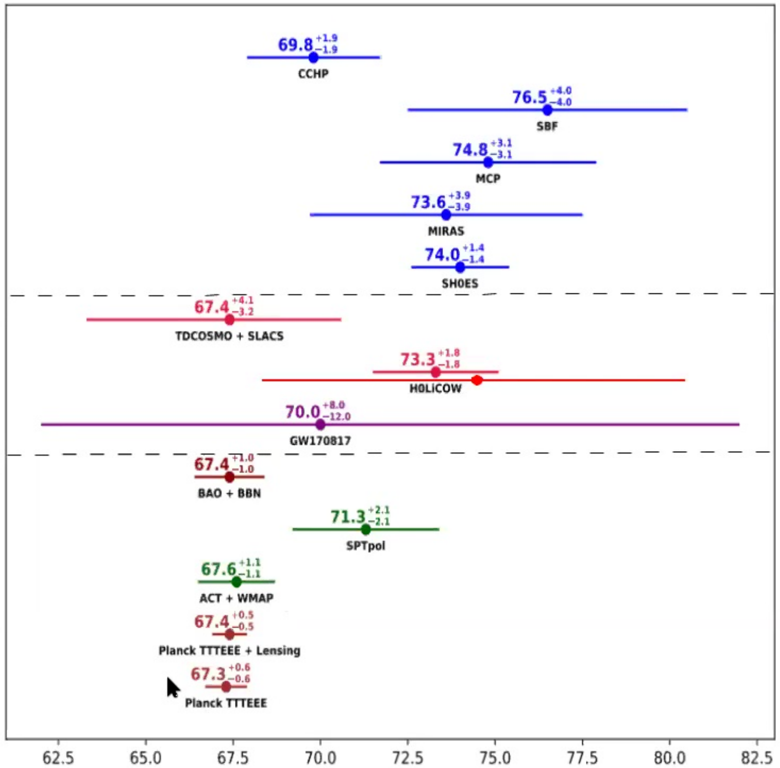


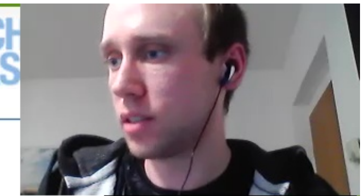




1) Data
2) Tension
3) Models
4) Conclusion

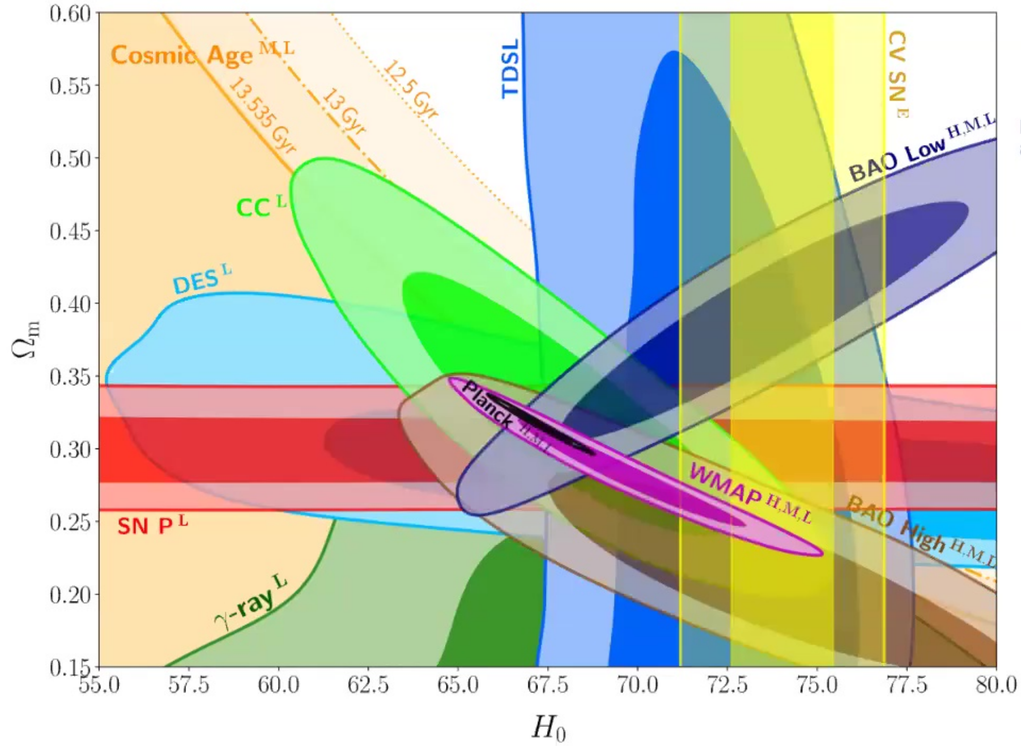
The Hubble tension





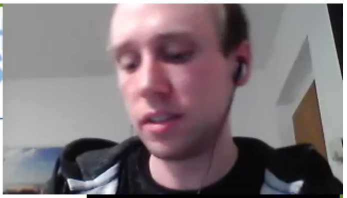
1) Data | 2) Tension | 3) Models | 4) Conclusion

