Splitting the cosmic web for more information

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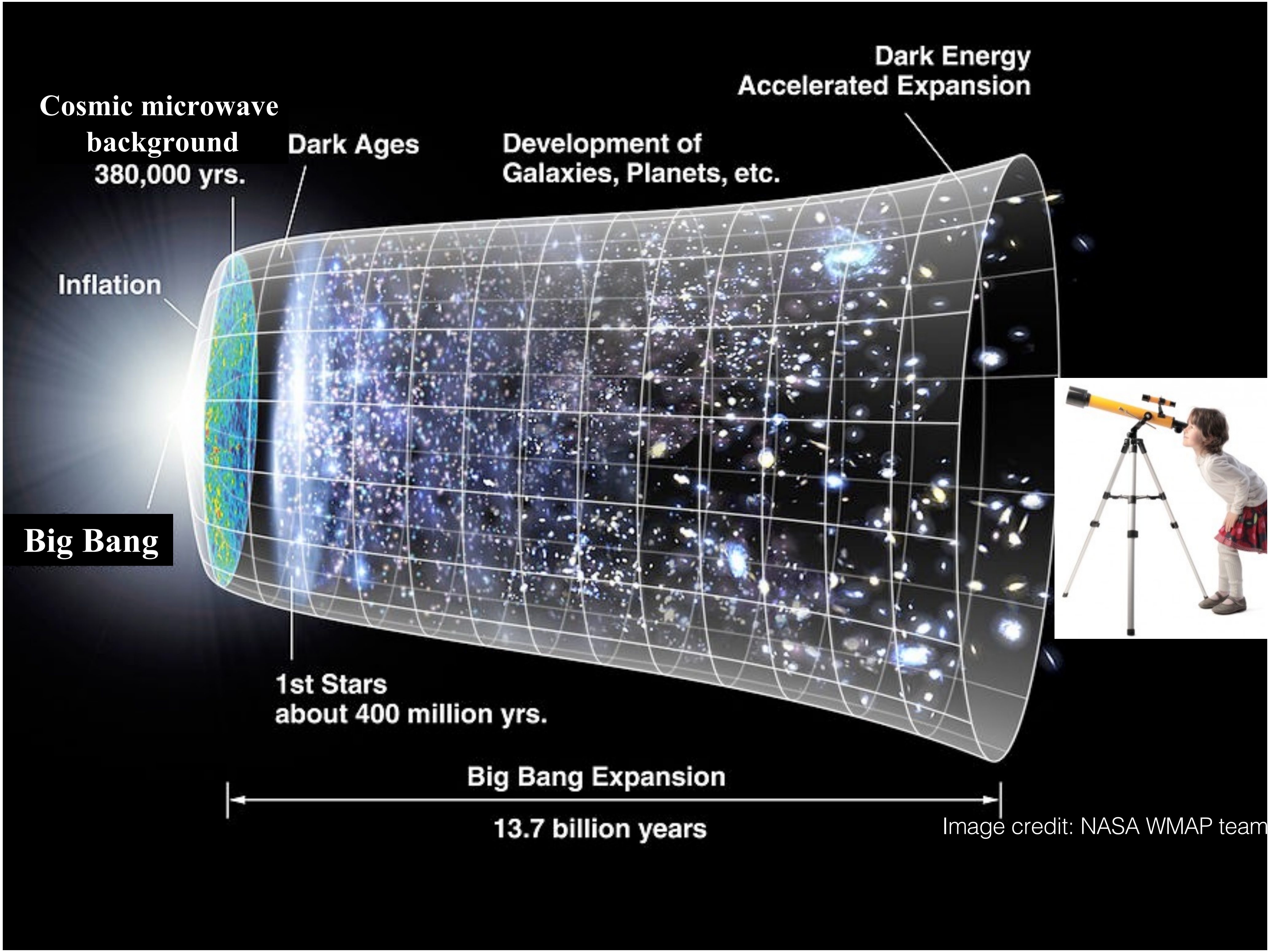
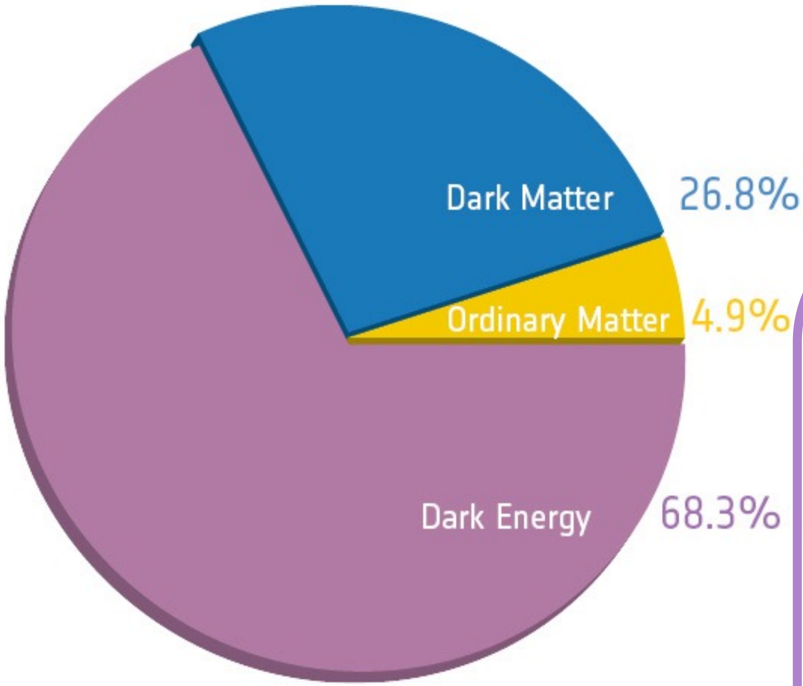
22 June, 2022


Dark Energy
Accelerated Expansion
Cosmic microwave
background
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Big Bang
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
Image credit: NASA WMAP team

Cosmology: knowns and unknowns



What is dark matter?

Where are the ordinary matter?

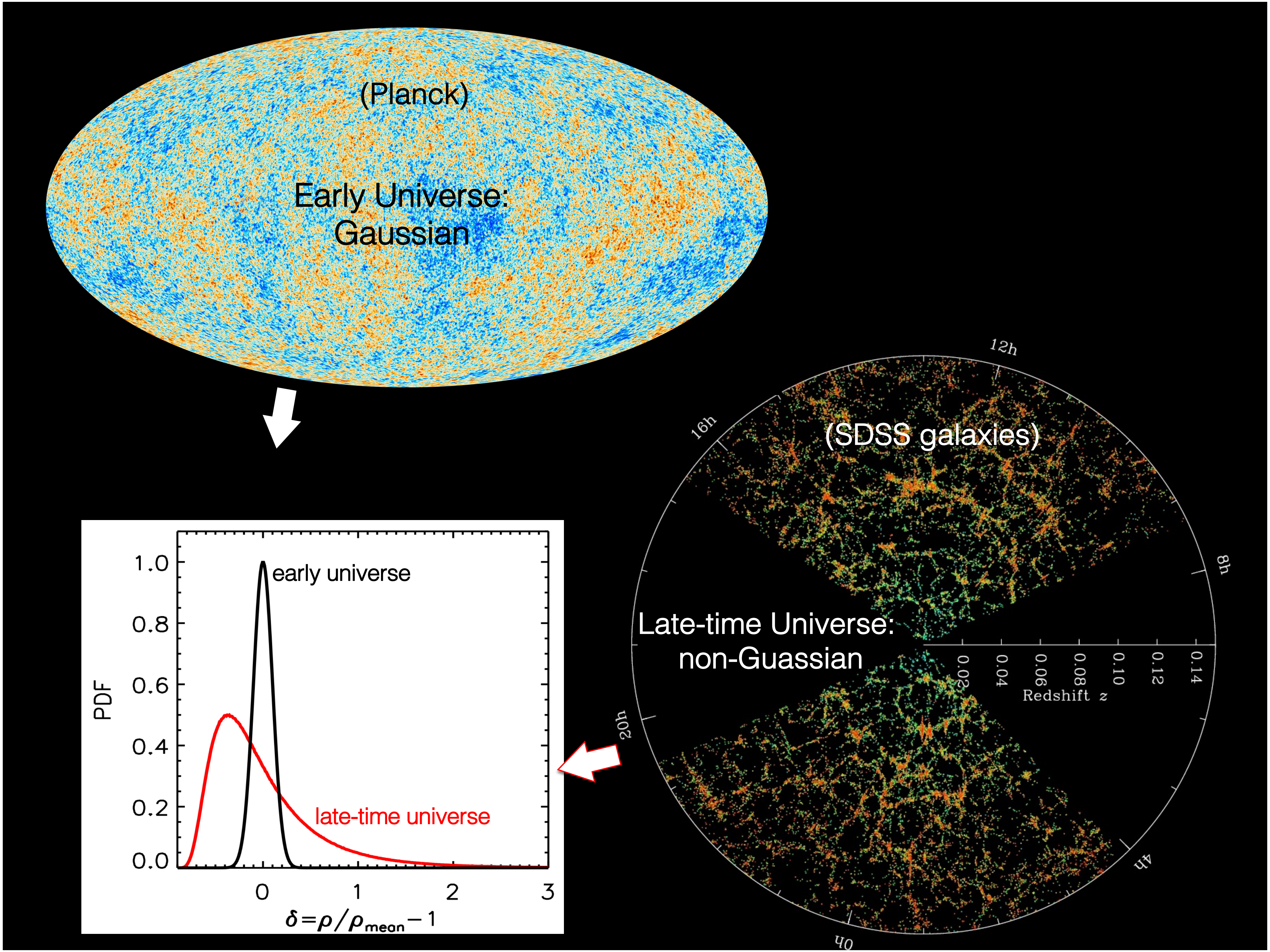
What is dark energy?

