Cosmology III: Large Scale Structure

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Outline

- Summary of the previous
- The scales in large scale structure
- Linear perturbations
- mildly non-linear
- non-linear
- Baryon Acoustic Oscillations
- weak lensing

Our universe

$$z \equiv \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} - 1$$

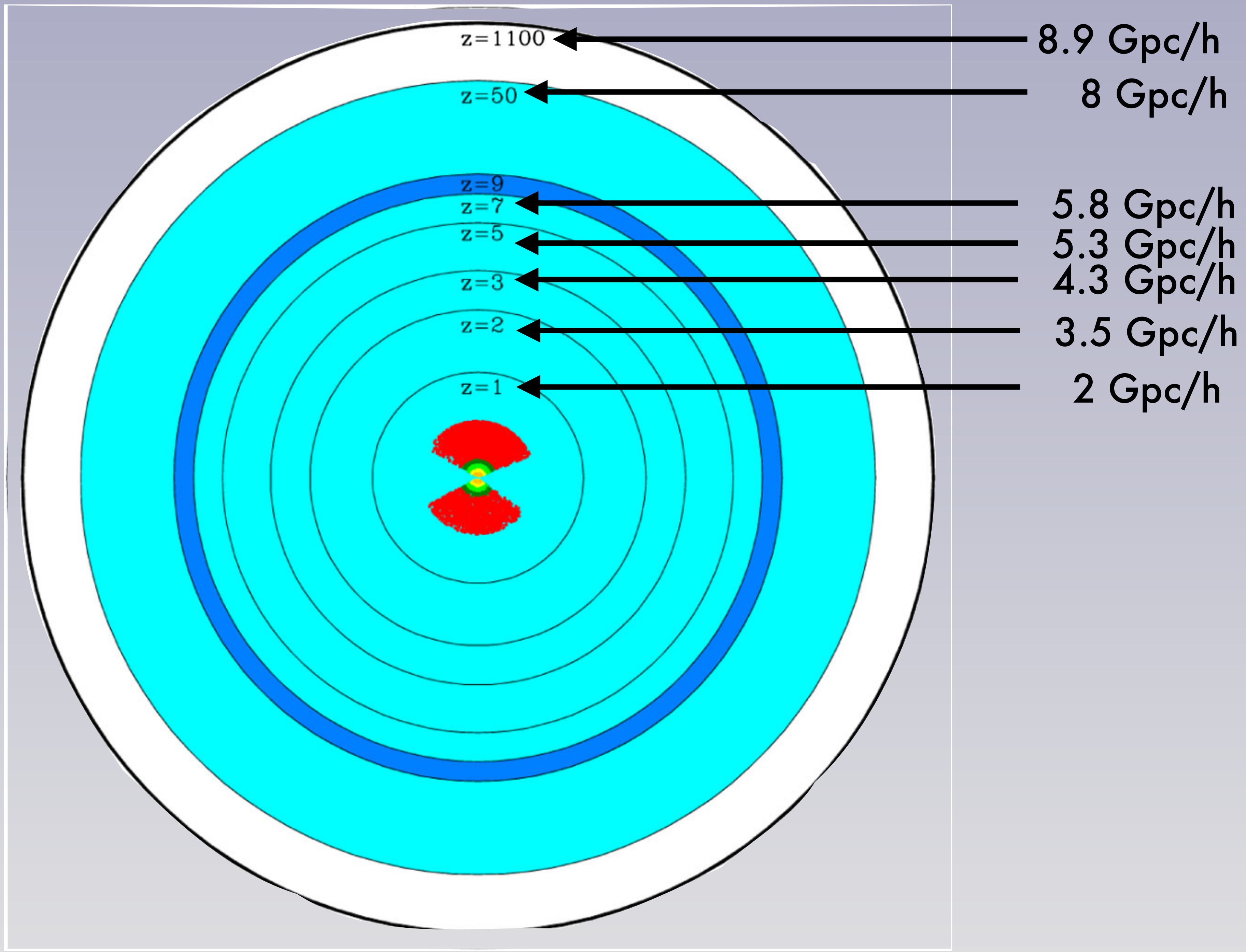


Image from Tegmark & Zaldarriaga, PRD, 2009

Our universe

$$z \equiv \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} - 1$$

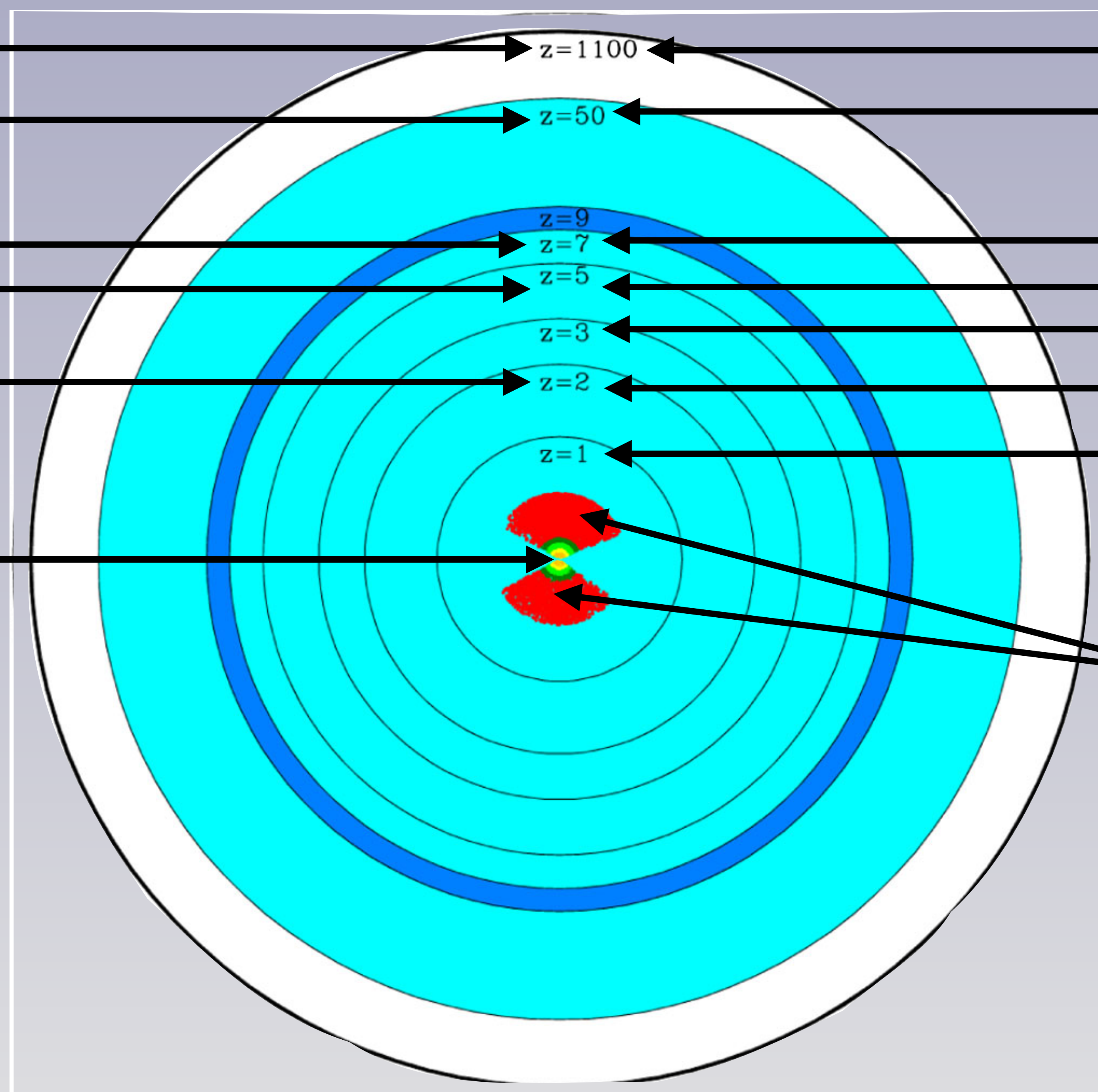


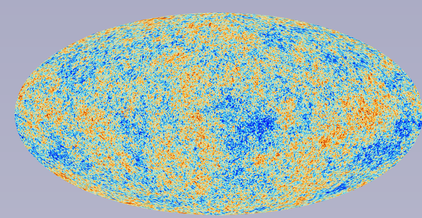
Image from Tegmark & Zaldarriaga, PRD, 2009

Expansion history

- Distance vs redshift:
  - expansion history of the space time
    - the matter contents.

$$H_0 d_A(z) = \frac{1}{1+z} \int \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\Lambda}}$$

