The Dark Energy Spectroscopic Instrument
Cosmological constraints

Julián Bautista, Aix-Marseille Université - CPPM

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Aix Marseille Université

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

News from April 4th 2024

The New York Times

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

SCIENCES ET AVENIR

UNIVERS

"L'énergie noire pourrait avoir évolué au fil du temps", selon Michael Levi, directeur de la collaboration DESI

F / Sciences

DÉCRYPTAGE - La mesure de 6 millions de galaxies par un télescope d'un nouveau type dévoile une variation inattendue de l'accélération de l'expansion du cosmos depuis le big bang.

COSMOLOGY

Quanta magazine

Dark Energy May Be Weakening, Major Astrophysics Study Finds

22

A generation of physicists has referred to the dark energy that permeates the universe as "the cosmological constant." Now the largest map of the cosmos to date hints that this mysterious energy has been changing over billions of years.

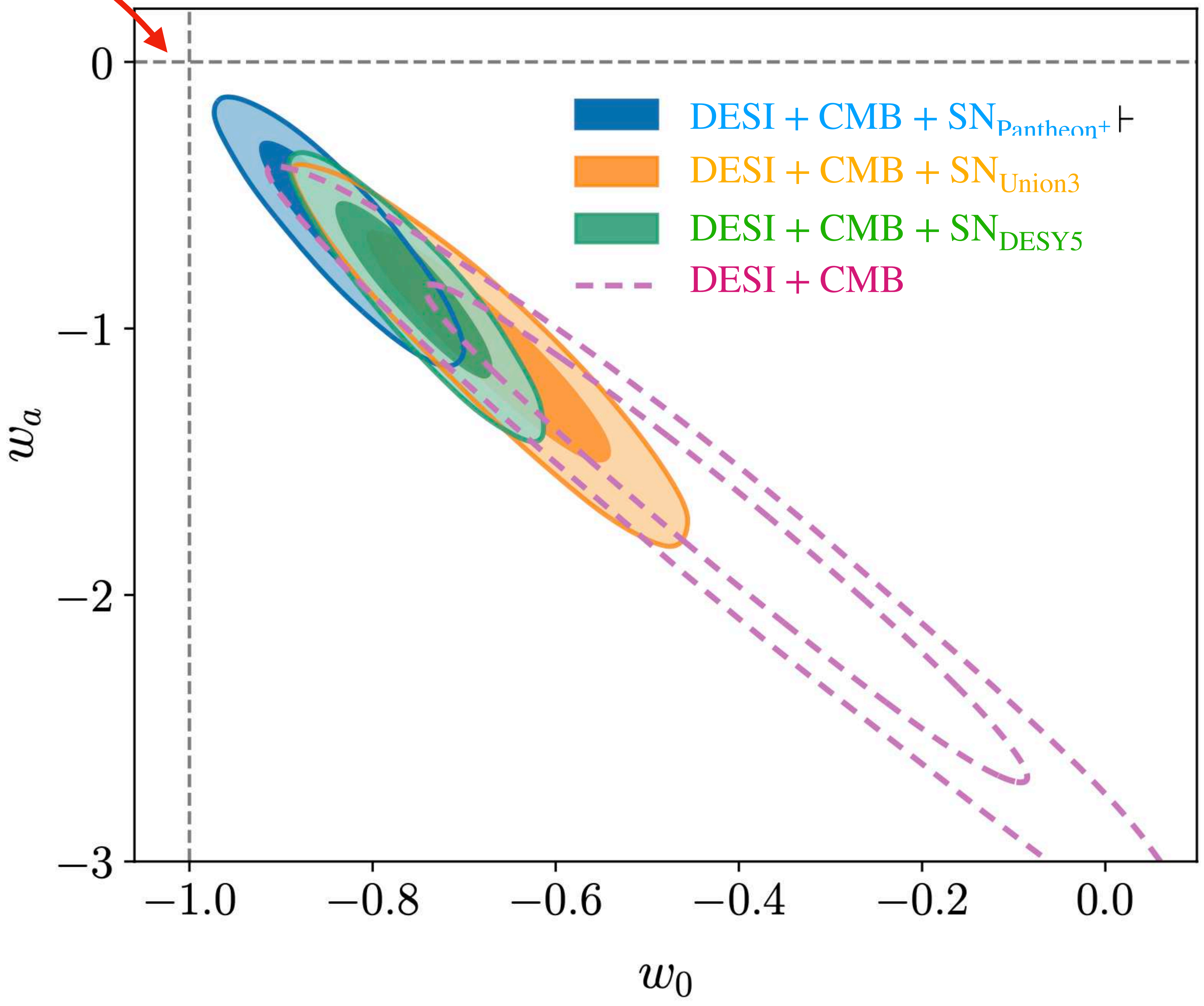
Constraints on evolving dark energy

Cosmological constant Λ

$w = -1$

Evolving dark energy

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



Tension with the cosmological constant:

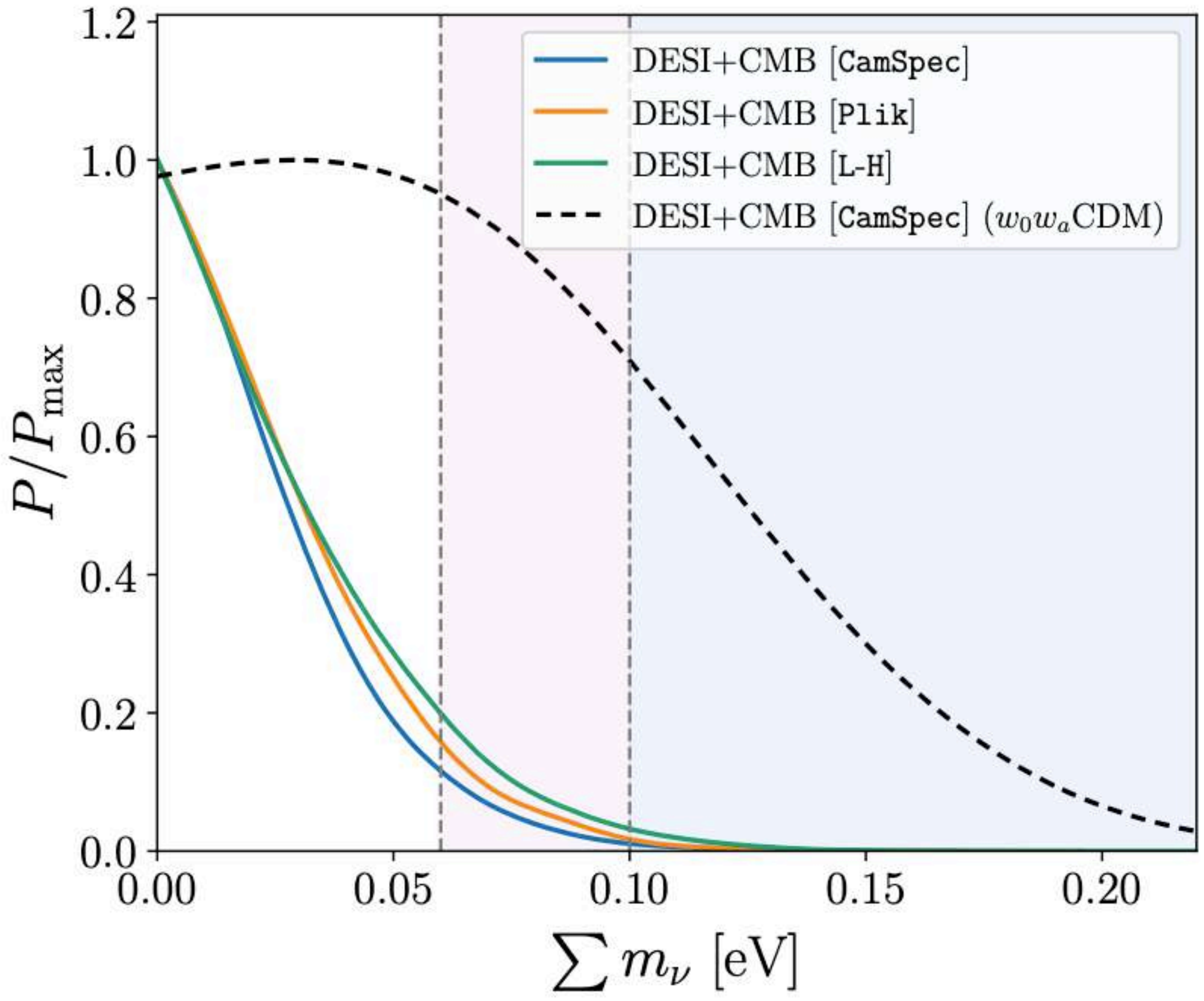
$\mathrm{DESI} + \mathrm{CMB} \Rightarrow 3.1\sigma$

$\mathrm{DESI} + \mathrm{CMB} + \mathrm{SN}_{\mathrm{Pantheon^+}} \Rightarrow 2.8\sigma$

$\mathrm{DESI} + \mathrm{CMB} + \mathrm{SN}_{\mathrm{Union3}} \Rightarrow 3.8\sigma$

$\mathrm{DESI} + \mathrm{CMB} + \mathrm{SN}_{\mathrm{DESY5}} \Rightarrow 4.2\sigma$

Constraints on neutrino masses



Assuming ΛCDM : $\sum m_\nu < 0.064$ eV

(95% CL) DESI + CMB

Assuming $w_0 w_a$CDM : $\sum m_\nu < 0.163$ eV

(95% CL) DESI + CMB + DES-SN5YR

Reaching lower bounds from oscillation experiments!

Plan

Dark energy and neutrino cosmology

Mapping galaxies with DESI

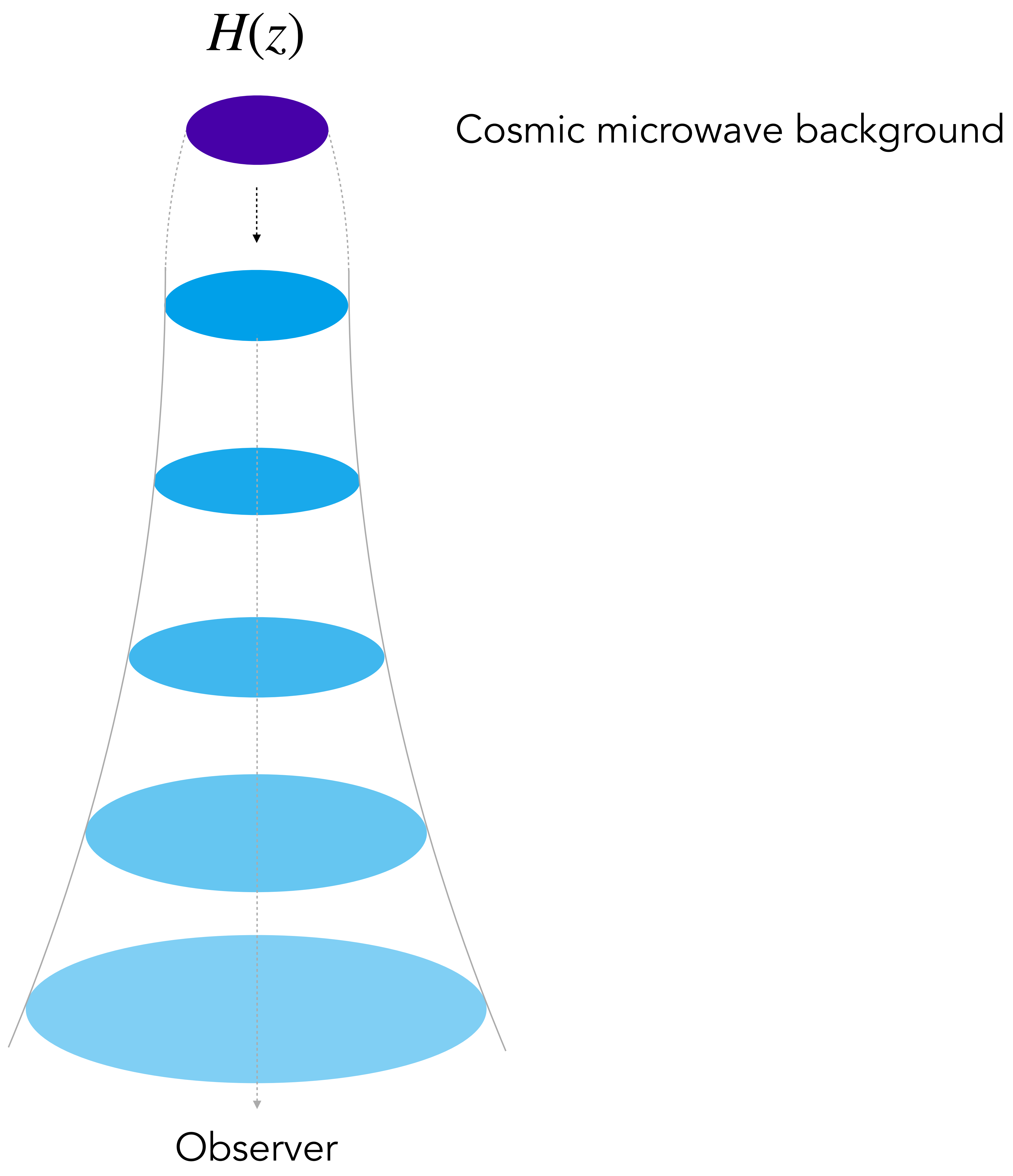
Dark energy constraints

Neutrino mass constraints

Modified gravity constraints

Accelerated expansion: dark energy or modified gravity?

Expansion of the Universe



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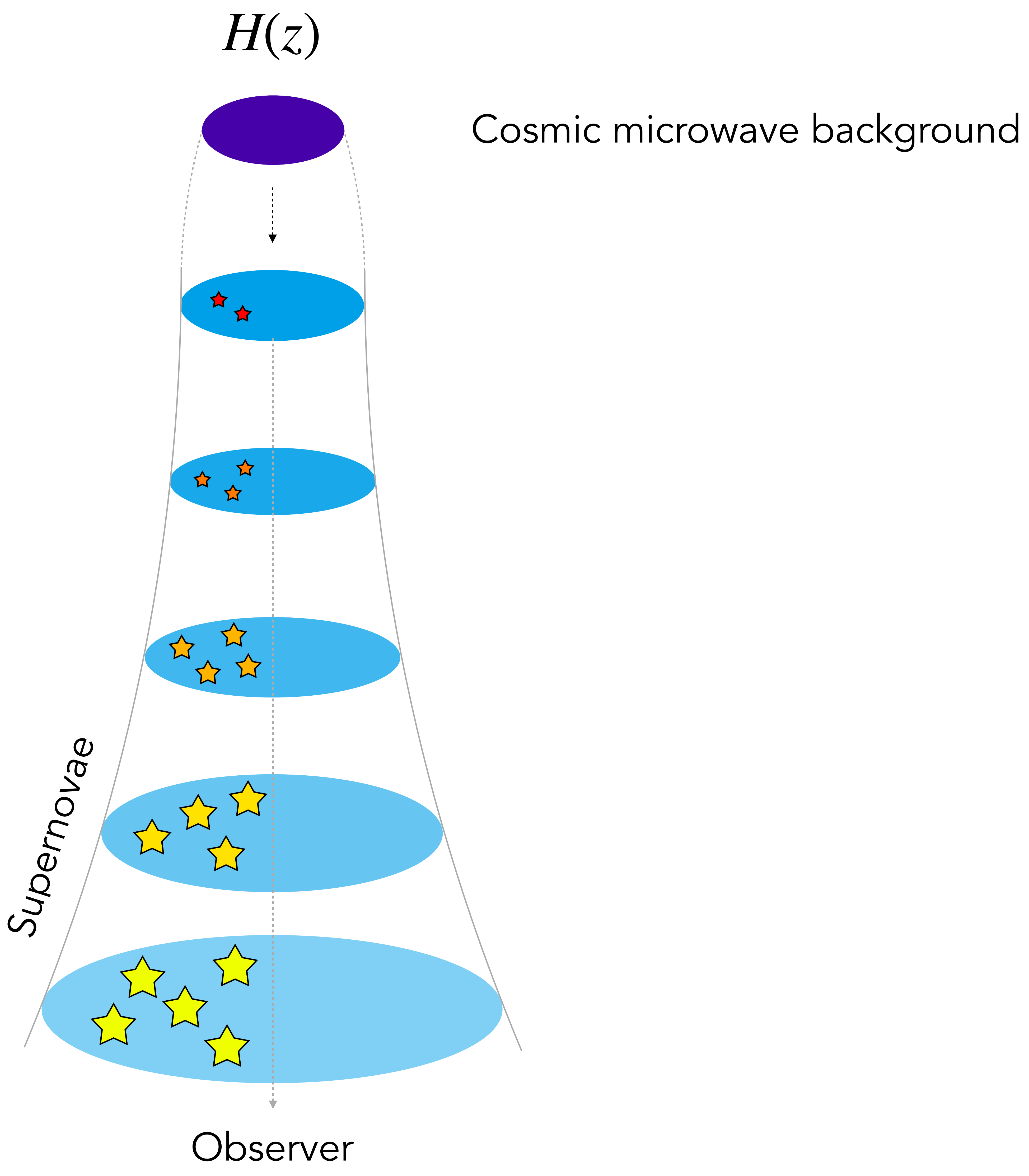

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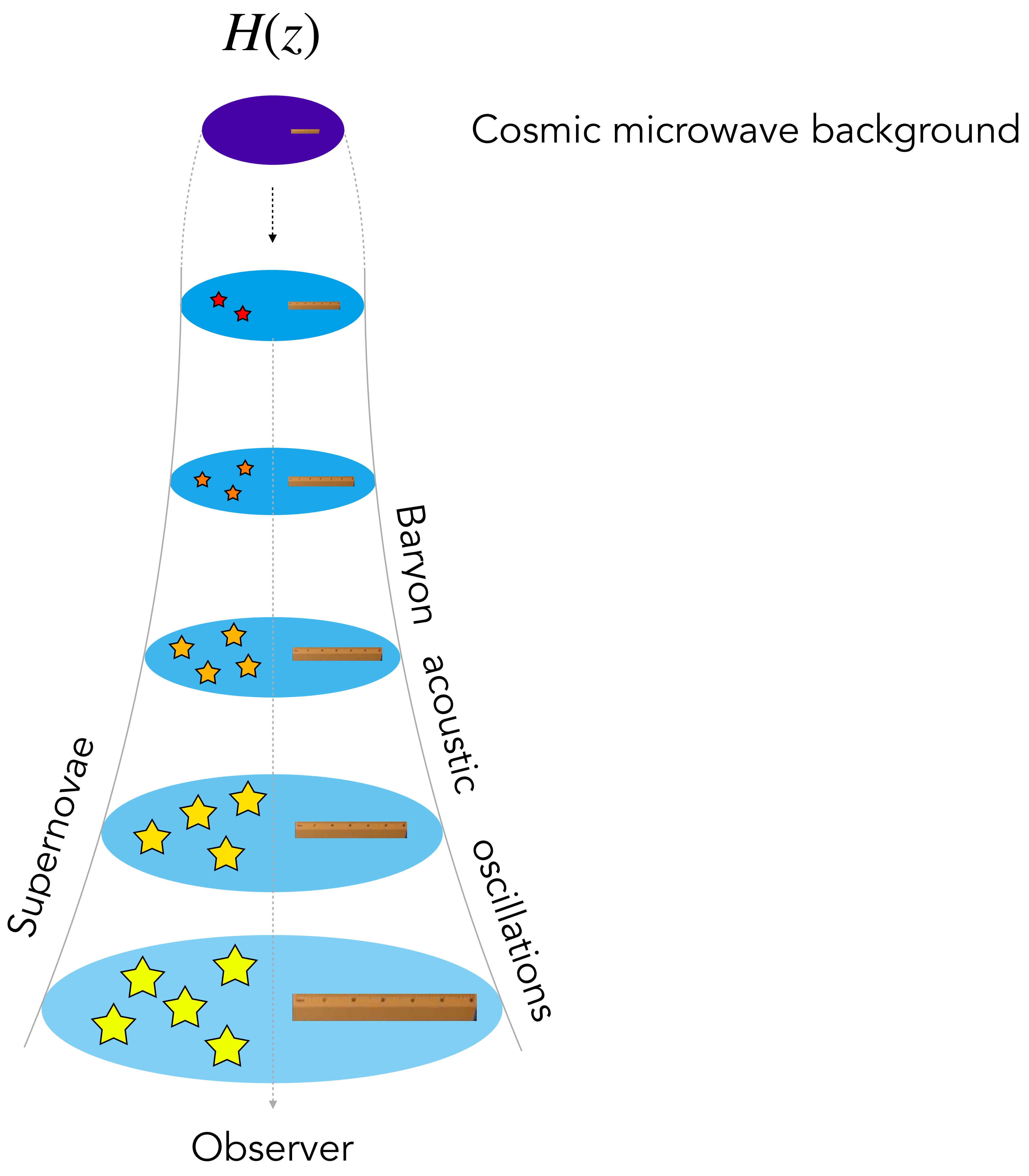
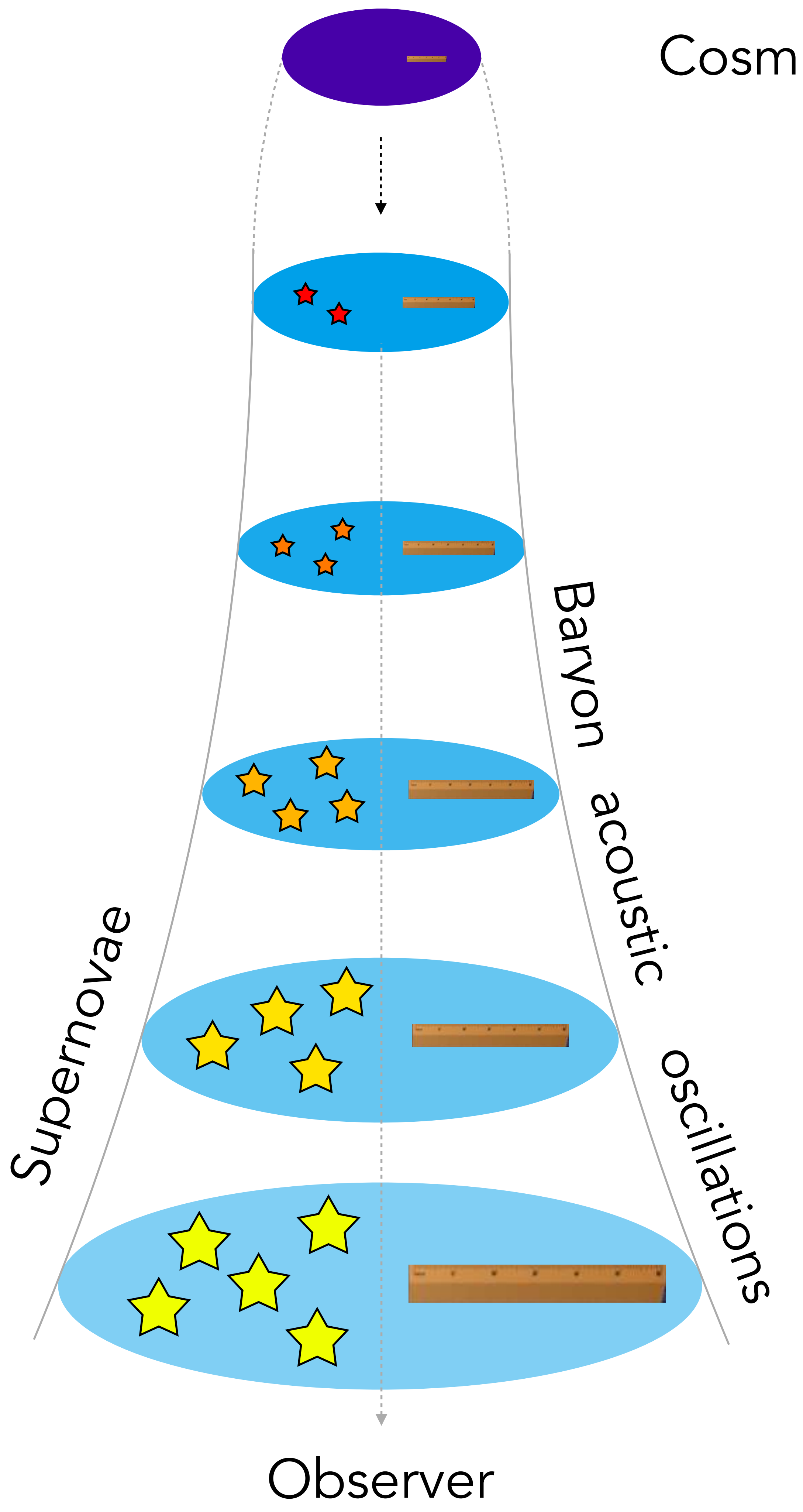


Accelerated expansion: dark energy or modified gravity?

Expansion of the Universe

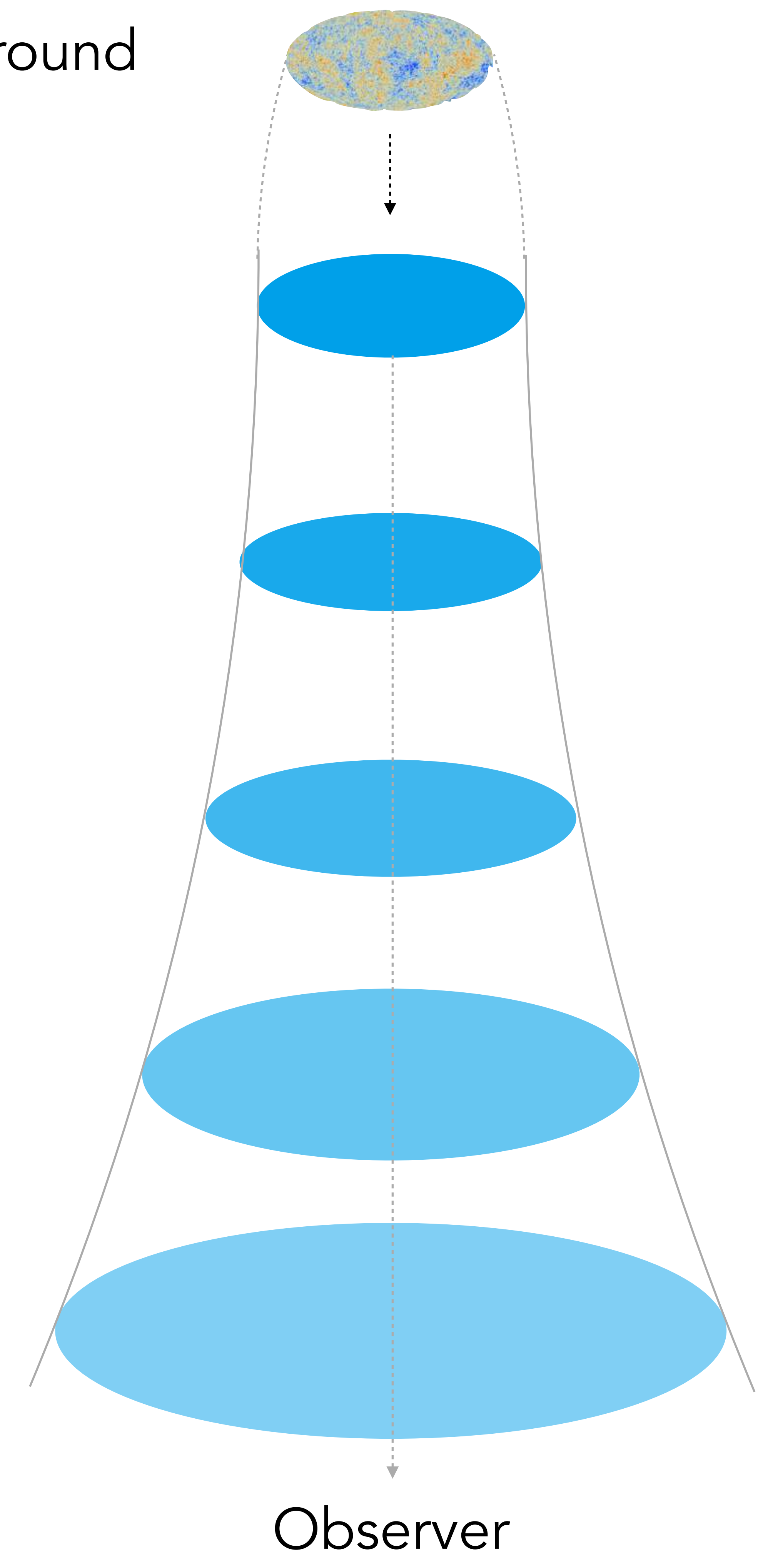
$H(z)$



Cosmic microwave background

Growth of structures

$f(z)\sigma_8(z)$



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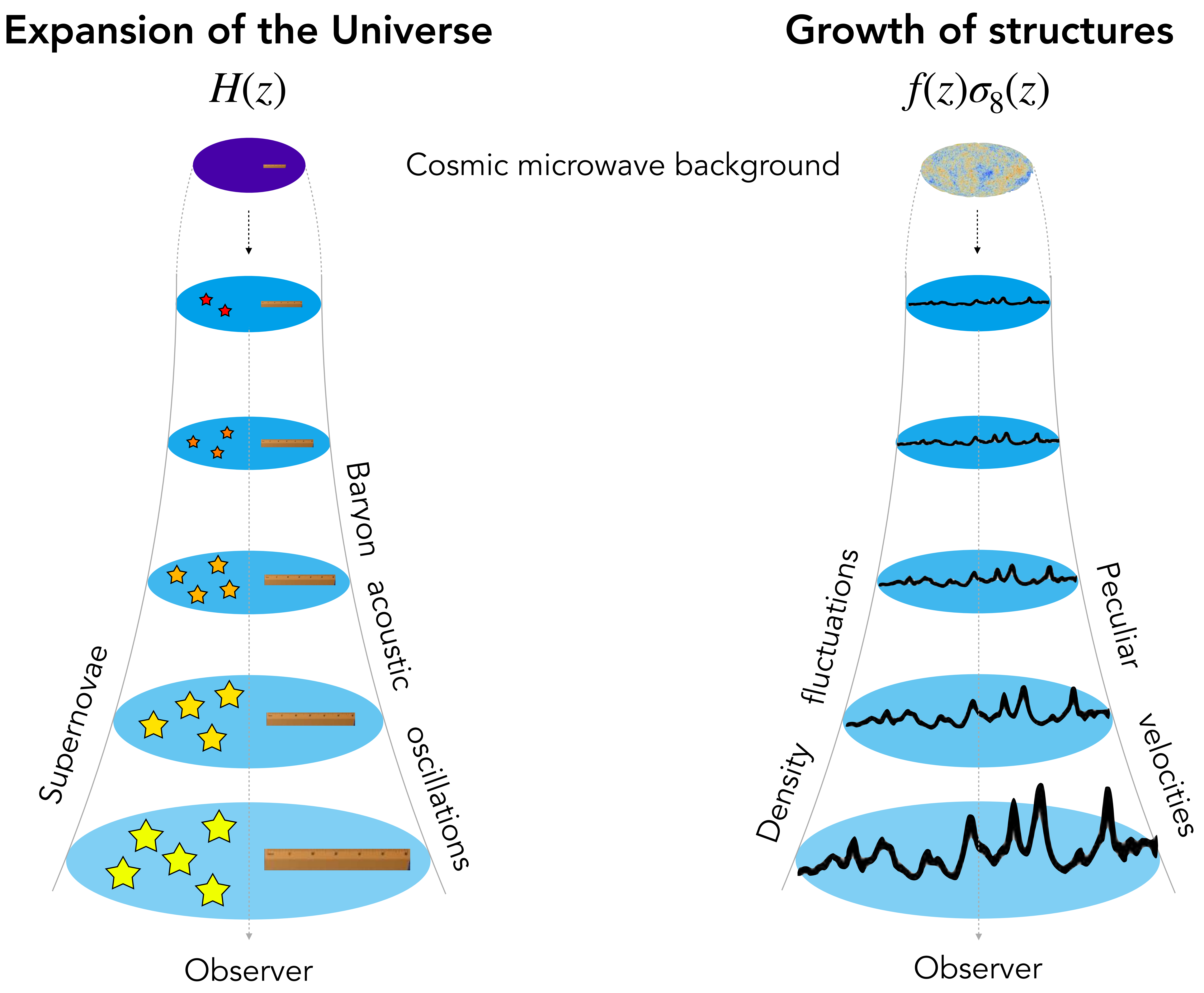

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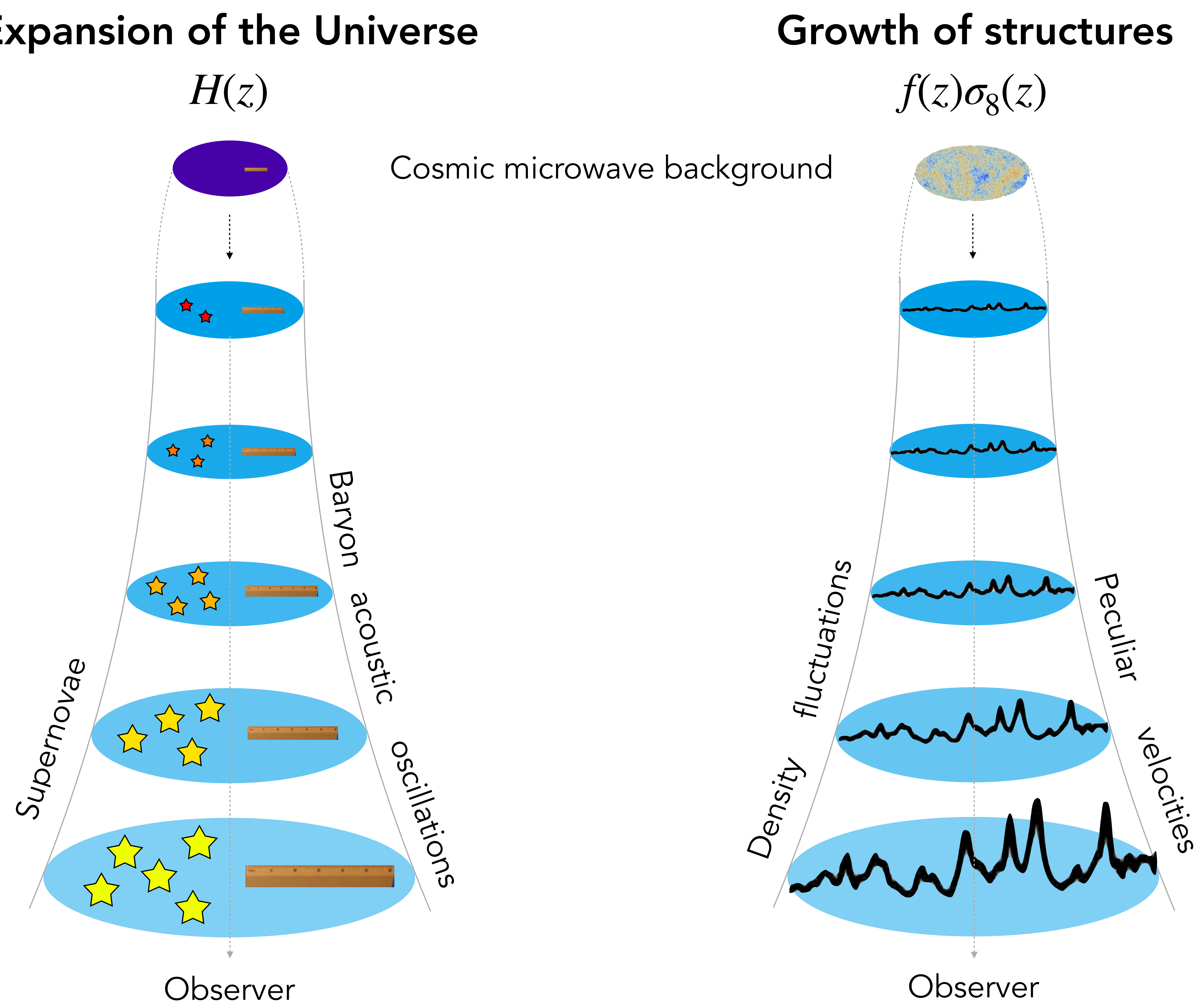
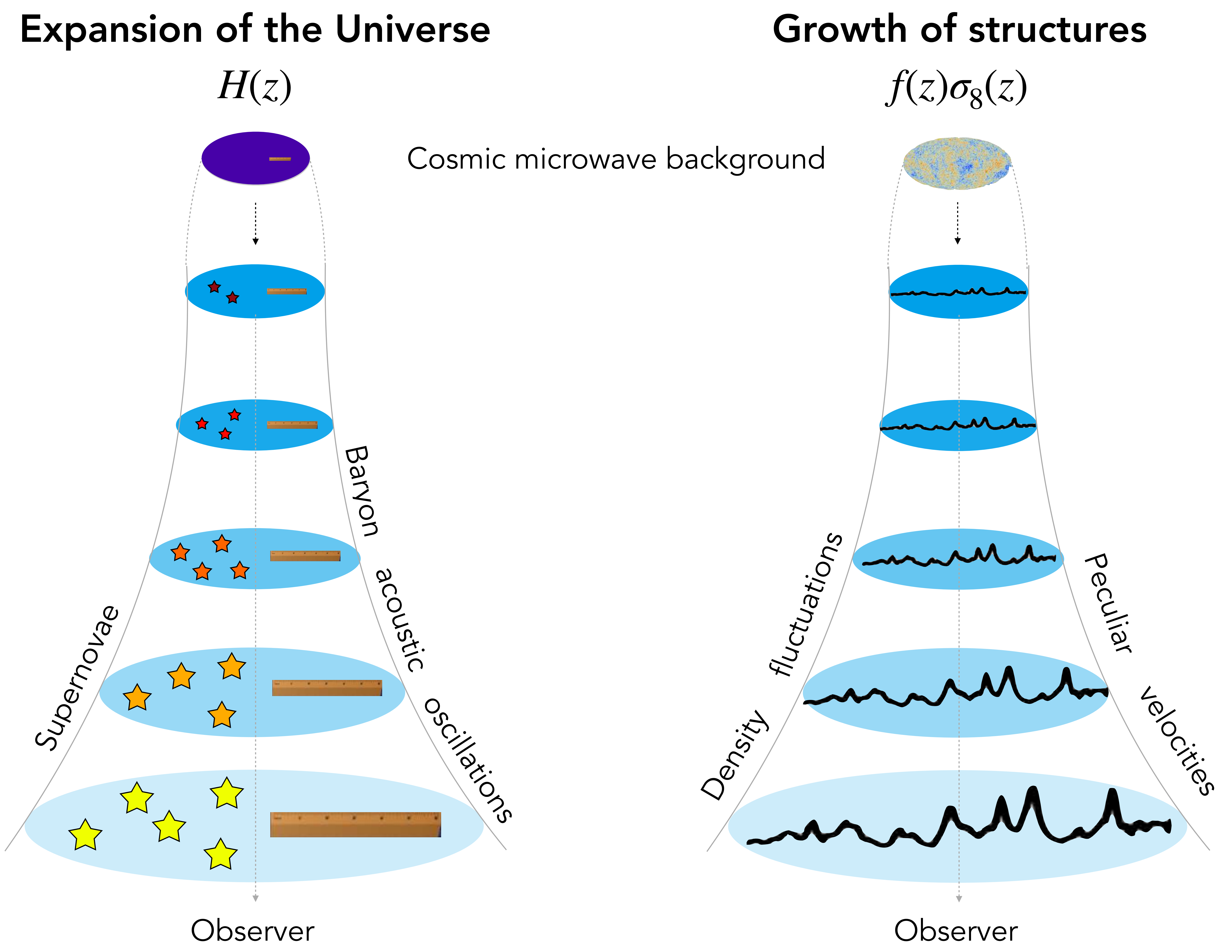


Less dark energy…

Accelerated expansion: dark energy or modified gravity?



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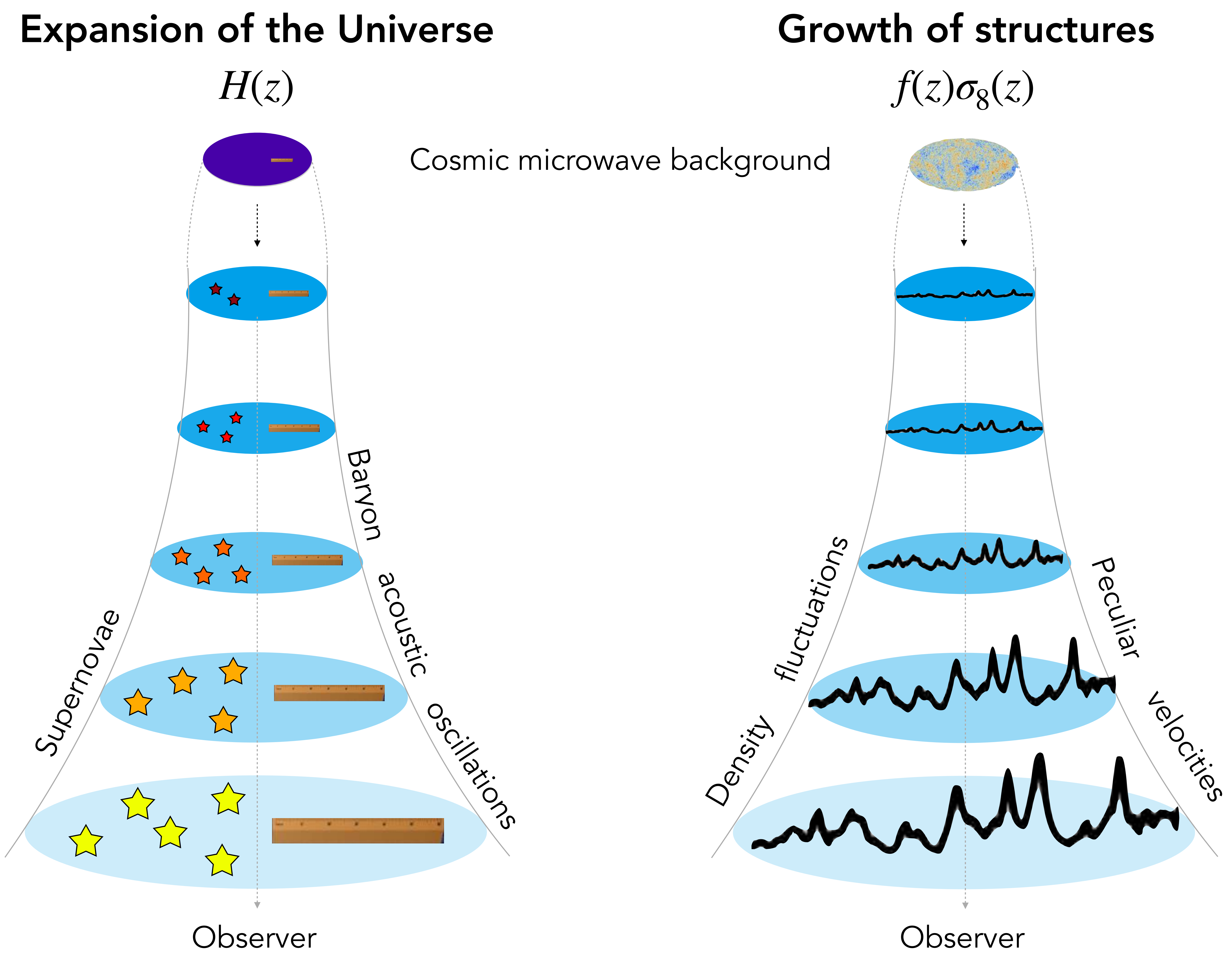
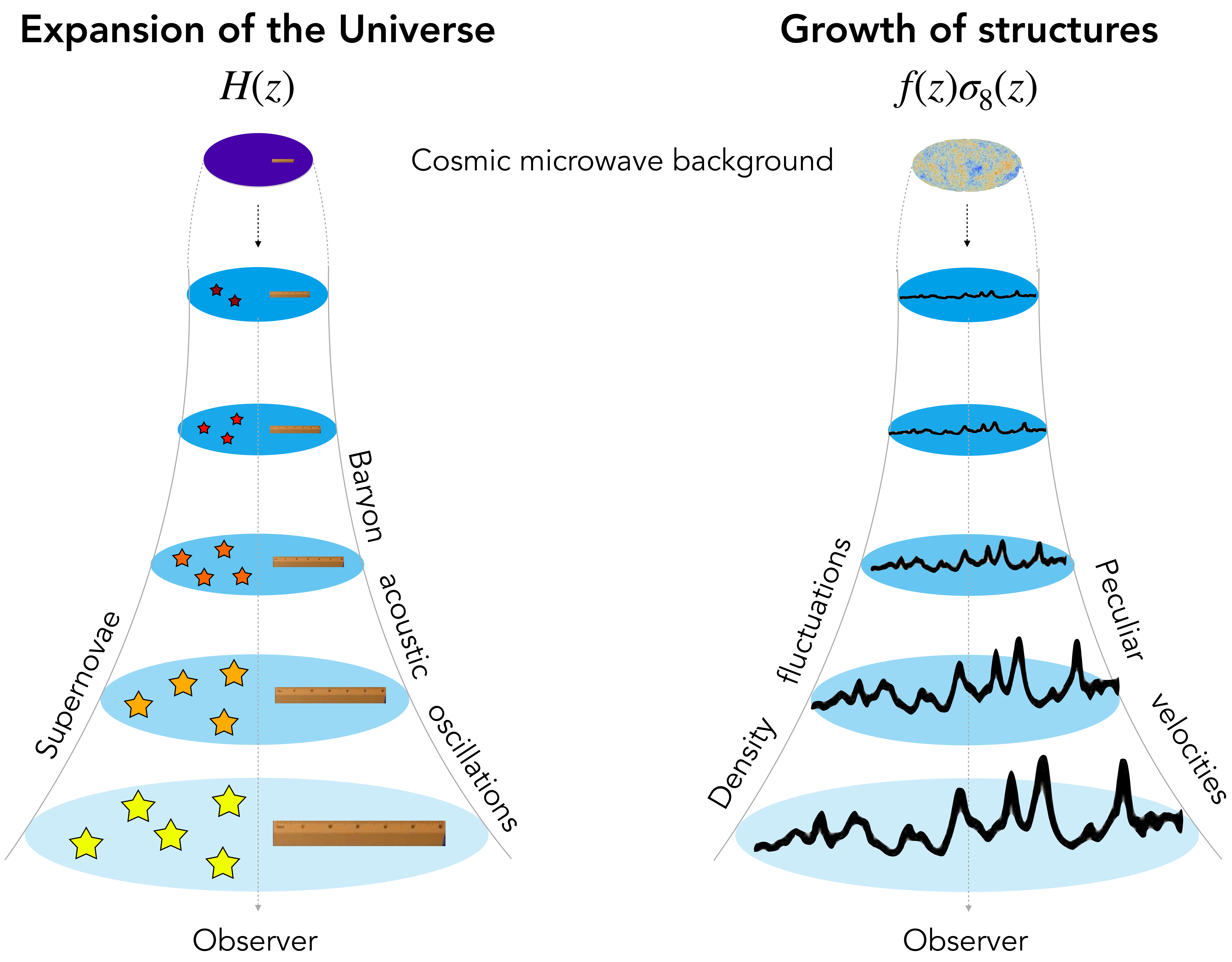


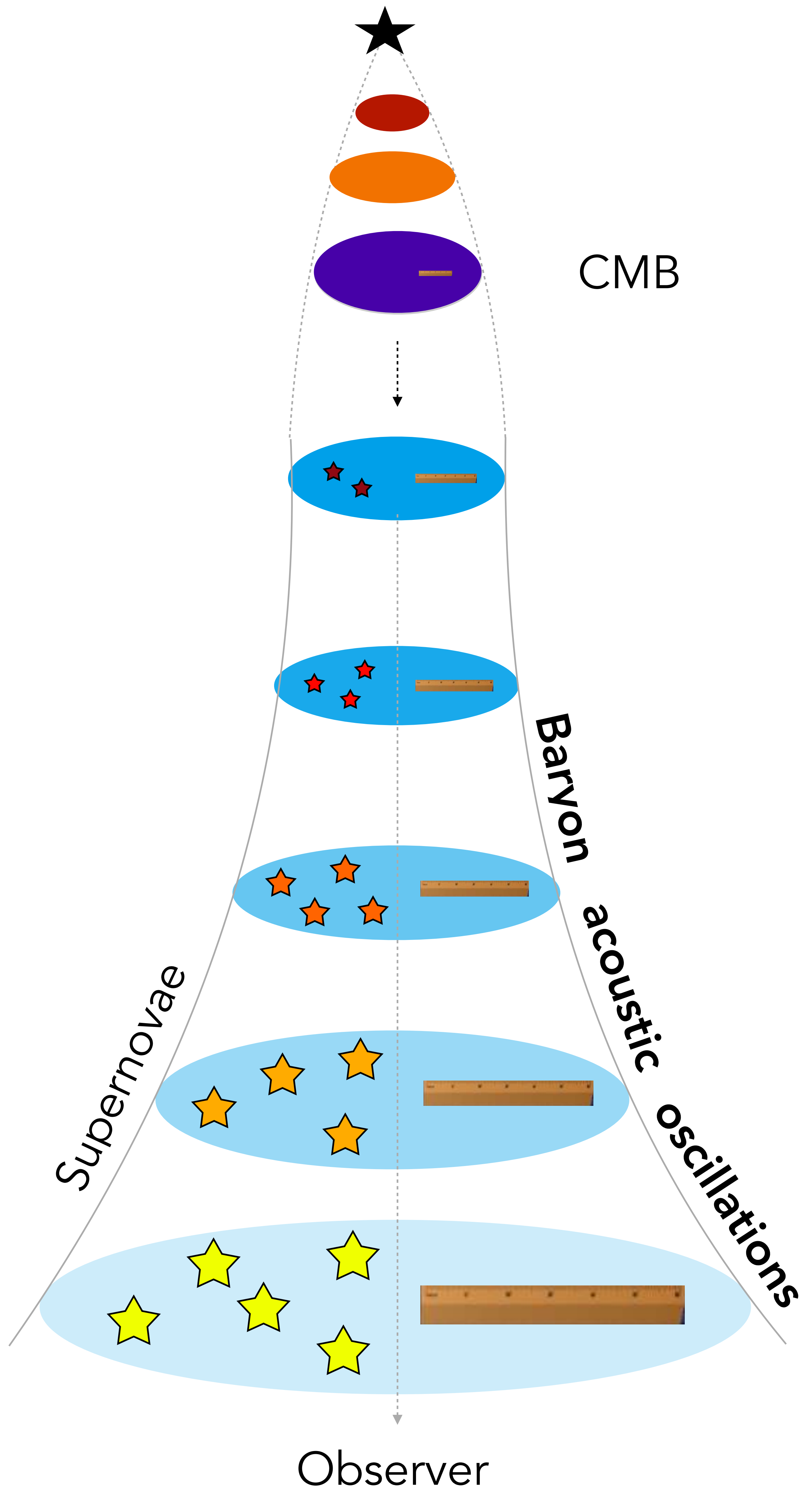
… or modified gravity?