The Hubble tension



Lin+2019
arXiv:1910.02978

1) Data 2) Tension 3) Models 4) Conclusion

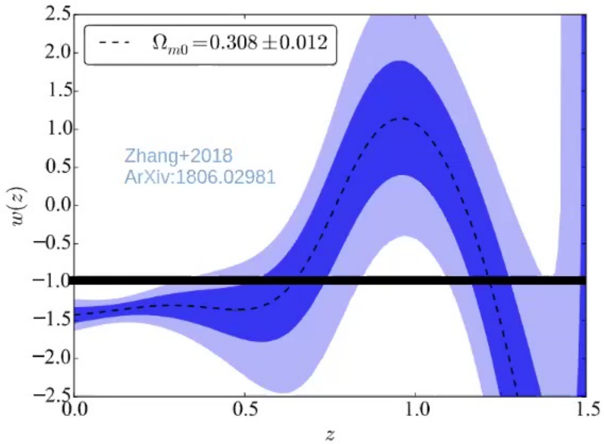


The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$\theta_s = \frac{r_s}{D_A(z_*)} = const$



Since rs is fixed after decoupling, we have to fix

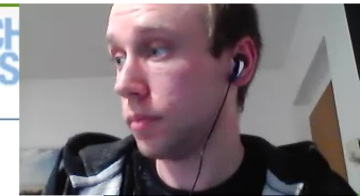
$$D_A(z_*) = \frac{1}{1+z_*} \cdot \frac{\int_0^{z_*} \frac{dz'}{H(z')/H_0}}{H_0}$$

$$H_0 \nearrow \quad \Rightarrow \quad H(z)/H_0 \searrow$$

$$H(z)/H_0 = \sqrt{\Omega_m(1+z)^3 + \Omega_{\rm DE}(z)}$$

$$\Omega_{\rm DE}(z) < \Omega_{\rm DE}(z=0) \quad \Rightarrow \quad w(z) < -1$$

1) Data 2) Tension 3) Models 4) Conclusion



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

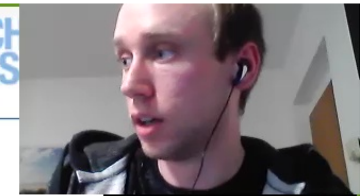
$\theta_s = \frac{r_s}{D_A(z_*)} = const$

Since rs is fixed after decoupling,
we have to fix

$$D_A(z_*) = \frac{1}{1+z_*} \cdot \frac{\int_0^{z_*} \frac{dz'}{H(z')/H_0}}{H_0}$$

$$H_0 \nearrow \quad \Rightarrow \quad H(z)/H_0 \searrow$$

$$H(z)/H_0 = \sqrt{\cancel{\Omega_m(1+z)}^3 + \Omega_{\mathrm{DE}}(z)}$$



The Hubble tension

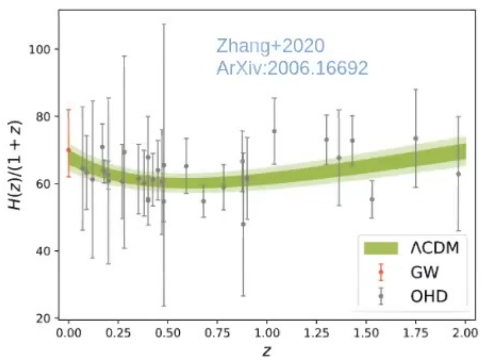
Option 1)

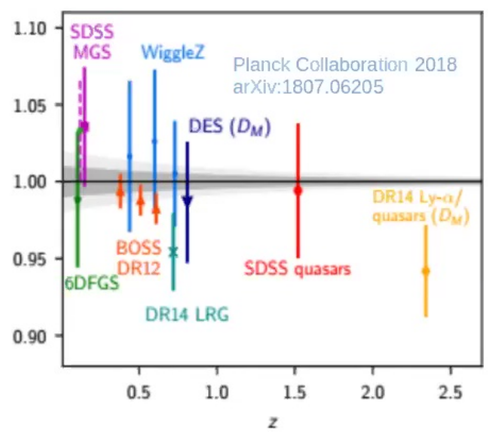
Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Since rs is fixed after decoupling, we have to fix

$$D_A(z_*) = \frac{1}{1+z_*} \cdot \frac{\int_0^{z_*} \frac{dz'}{H(z')/H_0}}{H_0}$$



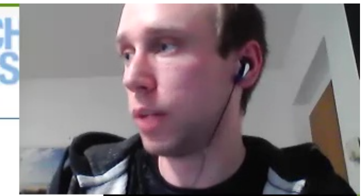


Strong constraints at z<2.5

1) Data 2) Tension **3) Models** 4) Conclusion

Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

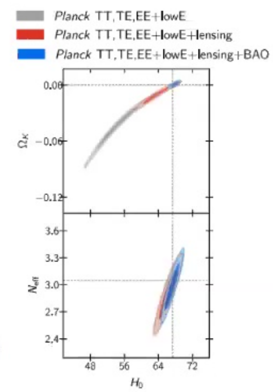
$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

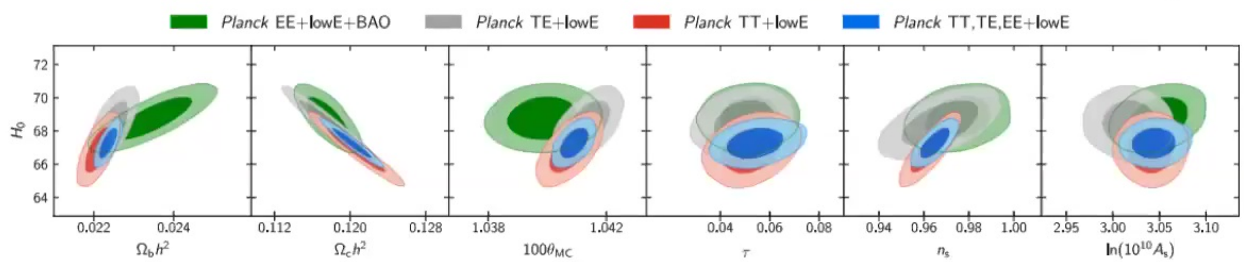
Change the inference of H_0 from the CMB by playing with degeneracies