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R} = \boxed{8\pi G T_{\mu\nu} - g_{\mu\nu}\Lambda}$$

Modified Gravity

Dark Energy

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G \rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$


(Planck)
Early Universe:
Gaussian
(SDSS galaxies)
Late-time Universe:
non-Guassian
12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
PDF
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
early universe
late-time universe
$\delta = \rho/\rho_{\rm mean} - 1$

Expansion history

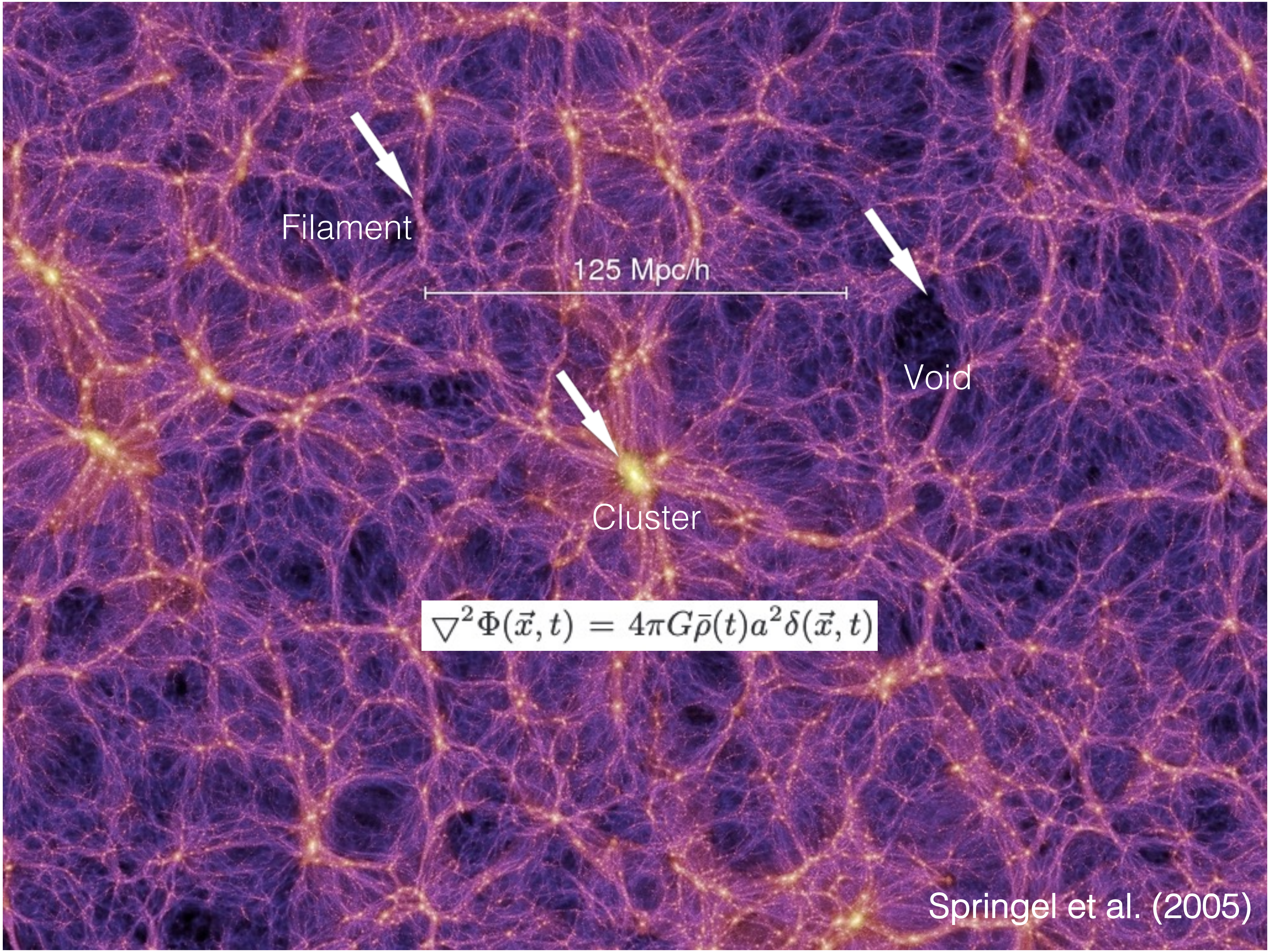
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G \rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

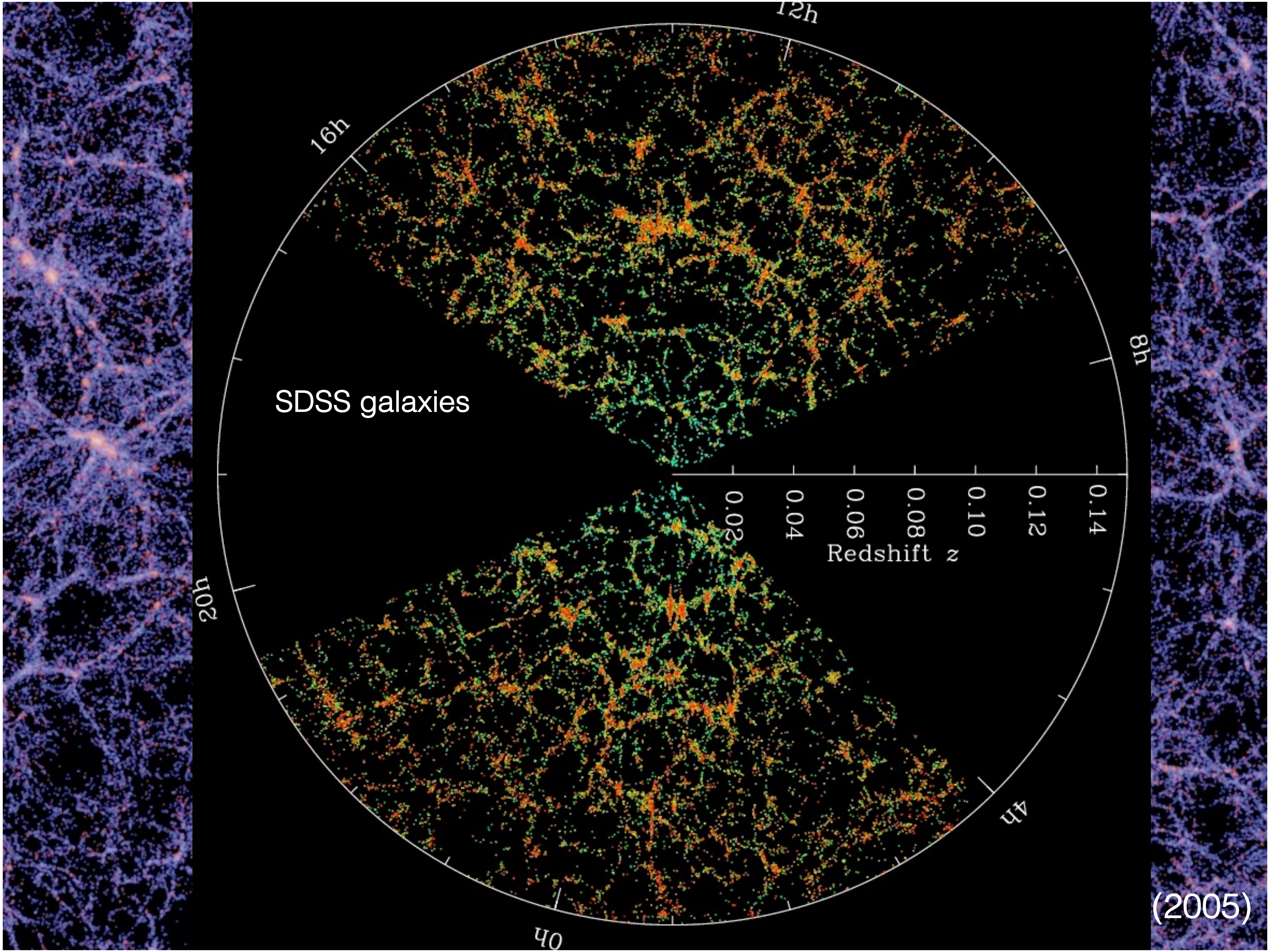
Growth of structure

$$\begin{aligned}
\frac{\partial \delta}{\partial t} + \frac{1}{a}\vec{\nabla}_x \cdot (1+\delta)\vec{v} &= 0 \\
\frac{\partial \vec{v}}{\partial t} + \frac{1}{a}\left(\vec{v}\cdot\vec{\nabla}_x\right)\vec{v} + \frac{\dot{a}}{a}\vec{v} &= -\frac{1}{a}\vec{\nabla}_x \phi \\
\nabla_x^2 \phi &= 4\pi G\, a^2\, \rho_u\, \delta
\end{aligned}$$

$$\Big\Downarrow \ \text{linear order}$$

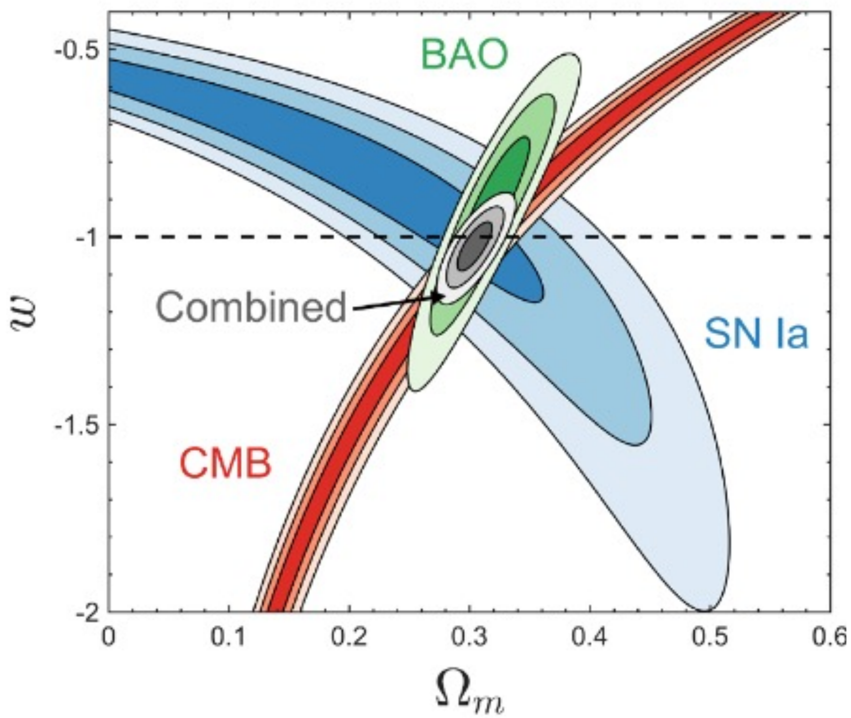
$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = \frac{3}{2}\Omega_0 H_0^2 \frac{1}{a^3}\,\delta$$


Filament
125 Mpc/h
Void
Cluster
$$\nabla^2\Phi(\vec{x},t) = 4\pi G\bar{\rho}(t)a^2\delta(\vec{x},t)$$
Springel et al. (2005)

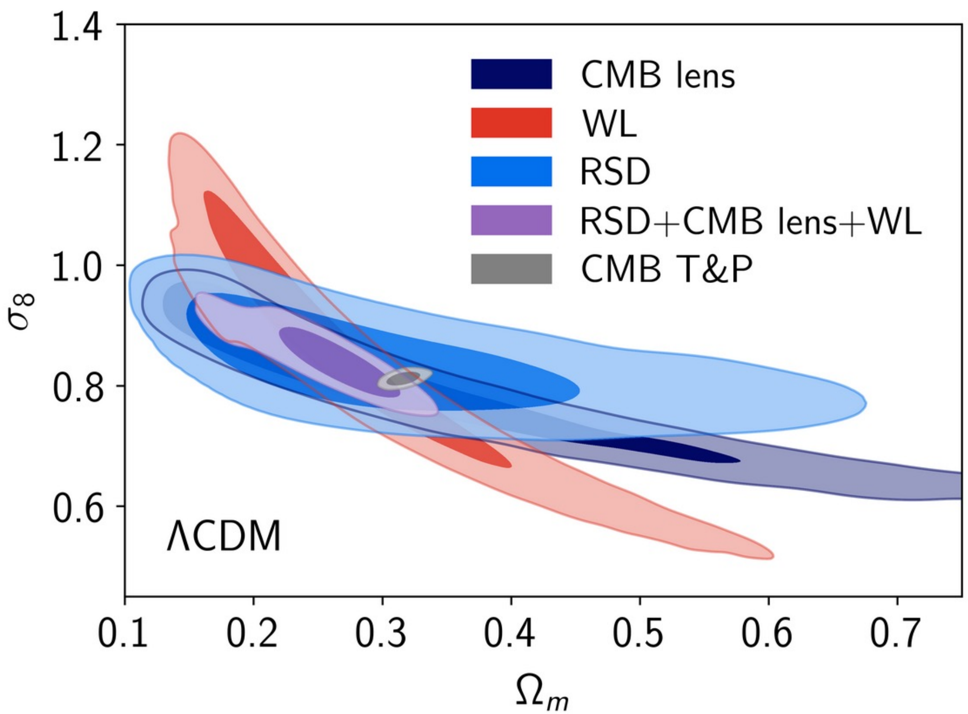

12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
SDSS galaxies
(2005)

