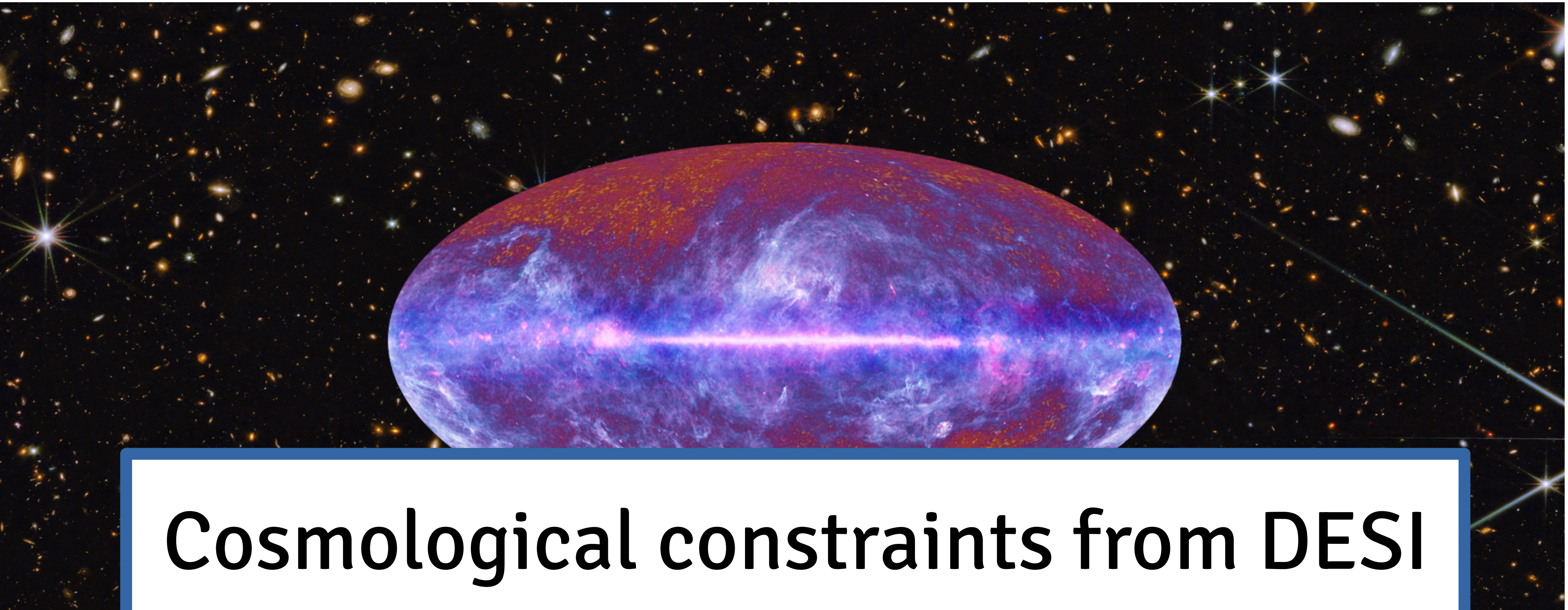
Nils Schöneberg

Munich, Tuesday 16.09.2025

nils.science@gmail.com

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN



Cosmological constraints from DESI

https://plancksatellite.org.uk/science/ and https://science.nasa.gov/mission/webb/multimedia/images/#first-images

Agenda

BAO

BAO+BBN

ShapeFit

Lyman-Alpha forest

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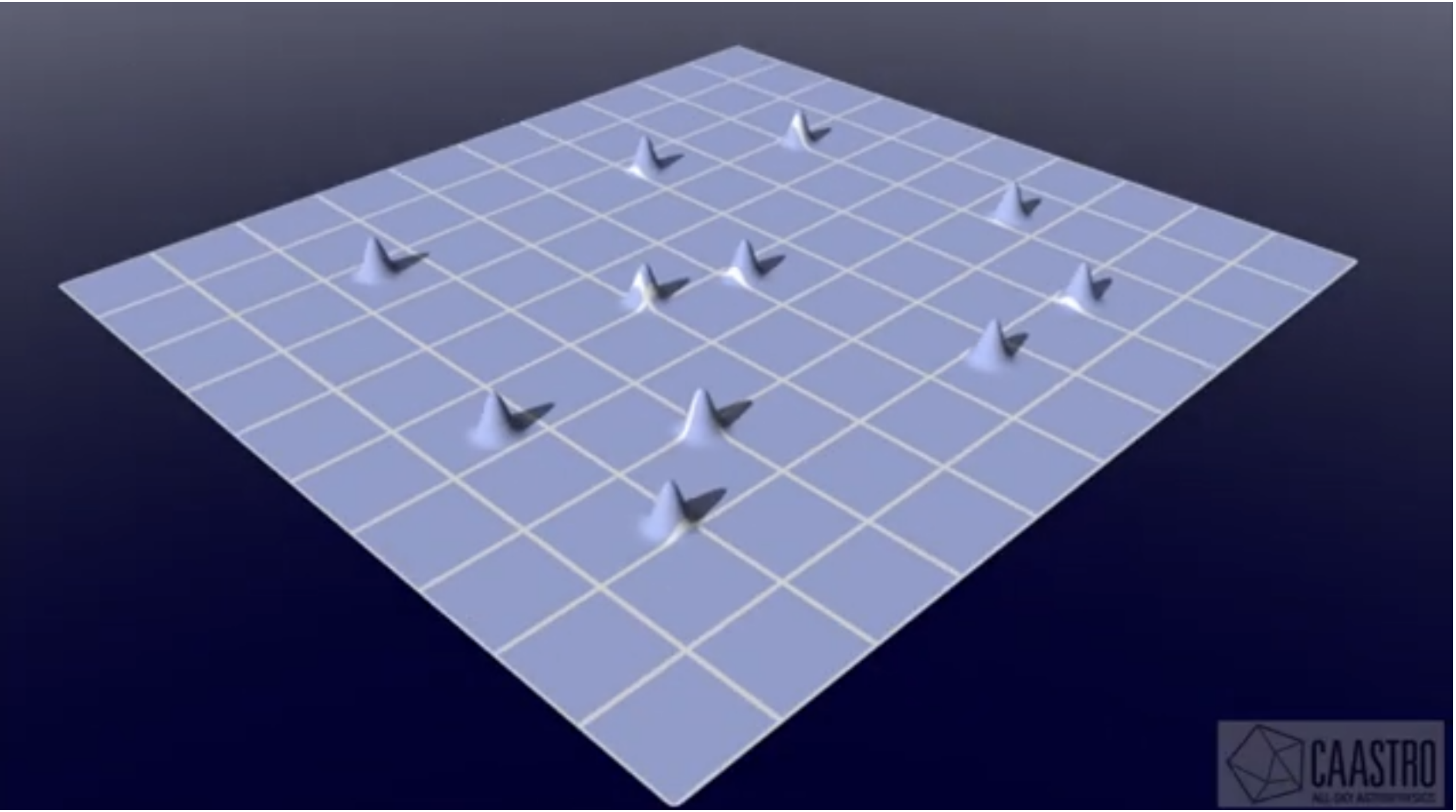
Agenda

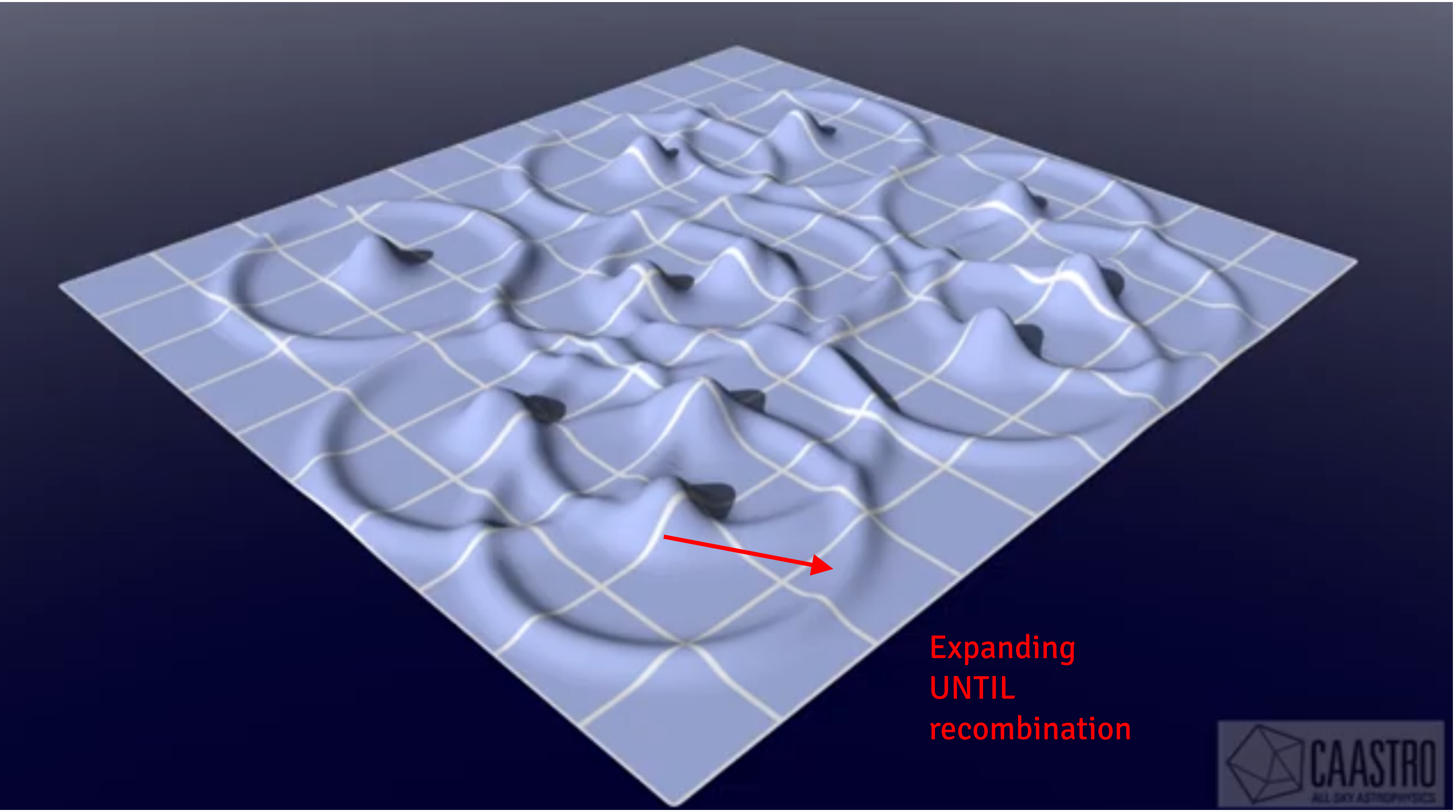
BAO

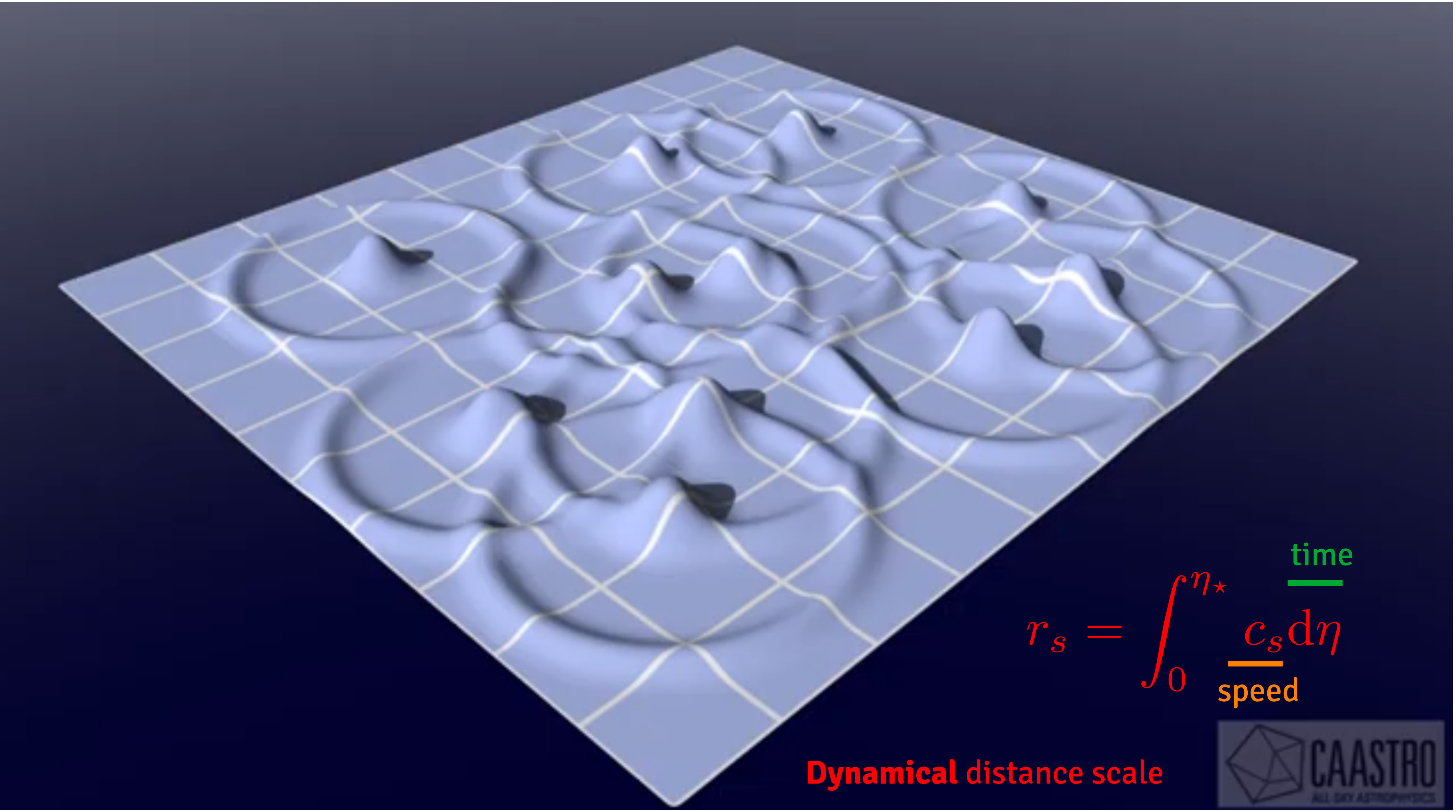
BAO+BBN

ShapeFit

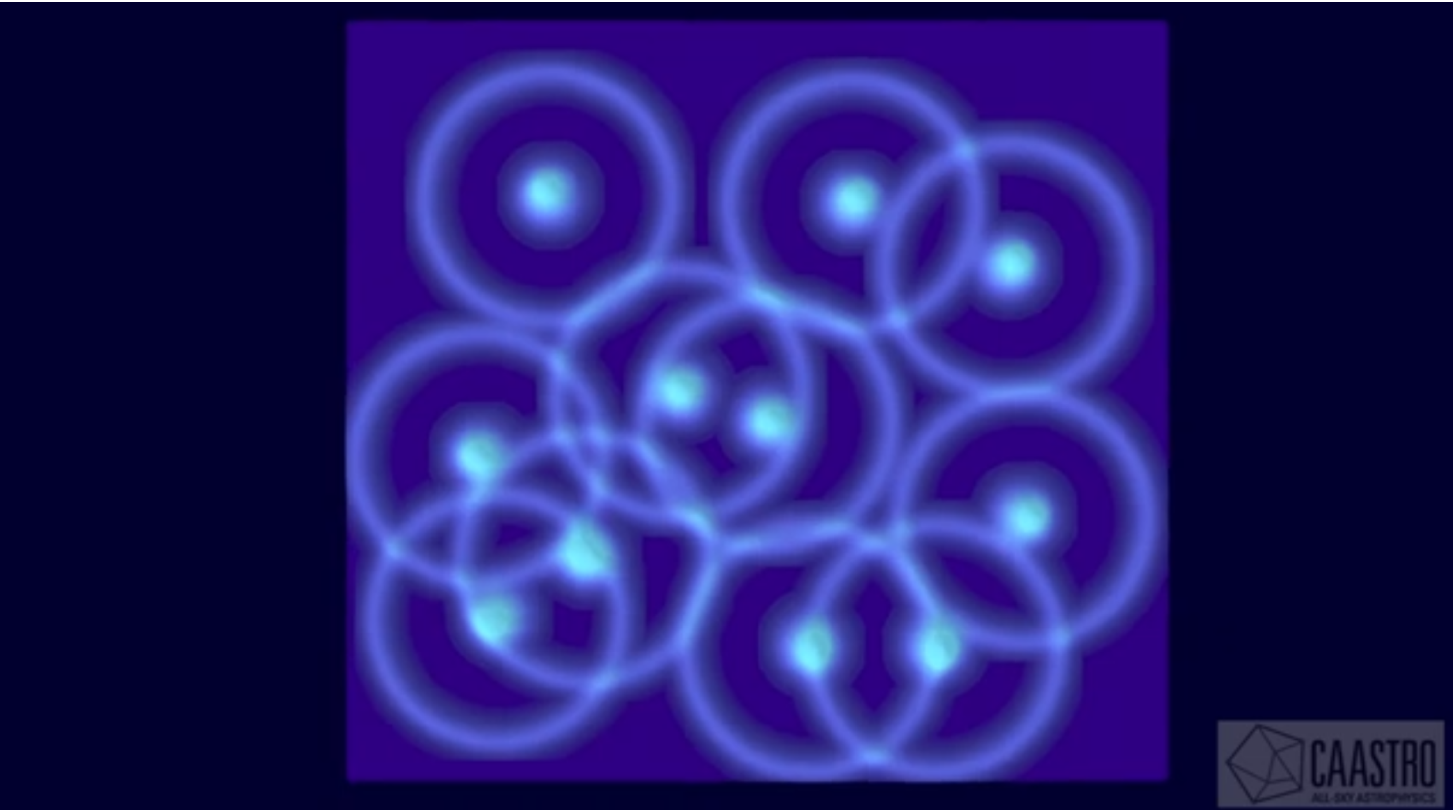
Lyman-Alpha forest

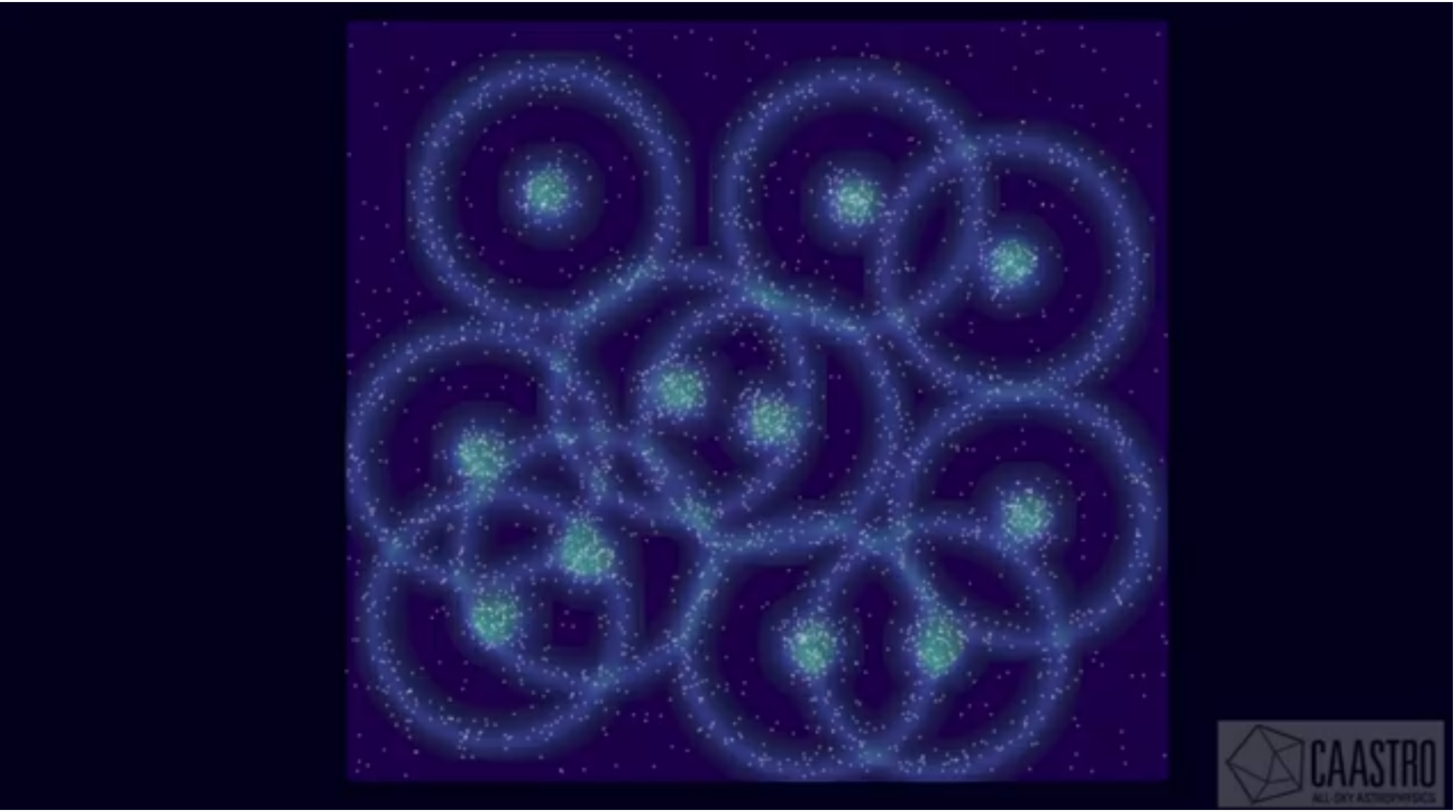

CAASTRO

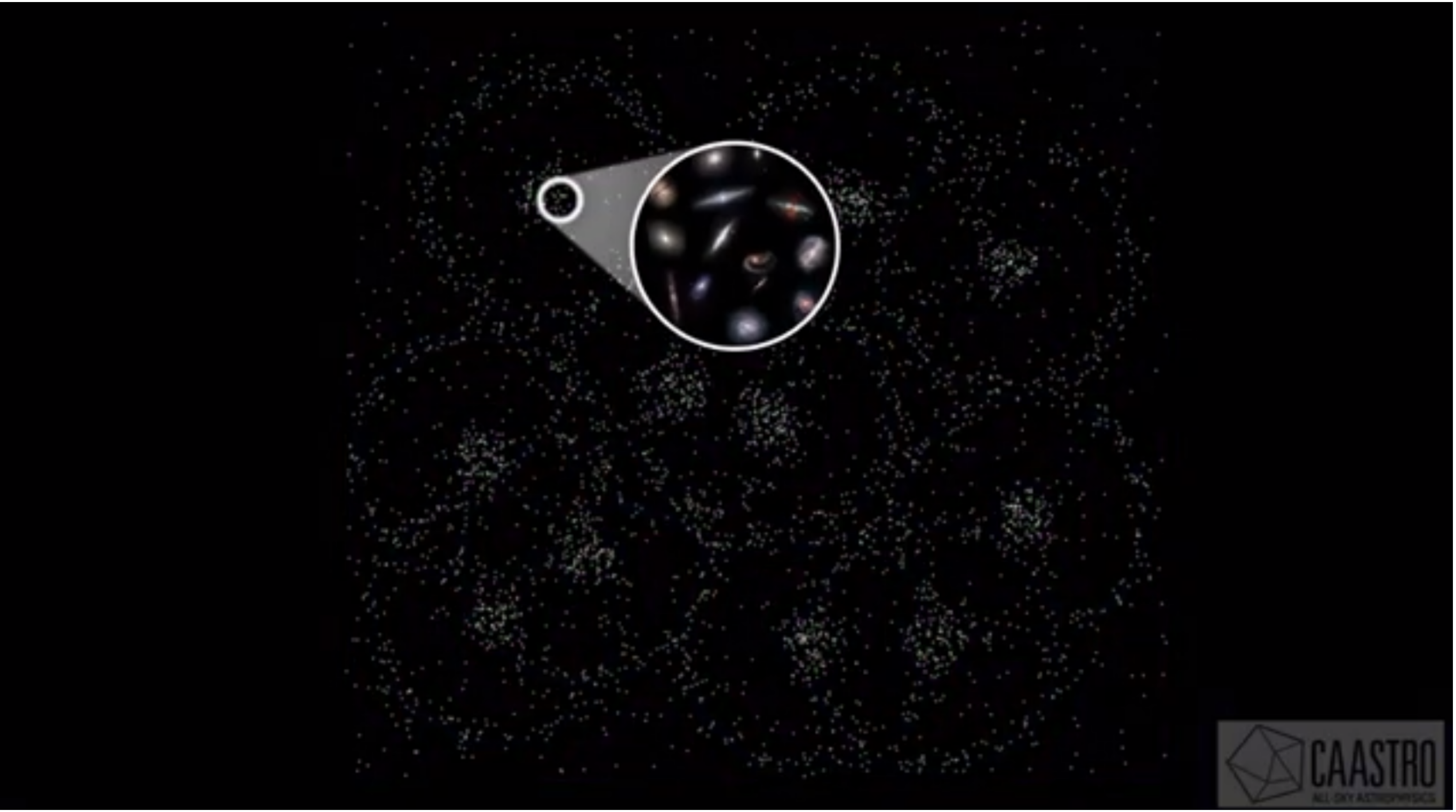

Expanding
UNTIL
recombination
CAASTRO



time
$$r_s = \int_0^{\eta_\star} \underbrace{c_s}_{\text{speed}} \overbrace{\mathrm{d}\eta}^{\text{time}}$$
speed
Dynamical distance scale
CAASTRO

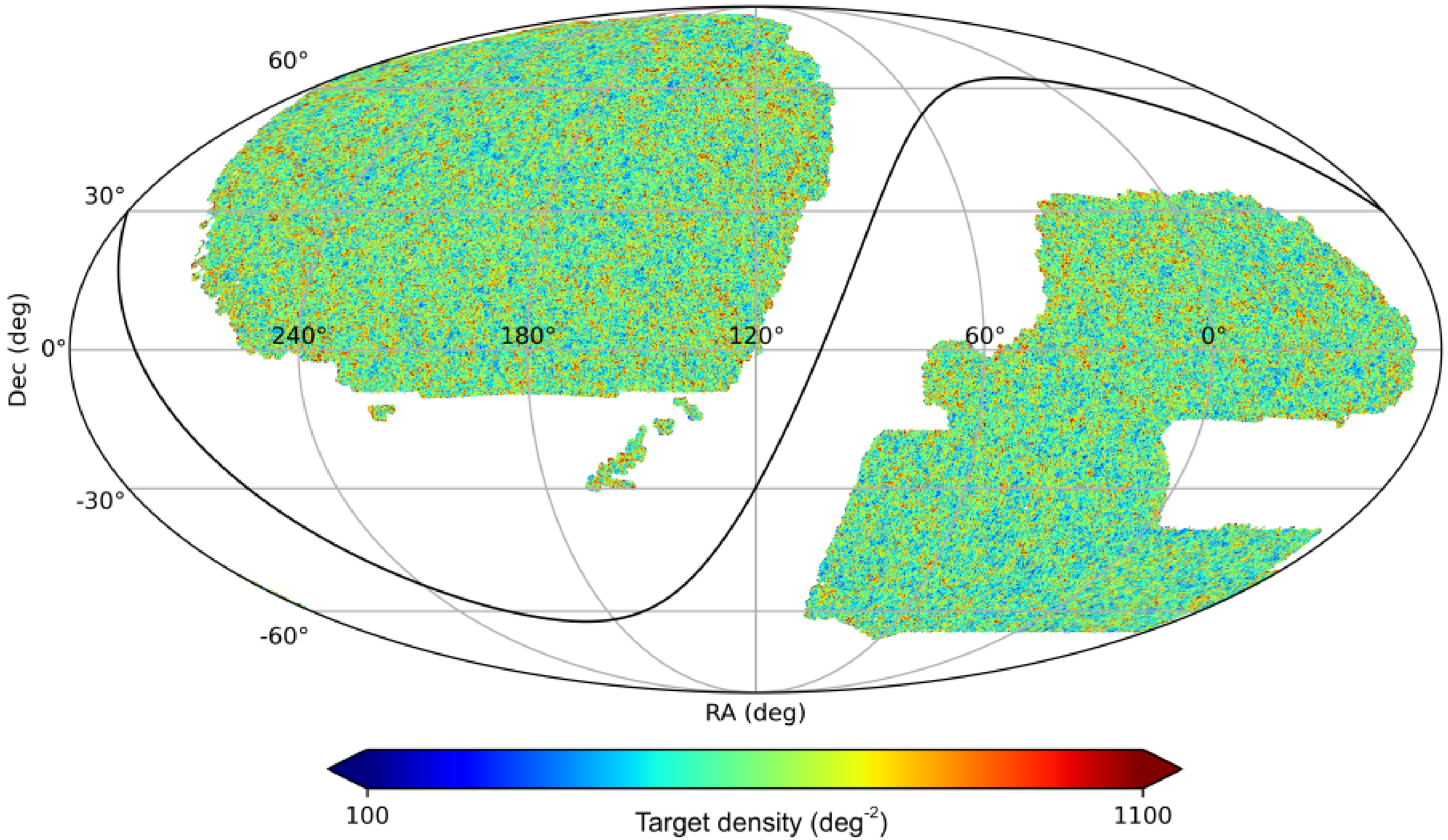

CAASTRO
ALL-SKY ASTROPHYSICS


CAASTRO
ALL-SKY ASTROPHYSICS


CAASTRO
ALL-SKY ASTROPHYSICS

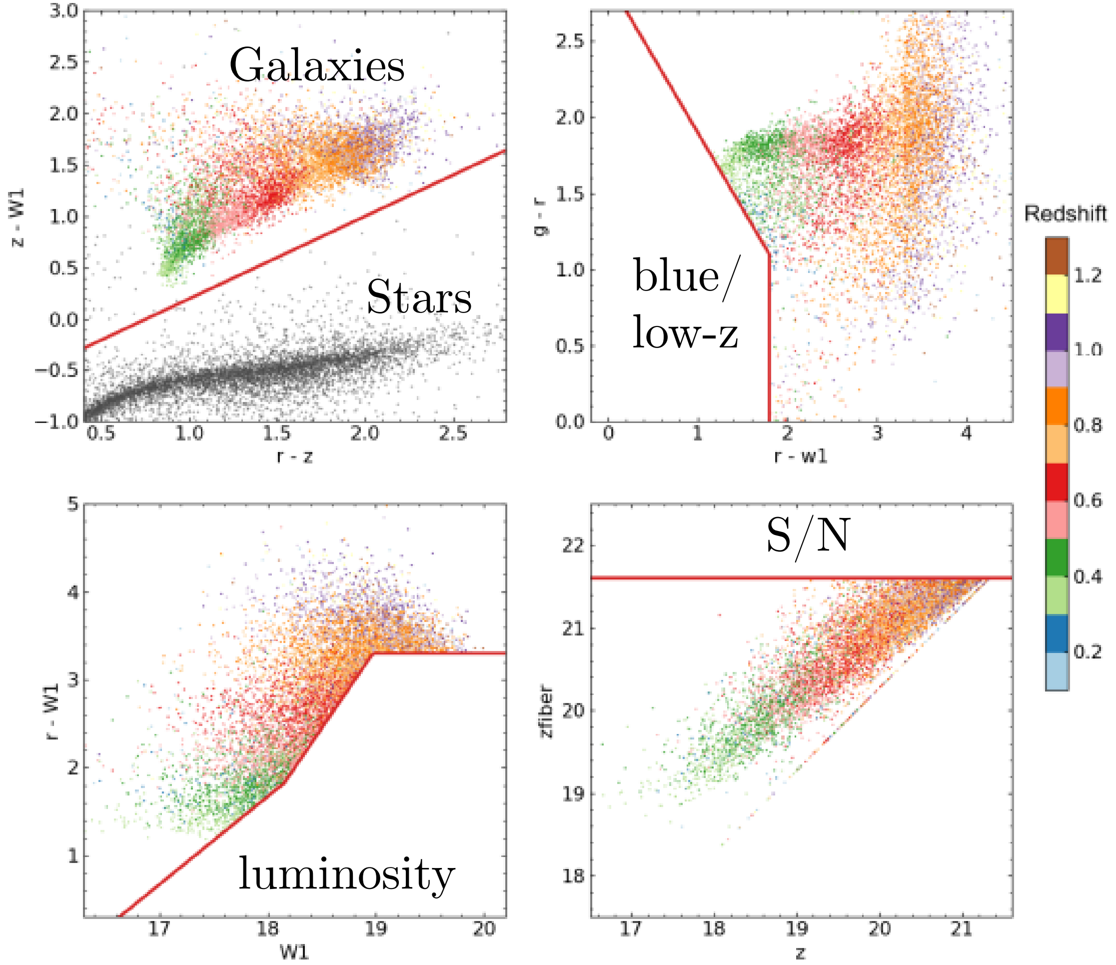
Target Selection (photometric)

- Present in all bands (grz + WISE W1)
- Not too close to other bright objects
- Not inside galactic plane

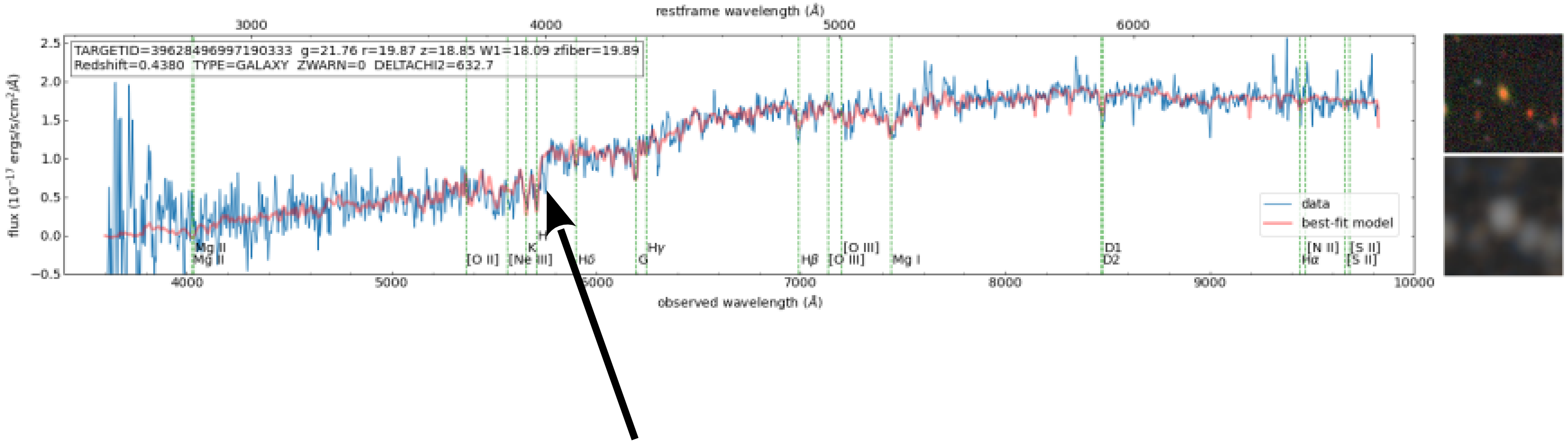


Selection cuts

Example:
Luminous red galaxies

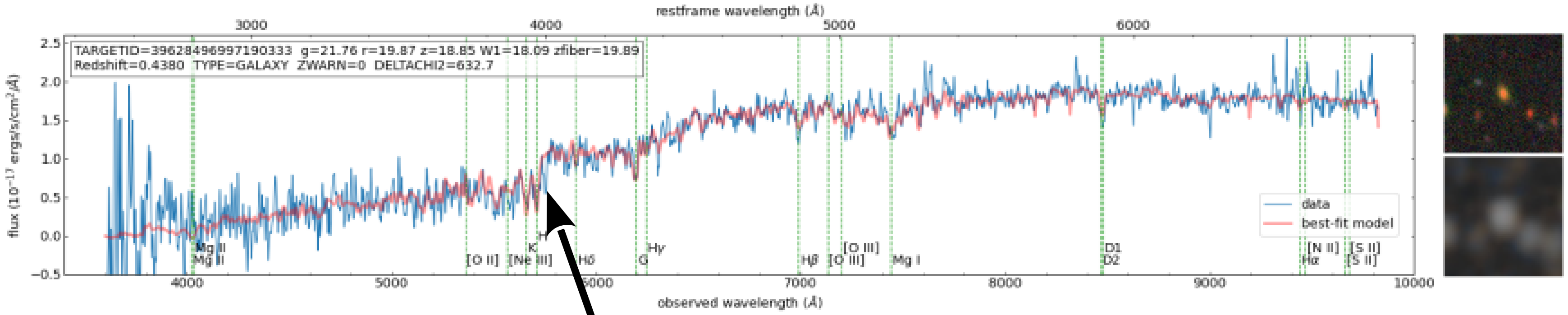


Spectral Analysis



4000Angstrom break
→ Redshift z

SPECTRAL ANALYSIS

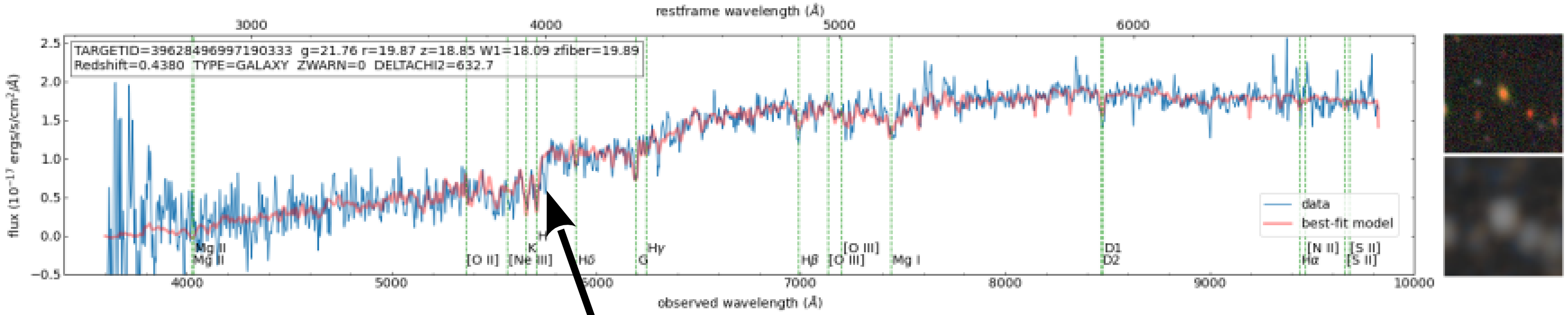


Redrock

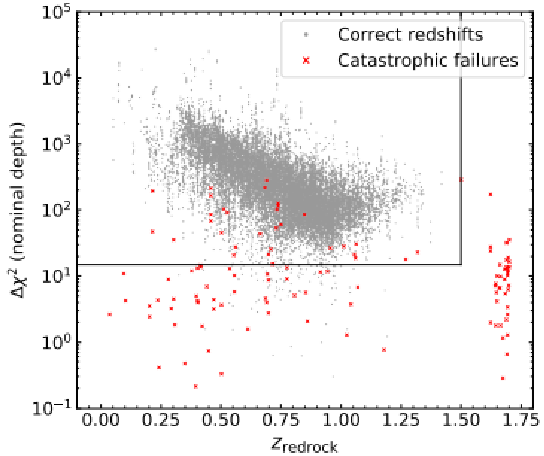
4000Angstrom break
→ Redshift z

+ Type (QSO or star or galaxy)

Spectral Analysis



Redrock



4000Angstrom break
→ Redshift z

+ Type (QSO or star or galaxy)

Comparison to deep survey
(or previous/visual)

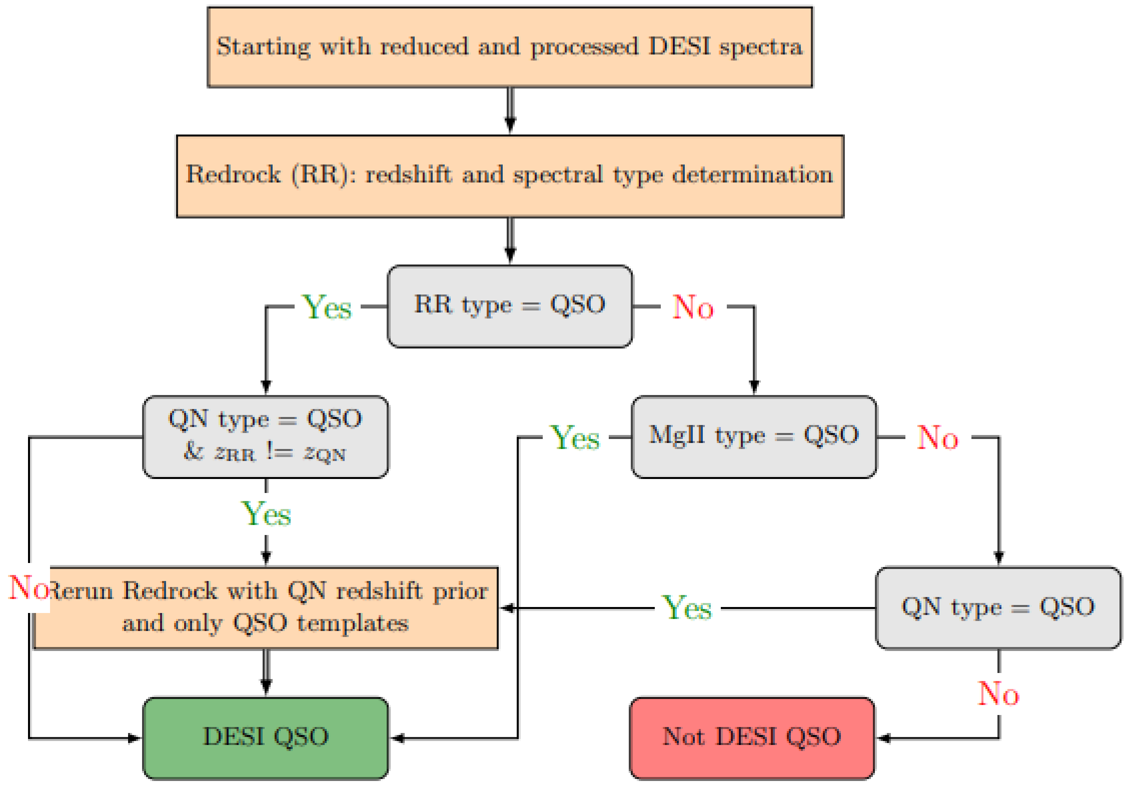
Quasar Catalog

RR = Redrock spectrum fitter

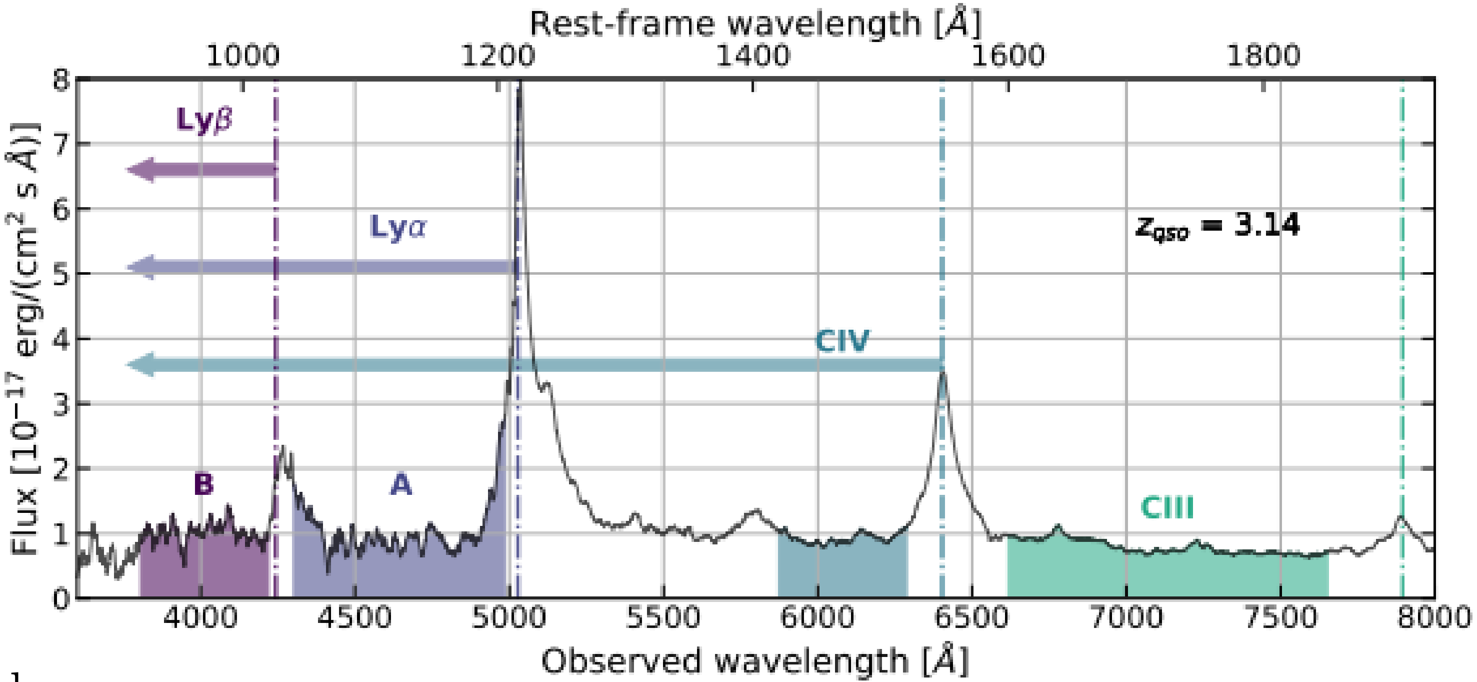
MgII = Line finder algorithm (QSO exhibit MgII broad line)

QN = neural network-based classifier (finding lines)

Lyman-α, C iv, C ii, Mg ii, H α and H β

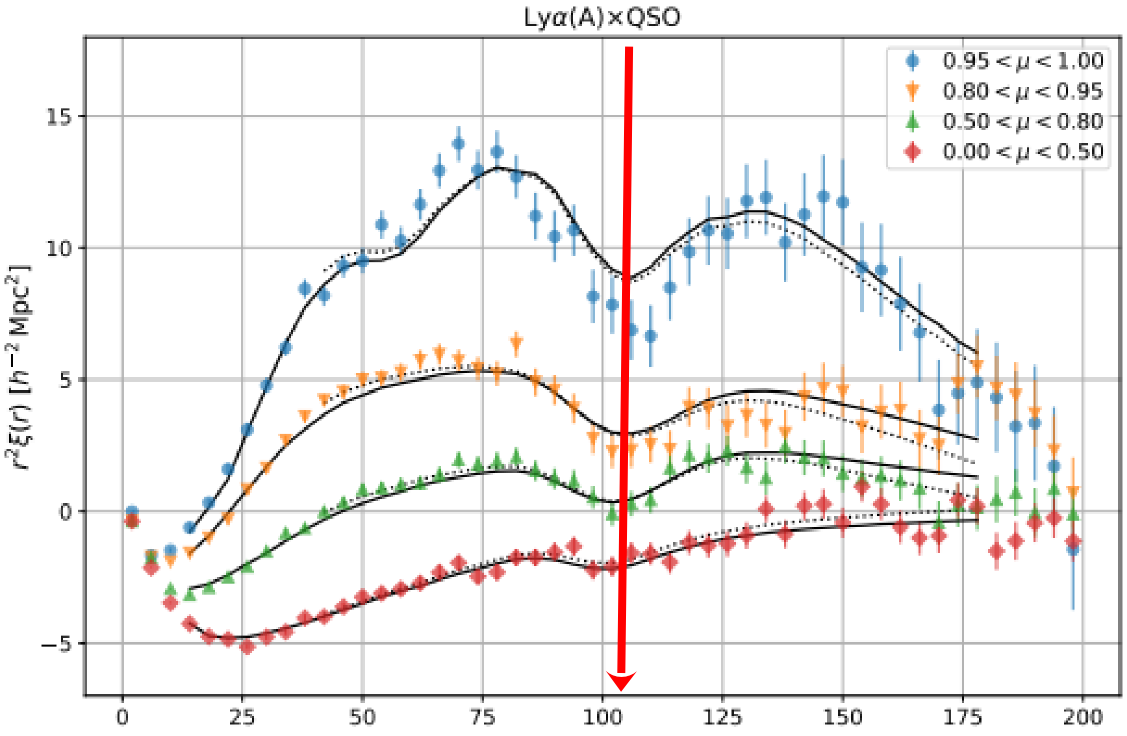


Lyman-α Catalog



Metals
Noise
HCD objects
Quasar redshift errors
...