Accelerated expansion: dark energy or modified gravity?



… or modified gravity?

BAO: Baryon Acoustic Oscillations



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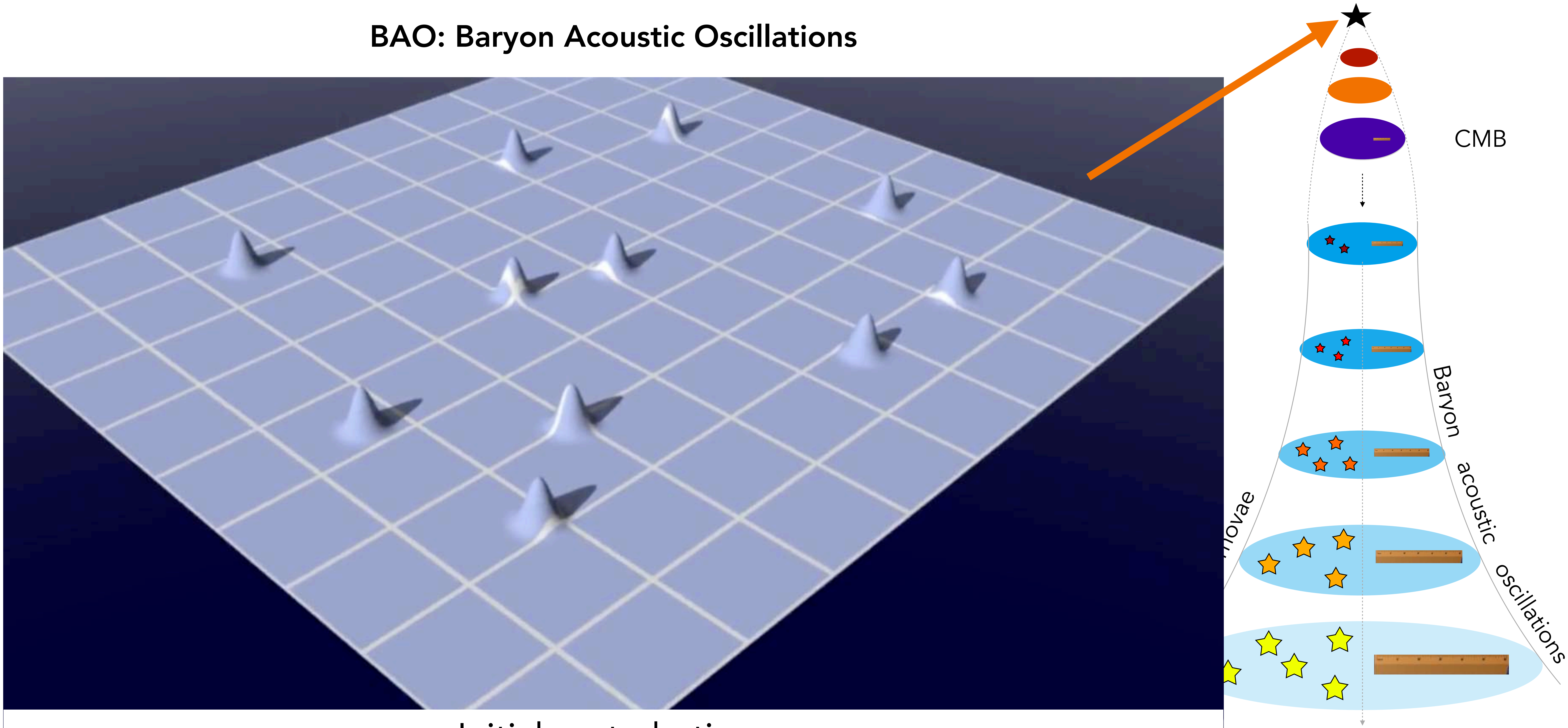
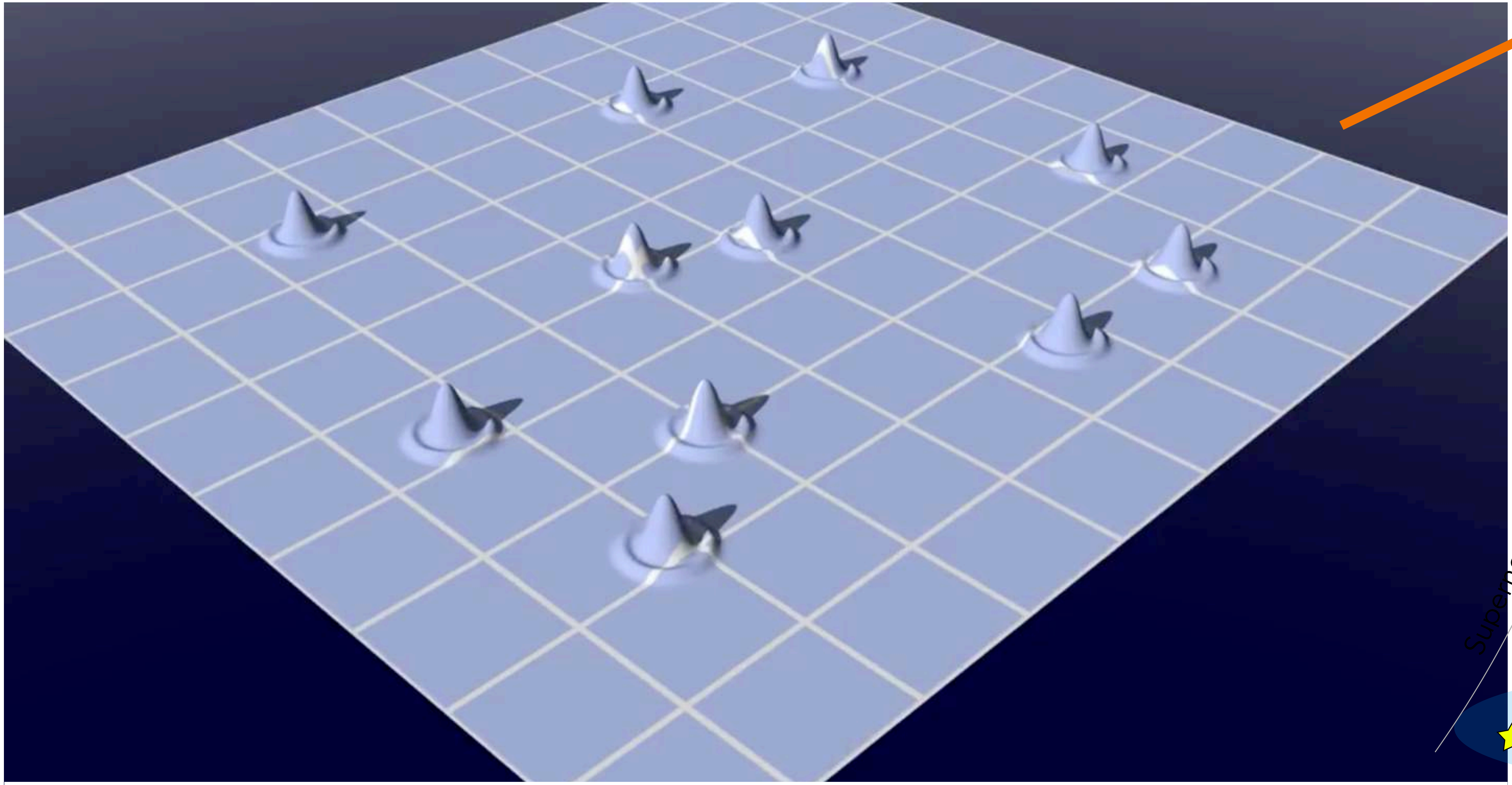


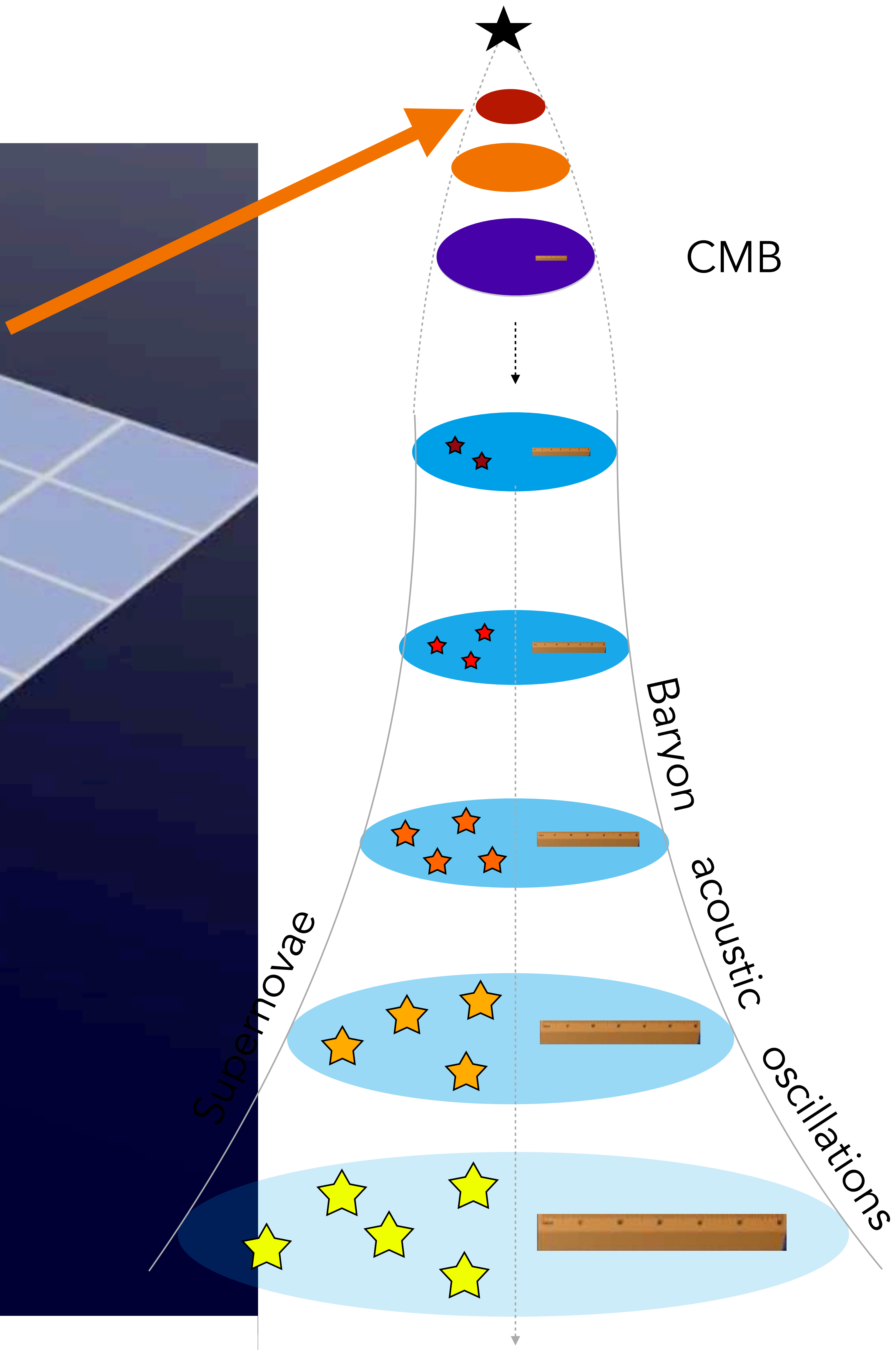
Initial perturbations

Credit: CAASTRO Link to video

BAO: Baryon Acoustic Oscillations



Sound wave propagation in plasma



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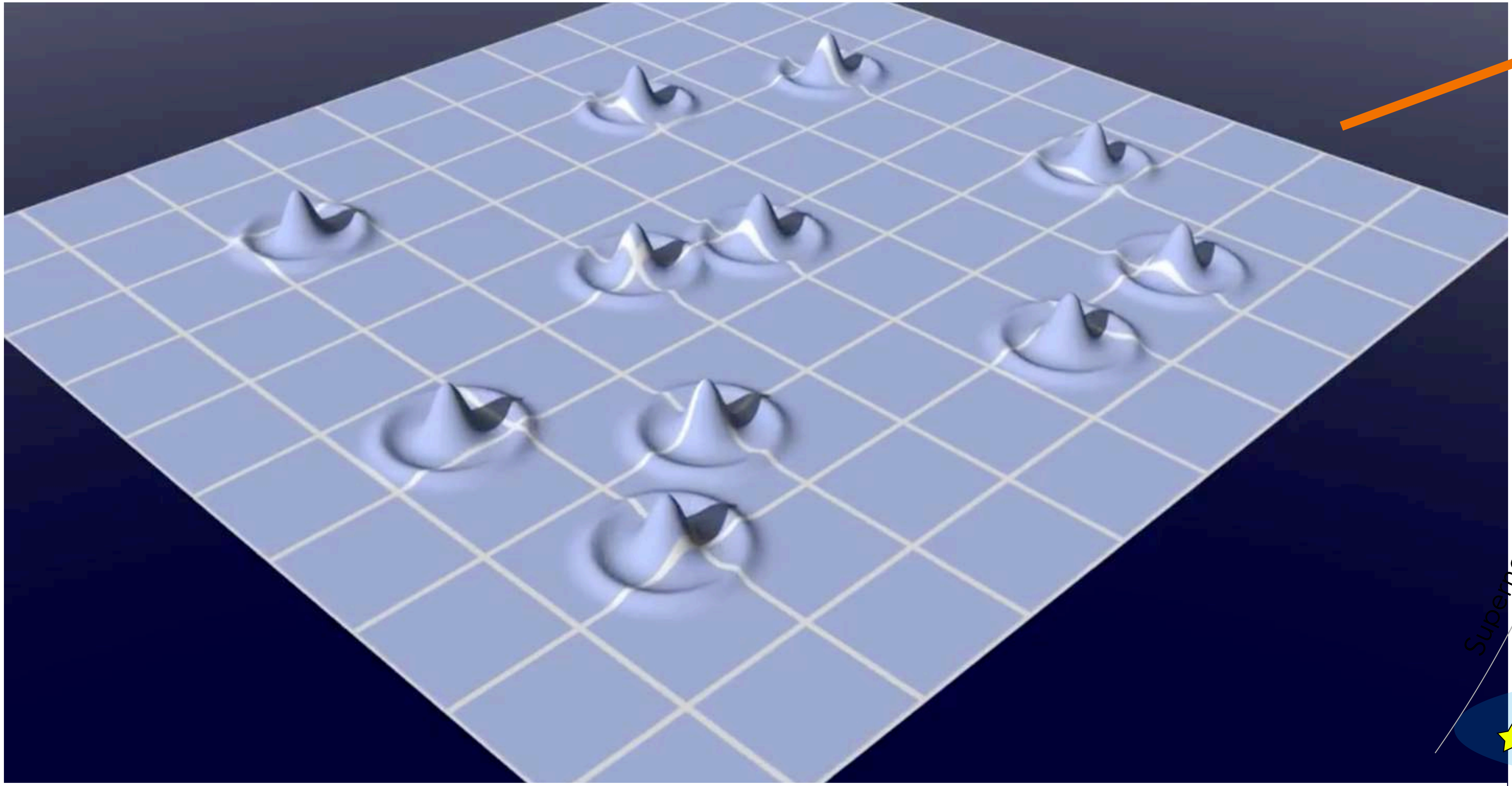

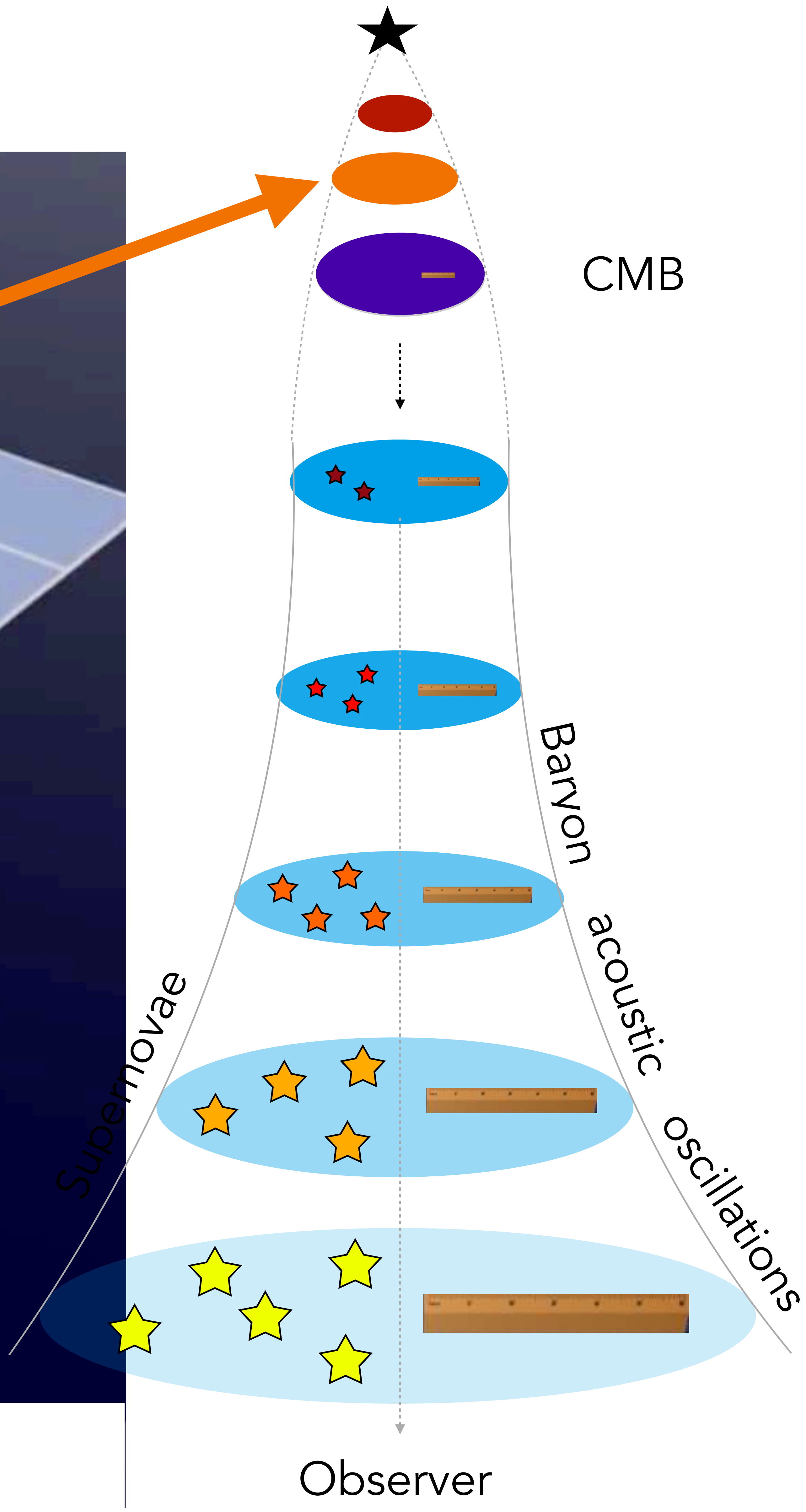

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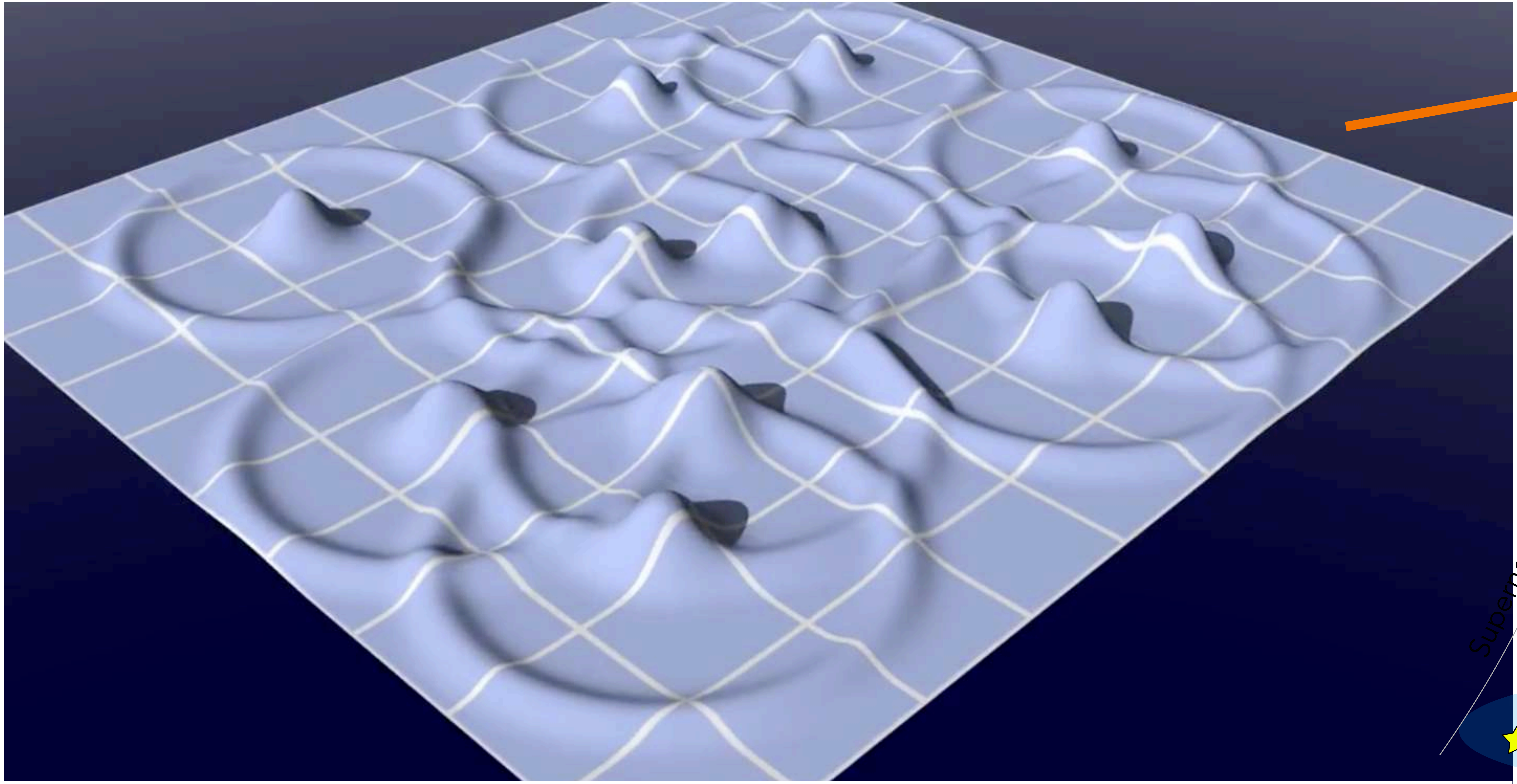
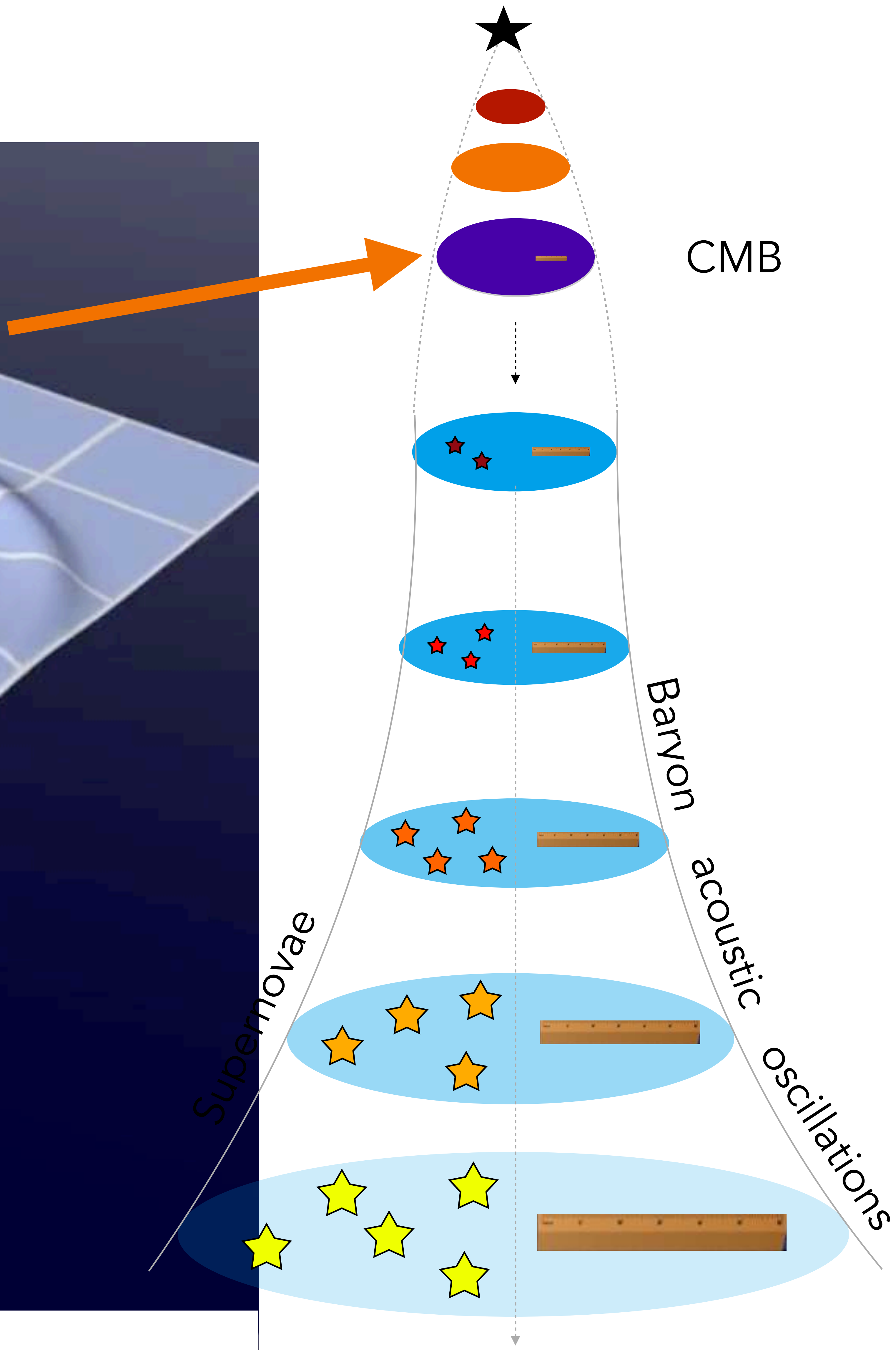


Sound wave propagation freezes at $r_d \sim 150$ kpc



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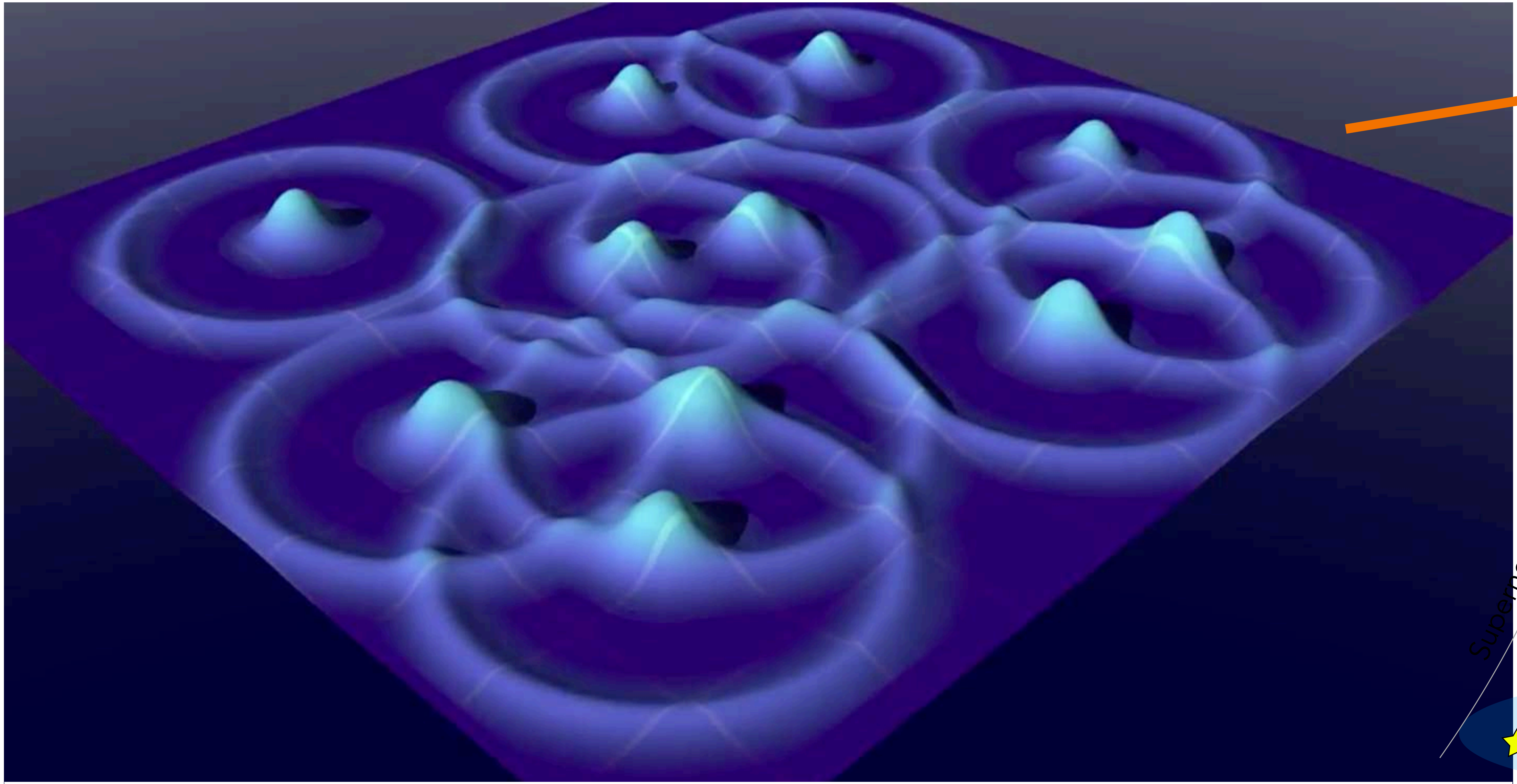

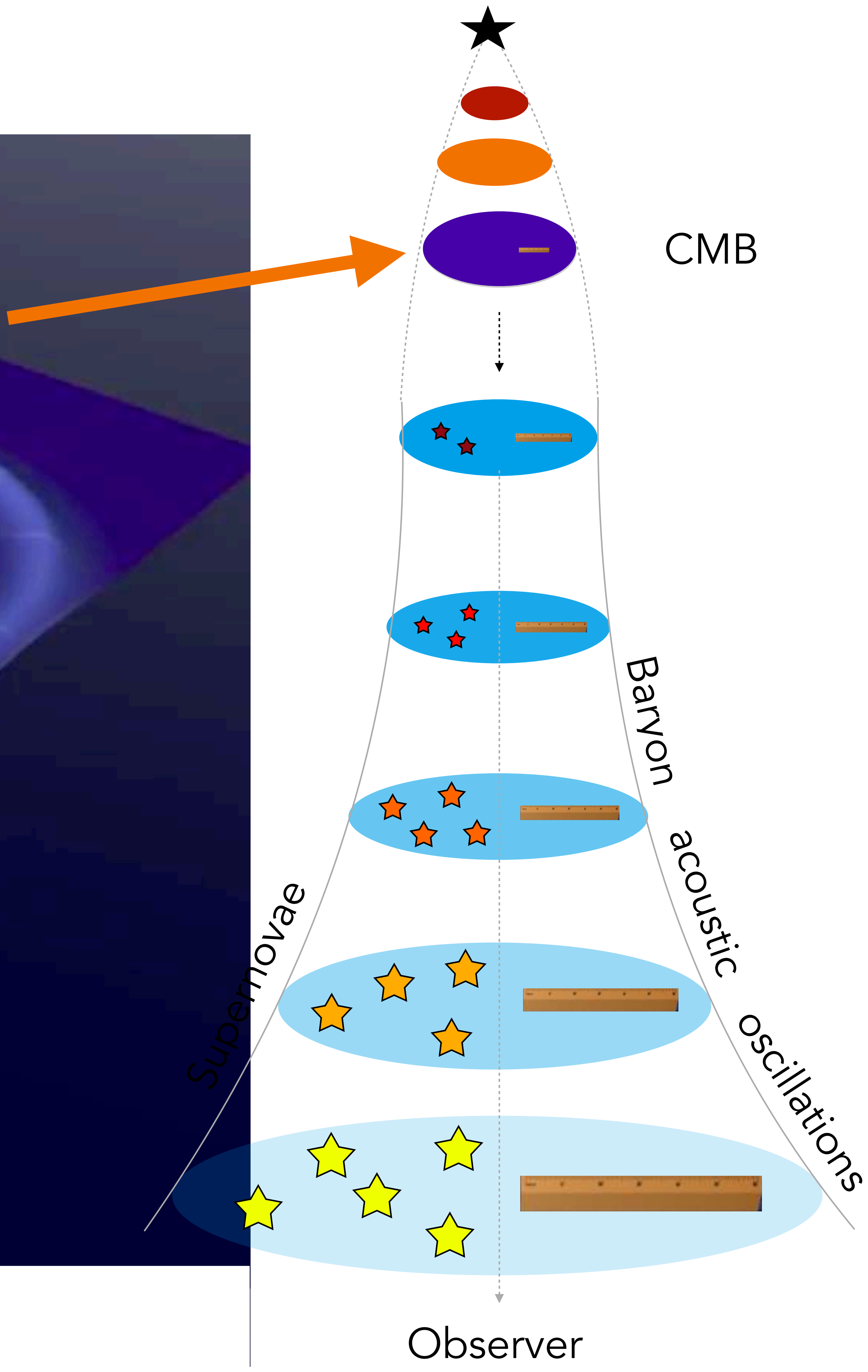

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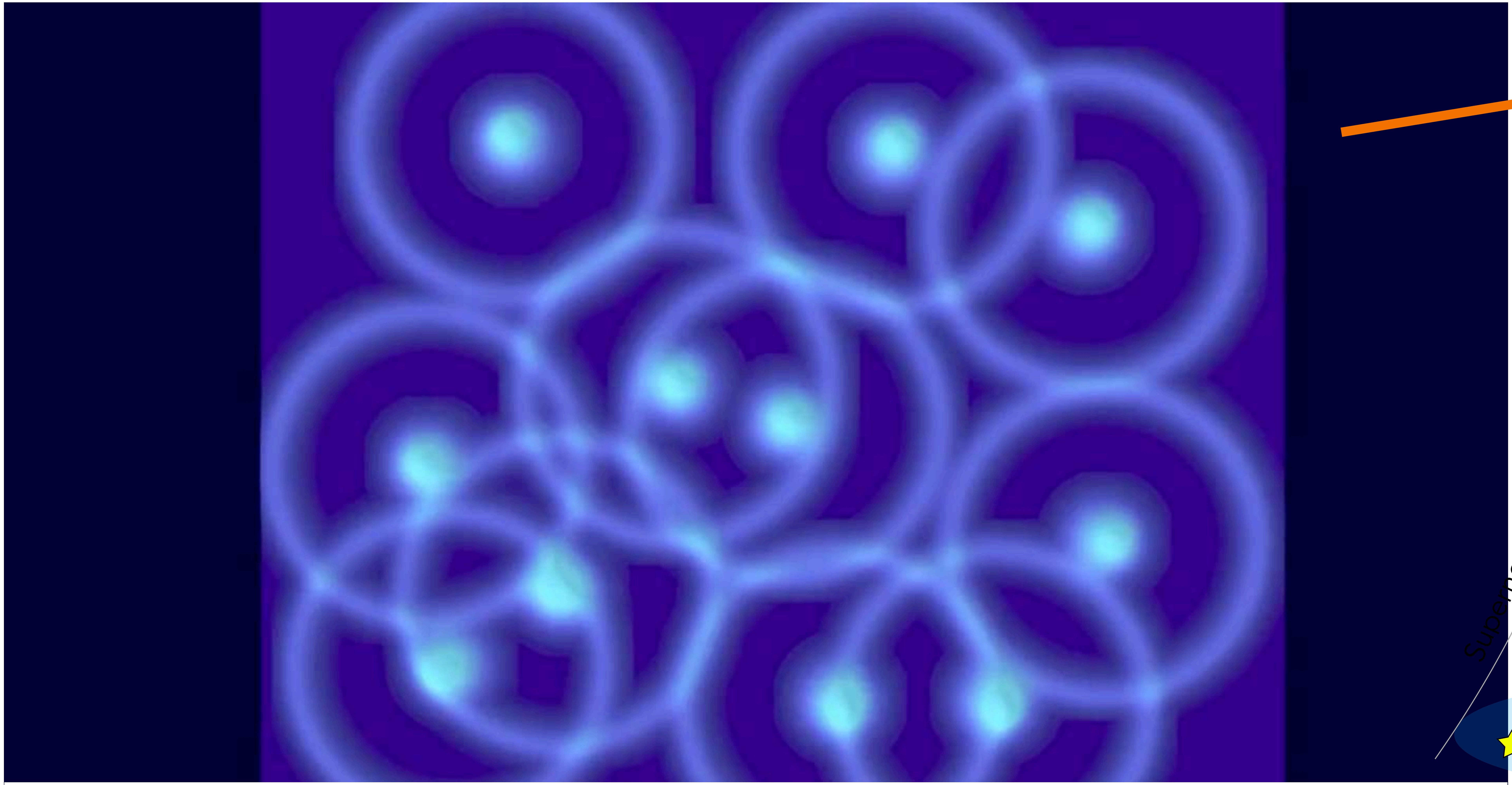
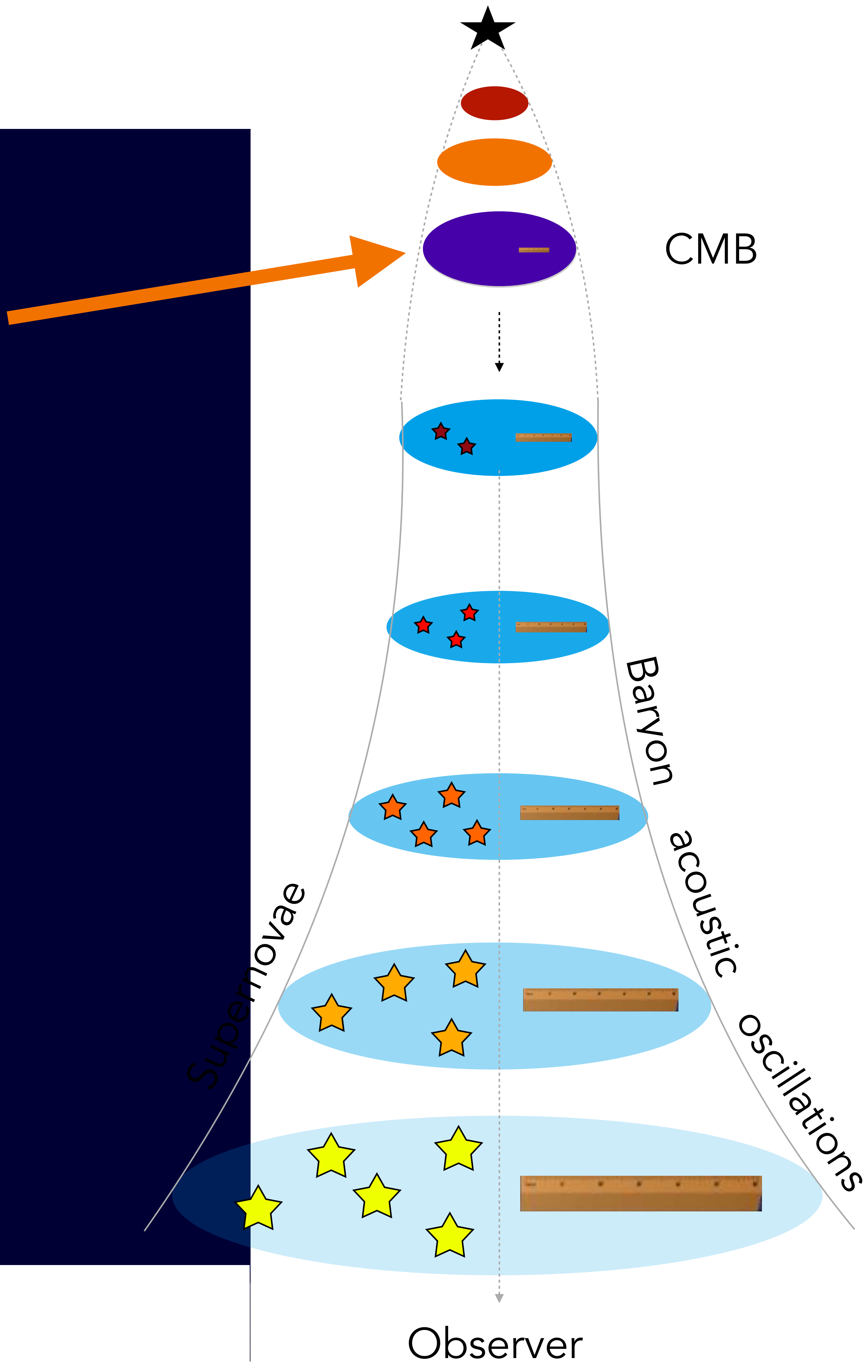