Distance measurements:
Standard ruler/candle
Baryon Accustic Ossilations
Distance ladder: SN Ia
CMB

Growth of structure:
Gravitational lensing
Clustering of galaxies
Cluster number counts
CMB, RSD



Dragan Huterer & Daniel L Shafe,
Rep. Prog. Phys. 81 (2018) 016901 (33pp)



eBOSS collaboration, 2021PhRvD.103h3533A

An almost perfect model

Nature of dark components unknown
Law of gravity needs to be tested
Observed H0 do not agree
Amplitude of fluctuations is low
Cold Spot too cold
Missing baryons
…

Density perturbation, growth rate, variance

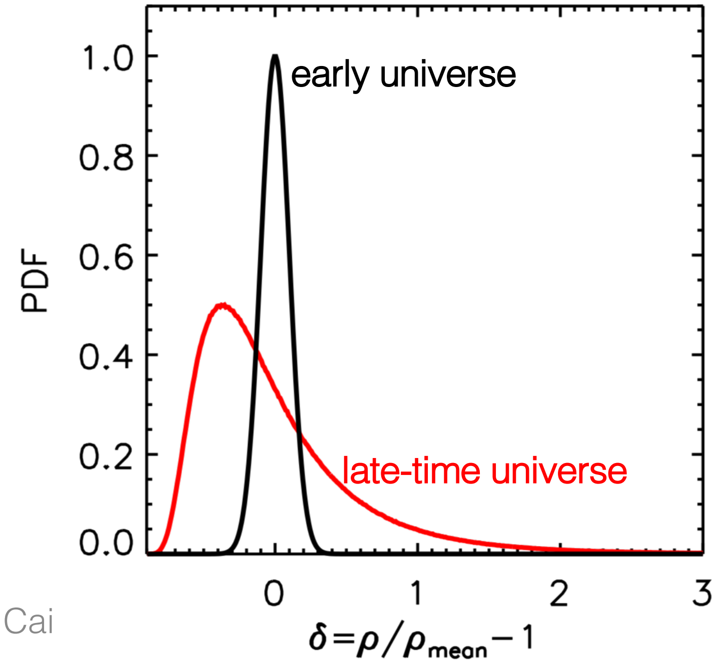
Density contrast $\delta = \rho/\bar{\rho} - 1$

Growth rate $f \equiv \frac{d\ln\delta}{d\ln a} \approx \Omega_m^{0.55}$

Variance $\sigma =< \delta^2 >= \sum_{\mathbf{k}} |\delta_{\mathbf{k}}|^2$

Power spectrum $P(\mathbf{k}) = |\delta_{\mathbf{k}}|^2$

Correlation function $\xi(r) = \frac{\mathrm{DD}}{\mathrm{DR}} - 1$



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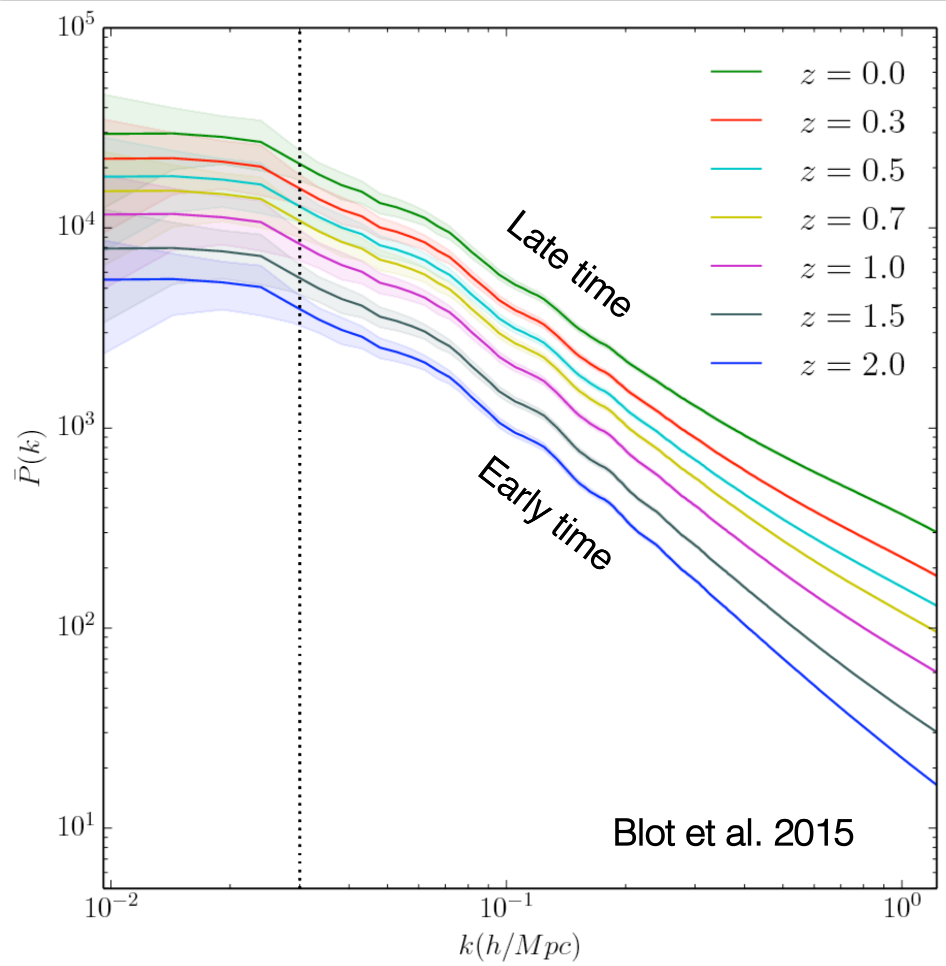
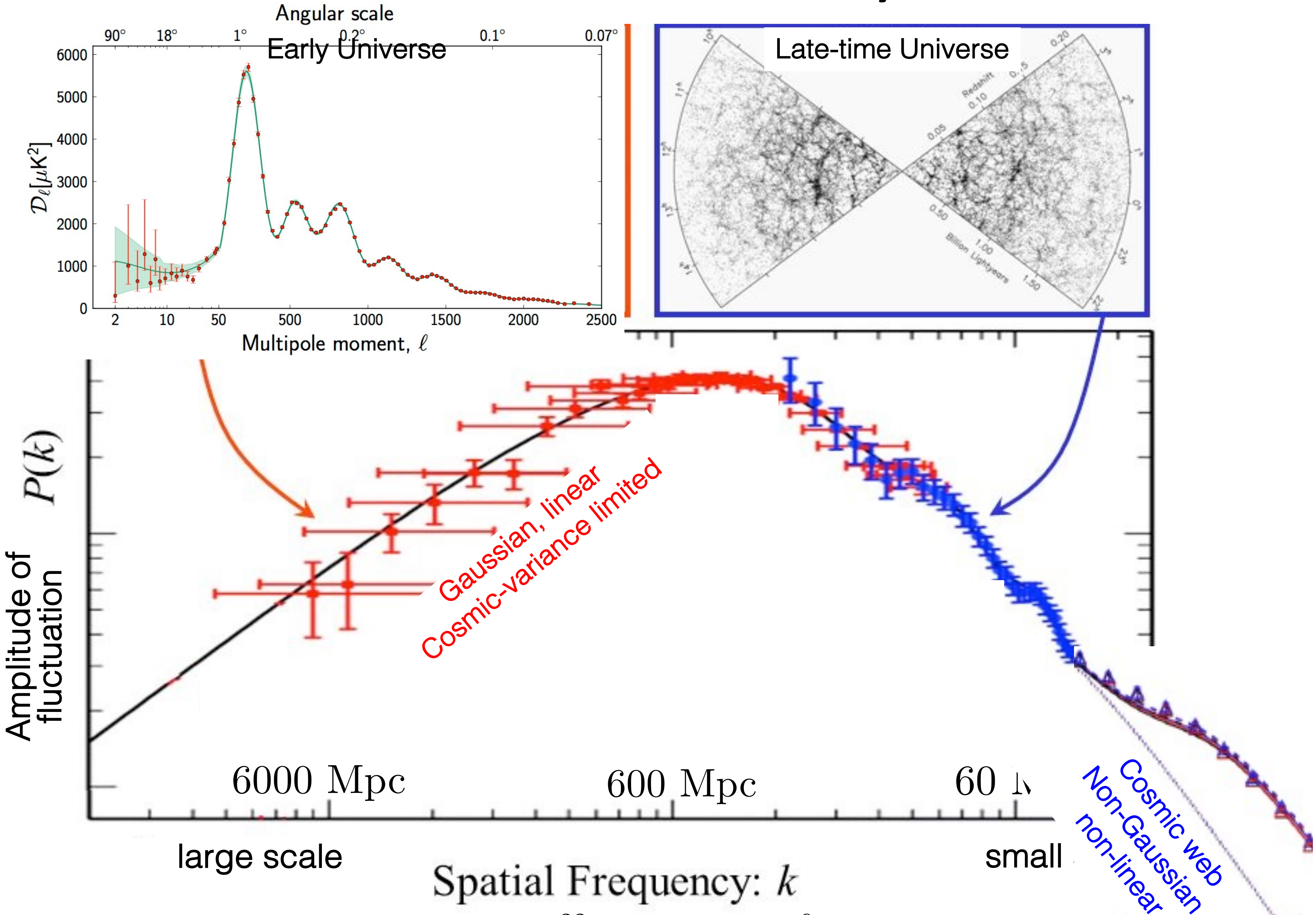


Large scale

small scale

Variance of the density field



$$1 \text{ Mpc} = 3.0 \times 10^{22} \text{ m} = 3.2 \times 10^{6} \text{ light years}$$

