Studying dark-energy with the structures of our Universe and eBOSS latest results

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Postdoc @ CPPM

CPPM Seminar - 18 Jan 2020

What is dark energy ? The acceleration problem

How the structures of the Universe can inform us about dark energy?

Observing structures with eBOSS and lessons about dark energy

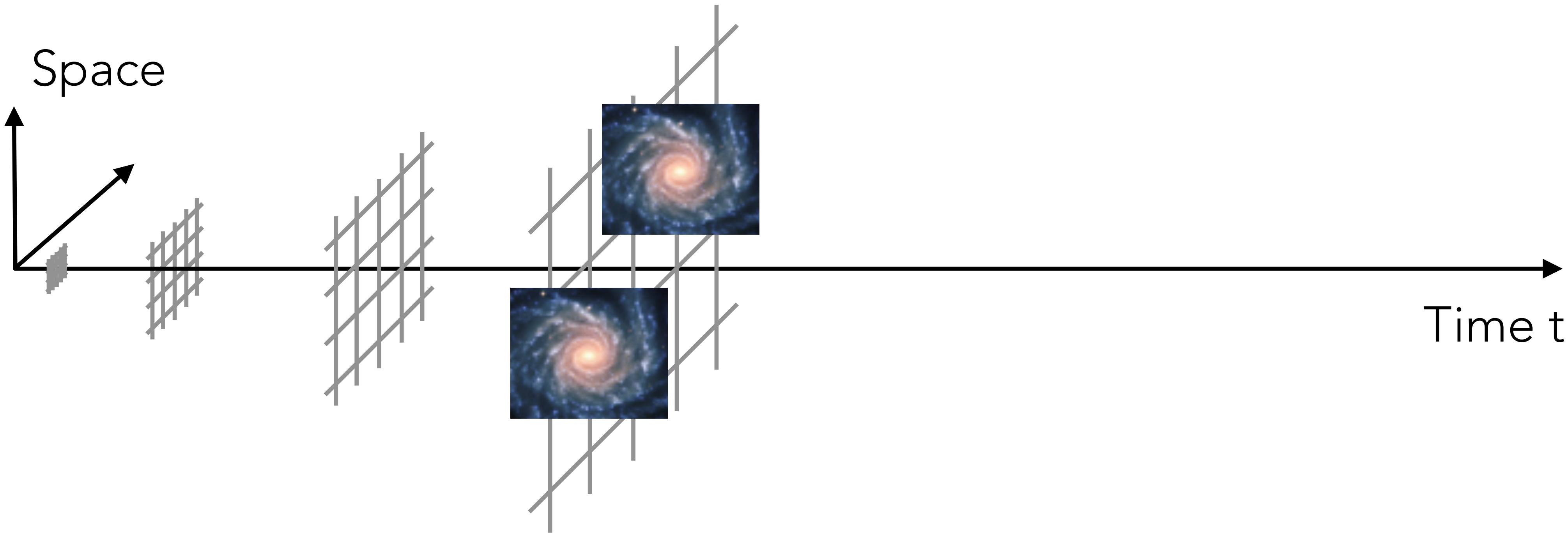
Future

What is dark energy ?

The acceleration problem

Spoiler: we don't know yet

The Universe is expanding, and accelerating !



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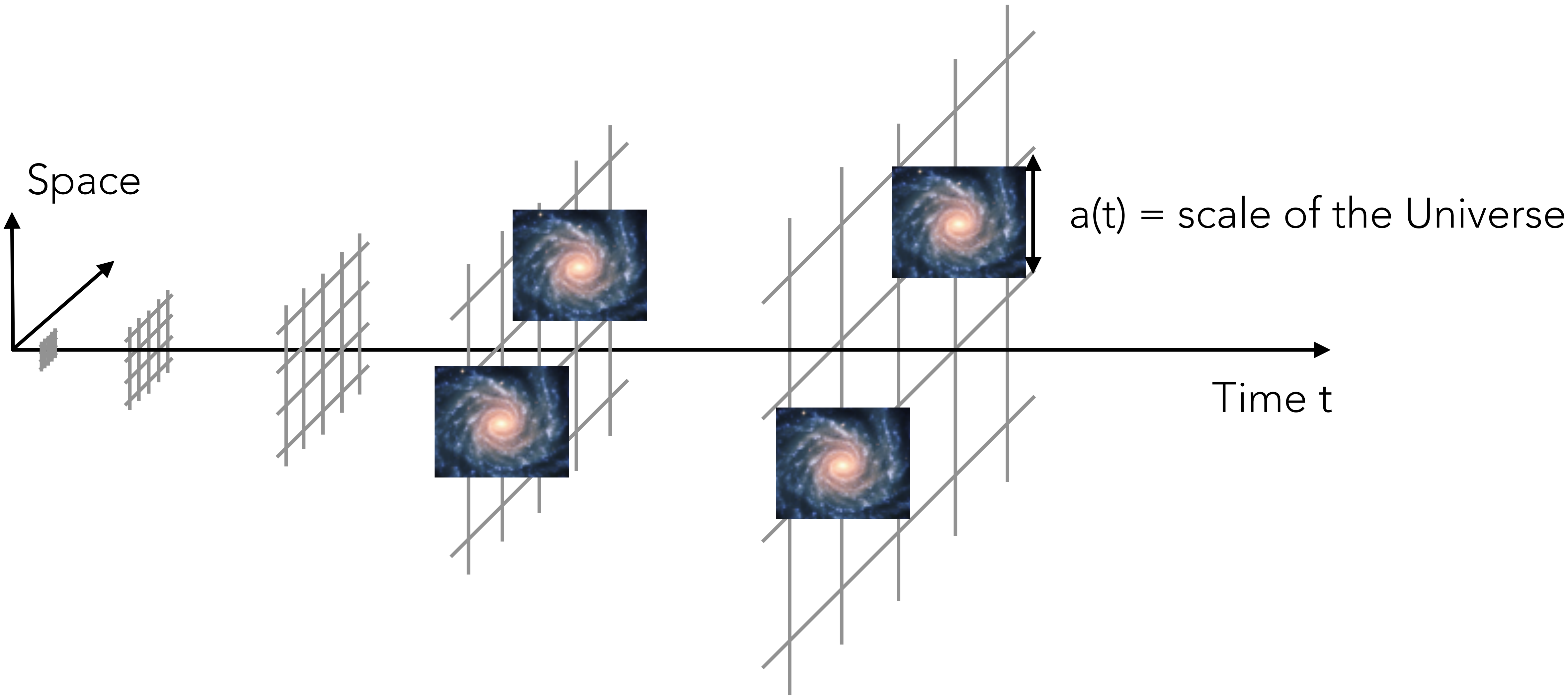

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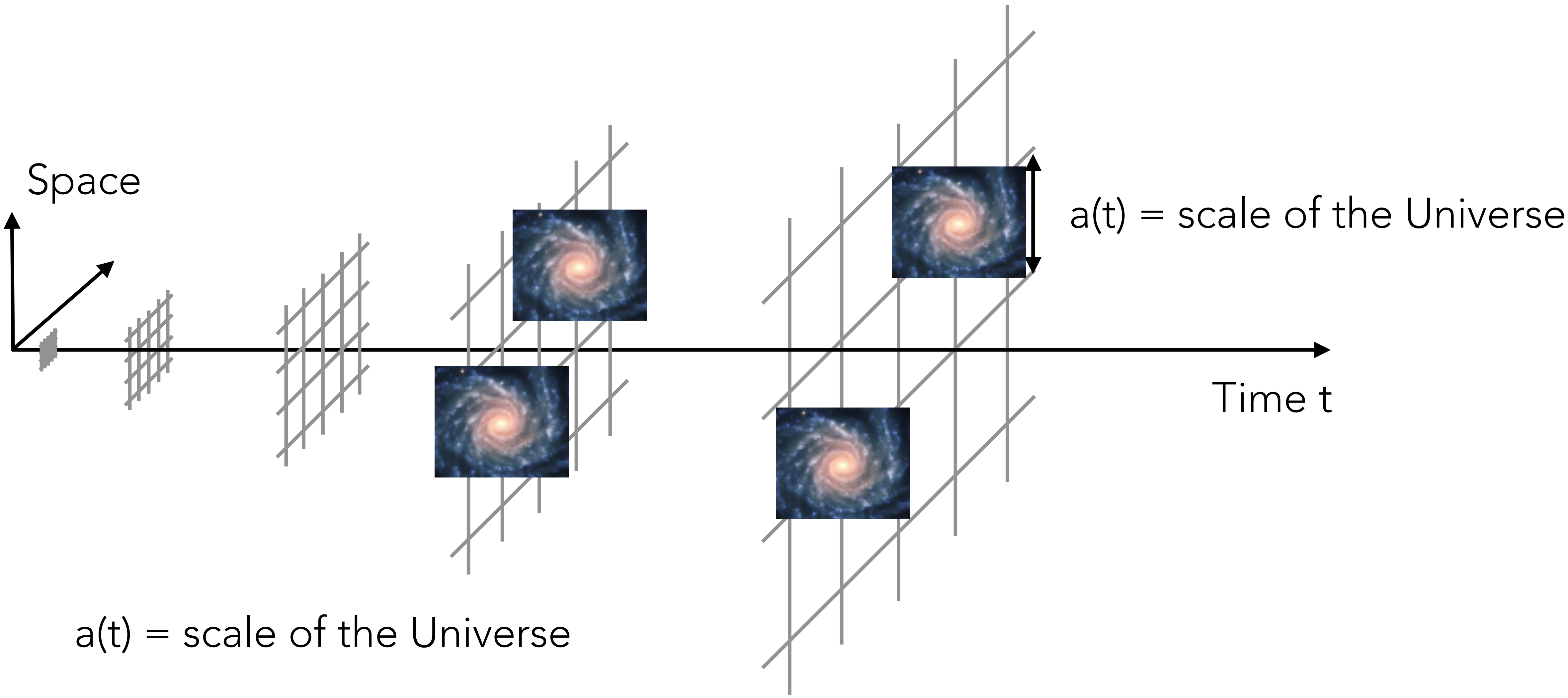
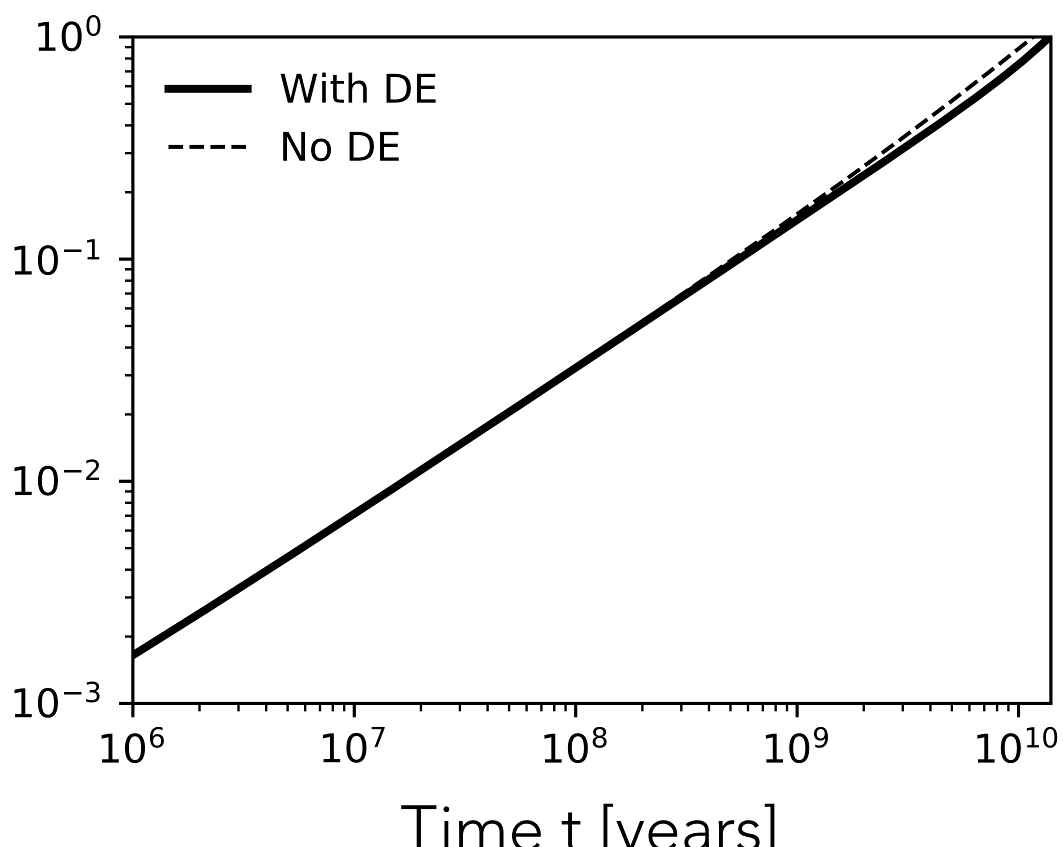


a(t) = scale of the Universe



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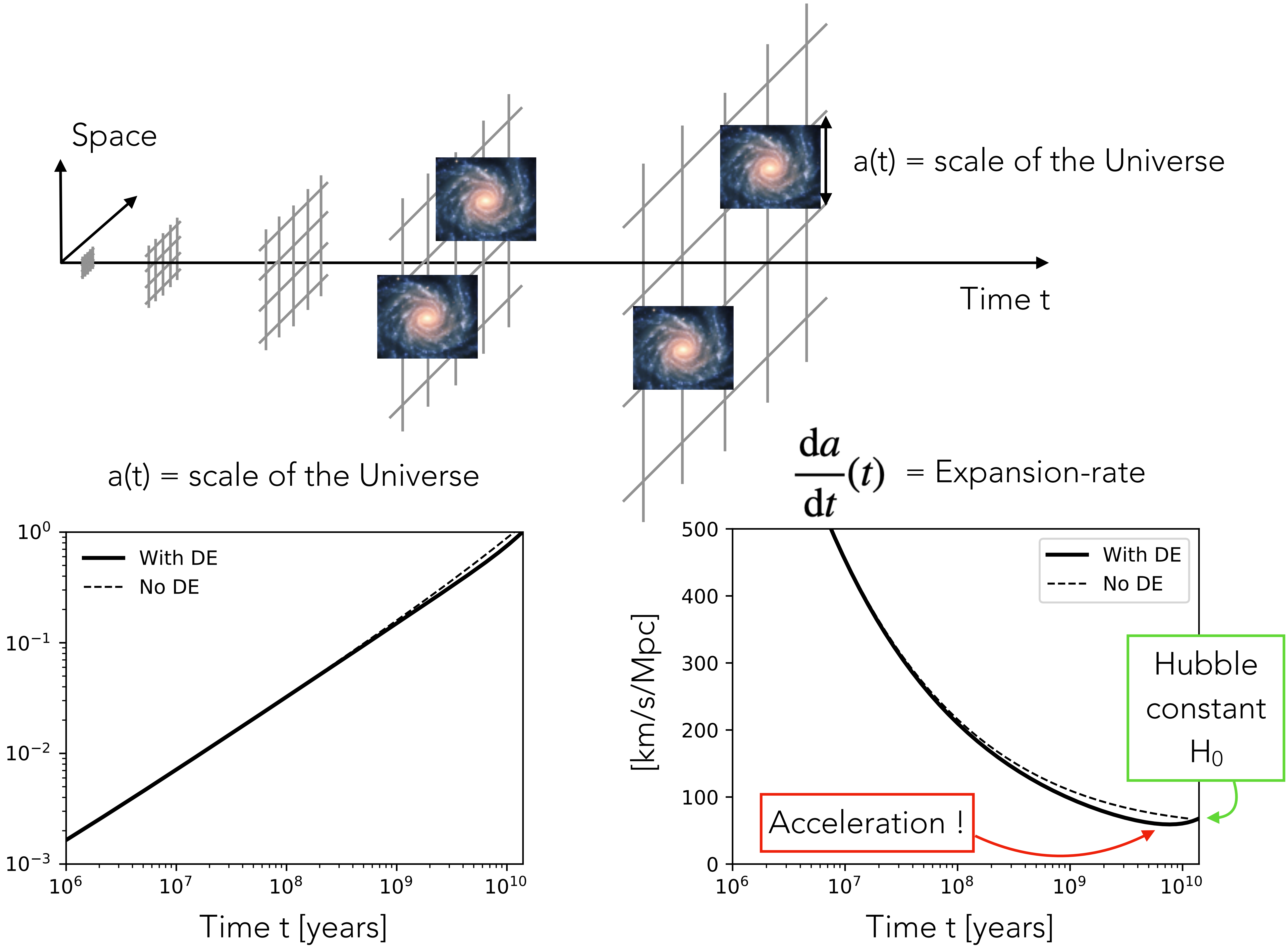

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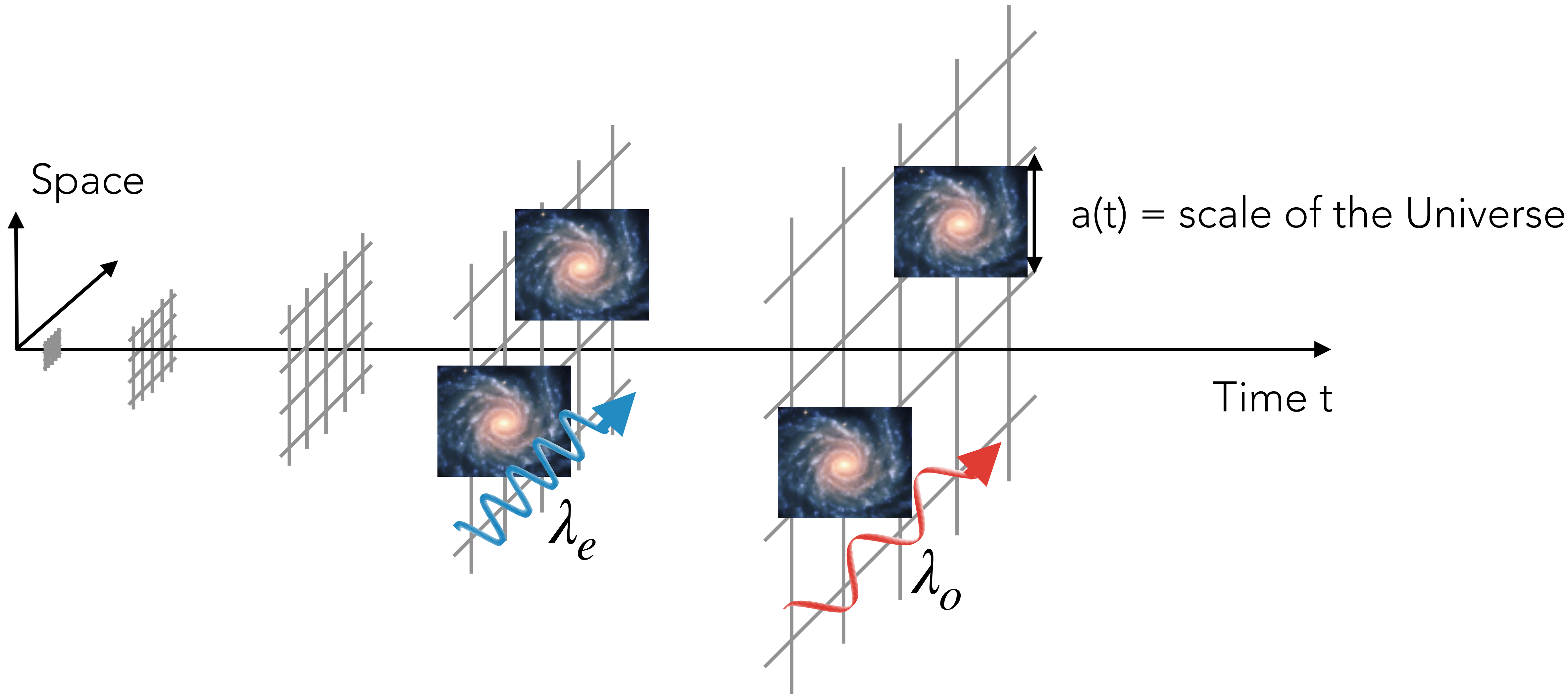


Redshift of photons:

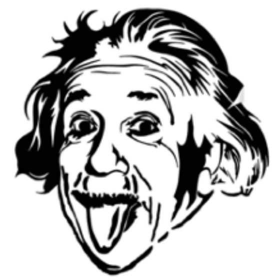
$$z = \frac{\lambda_o}{\lambda_e} - 1 = \frac{1}{a(t)} - 1$$

Today : z = 0

Past : z > 0 (galaxies appear to be redder)

Model for the expansion
General Relativity

Space-time properties



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Energy content of the Universe

+ smooth Universe

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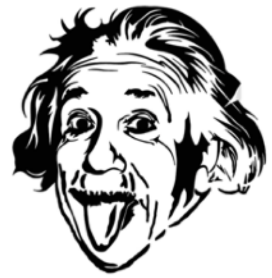

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Energy content of the Universe

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$$\left[\frac{\mathrm{d}a}{\mathrm{d}t}(t)\right]^2 \sim \Omega_m[a(t)]^{-3}$$

Expansion-rate

p^+, n, e^-,
dark matter

30%

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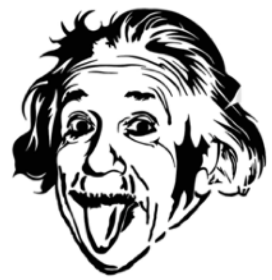

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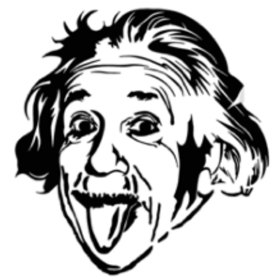

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$$\left[\frac{\mathrm{d}a}{\mathrm{d}t}(t)\right]^2 \sim \Omega_m[a(t)]^{-3} + \Omega_r[a(t)]^{-4} + \Omega_\Lambda$$

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dark energy
(cosmological constant)

70%

The only one causing acceleration of the expansion!

Model for the expansion
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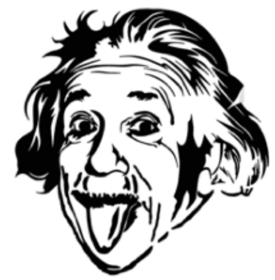

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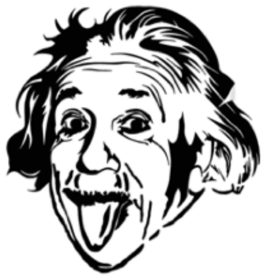

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Energy content of the Universe

+ smooth Universe

No fundamental origin for Λ !

$$\Omega_\Lambda [a(t)]^{-3(1+w_0+w_a)} e^{3w_a[1-a(t)]}$$

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Physically motivated theory ? Alternatives or extensions of General Relativity

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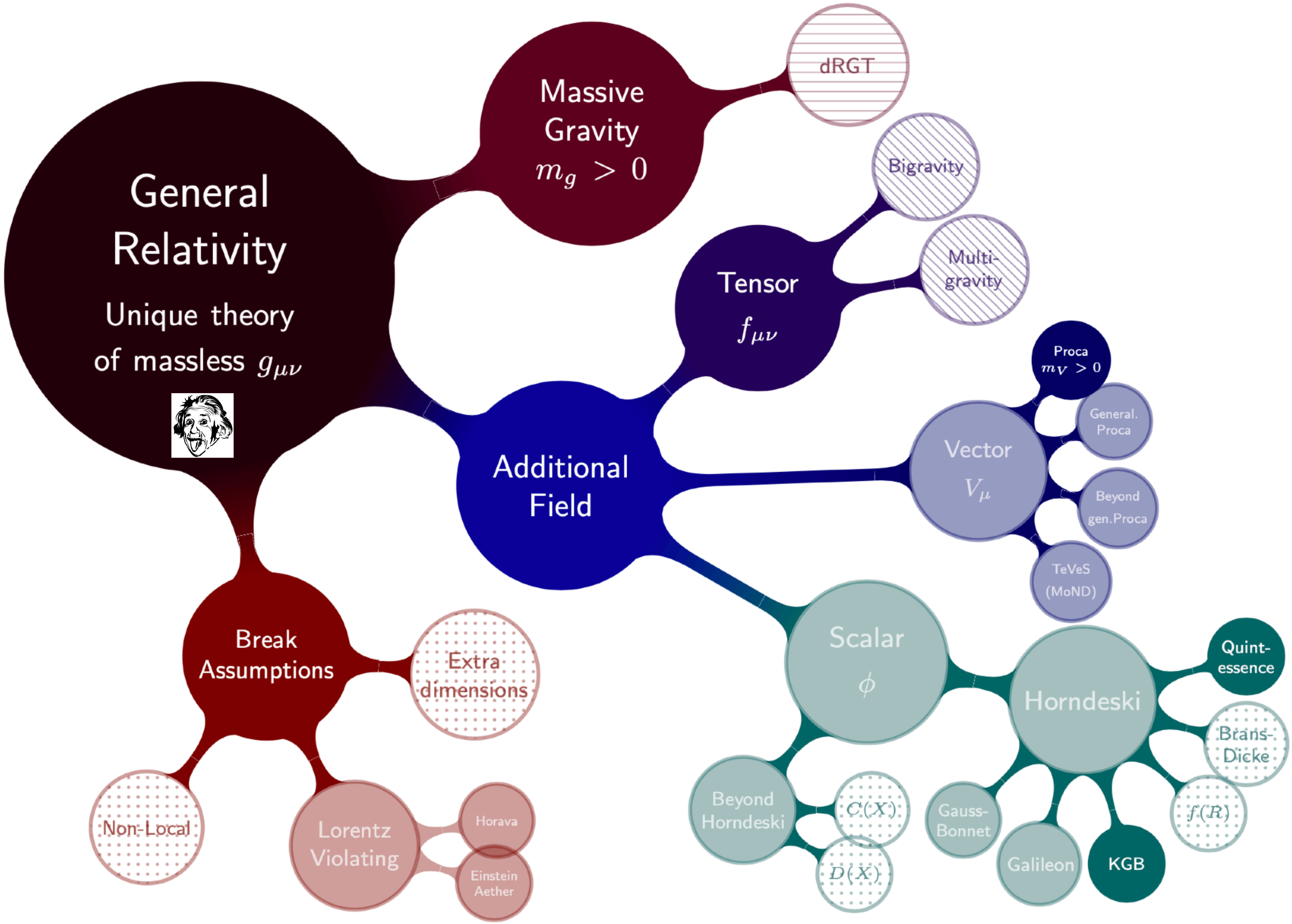
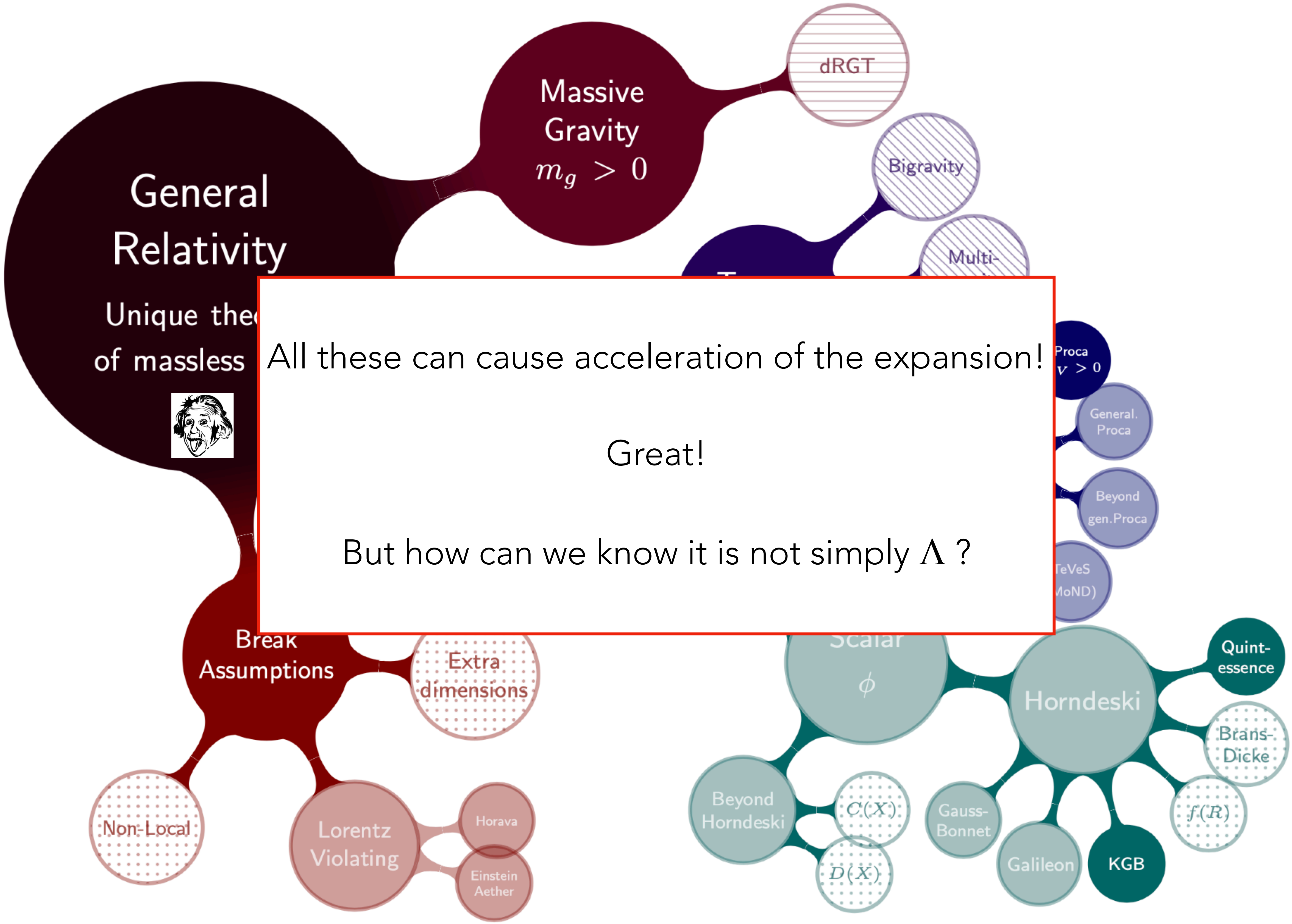


Review by Ezquiaga & Zumalacárregui 2018

Physically motivated theory ? Alternatives or extensions of General Relativity



All these can cause acceleration of the expansion!