Biggest degeneracies:

Ω_k Ω_m N_{eff}



Planck Collaboration 2018
arXiv:1807.06209



1) Data 2) Tension 3) Models 4) Conclusion

The Hubble tension

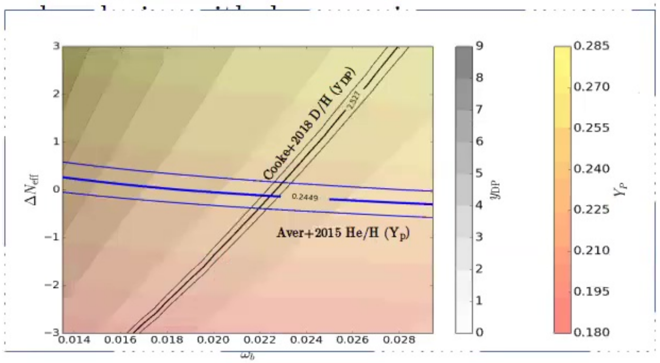
Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

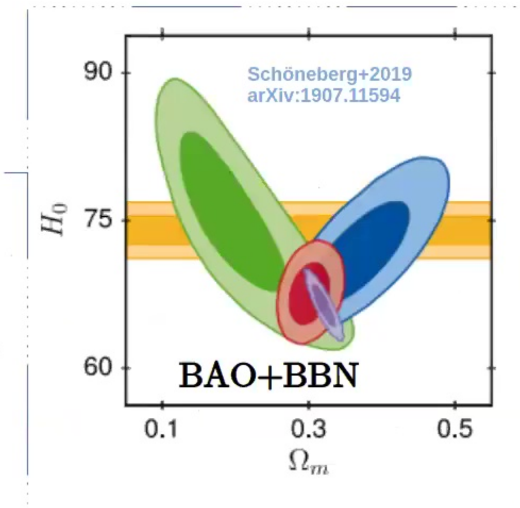
Option 2)

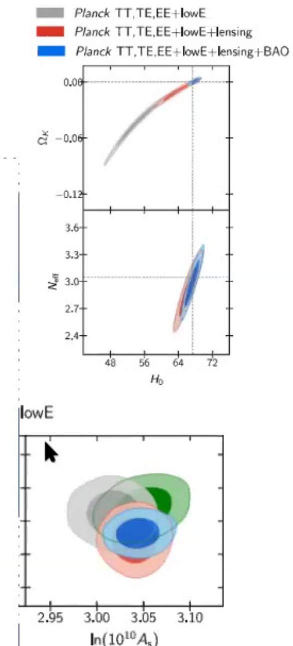
Change the inference of H_0 from the CMB

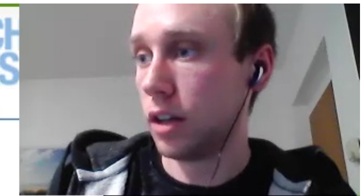


Biggest degeneracies:

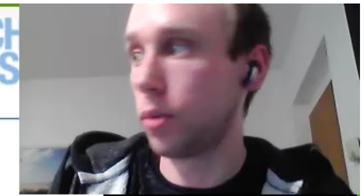
Ω_k Ω_m $N_{\rm eff}$







1) Data 2) Tension 3) Models 4) Conclusion



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

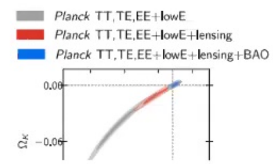
$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

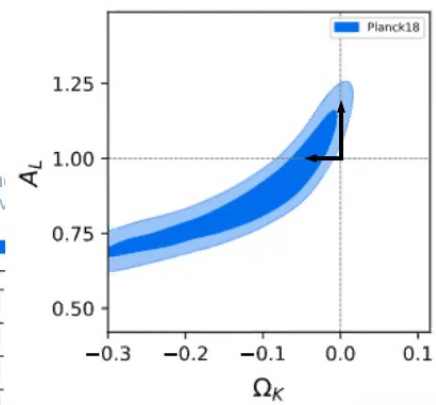
Change the inference of H_0 from the CMB by playing with degeneracies

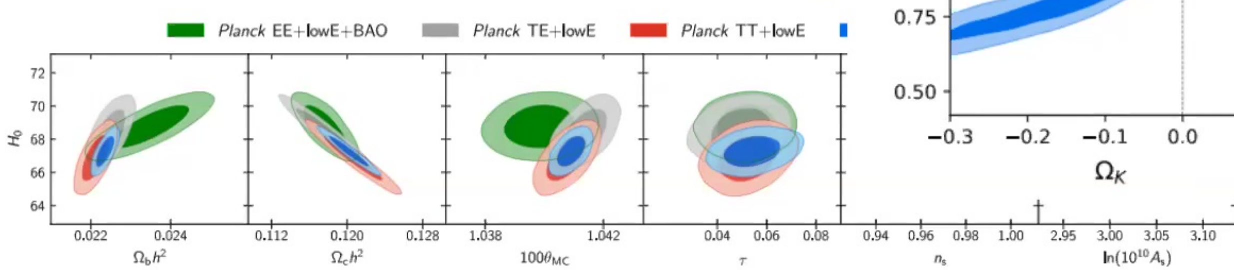
Biggest degeneracies:

Ω_k $\cancel{\Omega_m}$ $\cancel{N_{eff}}$

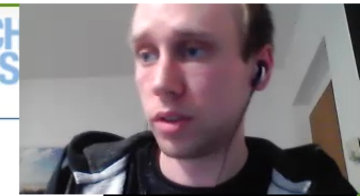


Di Valentino+2019
arXiv:1911.02087





1) Data 2) Tension $\boxed{\text{3) Models}}$ 4) Conclusion



The Hubble tension

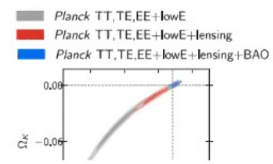
Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Biggest degeneracies:

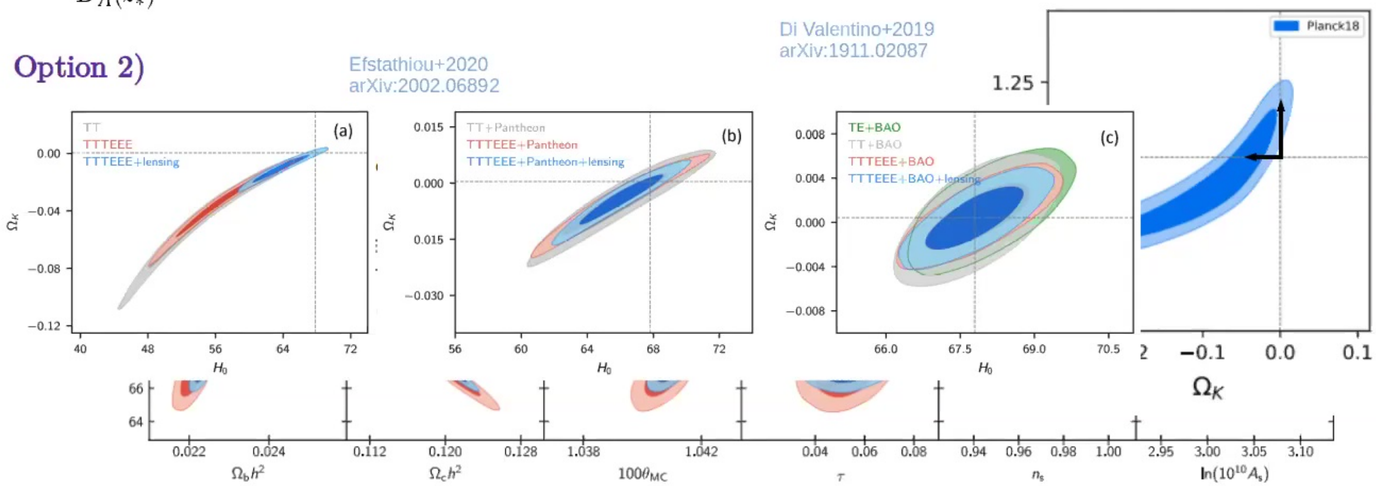
Ω_k $\cancel{\Omega_m}$ $\cancel{N_{eff}}$

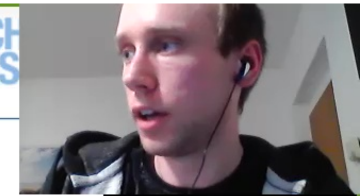


Option 2)

Efstathiou+2020
arXiv:2002.06892

Di Valentino+2019
arXiv:1911.02087





The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$\theta_s = \frac{r_s}{D_A(z_*)} = const$

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

Option 3)

Change the inference of H_0 from the CMB by changing r_s , while keeping

$\theta_s = \frac{r_s}{D_A(z_*)} = const$

$$\theta_s = \frac{r_s}{D_A(z_*)} = (1+z_*) \cdot \frac{H_0 r_s}{\int_0^{z_*} H_0/H(z')dz'}$$

$$H_0 \nearrow \quad \Rightarrow \quad r_s \searrow$$

The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$\theta_s = \frac{r_s}{D_A(z_*)} = const$

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

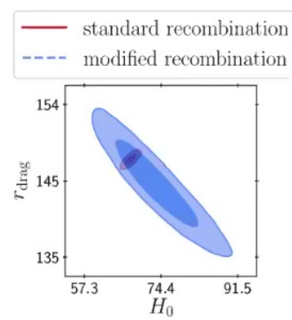
Option 3)

Change the inference of H_0 from the CMB by changing r_s , while keeping

$\theta_s = \frac{r_s}{D_A(z_*)} = const$

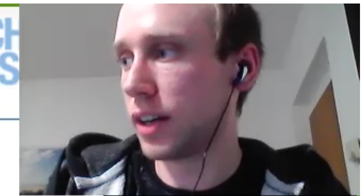
$$\theta_s = \frac{r_s}{D_A(z_*)} = (1+z_*) \cdot \frac{H_0 r_s}{\int_0^{z_*} H_0/H(z')dz'}$$

$$H_0 \nearrow \quad \Rightarrow \quad r_s \searrow$$



Chiang+2018
arXiv:1811.03624

1) Data 2) Tension 3) Models 4) Conclusion



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

Option 3)

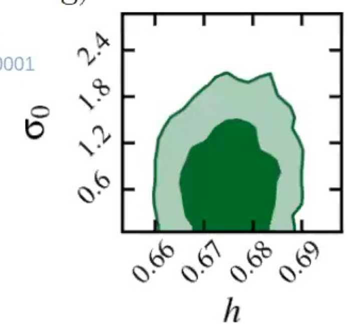
Change the inference of H_0 from the CMB by changing r_s , while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

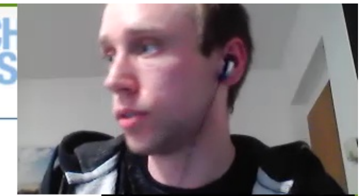
$$r_s = \int_z^\infty \frac{\boxed{c_s(z')}dz'}{H(z')}$$