Cosmic Web: Why bother

Large Scale

Pros

Simple – Gaussian
2-point statistics is complete
Easy to model

Cons

Limited by survey volume
Expensive to improve

Small Scale

Pros

Lots of info: $N \propto k^3$
Public data available
sensitive to dark components

Cons

Complex: cosmic web
Non-linear, non-Gaussian
Difficult to model

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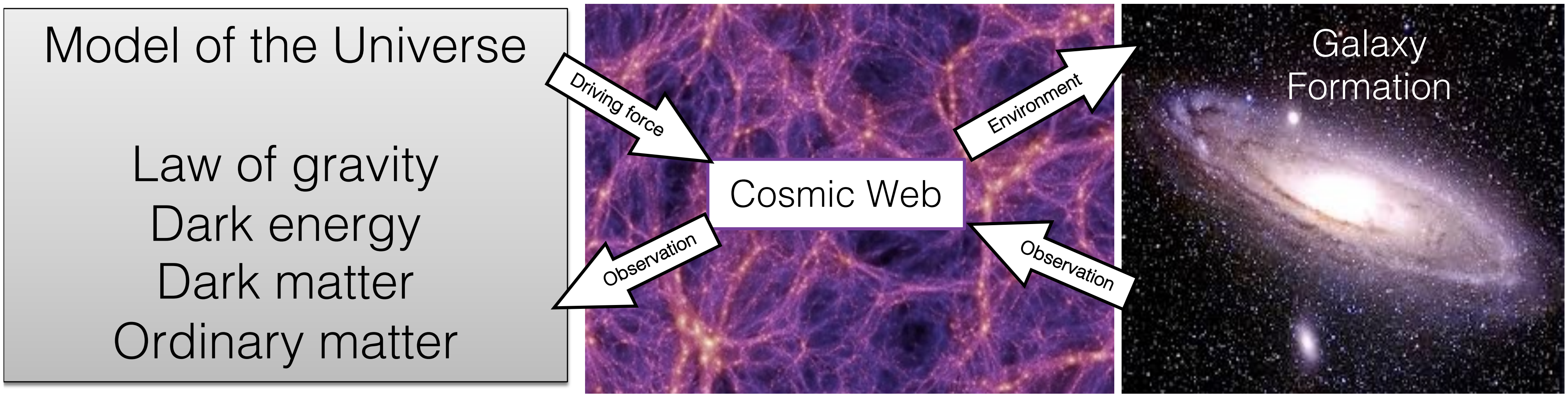
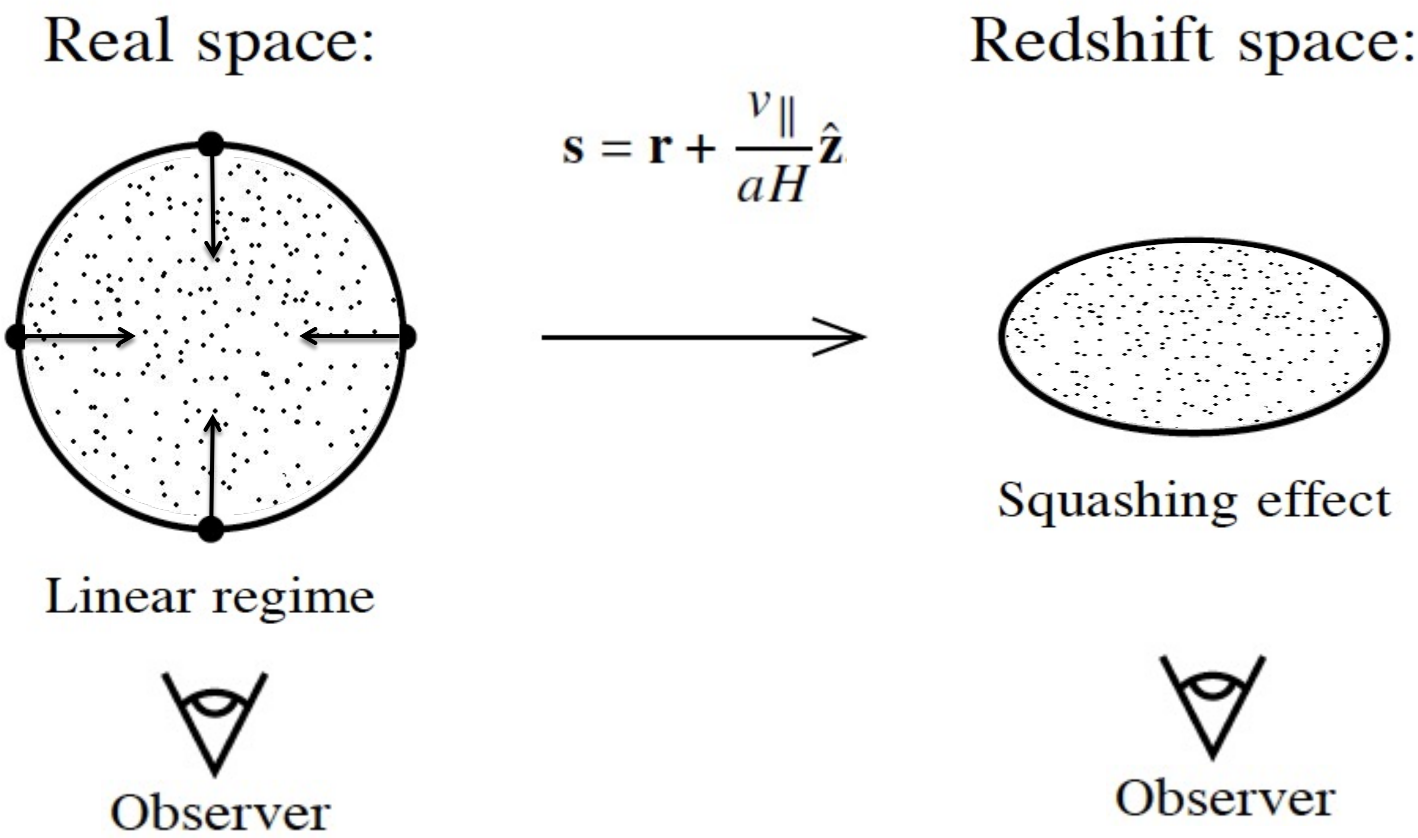
Comology: Cosmic-web: Galaxies



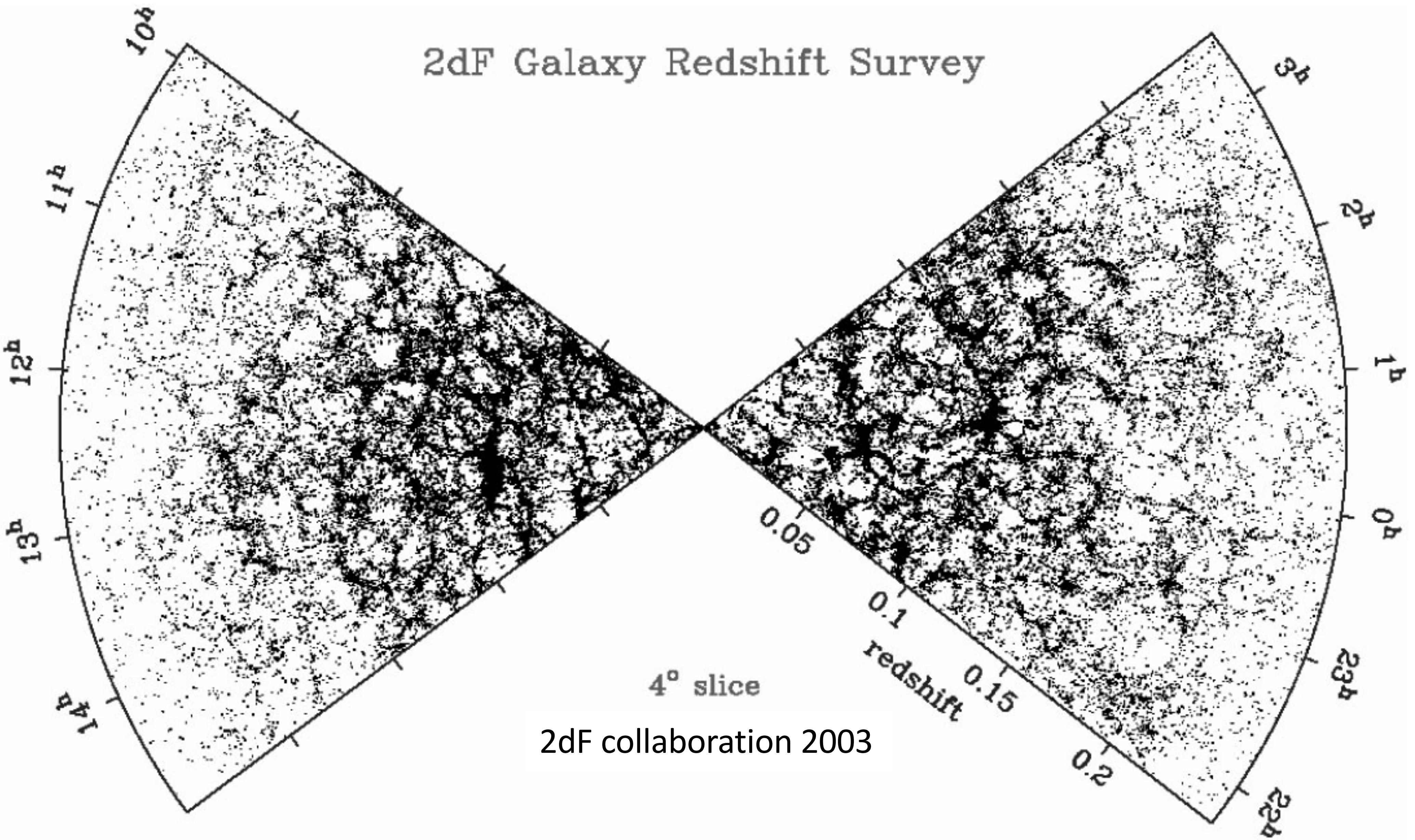
Redshift Space Distortion (RSD)



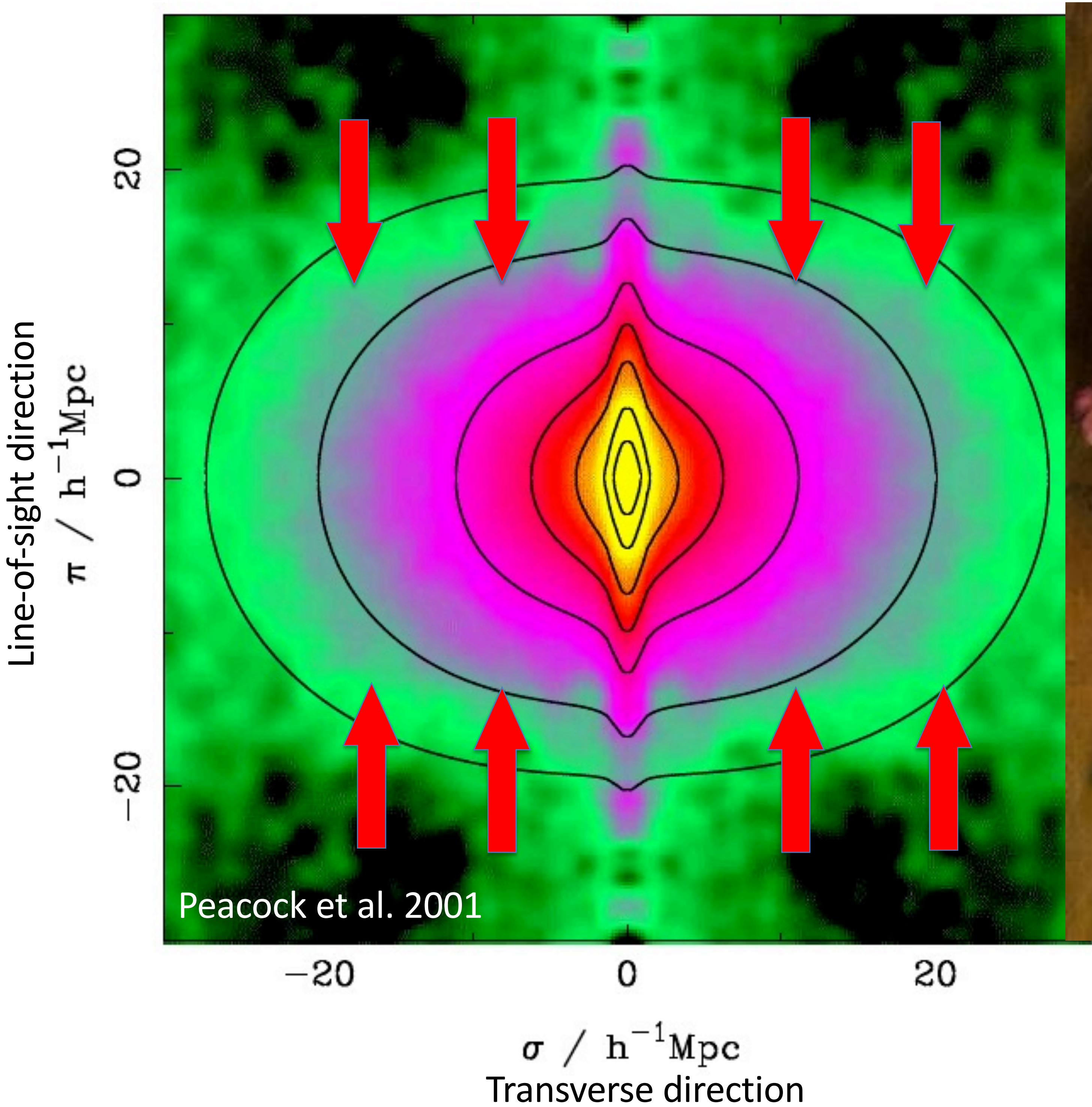
$$P_s = (b + f\mu^2)^2 P = (b/f + \mu^2)^2 f^2 P$$

