CPPM Seminar

Testing GR with cosmic density and velocity fields

First results from the DESI PV survey

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Aix Marseille Université

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Why test general relativity (GR)?

Why test general relativity (GR)?

GR is **compatible** with extremely high-precision measurements made:

- on Earth (clocks, GPS),
- in the Solar System (ephemerides),
- on stars (gravitational redshift),
- on binary and triple systems of pulsars (decay of period due to GW),
- in mergers of black holes and neutron stars (GW detections),
- in direct imaging of black holes (Event Horizon Telescope).

but.. all those tests happen in **strong** field regime

3 levels of **weird** in the Universe

1st level: the Universe is expanding… (1930)

2nd level: the Universe expansion is accelerating…
… due to a cosmological **constant** (2000)

3rd level: the Universe expansion is accelerating…
… due to an **evolving** kind of dark energy (2024)

What is **dark energy**?

or… is there a **problem with GR** on cosmic weak-field regime?

Plan

The expansion: modelling and observing it

Growth of structures : modelling and observing it

Peculiar velocity measurements and DESI first results

Near future with ZTF and LSST

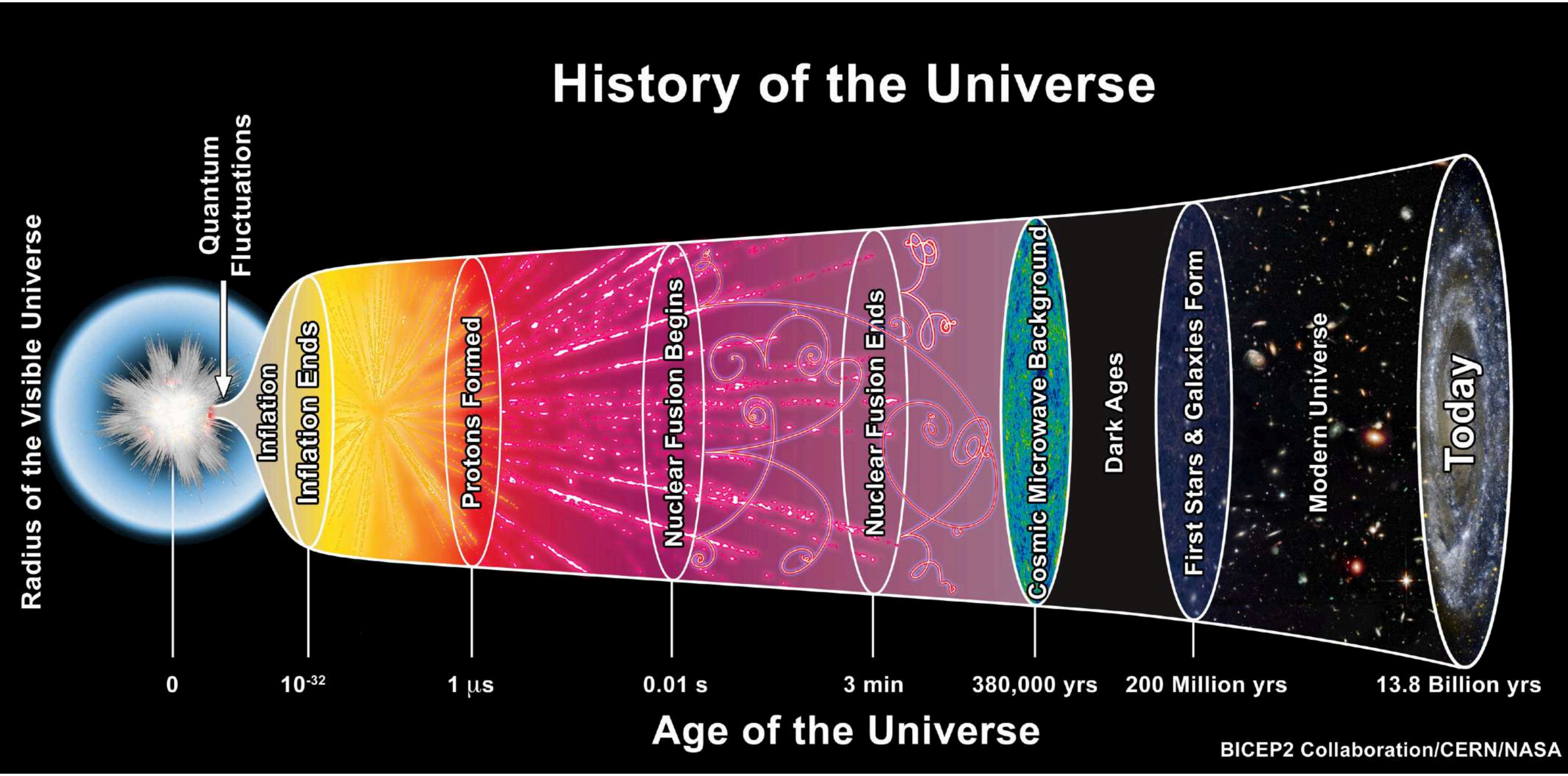
Plan

The expansion: modelling and observing it

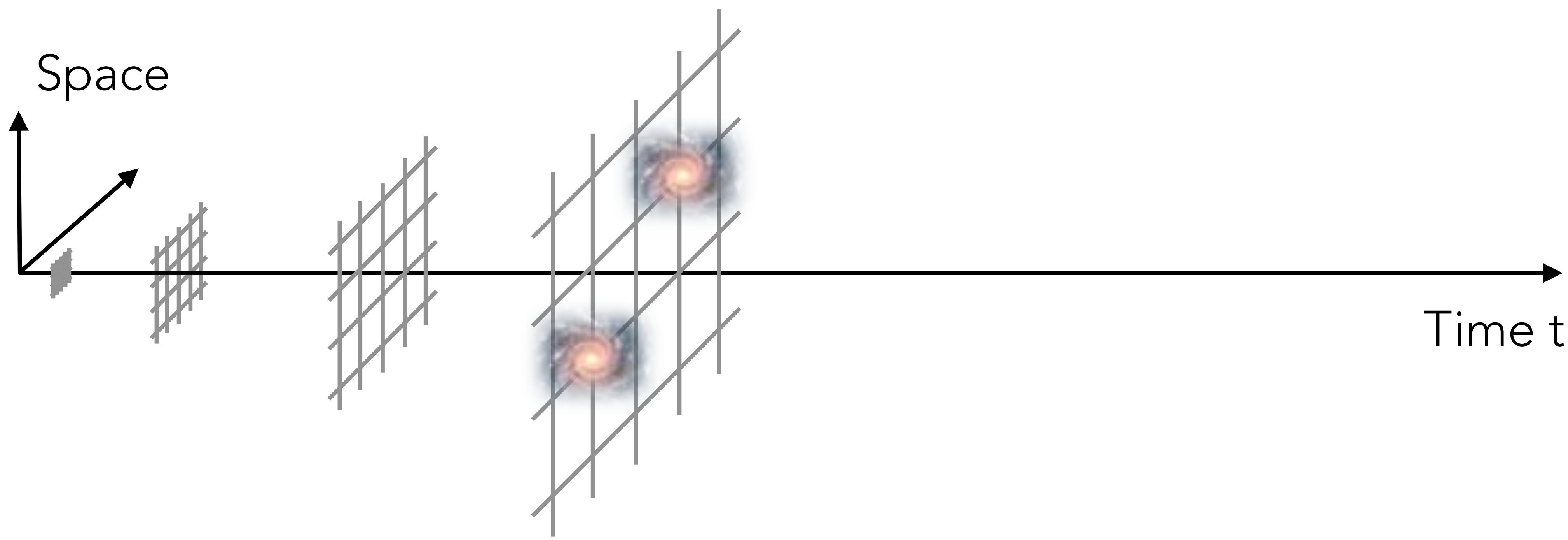
Growth of structures : modelling and observing it

Peculiar velocity measurements and DESI first results

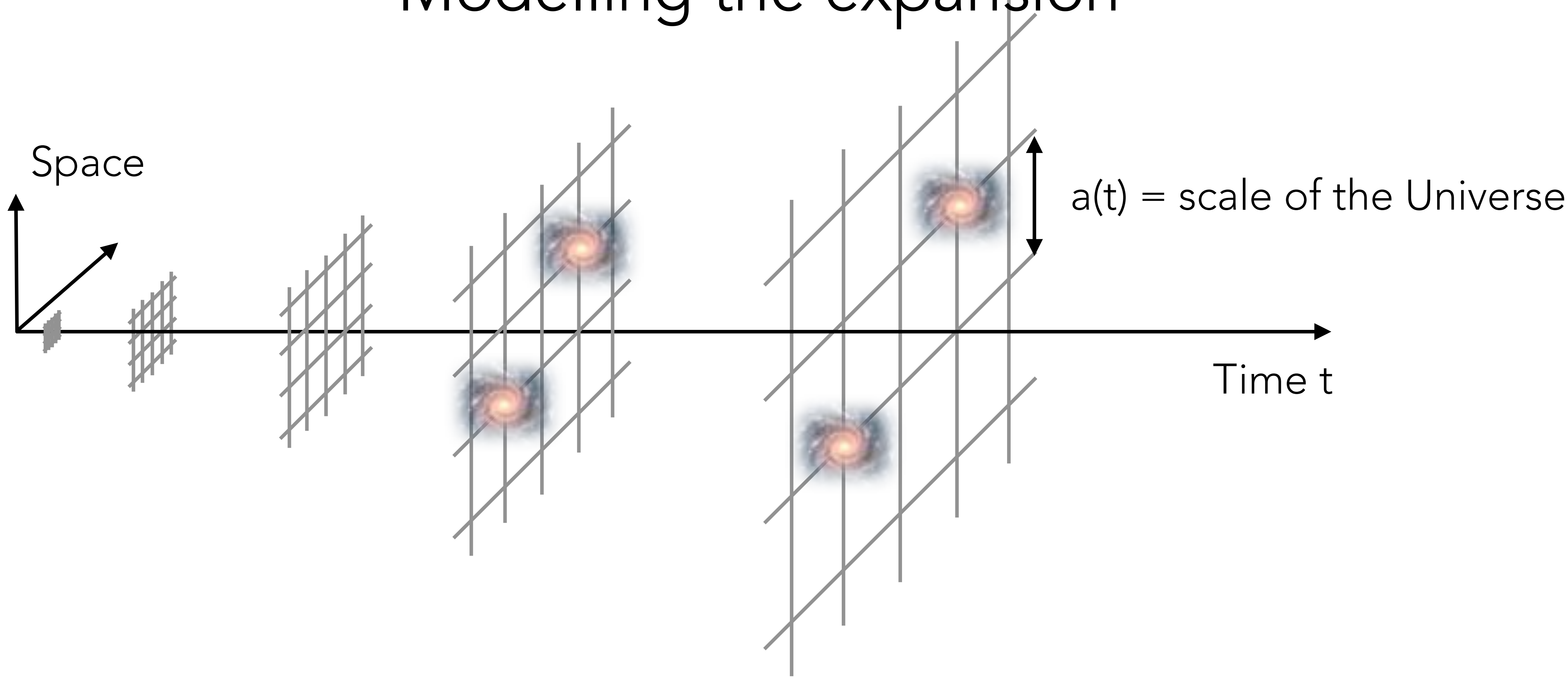
Near future with ZTF and LSST


History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^{-32}
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA

Modelling the expansion



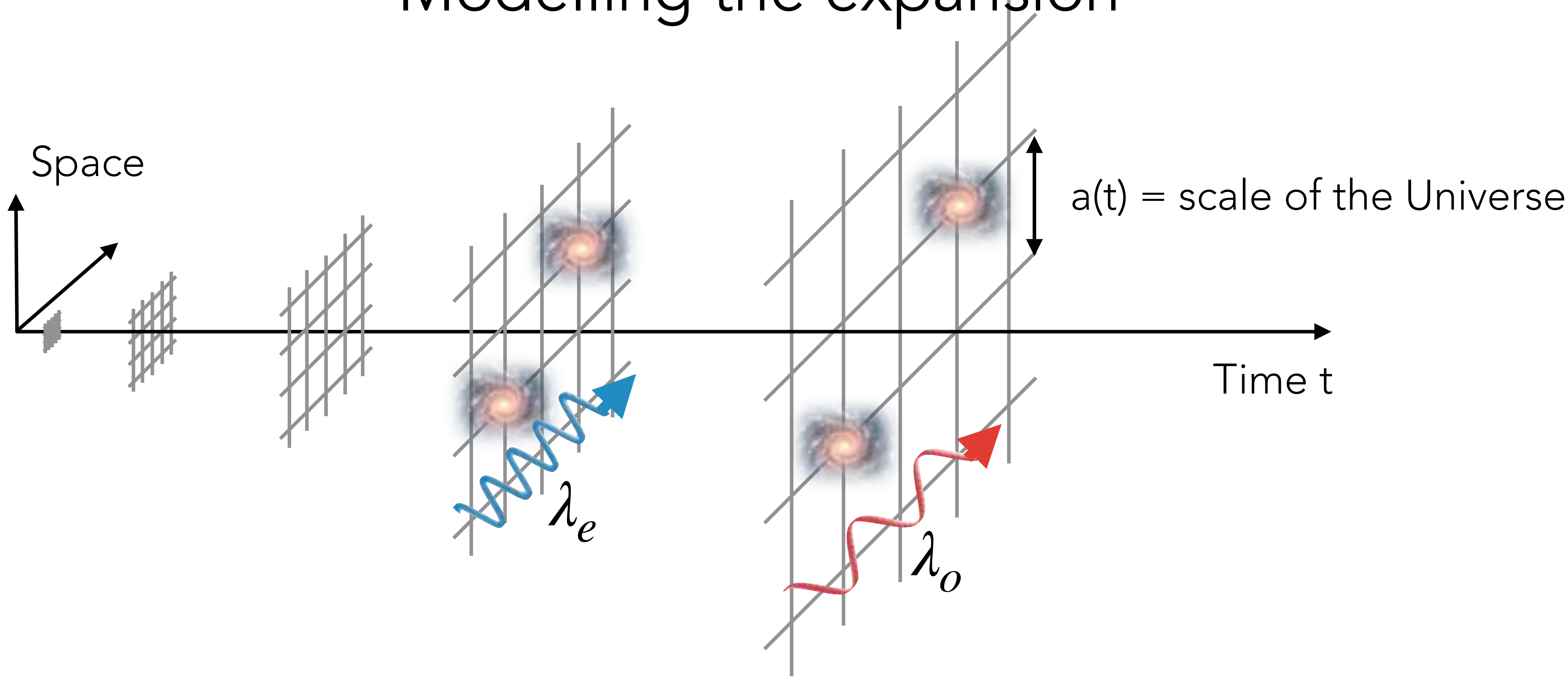
Modelling the expansion



Hubble expansion-rate: $H(t) \equiv \frac{1}{a(t)} \frac{\mathrm{d}a}{\mathrm{d}t}(t)$

Hubble constant: $H_0 \equiv H(t = \text{today})$

Modelling the expansion



Redshift of photons:

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

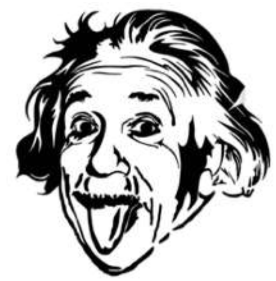
Big Bang

Today

$a \to 0$ Scale factor a a = 1

$z \to \infty$ Redshift z $z = 0$

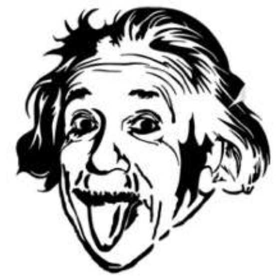
Modelling the expansion



Space-time properties = Energy content of the Universe

+ isotropic and homogeneous Universe

Modelling the expansion



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

+ isotropic and homogeneous Universe

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

Expansion-rate

Modelling the expansion

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

+ isotropic and homogeneous Universe

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

Expansion-rate

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

30%

Modelling the expansion

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

+ isotropic and homogeneous Universe

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

Expansion-rate

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

30%

photons,
neutrinos

0.008%

Modelling the expansion

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

+ isotropic and homogeneous Universe

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

Expansion-rate

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

30%

photons, neutrinos

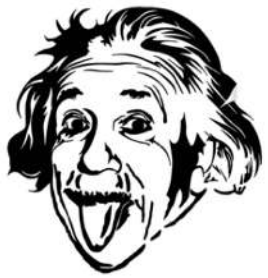
0.008%

dark energy (cosmological constant)

70%

The only one causing **acceleration** of the expansion!

Modelling the expansion



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

+ isotropic and homogeneous Universe

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

Expansion-rate

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

30%

photons,
neutrinos

0.008%

dark energy
(quintessence, phantom force)

70%

The only one causing **acceleration** of the expansion!

Modelling the expansion

Space-time properties = Energy content of the Universe

+ isotropic and homogeneous Universe

No fundamental origin for Λ !

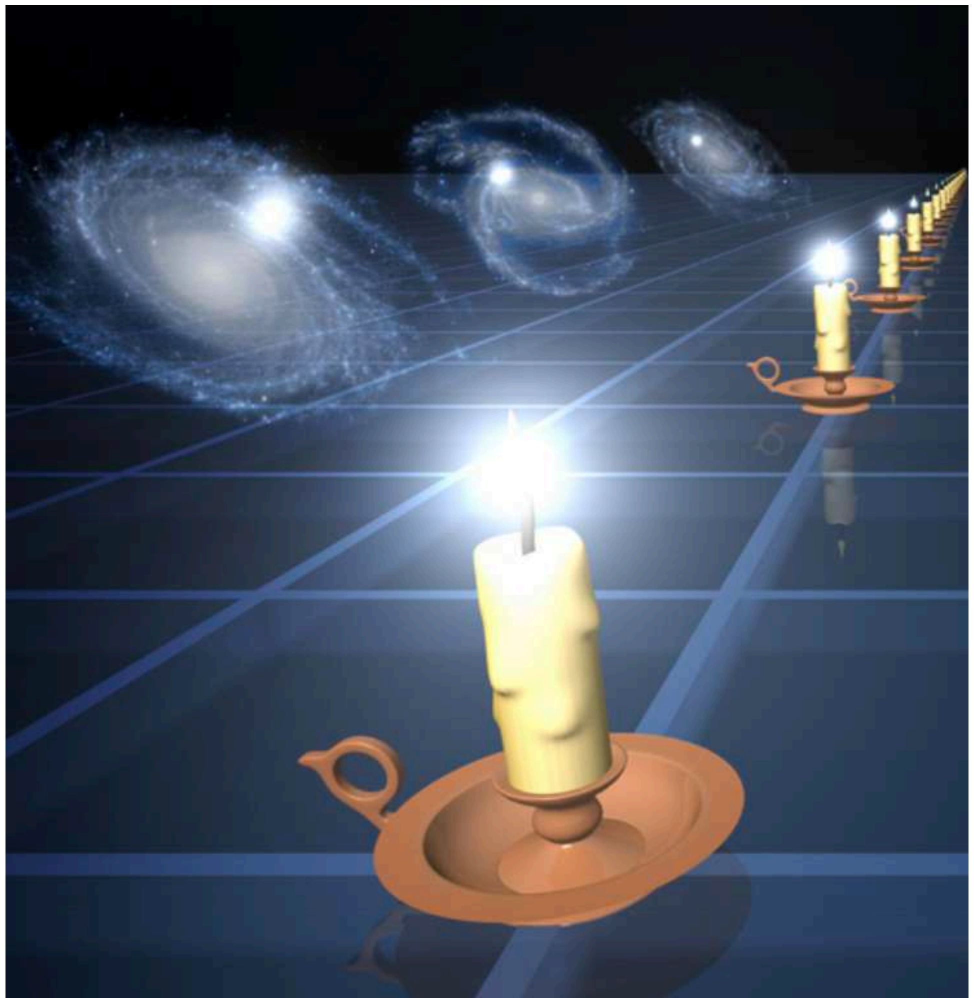
$$\Omega_\Lambda [a(t)]^{-3(1+w_0+w_a)} \mathrm{e}^{-3w_a[1-a(t)]}$$

dark energy
(quintessence, phantom force)

70%

The only one causing **acceleration** of the expansion!

Observing the expansion

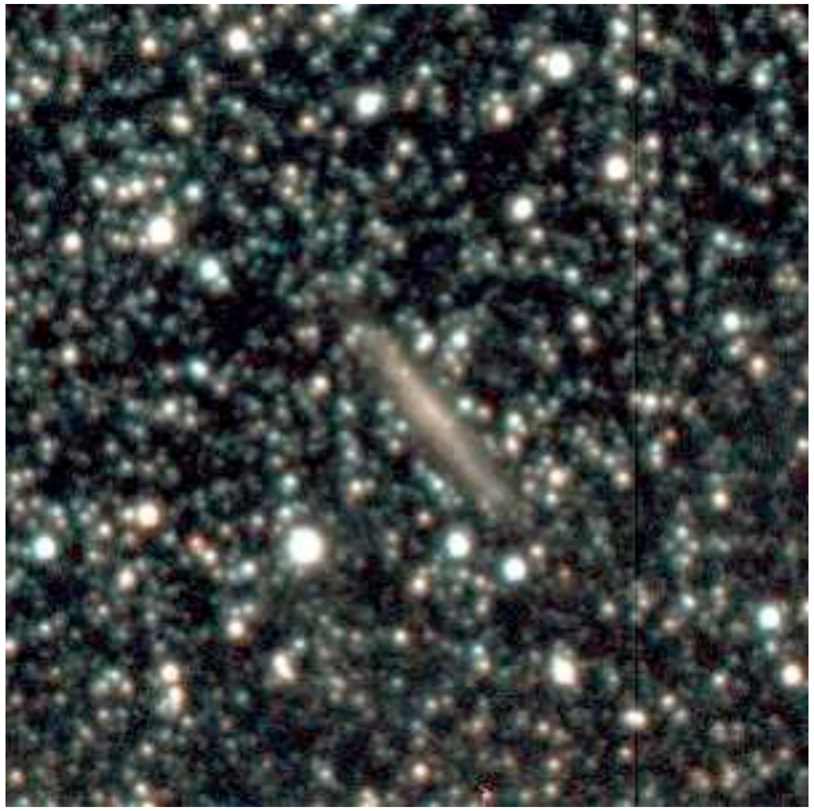


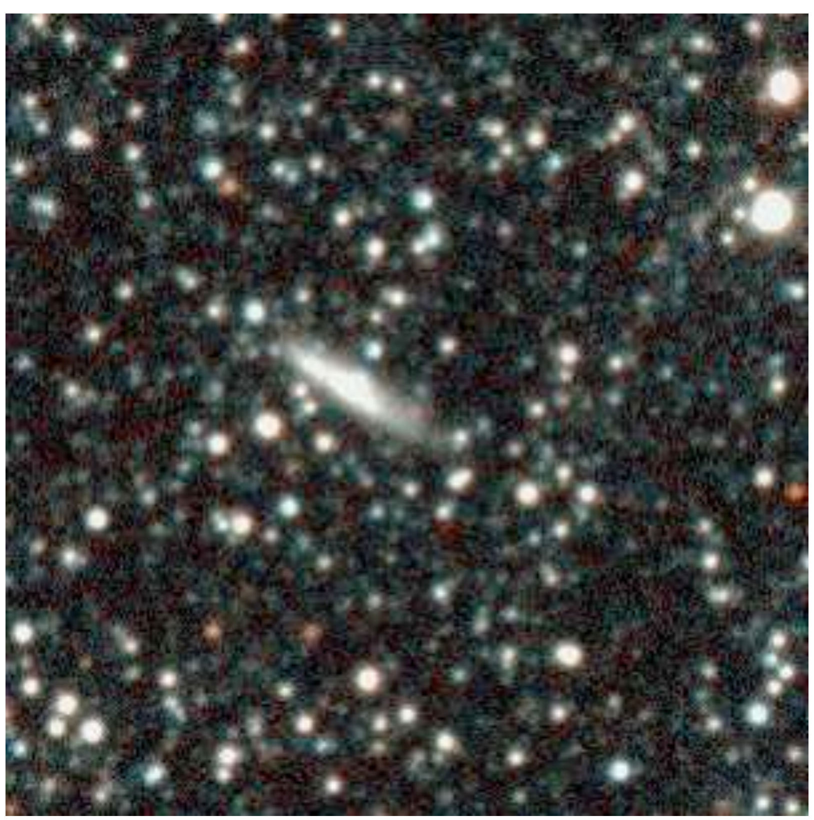
Type-Ia Supernovae (SNIa)
as standard candles

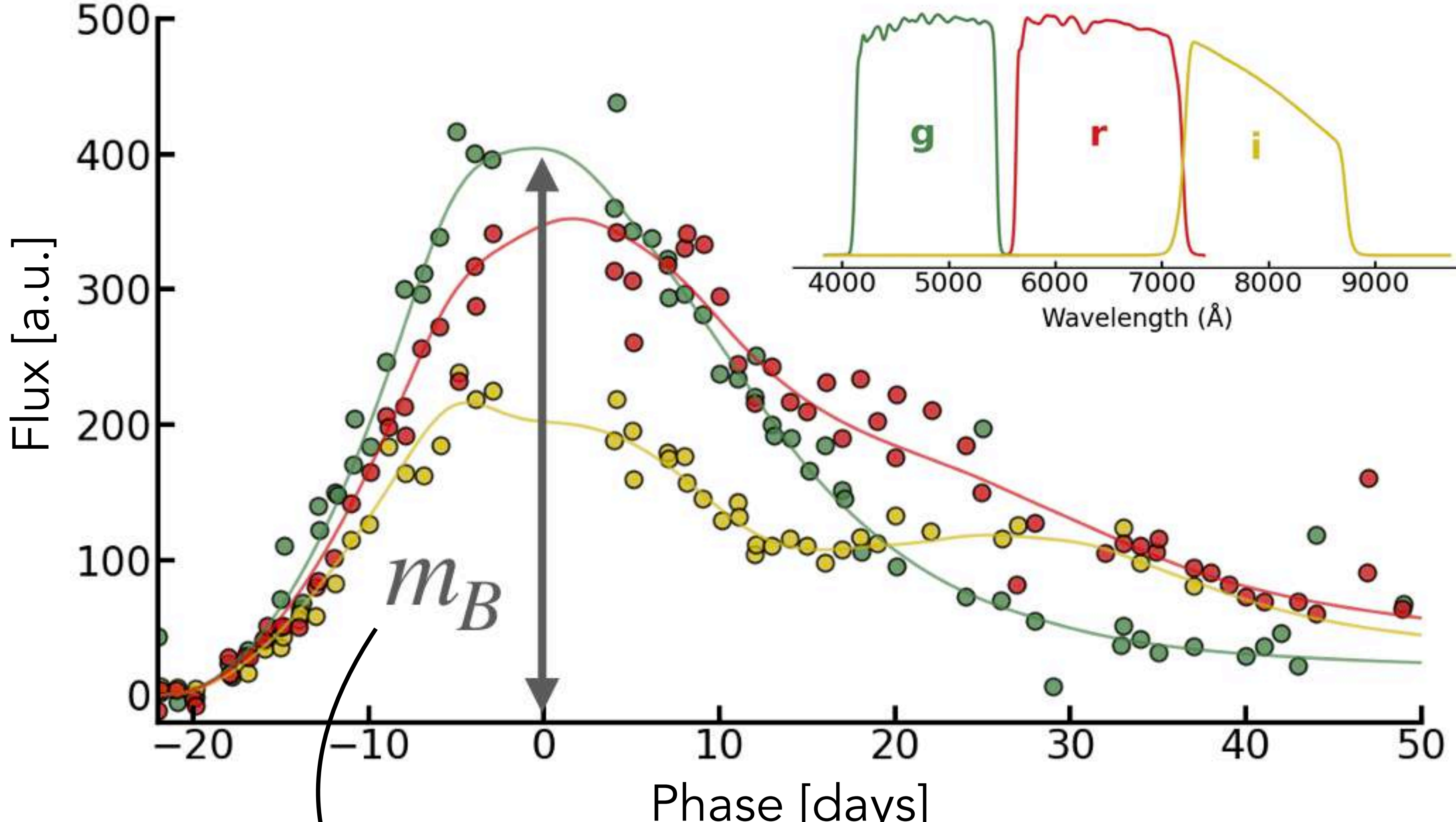
$$F = \frac{L_{\rm candle}}{4\pi D_L^2(z)}$$

Observing the expansion

Type-Ia supernovae







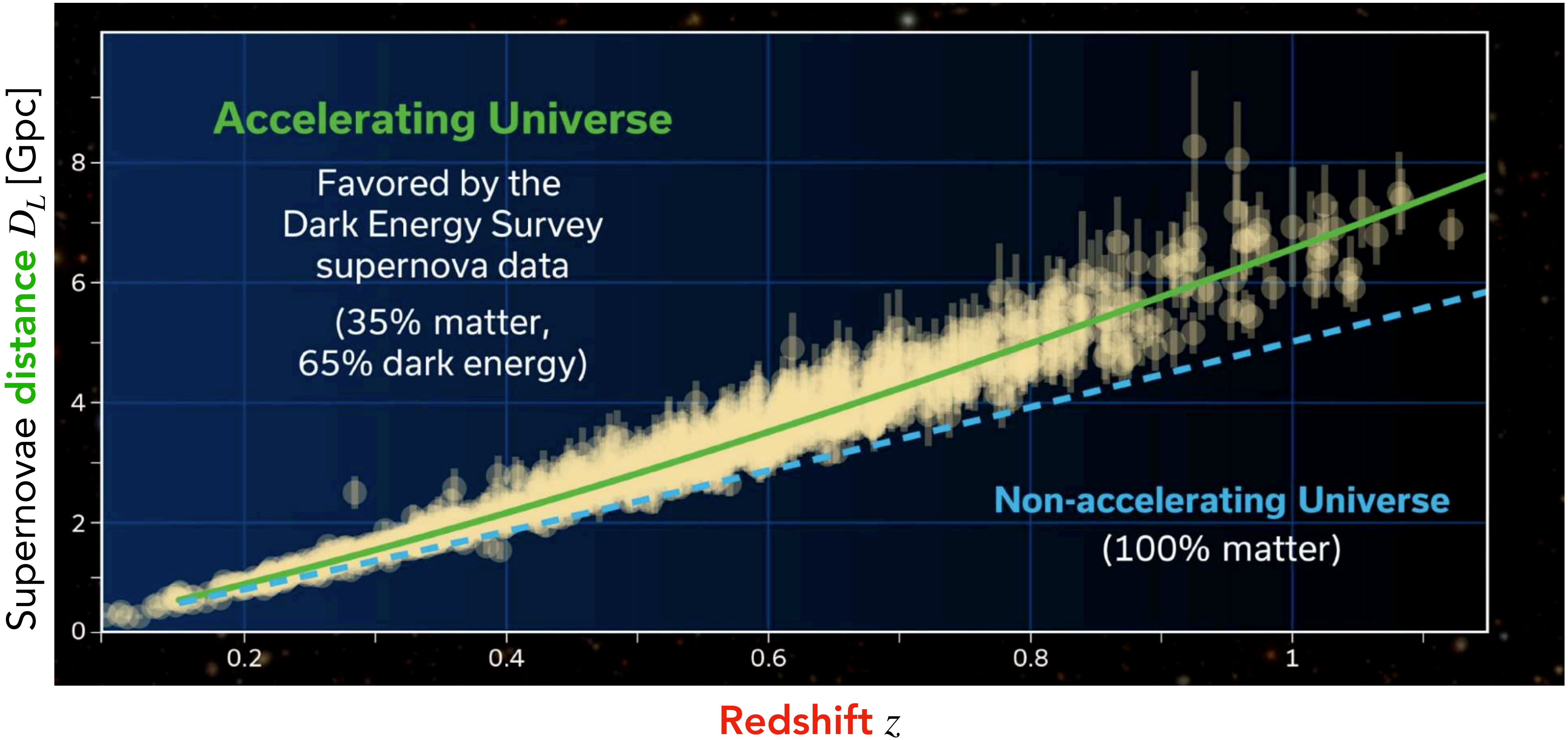
$$F = \frac{L_{\text{candle}}}{4\pi D_L^2(z)}$$ → Supernova luminosity **distance**

by Rafael Kebadian

Observing the expansion

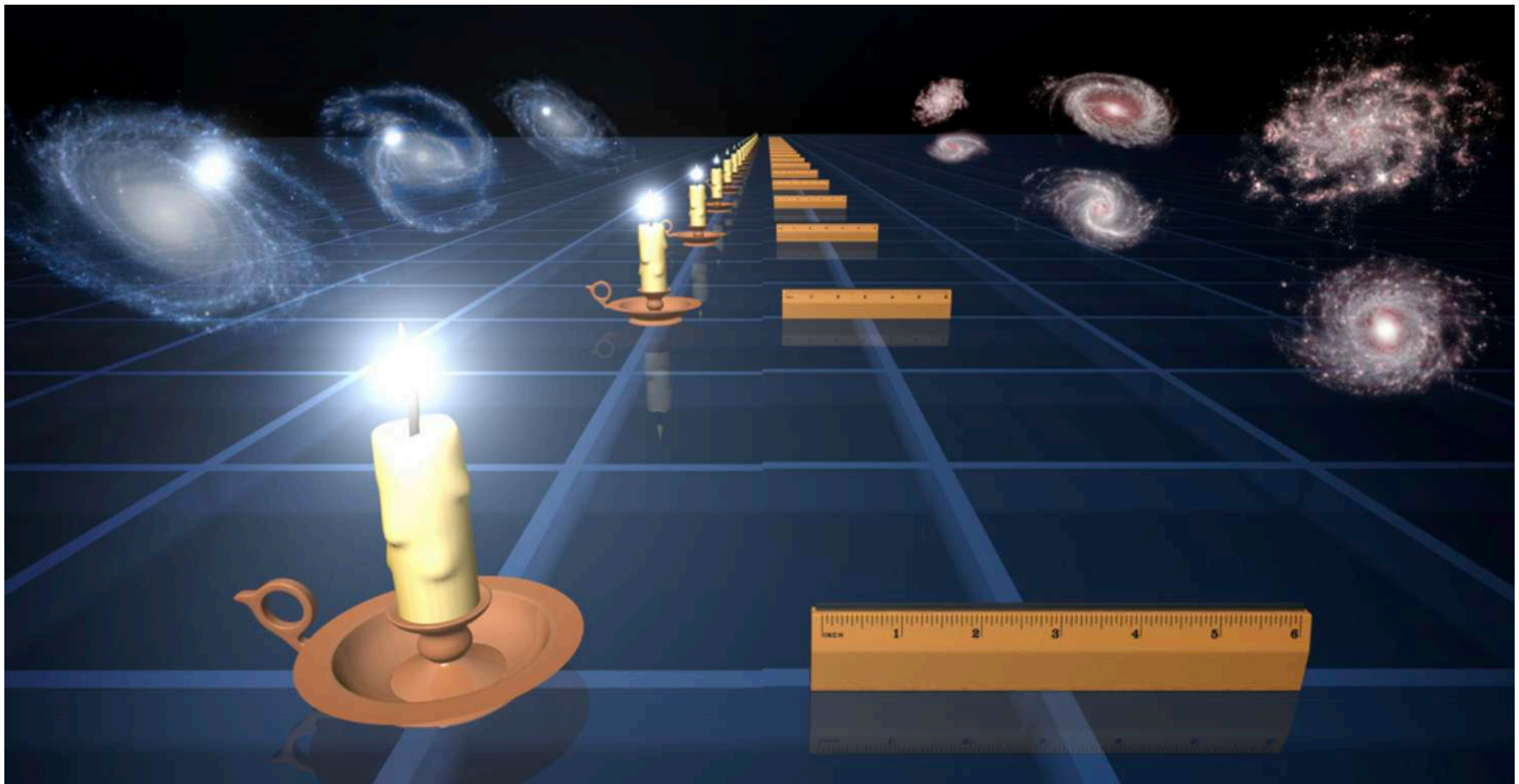
Type-Ia supernovae

~ 1500 SN from the DES collaboration



Distances in an expanding Universe: $$D(z) = \int_0^z \frac{c}{H(z)} \mathrm{d}z$$

Observing the expansion-rate

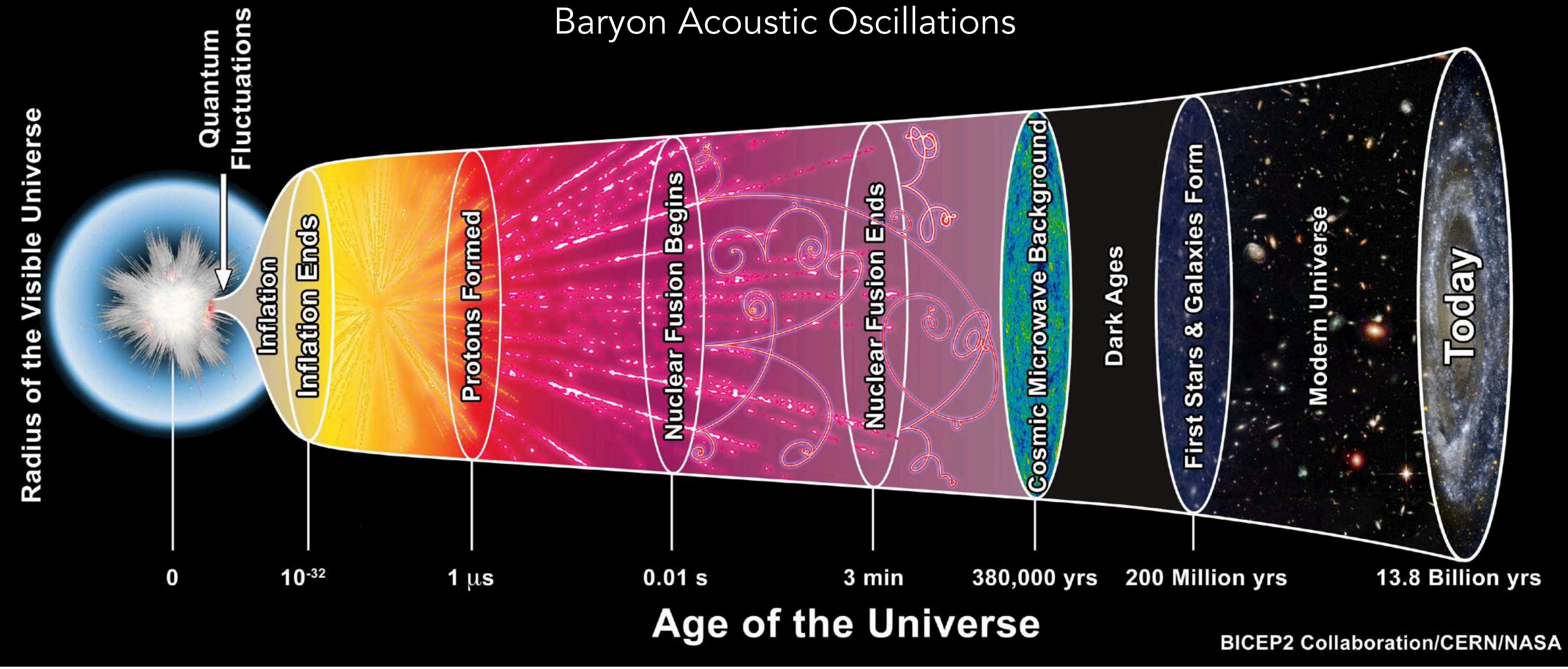


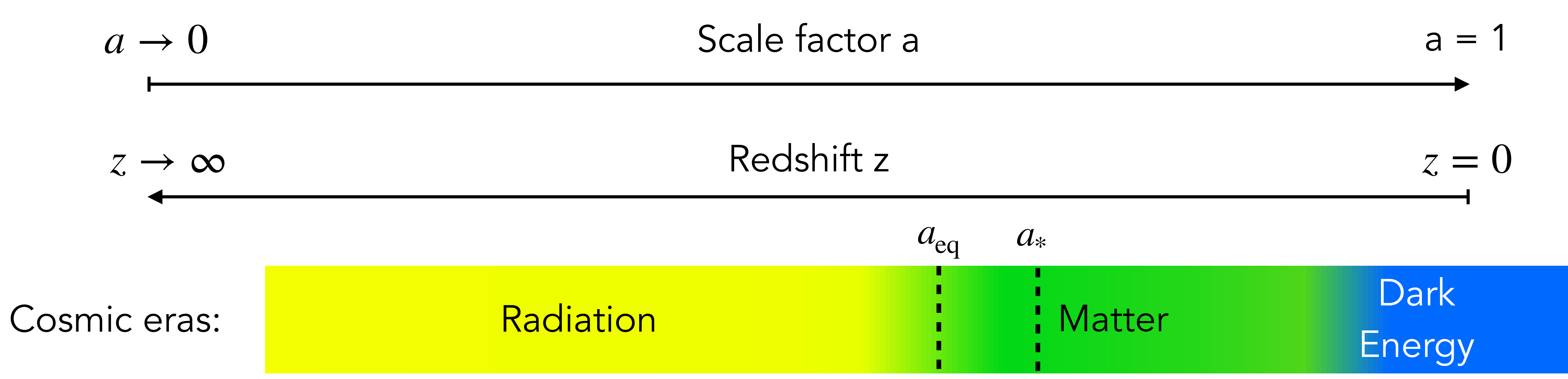
Type-Ia Supernovae (SNIa) as standard candles	Baryon Acoustic Oscillations (BAO) as standard ruler