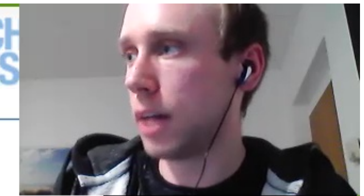
Non-standard baryon sound speed (DM-b DM- scattering)

Boddy+2018
arXiv:1808.00001



1) Data 2) Tension 3) Models 4) Conclusion





The Hubble tension

$$r_s = \int_z^\infty \frac{c_s(z')dz'}{\boxed{H(z')}}$$

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

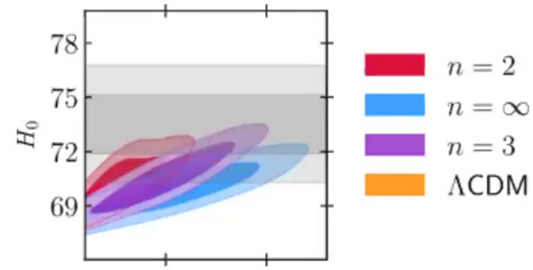
Change the inference of H_0 from the CMB by playing with degeneracies

Option 3)

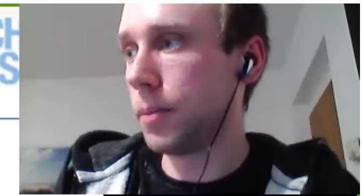
Change the inference of H_0 from the CMB by changing r_s , while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Poulin+2018
arXiv:1811.04083



1) Data 2) Tension 3) Models 4) Conclusion

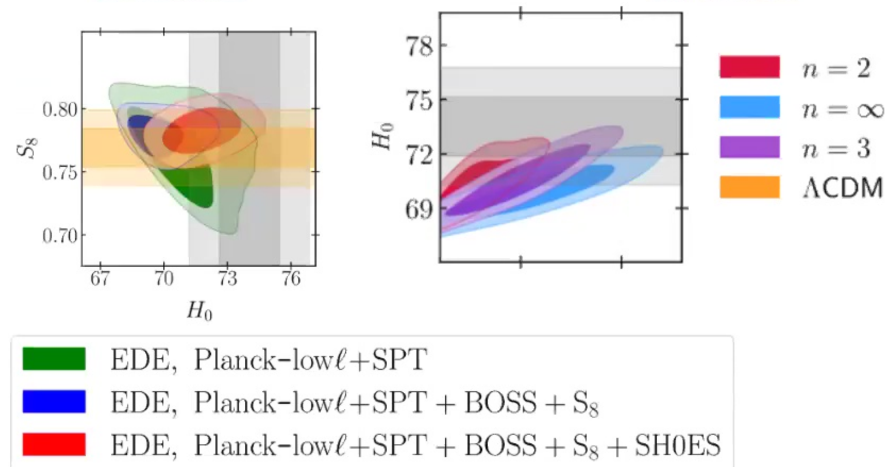


The early dark energy solution

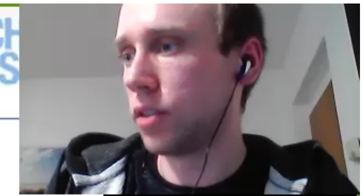
$$r_s = \int_z^\infty \frac{c_s(z')dz'}{\boxed{H(z')}}$$

Chudaykin+2020
arXiv:2011.04682

Poulin+2018
arXiv:1811.04083



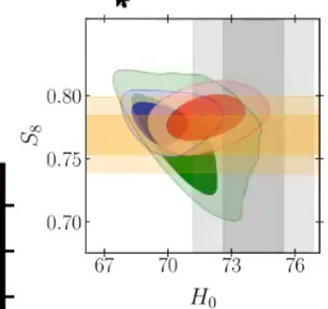
1) Data 2) Tension 3) Models 4) Conclusion

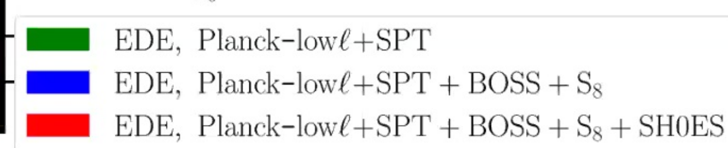


The early dark energy solution

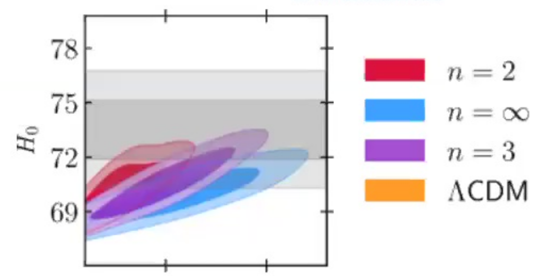
$$r_s = \int_z^\infty \frac{c_s(z')dz'}{\boxed{H(z')}}$$