Kaiser 1987

Y. Cai



2dF collaboration 2003



Beatitudes of Love: Romantic Meeting,
Stanley Spencer (1891-1959)

Nature **410**, 169–173 (2001)

A measurement of the cosmological mass density from clustering in the 2dF Galaxy Redshift Survey

John A. Peacock[1], Shaun Cole[2], Peder Norberg[2], Carlton M. Baugh[2], Joss Bland-Hawthorn[3], Terry Bridges[3], Russell D. Cannon[3], Matthew Colless[4], Chris Collins[5], Warrick Couch[6], Gavin Dalton[7], Kathryn Deeley[6], Roberto De Propris[6], Simon P. Driver[8], George Efstathiou[9], Richard S. Ellis[9,10], Carlos S. Frenk[2], Karl Glazebrook[11], Carole Jackson[4], Ofer Lahav[9], Ian Lewis[3], Stuart Lumsden[12], Steve Maddox[13], Will J. Percival[1], Bruce A. Peterson[4], Ian Price[4], Will Sutherland[7,1], Keith Taylor[3,10]

141,000 galaxies

Growth rate parameter $\beta \equiv \Omega^{0.6}/\mathrm{b} = 0.43 \pm 0.07$ (16%)

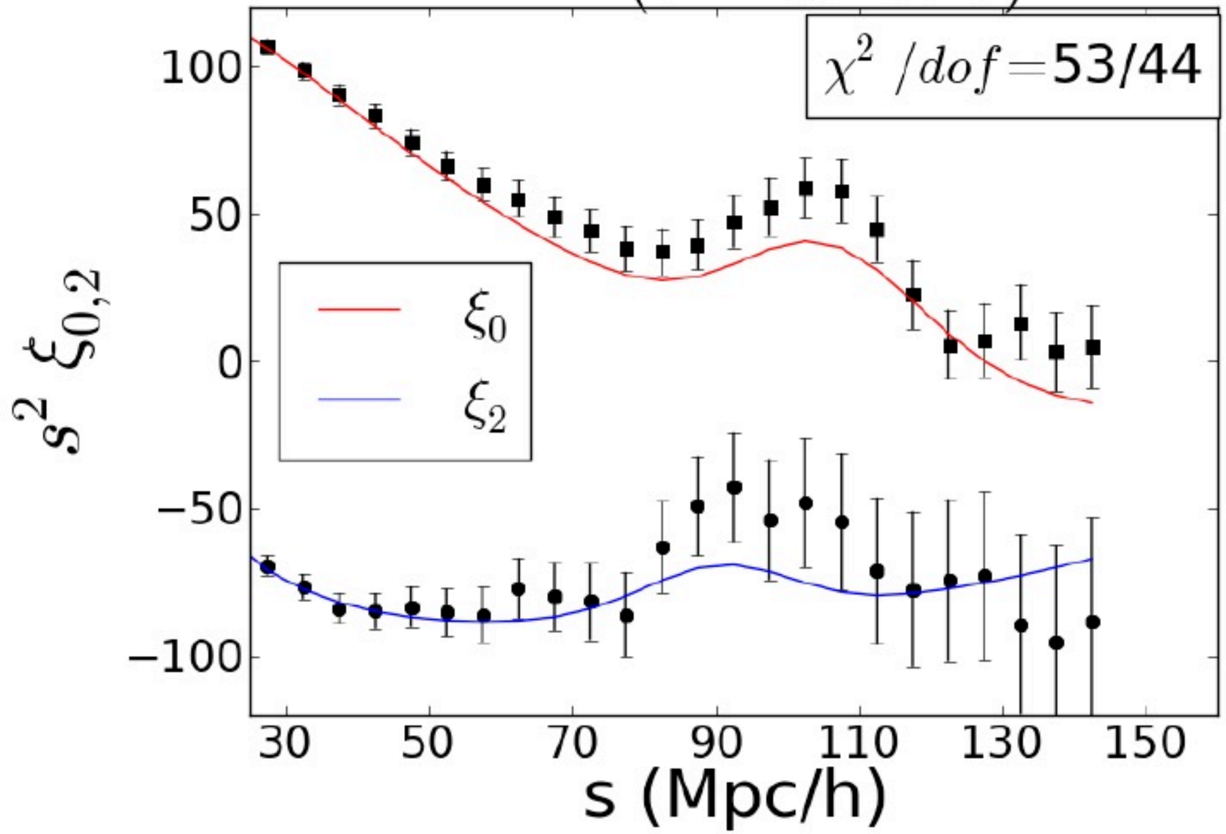
(considering $8\,h^{-1}\,\mathrm{Mpc} < r < 25\,h^{-1}\,\mathrm{Mpc}$)

$$P_s(\mathbf{k}) = P_r(k)\,(1+\beta\mu^2)^2\,(1+k^2\sigma_p^2\mu^2/2H_0^2)^{-1}$$

The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: On the measurement of growth rate using galaxy correlation functions

2017MNRAS.469.1369S

Siddharth Satpathy[1,2]⋆, Shadab Alam[1,2], Shirley Ho[1,2,3,4], Martin White[3,4],
Neta A. Bahcall[5] … [9],
Daniel J. Eisenst … D.
Olmstead[13], Will … z[12],
Hee-Jong Seo[14], …



Derived Parameters	
$f\sigma_8$	457 $\pm$ 0.052

1,198,006 galaxies

fitting range 25 h^{-1}M

RSD model

$$\mathbf{s} = \mathbf{r} + \frac{v_{\|}}{aH}\hat{\mathbf{z}}$$

Observed redshift = true redshift + peculiar velocity

$$1 + \xi^{s}(s_{\perp}, s_{\|}) = \int [1 + \xi(r)]\,\mathcal{P}(v_{\|}, \mathbf{r})\mathrm{d}v_{\|}$$

Peebles 1980

Observed galaxy distribution = true galaxy distribution $\ast$ velocity distribution

$$1 + \xi^{s}(s_{\perp}, s_{\|}) = \int (1 + \xi(r))\,\frac{1}{\sqrt{2\pi\sigma_{\|}^{2}(r,\mu)}}\exp\left\{-\frac{[v_{\|} - v_{r}(r)\mu]^{2}}{2\sigma_{\|}^{2}(r,\mu)}\right\}\mathrm{d}v_{\|}$$

Fisher 1995

Observed galaxy distribution = true galaxy distribution $\ast$ **Gaussian** velocity distribution

What we need to know for RSD modeling

- Real-space correlation function
- Pairwise velocity distributions

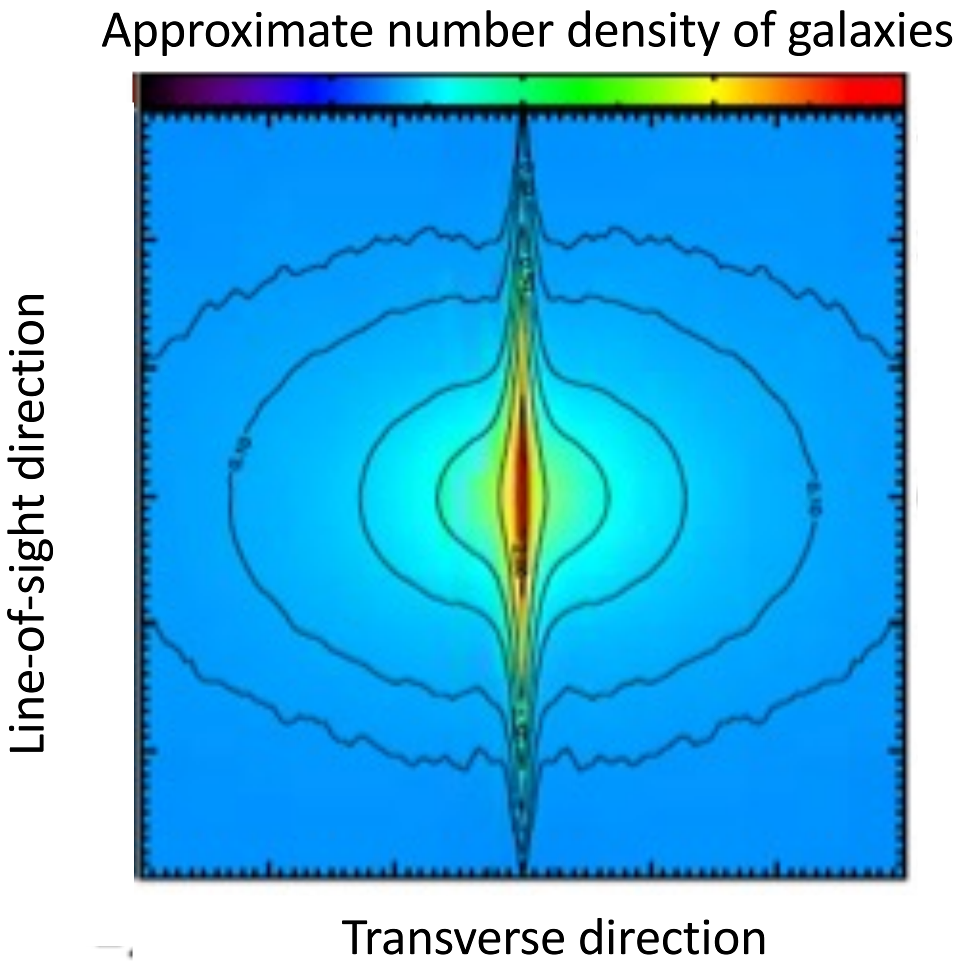
In the Gaussian limit:

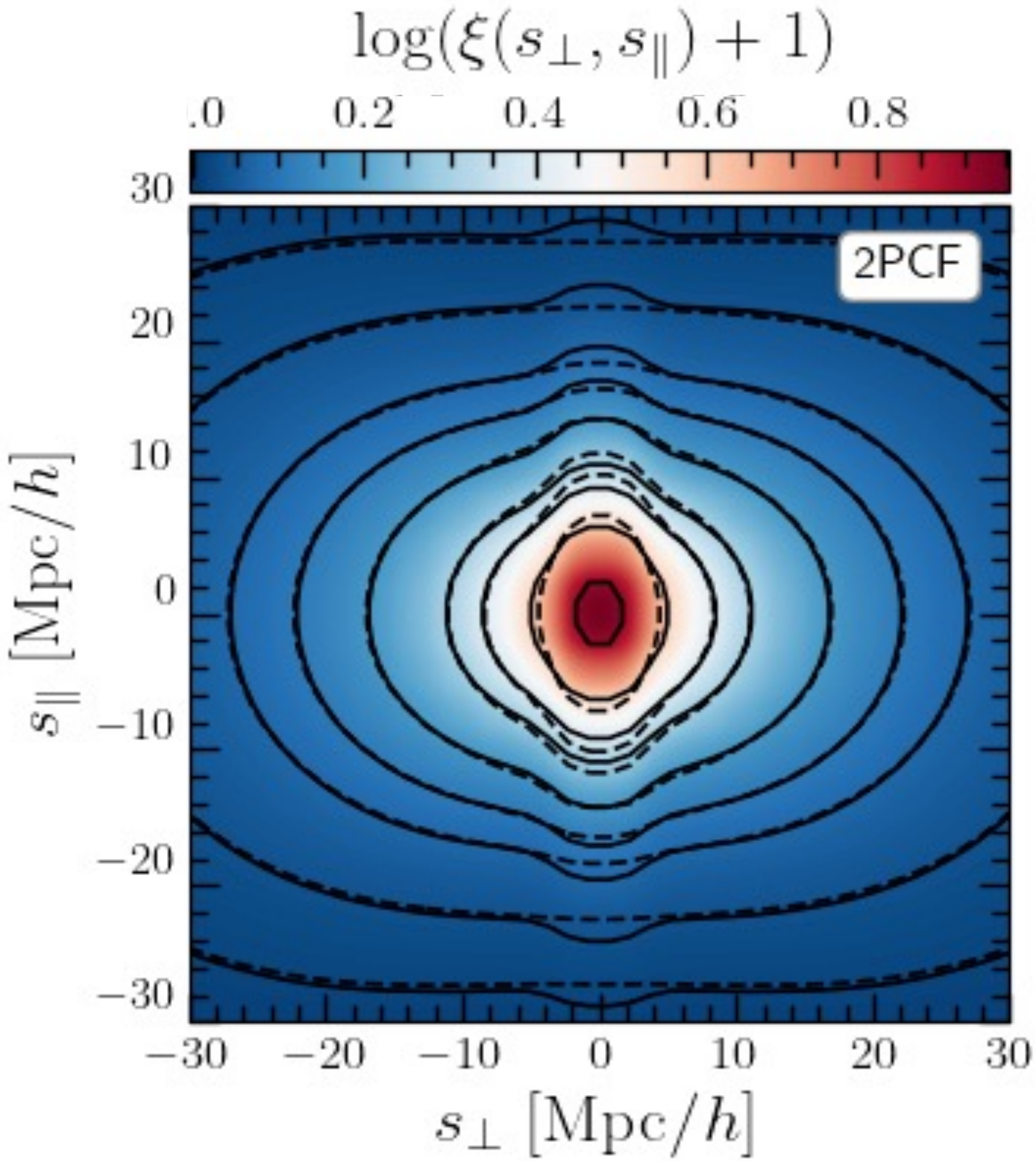
Streaming velocity profile v(r)

Velocity dispersion profile sigma_v(r)

Question 1

- Why with a factor of 10 increase for the number of galaxies, the constraining power for the growth does not increase by a factor of sqrt(10)?

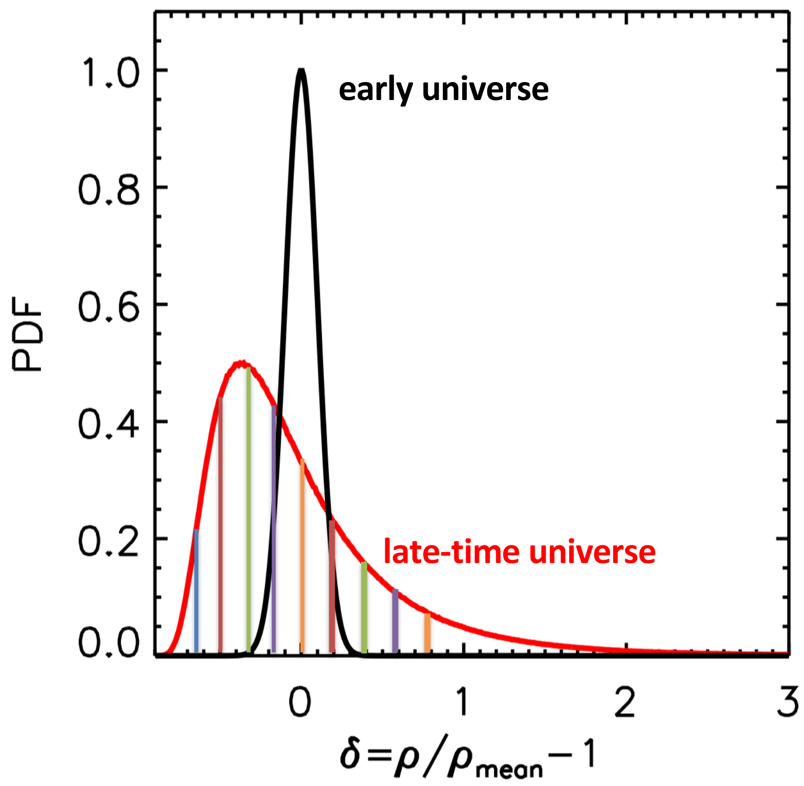

Approximate number density of galaxies
Line-of-sight direction
Transverse direction

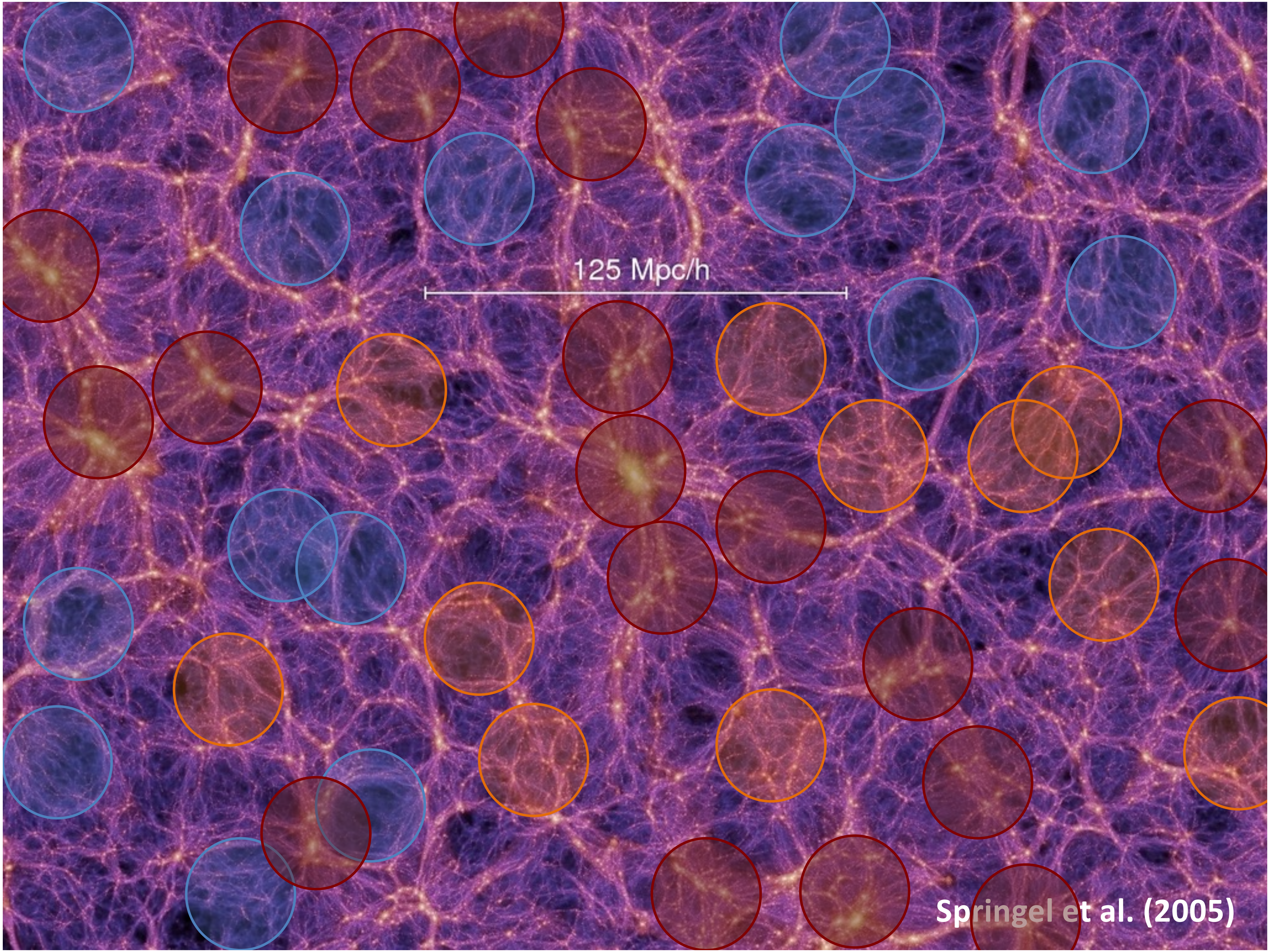


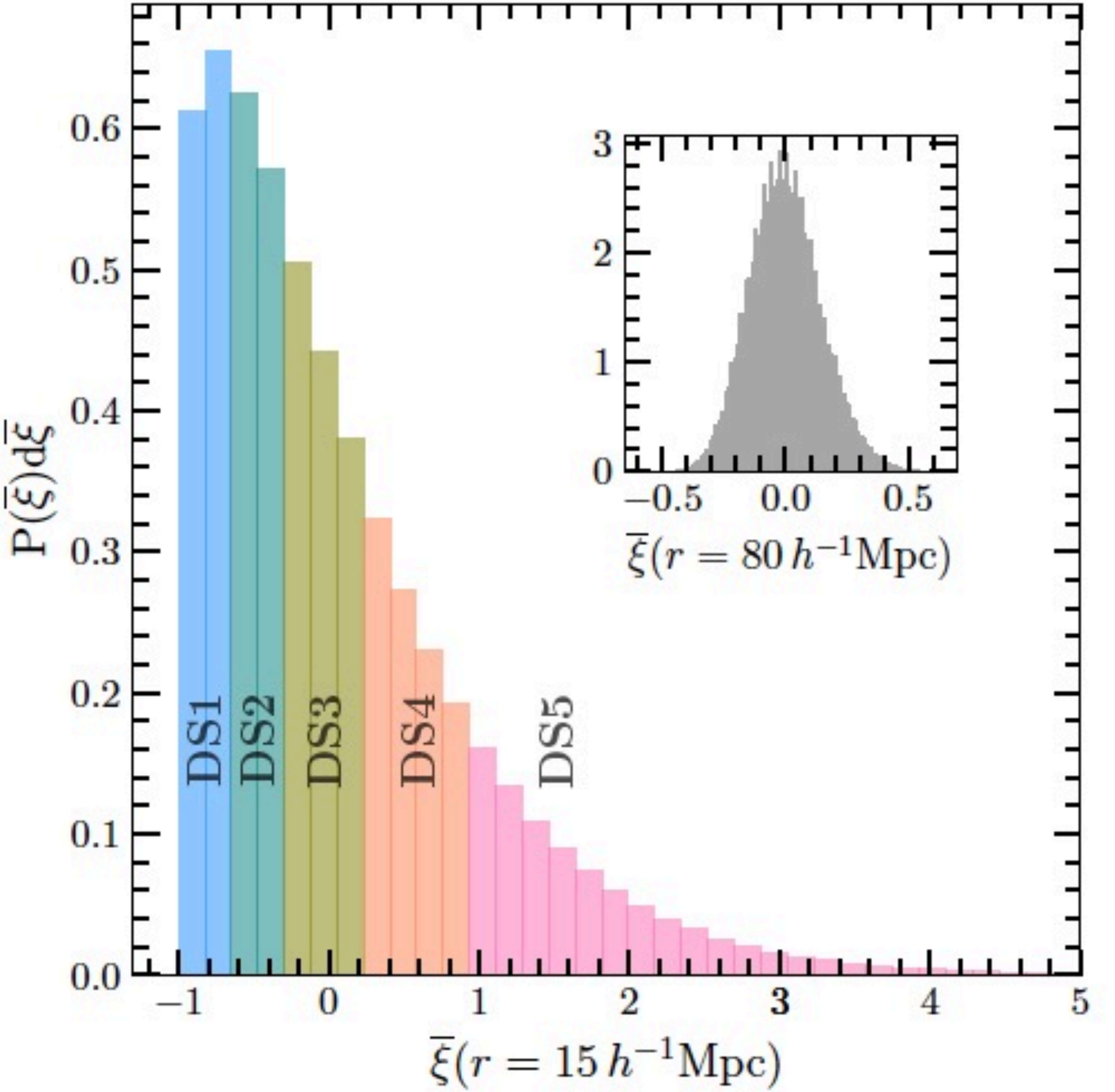
Simulation vs. model (Fisher 1995)