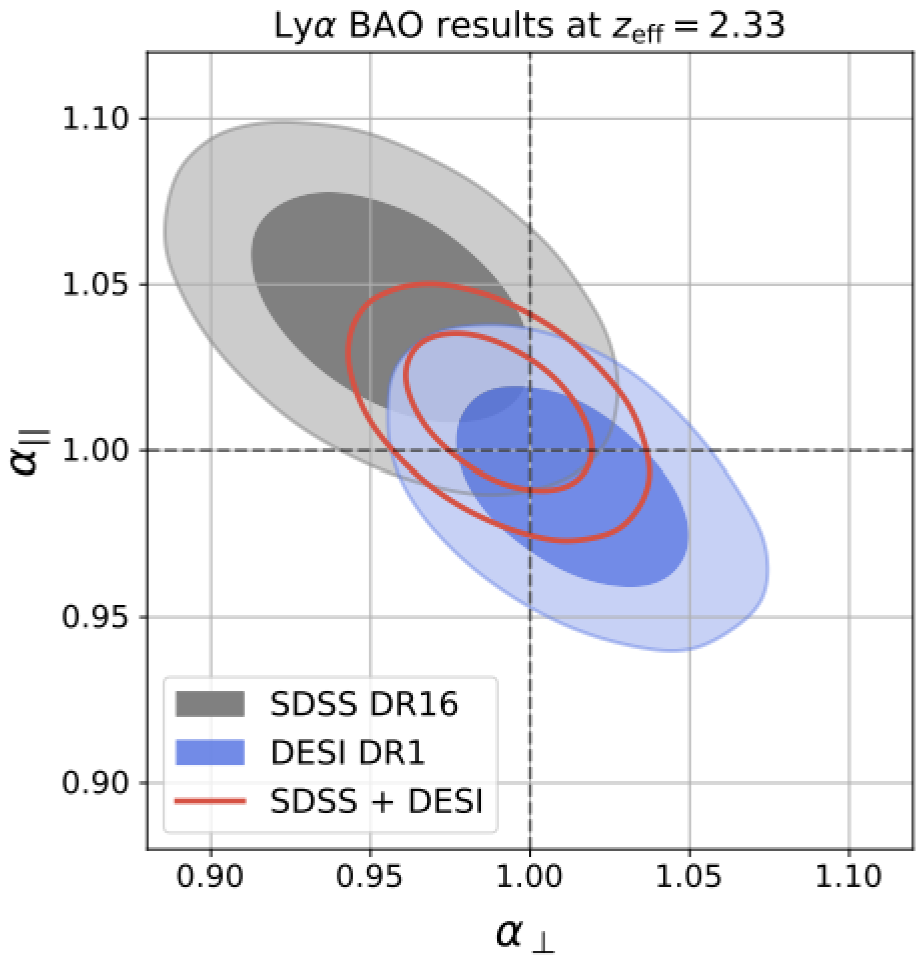
Lyman-α BAO



BAO peak

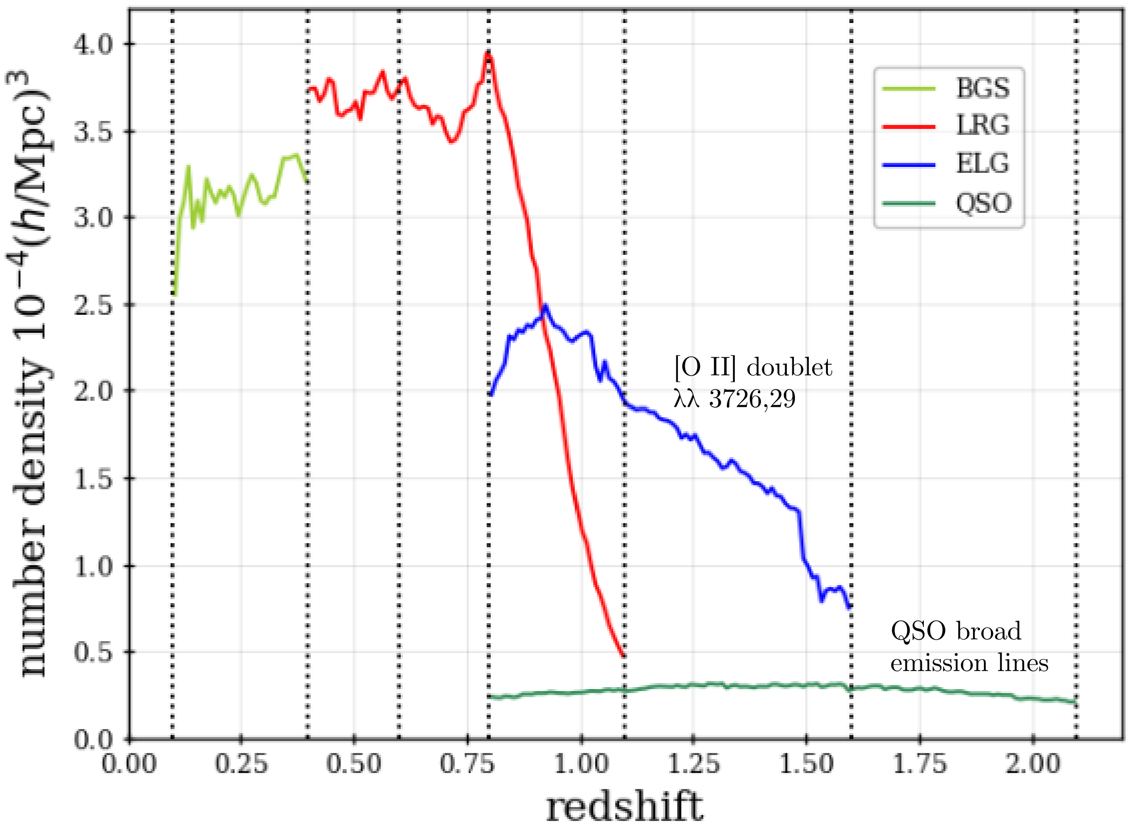
$$147\text{Mpc} = 100\ \text{Mpc}/\text{h} \quad (\text{h}=0.68)$$

BAO results from Lyman-α



DESI TARGETS

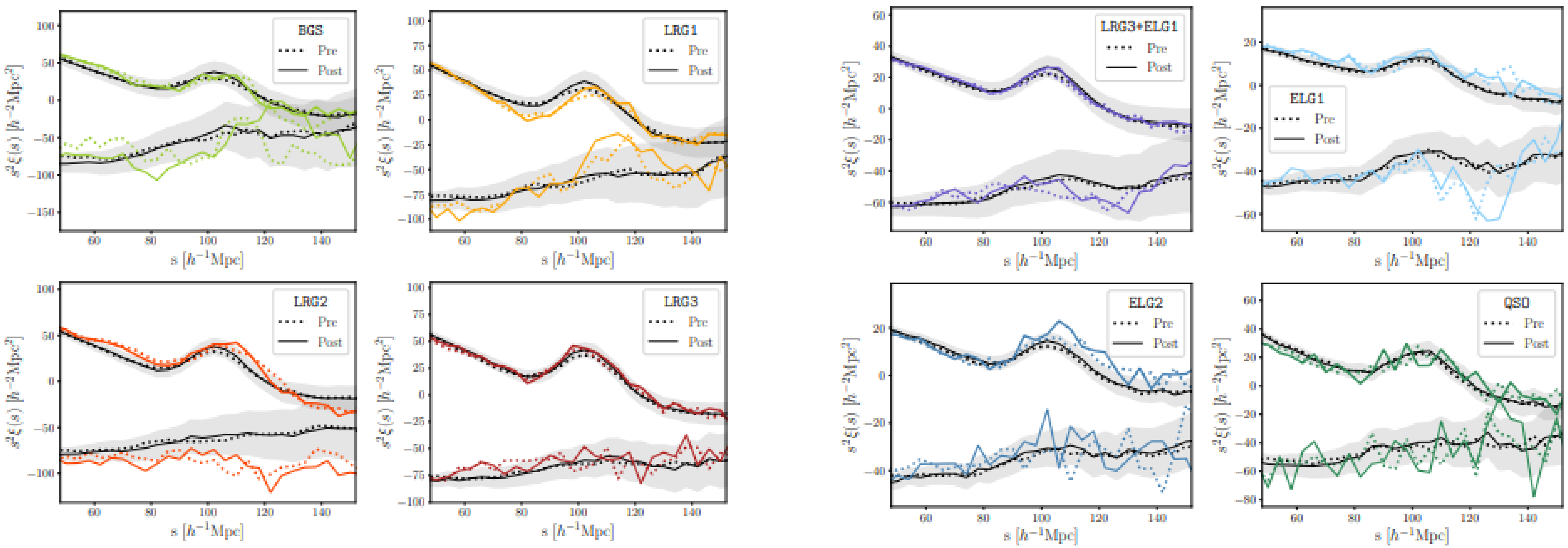
- BGS
  (bright time)
- LRG
- ELG
- QSO
- Lyman-α



Nils Schöneberg nils.science@gmail.com

Galaxy+Quasar BAO

Black = Abacus mock, color=measurement

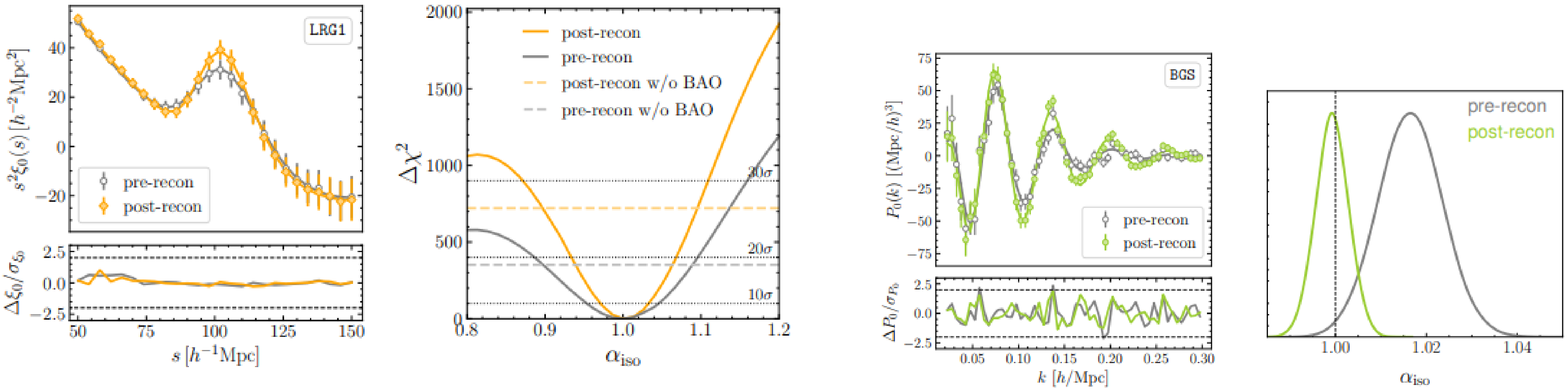


Reconstruction = move with $\nabla\phi$ to move back

(Zel'dovic approximation)

Galaxy+Quasar BAO

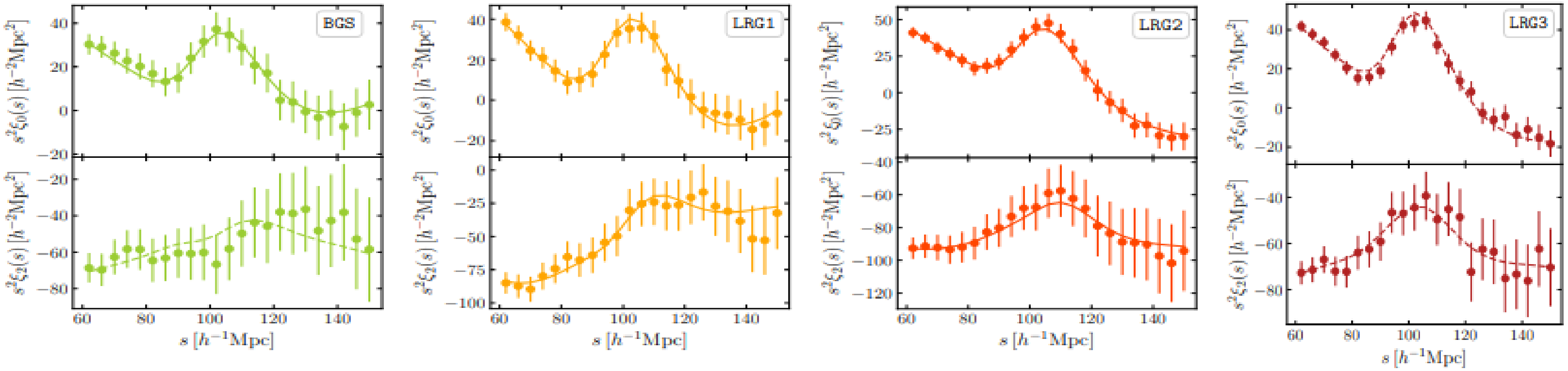
MOCK reconstruction

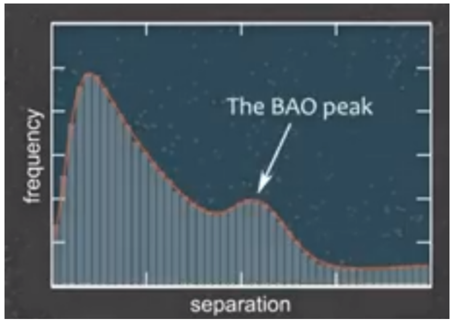


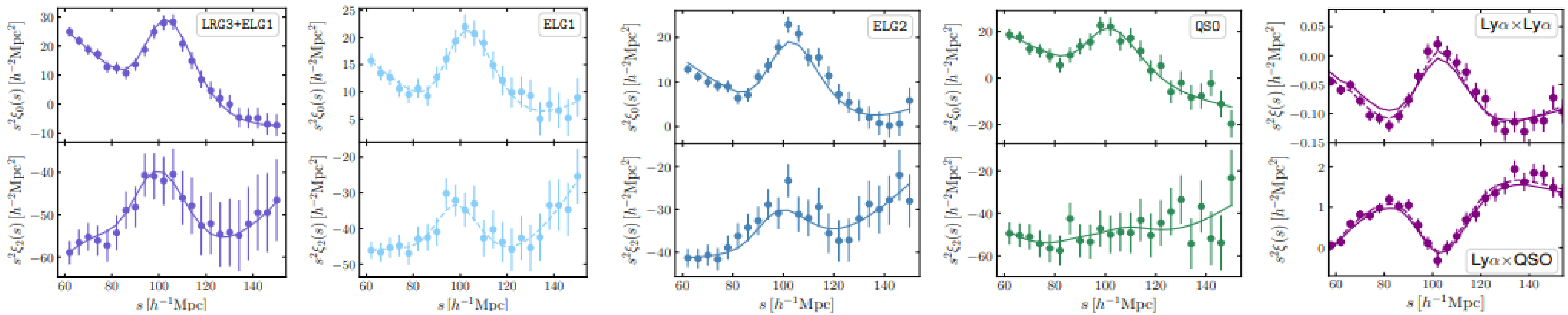
Reconstruction = move with $\nabla\phi$ to move back

(Zel'dovic approximation)

The BAO measurements

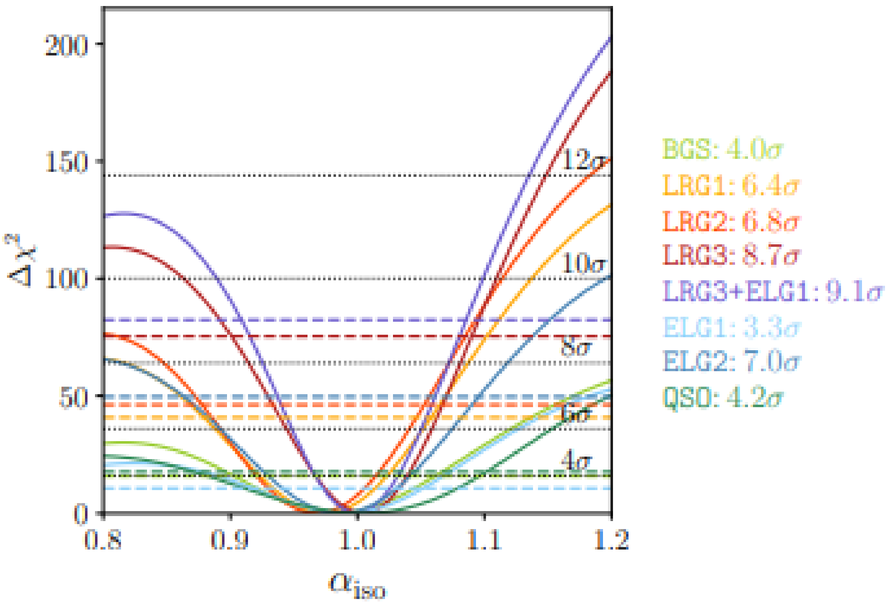


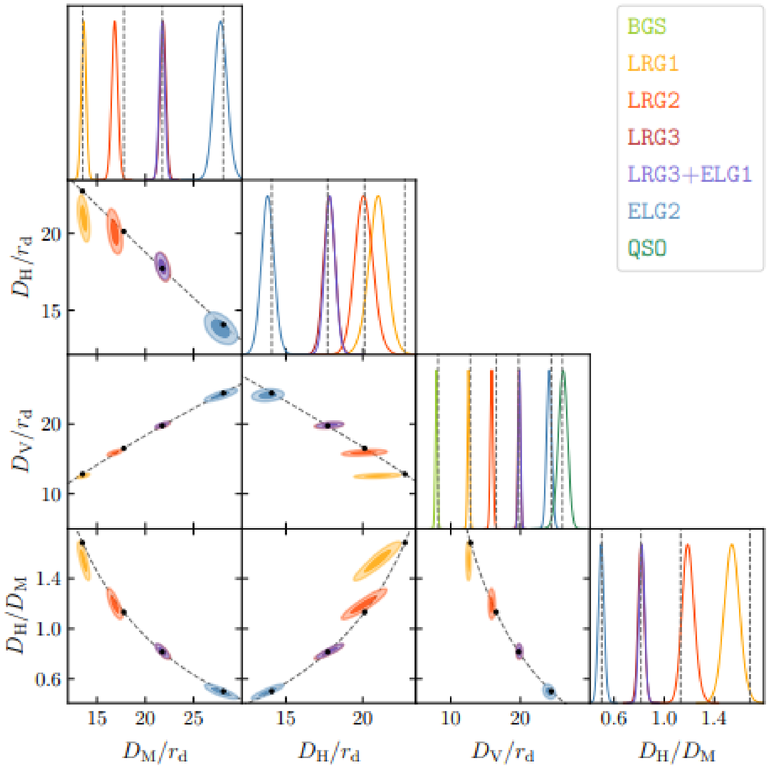




The BAO measurements

- Convert via template fit into BAO measurements

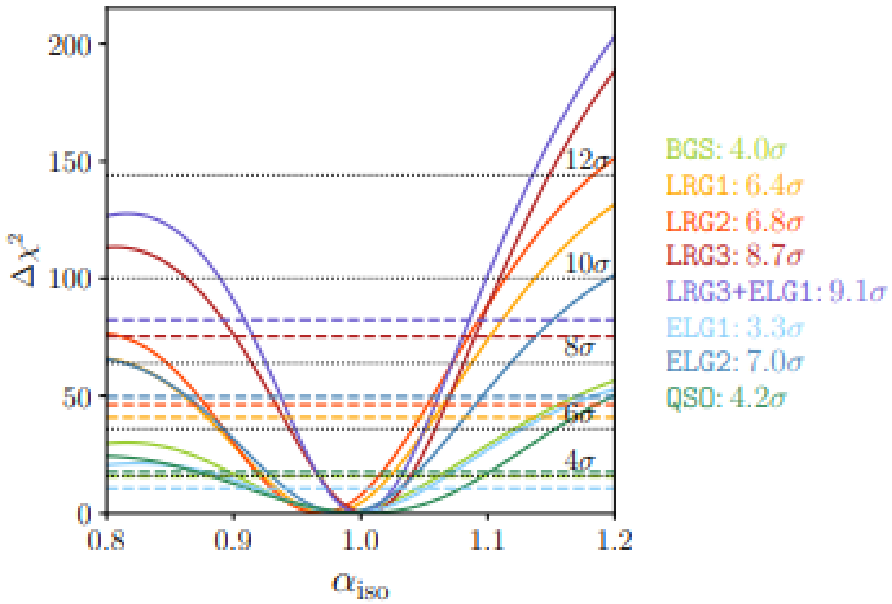


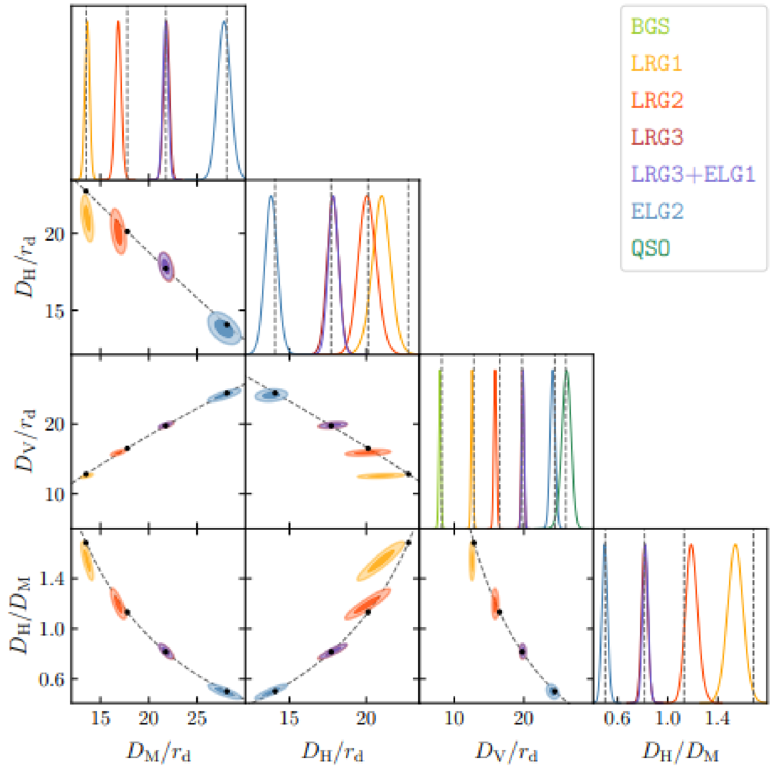


$z_{\rm eff} = 0.51$ (LRG1), 0.71 (LRG2), 0.93 (LRG3), and 1.32 (ELG2).

The BAO measurements

- Convert via template fit into BAO measurements





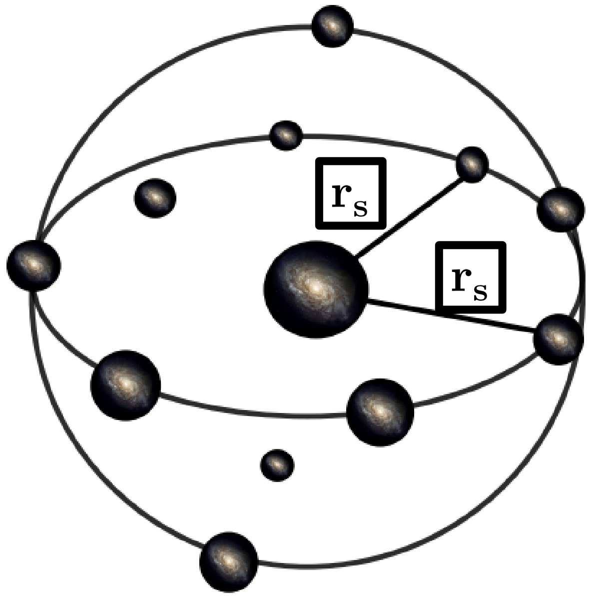
$z_{\rm eff}$ = 0.51 (LRG1), 0.71 (LRG2), 0.93 (LRG3), and 1.32 (ELG2).

→ **What kind of science can I do with this?**

BAO and the sound horizon

General idea:

Clustering is enhanced at the sound horizon scale

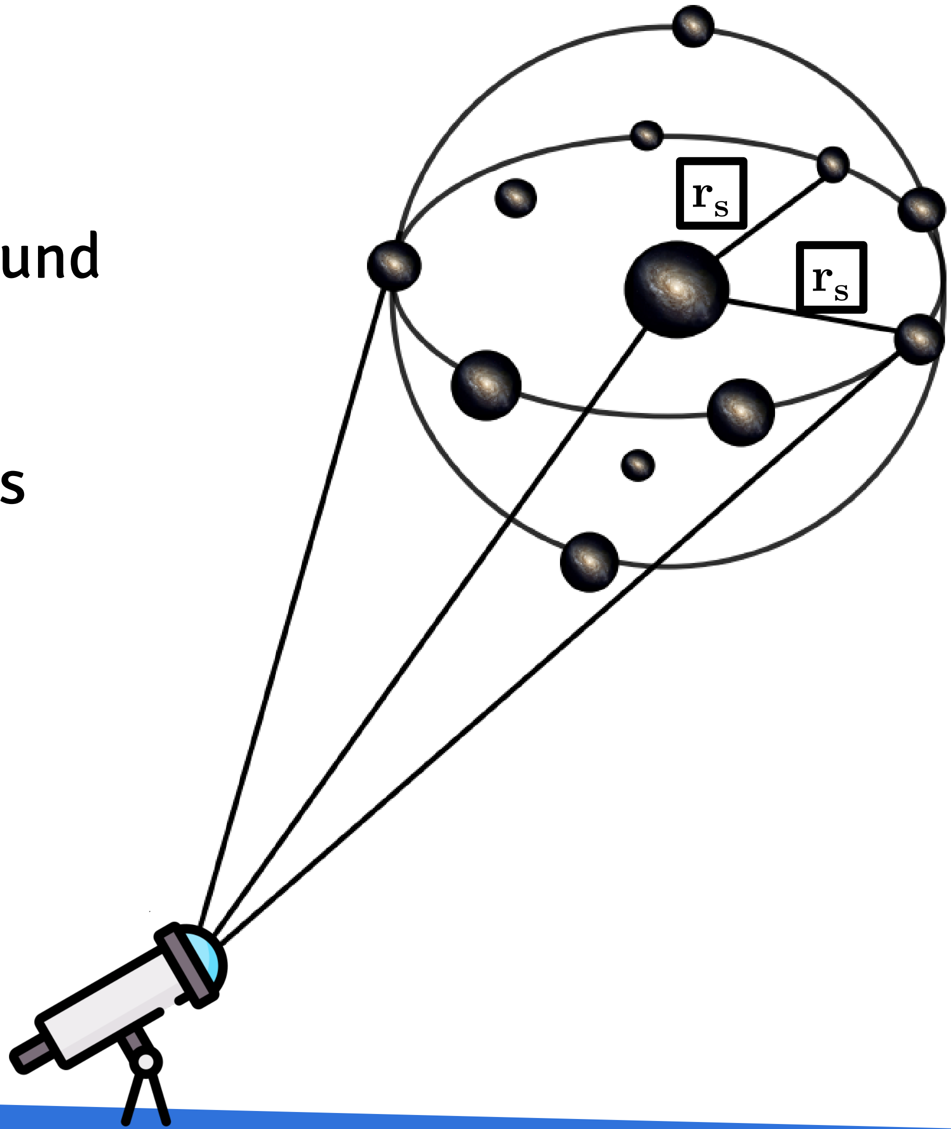


BAO and the sound horizon

General idea:

Clustering is enhanced at the sound horizon scale

We measure it with telescopes



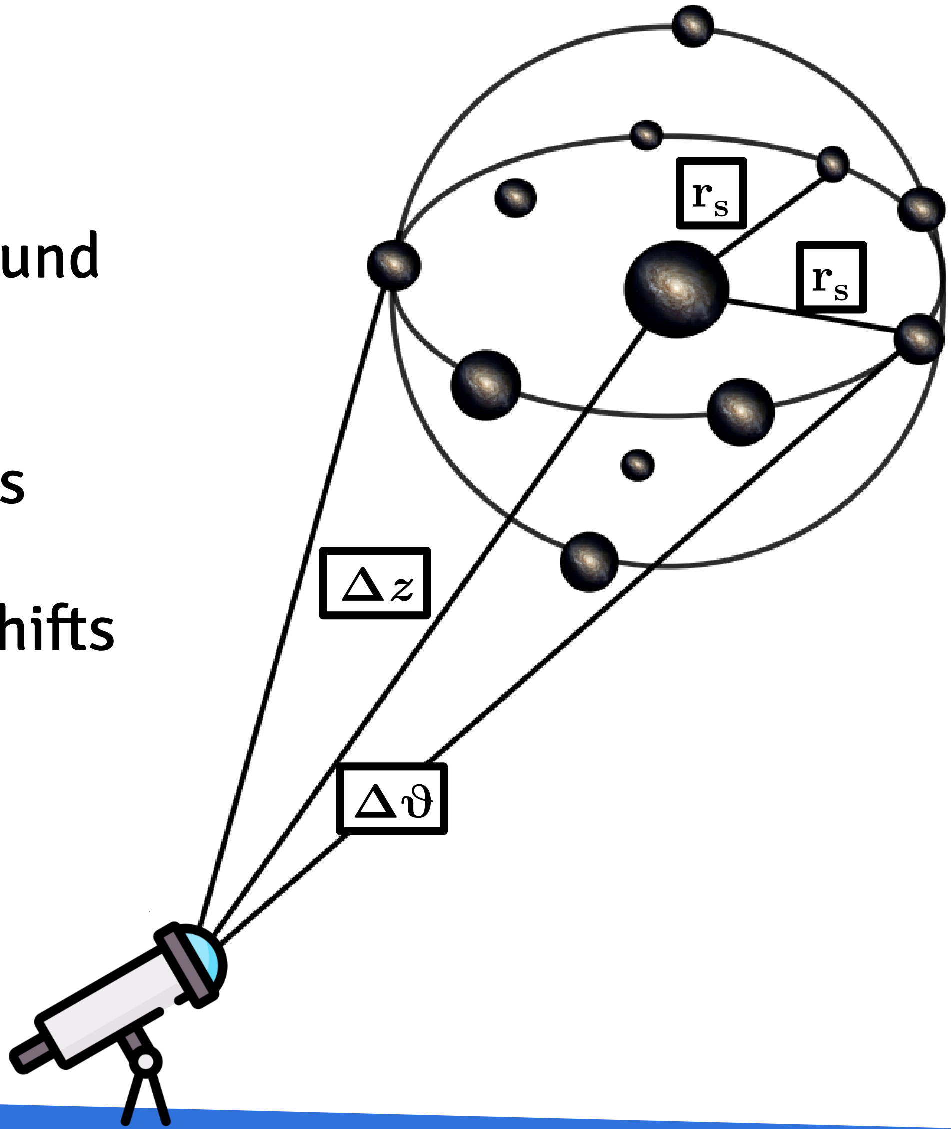
BAO AND THE SOUND HORIZON

General idea:

Clustering is enhanced at the sound horizon scale

We measure it with telescopes

We only observe angles and redshifts



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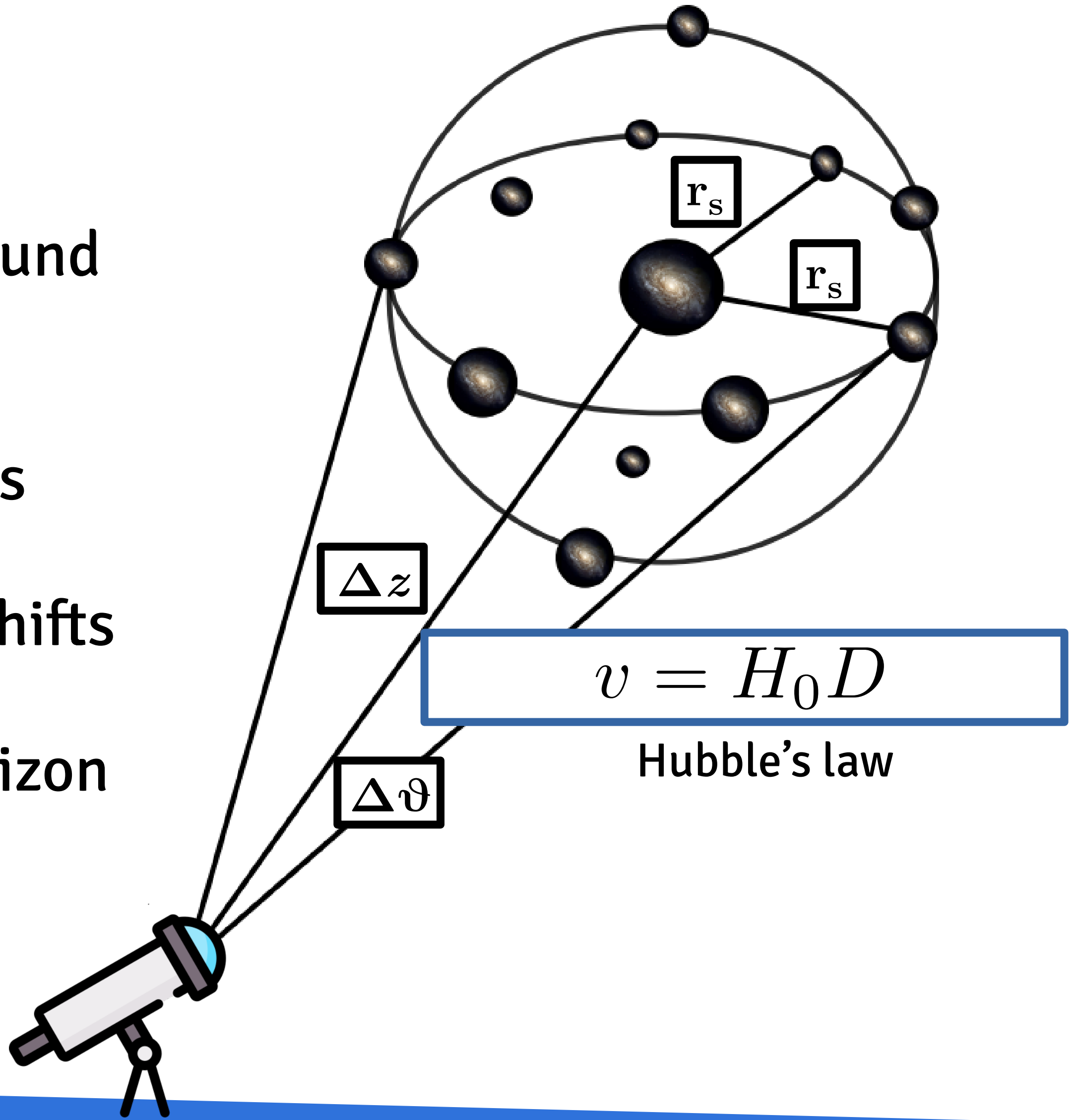
We can go back to the sound horizon



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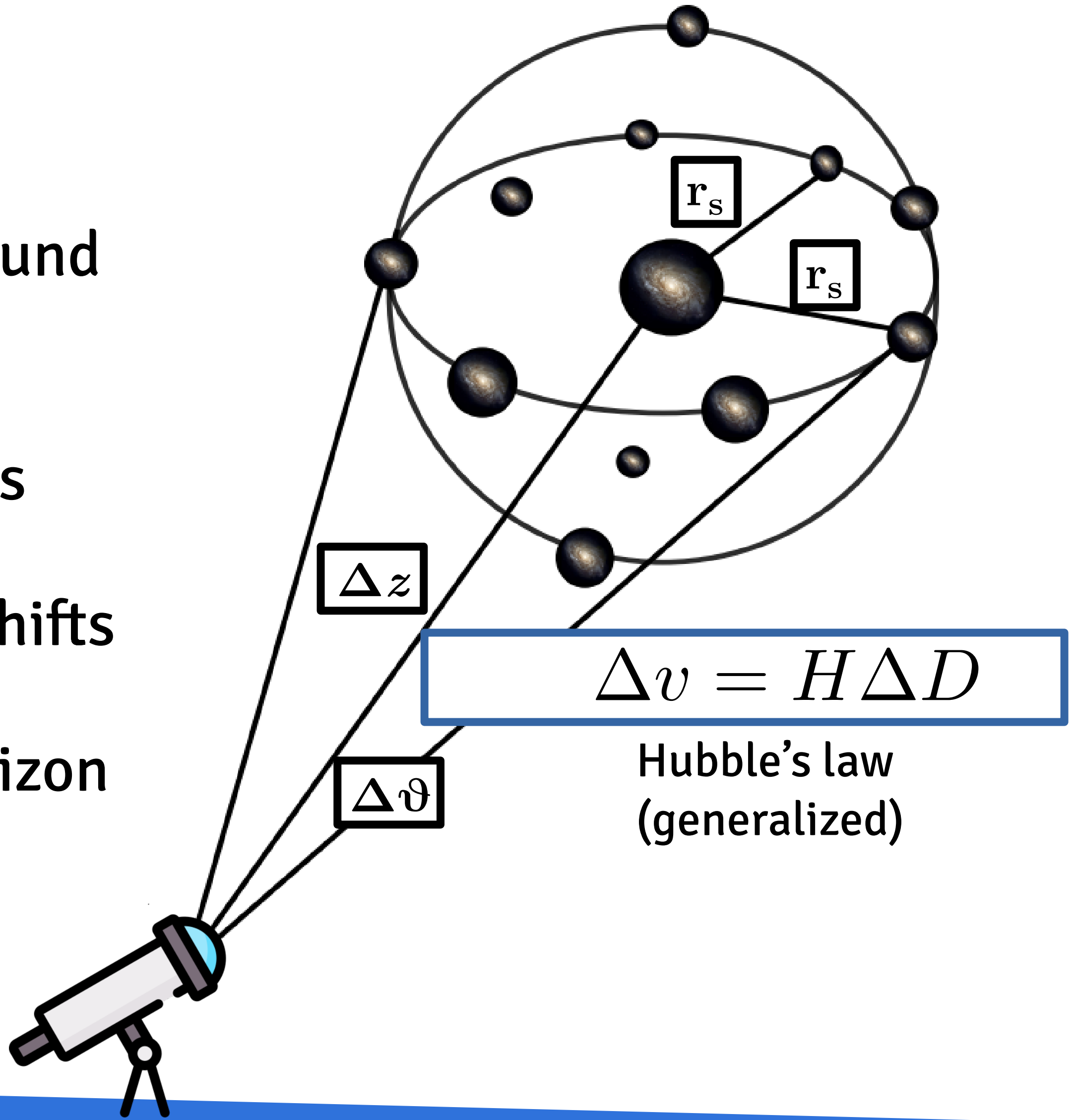

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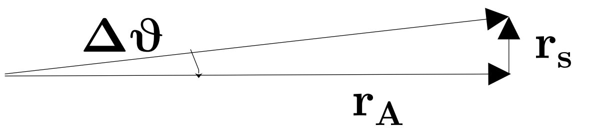
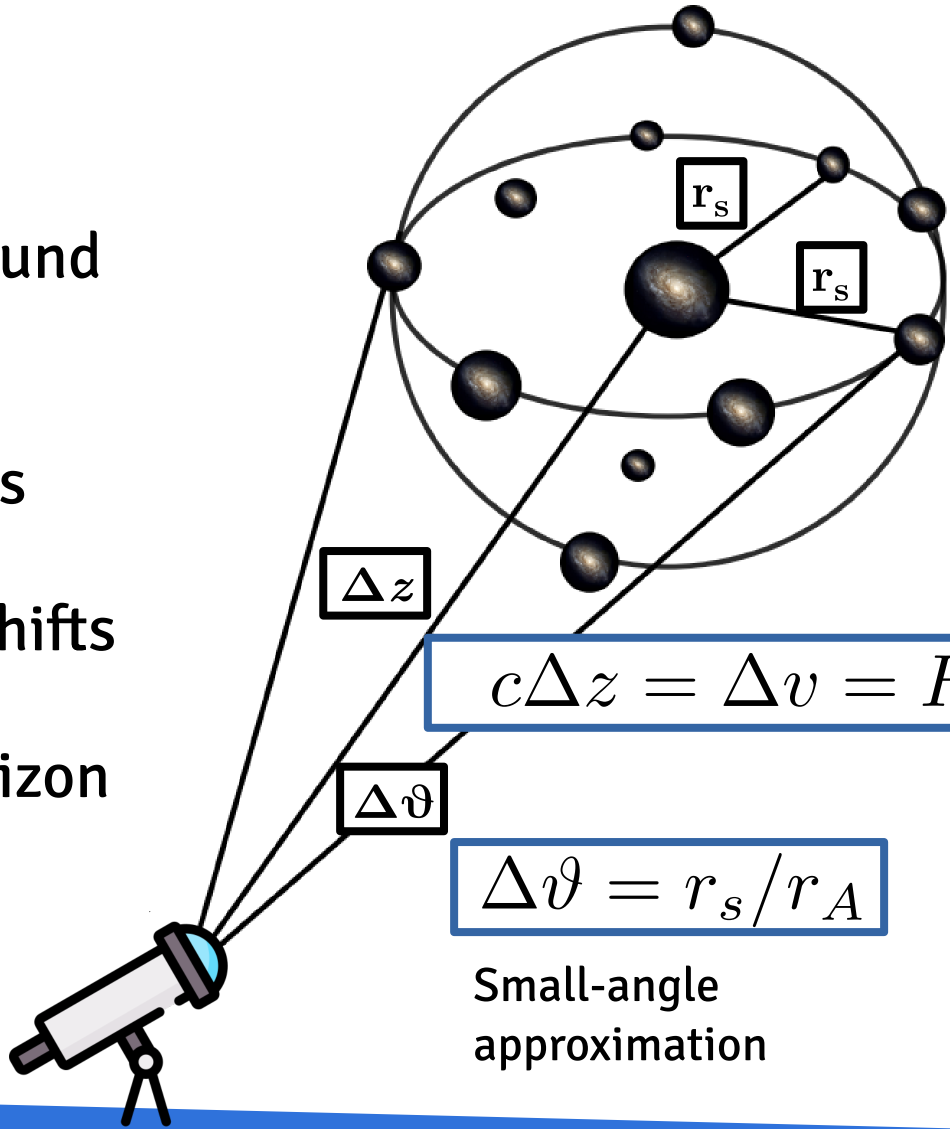




$$c\Delta z = \Delta v = H r_s$$

$$\Delta\vartheta = r_s / r_A$$

Small-angle approximation

BAO and the sound horizon

General idea:

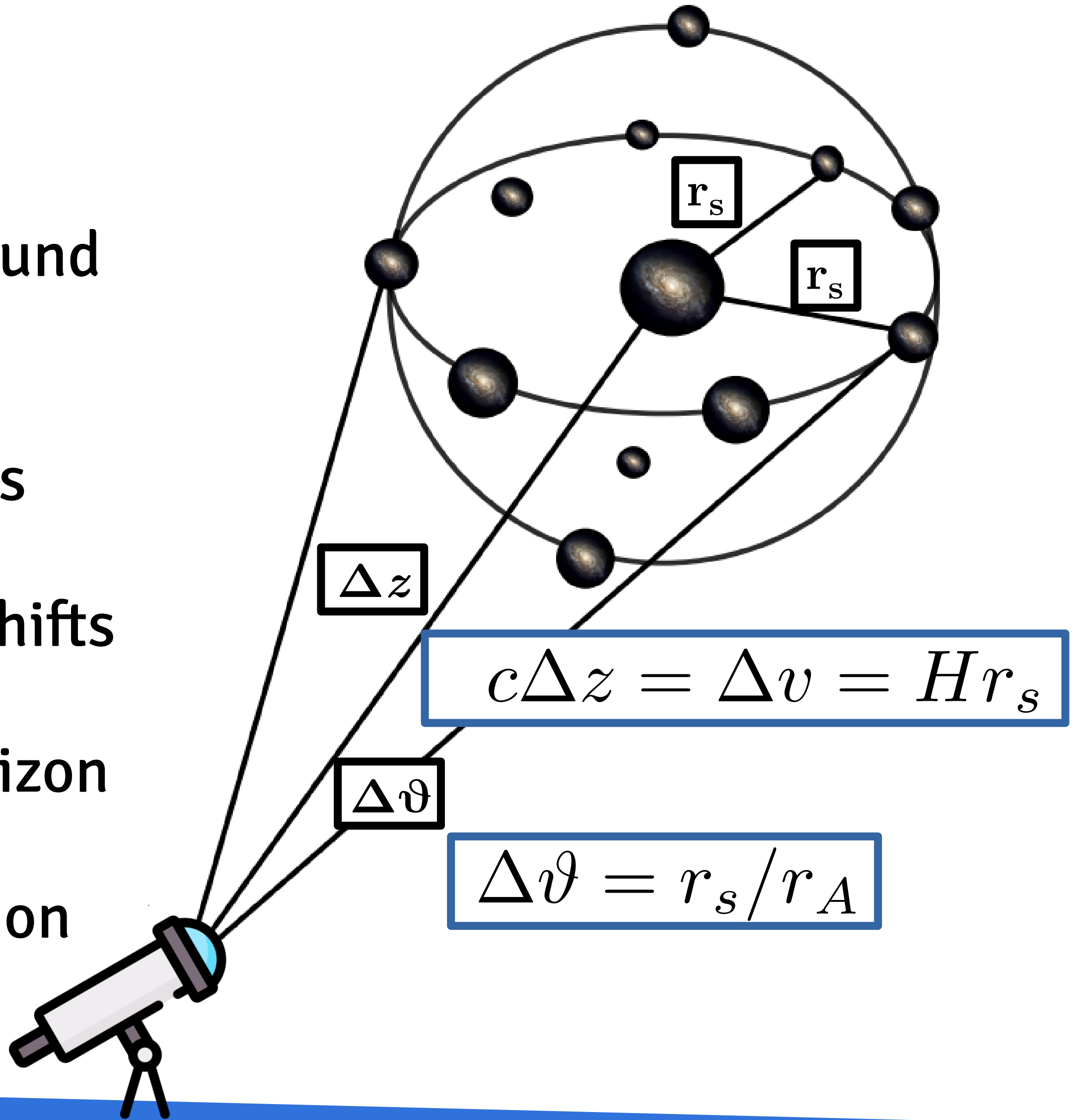
Clustering is enhanced at the sound horizon scale

We measure it with telescopes

We only observe angles and redshifts

We can go back to the sound horizon

→ This introduces dependency on cosmological distances



BAO AND THE SOUND HORIZON

General idea:

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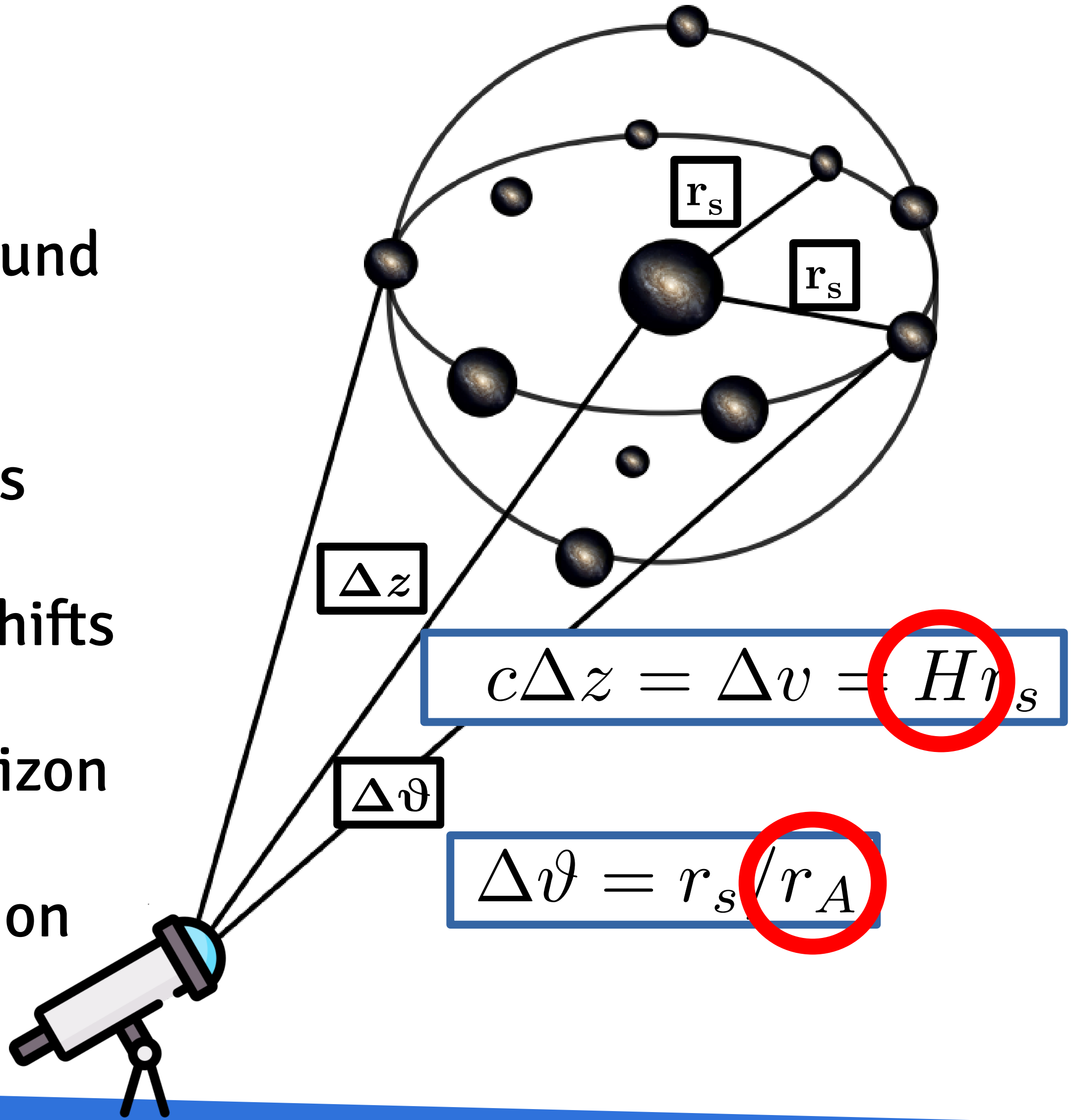


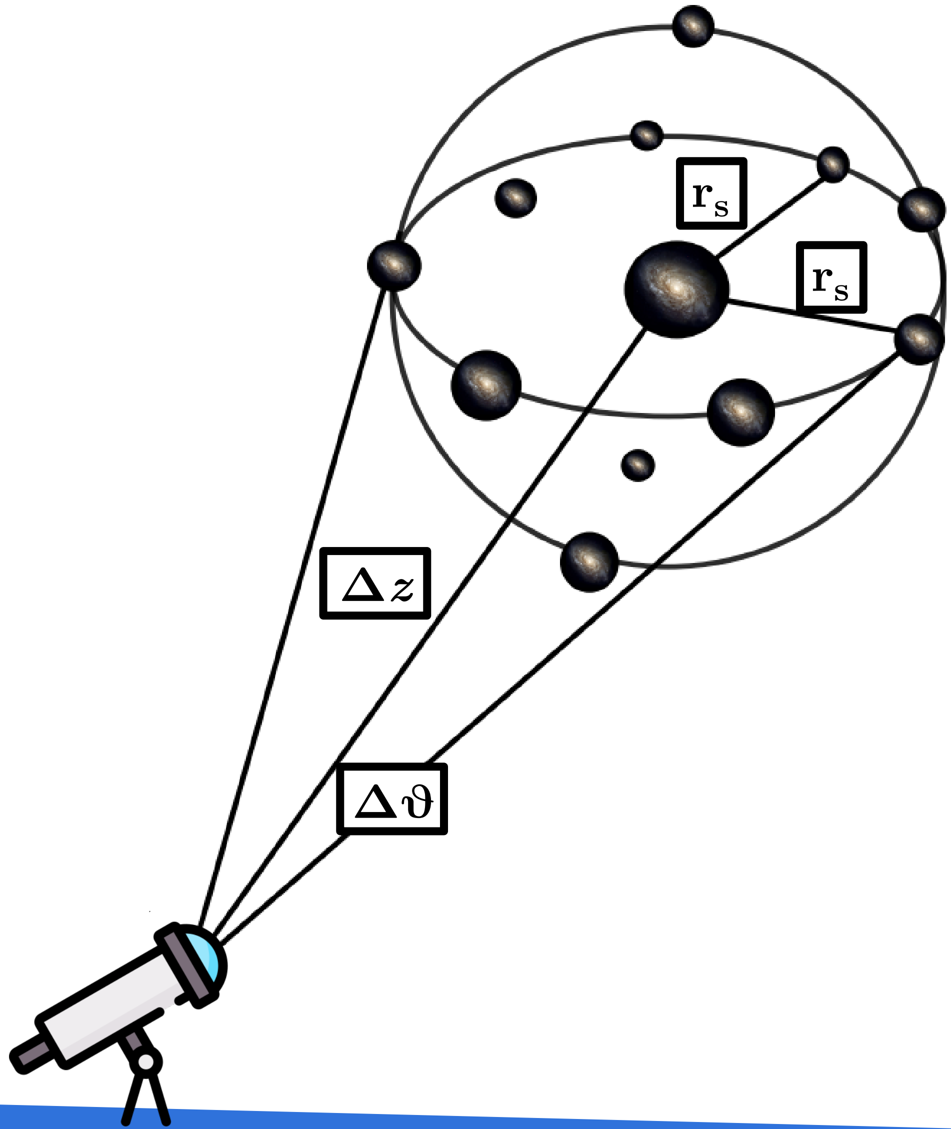
BAO and the sound horizon

Substitution

$$H(z) = H_0 E(z)$$

$$\Delta z = H_0 r_s \cdot E(z)$$

$$\Delta\vartheta = \frac{r_s}{\int \frac{dz}{H(z)}} = \frac{H_0 r_s}{\int \frac{dz}{E(z)}}$$

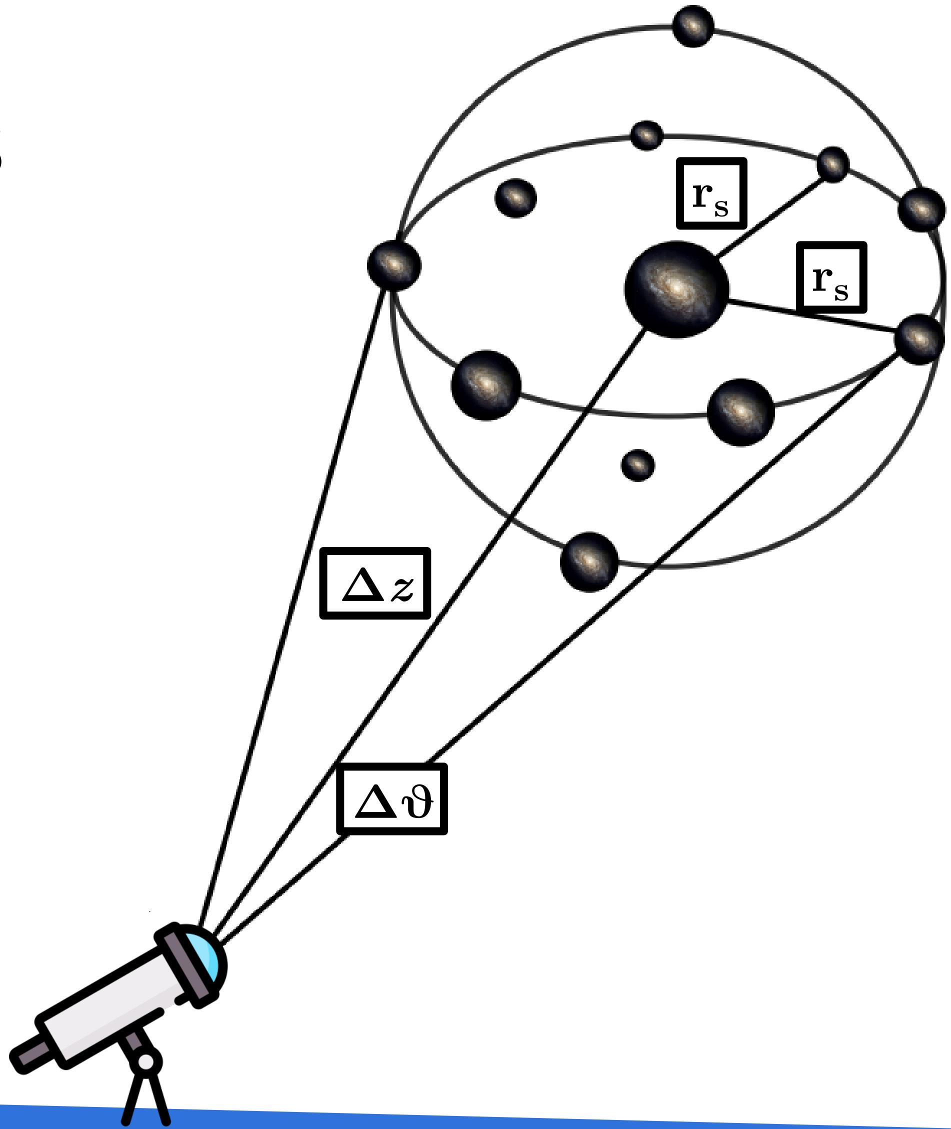


BAO and the sound horizon

Two measurements

$$\Delta z = H_0 r_s \cdot E(z)$$

$$\Delta\vartheta = \frac{r_s}{\int \frac{dz}{H(z)}} = \frac{H_0 r_s}{\int \frac{dz}{E(z)}}$$



DESI cosmology

- What can BAO only say about cosmology?

