Physics with Large-Scale Structures (LSS)

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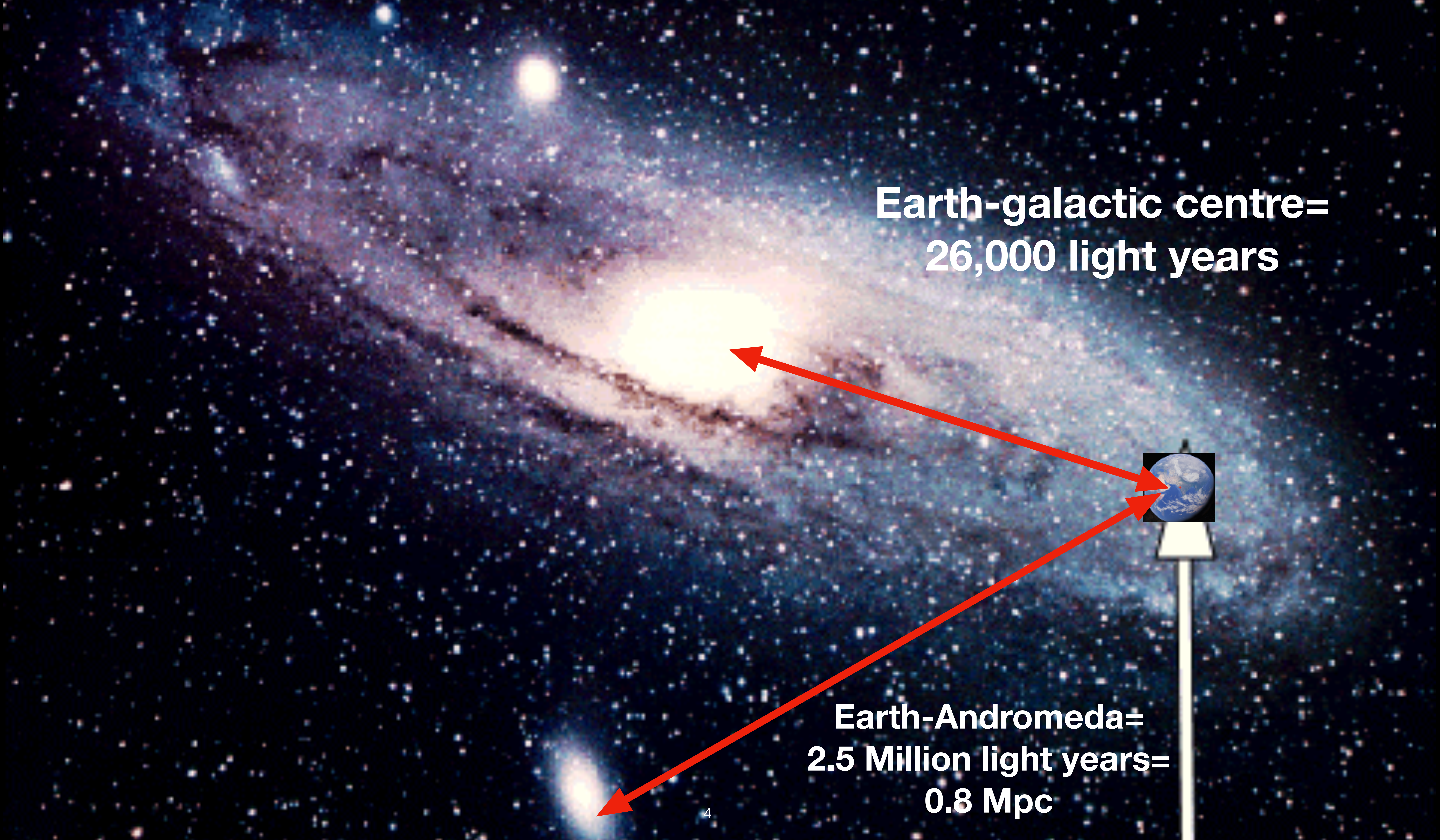
15th February 2022

Nariman Point, Mumbai, Maharashtra
नरीमन पॉइंट, मुंबई, महाराष्ट्र
NARIMAN POINT
नरिमन पॉइंट
Dr. Shyama Prasad Mukherjee Chowk
Gateway Of India Mumbai
Khardevi Aai Temple
खारदेवी आई मंदिर
Colaba Market
Bay view Cafe
बे व्यू कॅफे
UIDAI Regional Office
यूआईडीएआई रिजनल ऑफिस
World Trade Centre
वर्ल्ड ट्रेड सेंटर
CUFFE PARADE
कफ परेड
Sassoon Dock
ससून डॉक
Colaba Reef
Geeta NagarCha Maharaja
Rani Laxmi Bai Park
रानी लक्ष्मी बाई पार्क
GANESH MURTI NAGAR
गणेश मुर्ती नगर
Bombay Baptist Church
बॉम्बे बॅप्टिस्ट चर्च
Tata Institute of Fundamental Research
Dhobi Ghat
~4 km
Shiva Temple
Kohli Stadium
कोहली स्टेडियम
Canara Bank
कॅनरा बँक
28 min
every 6 min
NOFRA
नोफ्रा
Oyster Rock
US Club
यूएस क्लब
St. Joseph R.C. Church
सेंट जोसेफ आर.सी. चर्च
INHS Asvini
आई. एन. एच. एस. अस्विनी
NAVY NAGAR

Earth-Sun = 150 million km = 8 light minutes

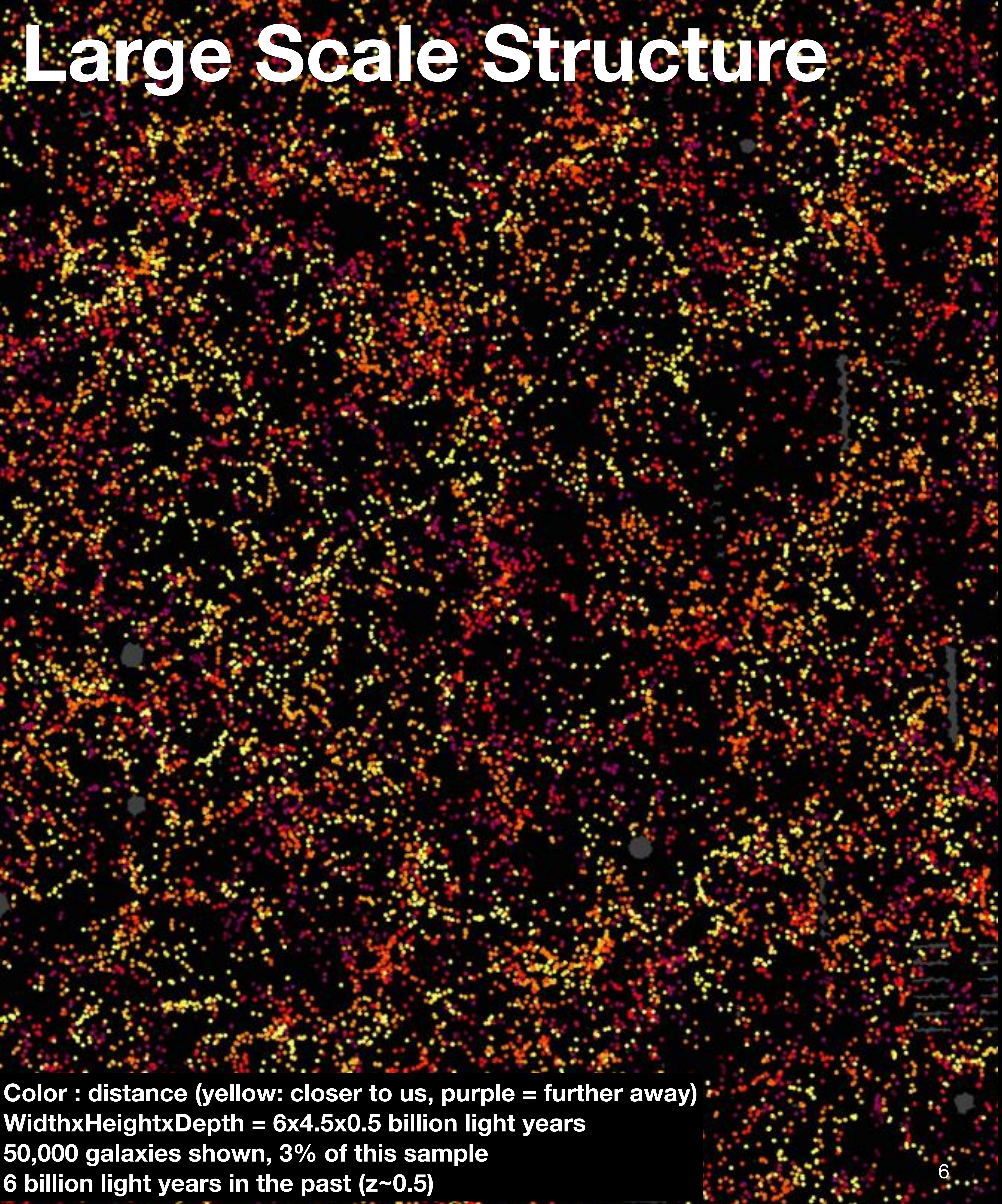

Earth-galactic centre=
26,000 light years
Earth-Andromeda=
2.5 Million light years=
0.8 Mpc

Large Scale Structure

Color : distance (yellow: closer to us, purple = further away)
WidthxHeightxDepth = 6x4.5x0.5 billion light years
50,000 galaxies shown, 3% of this sample
6 billion light years in the past (z~0.5)

Data from Sloan Digital Sky Survey,
Image credit: Daniel Eisentien

Large Scale Structure



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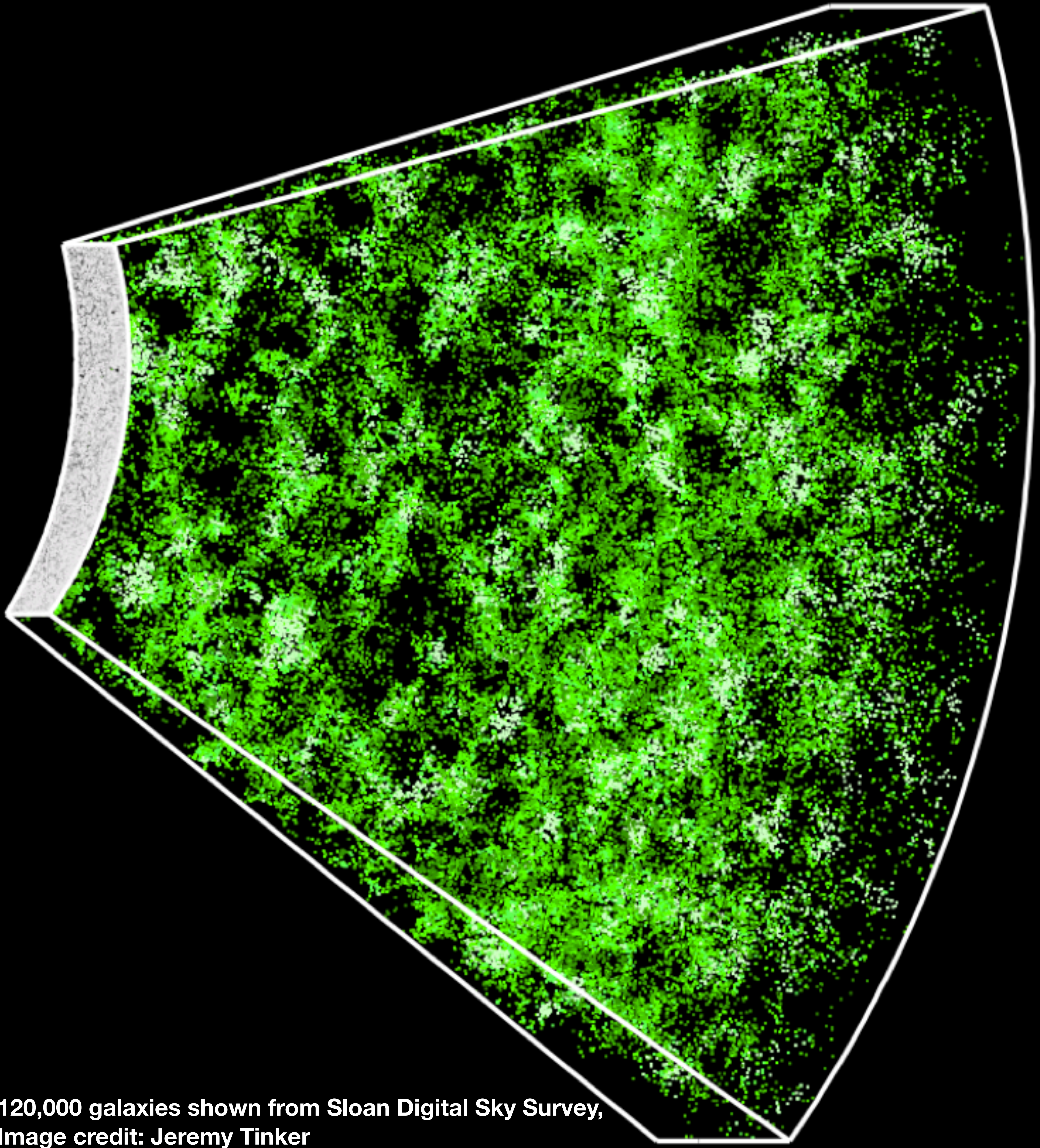