Great!

But how can we know it is not simply Λ ?

Review by Ezquiaga & Zumalacárregui 2018

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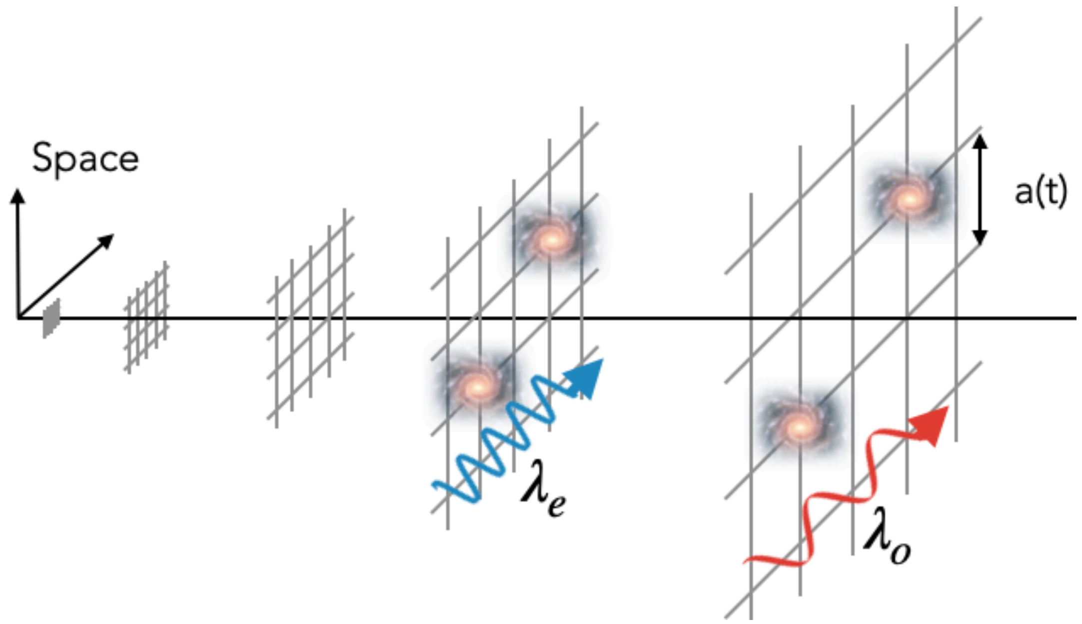
The acceleration problem



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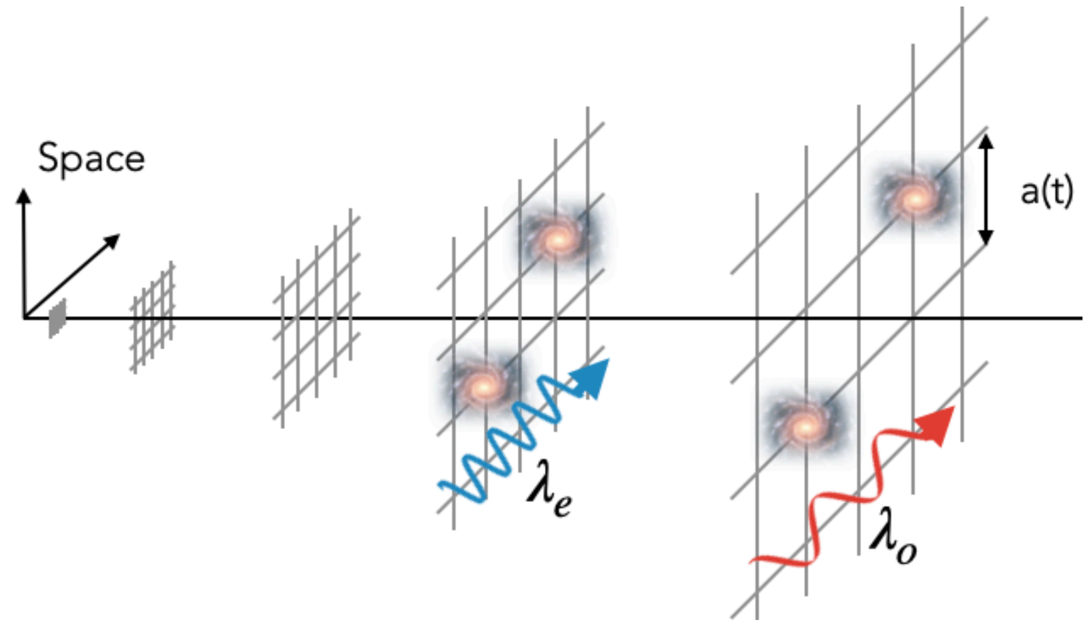

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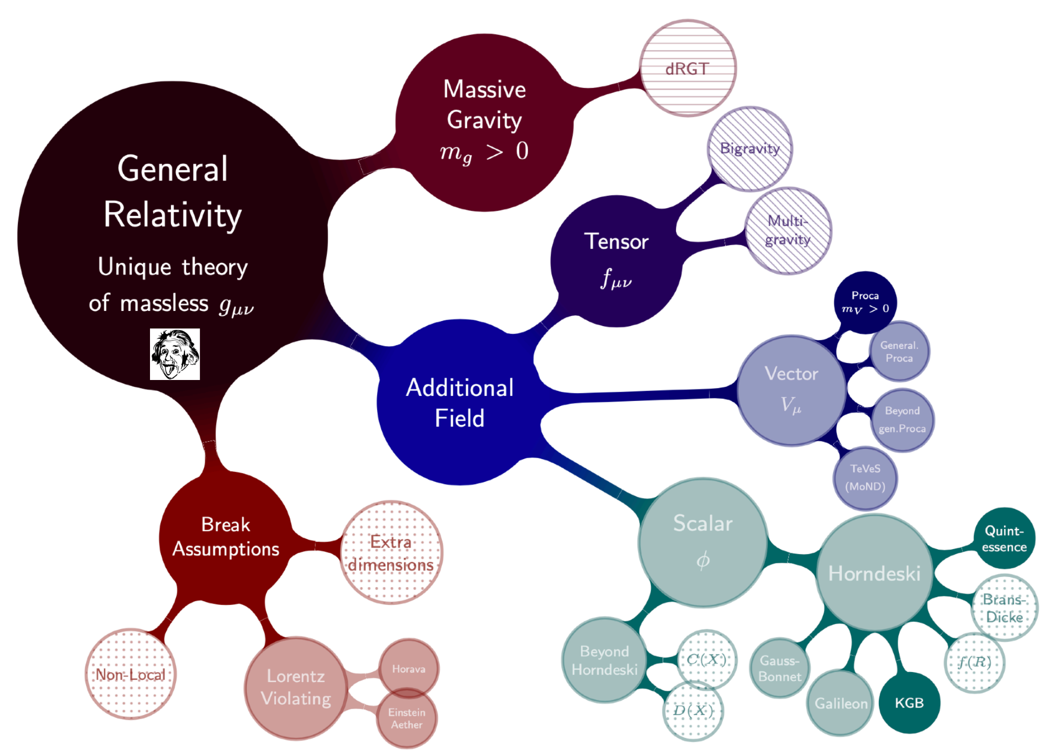
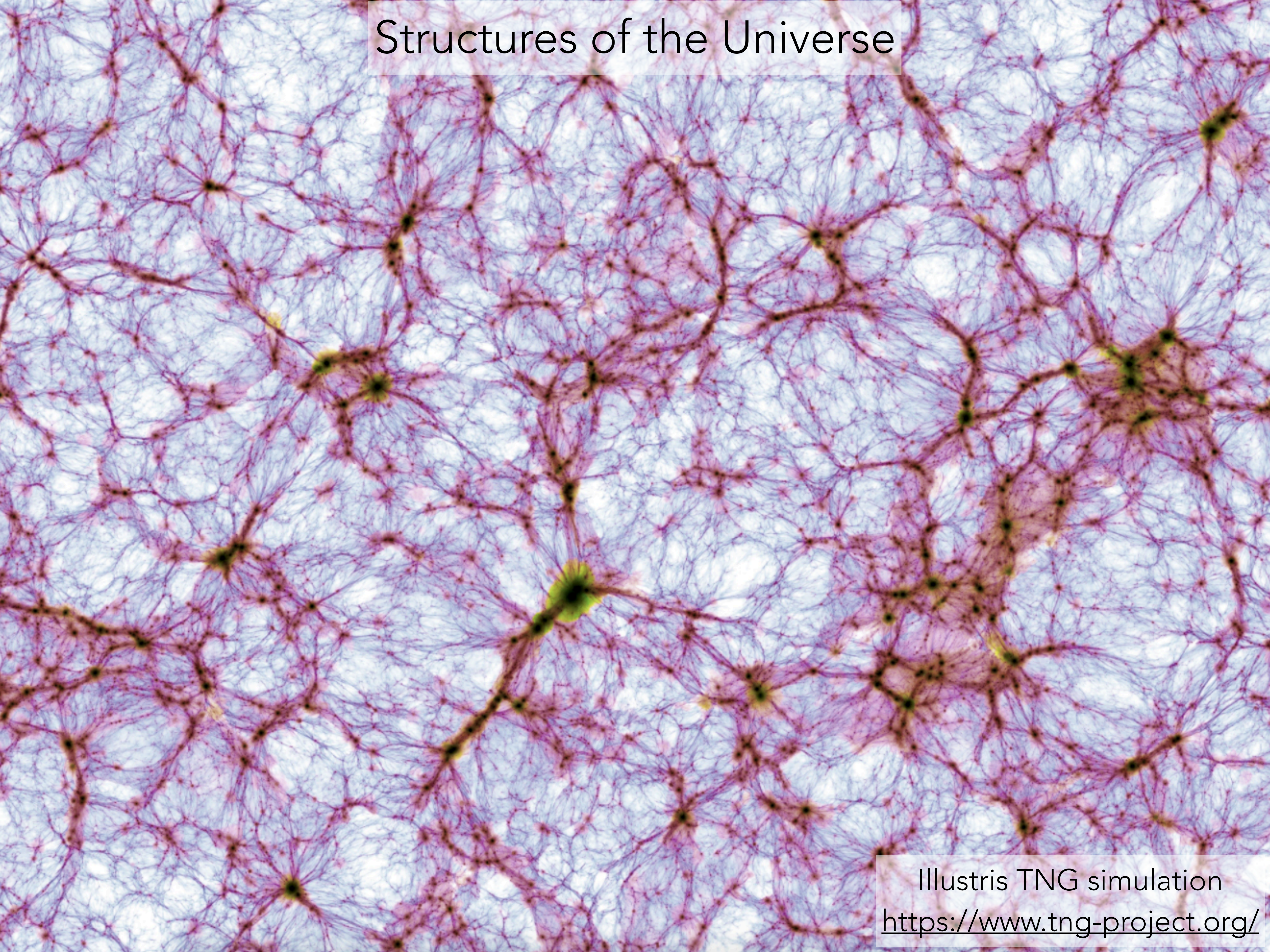


Structures of the Universe

and how can they teach us about dark energy

Structures of the Universe



Illustris TNG simulation
https://www.tng-project.org/

Model for the structures

smooth Universe

$$\rho(t)$$

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density perturbations: $$\delta(\mathbf{x}, t) = \frac{\rho(\mathbf{x}, t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

velocities: $$\mathbf{v}(\mathbf{x}, t)$$

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Space-time properties = Energy content of the Universe

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$$\ddot{\delta} + \boxed{\text{expansion, pressure}}\,\dot{\delta} - \boxed{\text{gravity}}\,\delta = 0$$

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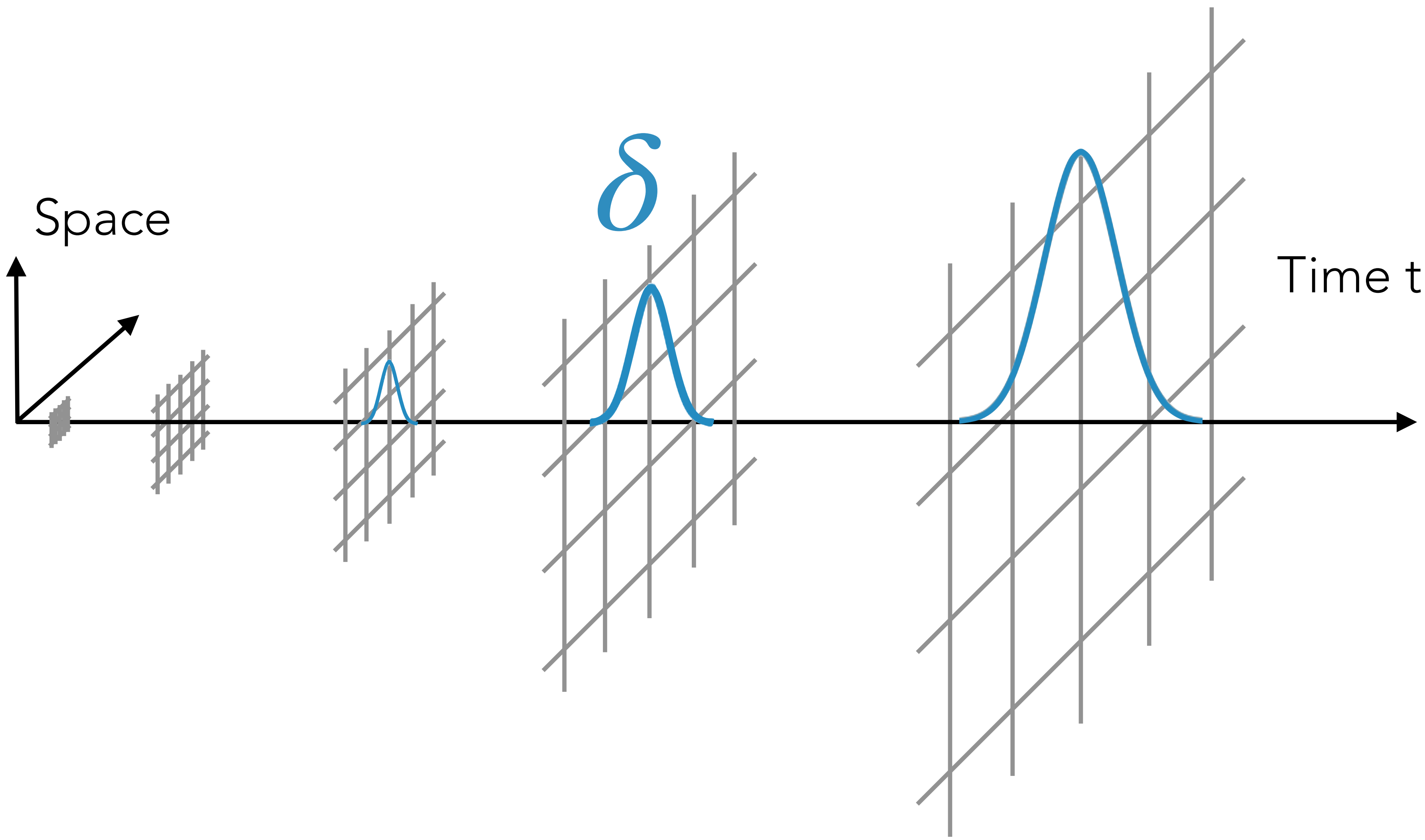

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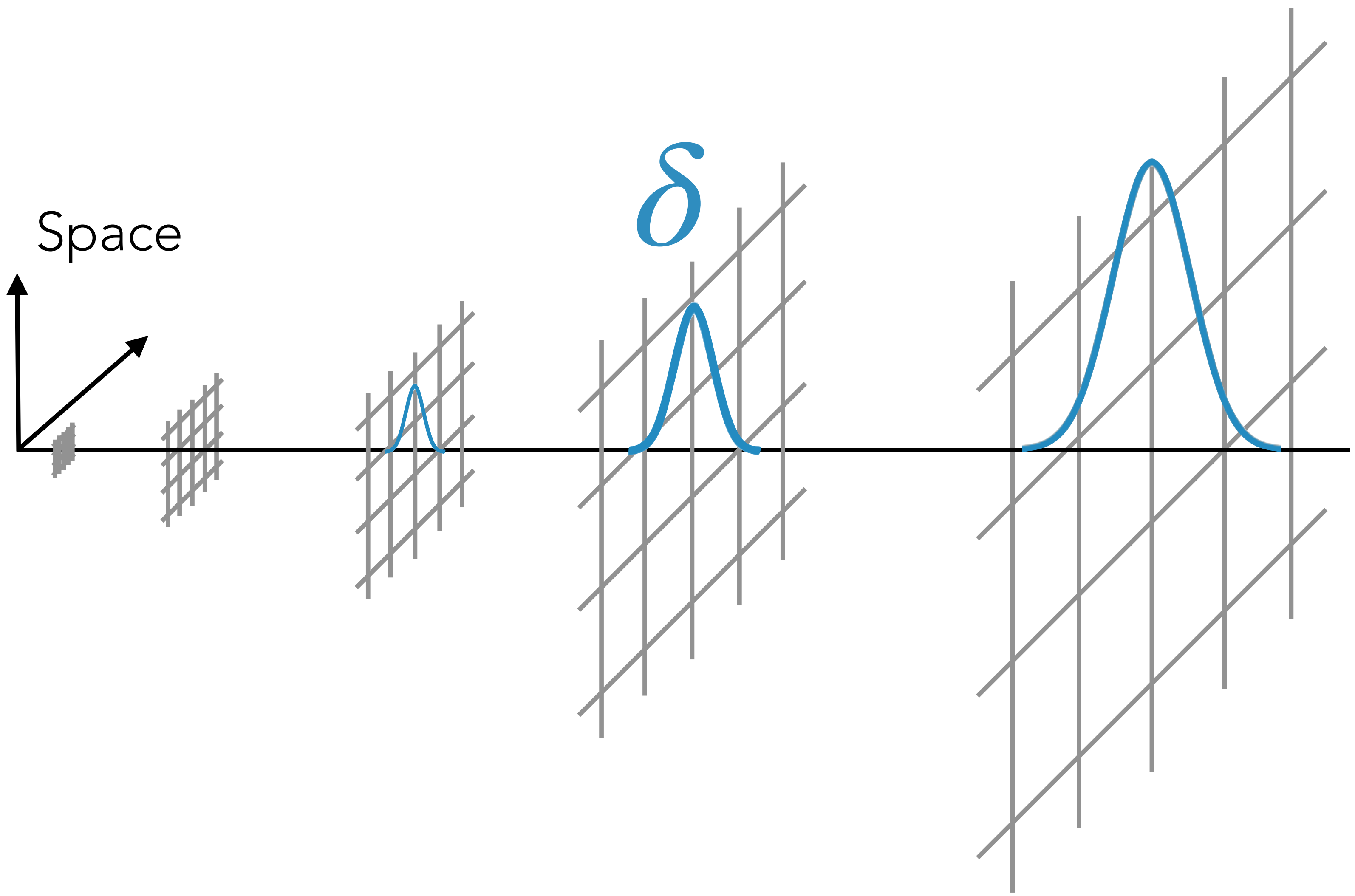
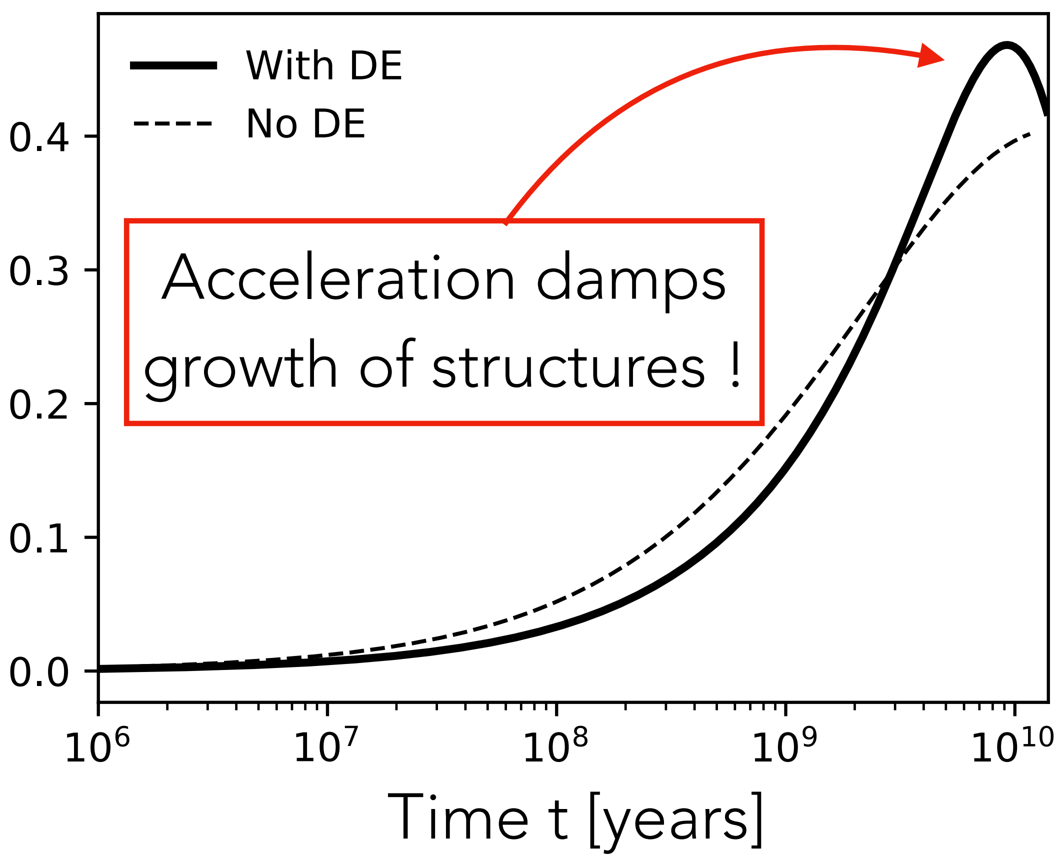


$$\frac{\mathrm{d}\delta}{\mathrm{d}t}(t) \sim \text{Growth-rate}$$



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Structures

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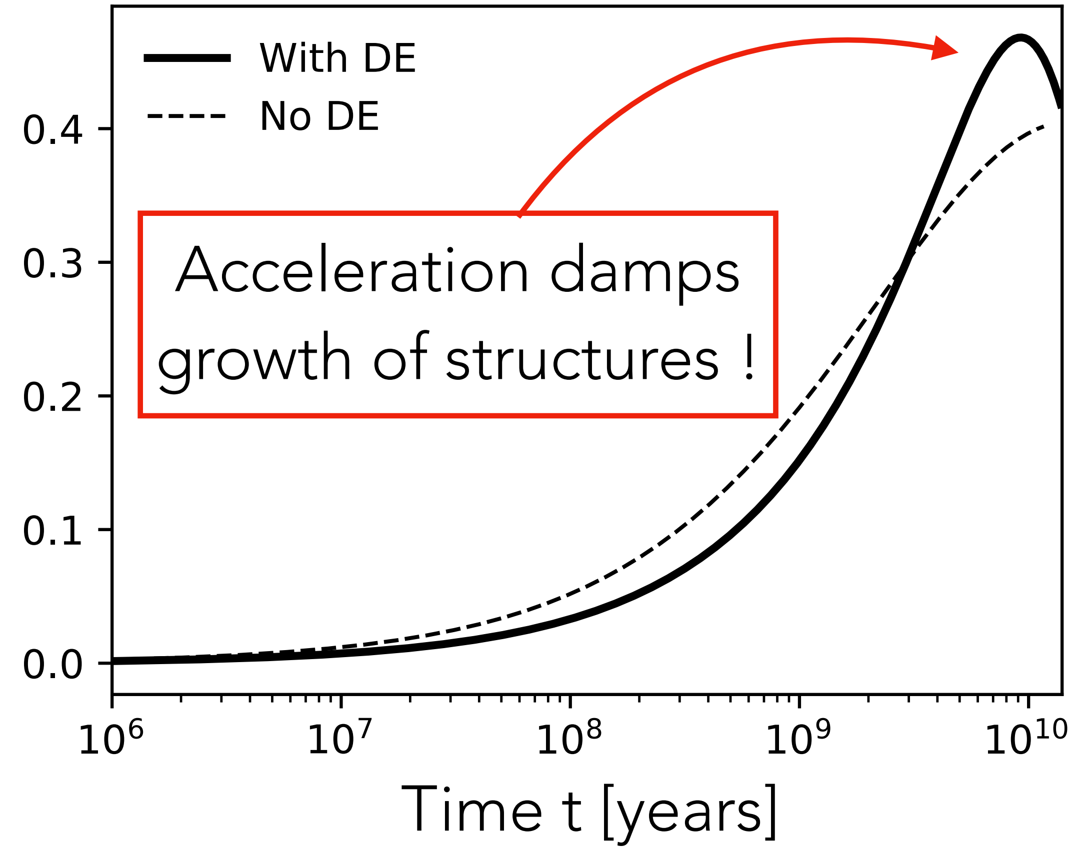
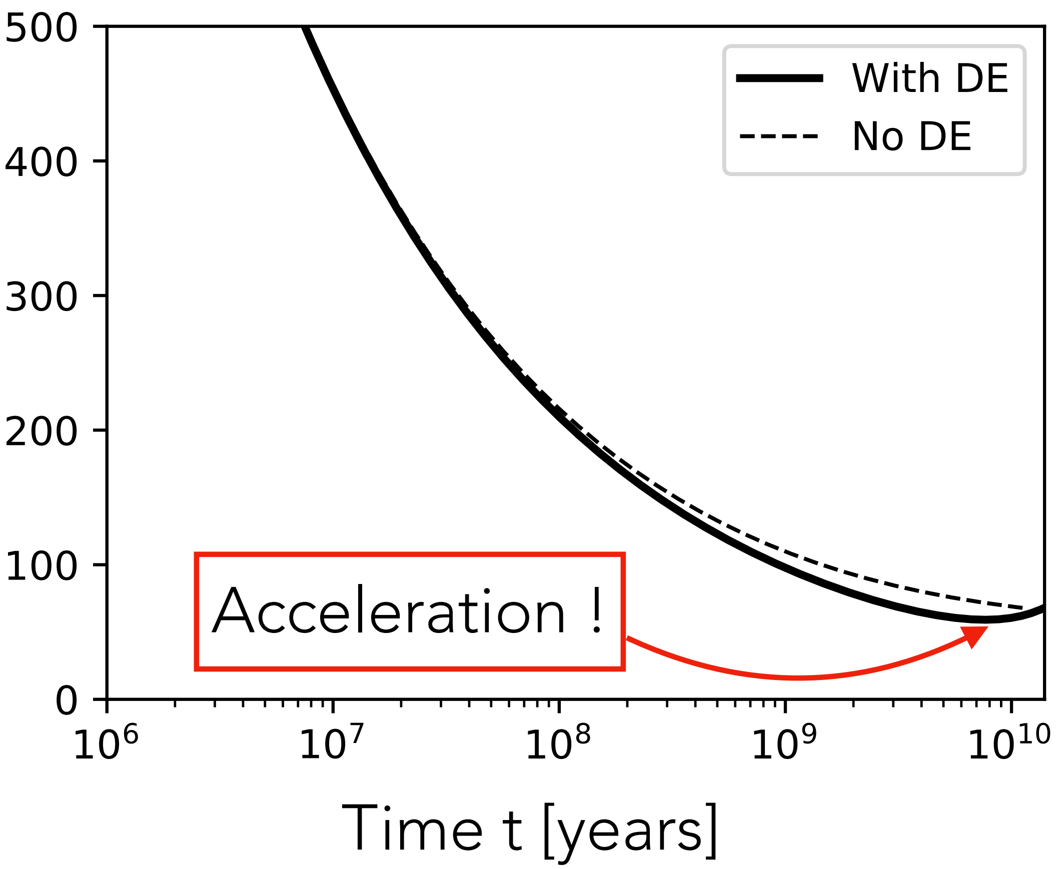