DESI COSMOLOGY

- What can BAO only say about cosmology?

$$\Omega_m = 0.2975 \pm 0.0086$$

DESI cosmology

- What can BAO only say about cosmology?

$$\Omega_m = 0.2975 \pm 0.0086$$

Already provocative!

Status of Ω_m tension

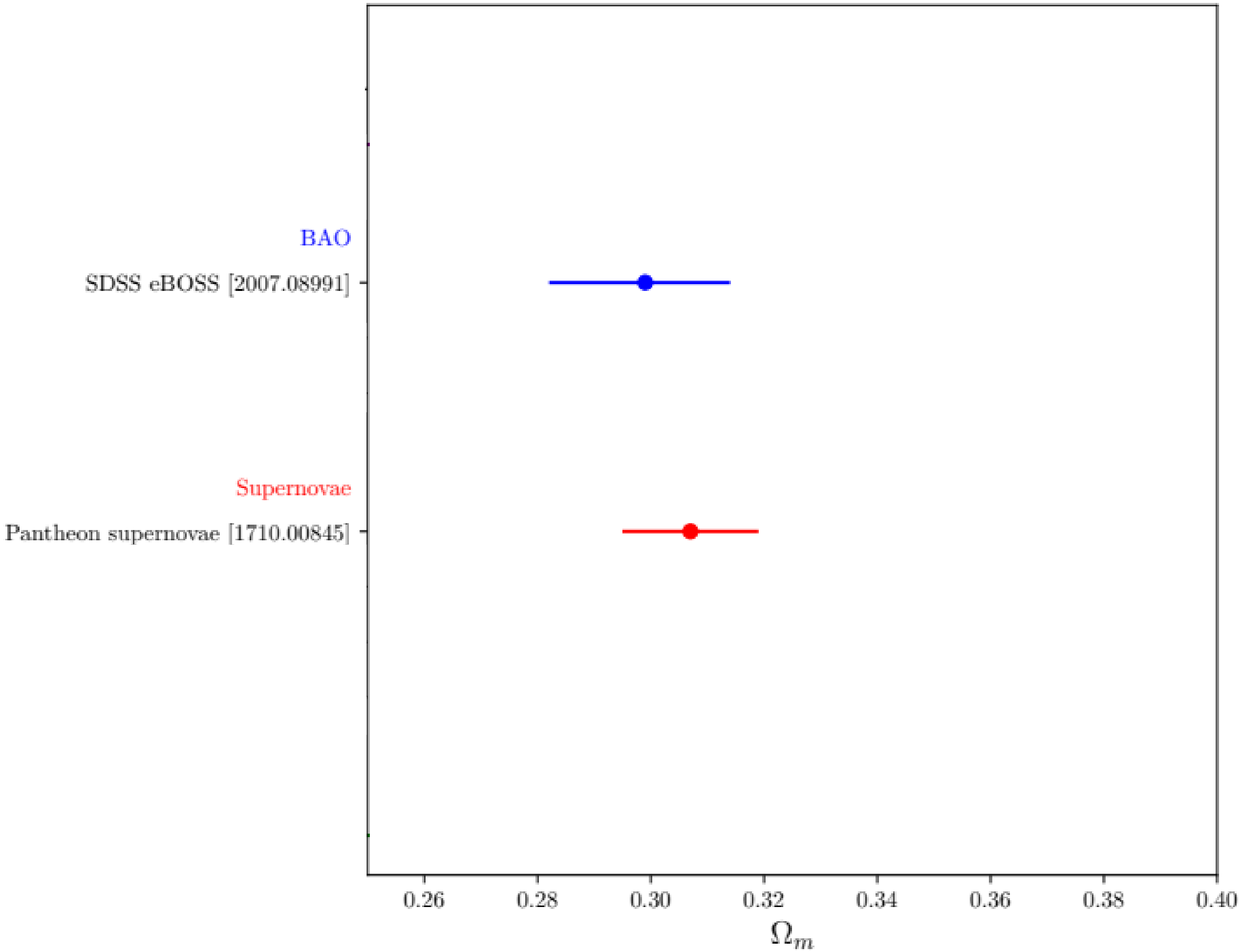
Emerging more and more as a new problem

SDSS BAO $\Omega_m = 0.299^{+0.015}_{-0.017}$

Pantheon supernovae $\Omega_m = 0.307^{+0.012}_{-0.012}$

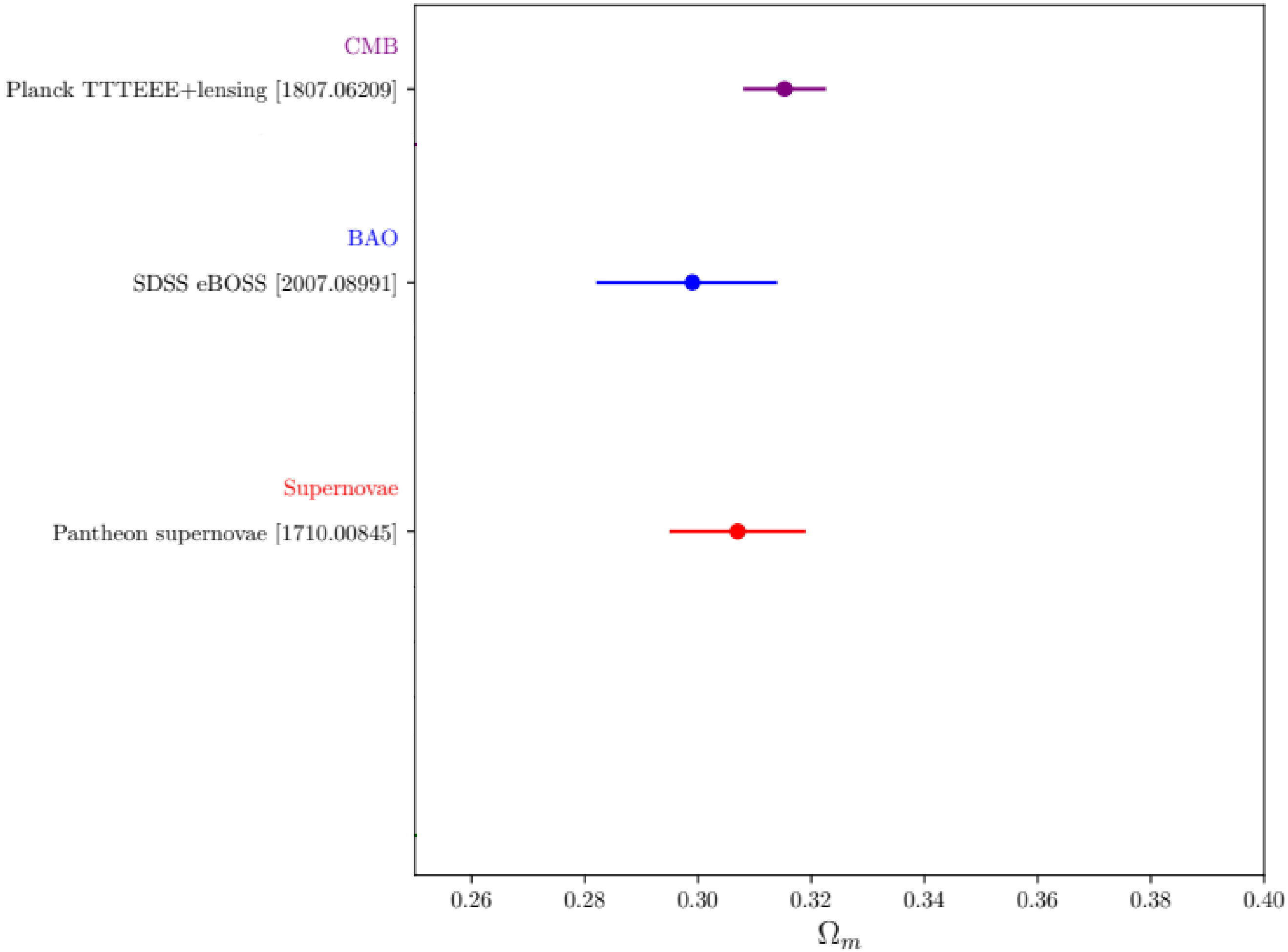
Status of Ω_m tension

Emerging more and more as a new problem



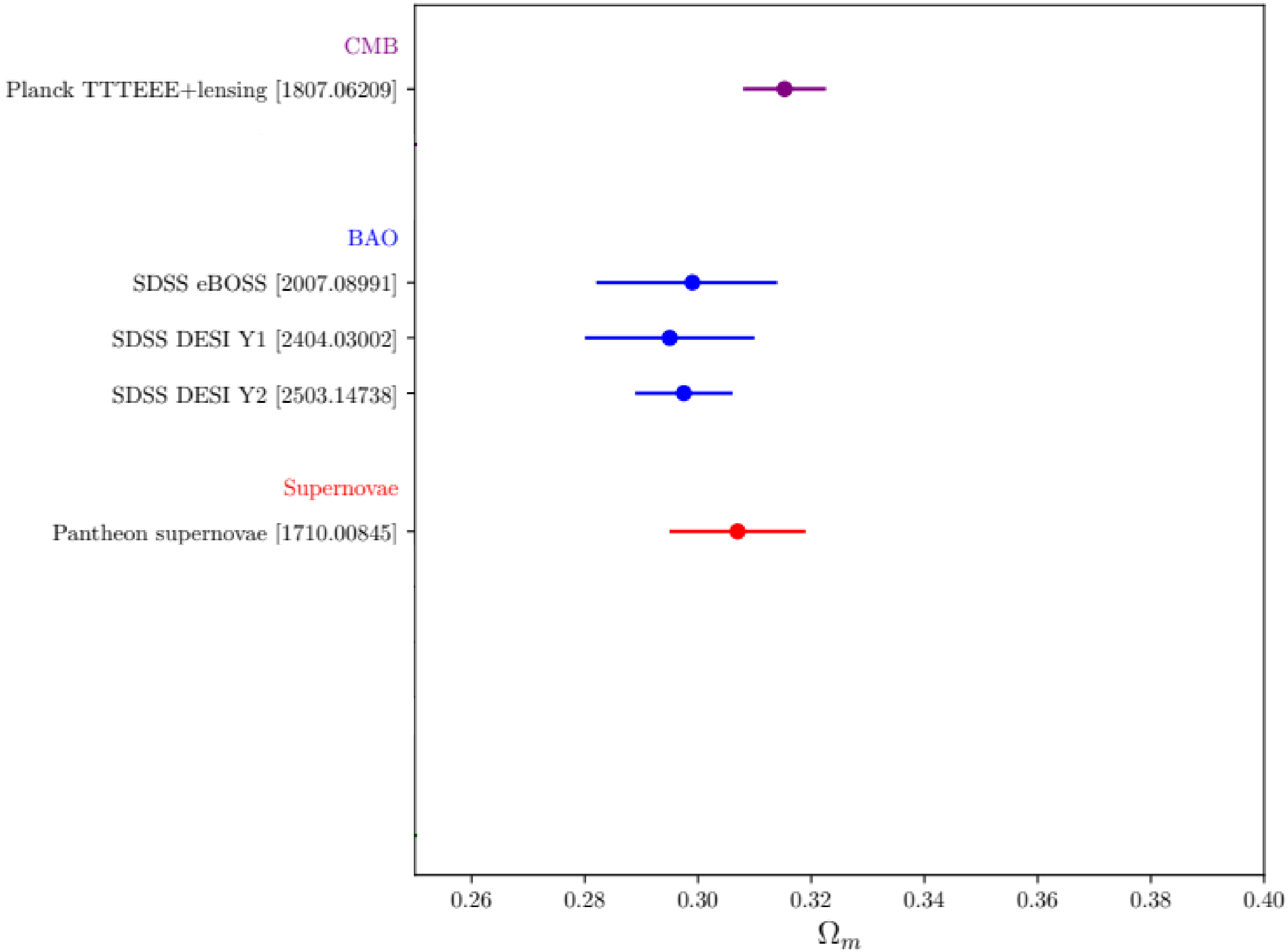
Status of Ω_m tension

Emerging more and more as a new problem



STATUS OF Ω_M TENSION

Emerging more and more as a new problem



STATUS OF Ω_M TENSION

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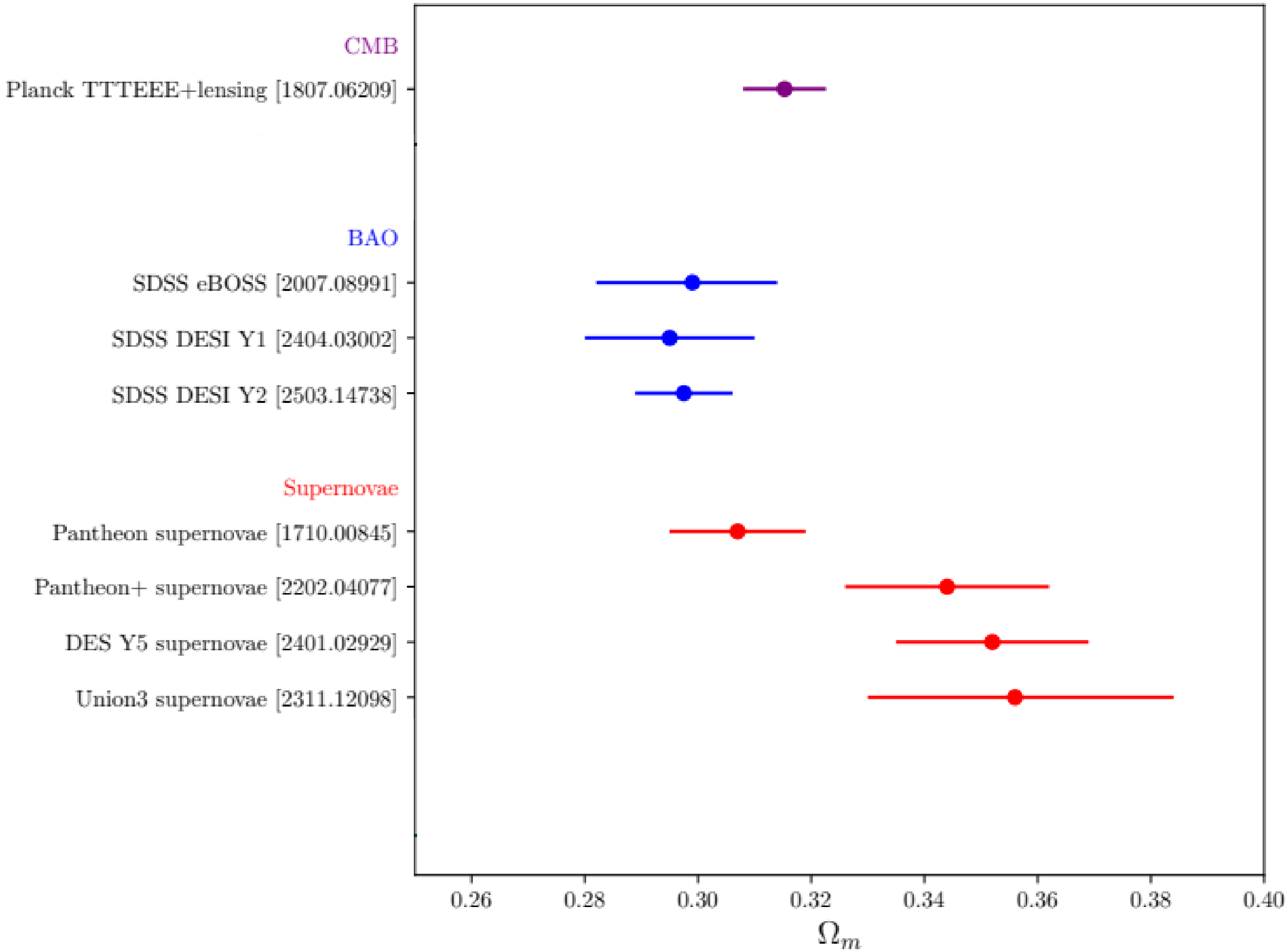

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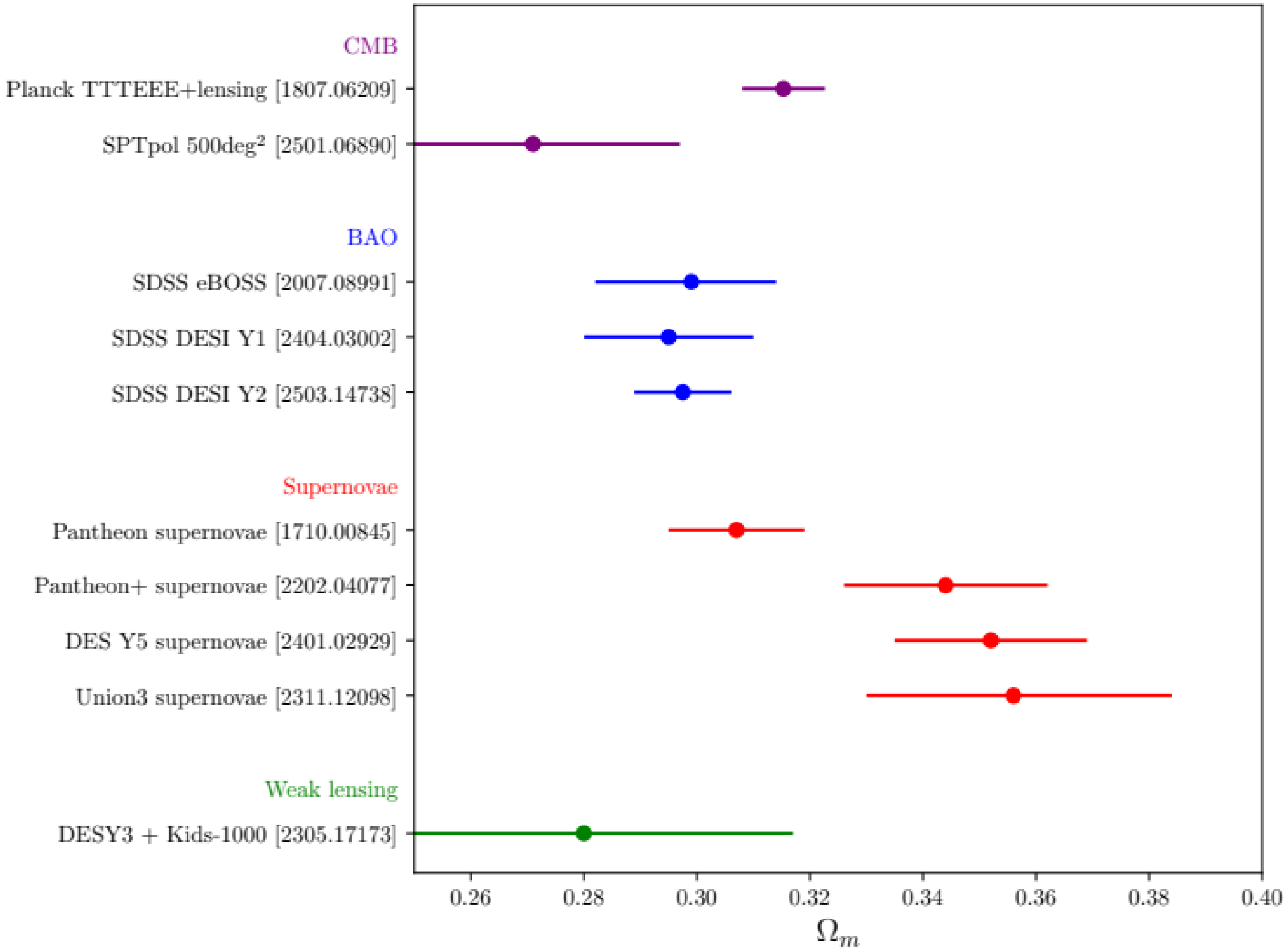
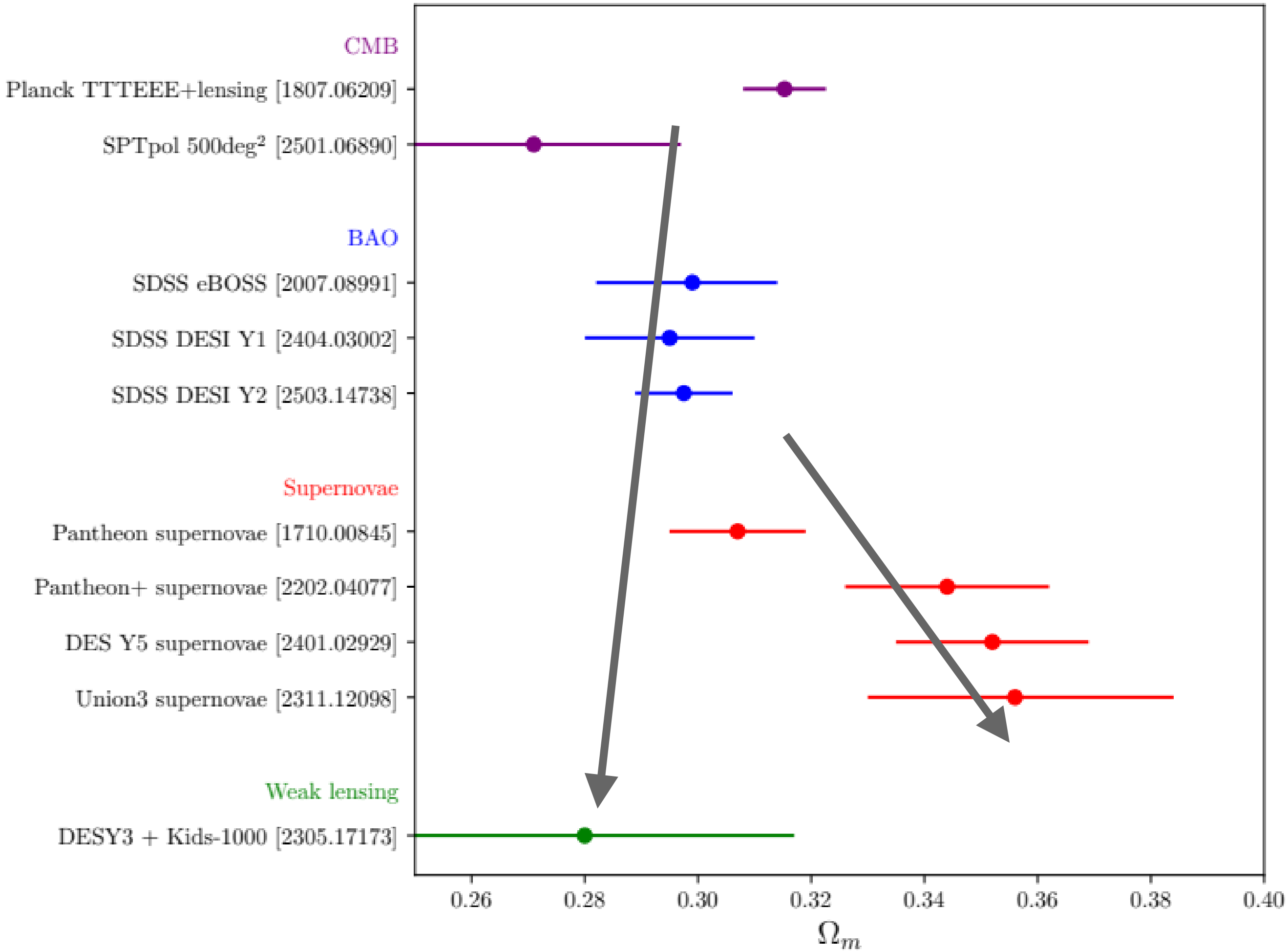


STATUS OF Ω_M TENSION

Emerging more and more as a new problem



STATUS OF Ω_M TENSION

Emerging more and more as a new problem

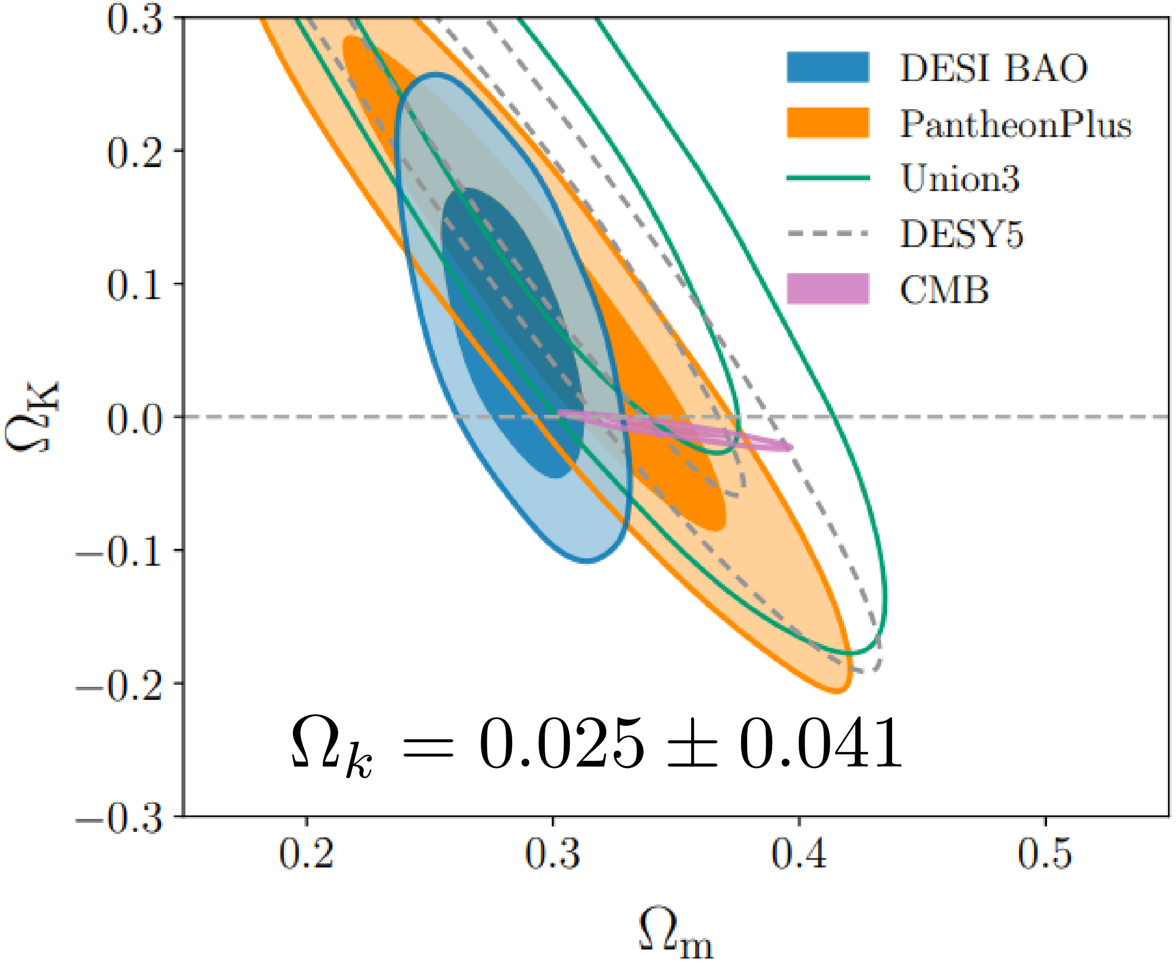
→ Might not seem like a big issue (~2σ)

→ Actually becomes a big challenge to understanding dark energy/gravity

Image DR1
Numbers DR2

SIMPLE EXTENSIONS

$\Omega_m = 0.293 \pm 0.012$



$\Omega_k = 0.025 \pm 0.041$

DESI cosmology

- What can BAO only say about cosmology?

$$\Omega_m = 0.2975 \pm 0.0086$$

Already provocative!

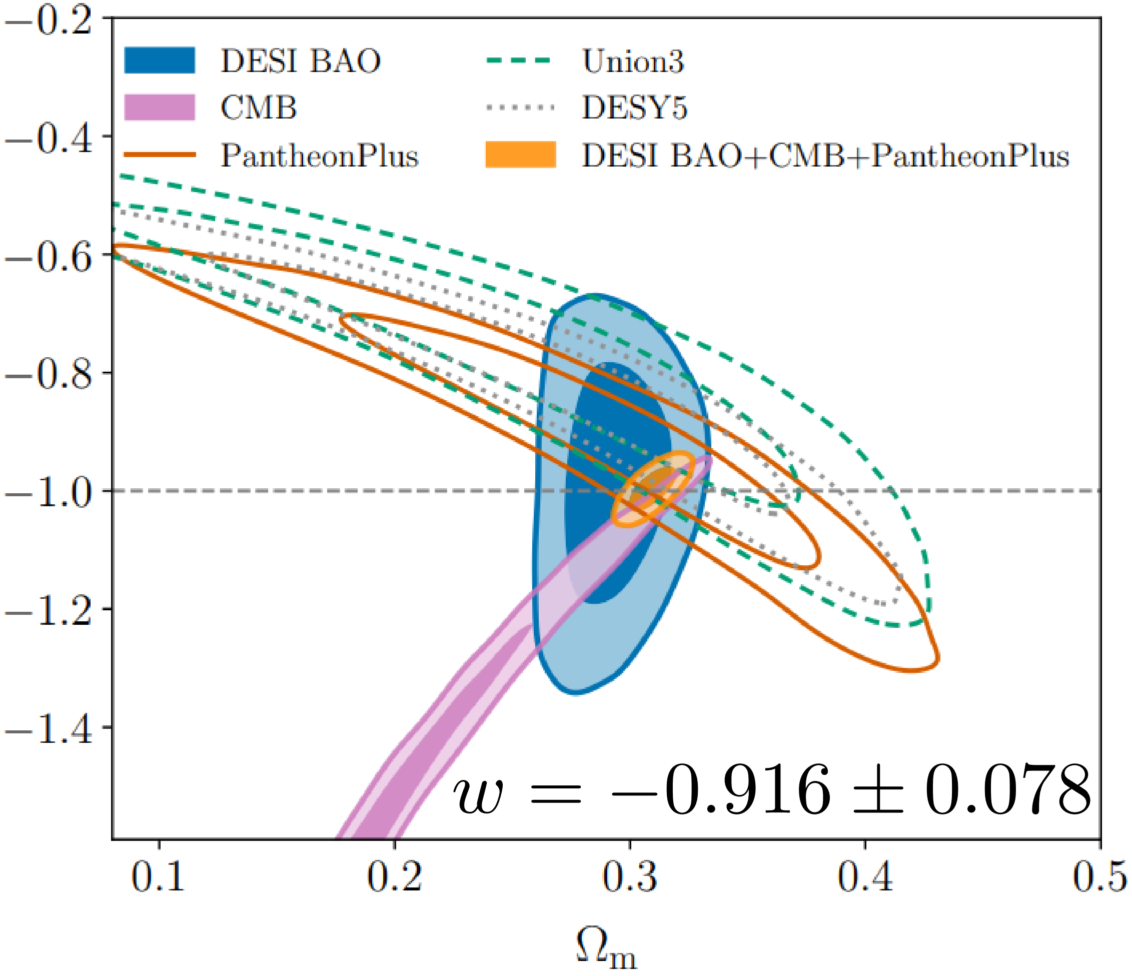
$$\Omega_k = 0.025 \pm 0.041$$

Image DR1
Numbers DR2

Simple extensions

$$\Omega_m = 0.2969 \pm 0.0089$$

$$w = \frac{P_{\mathrm{DE}}}{\rho_{\mathrm{DE}}}$$



$$w = -0.916 \pm 0.078$$ (-1.1σ)

DESI cosmology

- What can BAO only say about cosmology?

$$\Omega_m = 0.2975 \pm 0.0086$$

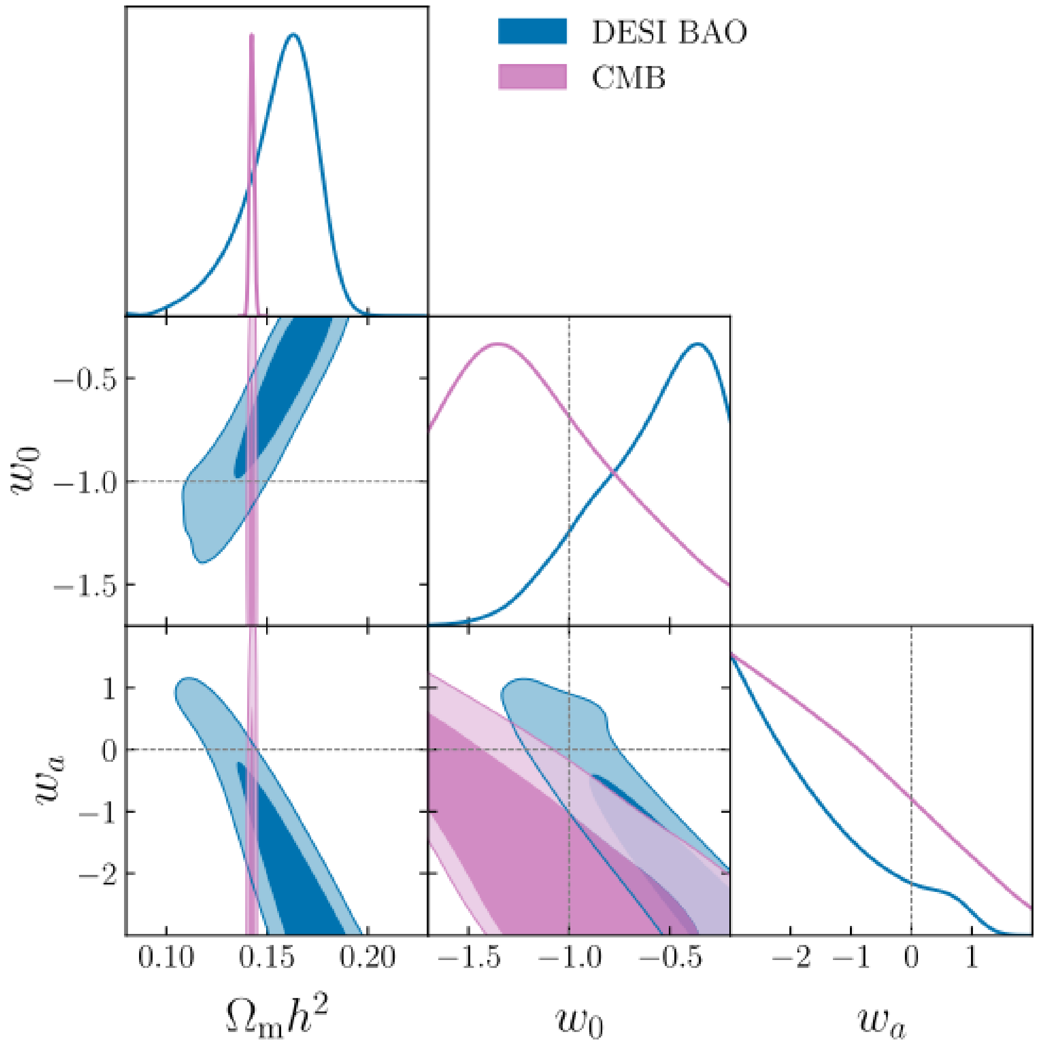
Already provocative!

$$\Omega_k = 0.025 \pm 0.041$$

$$w = -0.916 \pm 0.078$$ (-1.1σ)

Image DR1
Numbers DR2

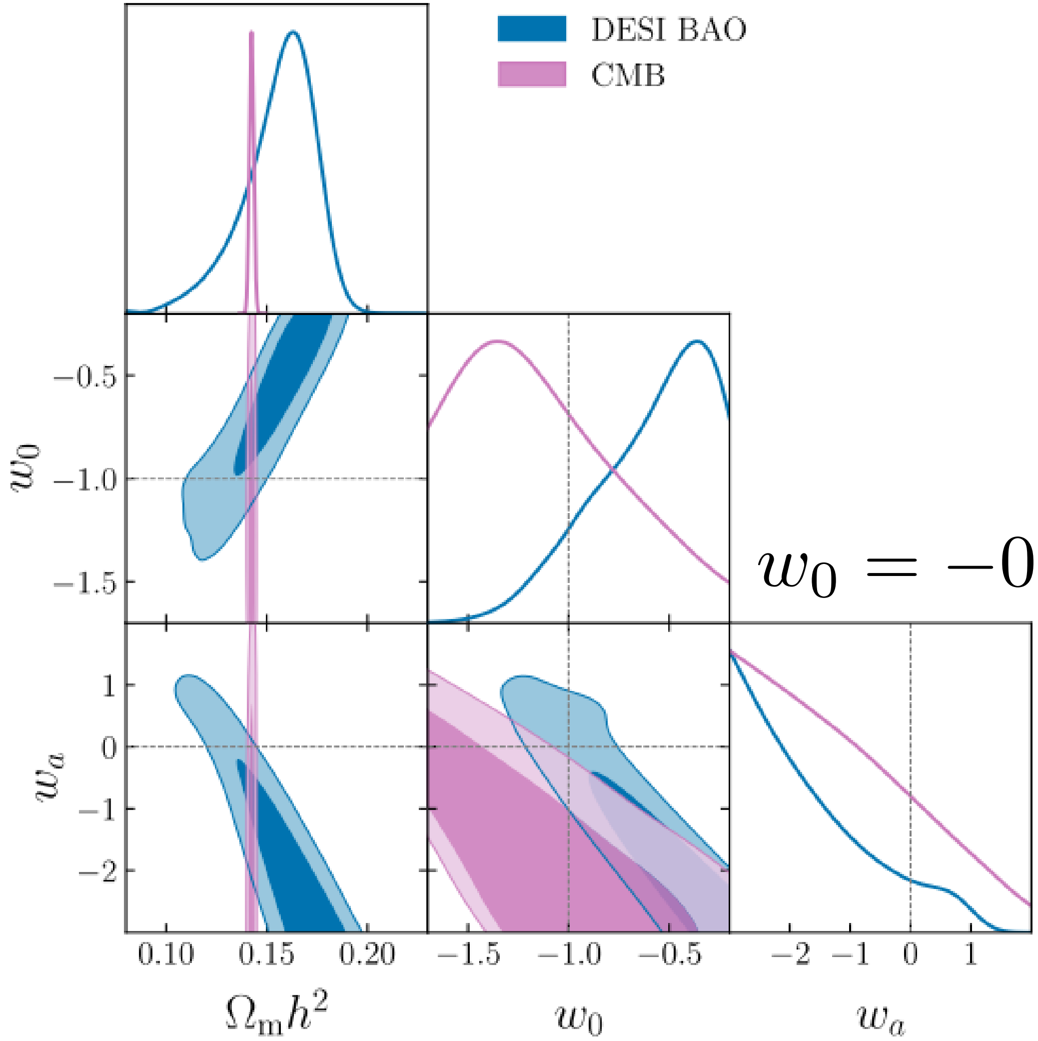
Simple extensions



$$\frac{P_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a \frac{z}{1+z}$$

Image DR1
Numbers DR2

SIMPLE EXTENSIONS



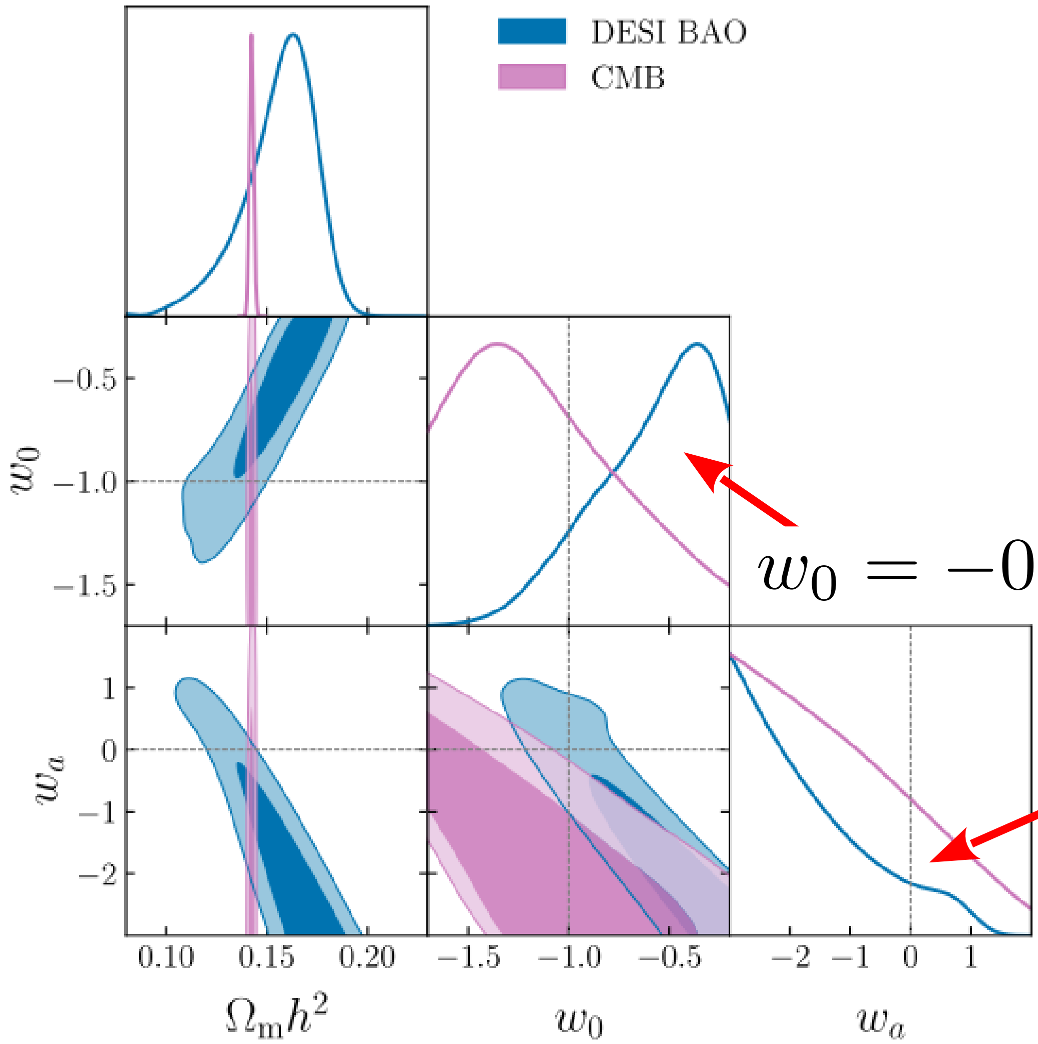
$$w_0 = -0.48^{+0.35}_{-0.17}$$

$$w_a < -1.34$$

$$\frac{P_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a \frac{z}{1+z}$$

Image DR1
Numbers DR2

SIMPLE EXTENSIONS



$$w_0 = -0.48^{+0.35}_{-0.17}$$

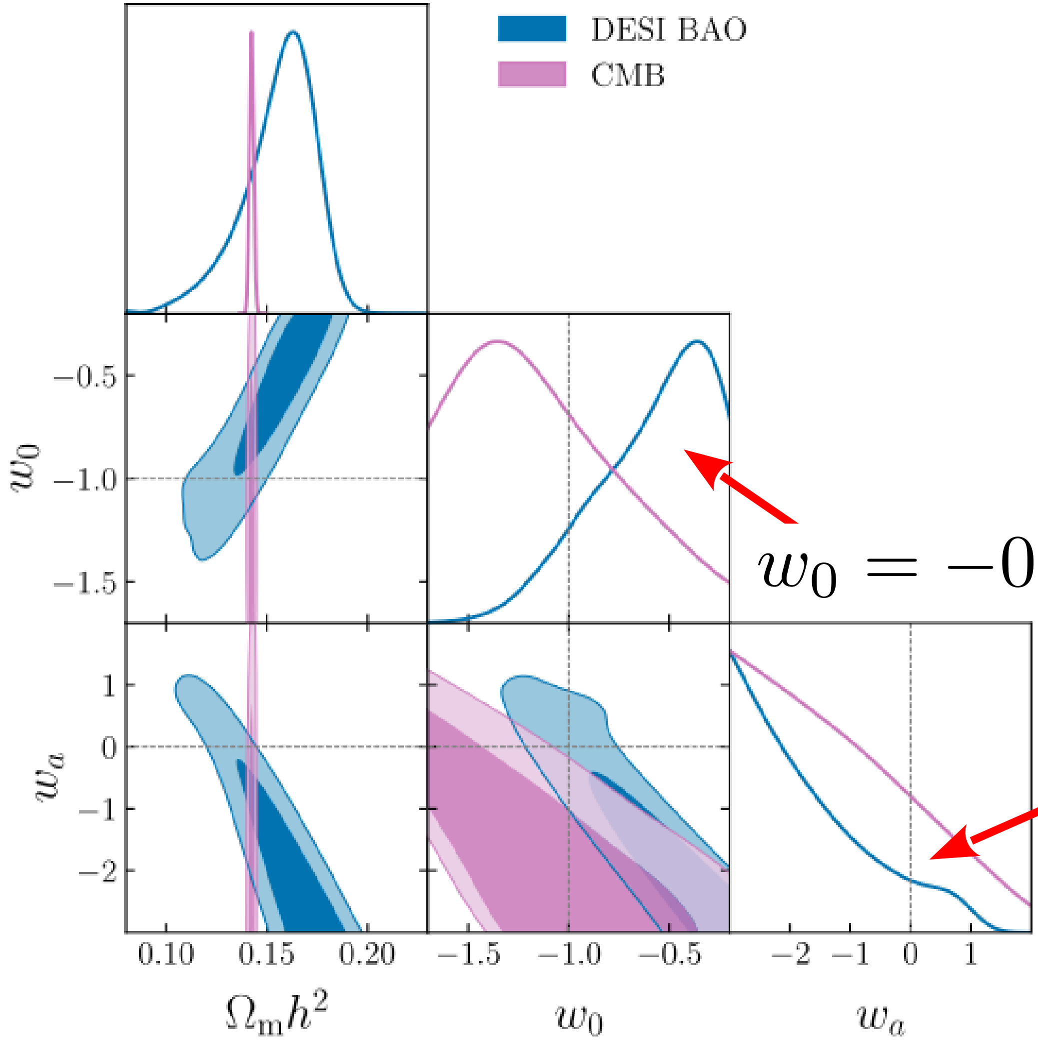
debatable

$$w_a < -1.34$$

$$\frac{P_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a \frac{z}{1+z}$$

Image DR1
Numbers DR2

Simple extensions



$$w_0 = -0.48^{+0.35}_{-0.17}$$

prior-driven (?)