CMB



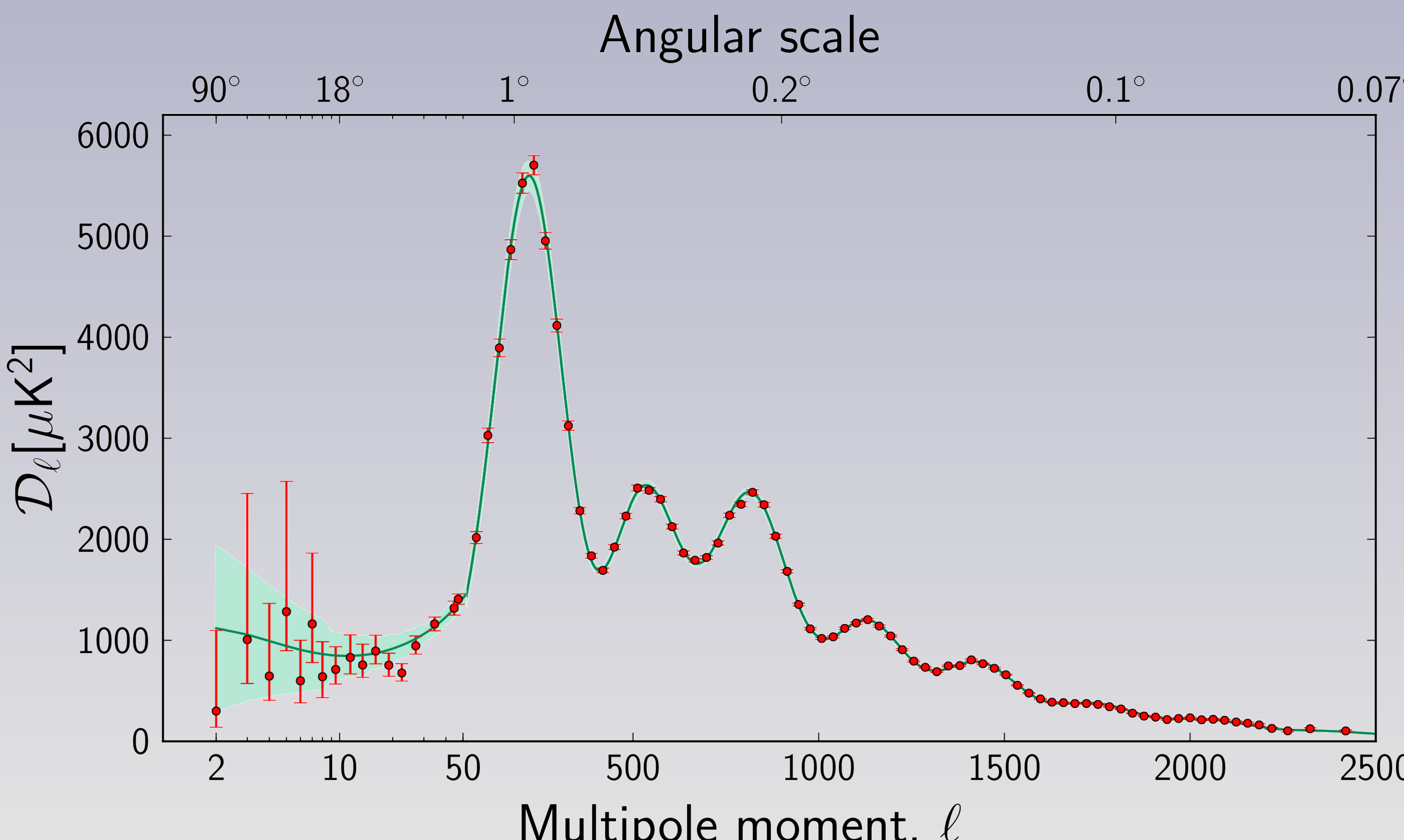
+

$$T(\phi,\theta) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\phi,\theta)$$

$$a_{lm} = \int_{\Omega} d\Omega\, T(\phi,\theta) Y^{*}_{lm}$$

$$D_l^{TT} \equiv \frac{1}{2l+1}\sum_{m=-l}^{l} |a_{lm}|^2$$

=

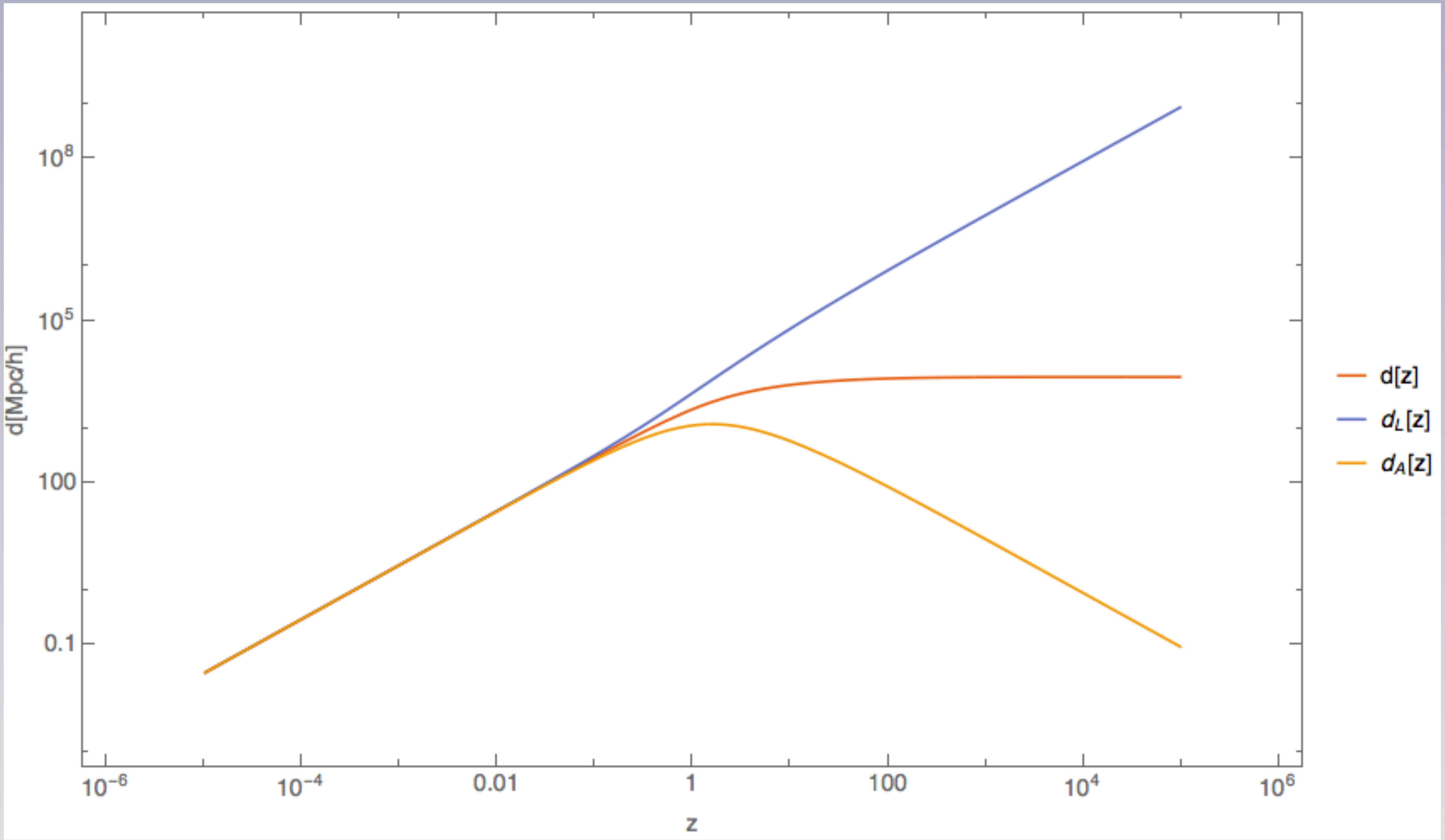


CMB

- Ratio of peaks: baryons vs DM Ω_{b}
- Height of peaks: DM and primordial power Ω_{DM} $A_{\mathrm{s}}, n_{\mathrm{s}}$
- Overal position of all peaks: age of universe, spatial curvature H_0, Ω_k
- Lensing: DE Ω_Λ
- Damping: reionization τ
- Sunyaev-Zel'dovich: cluster masses Ω_{DM}
- ... (Polarization not discussed yet)

$\boxed{m_\nu \;\; H_{\mathrm{Inflation}}}$

Distances



Large Scale Sctructure

- Galaxy sizes: O(kpc) = O(10^3 ly)
- Cluster sizes: O(Mpc) = O(10^6 ly)

Linear perturbations

- Very much same as CMB:
- Cold Dark Matter clusters
  - density perturbations grow
- Before CMB decoupling:
  - Baryons have pressure, oscillate
- After CMB decoupling:
  - Baryons cluster pressureless, like CDM

Linear perturbations

- Cold Dark Matter clusters
  - density perturbations grow
- Baryons cluster pressureless, like CDM
- Neutrinos: special case
  - large scales: like massive particles
  - small scales: like massless particles
- Dark Energy:
  - Slows down clustering of DM
  - Can cluster itself
- Modified Gravity
  - speaks for itself

Linear perturbations

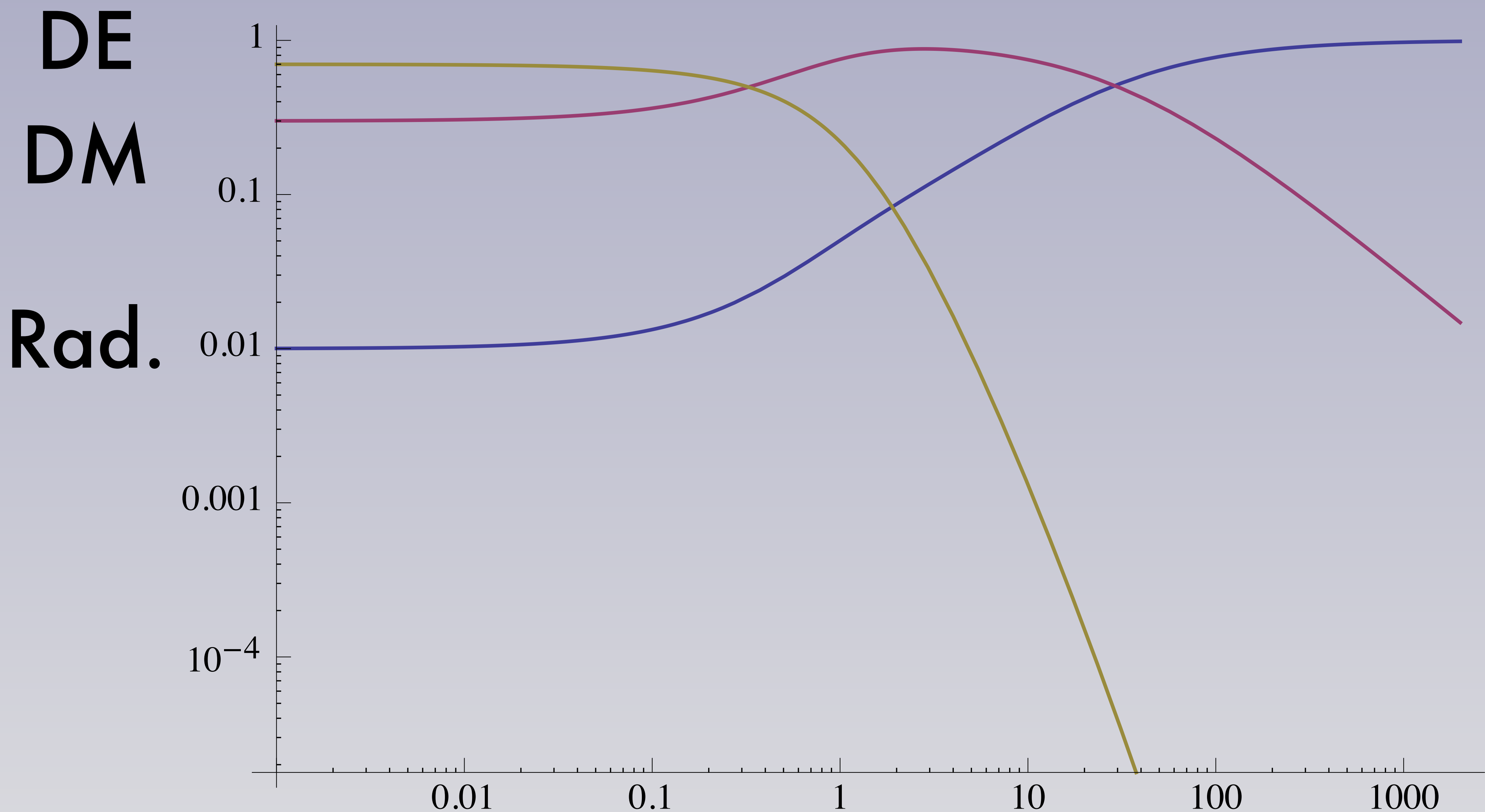
Same as in CMB story:

$$\boxed{\Phi'' + 3(1+w)\mathcal{H}\Phi' + wk^2\Phi = 0}$$

Super Hubble:

$$k \ll \mathcal{H} \equiv aH = \dot{a} \longrightarrow \Phi = const.$$

[following Daniel Baumann's notes]



DE
DM
Rad.
1
0.1
0.01
0.001
10^{-4}
0.01
0.1
1
10
100
1000

Linear perturbations

Same as in CMB story:

$$\boxed{\Phi'' + 3(1+w)\mathcal{H}\Phi' + wk^2\Phi = 0}$$

Sub-hubble, radiation domination

$$w = \tfrac{1}{3} \qquad \Phi'' + \frac{4}{\tau}\Phi' + \frac{k^2}{3}\Phi = 0$$

$$\Phi_{\boldsymbol{k}}(\tau) \approx -6\mathcal{R}_{\boldsymbol{k}}(0)\,\frac{\cos\left(\frac{1}{\sqrt{3}}k\tau\right)}{(k\tau)^2}$$

$$x = k\tau$$

$$a(\tau)d\tau = dt$$

[following Daniel Baumann’s notes]

Linear perturbations

Same as in CMB story:

$$\boxed{\Phi'' + 3(1+w)\mathcal{H}\Phi' + wk^2\Phi = 0}$$

Sub-hubble, radiation domination

$$w = 0 \qquad \Phi'' + \frac{6}{\tau}\Phi' = 0$$

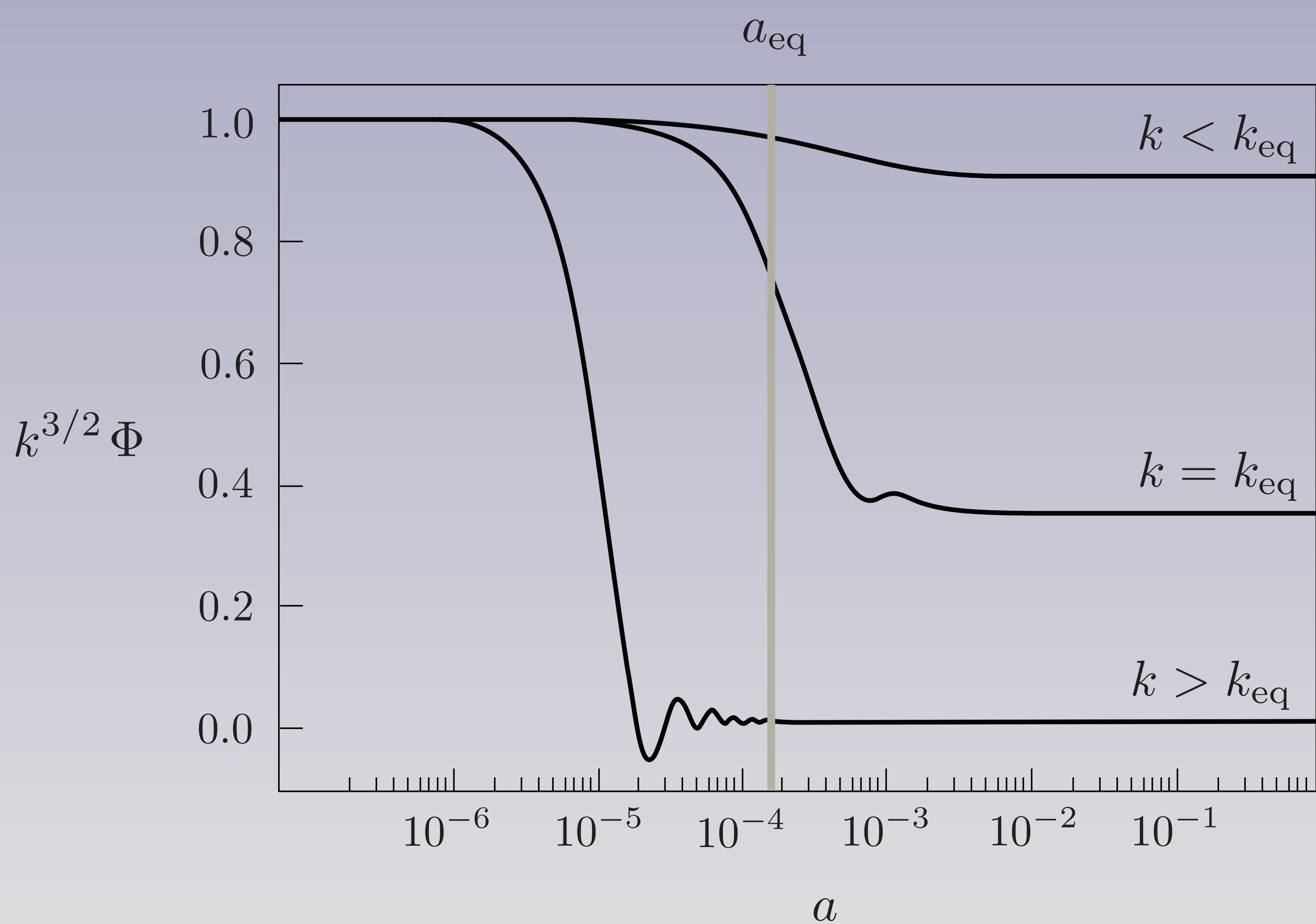
$$\Phi \propto \begin{cases} const. \\ \tau^{-5} \propto a^{-5/2} \end{cases}$$

$$x = k\tau$$

$$a(\tau)d\tau = dt$$

[following Daniel Baumann's notes]

Linear perturbations



[following Daniel Baumann's notes]

Linear perturbations

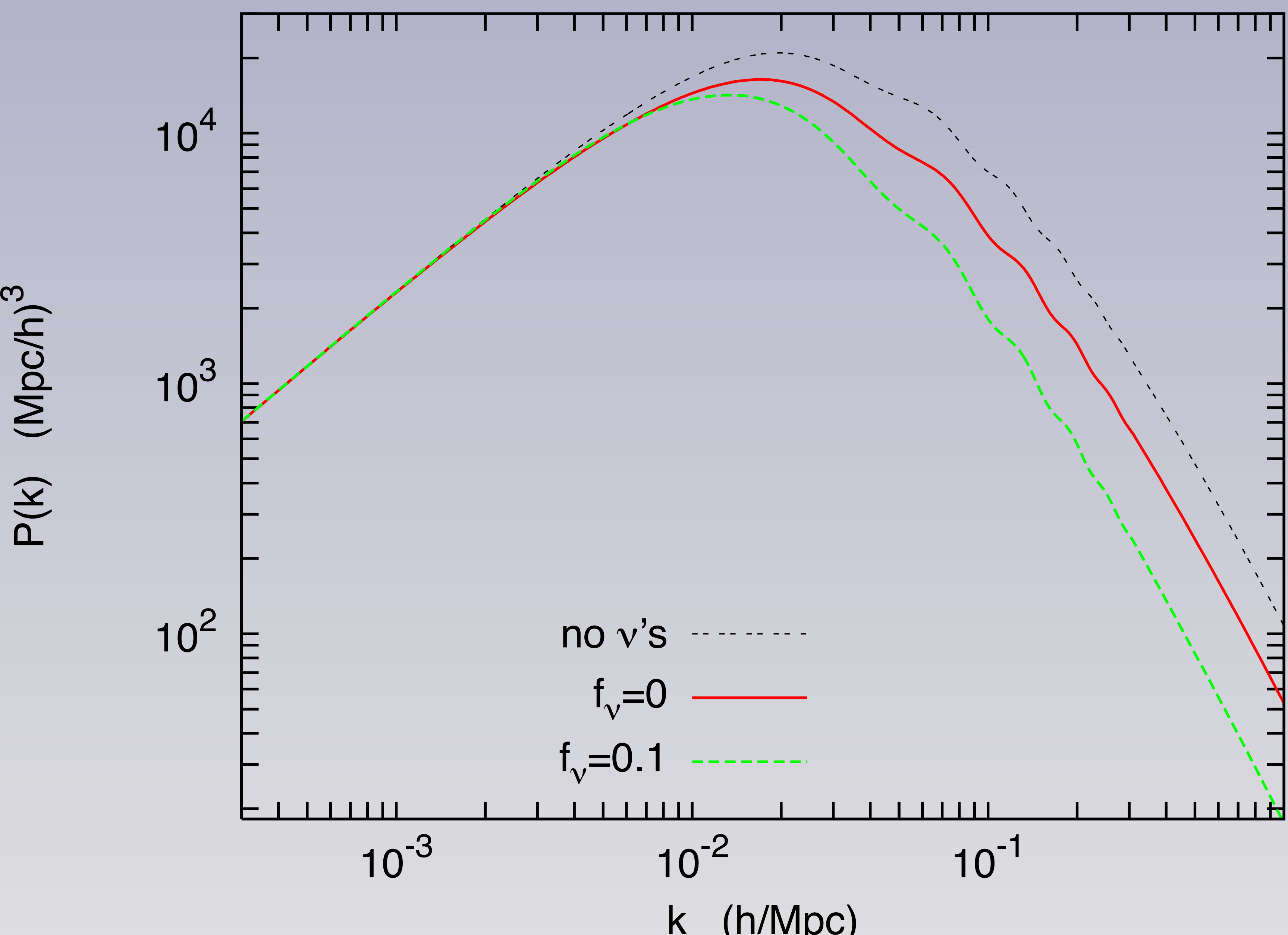
$$\nabla^2\Phi = 4\pi G a^2 \bar{\rho}_m \Delta_m$$

If $\Phi = \text{constant}$, then $\Delta_m \propto a$, since $\bar{\rho}_m \propto a^{-3}$.