Smooth Universe

$$\underbrace{\left[\frac{\mathrm{d}a}{\mathrm{d}t}(t)\right]^2}_{\text{Expansion-rate}} \sim \underbrace{\Omega_m[a(t)]^{-3}}_{\substack{\text{p}^+\text{, n, e}^-\text{,} \\ \text{dark matter} \\ \mathbf{30\%}}} + \underbrace{\Omega_r[a(t)]^{-4}}_{\substack{\text{photons,} \\ \text{neutrinos} \\ \mathbf{0.008\%}}} + \underbrace{\Omega_\Lambda[a(t)]^{-3(1+w_0+w_a)}e^{3w_a[1-a(t)]}}_{\substack{\text{dark energy} \\ \text{(quintessence, phantom force)} \\ \mathbf{70\%}}}$$

$$\frac{\mathrm{d}a}{\mathrm{d}t}(t) \;=\; \text{Expansion-rate}$$



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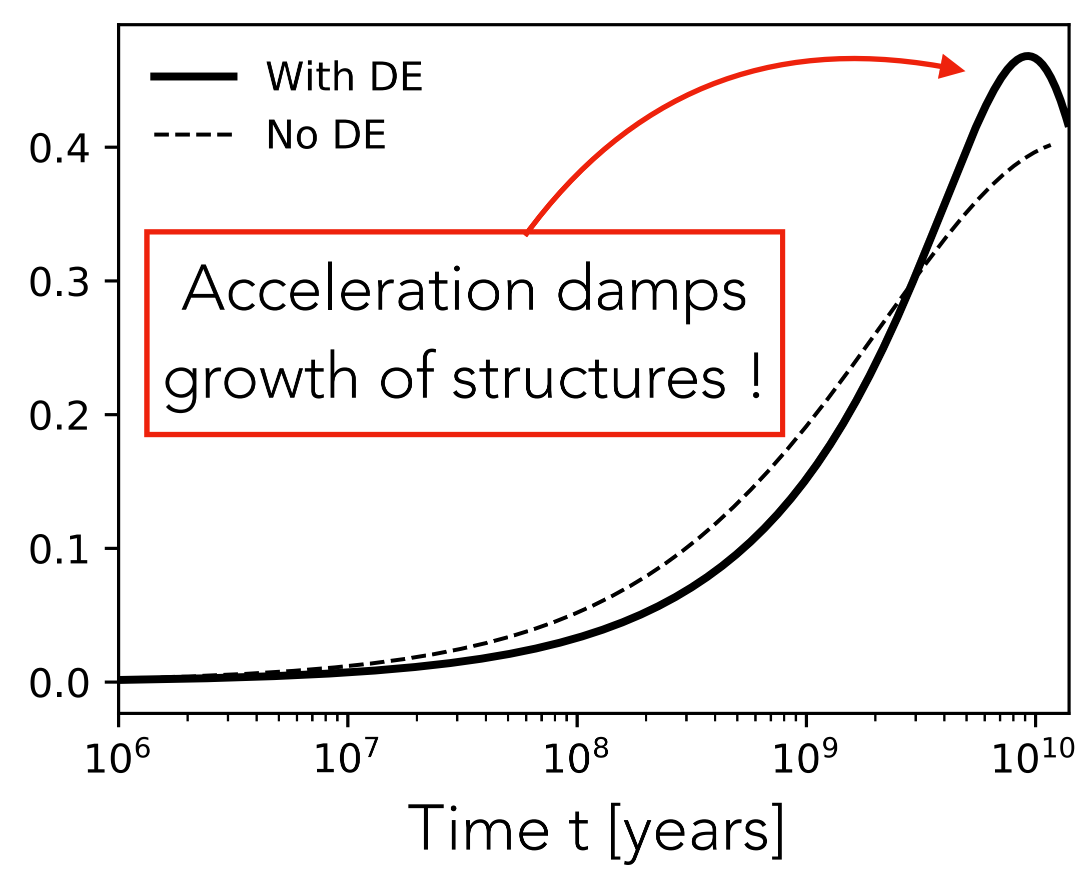

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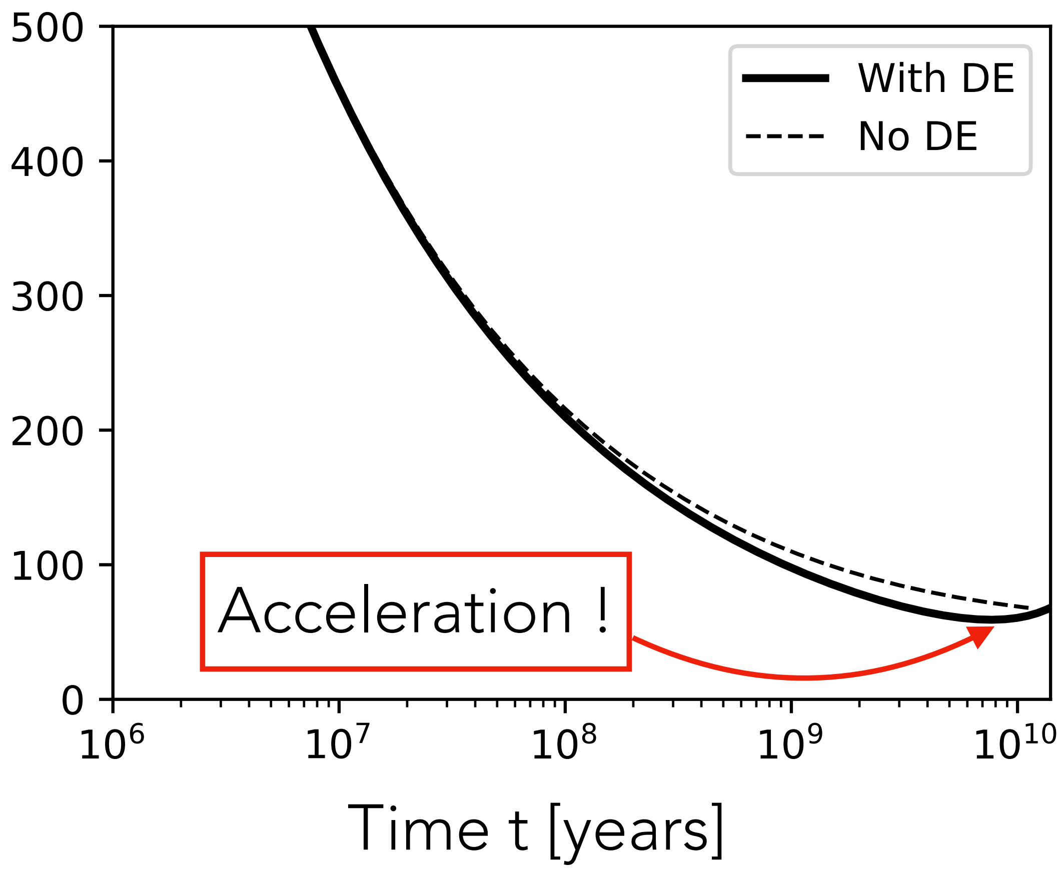

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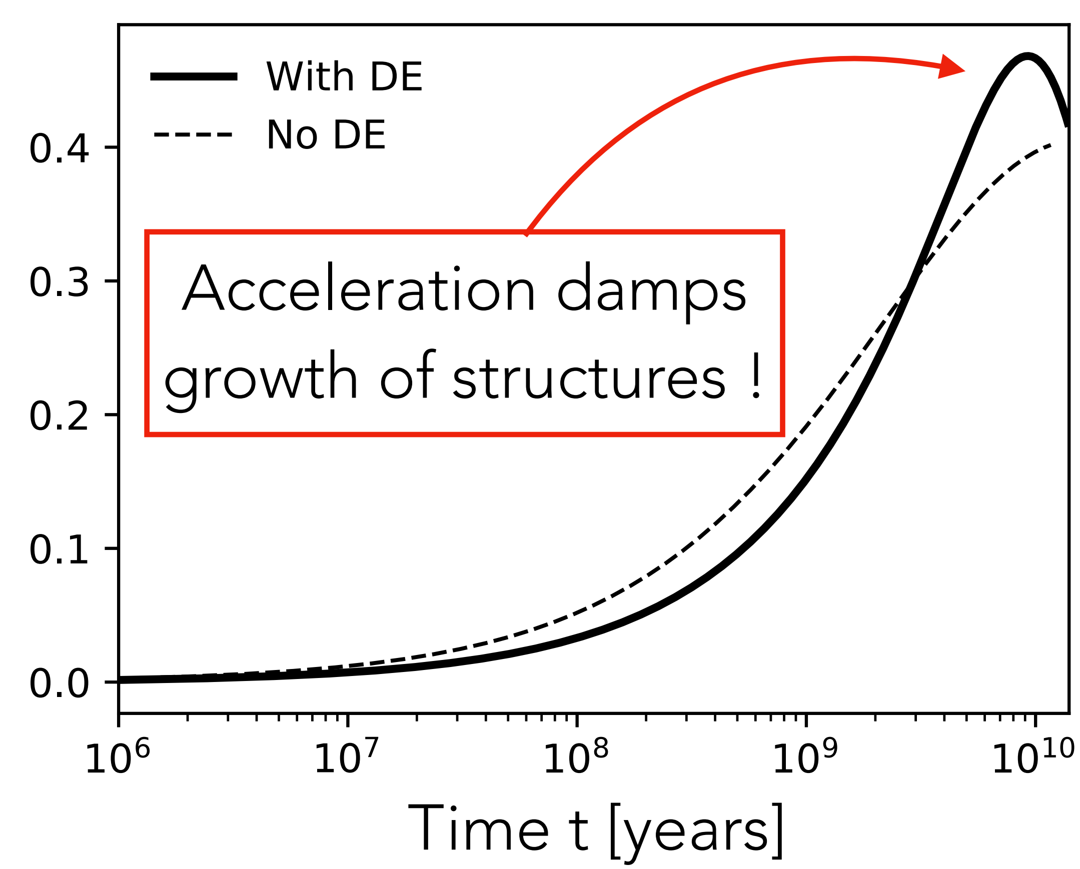

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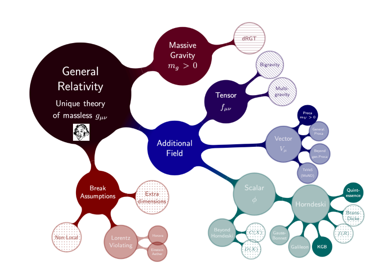
Expansion-rate and growth-rate can **break degeneracies** between Λ and alternatives to general relativity



Statistics of the structures

One Universe,
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$$\delta(\mathbf{x})$$

not so useful by itself,
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Correlation function: $$\langle \delta(\mathbf{x})\delta(\mathbf{y}) \rangle$$

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Fourier Transform

Power-spectrum:	$\langle \tilde{\delta}(\mathbf{k}) \tilde{\delta}(\mathbf{k}') \rangle$	

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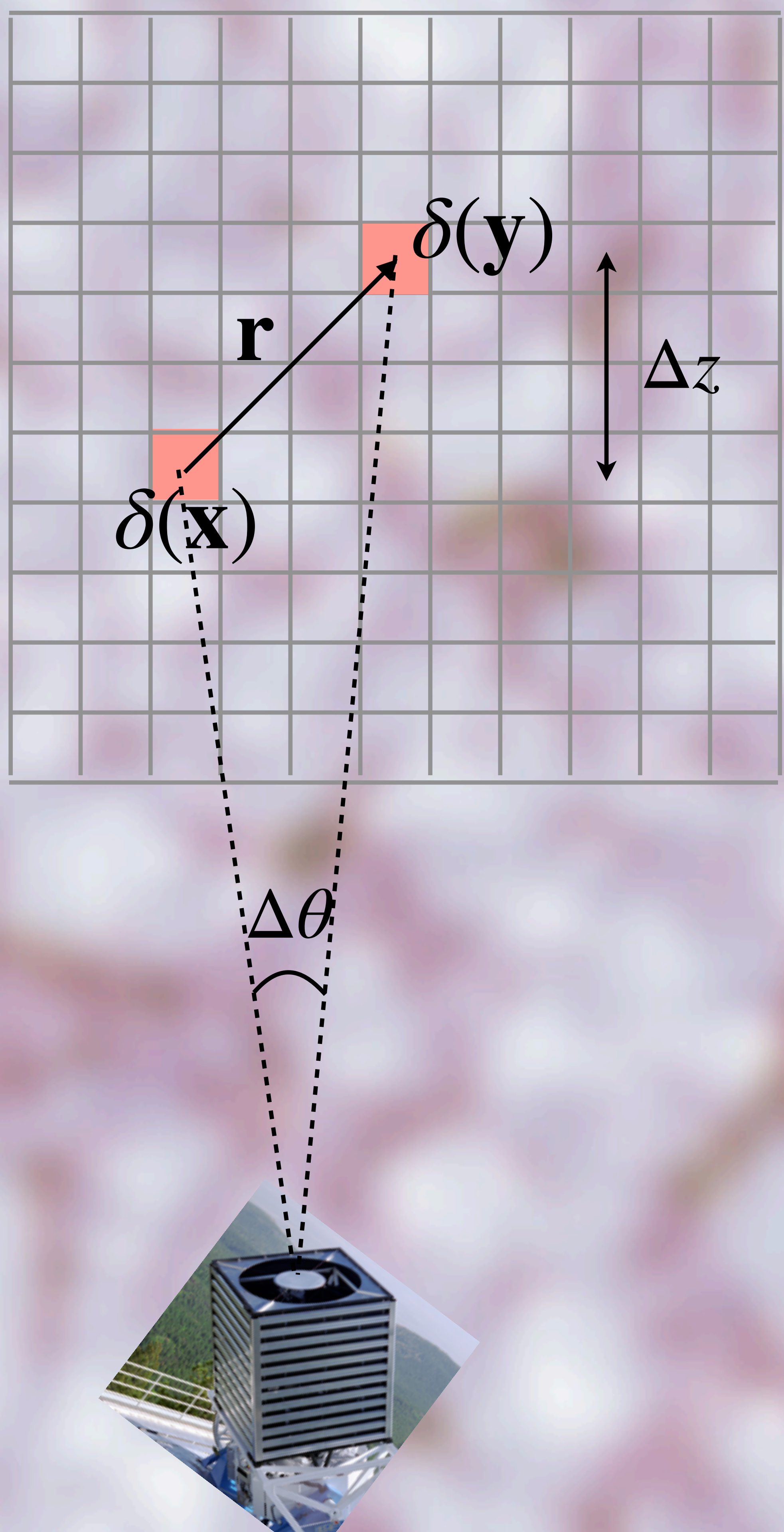
Higher-order: $\langle \delta(\mathbf{x_1})\delta(\mathbf{x_2}) \ldots \delta(\mathbf{x_n}) \rangle$ also very interesting

Correlation function: $\langle \delta(\mathbf{x})\delta(\mathbf{y}) \rangle$

$\langle \,.\, \rangle =$ average over all pairs in the volume

$$\langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r}) \rangle = \xi(\mathbf{r}) = \xi(r_{\parallel}, r_{\perp})$$



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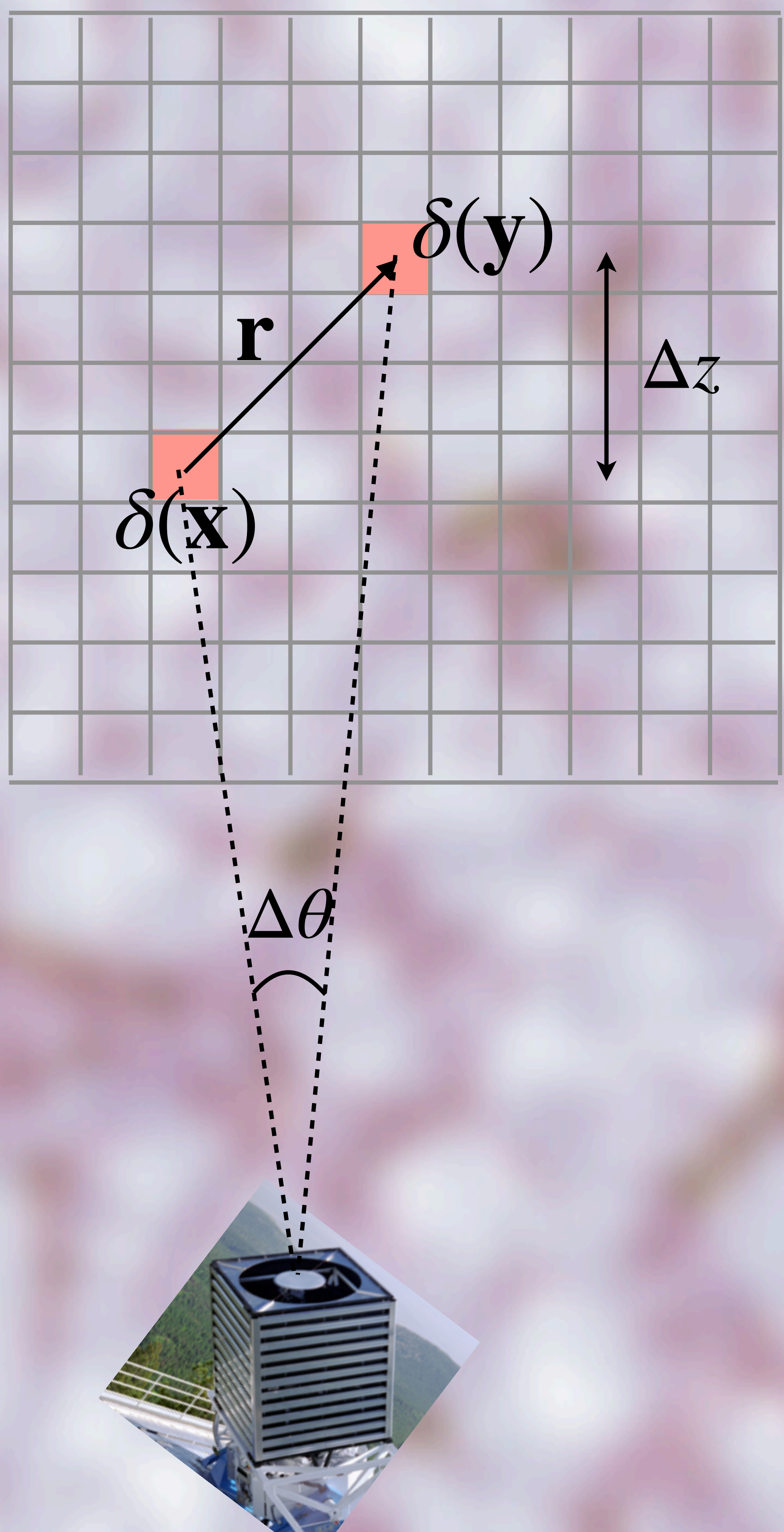

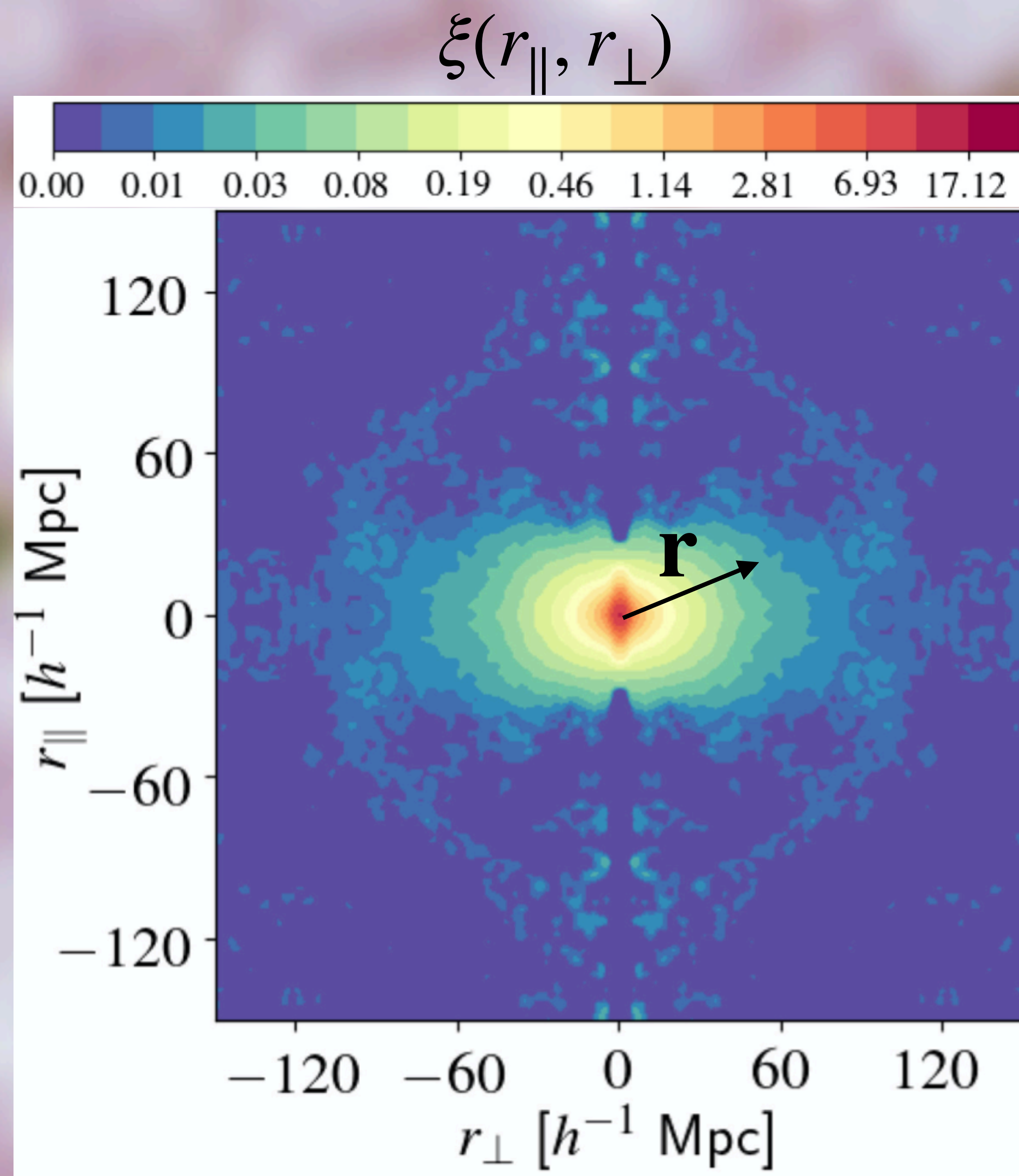

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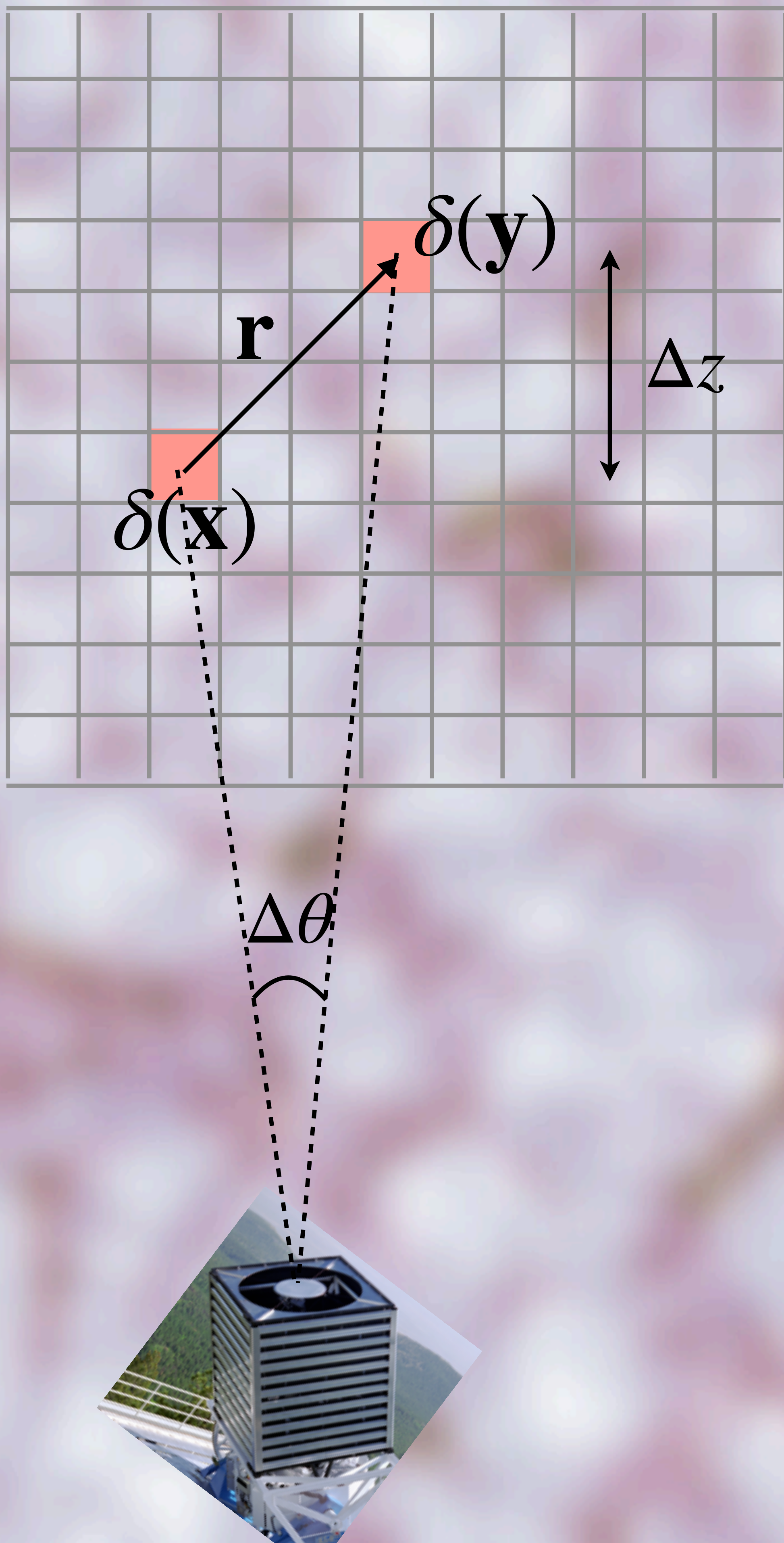
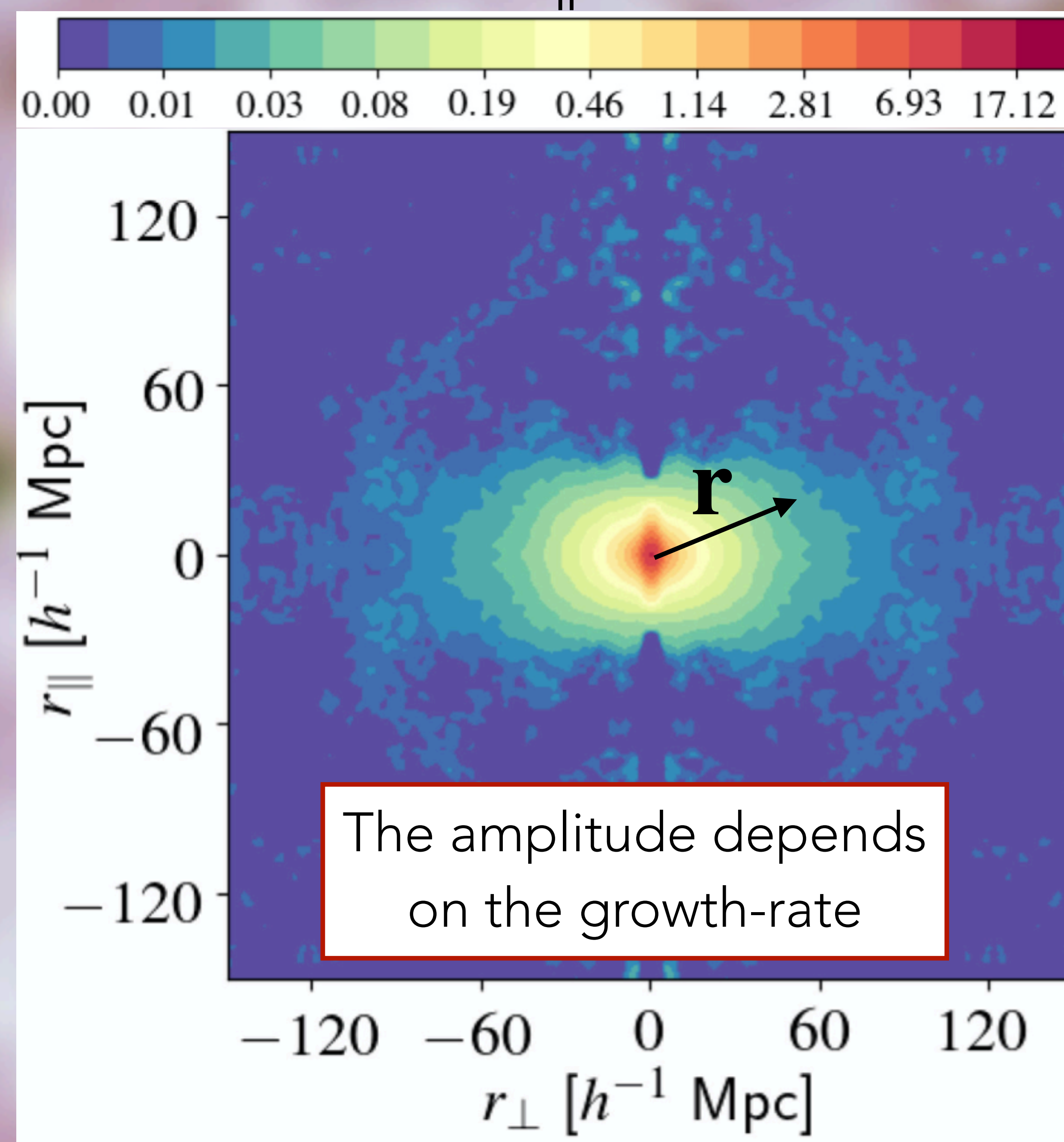