$$w_a < -1.34$$

$$\frac{P_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a \frac{z}{1+z}$$

Image DR1
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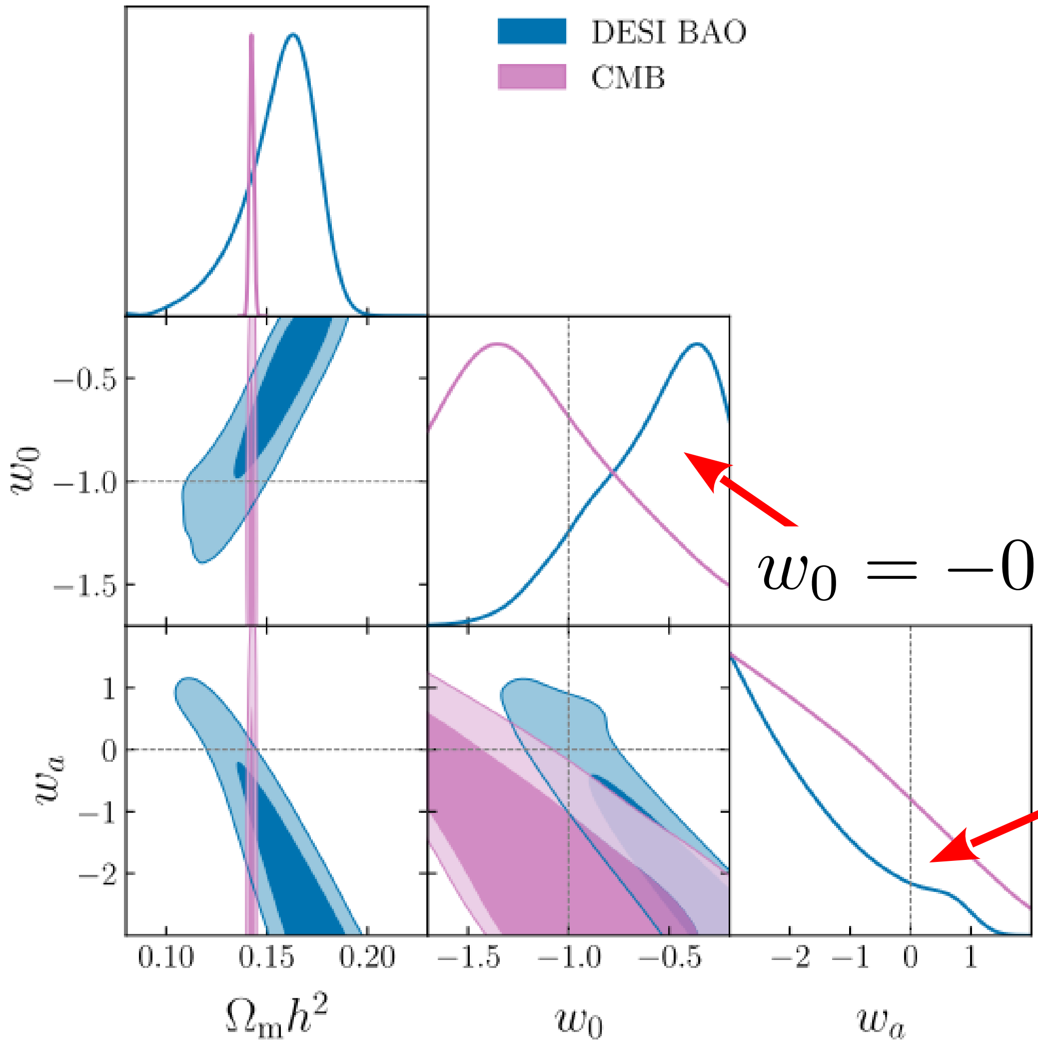
Simple extensions



$$\Omega_m = 0.352^{+0.041}_{-0.018}$$

$$w_0 = -0.48^{+0.35}_{-0.17}$$

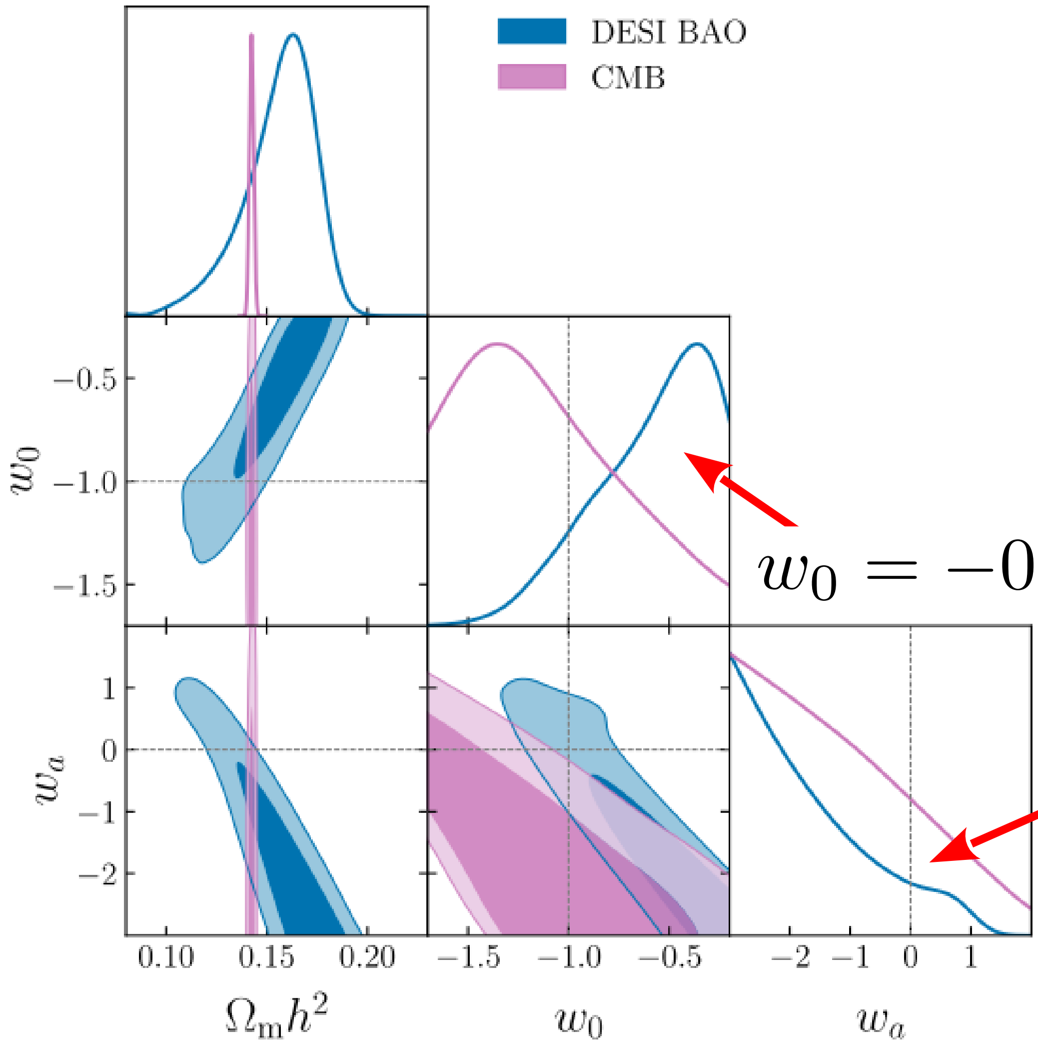
prior-driven (?)

$$w_a < -1.34$$

$$\frac{P_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a \frac{z}{1+z}$$

Image DR1
Numbers DR2

Simple extensions



$$\boxed{\Omega_m = 0.352^{+0.041}_{-0.018}}$$

Pushed up by 2.7σ !!

$$w_0 = -0.48^{+0.35}_{-0.17}$$

prior-driven (?)

$$w_a < -1.34$$

$$\frac{P_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a \frac{z}{1+z}$$

DESI COSMOLOGY

- What can BAO only say about cosmology?

$$\Omega_m = 0.2975 \pm 0.0086$$

Already provocative!

$$\Omega_k = 0.025 \pm 0.041$$

$$w = -0.916 \pm 0.078$$ (-1.1σ)

$w_0 + w_a$ **unconstrained, BUT** $\Omega_m = 0.352^{+0.041}_{-0.018}$

nils.science@gmail.com

DESI cosmology

- What can BAO only say about cosmology?

$$\Omega_m = 0.2975 \pm 0.0086$$

Already provocative!

$$\Omega_k = 0.025 \pm 0.041$$

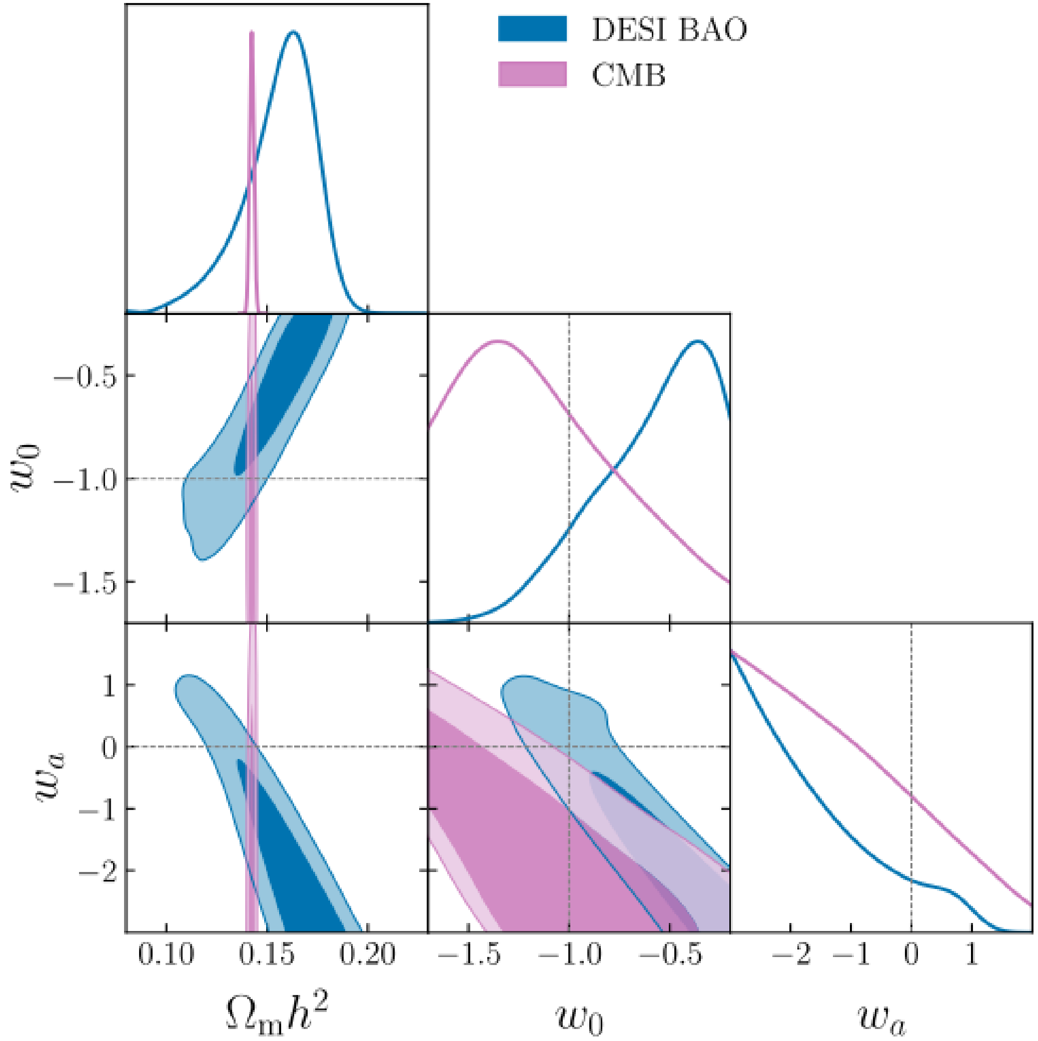
$$w = -0.916 \pm 0.078$$ (-1.1σ)

$w_0 + w_a$ **unconstrained, BUT** $\Omega_m = 0.352^{+0.041}_{-0.018}$

Something weird is going on with enough flexibility
$\rightarrow$ *Highlight with different data*

Image DR1
Numbers DR2

Simple extensions



$$\frac{P_{DE}}{\rho_{DE}} = w_0 + w_a \frac{z}{1+z}$$

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Numbers DR2

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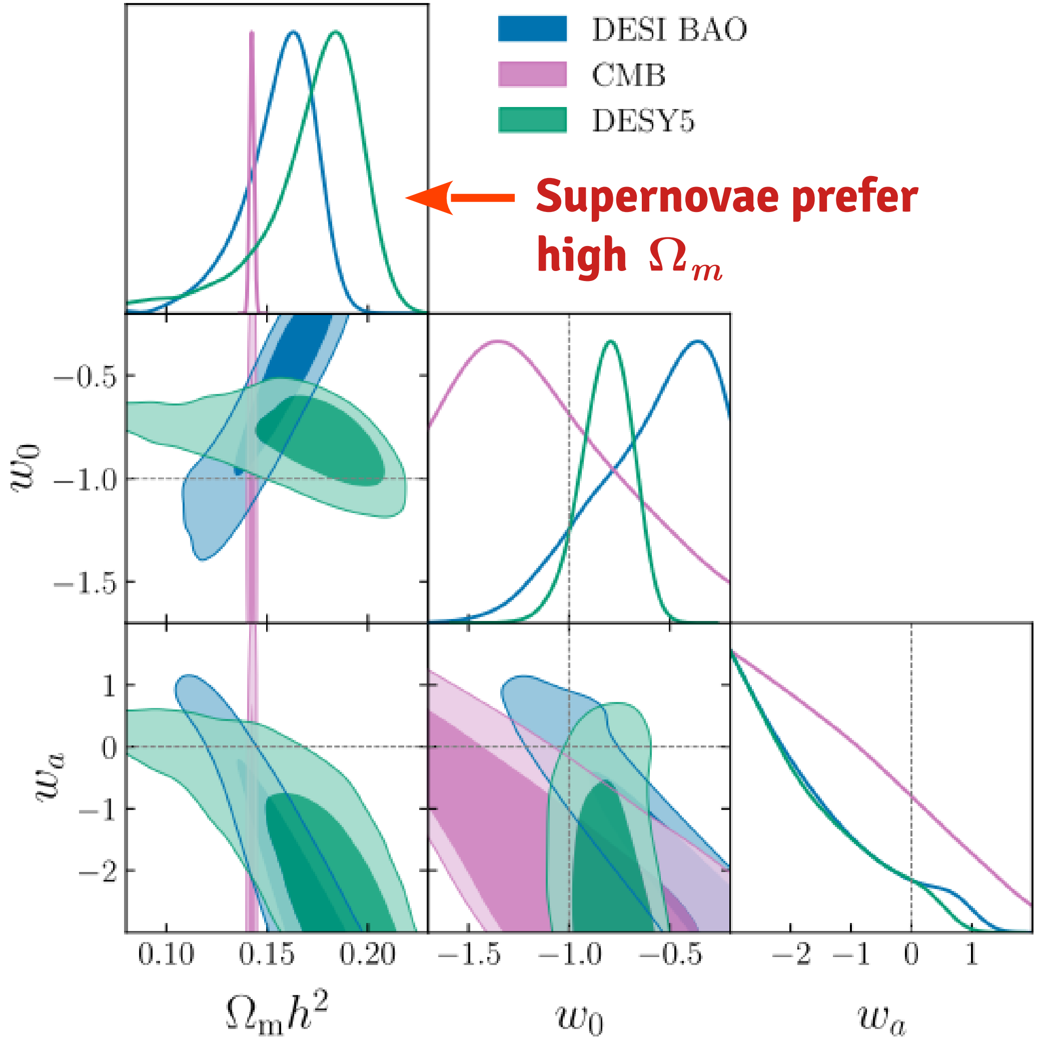

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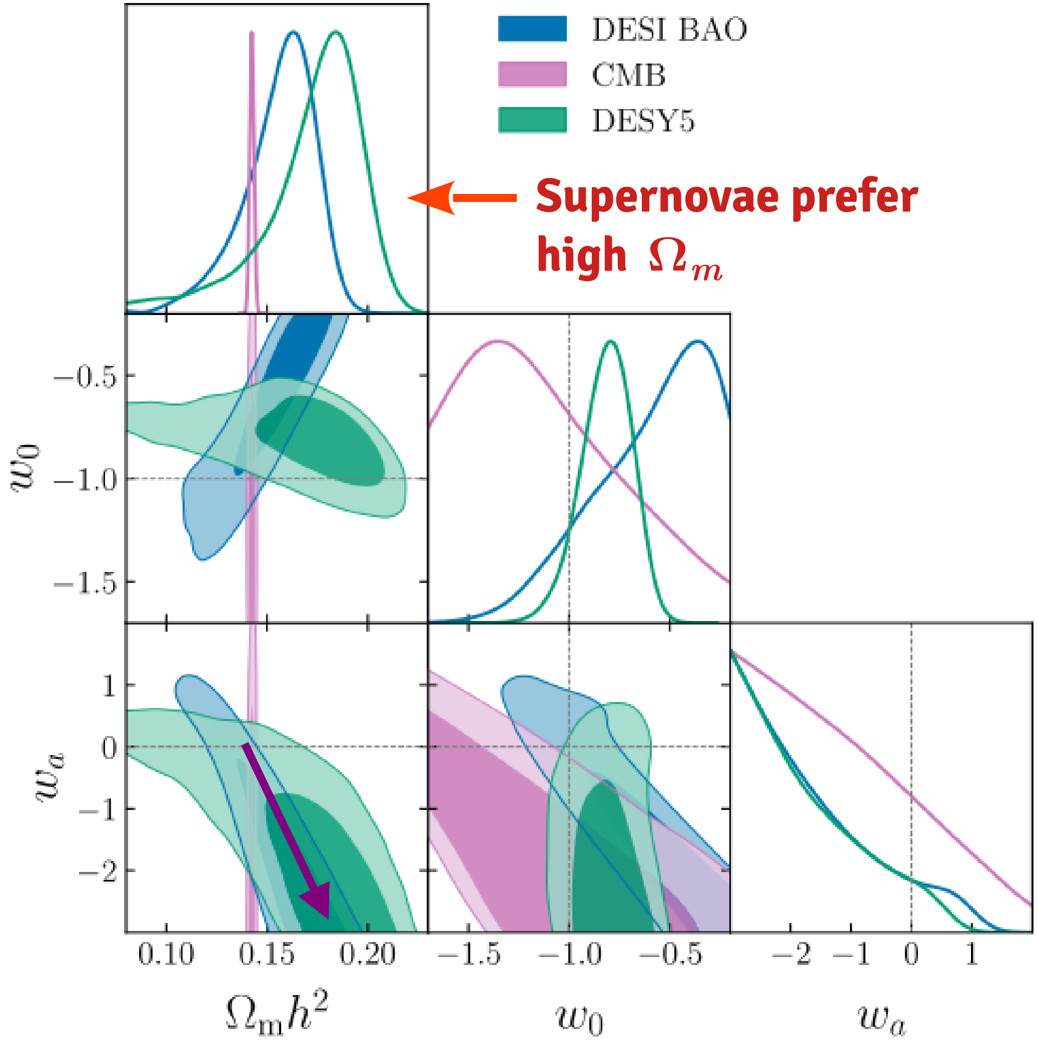

Supernovae prefer high Ω_m

Ω_m tension can be 'relieved' by going to $w_a < 0$

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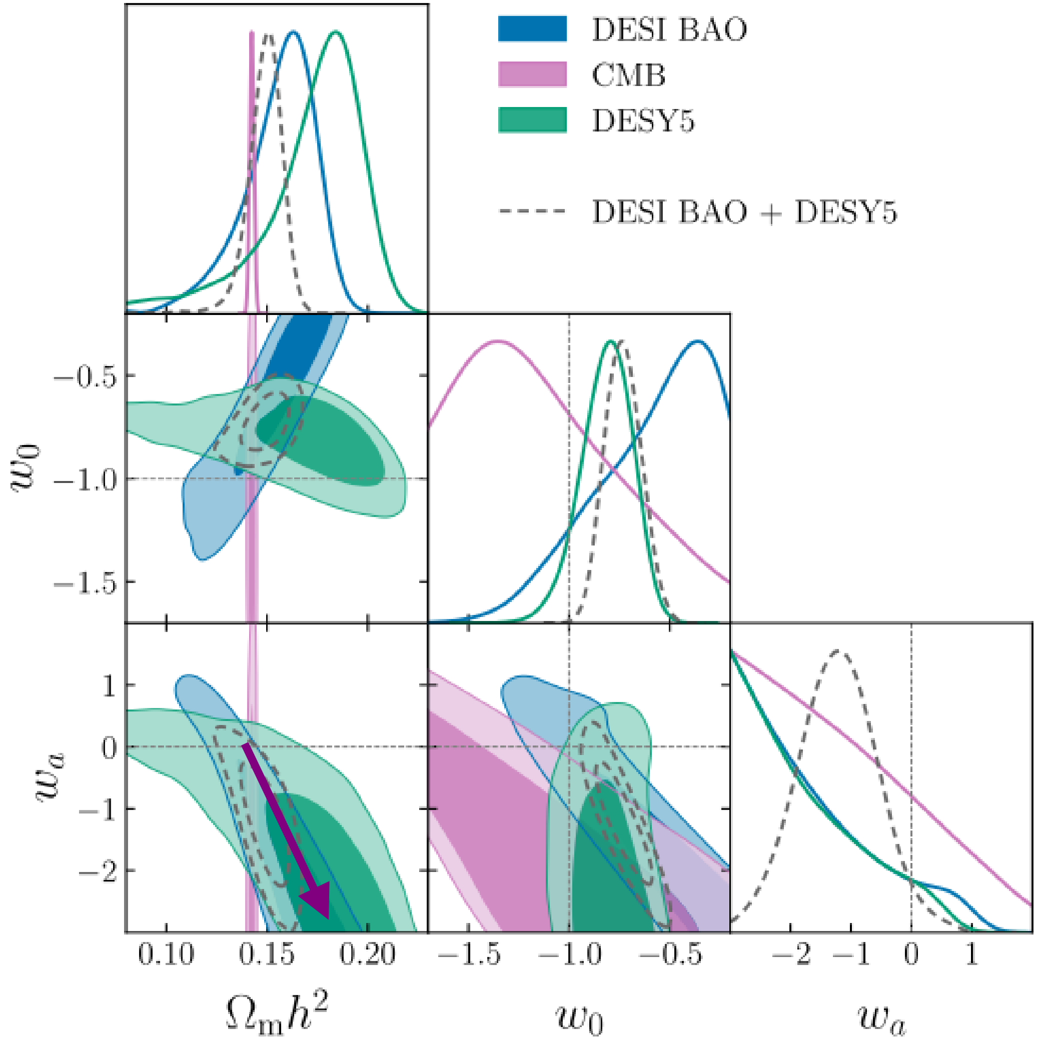

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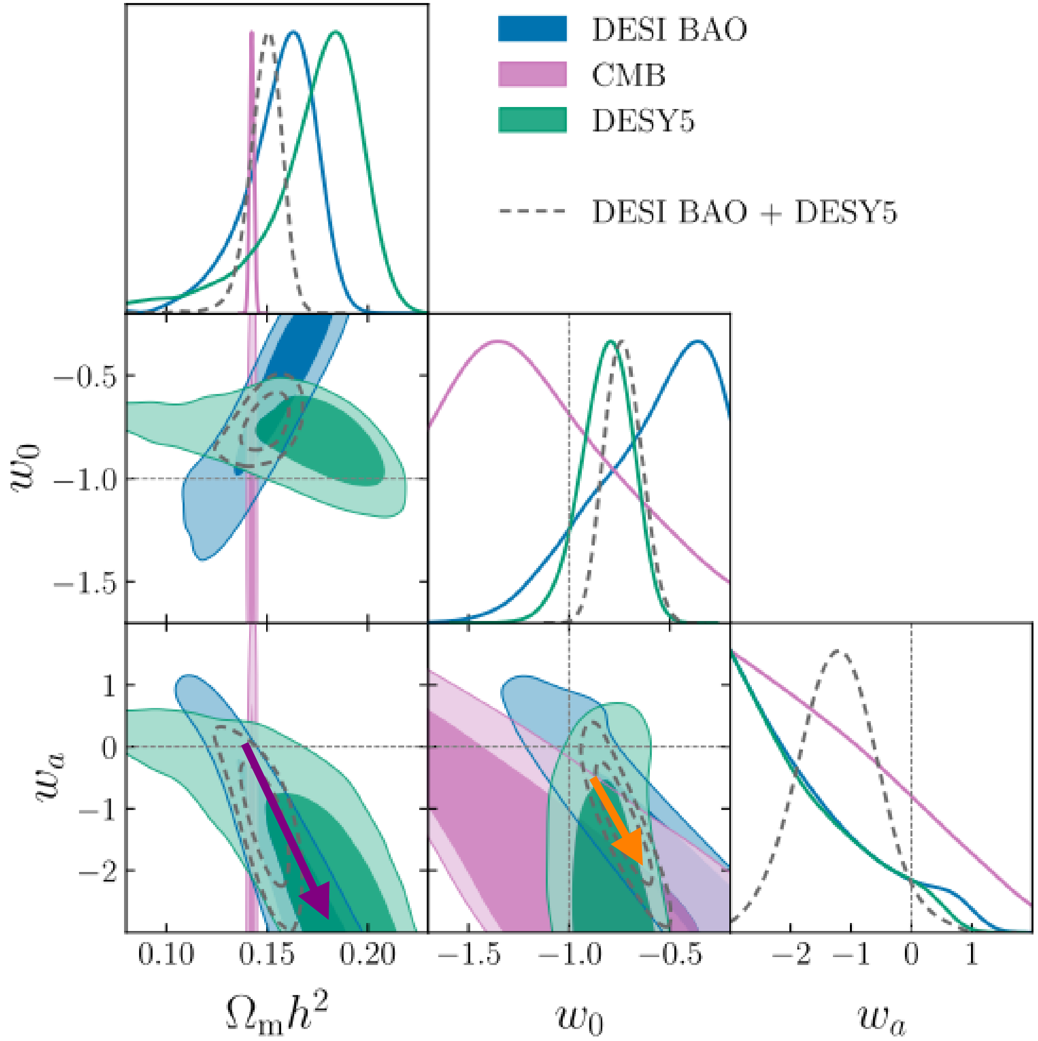

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Combined preference for $w_a < 0$

→ Lower values prevented by w_0

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DESI cosmology

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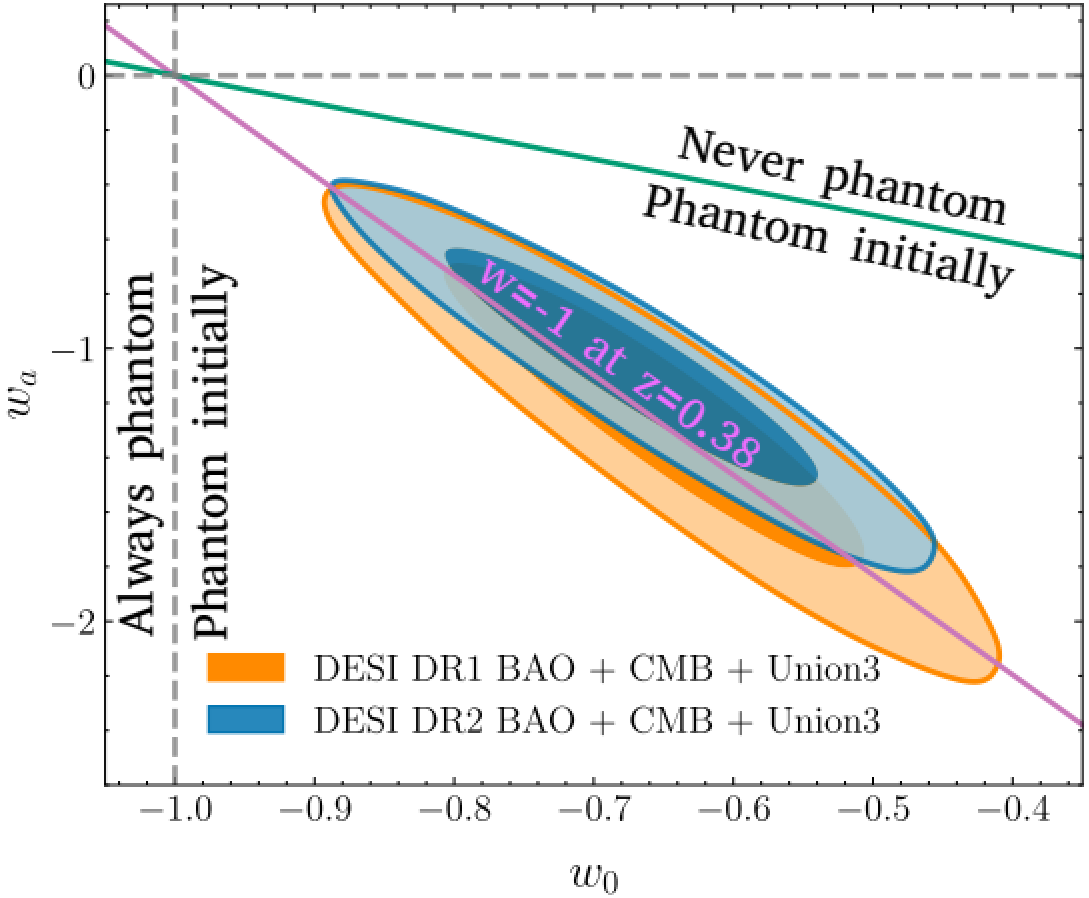
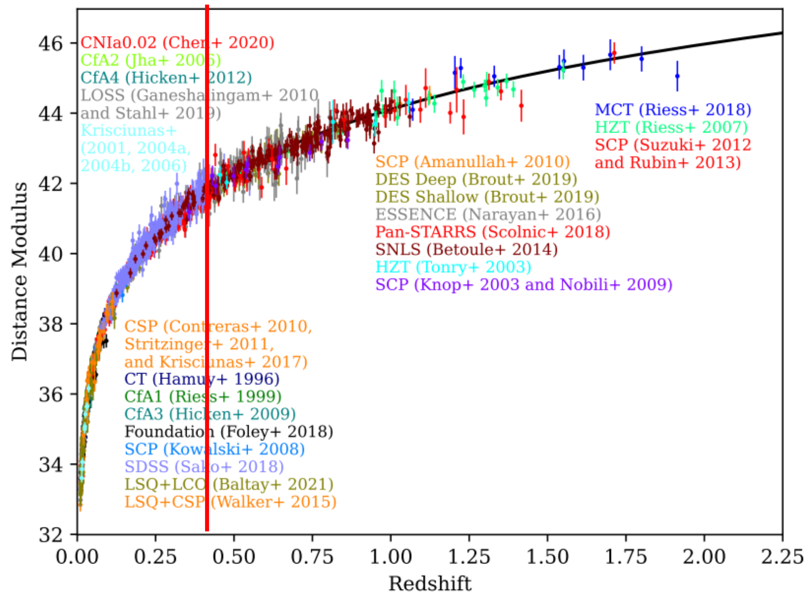
$w_0 + w_a$ **unconstrained, BUT** $\Omega_m = 0.352^{+0.041}_{-0.018}$

$w_a < 0$ **results in** Ω_m **agreement with supernovae Ia**

Simple extensions

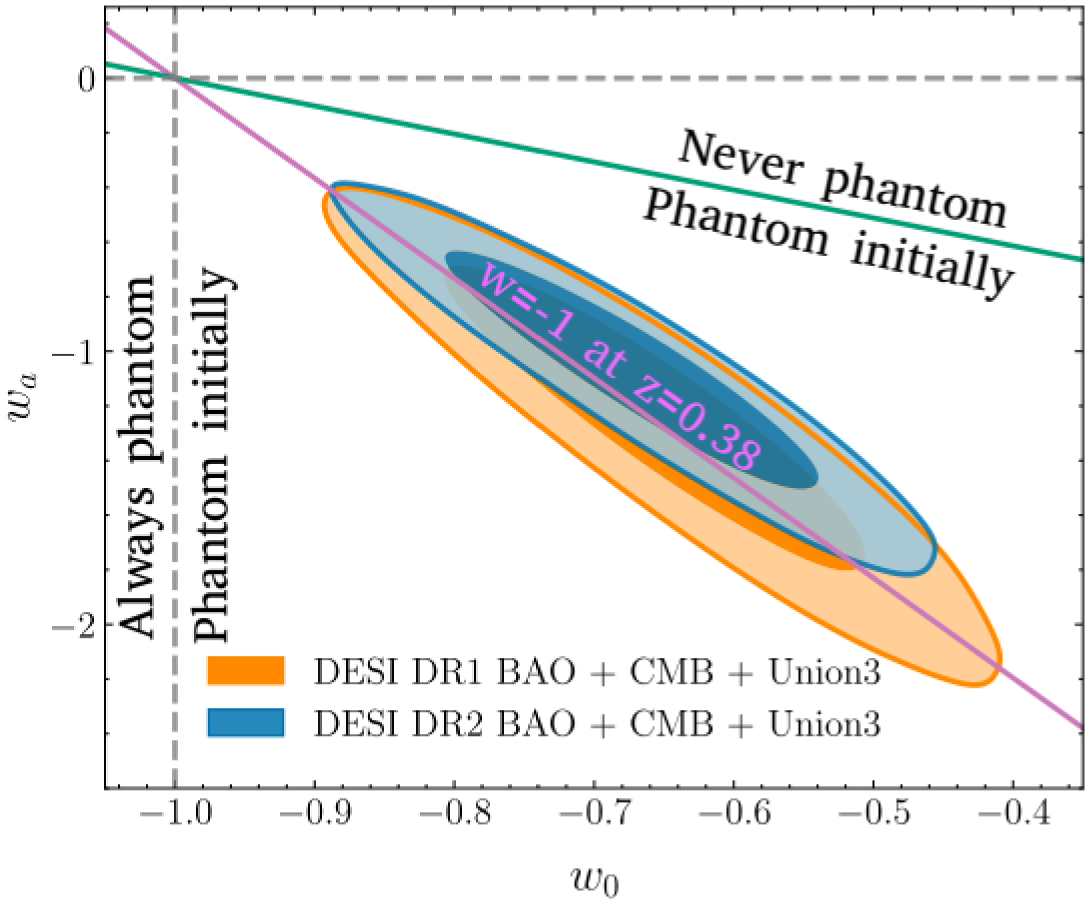


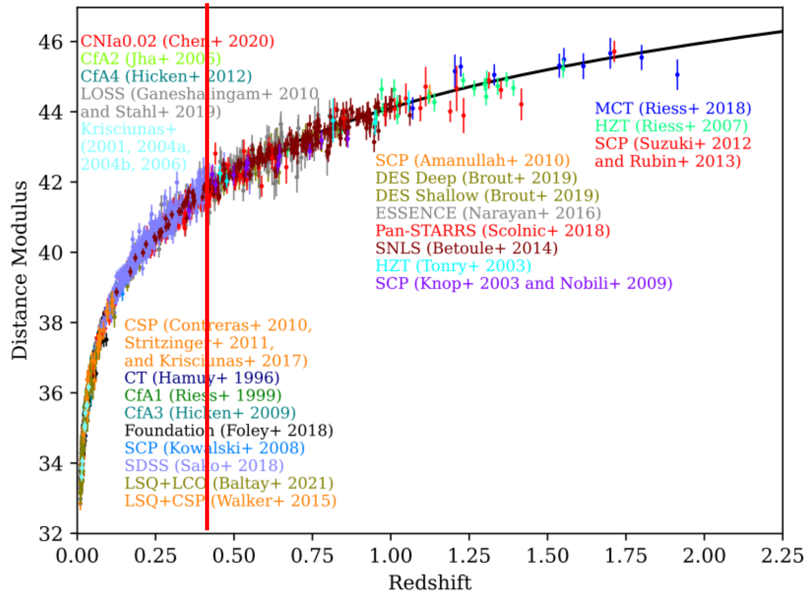


Ω_m agreement
While keeping w=-1 at z=0.4
(supernovae, CMB)

Inspired byCortês+Liddle 2404.08056

Simple extensions





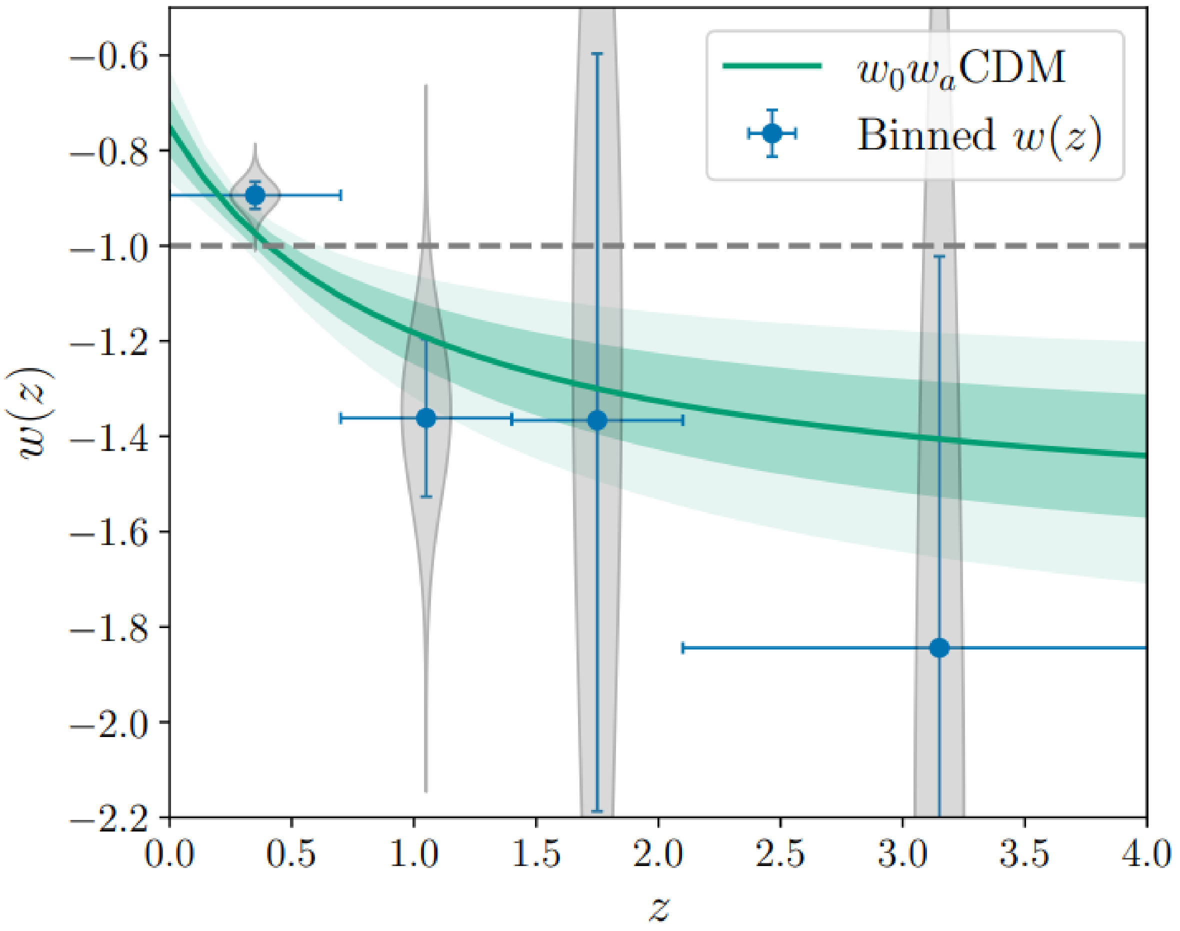
Ω_m agreement
While keeping w=-1 at z=0.4
(supernovae, CMB)

To keep θ_s constant

Inspired byCortês+Liddle 2404.08056

"Mirage" cosmological constant
Linder 0708.0024

Simple extensions



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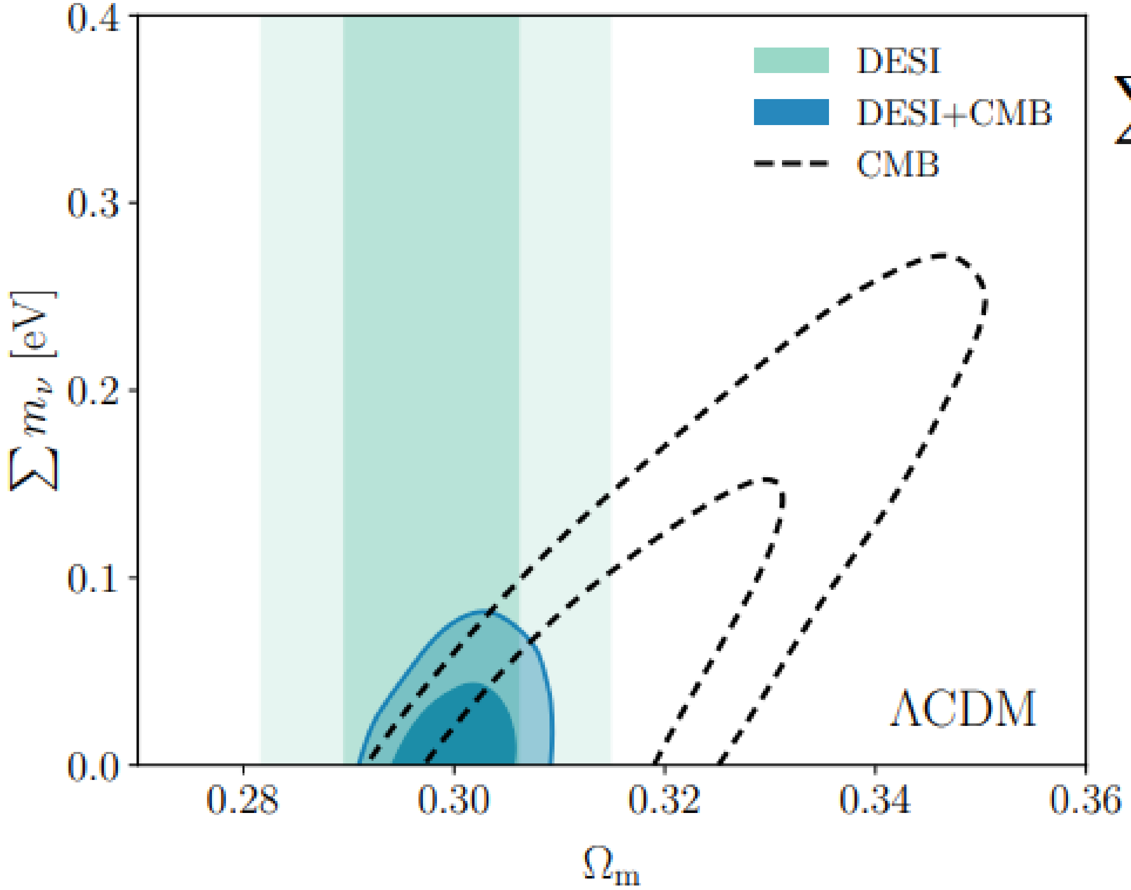
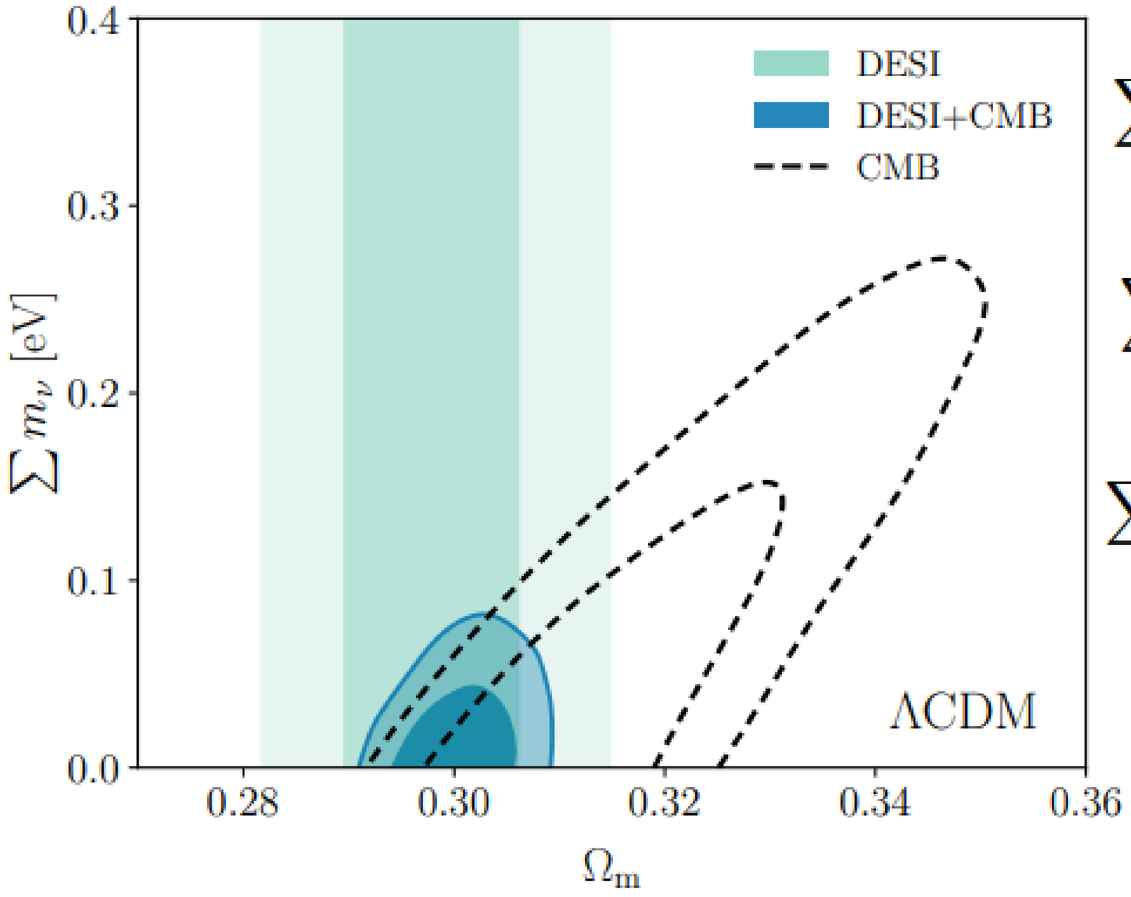
Too early to tell !