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

Observing the expansion

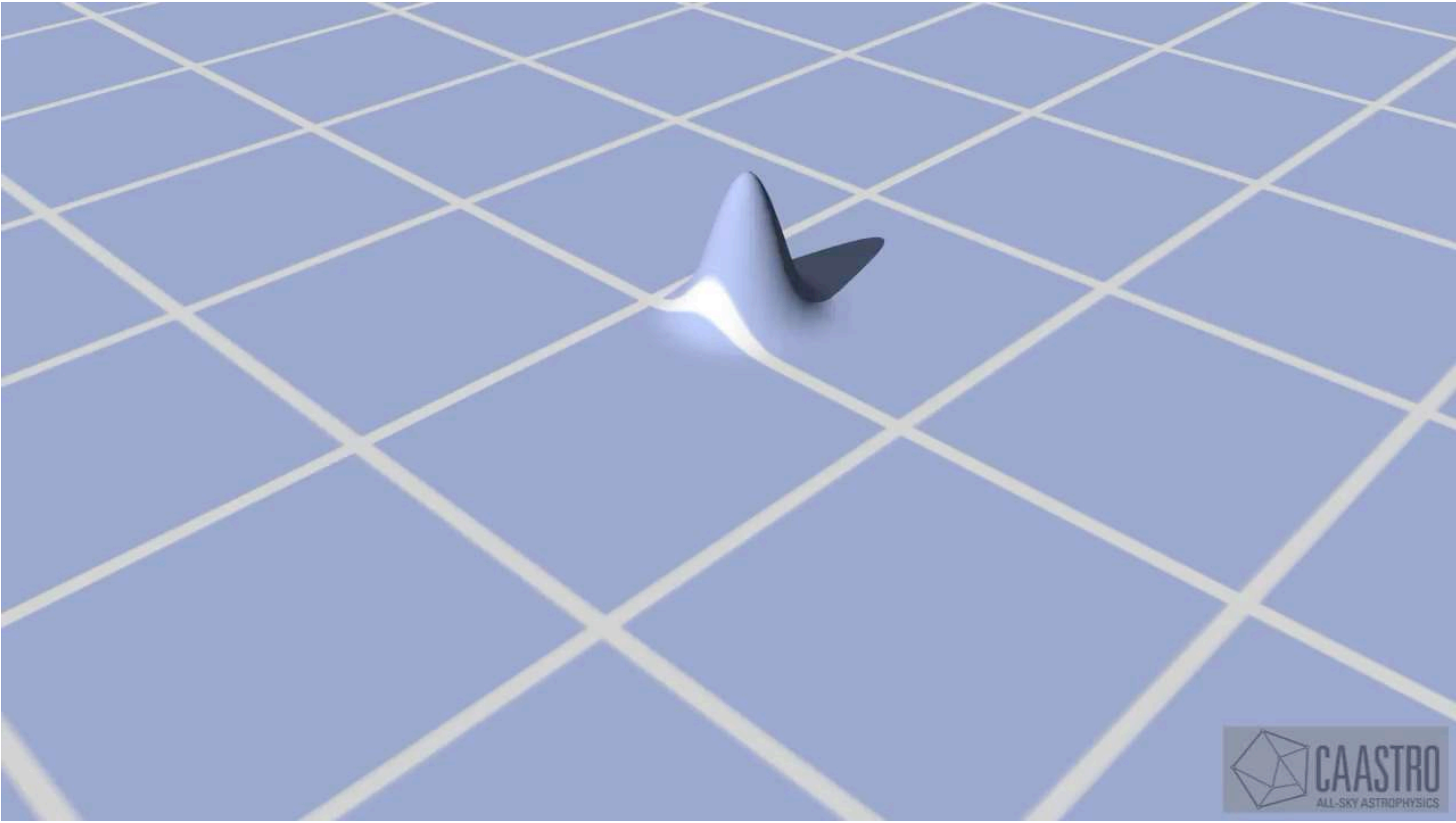
Baryon Acoustic Oscillations





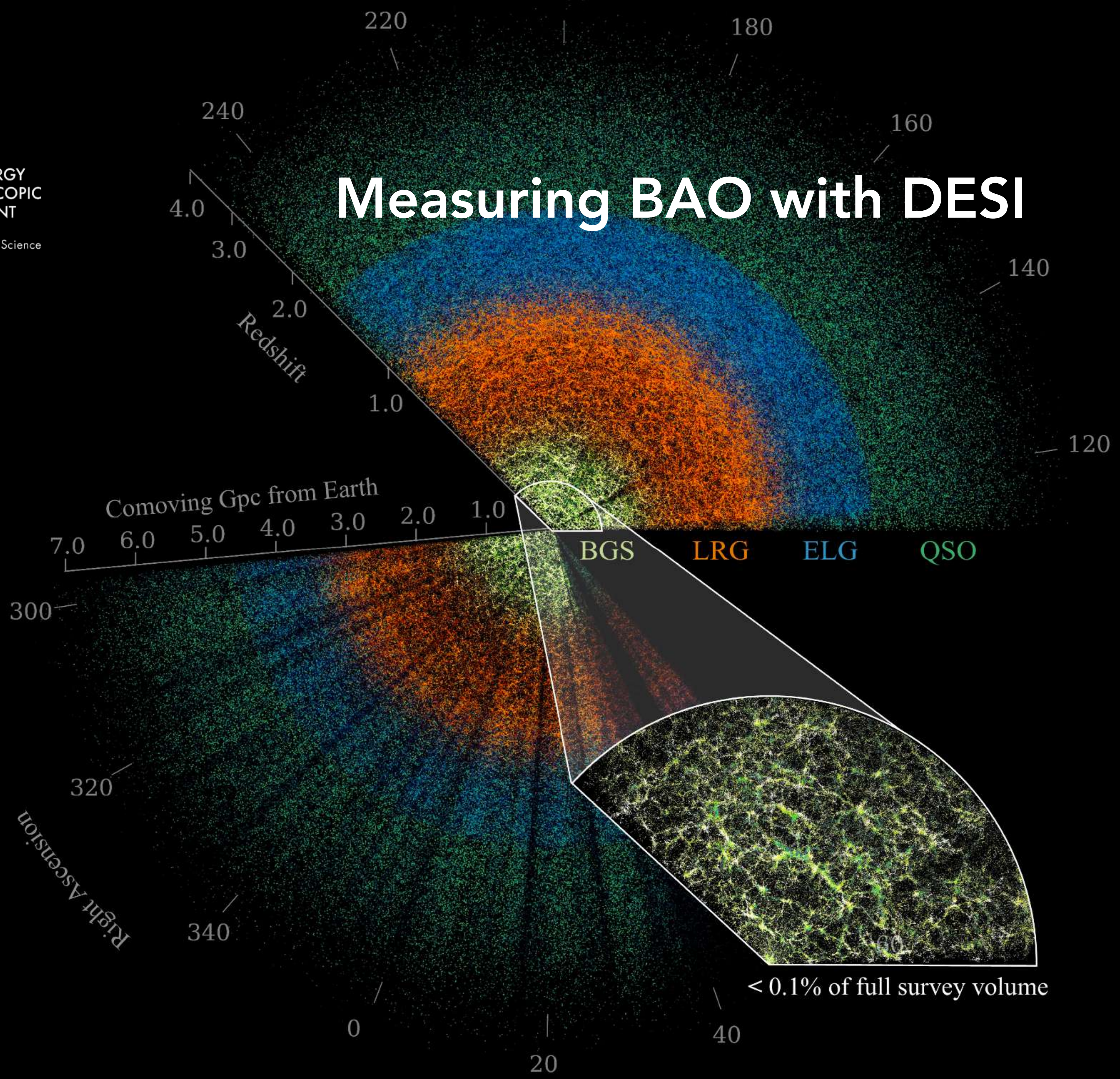
Observing the expansion

Baryon Acoustic Oscillations



Measuring BAO with DESI

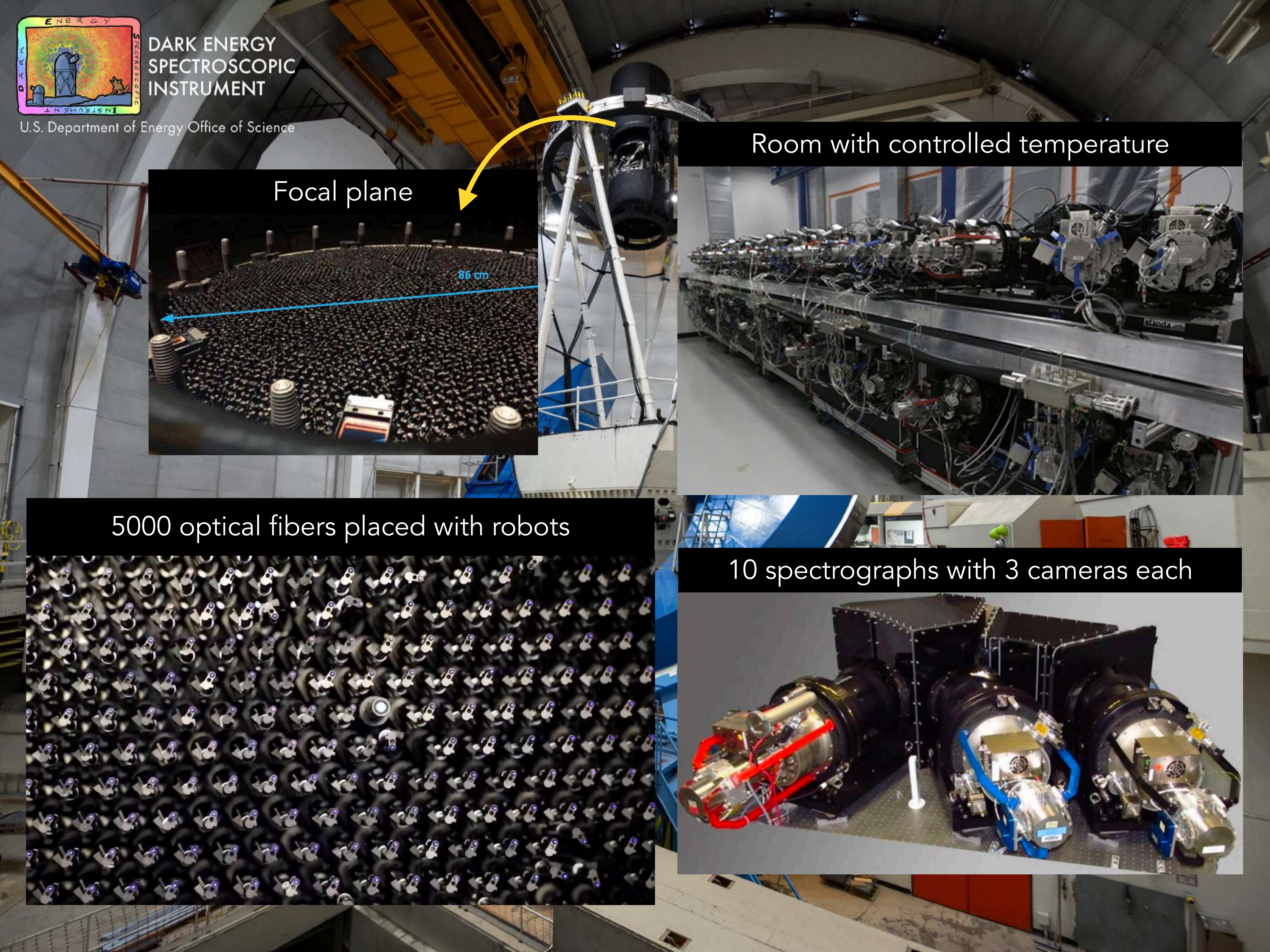
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



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

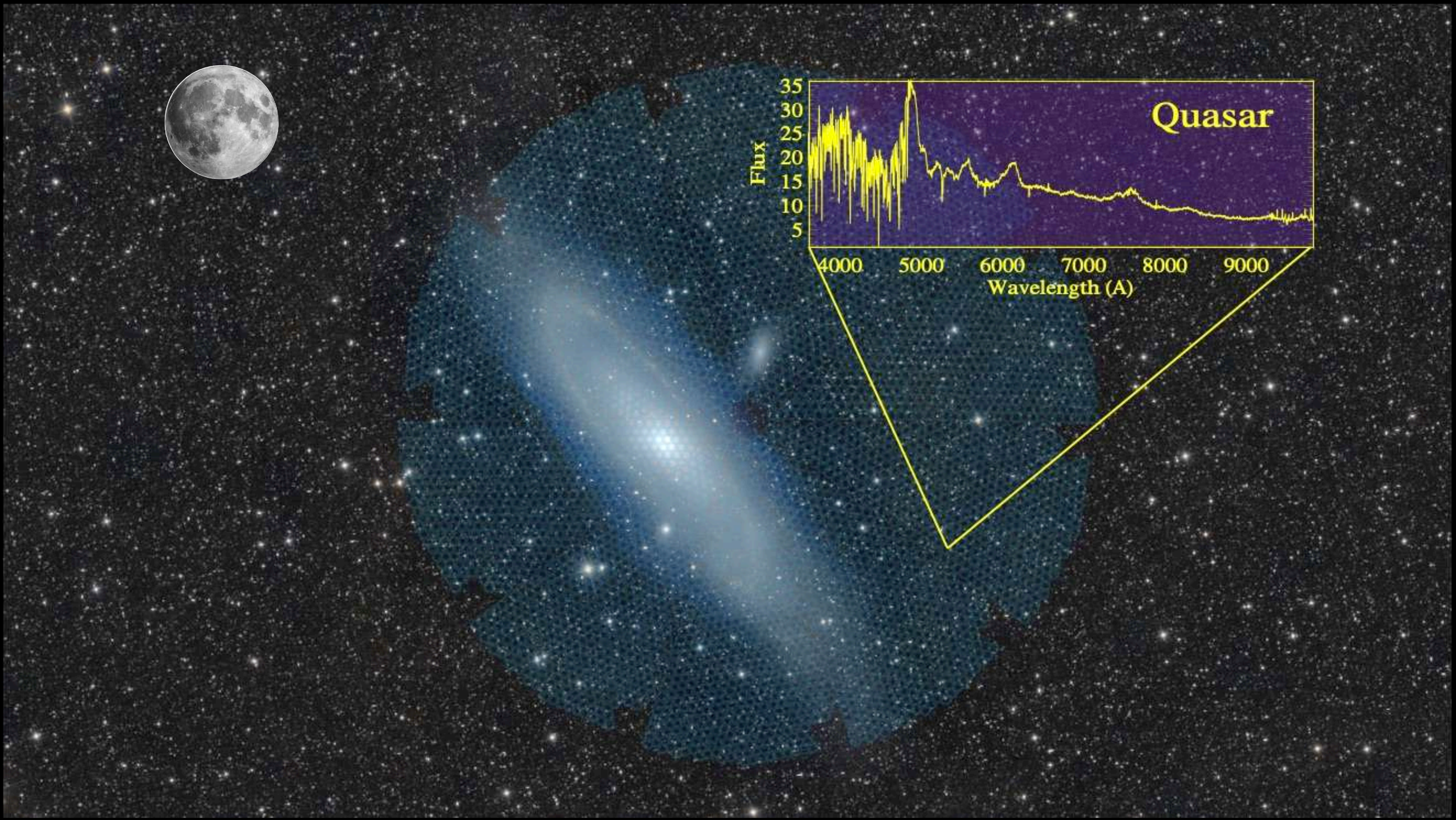
The instrument

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


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
U.S. Department of Energy Office of Science
Focal plane
86 cm
Room with controlled temperature
5000 optical fibers placed with robots
10 spectrographs with 3 cameras each

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

Field of view
8 deg^2



Measuring BAO with DESI

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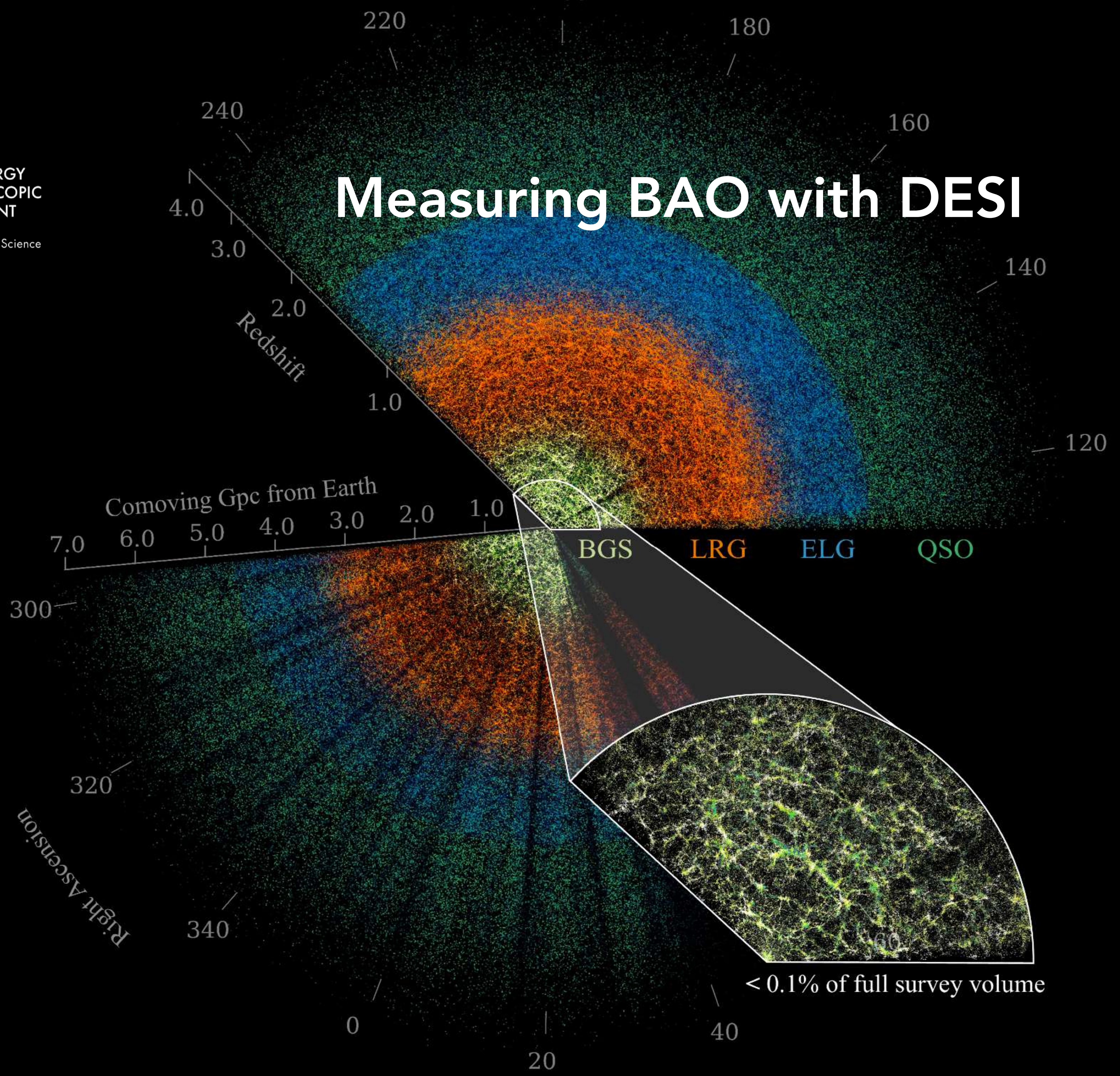

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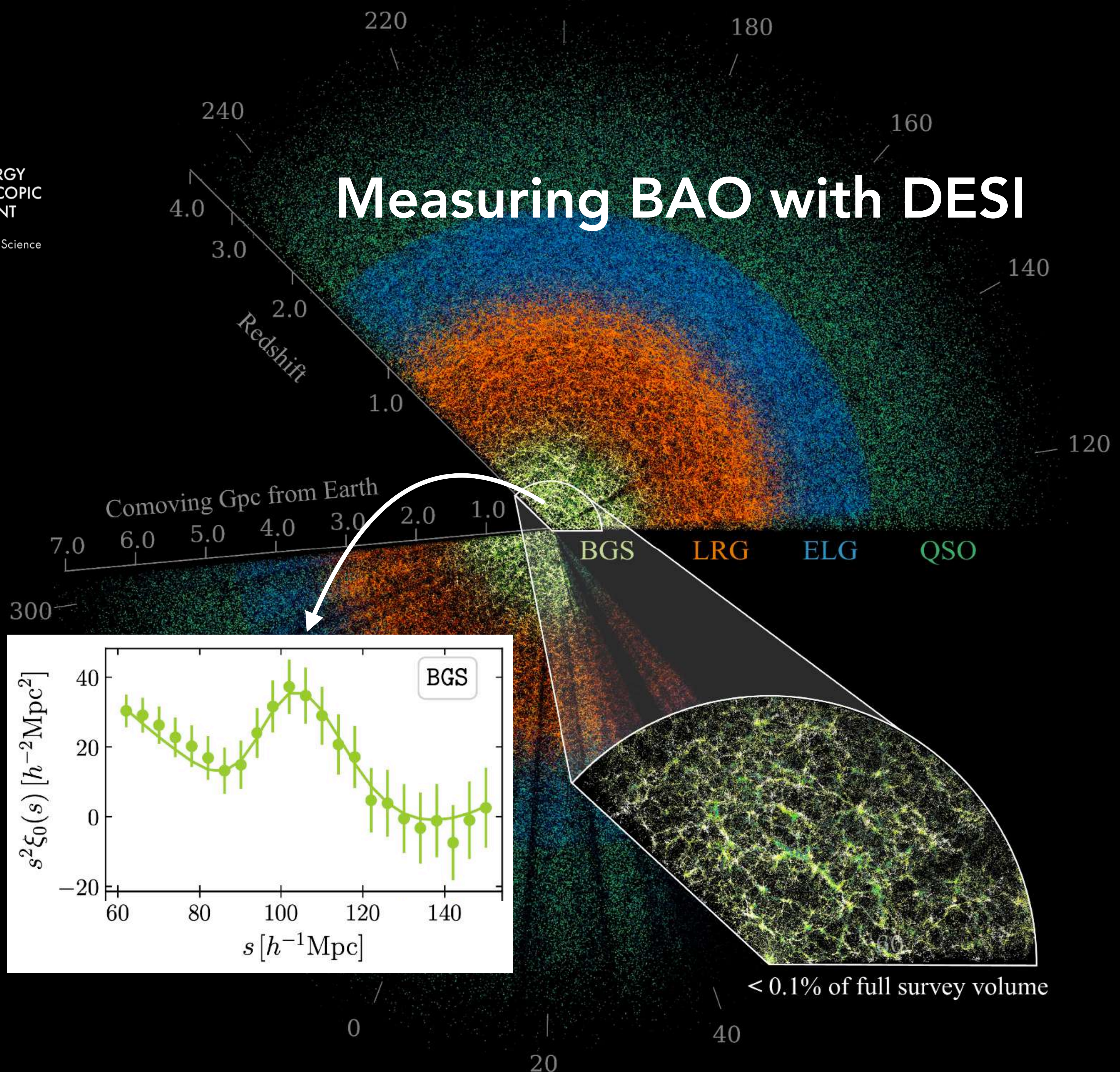

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U.S. Department of Energy Office of Science

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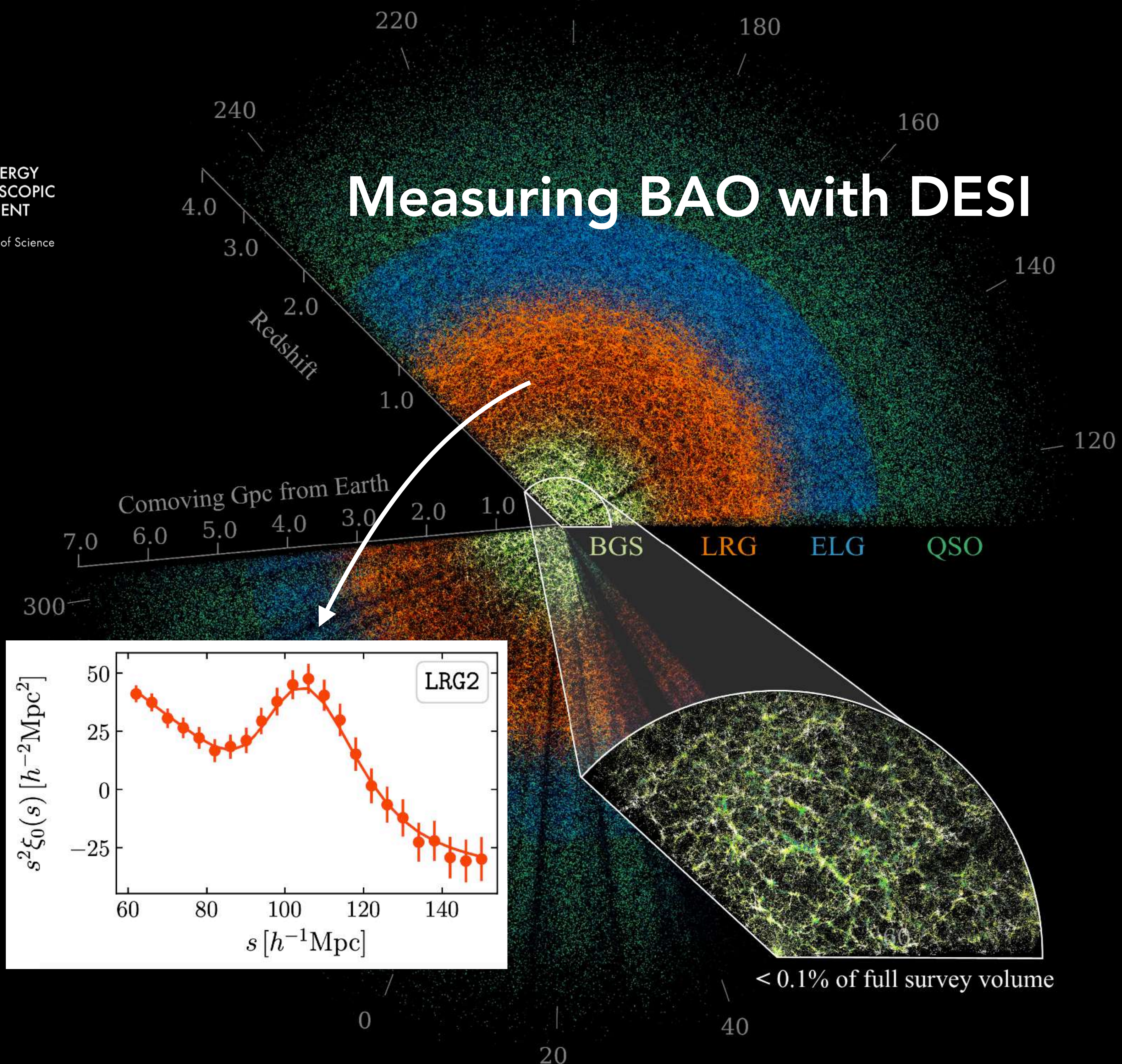

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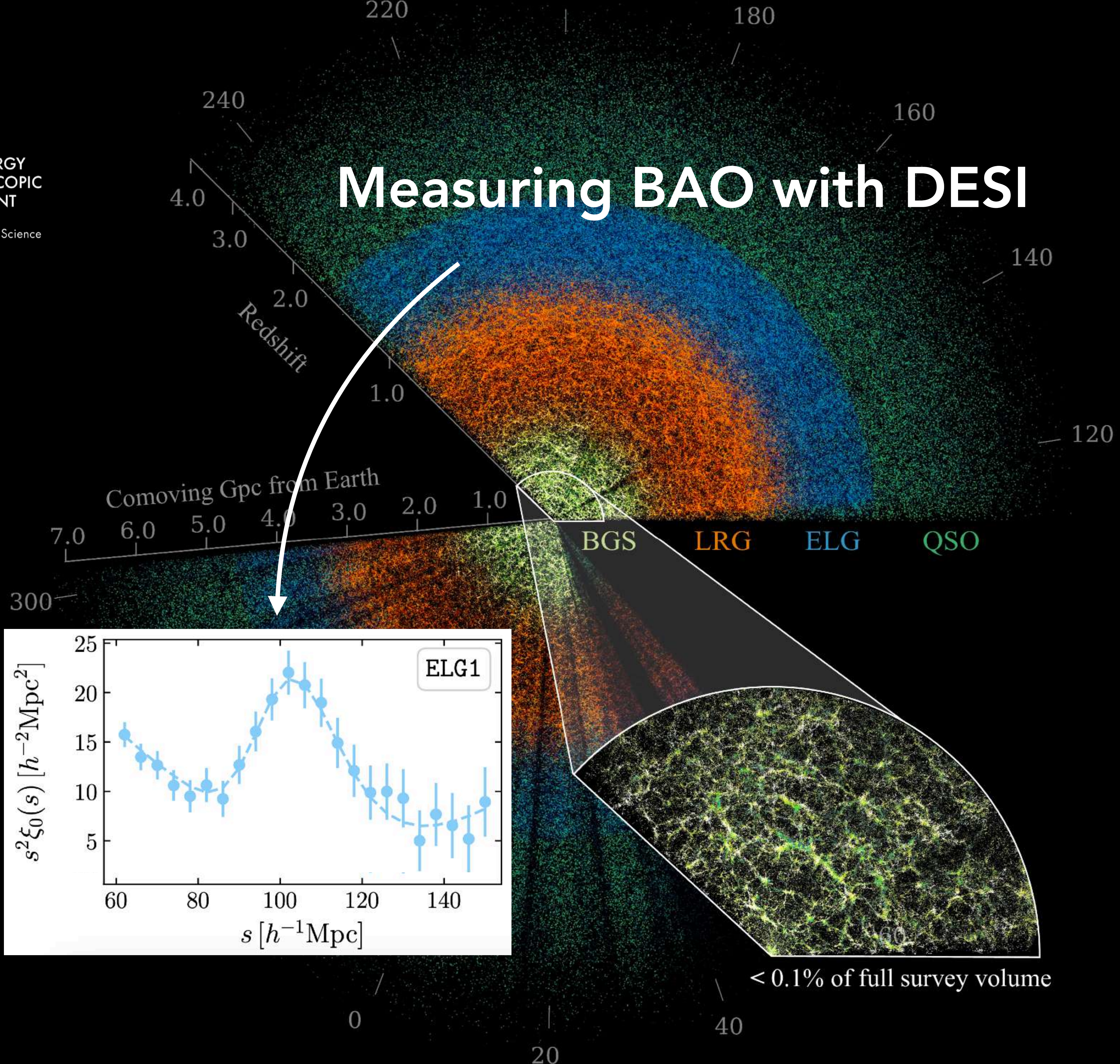

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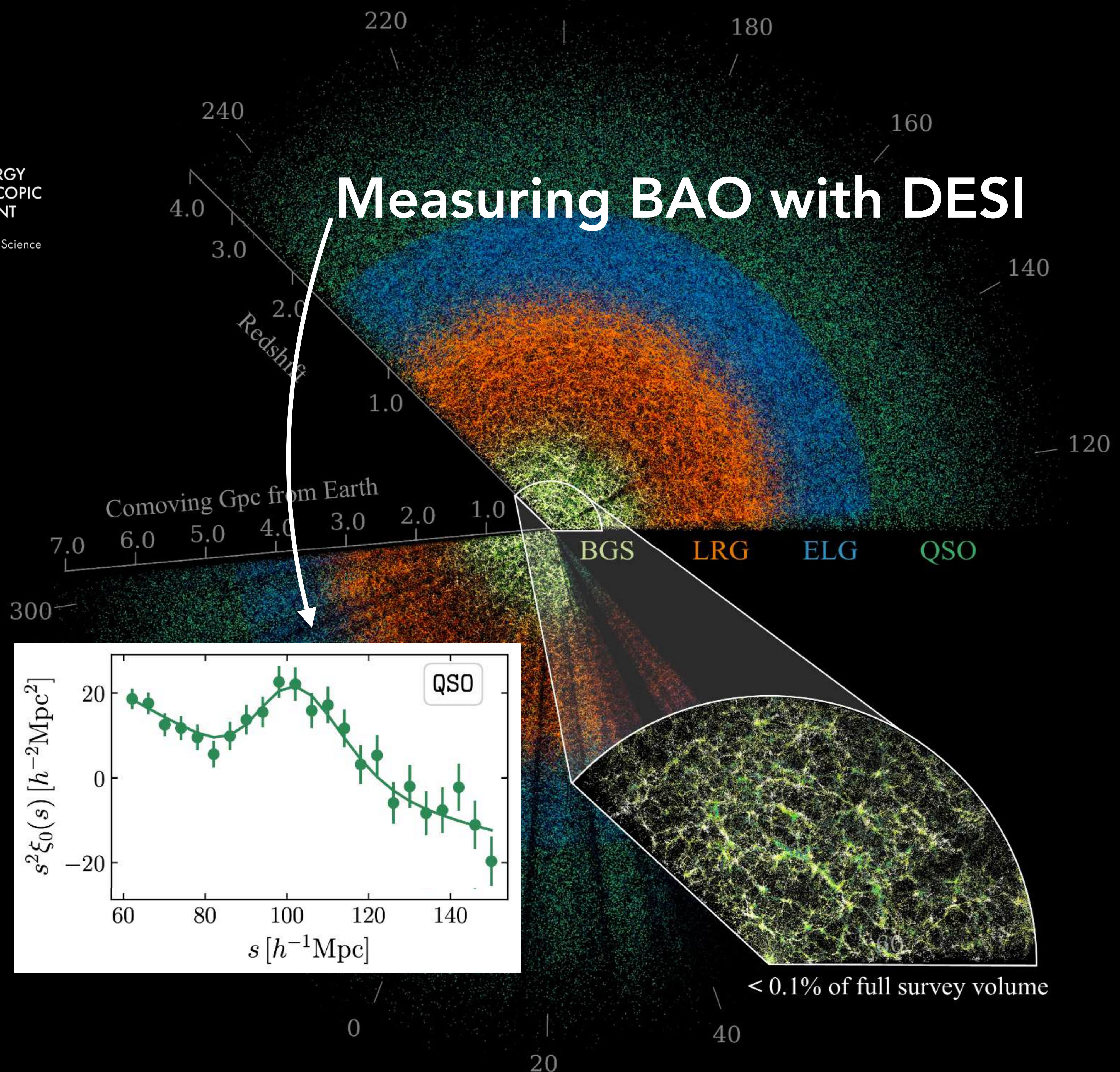
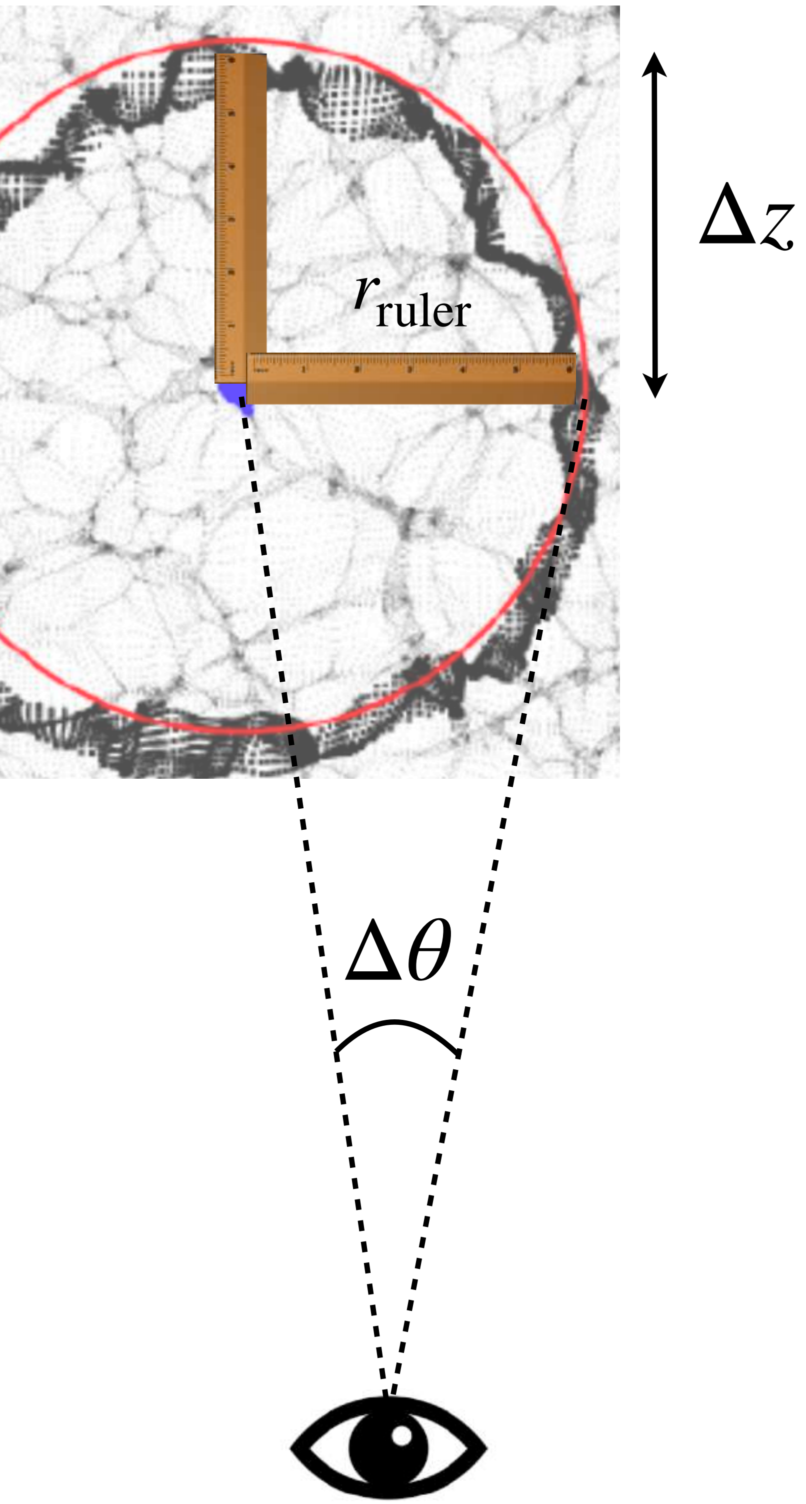