[following Daniel Baumann's notes]

Power spectra

$$\left\langle \delta_m(\vec{k})\delta_m(\vec{k}')\right\rangle = (2\pi)^3 P(k)\delta^{(3)}(\vec{k}-\vec{k}')$$

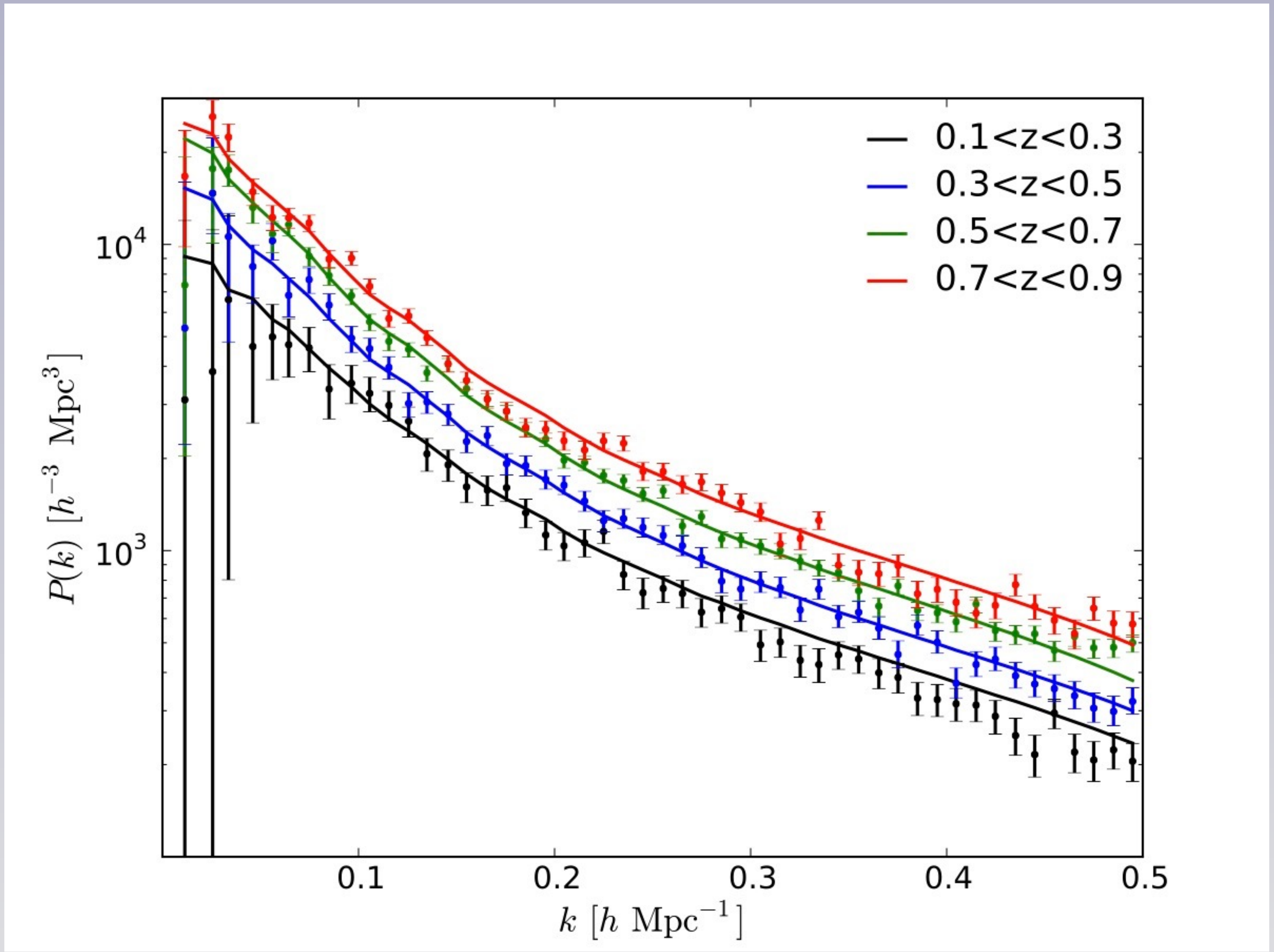


$$f_\nu \equiv \frac{\rho_\nu}{(\rho_{\rm cdm}+\rho_{\rm b}+\rho_\nu)} = \frac{\Omega_\nu}{\Omega_{\rm m}}$$

from [Lesgourgues & Pastor 2006]