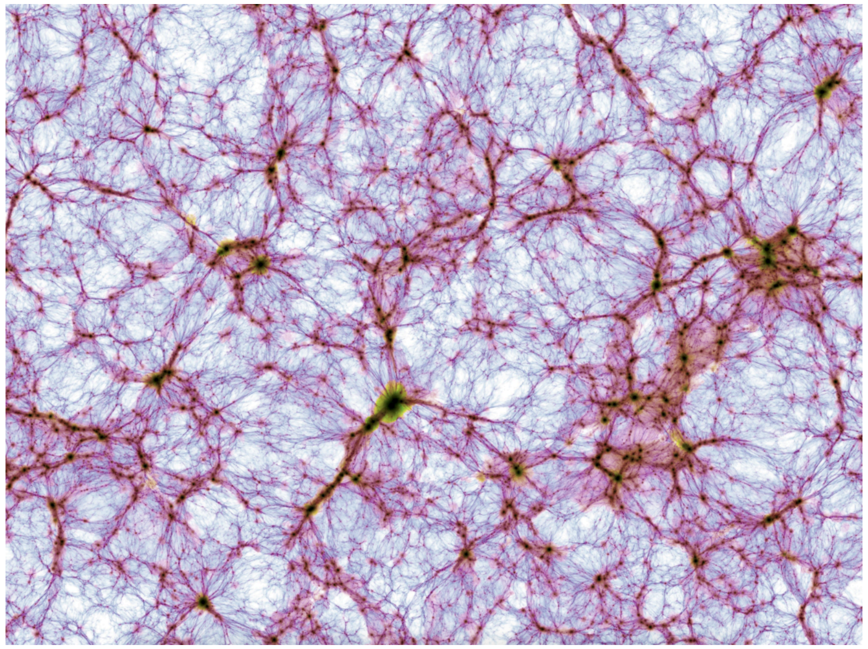
$\xi(r_\parallel, r_\perp)$



Structures of the Universe

and how can they teach us about dark energy

Universe is not smooth



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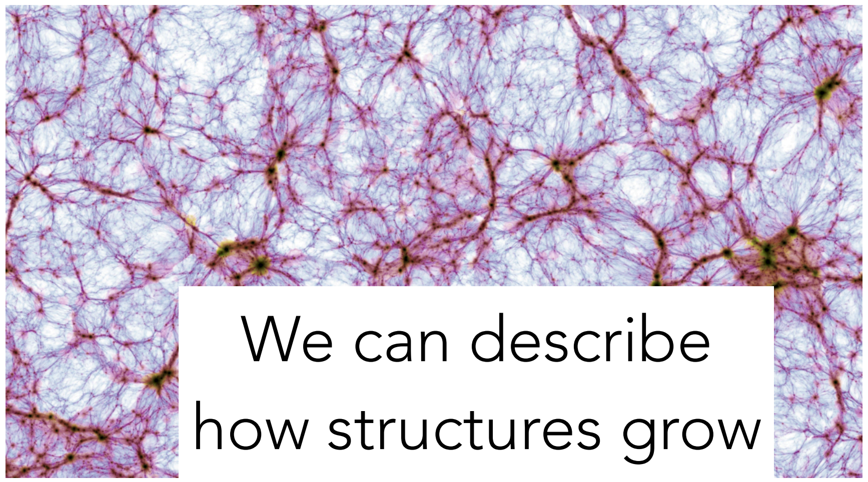

We can describe how structures grow

$$\ddot{\delta} + \boxed{\text{expansion, pressure}}\,\dot{\delta} - \boxed{\text{gravity}}\,\delta = 0$$

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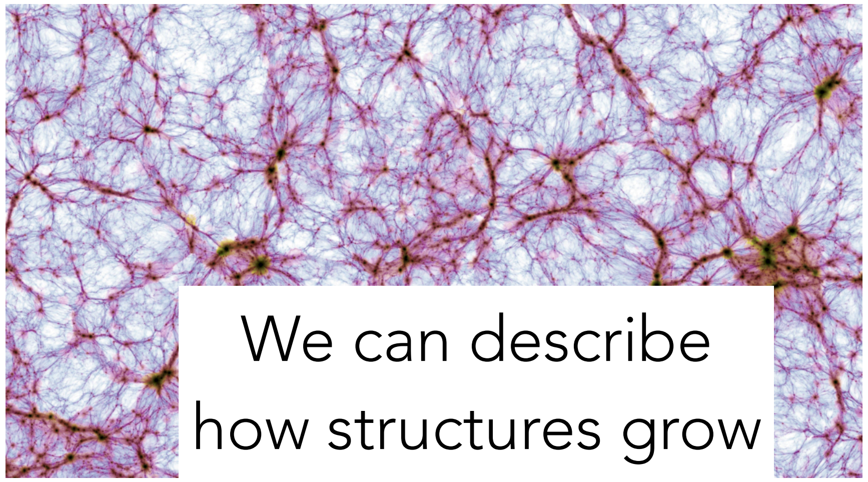

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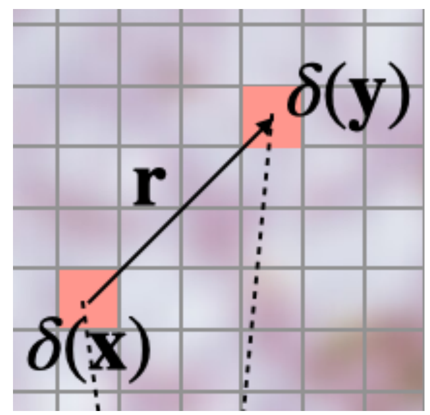

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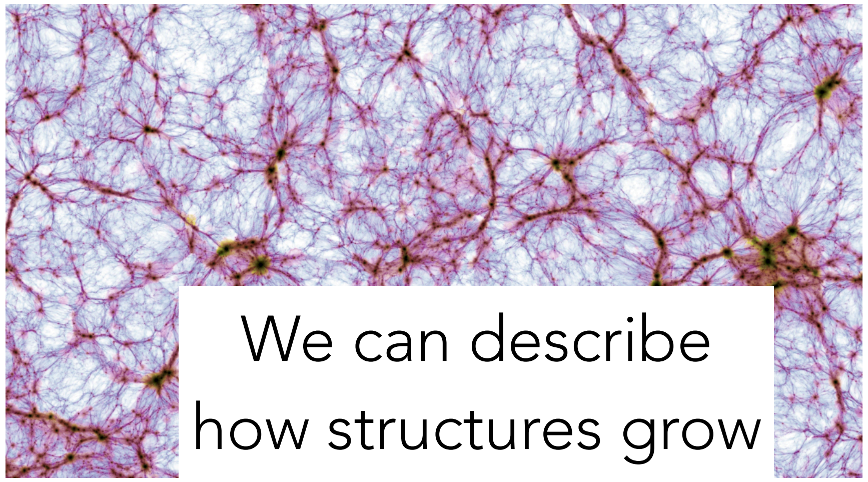

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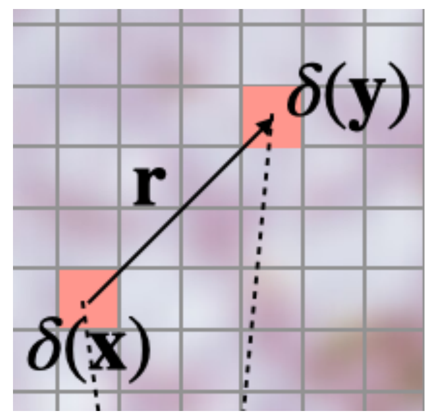
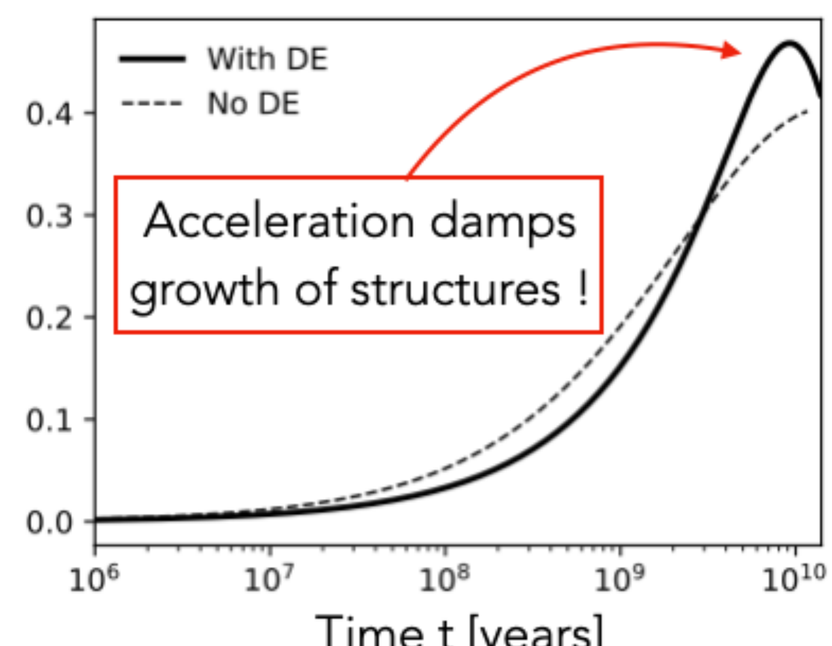


that depend on the growth-rate

and learn about dark energy

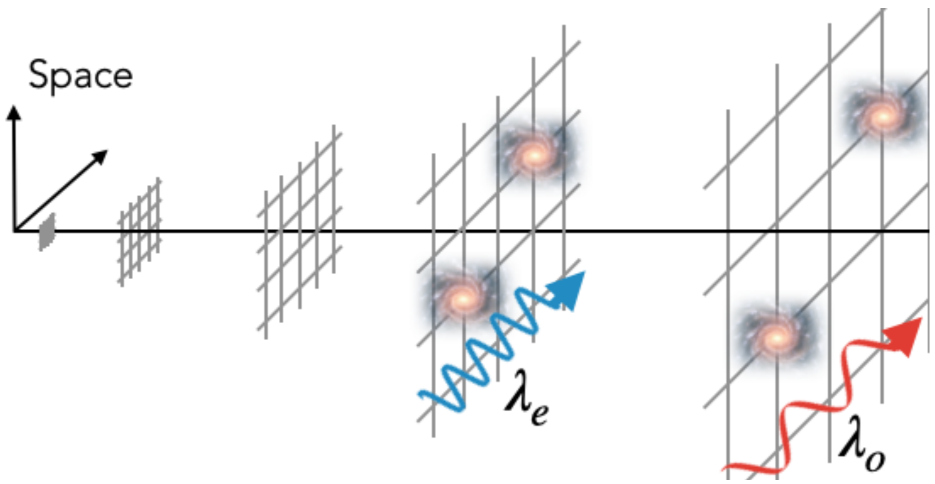
$$\frac{\mathrm{d}\delta}{\mathrm{d}t}(t) \sim \text{Growth-rate}$$



Observations

and how we measure
the expansion and growth-rates

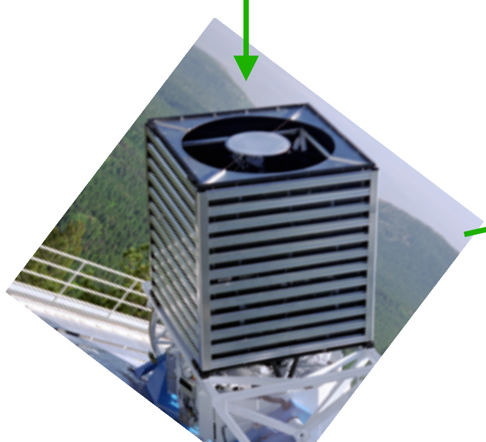
Observing redshifts



Redshift

$$z = \frac{\lambda_o}{\lambda_e} - 1 = \frac{1}{a(t)} - 1$$

Galaxy



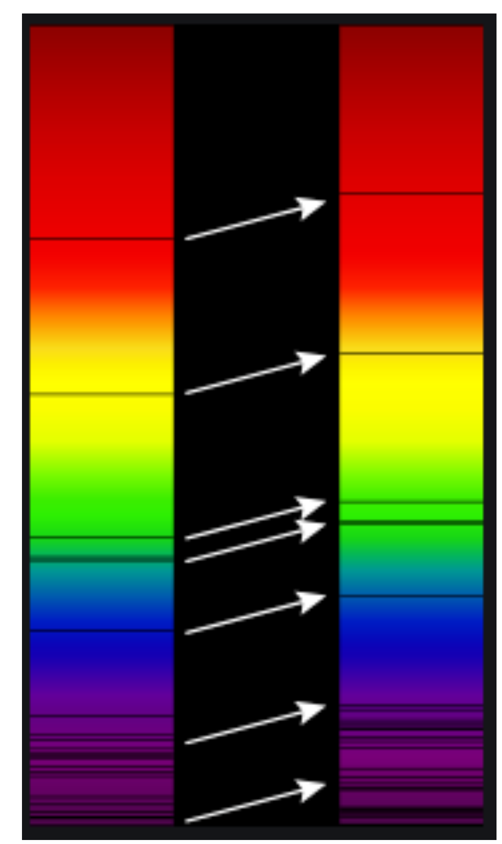
Telescope

Get spectrum

(source: Pink Floyd)

rest frame

observed frame



(source: wikipedia)

Redshift

z

Redshifts are 'easy' to measure

Observing the expansion-rate

$$\frac{\mathrm{d}a}{\mathrm{d}t}(t)$$

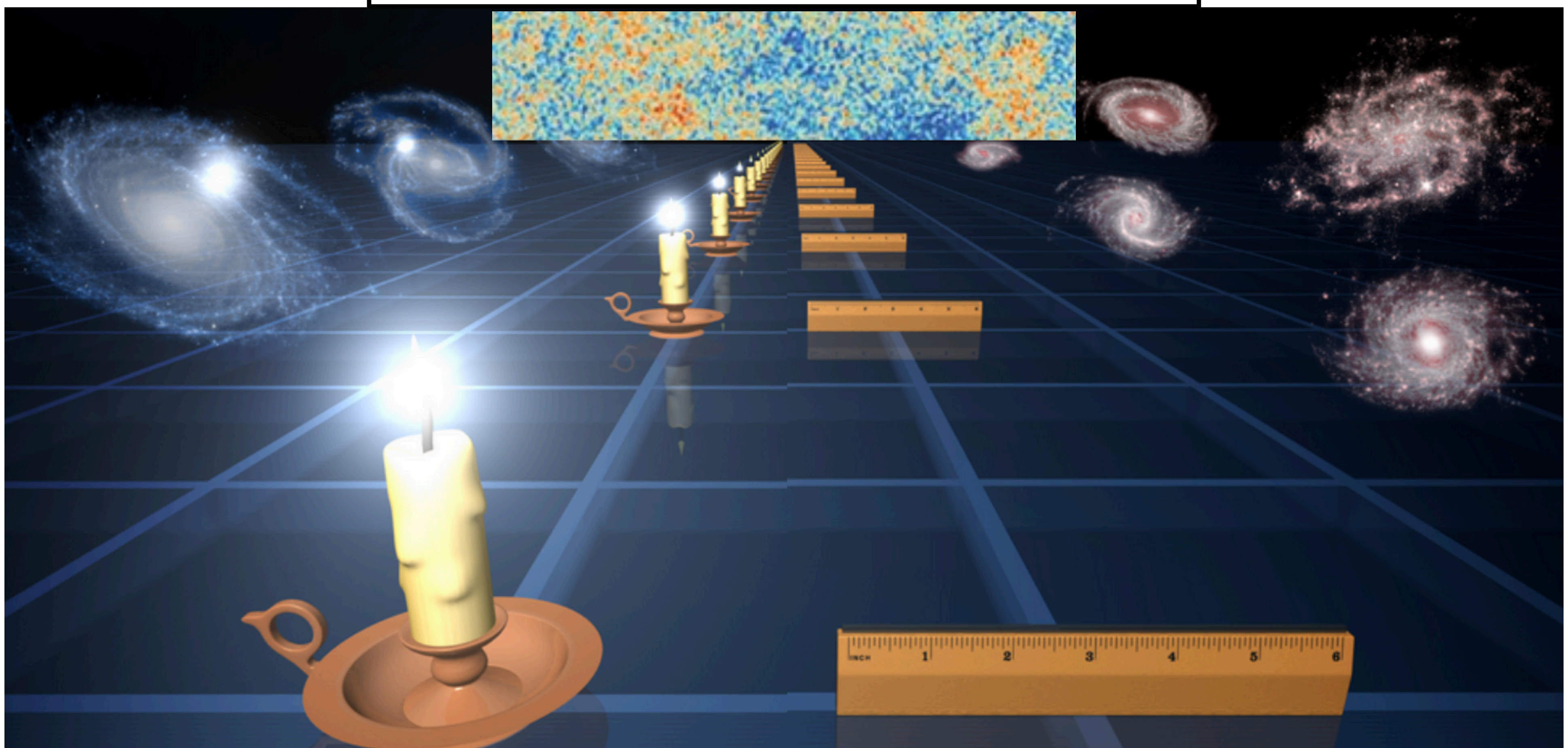
Type-Ia Supernovae (SNIa)
as standard candles
$0 < z < 1.5$
5 Gy $< t <$ 13.8 Gy

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

Observing the expansion-rate

$$\frac{\mathrm{d}a}{\mathrm{d}t}(t)$$

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

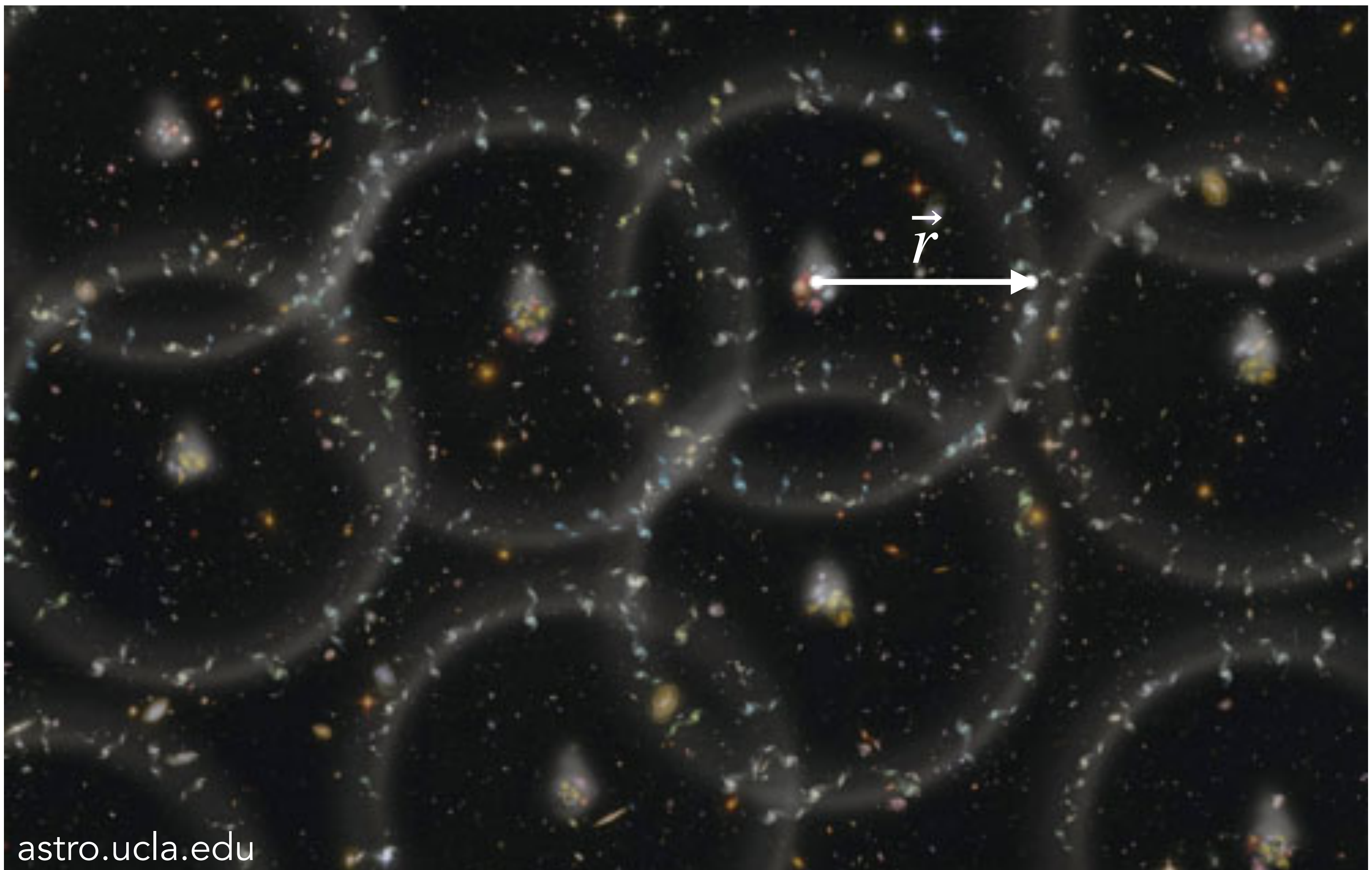


Type-Ia Supernovae (SNIa) as standard candles	Baryon Acoustic Oscillations (BAO) as standard ruler
$0 < z < 1.5$	$0.1 < z < 2.5$
5 Gy < t < 13.8 Gy	3 Gy < t < 13 Gy

$$F = \frac{L_{\rm candle}}{4\pi D_L^2(z)} \qquad \Delta\theta = \frac{r_{\rm ruler}}{D_M(z)} \qquad \Delta z = \frac{r_{\rm ruler}}{D_H(z)}$$

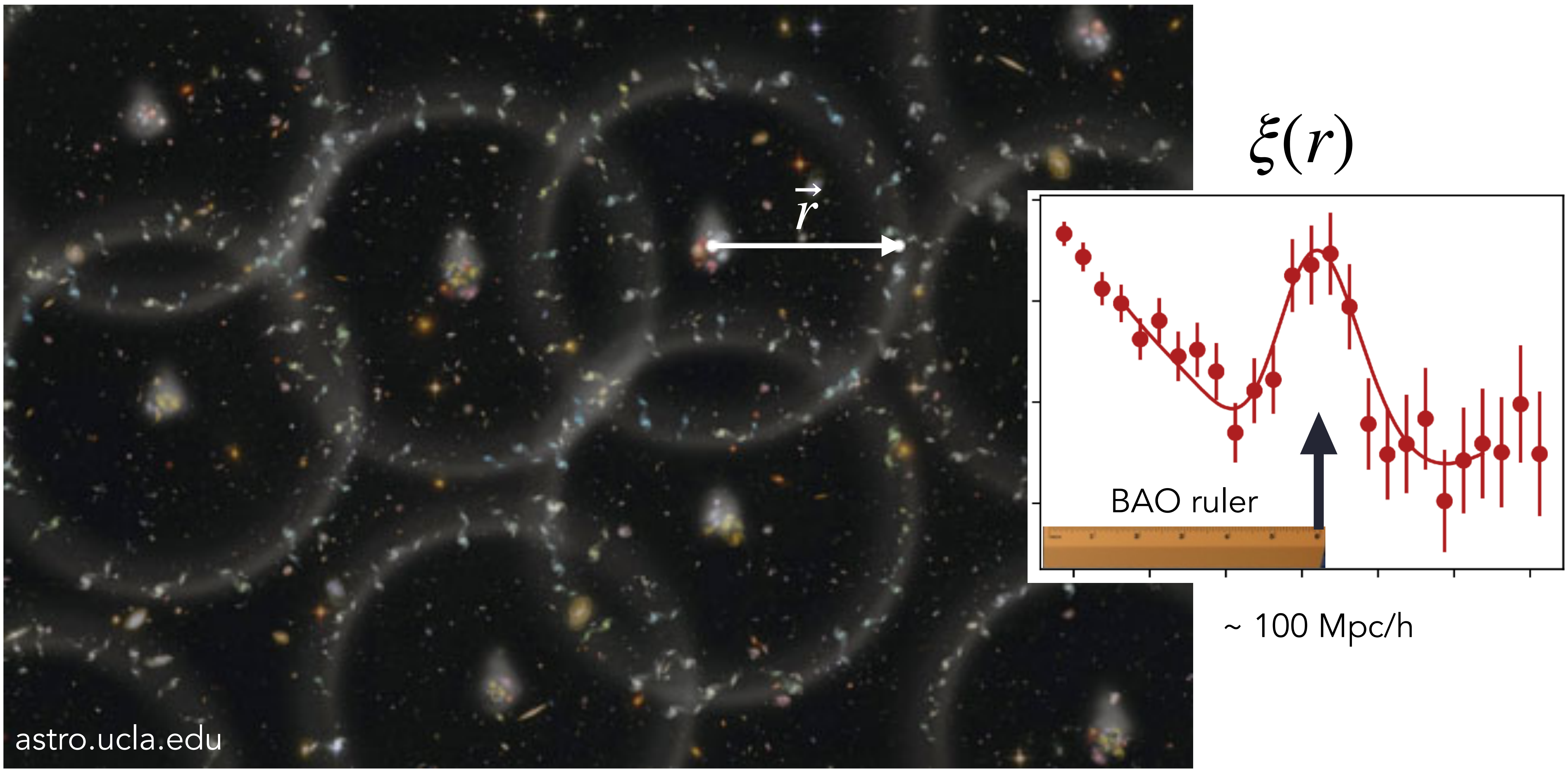
Observing the expansion-rate

Baryon Acoustic Oscillations (BAO)
as standard ruler



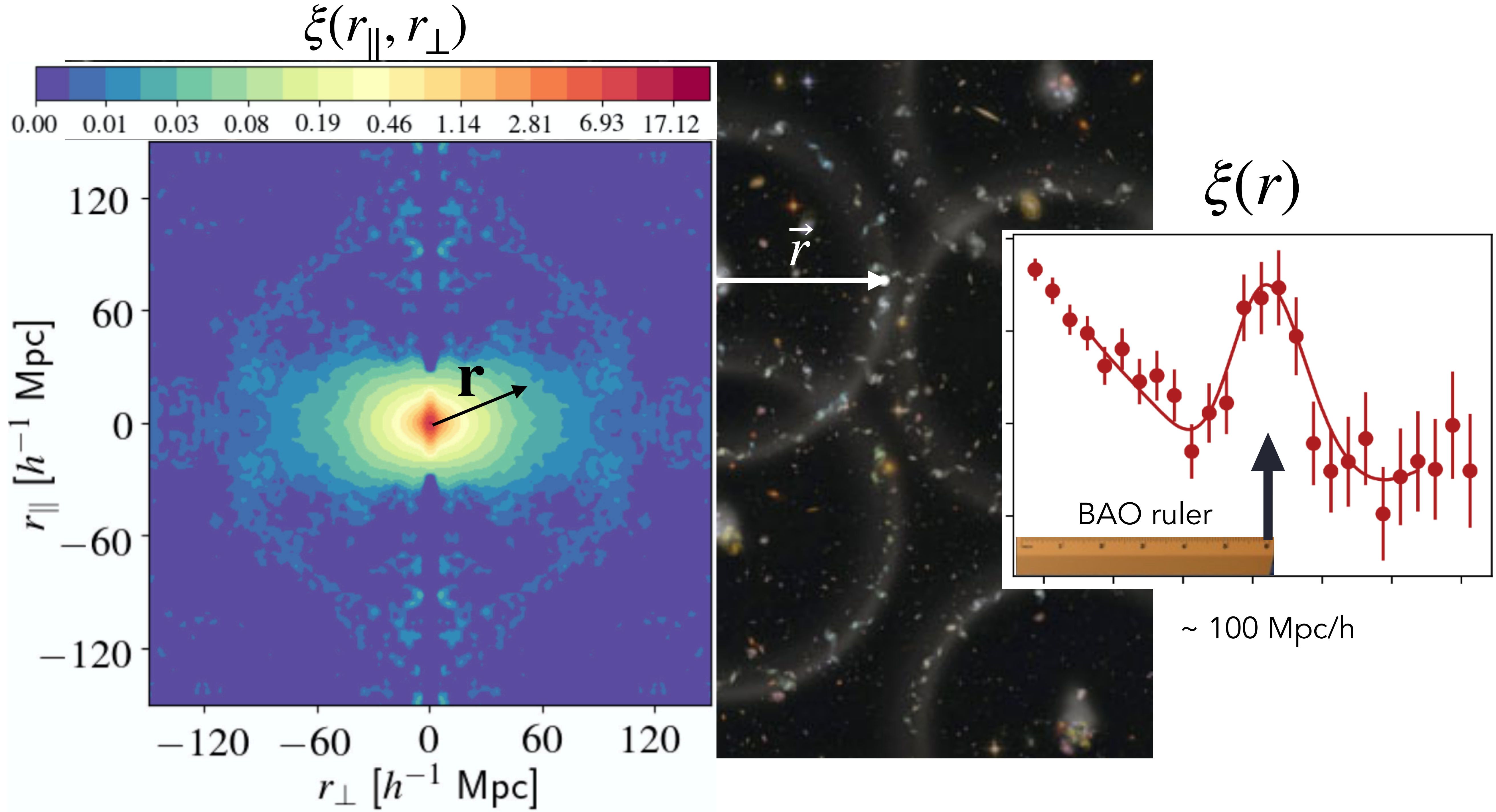
Observing the expansion-rate

Baryon Acoustic Oscillations (BAO)
as standard ruler



Observing the expansion-rate

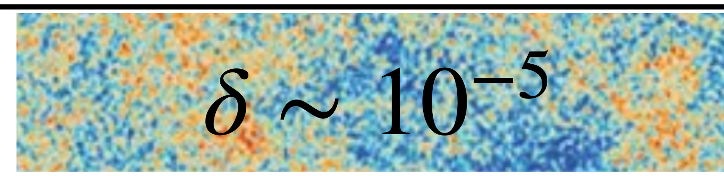
Baryon Acoustic Oscillations (BAO)
as standard ruler