BAO leave this imprint in the matter distribution



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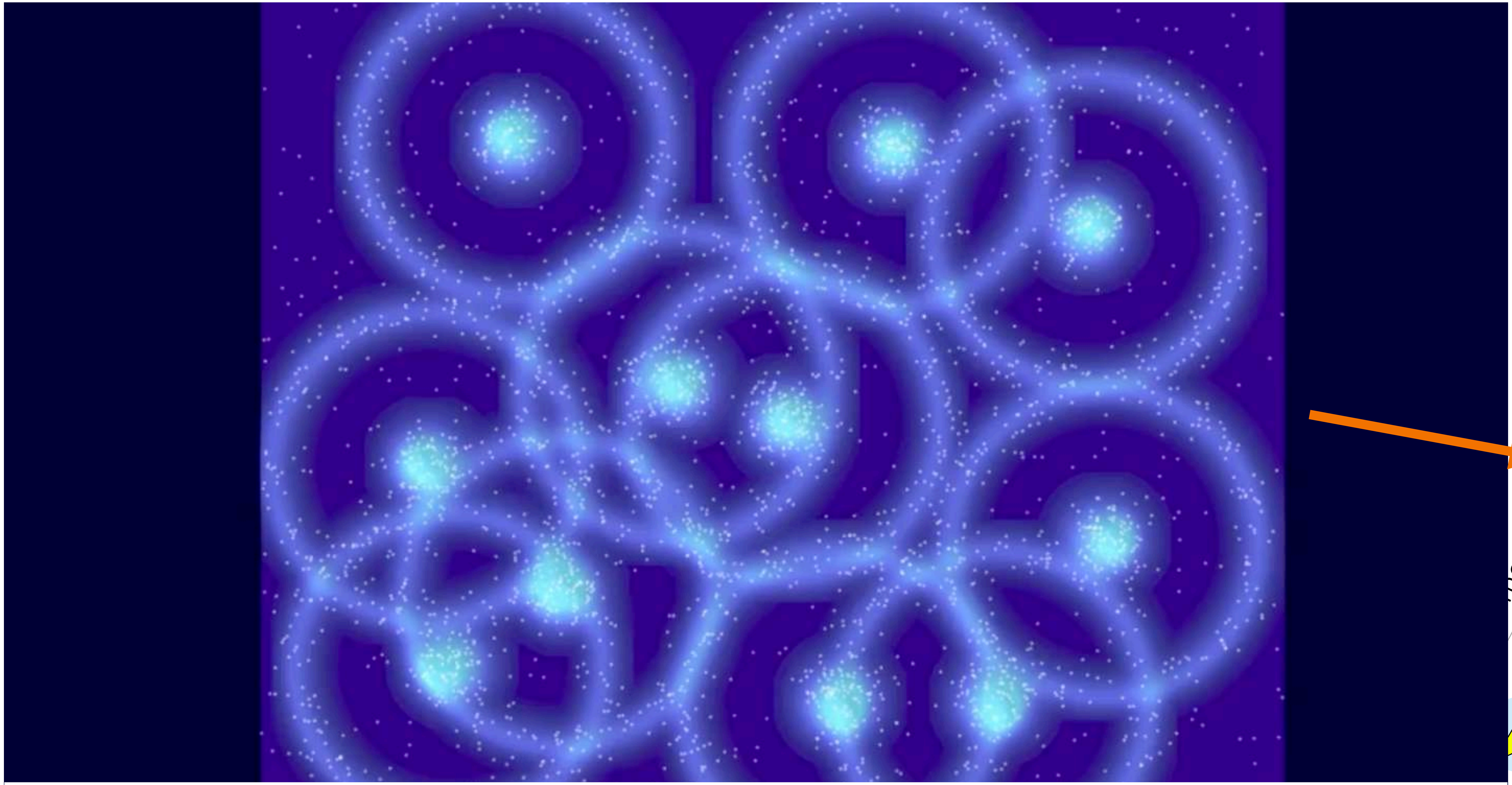
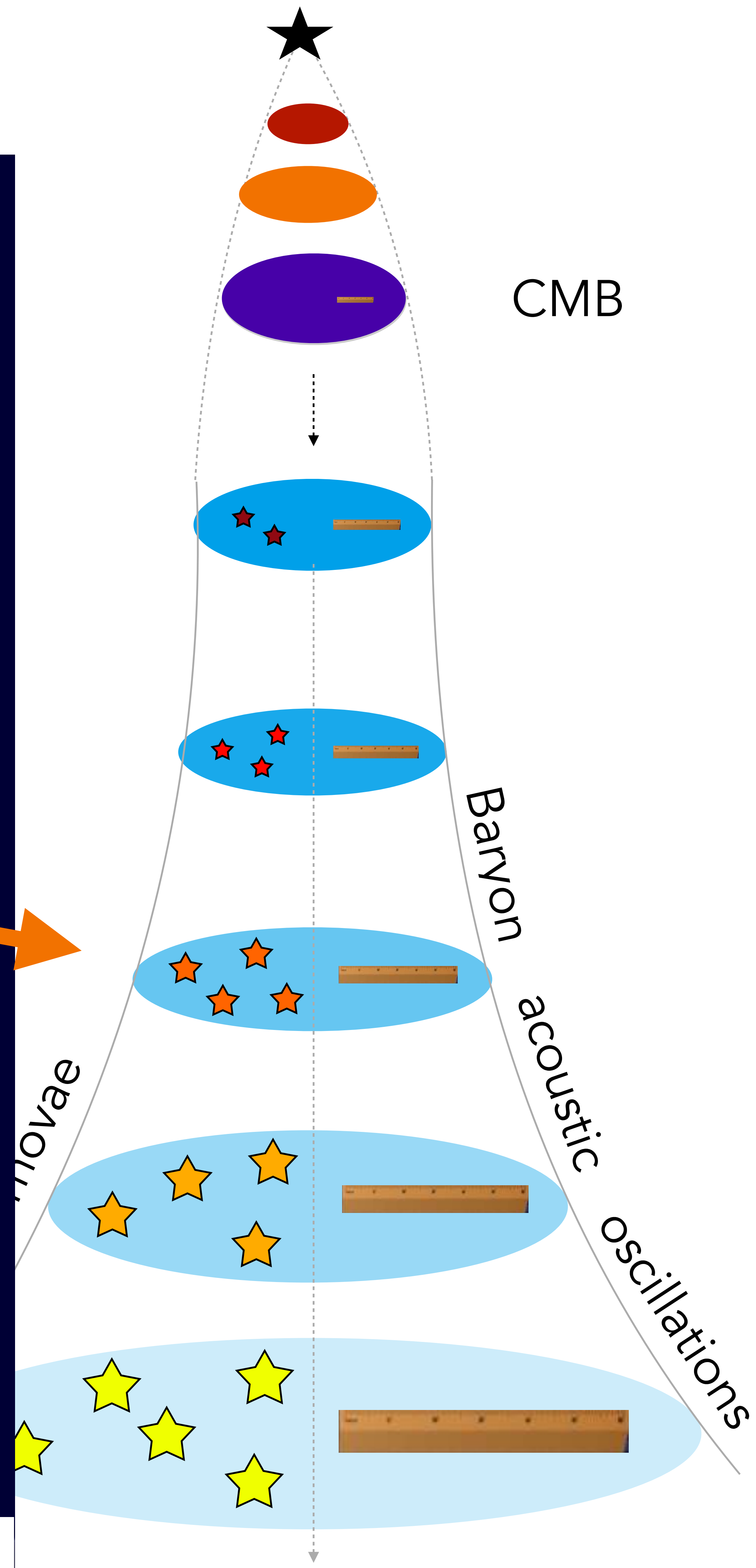


and galaxies (dots) form



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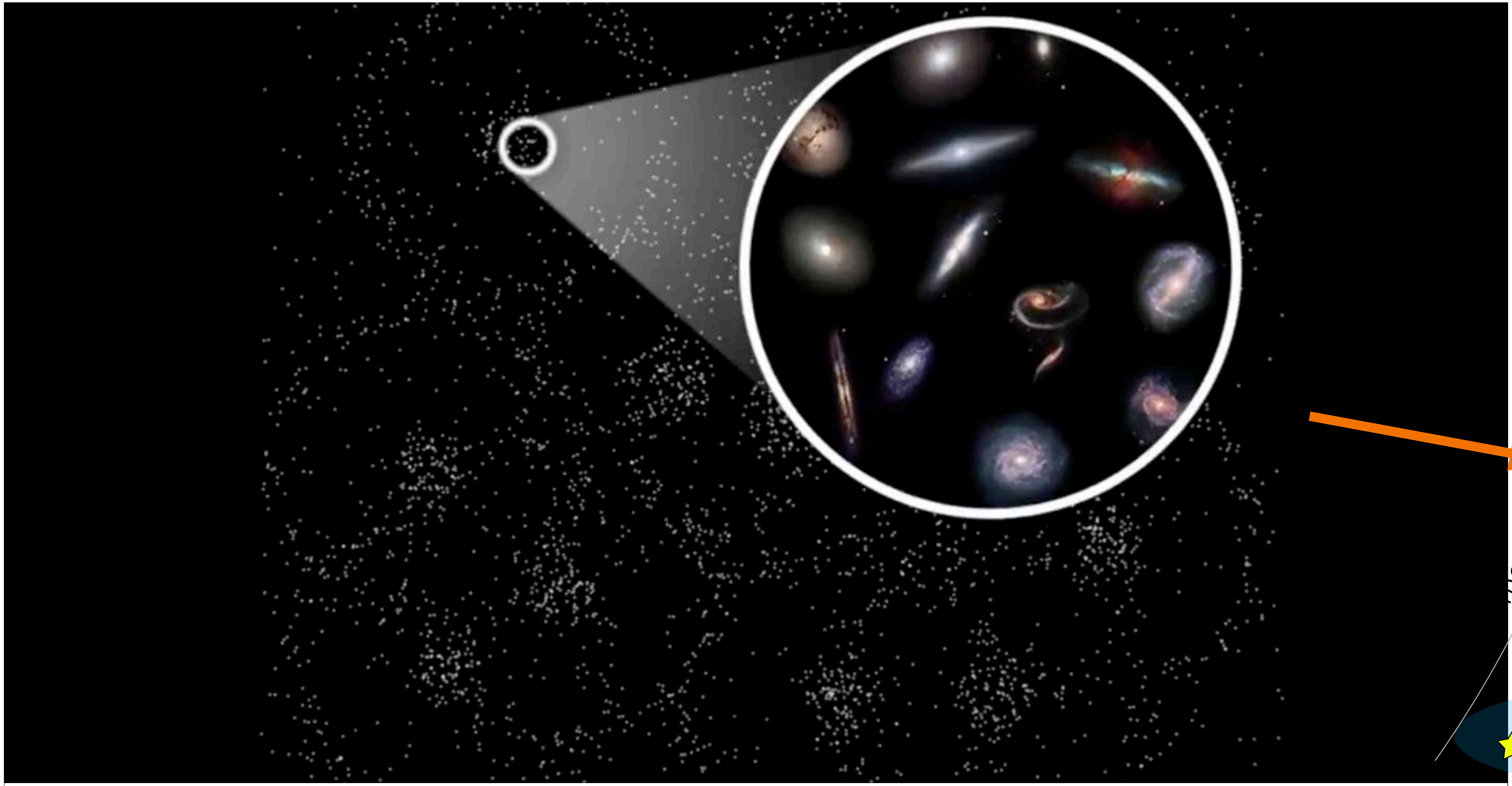

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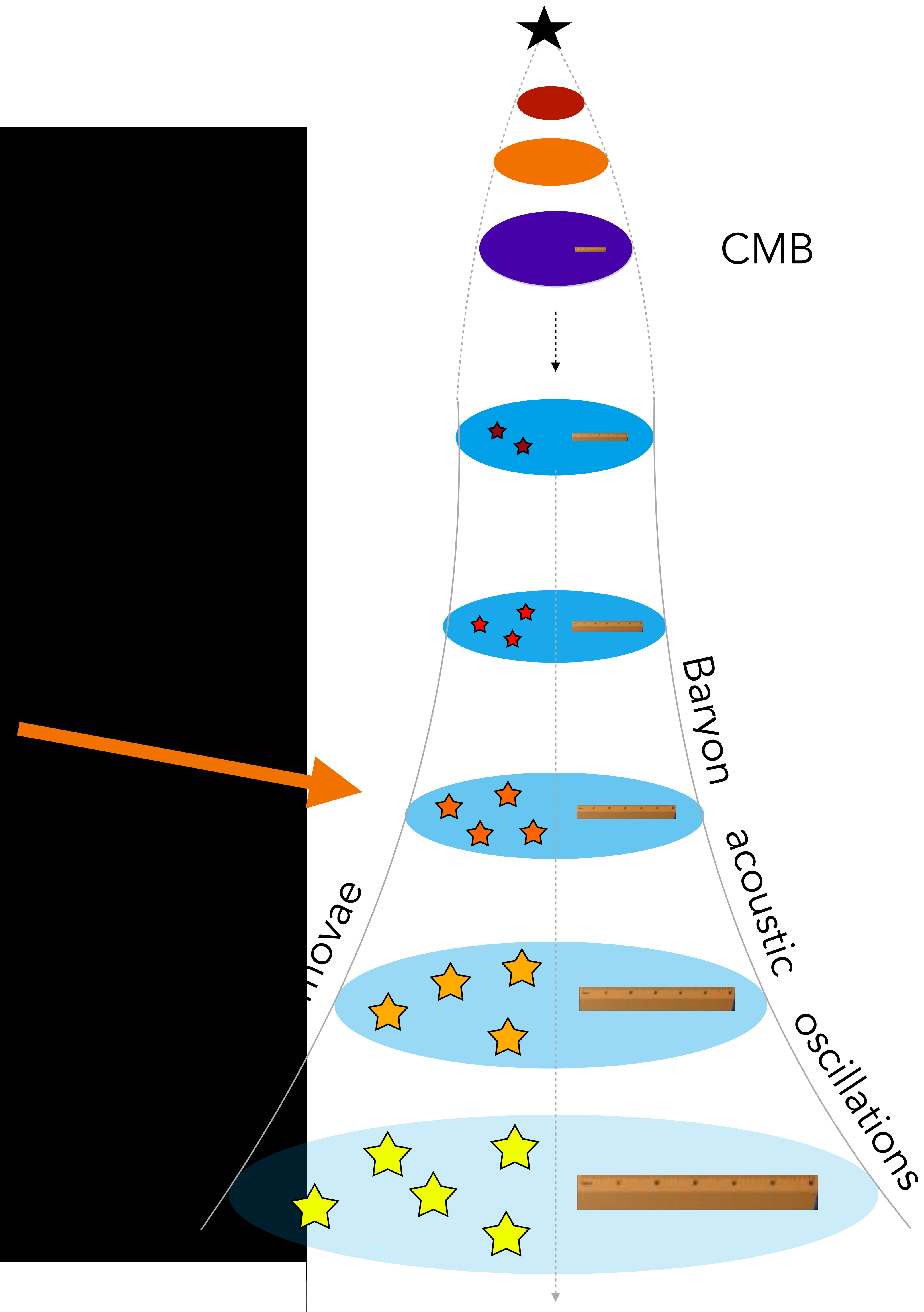

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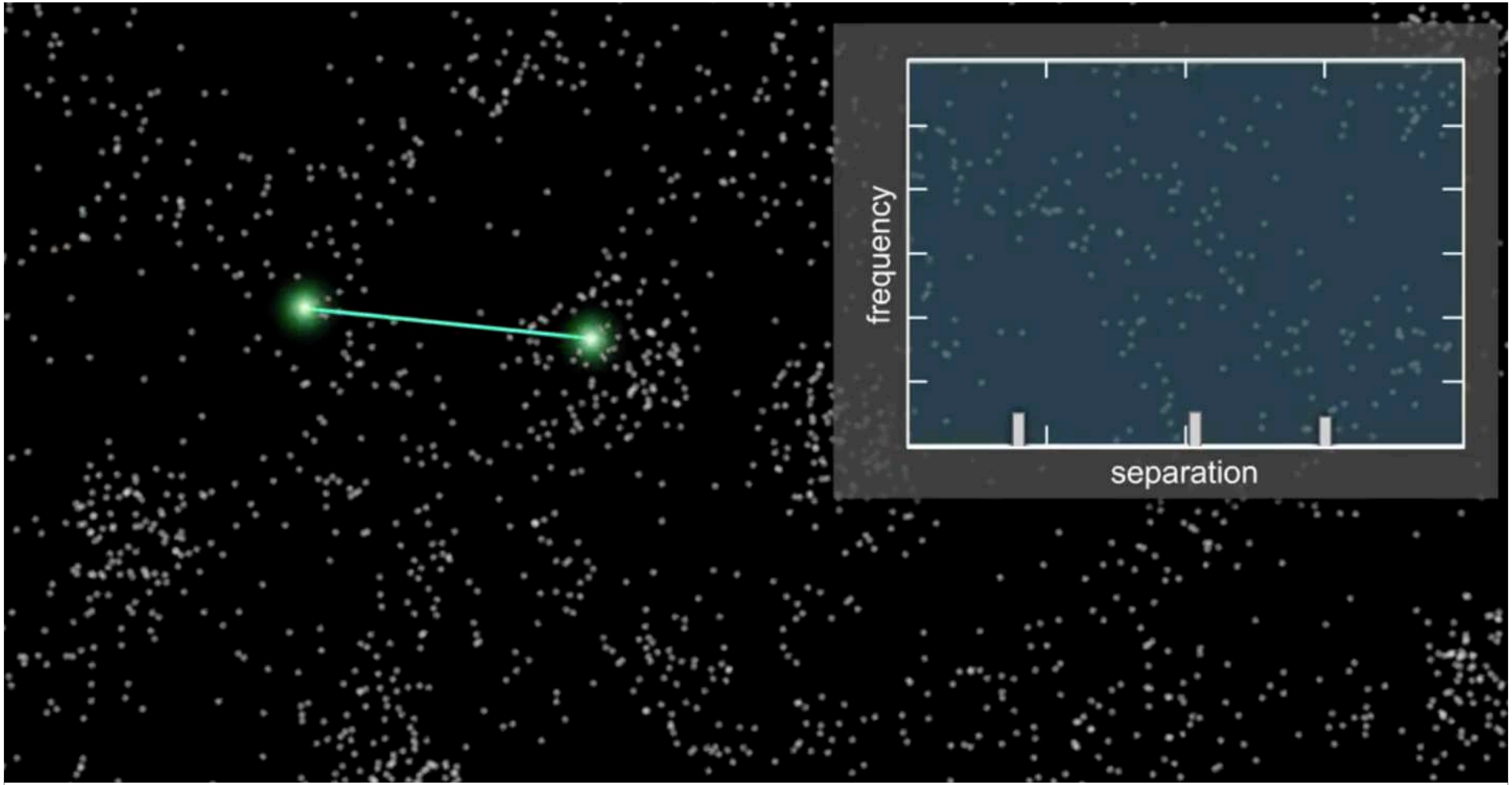

We count pairs of galaxies versus separation

Credit: CAASTRO Link to video

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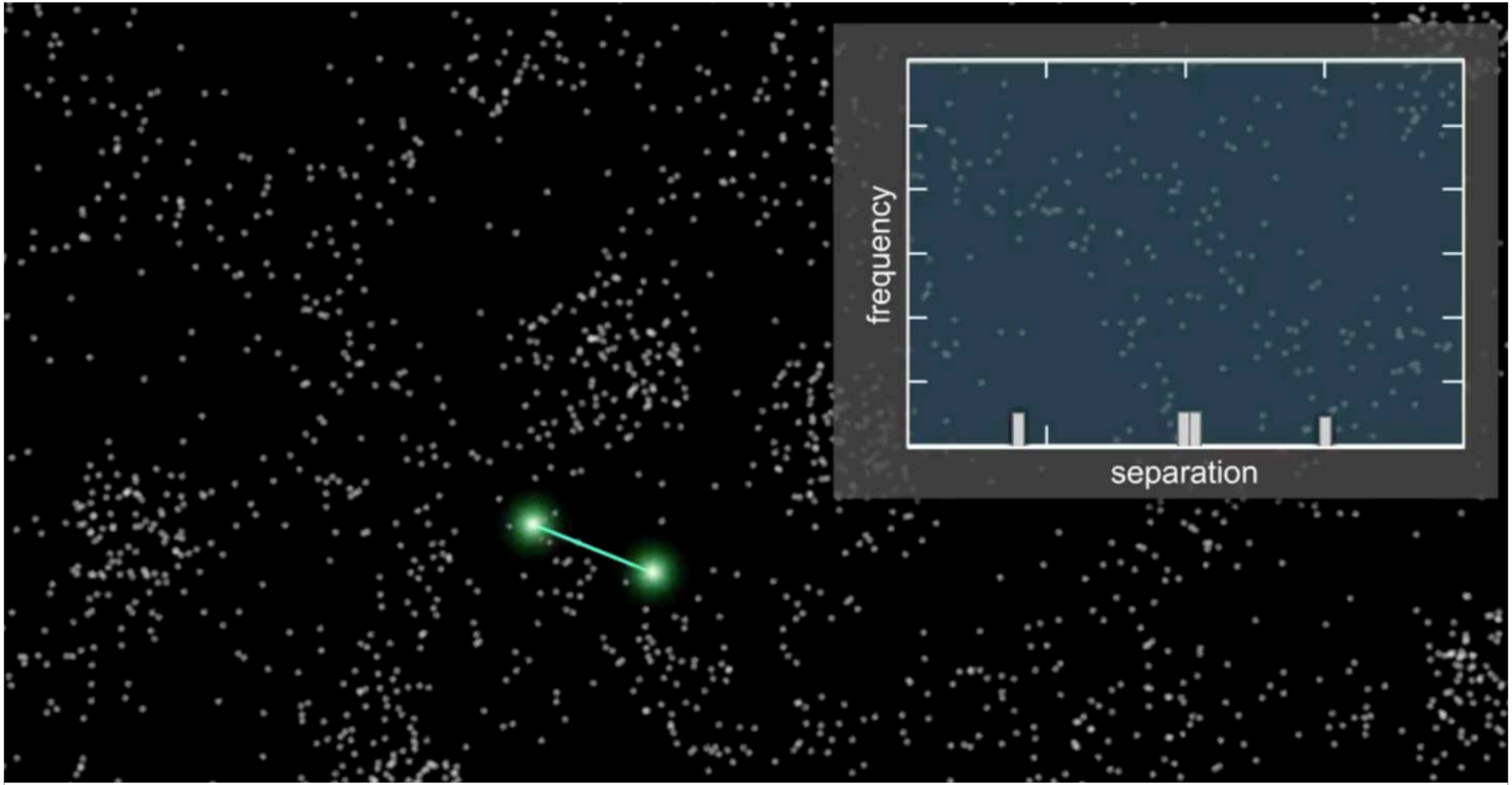

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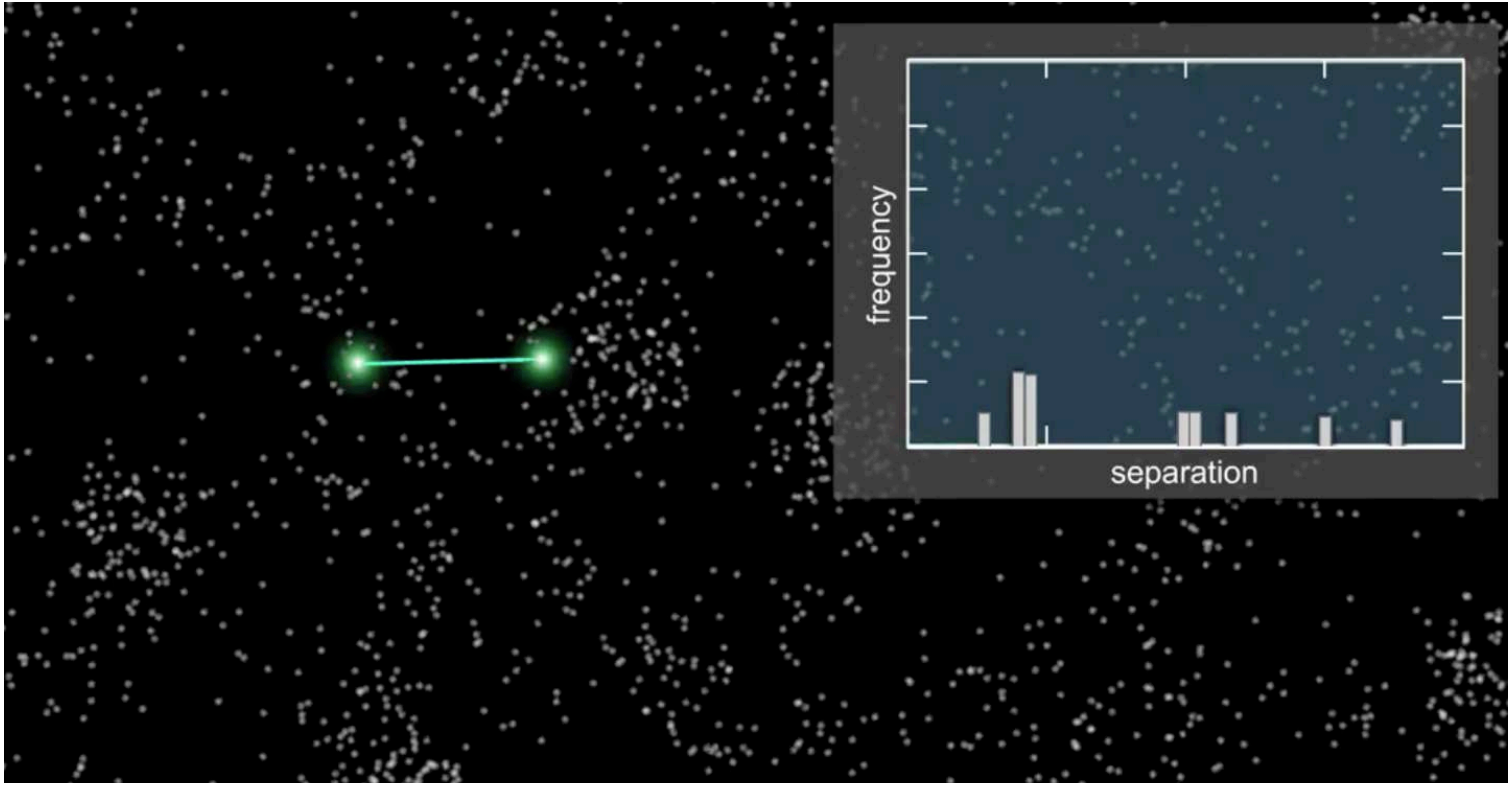

for all pairs of galaxies

Credit: CAASTRO Link to video

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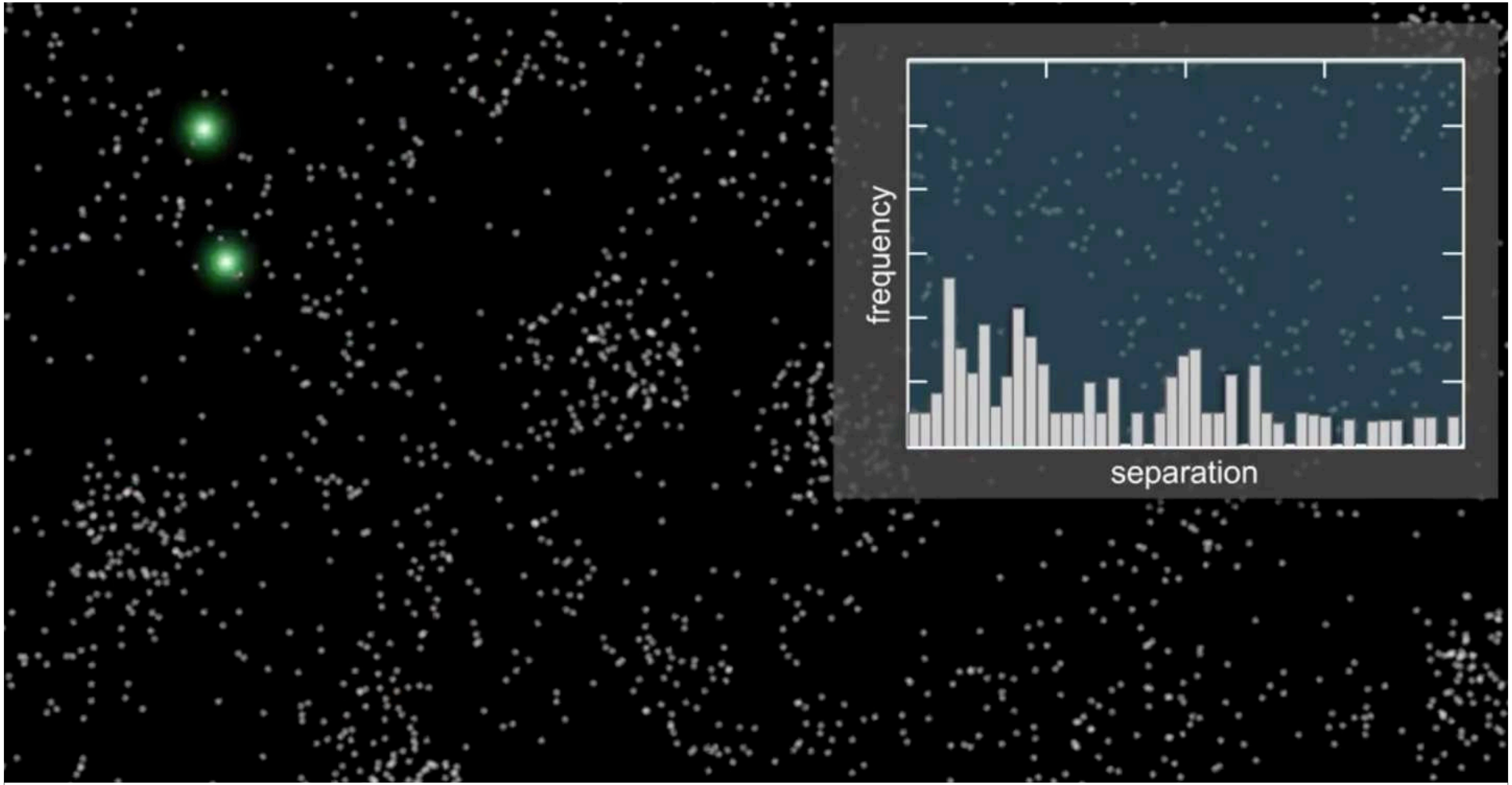

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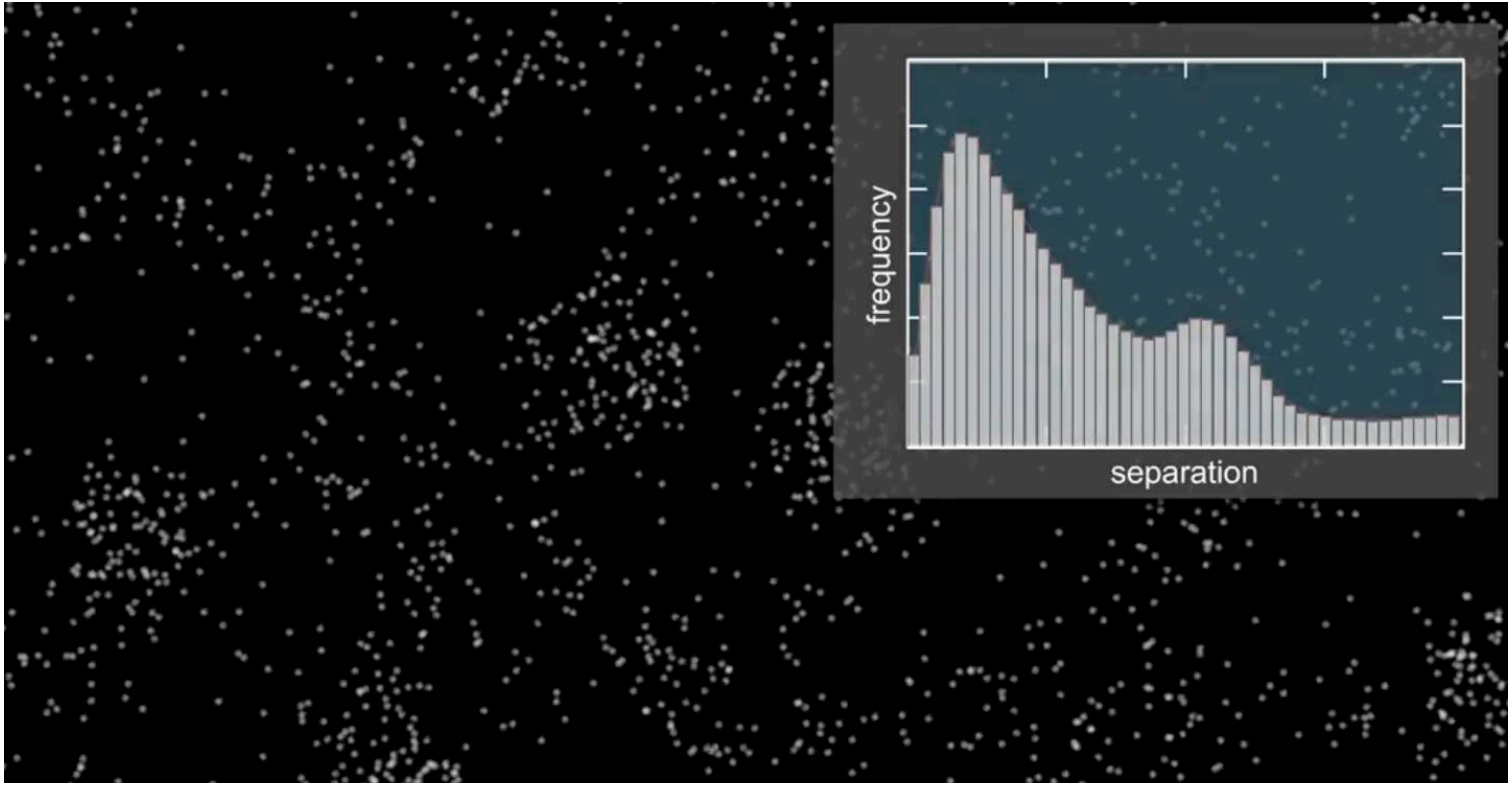
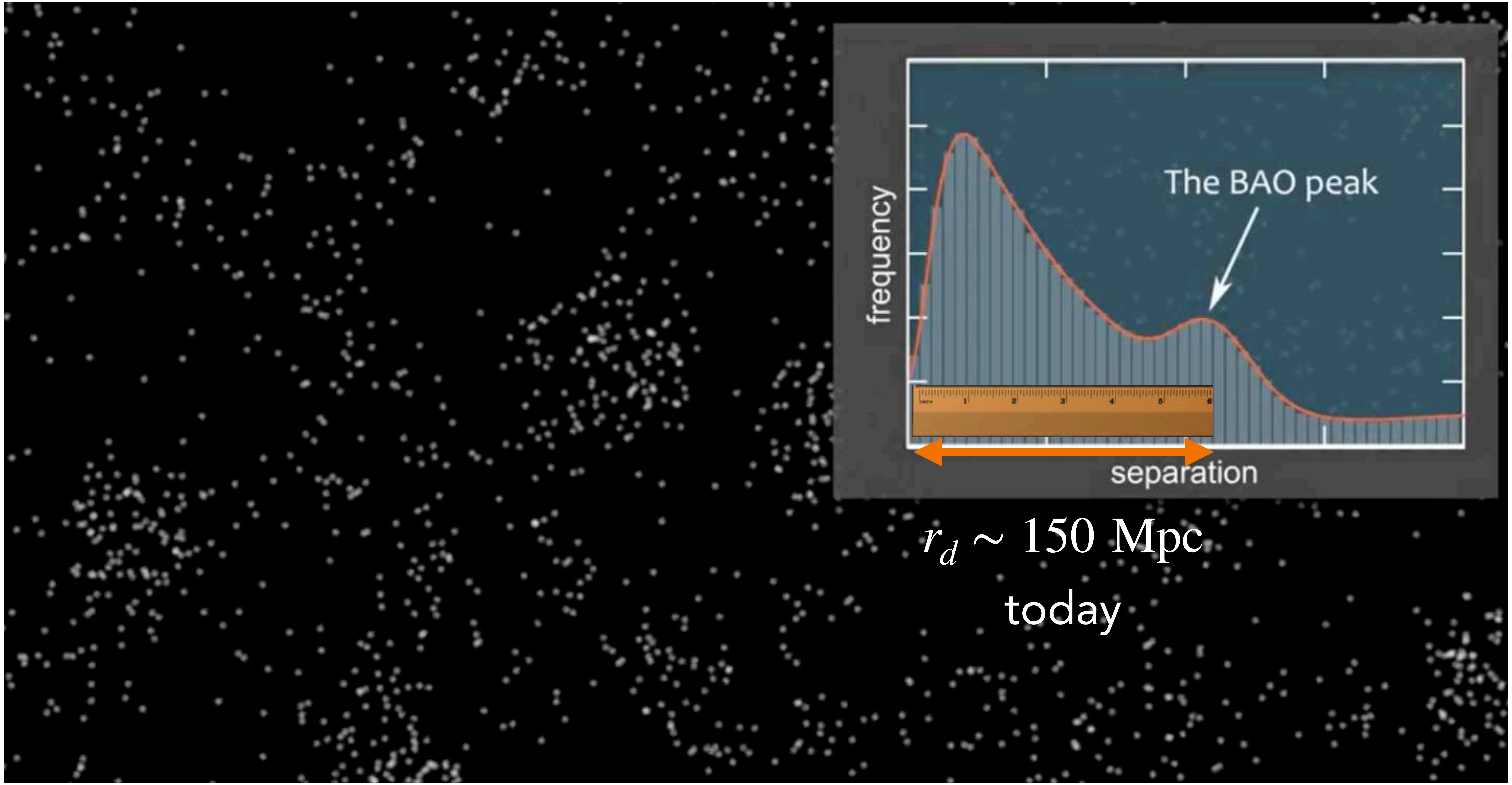


The correlation function

Credit: CAASTRO Link to video

BAO: Baryon Acoustic Oscillations



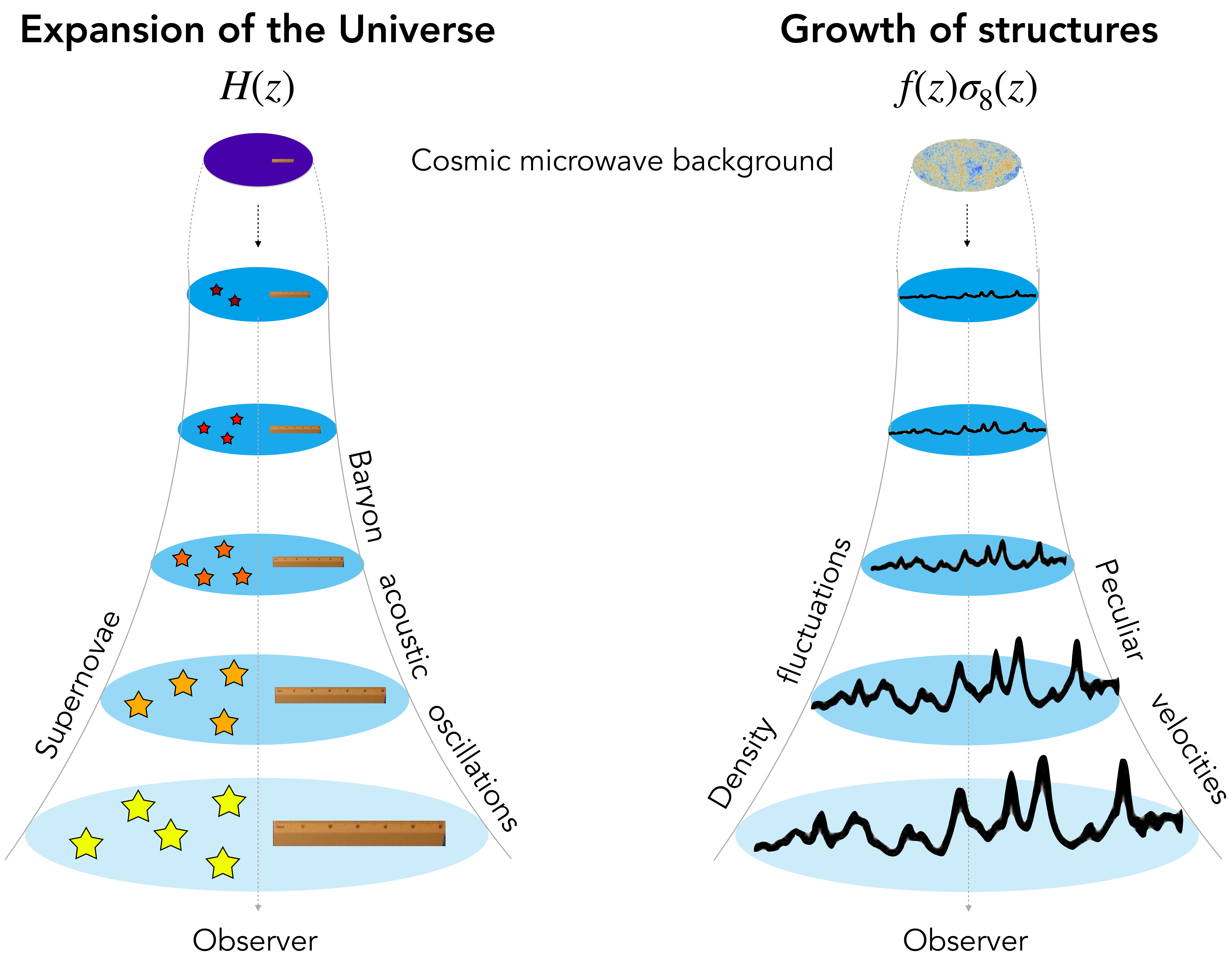
$r_d \sim 150$ Mpc

today

The correlation function

Credit: CAASTRO Link to video

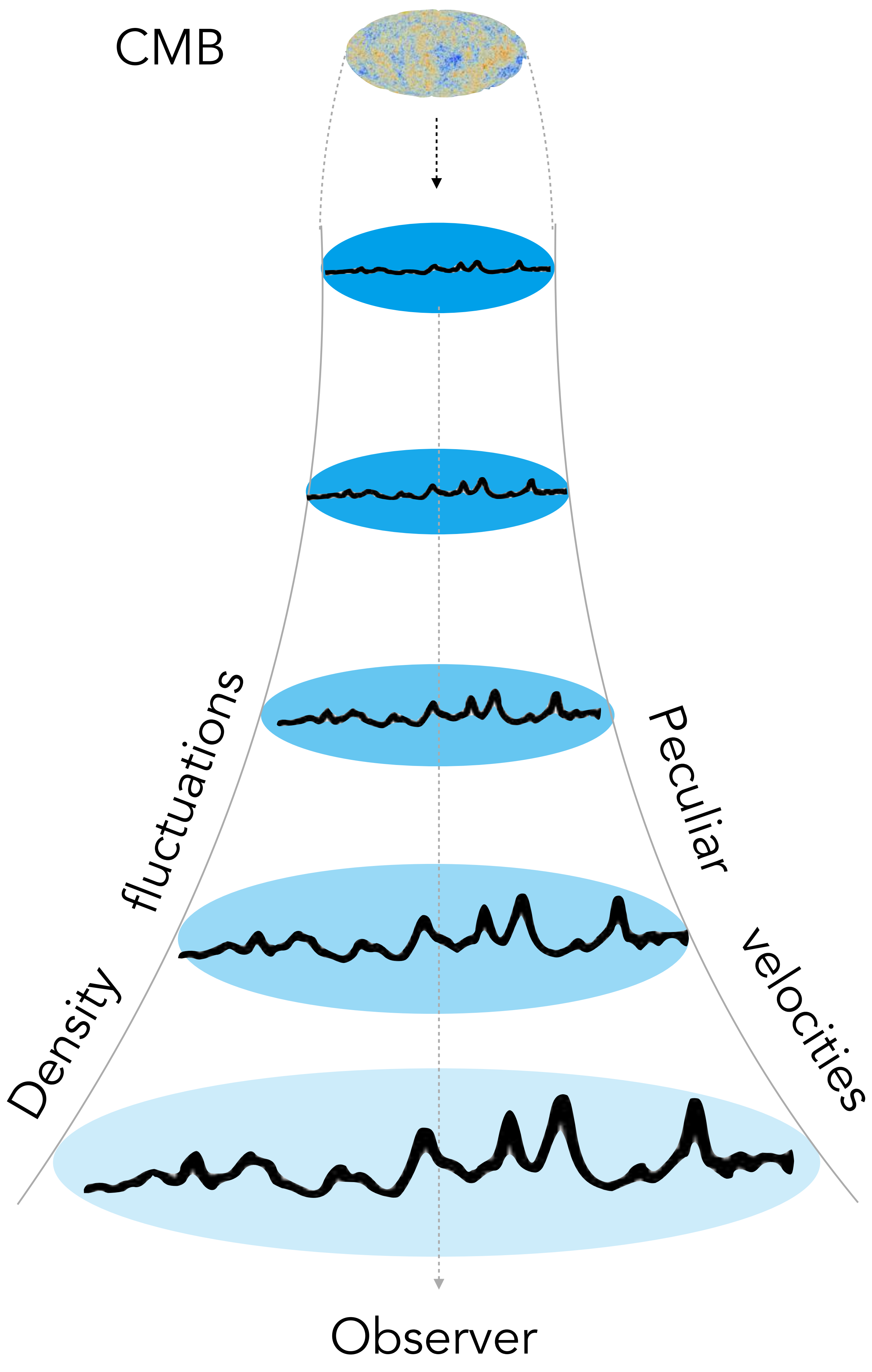
Accelerated expansion: dark energy or modified gravity?



Accelerated expansion: dark energy or modified gravity?