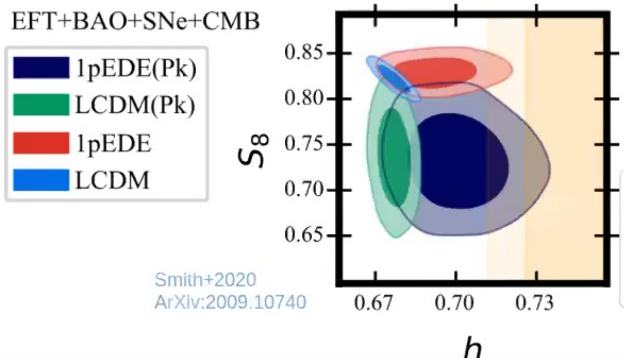
Chudaykin+2020
arXiv:2011.04682





Poulin+2018
arXiv:1811.04083



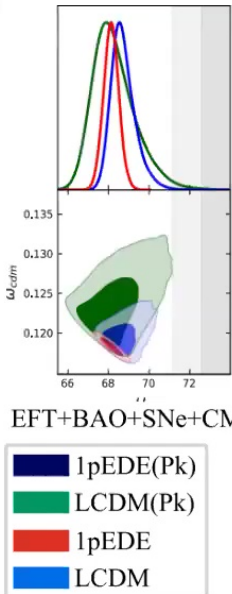


Smith+2020
ArXiv:2009.10740

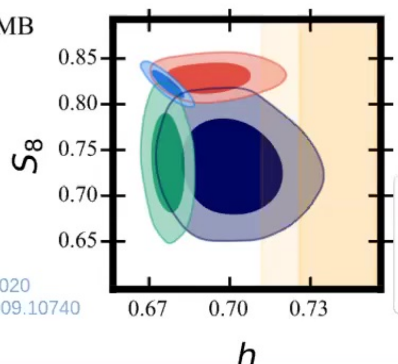
1) Data 2) Tension 3) Models 4) Conclusion

The early dark energy solution

$$r_s = \int_z^\infty \frac{c_s(z')dz'}{\boxed{H(z')}}$$

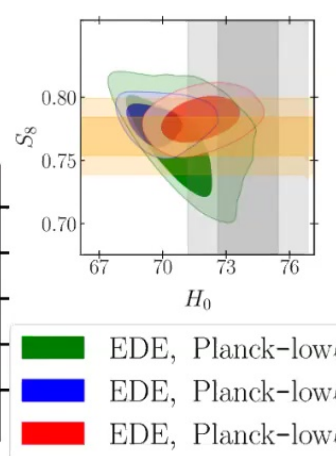


Ivanov+2020
arXiv:2006.11235

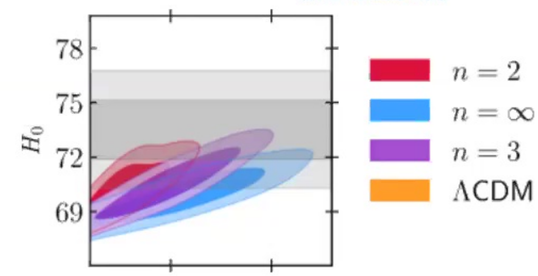


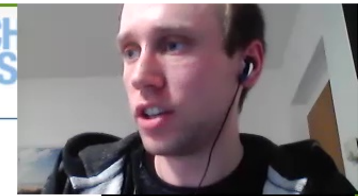
Smith+2020
ArXiv:2009.10740

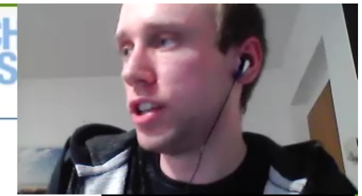
Chudaykin+2020
arXiv:2011.04682



Poulin+2018
arXiv:1811.04083







The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

Option 3)

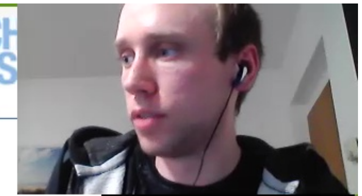
Change the inference of H_0 from the CMB by changing r_s , while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

$$r_s = \int_z^\infty \frac{c_s(z')dz'}{\boxed{H(z')}}$$

Many more opportunities!

1) Data 2) Tension 3) Models 4) Conclusion



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

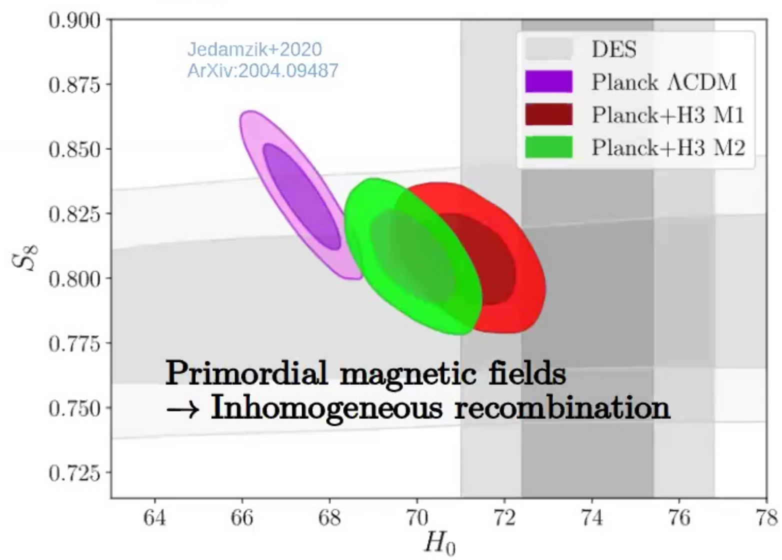
Change the inference of H_0 from the CMB by playing with degeneracies

Option 3)

Change the inference of H_0 from the CMB by changing r_s , while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