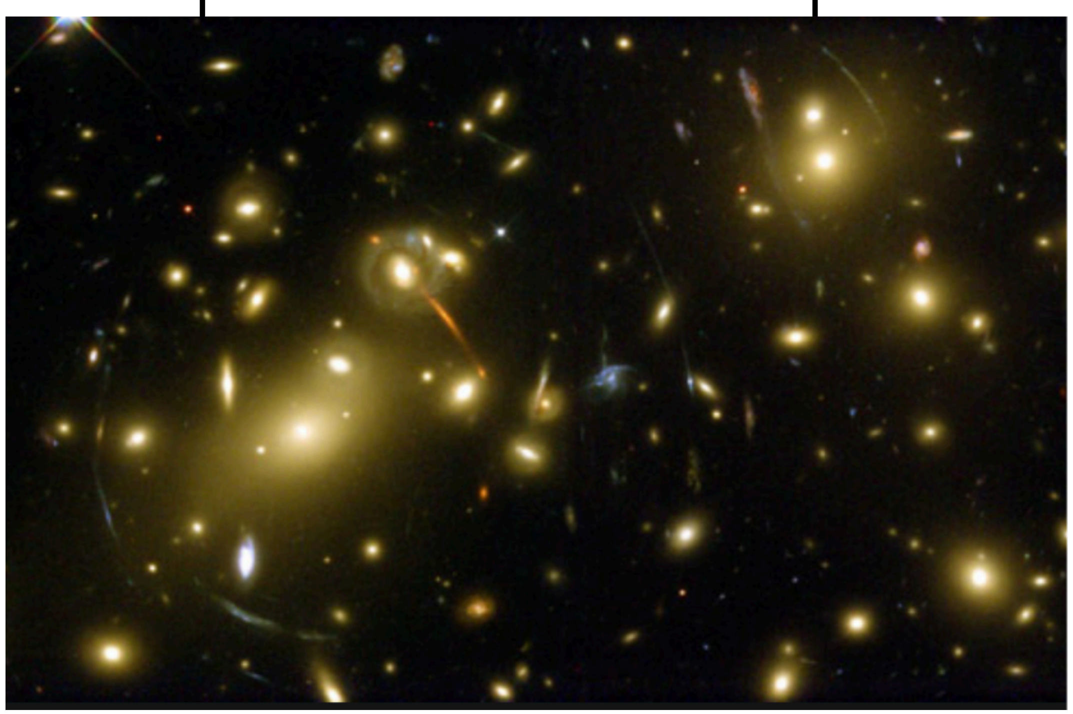
Observing the growth-rate

$$\frac{\mathrm{d}\delta}{\mathrm{d}t}(t)$$

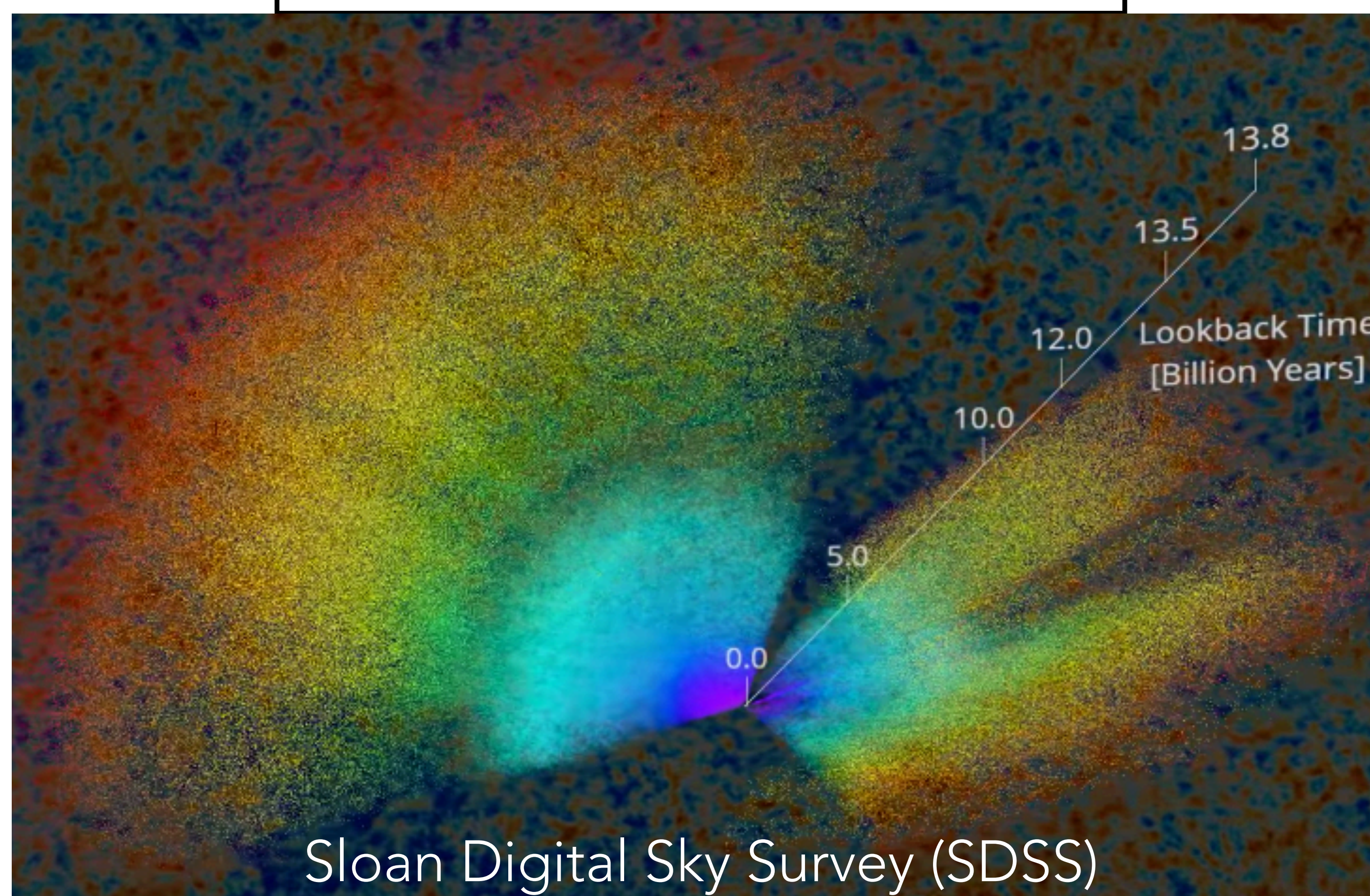
Cosmic microwave background (CMB)
z ~ 1100 or t ~ 380 000 years



Gravitational lensing
0 < z < 1
6 Gy < z < 13.8 Gy



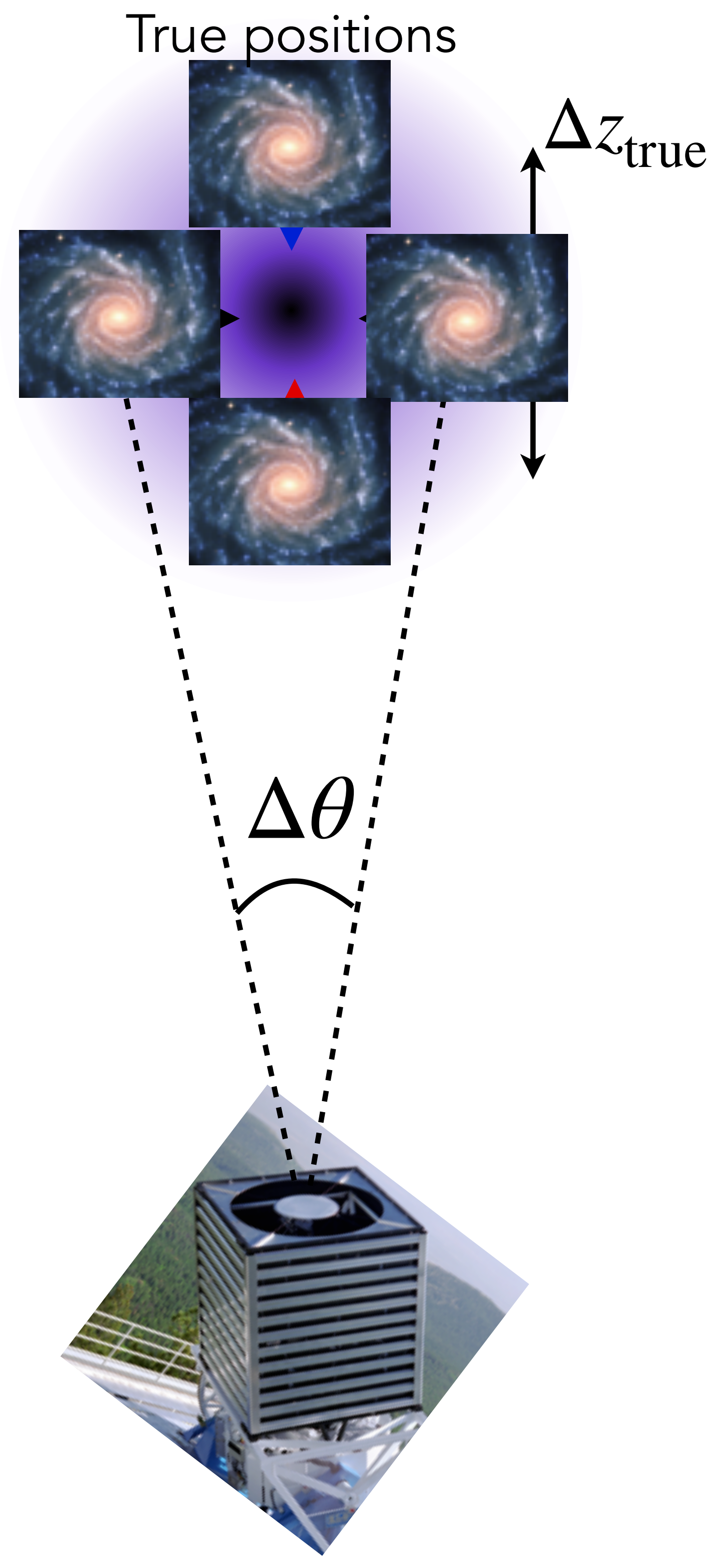
Redshift surveys of
galaxies, quasars, clusters, voids



Observing the growth-rate
with redshift-space distortions (RSD)

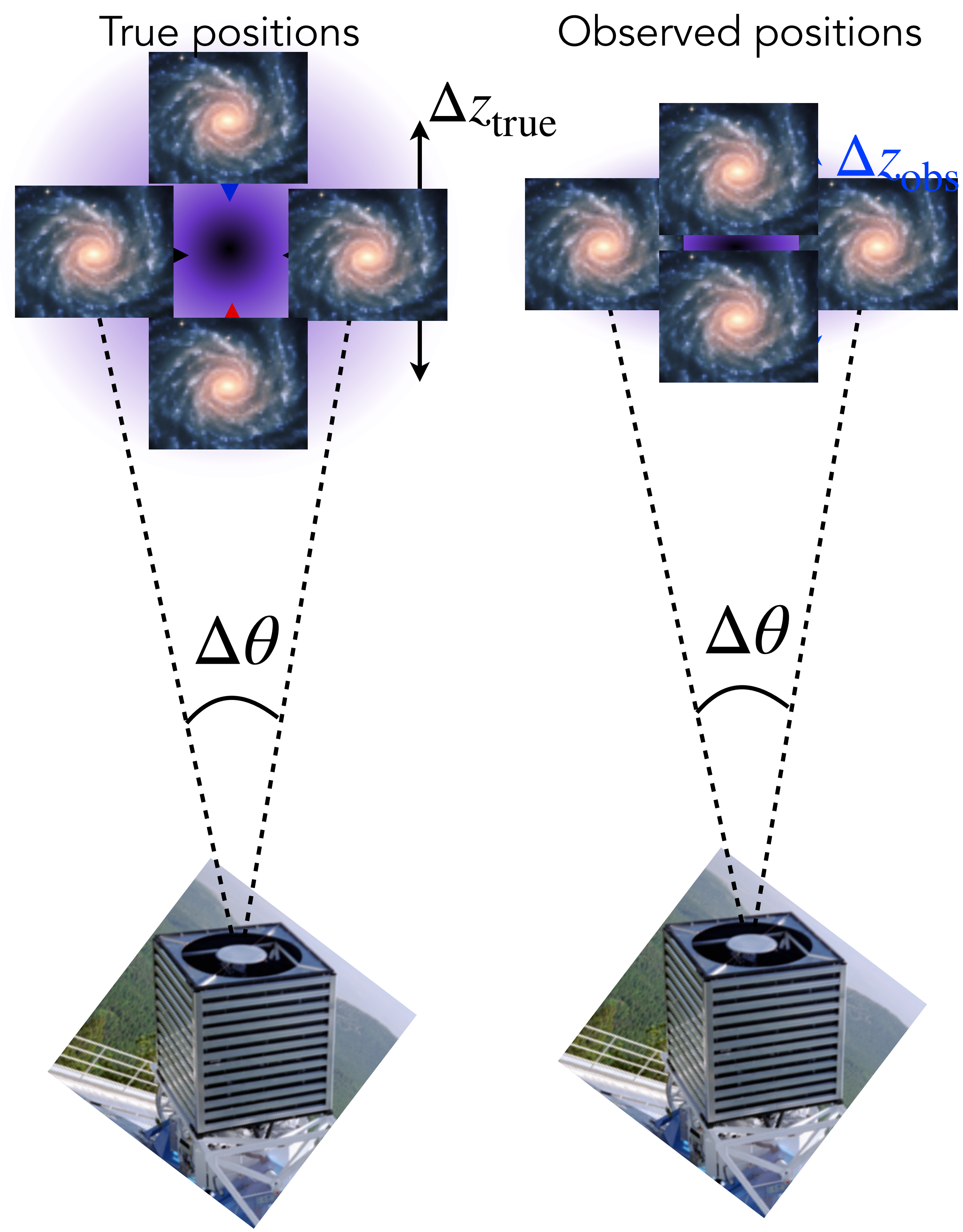
Observing the growth-rate with redshift-space distortions (RSD)

Peculiar velocities modify redshifts and squeeze structures in the radial direction



Observing the growth-rate with redshift-space distortions (RSD)

Peculiar velocities modify redshifts and squeeze structures in the radial direction



Observing the growth-rate
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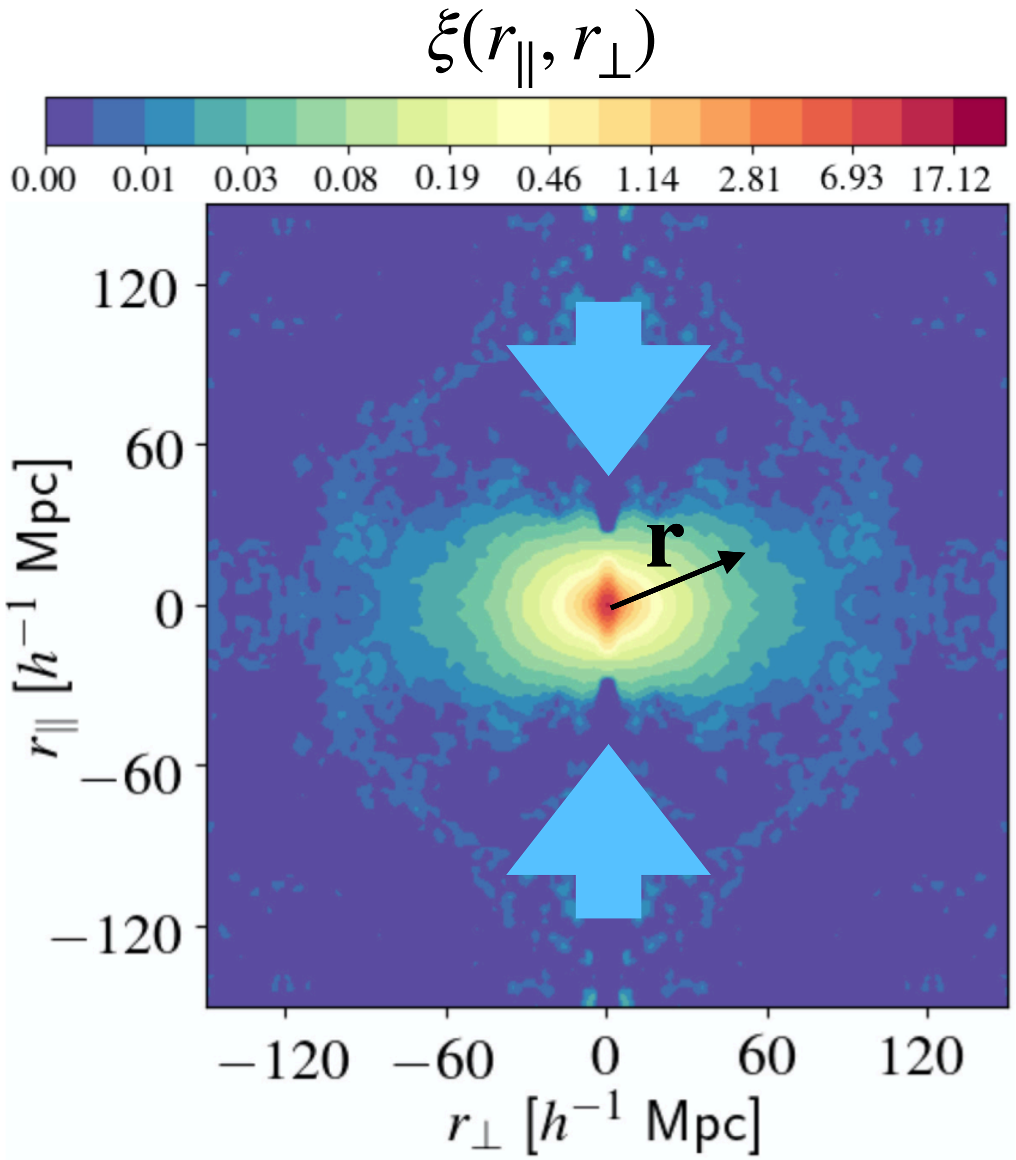
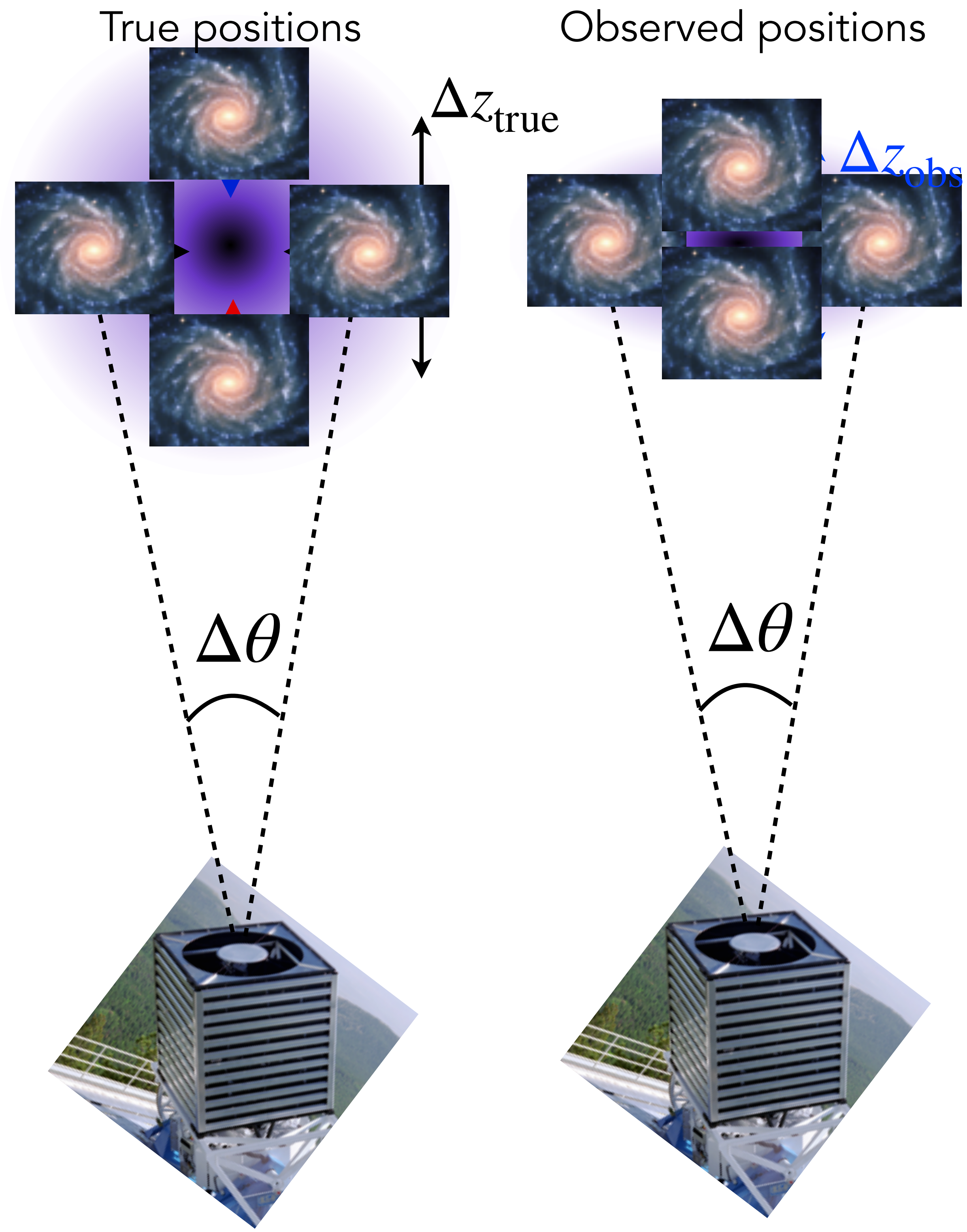
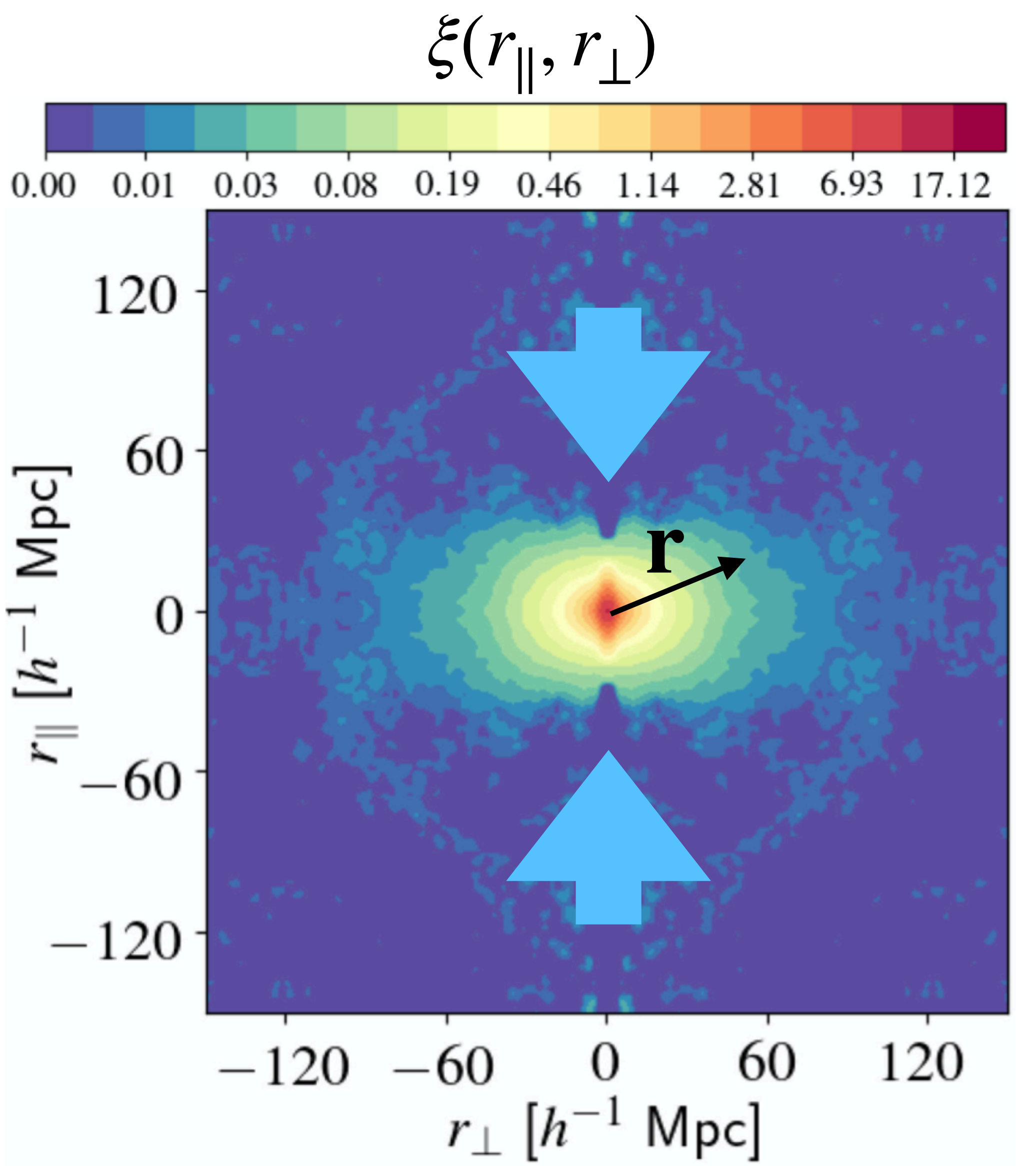
Peculiar velocities modify redshifts and squeeze structures in the radial direction



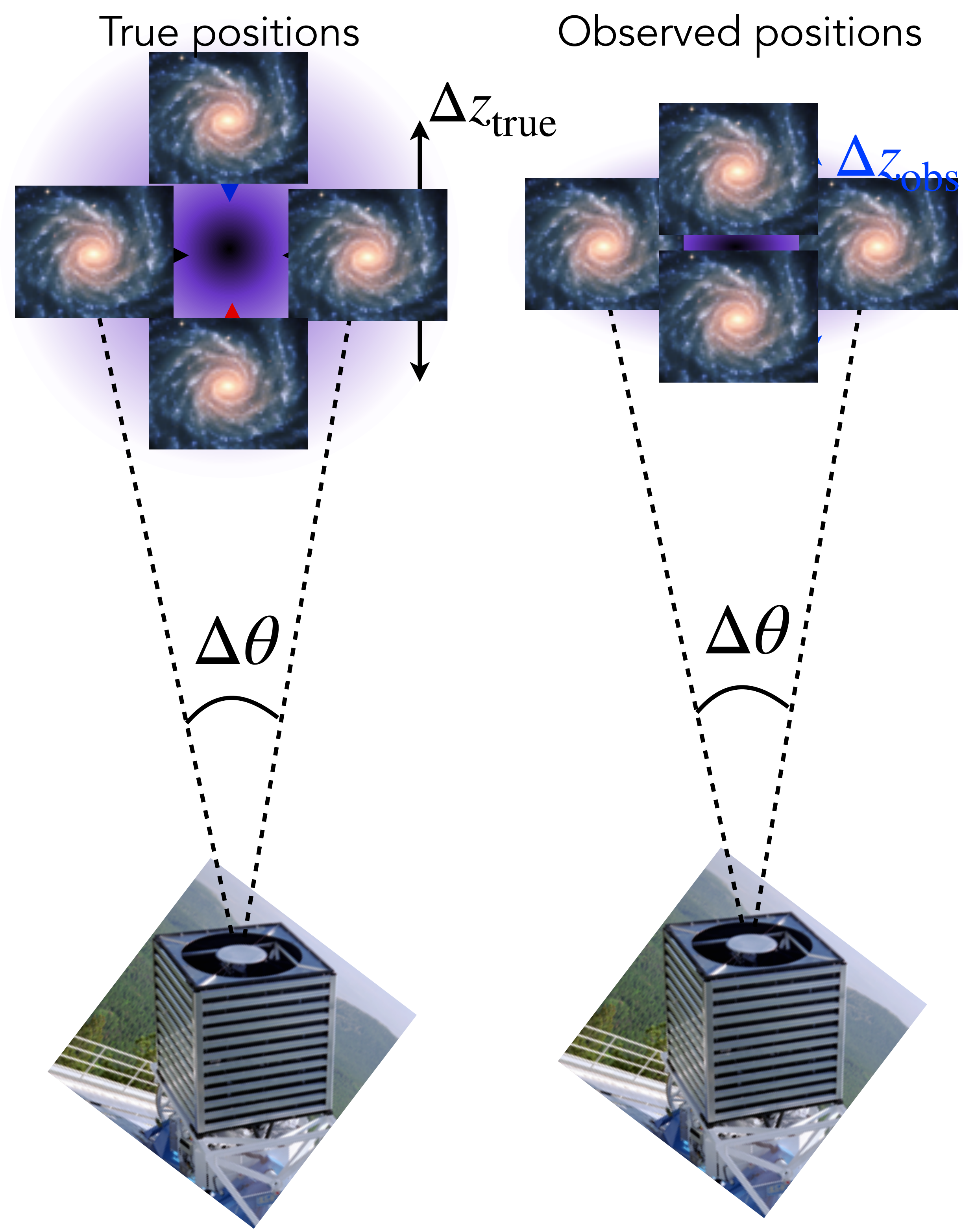


Observing the growth-rate with redshift-space distortions (RSD)

Peculiar velocities modify redshifts and squeeze structures in the radial direction