120,000 galaxies shown from Sloan Digital Sky Survey,
Image credit: Jeremy Tinker

LSS can help address some of fundamental questions

- Is General Relativity complete?
- Is dark energy dynamic?
- Role of black-hole in Structure formation?
- Sum of Neutrino mass and maybe solving Neutrino Hierarchy problem?

Big Picture

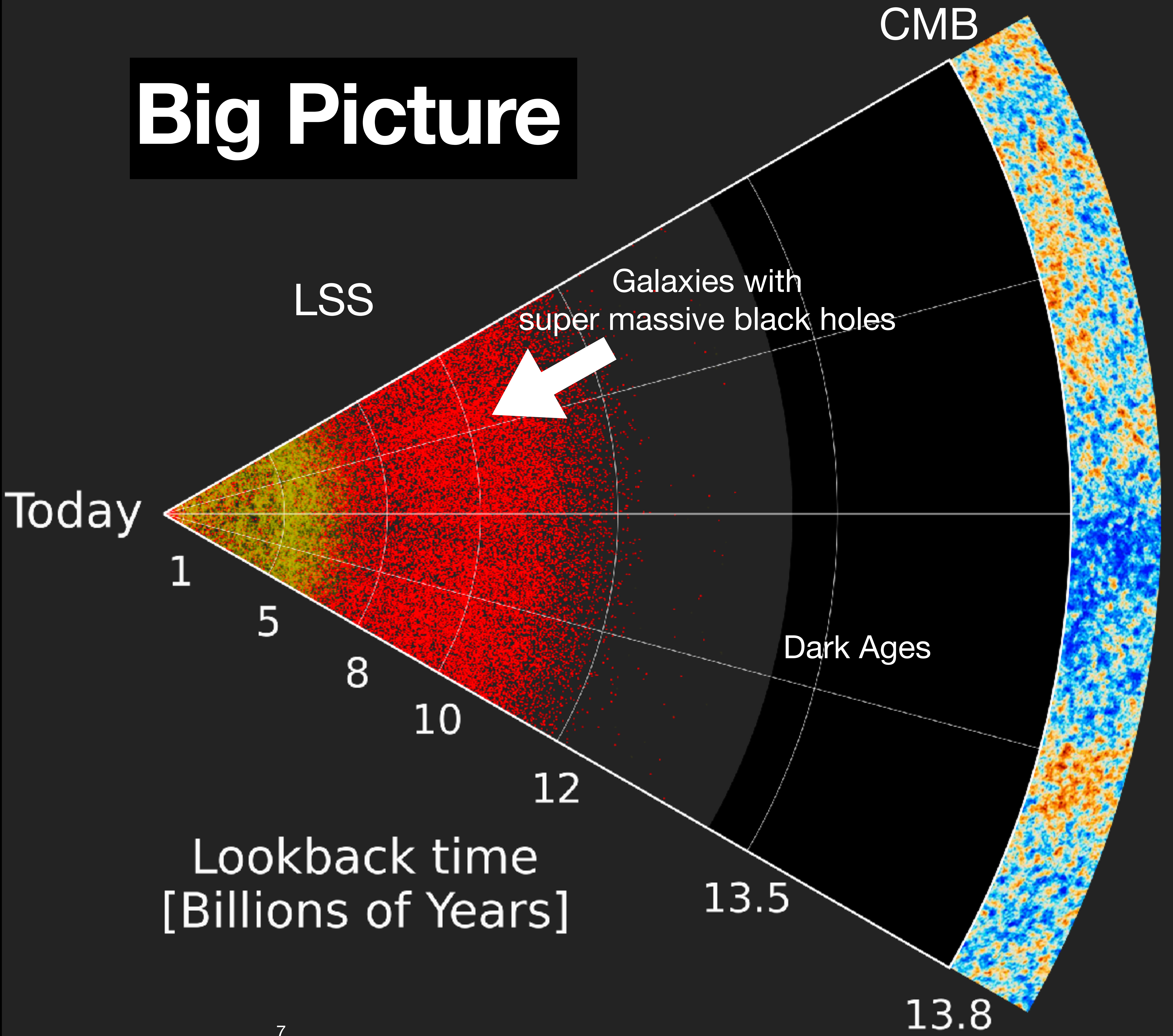
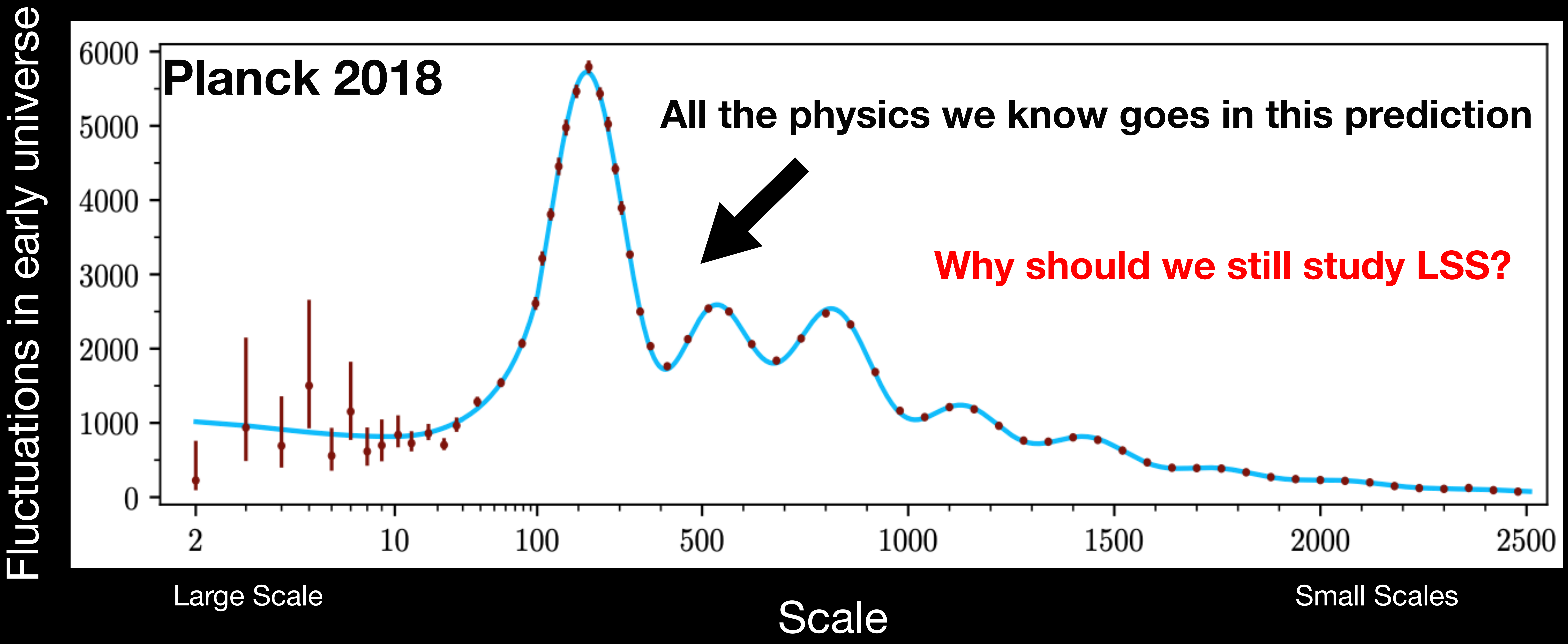


Image: Anand Raichoor

We definitely see the peaks: triumph of physics

sub-precent measurements in cosmology Planck 2018



Planck 2018: Overview paper

LSS can perform precision test of gravity, dark energy, subtle relativistic effects, physics of black-holes and measure sum of neutrino masses

- GR can explain all observation and allowed deviations must be below 5% in strength.

a) Pullen, **Alam**, Ho, MNRAS 449, 4326 (2015)
b) **Alam** et. al. MNRAS 453, 1754 (2015)
c) **Alam** et. al. MNRAS 456, 3743-3756 (2016)
d) Pullen, **Alam**, Ho MNRAS 460, 4098-4109 (2016)
e) Satpathy, **Alam** et. al. MNRAS 469, 1369-1382 (2017)
f) **Alam** et. al. MNRAS 465, 4853-4865 (2017)
g) Singh, **Alam** et. al. MNRAS 482, 785-806 (2019)
h) Hang, **Alam** et. al. MNRAS 501, 1481-1498 (2021)

- Dark Energy equation of state cannot vary more than 4% at 1 sigma.

a) **Alam** et. al. MNRAS 470, 617-2652 (2017)
b) Zhang, Pullen, **Alam** et. al. MNRAS 501, 1013-1027 (2021)
c) Hang, **Alam** et. al. MNRAS 507, 510-523 (2021)

- LSS measures subtle light propagation effects: new tests of equivalence principle.

a) **Alam** et. al. MNRAS (2017) 470 (3): 2822-2833
b) **Alam** et. a.l MNRAS (2017) 471(2): 2077-2087
c) Zhu, **Alam**, et. al. MNRAS (2017) 471(2): 2345-2356

- Black-holes can turn on, why does that happen and how it affects the structure we see around us?

a) **Alam** et. al. MNRAS 483, 4501-4517 (2019)
b) **Alam** et. al. MNRAS 497, 581-595 (2020)
c) **Alam** et. al. MNRAS 503, 59-76 (2021)
d) **Alam** et. al. MNRAS 504, 857-870 (2021)
e) **Alam** et. al. MNRAS 504, 4667-4686 (2021)

- Sum of neutrino masses is below 0.12 eV (at 2 sigma).
  LSS may rule out inverted hierarchy in 5 years.

a) **Alam*** et. al. MNRAS 470, 617-2652 (2017)
b) **Alam*** et. al. Phys. Rev. D **103**, 083533 (2021)

**alphabetical papers*

The litrature is vast and I am only citing my own work. This is in no way representation of the field.