Growth of structures

$f(z)\sigma_8(z)$



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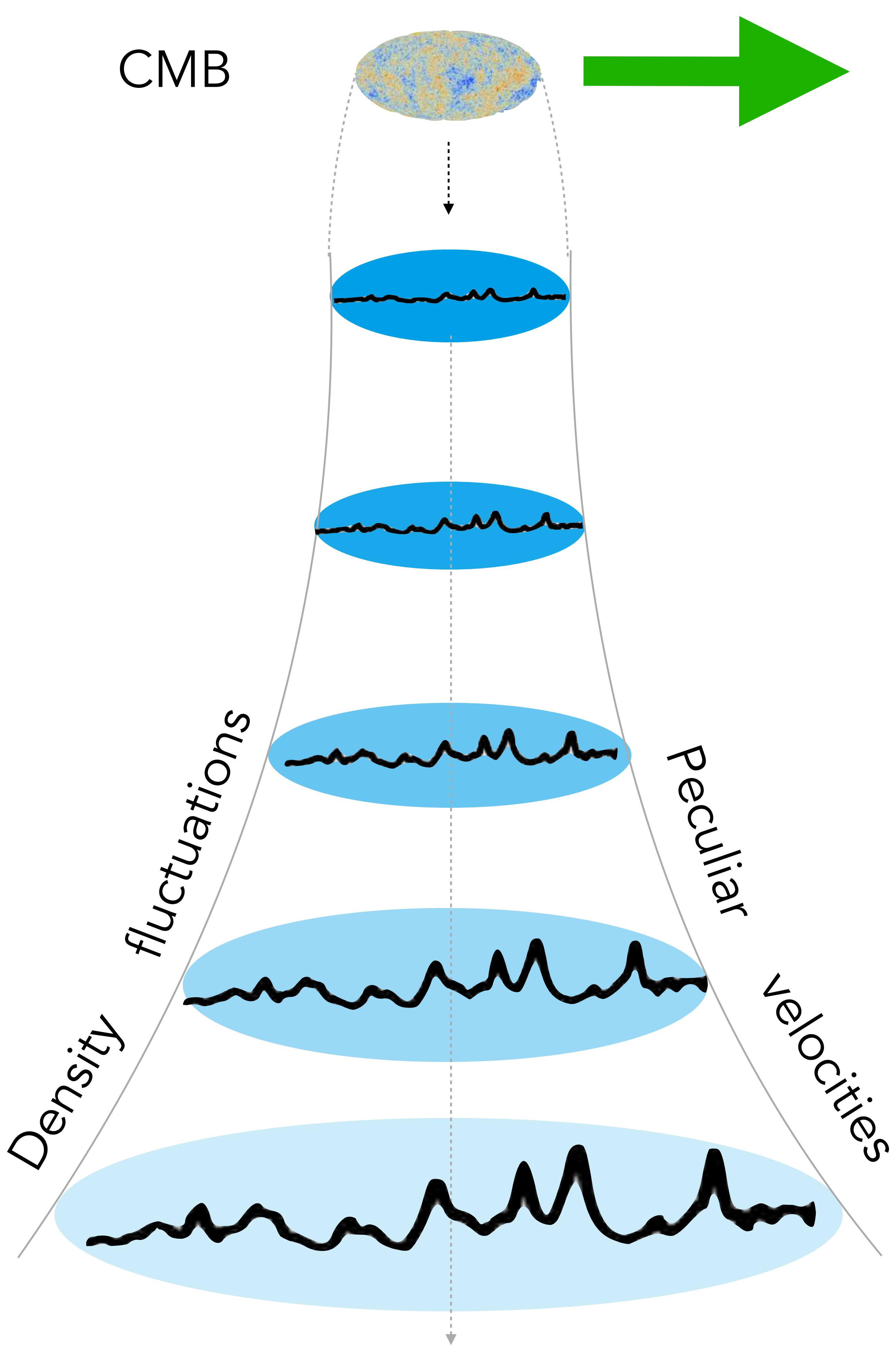

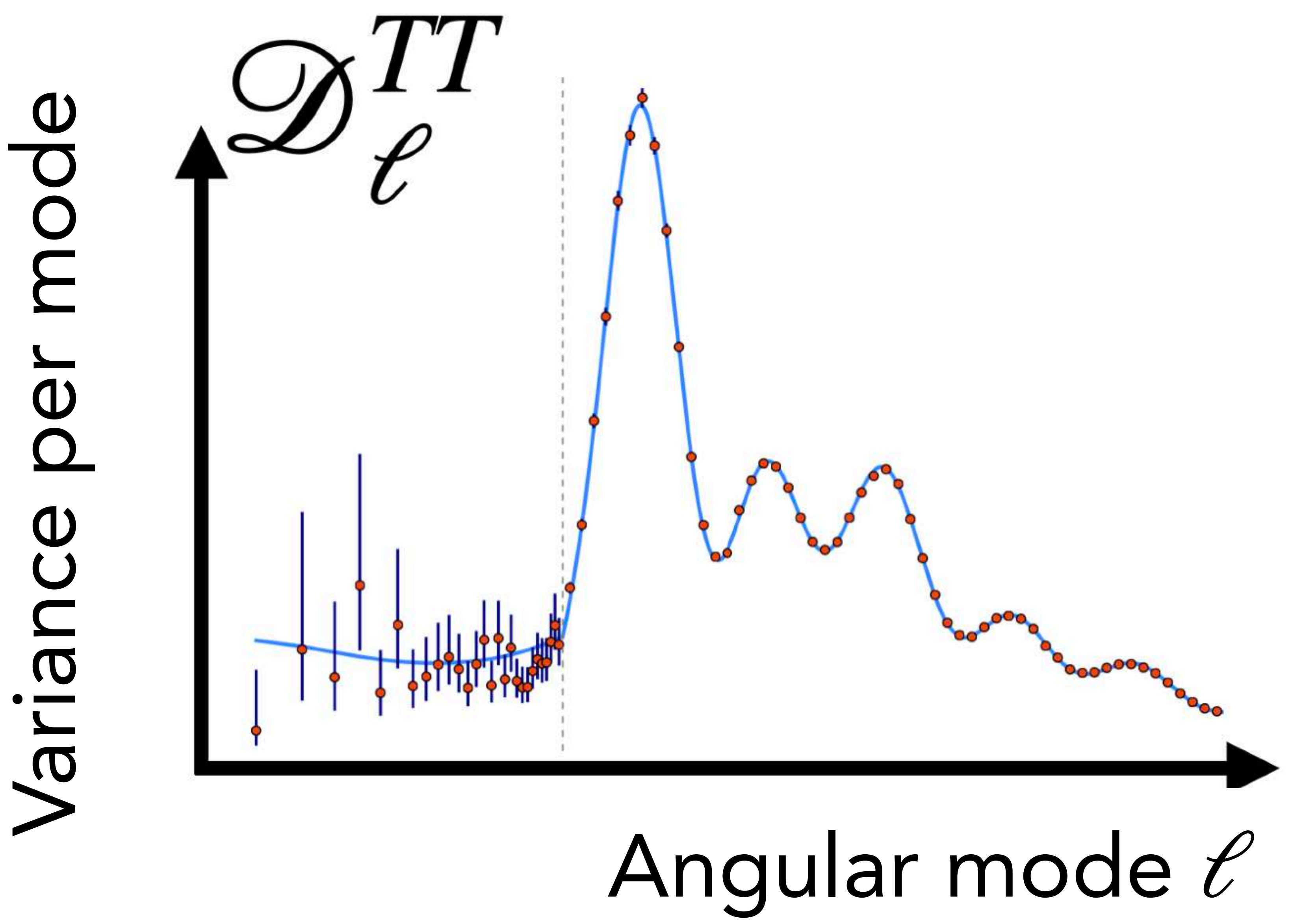

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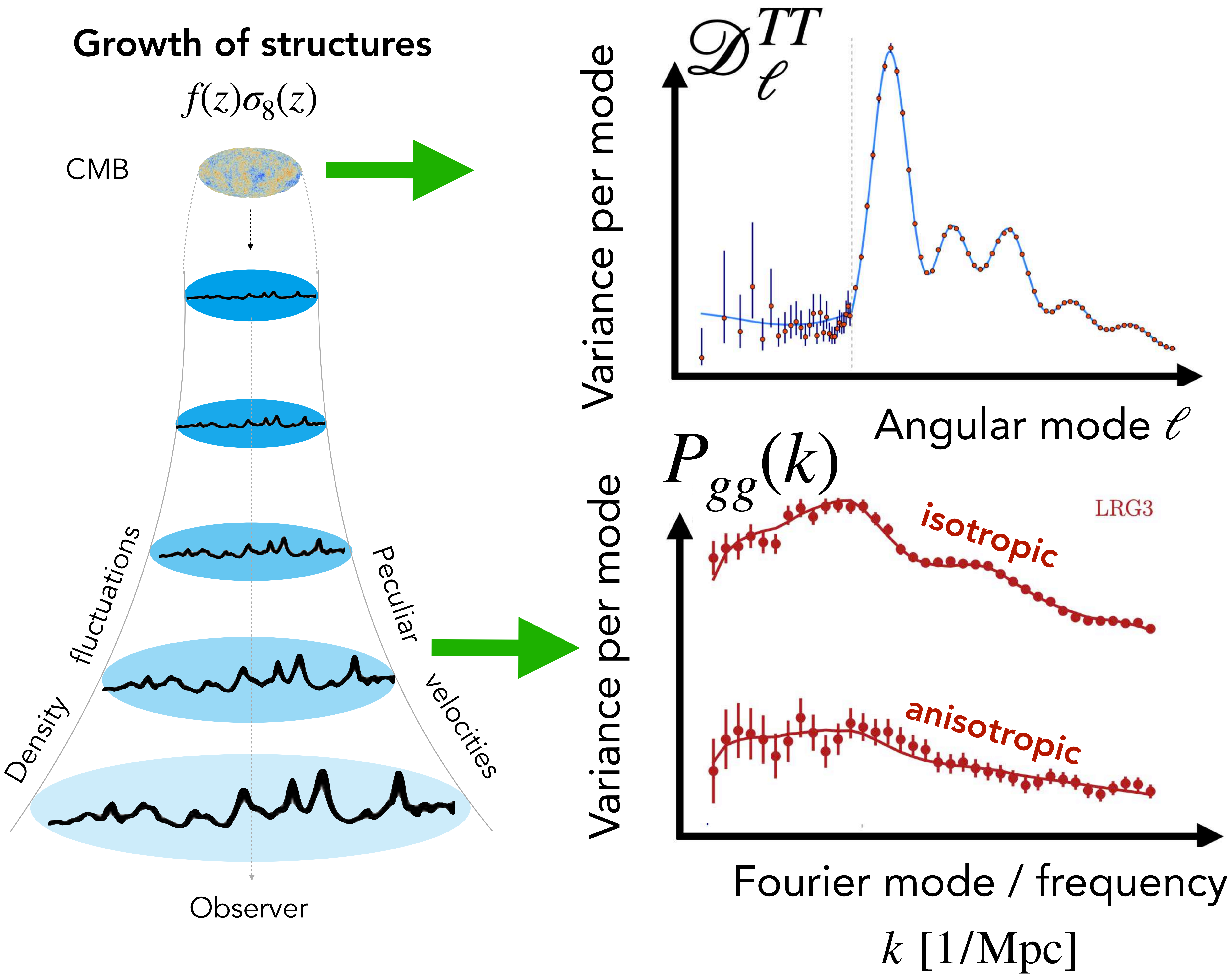

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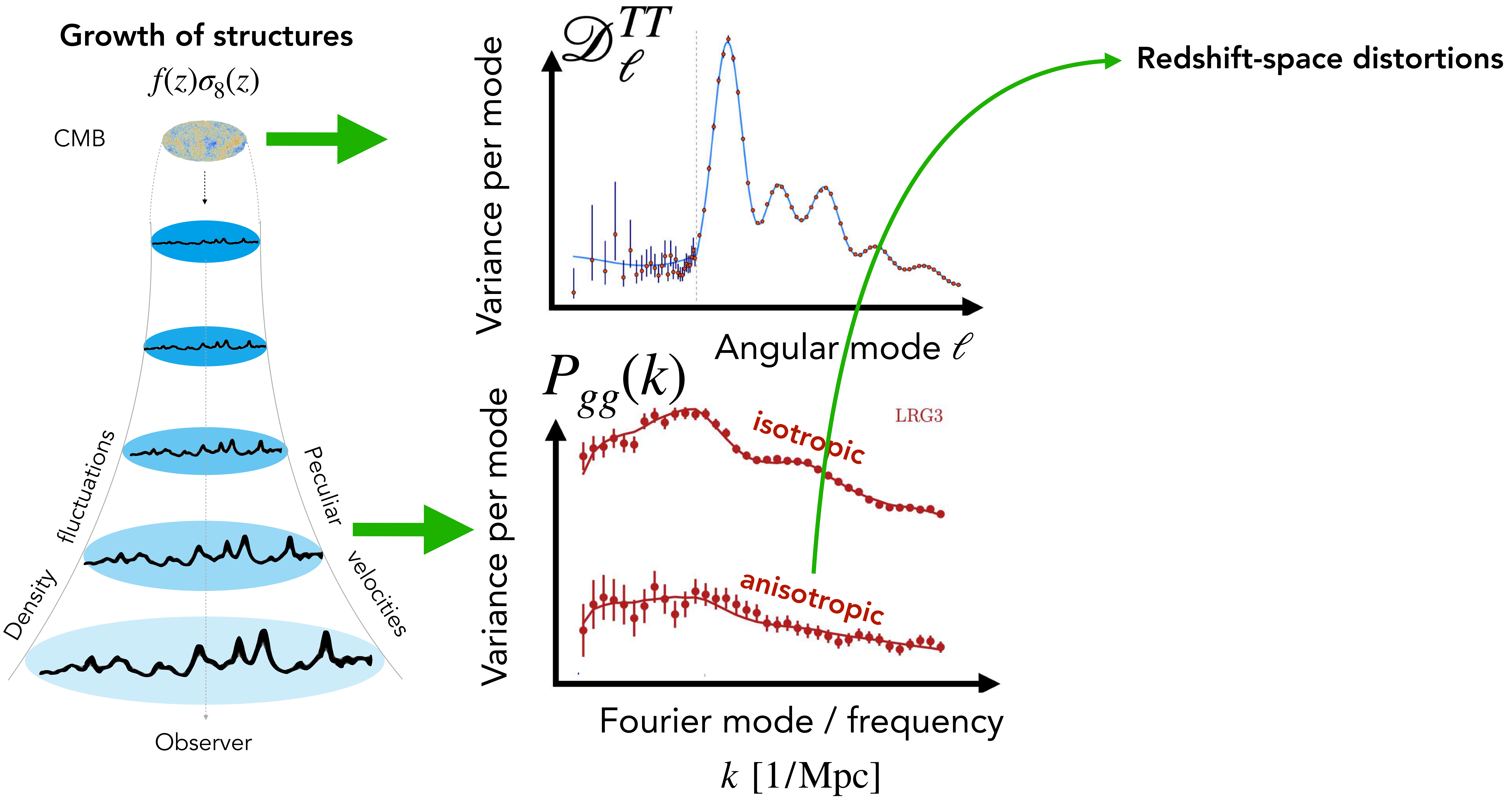

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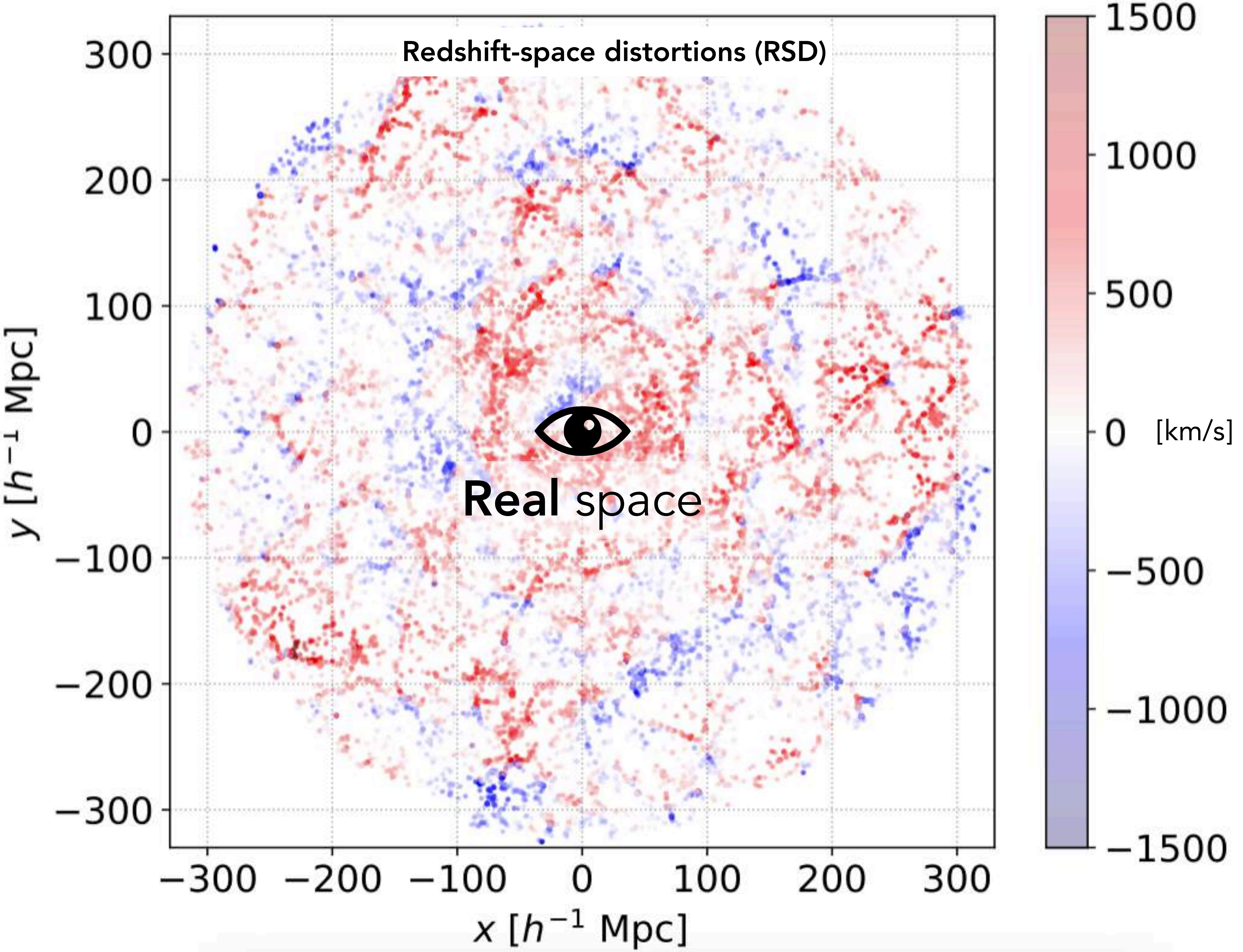
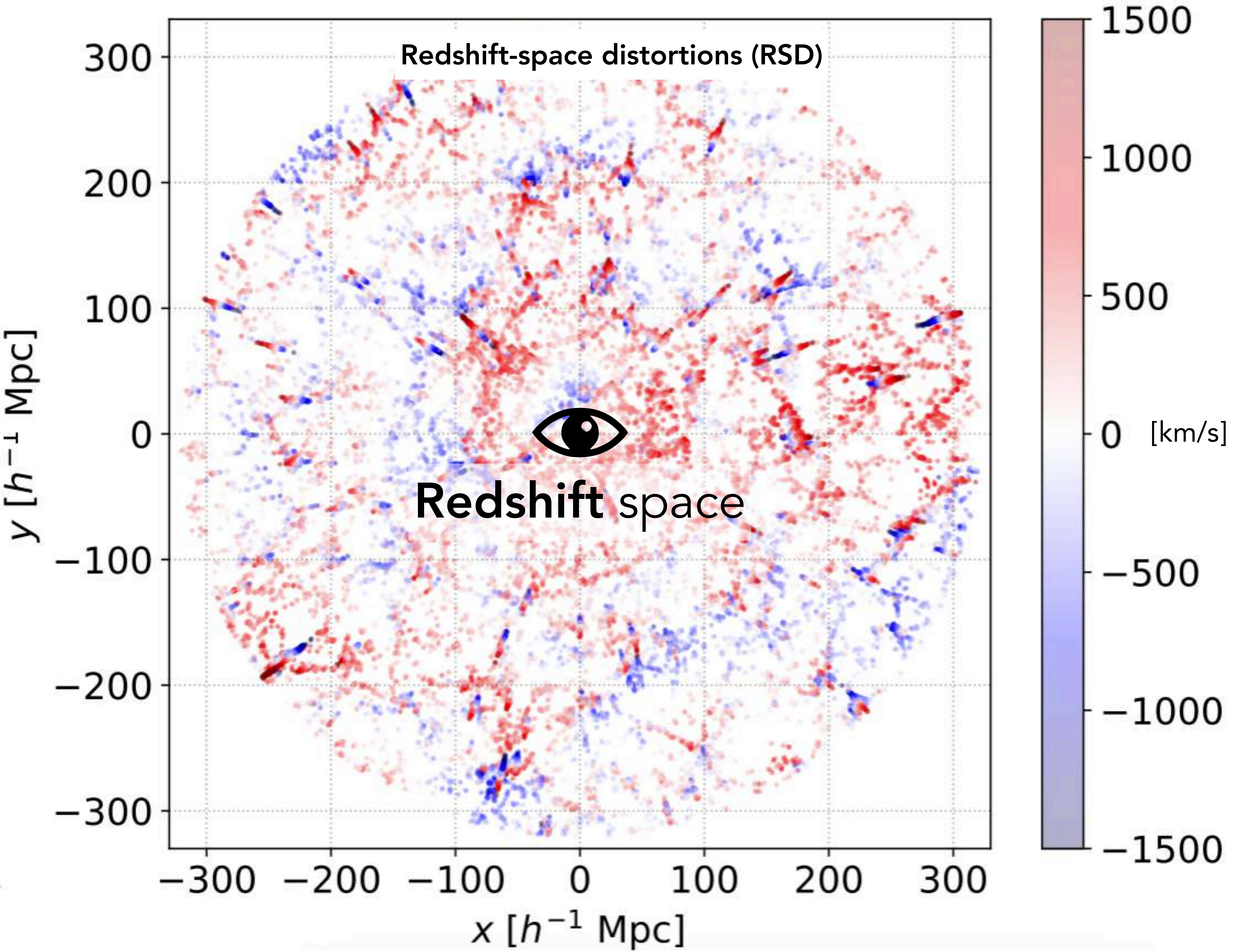

Redshift-space distortions (RSD)
Real space
300
200
100
0
−100
−200
−300
y [h⁻¹ Mpc]
x [h⁻¹ Mpc]
1500
1000
500
0
−500
−1000
−1500
[km/s]


Redshift-space distortions (RSD)
Redshift space
[km/s]
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y [h⁻¹ Mpc]
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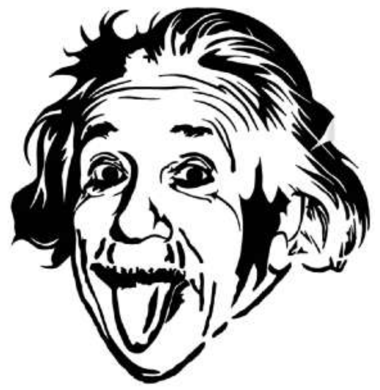
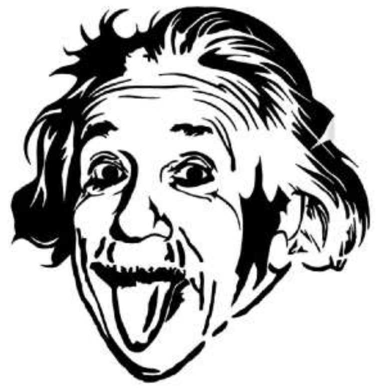
Model of the expansion of the Universe



Space-time properties $=$ Energy content of the Universe

(+ assumption of isotropic and homogeneous Universe)

Model of the expansion of the Universe



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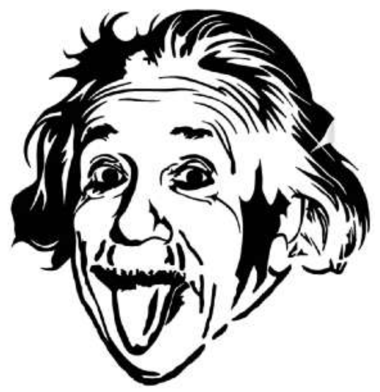
$$\left[\frac{H(t)}{H_0}\right]^2 =$$

Expansion-rate

Model of the expansion of the Universe



Space-time properties **=** Energy content of the Universe

(+ assumption of isotropic and homogeneous Universe)

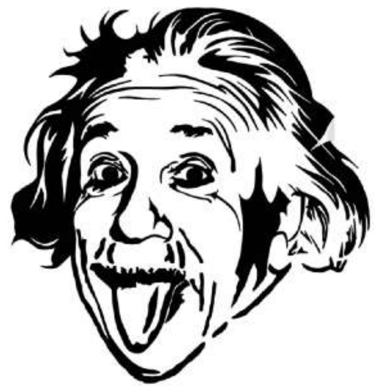
$$\left[\frac{H(t)}{H_0}\right]^2 = \Omega_m[a(t)]^{-3}$$

Expansion-rate

Matter
Baryons +
Dark Matter
30%

dilutes
with volume

Model of the expansion of the Universe



Space-time properties **=** Energy content of the Universe

(+ assumption of isotropic and homogeneous Universe)

$$\left[\frac{H(t)}{H_0}\right]^2 = \Omega_m [a(t)]^{-3} + \Omega_r [a(t)]^{-4}$$

Expansion-rate

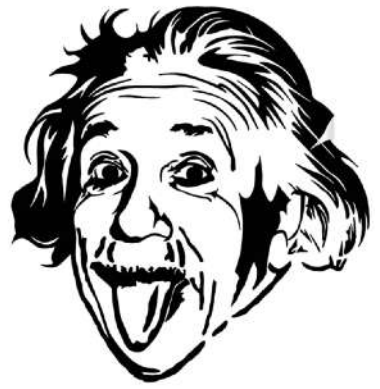
Matter
Baryons +
Dark Matter
30%

dilutes
with volume

Radiation
Photons +
Neutrinos
0.01%

dilutes
with volume
and redshift

Model of the expansion of the Universe



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Massive neutrinos

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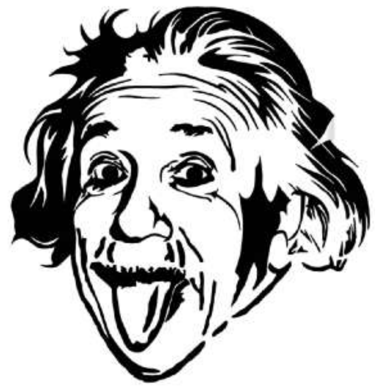

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Massive neutrinos

$$\left[\frac{H(t)}{H_0}\right]^2 = \Omega_m[a(t)]^{-3} + \Omega_r[a(t)]^{-4} + \Omega_\Lambda$$

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Baryons +
Dark Matter
30%

dilutes
with volume

Radiation
Photons +
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0.01%

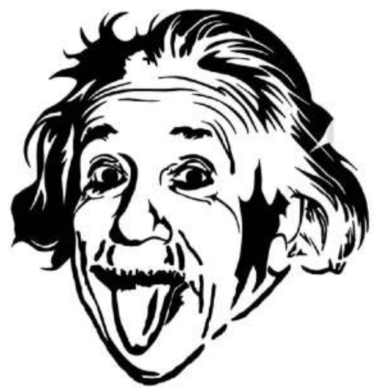
dilutes
with volume
and redshift

Dark energy
as a cosmological constant

70%

does not dilute!

Model of the expansion of the Universe



Space-time properties $=$ Energy content of the Universe

(+ assumption of isotropic and homogeneous Universe)

Massive neutrinos

$$\left[\frac{H(t)}{H_0}\right]^2 = \Omega_m[a(t)]^{-3} + \Omega_r[a(t)]^{-4} + \Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)}\mathrm{e}^{3w_a[1-a(t)]}$$

Expansion-rate

Matter
Baryons +
Dark Matter
30%

dilutes
with volume

Radiation
Photons +
Neutrinos
0.01%

dilutes
with volume
and redshift

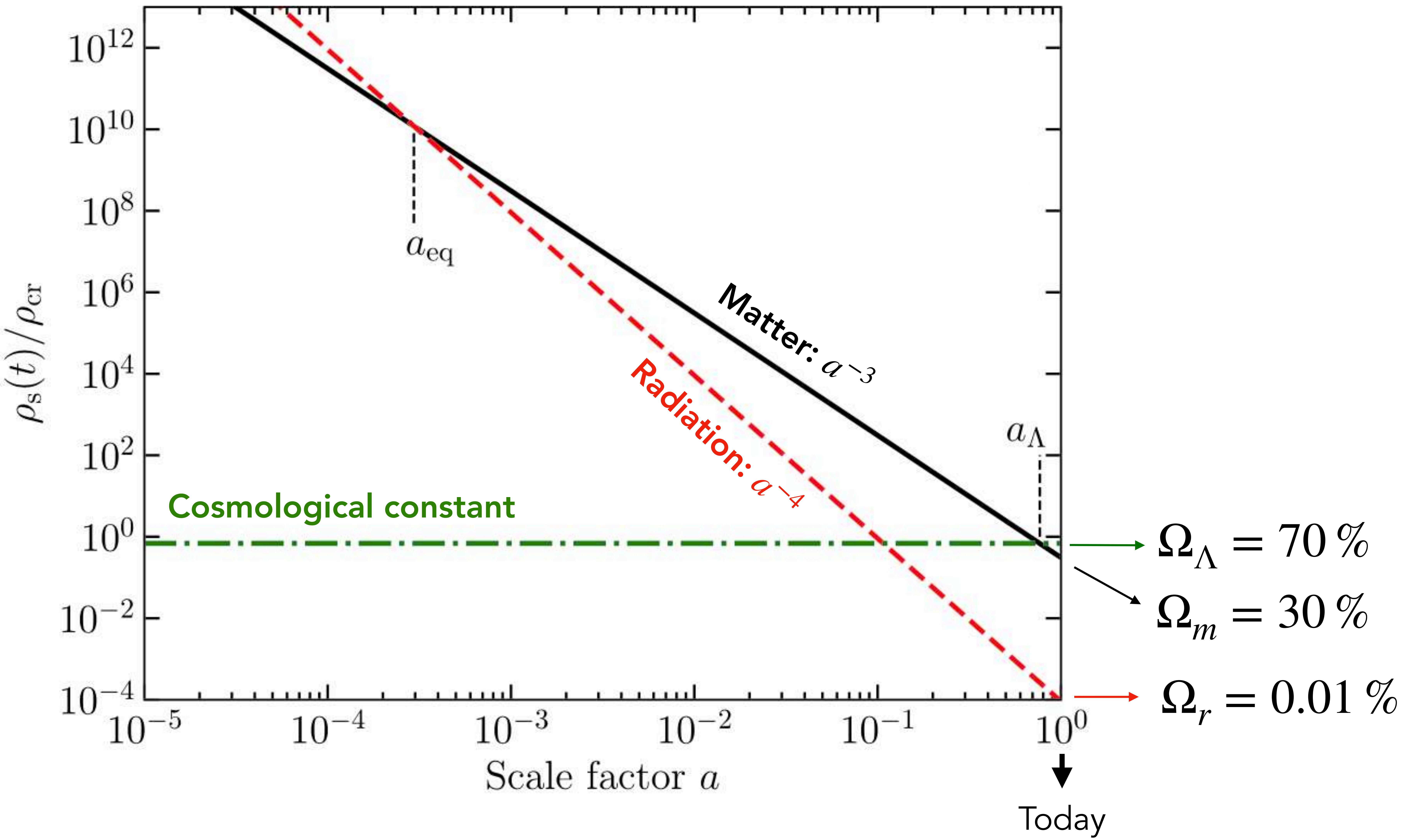
Evolving dark energy
(quintessence, phantom force)

70%

Two new parameters

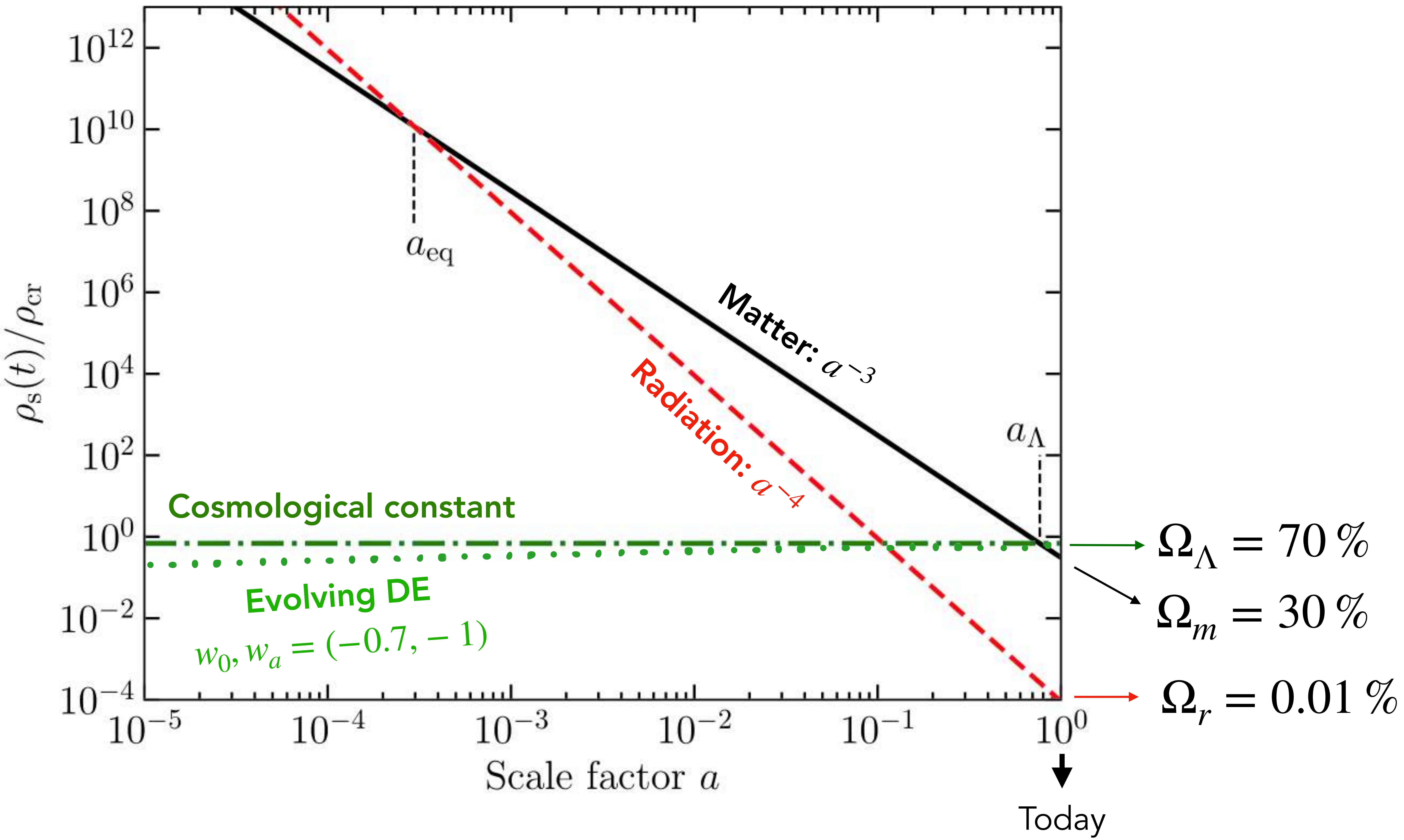
w_0, w_a

Evolution of densities



The combination of densities drives the expansion rate $H(t)$

Evolution of densities



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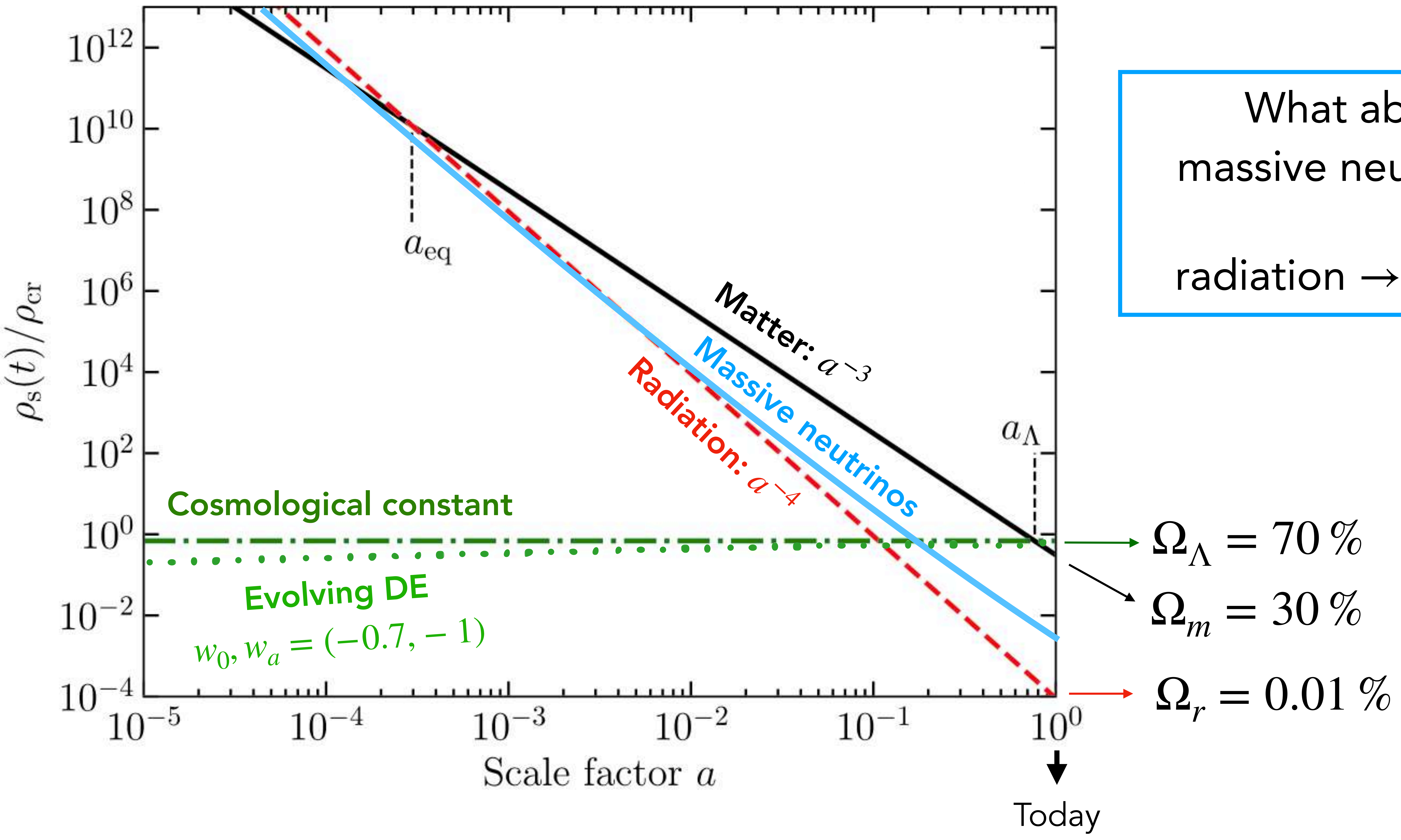


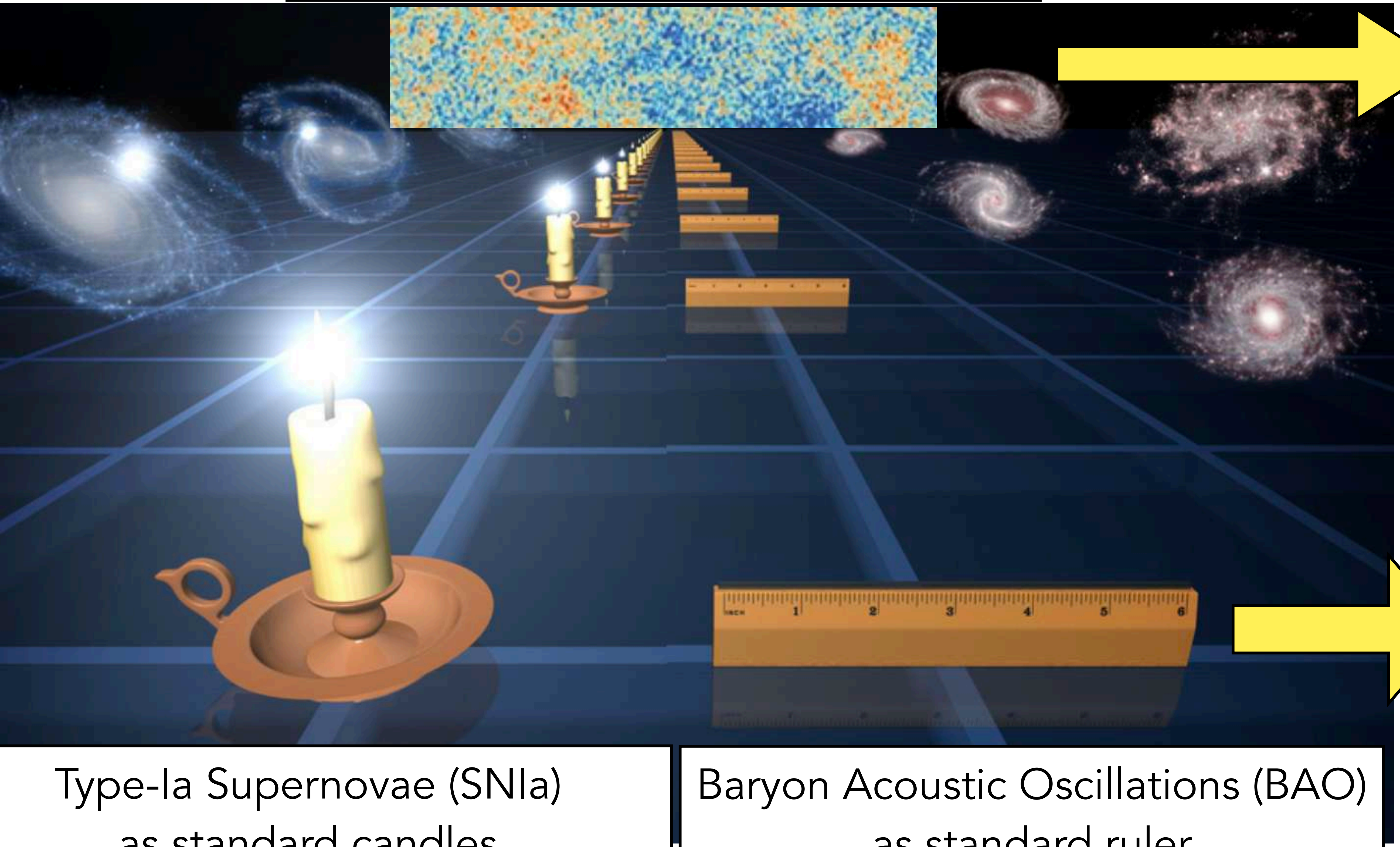
What about massive neutrinos?

radiation → matter

The combination of densities drives the expansion rate $H(t)$

Measuring distances

Cosmic microwave background (CMB)
z ~ 1100 or t ~ 380 000 years



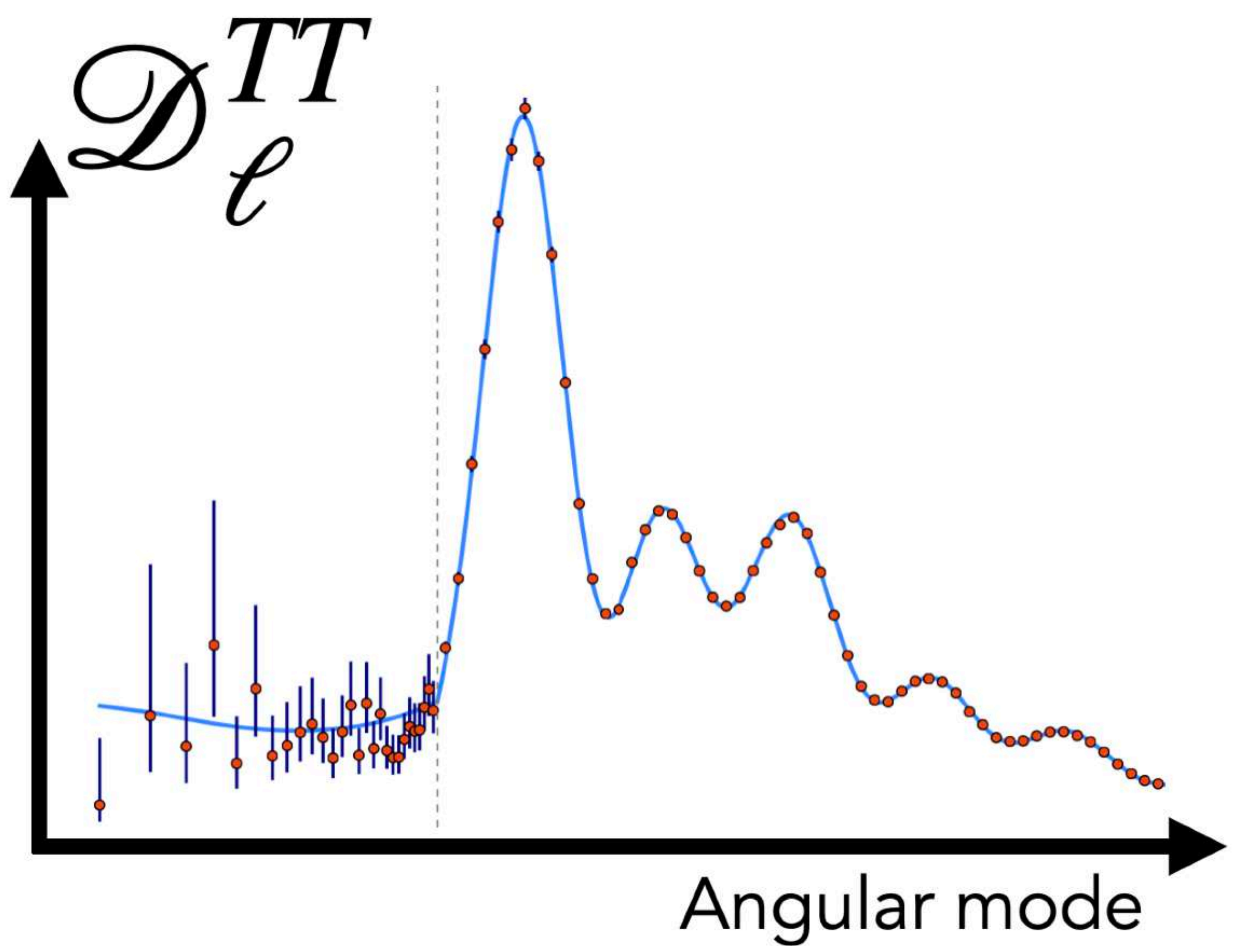
Type-Ia Supernovae (SNIa)
as standard candles

$$F = \frac{L_{\rm candle}}{4\pi D_L^2(z)}$$

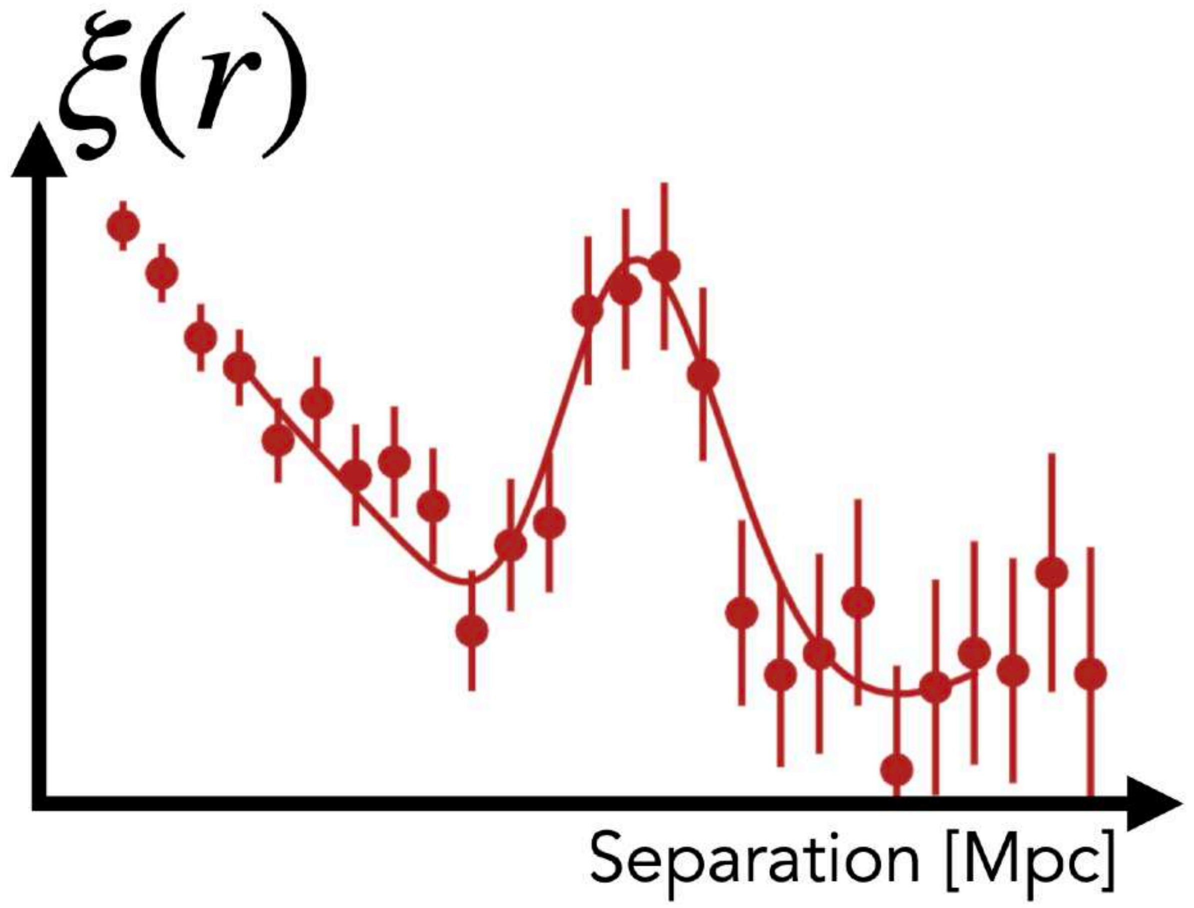
Baryon Acoustic Oscillations (BAO)
as standard ruler

$$\Delta\theta = \frac{r_{\rm ruler}}{D_M(z)} \quad \text{and} \quad \Delta z = \frac{r_{\rm ruler}}{D_H(z)}$$