Constraints on neutrinos



$$\sum m_\nu < 0.064\,\mathrm{eV} \quad (95\%,\ \mathrm{DESI{+}CMB})$$

CONSTRAINTS ON NEUTRINOS



$$\sum m_\nu < 0.064\,\mathrm{eV} \quad (95\%,\ \mathrm{DESI{+}CMB})$$

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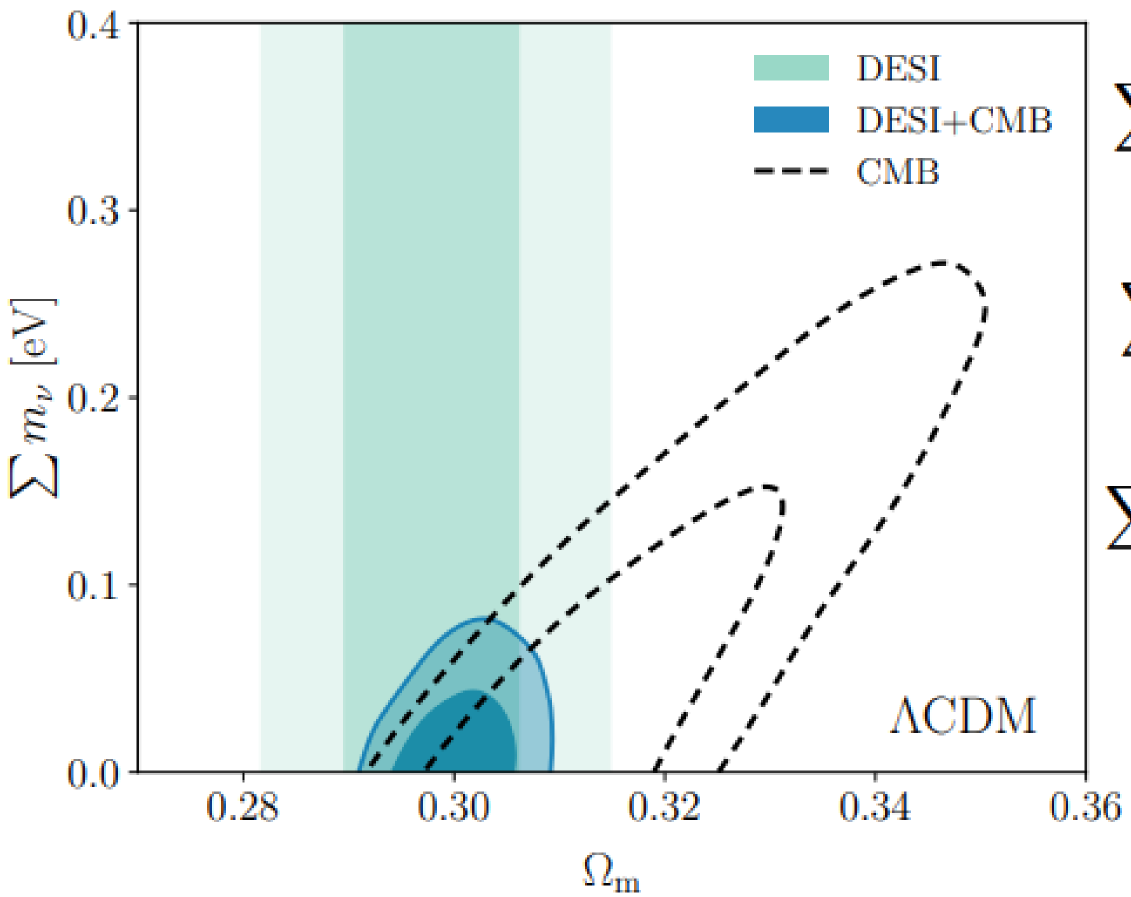
Depends on CMB likelihood

Constraints on neutrinos



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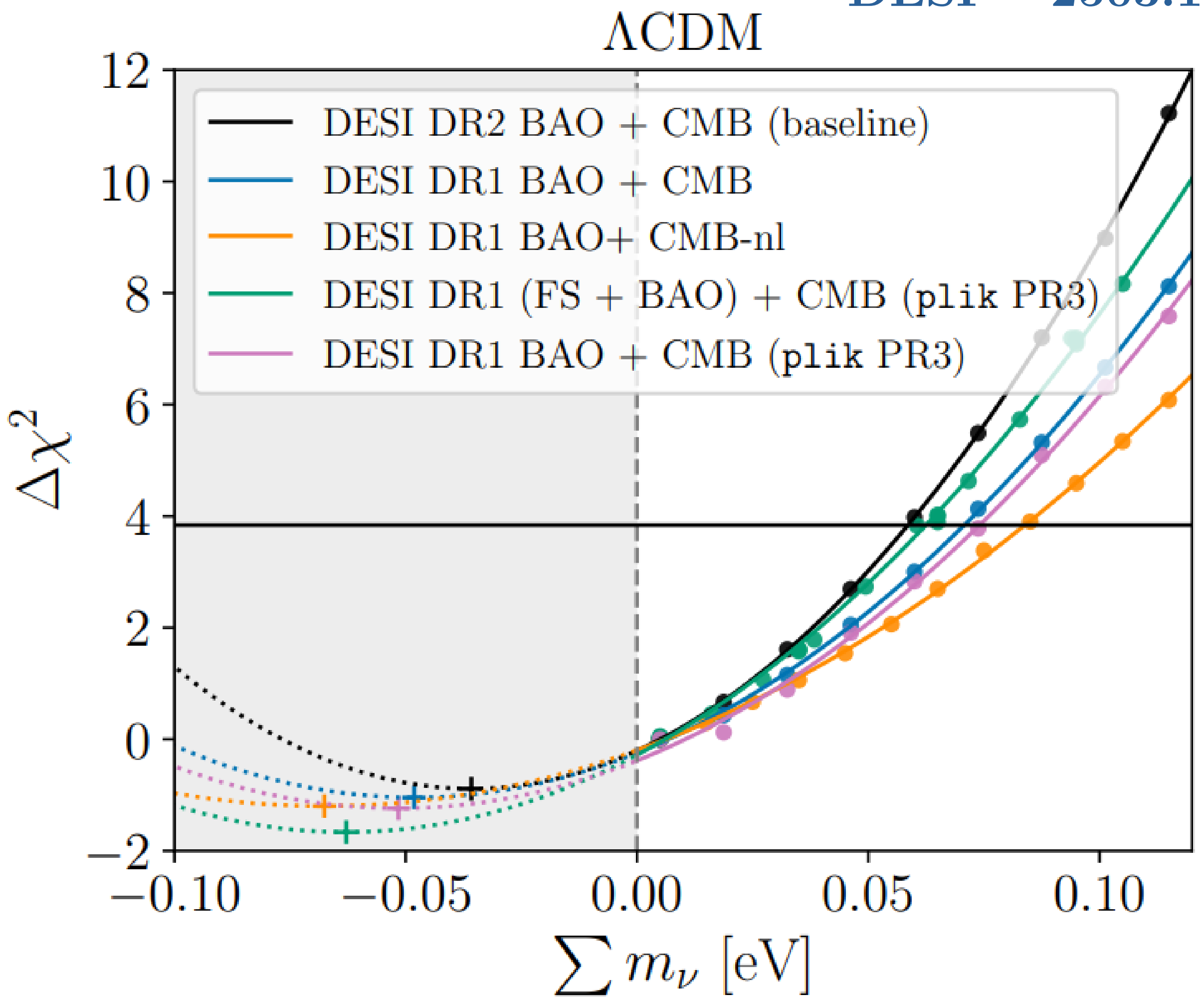
Depends on CMB likelihood

Mostly 'indirect' limit
→ Basically Ω_m prior

Constraints on neutrinos

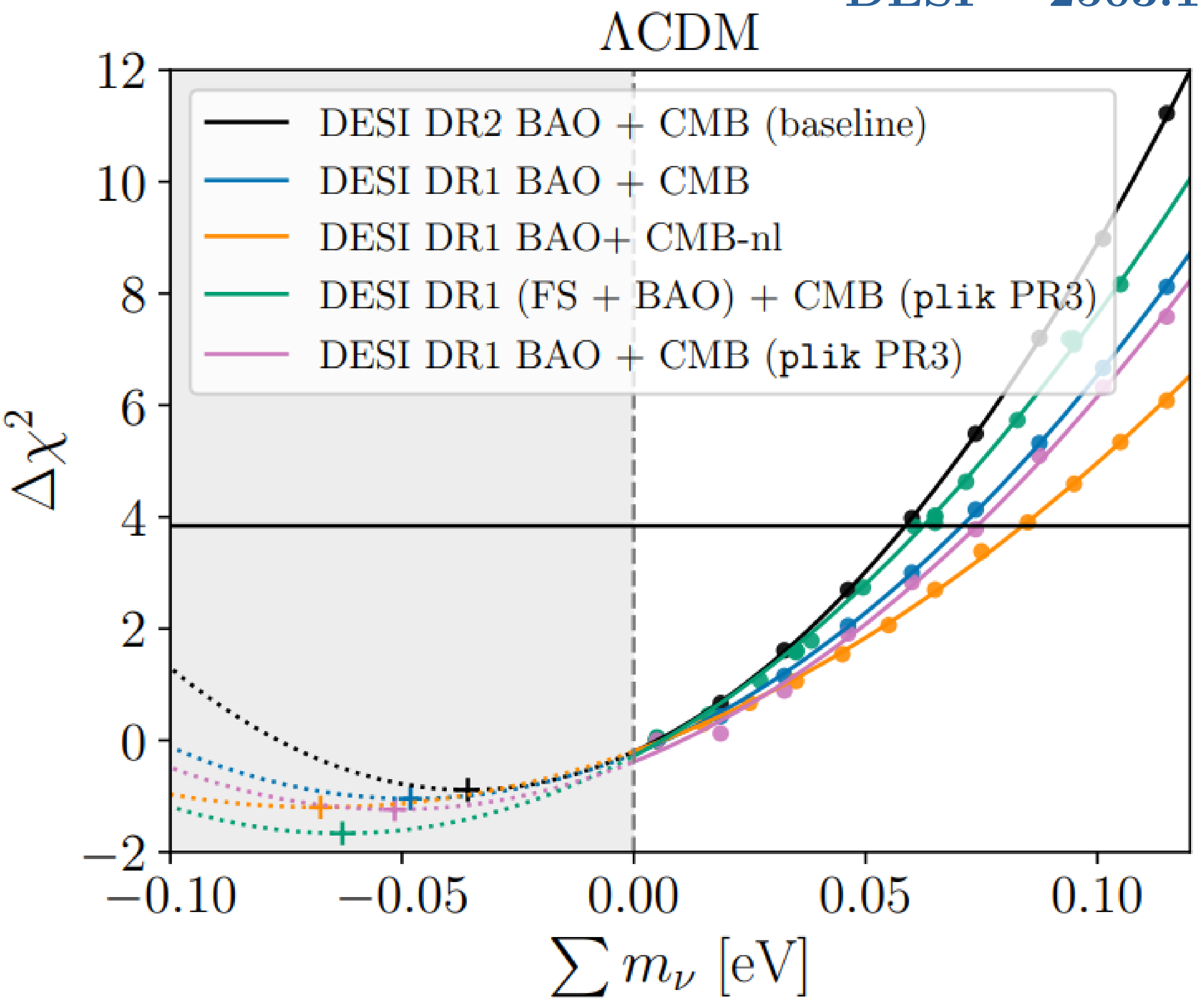
DESI -- 2503.14744



Constraints on neutrinos

DESI -- 2503.14744

- Take with grain of salt



Constraints on neutrinos

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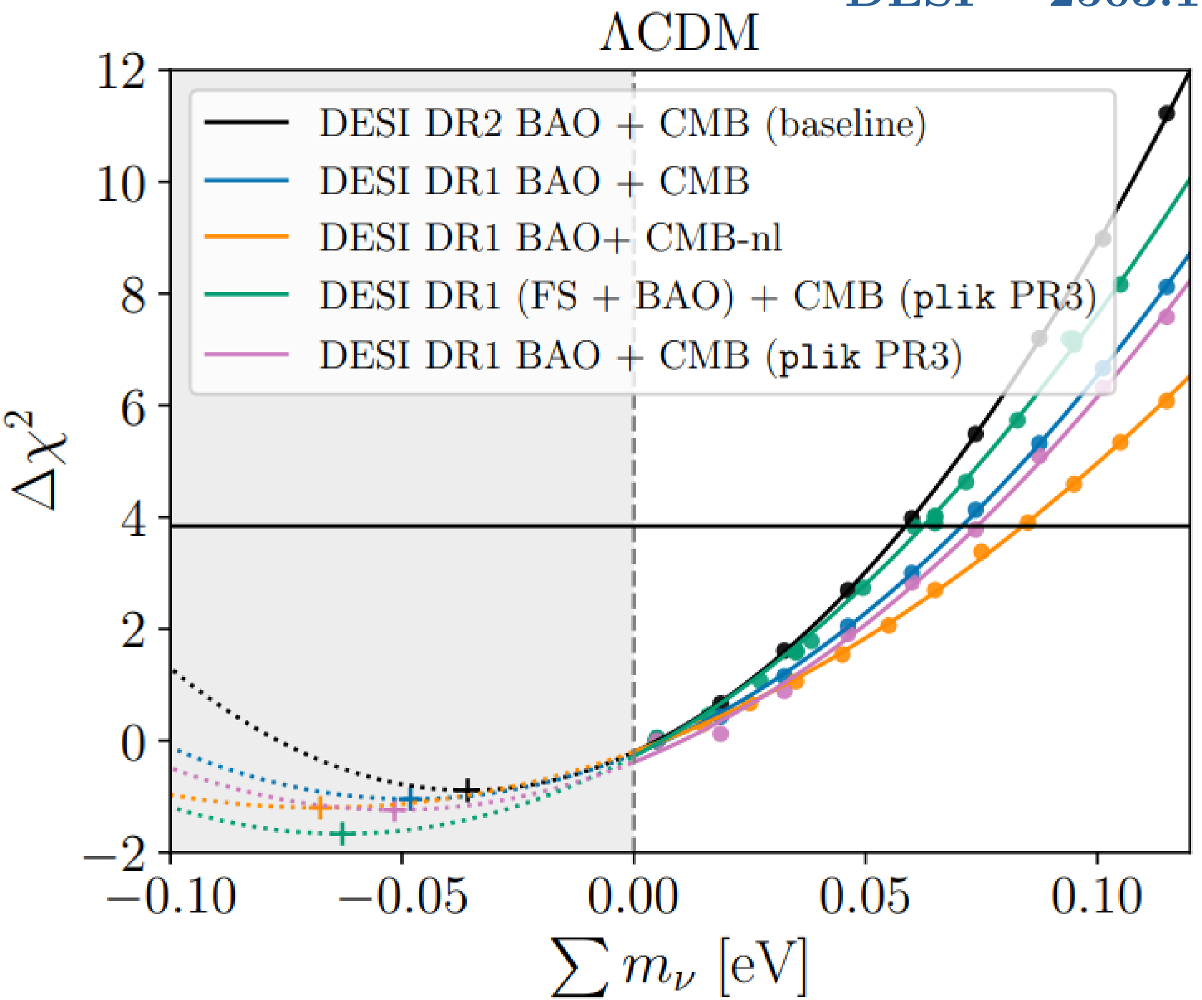

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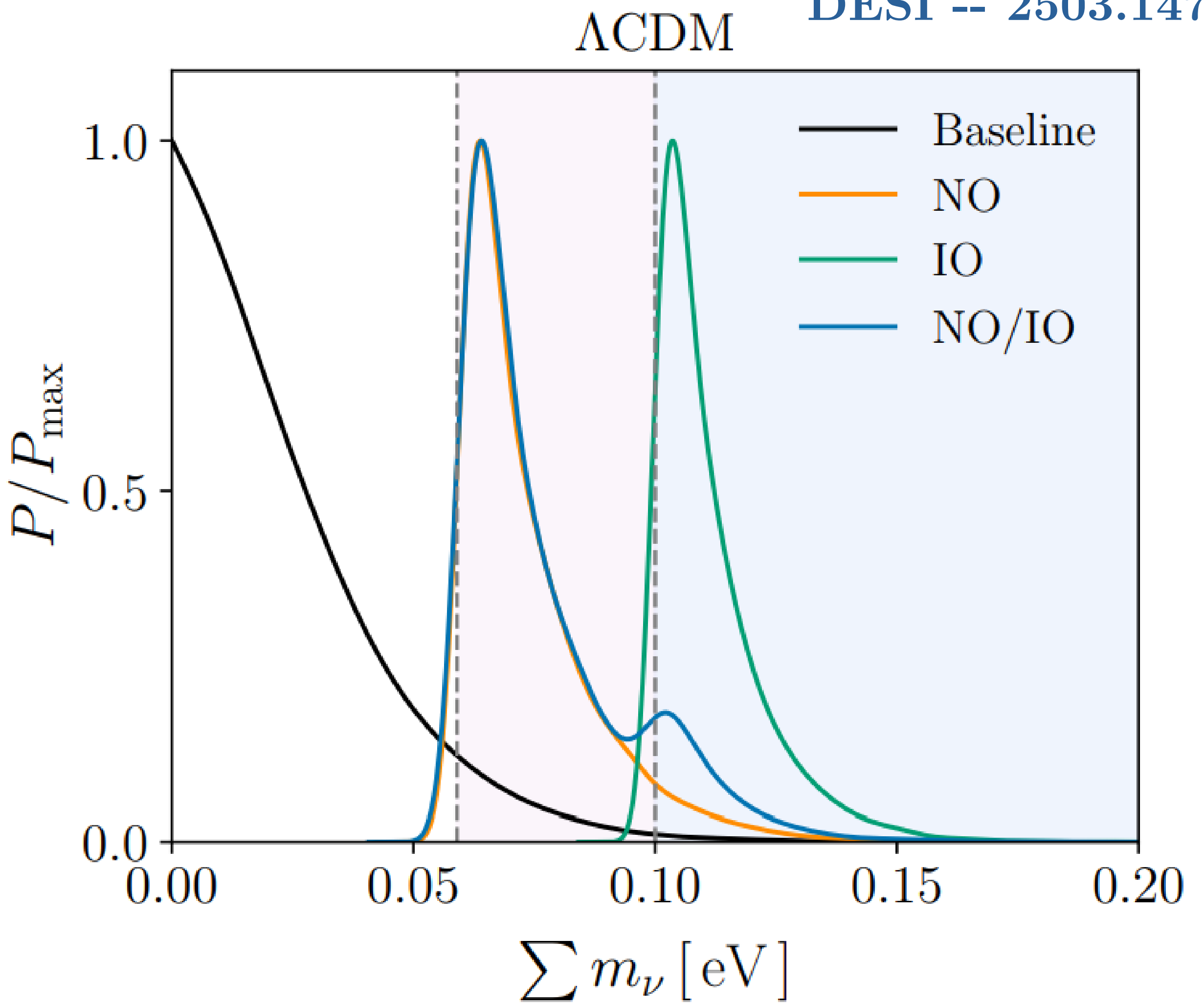

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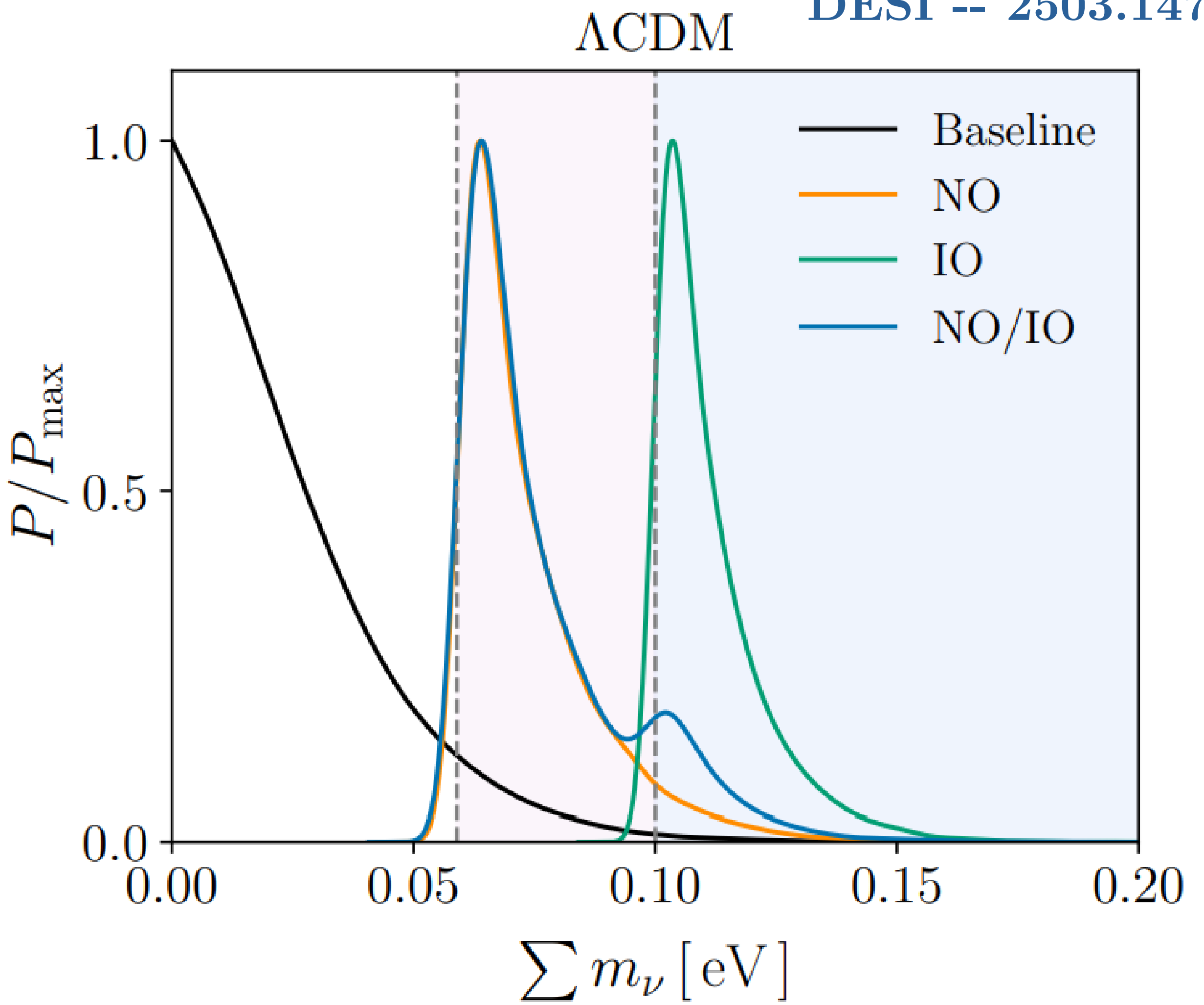
$\rightarrow$ Do model comparison (evidence or $\Delta\chi^2$)

DESI -- 2503.14744



Enhancing BAO

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  - Combining with early universe data (BAO+BBN)
  - Extracting other pieces of the galaxy power spectrum
  - Going to other late universe data
    - Weak lensing
    - Galaxy properties
    - (Transients)

Agenda

BAO

BAO+BBN

ShapeFit

Lyman-Alpha forest

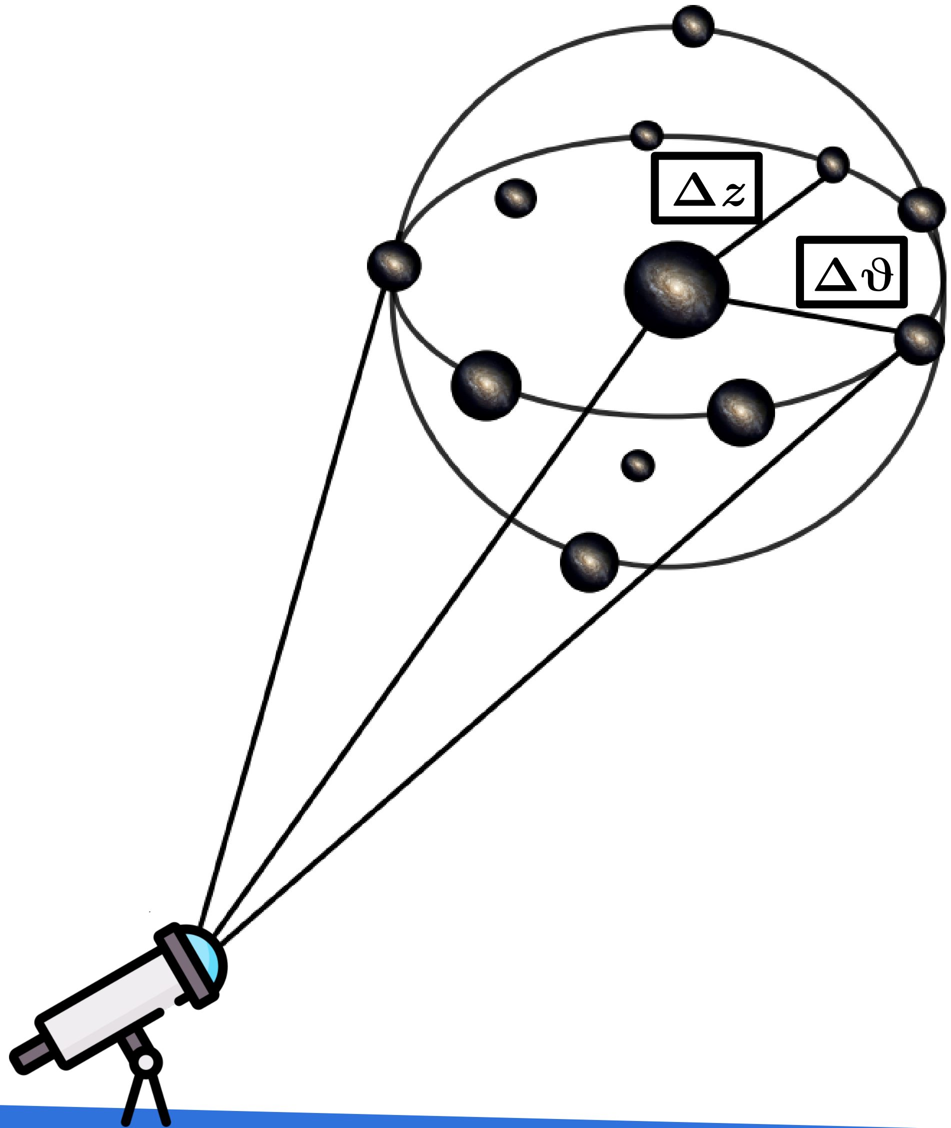
BAO + BBN

General idea:

Reminder:

$$\Delta z = H_0 r_s \cdot E(z)$$

$$\Delta\vartheta = \frac{r_s}{\int \frac{dz}{H(z)}} = \frac{H_0 r_s}{\int \frac{dz}{E(z)}}$$



BAO + BBN

General idea:

1) BAO determines $\Omega_{\rm m}$ and $H_0\ r_{\rm s}$

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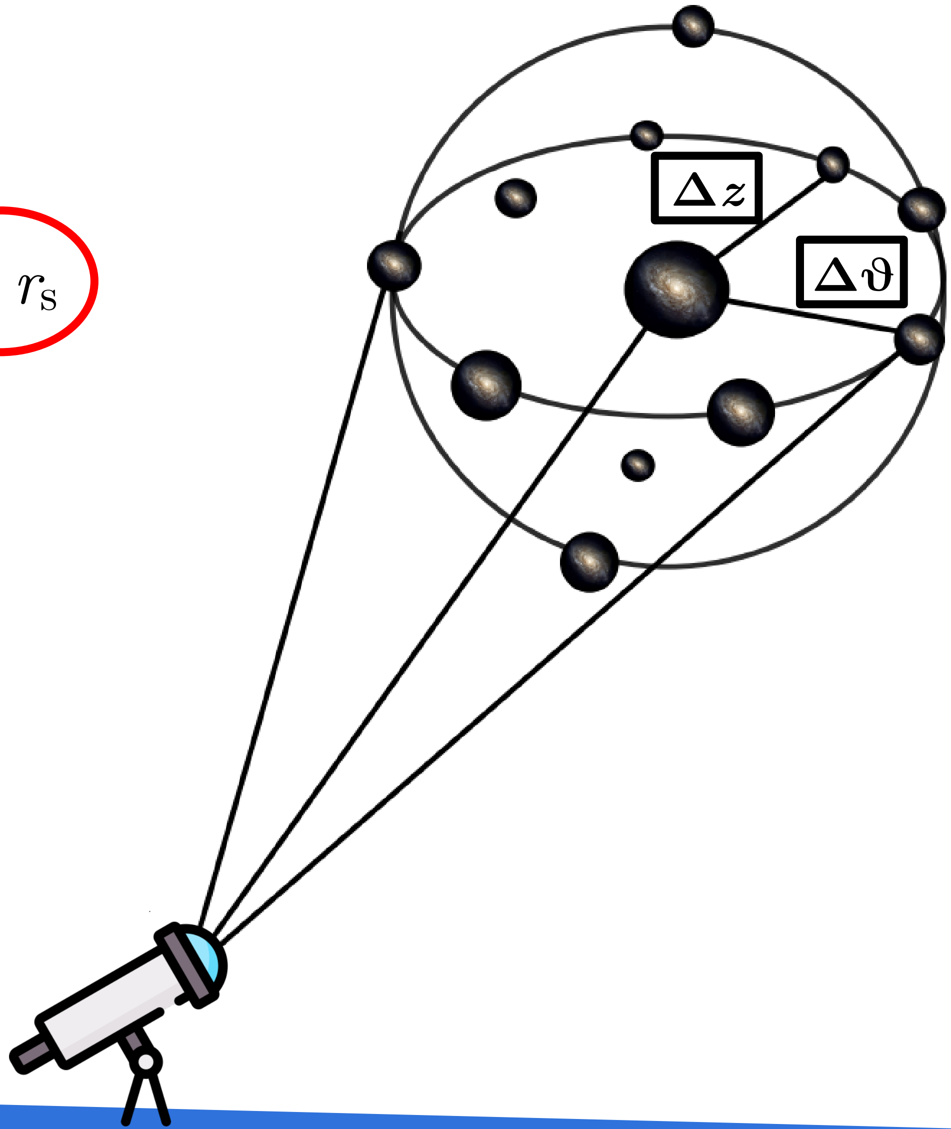

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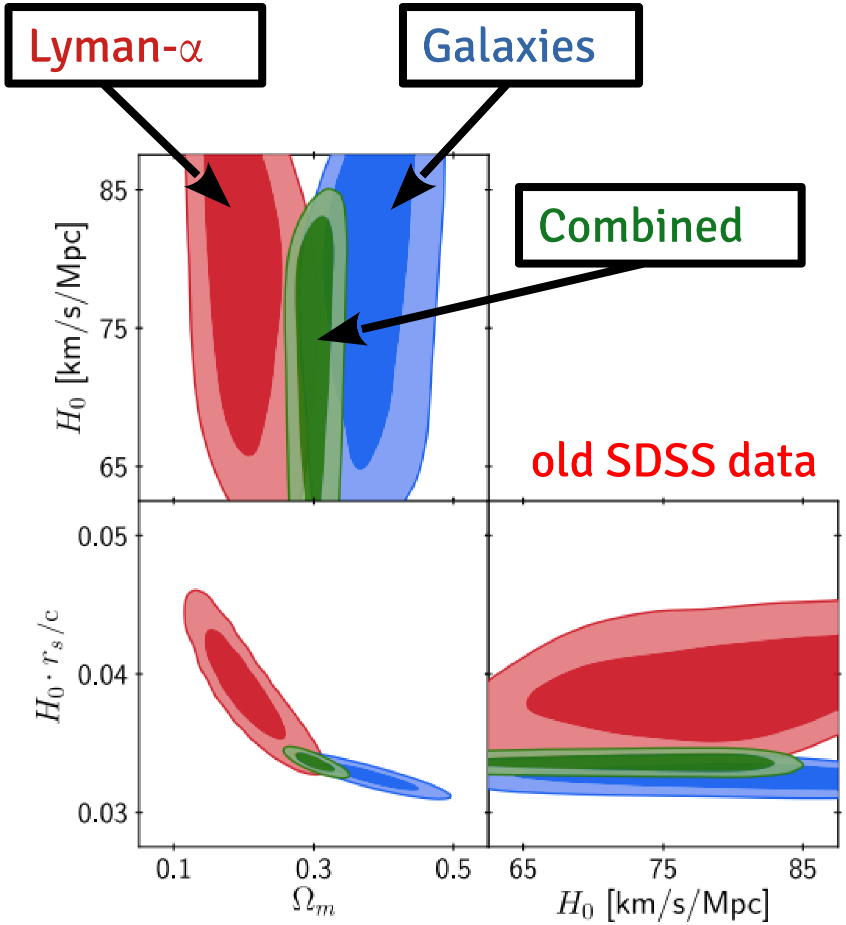

arXiv:1907.11594 → JCAP 10 (2019) 029
Nils Schöneberg, Julien Lesgourgues, Deanna C. Hooper

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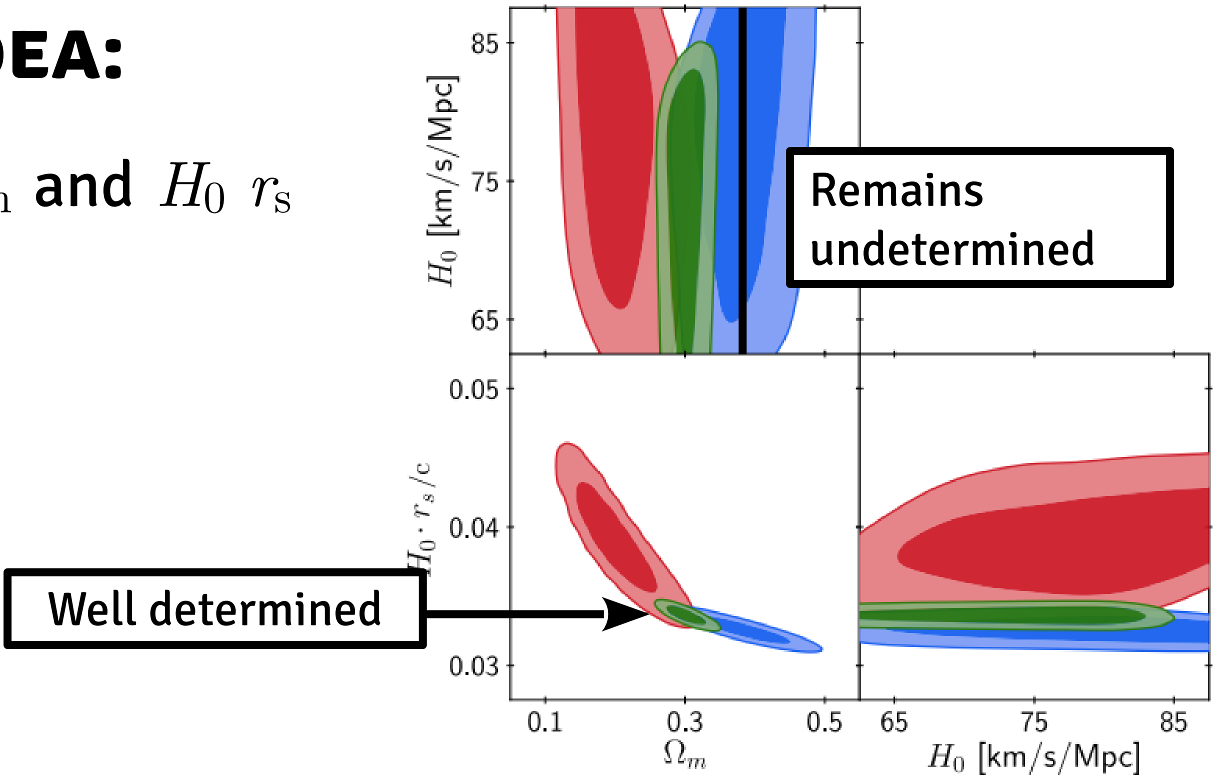

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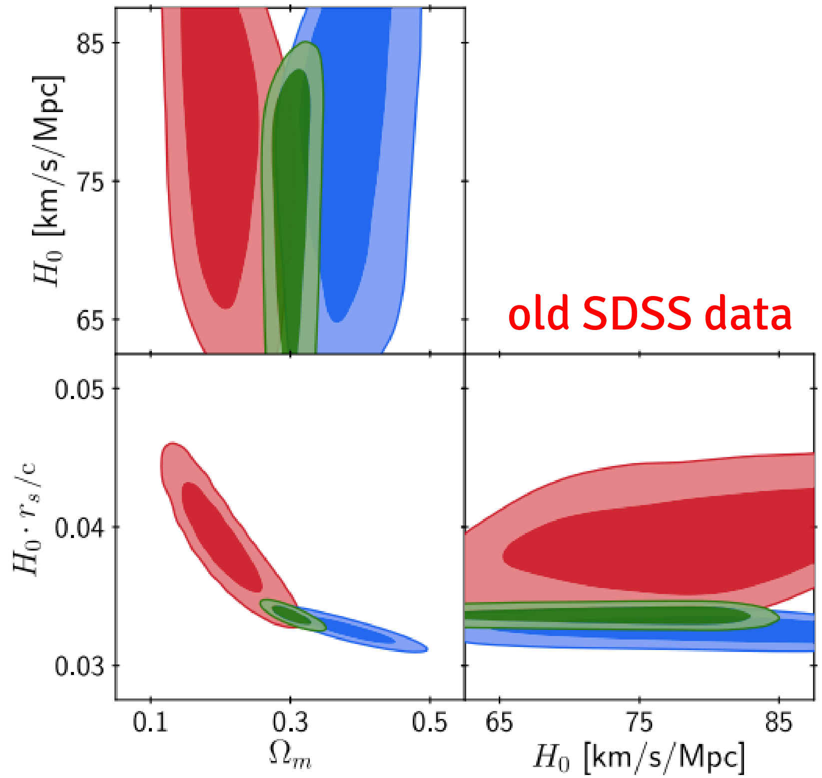
$$\boxed{\mathbf{T_0\ ,\ \Omega_b\ h^2}}$$

$$H_0 r_s = \int_{z_\mathrm{rec}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

$$\boxed{\mathbf{\Omega_m\ ,\ \Omega_r\ h^2,\ H_0}}$$



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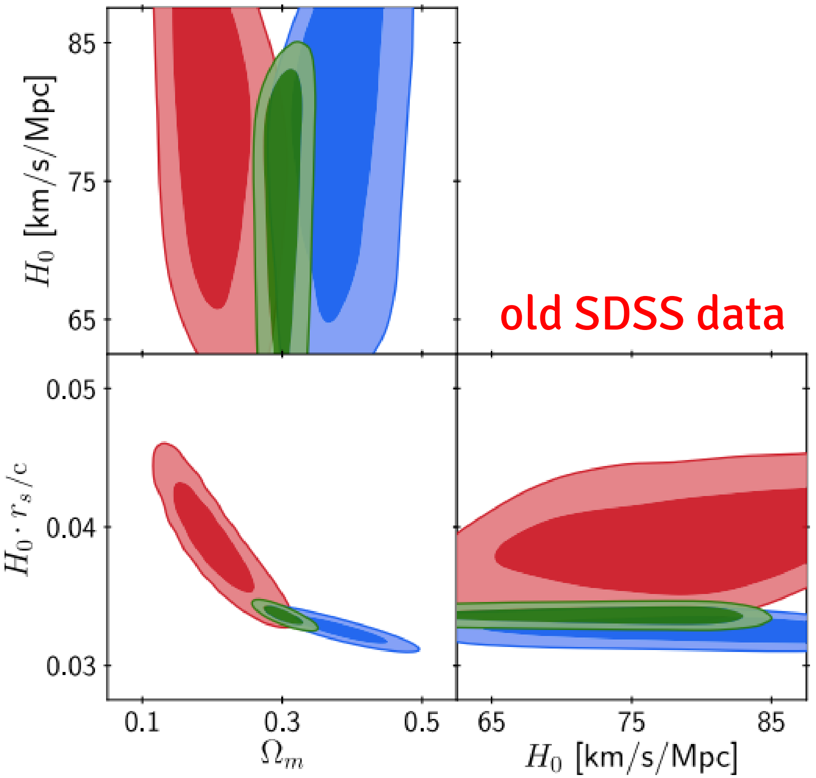

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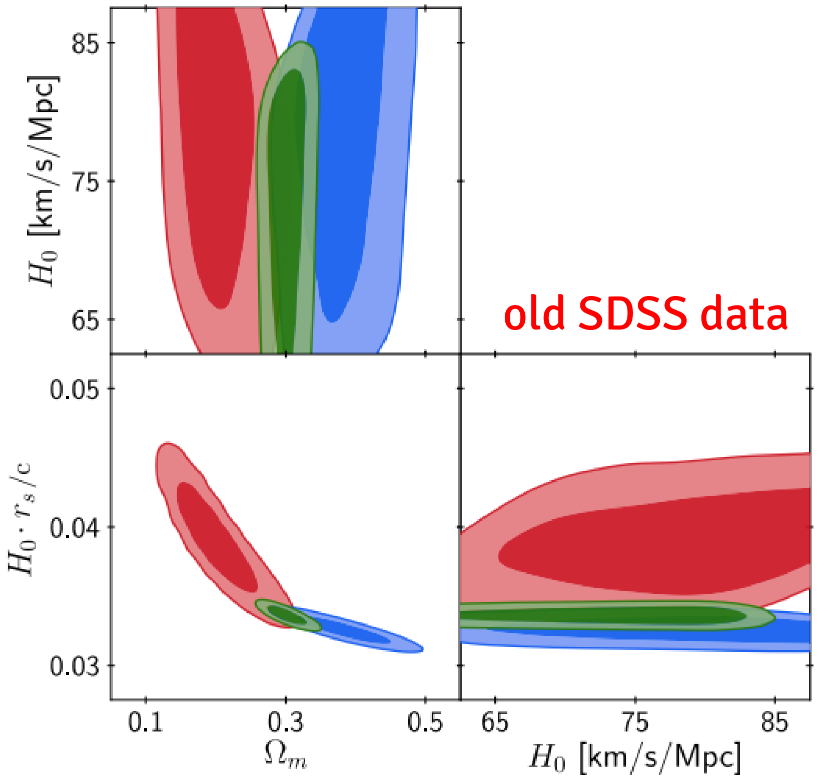

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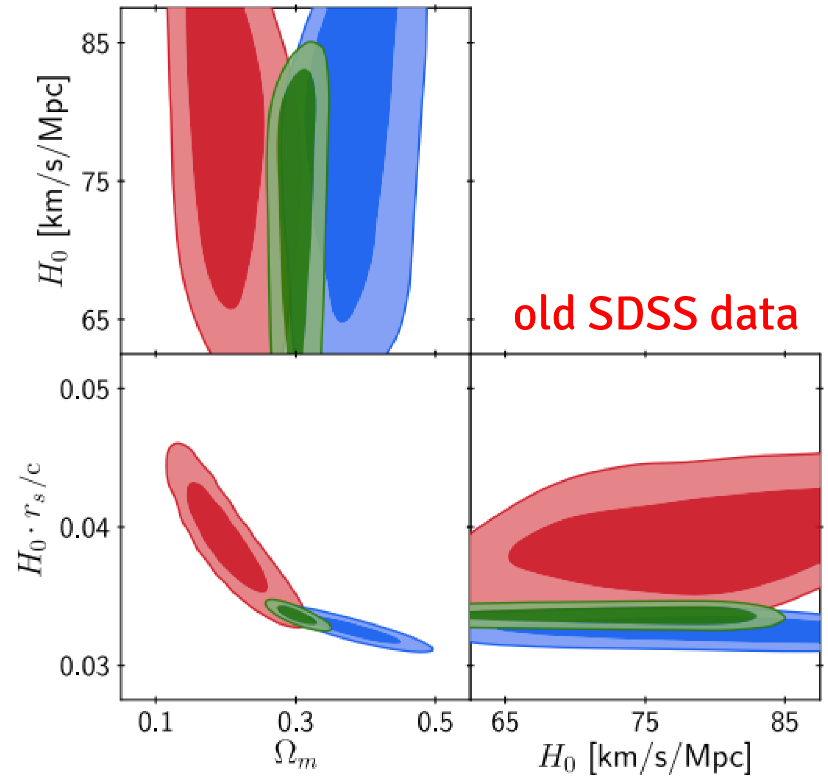

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Gruber price cosmology 2025:
Ryan Cooke, Max Pettini $\rightarrow$ D/H measurement
more baryons → earlier D fusion → hotter D burning → less final D/H leftover

$\boxed{T_0\ ,\ \Omega_\mathrm{b}\, h^2}$

$$H_0 r_s = \int_{z_\mathrm{rec}}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)/H_0}$$

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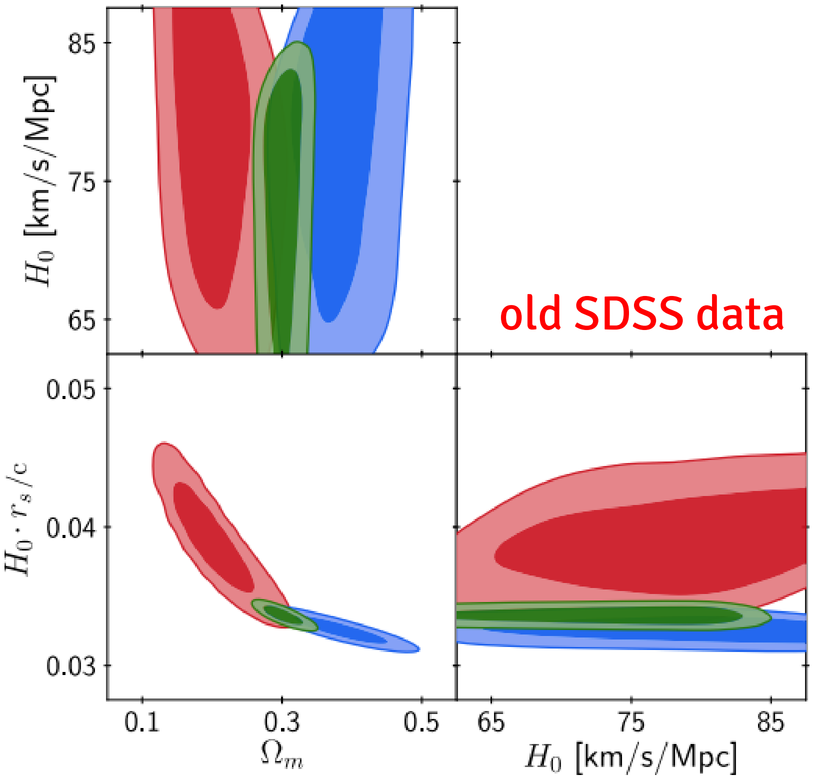

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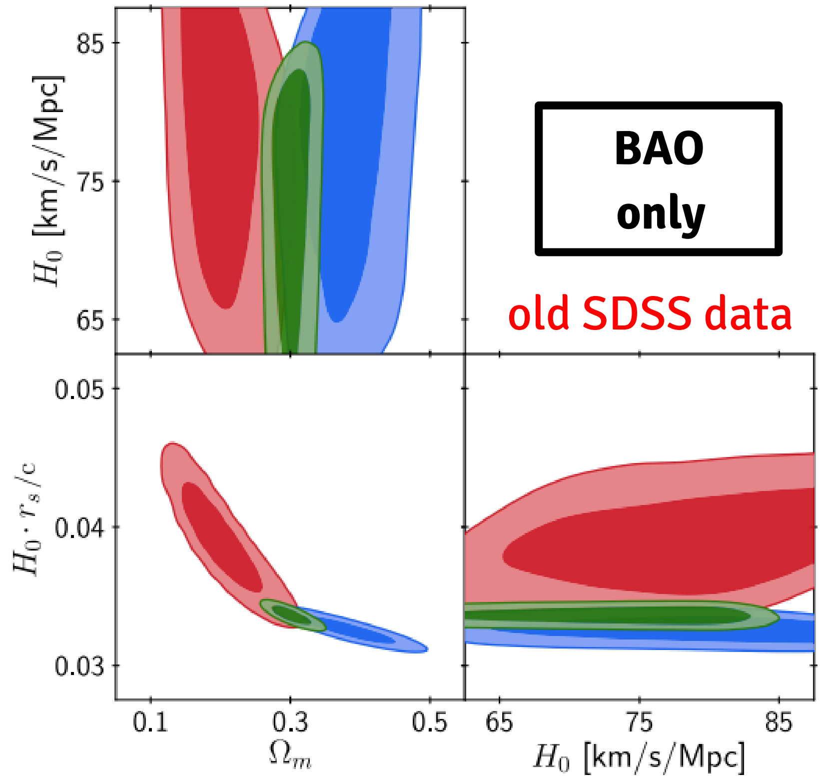

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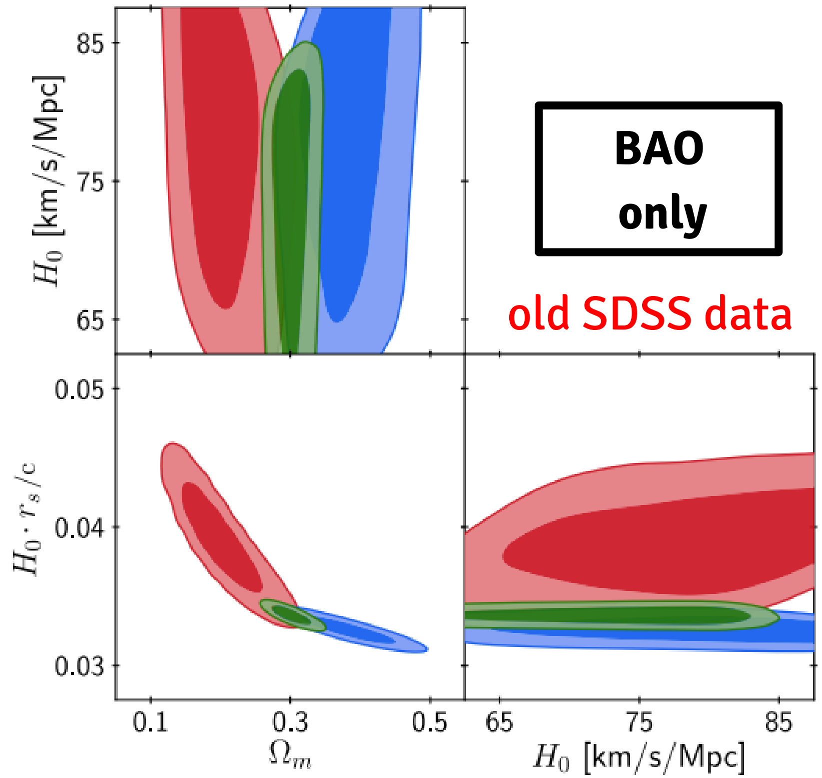

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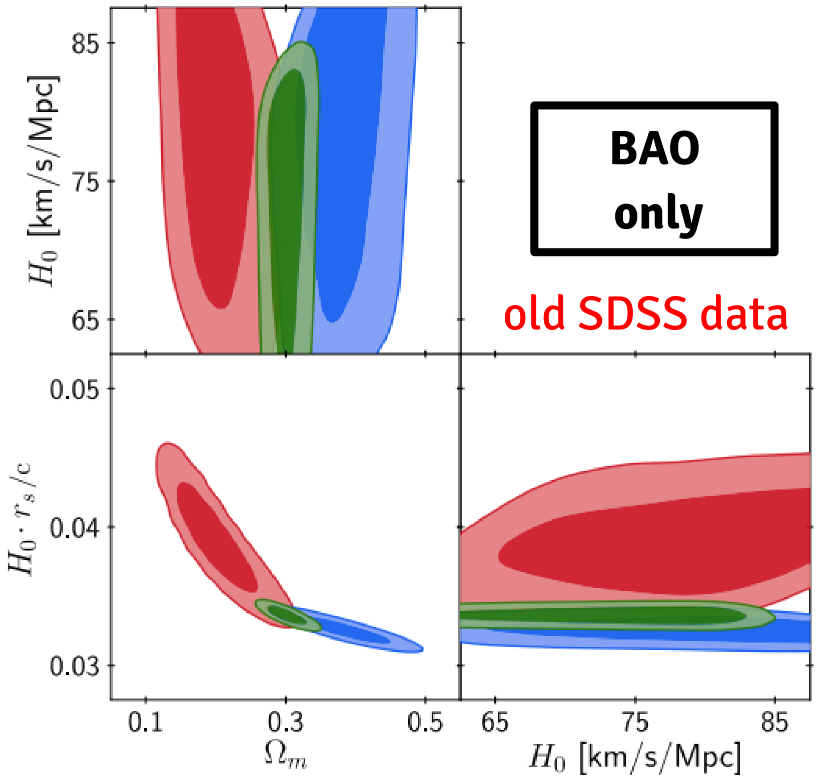

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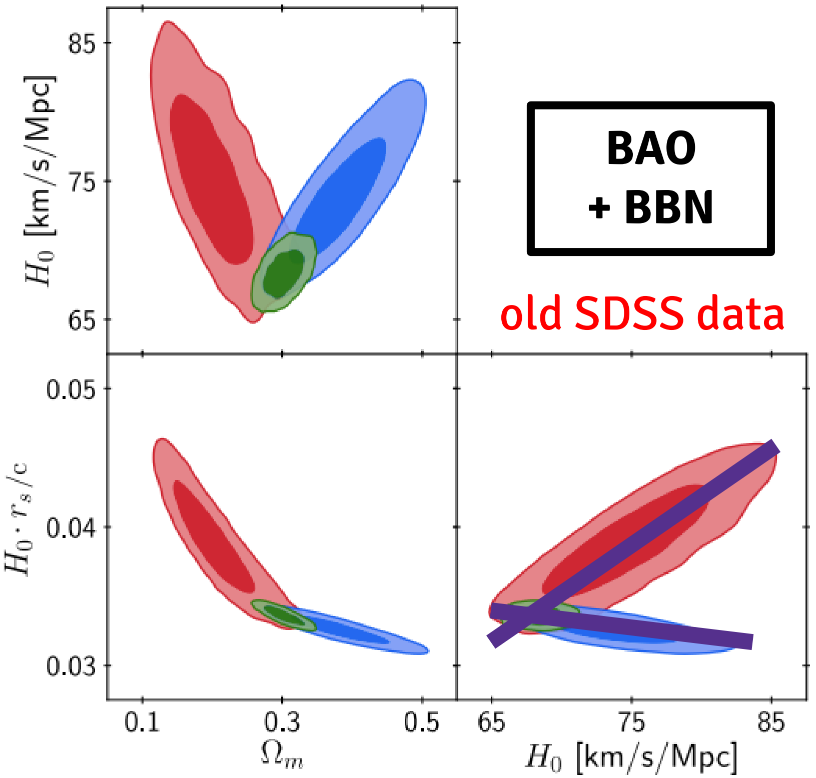