How to use LSS

Quantifying LSS
- Observations
- Theory

Physical features in LSS
- Baryon Acoustic Oscillations
- Redshift Space Distortions

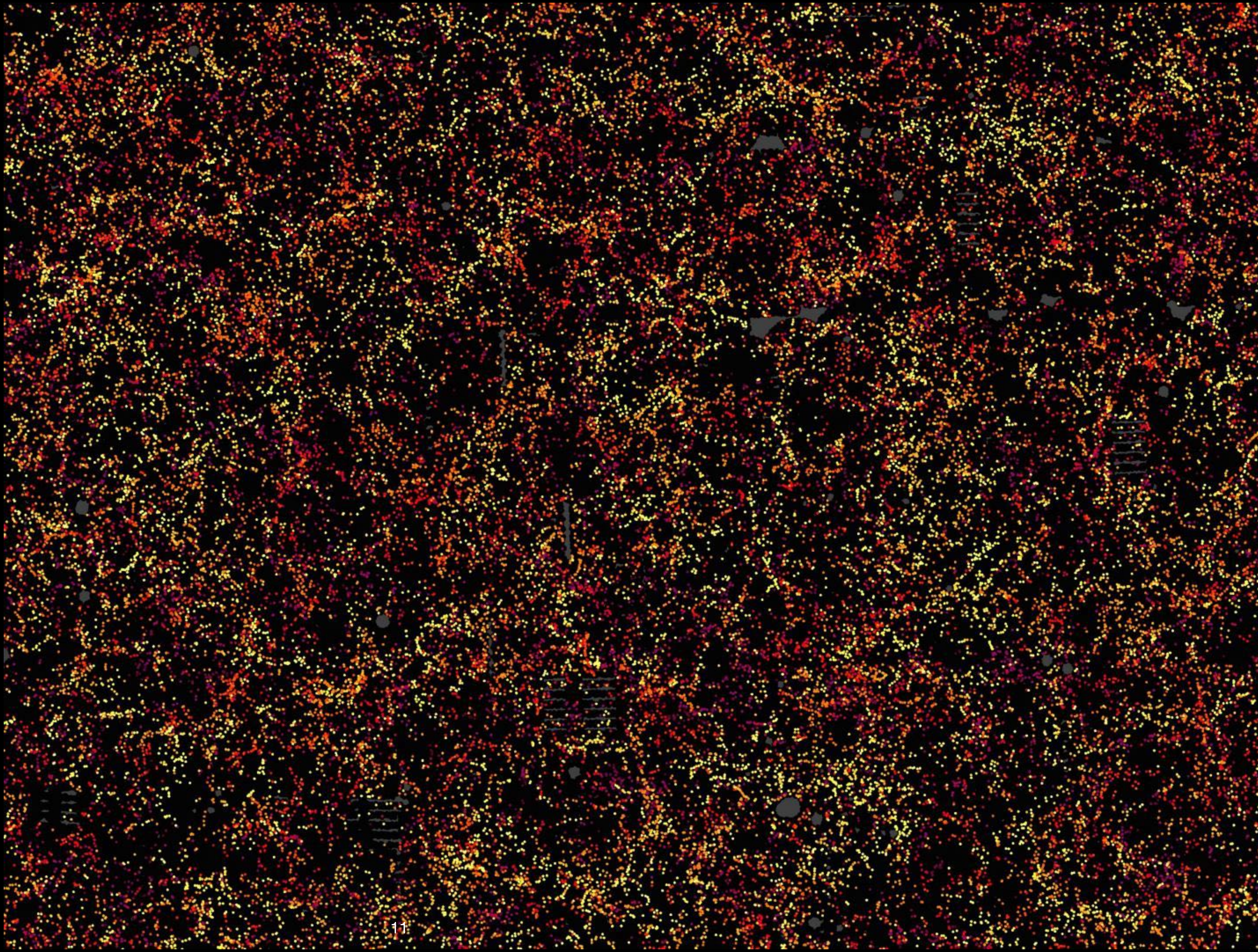
Using BAO and RSD
- Basic properties of Universe
- Signature of beyond GR physics
- Sum of Neutrino Masses