Distances in cosmology: $D(z) \propto \int_0^z \frac{c\mathrm{d}z'}{H(z')}$



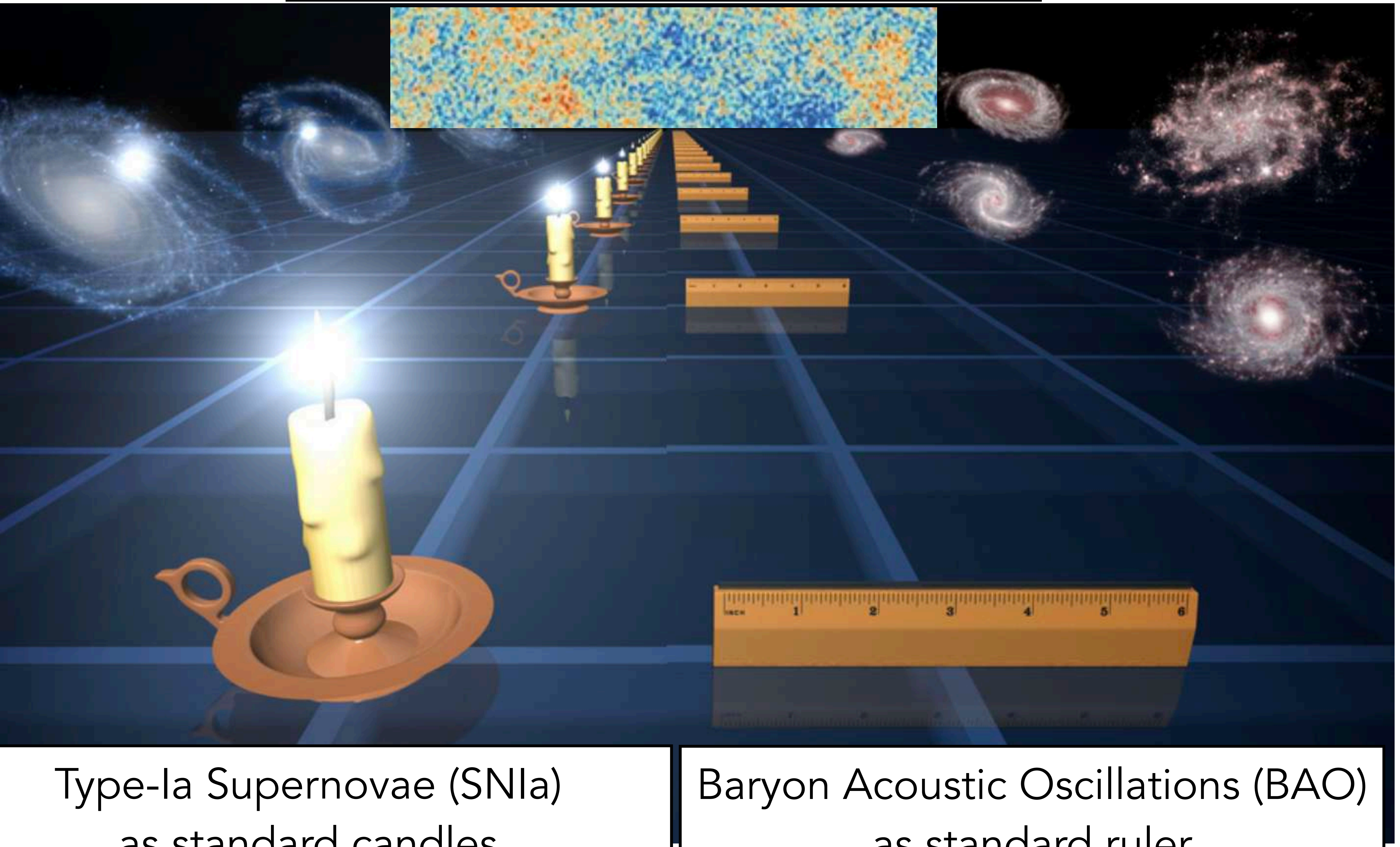
$$100\theta_* = 1.04109 \pm 0.00030$$
$$\theta_* \equiv r_*/D_{\rm M}$$



$$r_{\rm ruler} \sim 101 h^{-1}\mathrm{Mpc}$$
(comoving)

Measuring distances

Cosmic microwave background (CMB)
z ~ 1100 or t ~ 380 000 years



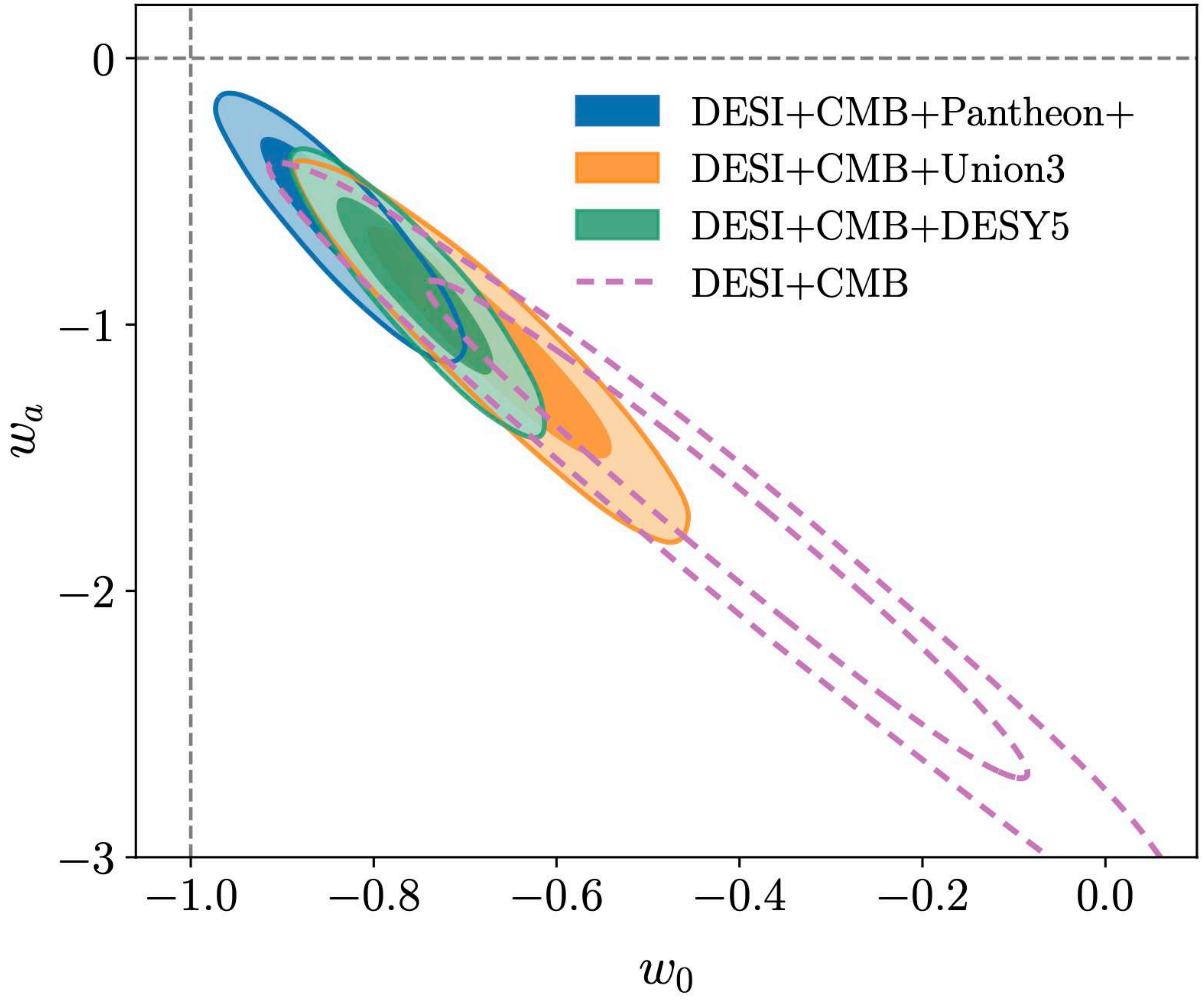
Type-Ia Supernovae (SNIa)
as standard candles

$$F = \frac{L_{\text{candle}}}{4\pi D_L^2(z)}$$

Baryon Acoustic Oscillations (BAO)
as standard ruler

$$\Delta\theta = \frac{r_{\text{ruler}}}{D_M(z)} \quad \text{and} \quad \Delta z = \frac{r_{\text{ruler}}}{D_H(z)}$$

Distances in cosmology: $D(z) \propto \int_0^z \frac{c\,dz'}{H(z')}$

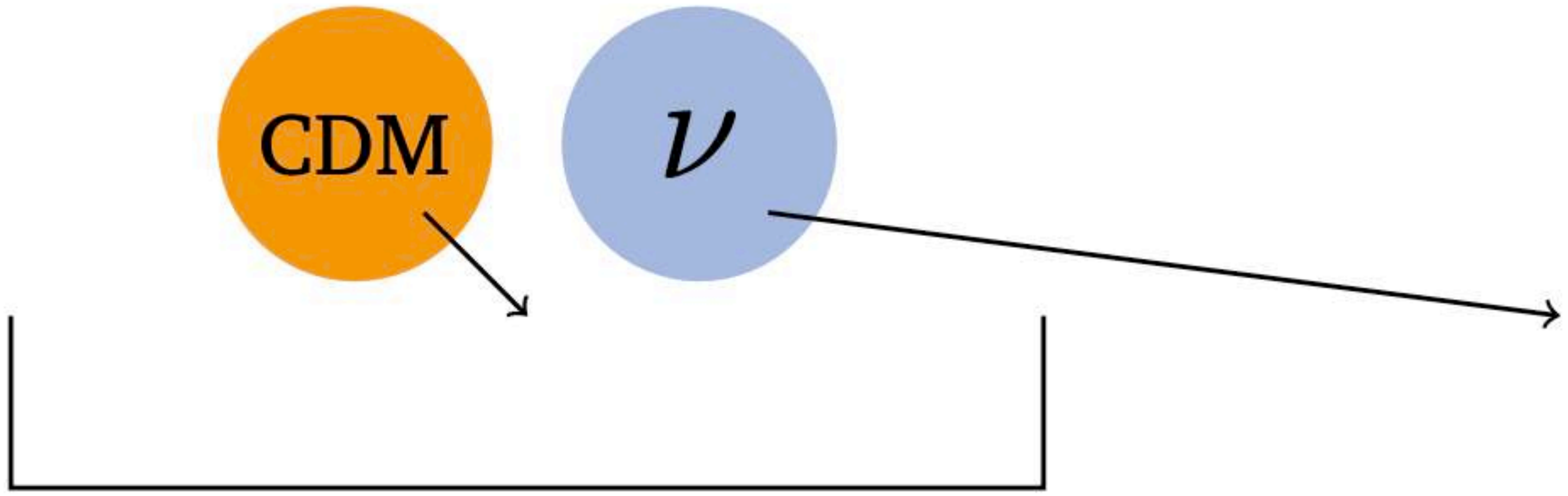


Modelling impact of neutrino masses

by W. Elbers

Modelling impact of neutrino masses

Massive neutrinos act as **hot** dark matter



They escape **shallow** potential wells

by W. Elbers

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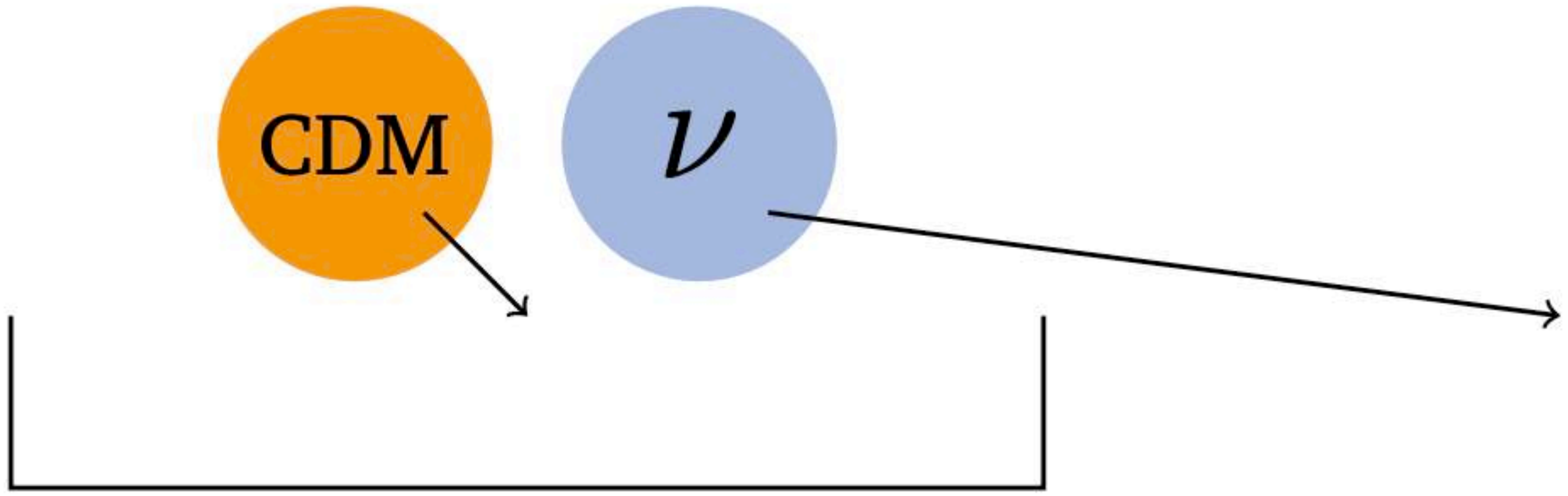
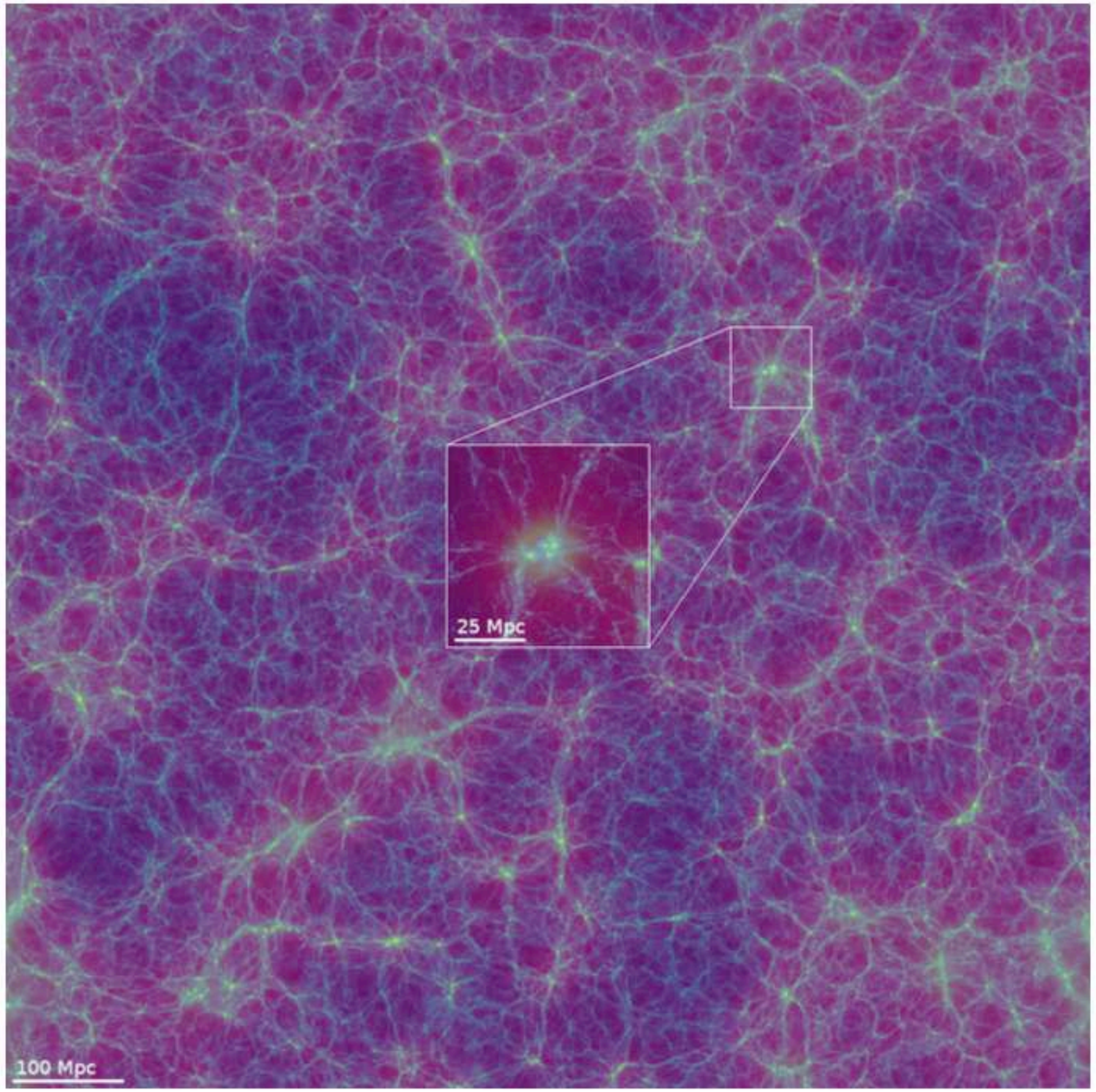
Massive neutrinos act as **hot** dark matter



They escape **shallow** potential wells

Small neutrino mass, $\sum m_\nu = 0.06\,\mathrm{eV}$

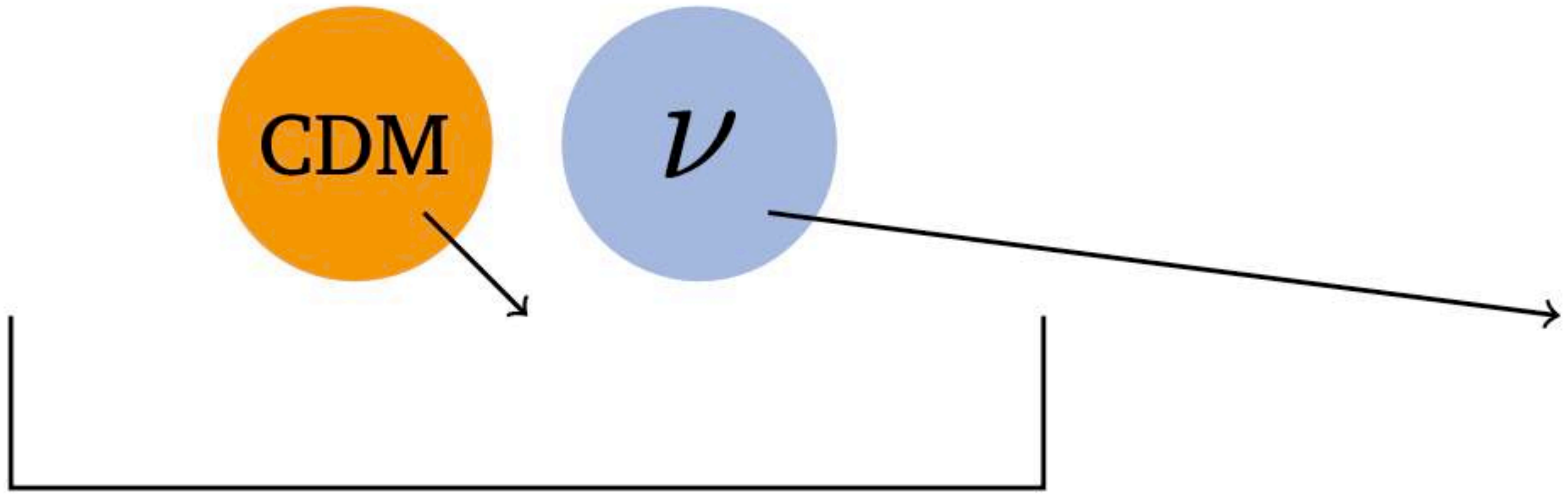


Images from the FLAMINGO simulations.

by W. Elbers

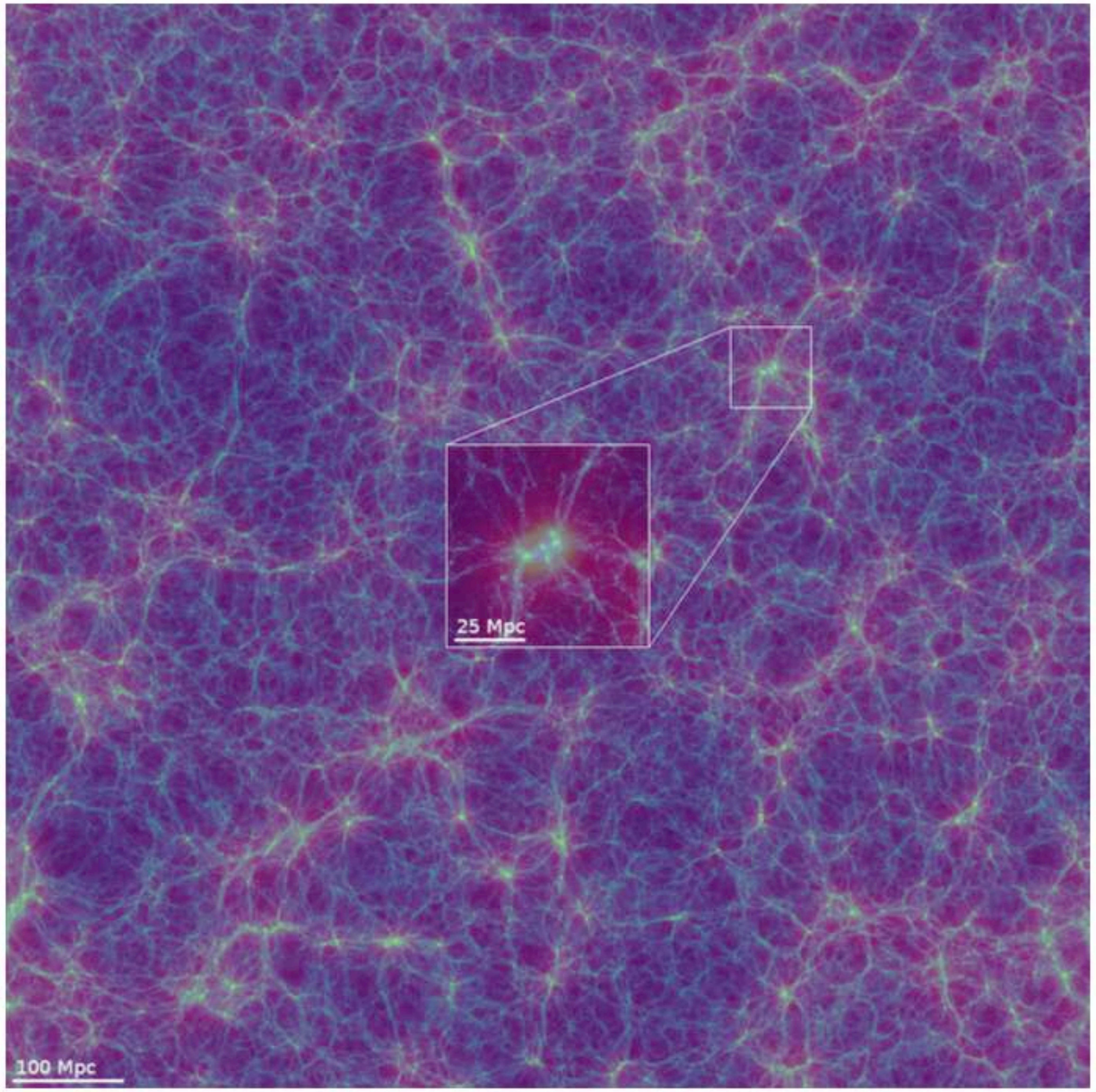
Modelling impact of neutrino masses

Massive neutrinos act as **hot** dark matter



They escape **shallow** potential wells

Large neutrino mass, $\sum m_\nu = 0.48\,\mathrm{eV}$



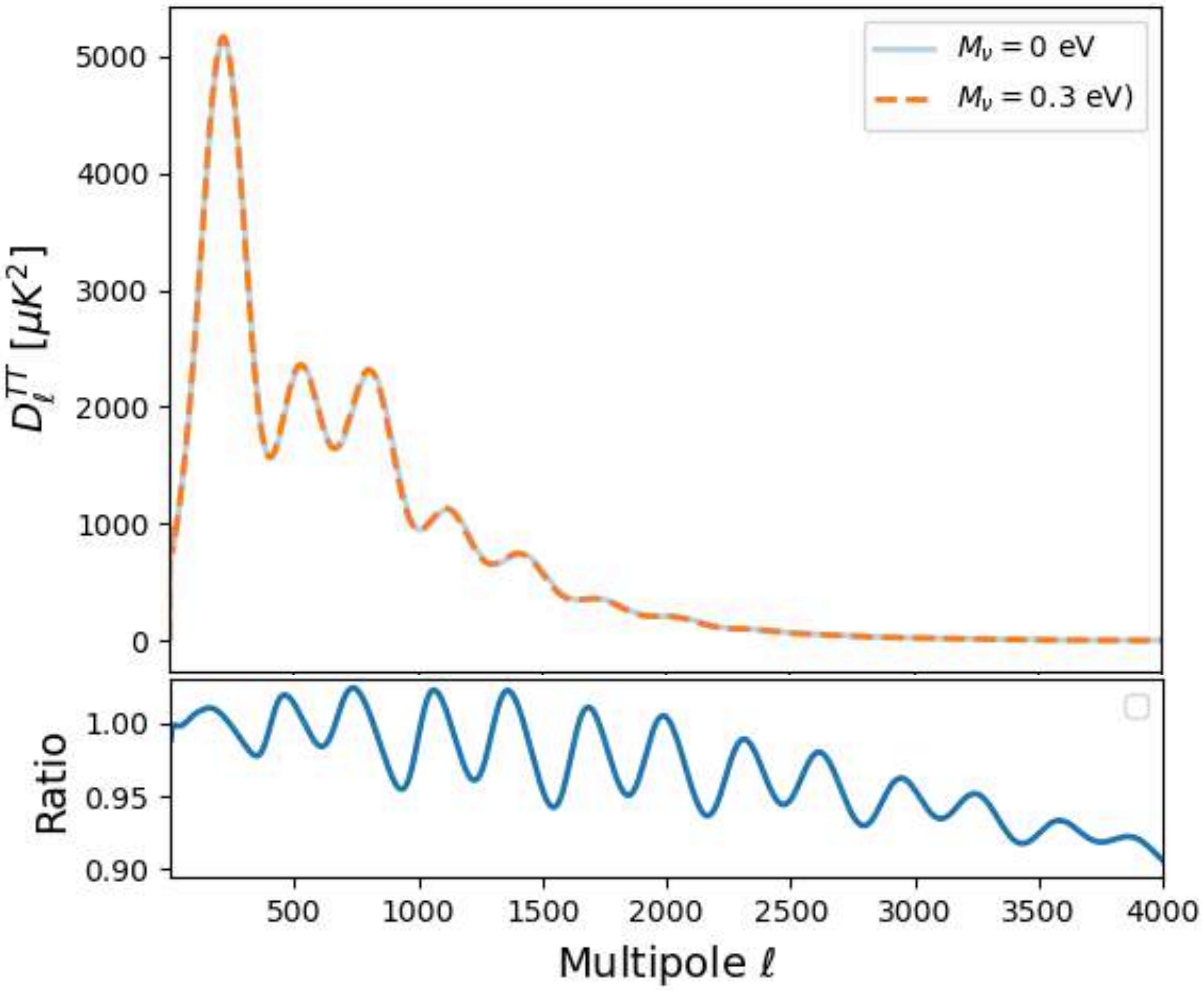
Images from the FLAMINGO simulations.

by W. Elbers

Modelling impact of neutrino masses

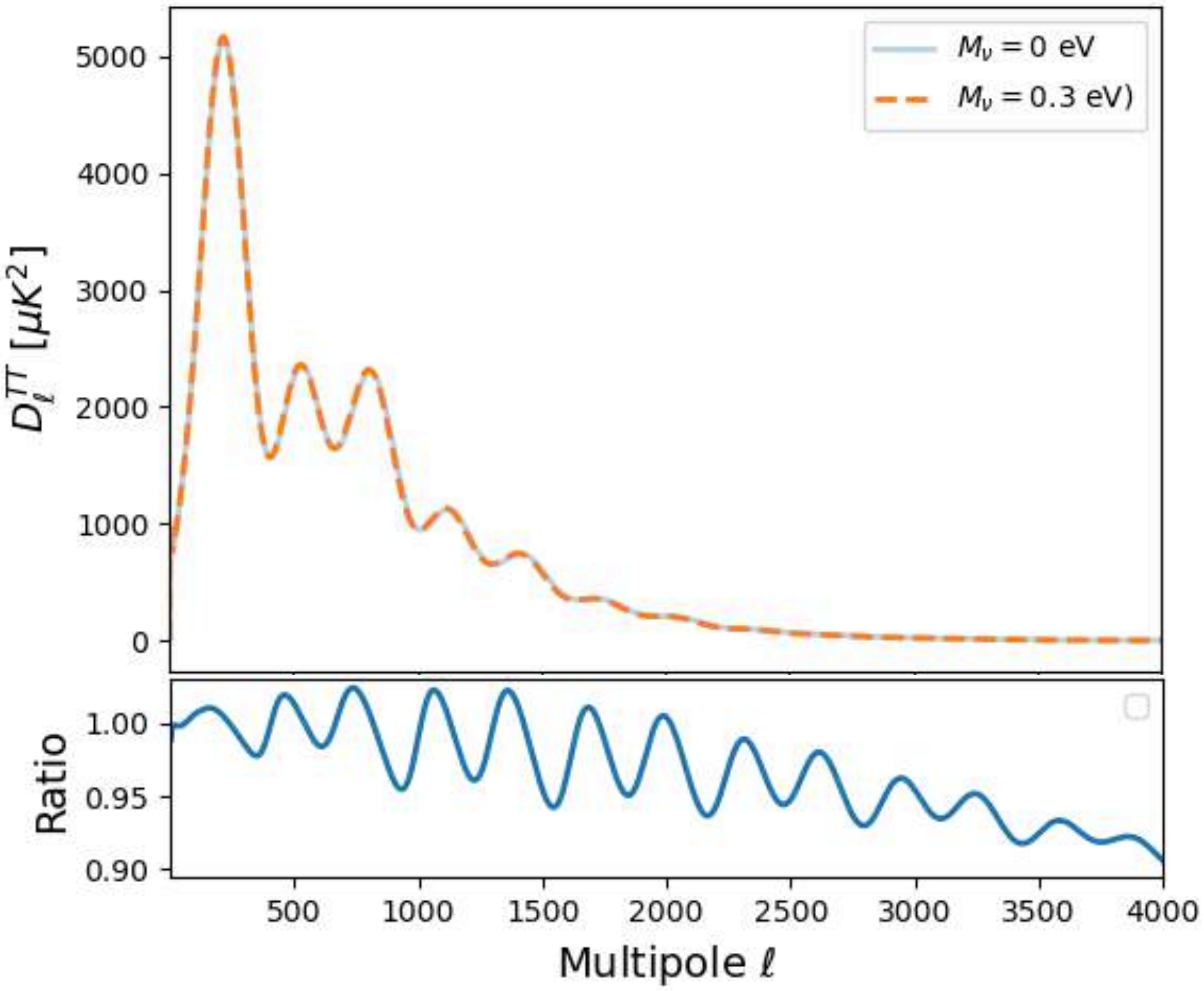
Modelling impact of neutrino masses

On the CMB angular power spectrum



Modelling impact of neutrino masses

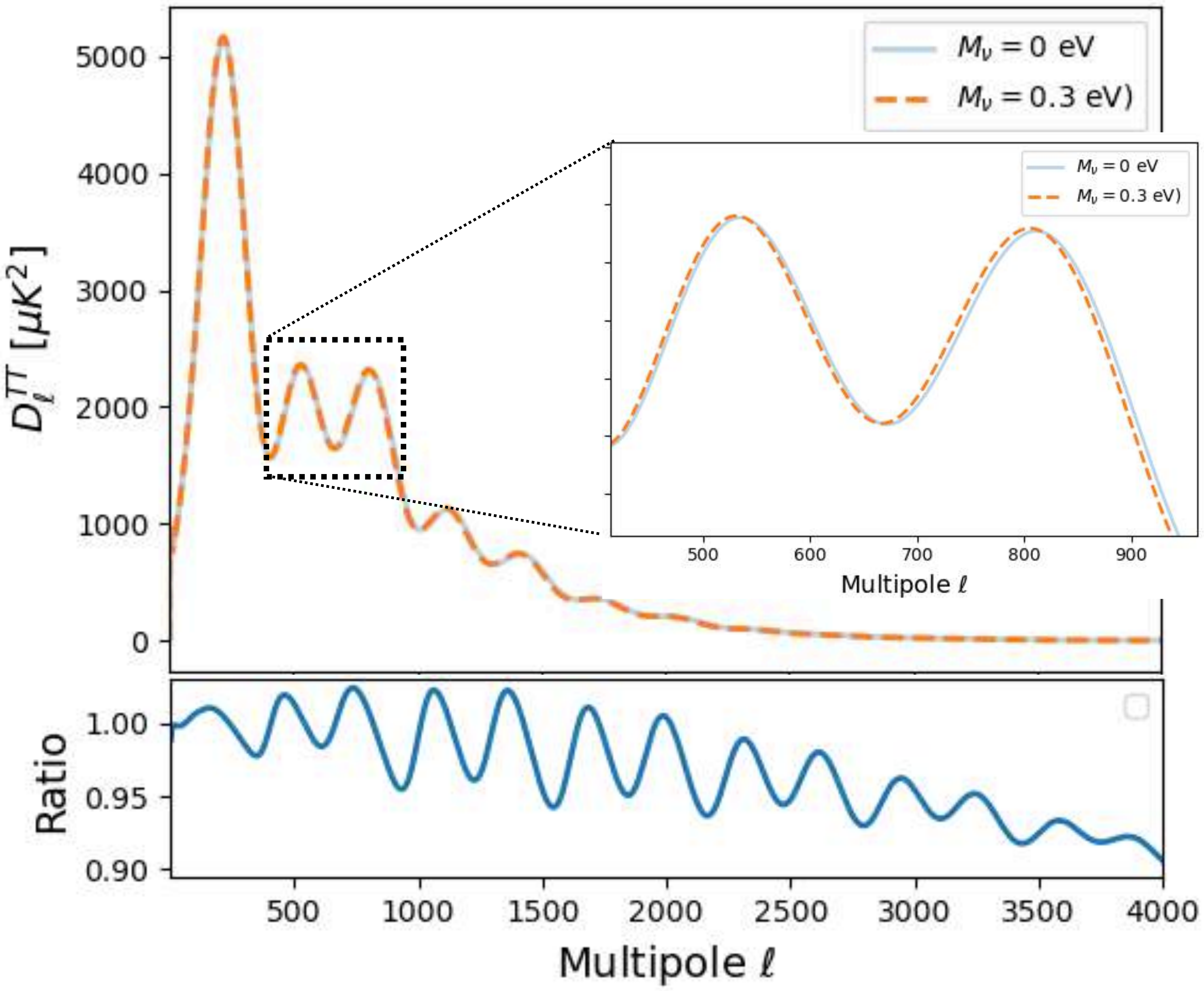
On the CMB angular power spectrum



Damping of power on small scales

Modelling impact of neutrino masses

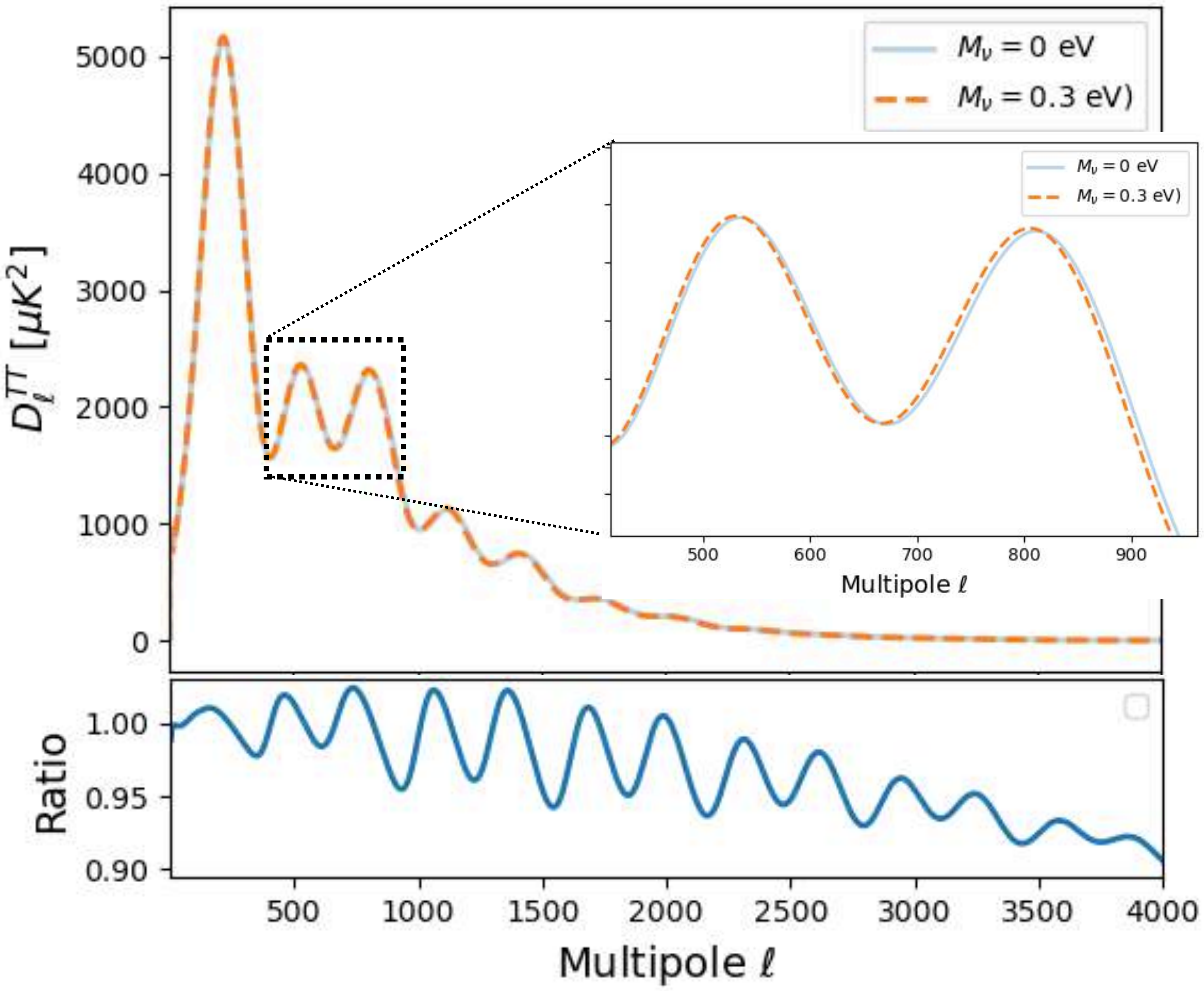
On the CMB angular power spectrum



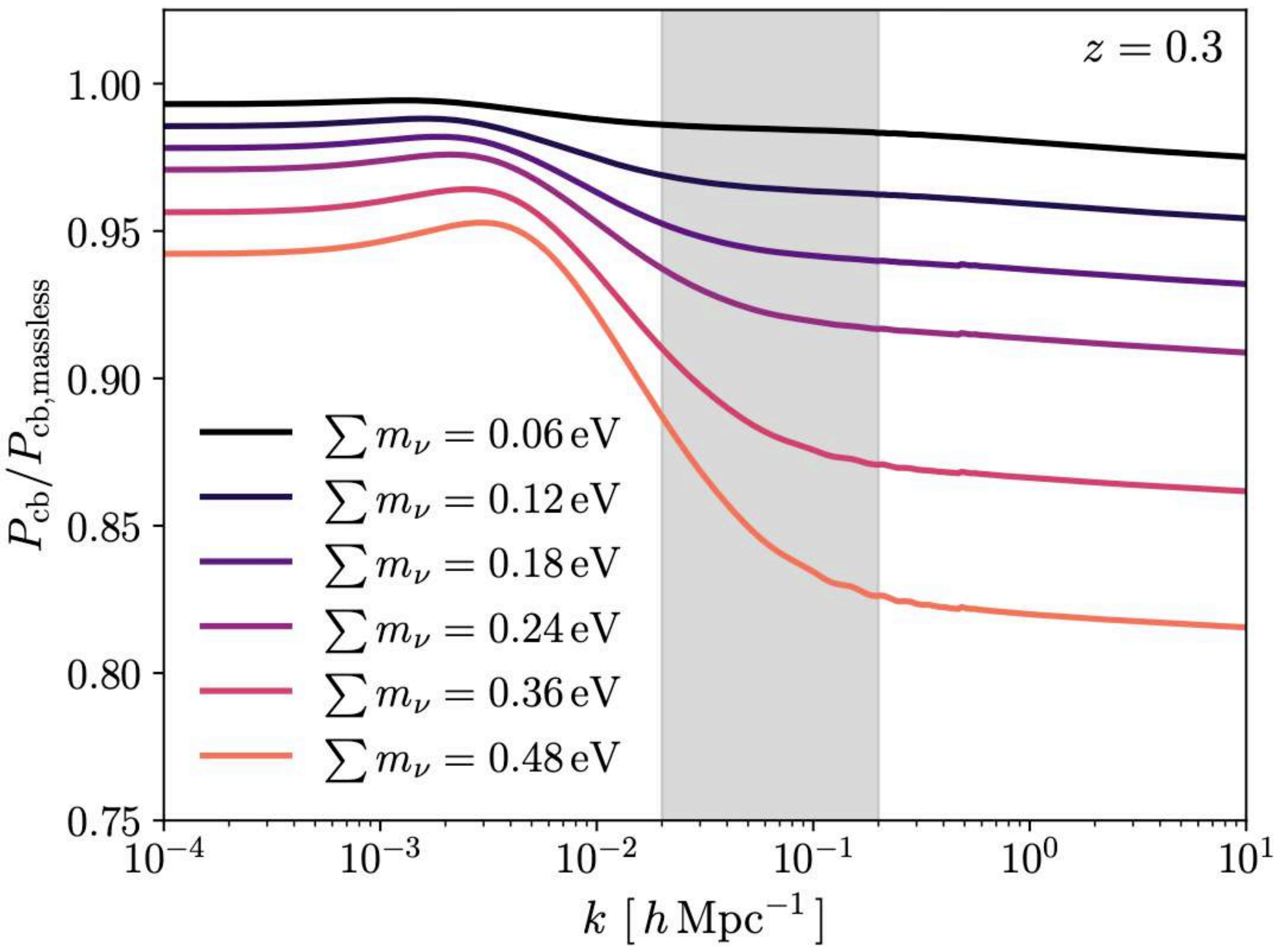
Damping of power on small scales

Modelling impact of neutrino masses

On the CMB angular power spectrum



On the galaxy power spectrum



Damping of power on small scales

Plan

Dark energy and neutrino cosmology

Mapping galaxies with DESI

Dark energy constraints

Neutrino mass constraints

Modified gravity constraints

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The Dark Energy Spectroscopic Instrument

Thanks to our sponsors and
72 Participating Institutions!