Observing the expansion

Baryon Acoustic Oscillations

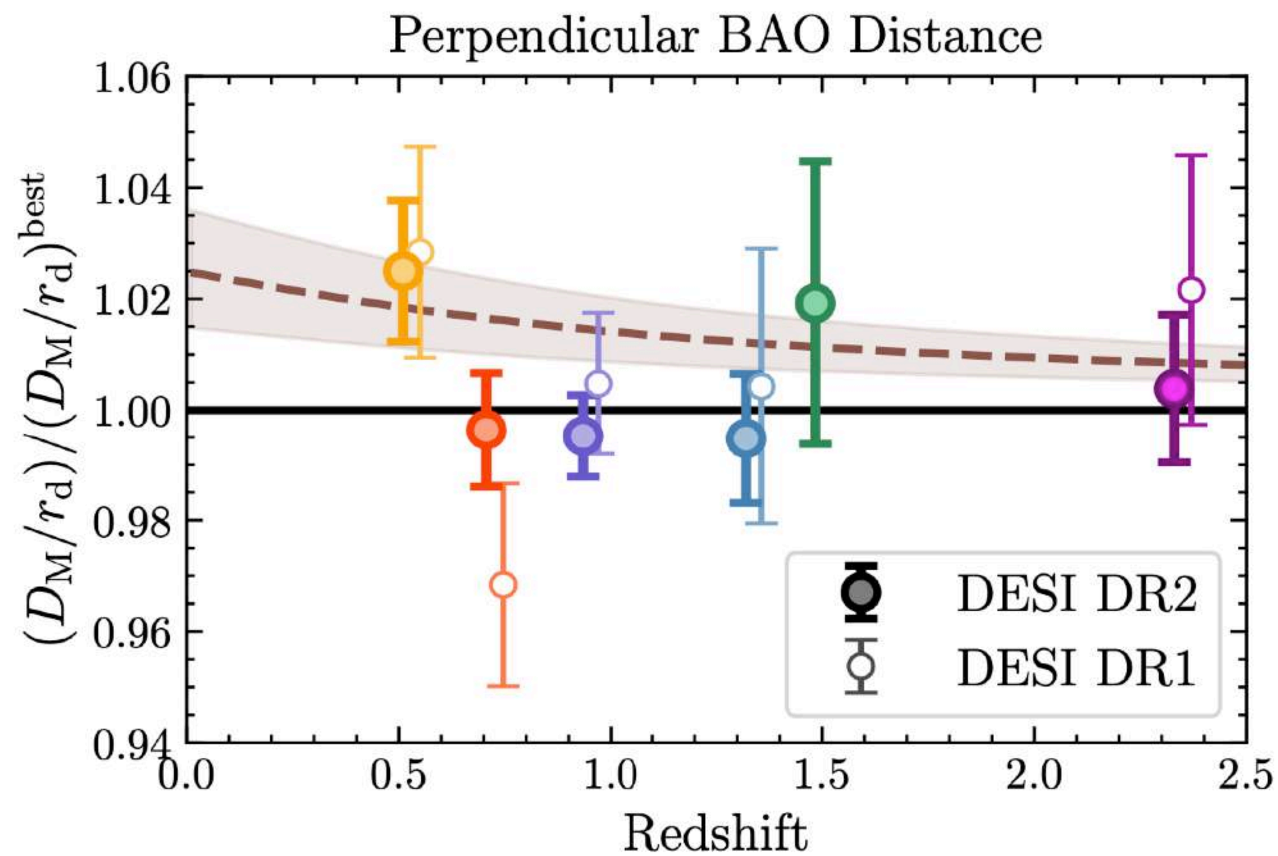


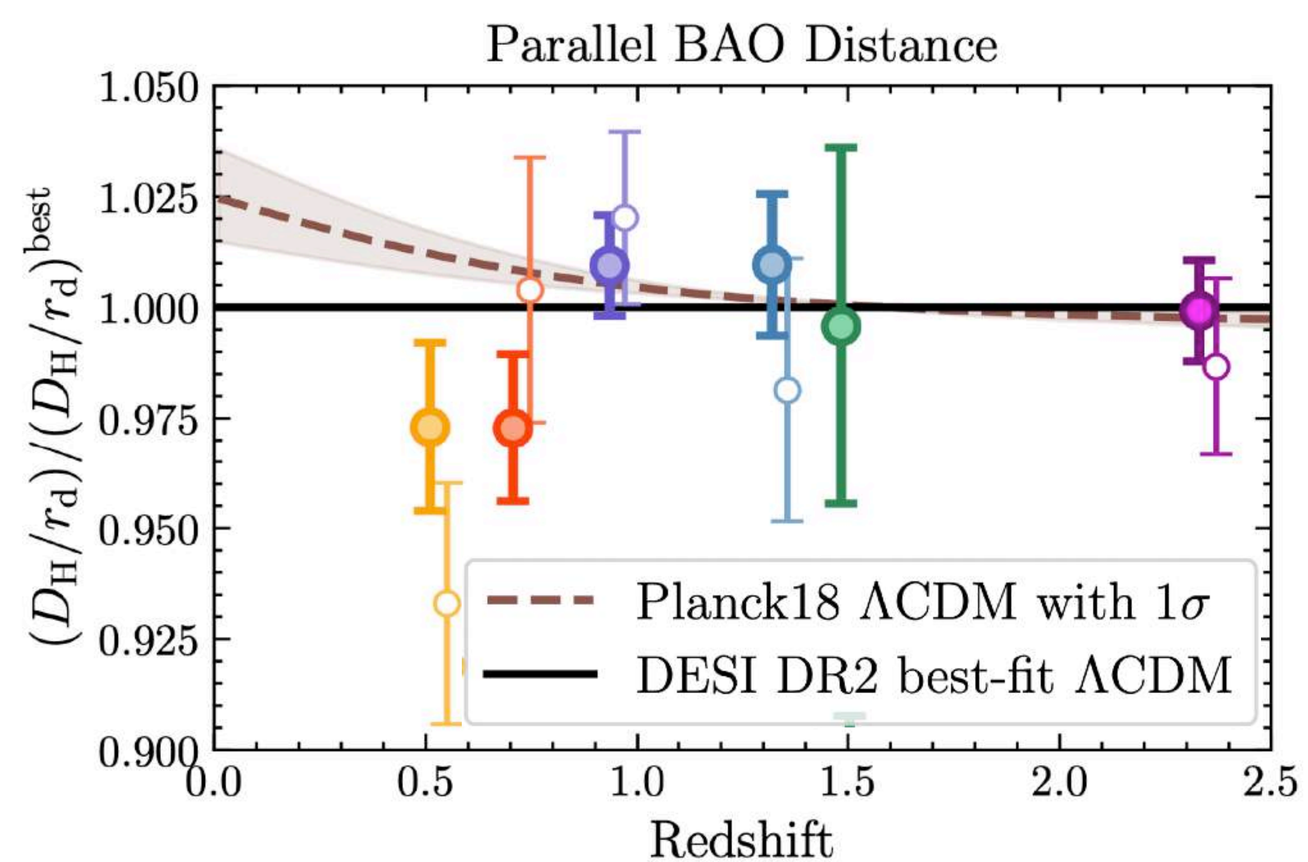
$$\Delta\theta = \frac{r_{\rm ruler}}{D_M(z)}$$

Angular distance

$$\Delta z = \frac{r_{\rm ruler}}{D_H(z)}$$

Hubble distance

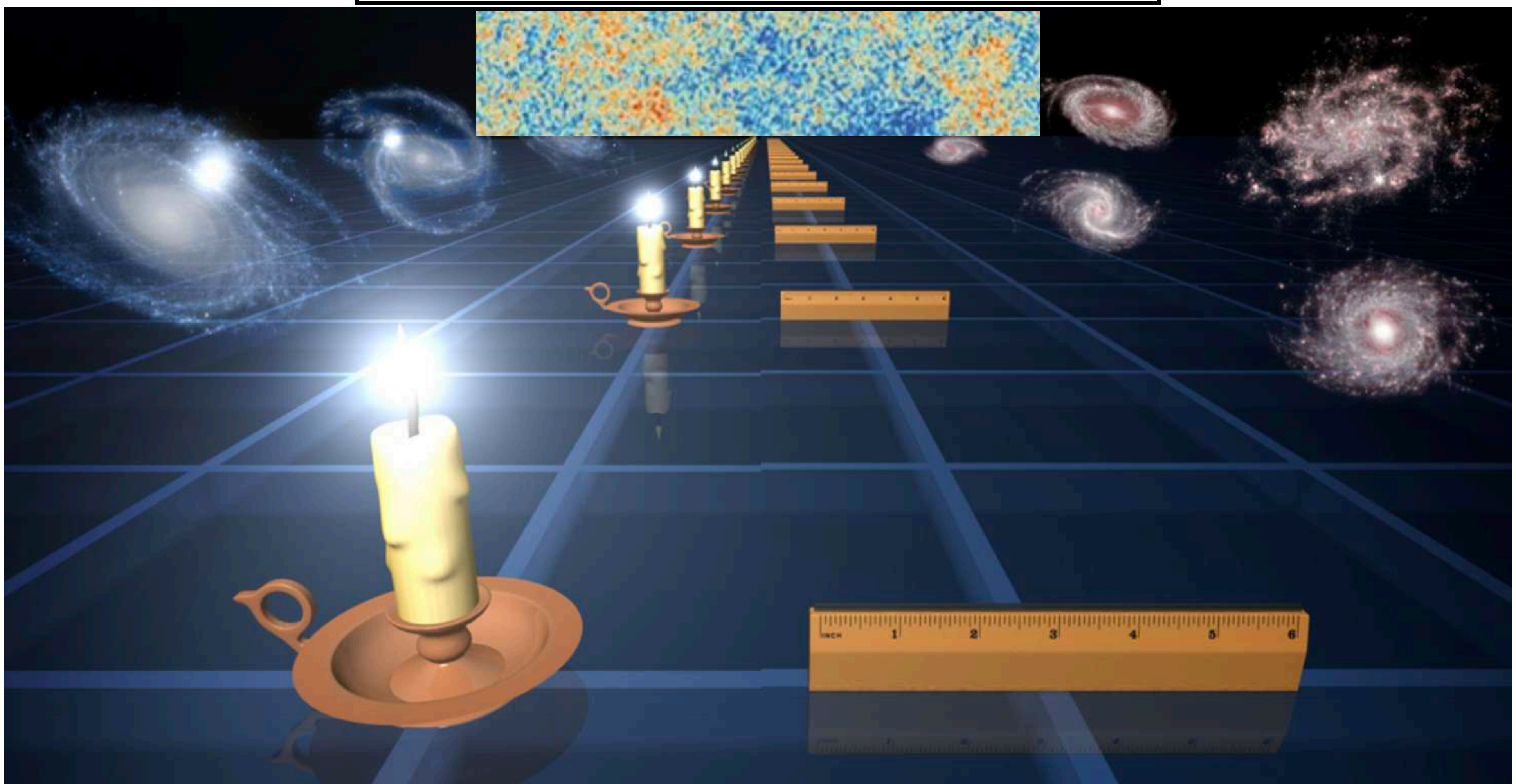




DESI DR2 Results 2025

Observing the expansion

Cosmic microwave background (CMB)



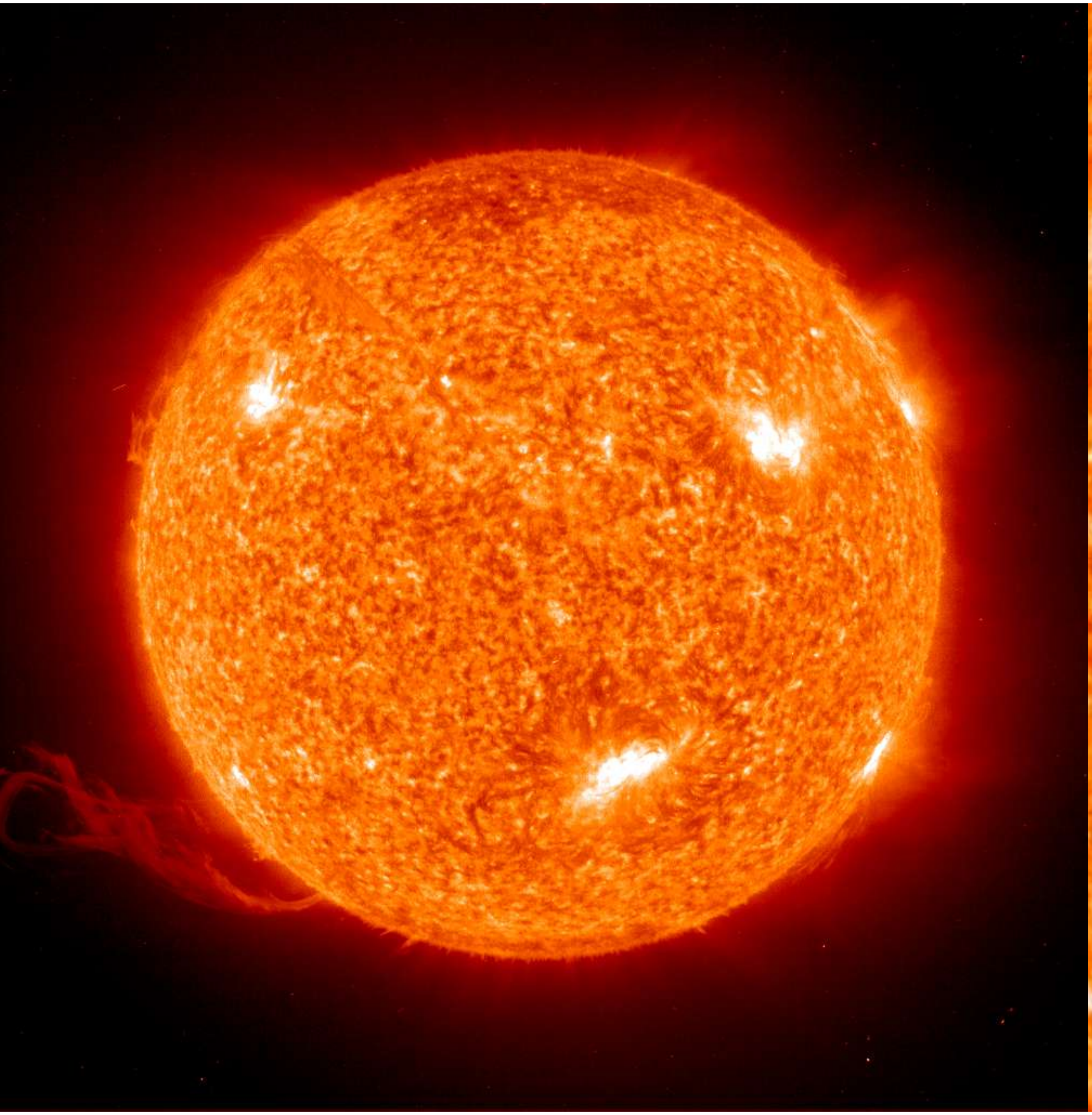
Type-Ia Supernovae (SNIa) as standard candles

Baryon Acoustic Oscillations (BAO) as standard ruler

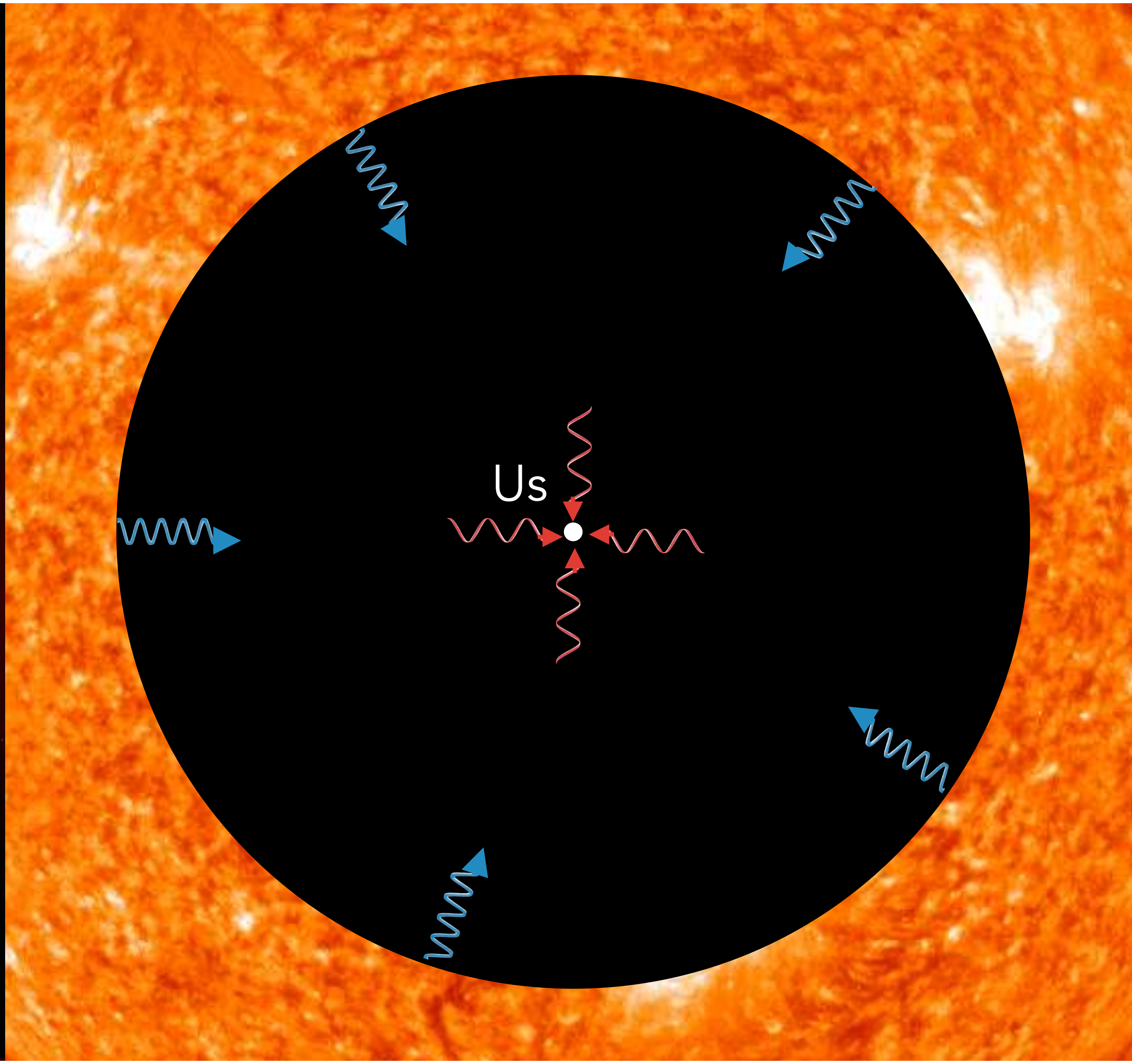
$$F = \frac{L_{\rm candle}}{4\pi D_L^2(z)} \qquad \Delta\theta = \frac{r_{\rm ruler}}{D_M(z)} \qquad \Delta z = \frac{r_{\rm ruler}}{D_H(z)}$$

Cosmic Microwave Background

The Sun



The CMB



Photosphere temperature 5,772 K

Photosphere is at 8 light-minutes

CMB temperature at emission 3,000 K

CMB temperature today 2,73 K

Light emitted 13,5 billion years ago

Cosmic Microwave Background

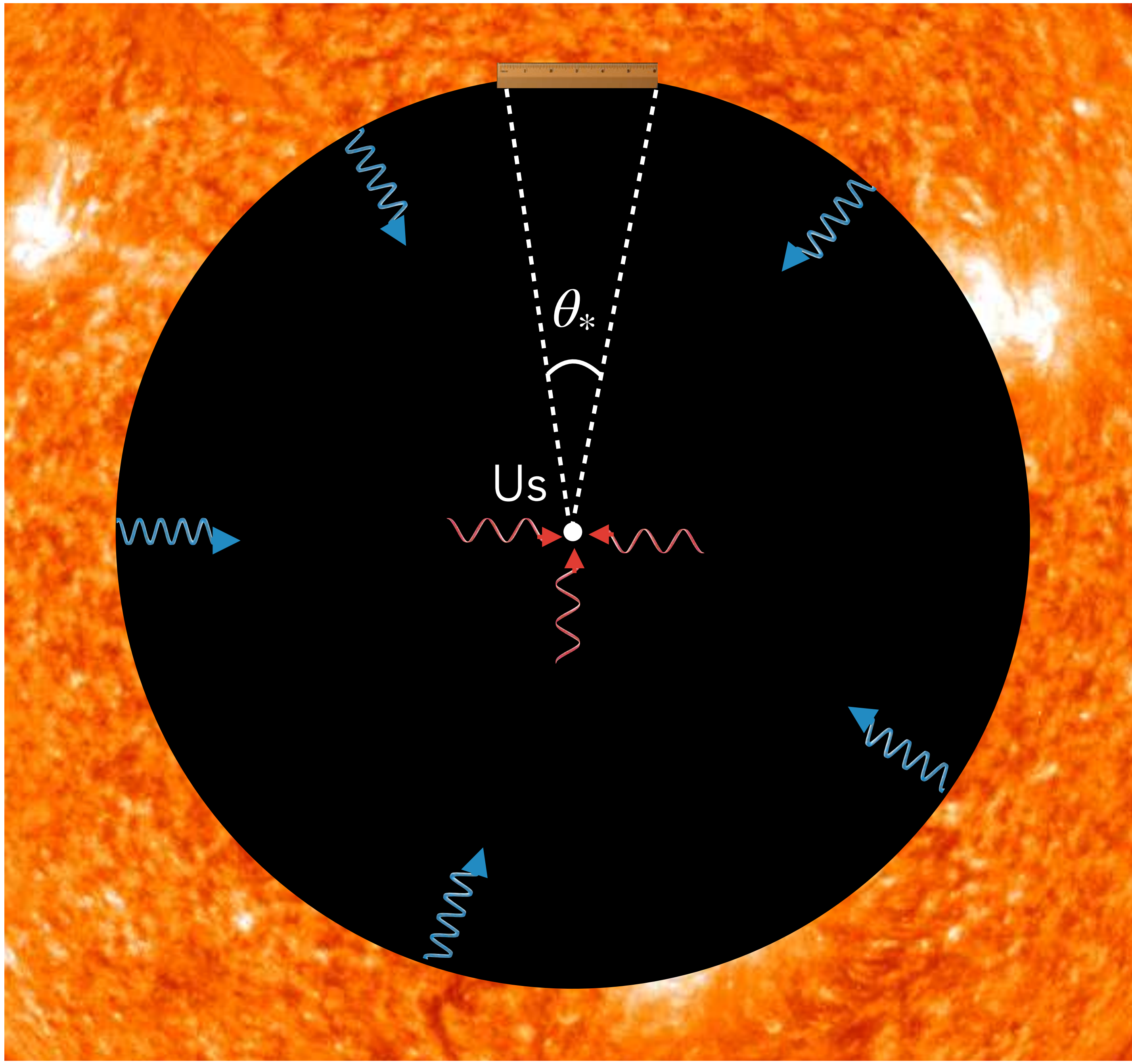
Last-scattering surface at redshift
$z \sim 1089$

BAO is imprinted in the CMB

$$100\theta_* = 1.04108 \pm 0.00026$$
(Planck final analysis PR4)

One of the best cosmological parameters ever measured!

The CMB

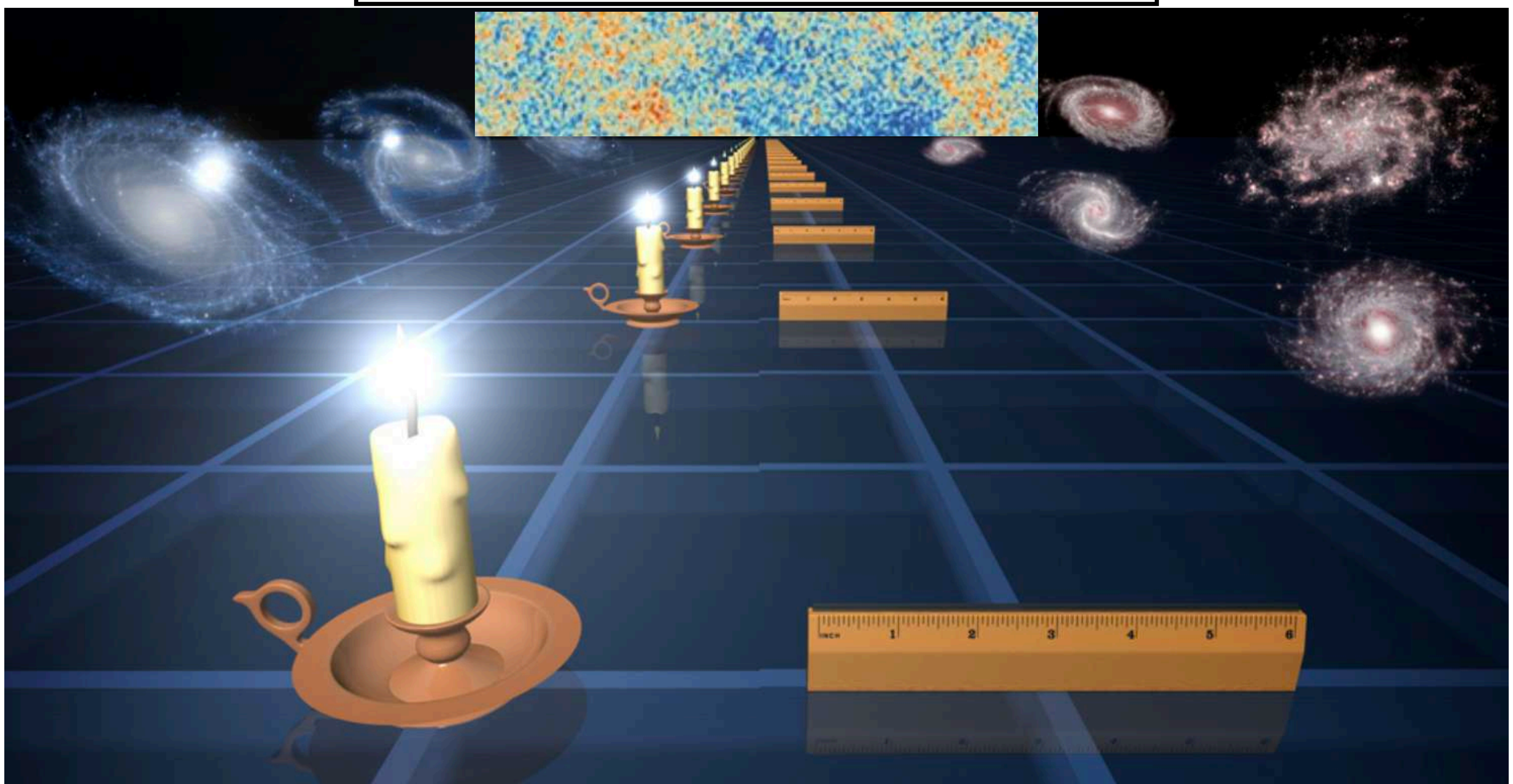


CMB temperature at emission 3,000 K
CMB temperature today 2,73 K

Light emitted 13,5 billion years ago

Observing the expansion

Cosmic microwave background (CMB)



Type-Ia Supernovae (SNIa) as standard candles

Baryon Acoustic Oscillations (BAO) as standard ruler

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

Observing the expansion

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

Distances in cosmology: $D_x(z) \approx \int_0^z \frac{c}{H(z')} dz'$

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

Expansion-rate

p^+, n, e^-, dark matter
30%

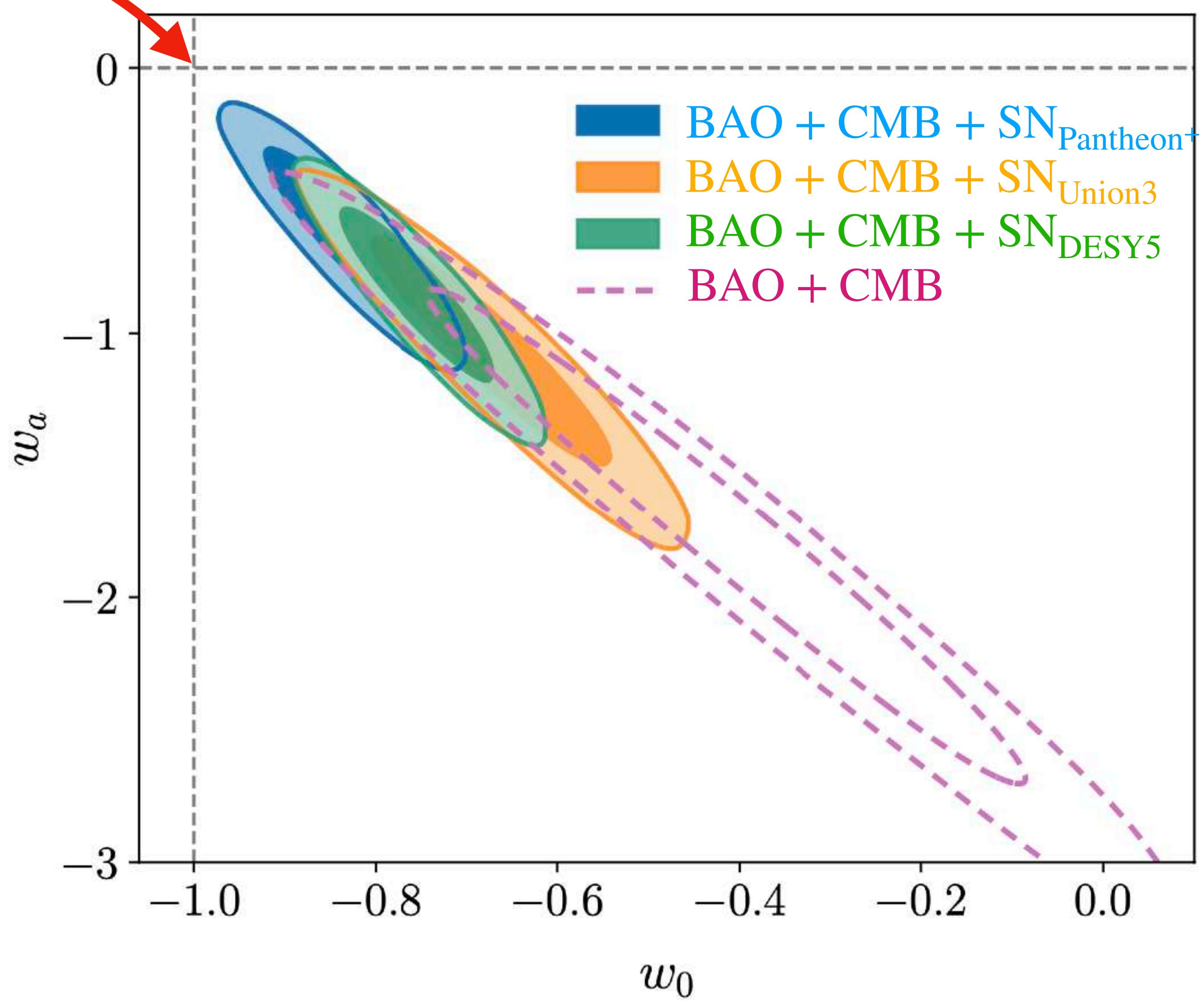
photons, neutrinos
0.008%

dark energy (quintessence, phantom force)
70%

Constraints on evolving dark energy

Cosmological constant Λ

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



Tension with the cosmological

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

$\mathrm{BAO + CMB + SN_{Pantheon^+}} \Rightarrow 2.8\sigma$

$\mathrm{BAO + CMB + SN_{Union3}} \Rightarrow 3.8\sigma$

$\mathrm{BAO + CMB + SN_{DESY5}} \Rightarrow 4.2\sigma$

DESI DR2 Results II (2025)

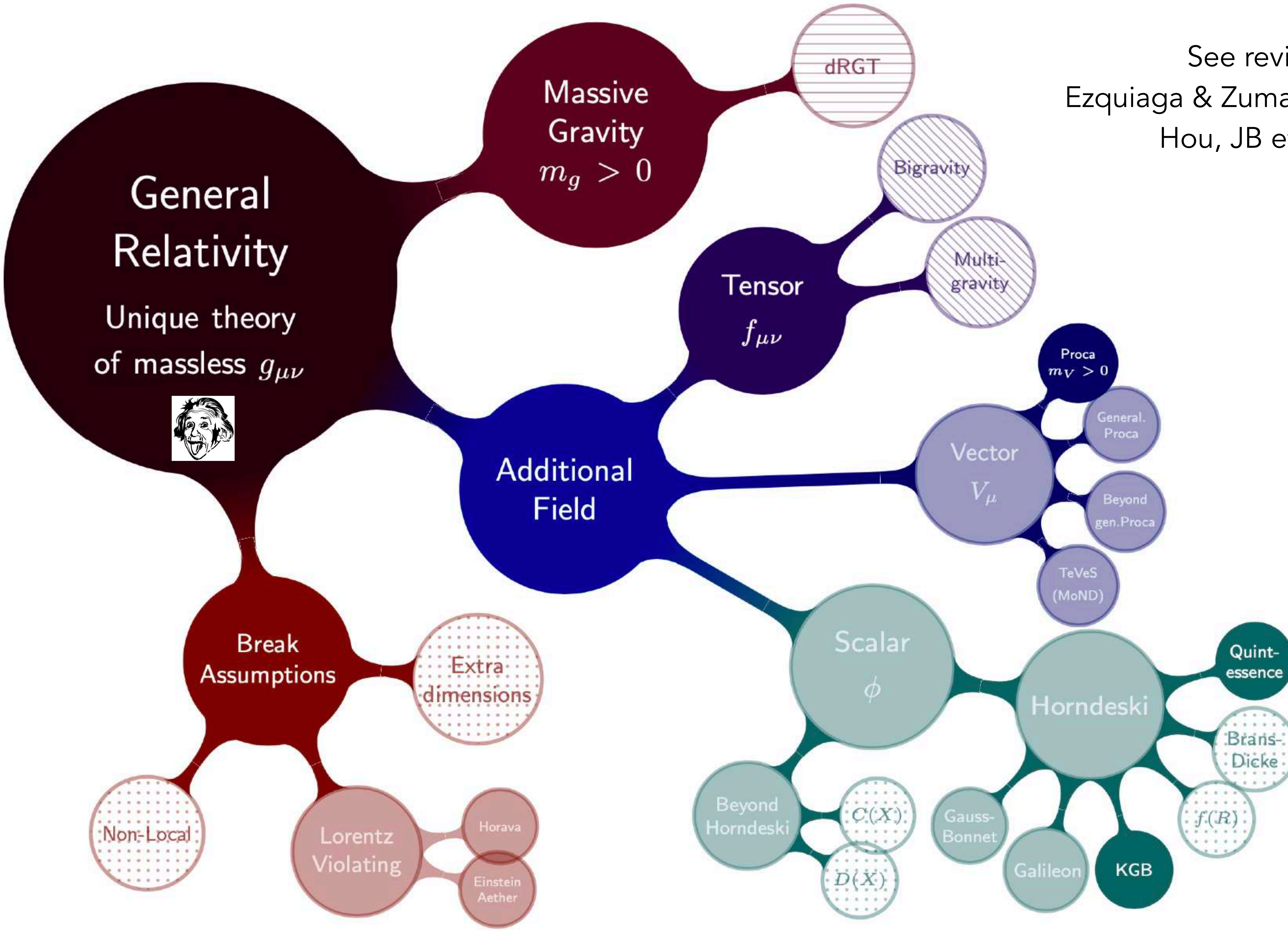
Third level of weird in the Universe (2025)

Will this tension remain with more data?
What is **dark energy**?

What if general relativity is incomplete?

Several theories try to explain an accelerated expansion

See reviews by
Ezquiaga & Zumalacárregui 2018;
Hou, JB et al. 2023



So... **dark energy** or **alternative/extended GR**?

Plan

The expansion: modelling and observing it

Growth of structures : modelling and observing it

Peculiar velocity measurements and DESI first results

Near future with ZTF and LSST

Our Universe is not homogeneous.. and it's complex !

Growth of structures

Dense regions get denser

Void regions get emptier

Peculiar velocities

Matter moves around

Matter clumps into **halos**

Galaxies form inside halos

Supernovae explode inside galaxies

10 Mpc (comoving)

Illustris hydrodynamical n-body simulation

Growth of structures: modelling it

Homogeneous density

$\bar{\rho}(t)$

➡

Inhomogeneous density

$\rho(\vec{x},t) = \bar{\rho}(t)\left[1+\delta(\vec{x},t)\right]$

Continuity + Euler fluid equation and Poisson equation for gravity

Assume small contrast ($\delta \ll 1$) and keep **linear** terms only:

$$\ddot{\delta}(\vec{x},t) + \boxed{\text{expansion H(t)}}\,\dot{\delta}(\vec{x},t) - \boxed{\text{gravity G}}\,\delta(\vec{x},t) = 0$$

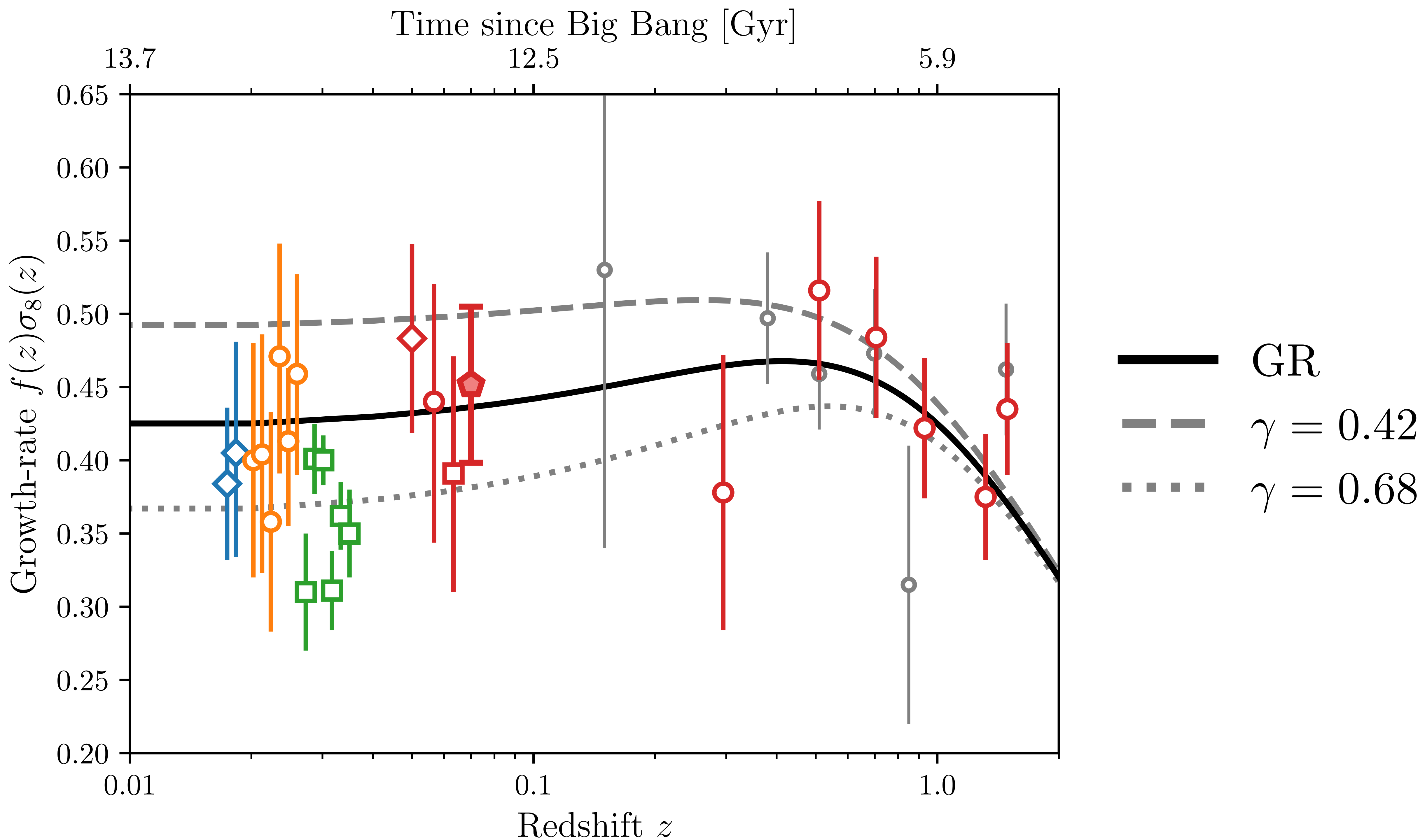
Growth rate of structures $f(t)$

$$\dot{\delta}(\vec{x},t) \sim f(t)\ \delta(\vec{x},t_0)$$

In GR: $f(t) \approx [\Omega_m(t)]^\gamma$ where $\gamma = 0.55$

Measurements of the growth rate can show deviations from GR!