E. Paillas, YC, N. Padilla, A. Sánchez 2021

Density-split RSD




125 Mpc/h
Springel et al. (2005)



P($\bar{\xi}$)d$\bar{\xi}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
DS1
DS2
DS3
DS4
DS5
−1
0
1
2
3
4
5
$\bar{\xi}(r = 15\,h^{-1}\mathrm{Mpc})$
0
1
2
3
−0.5
0.0
0.5
$\bar{\xi}(r = 80\,h^{-1}\mathrm{Mpc})$

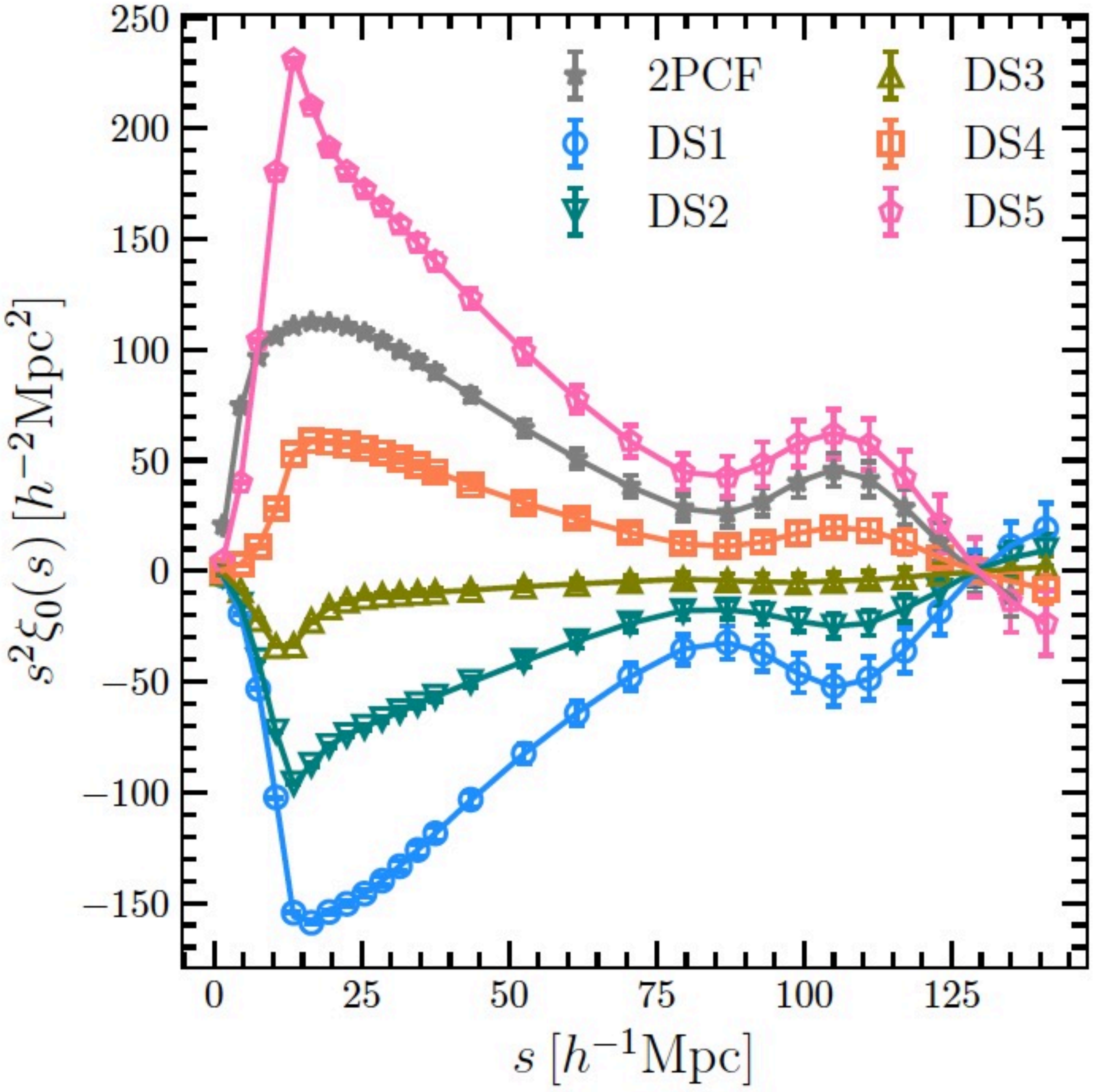
RSD modeling with split densities

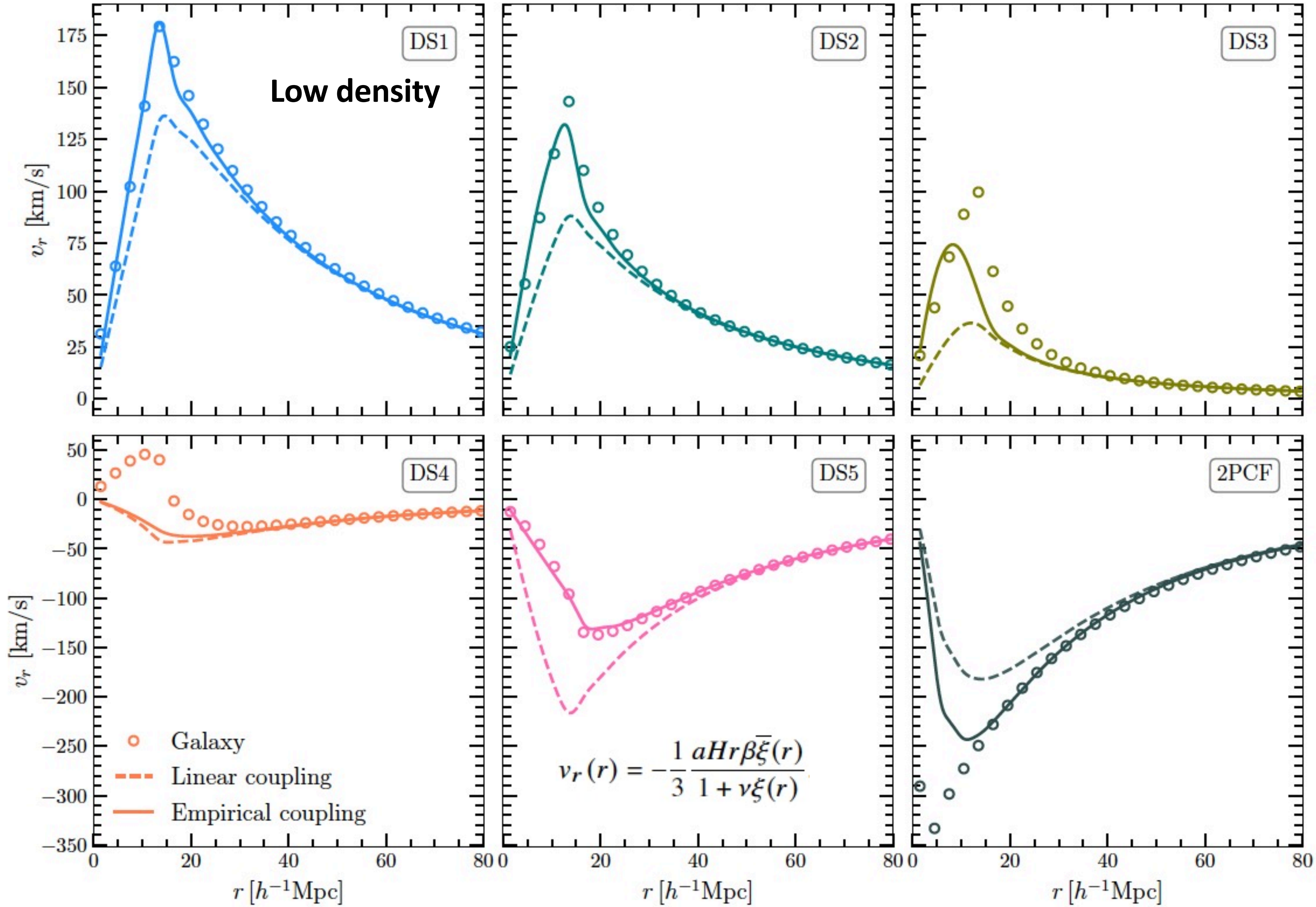
- Real-space density profiles delta(r)
- Velocity distributions

  In the Gaussian limit:

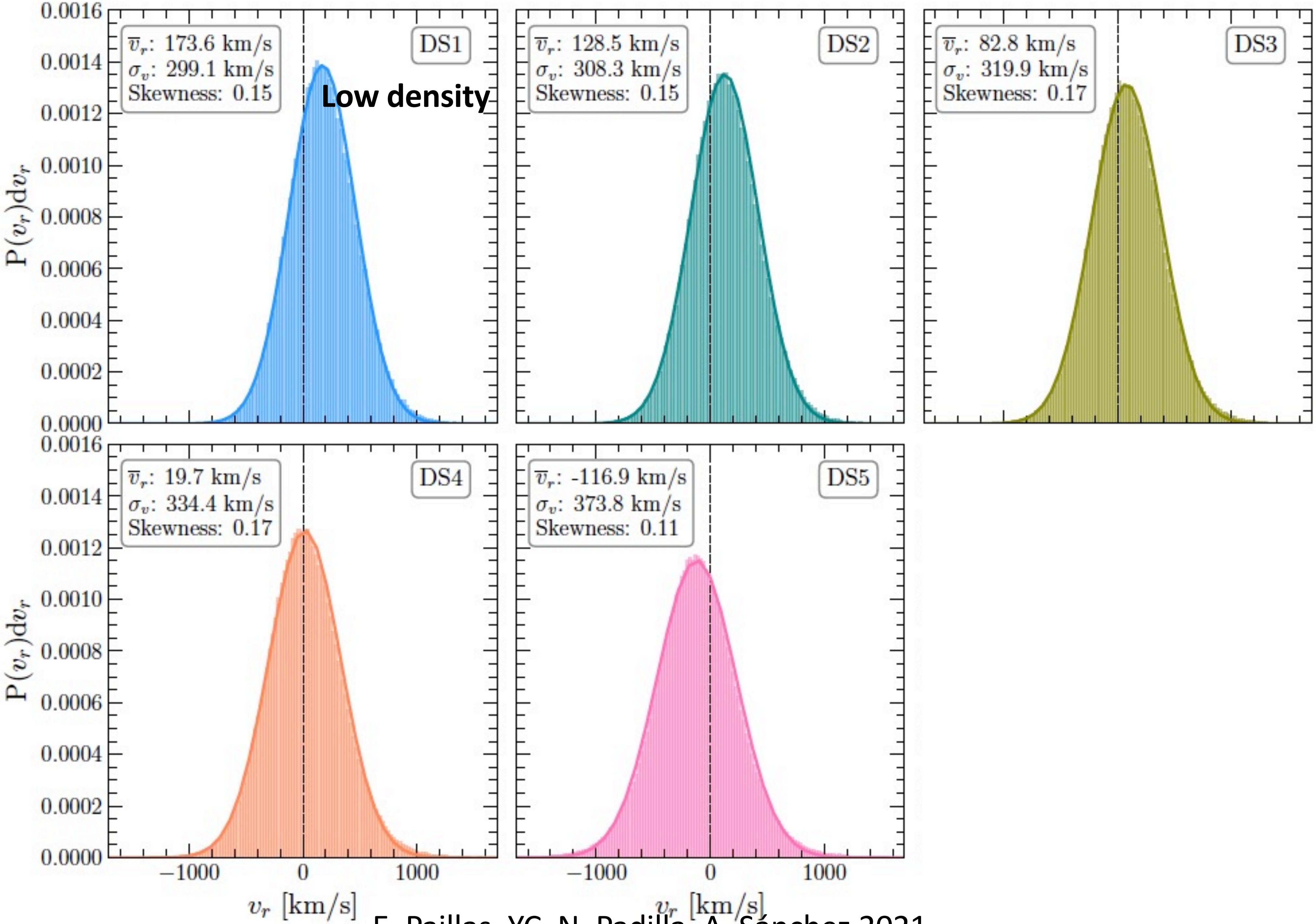
    Streaming velocity profile v(r)

    Velocity dispersion profile sigma_v(r)

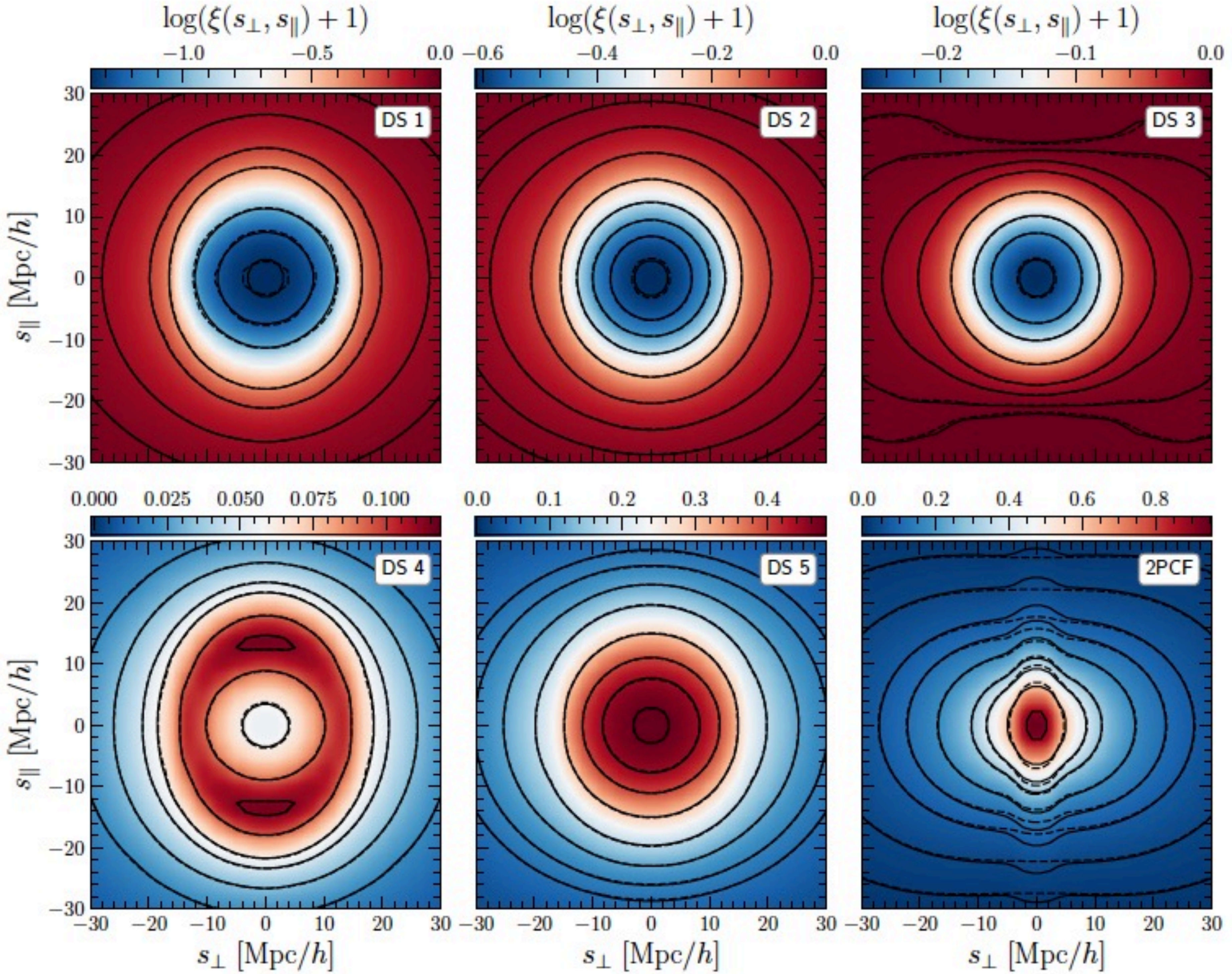

2PCF
DS1
DS2
DS3
DS4
DS5
250
200
150
100
50
0
−50
−100
−150
0
25
50
75
100
125
$s^2\xi_0(s)\ [h^{-2}\mathrm{Mpc}^2]$
$s\ [h^{-1}\mathrm{Mpc}]$



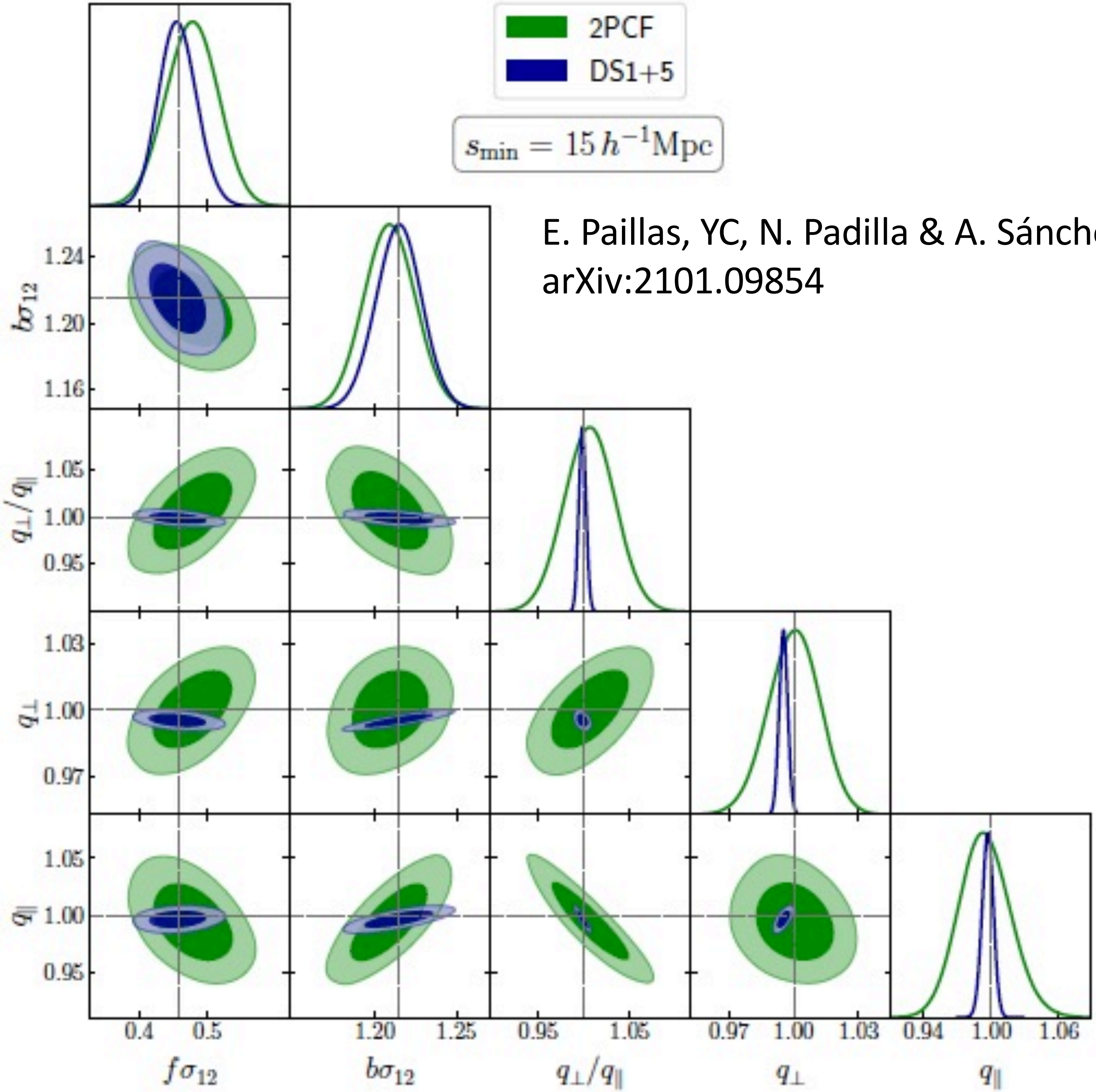
DS1
Low density
DS2
DS3
DS4
DS5
2PCF
v_r [km/s]
$r\,[h^{-1}\mathrm{Mpc}]$
Galaxy
Linear coupling
Empirical coupling
$v_r(r) = -\frac{1}{3}\frac{aHr\beta\bar{\xi}(r)}{1+\nu\xi(r)}$



E. Paillas, YC, N. Padilla, A. Sánchez 2021



$\log(\xi(s_\perp, s_\parallel) + 1)$
DS 1
DS 2
DS 3
DS 4
DS 5
2PCF
$s_\parallel$ [Mpc/h]
$s_\perp$ [Mpc/h]



E. Paillas, YC, N. Padilla & A. Sánchez
arXiv:2101.09854

Summary

- Standard model of the Universe seem to fit,
  but there are issues to resolve
- Big surveys of large-scale structure promises tight constraints for cosmology, but we are limited by systematics
- RSD measures the growth of structure
- RSD with splitting densities:
  improves modelling accuracy
  tighten constraints for the growth