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The instrument

Mayall Telescope @ Kitt Peak, Arizona USA
4m mirror
10 spectrographs
30 cameras


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SPECTROSCOPIC
INSTRUMENT
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Focal plane
86 cm


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Focal plane
86 cm
5000 optical fibers placed with robots


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DARK ENERGY SPECTROSCOPIC INSTRUMENT
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Focal plane
86 cm
5000 optical fibers placed with robots
Room with controlled temperature
standa
10 spectrographs with 3 cameras each

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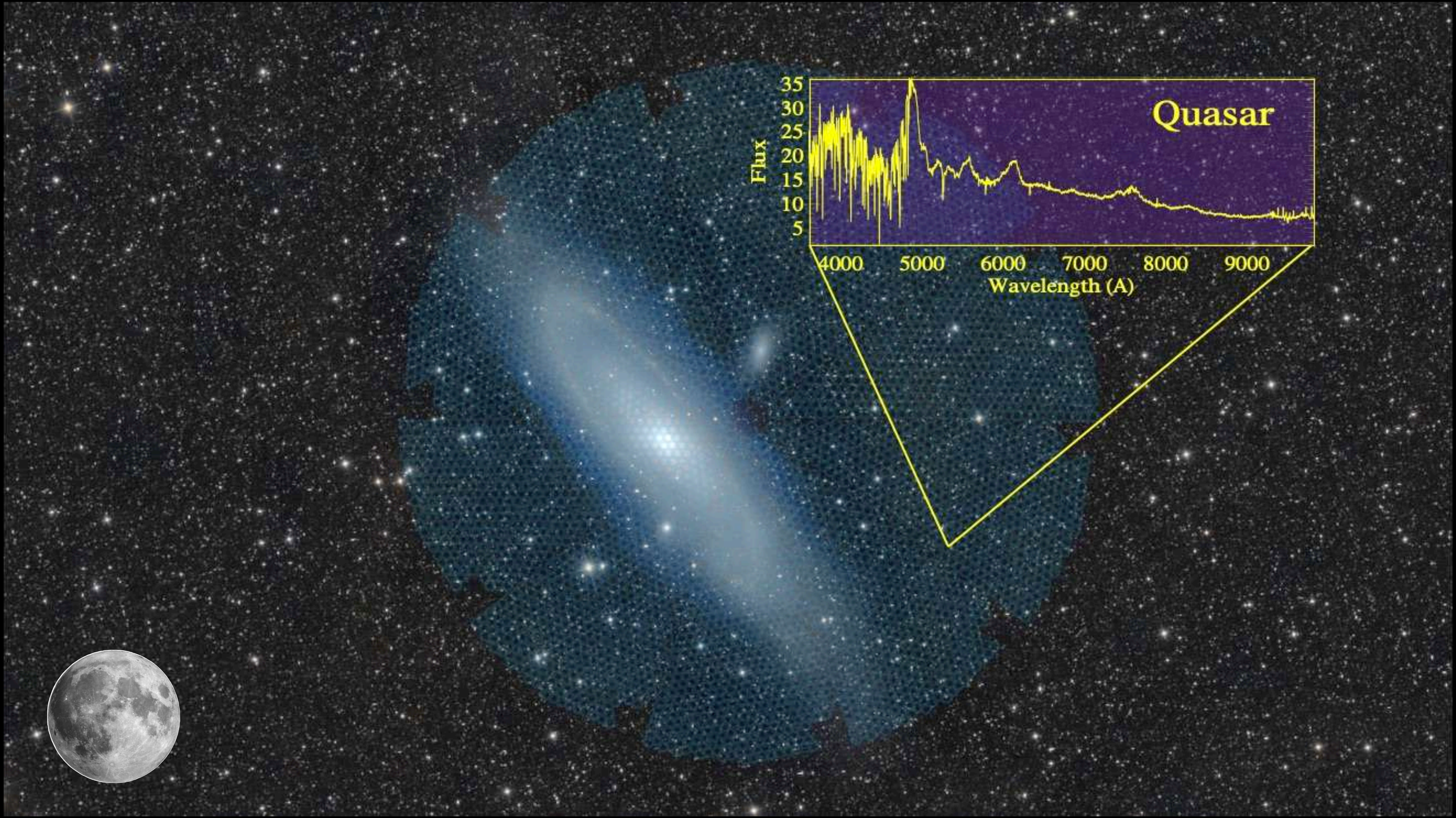
Field of view

8 deg^2



DESI Targets and spectra

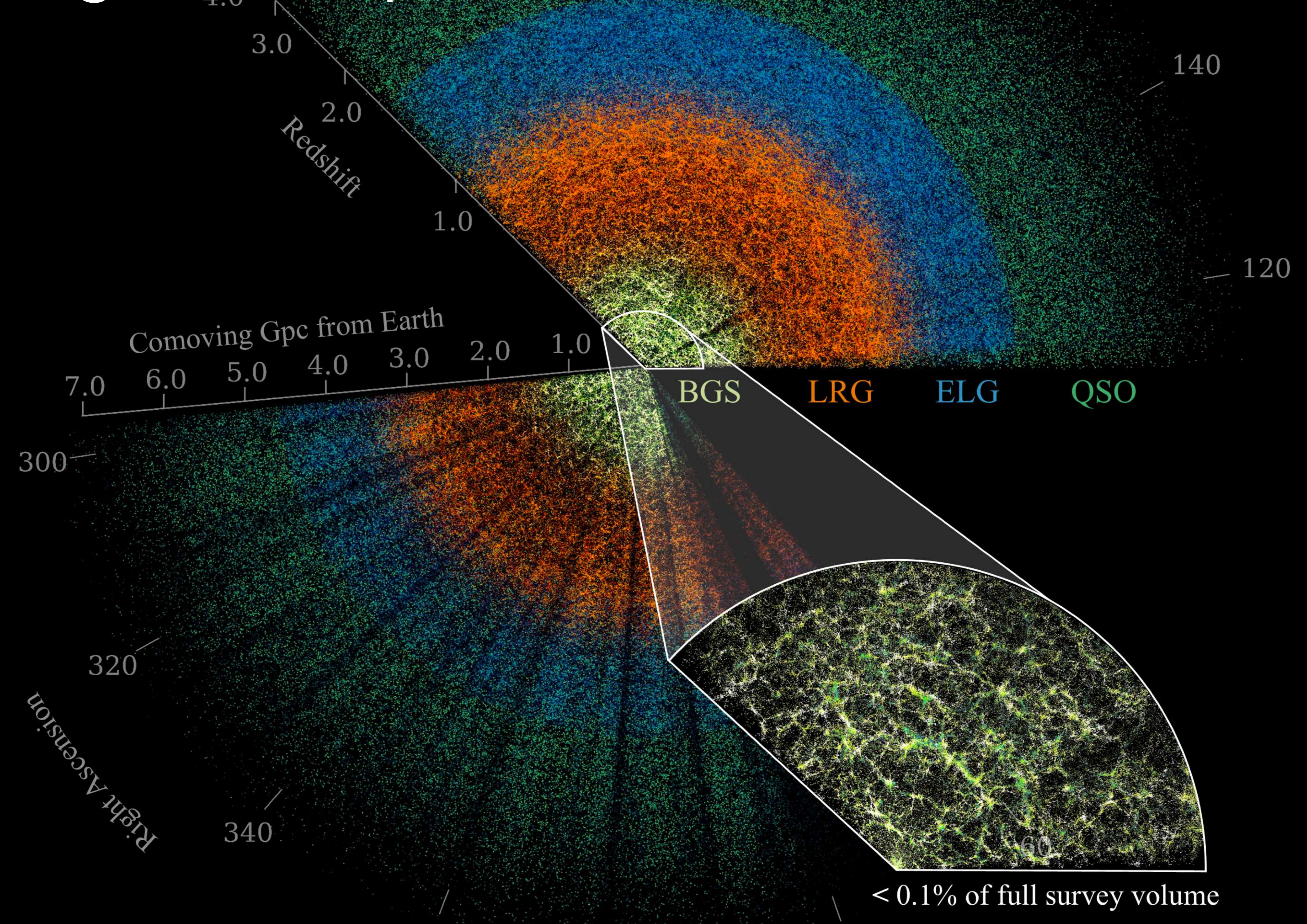
10 million Milky Way stars

13.5 million
Bright Galaxy Survey
$0.0 < z < 0.4$

8 million
Luminous Red Galaxies
$0.4 < z < 1.0$

16 million
Emission Line Galaxies
$0.6 < z < 1.6$

3 million
Quasi Stellar Objects
Lyα forests $2.1 < z < 4.5$
QSO tracers $0.9 < z < 2.1$



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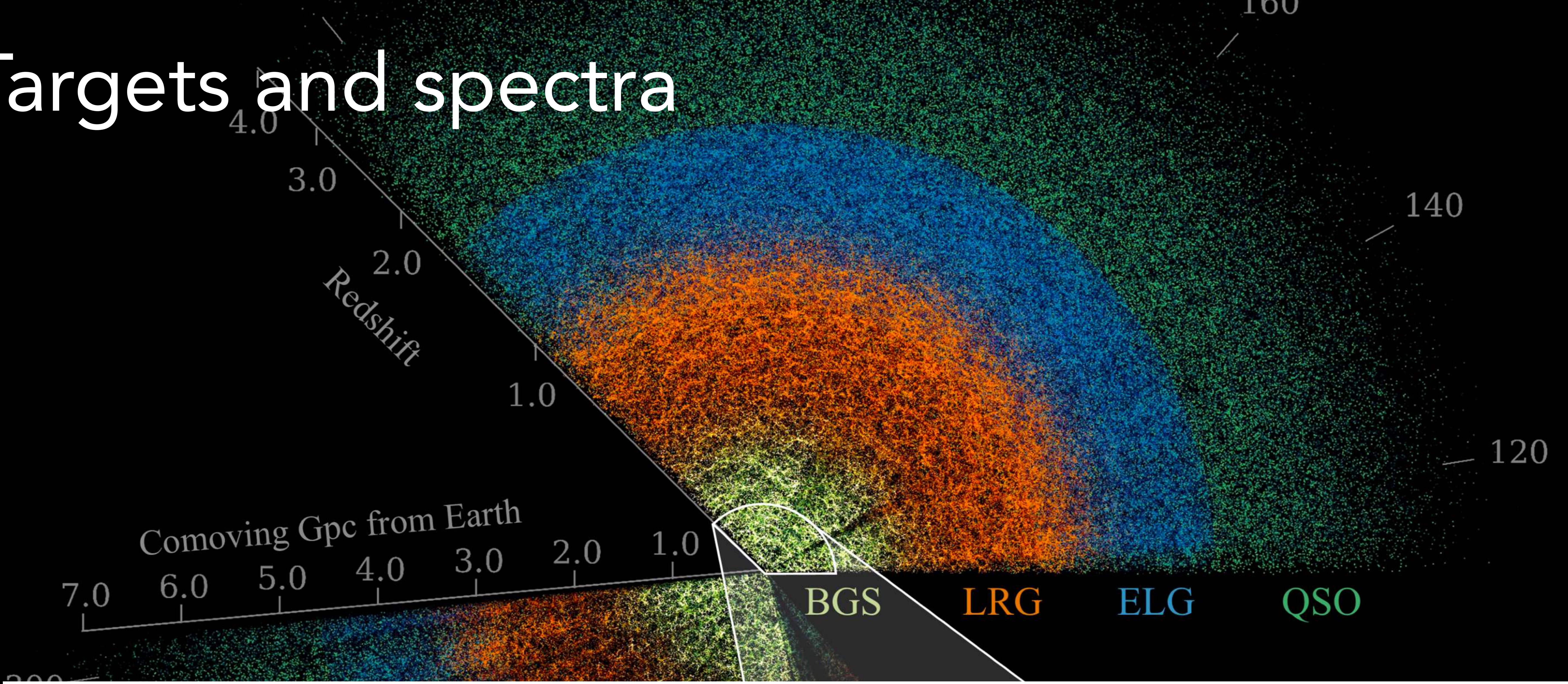
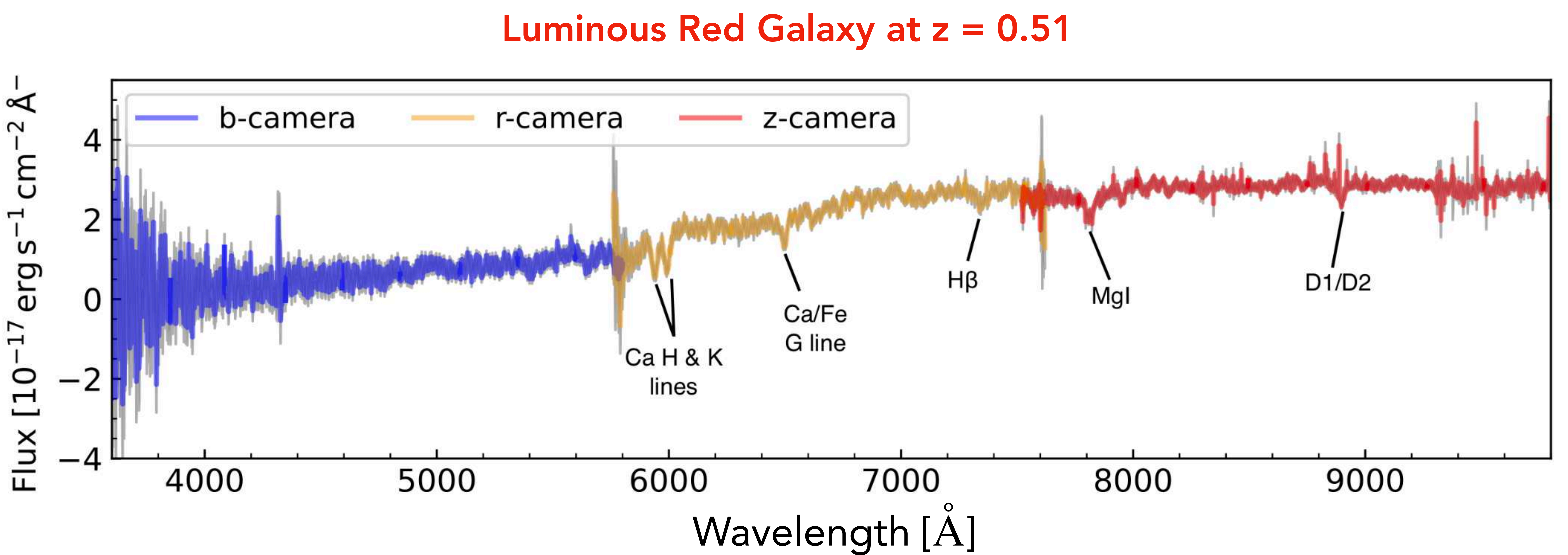
DESI Targets and spectra



8 million
Luminous Red Galaxies
$0.4 < z < 1.0$



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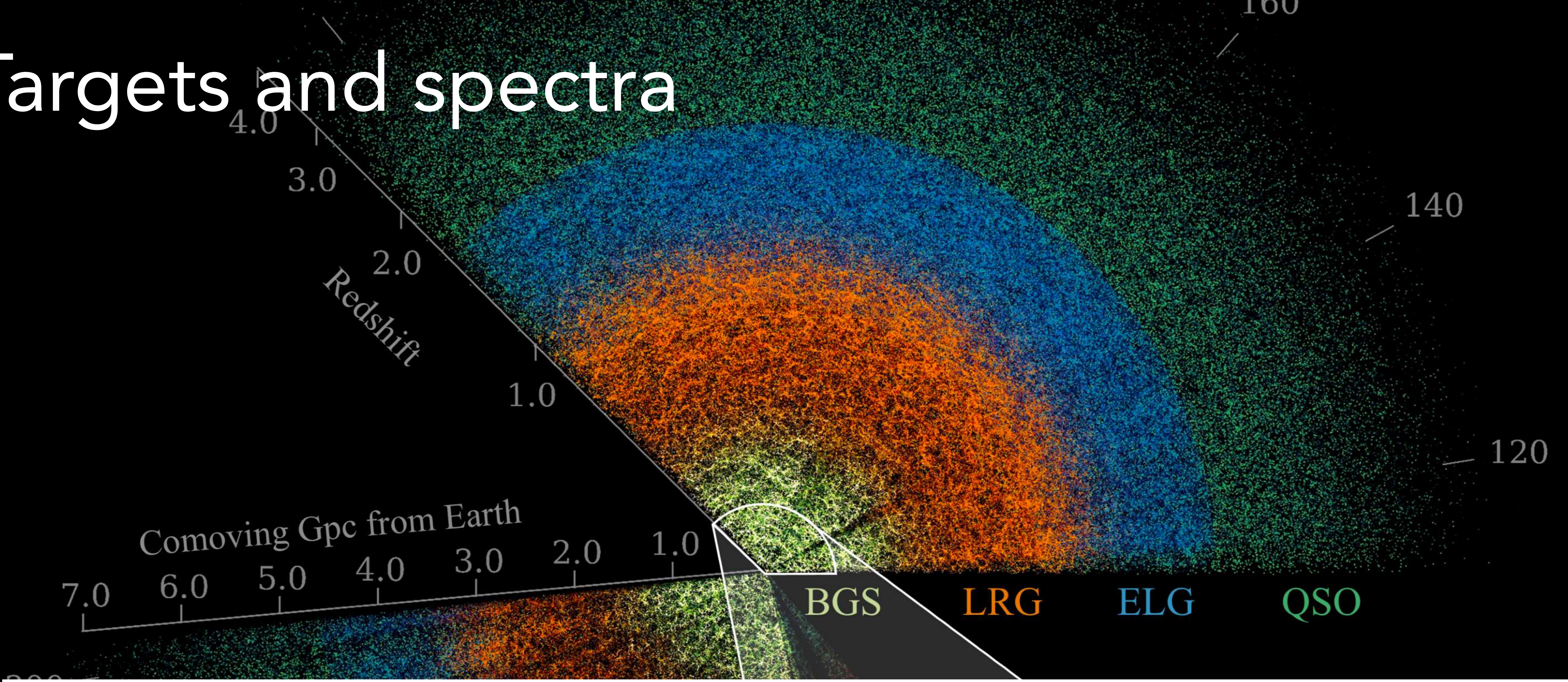
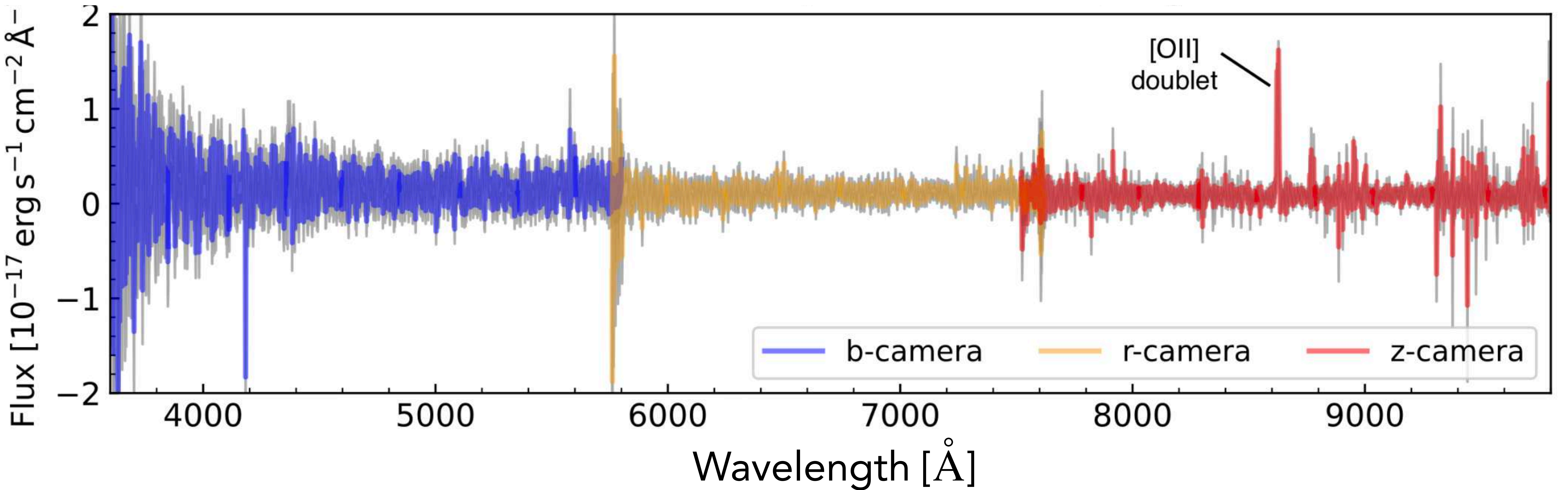
DESI Targets and spectra

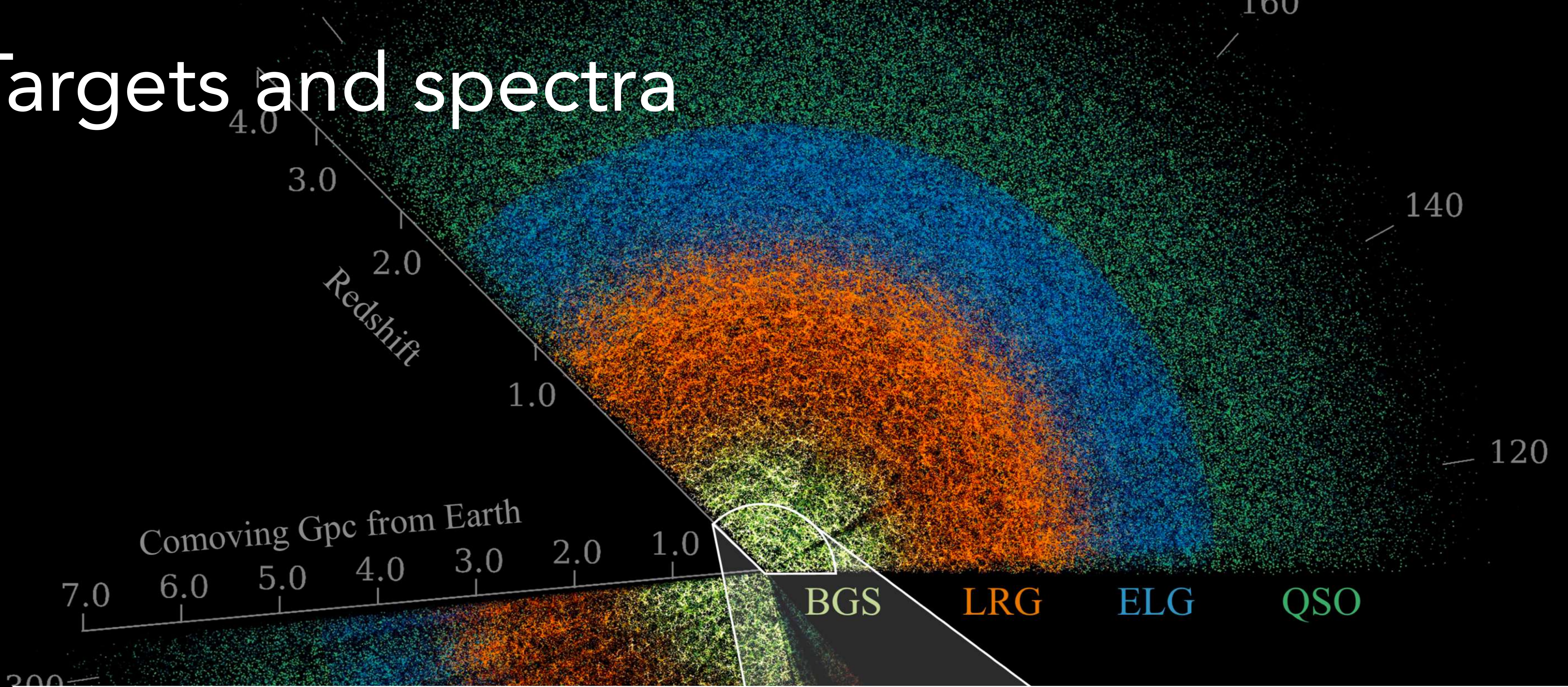


16 million
Emission Line Galaxies
$0.6 < z < 1.6$

Emission Line Galaxy z = 1.31



DESI Targets and spectra



3 million
Quasi Stellar Objects
Lyα forests $2.1 < z < 4.5$
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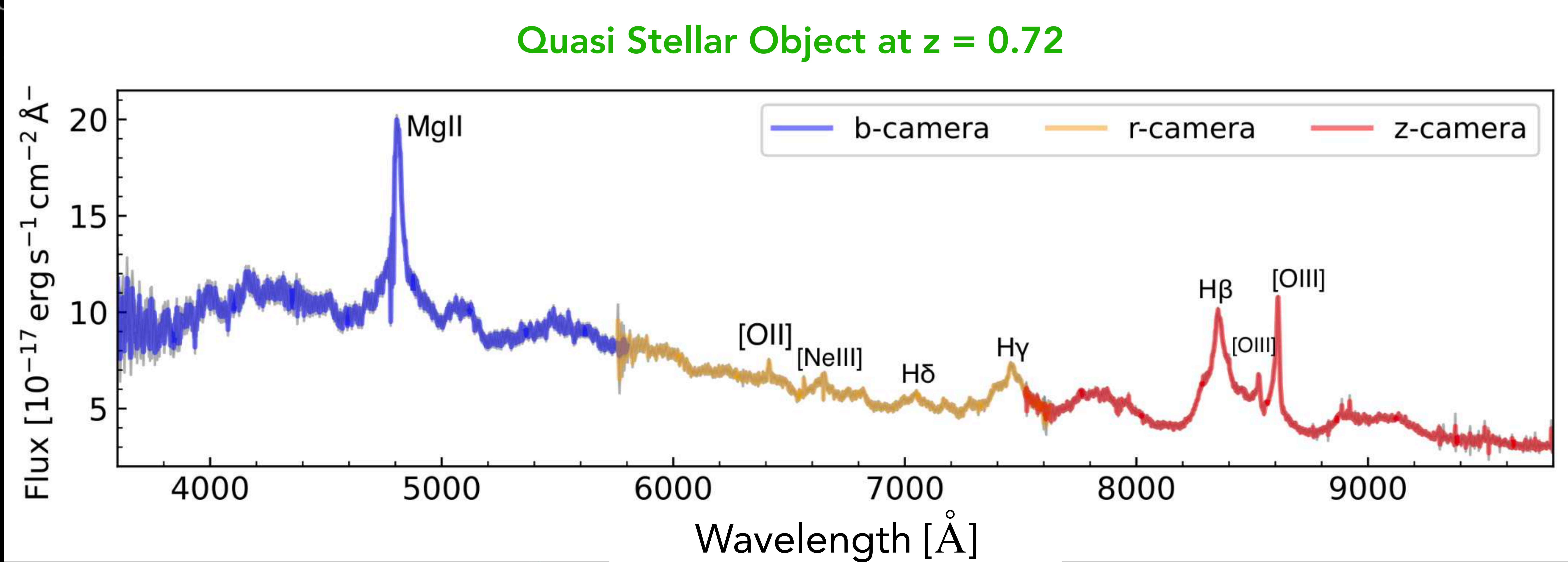


DESI Data Release 2

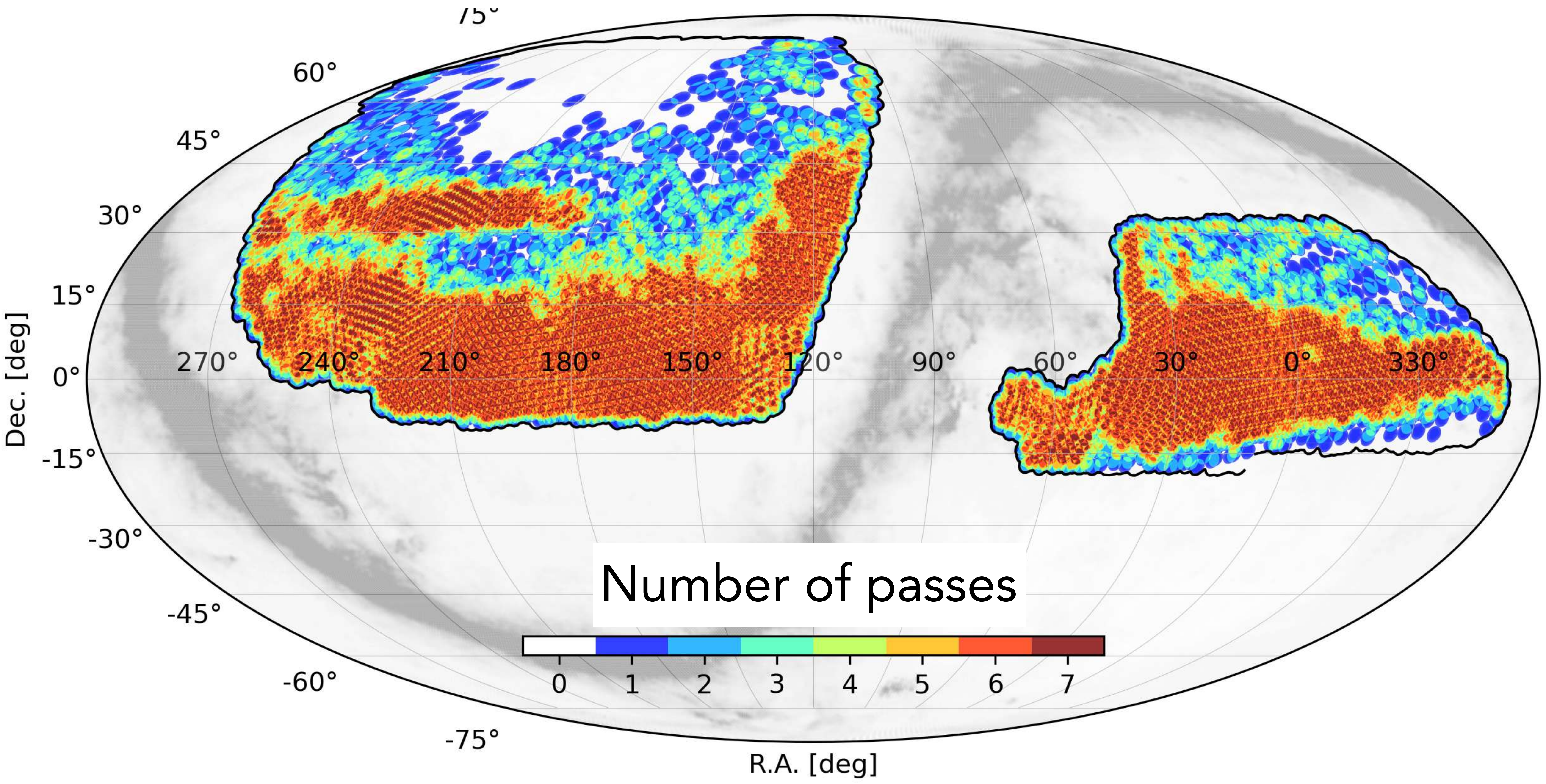
3 years of observations: 2021 - 2024

1.8 of 13.5 million
Bright Galaxy Survey
$0.0 < z < 0.4$

4.5 of 8.0 million
Luminous Red Galaxies
$0.4 < z < 1.0$

6.5 of 16.0 million
Emission Line Galaxies
$0.6 < z < 1.6$

2.0 of 3.0 million
Quasi Stellar Objects
Lyα forests $2.1 < z < 4.5$
QSO tracers $0.9 < z < 2.1$



The largest extragalactic redshift survey to date!

Plan

Dark energy and neutrino cosmology

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Neutrino mass constraints

Modified gravity constraints

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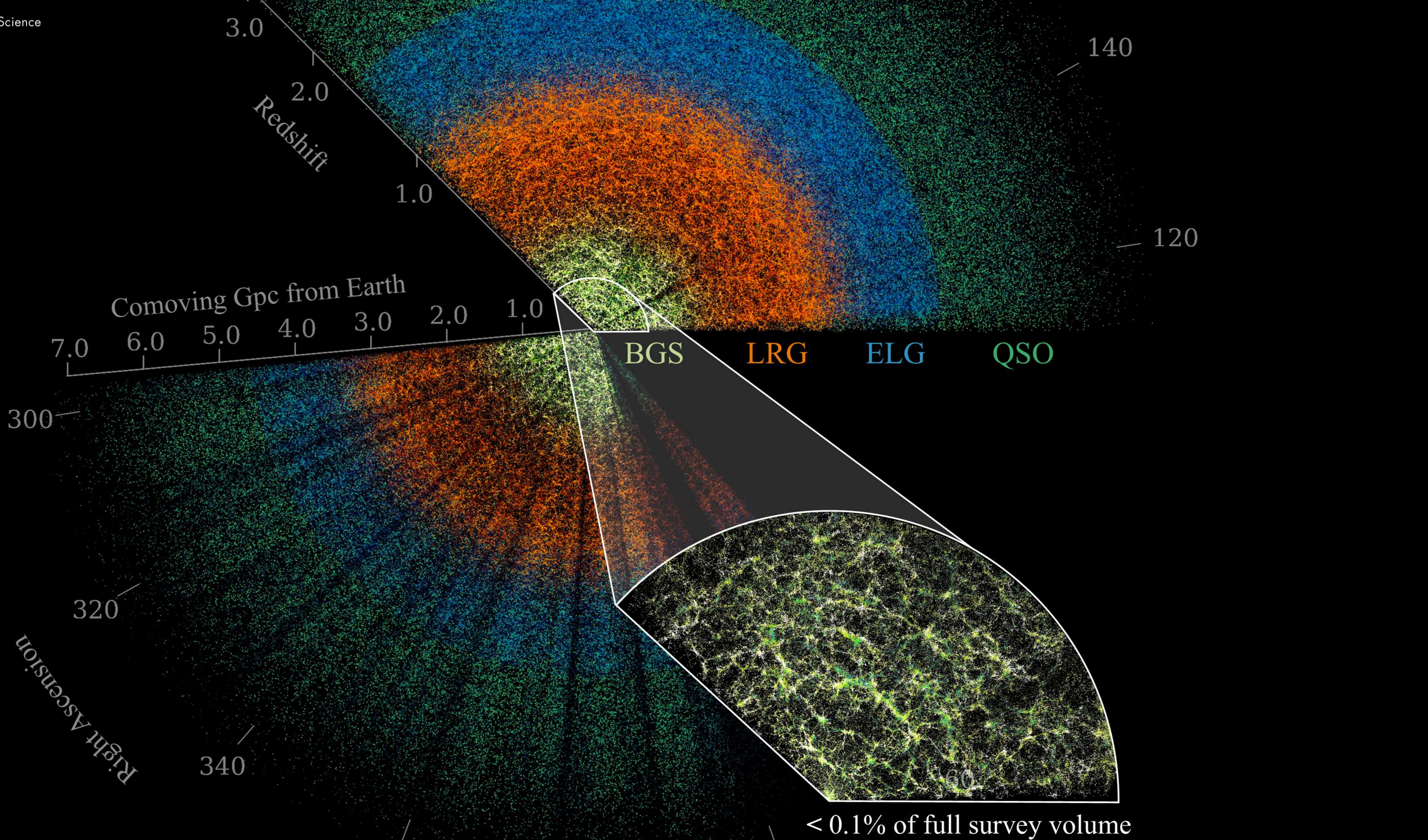
Measuring BAO with DESI



Measuring BAO with DESI

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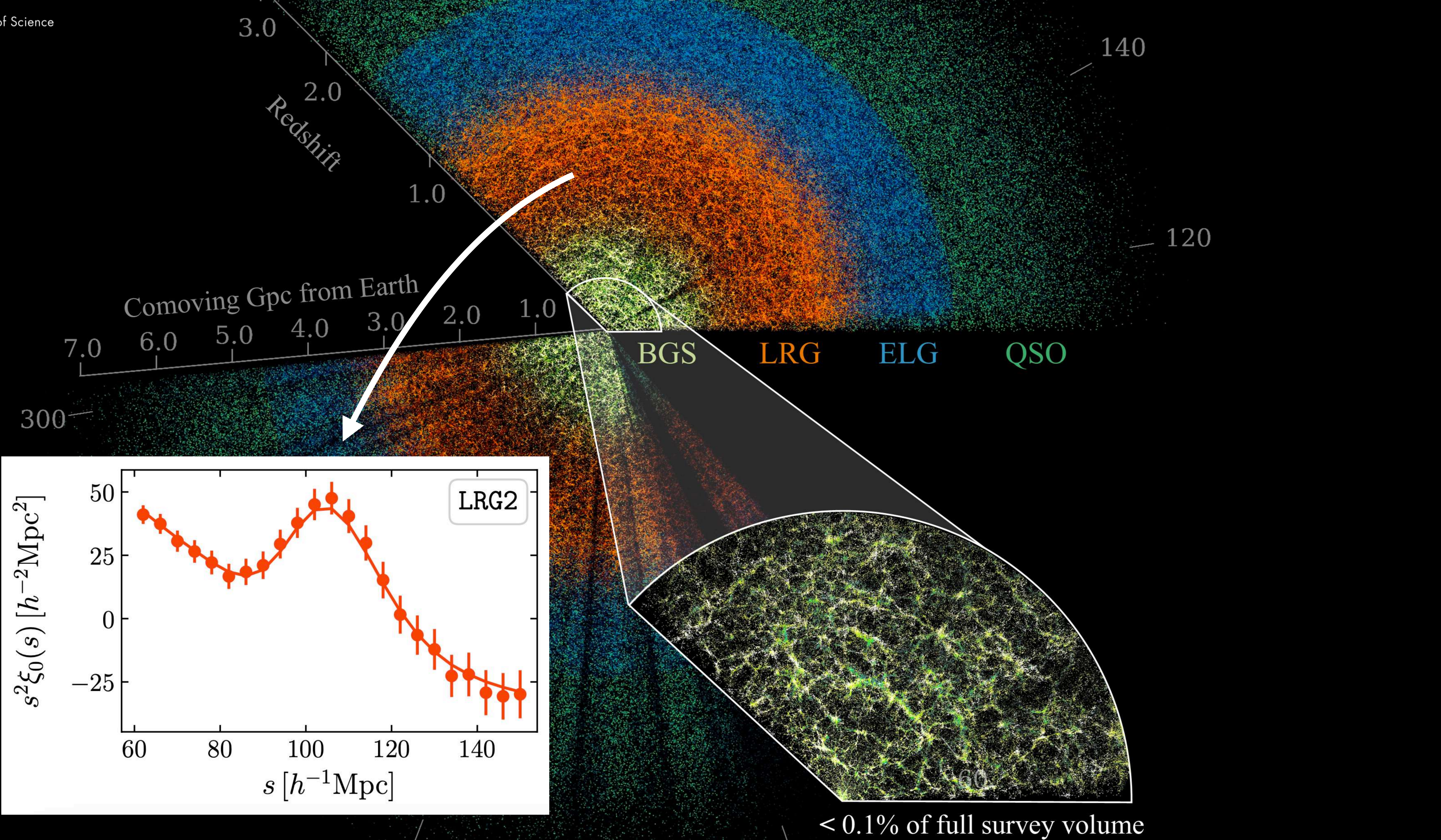
Measuring BAO with DESI



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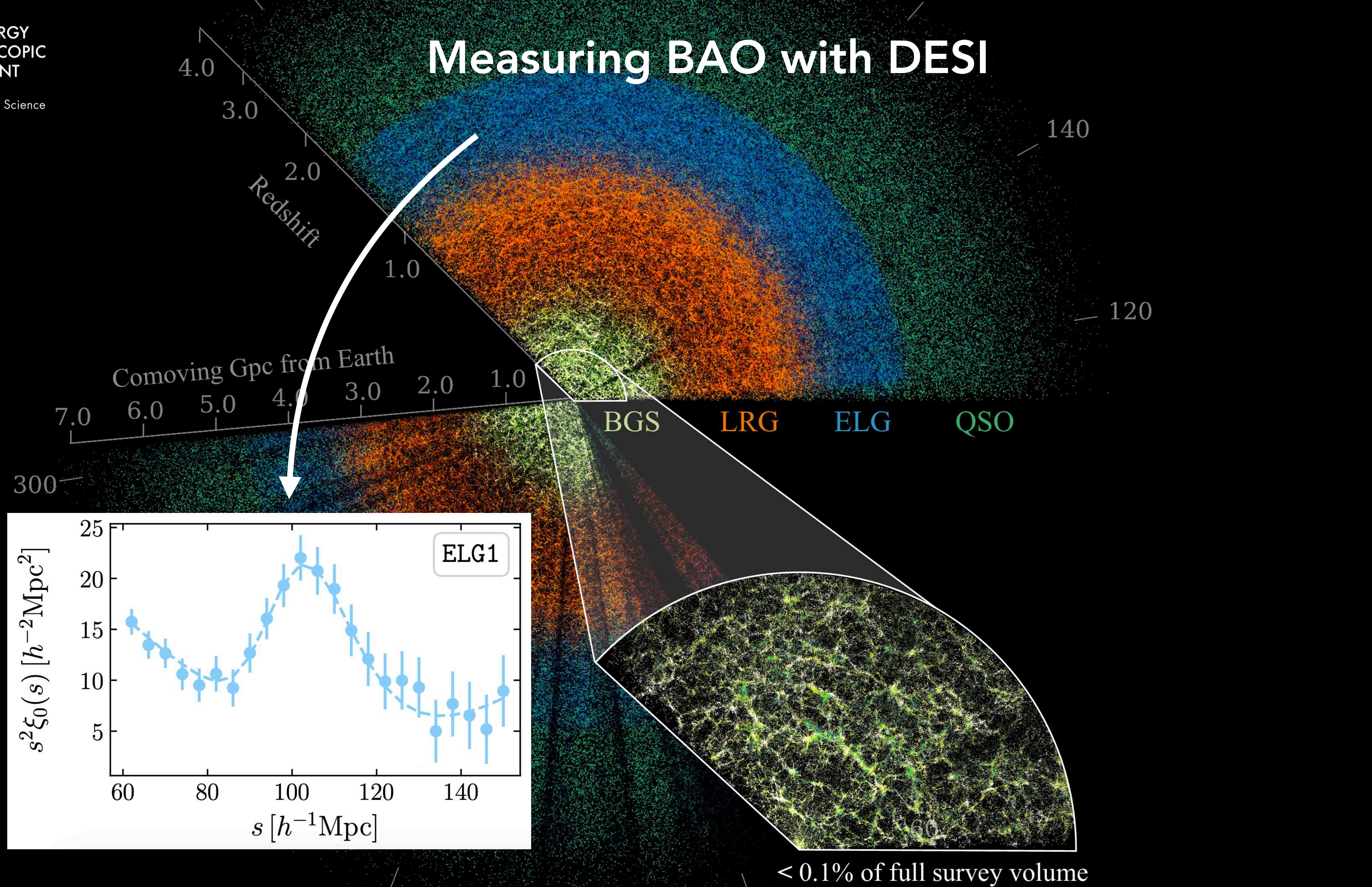
Measuring BAO with DESI



Measuring BAO with DESI

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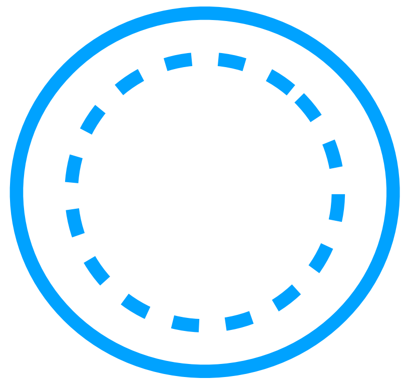
DESI BAO Distance Ladder

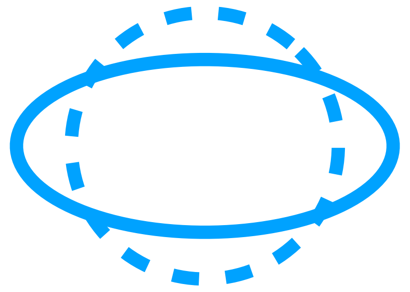
Isotropic BAO

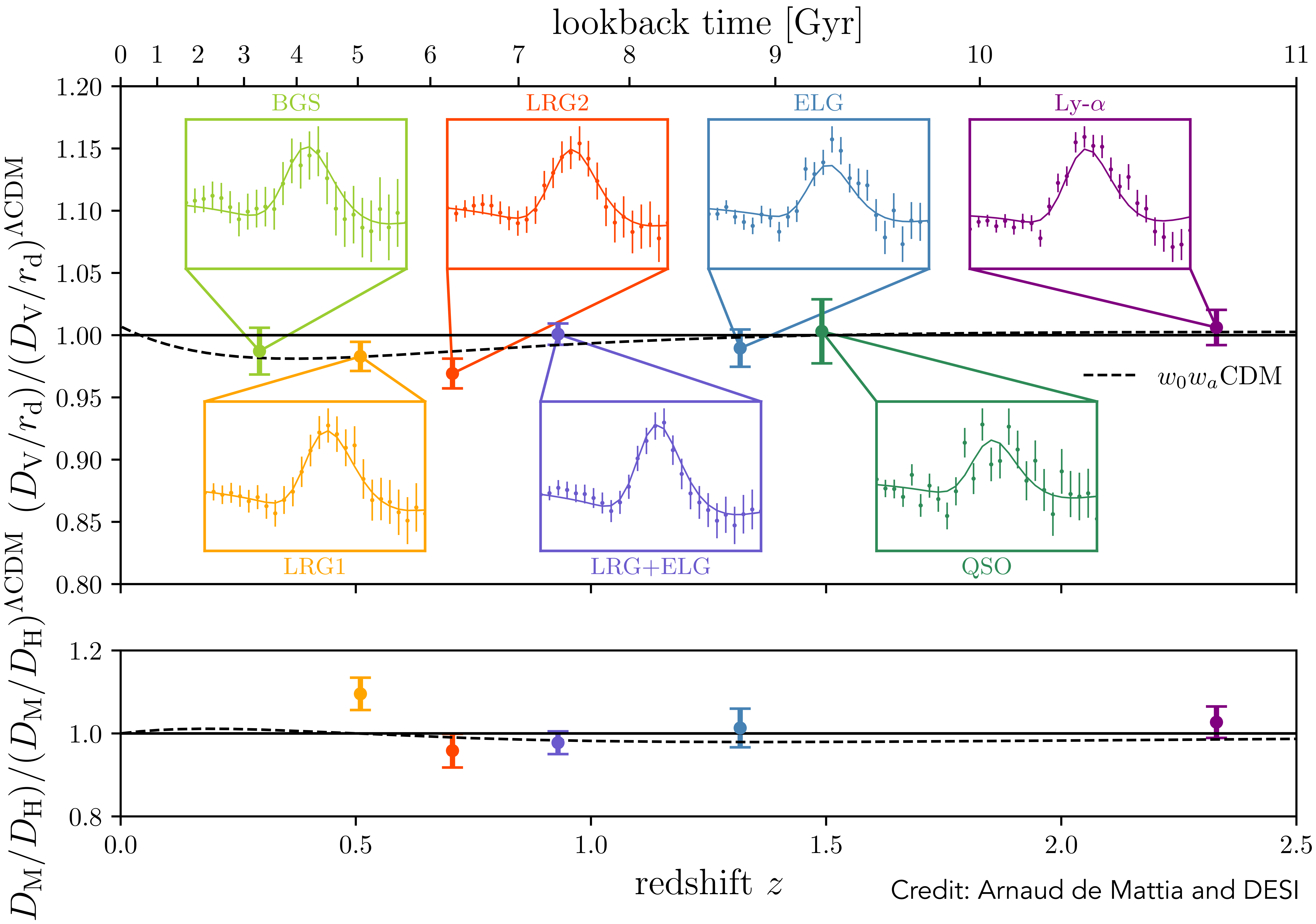
$$\frac{D_V(z)}{r_{\mathrm{drag}}}$$



Anisotropic BAO

$$\frac{D_M(z)}{D_H(z)}$$





Credit: Arnaud de Mattia and DESI

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Why should we trust this analysis ?