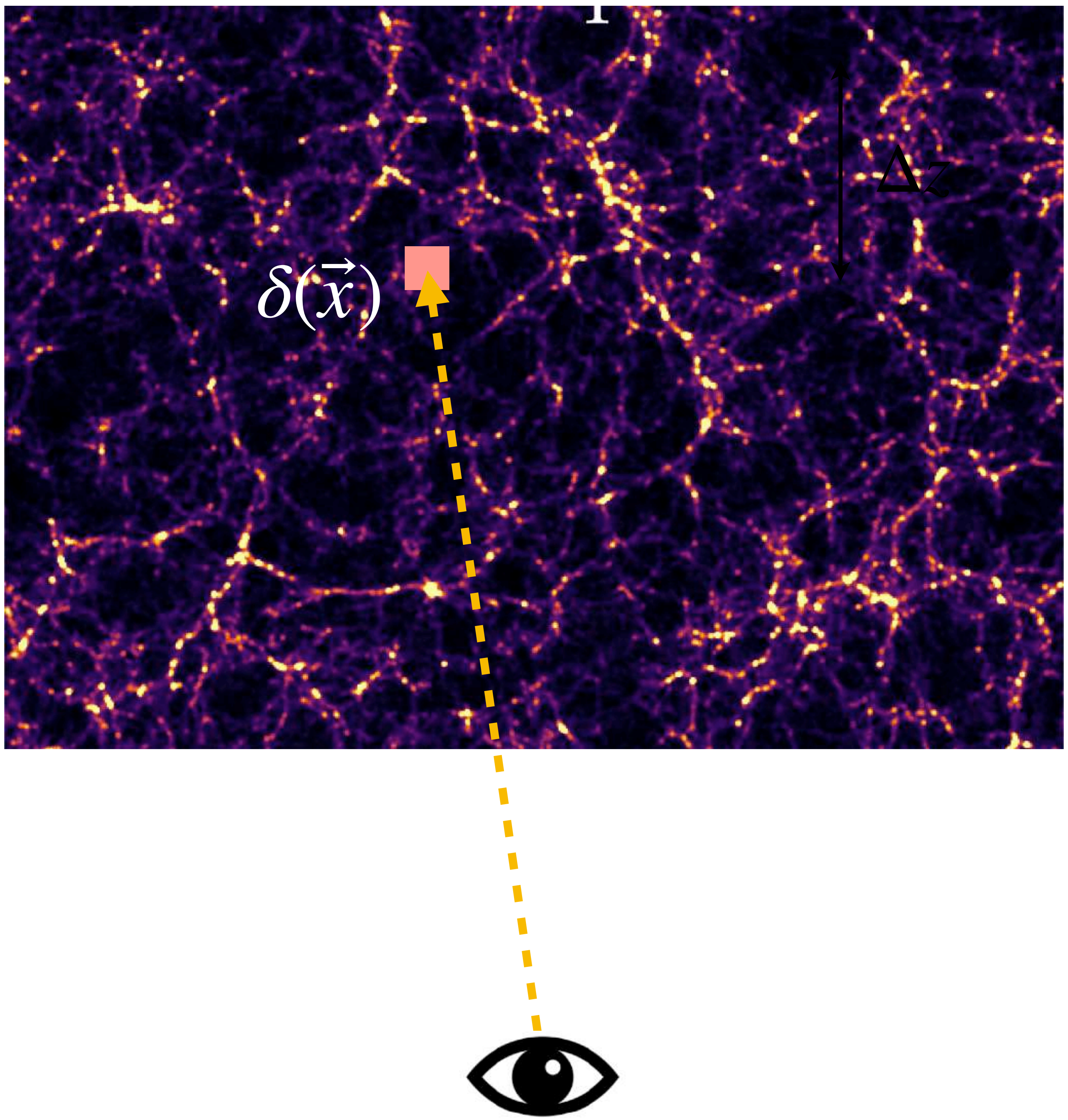
Growth rate of structures $f(t)$



Measurements of the growth rate can show deviations from GR!

Statistics of the density field

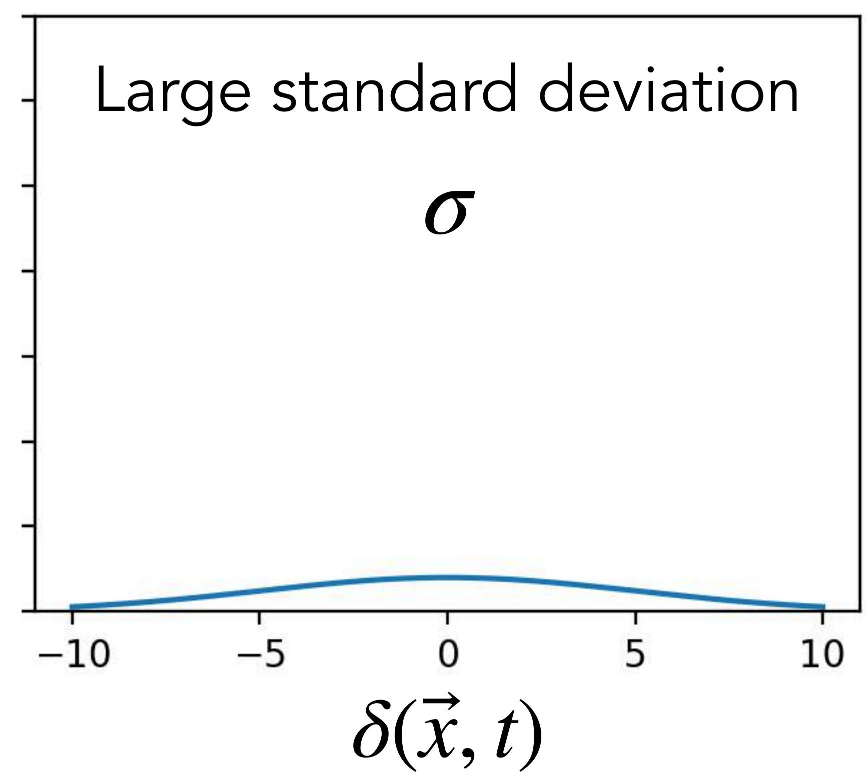
Matter density field $\delta(\vec{x}, t)$



Variance

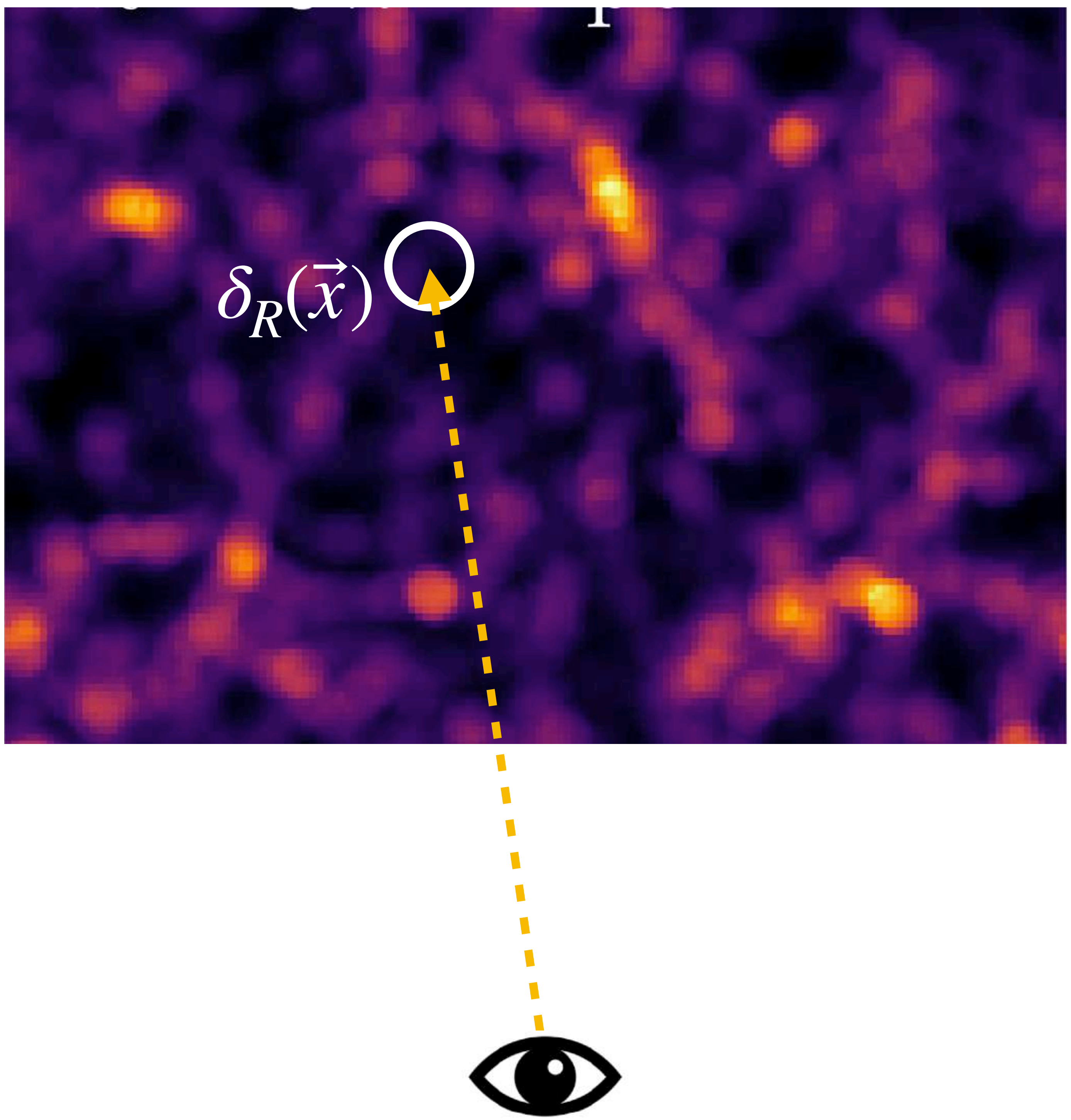
$$\sigma^2 \equiv \langle \delta(\vec{x}) \delta(\vec{x}) \rangle$$

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



Statistics of the density field

Matter density field $\delta(\vec{x}, t)$
smoothed over $R = 8h^{-1}\mathrm{Mpc}$



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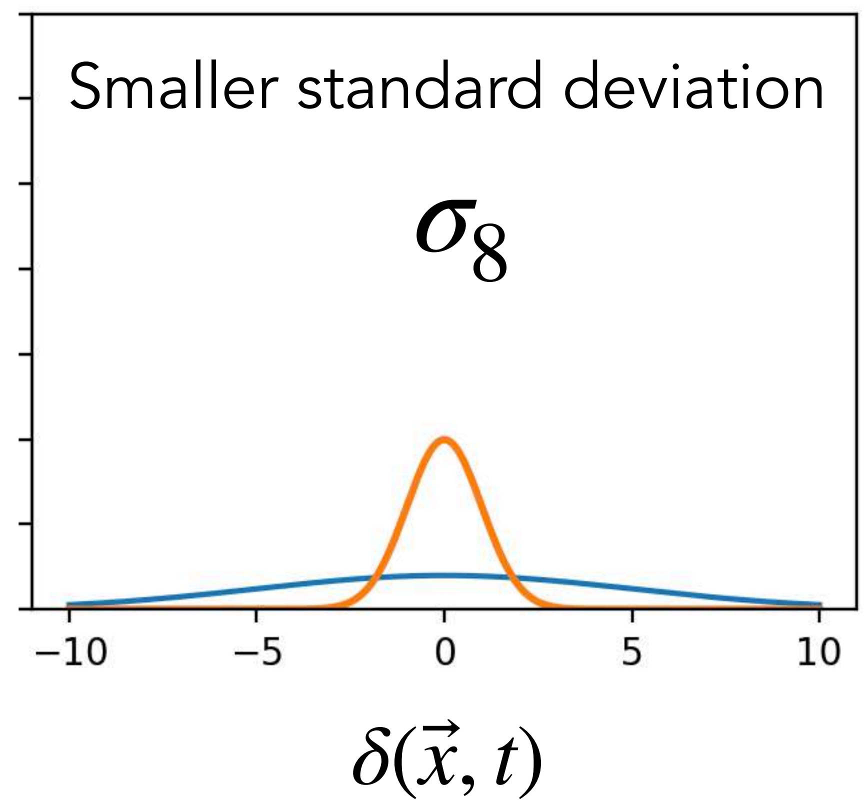
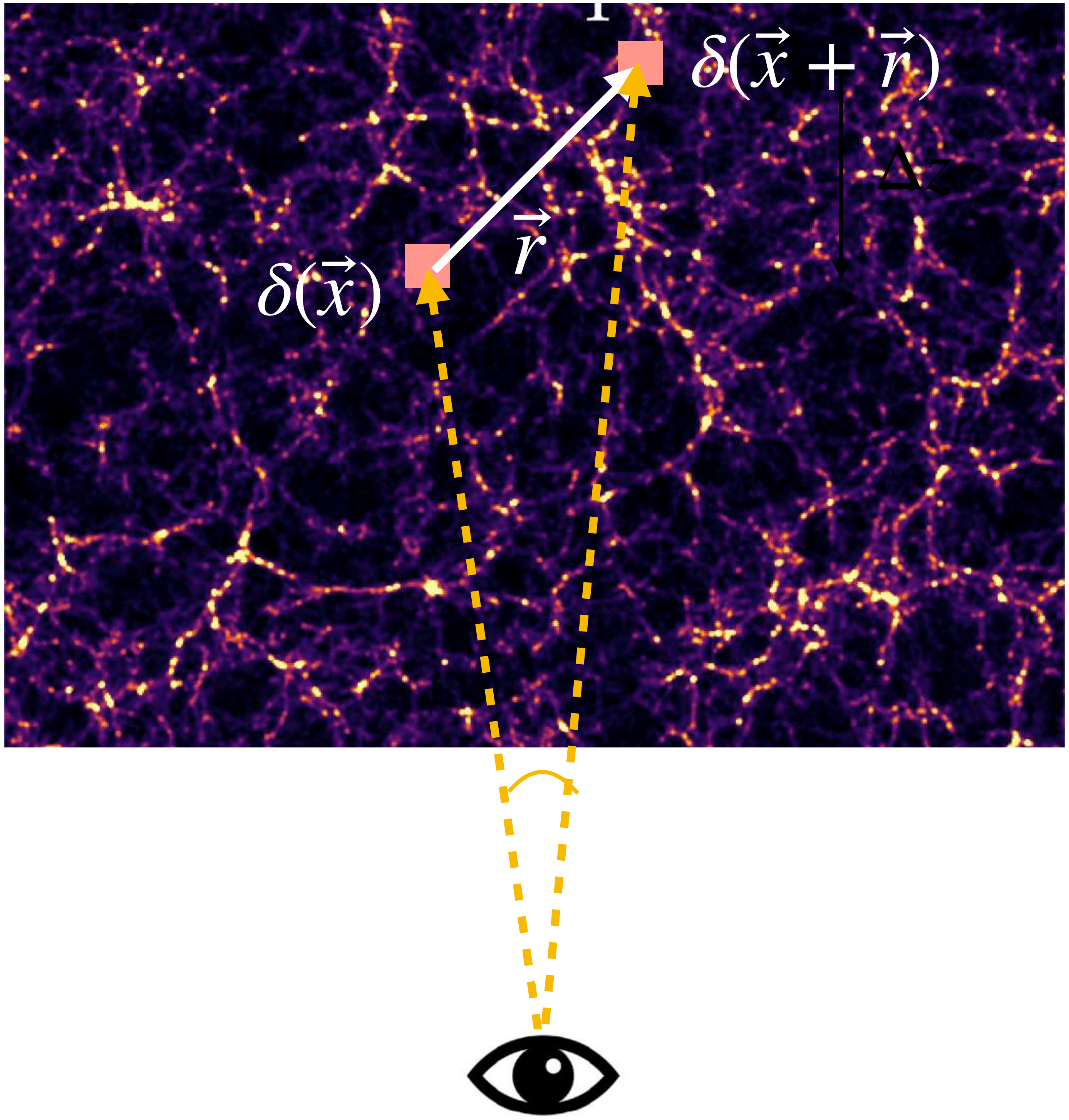


$\sigma_8 \approx 0.8$ **is a cosmological parameter**

Statistics of the density field

Matter density field $\delta(\vec{x}, t)$



Variance

$$\sigma^2 \equiv \langle \delta(\vec{x})\delta(\vec{x}) \rangle$$

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

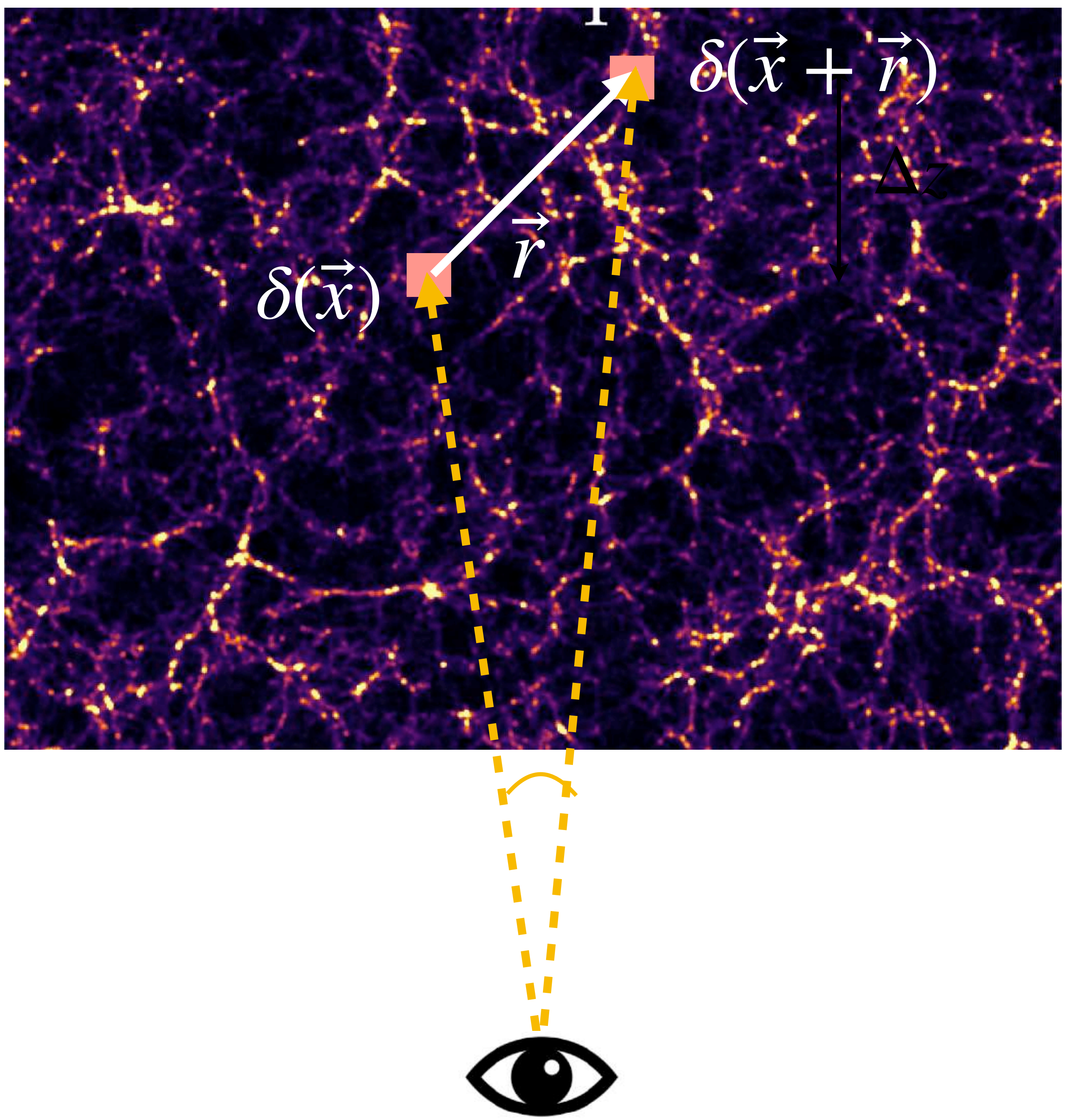
Correlation function

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

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

Statistics of the density field

Matter density field $\delta(\vec{x}, t)$



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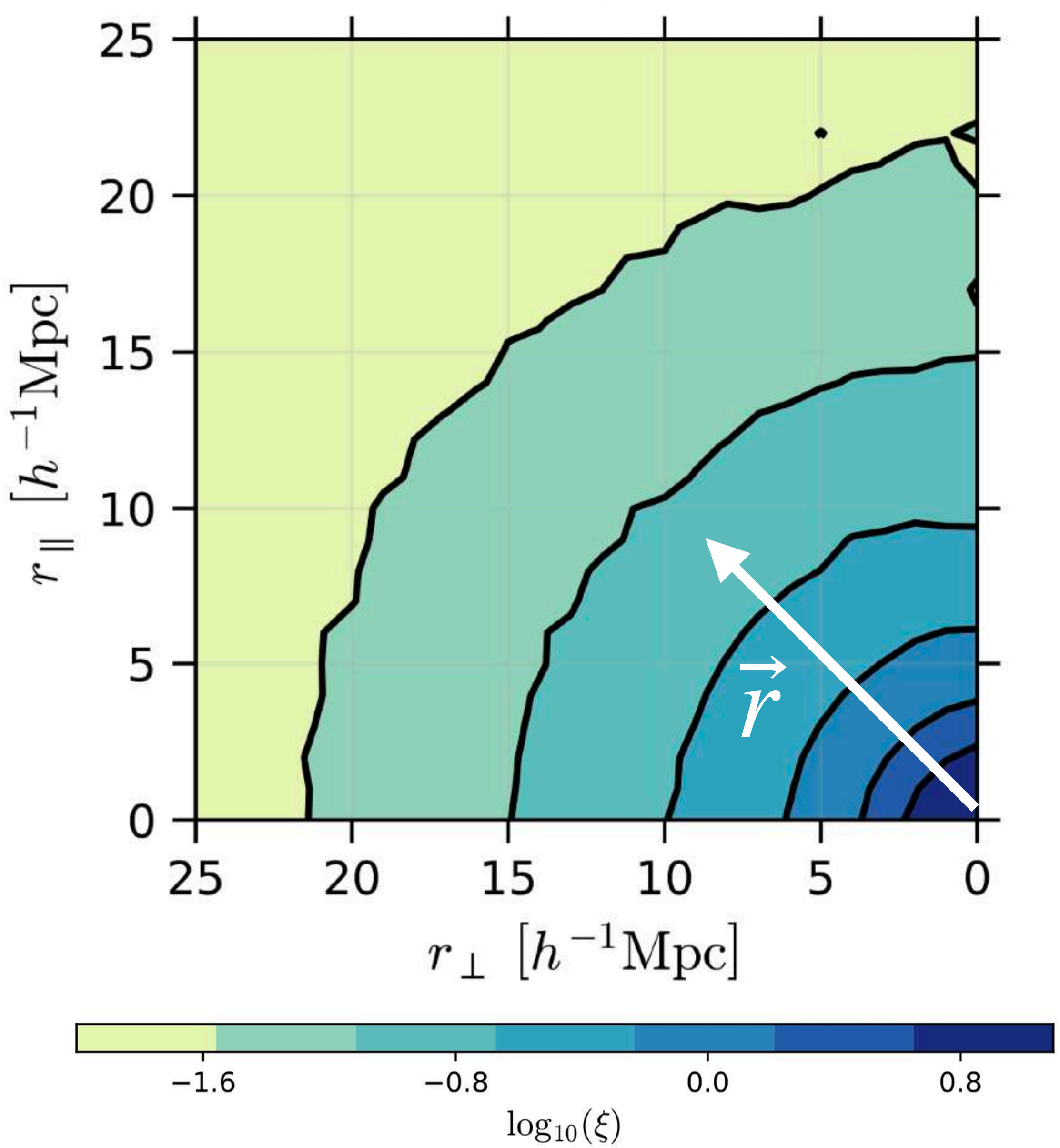
$$\xi(\vec{r}) \equiv \langle \delta(\vec{x})\delta(\vec{x} + \vec{r}) \rangle = \xi(r_{\parallel}, r_{\perp})$$

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

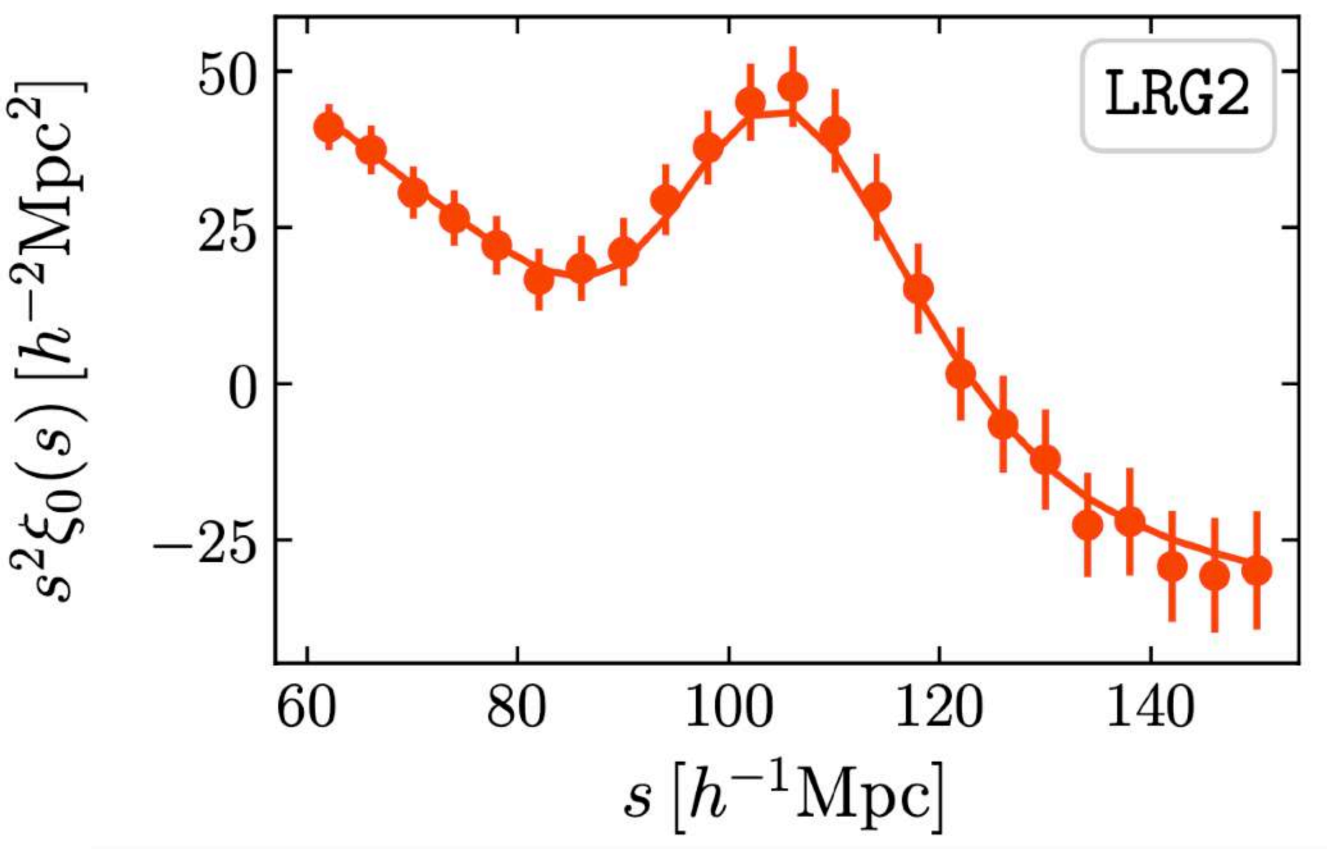


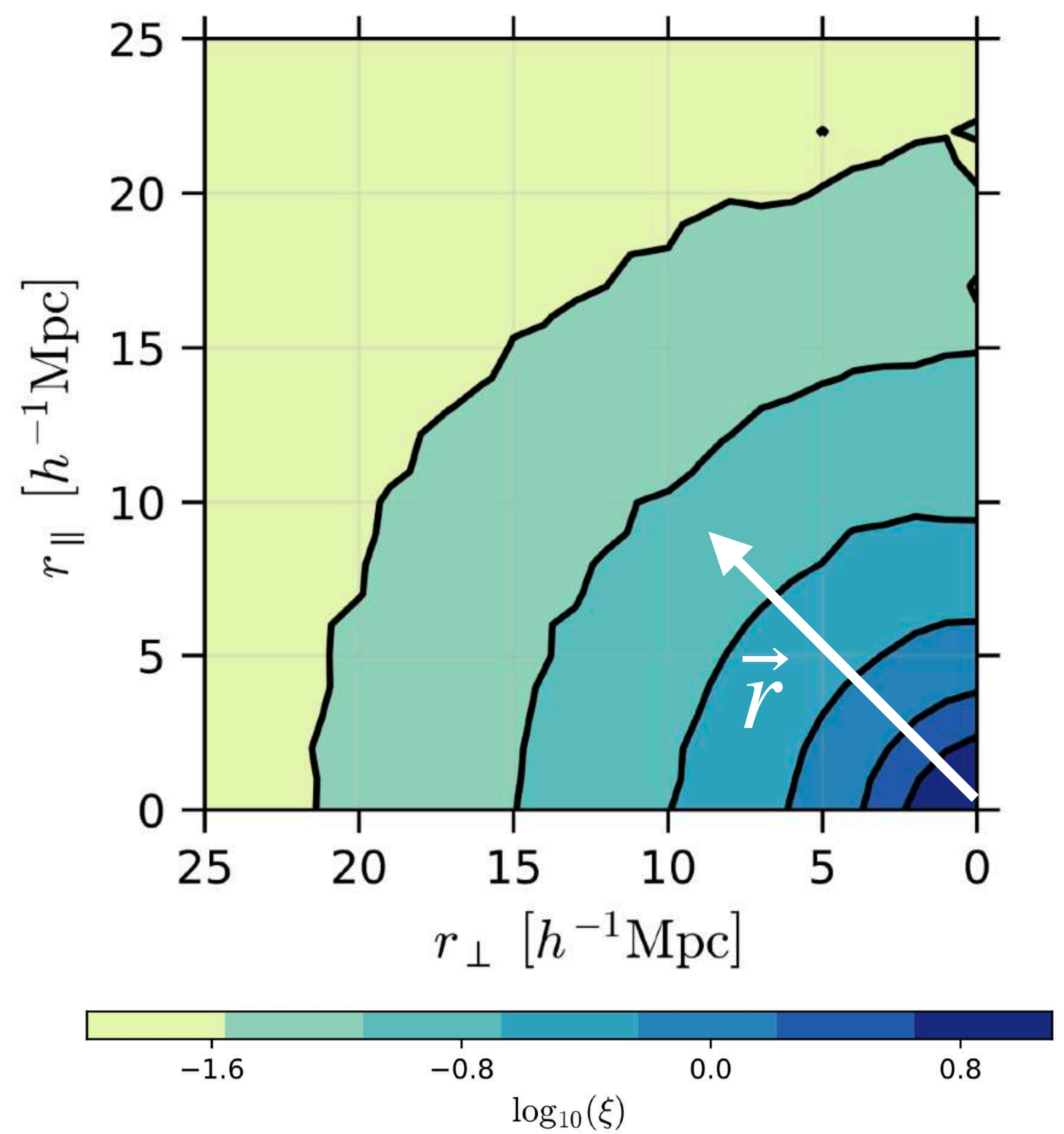
Statistics of the density field

Correlation function

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

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



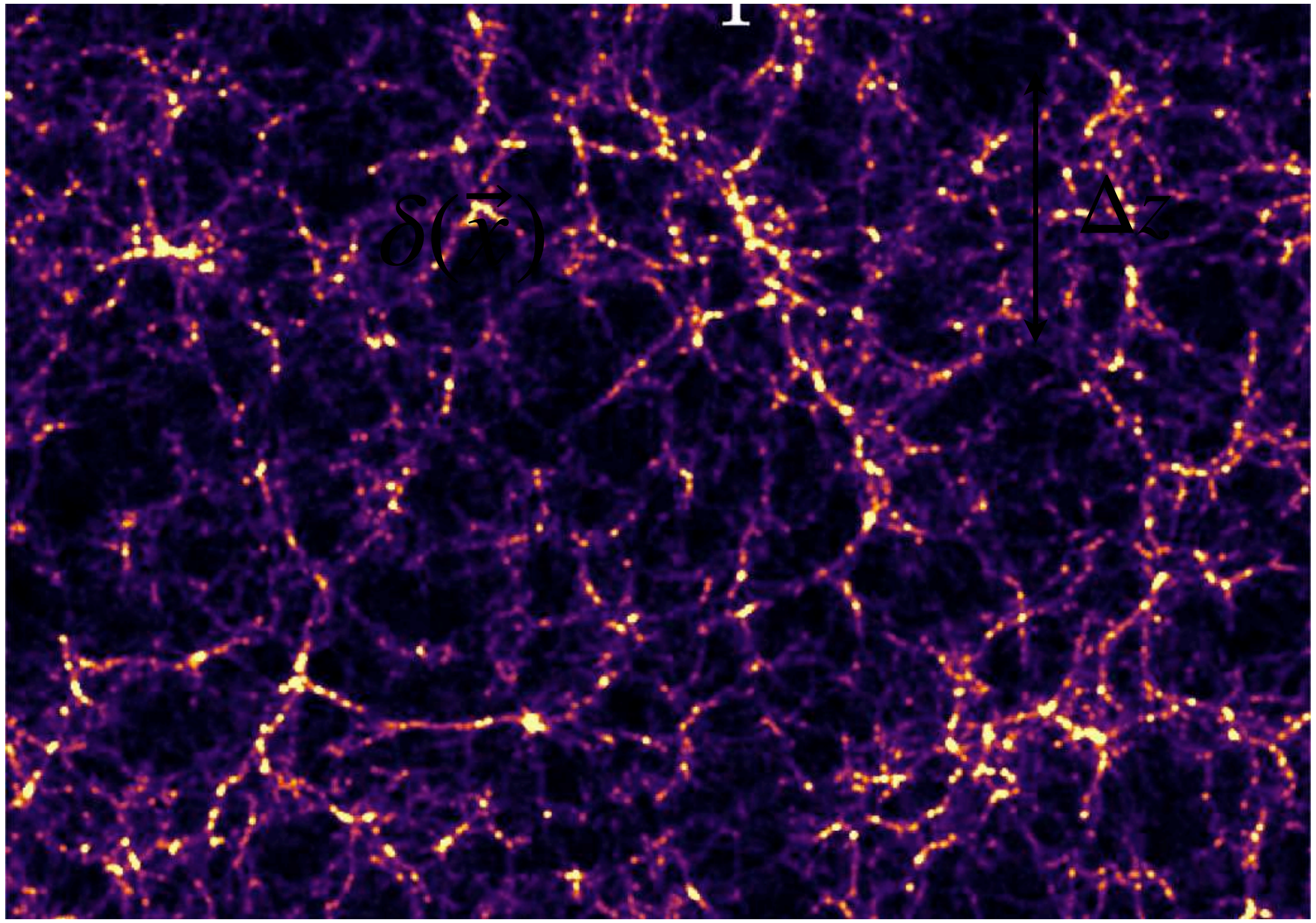


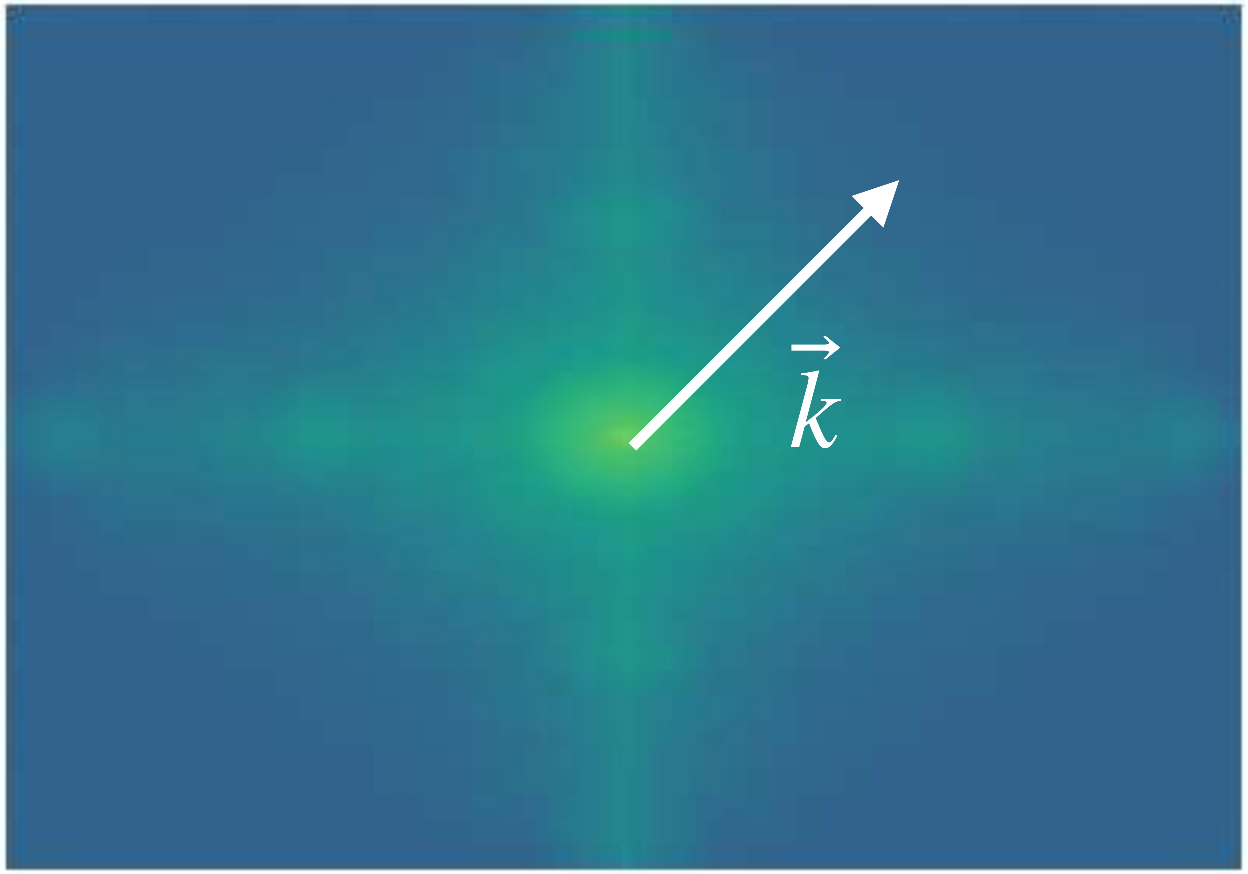
Statistics of the density field

FFT

Matter density field $\delta(\vec{x}, t)$

Fourier amplitudes $\tilde{\delta}(\vec{k}, t)$



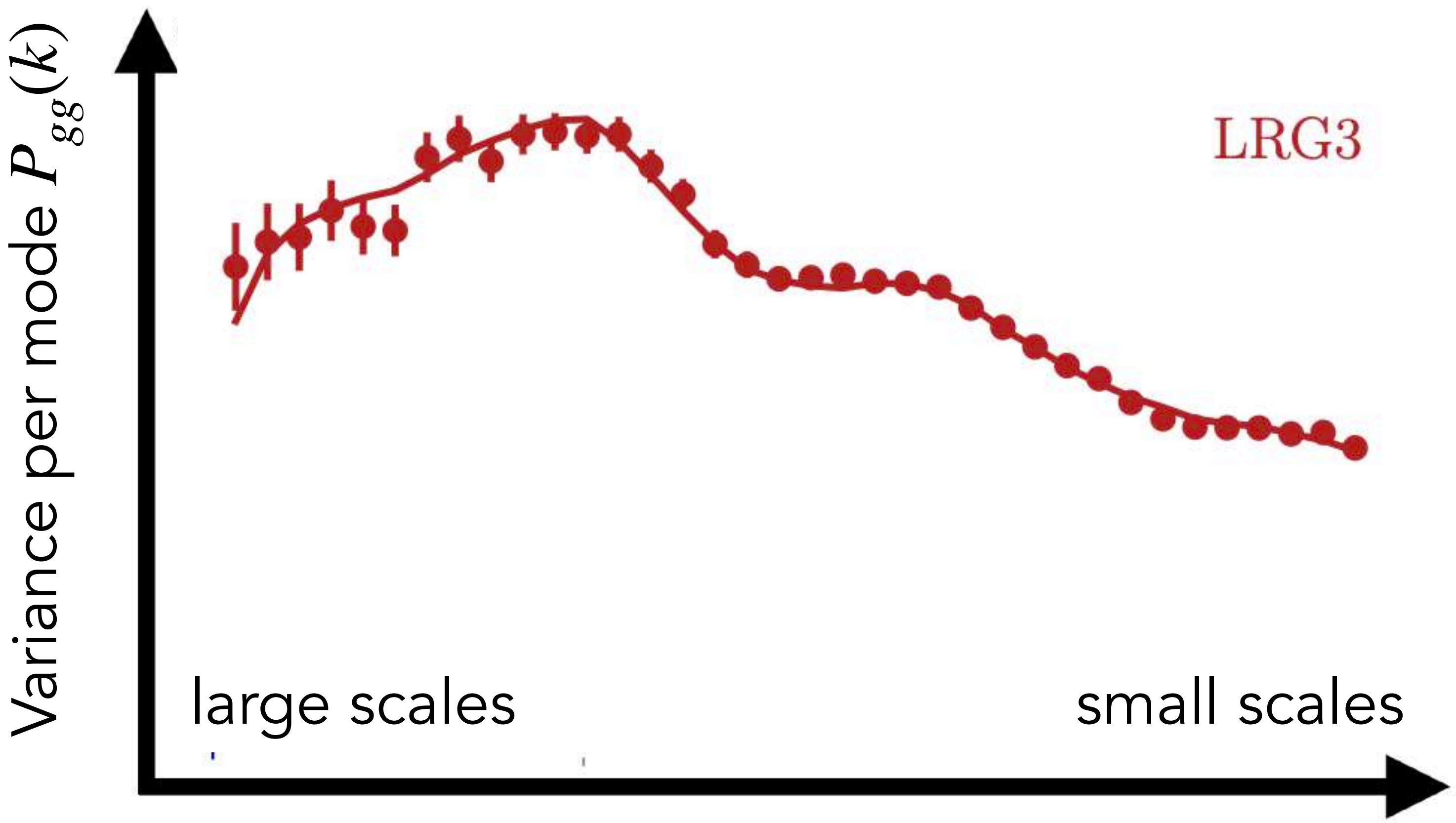


Statistics of the density field

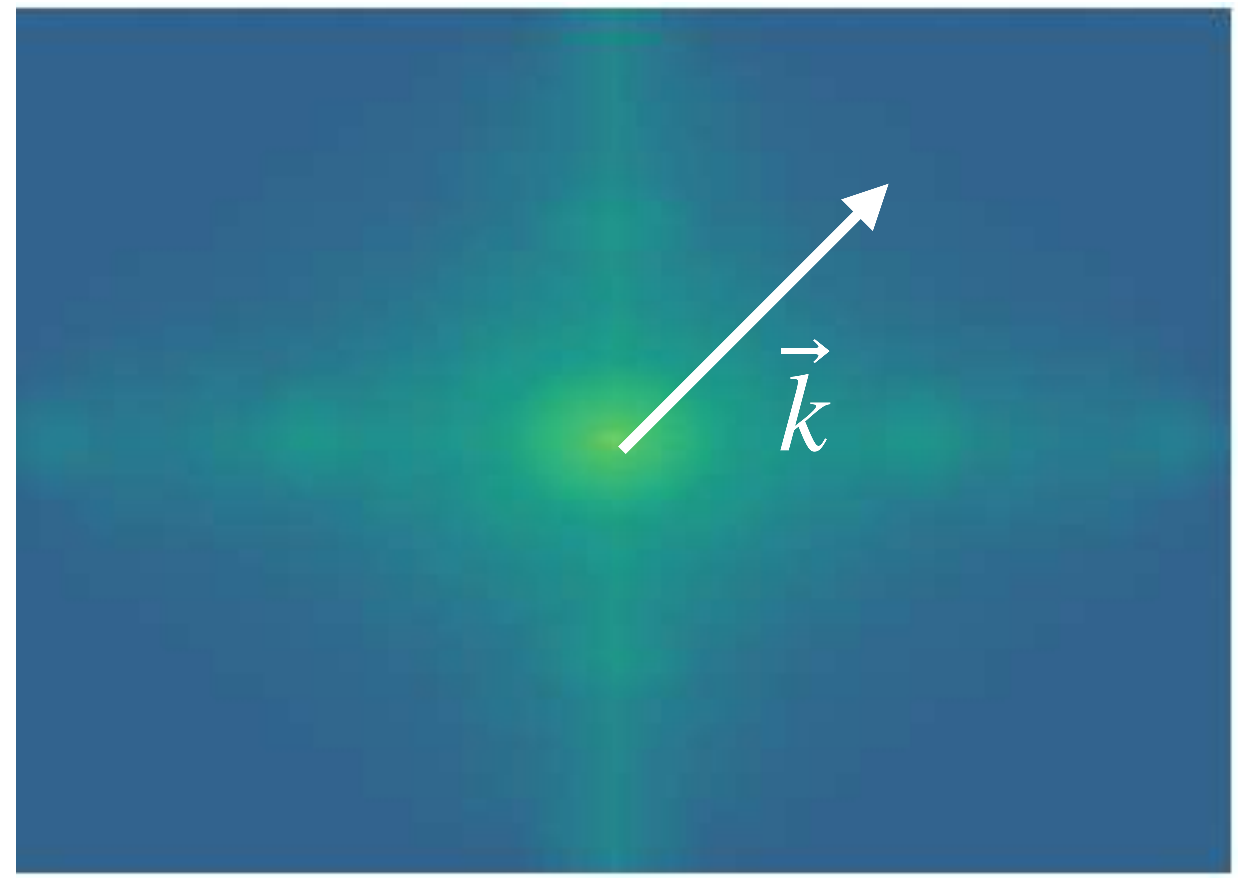
Power spectrum

$$(2\pi)^3\delta_D(\vec{k}+\vec{k}')P(\vec{k}) = \left\langle \delta_g(\vec{k})\delta_g^*(\vec{k}') \right\rangle$$