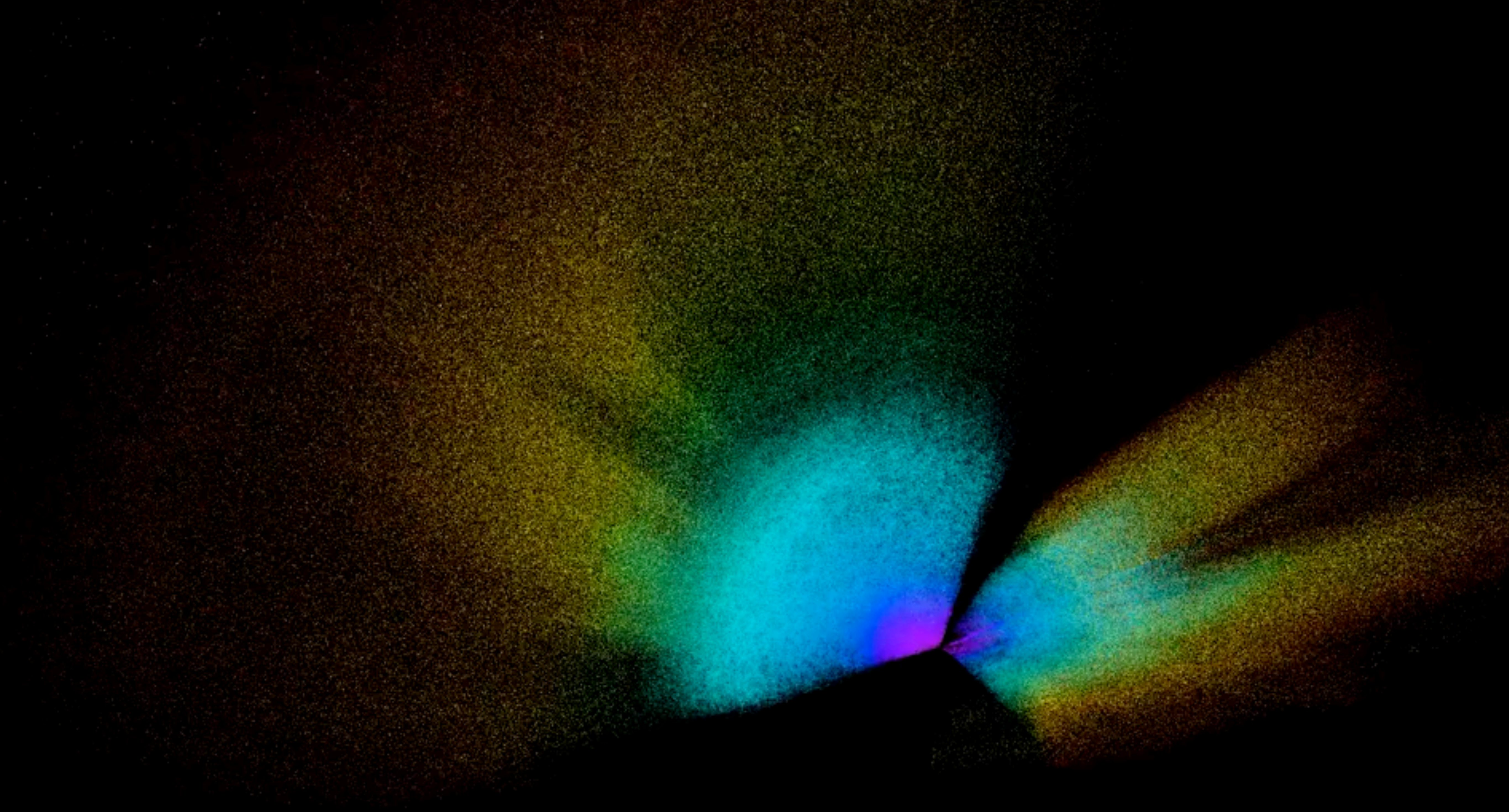


The amplitude of this squeezing depends on the growth-rate



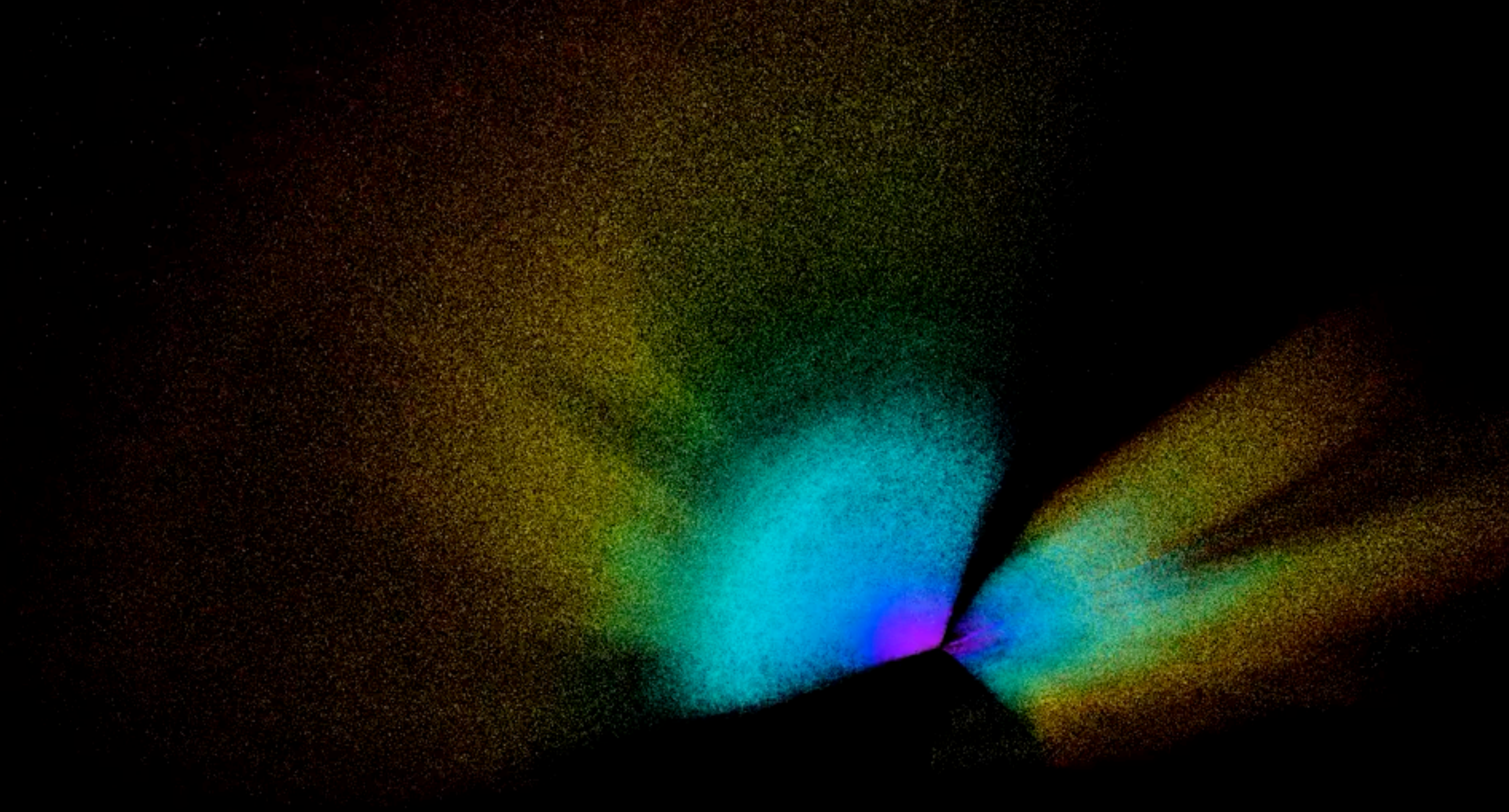
eBOSS

and the state-of-the-art map of the Universe's structures



20 years of redshift surveys with SDSS

https://www.youtube.com/watch?v=KJJXbcf8kxA (by EPFL.ch)



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eBOSS

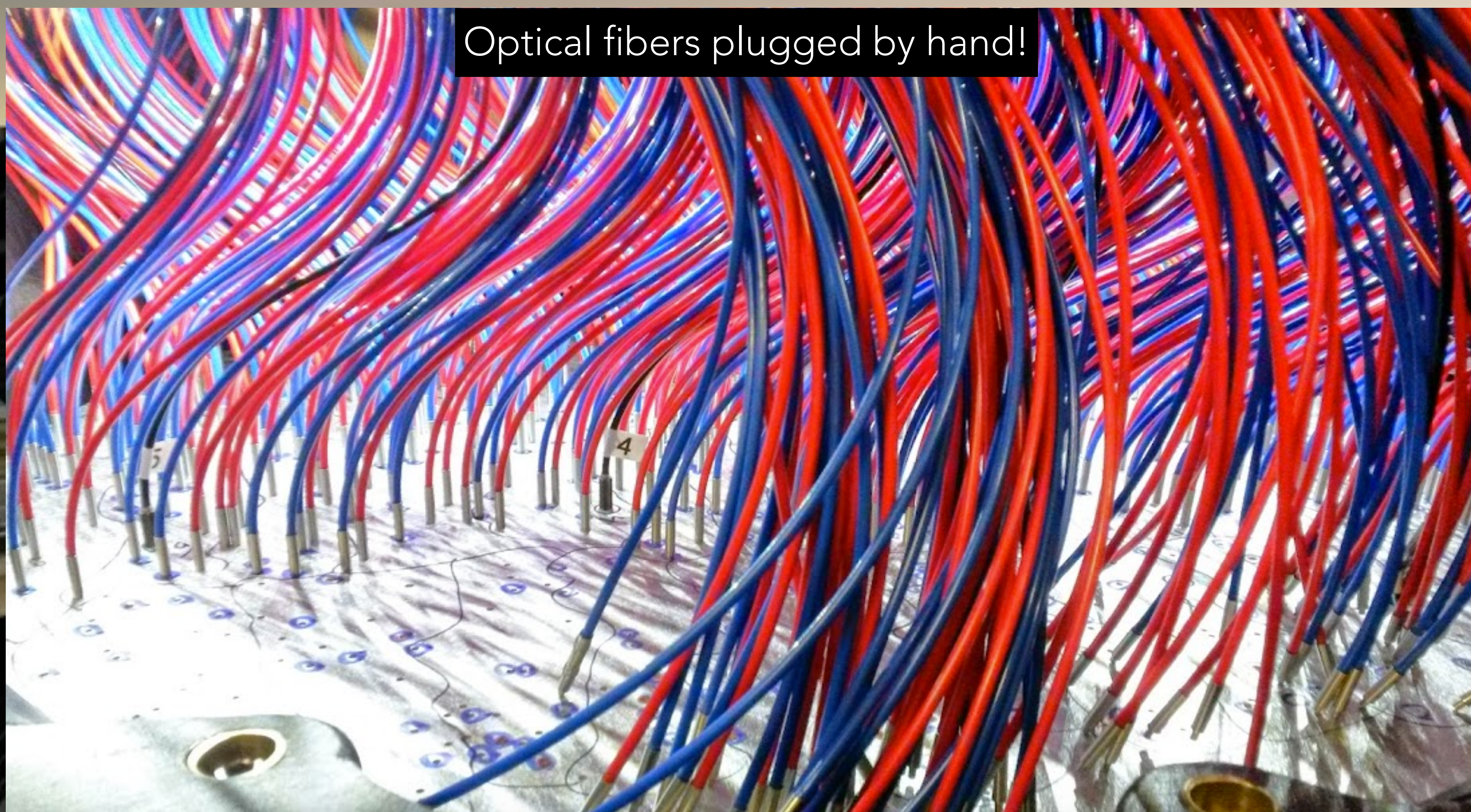
extended Baryon Oscillation Spectroscopic Survey

Dawson et al. 2016

Sloan Digital Sky Survey Telescope
Apache Point Observatory, New Mexico, USA

eBOSS

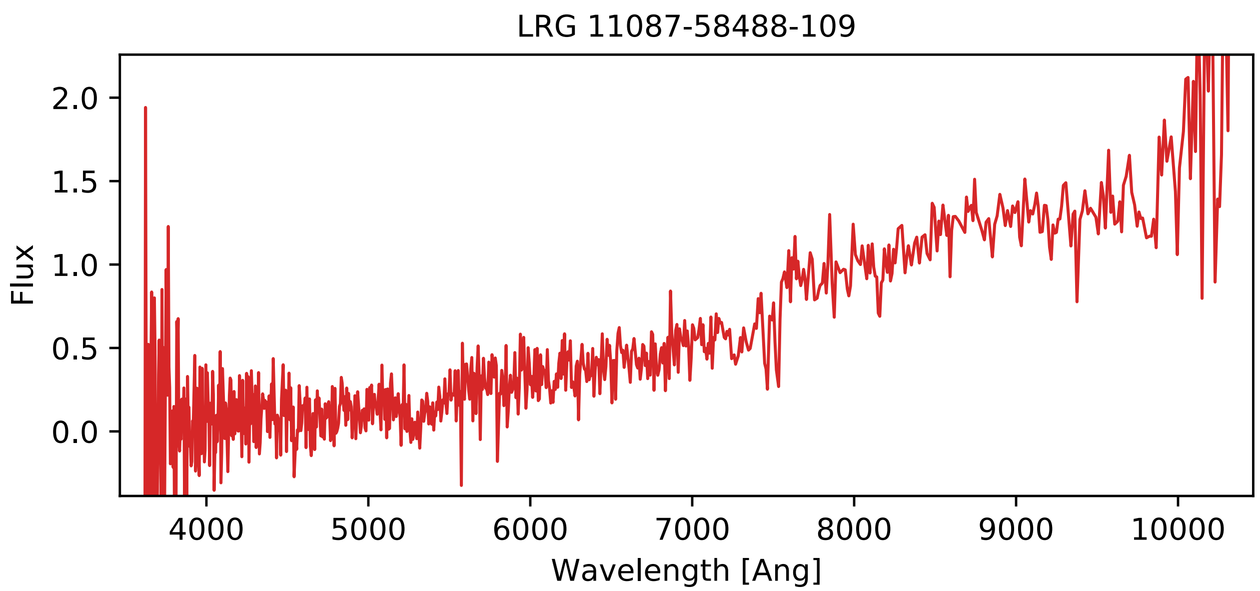
extended Baryon Oscillation Spectroscopic Survey



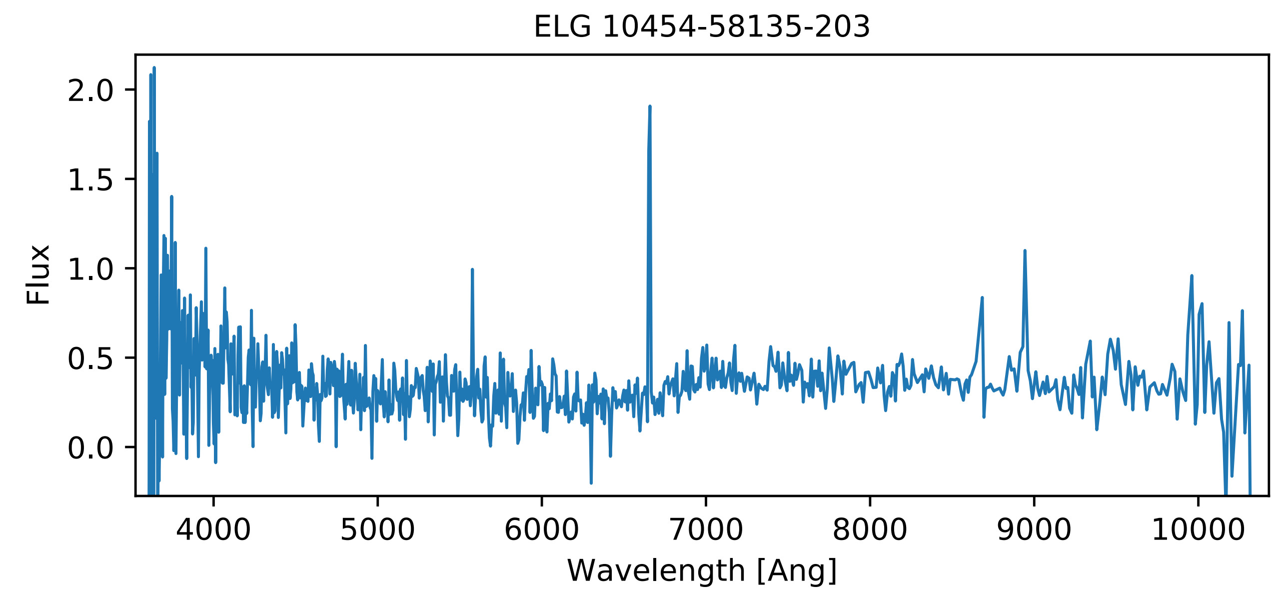
1-meter focal plane

eBOSS Spectra

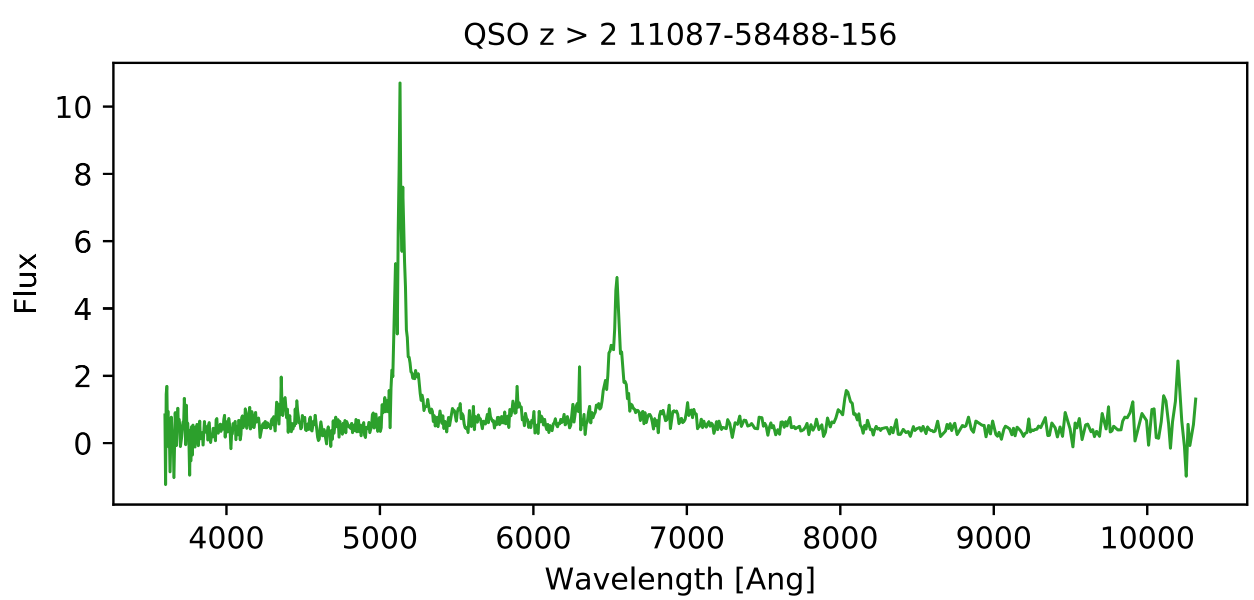
Luminous Red Galaxies (0.6 < z < 1.0)



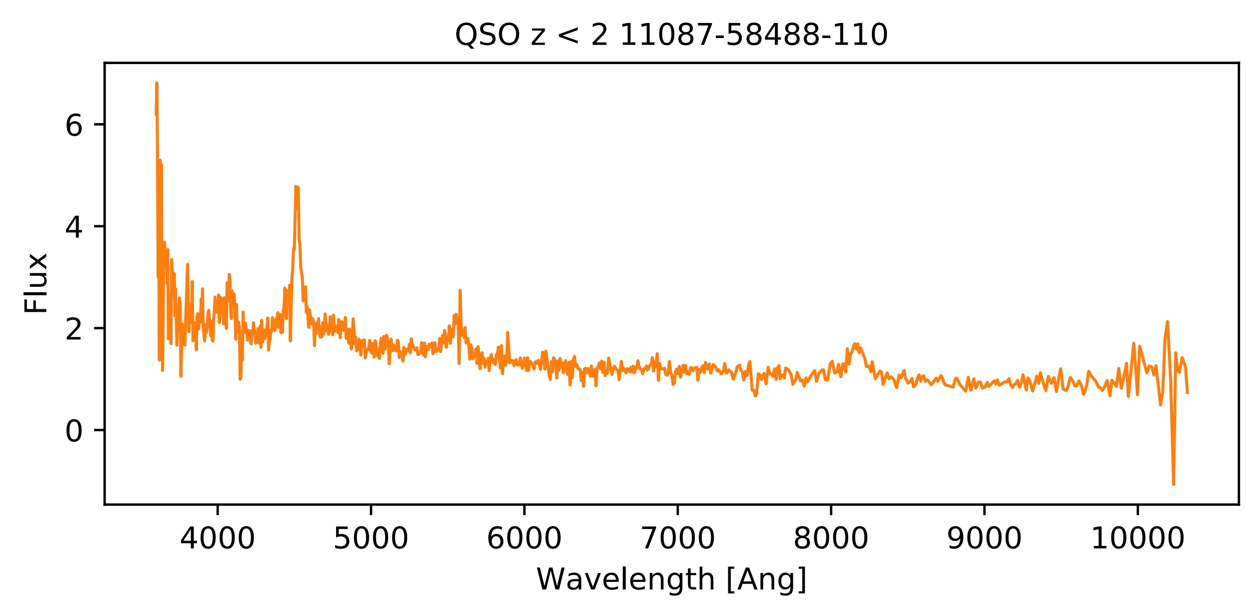
Emission Line Galaxies (0.7 < z < 1.1)



Quasars (z > 2) for Lyman-alpha forest



Quasars for clustering (0.8 < z < 2.2)



Redshifts obtained with PCA templates, neural networks
and some visual inspection (for QSOs)

Extracting cosmological overdensities

(Ross, **Bautista**, Tojeiro et al. 2020)

Galaxy overdensity: $$\delta_g(\overrightarrow{x}) = \frac{n_g(\overrightarrow{x})}{\bar{n}_g} - 1$$

Random catalog

Extracting cosmological overdensities

(Ross, **Bautista**, Tojeiro et al. 2020)

Galaxy overdensity: $$\delta_g(\overrightarrow{x}) = \frac{n_g(\overrightarrow{x})}{\bar{n}_g} - 1$$

Random catalog

Features or systematics to take into account:

Survey footprint	Observational completeness	Fake overdensities caused by photometry
"Collisions" of fibers	Reconstruction of linear density field for BAO	Spectra without confident redshift measurement

Extracting cosmological overdensities

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Random catalog

Features or systematics to take into account:

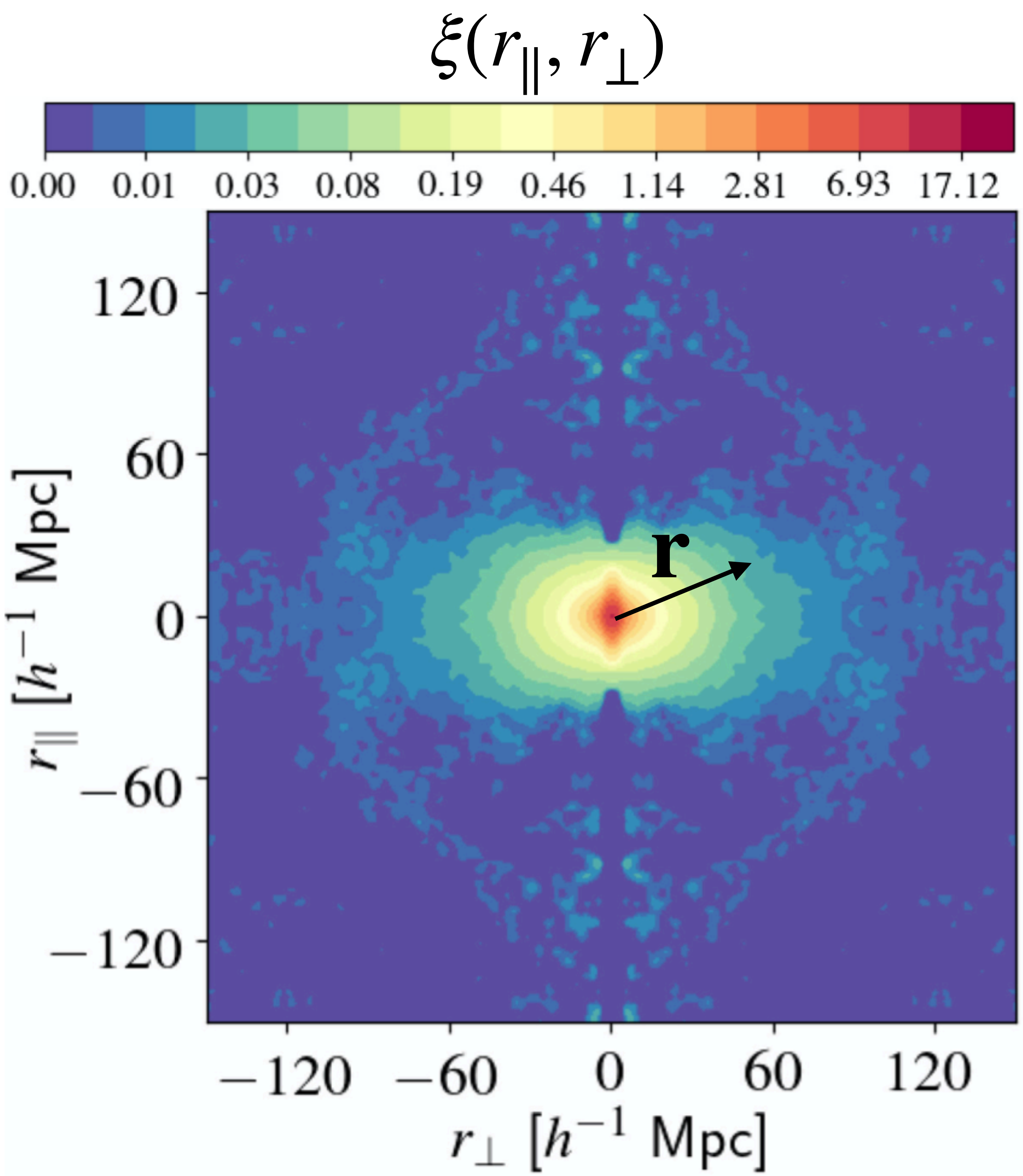
Survey footprint	Observational completeness	Fake overdensities caused by photometry
"Collisions" of fibers	Reconstruction of linear density field for BAO	Spectra without confident redshift measurement

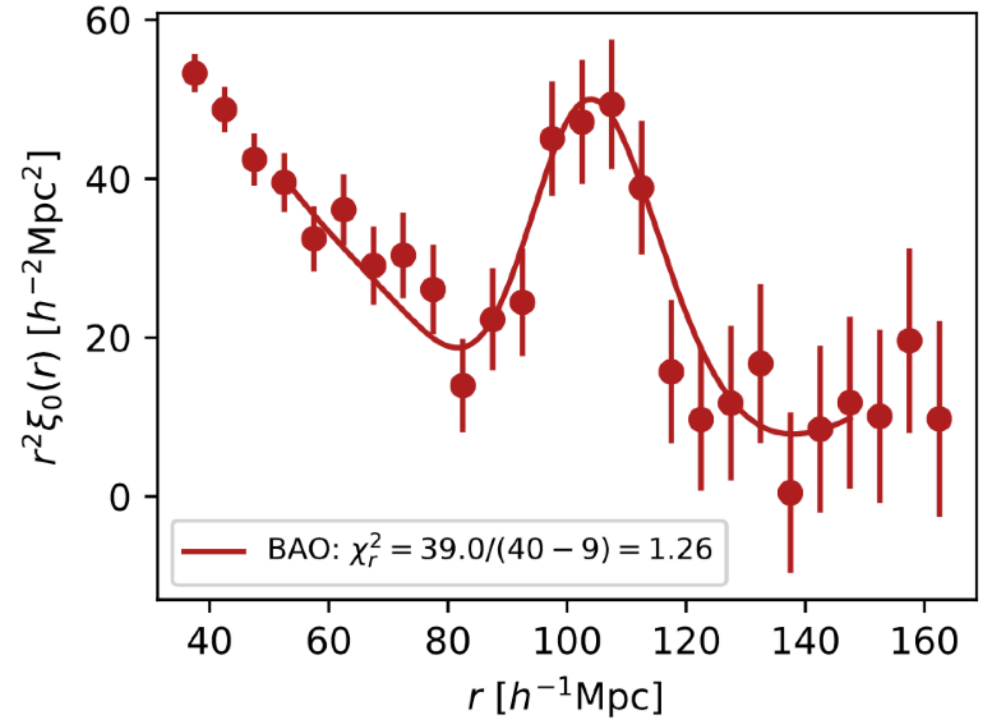
1000 simulated surveys used to test methods, covariance, systematic errors

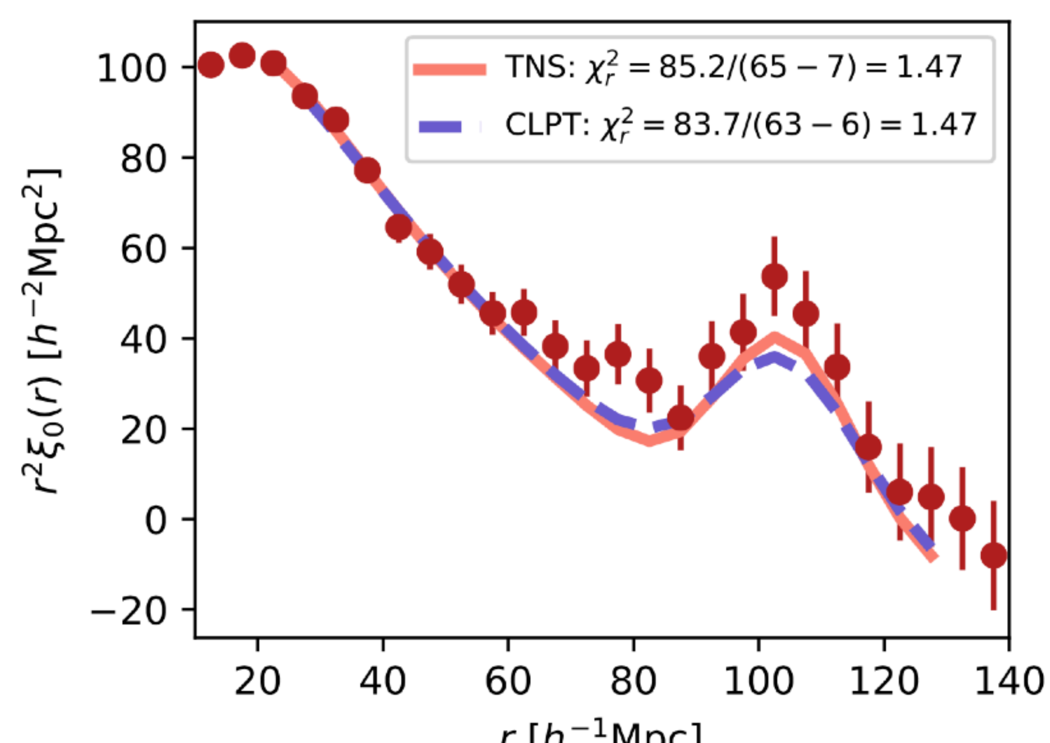
(Zhao, Chuang, **Bautista**, et al. 2020)

Correlation function $\xi(\mathbf{r})$ of galaxies

(**Bautista**, Paviot, Vargas-Magaña, de la Torre, et al. 2020)