- Largest sample ever
- Blind analysis
- Unified BAO pipeline
- Huge variety of systematic tests

No detected impact

- observational effects in data (imaging, fiber assignment etc)
- reconstruction algorithm
- covariance matrix construction

- incomplete theory modelling
- choice of fiducial cosmology
- galaxy-halo (HOD) model uncertainties

Small systematic uncertainty (< 0.3%)

Constraints on evolving dark energy

Cosmological constant Λ

$$w = -1$$

Constraints on evolving dark energy

Cosmological constant Λ

$$w = -1$$

Evolving dark energy

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

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Cosmological constant Λ

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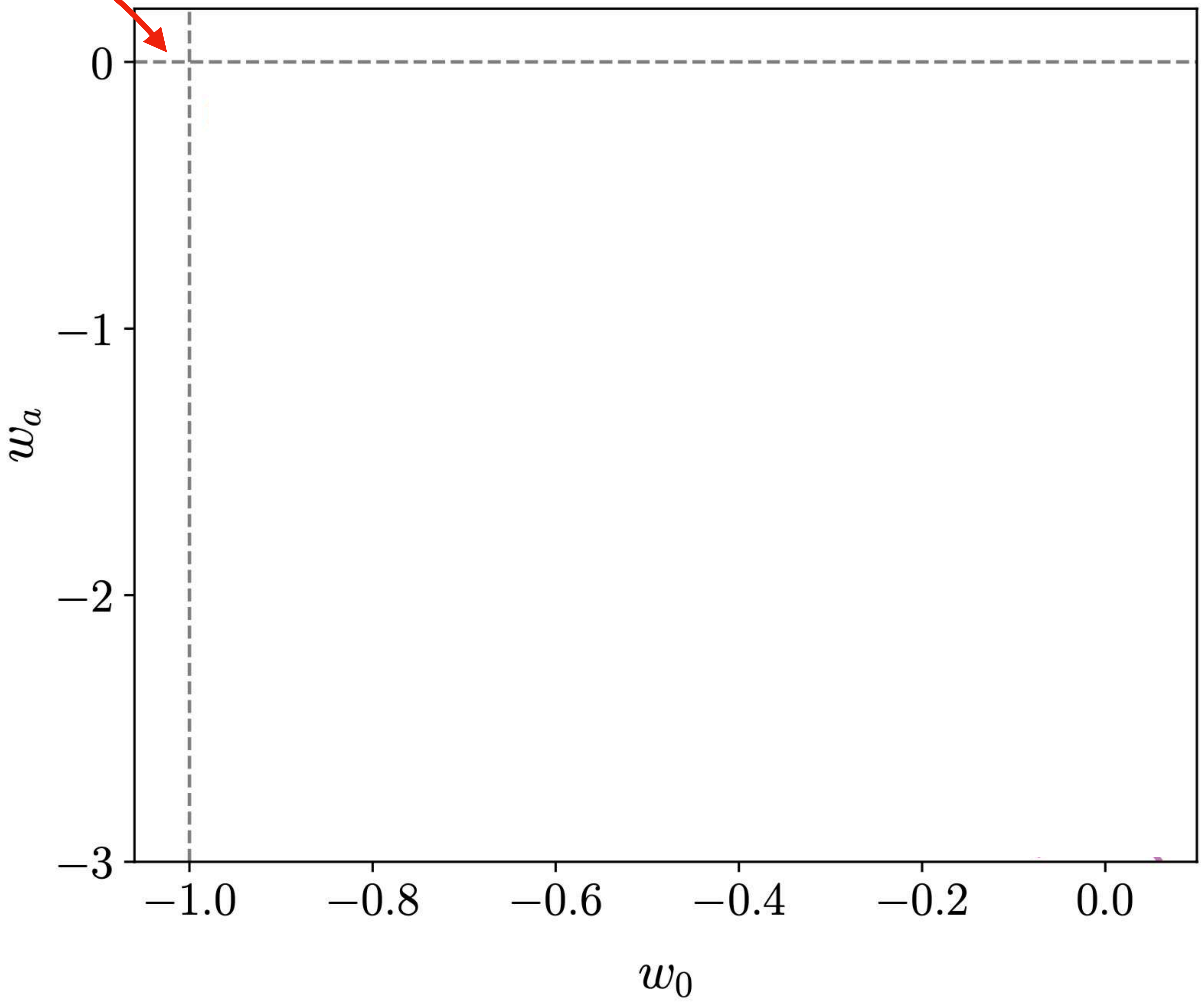
Evolving dark energy

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



Constraints on evolving dark energy

Cosmological constant Λ

$w = -1$

Evolving dark energy

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

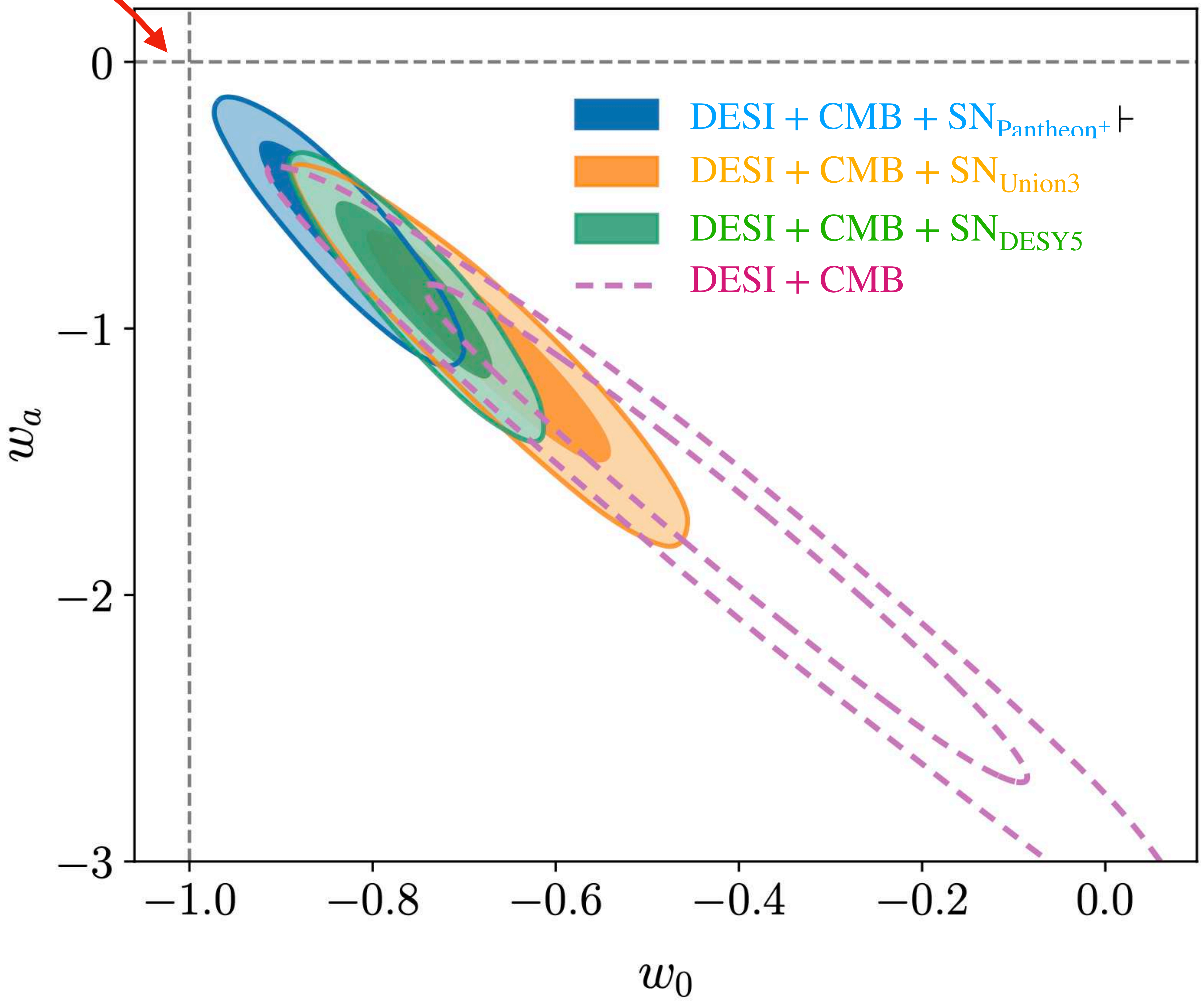
Tension with the cosmological constant:

$\mathrm{DESI} + \mathrm{CMB} \Rightarrow 3.1\sigma$

$\mathrm{DESI} + \mathrm{CMB} + \mathrm{SN}_{\mathrm{Pantheon}^+} \Rightarrow 2.8\sigma$

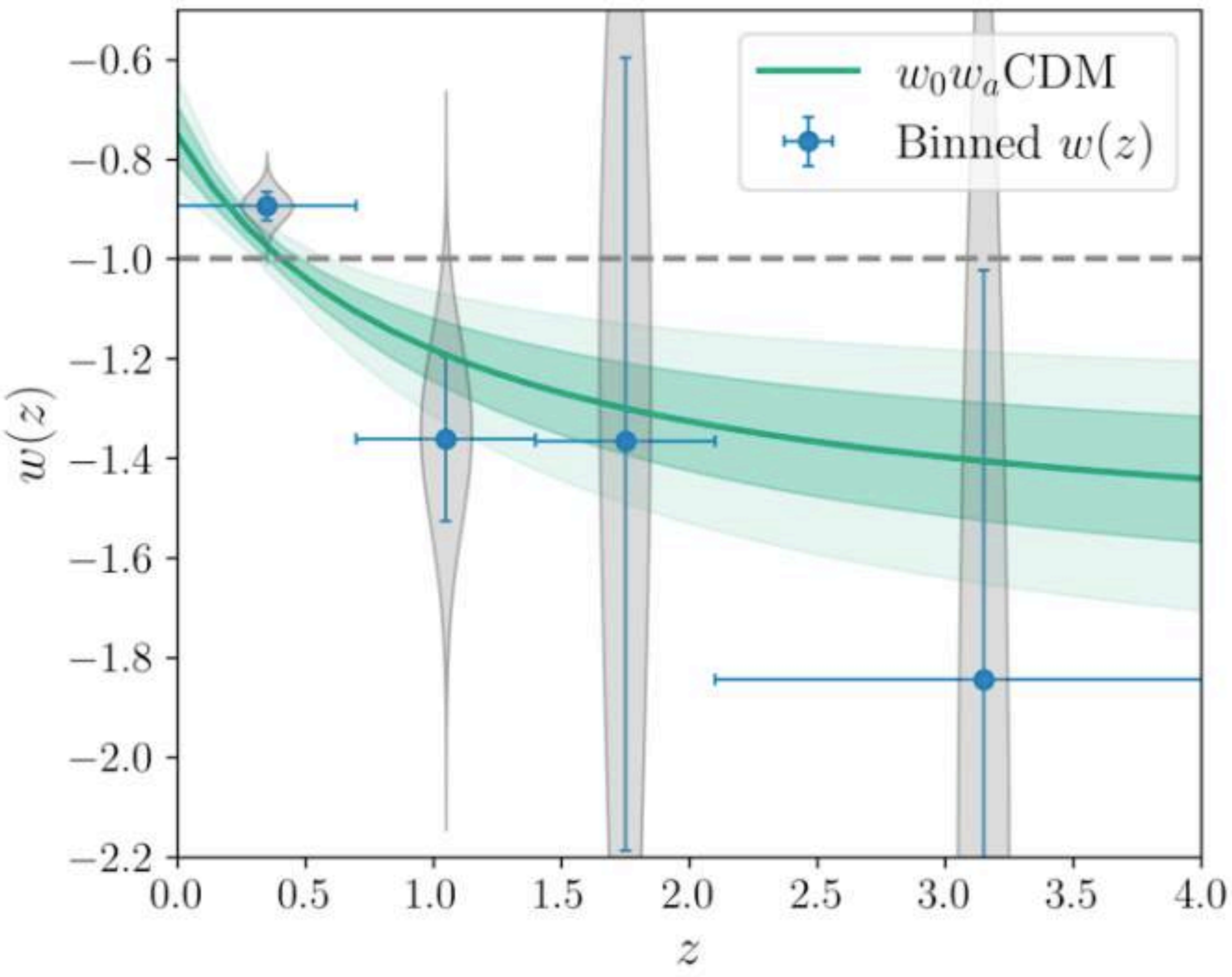
$\mathrm{DESI} + \mathrm{CMB} + \mathrm{SN}_{\mathrm{Union3}} \Rightarrow 3.8\sigma$

$\mathrm{DESI} + \mathrm{CMB} + \mathrm{SN}_{\mathrm{DESY5}} \Rightarrow 4.2\sigma$



Constraints on evolving dark energy

Parametric model for $w(z)$



Consistent with standard w_0, w_a model

Lodha et al., 2025

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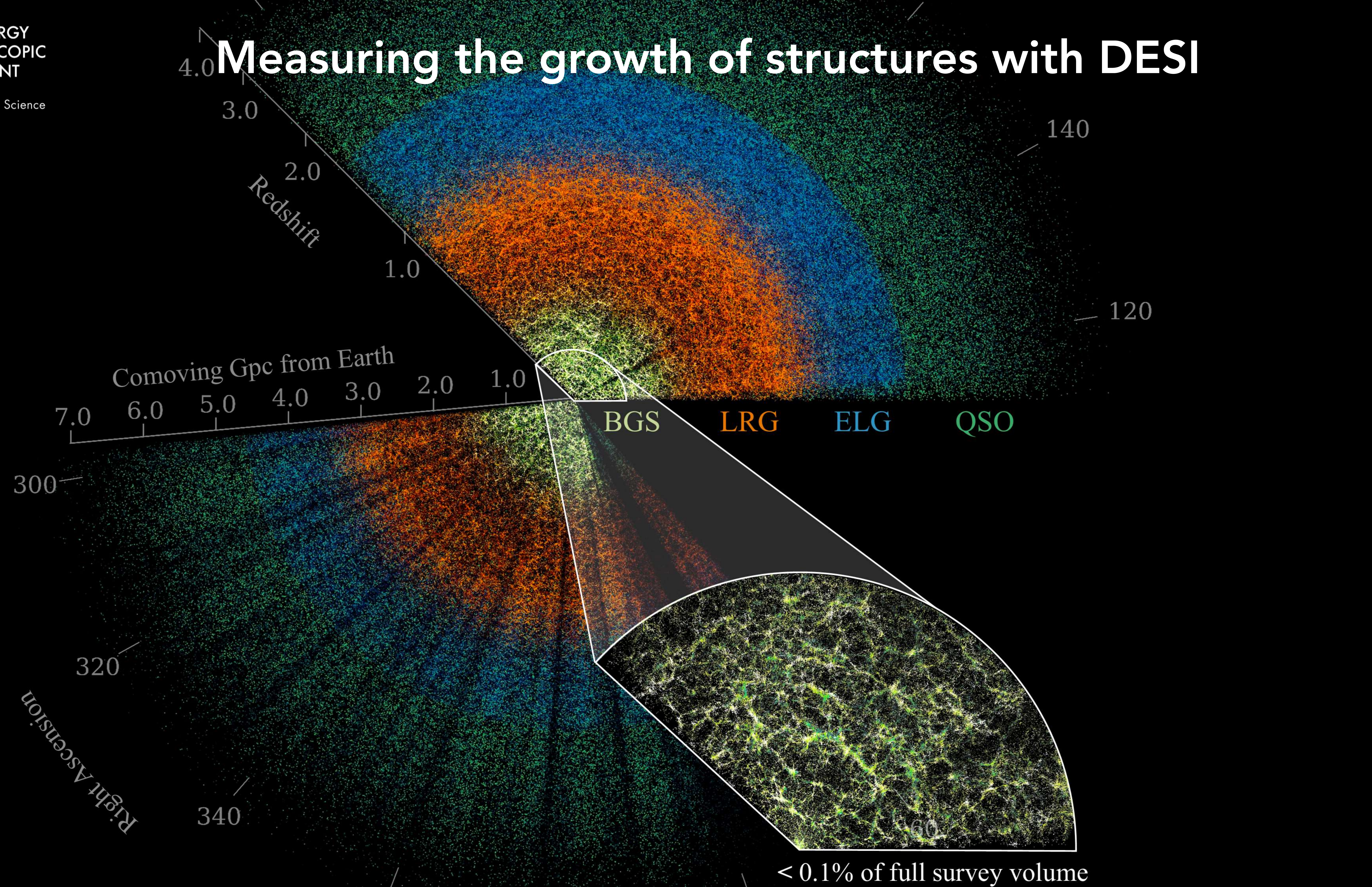
Measuring the growth of structures with DESI



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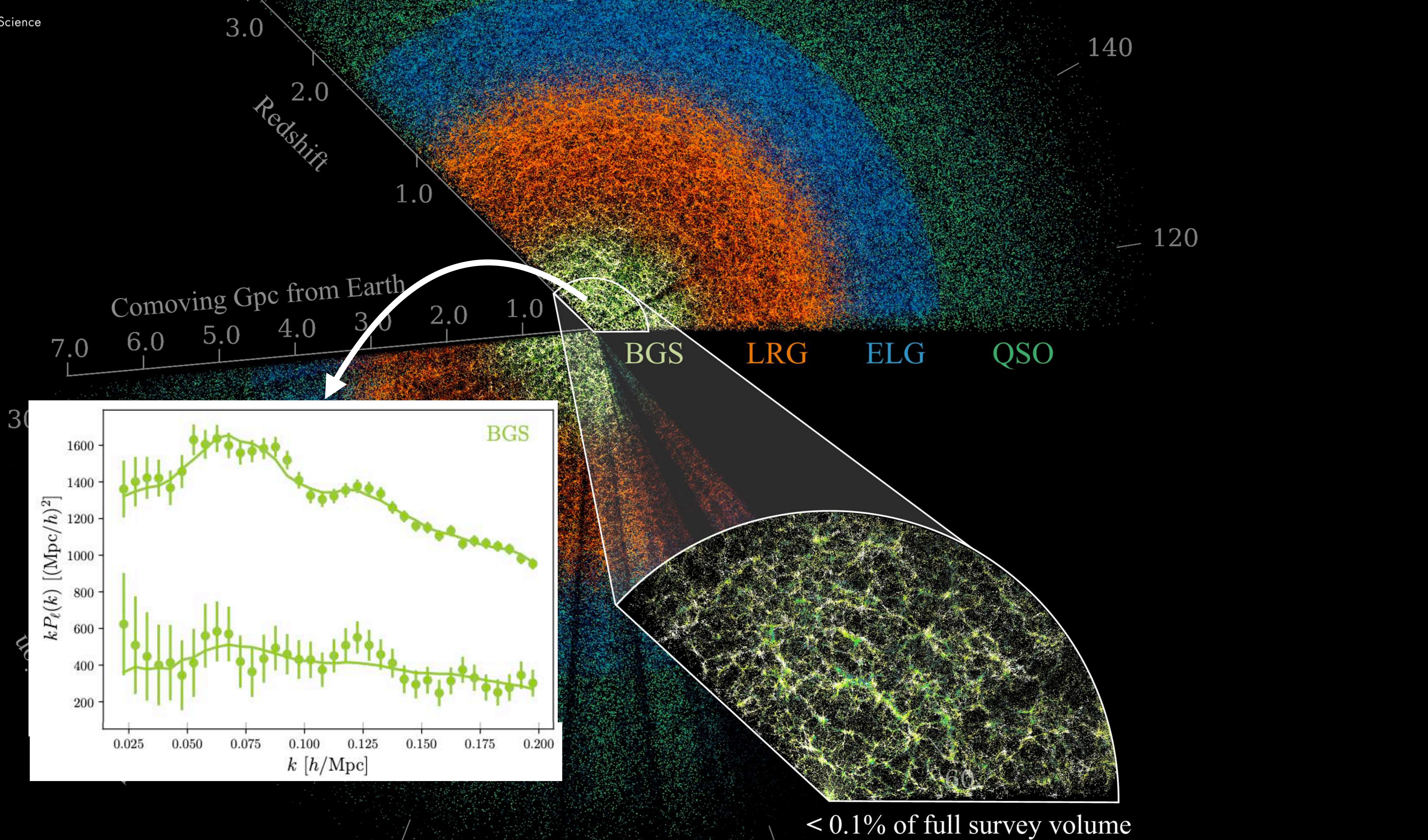
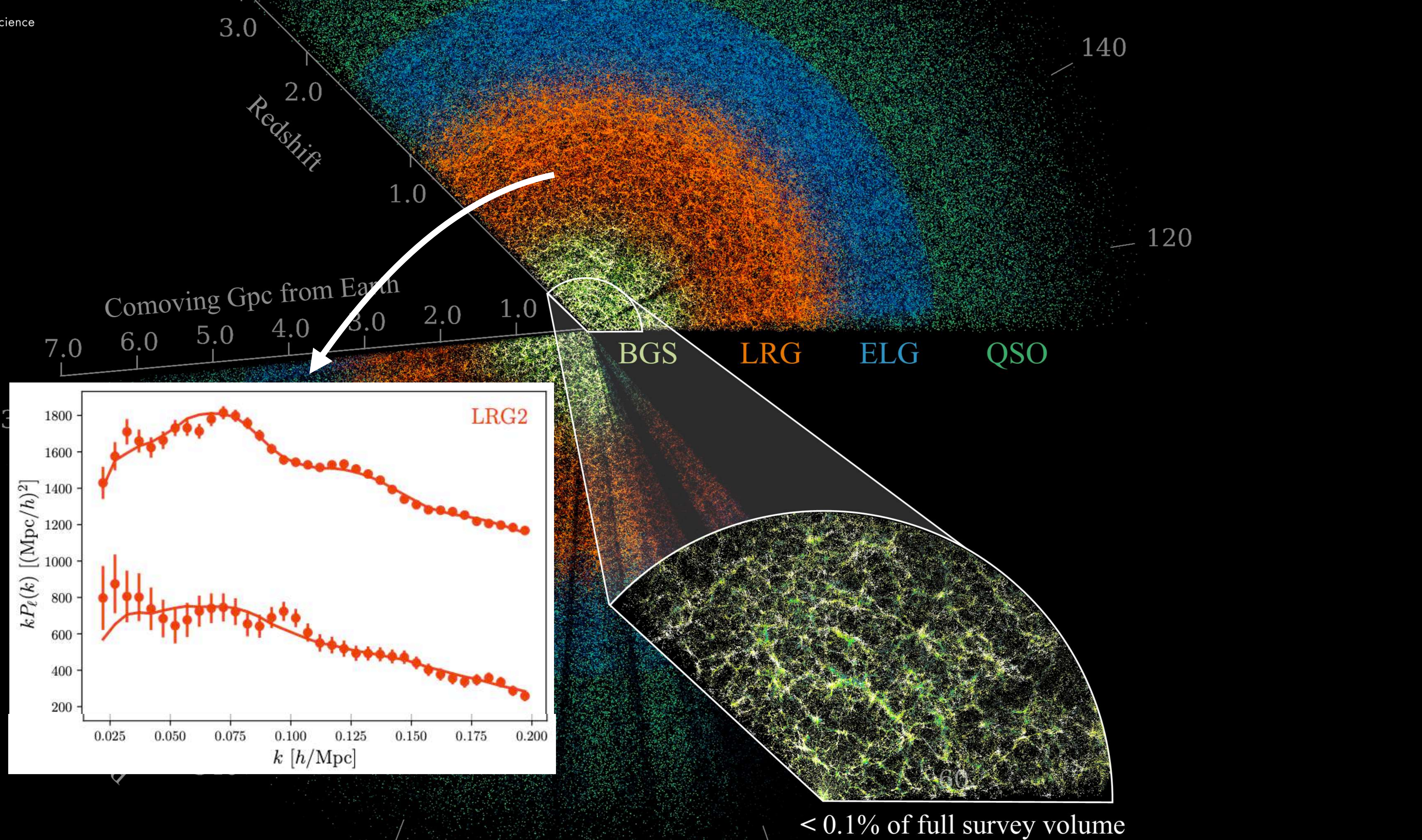


Measuring the growth of structures with DESI



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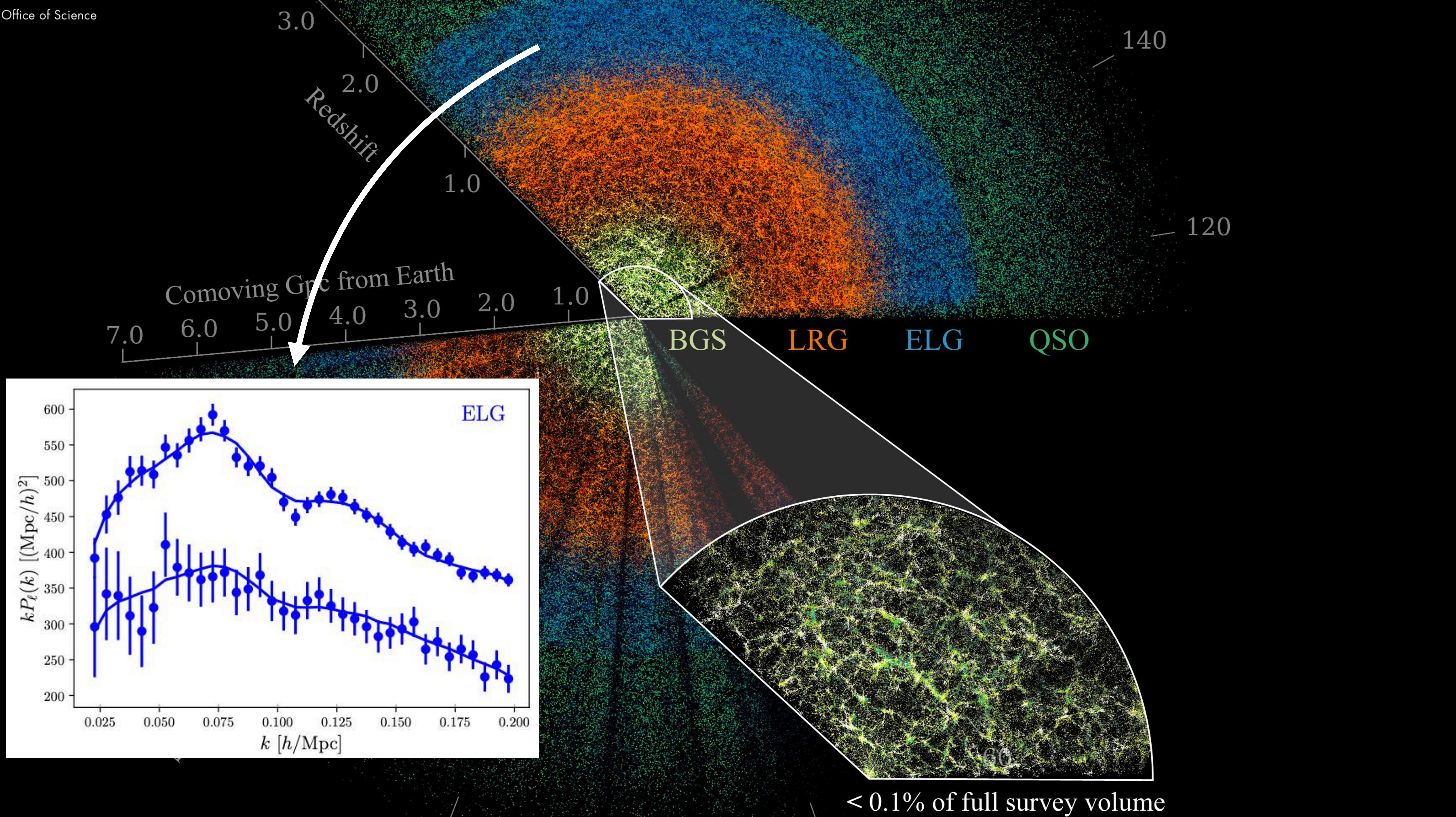
Measuring the growth of structures with DESI



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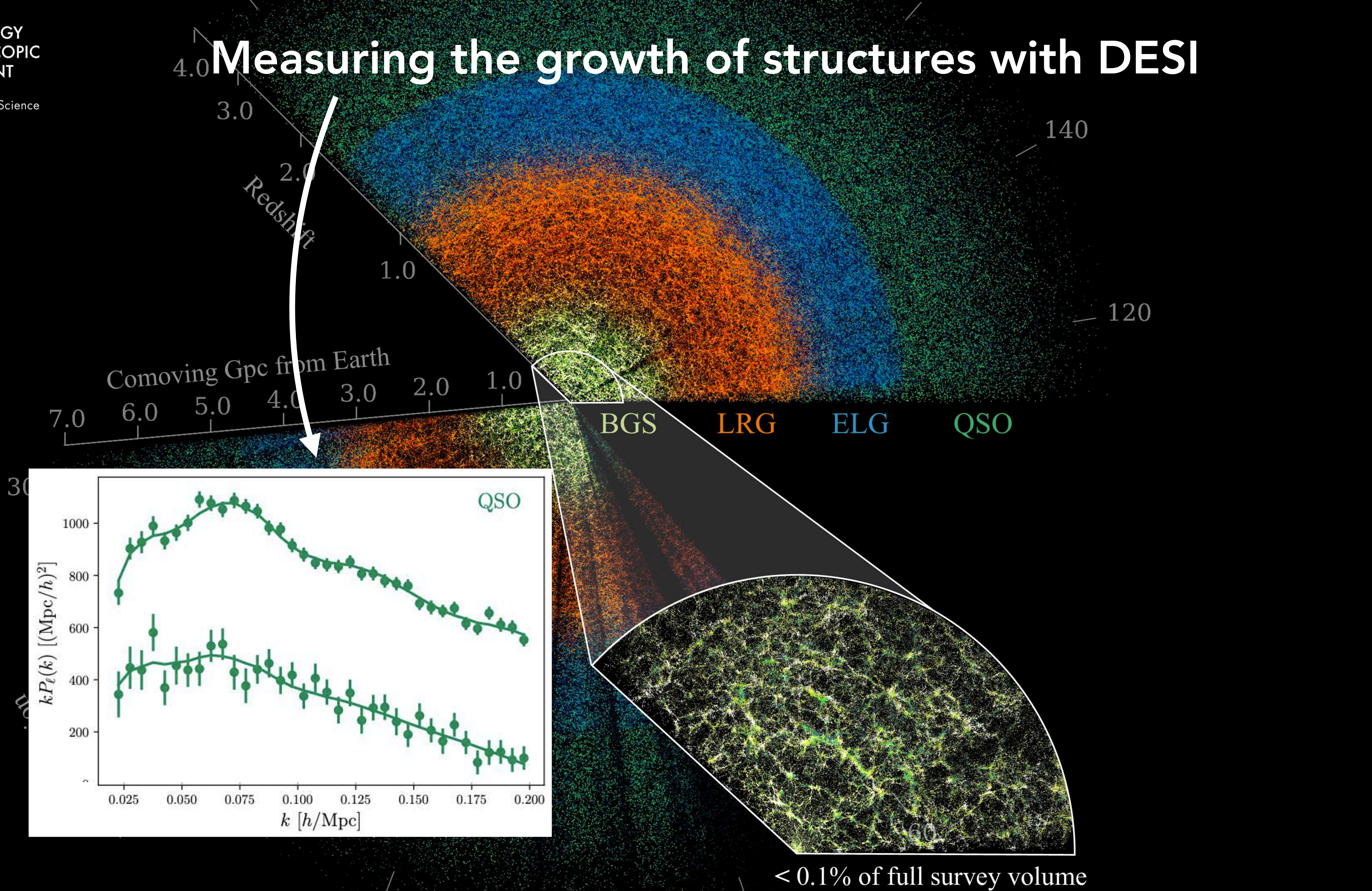
Measuring the growth of structures with DESI



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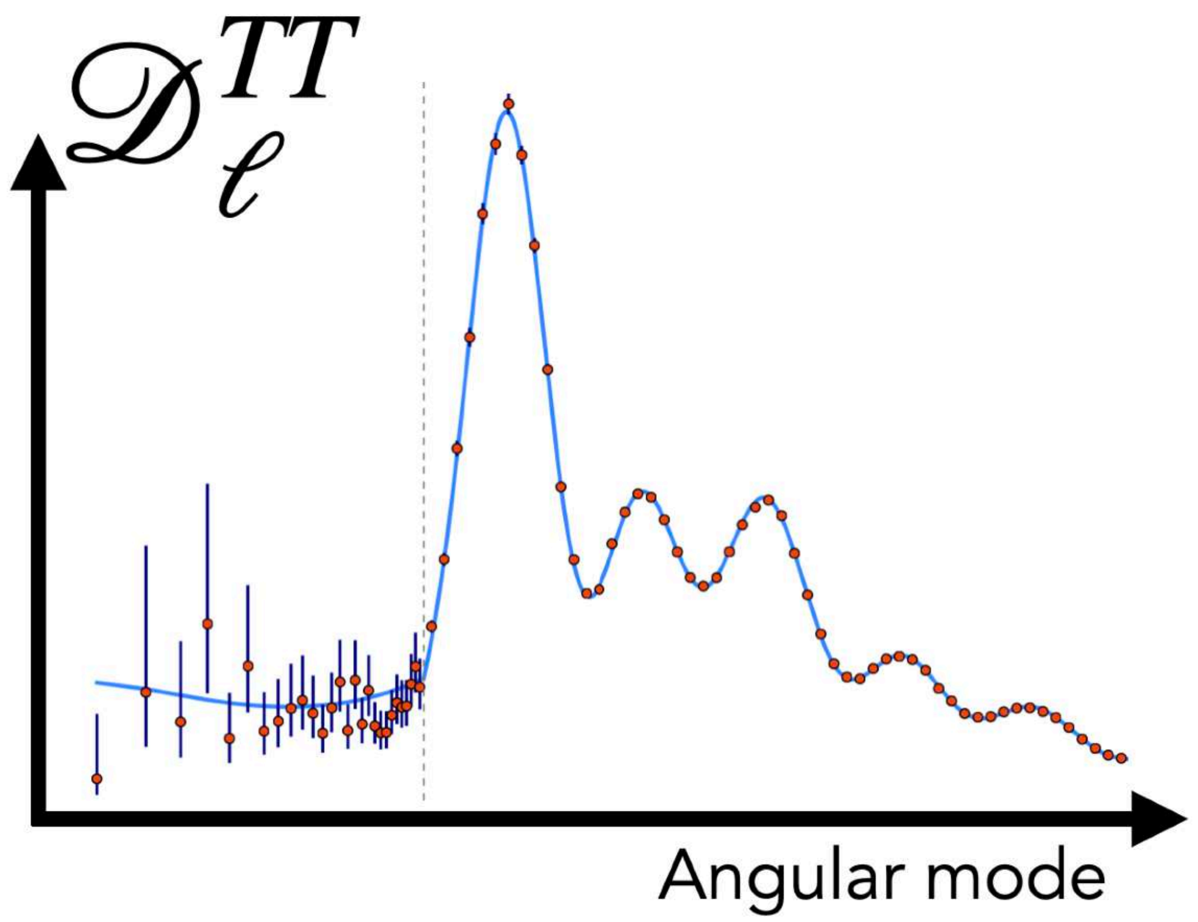
The DESI full-shape

Results on DR1 (work in progress for DR2)

The DESI full-shape

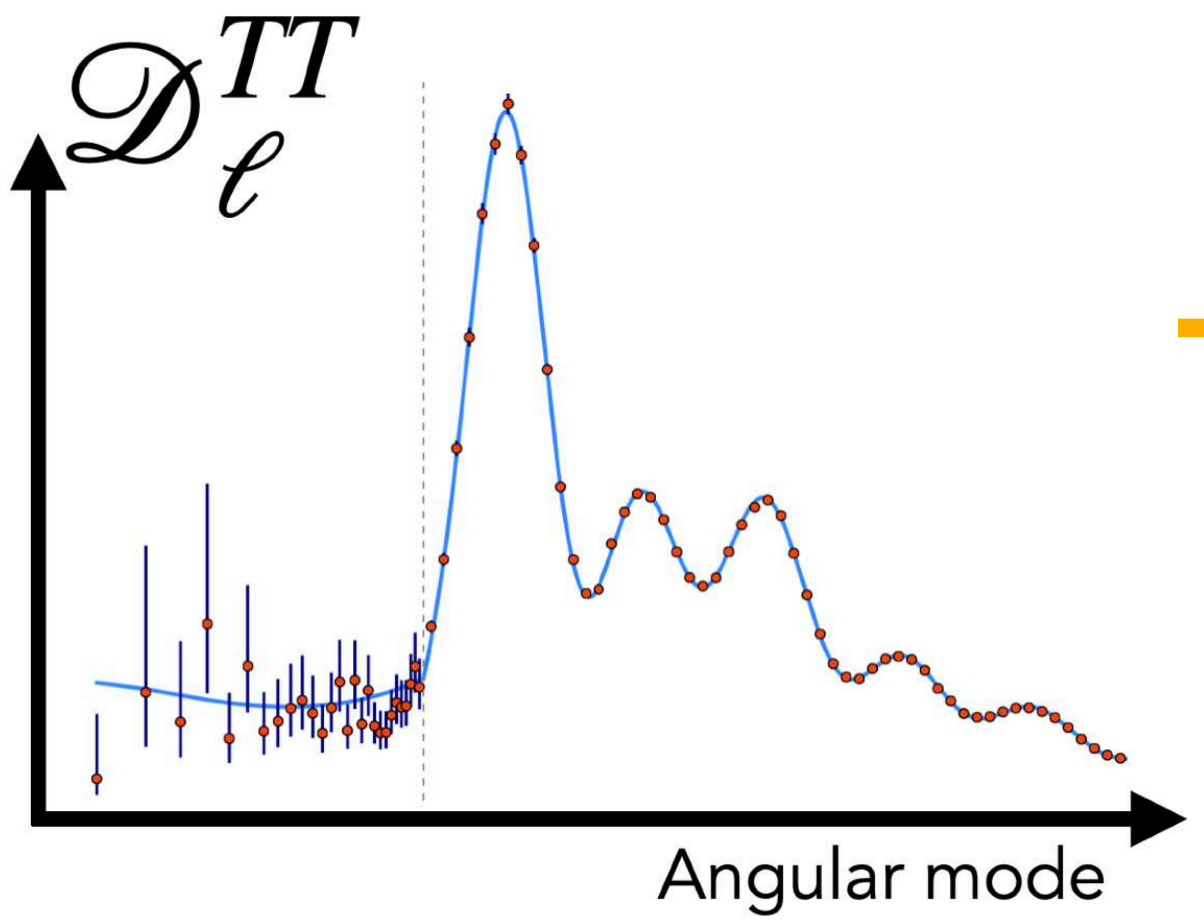
CMB



Results on DR1 (work in progress for DR2)

The DESI full-shape

CMB



$$\left\{\theta_*, \omega_c, \omega_b, A_s, n_s, \tau, [\Omega_k, \sum m_\nu, w_0, w_a, N_{\text{eff}}, \ldots]\right\}$$

"vanilla"	extensions

Results on DR1 (work in progress for DR2)

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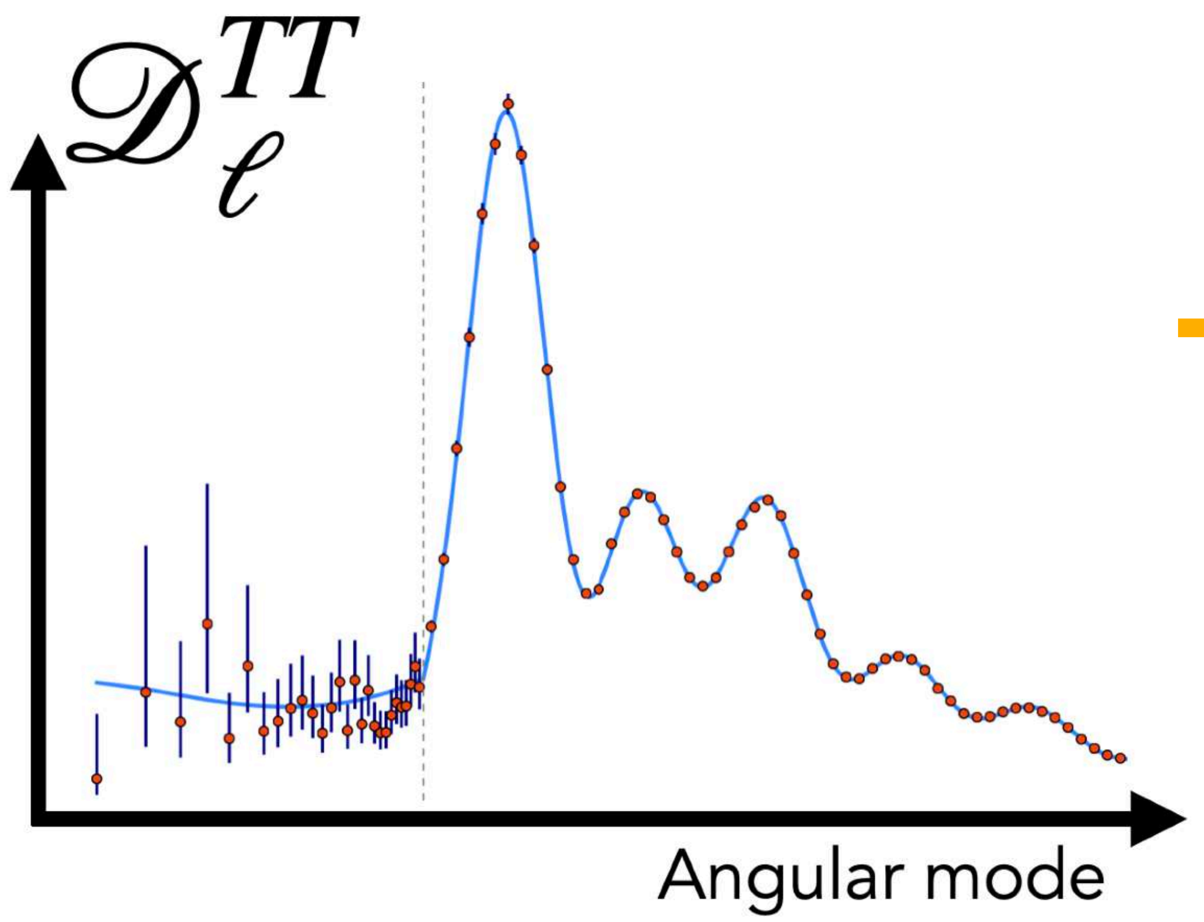
The DESI full-shape

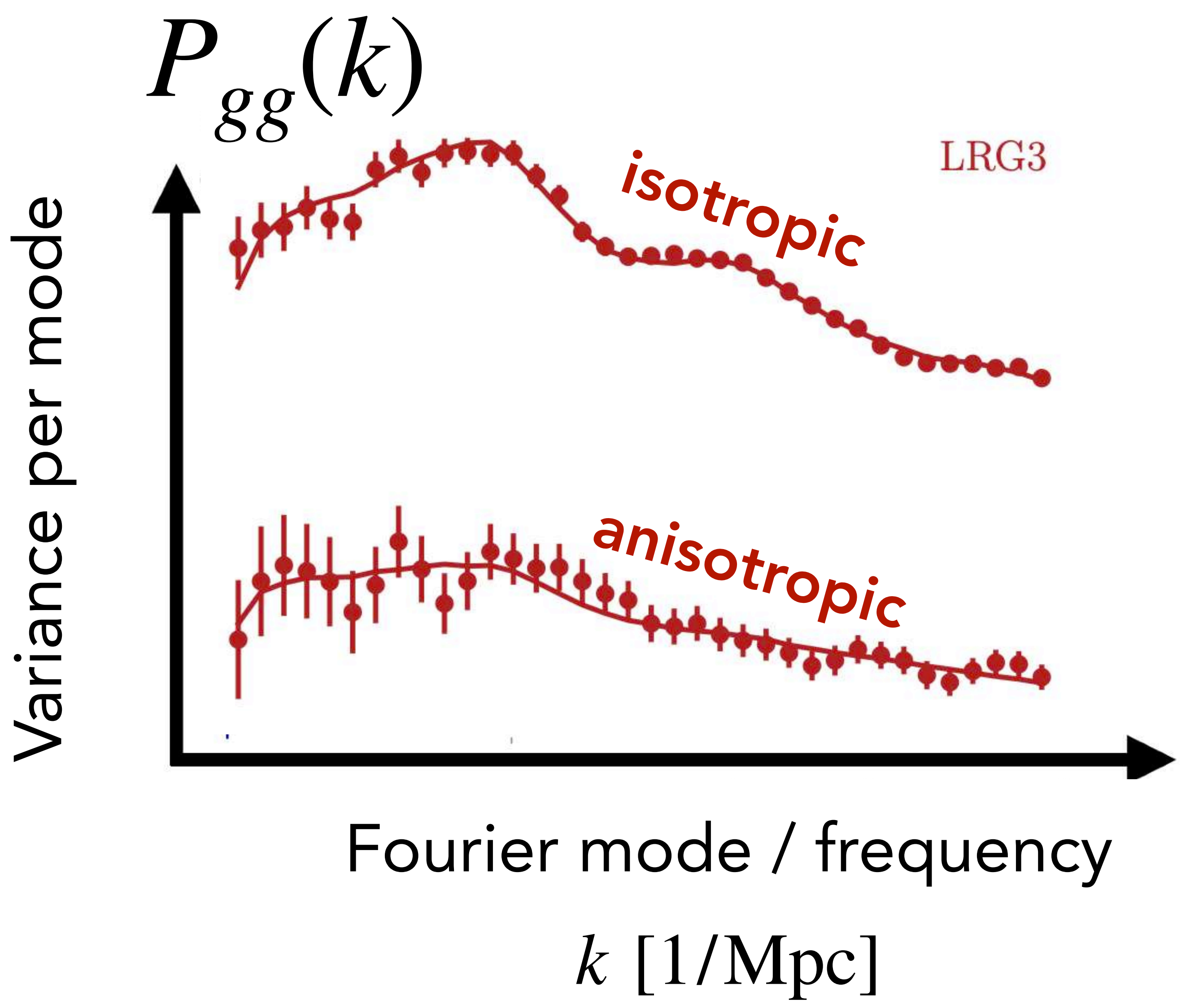
CMB



$$\left\{\theta_*, \omega_c, \omega_b, A_s, n_s, \tau, [\Omega_k, \sum m_\nu, w_0, w_a, N_{\rm eff}, \ldots]\right\}$$

"vanilla" extensions

LSS



Results on DR1 (work in progress for DR2)

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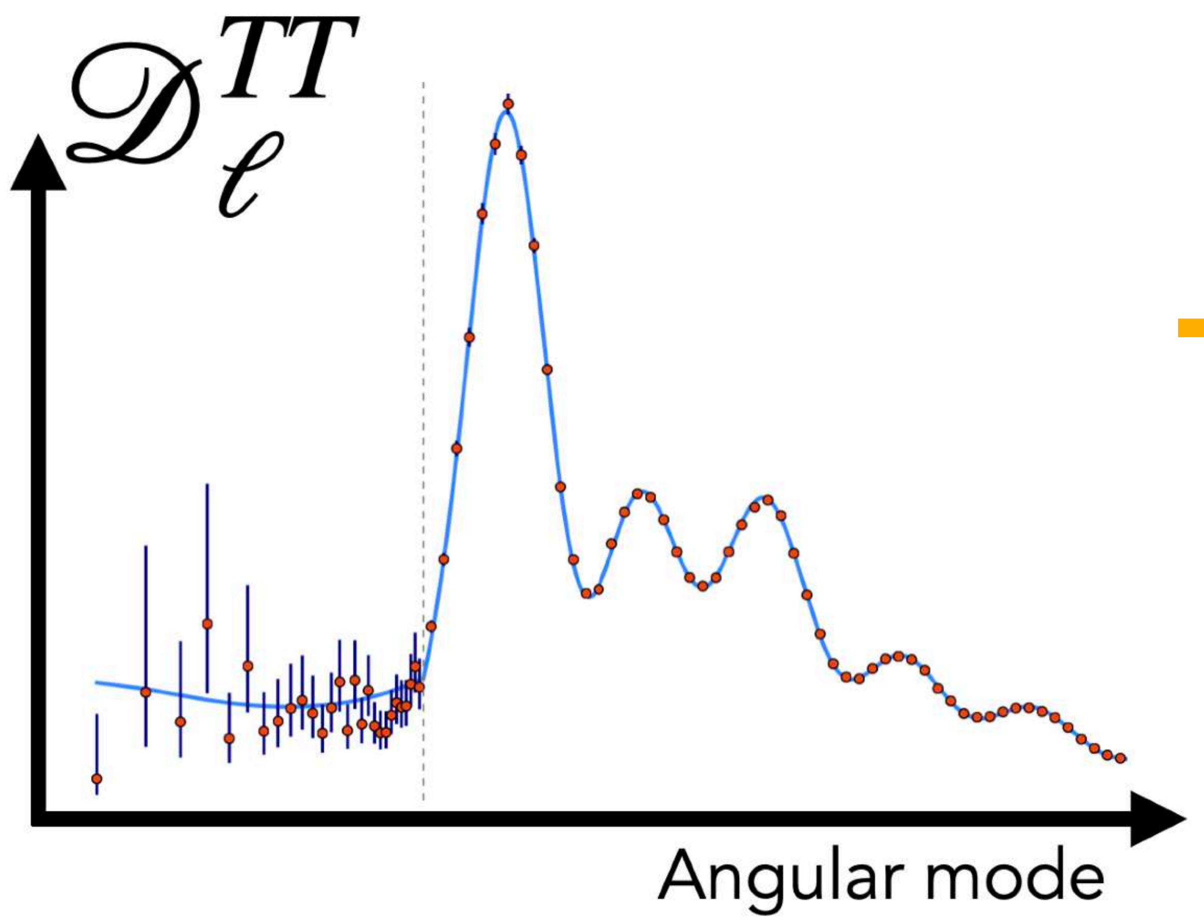
The DESI full-shape

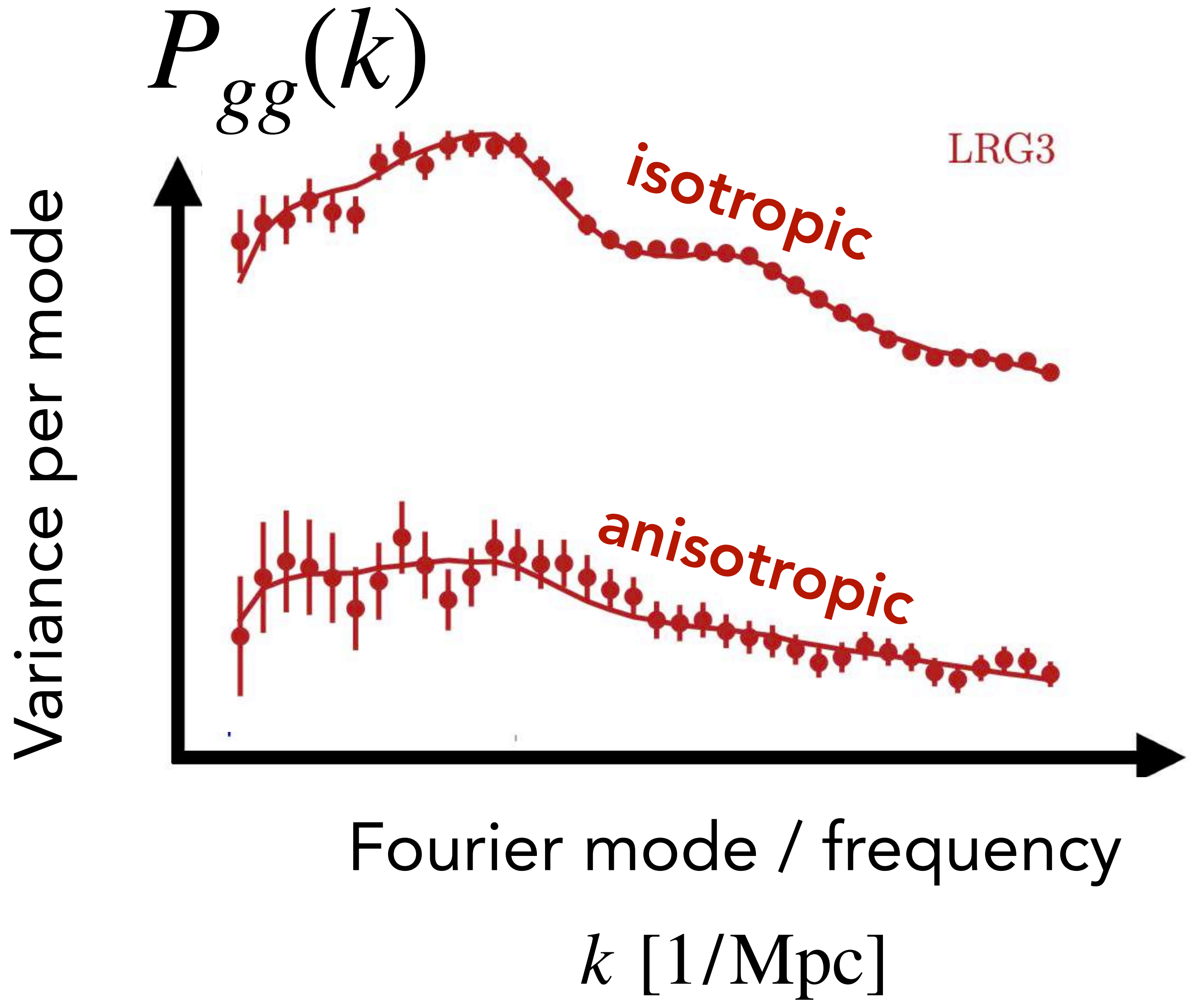
CMB



$$\left\{\theta_*, \omega_c, \omega_b, A_s, n_s, \tau, [\Omega_k, \sum m_\nu, w_0, w_a, N_{\rm eff}, \ldots]\right\}$$