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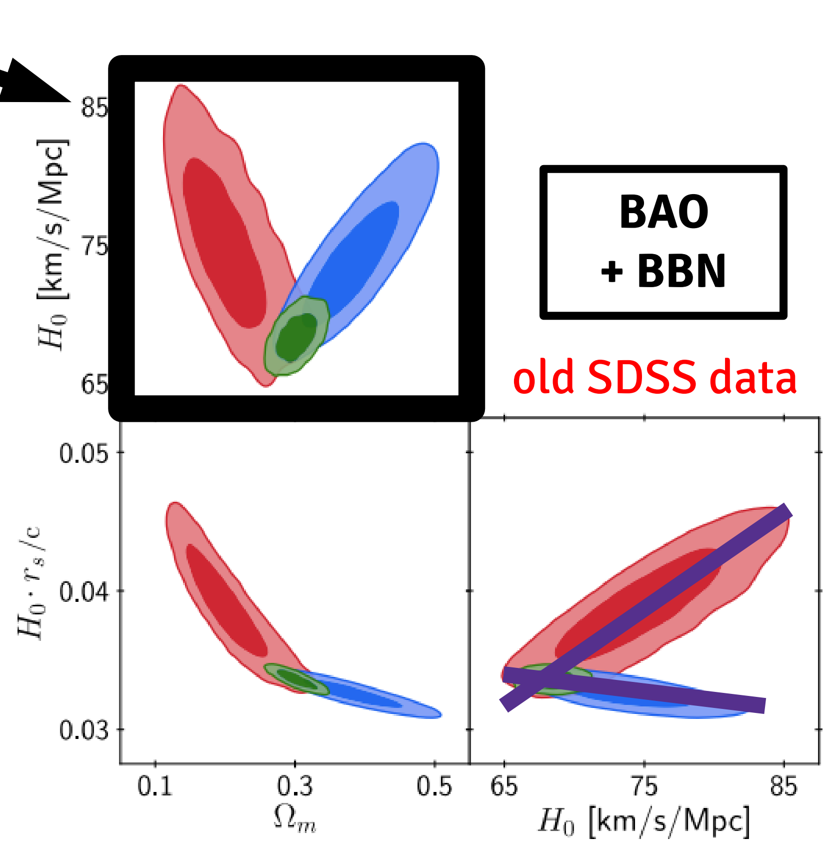

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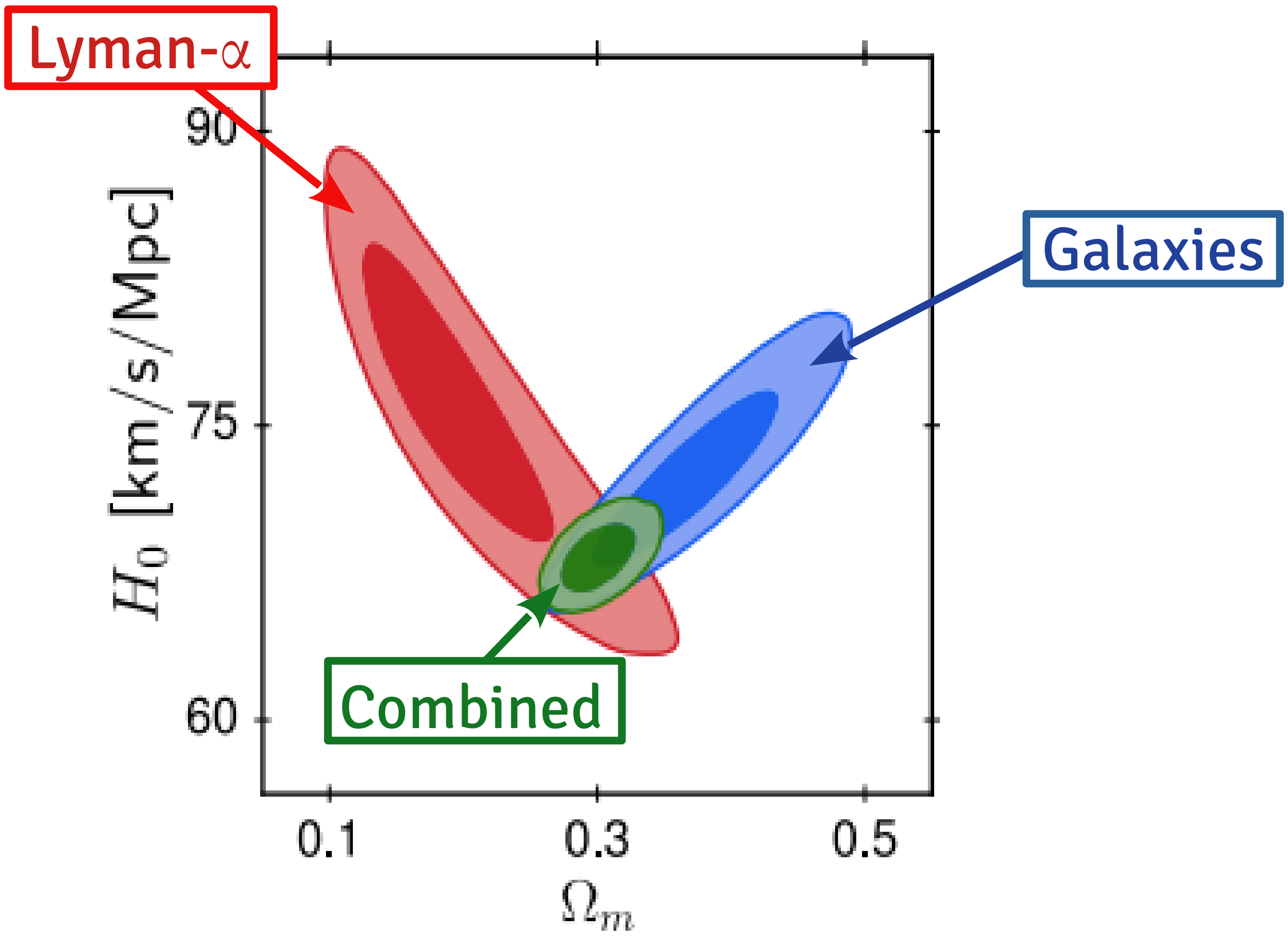

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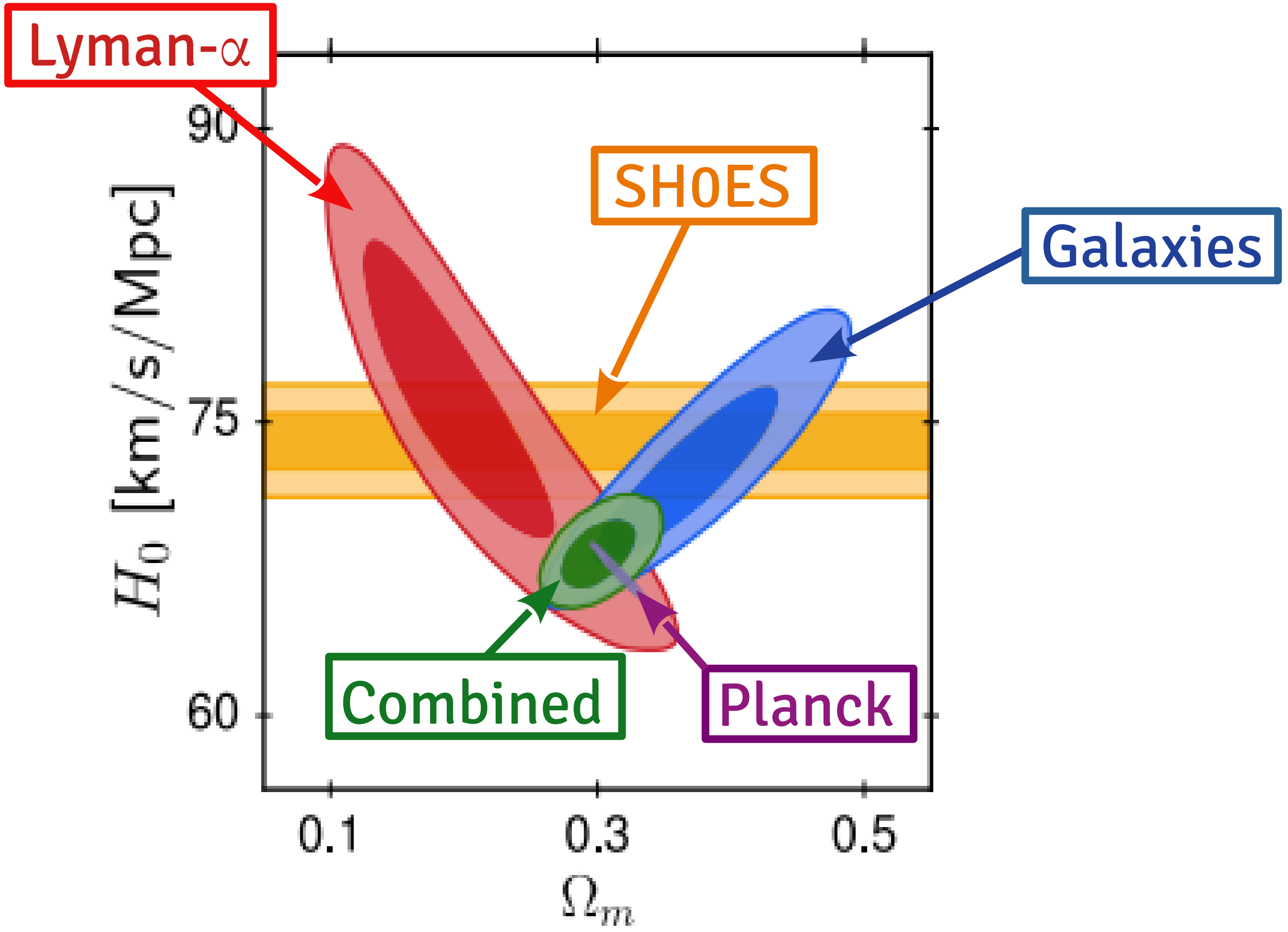

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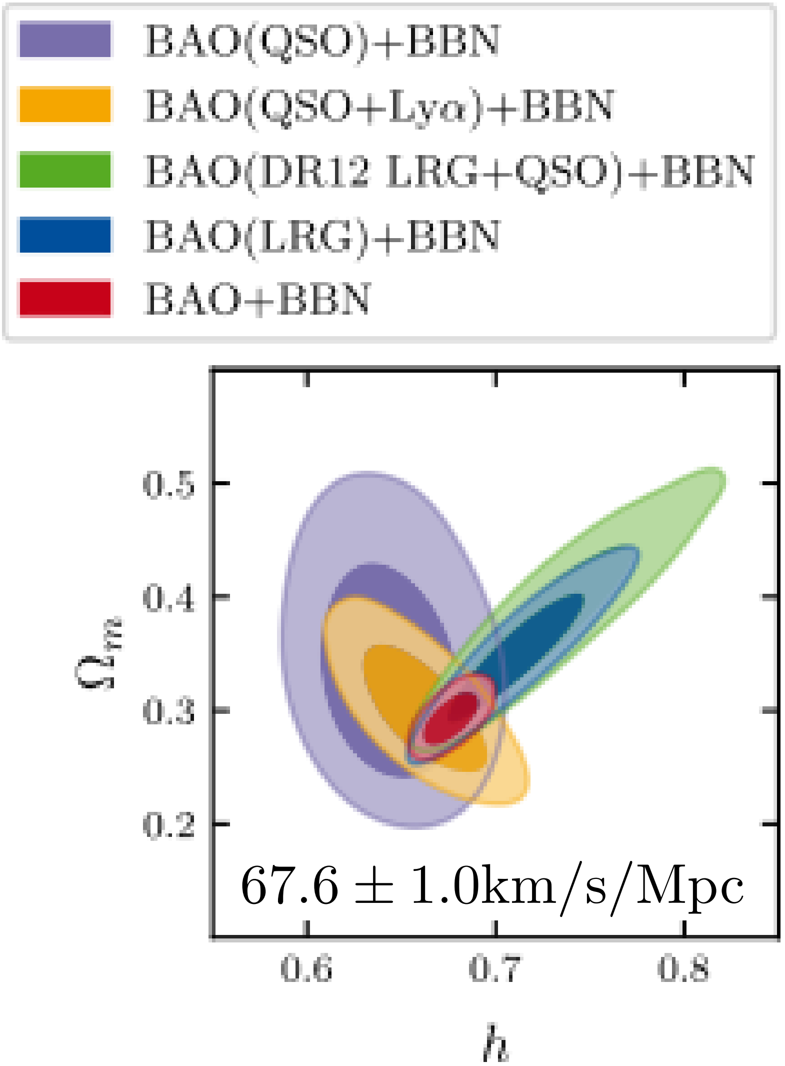
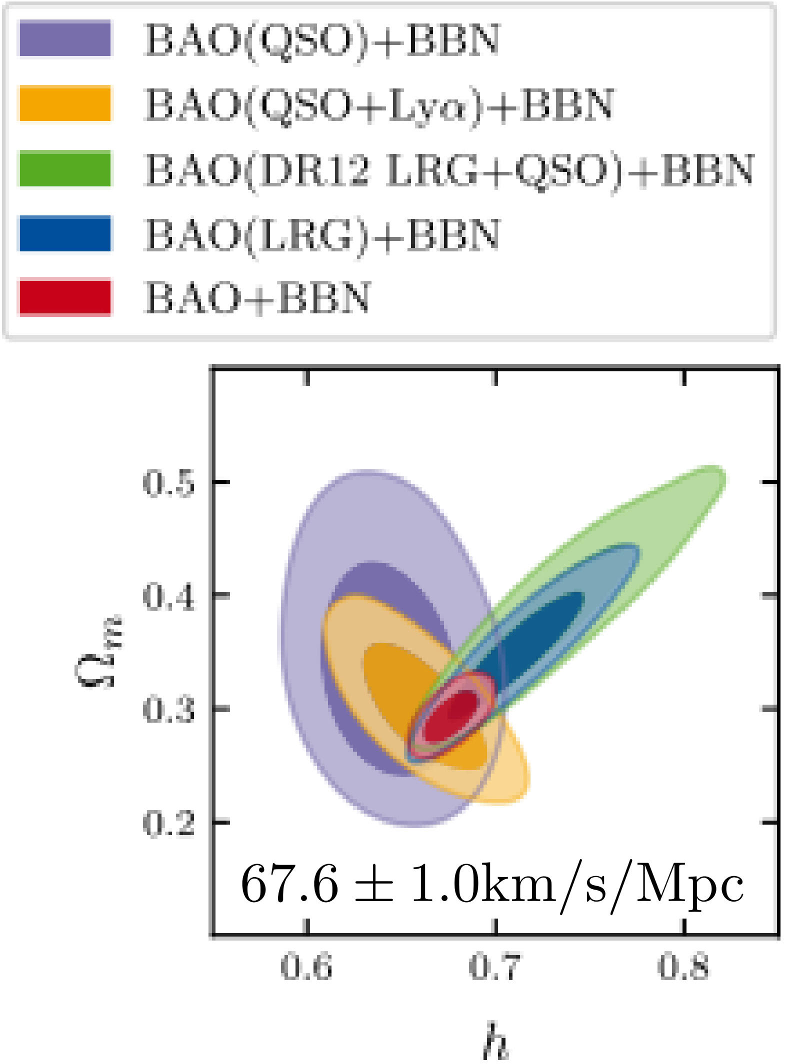
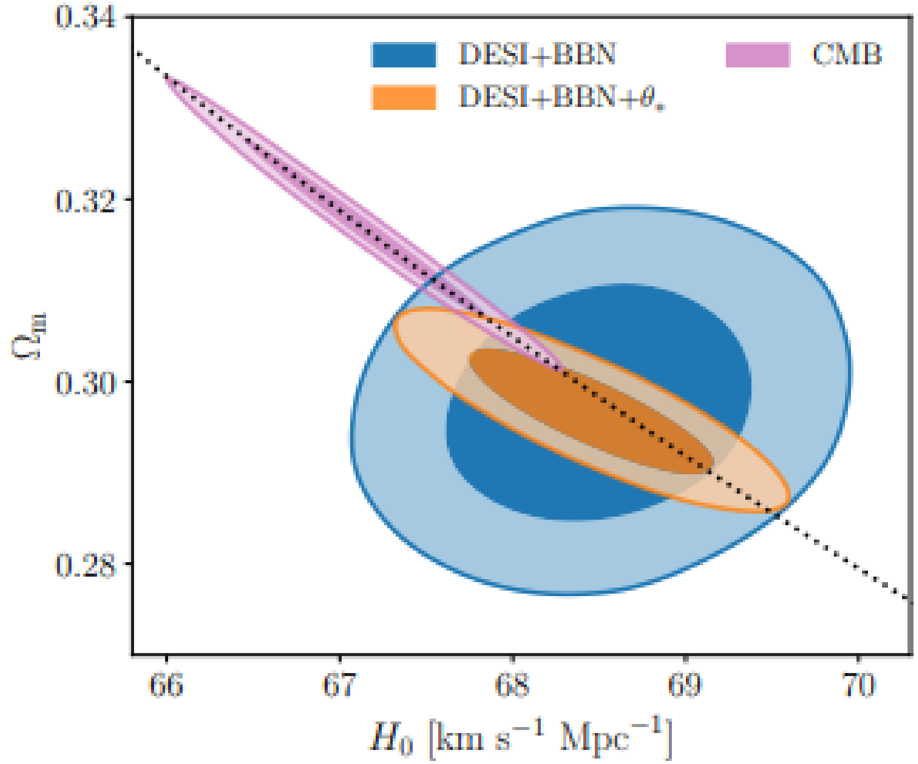


New (legacy) SDSS data

arXiv:2209.14330 → JCAP 11 (2022) 039
Nils Schöneberg, Licia Verde, Héctor Gil-Marín, Samuel Brieden



$67.6 \pm 1.0 \mathrm{km/s/Mpc}$



$68.51 \pm 0.51 \mathrm{km/s/Mpc} (3.8\sigma)$

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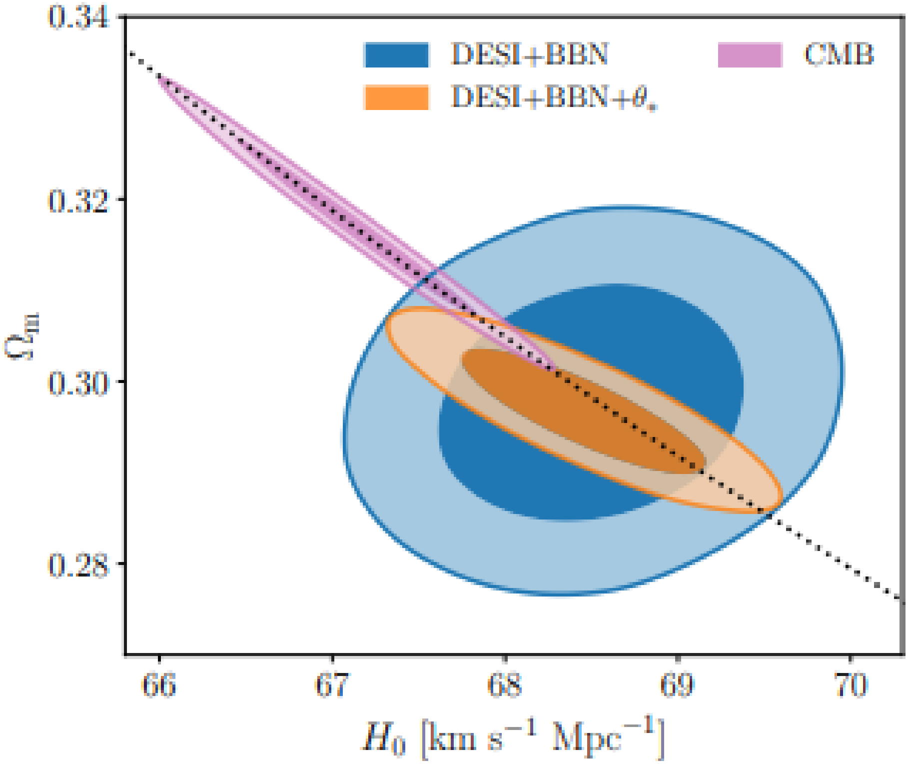

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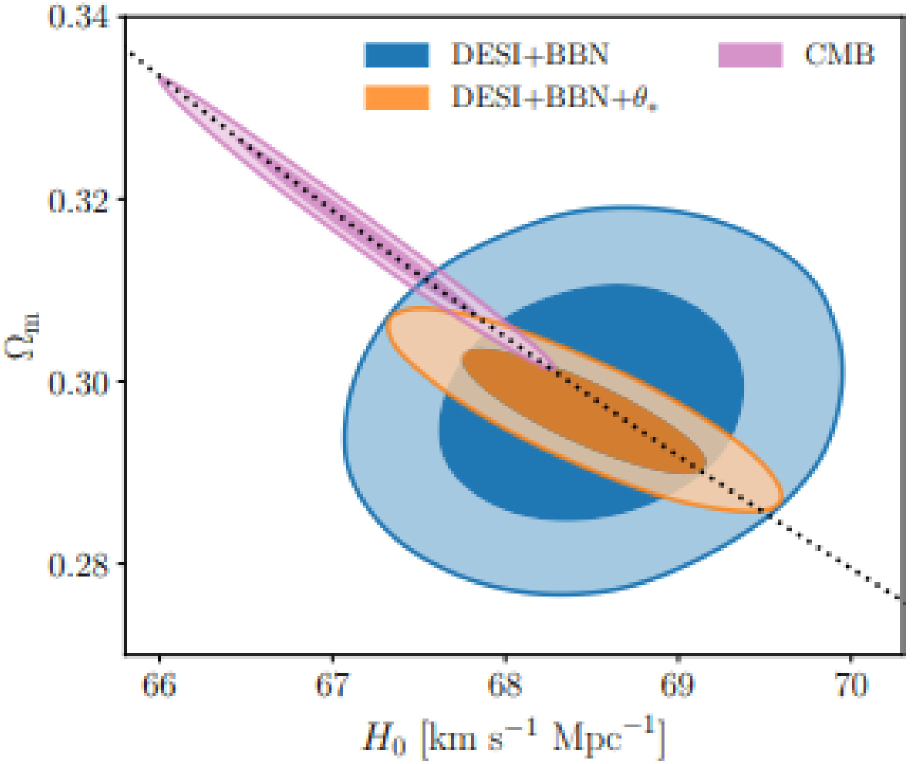
BAO is not the only information feature contained in the galaxy positions ...

→ Look for different features in the power spectrum



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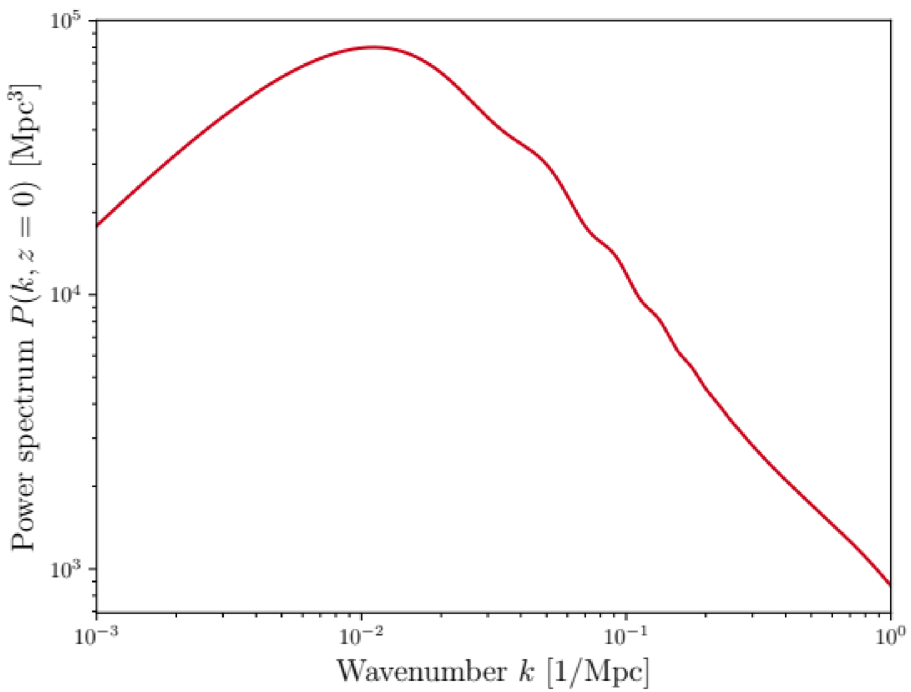

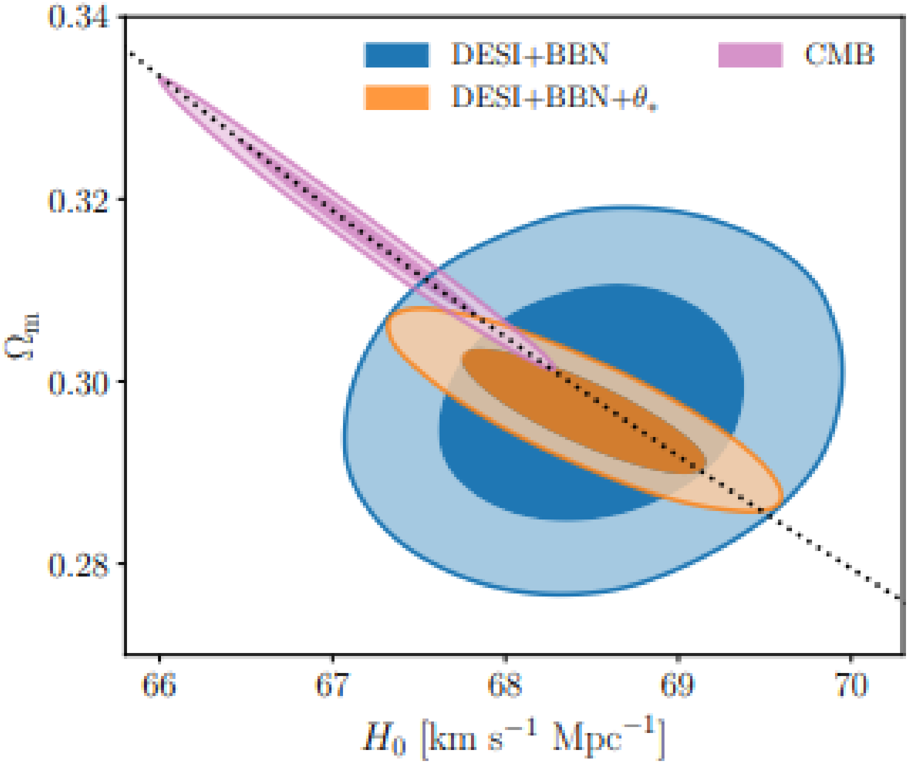

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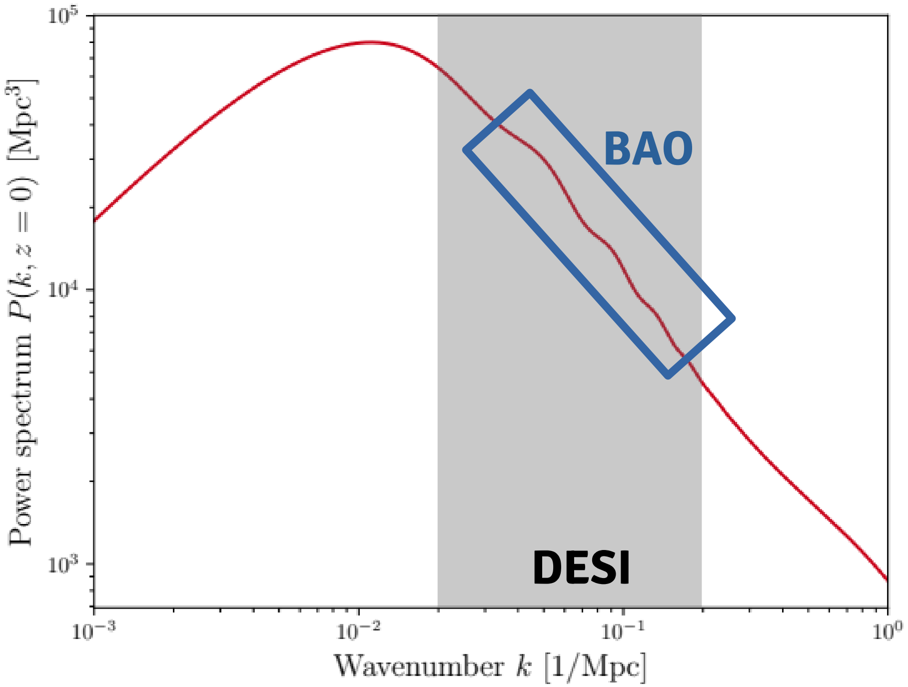

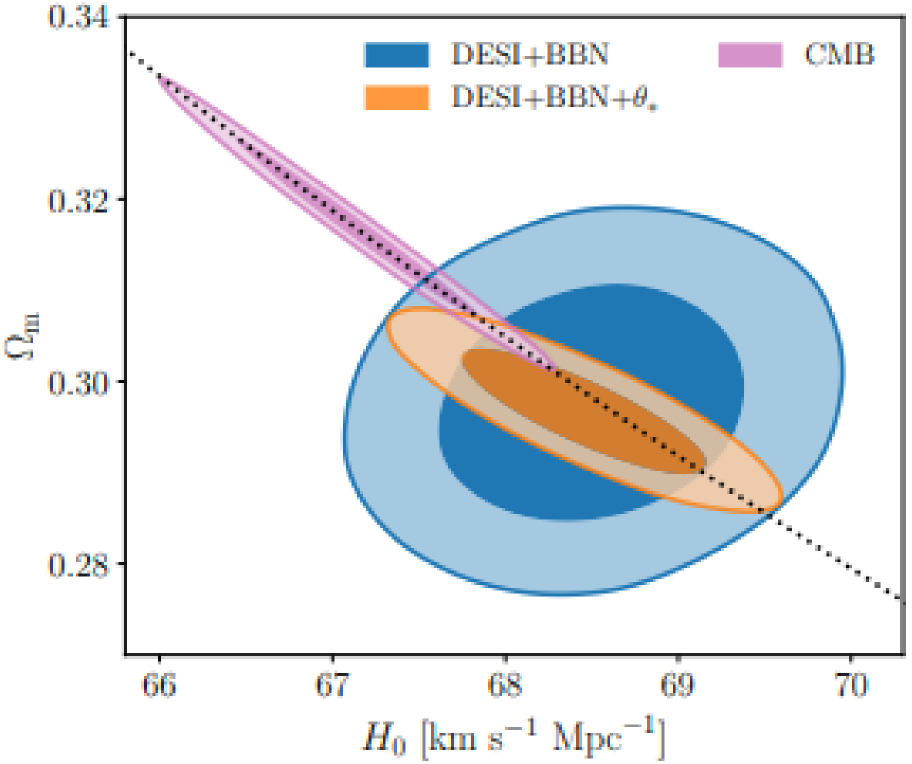

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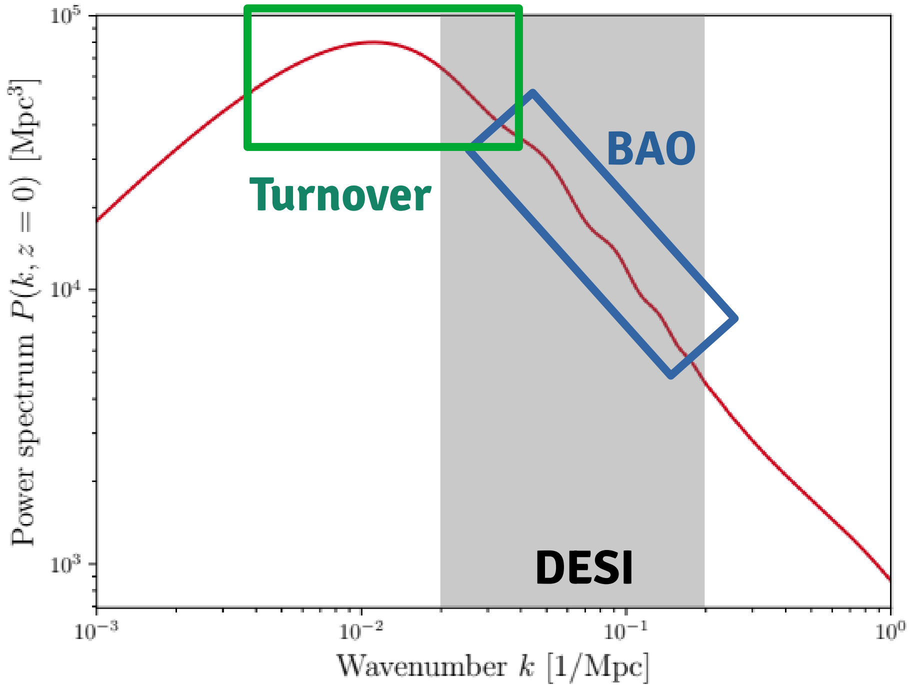

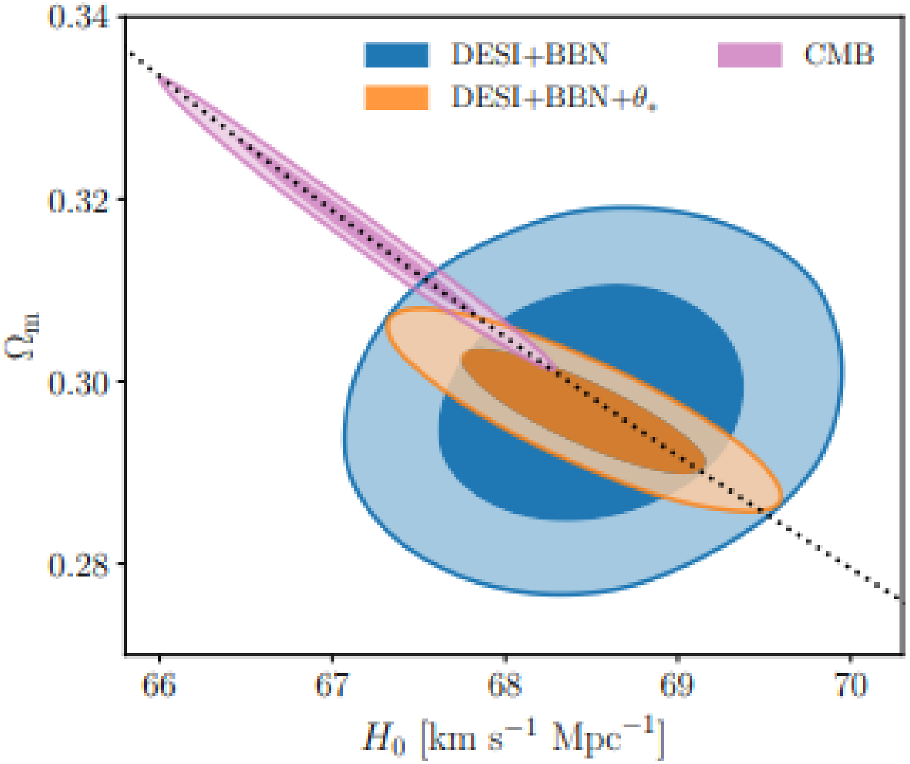

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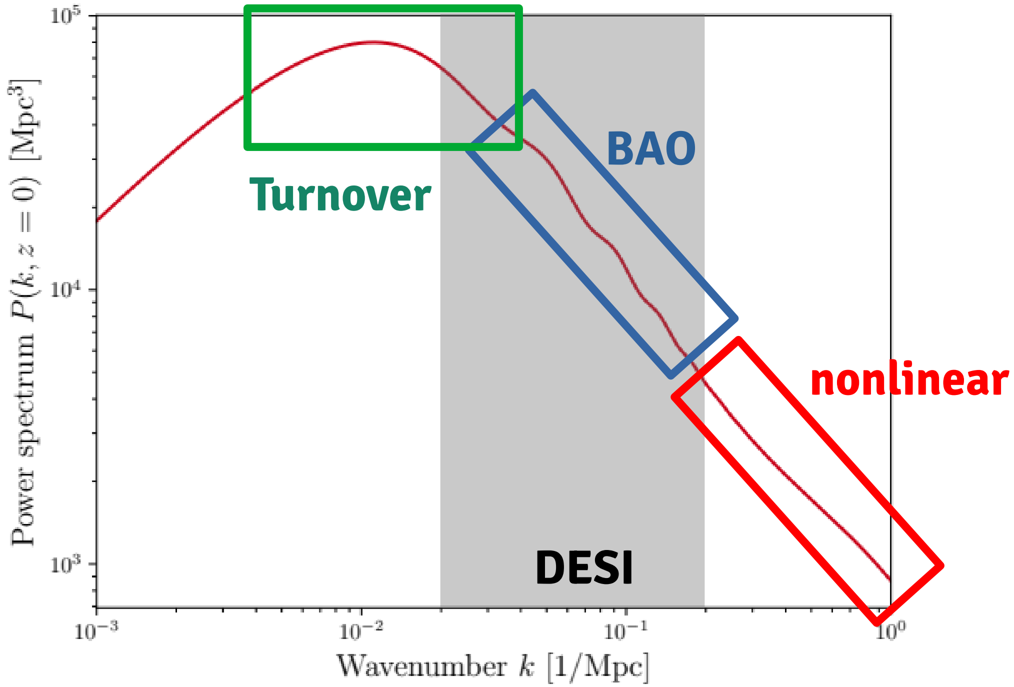

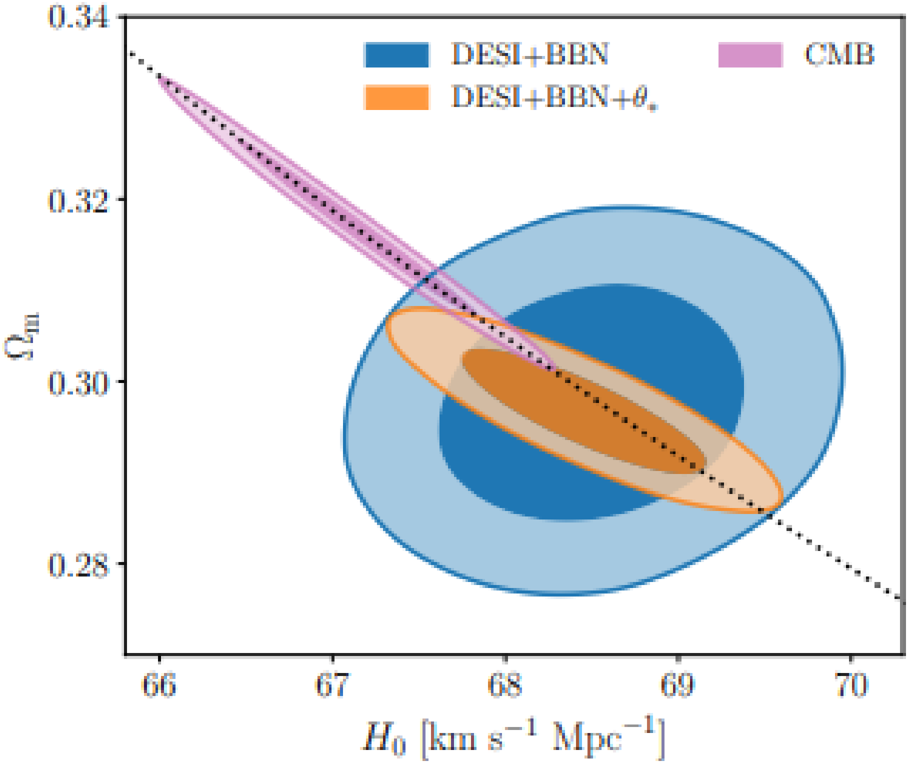

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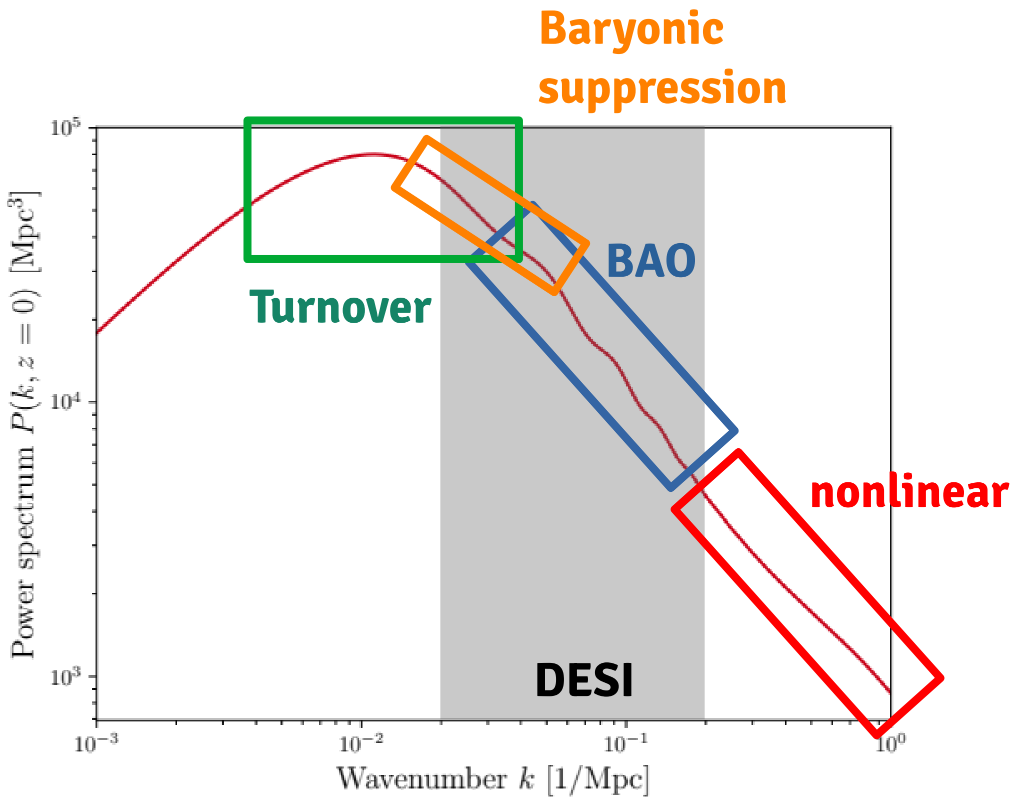
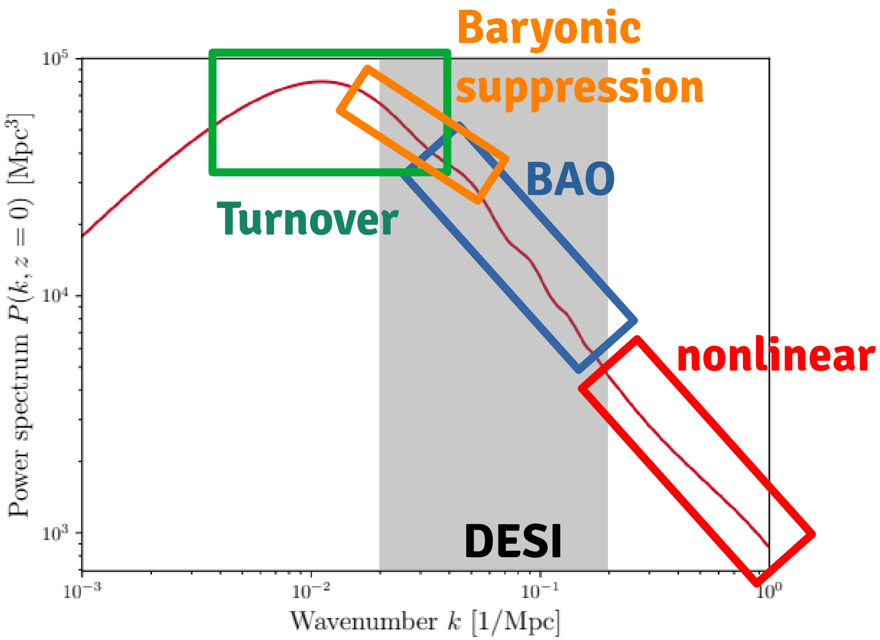
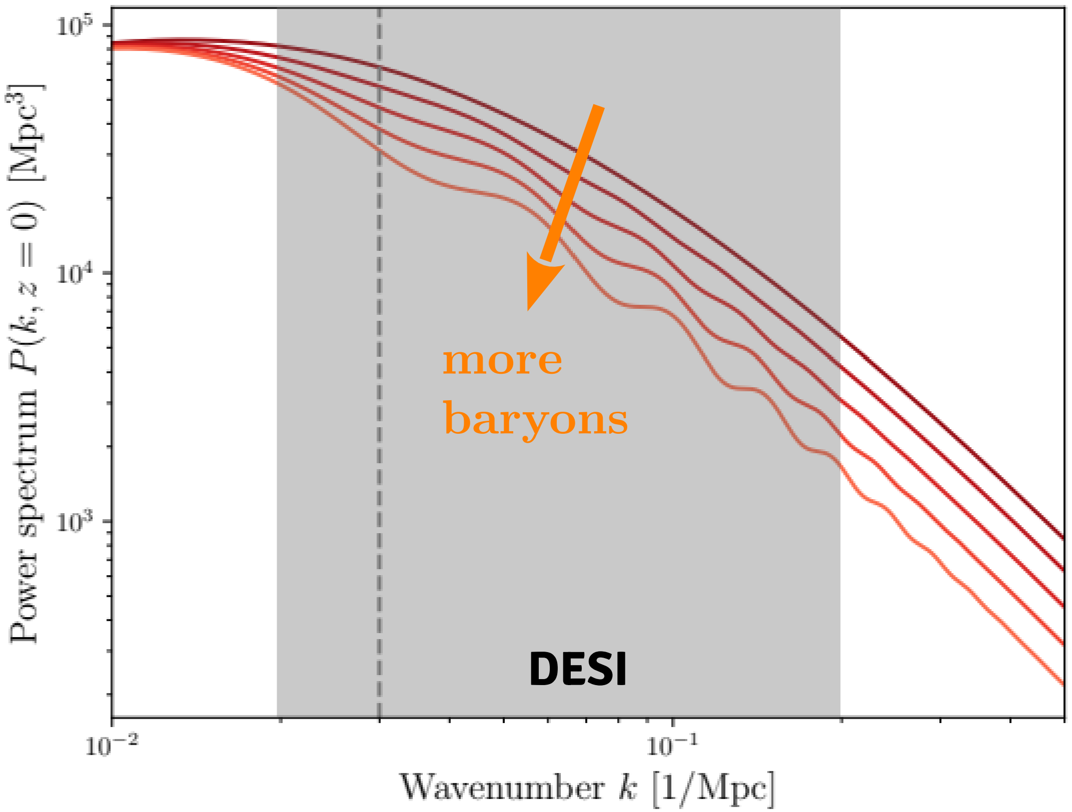
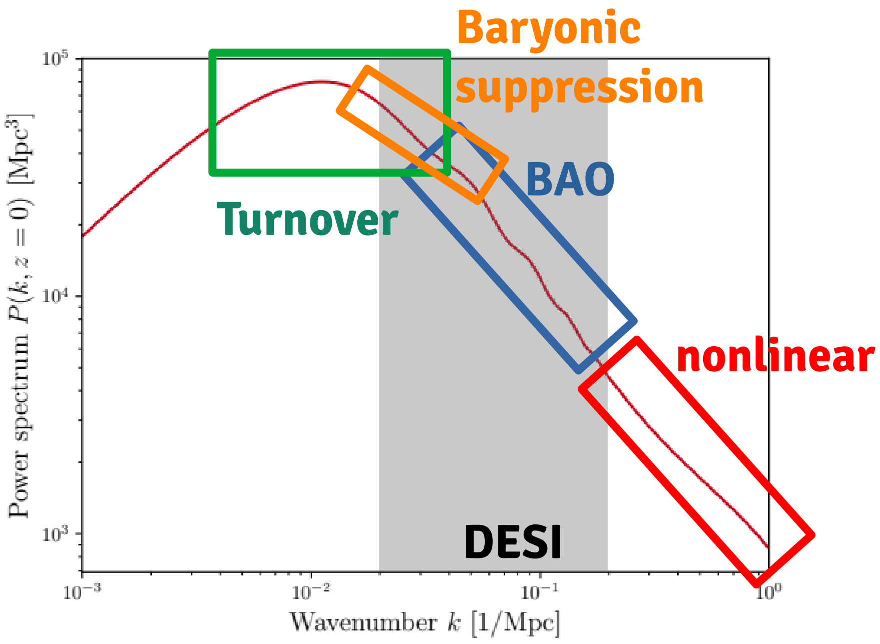


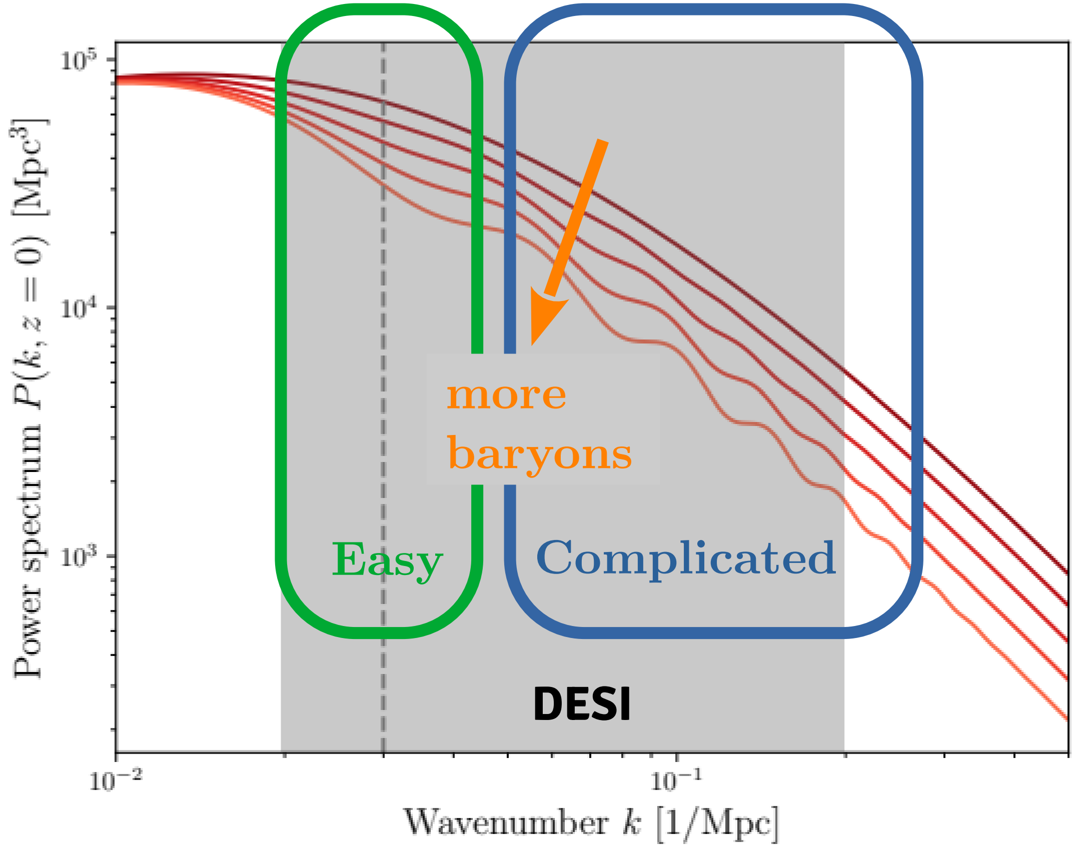

Baryonic suppression
BAO
Turnover
nonlinear
DESI
Power spectrum $P(k, z = 0)$ [Mpc^3]
Wavenumber k [1/Mpc]
10^5
10^4
10^3
10^{-3}
10^{-2}
10^{-1}
10^0