Fourier analogous of the correlation function



Fourier amplitudes $\tilde{\delta}(\vec{k}, t)$

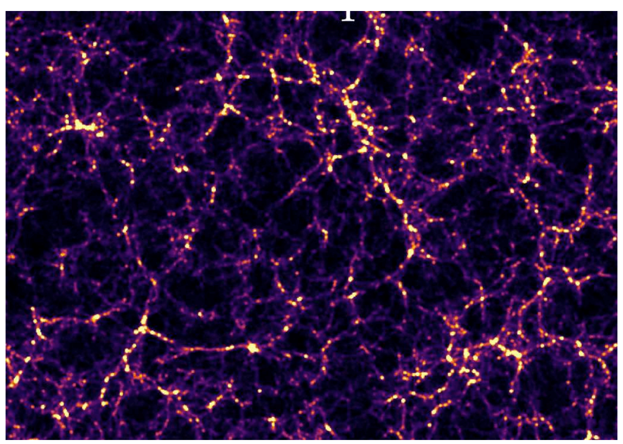


Statistics of the density field

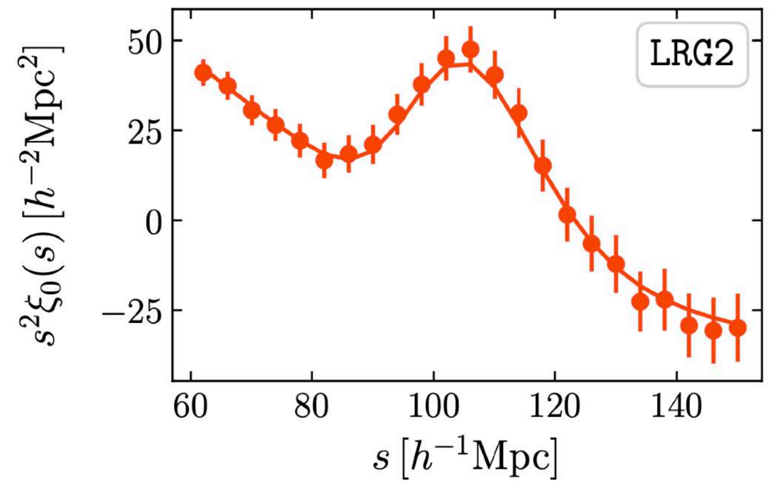
Statistical measurement

Galaxy survey

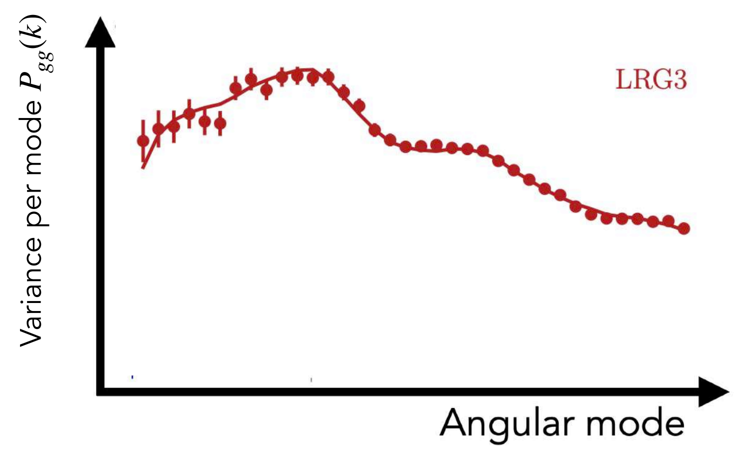
$\delta(\vec{x}, t)$



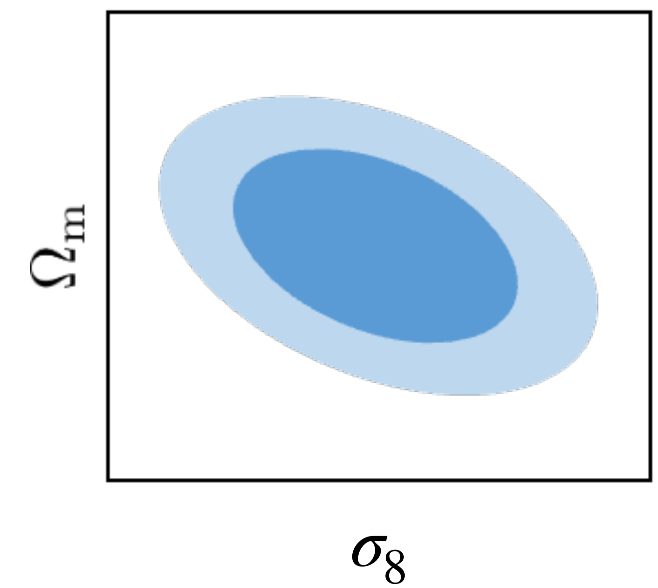
Correlation function



Power spectrum



Cosmological parameters



The full shape of $\xi(\vec{r})$ or $P(\vec{k})$ depends on cosmological parameters (and on the gravity model!)

What about peculiar velocities?

What about peculiar velocities?

Continuity equation

$$\overrightarrow{\nabla} \cdot \vec{v}(\vec{x}, t) \sim \dot{\delta}(\vec{x}, t)$$

What about peculiar velocities?

Continuity equation

$$\vec{\nabla} \cdot \vec{v}(\vec{x}, t) \sim \dot{\delta}(\vec{x}, t) \sim f(t)\,\delta(\vec{x}, t)$$

Growth-rate of structures

Smooth field on spheres of 8 Mpc/h
Its spatial variance is

$$\langle \delta^2(\vec{x}, t) \rangle_{8h^{-1}\mathrm{Mpc}} = \sigma_8^2(t)$$

Velocity field $\vec{v}(\vec{x}, t)$ is correlated spatially like $\delta(\vec{x}, t)$

Its amplitude is proportional to:

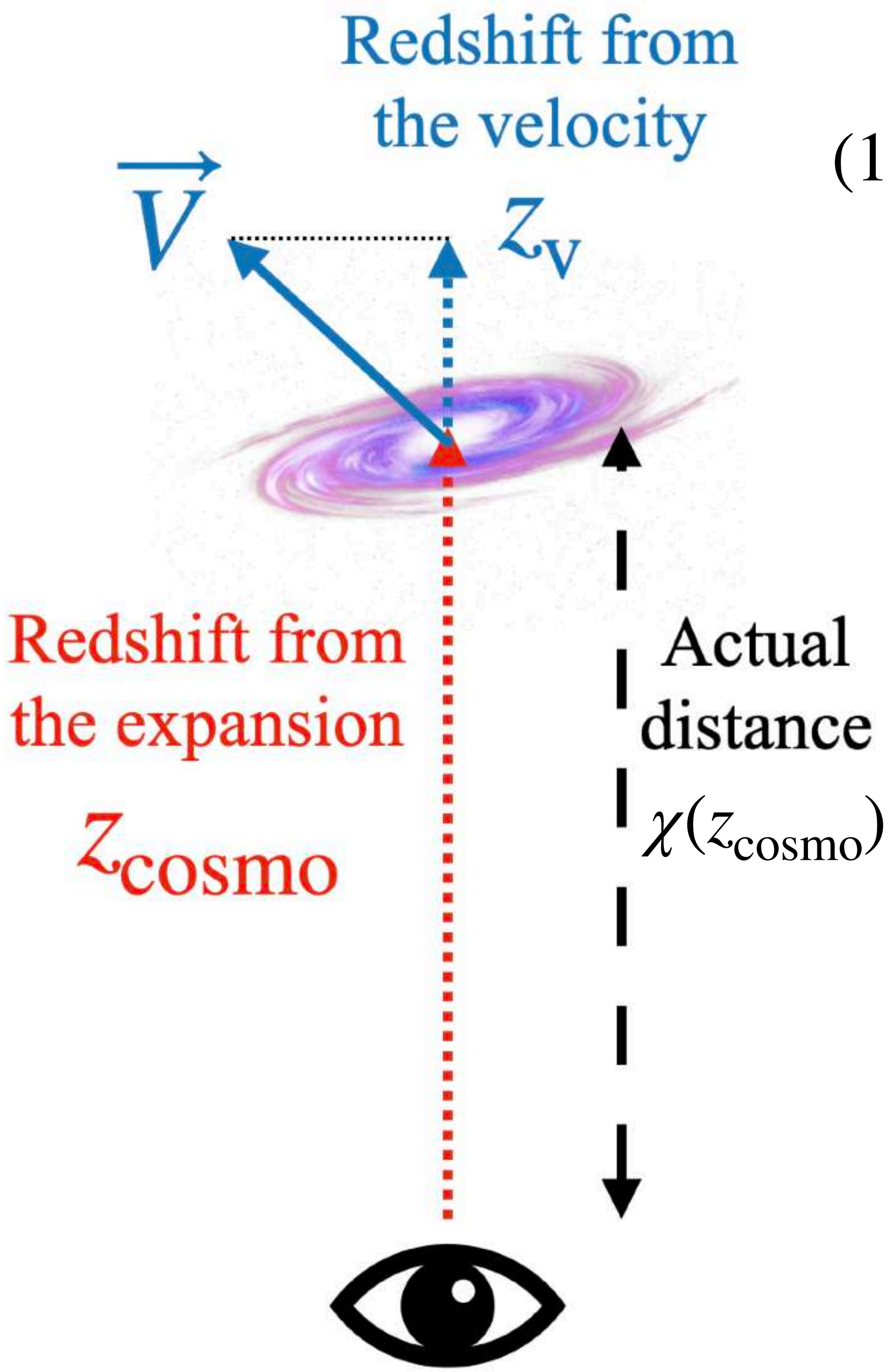
$$f(t)\sigma_8(t)$$

Redshift-space distortions (RSD)

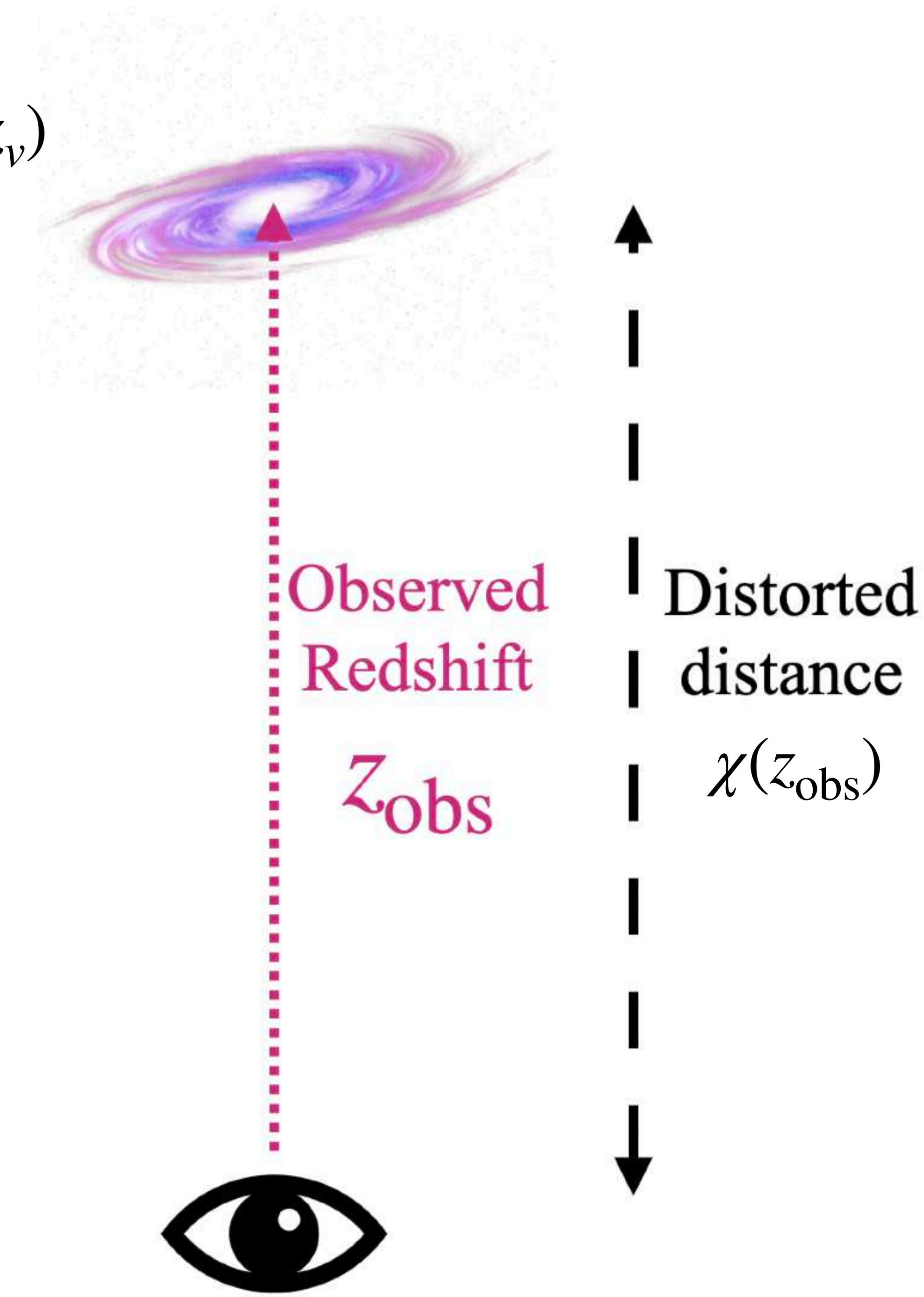
We measure redshifts : peculiar velocities affect our distance inferences

Observed redshift is :

$$(1 + z_{obs}) = (1 + z_{cosmo})(1 + z_v)$$



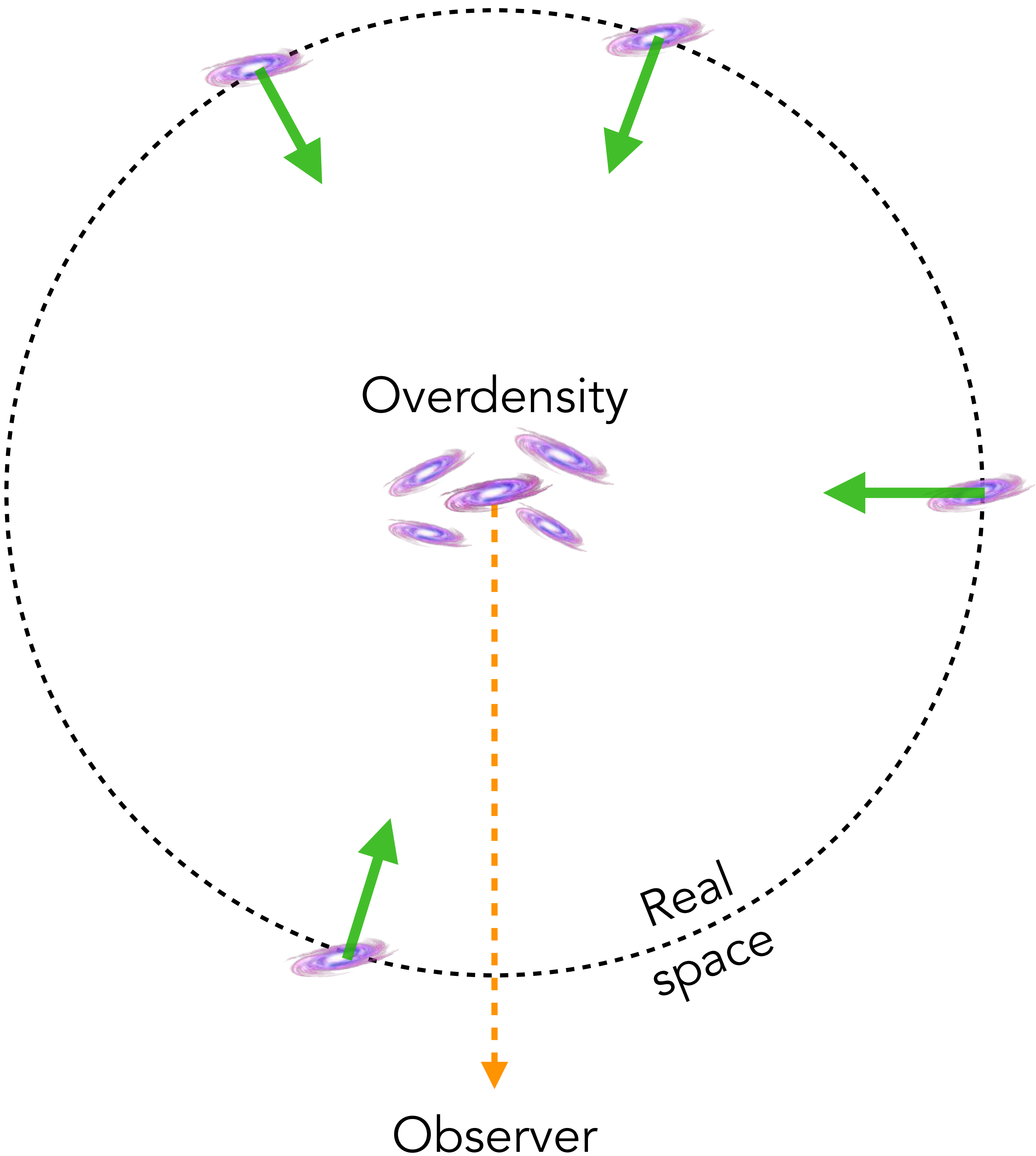
Real space



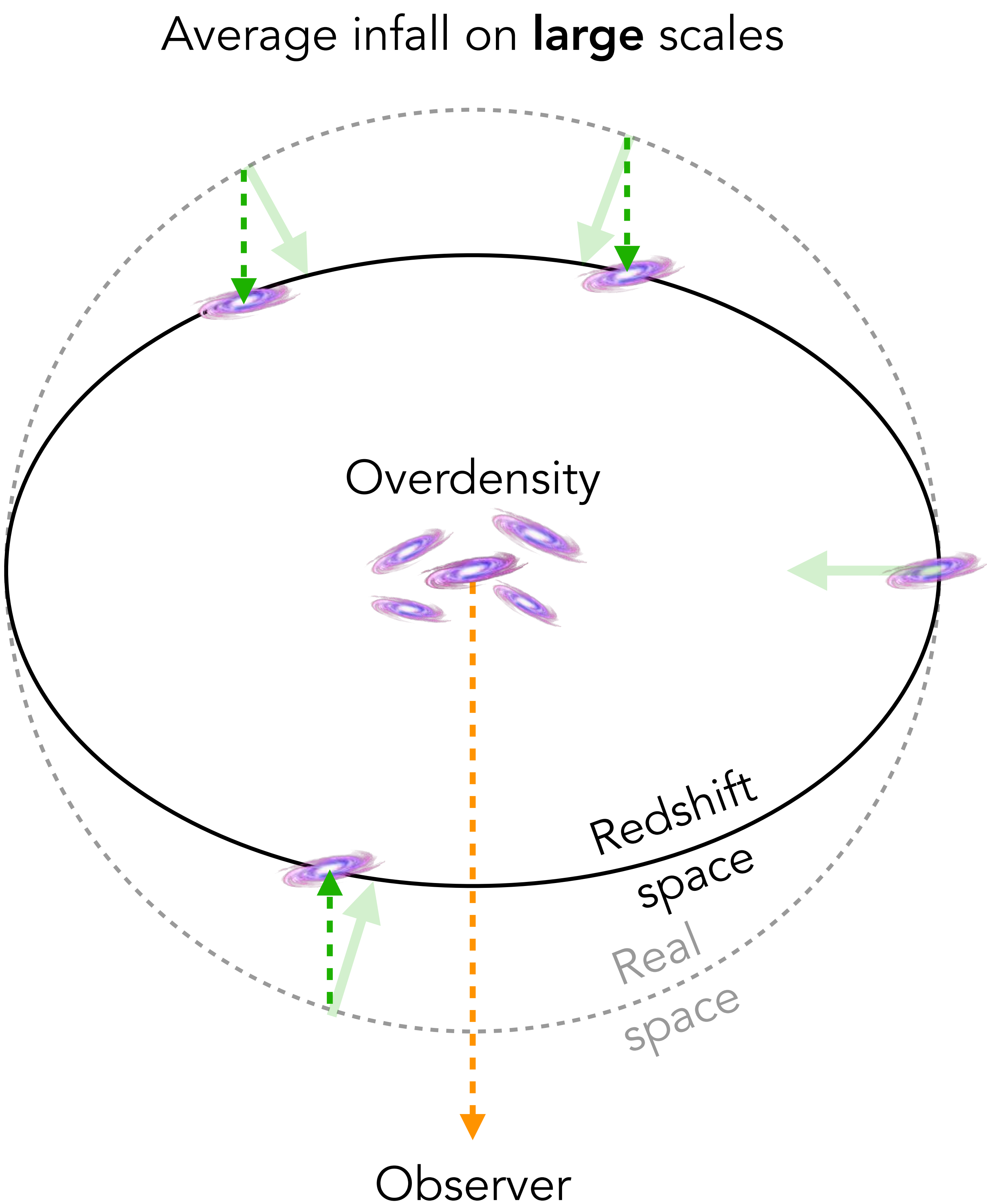
Redshift space

Redshift-space distortions (RSD)

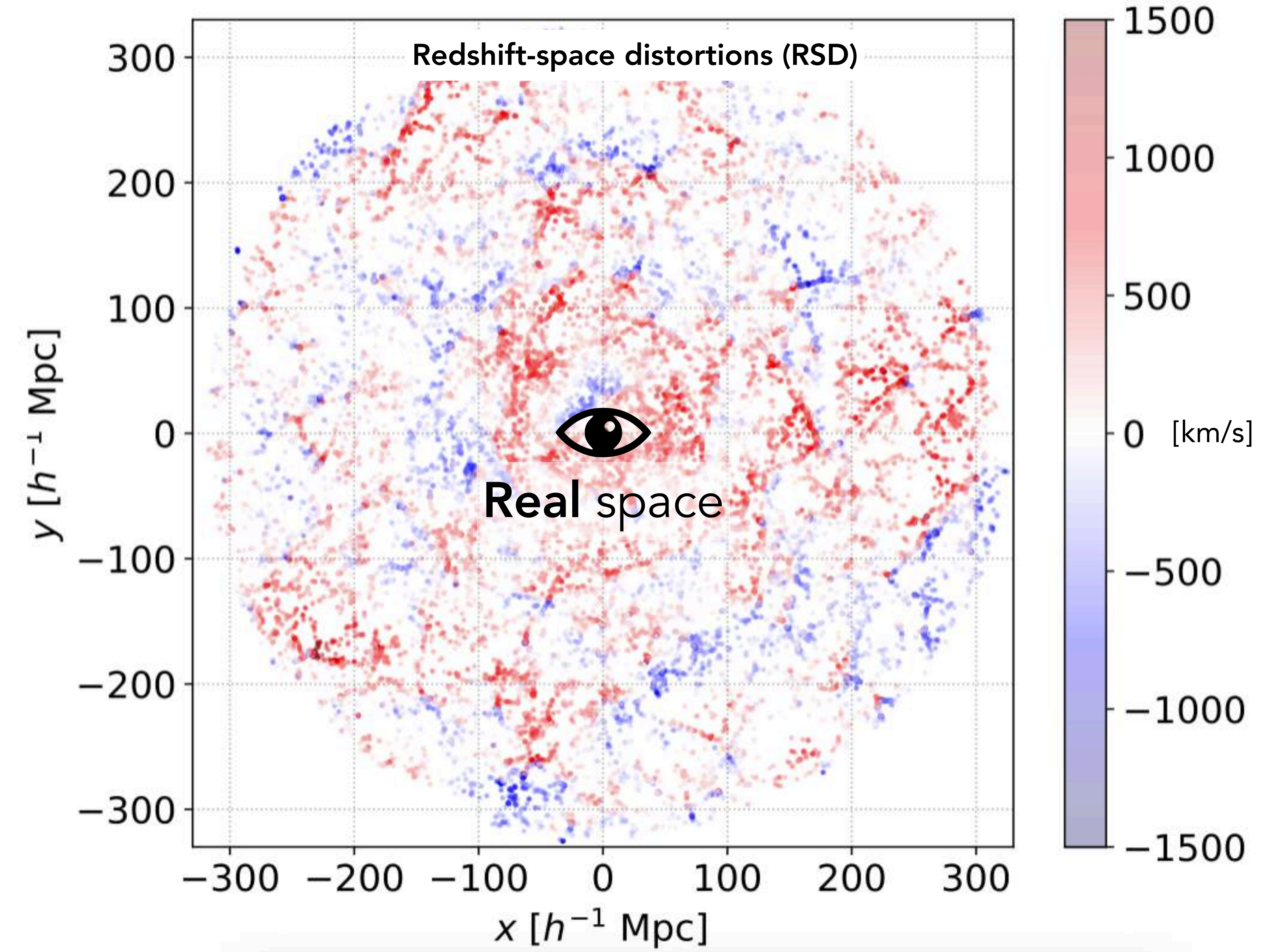
Average infall on **large** scales



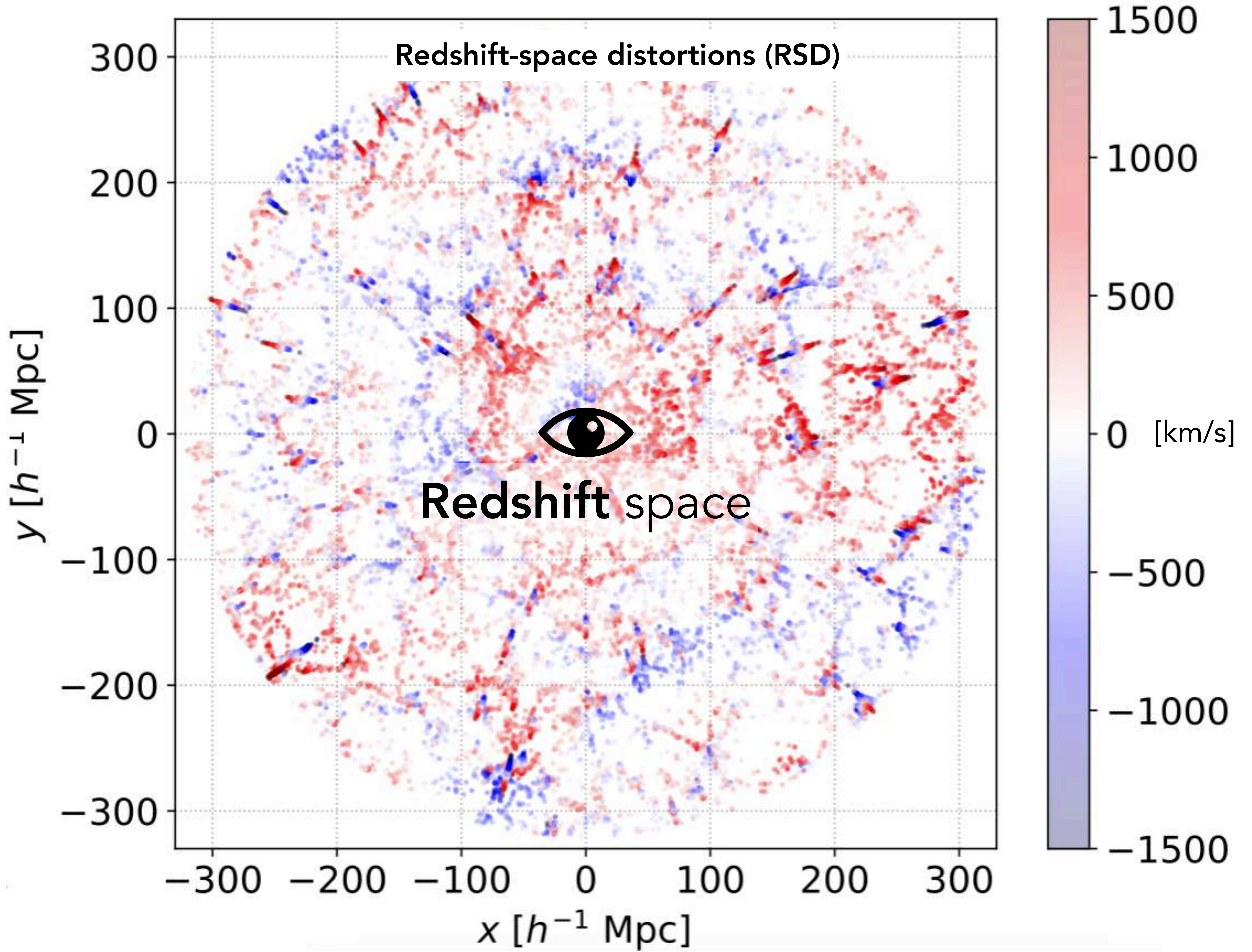
Redshift-space distortions (RSD)



Squashing on radial direction on **large** scales

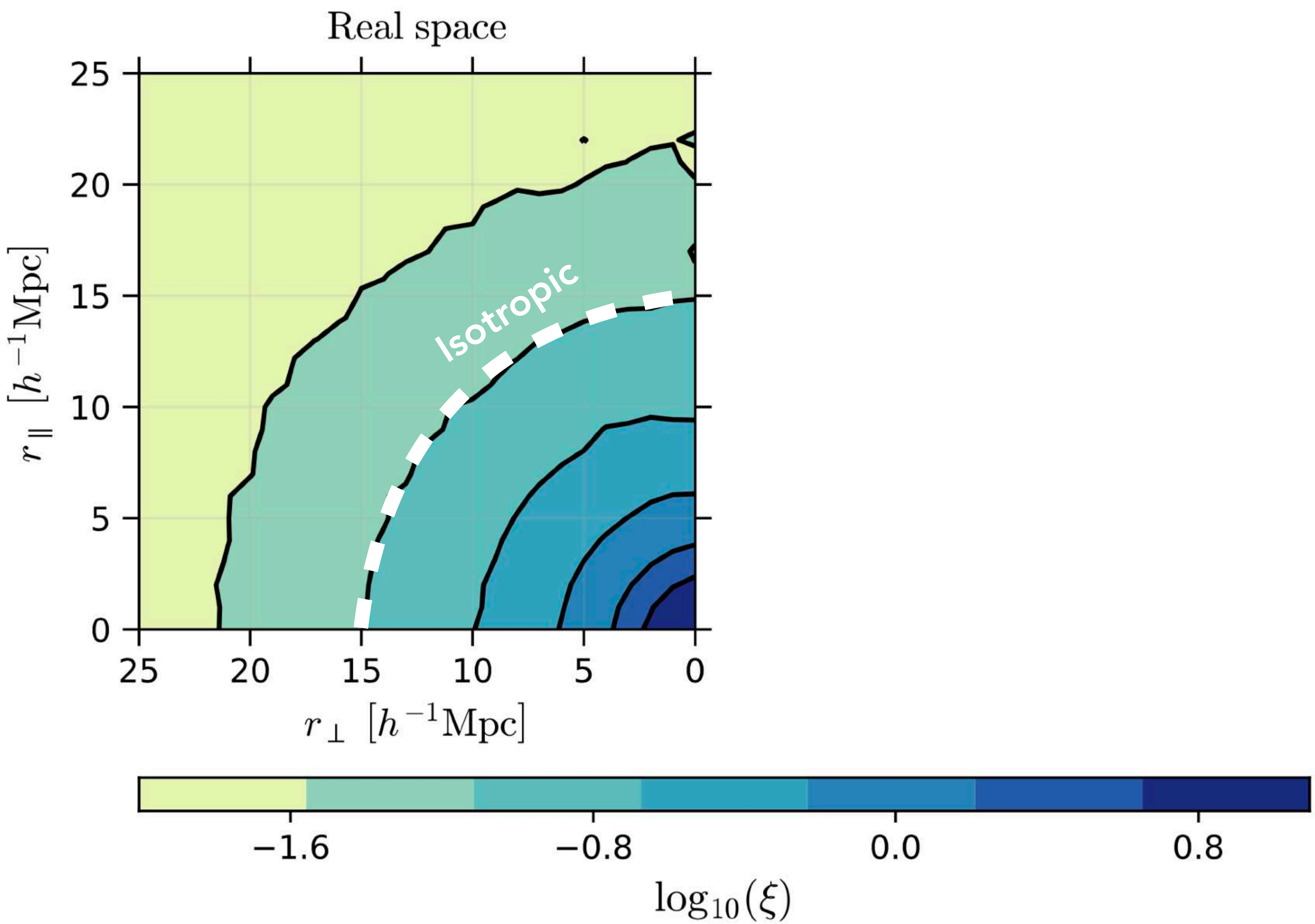


Redshift-space distortions (RSD)
Real space
300
200
100
0
−100
−200
−300
y [h⁻¹ Mpc]
−300
−200
−100
0
100
200
300
x [h⁻¹ Mpc]
1500
1000
500
0
[km/s]
−500
−1000
−1500


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

Redshift-space distortions (RSD)

Impact on correlation function $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$



Simulation by Kuruvilla & Porciani 2018

Redshift-space distortions (RSD)

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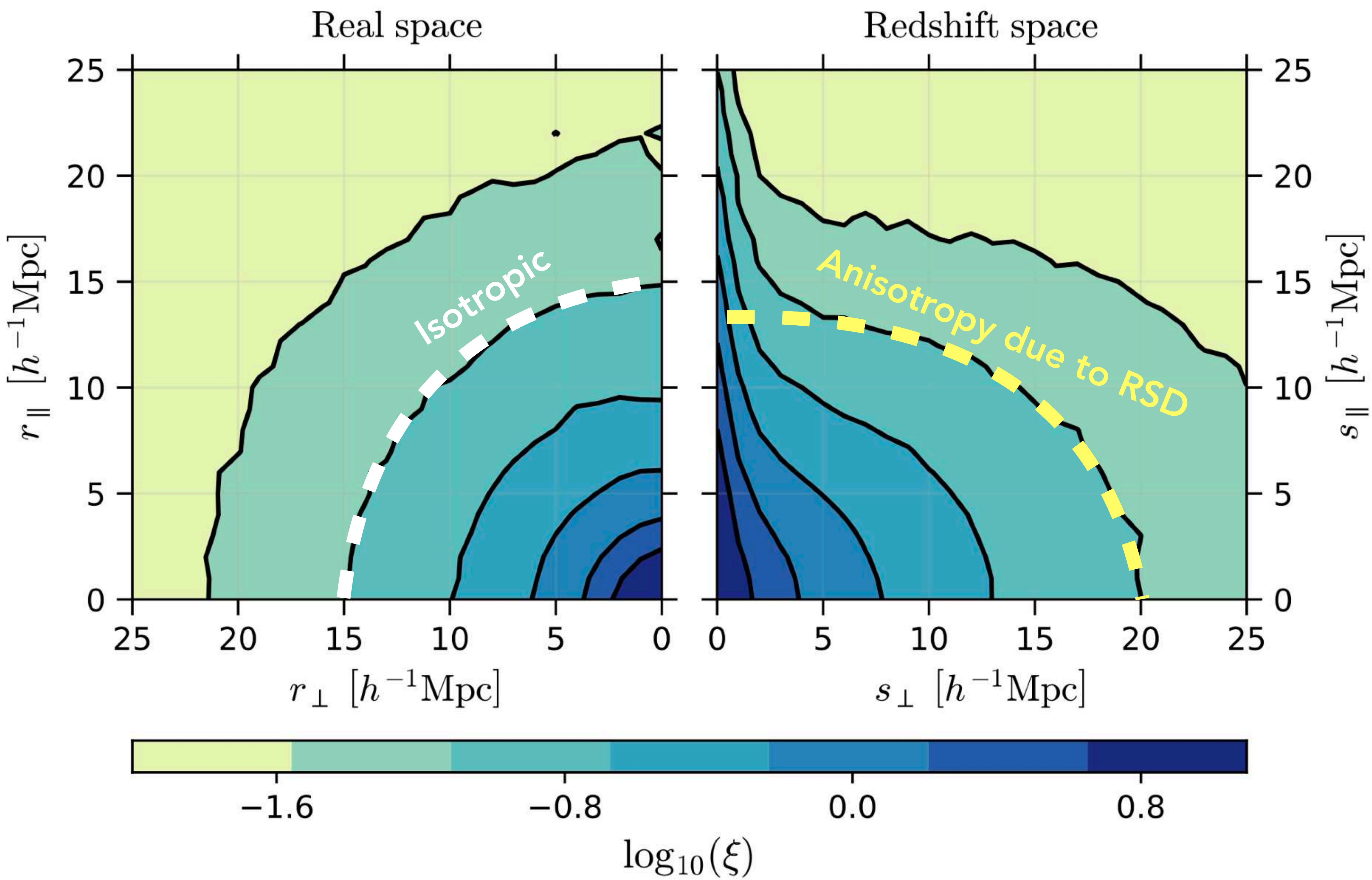