"vanilla" | extensions

LSS



"Traditional way"

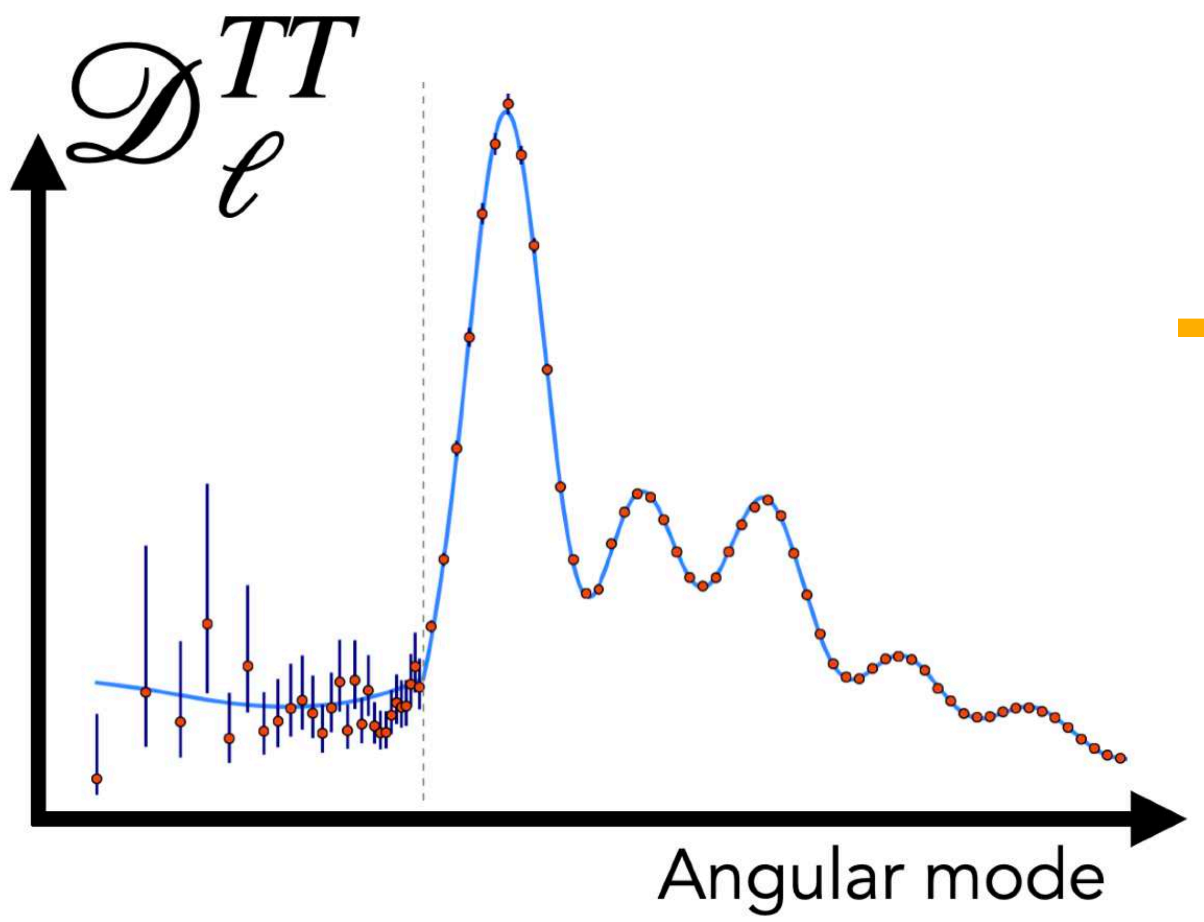
$$\left\{\frac{D_M}{r_d}, \frac{D_H}{r_d}, f\sigma_8, m\right\}$$

$$\left\{\Omega_\Lambda, w_0, w_a, \Omega_k, \Omega_m, h, \sigma_8, \sum m_\nu, N_{\rm eff}, \gamma, \ldots\right\}$$

Results on DR1 (work in progress for DR2)

The DESI full-shape

CMB



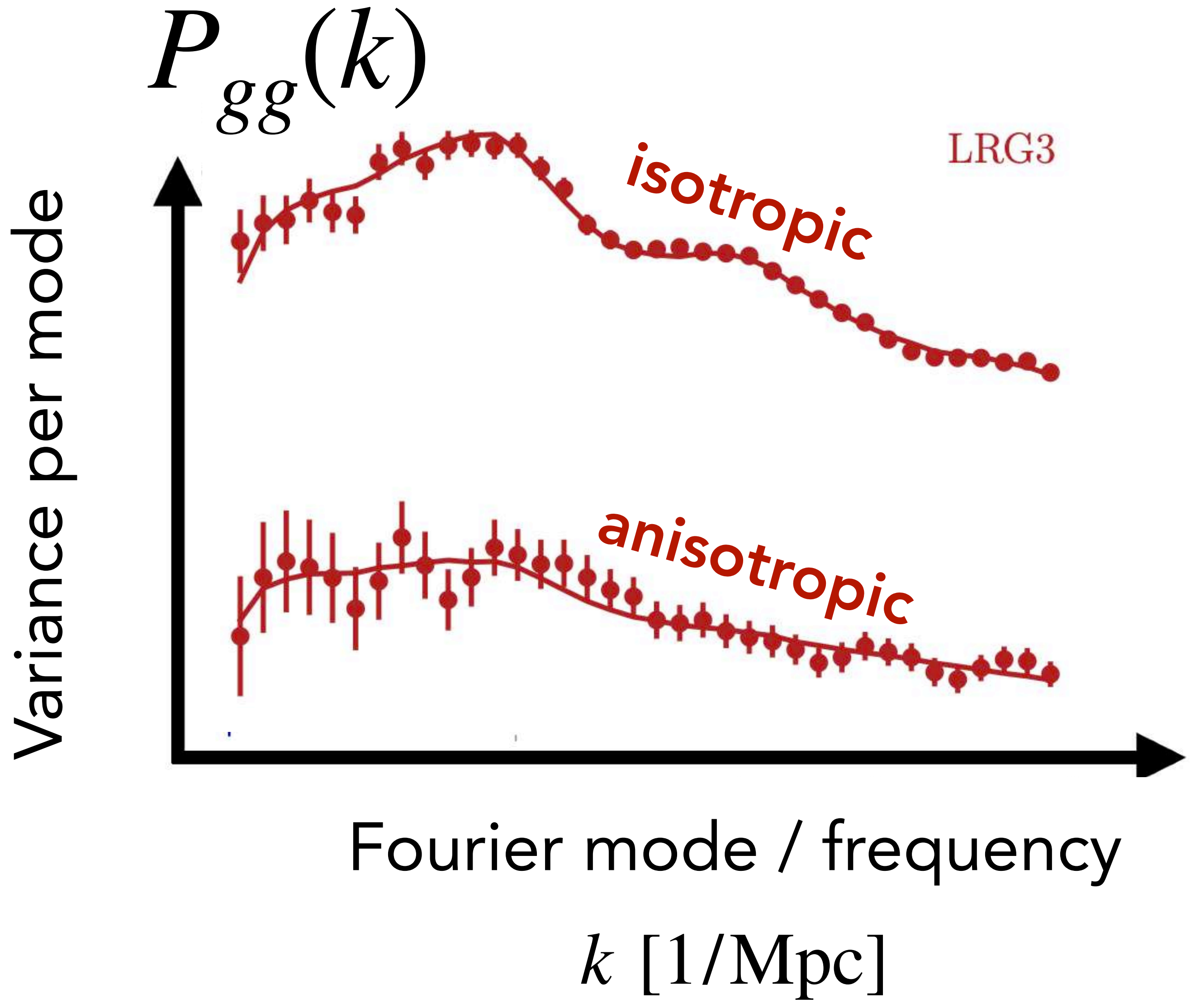
$$\left\{\theta_*, \omega_c, \omega_b, A_s, n_s, \tau, [\Omega_k, \sum m_\nu, w_0, w_a, N_{\rm eff}, \ldots]\right\}$$

"vanilla" extensions

"Traditional way"

$$\left\{\frac{D_M}{r_d}, \frac{D_H}{r_d}, f\sigma_8, m\right\}$$

LSS

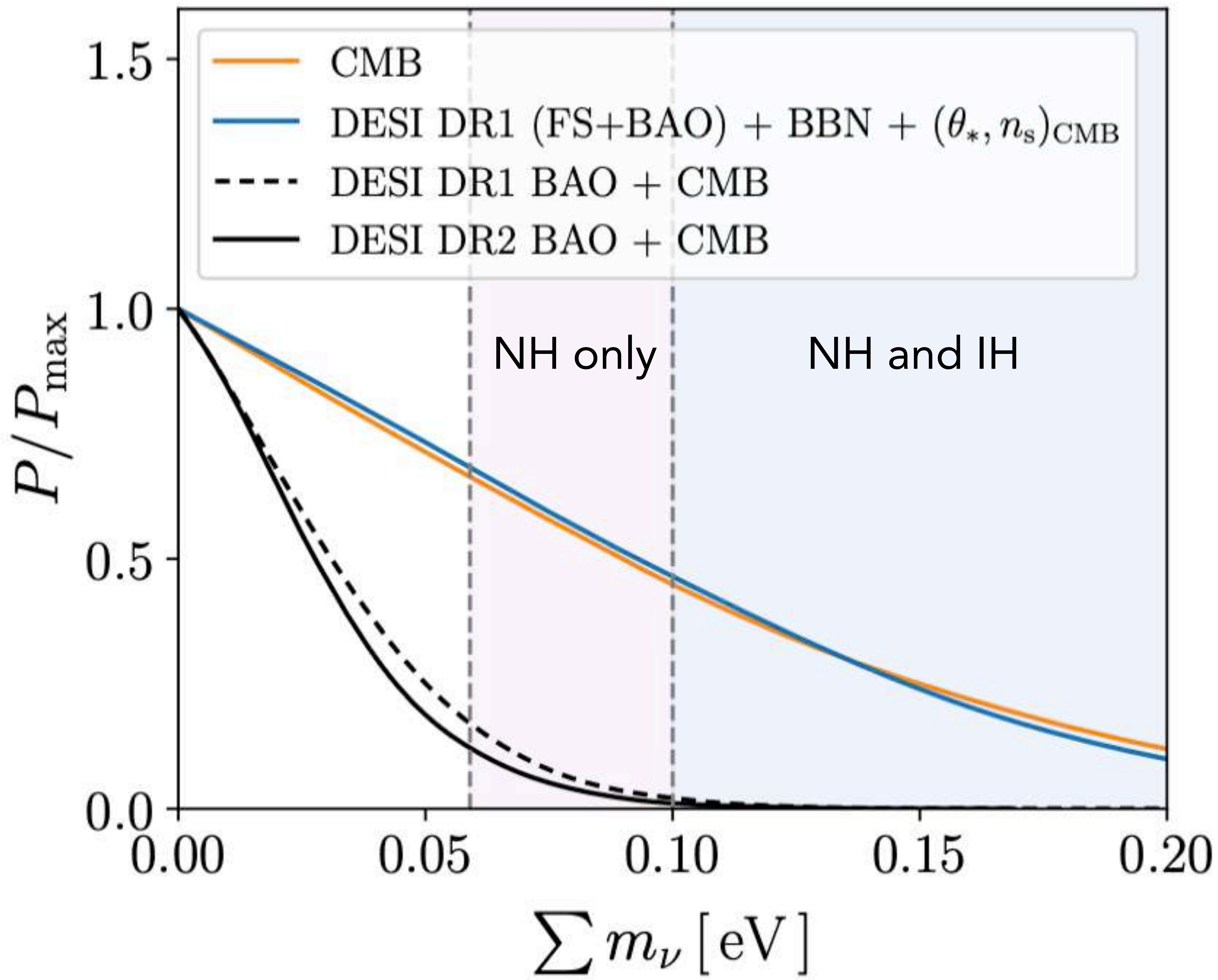


"Recent way"

$$\left\{\Omega_\Lambda, w_0, w_a, \Omega_k, \Omega_m, h, \sigma_8, \sum m_\nu, N_{\rm eff}, \gamma, \ldots\right\}$$

Results on DR1 (work in progress for DR2)

Constraints on neutrino masses



Assuming ΛCDM : $\sum m_\nu < 0.064$ eV

(95% CL) DESI + CMB

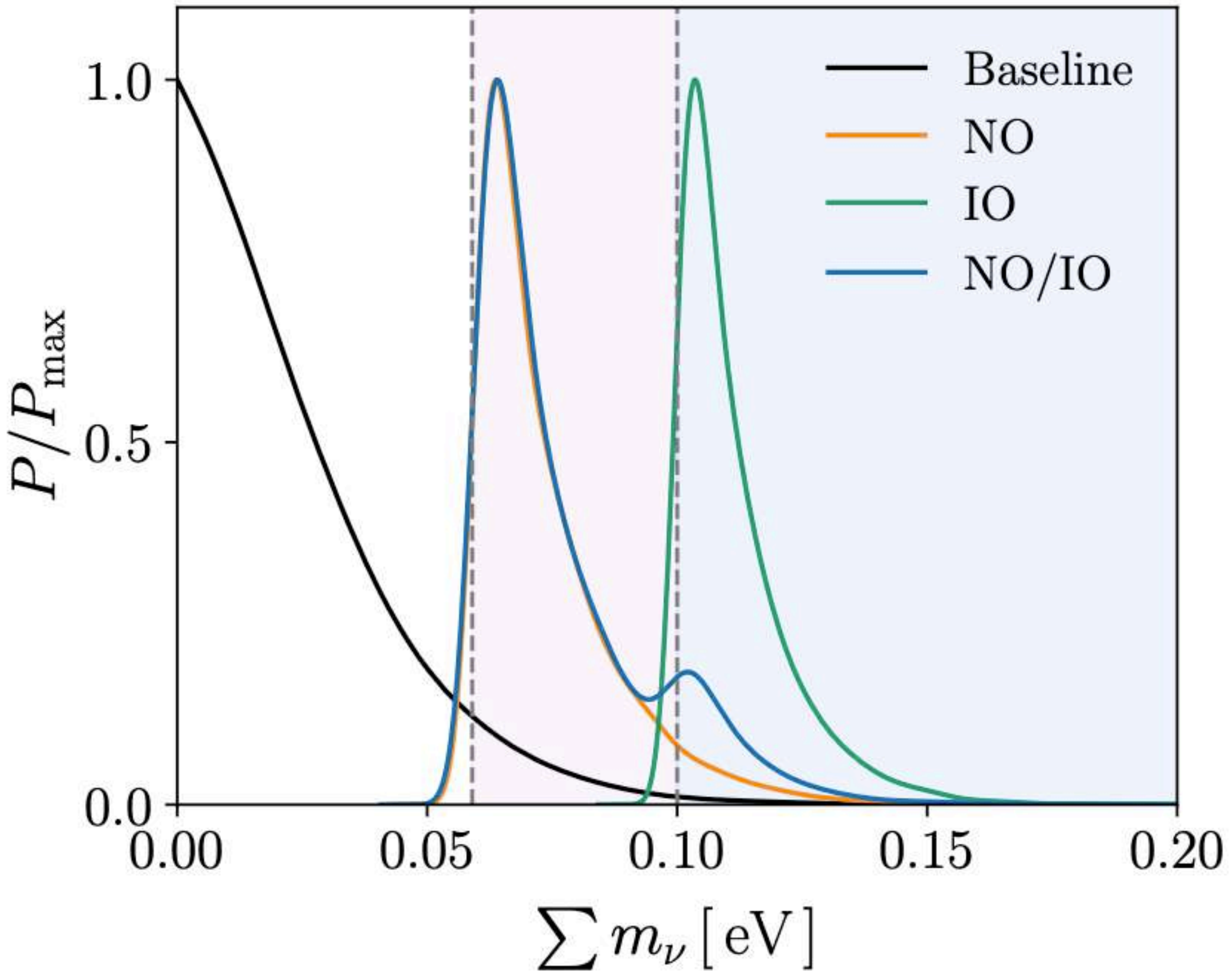
Assuming $w_0 w_a$CDM : $\sum m_\nu < 0.163$ eV

(95% CL) DESI + CMB + DES-SN5YR

Reaching lower bounds from oscillation experiments!

Constraints on neutrino masses

Using priors on Δm^2_{21} and $|\Delta m^2_{31}|$



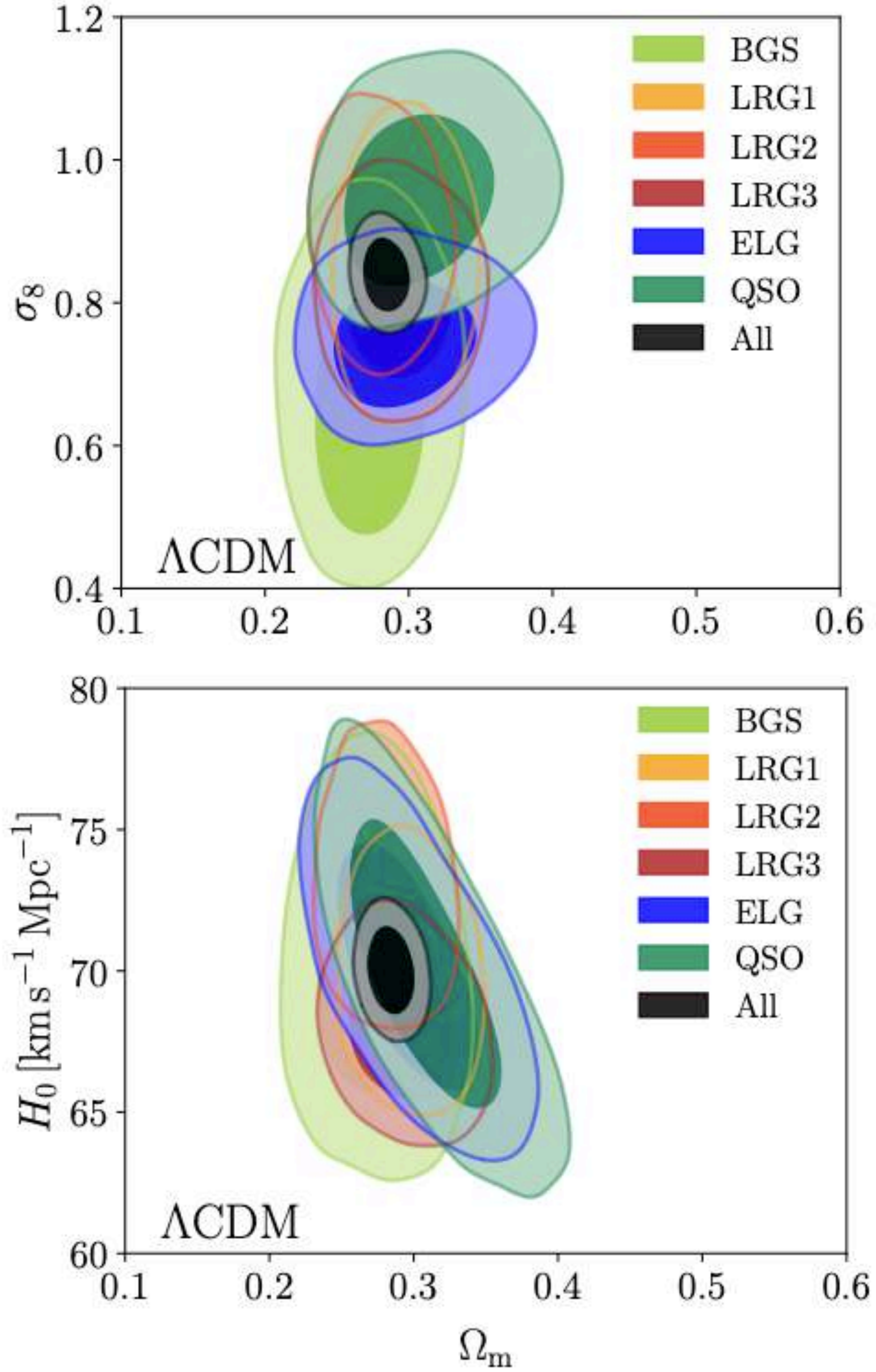
Mass of lightest neutrino

Assuming ΛCDM : $m_{\nu_e} < 0.023$ eV

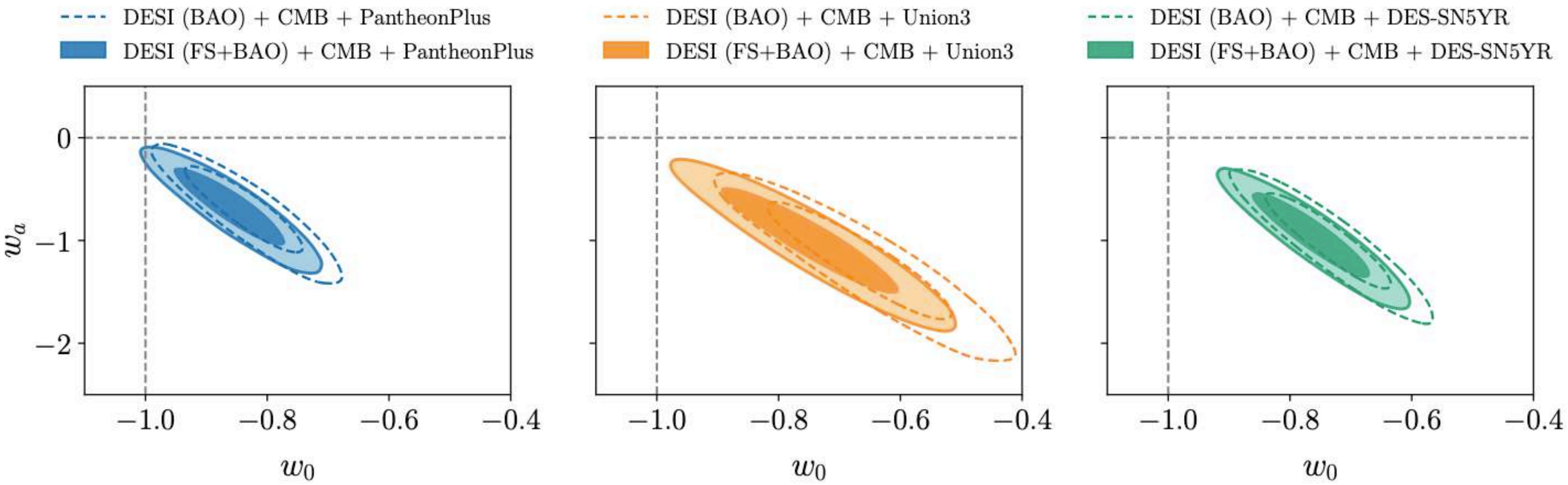
(95% CL) DESI + CMB

DESI Growth of structures

In ΛCDM



Assuming w_0w_aCDM, no significant changes



Constraints on modified gravity

From Camille Bonvin's talk:

$$-k^2\Psi = 4\pi G a^2 \mu \delta\rho$$ from redshift-space distortions

$$-k^2(\Phi + \Psi) = 4\pi G a^2 \Sigma \delta\rho$$ from weak lensing

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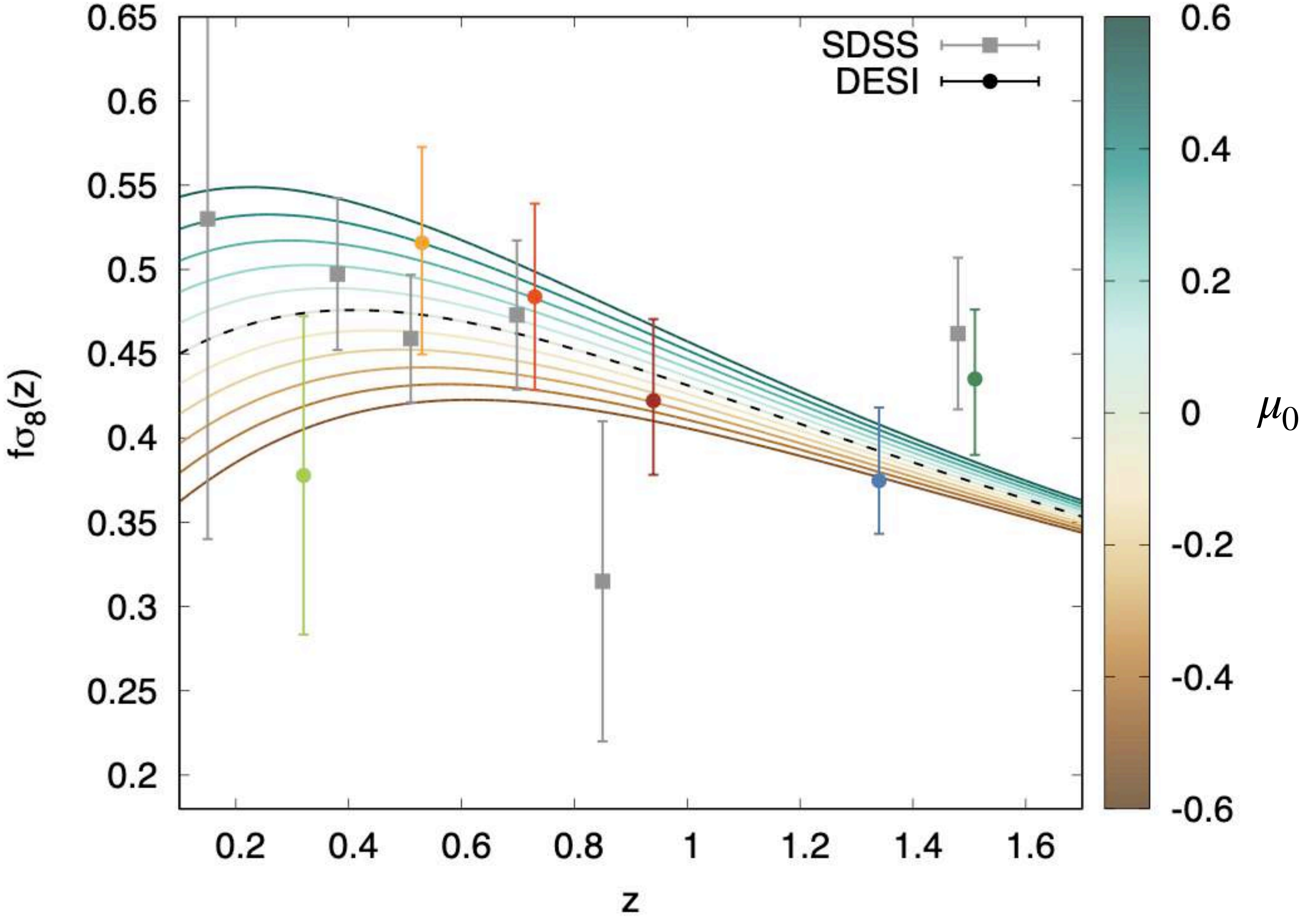
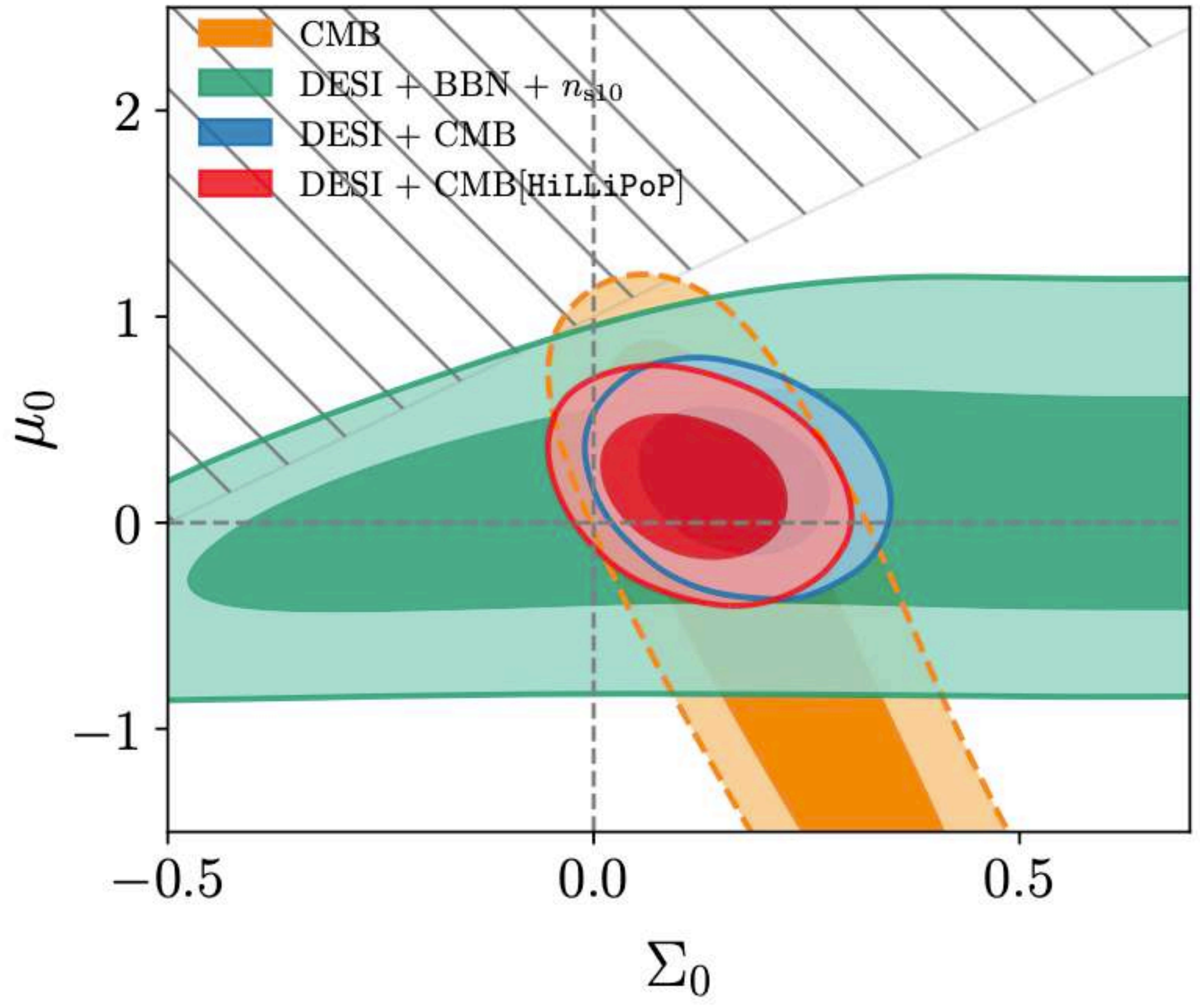
Testing extensions of GR

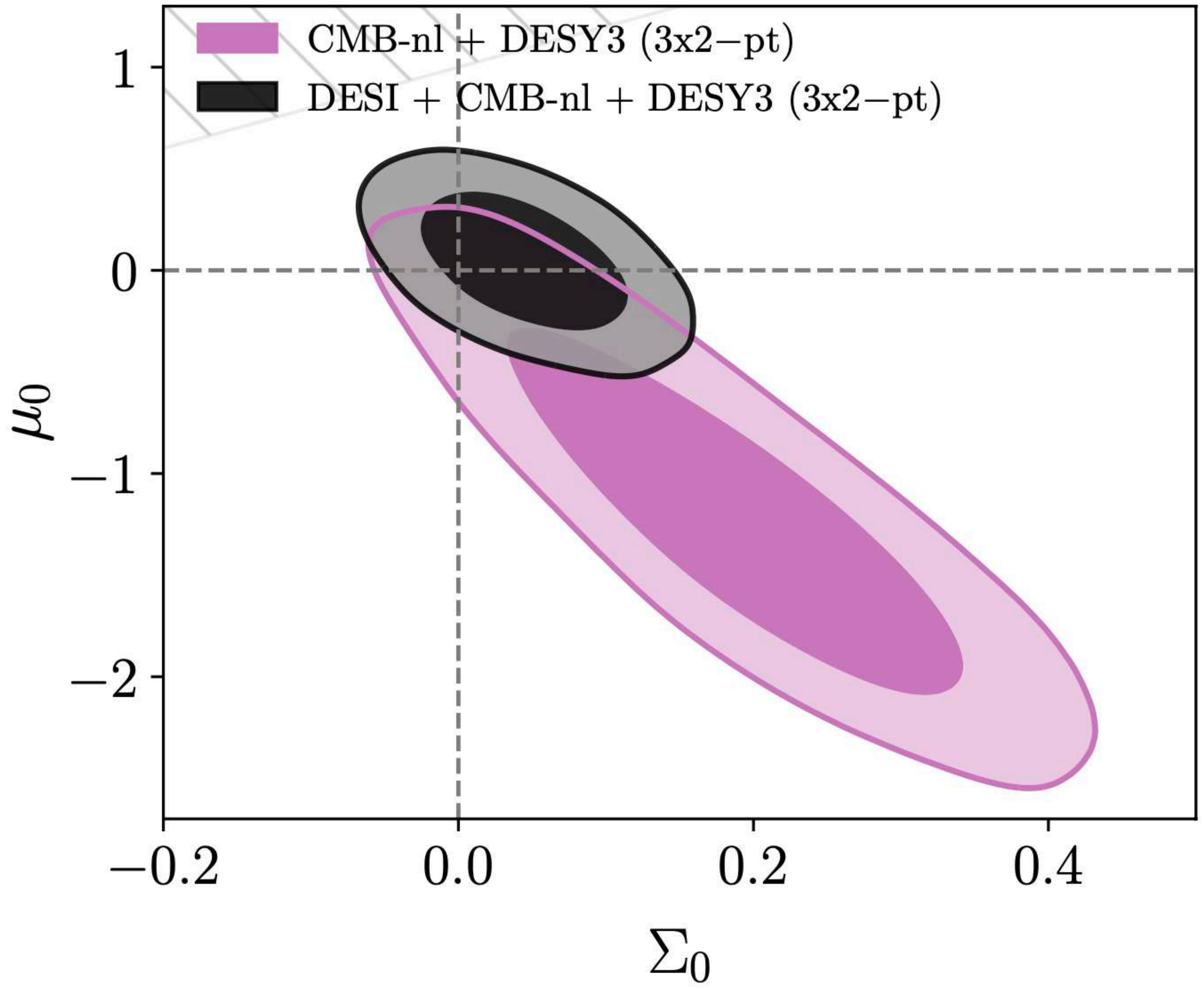


Growth rates are consistent with GR predictions

Constraints on modified gravity

Constraints on modified gravity





No significant departures from GR yet...

Conclusions

DESI is the current largest spectroscopic survey (~14 million redshifts)

Evidence for evolving dark energy at 3 sigma from DESI+CMB+SN

Neutrino masses constraints very close to ground experiments

No deviations from general relativity so far

Exciting times for Physics!

Backup

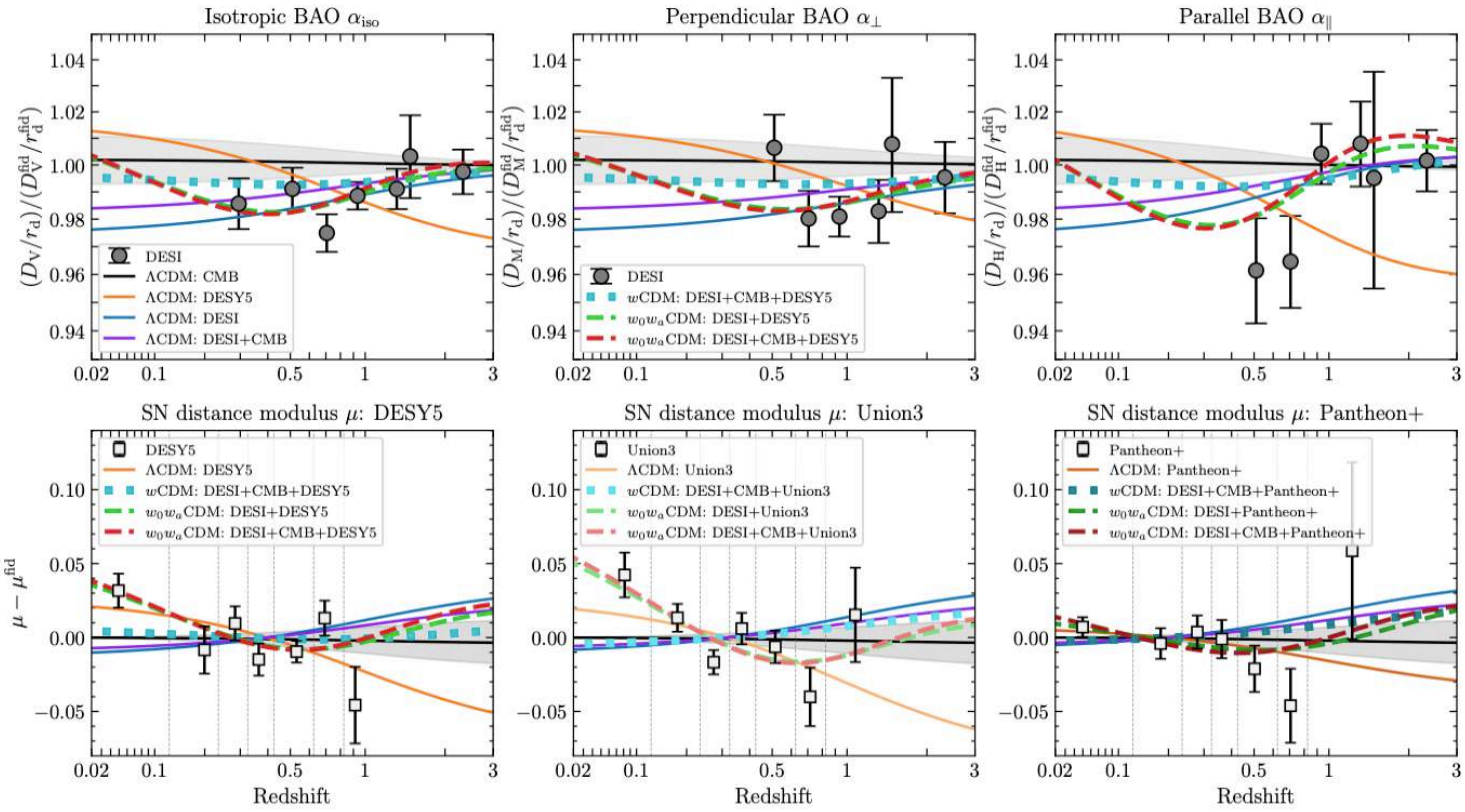
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Low-redshift supernovae causing tension?

DESI BAO

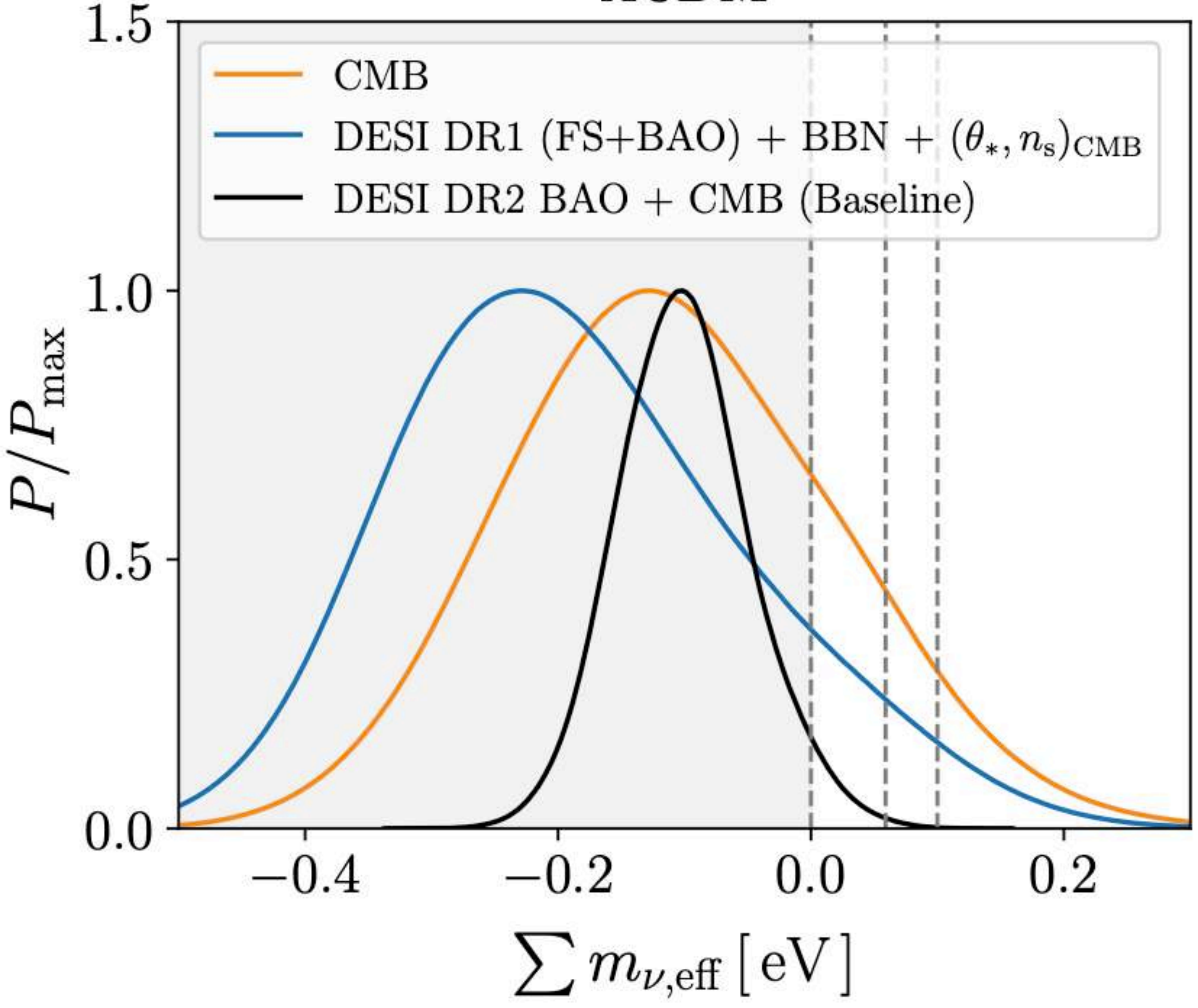
SN



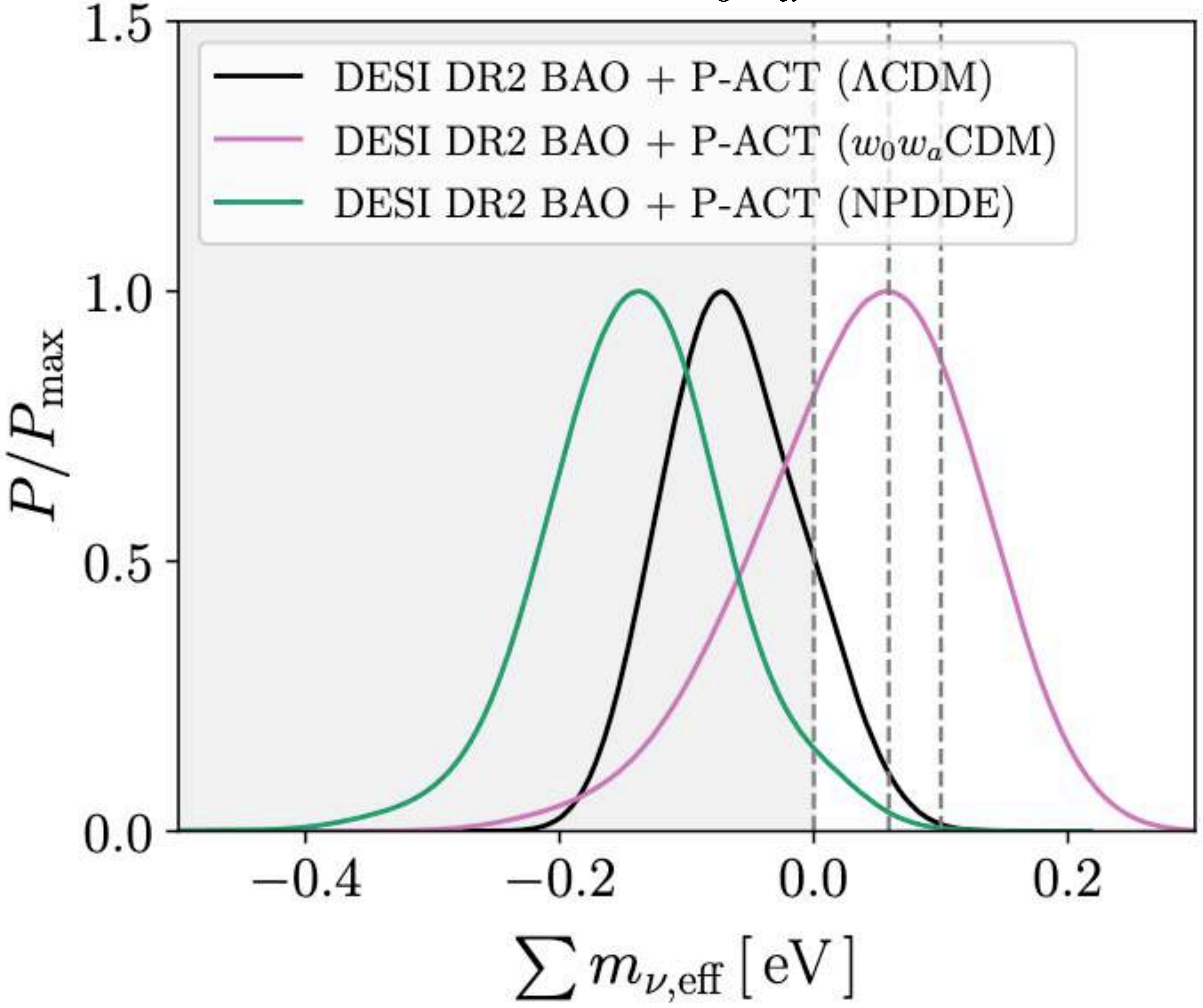
ZTF is producing a new low redshift SN sample!

Negative neutrino masses?

Assuming an effective neutrino mass



Assuming w_0w_aCDM



Tension with oscillation constraints

Maximum posterior is positive!