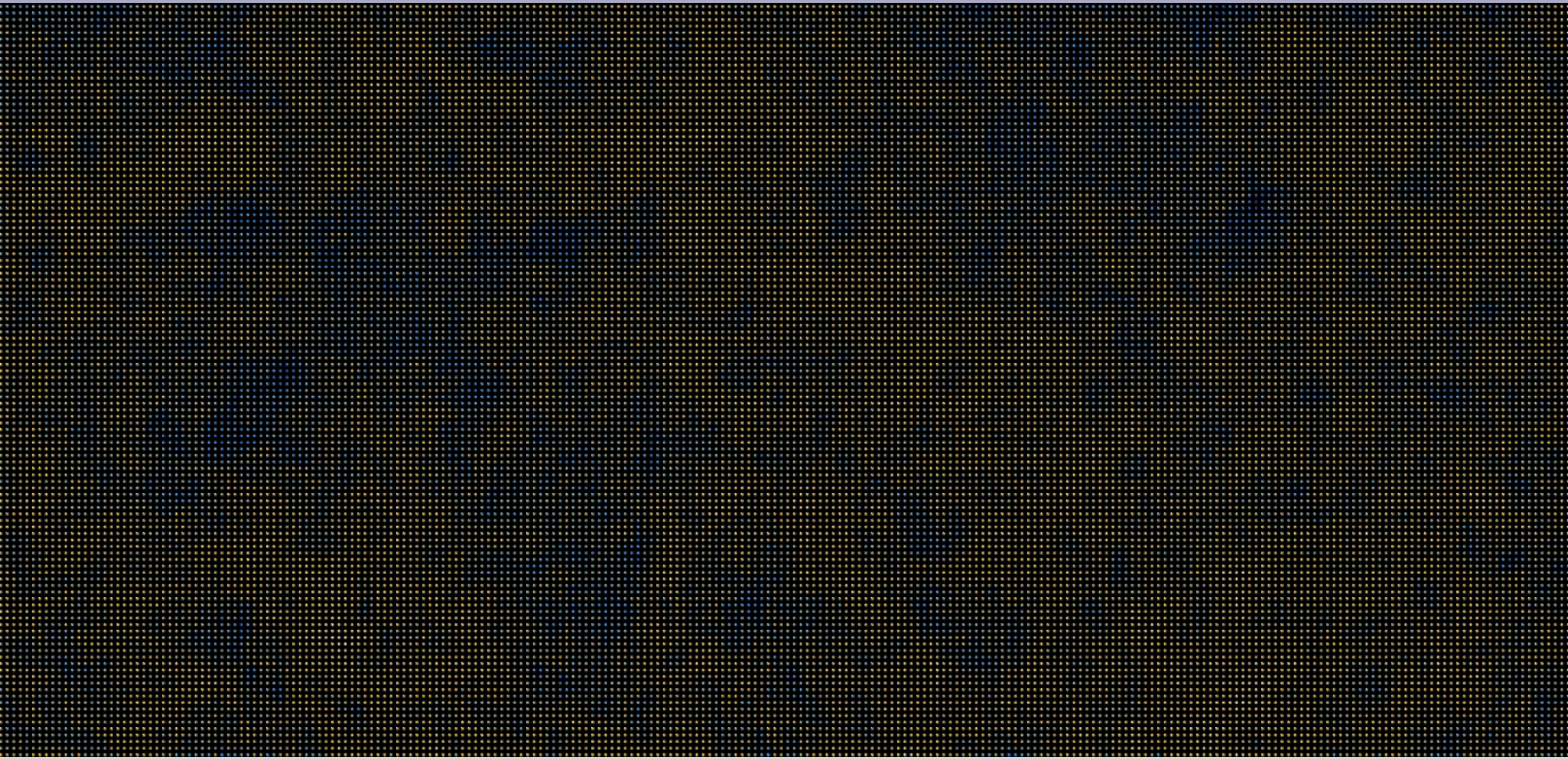
Power spectra observed

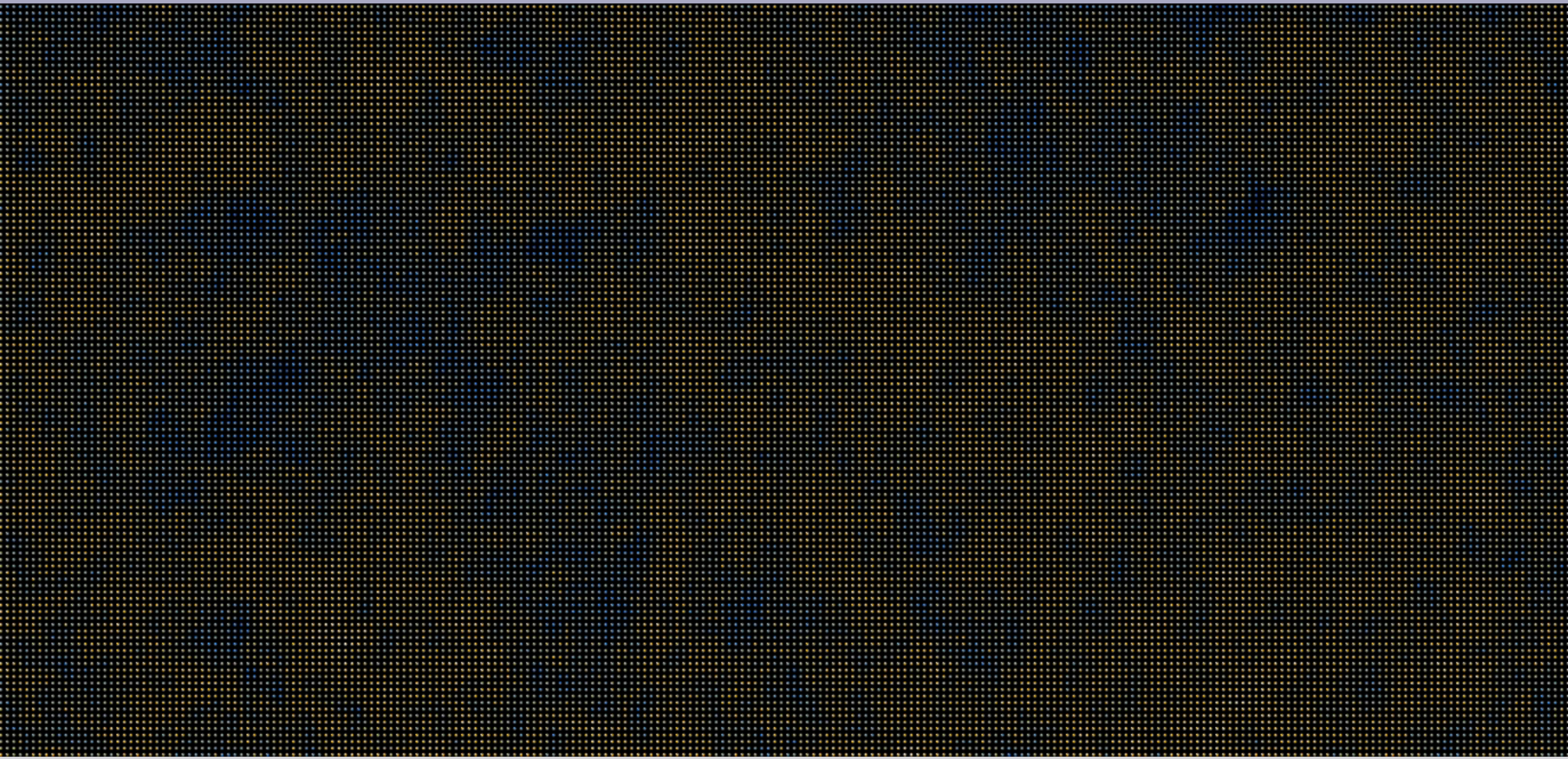
- For example WiggleZ

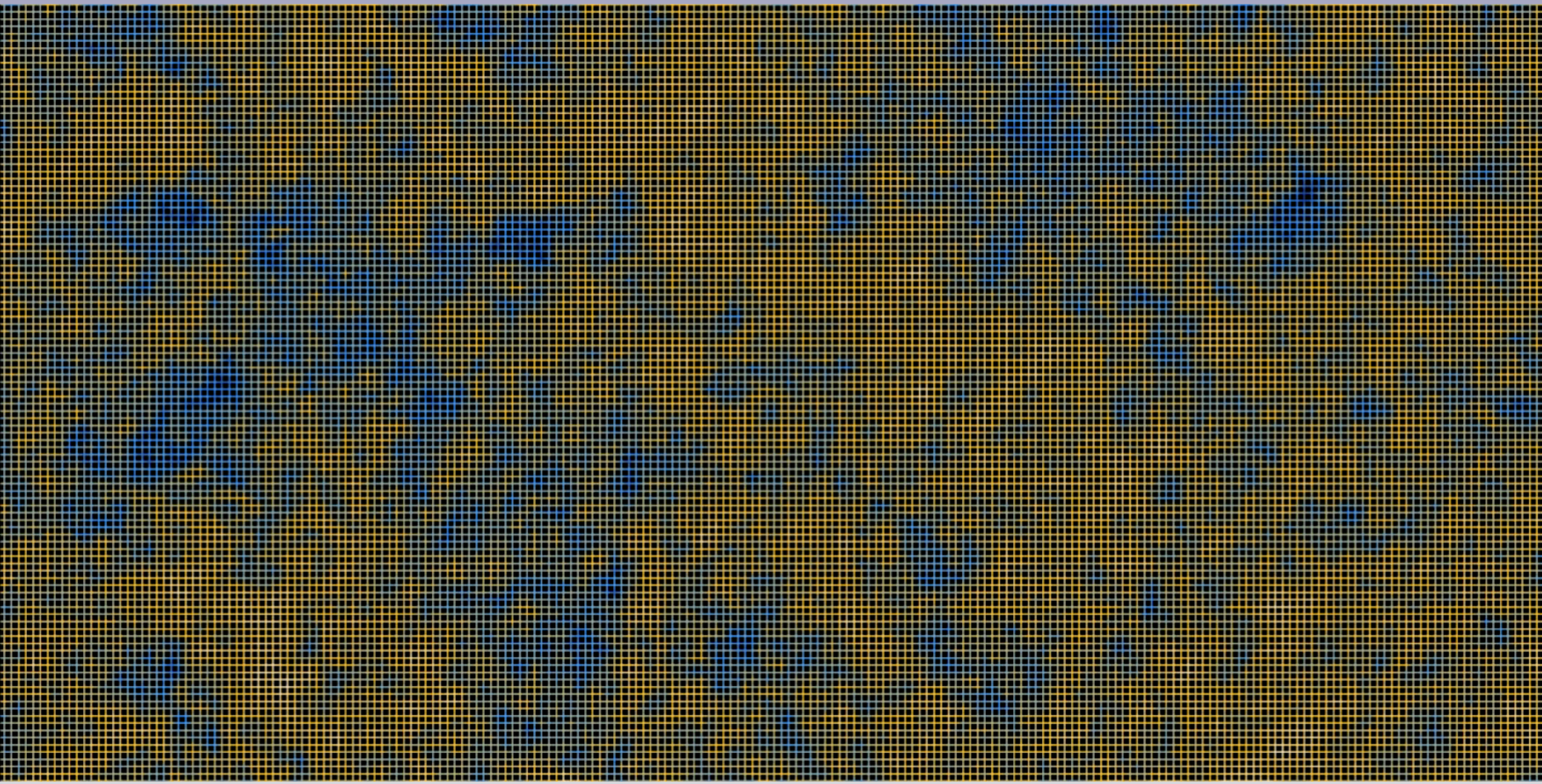


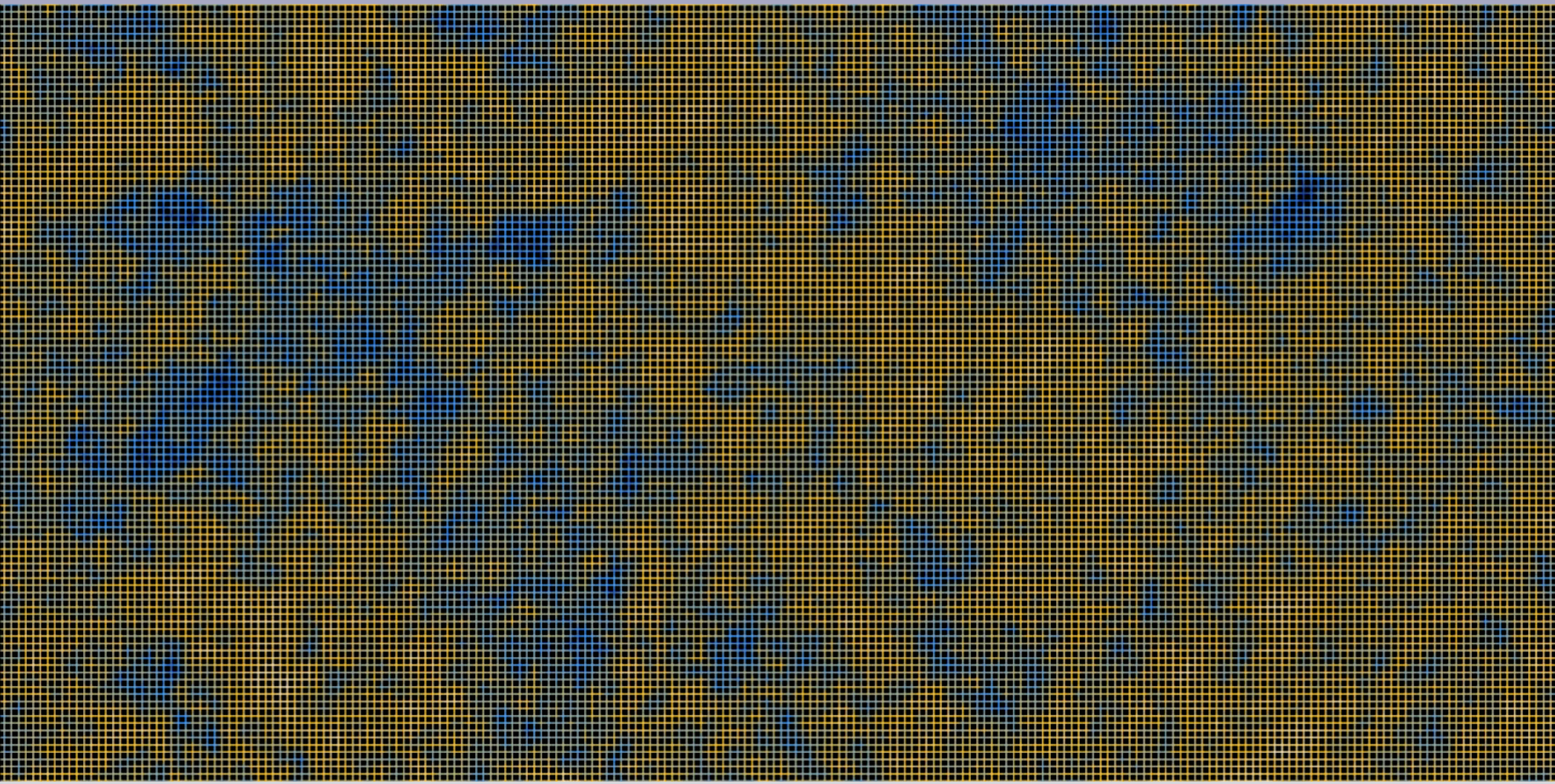
But wait...