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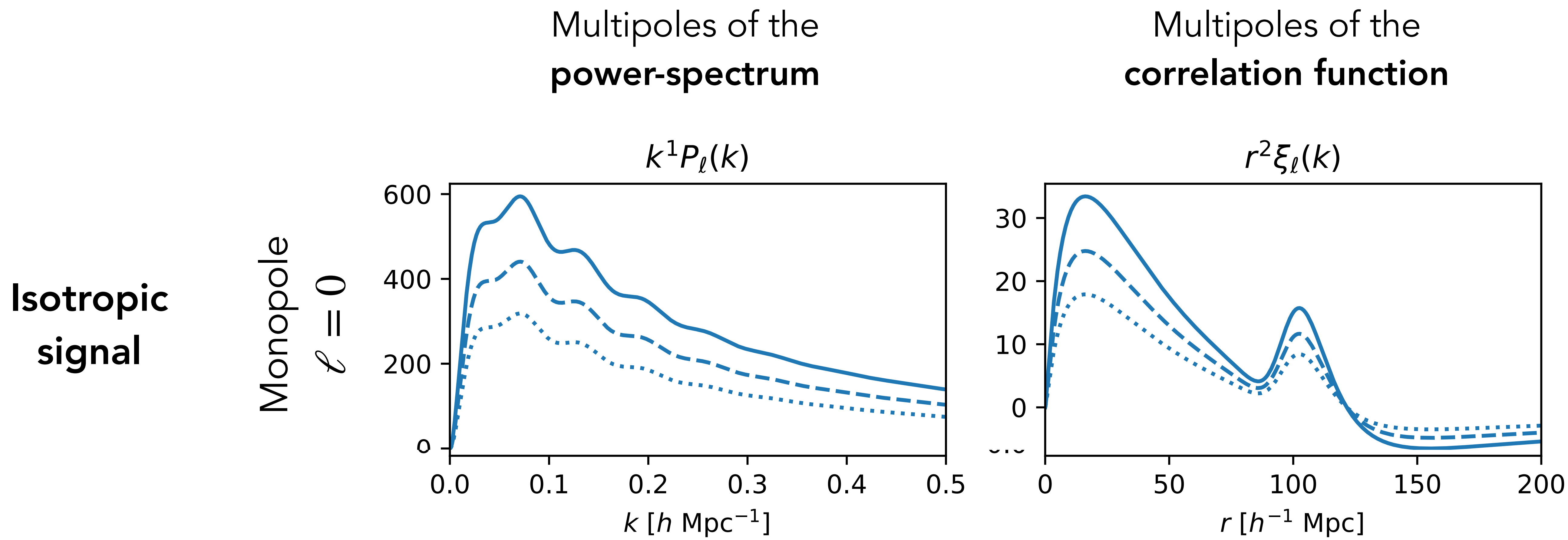


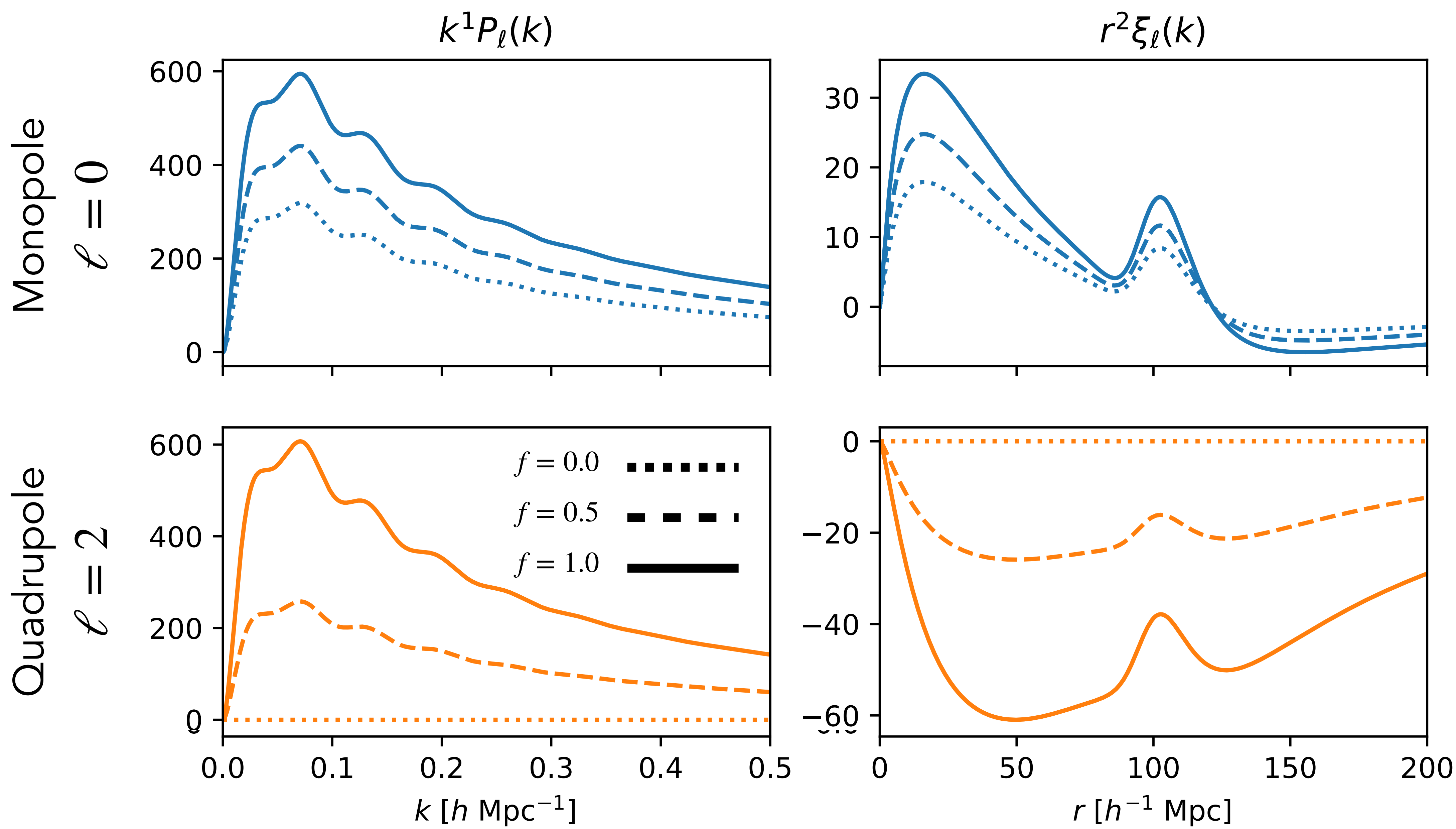
Redshift-space distortions (RSD)

Multipoles of the **power-spectrum**

Multipoles of the **correlation function**

Isotropic signal

Anisotropic signal



Anisotropic clustering constrains the growth rate of structures $f(t)\sigma_8(t)$

Measuring the growth of structures with DESI

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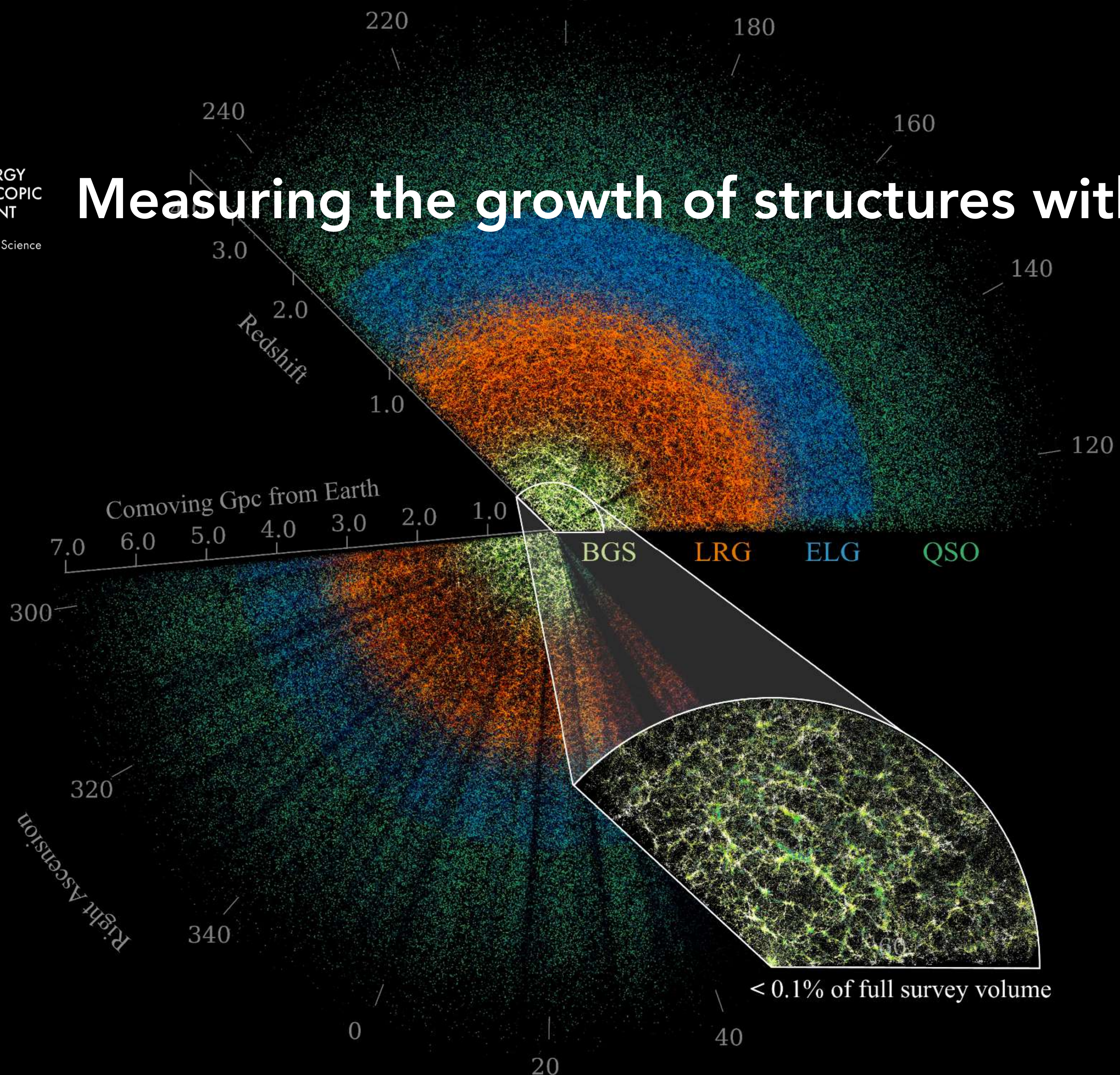
U.S. Department of Energy Office of Science



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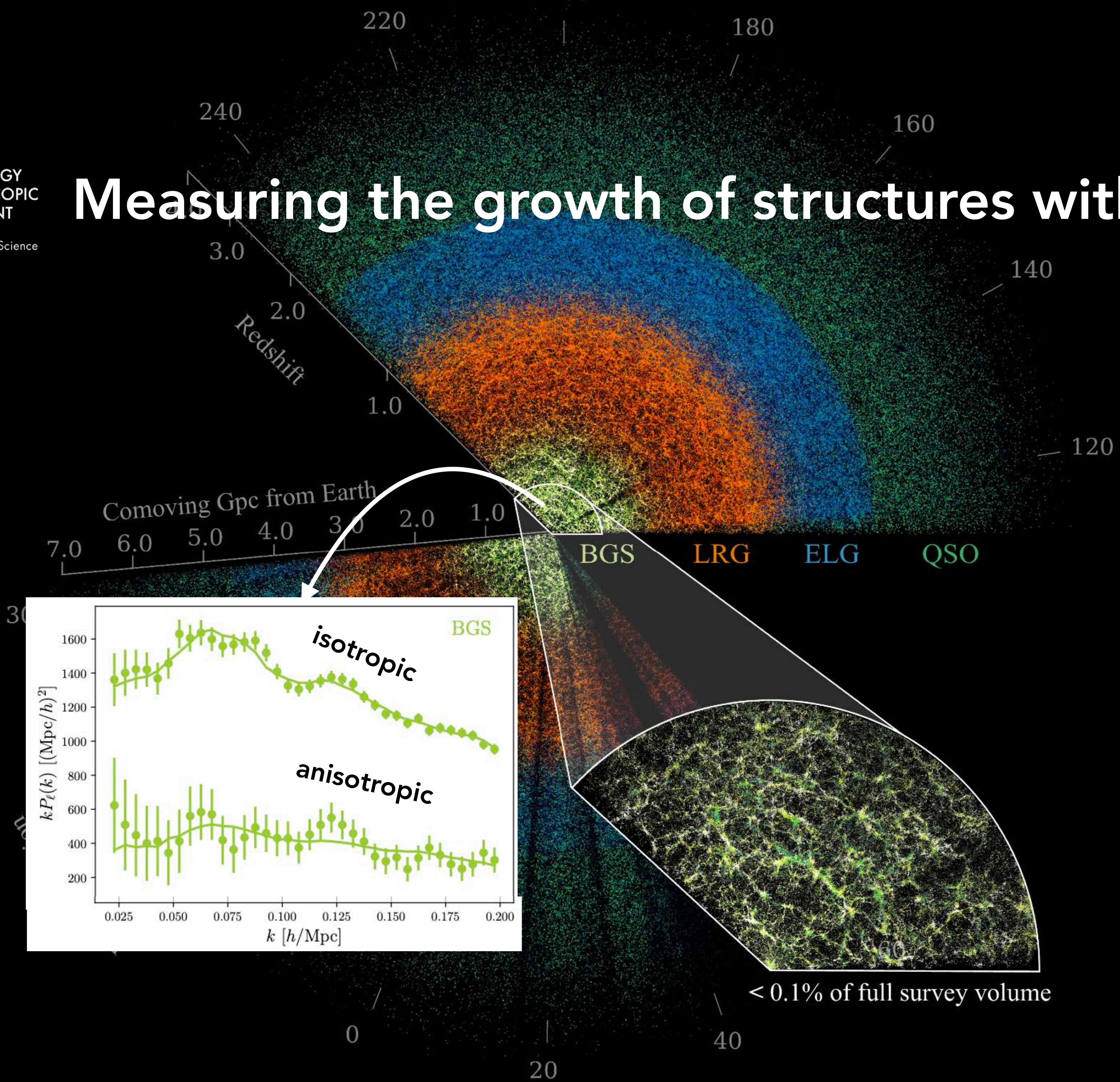
Measuring the growth of structures with DESI



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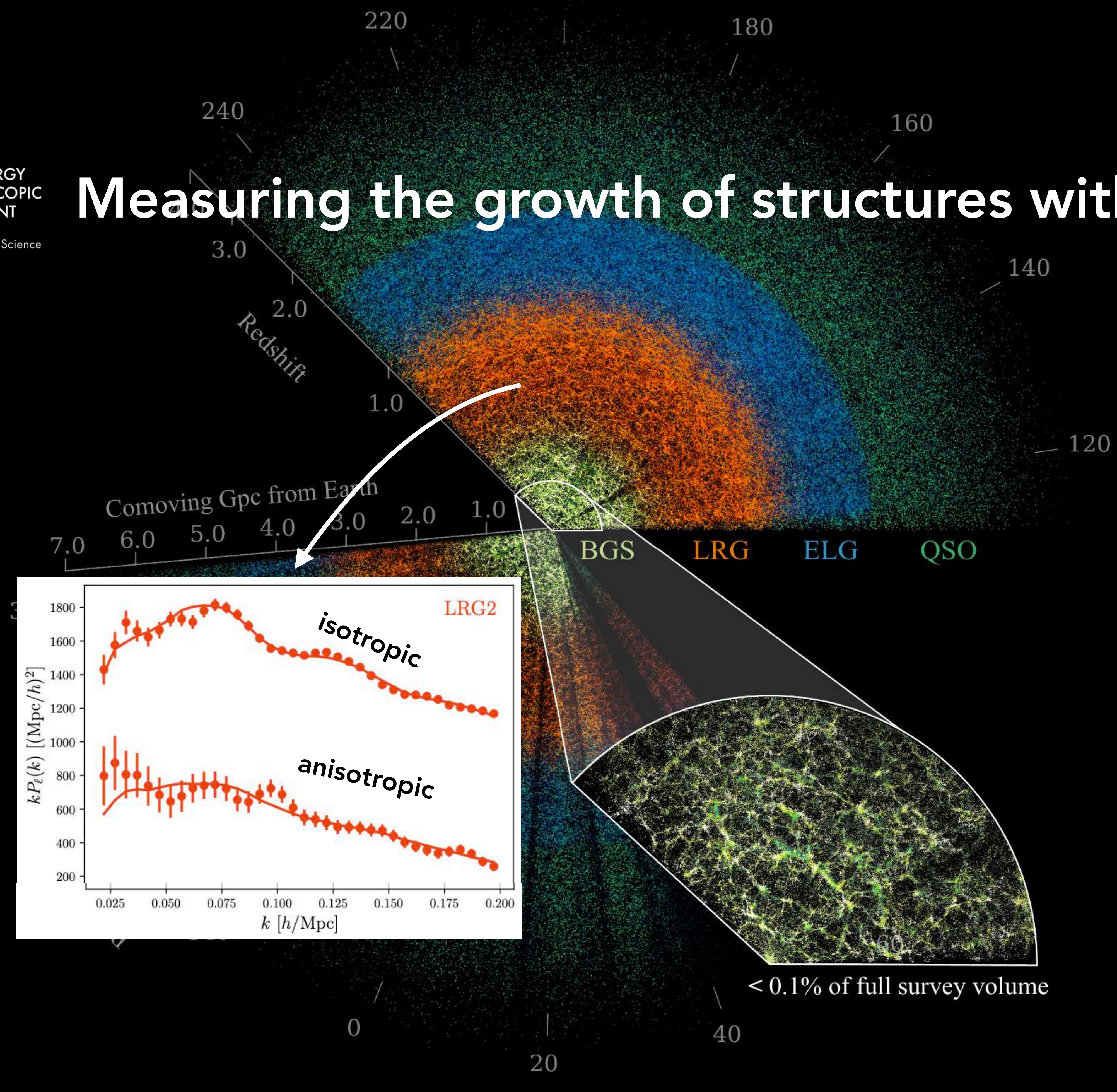
Measuring the growth of structures with DESI



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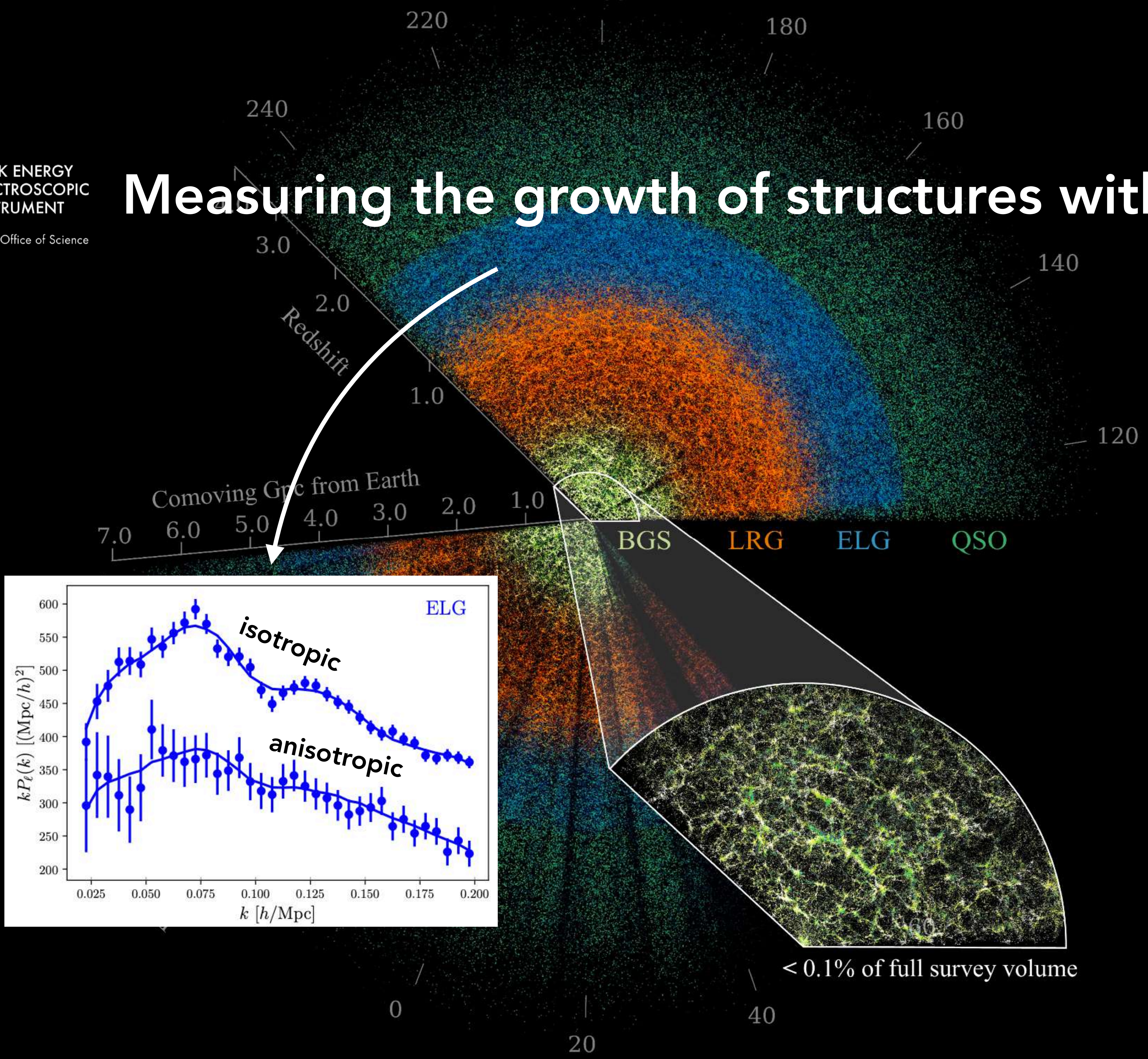

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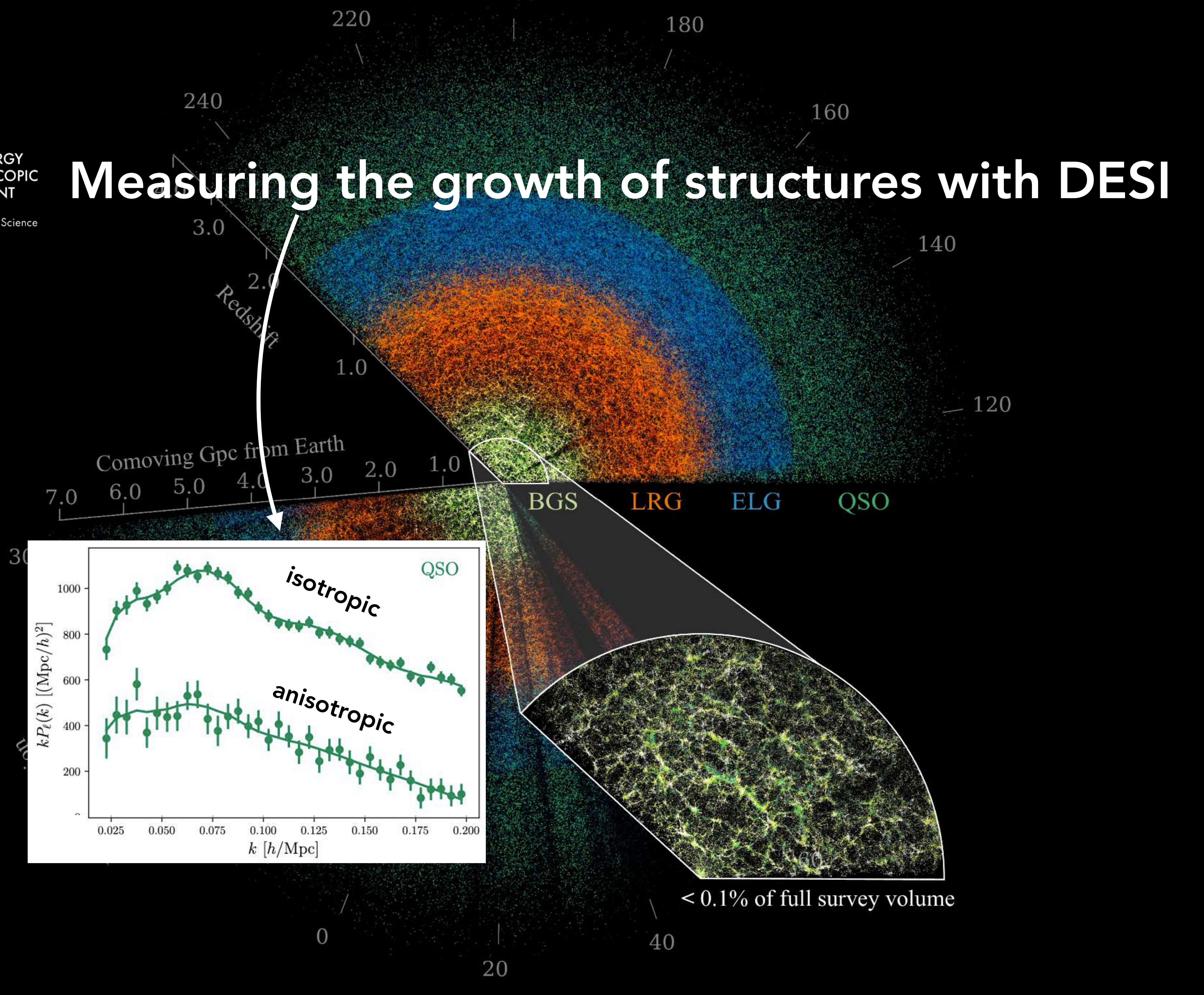
Measuring the growth of structures with DESI



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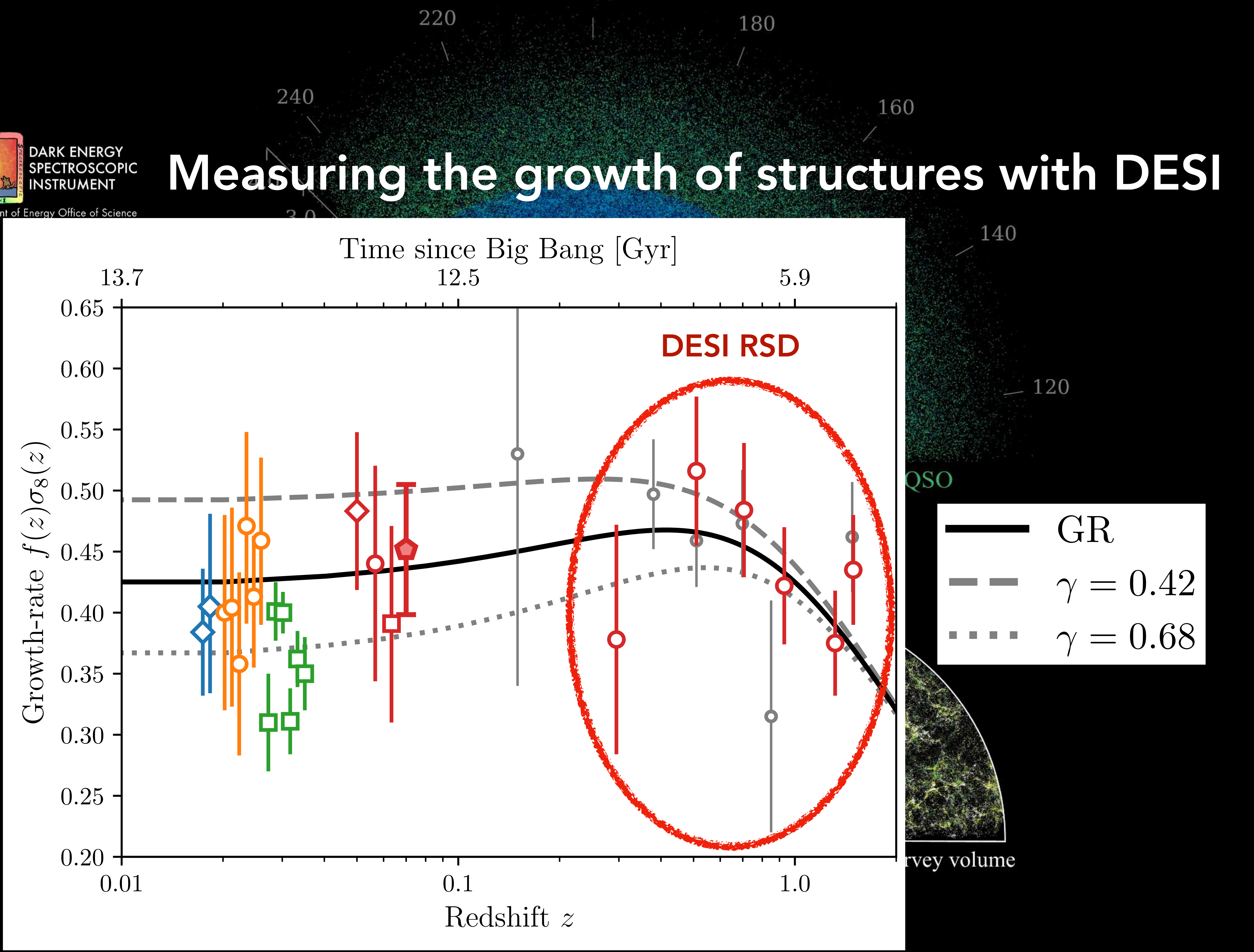
Measuring the growth of structures with DESI



Plan

The expansion: modelling and observing it

Growth of structures : modelling and observing it

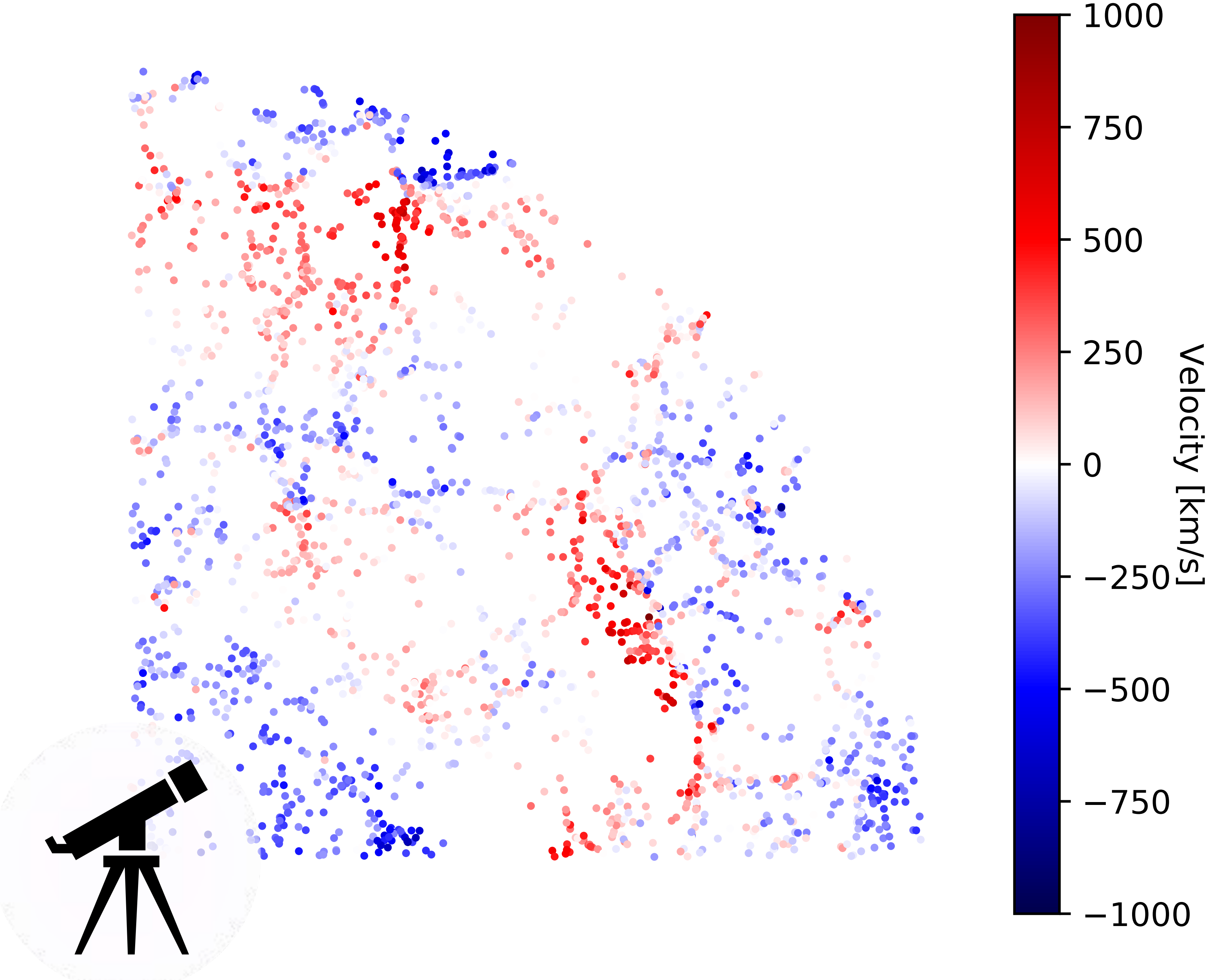
Peculiar velocity measurements and DESI first results

Near future with ZTF and LSST

Peculiar velocity measurements

Redshift survey → Density field in redshift-space

$$\delta_g(\vec{s})$$



Spatial correlations

$$\langle \delta_g(\vec{s})\delta_g(\vec{s}+\Delta\vec{s}) \rangle$$

Cosmological parameters

$$H_0, \Omega_x, w(z), f(z), \sigma_8(z)$$

Peculiar velocity measurements

Redshift survey

+

Distance survey

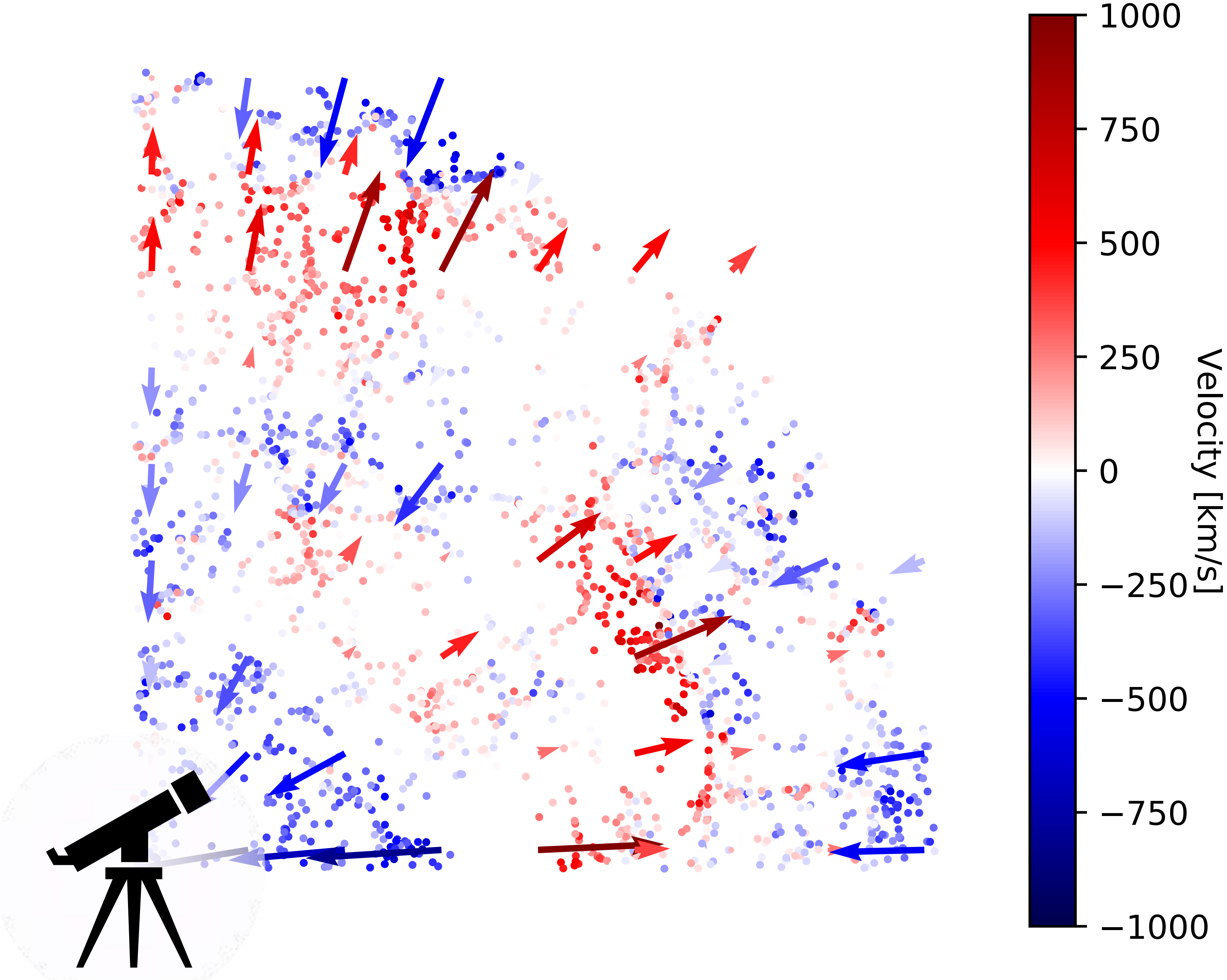
Density field in redshift-space

$\delta_g(\vec{s})$

+

Radial velocity field in redshift space

$v_r(\vec{s})$



Spatial correlations

$$\langle \delta_g(\vec{s})\delta_g(\vec{s}+\Delta\vec{s})\rangle$$

$$\langle \delta_g(\vec{s})v_r(\vec{s}+\Delta\vec{s})\rangle$$

$$\langle v_r(\vec{s})v_r(\vec{s}+\Delta\vec{s})\rangle$$

3 x 2pt functions

BETTER

Cosmological parameters

$H_0, \Omega_x, w(z), f(z), \sigma_8(z)$

Peculiar velocity measurements

Observed redshift is :

$$(1 + z_{\rm obs}) = (1 + z_{\rm cosmo})(1 + z_v)$$

Spectroscopic survey → $z_{\rm obs}$

Distance indicator → $z_{\rm cosmo}$

z_v → Radial peculiar velocity

	Tully-Fisher	**Fundamental plane**	**Type-Ia supernova**
Intrinsic scatter (in distance)	$\frac{\sigma_D}{D} \sim 20\,\%$	$\frac{\sigma_D}{D} \sim 20\,\%$	$\frac{\sigma_D}{D} \sim 7\,\%$
Future datasets	WALLABY ~ 30k **DESI ~ 53k**	Taipan ~ 50k **DESI ~ 133k**	ZTF ~ 5 to 20k LSST ~ 30 to 100 k

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DESI PV Data Release 1

Batch of 7 papers submitted end of 2025

Data sets

Caitlin Ross et al.: **Fundamental Plane** sample
Kelly Douglass et al.: **Tully-Fisher** sample
Anthony Carr et al.: Zero-point calibration and H_0