Future outlook and summary

LSS is the emergent phenomenon of the Universe

The intricate Structure formed by galaxies

Galaxies traces the underlying distribution of the matter



LSS is the **emergent phenomenon** of the Universe

Quantifying the LSS through two-point function

$$\rho(\vec{r}) = \bar{\rho}(1 + \delta(\vec{r}))$$

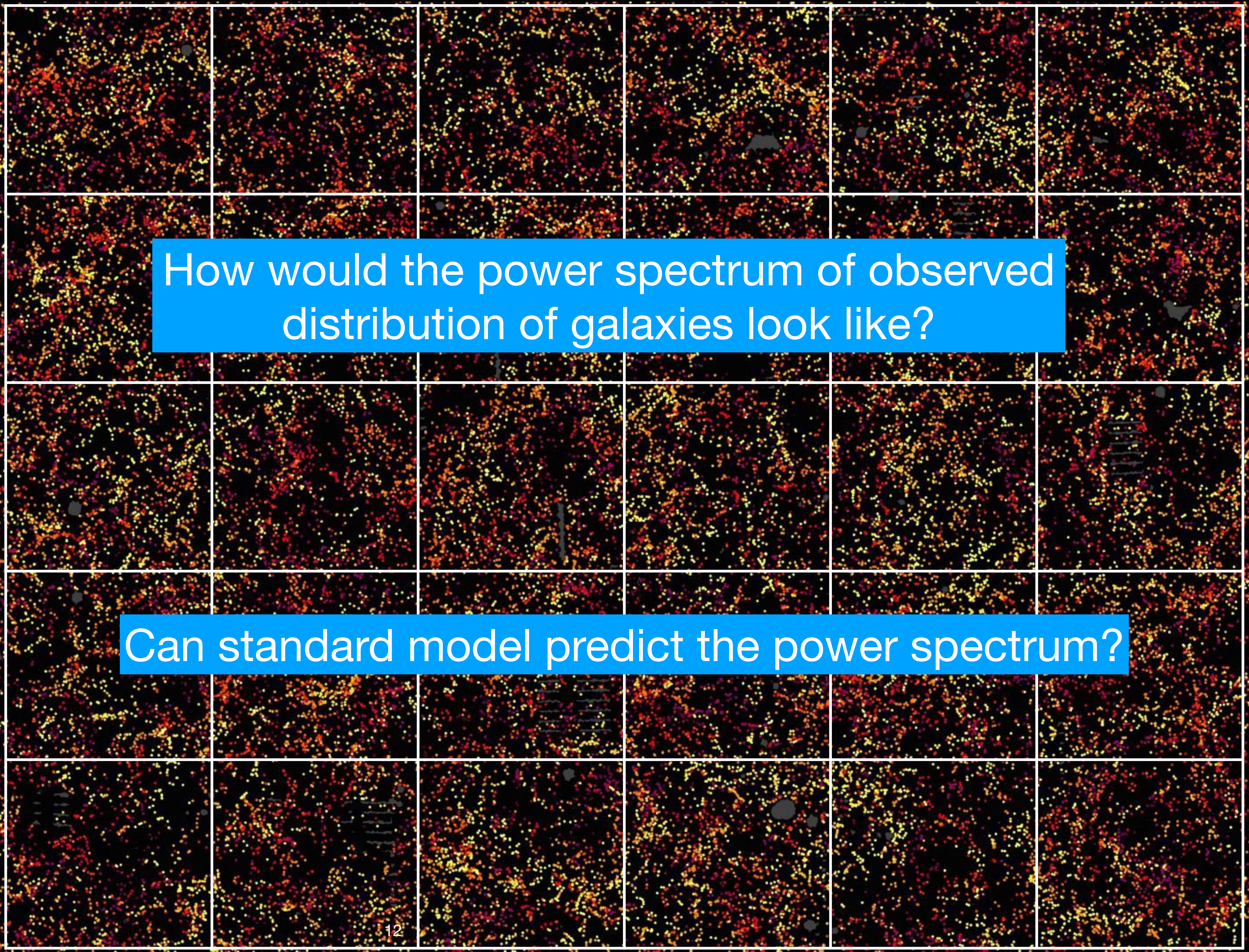
Correlation Function

$$\xi(r) = \langle \delta(\vec{x})\delta(\vec{x} + \vec{r}) \rangle$$

$$\delta(\vec{r}) = \int \delta(\vec{k}) e^{-i\vec{k}\cdot\vec{r}} d\vec{k}$$

Power Spectrum

$$P(k) = \left\langle \delta(\vec{k})\delta^*(\vec{k}) \right\rangle$$



Homogeneous and Isotropic Universe

Einstein Field Equation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

FLRW metric

$$ds^2 = -c^2dt^2 + a^2(t)dX^2$$

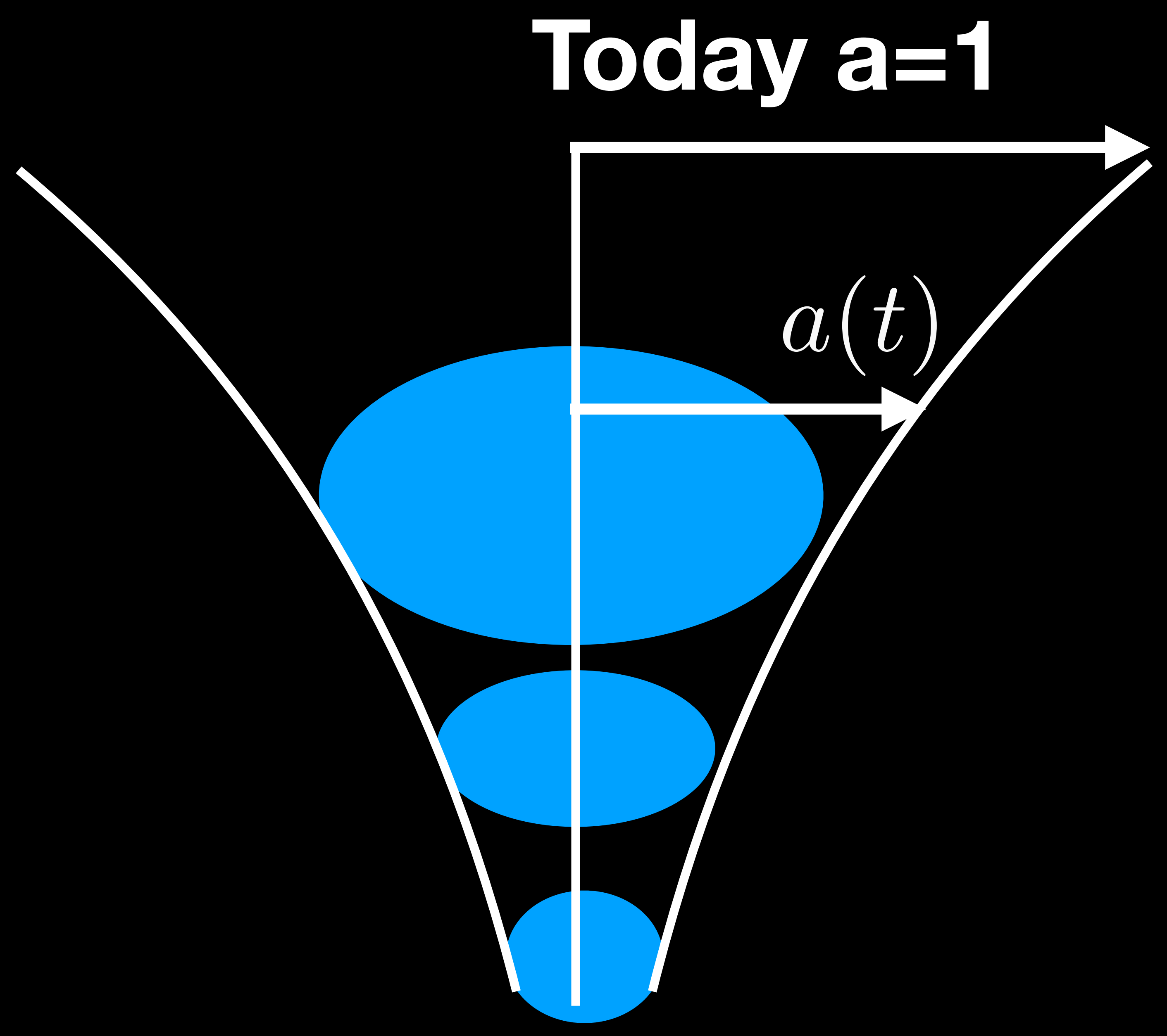
Hubble's rate

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

Density evolution

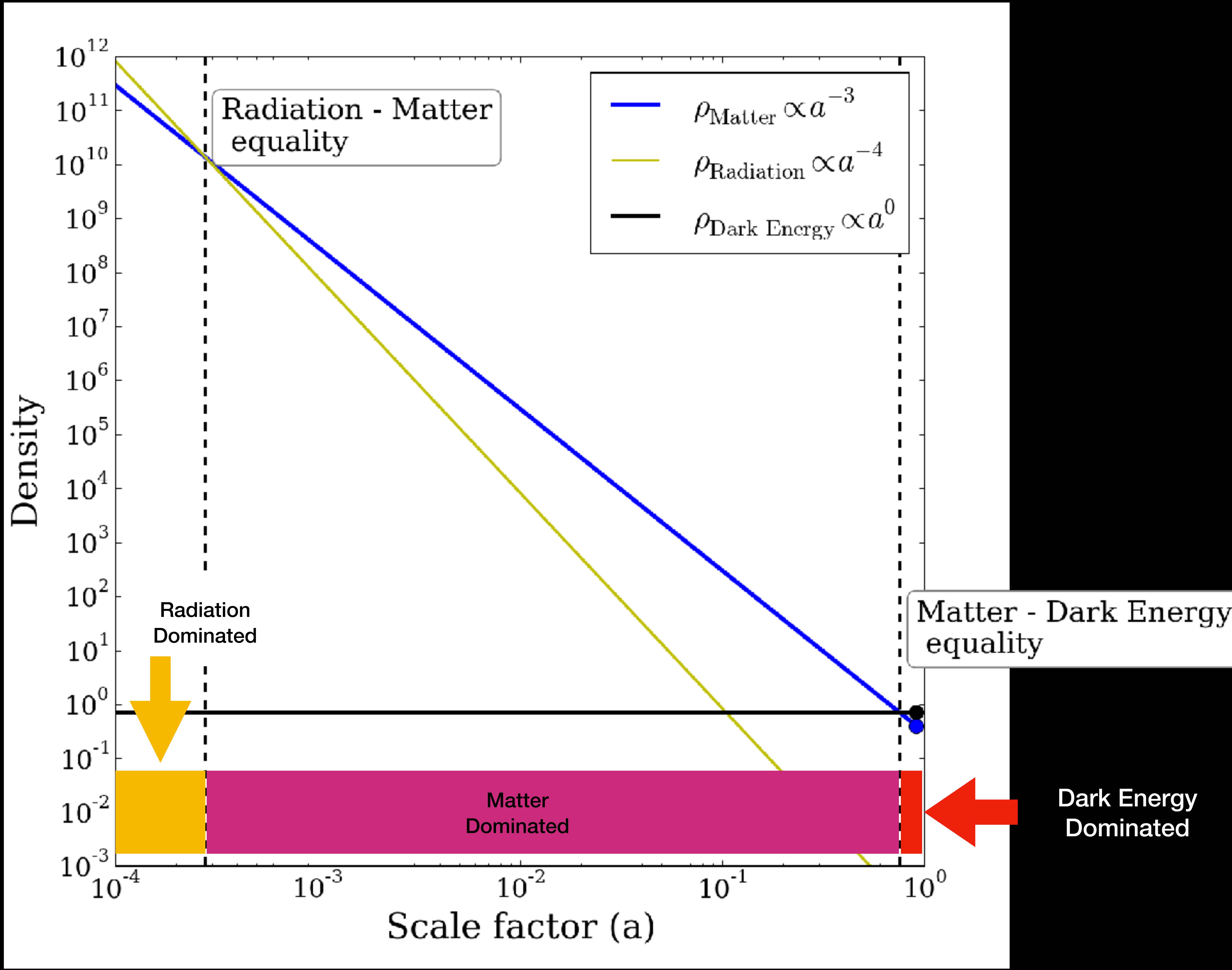
$$\rho \propto a^{-3(w+1)}$$

$$w = 0(\text{matter}), w = 1/3(\text{radiation}), w = -1(\text{dark energy})$$



Different phases of the universe

Initial conditions?

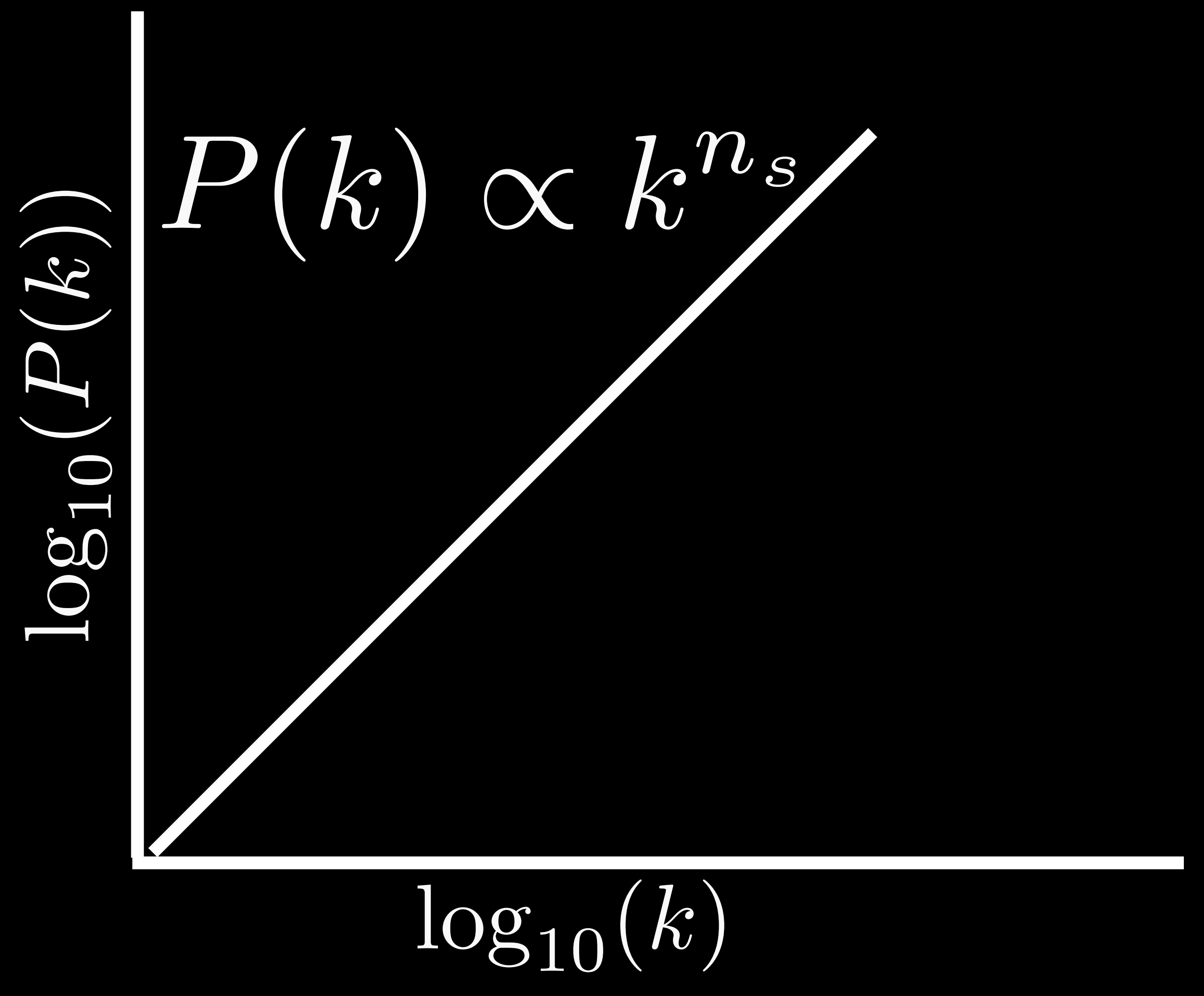


Dark Energy Dominated

Initial conditions of the Universe

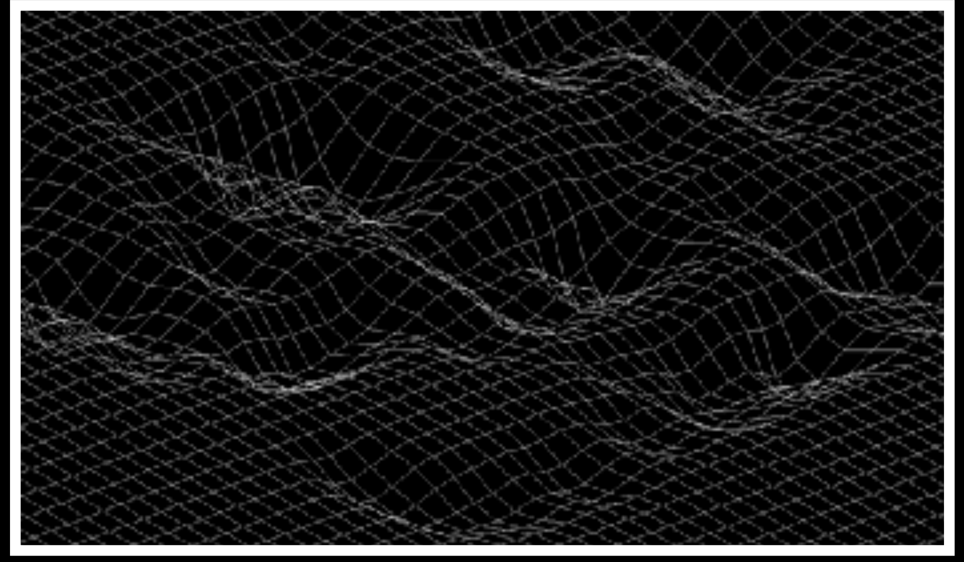
Standard model of Cosmological Structure formation

https://articles.adsabs.harvard.edu/pdf/1972MNRAS.160P...1Z



Scale-invariant in metric-perturbation

$$\Delta_\Phi(k) = \text{constant}$$



Mon. Not. R. astr. Soc. (1972) **160,** *Short Communication.*

A HYPOTHESIS, UNIFYING THE STRUCTURE AND THE ENTROPY OF THE UNIVERSE

Ya. B. Zeldovich

(Received 1972 September 4)

SUMMARY

A hypothesis about the averaged initial state and its perturbations is put forward, describing the entropy of the hot Universe (due to damping of short waves) and its structure (clusters of galaxies due to long wave perturbations).

No *a priori* preference can be given to small or big perturbation theories—the analyses of observations is the unique approach to the problem.