- Linear perturbation theory
- Are all quantities always small?
- No, not below $k = 0.1\ h/\mathrm{Mpc}$ at $z=0$.









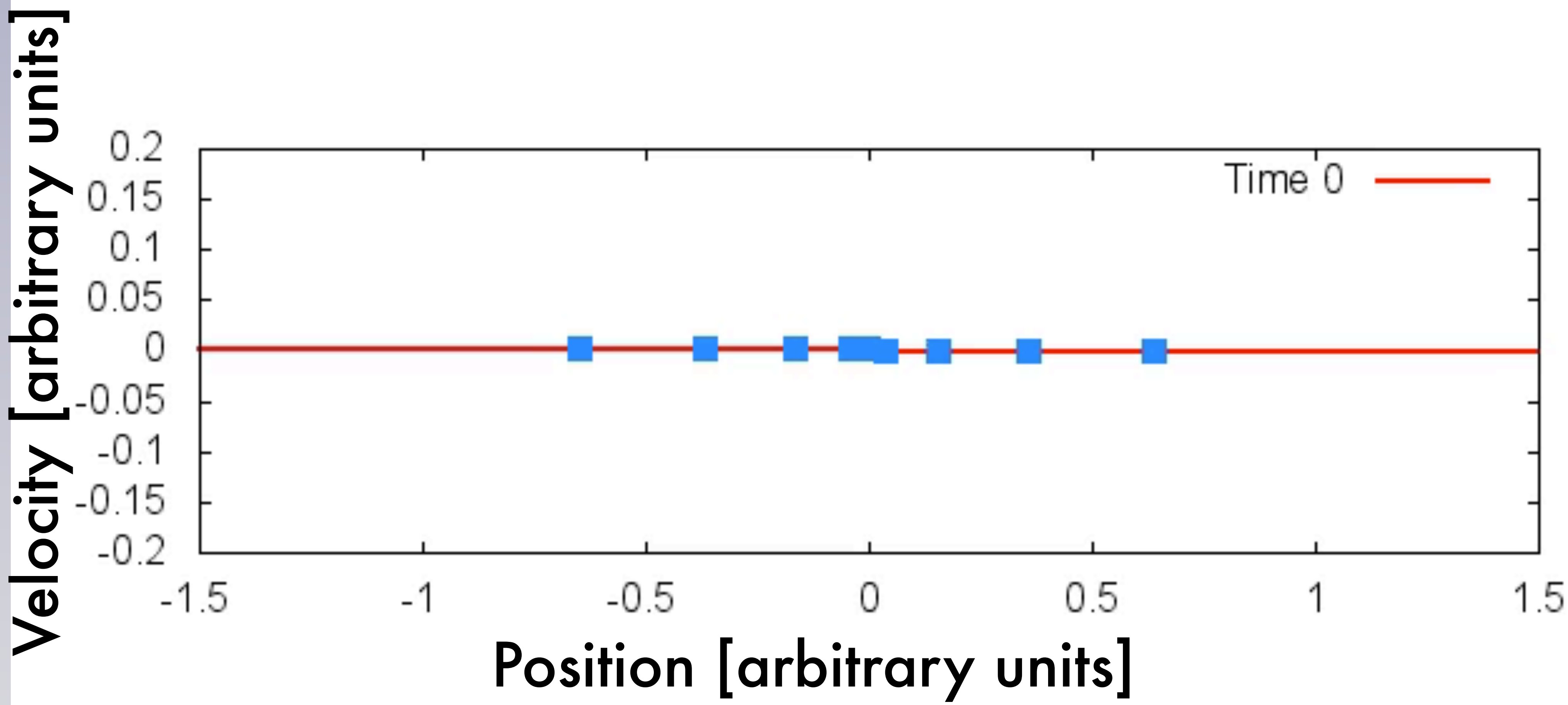
Need to go nonlinear?

- Galaxies are highly nonlinear objects
- Hopefully are tracers of linear density field
- Can we be sure?

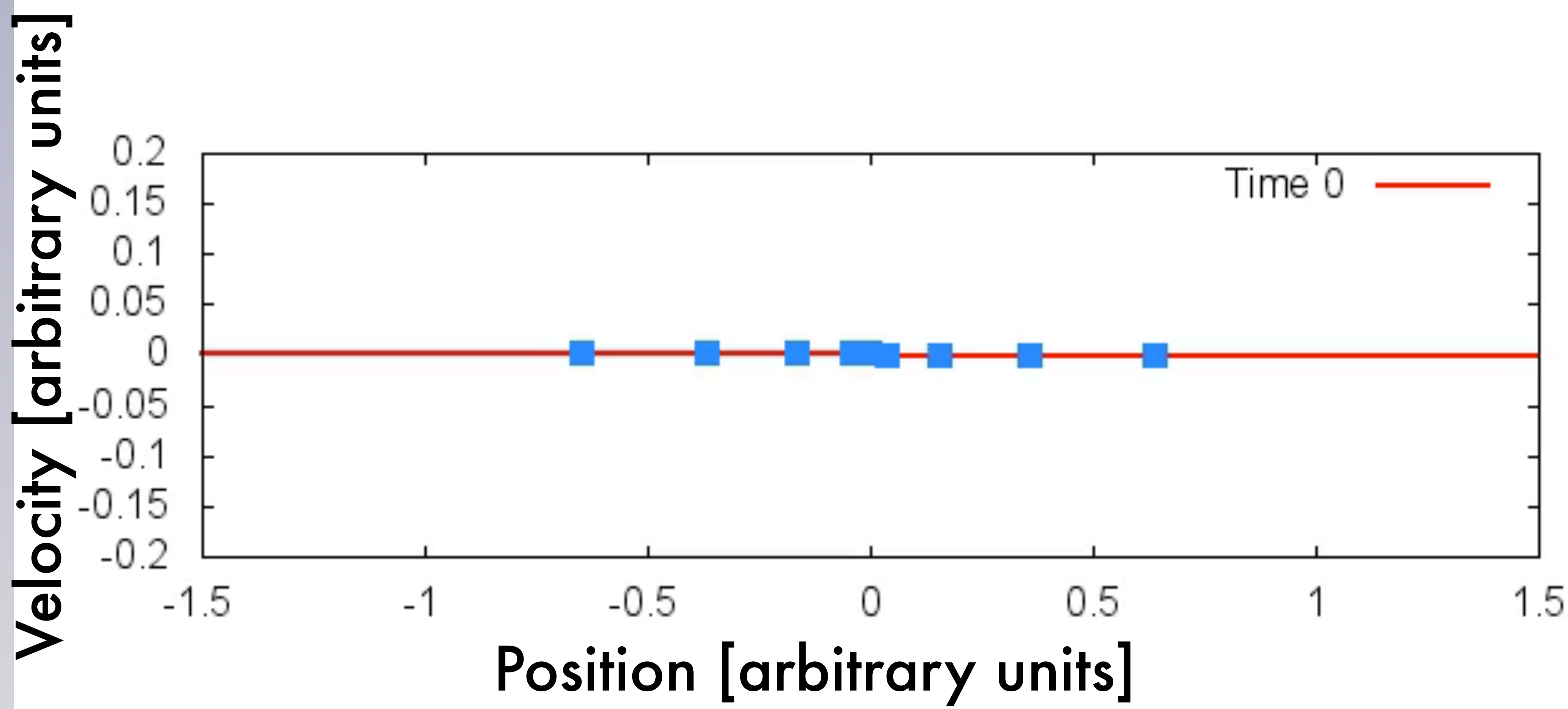
N-body simulations

- Gadget
- Ramses
- ...