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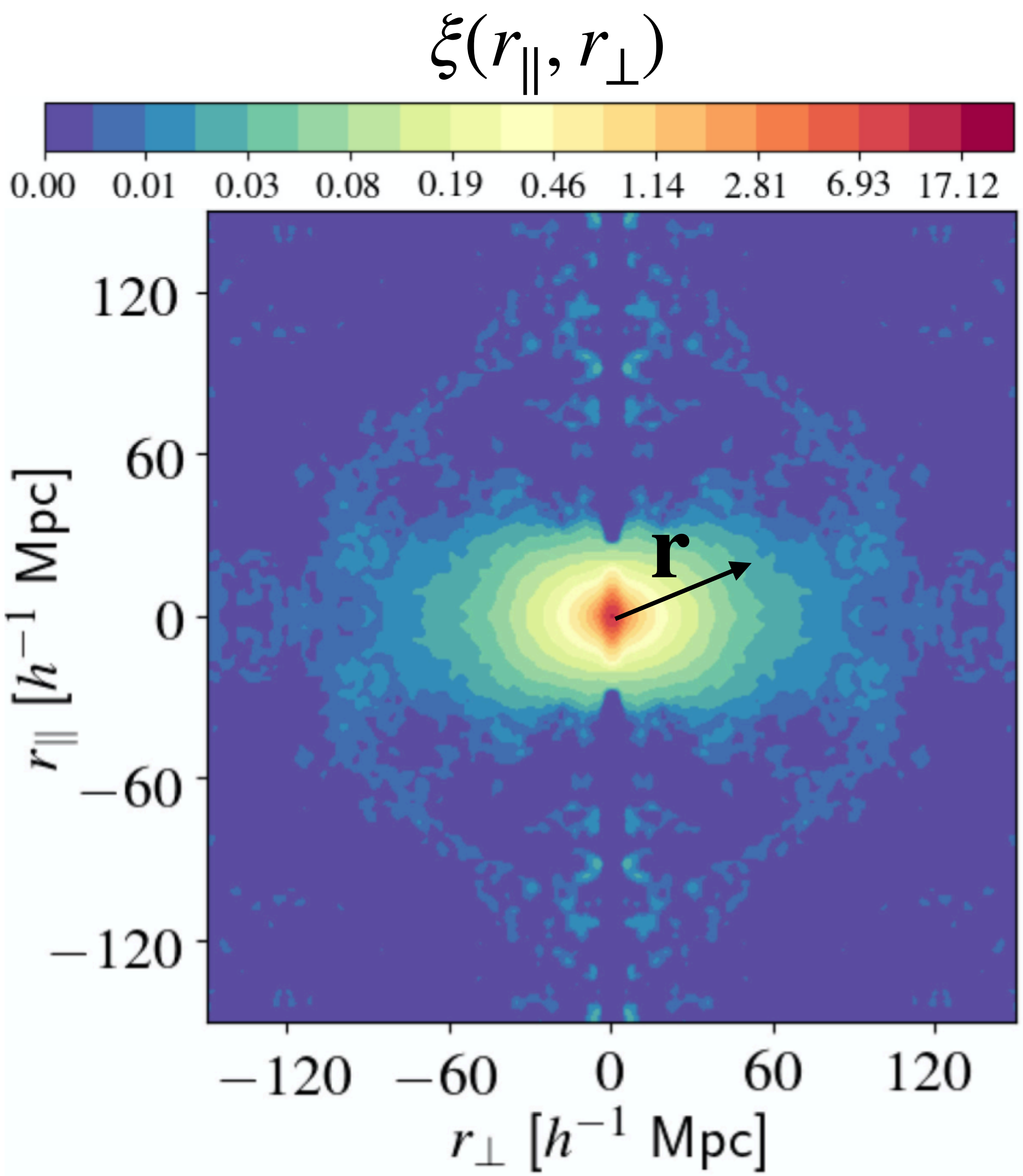
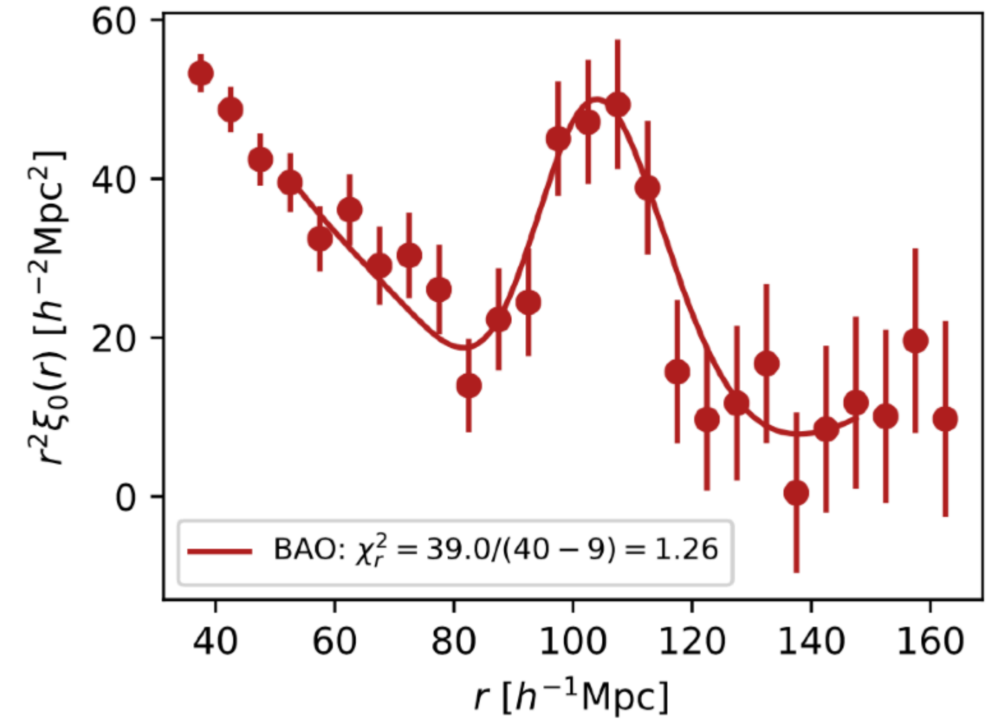
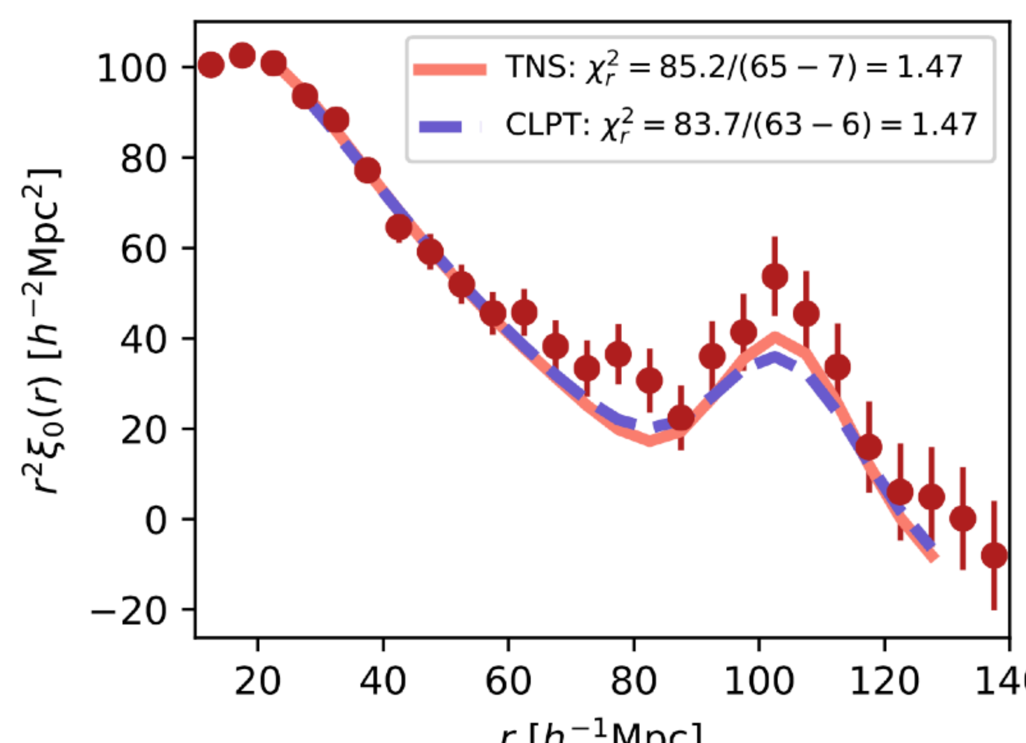


BAO - Expansion-rate

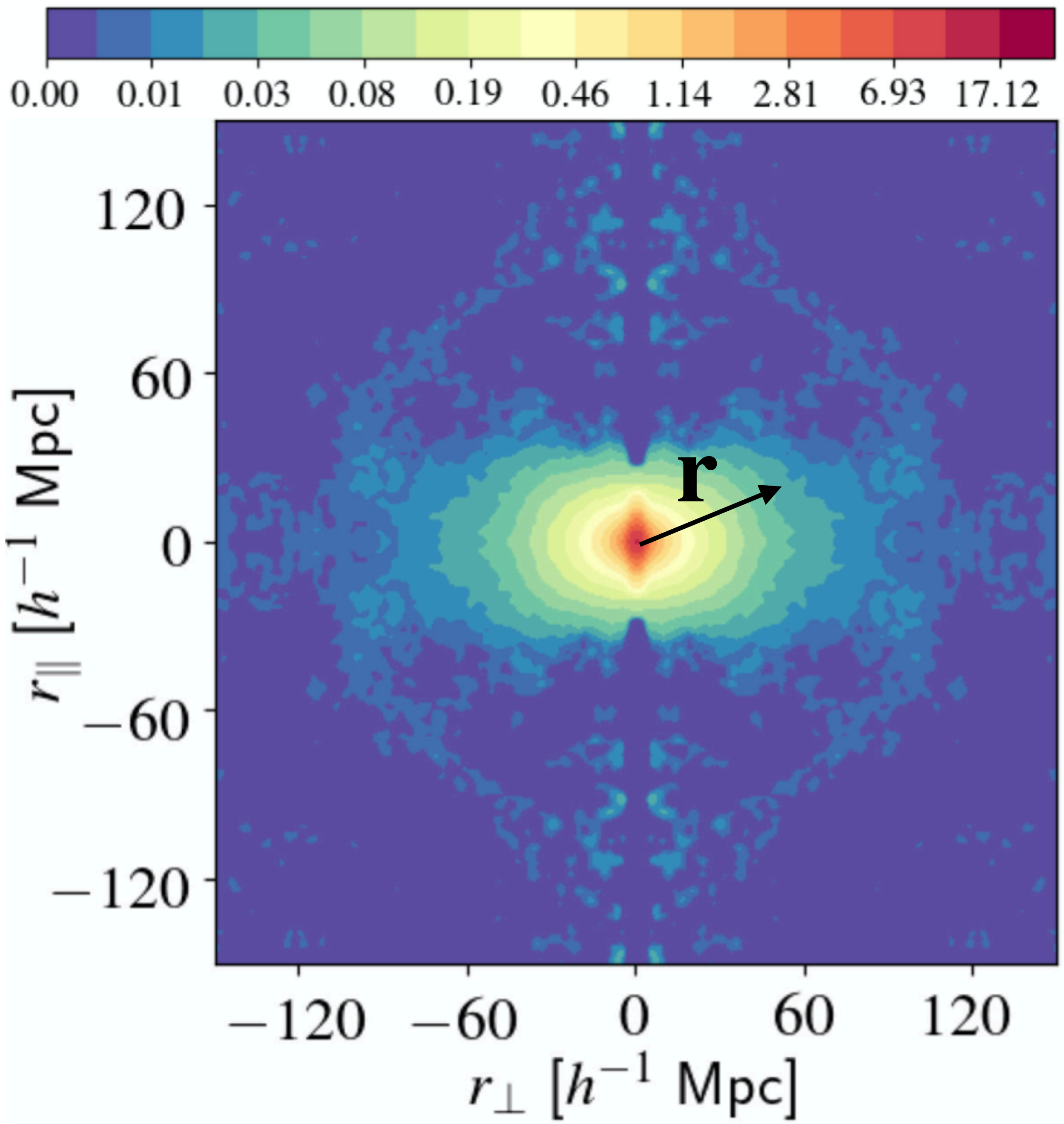




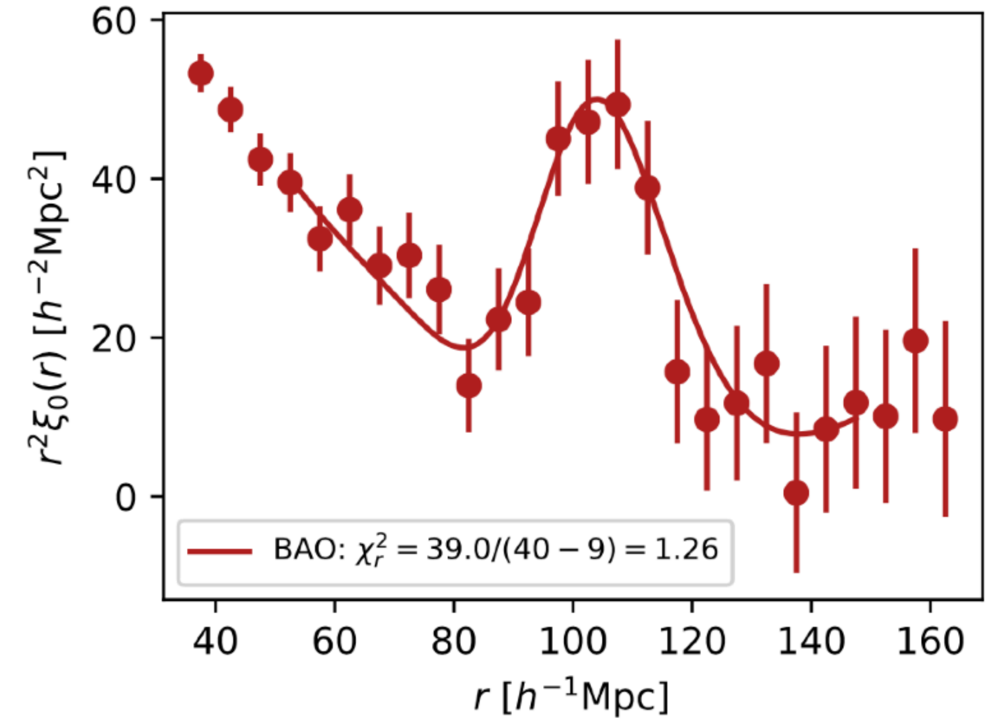
Correlation function $\xi(\mathbf{r})$ of galaxies

(**Bautista**, Paviot, Vargas-Magaña, de la Torre, et al. 2020)

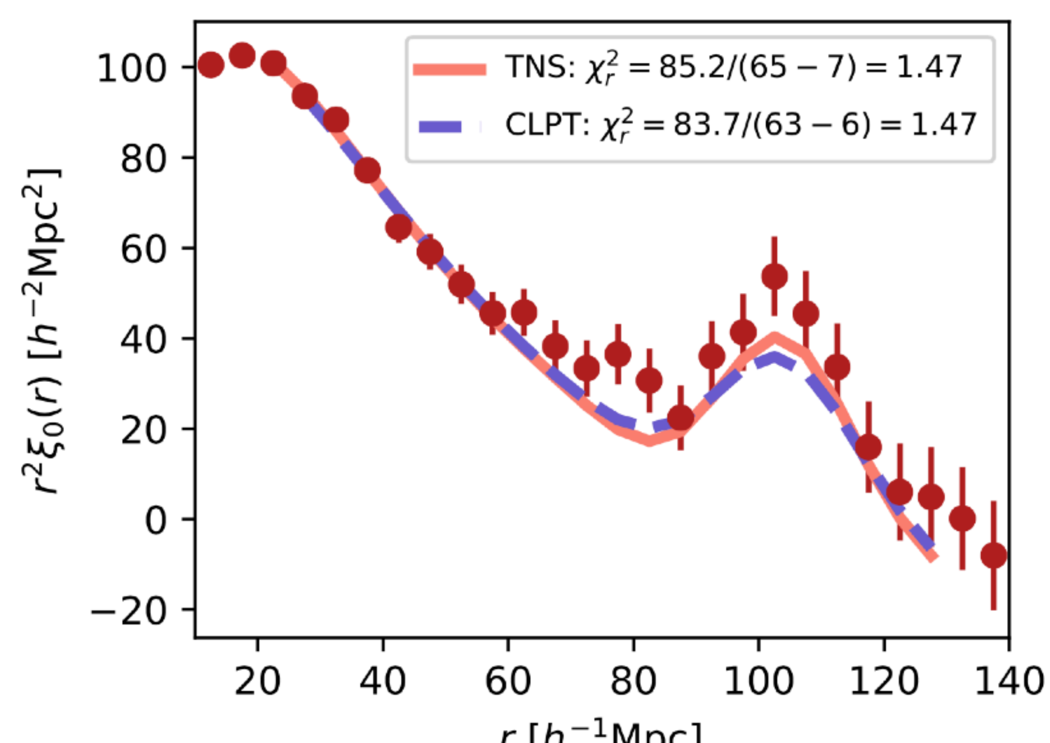
$\xi(r_{\parallel}, r_{\perp})$



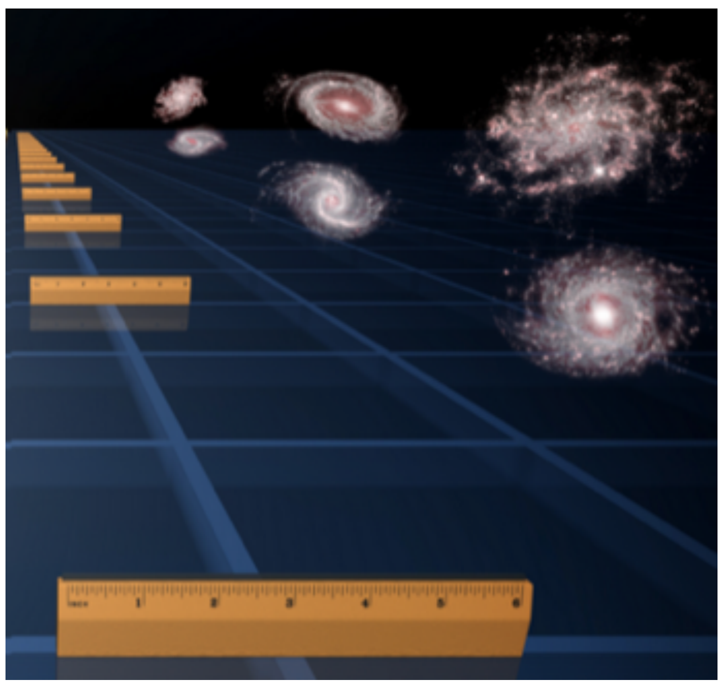
BAO - Expansion-rate

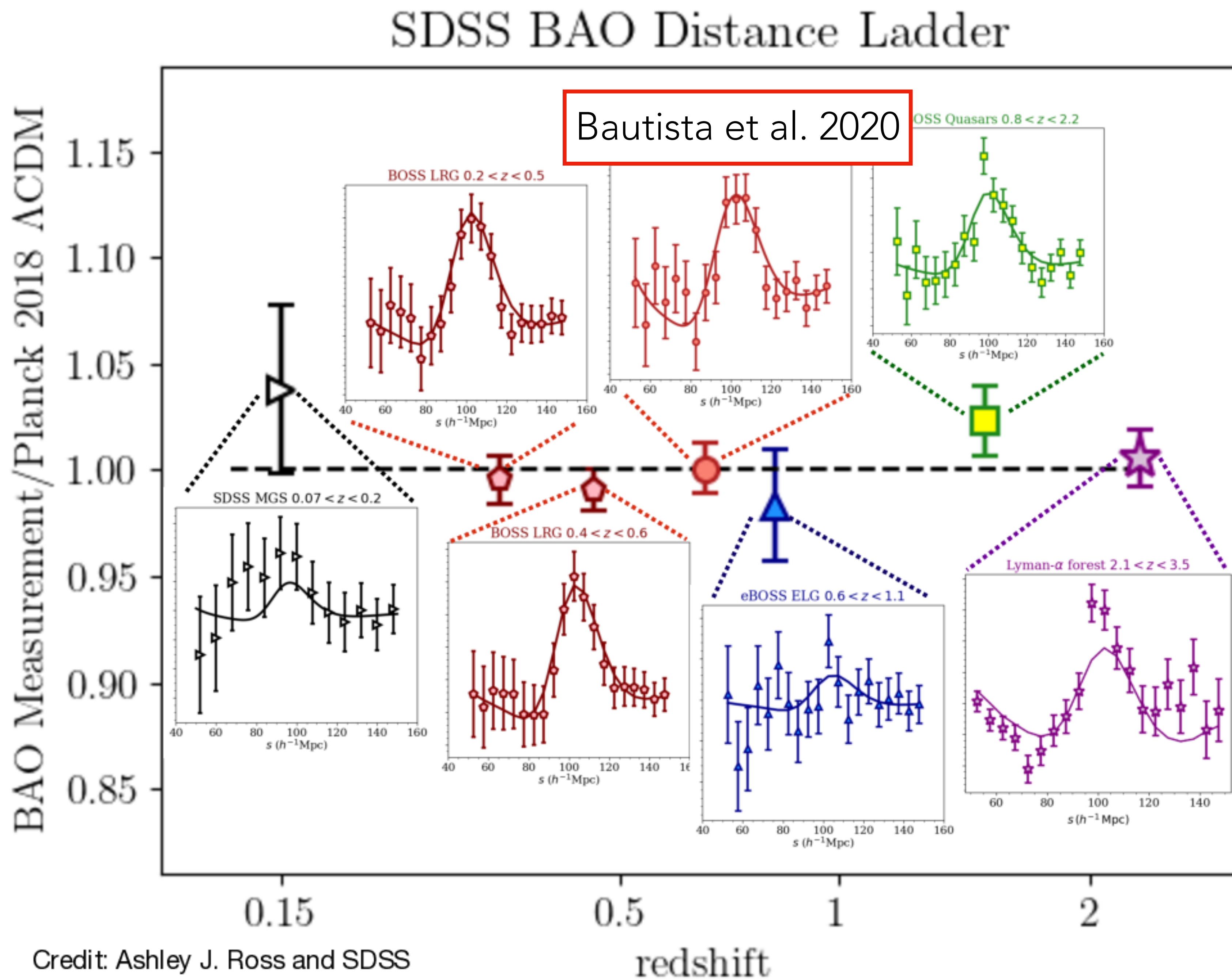


RSD - Growth-rate



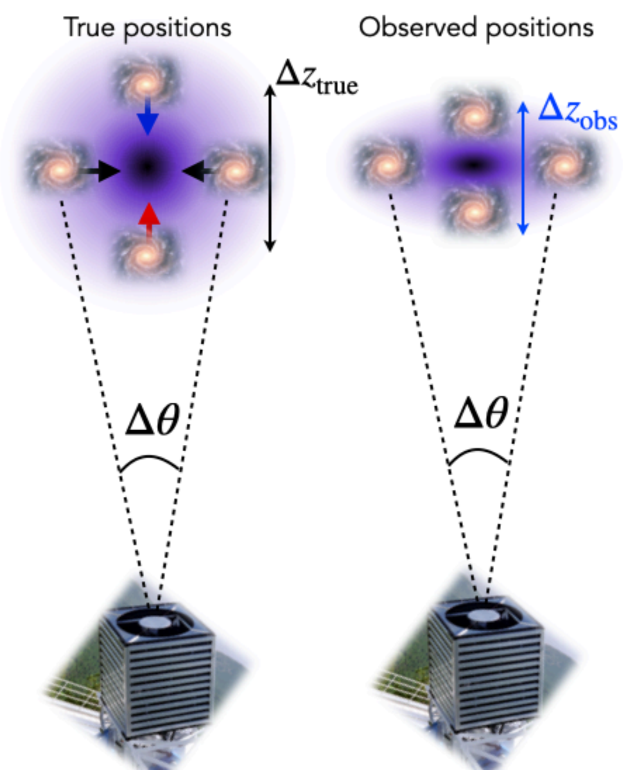
Expansion-rate
with Baryon Acoustic Oscillations (BAO)

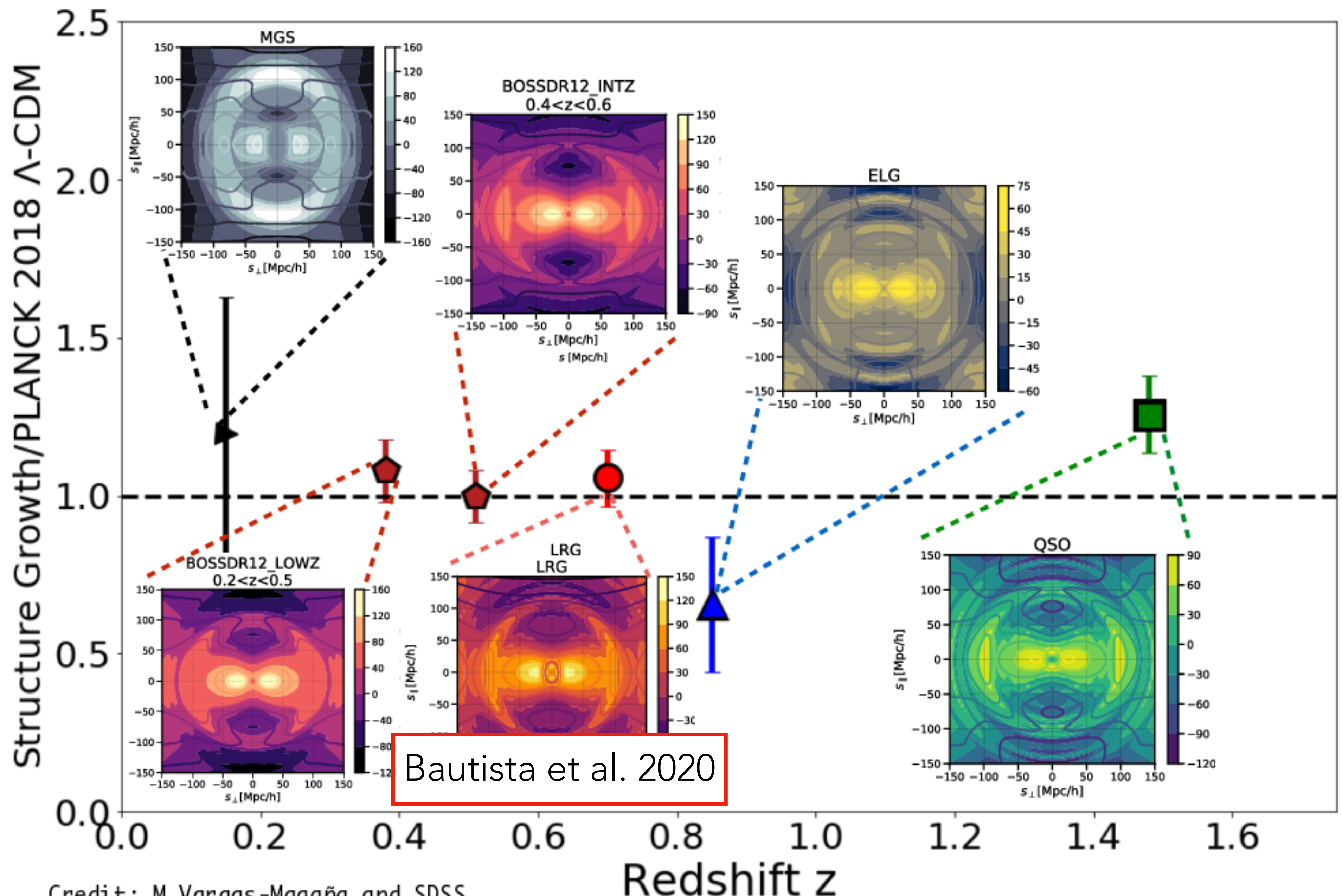




Credit: Ashley J. Ross and SDSS

Growth-rate with redshift-space distortions (RSD)





Credit: M.Vargas-Magaña and SDSS.