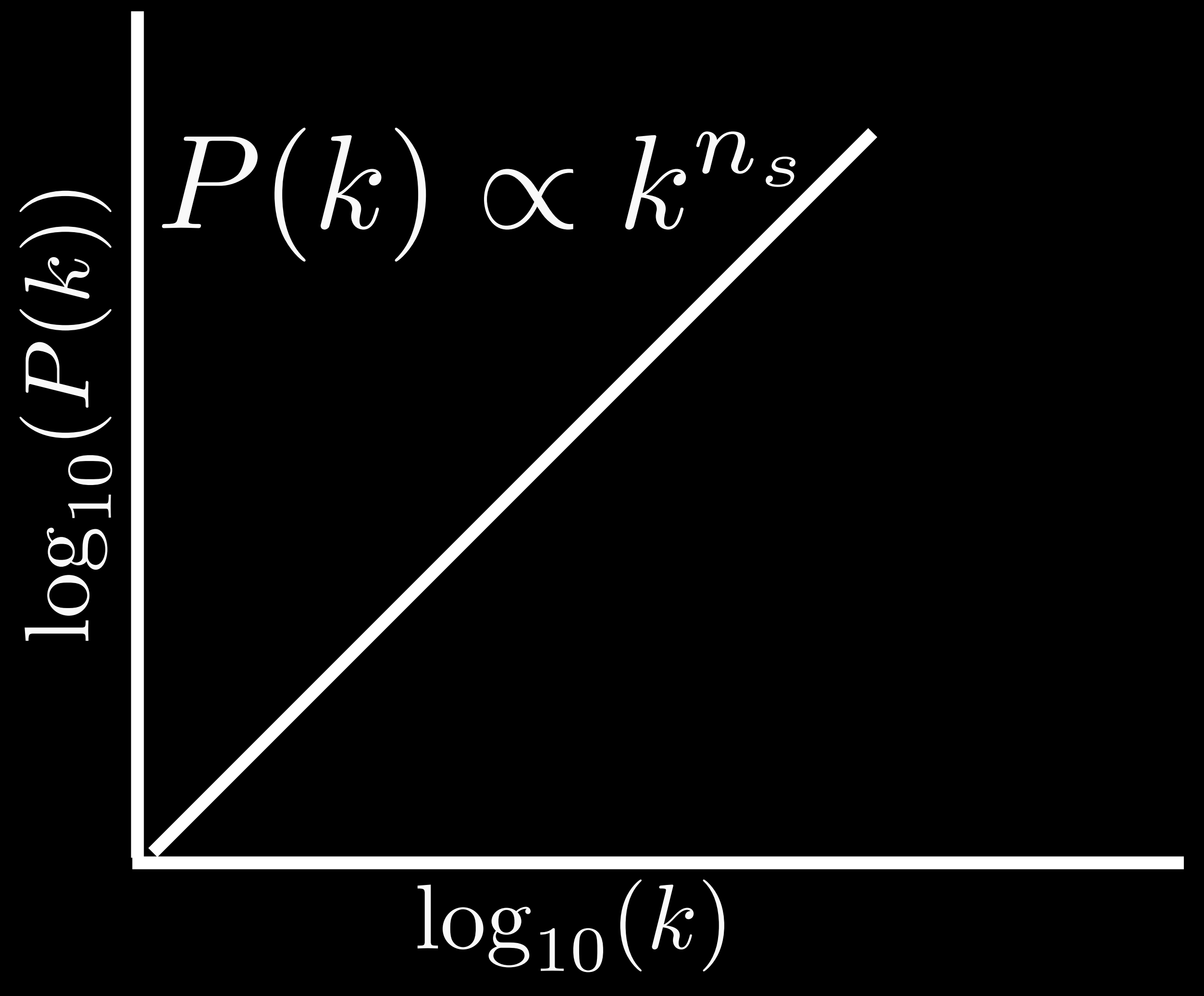
Density-potential relation (Poisson's equation)

$$P(k) \propto \Delta_m/k^3 \propto \Delta_\Phi k^4/k^3 \propto k$$

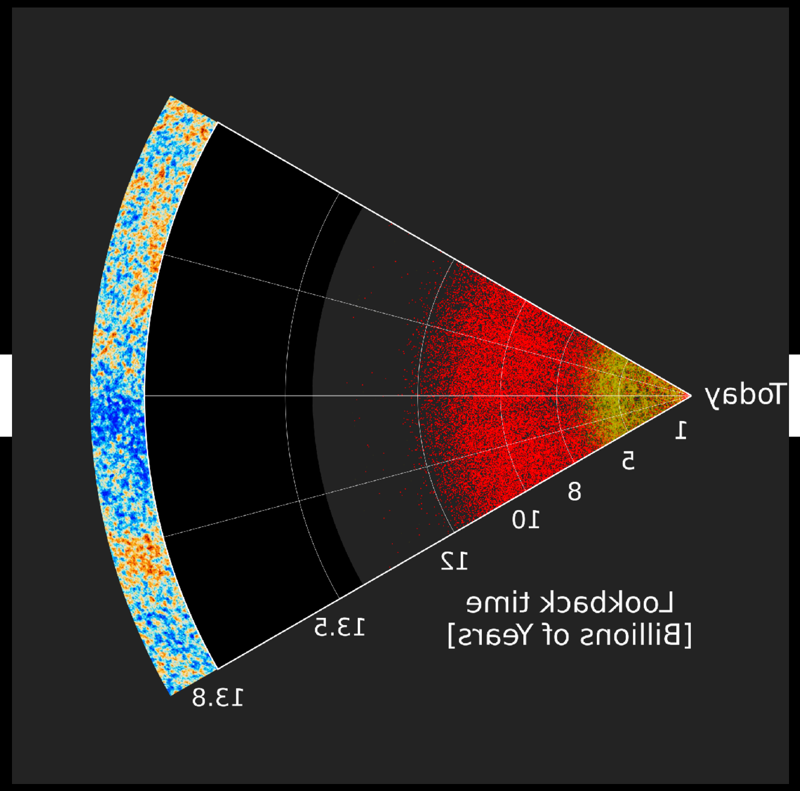
10 years later inflationary theories predicted that the index is close to one with small tilt which is sensitive to inflationary potential

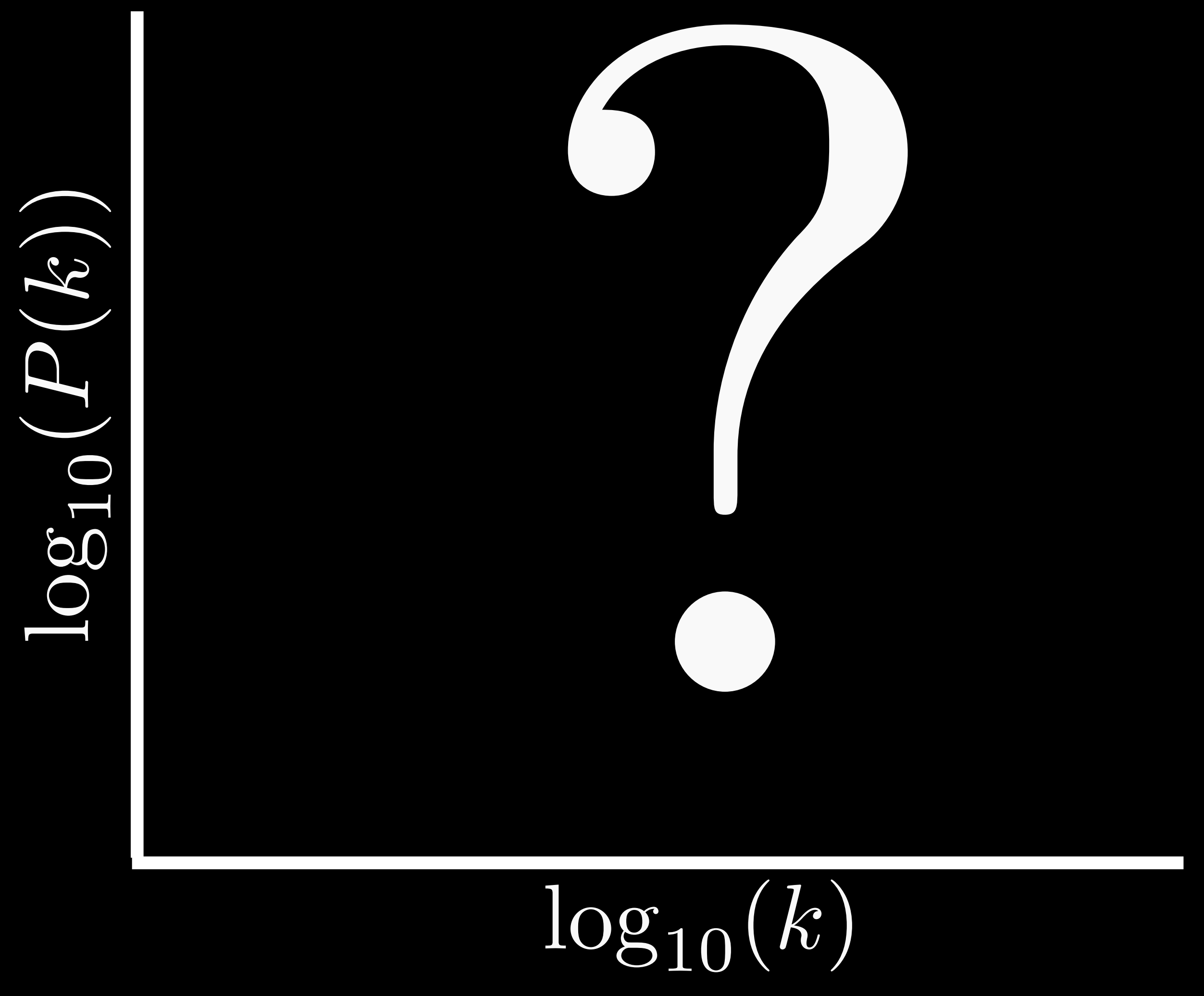
Distribution of matter in the Universe

Standard model of Cosmological Structure formation



Primordial power spectrum processed through the physics of early universe





Summary of Relativistic perturbation theory

Perturbed Einstein Field Equation

$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu} + \Lambda \delta g_{\mu\nu}$$

Spatially flat FRW metric

$$ds^2 = a^2 \eta_{\mu\nu} dx^\mu dx^\nu$$

Conformal Friedman equations

$$\mathcal{H}^2 = \frac{1}{3} a^2 (8\pi G \rho + \Lambda)$$

$$\dot{\mathcal{H}} = \frac{1}{6} a^2 \left[2\Lambda - 8\pi G(\rho + 3P)\right]$$

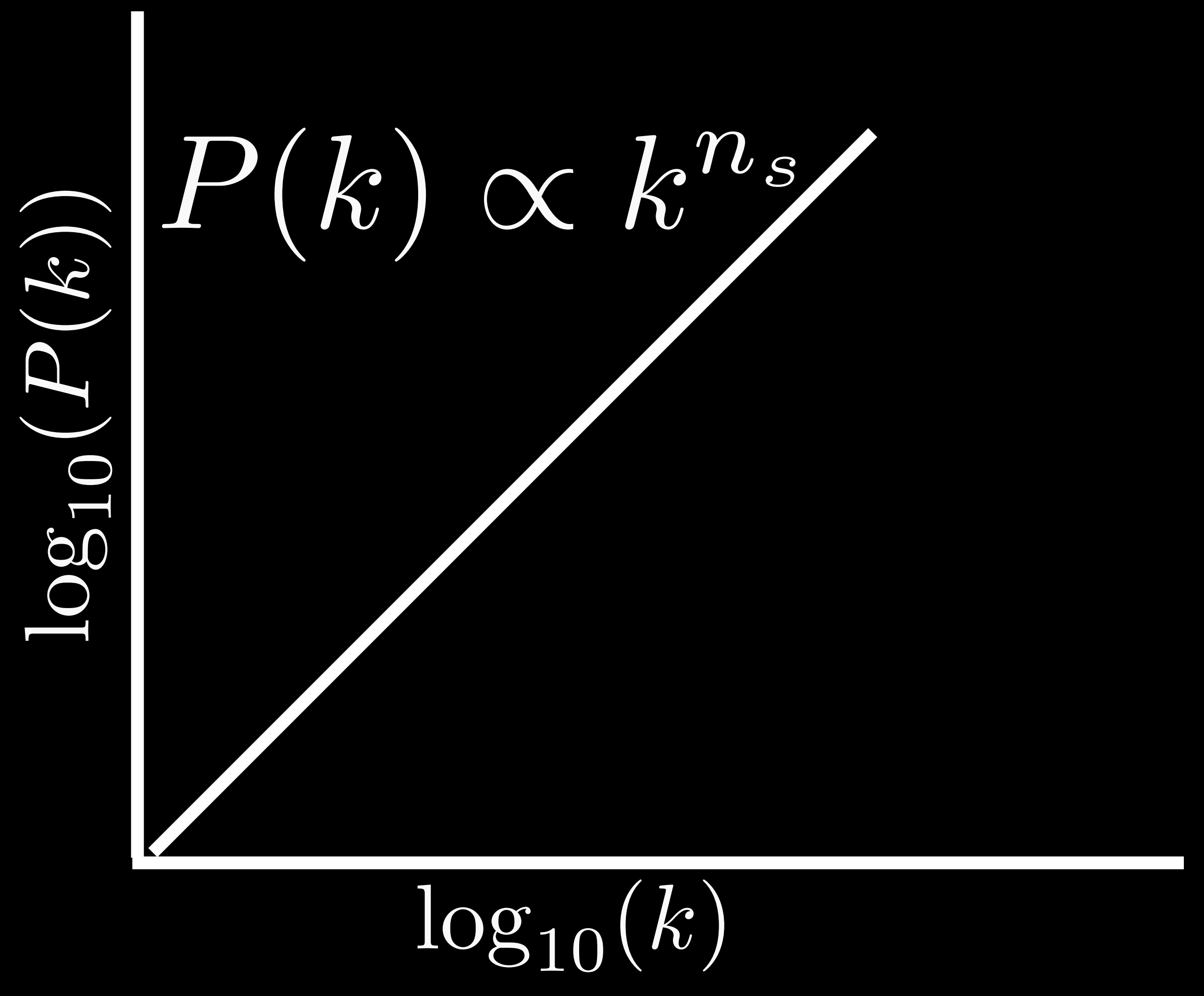
- Three components of the universe
  Dark Matter (CDM)
  Radiation
  Baryons (Everything we are made up of)