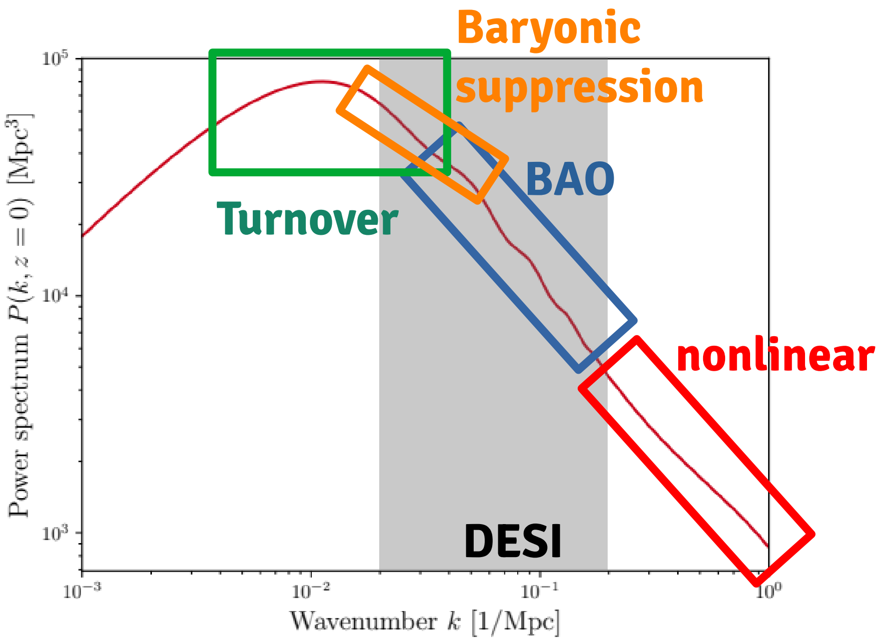

more baryons
DESI
Power spectrum $P(k, z = 0)$ [Mpc^3]
Wavenumber k [1/Mpc]
10^5
10^4
10^3
10^{-2}
10^{-1}

Nils Schöneberg

nils.science@gmail.com






Baryonic suppression
BAO
Turnover
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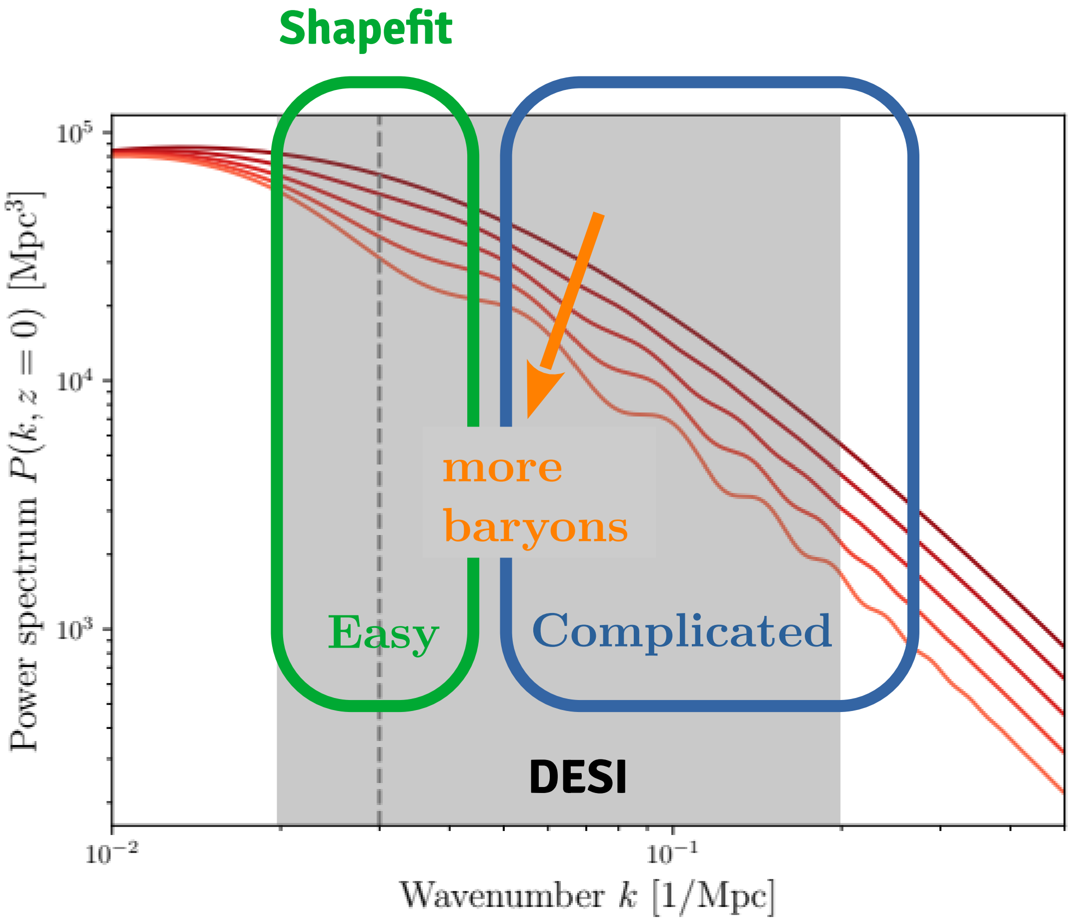
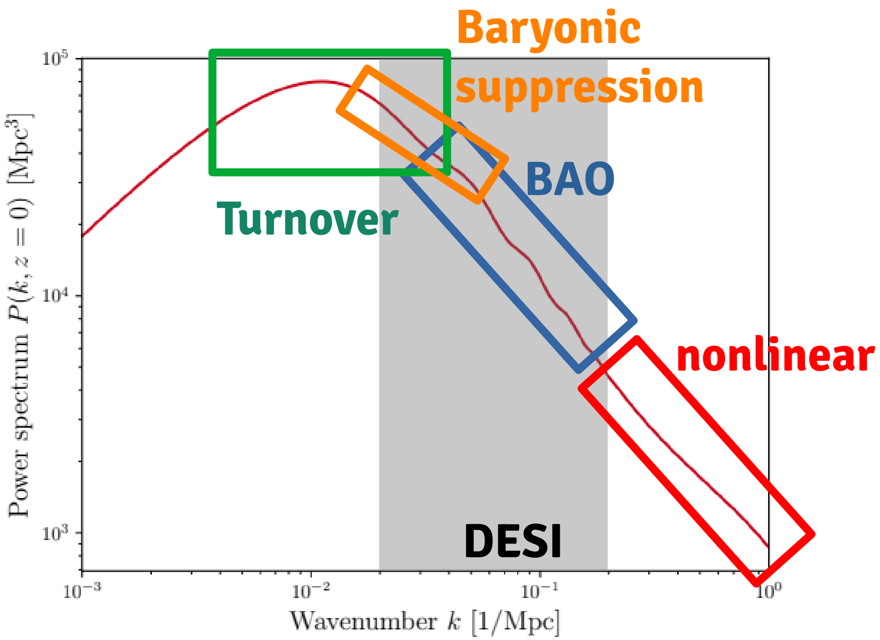
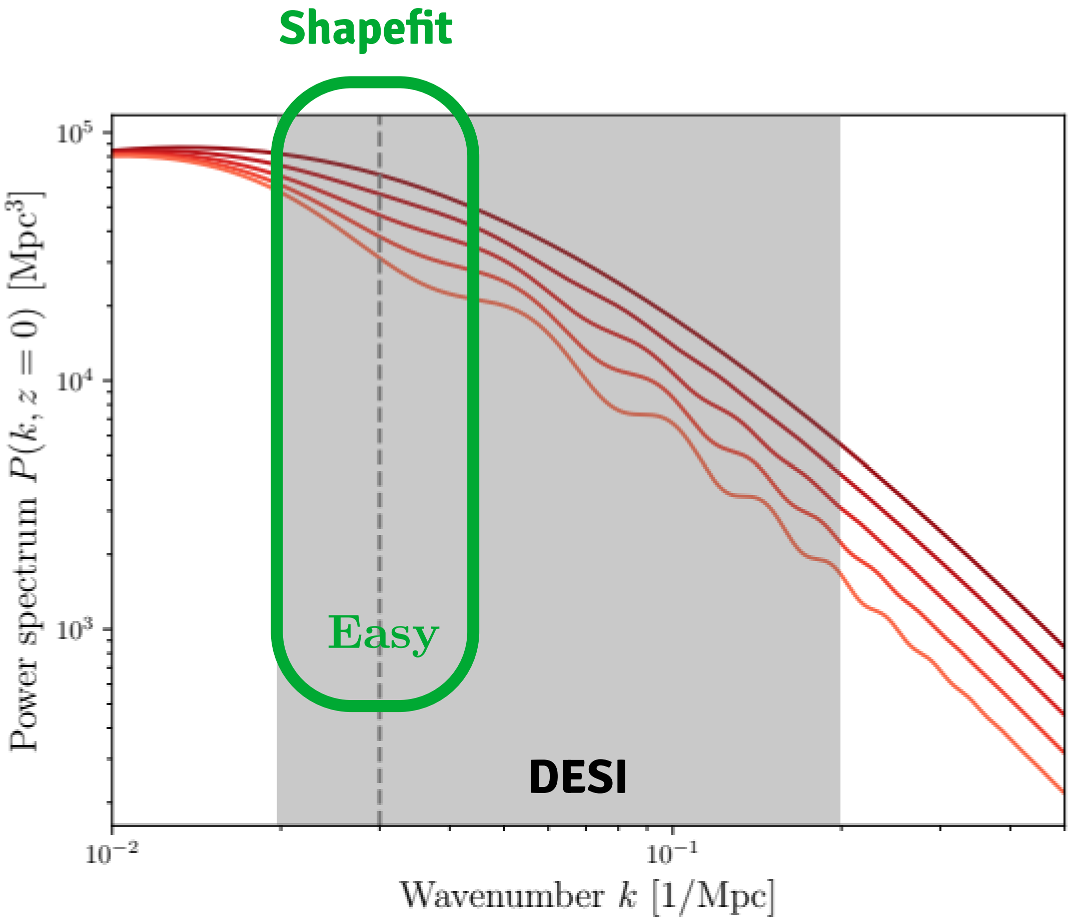
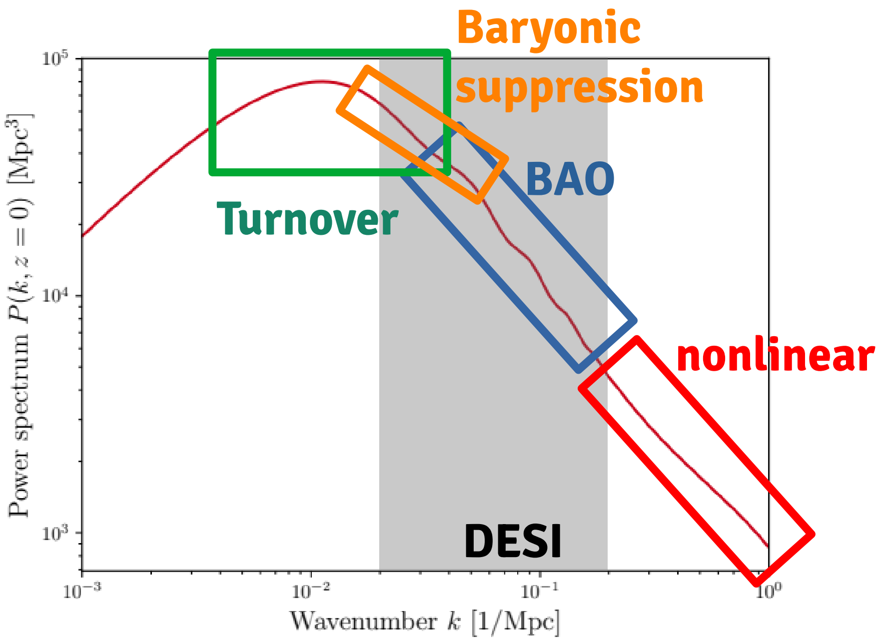
DESI
Power spectrum $P(k, z=0)$ [Mpc^3]
Wavenumber k [1/Mpc]

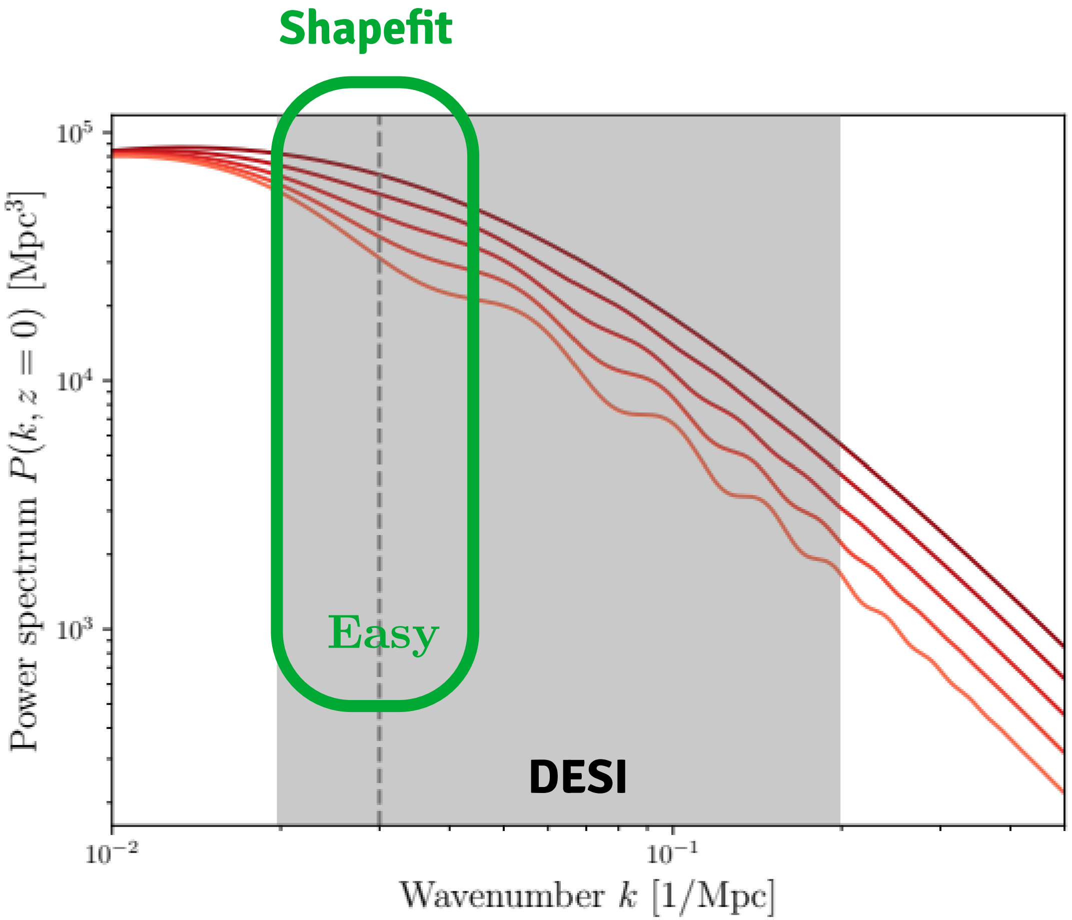

Shapefit
more baryons
Easy
Complicated
DESI
Power spectrum $P(k, z=0)$ [Mpc^3]
Wavenumber k [1/Mpc]


Baryonic
suppression
BAO
Turnover
nonlinear
DESI
Power spectrum $P(k, z = 0)$ [Mpc^3]
Wavenumber k [1/Mpc]


Shapefit
Easy
DESI
Power spectrum $P(k, z = 0)$ [Mpc^3]
Wavenumber k [1/Mpc]

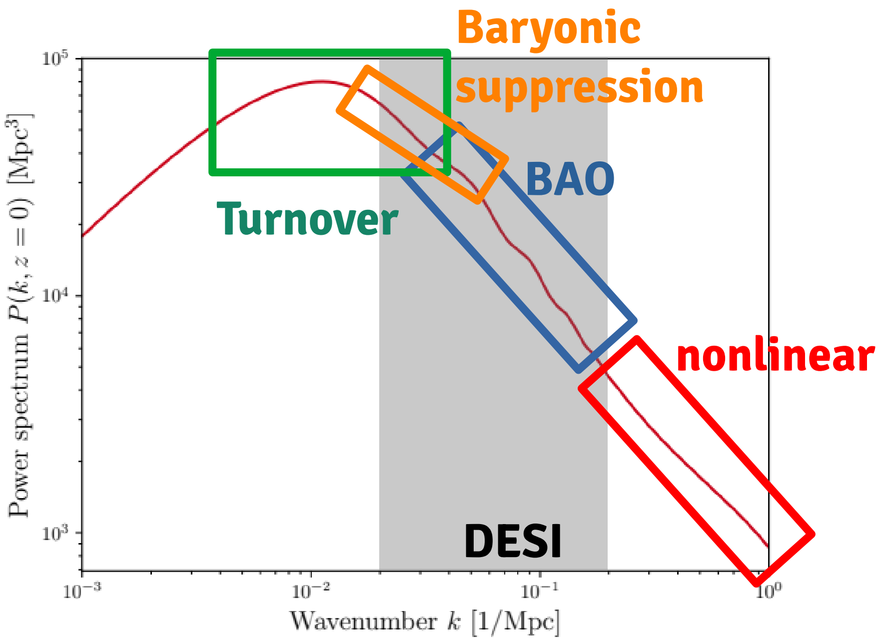
Sensitive to $\Omega_b h^2, \Omega_m h^2, n_s$

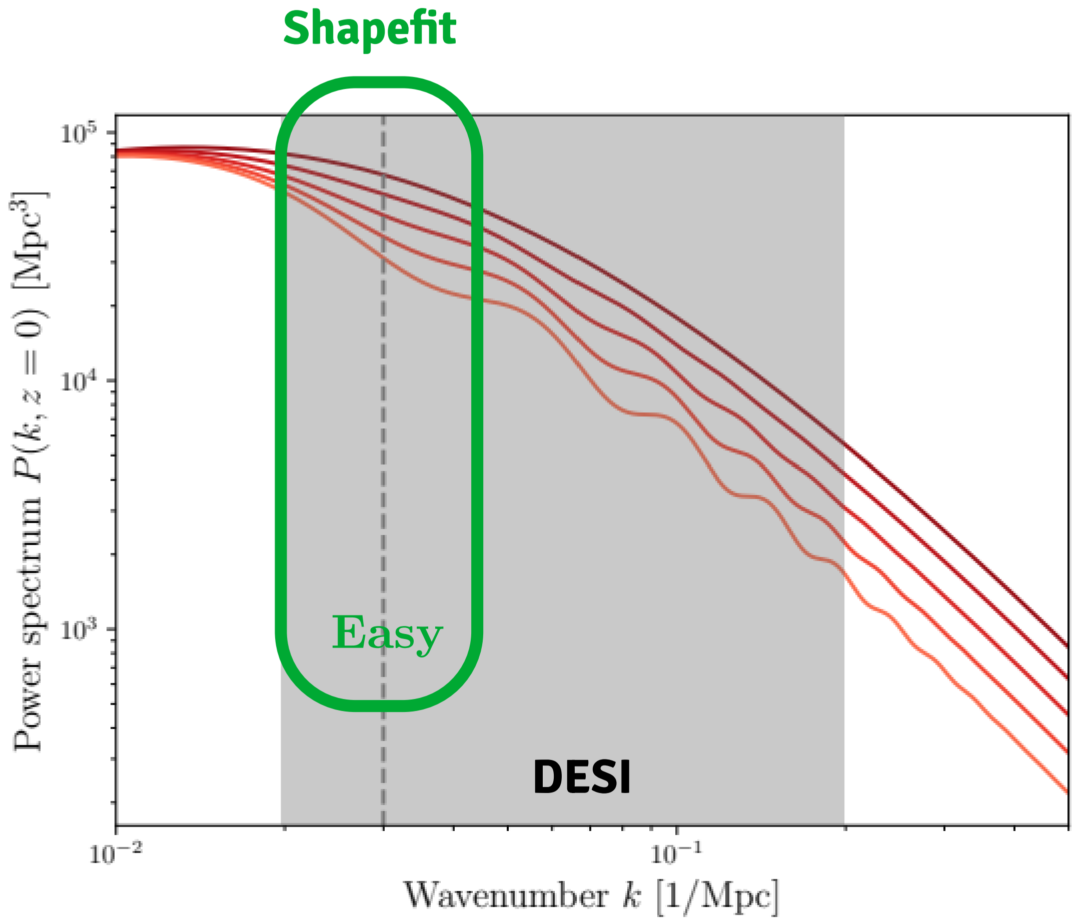




Sensitive to $\cancel{\Omega_b h^2}, \Omega_m h^2, n_s$

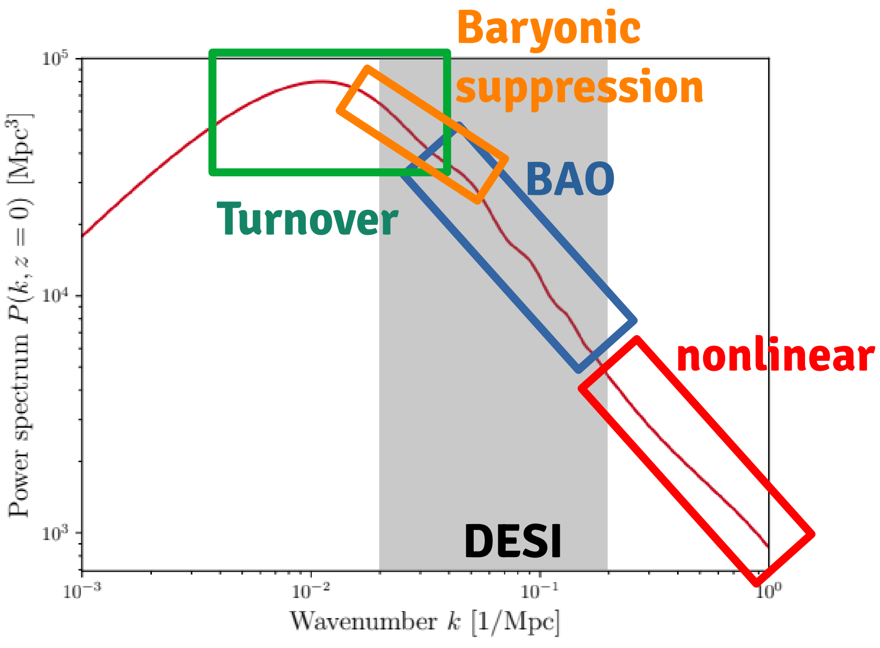
BBN

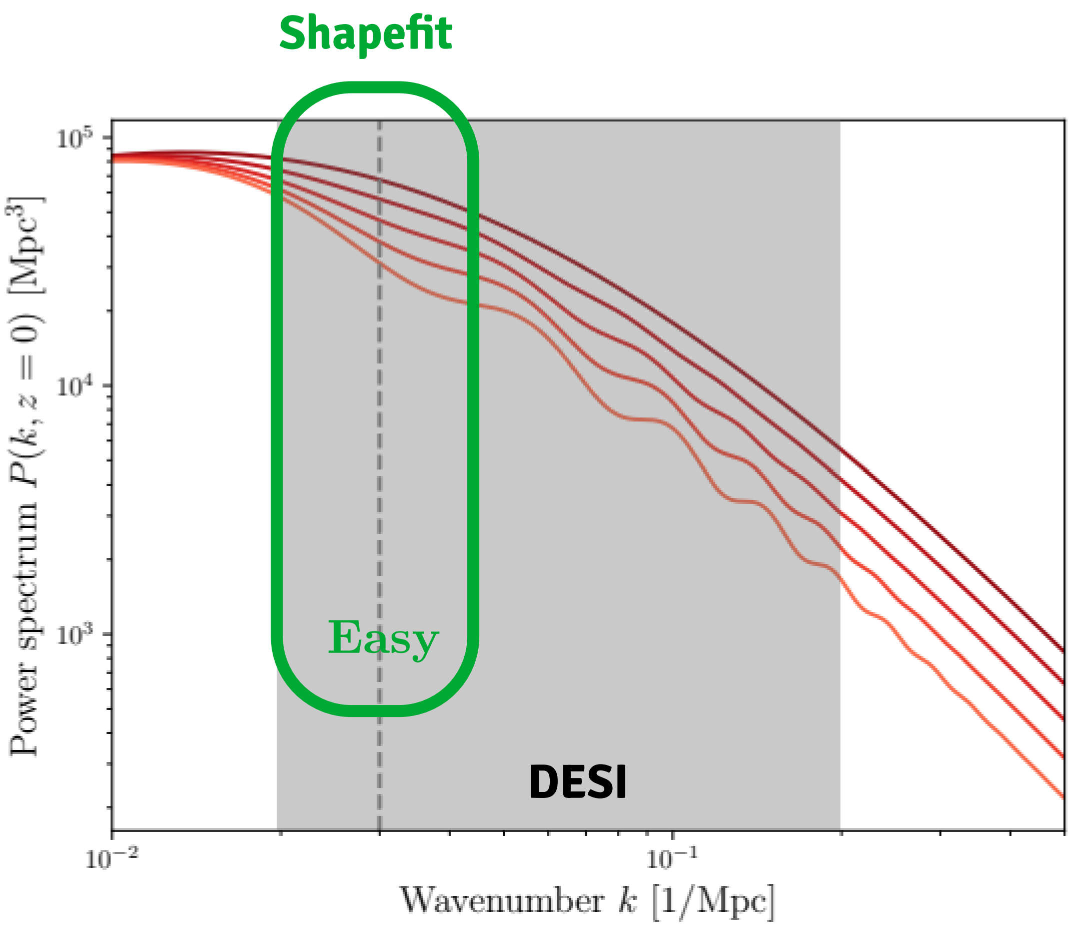




Sensitive to $\cancel{\Omega_b h^2}, \Omega_m h^2, \cancel{n_s}$

BBN prior





Sensitive to $\cancel{\Omega_b h^2}$, $\Omega_m h^2$, $\cancel{n_s}$

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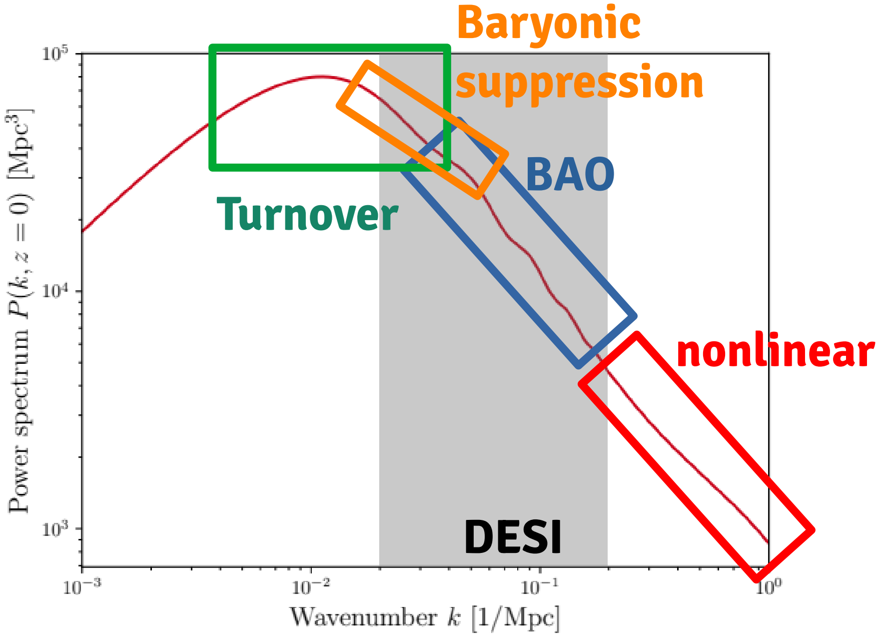

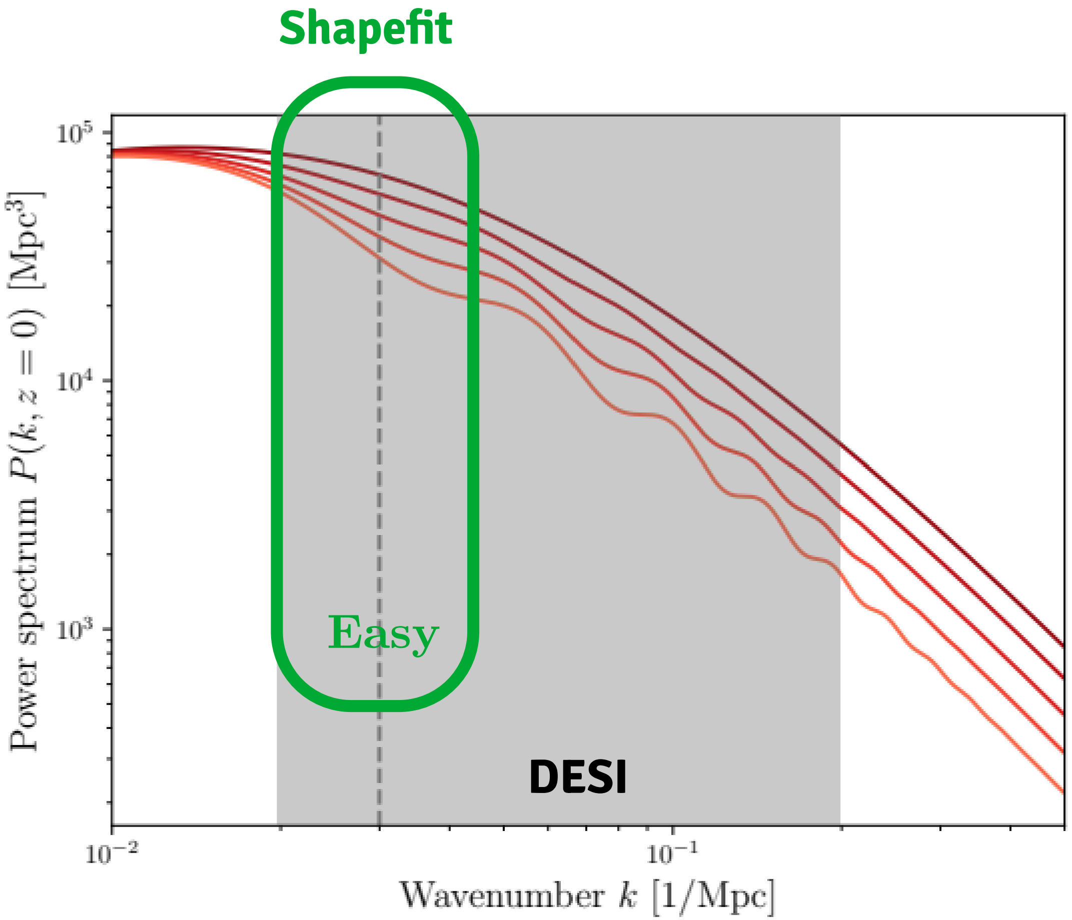

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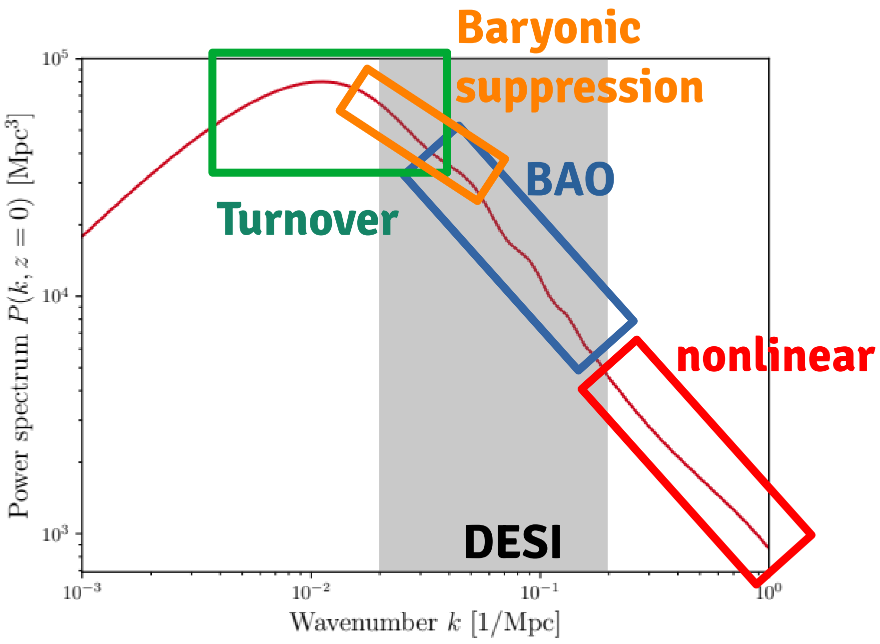

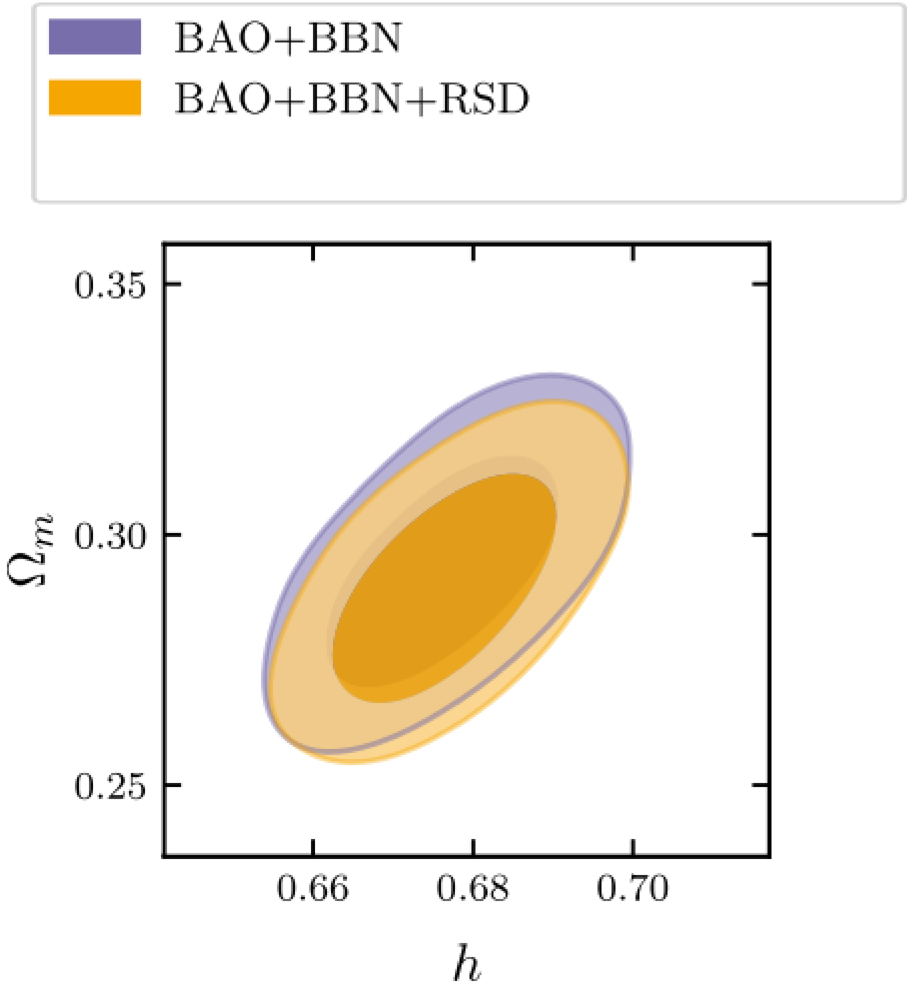

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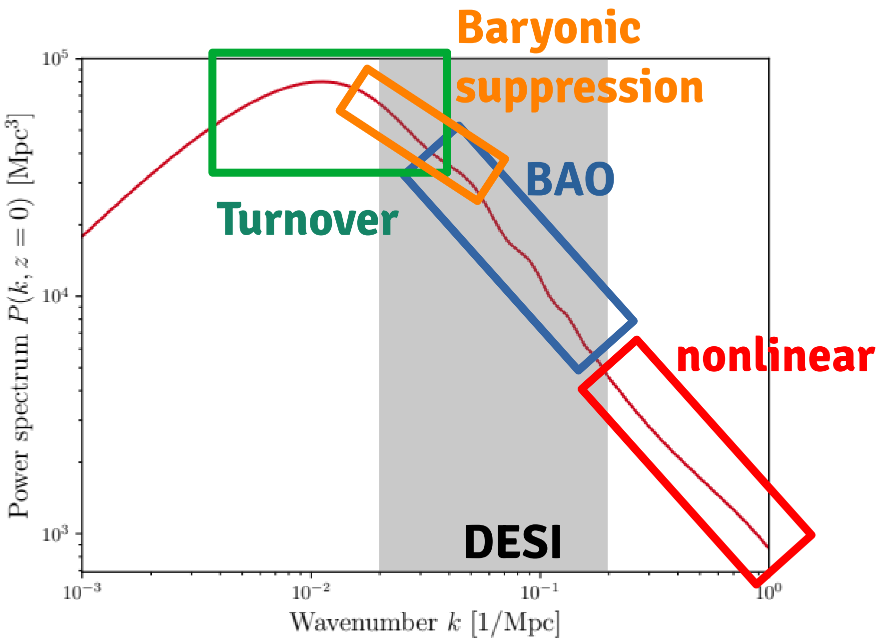

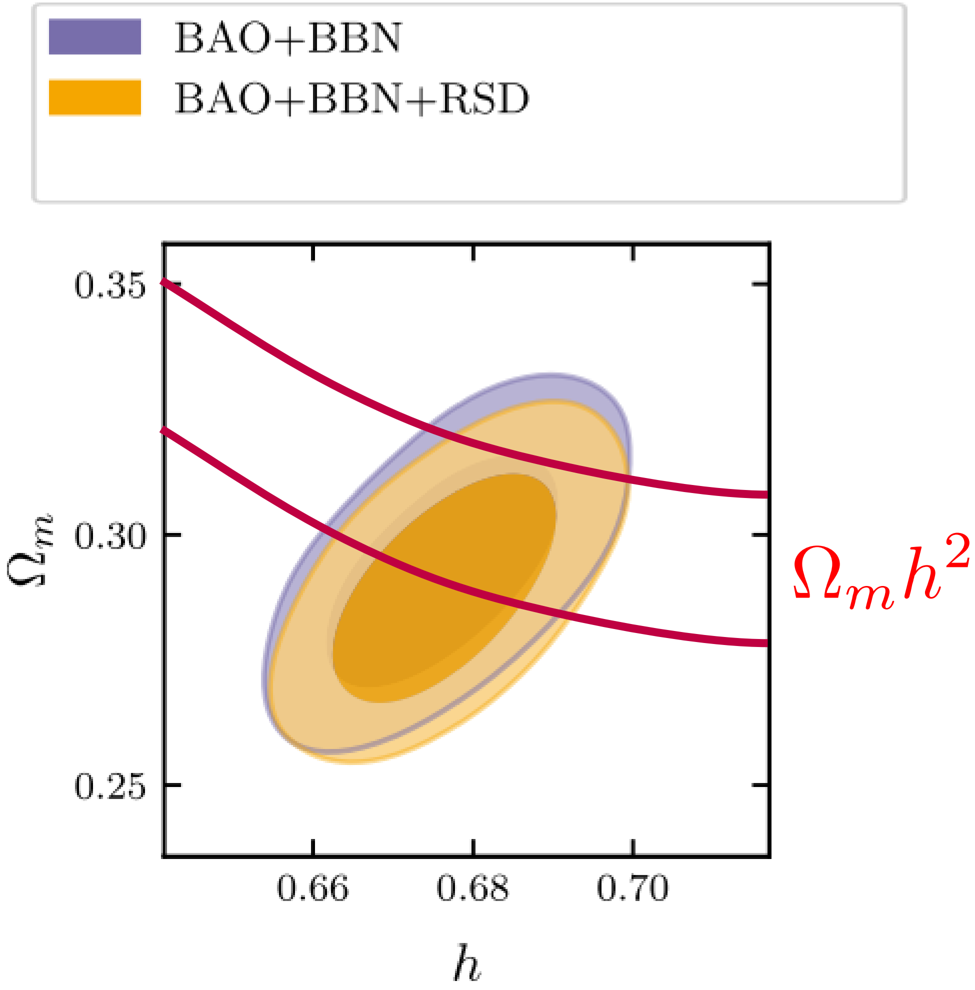

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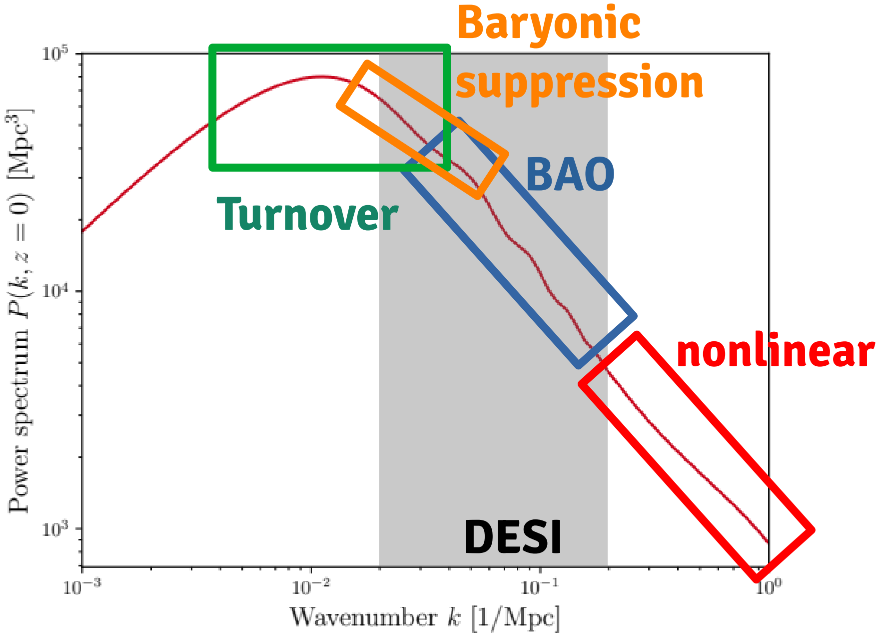
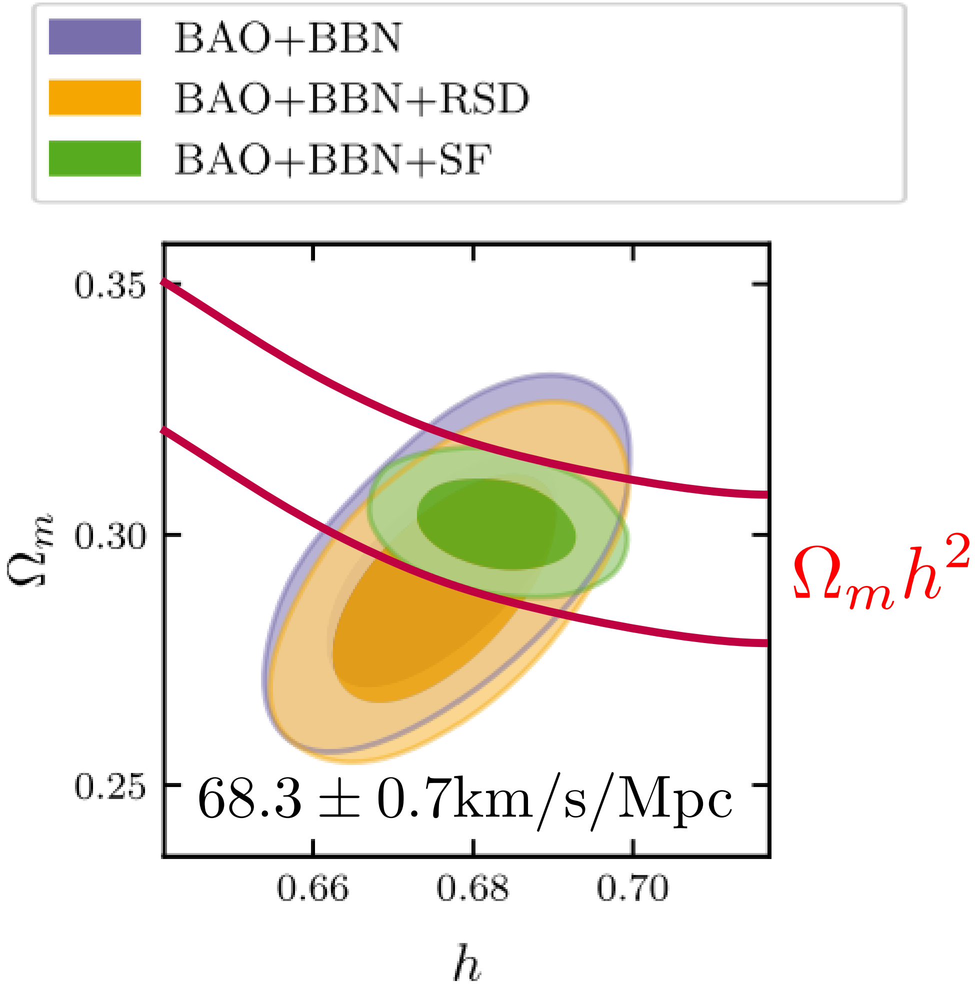


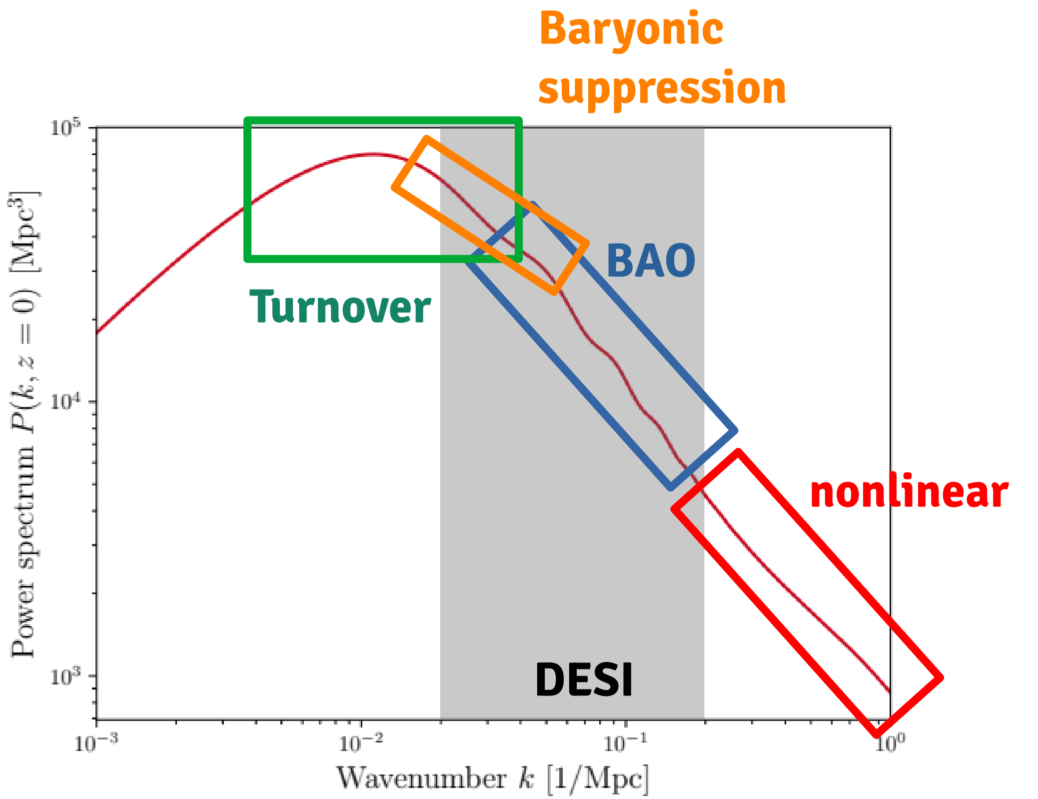


GALAXY CLUSTERING INFORMATION

- This is currently all available information

  → Full-shape analyses are not inherently 'better'