Mocks

JB et al.: Mock catalogs from n-body simulations

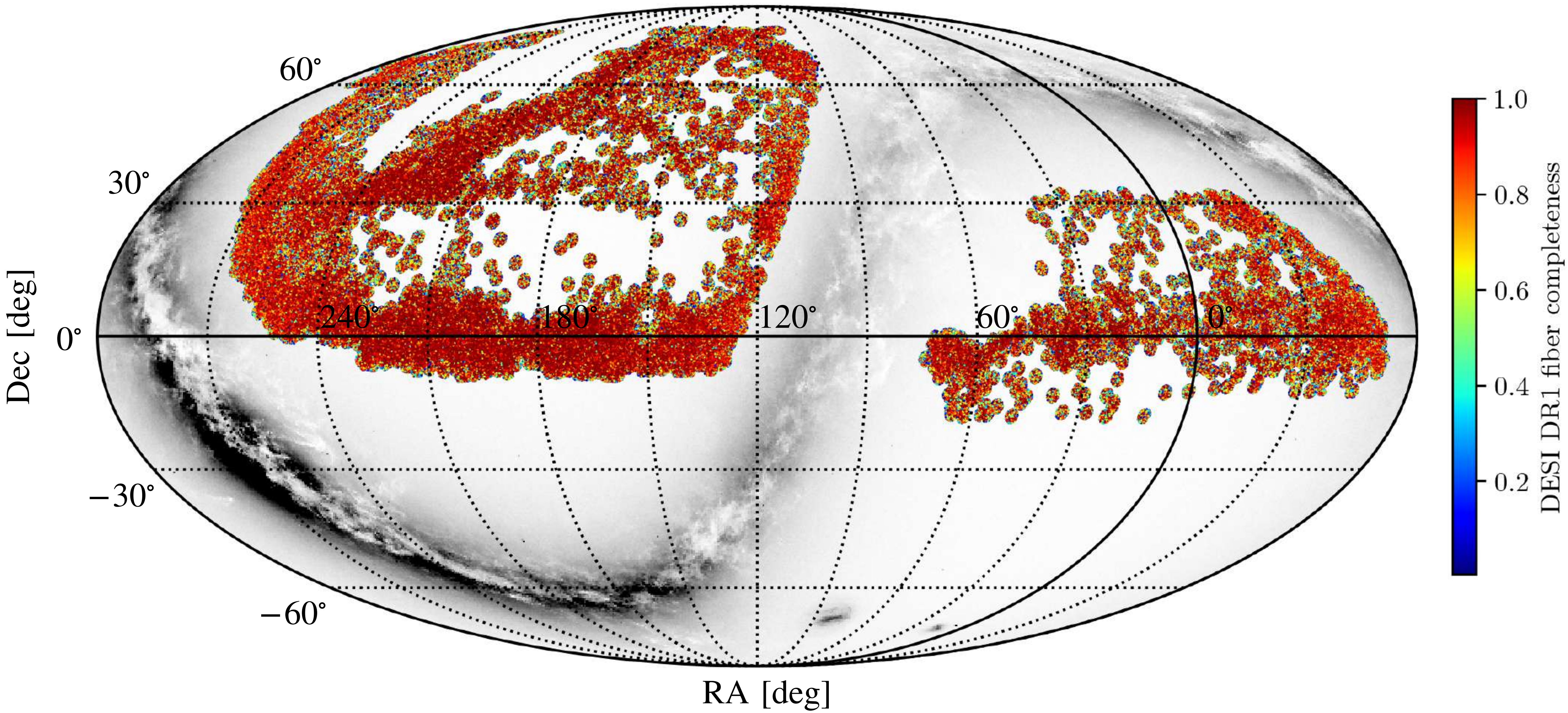
Measurements of $f\sigma_8$

Yan Lai et al.: **Growth rate** with maximum likelihood fields
Fei Qin et al.: **Growth rate** with momentum power spectra
Ryan Turner et al.: **Growth rate** with correlation functions
Andy Nguyen et al.: **Growth rate** with DESI and Pantheon+ SN

Key points

Internal combination of FP and TF samples
675 n-body based mock catalog realisations
First ever consistency check among methodologies

DESI PV Data Release 1



DR1 Fundamental Plane sample: 98 292 velocities
DR1 Tully-Fisher sample: 10 262 velocities
DR1 density sample at z < 0.1: 415 523 galaxies

Already surpassed past PV samples

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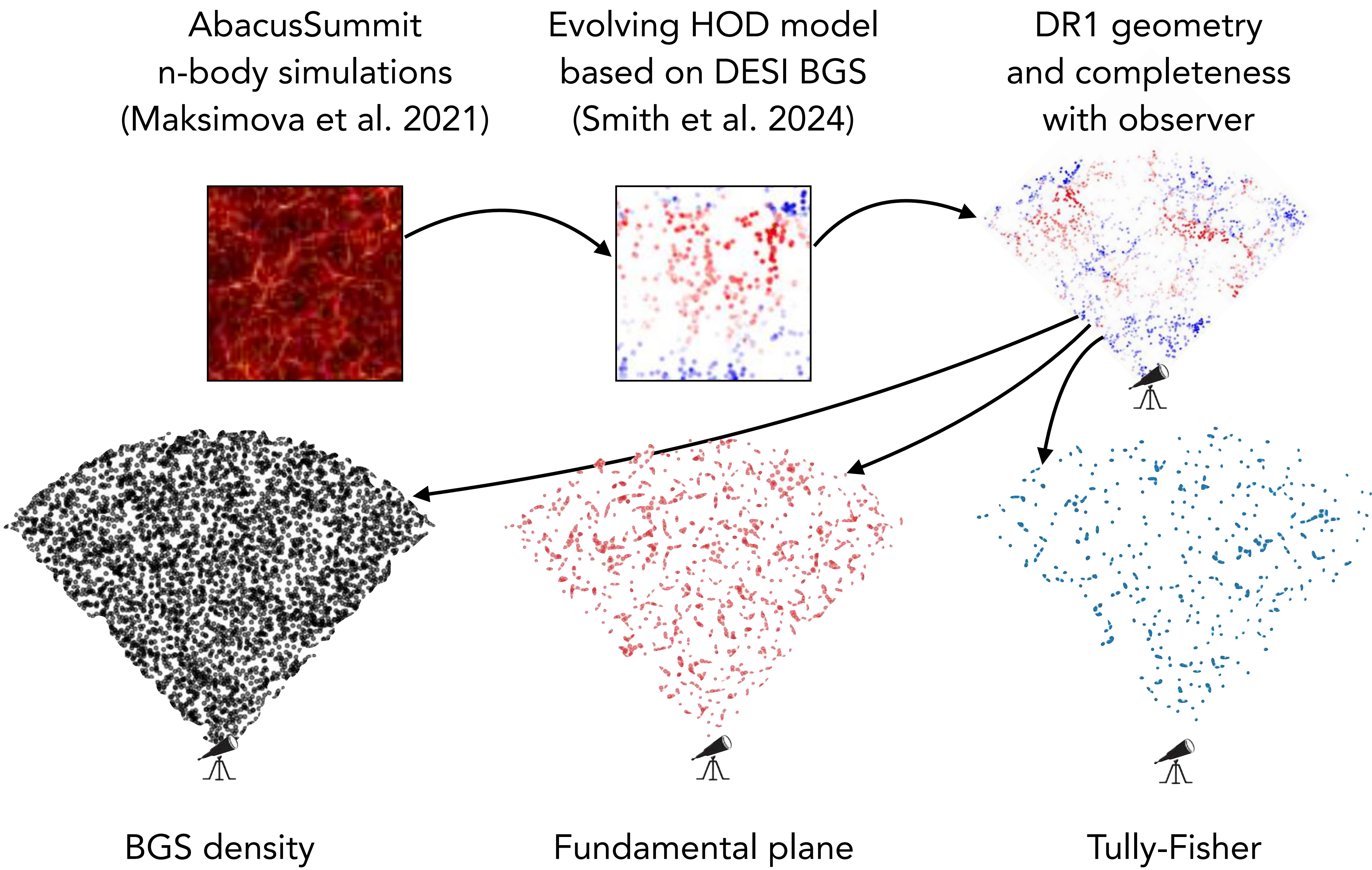
DESI PV DR1 Mock catalogs

JB et al.



675 realisations

Largest and most accurate set of mocks for PV cosmology

DESI PV Methodologies

Maximum likelihood estimator (MLE)

Lai et al.

Configuration space $\xi(r)$

Turner et al.

Fourier space $P(k)$

Qin et al.

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DESI PV Methodologies

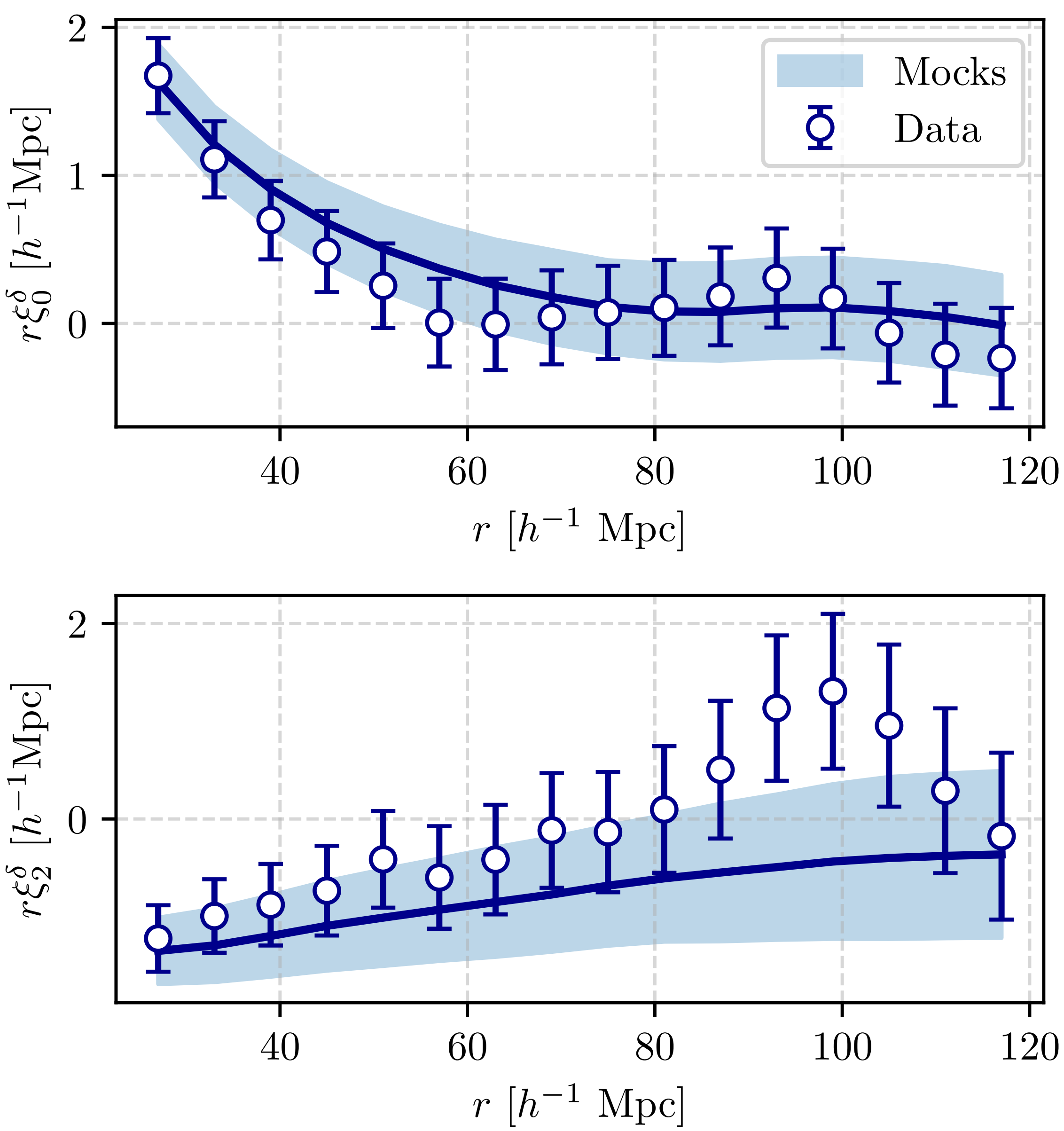
Configuration space $\xi(r)$

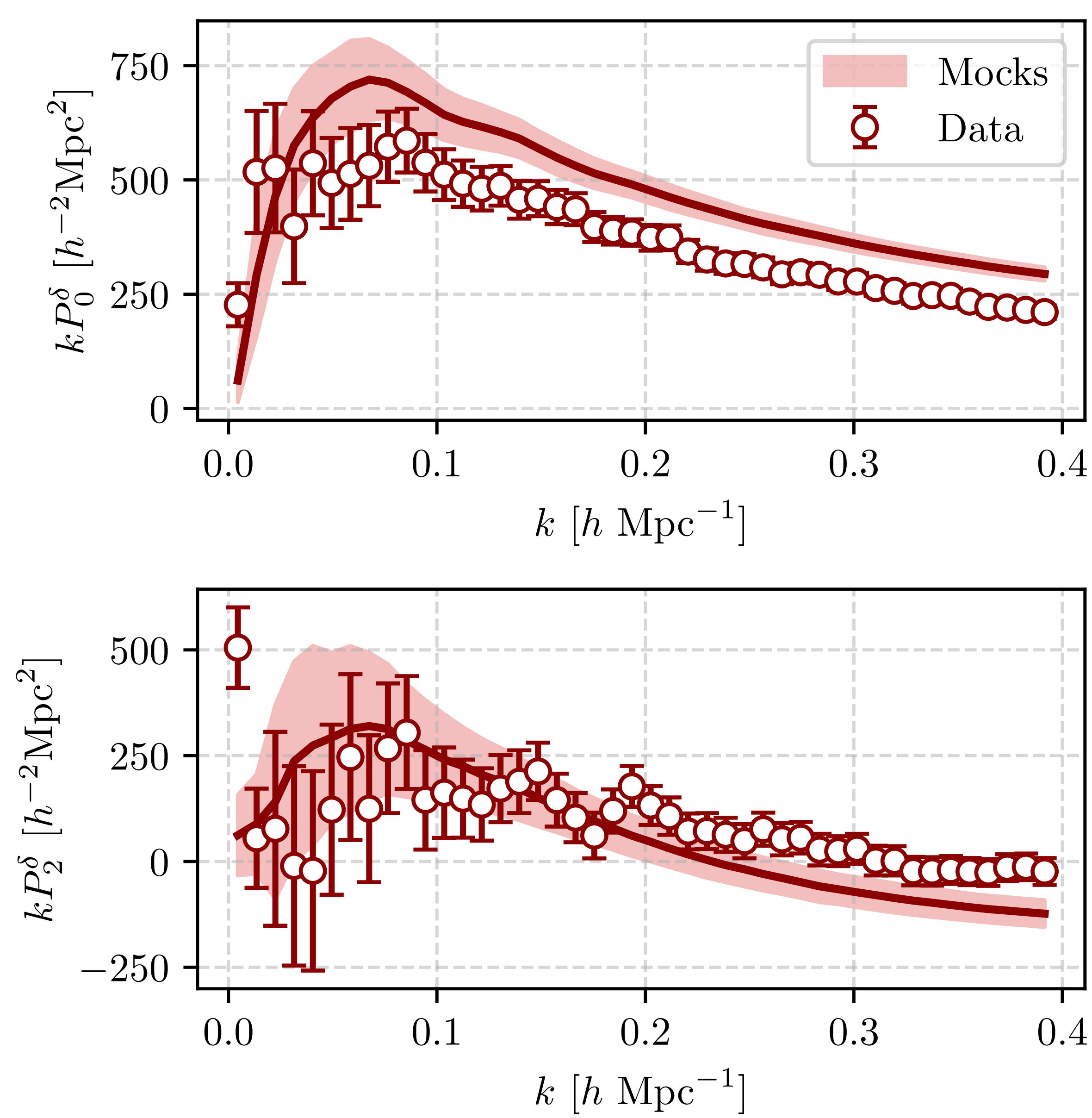
Turner et al.

Fourier space $P(k)$

Qin et al.

Density-density





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DESI PV Methodologies

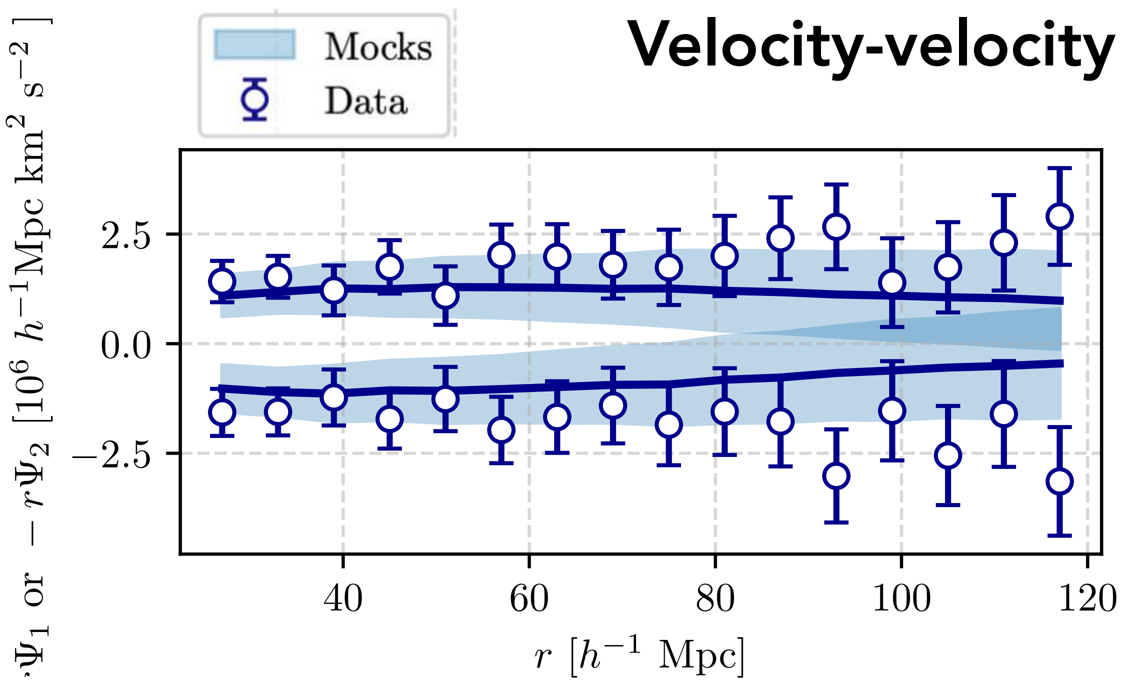
Configuration space $\xi(r)$

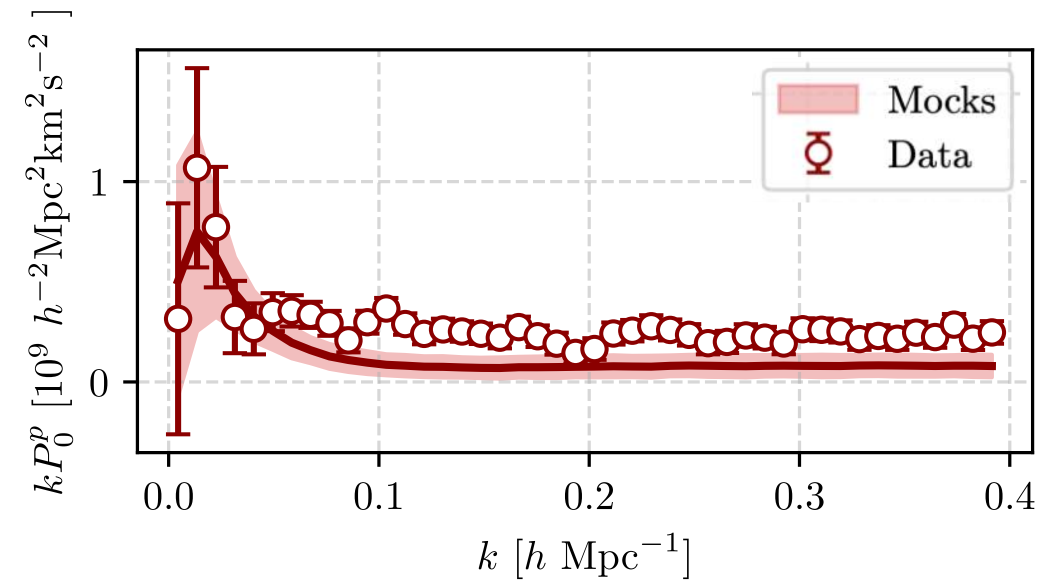
Turner et al.

Fourier space $P(k)$

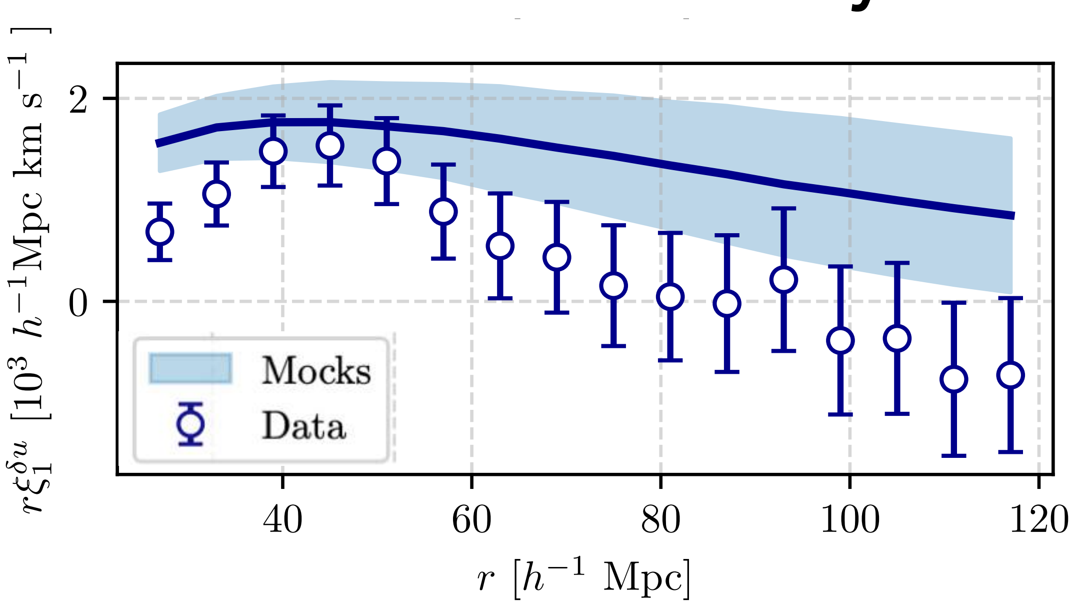
Qin et al.

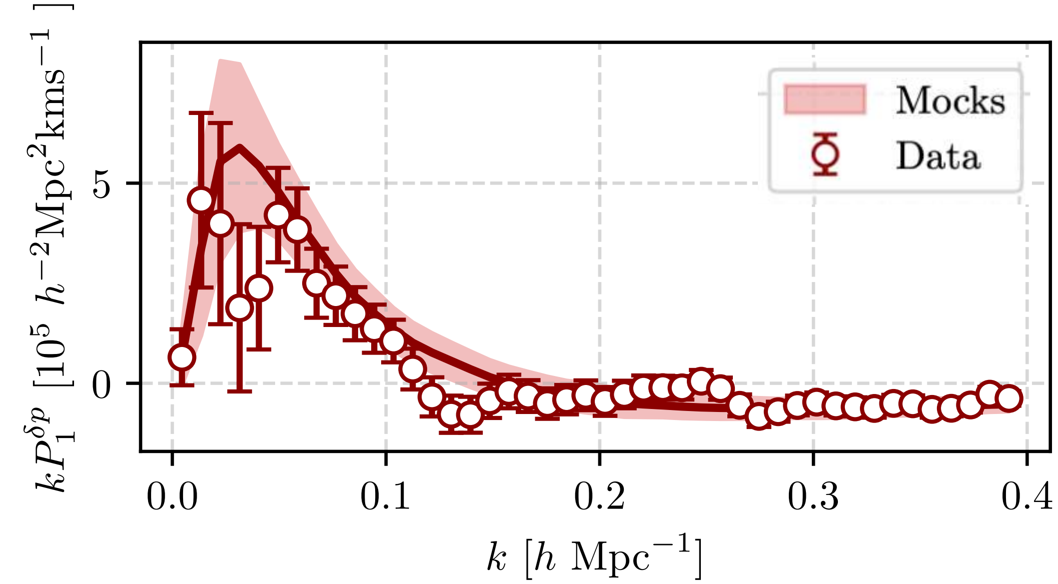
Velocity-velocity or momentum-momentum





Density cross velocity/momentum





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DESI PV Growth rate measurement

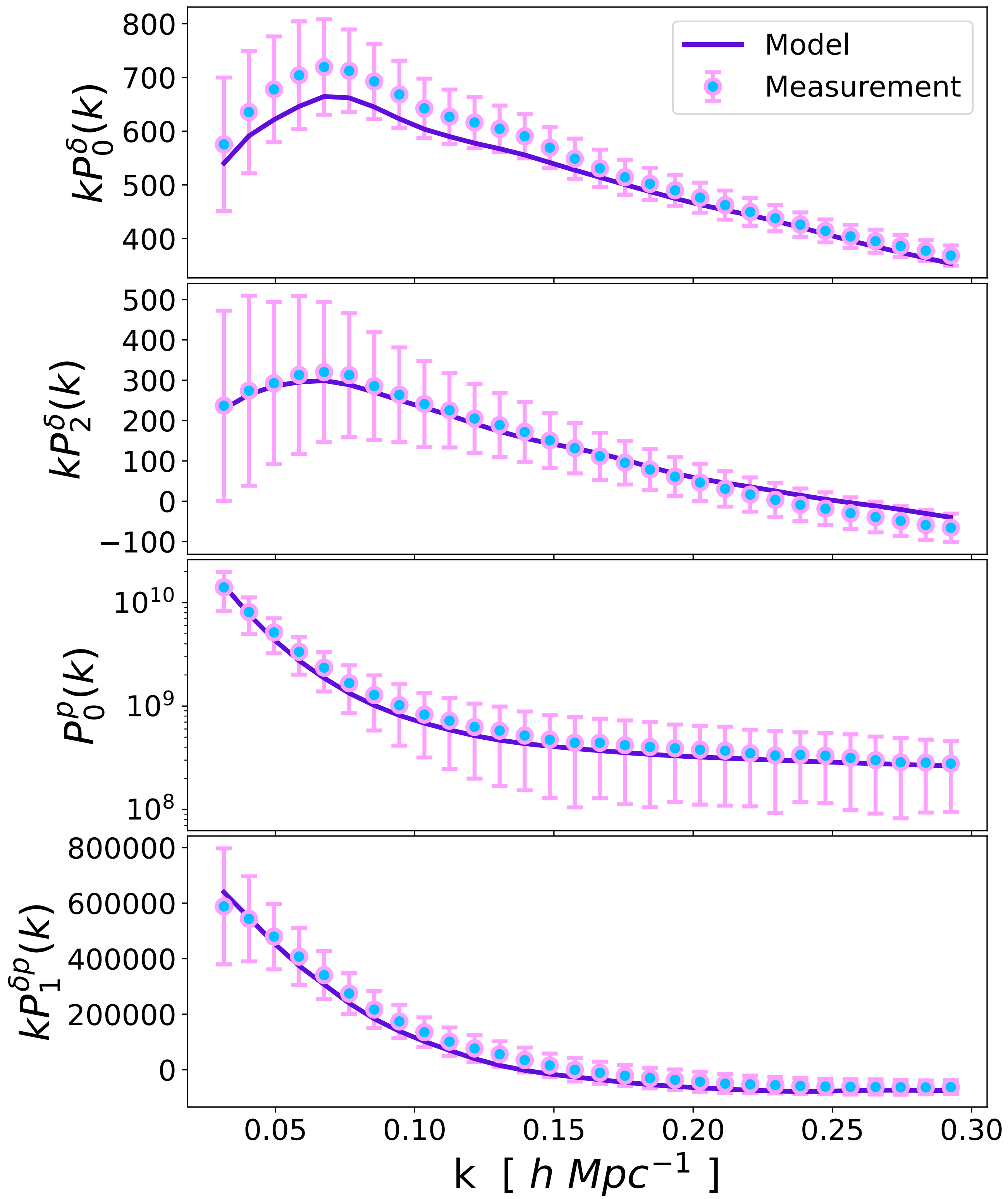
Fourier space $P(k)$

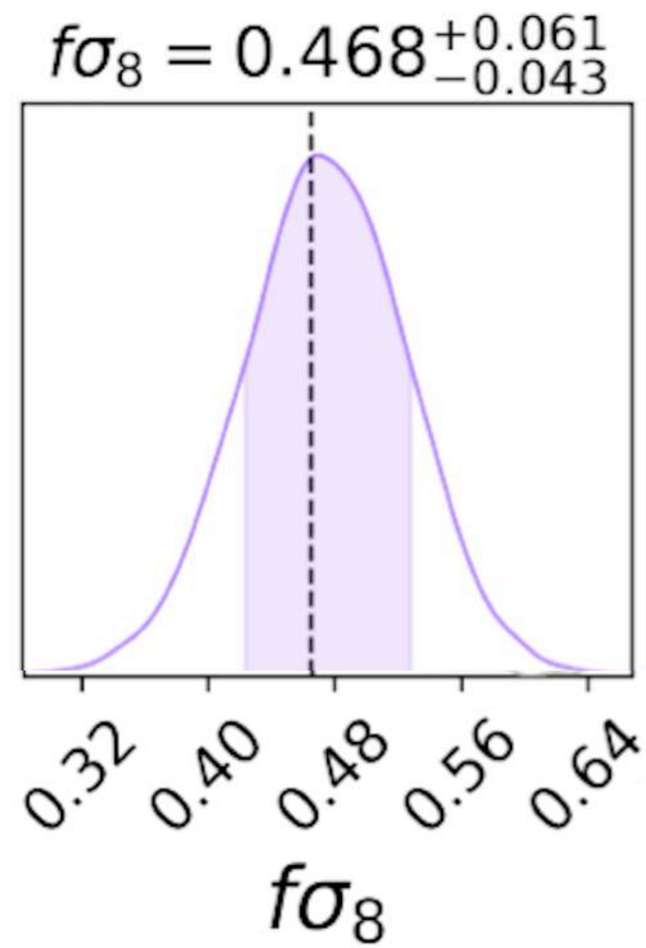
Qin et al.

Density-density

Velocity-velocity

Density-velocity





No bias on $f\sigma_8$

Excellent fit to simulations

DESI PV Growth rate measurement

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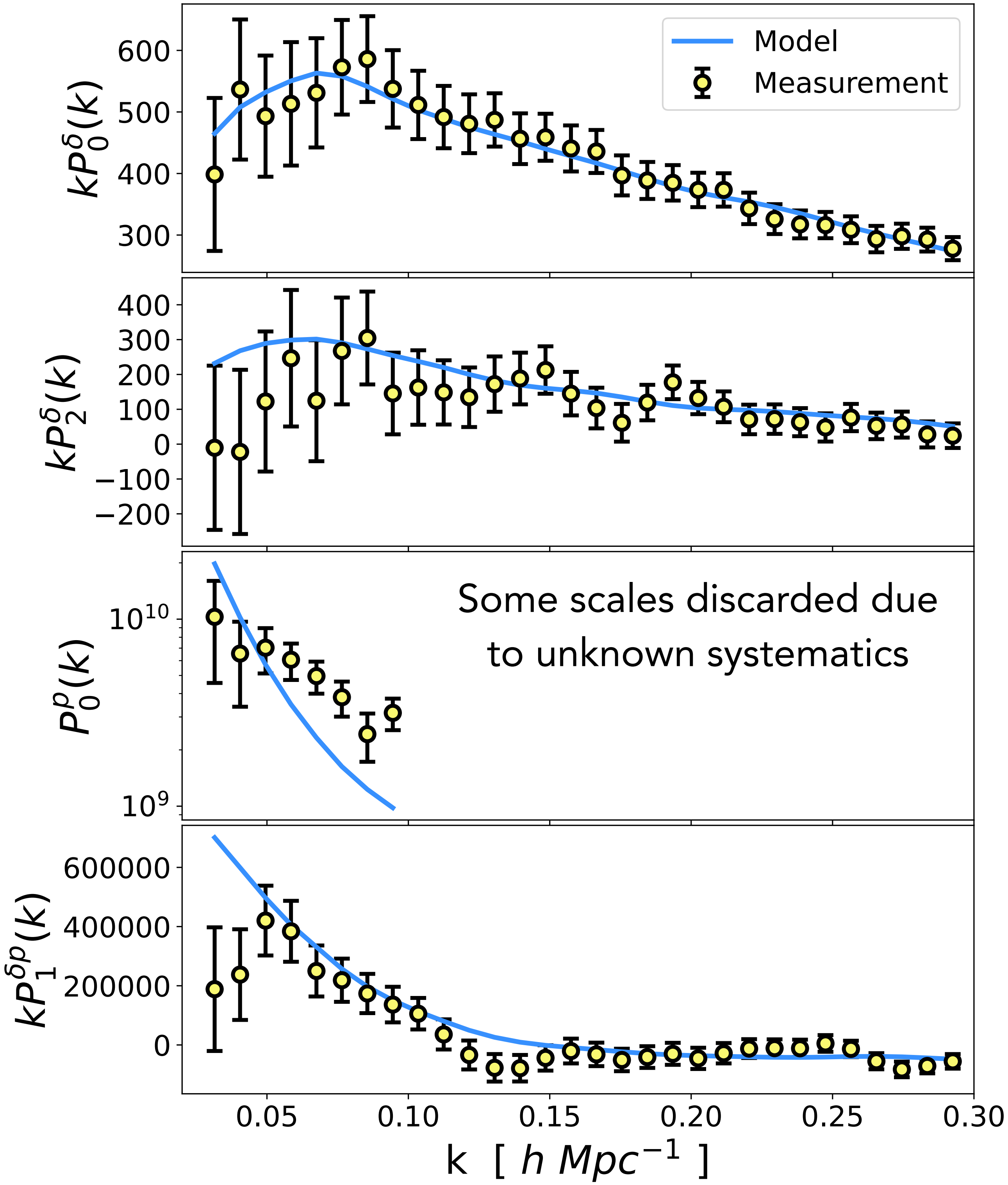
Density-density

Velocity-velocity

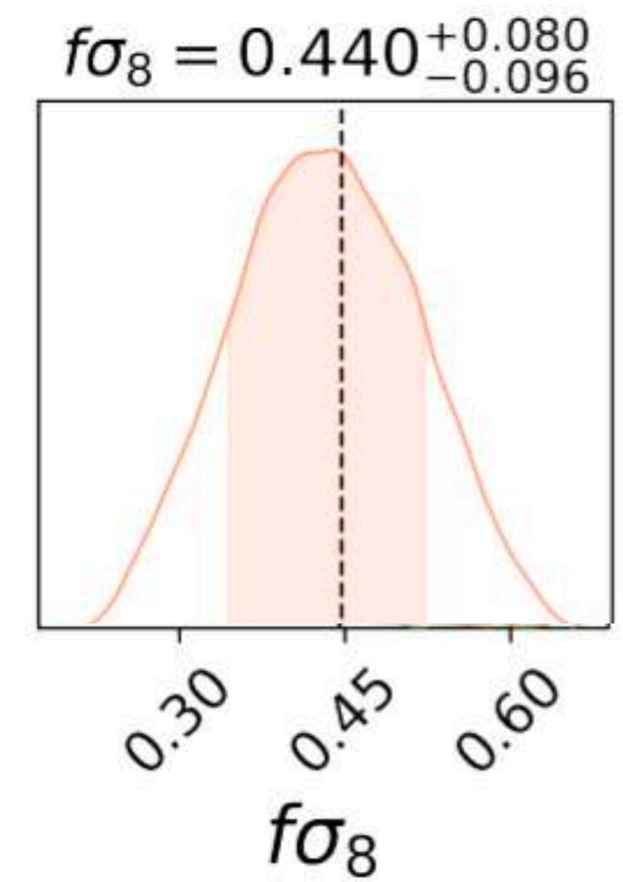
Density-velocity



Best-fit on data

Fourier space $P(k)$

Qin et al.