- Three Phases of the Universe
  Radiation dominated phase
  Matter dominated
  Dark Energy dominated

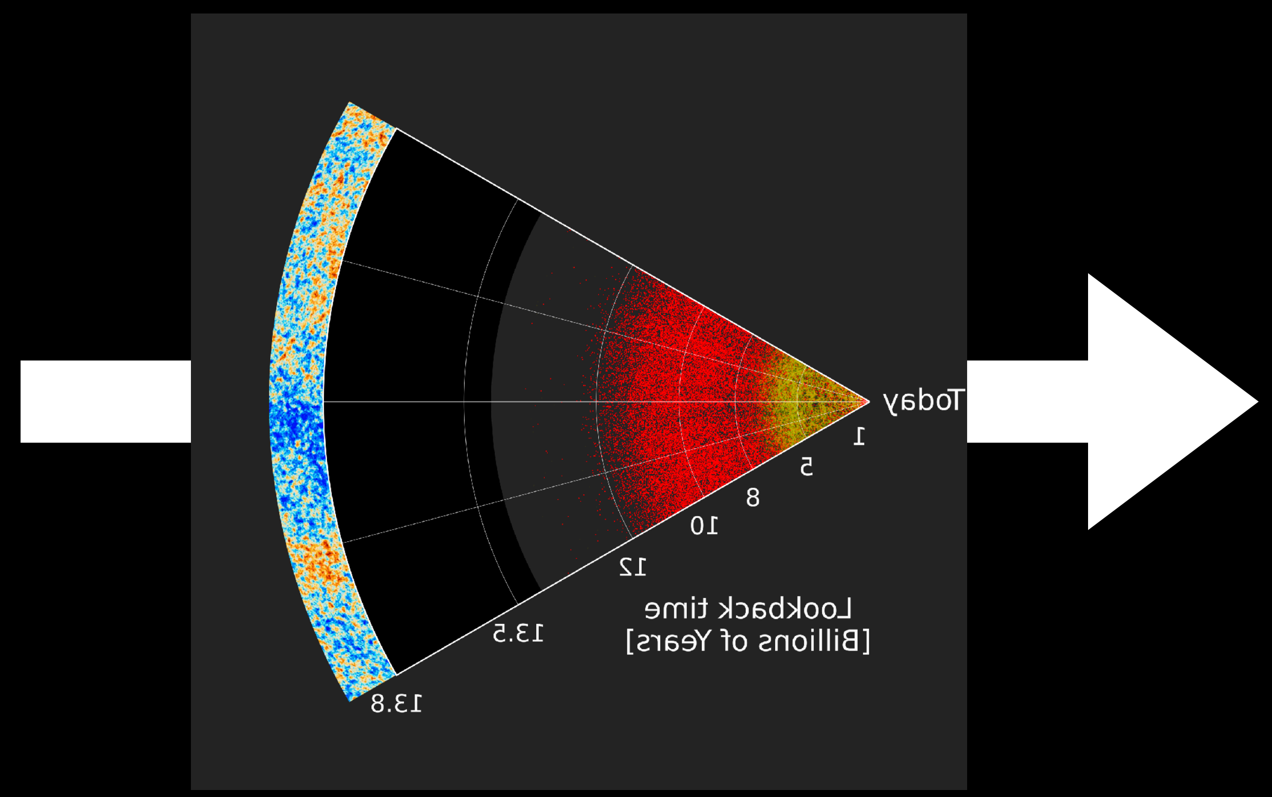
- Two scales
  Sub-horizon
  Super-horizon