  → Can be understood as BAO + amplitude + baryonic suppression



Agenda

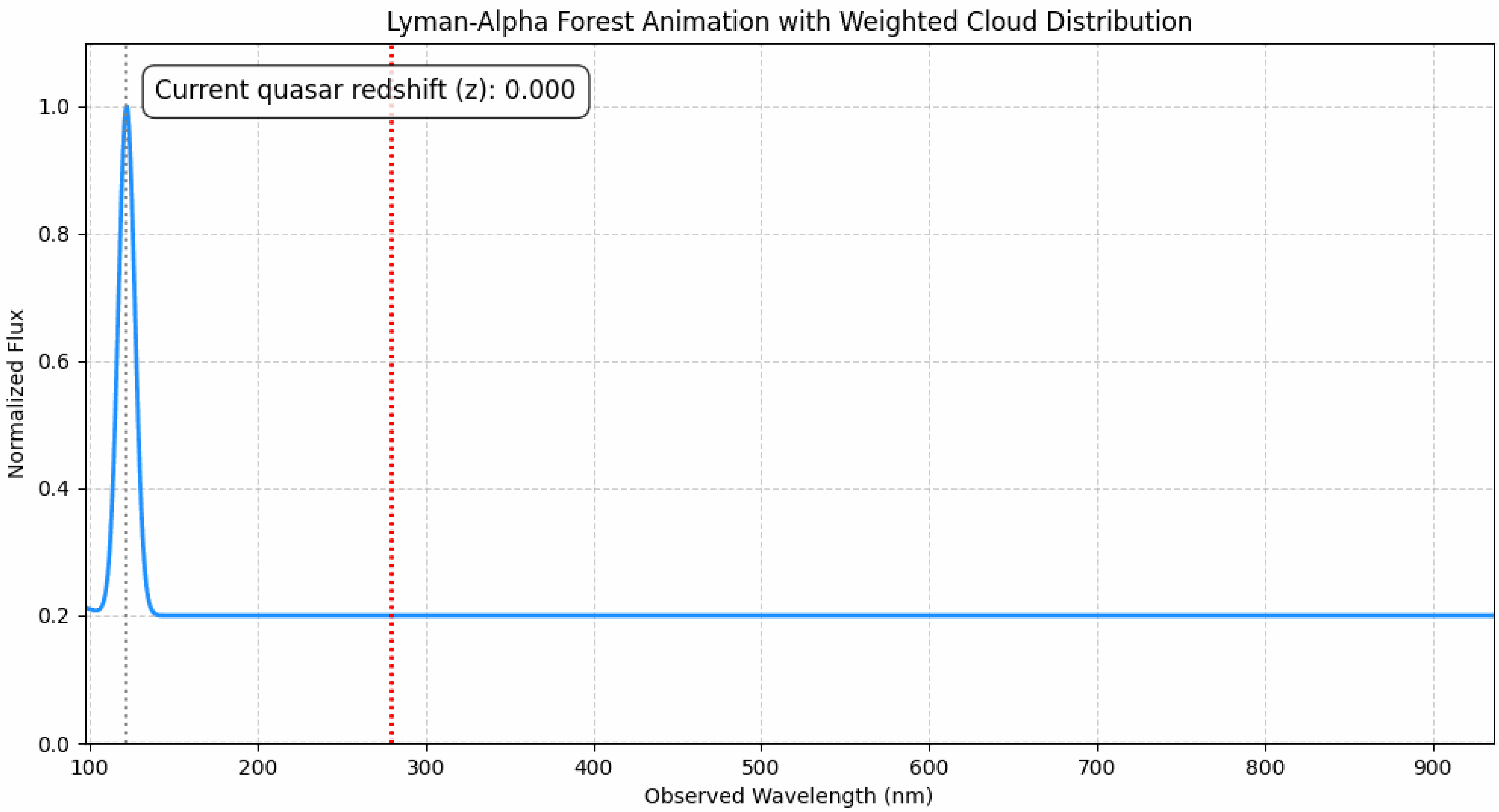
BAO

BAO+BBN

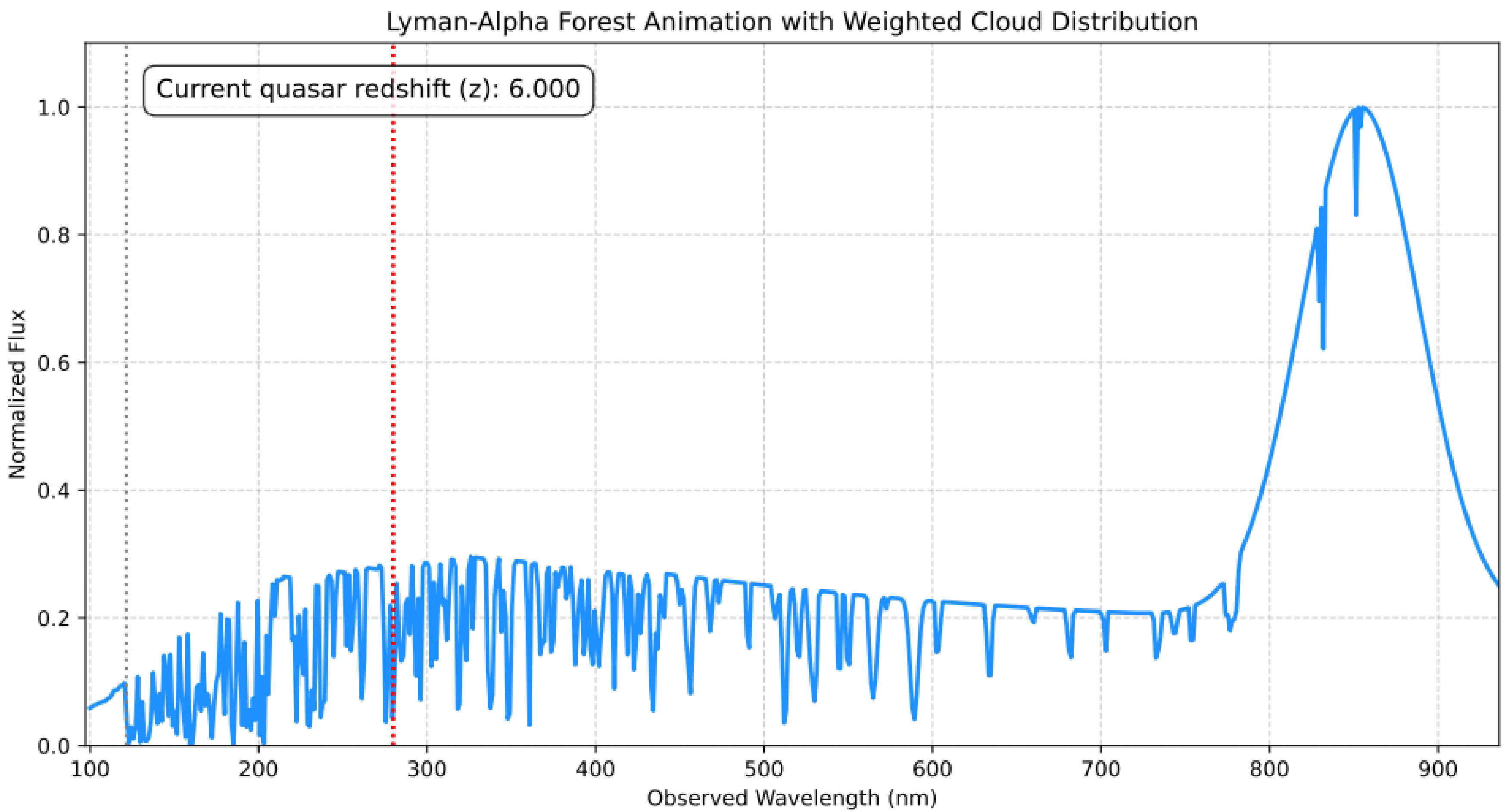
ShapeFit

Lyman-Alpha forest

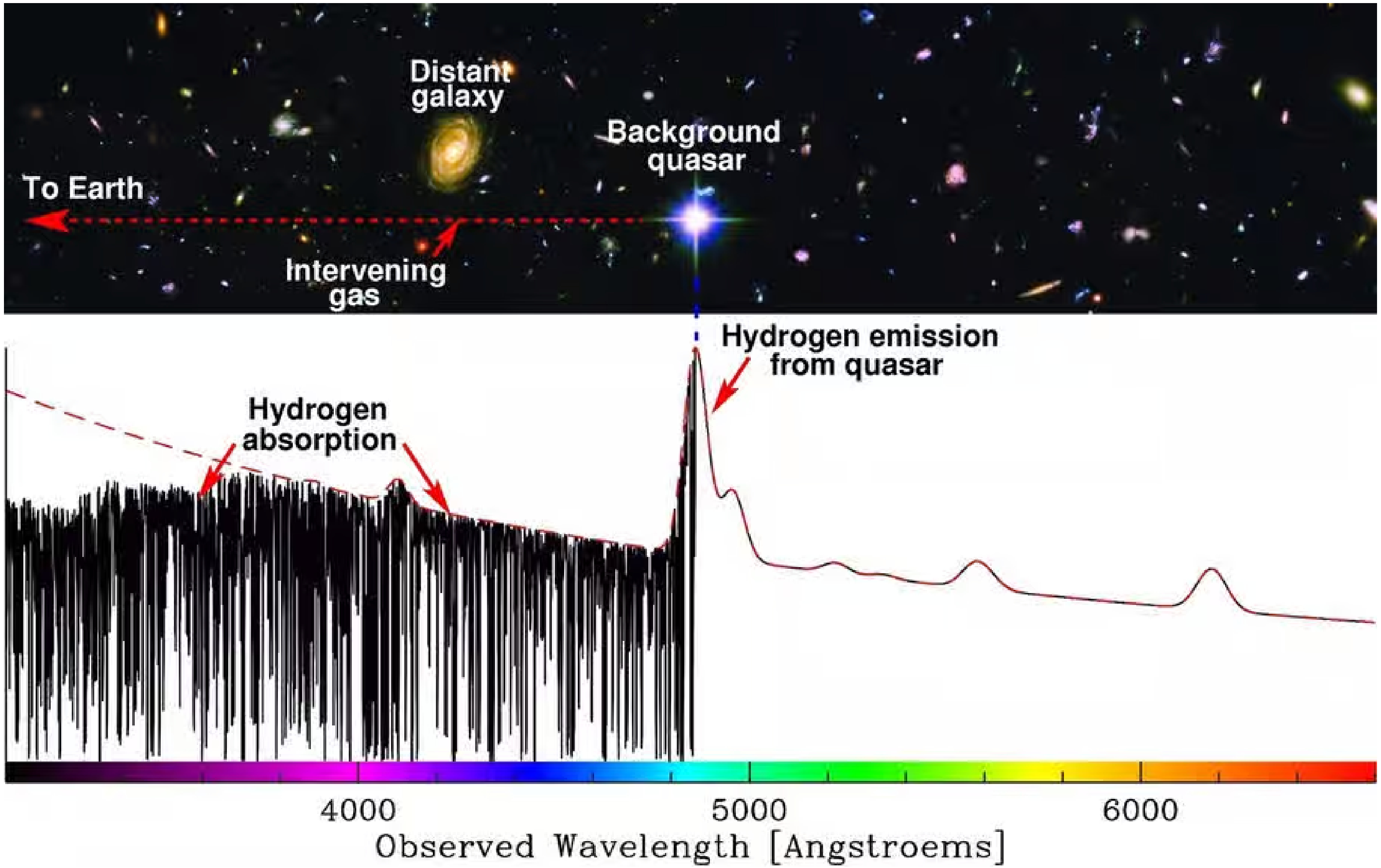
Lyman-Alpha forest



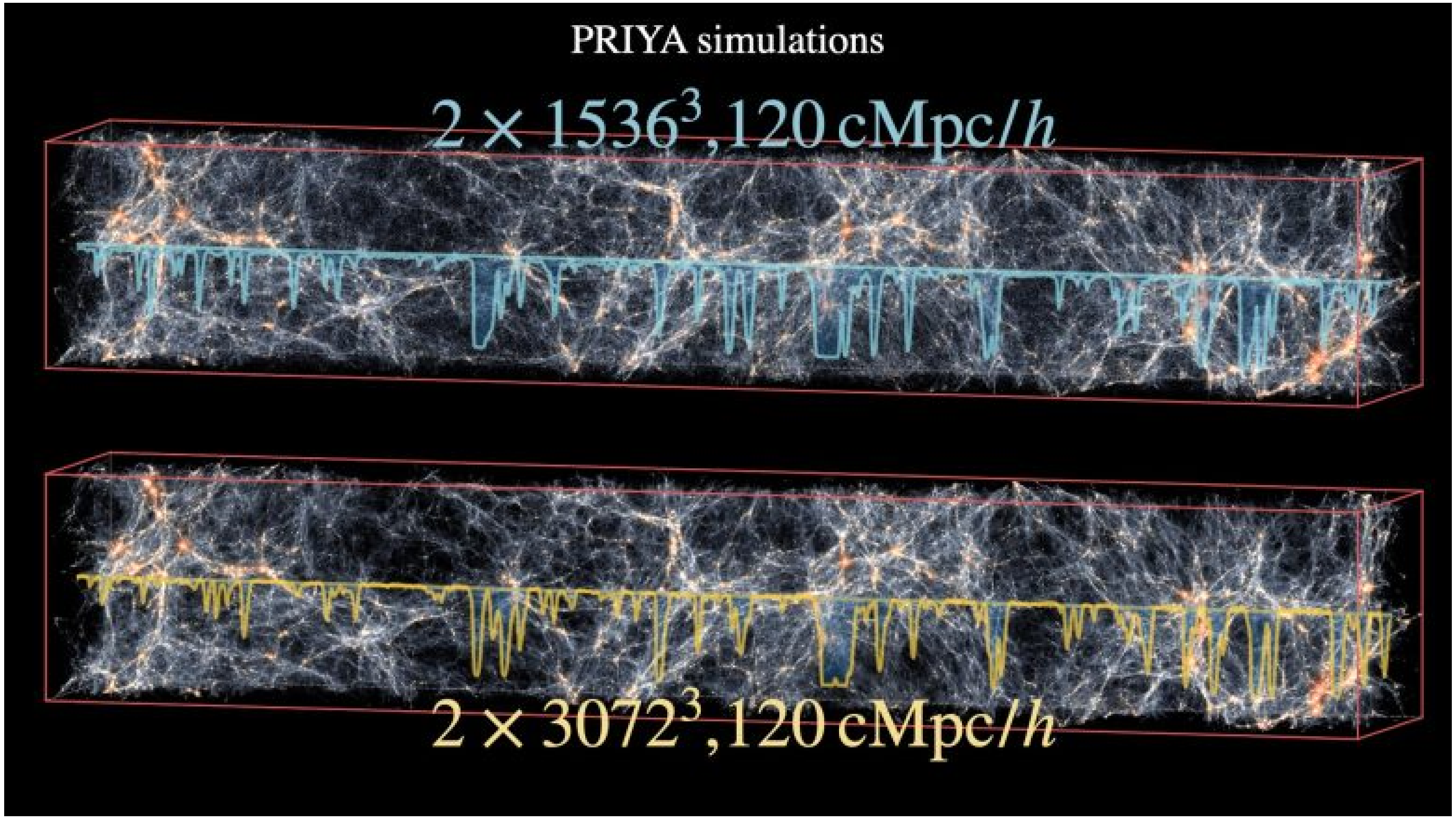
Lyman-Alpha forest



Lyman-Alpha forest



Lyman-Alpha forest



Lyman-Alpha forest

Absorption lines →

cloud redshifts/cloud distribution →

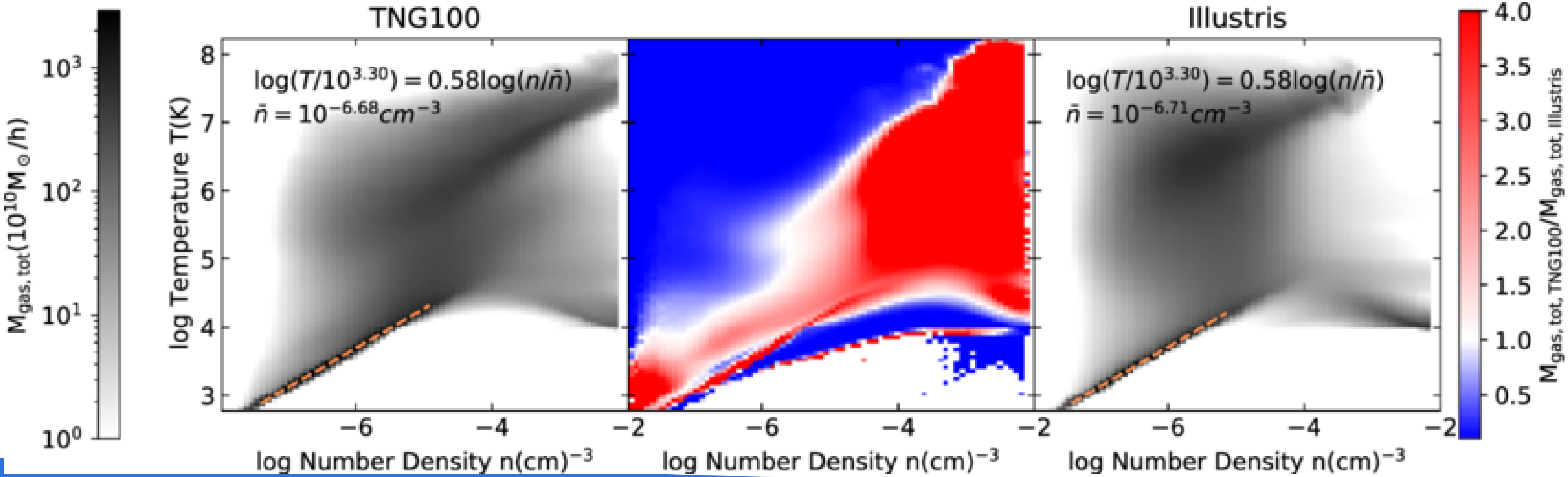
cosmological parameters

Lyman-Alpha forest

Absorption lines →

cloud redshifts/cloud distribution →

cosmological parameters

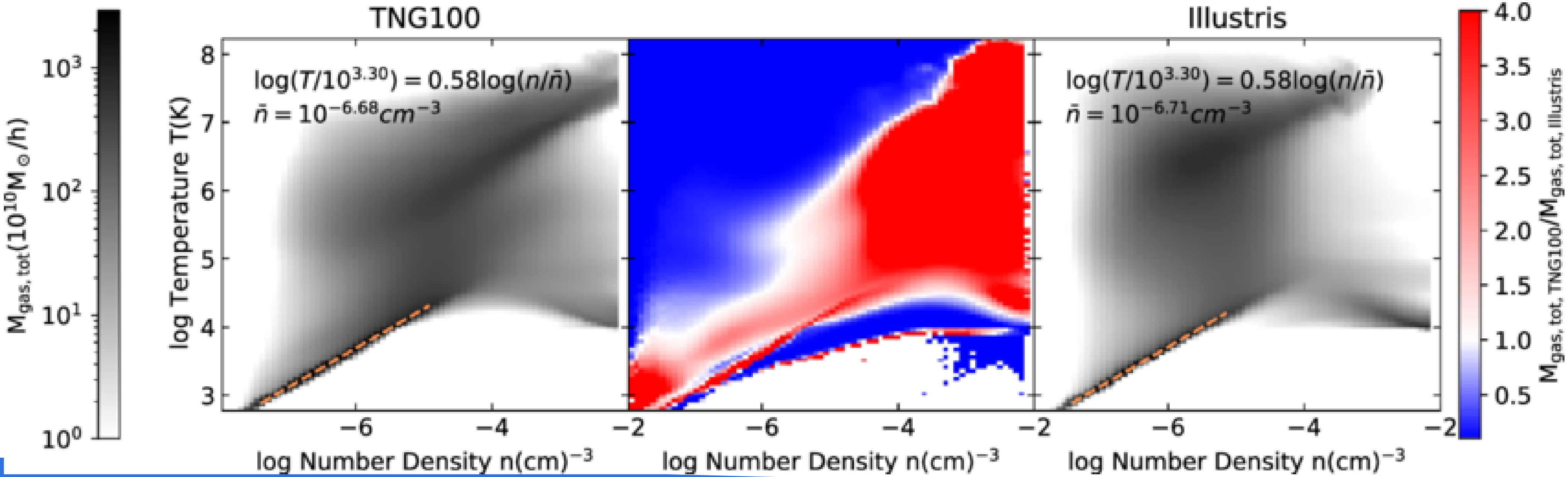


Lyman-Alpha forest

Absorption lines → $T \propto T_0 \cdot (1+\delta_{\mathrm{HI}})^{\gamma-1}$

cloud redshifts/cloud distribution →

cosmological parameters



Lyman-Alpha forest

Absorption lines →

cloud redshifts/cloud distribution →

cosmological parameters

$$T \propto T_0 \cdot (1 + \delta_{\mathrm{HI}})^{\gamma-1}$$

Lyman-Alpha forest

Absorption lines →

cloud redshifts/cloud distribution →

cosmological parameters

$$\kappa_\alpha \propto \kappa_0(z) T^{-\gamma_\alpha} (1+\delta_{\mathrm{HI}})^2 \qquad \text{(FGPA)}$$

$$T \propto T_0 \cdot (1+\delta_{\mathrm{HI}})^{\gamma-1}$$

Lyman-Alpha forest

Absorption lines →

cloud redshifts/cloud distribution →

cosmological parameters

$$\kappa_\alpha \propto \kappa_0(z) T^{-\gamma_\alpha} (1+\delta_{\rm HI})^2 \qquad \text{(FGPA)}$$

$$T \propto T_0 \cdot (1+\delta_{\rm HI})^{\gamma-1}$$

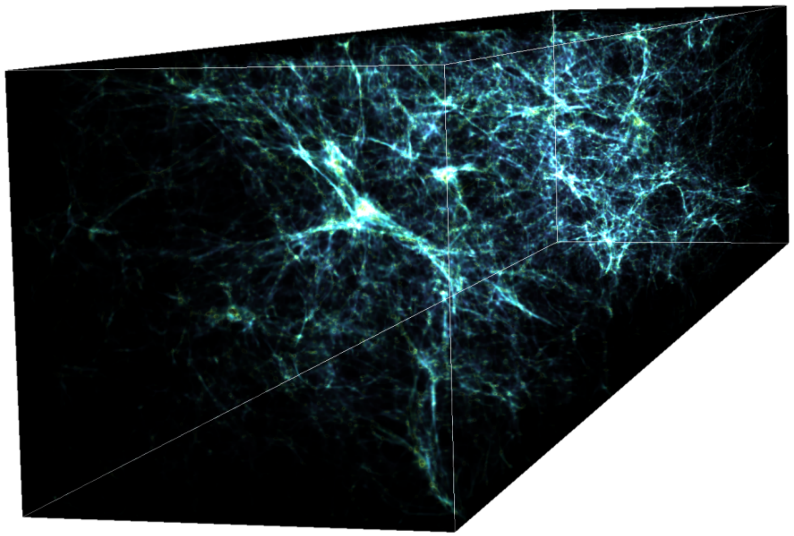
3 IGM parameters

Lyman-Alpha forest

Absorption lines →

cloud redshifts/cloud distribution →

cosmological parameters



Lyman-Alpha forest

Absorption lines →

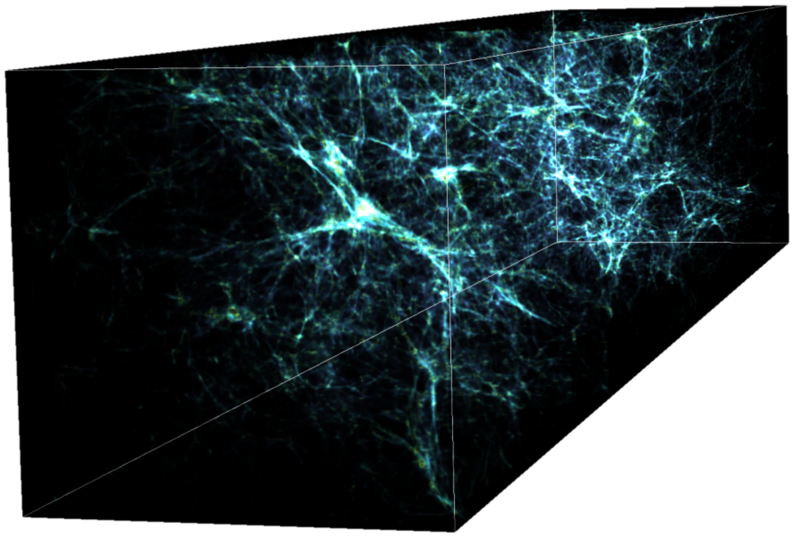
cloud redshifts/cloud distribution →

cosmological parameters

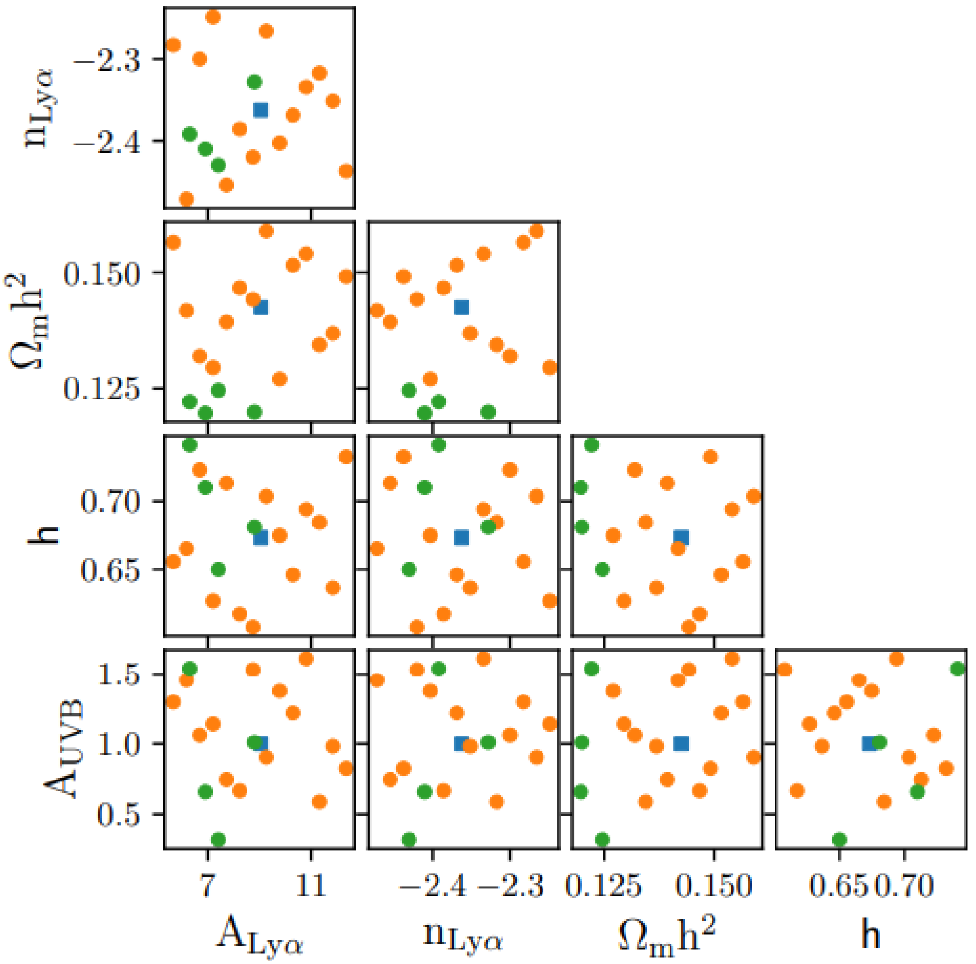
→ We need high-resolution Lyman-Alpha simulations

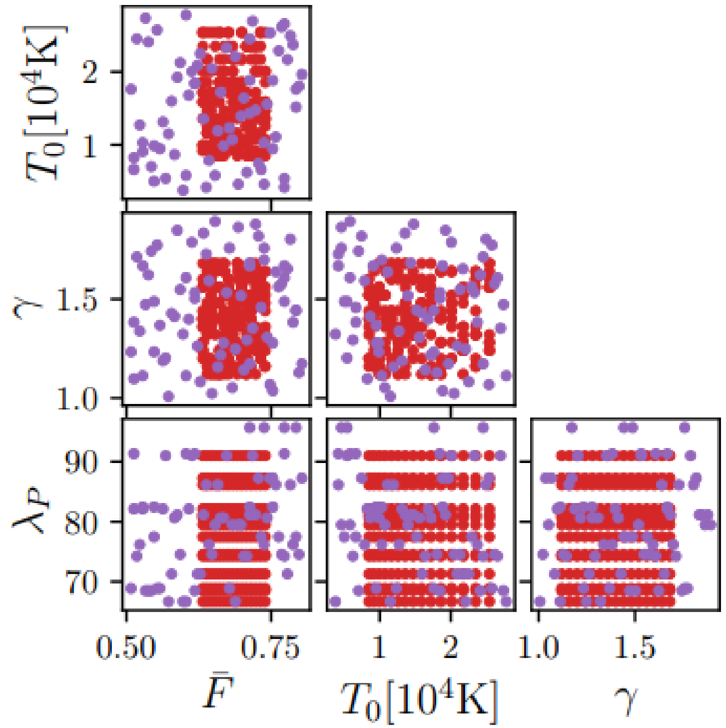
e.g. Nyx Lyssa simulations, 120cMpc boxes, $3 * 4096^3$

Very expensive! → We need emulation



Lyman-Alpha forest



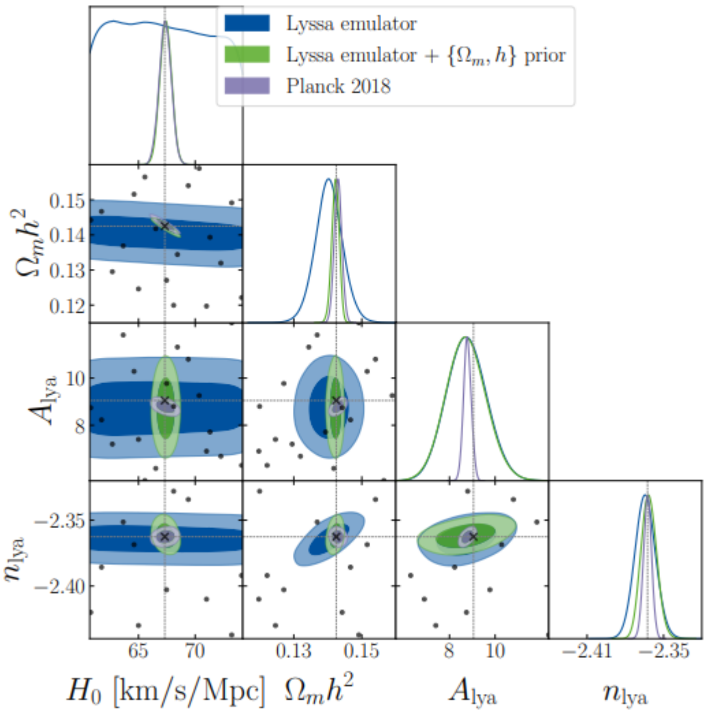


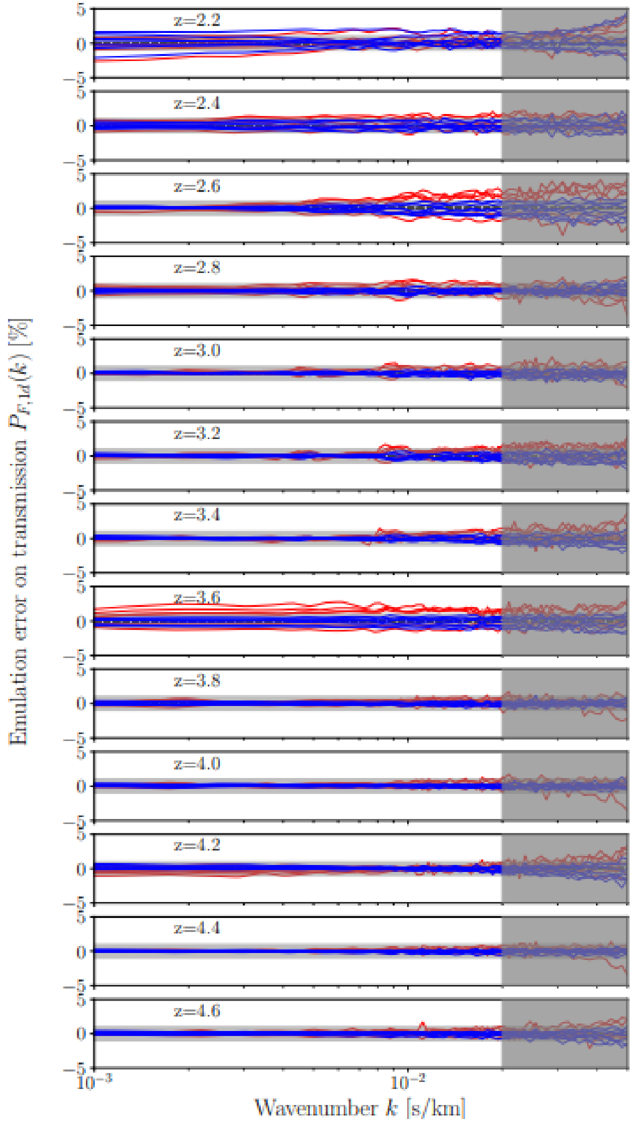
Lyman-Alpha forest

Leave-one-out tests

About 1% accuracy at most higher redshifts, lower accuracy at lower redshifts, and at *z=3.6*

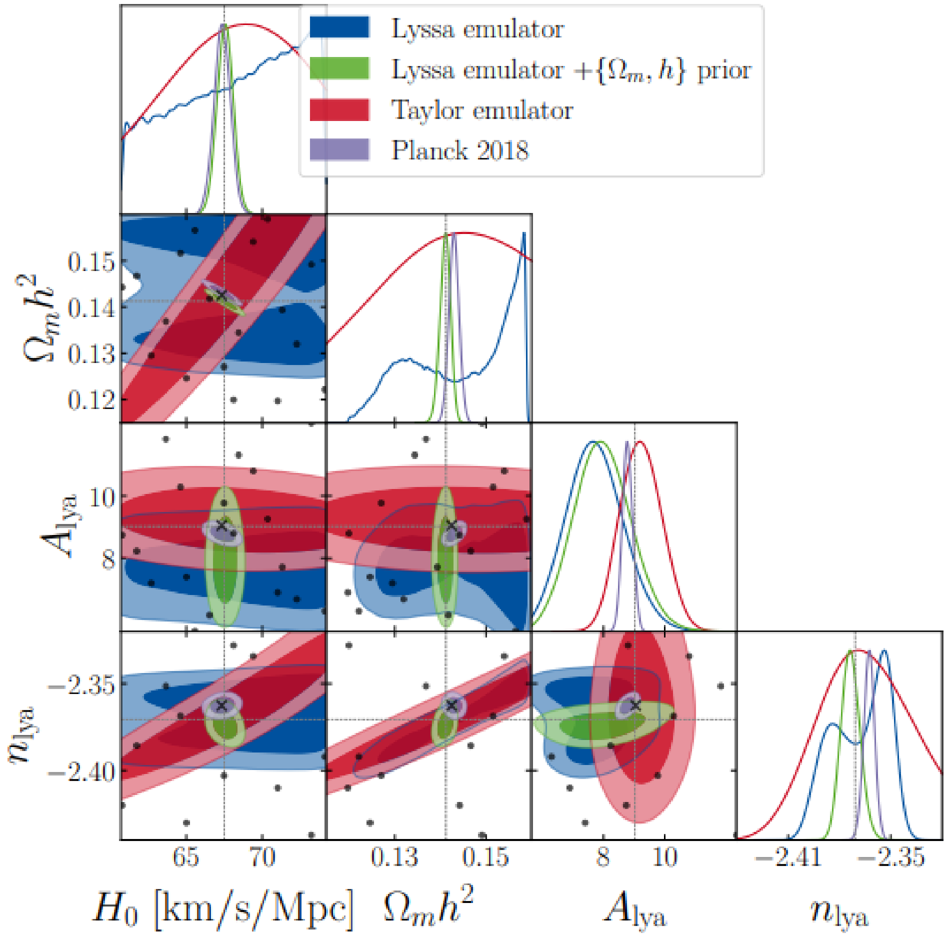
We can get the fiducial simulation back with nice error bars





Lyman-Alpha forest

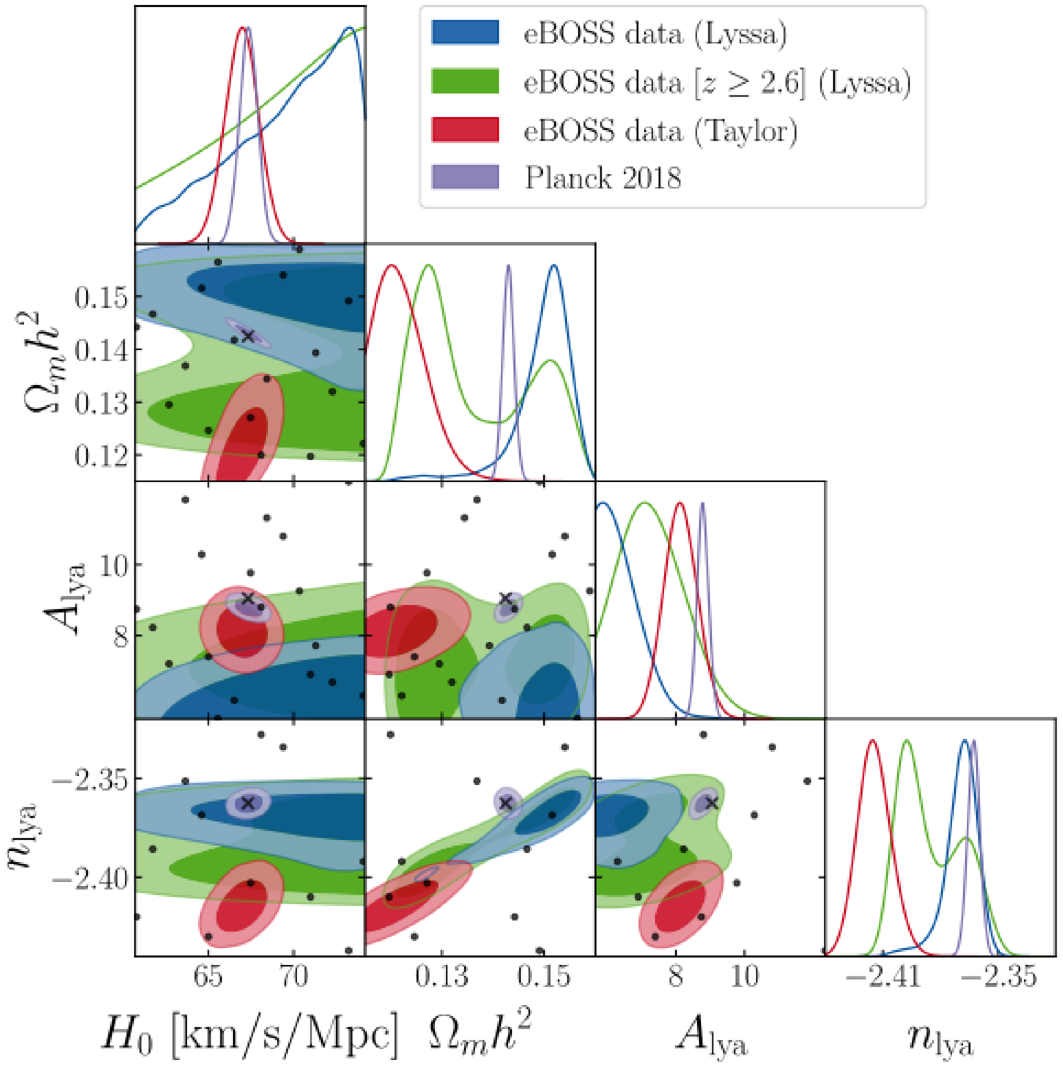
Fitting non-Nyx simulations (old), just to see if simulation suites match approximately



Lyman-Alpha forest

Fitting eBOSS data

→ Large differences compared to old emulator based on Taylor approximation

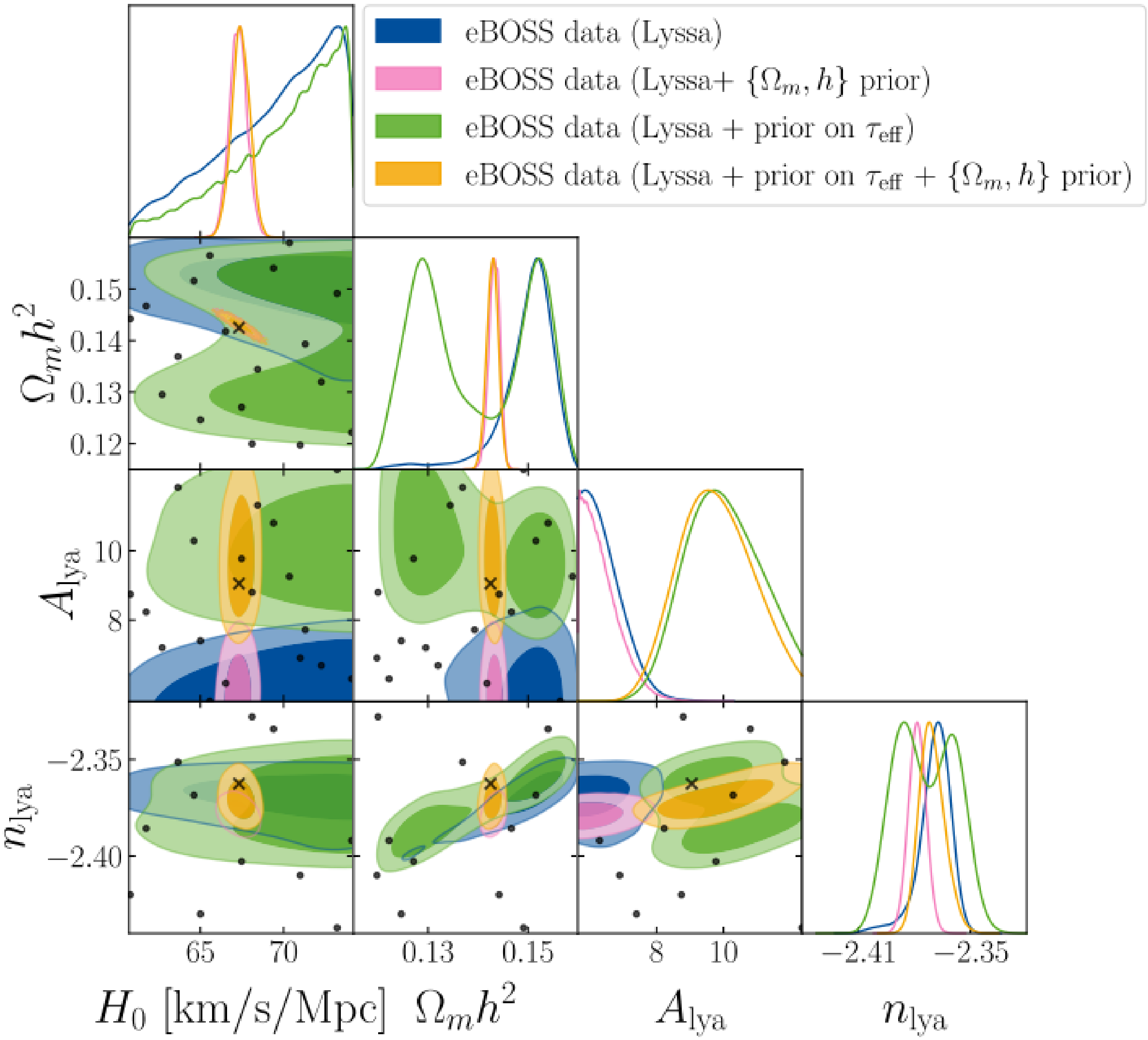


Lyman-Alpha forest

Fitting eBOSS data

→ Large differences compared to old emulator based on Taylor approximation

→ Large differences caused by prior on optical depth. Interpretation of the results is subject to assumptions on IGM optical depth

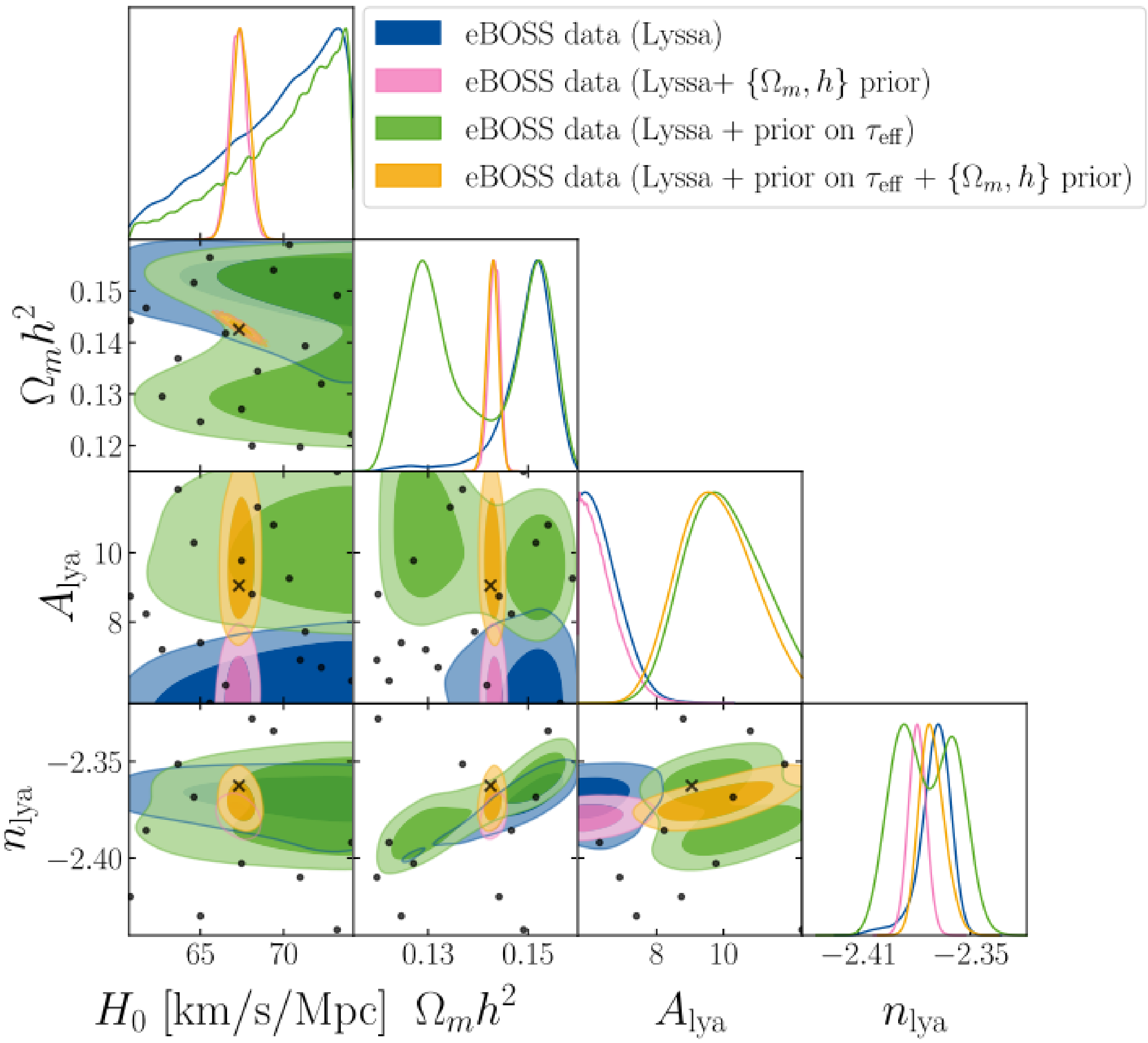


Lyman-Alpha forest

Fitting eBOSS data

→ Large differences compared to old emulator based on Taylor approximation

→ Large differences caused by prior on optical depth.
Interpretation of the results is subject to assumptions on IGM optical depth
(bias mostly in amplitude, not slope)



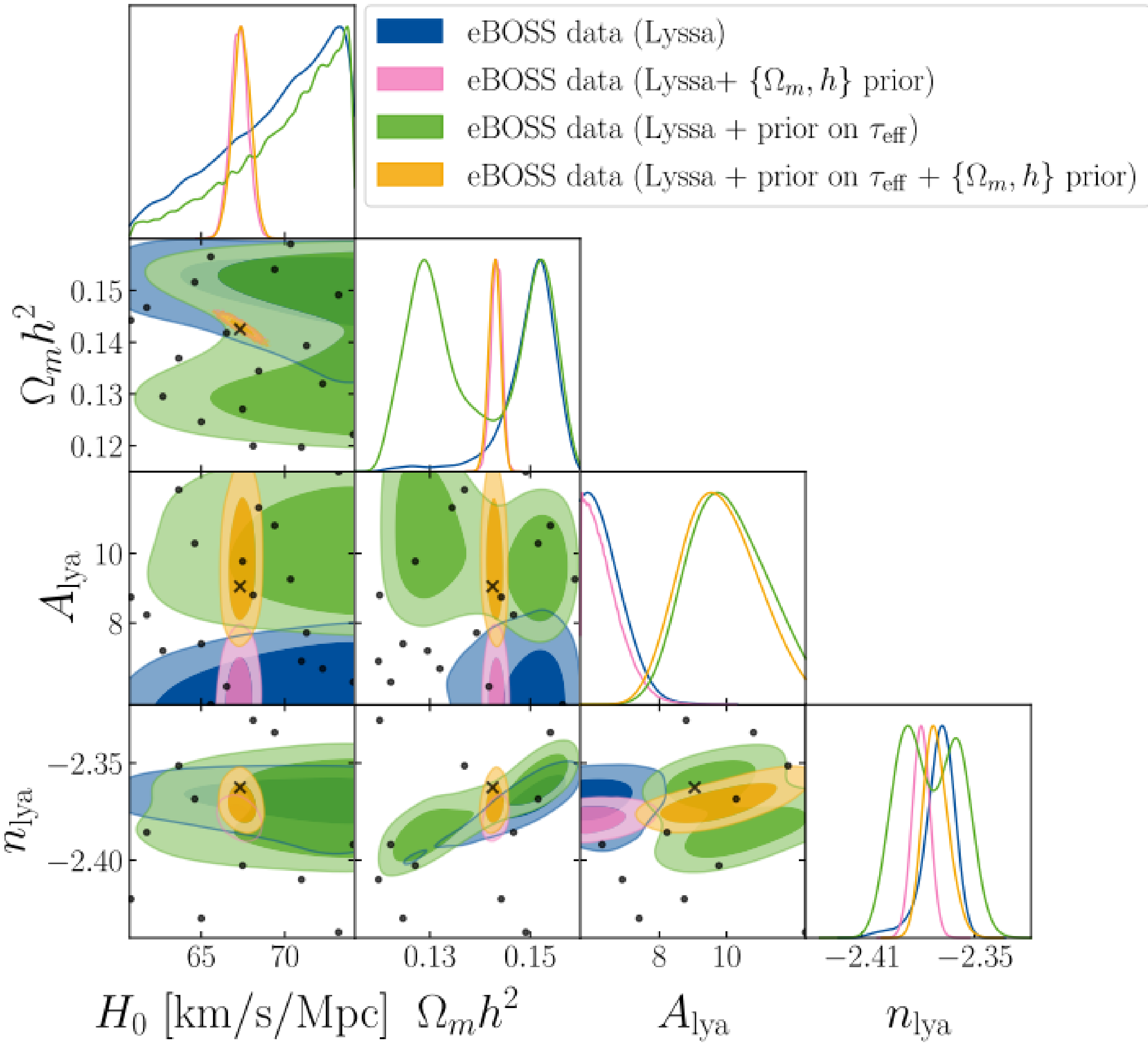
Lyman-Alpha forest

Fitting eBOSS data

→ Large differences compared to old emulator based on Taylor approximation

→ Large differences caused by prior on optical depth.
Interpretation of the results is subject to assumptions on IGM optical depth
(bias mostly in amplitude, not slope)

→ Further emulator tests will be required in the future, especially in the context of DESI data



Summary

- BAO DESI
  - Interesting tension, don't over-interpret results (yet)
  - Be careful about neutrino mass bounds
- BAO+BBN DESI
  - Uses D/H measurements to calibrate r_s
  - Very precise H0 values
- ShapeFit
  - Measures equality scale ($\Omega_m h^2$) → helps BAO+BBN
- Lyman-Alpha
  - New results, but careful about IGM assumptions

Beyond Desi

- Hubble tension theory models
- Local distance ladder
- CMB analytic description
- Accelerating cosmological inference

  (CLASS, MontePython, sampling ideas (GPry))