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



1) Data 2) Tension 3) Models 4) Conclusion

The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

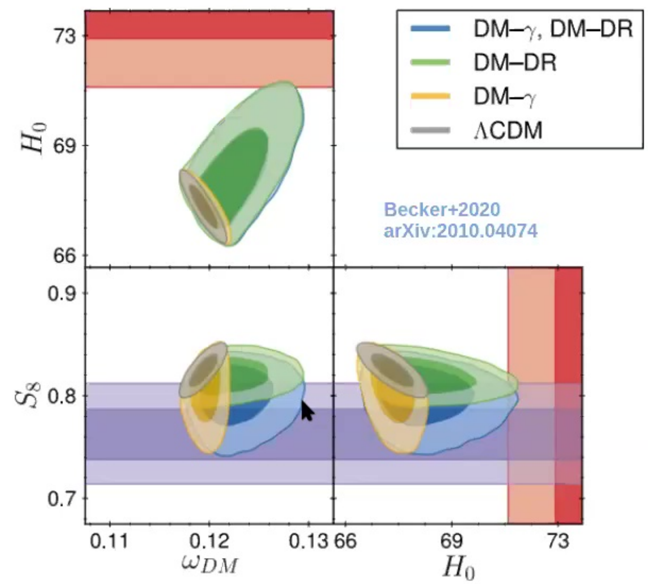
Option 3)

Change the inference of H_0 from the CMB by changing r_s, while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Keep damping of CMB fixed even through higher H_0

Same idea as $\mathbf{N_{eff}}$, but aided by perturbations



1) Data 2) Tension 3) Models 4) Conclusion

The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

Change the inference of H_0
by playing with degeneracie

Option 3)

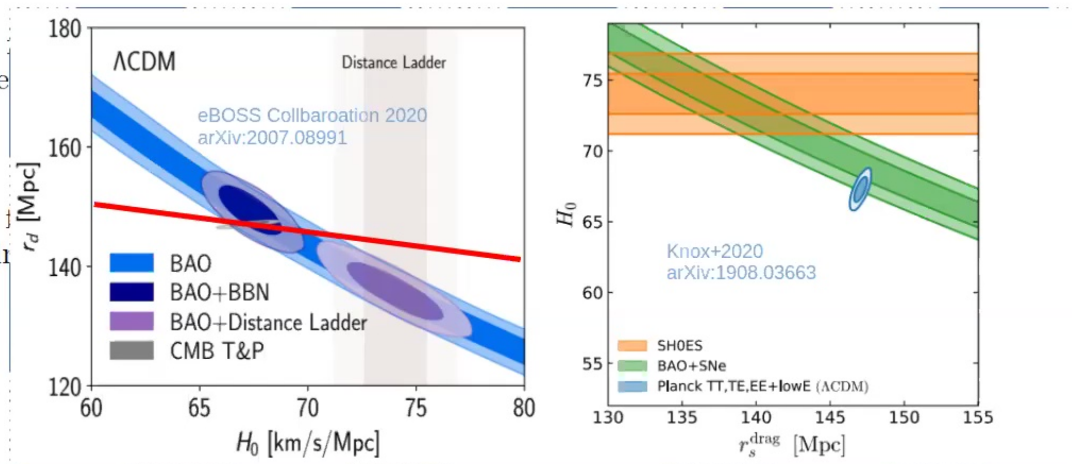
Change the inference of H_0
by changing r_s , while keepi

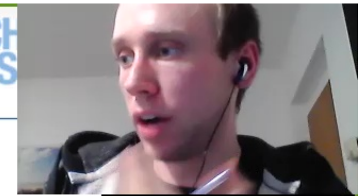
$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

There is a more general problem!

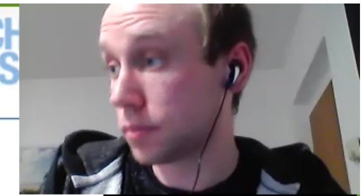
Jedamzik+2020
ArXiv:2010.04158

Fixed θ_s , $\Omega_m h^2$





1) Data 2) Tension 3) Models 4) Conclusion



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

Change the inference of H_0
by playing with degeneracie

Option 3)

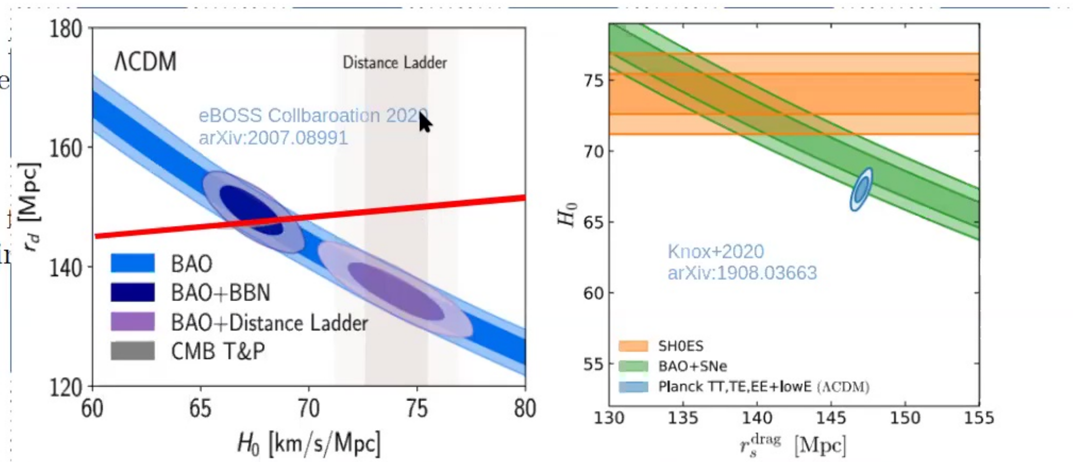
Change the inference of H_0
by changing r_s , while keepi

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

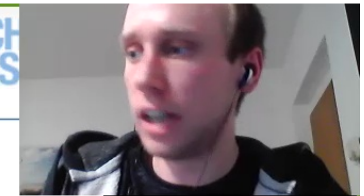
There is a more general problem!