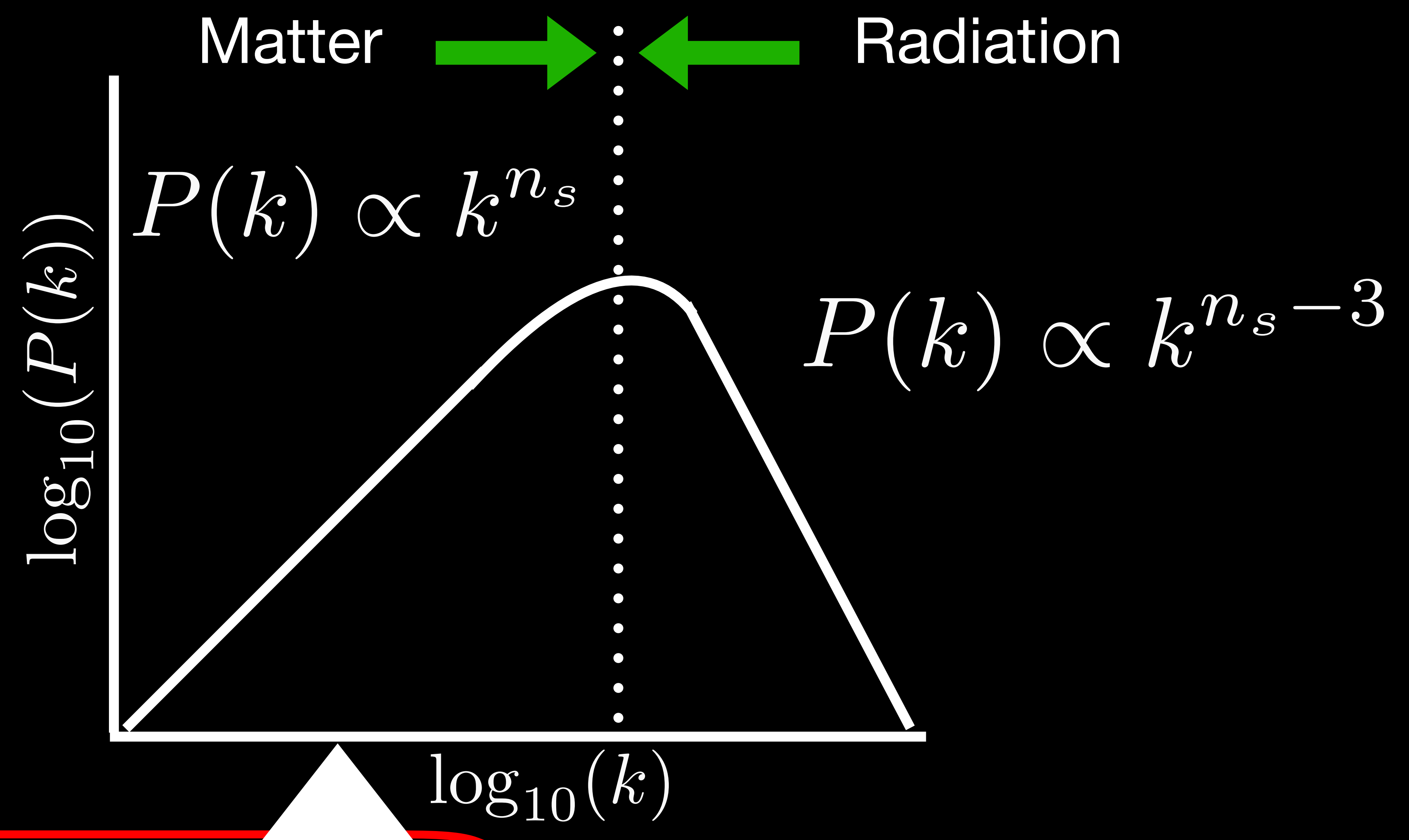
Distribution of matter in the Universe

Standard model of Cosmological Structure formation

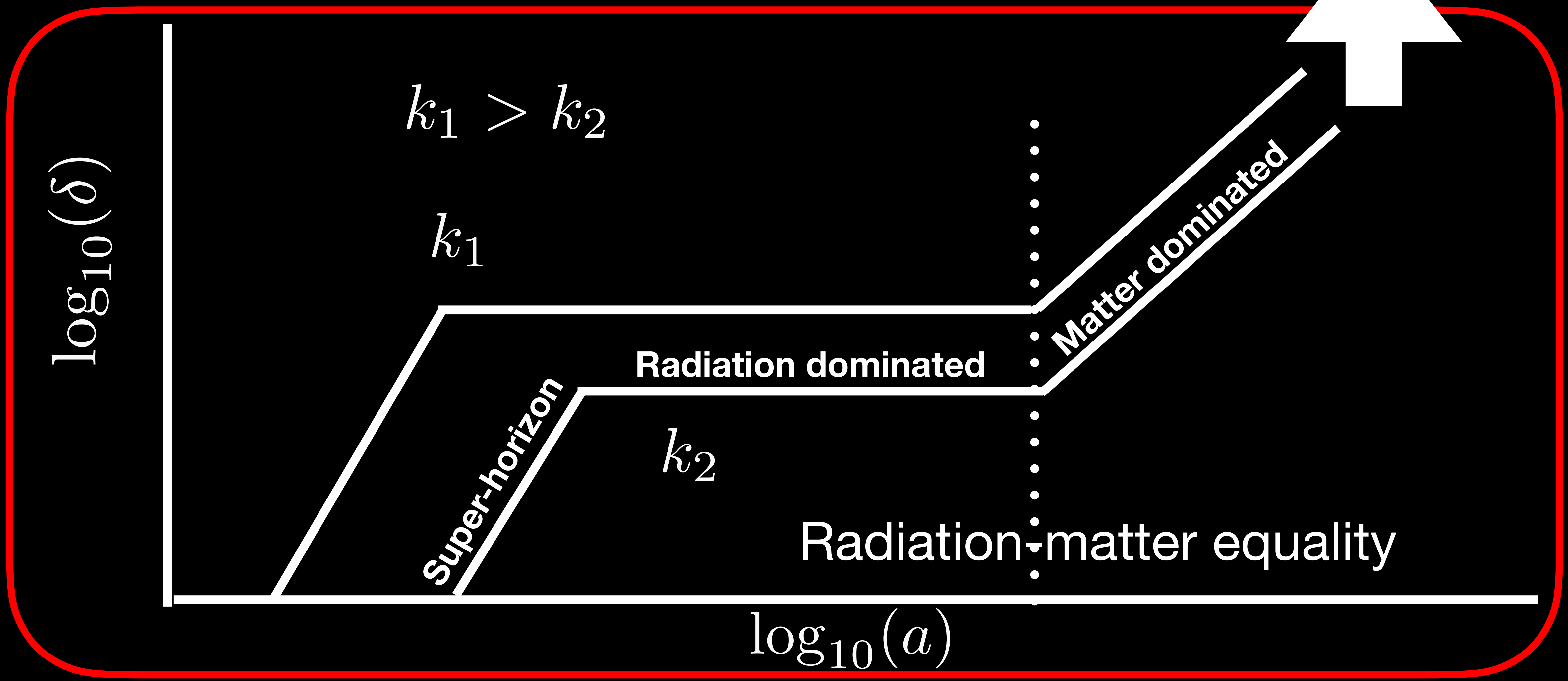


Primordial power spectrum processed through the physics of early universe





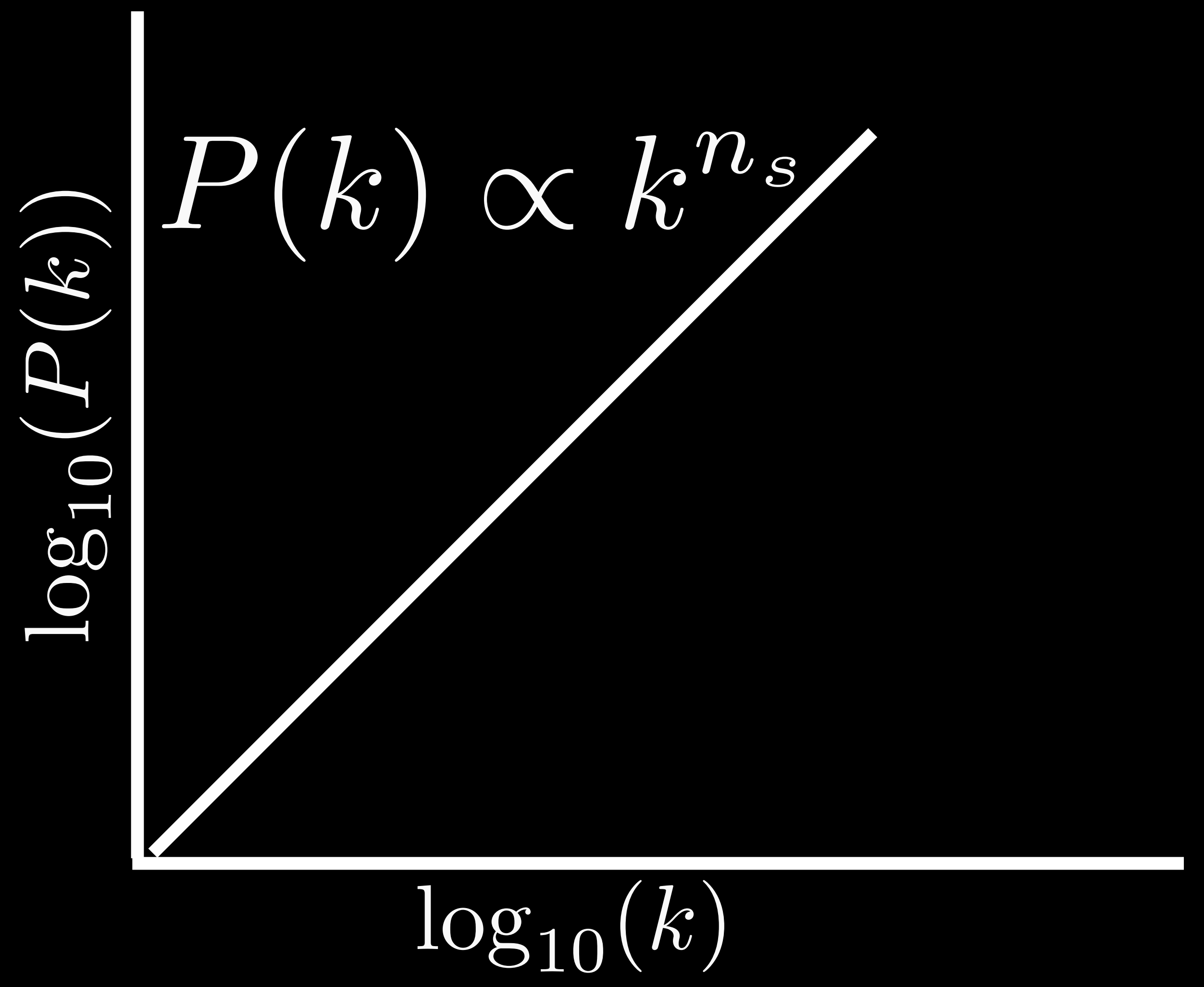
Cold Dark Matter (CDM)



$a/k = H^{-1}$

Distribution of matter in the Universe

Standard model of Cosmological Structure formation



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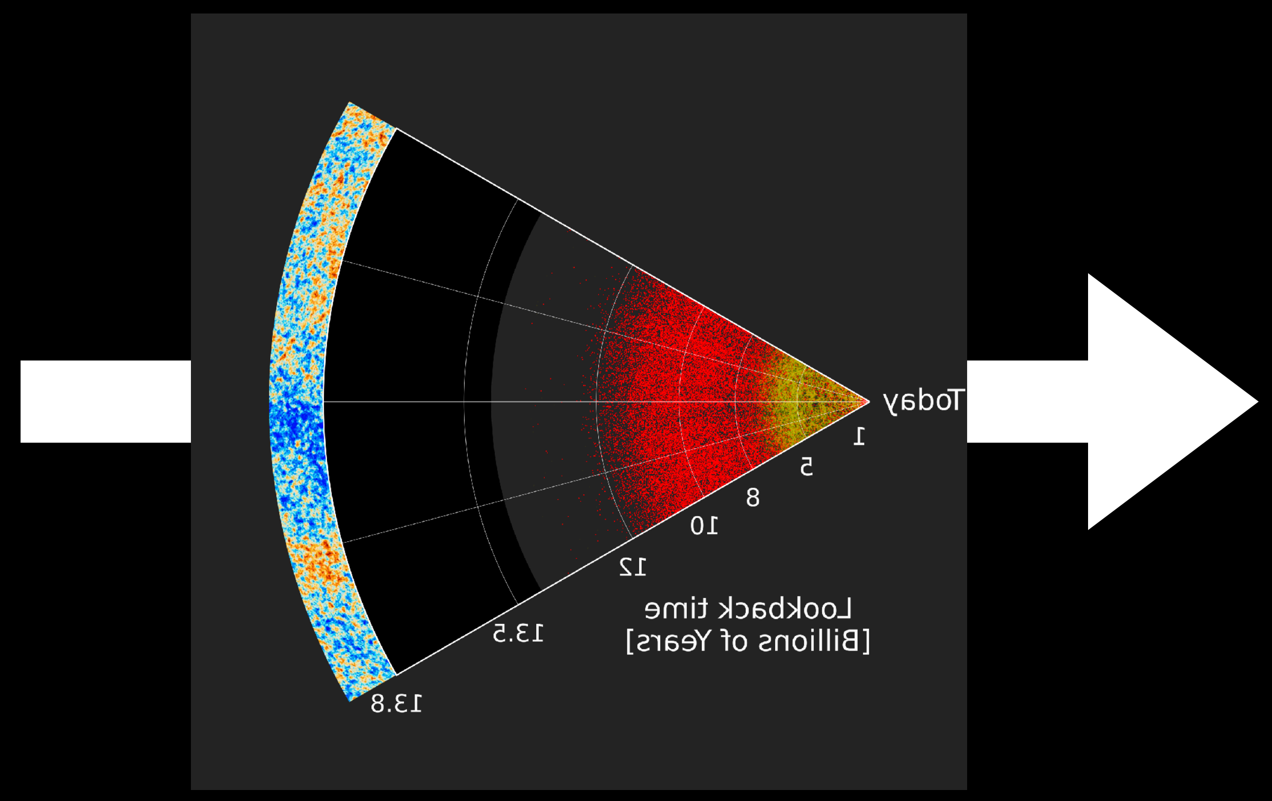
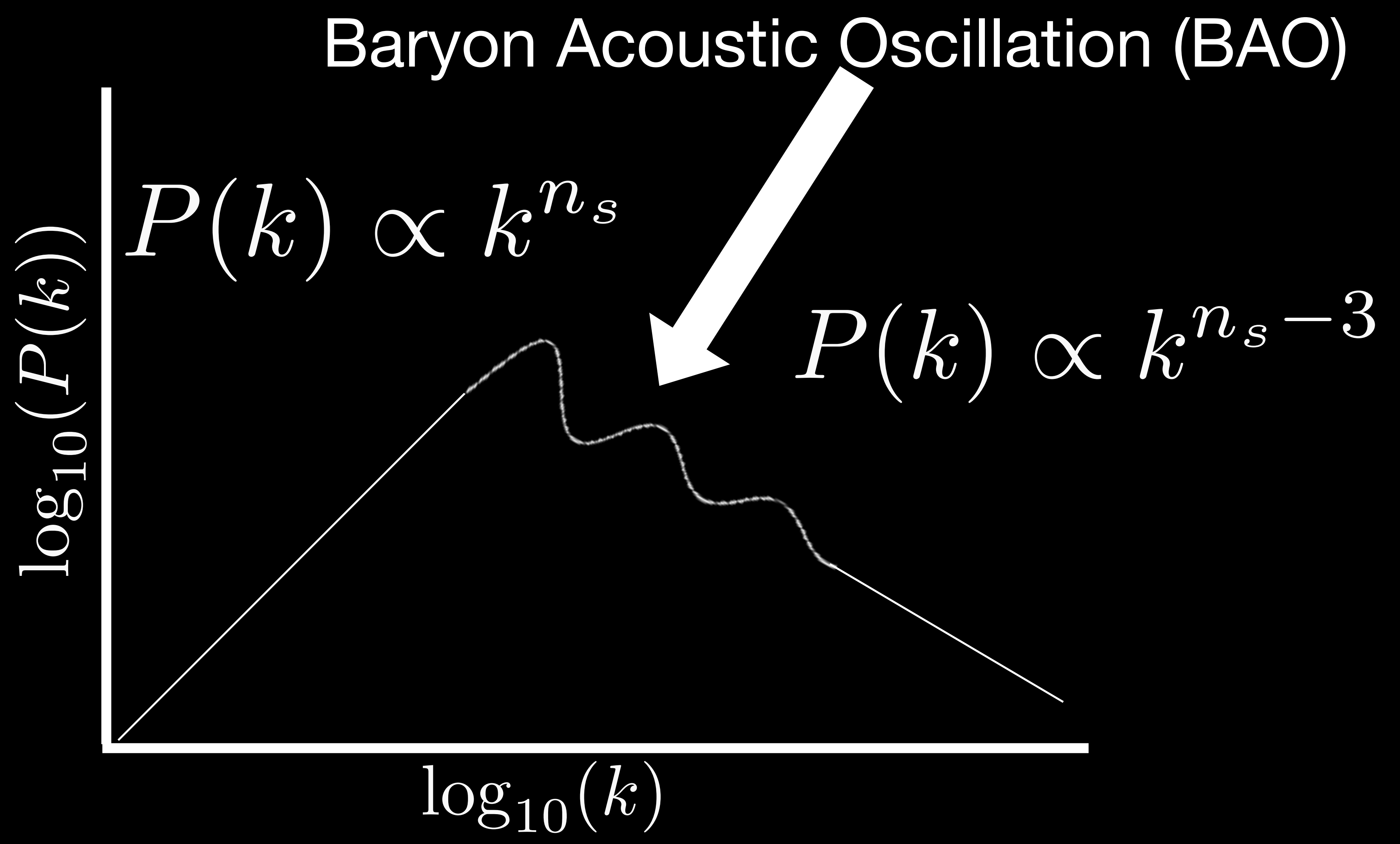
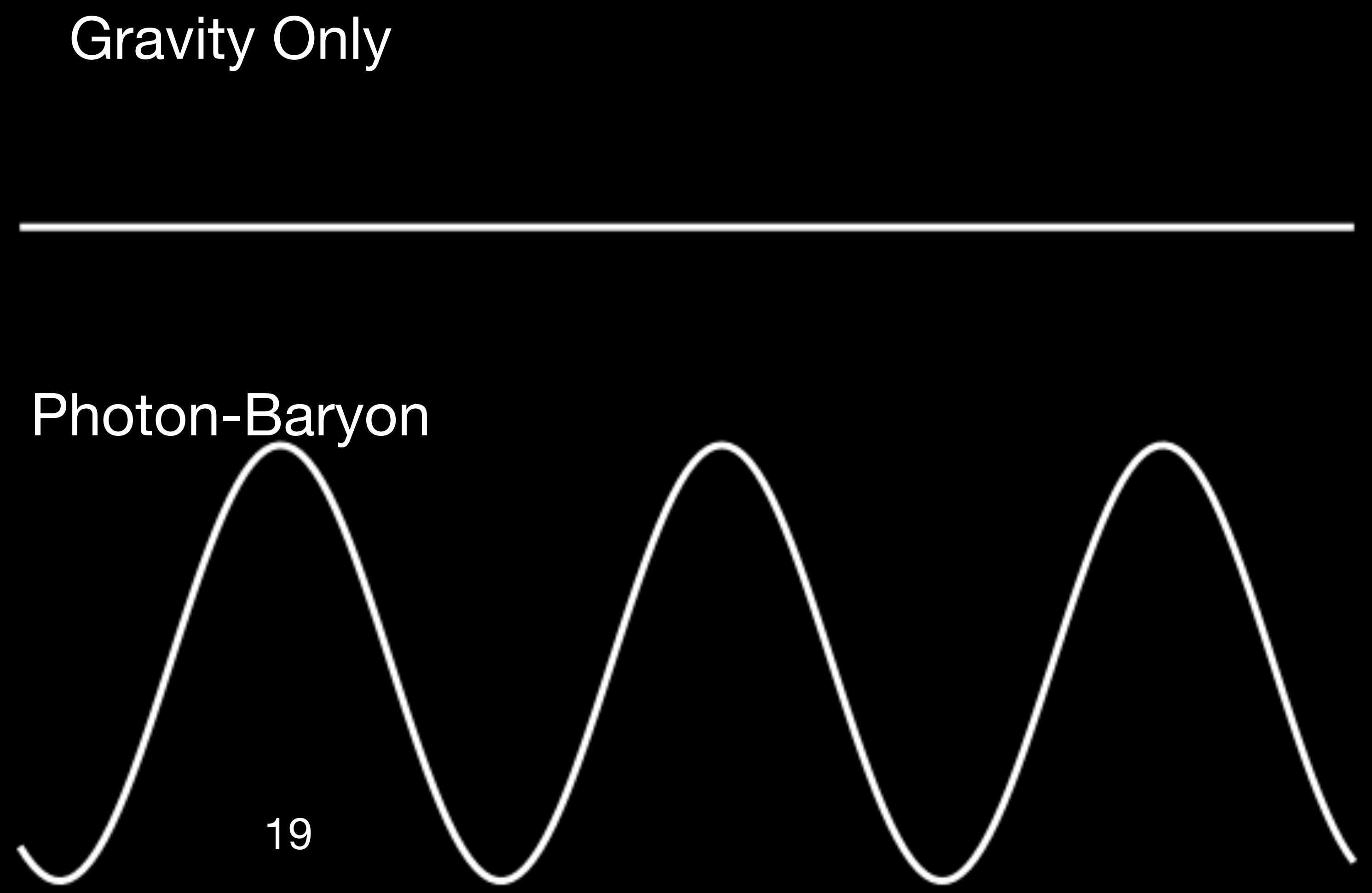