Consistency with GR+LCDM

DESI PV Growth rate measurement

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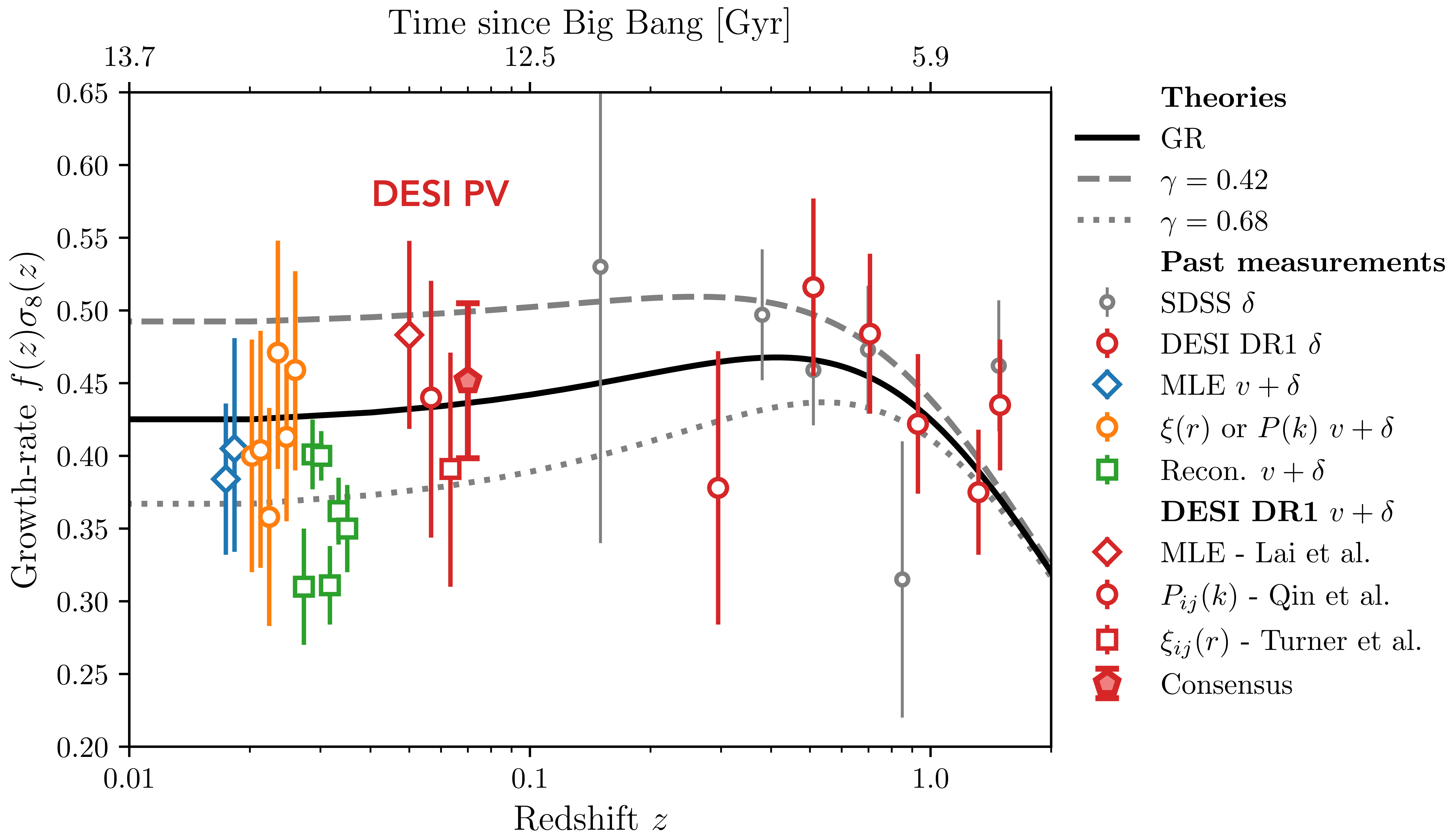


RSD + PV: $\langle \delta_g \delta_g \rangle, \langle \delta_g v_r \rangle, \langle v_r v_r \rangle$

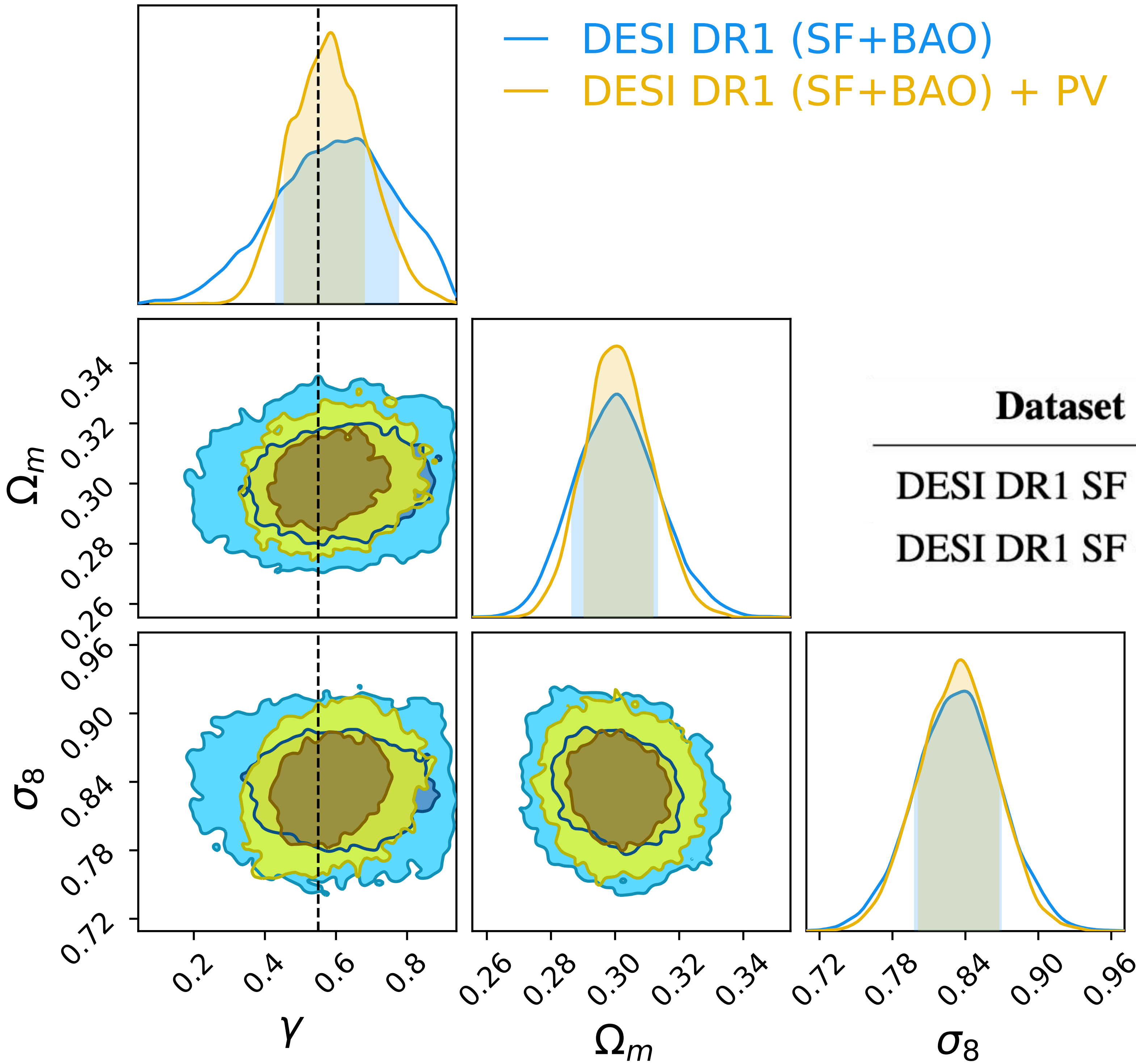
RSD: $\langle \delta_g \delta_g \rangle$

Cosmological implications

Testing departures from GR

$$f(z) = \left[\Omega_m(z)\right]^{\gamma}$$

$$\gamma = 0.55 \ (\text{GR})$$



Dataset	γ	Ω_m	σ_8
DESI DR1 SF	$0.610^{+0.160}_{-0.160}$	$0.301^{+0.013}_{-0.017}$	$0.832^{+0.039}_{-0.039}$
DESI DR1 SF + PV	$0.581^{+0.097}_{-0.120}$	$0.301^{+0.010}_{-0.010}$	$0.834^{+0.031}_{-0.031}$

30% improvement on γ and Ω_m uncertainty thanks to PV

Consistency with GR

Plan

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Growth of structures : modelling and observing it

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Near future with ZTF and LSST

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Spectroscopic survey

Distance indicator

Radial peculiar velocity

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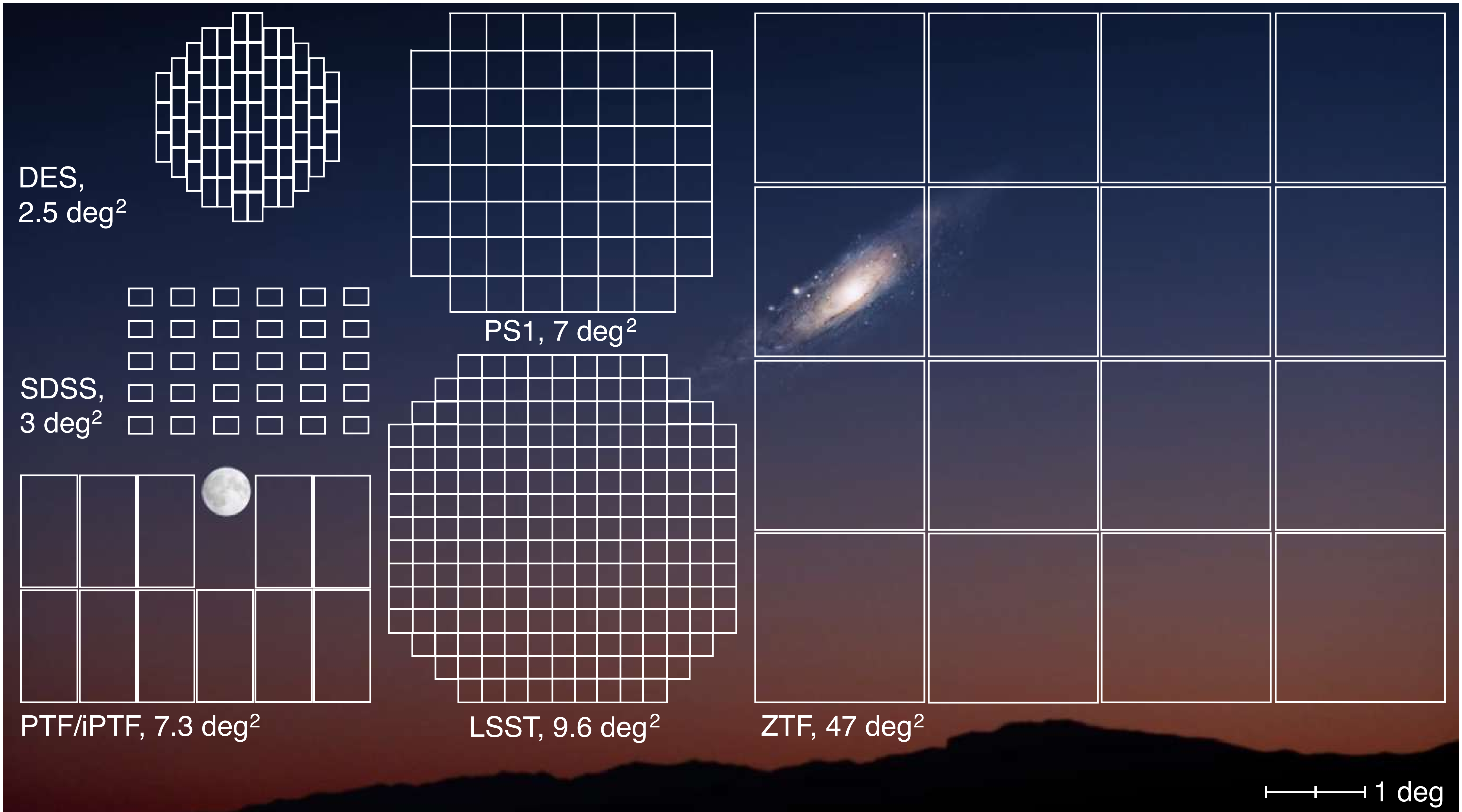
Future datasets	WALLABY ~ 30k DESI ~ 53k	Taipan ~ 50k DESI ~ 133k	ZTF ~ 5k to 20k LSST ~ 30 to 100 k

Photometric surveys to detect supernovae

ZTF

Rubin-LSST



Photometric surveys to detect supernovae

ZTF

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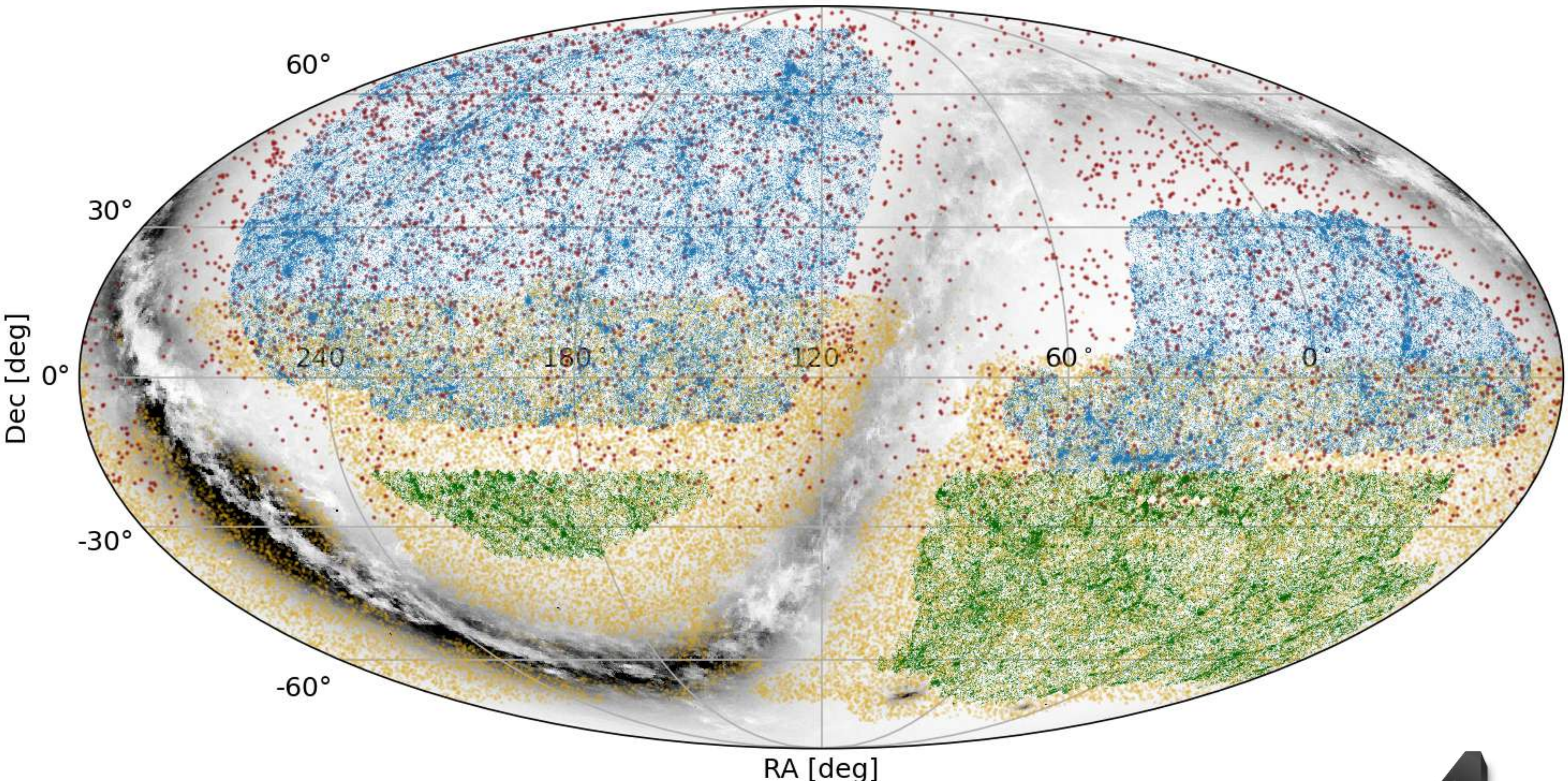

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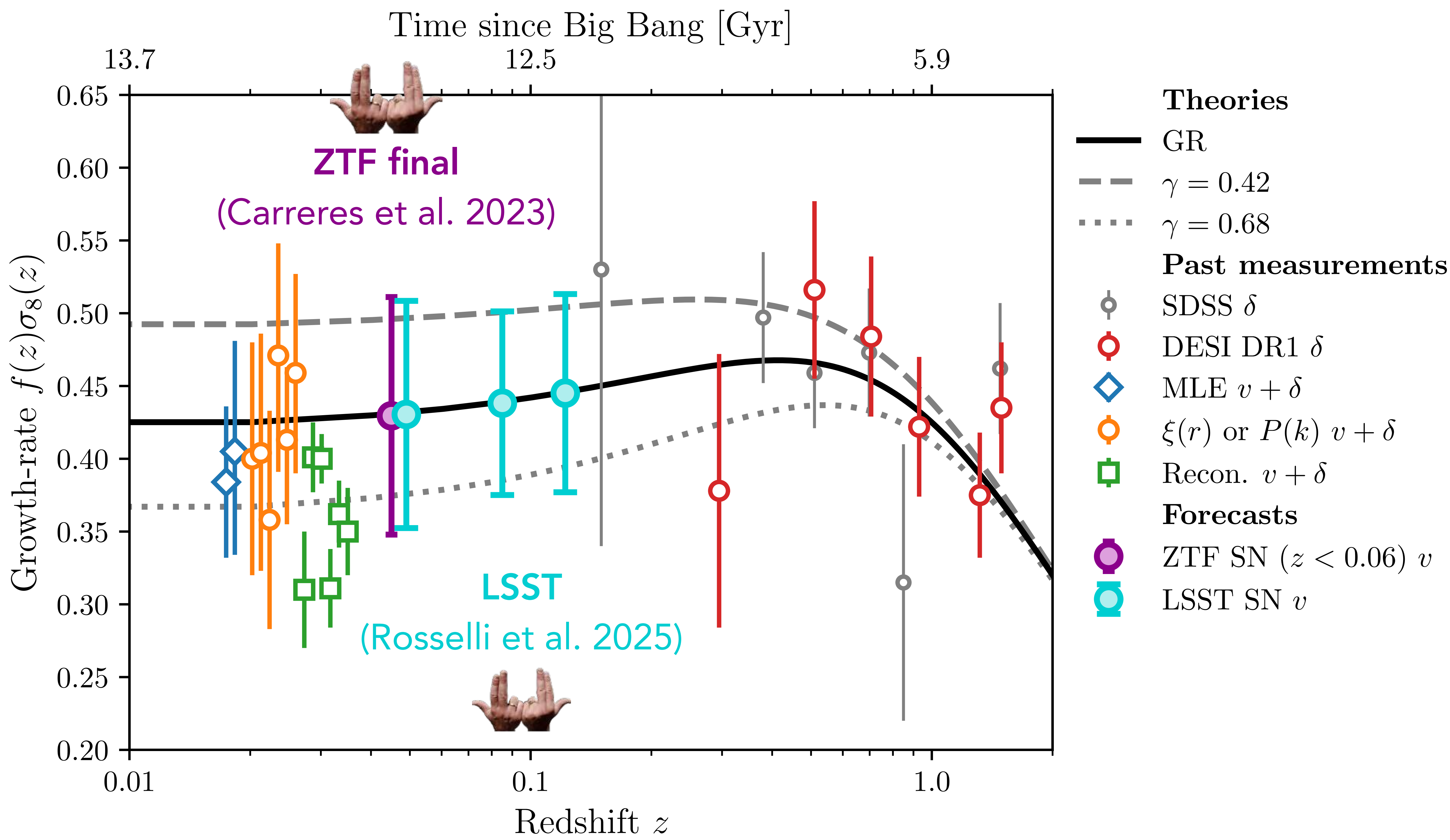
Great overlap with DESI and 4MOST

Future growth rate measurements



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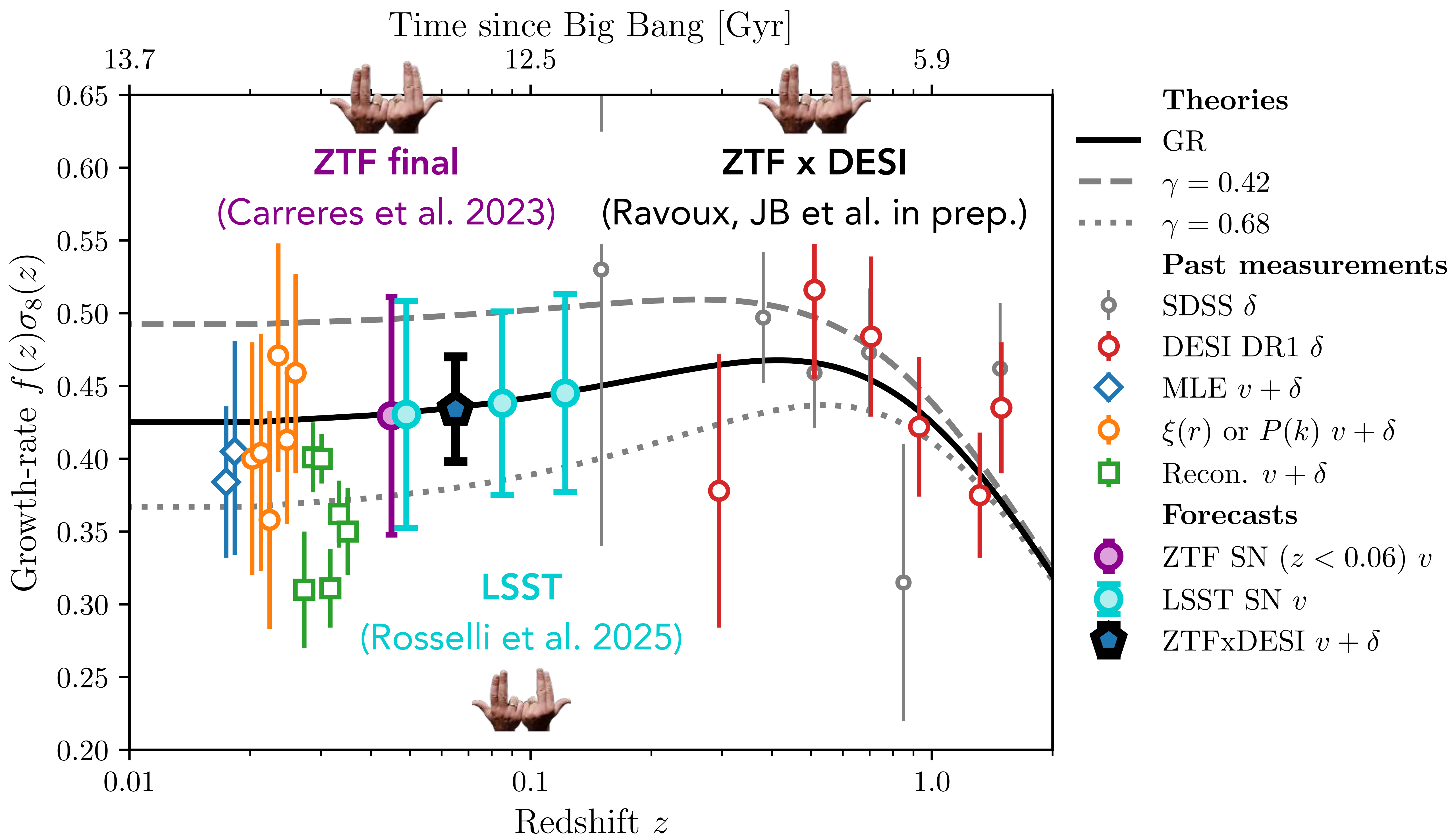
RSD: $\langle \delta_g \delta_g \rangle$

Future growth rate measurements

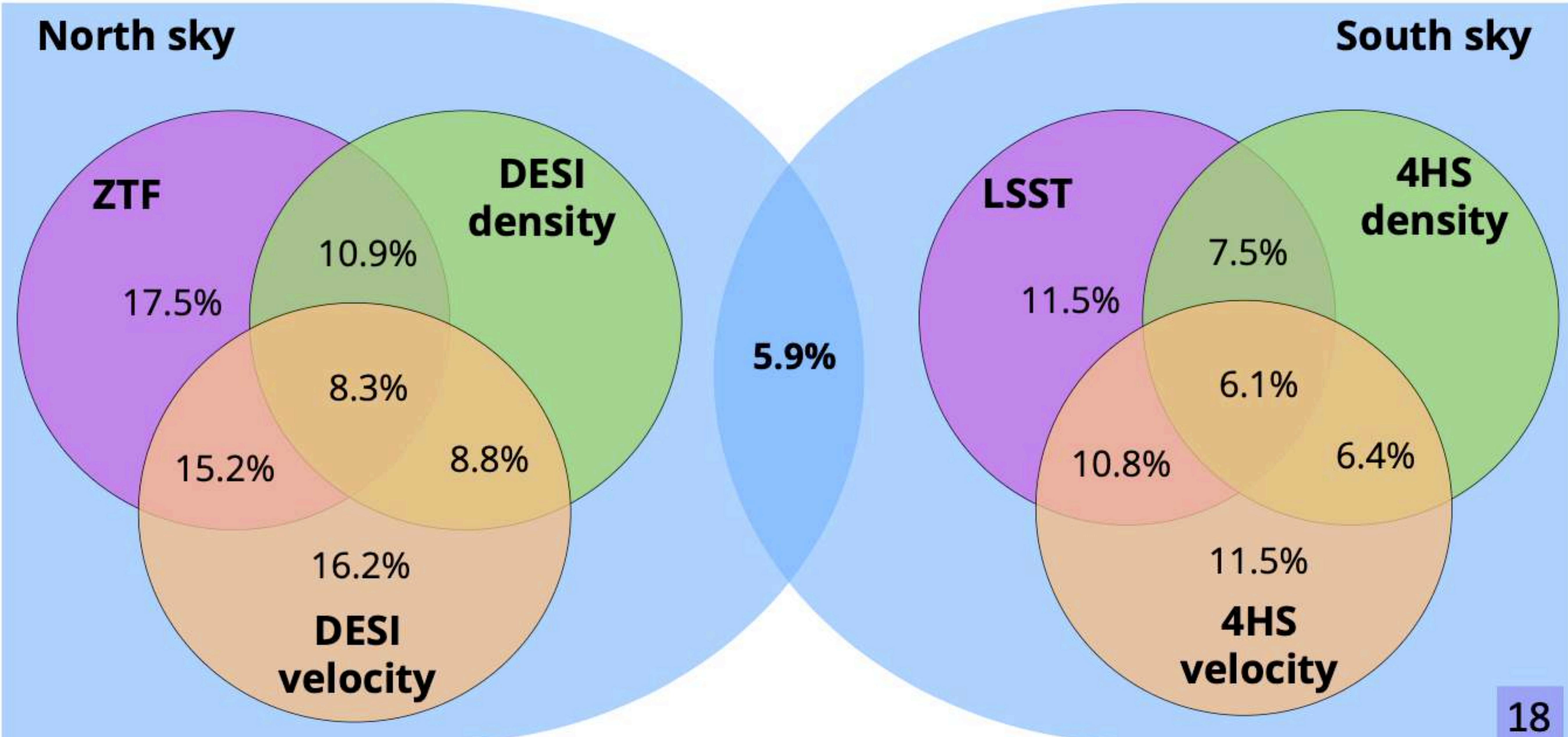


RSD + PV: $\langle \delta_g \delta_g \rangle, \langle \delta_g v_r \rangle, \langle v_r v_r \rangle$

RSD: $\langle \delta_g \delta_g \rangle$

Future growth rate measurements

Uncertainty on $f\sigma_8$

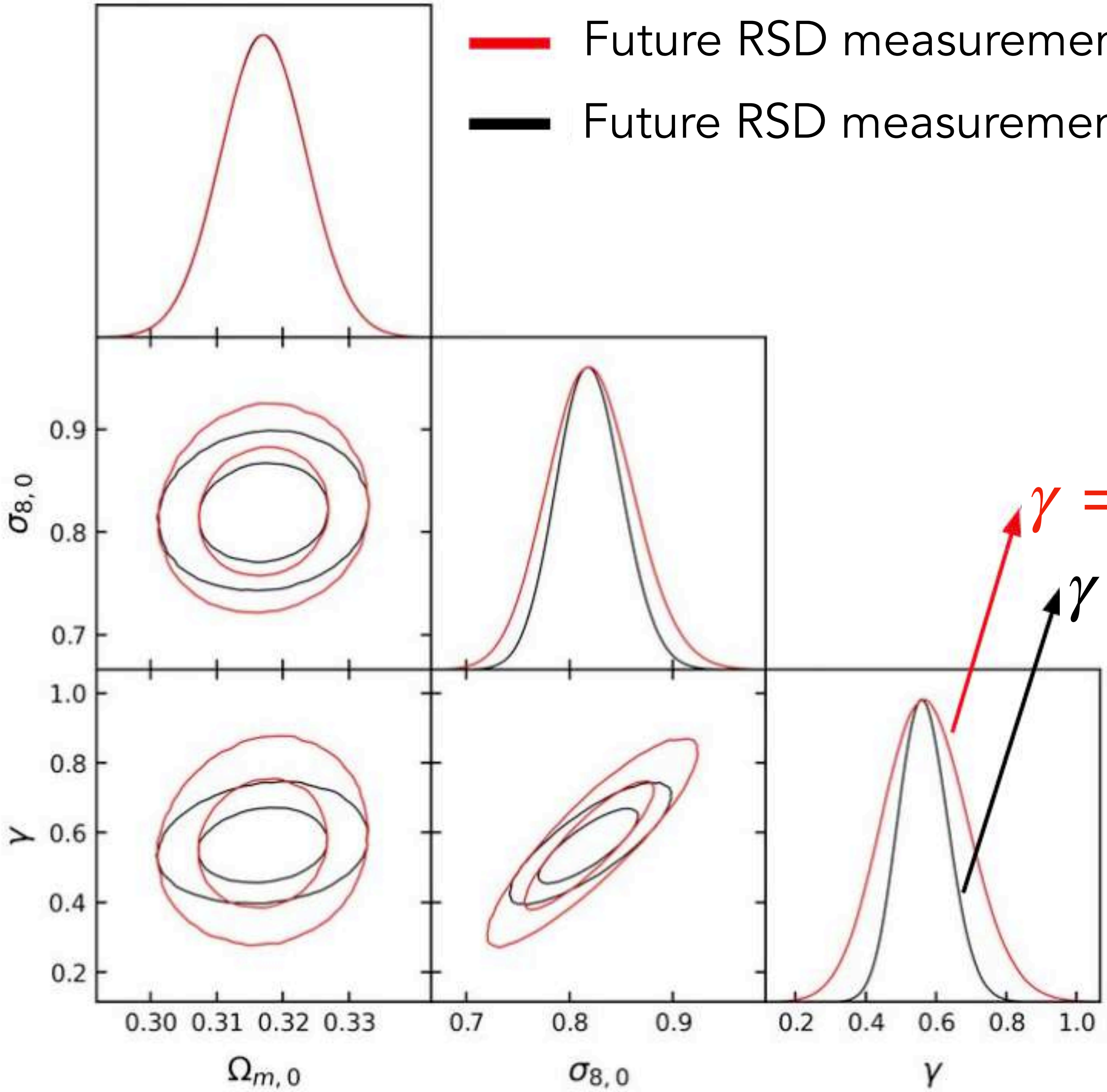


by Camille DEMAY (M2 internship)

Future growth rate measurements

Uncertainty on γ

In GR: $f(t) \approx [\Omega_m(t)]^\gamma$ where $\gamma = 0.55$



$\gamma = 0.57 \pm 0.12$

$\gamma = 0.57 \pm 0.07$

Factor 2 improvement!

by Camille DEMAY (M2 internship)

From CPPM to the world

Leadership of the ‘Peculiar Velocity’ working group (JB)
Lead authors of first publications and preparation of future ones

Lead author of growth rate measurement (Kebadian in prep.)
Key contributors to new ZTF data reduction pipeline (Racine, Feinstein)

Organisation of Peculiar Velocity workshop on campus (Racine, Fouchez)
Active participation to commissioning and alert system (Fouchez, Sánchez)
Leadership of ‘Peculiar Velocity’ topical group (Rosselli → Carreres, Ravoux)

Jul emoji actively used in all 3 collaboration Slacks

Conclusion

The accelerated nature of the expansion is a mystery

Evidence for evolving dark energy : 3rd level of weird!

Combining expansion and growth rate measurements
can distinguish between dark energy or alternatives to GR

Peculiar velocity surveys help a lot at low-redshift
when the expansion is accelerated

First PV measurements from DESI DR1

Future is promising by combining several surveys
and CPPM is present

Observing the expansion-rate

BAO

Angular distance

$$\frac{D_M(z)/r_d}{[D_M(z)/r_d]_{\text{Planck}}}$$

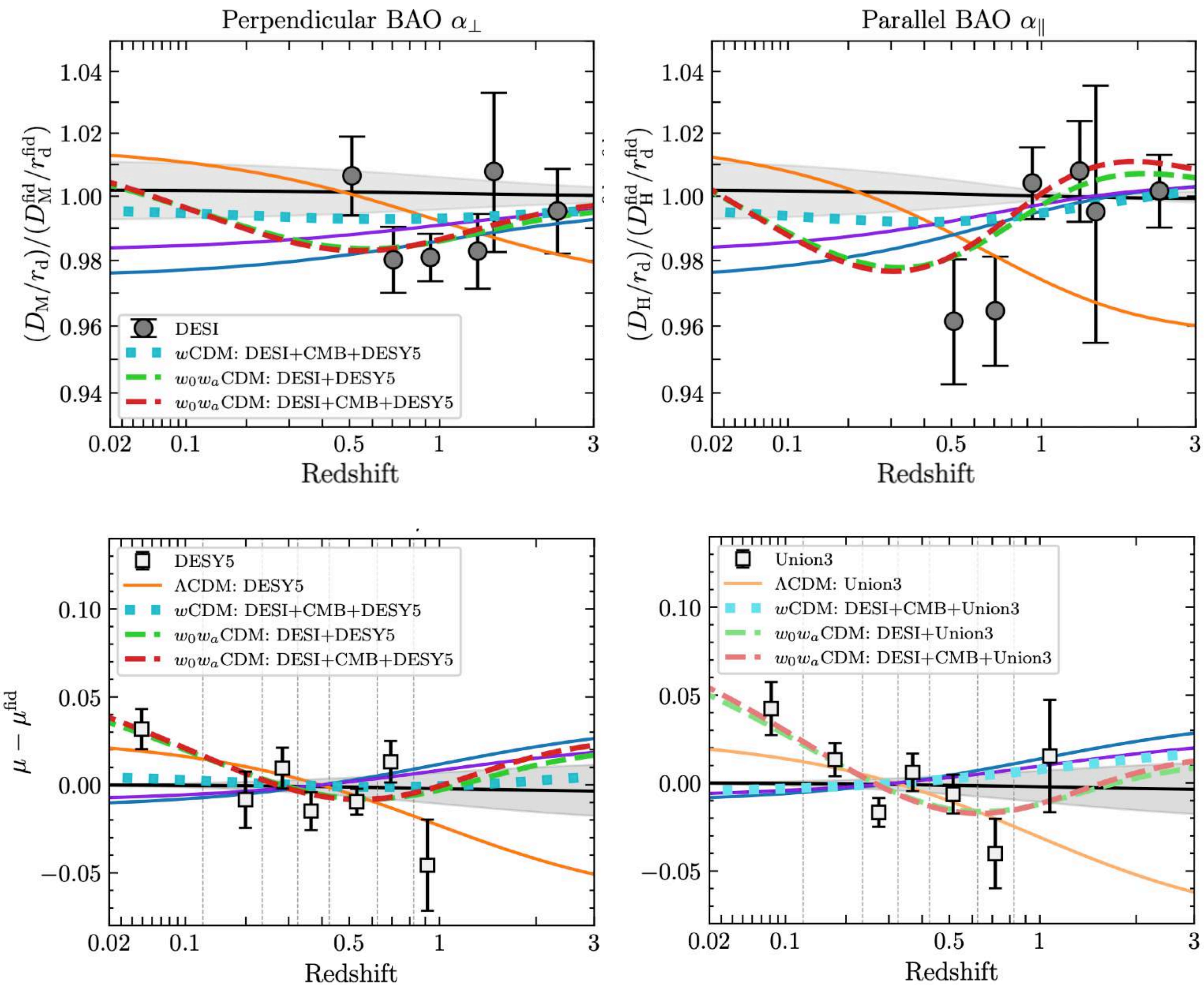
Hubble distance

$$\frac{D_H(z)/r_d}{[D_H(z)/r_d]_{\text{Planck}}}$$

SNIa

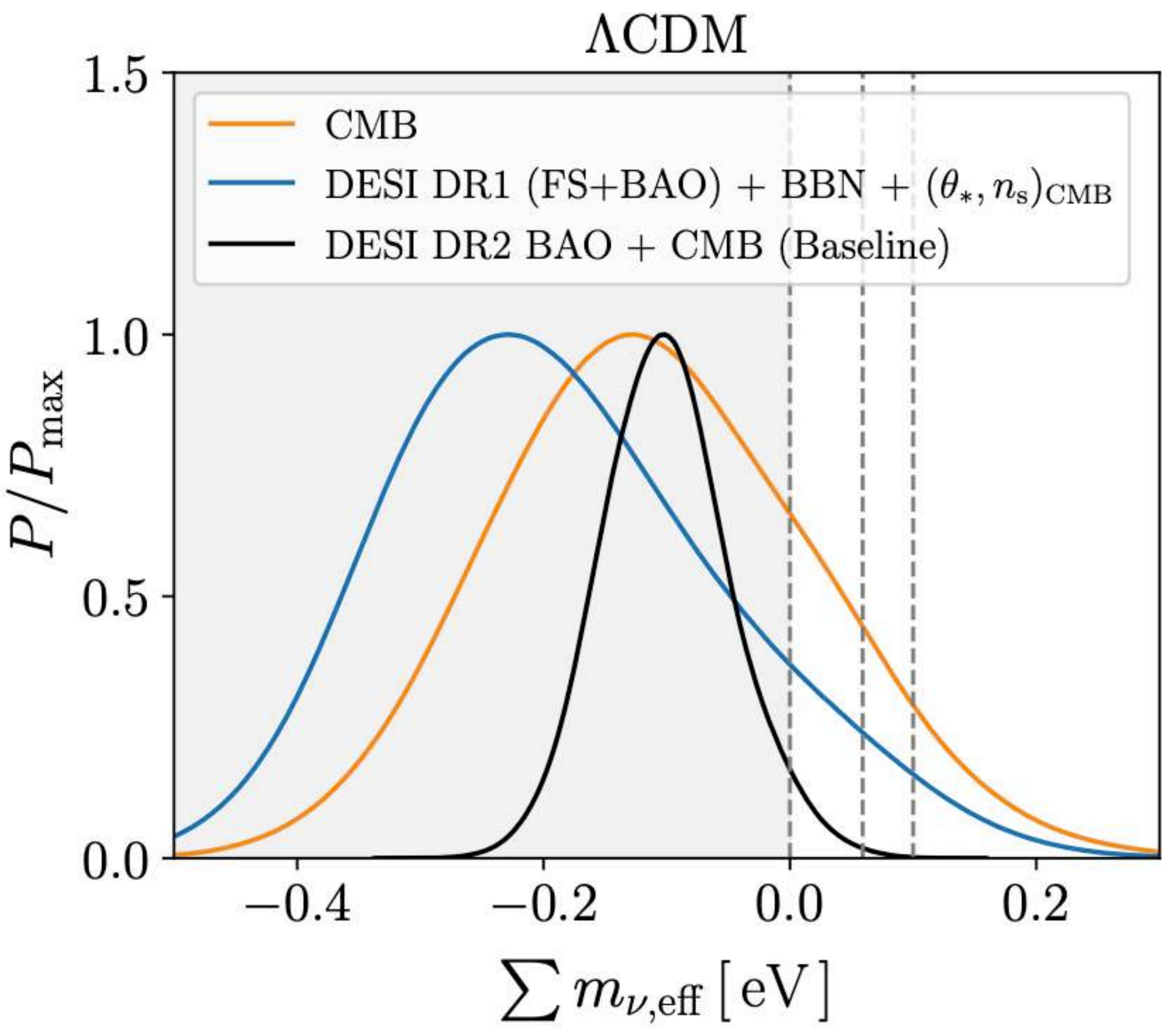
Luminosity distance

$$\frac{D_L(z)}{[D_L(z)]_{\text{Planck}}}$$



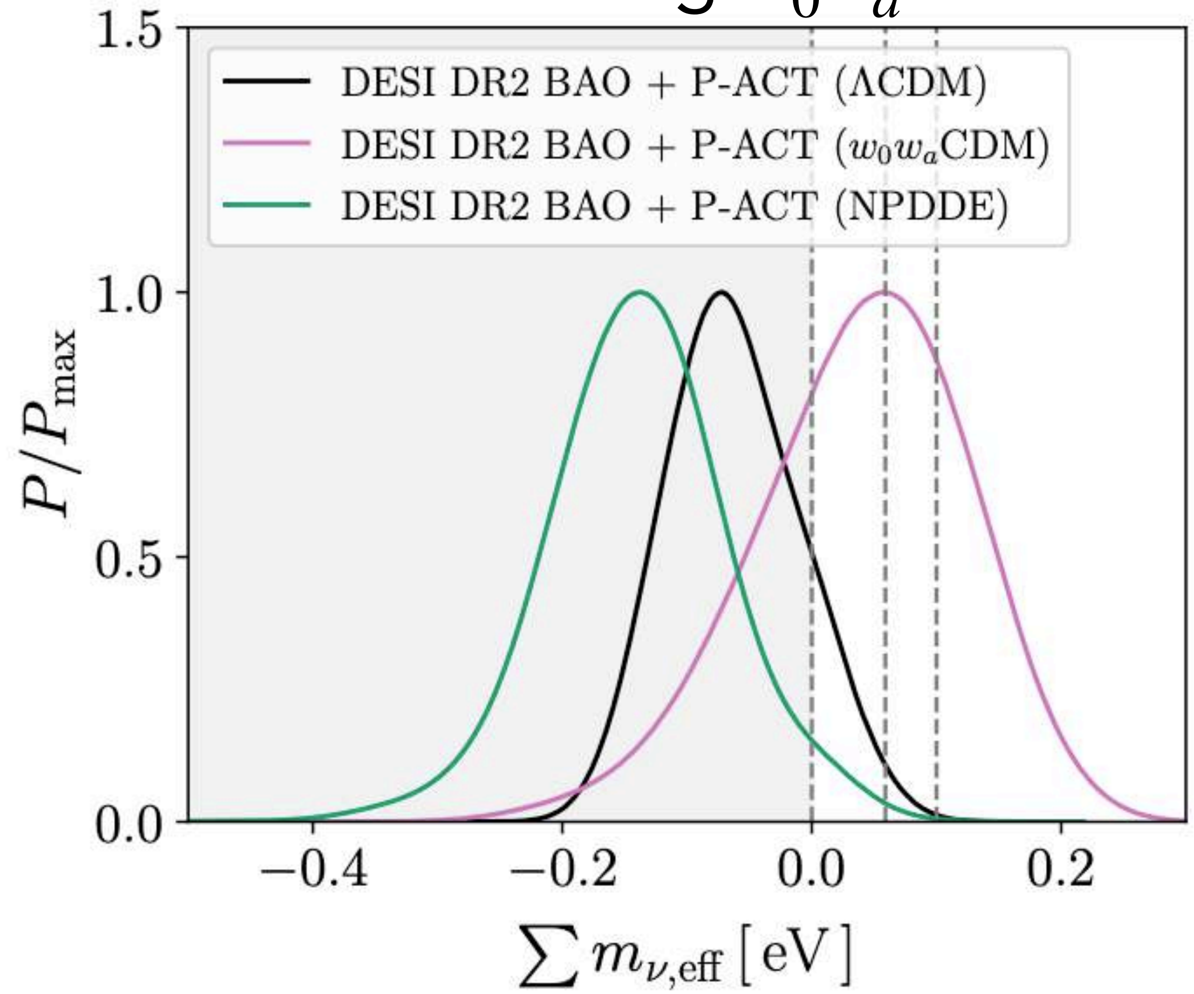
Low-redshift supernovae causing tension with Λ?

Neutrino masses



Tension with oscillation constraints

Assuming $w_0 w_a$CDM



Maximum posterior is positive!