N-body simulation: simulating phase space



N-body simulation: simulating phase space

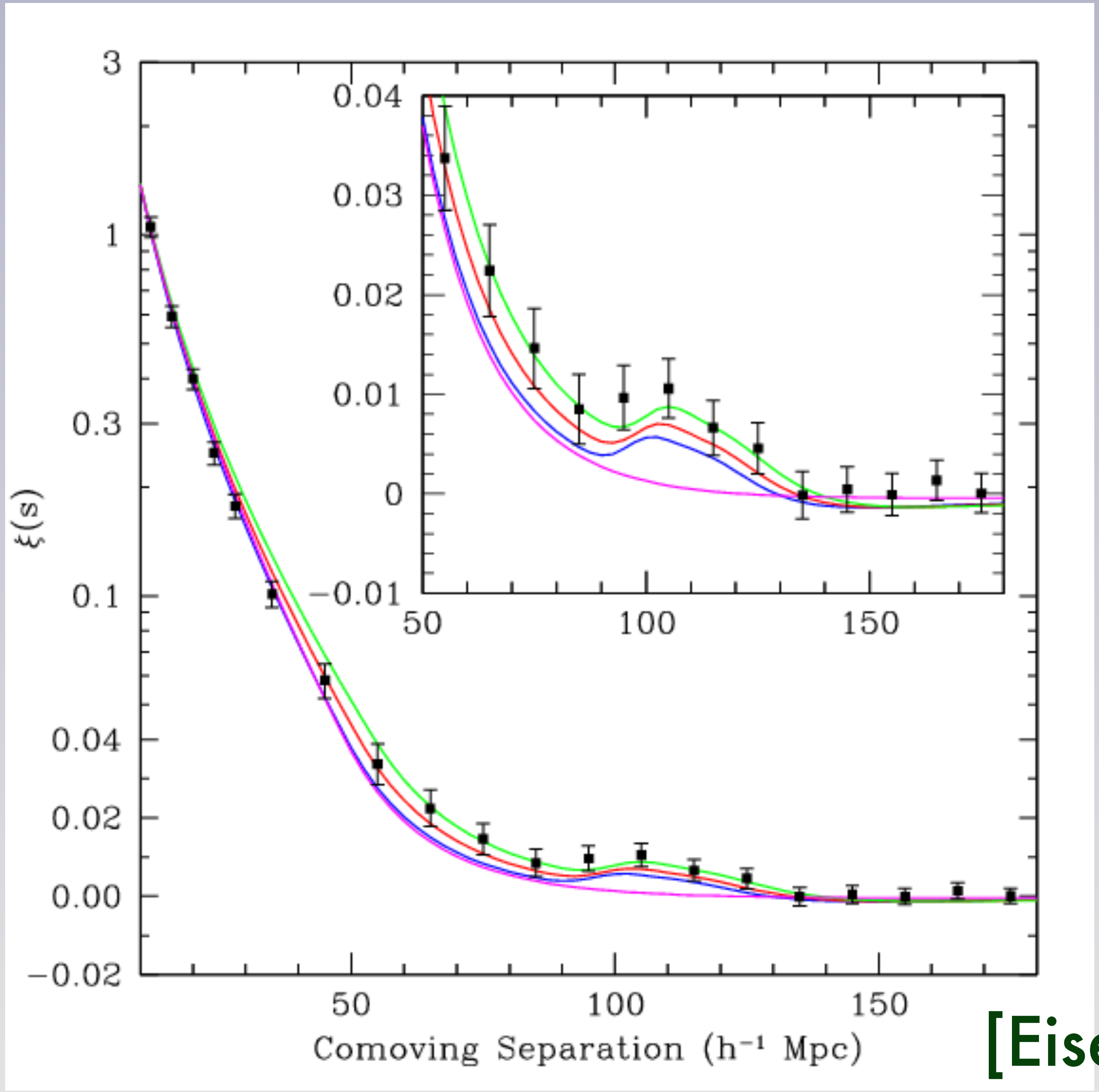


http://icc.dur.ac.uk/Eagle/Downloads/Videos/2x2videos.mp4

[Eagle simulation http://icc.dur.ac.uk/Eagle]

Baryon Acoustic Oscillations

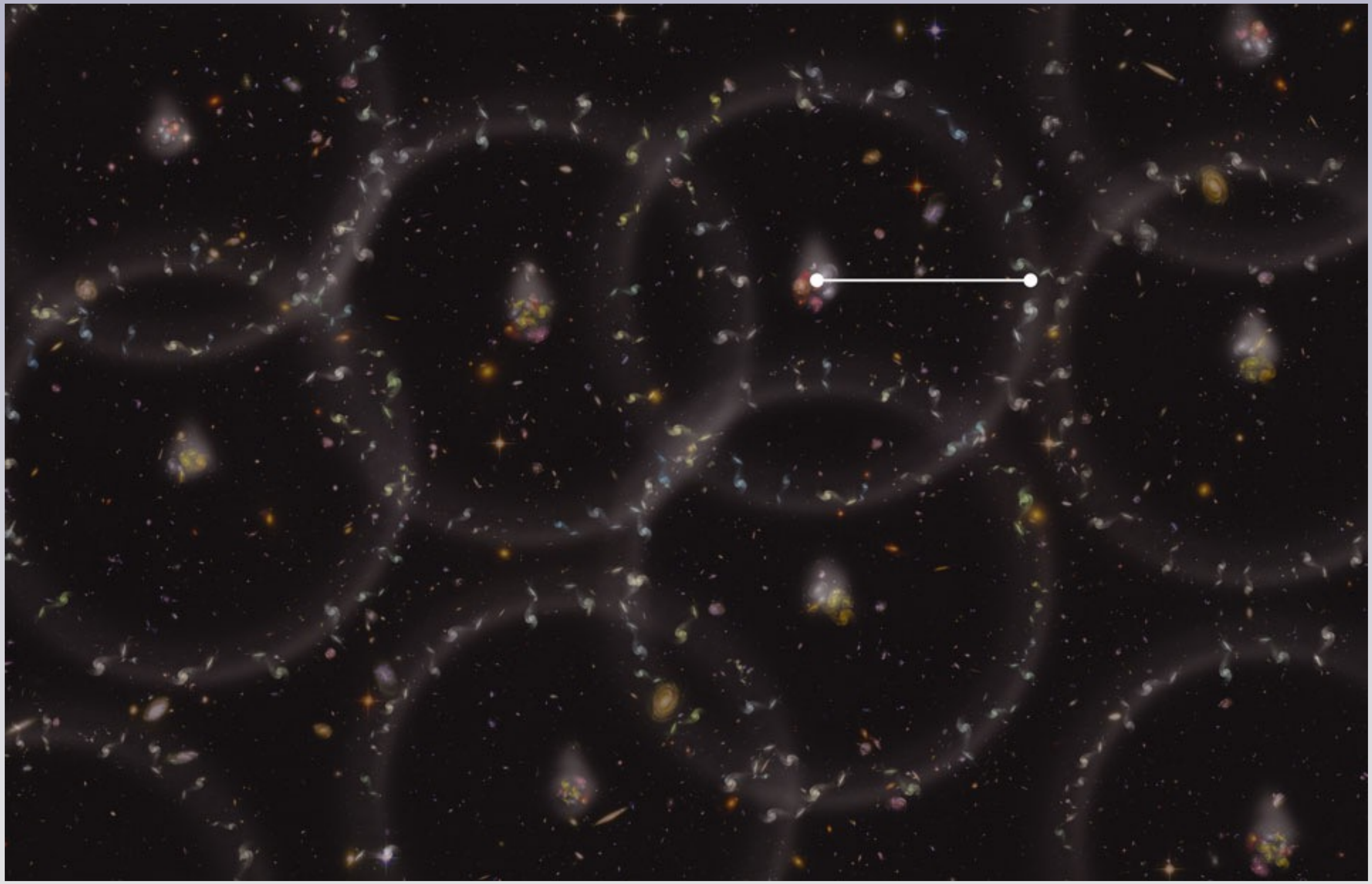
- Same peaks as in CMB



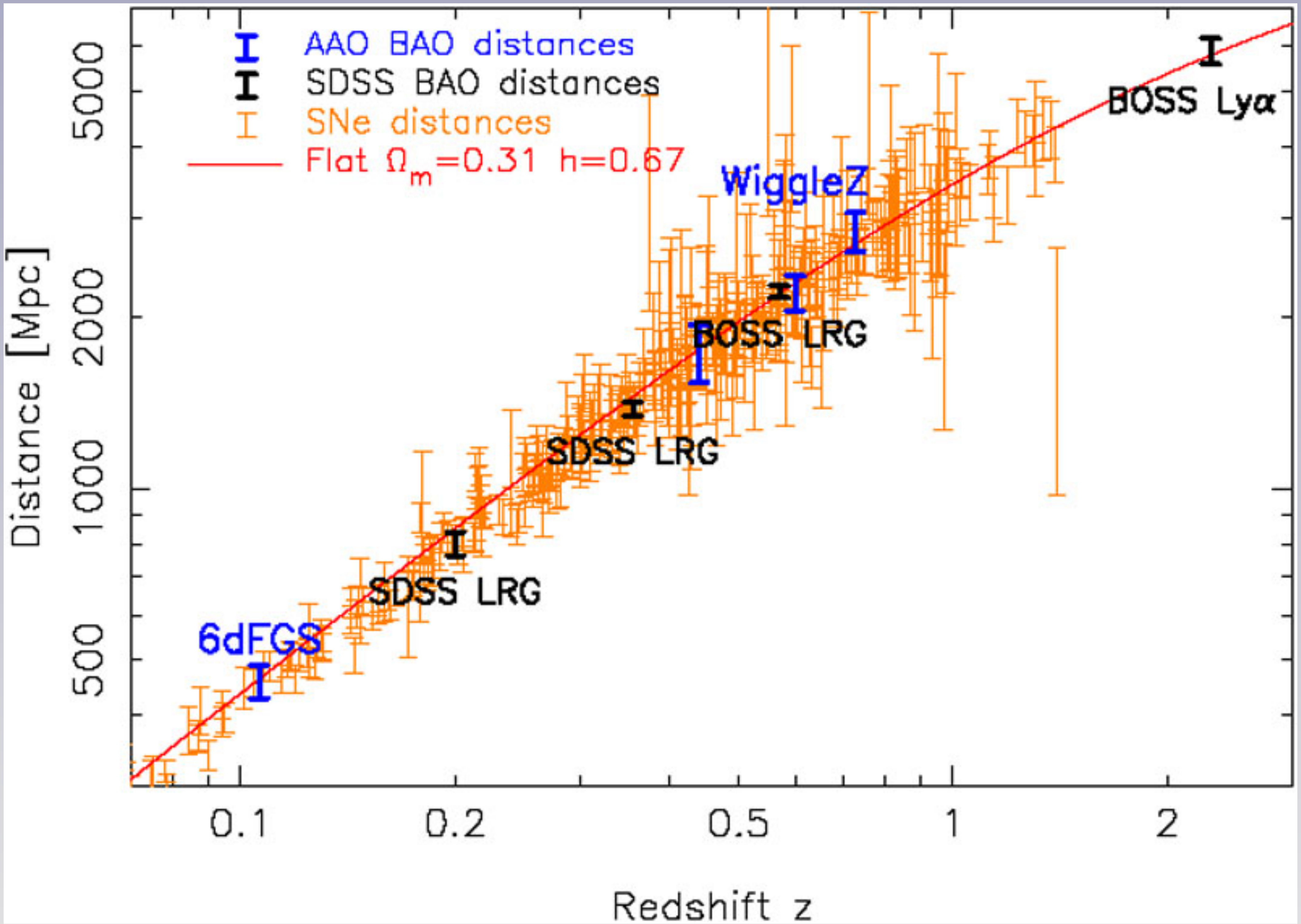
[Eisenstein et al., 2005]