Also using cosmic-voids: Aubert, Cousinou, Escoffier, et al. 2020

Cosmological implications

$$\left[\frac{\mathrm{d}a}{\mathrm{d}t}(t)\right]^2 \sim \Omega_m[a(t)]^{-3} + \Omega_r[a(t)]^{-4} + \Omega_\Lambda$$

Expansion-rate

p^+, n, e^-, dark matter

30%

photons, neutrinos

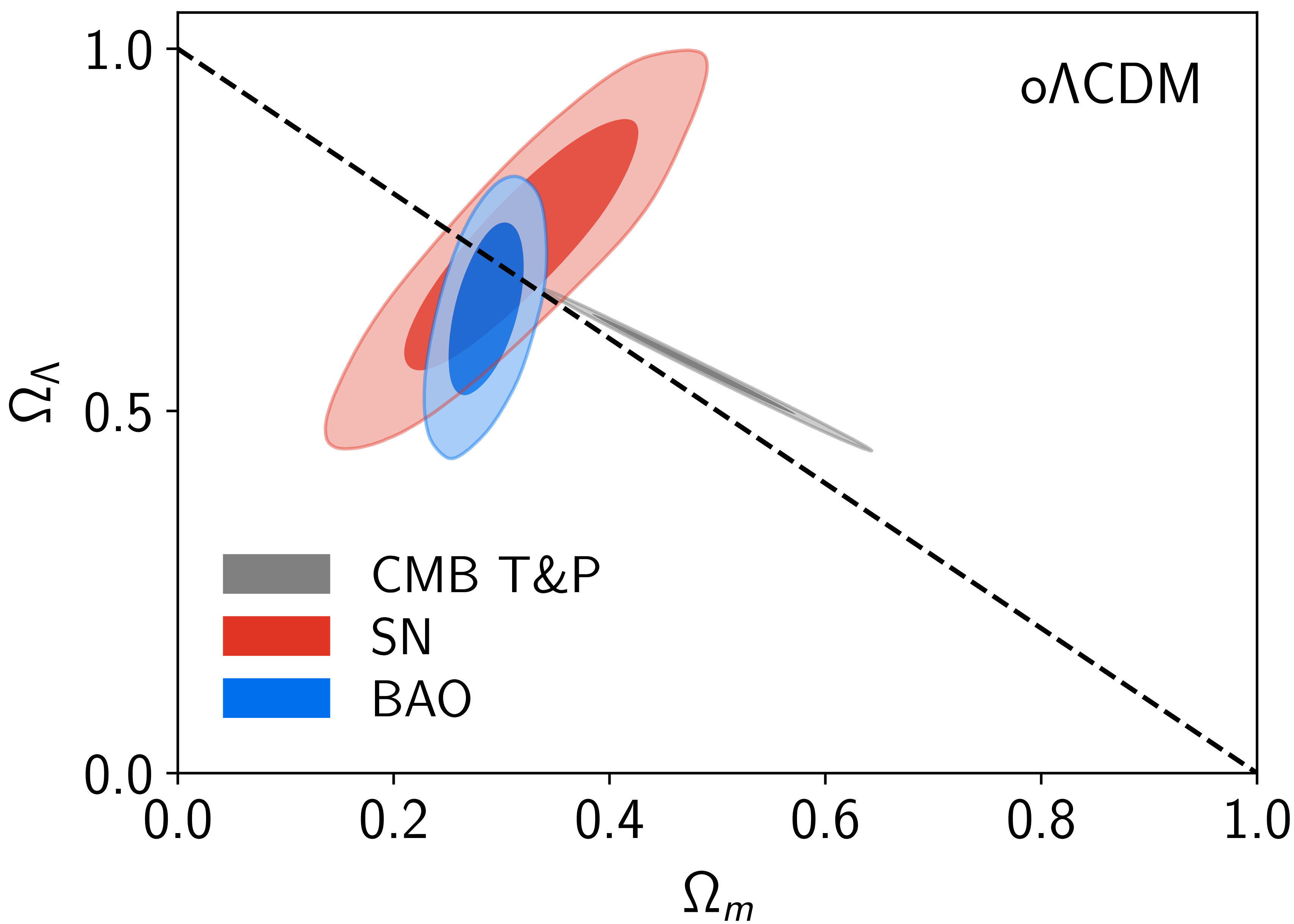
0.008%

dark energy (cosmological constant)

70%

(eBOSS Collaboration, 2020)

Cosmological constant



Cosmological implications

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

Expansion-rate

p^+, n, e^-, dark matter

30%

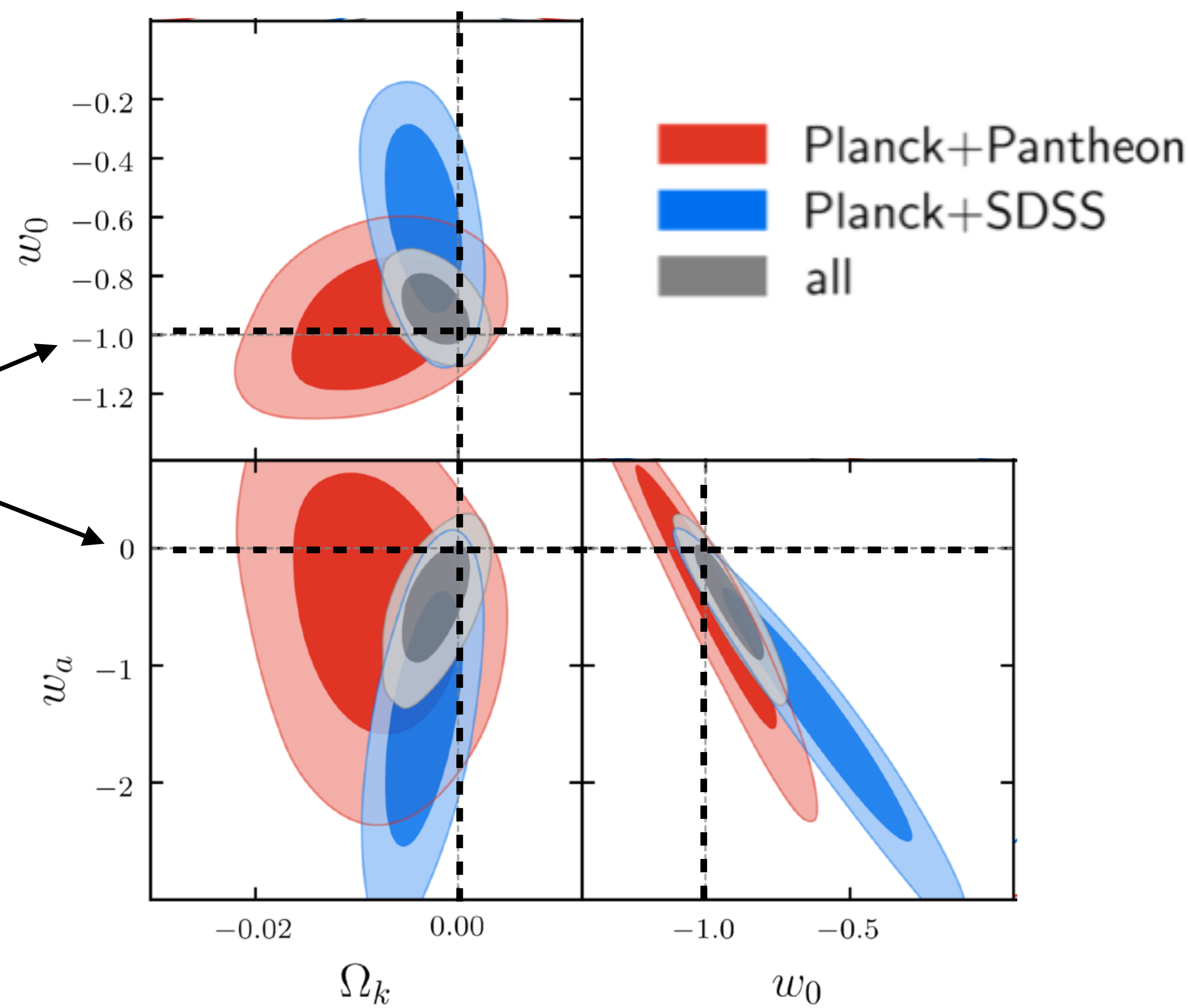
photons, neutrinos

0.008%

dark energy (quintessence, phantom force)

70%

Cosmological constant

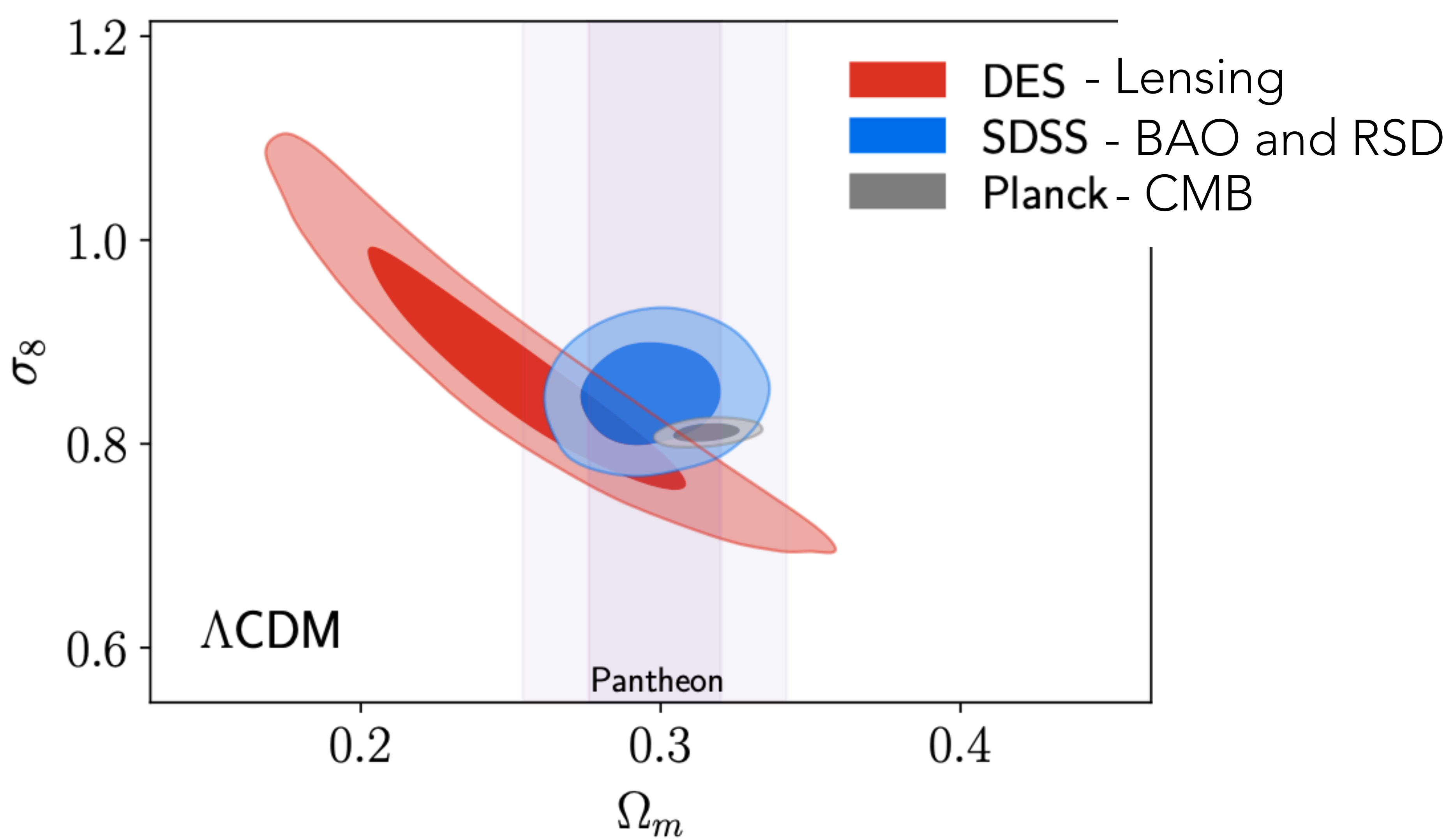


(eBOSS Collaboration, 2020)

Cosmological implications

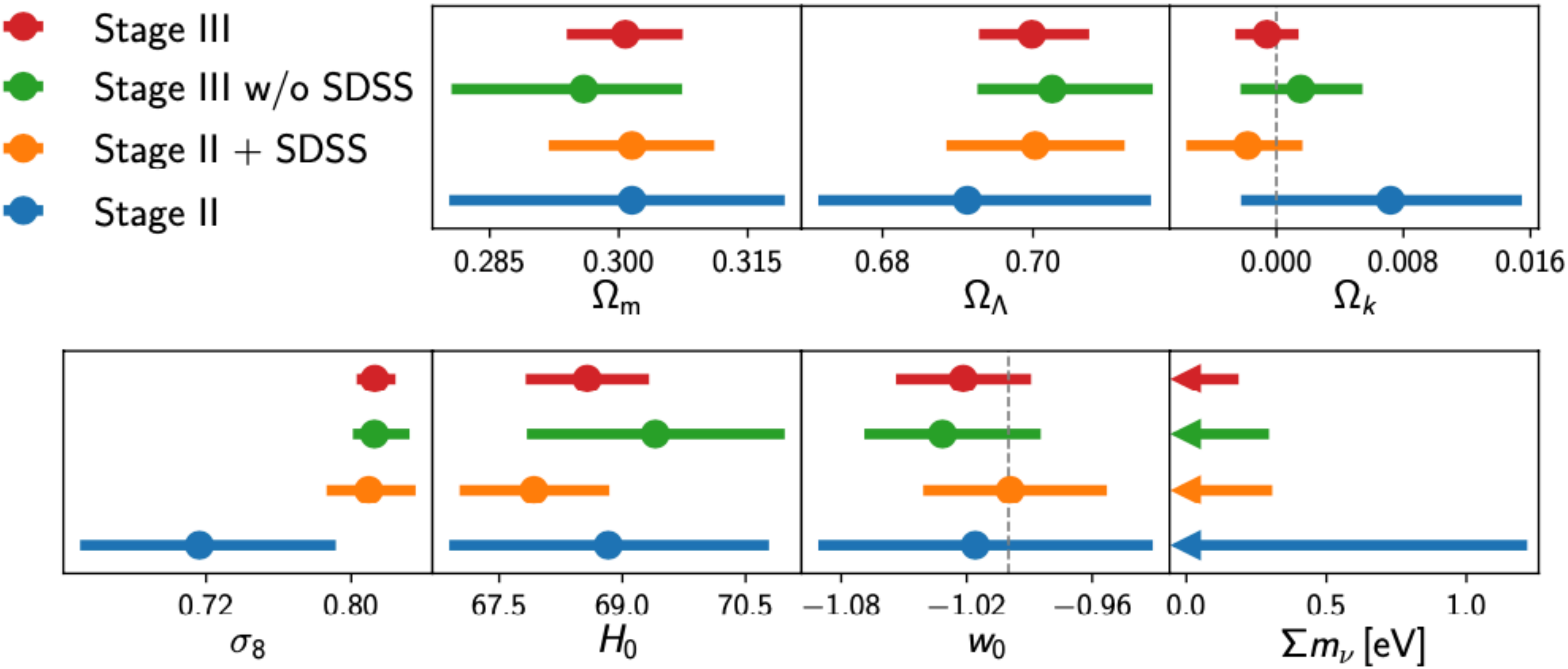
$$\ddot{\delta} + \boxed{\text{expansion, pressure}}\,\dot{\delta} - \boxed{\text{gravity}}\,\delta = 0$$

Variance of δ
(with 8 Mpc/h smoothing)



(eBOSS Collaboration, 2020)

Cosmological implications



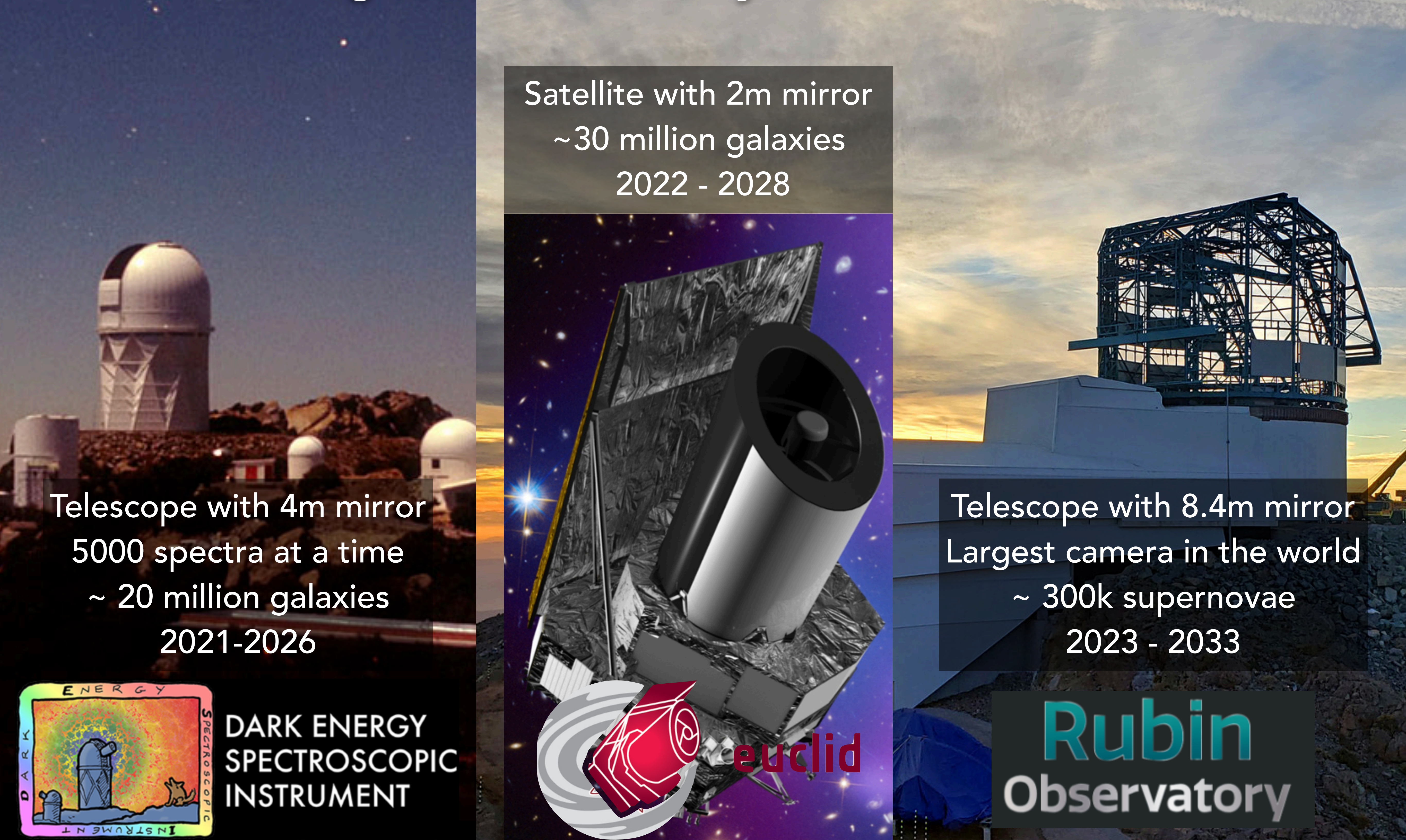
(eBOSS Collaboration, 2020)

Stage III: SDSS final, Planck CMB, Pantheon SN Ia, and DES 3x2pt
Stage II: SDSS DR7, WMAP CMB, JLA SN Ia

Future

and making high-resolution maps

Next-generation surveys of the structures



Telescope with 4m mirror
5000 spectra at a time
~ 20 million galaxies
2021-2026

Satellite with 2m mirror
~30 million galaxies
2022 - 2028

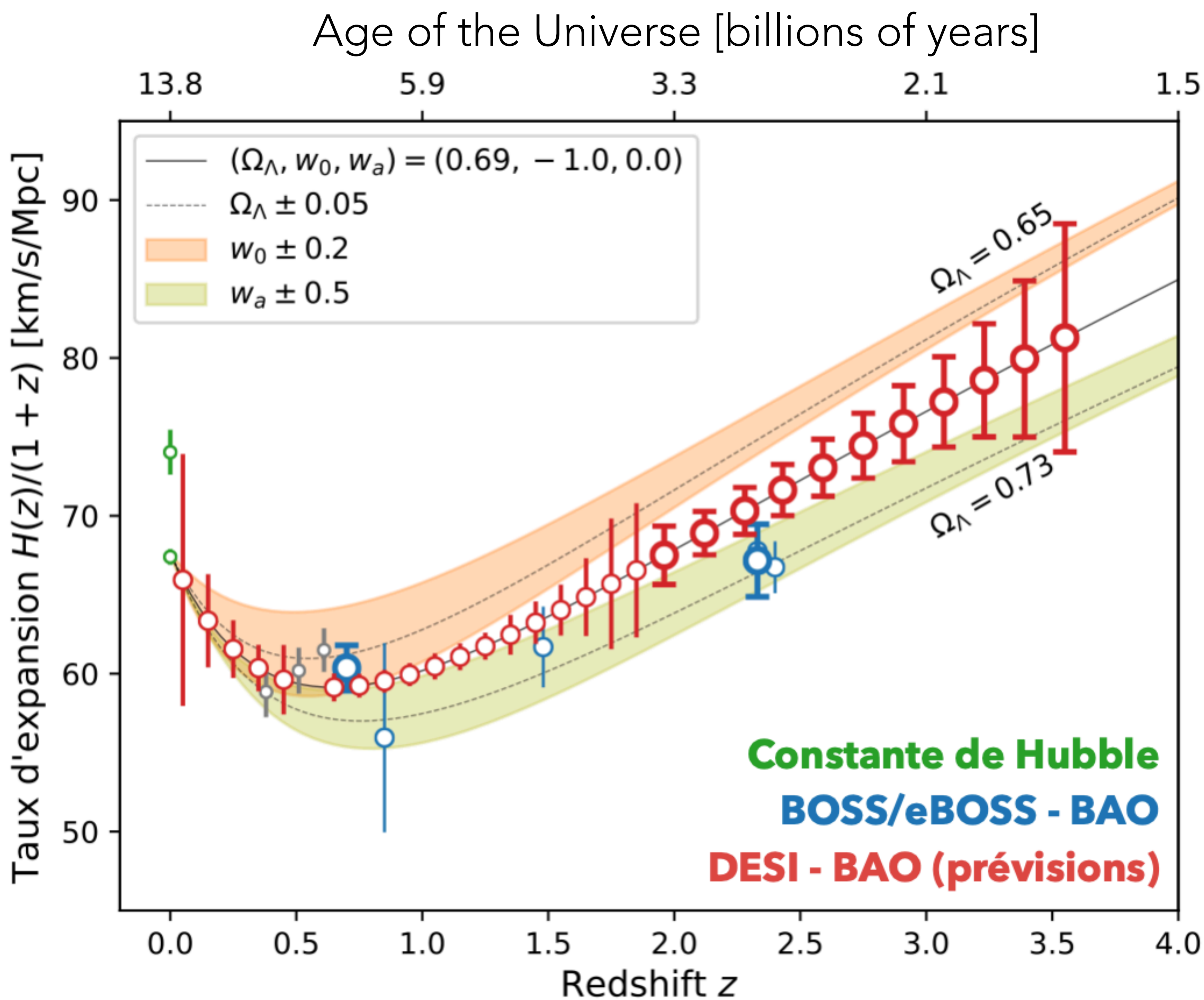
Telescope with 8.4m mirror
Largest camera in the world
~ 300k supernovae
2023 - 2033

Key participation of CPPM in these projects

Expansion-rate

Expansion rate

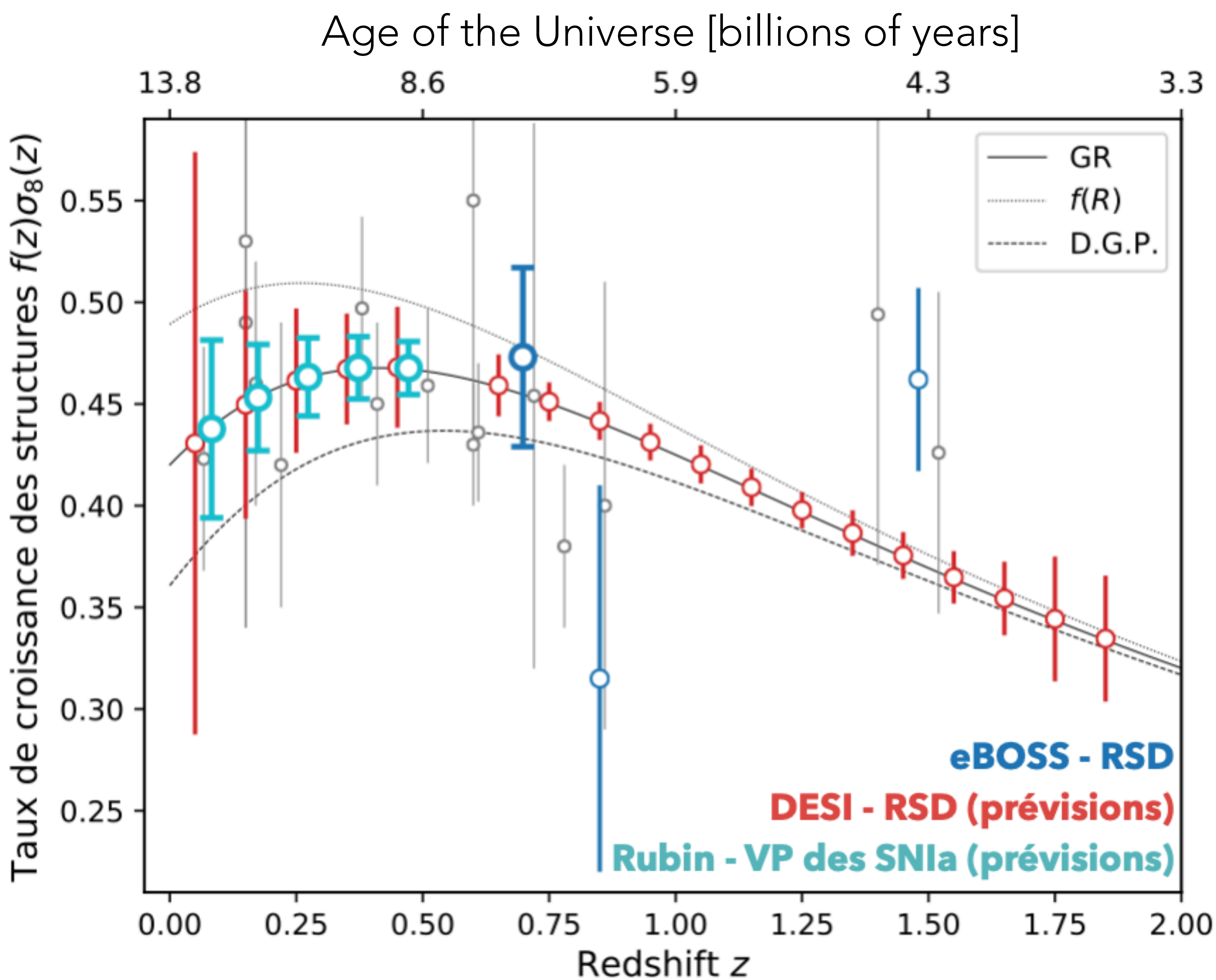
$$\frac{\mathrm{d}a}{\mathrm{d}t}(t)$$



Growth-rate

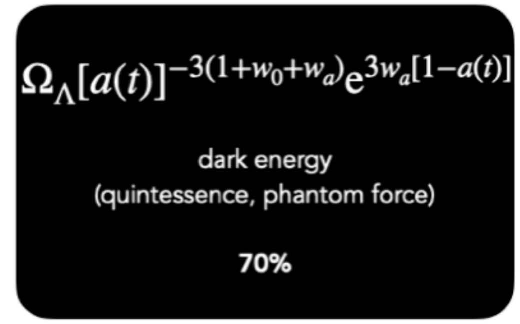
Growth-rate

$$\frac{\mathrm{d}\delta}{\mathrm{d}t}(t)$$



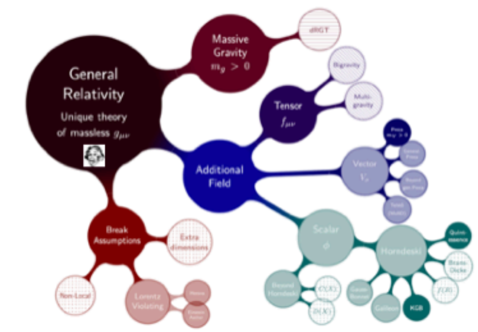
Conclusion

What is dark energy? We don't know yet



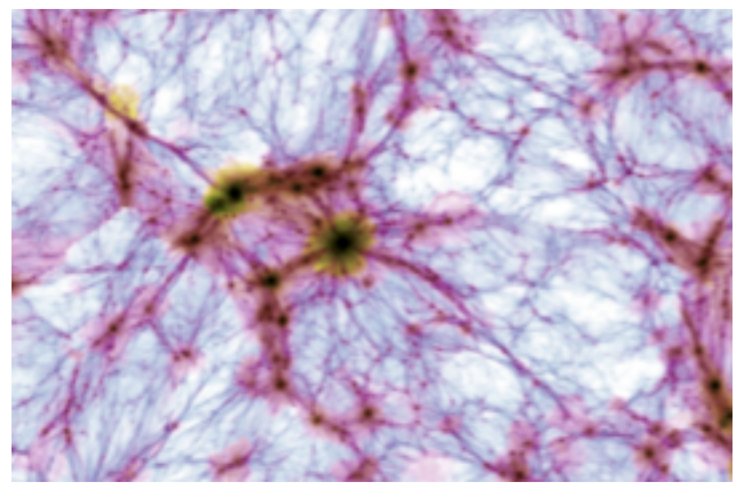
Empirical dark-energy?

or

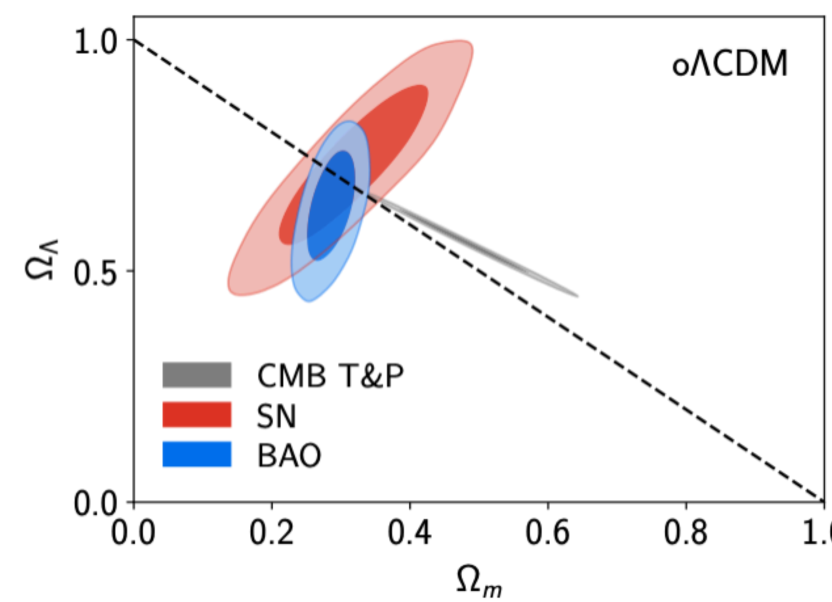


Alternative to GR?

Statistics of the structures of our Universe can inform us



SDSS produced the state-of-the-art map of the structures measuring expansion-rates and growth-rates



Future is promising with next-gen surveys