Jedamzik+2020
ArXiv:2010.04158

Fixed θ_s , CMB degeneracy direction



1) Data 2) Tension 3) Models 4) Conclusion



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

Change the inference of H_0 ...
by playing with degeneracie...

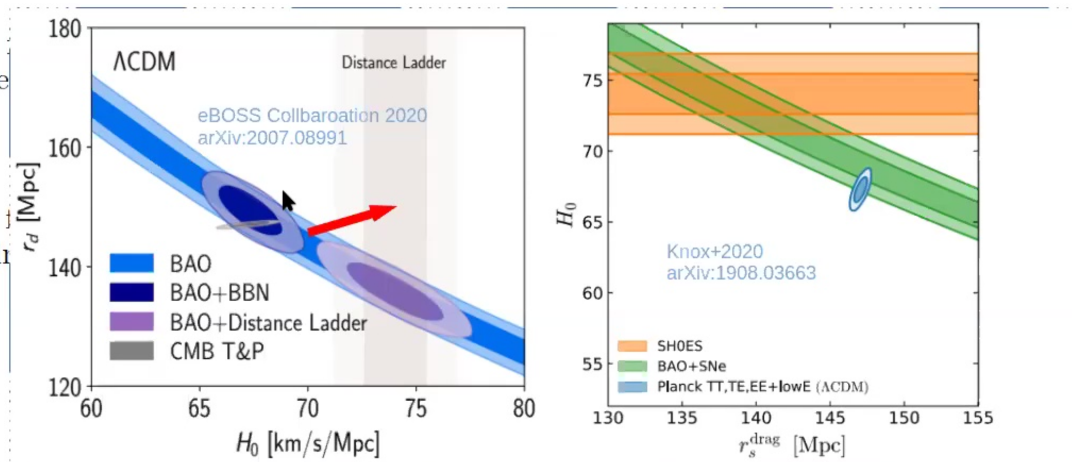
Option 3)

Change the inference of H_0 ...
by changing r_s , while keepi...

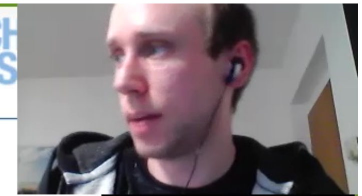
$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

There is a more general problem!

Possible movement of contours!
(as these are model-dependent)



1) Data   2) Tension   3) Models   4) Conclusion



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Looking grim...
Phantom DE or different $\Omega_m(z)$

Possible upshot: DE-DM interactions

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

Option 3)

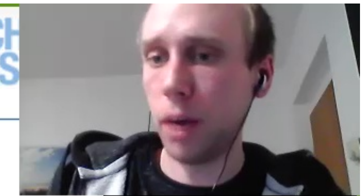
Change the inference of H_0 from the CMB by changing r_s , while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

1) Data 2) Tension 3) Models 4) Conclusion

Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

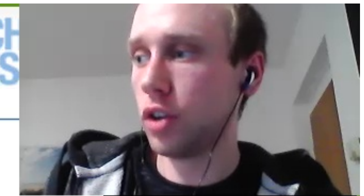
Looking grim...
Degeneracies are well constrained from different probes

Option 3)

Change the inference of H_0 from the CMB by changing r_s , while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

1) Data 2) Tension 3) Models **4) Conclusion**



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_\Lambda(z_*)} = const$$

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

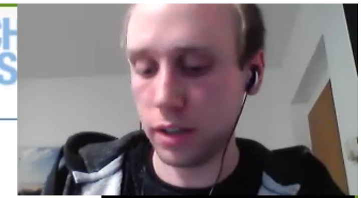
Option 3)

Change the inference of H_0 from the CMB by changing r_s , while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Looking okay...
Lots of things still need to be ironed out!

1) Data 2) Tension 3) Models 4) Conclusion



The Hubble tension

Option 1)

Change H(z) after decoupling, but keep

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 2)

Change the inference of H_0 from the CMB by playing with degeneracies

Option 3)

Change the inference of H_0 from the CMB by changing r_s, while keeping

$$\theta_s = \frac{r_s}{D_A(z_*)} = const$$

Option 4)

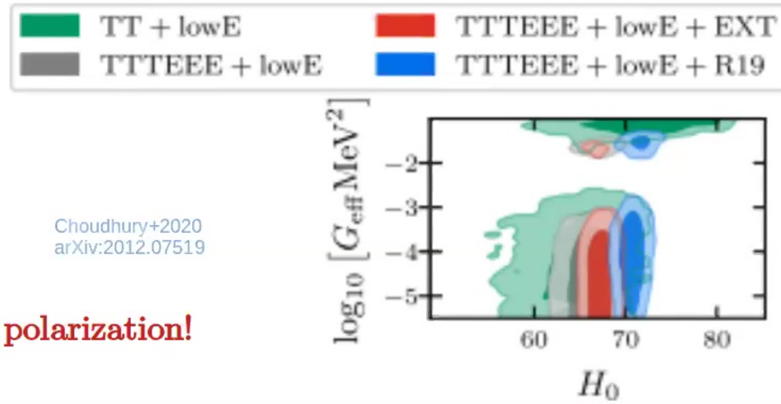
Self-interacting neutrinos
High θ_s, high N_{eff}, low r_s, high $H_0 = 70$
→ Compensations
Requires late ΔN_{eff} to avoid BBN

Kreisch+2019 arXiv:1902.00534

Oldengott+2017 arXiv:1706.02123

Lancaster+2017 arXiv:1704.06657

Choudhury+2020 arXiv:2012.07519



Not liked by Planck polarization!

1) Data 2) Tension 3) Models 4) Conclusion


Institute for Theoretical Particle Physics and Cosmology
Thank you for listening!
Any questions?