Baryon Acoustic Oscillations

- Same peaks as in CMB

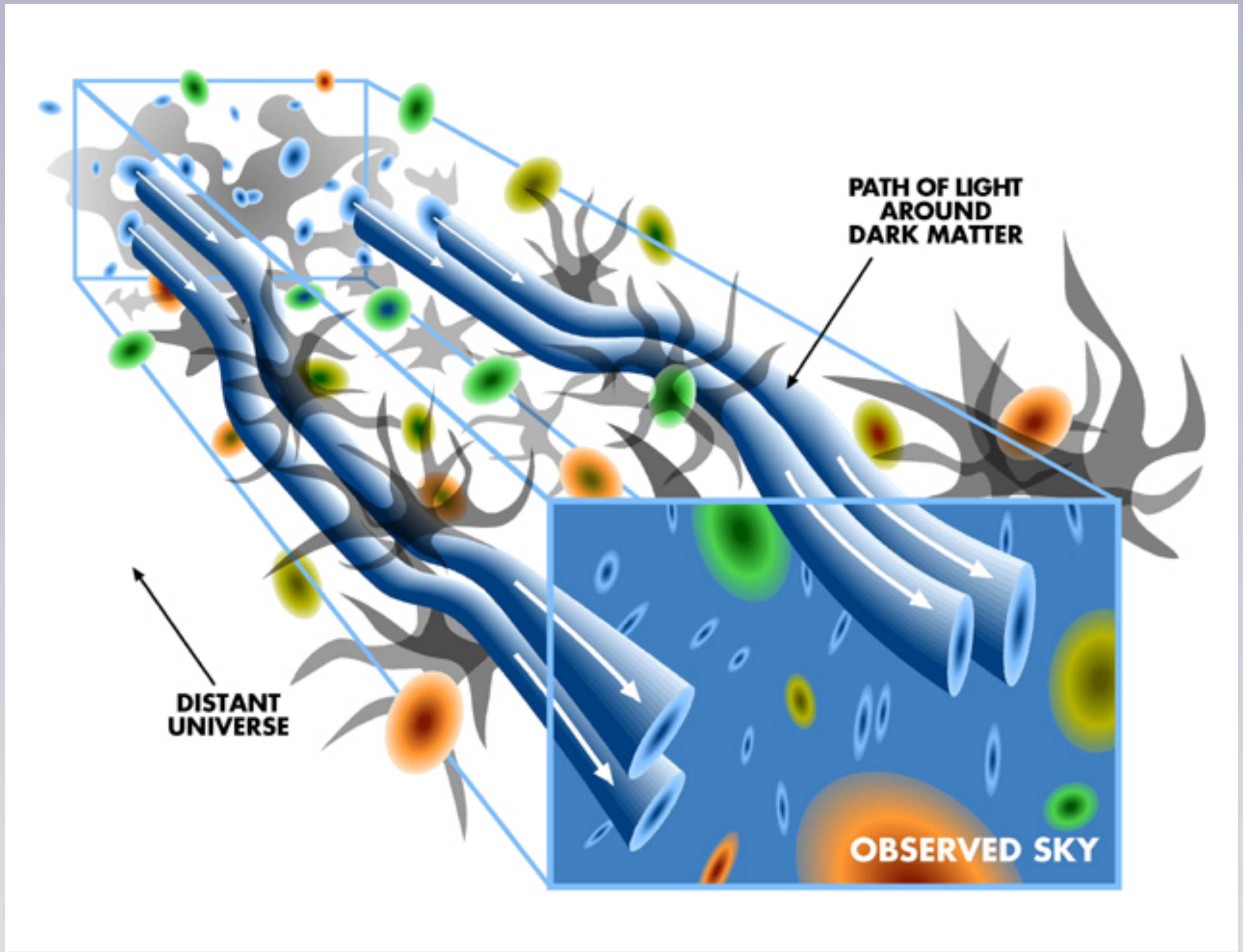


BAO as a distance measure



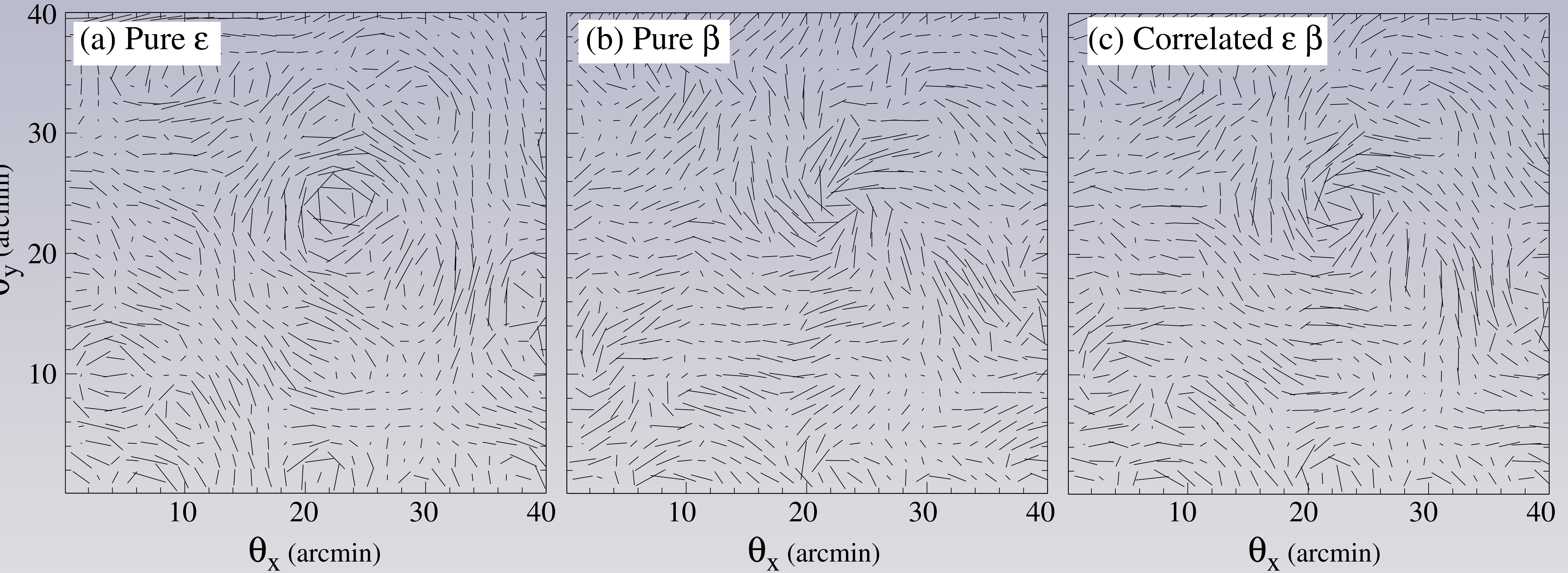
Weak lensing

- Probe the potential, not the galaxies
- LSST, Euclid, ...



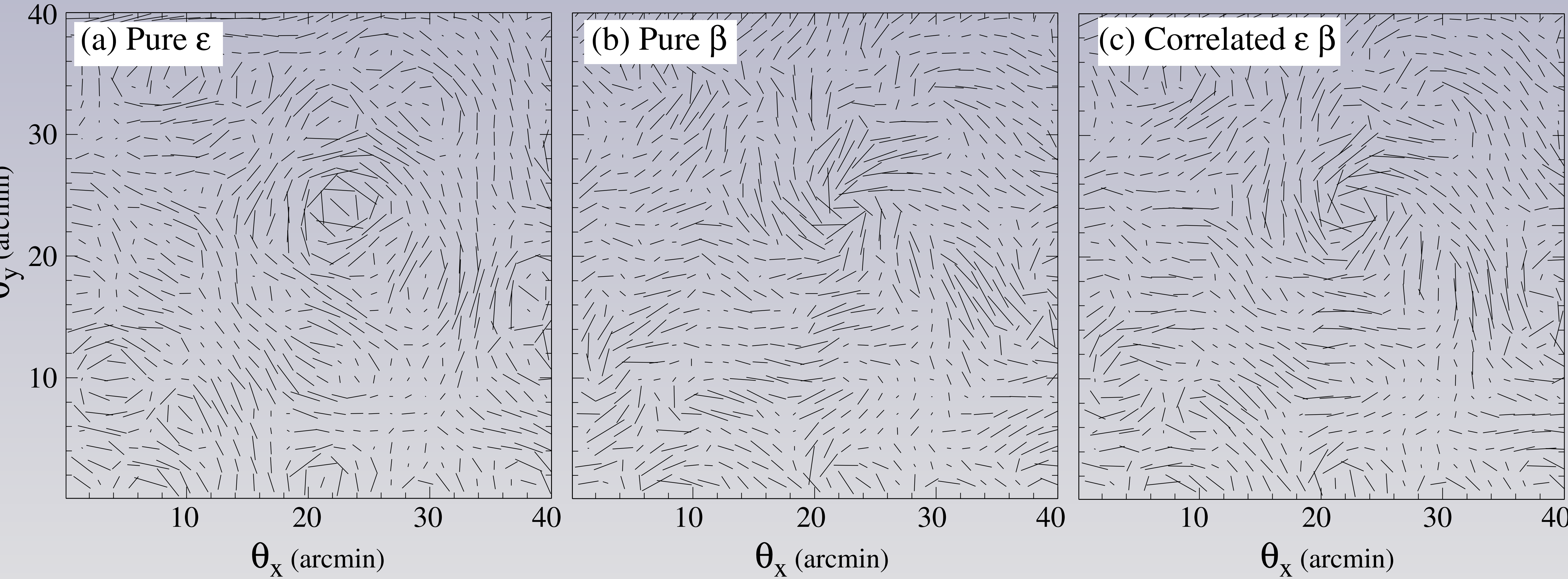
[http://lsst.org/lsst/science/scientist_cosmic_shear]

Weak lensing



[Hu & White, 2001]

Weak lensing



[Hu & White, 2001]