Baryon-Photon Plasma

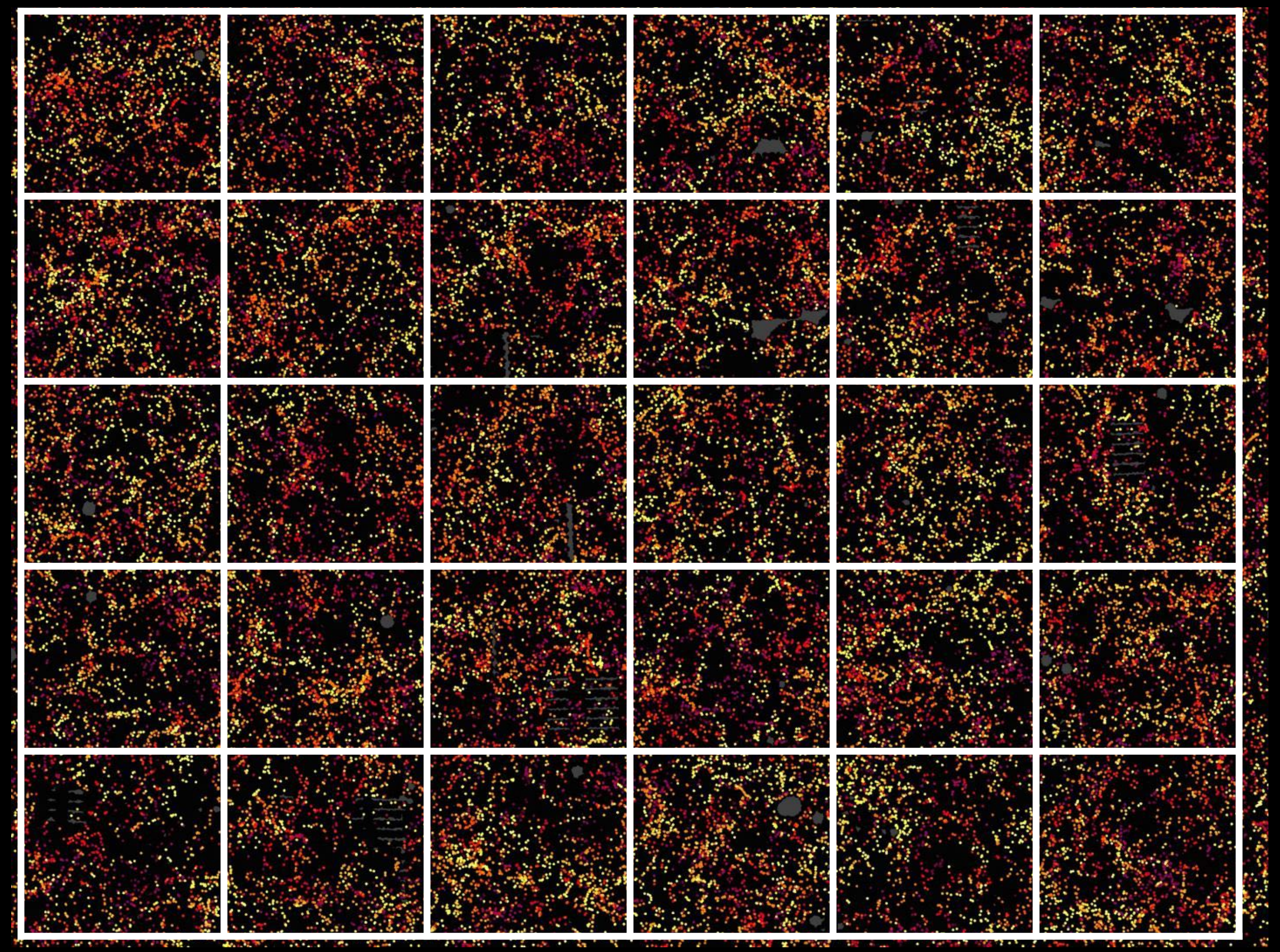
$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = \delta\left(4\pi G\rho_o - c_s^2 k^2/a^2\right)$$

$$c_s \approx c/\sqrt{3}$$

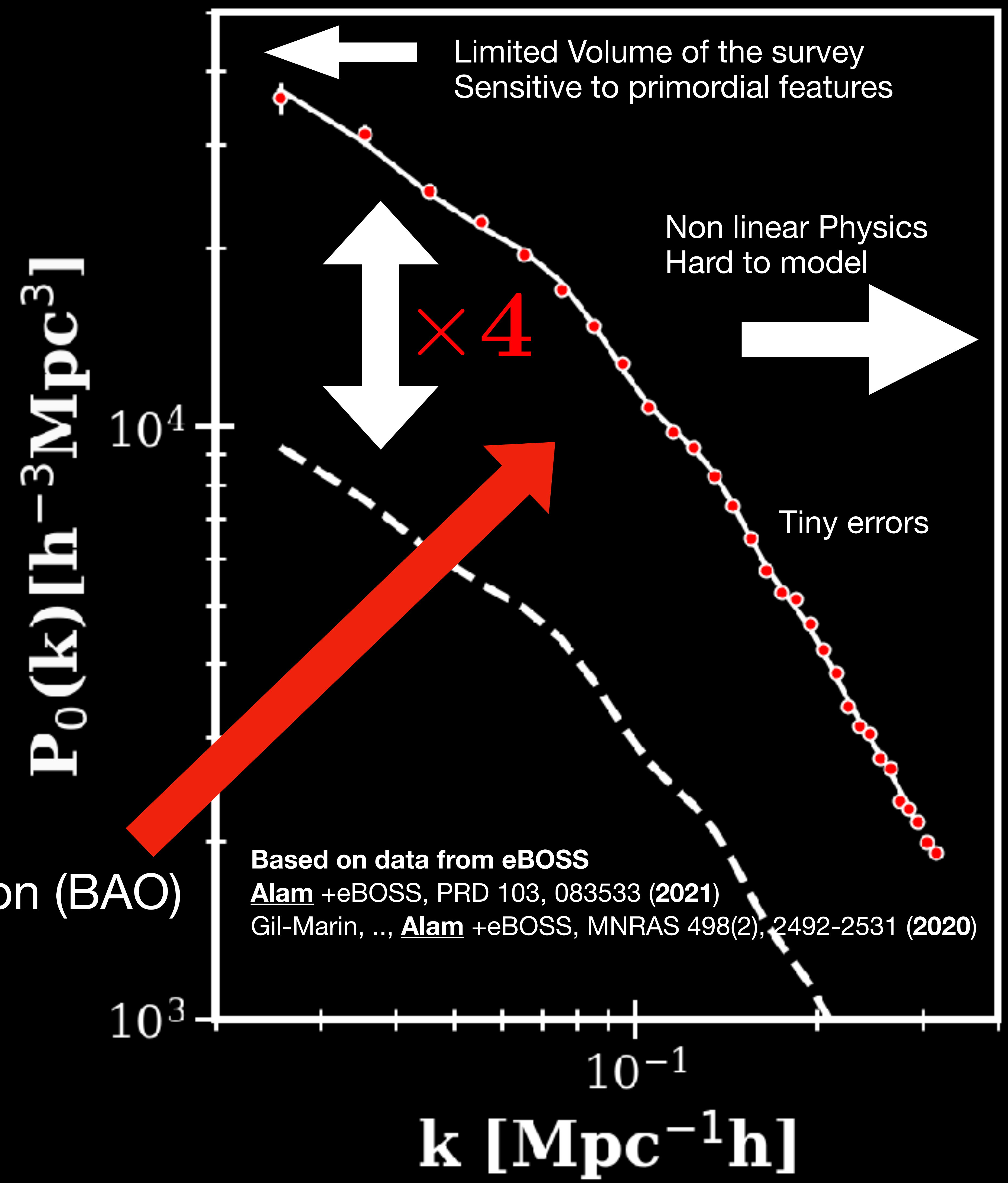


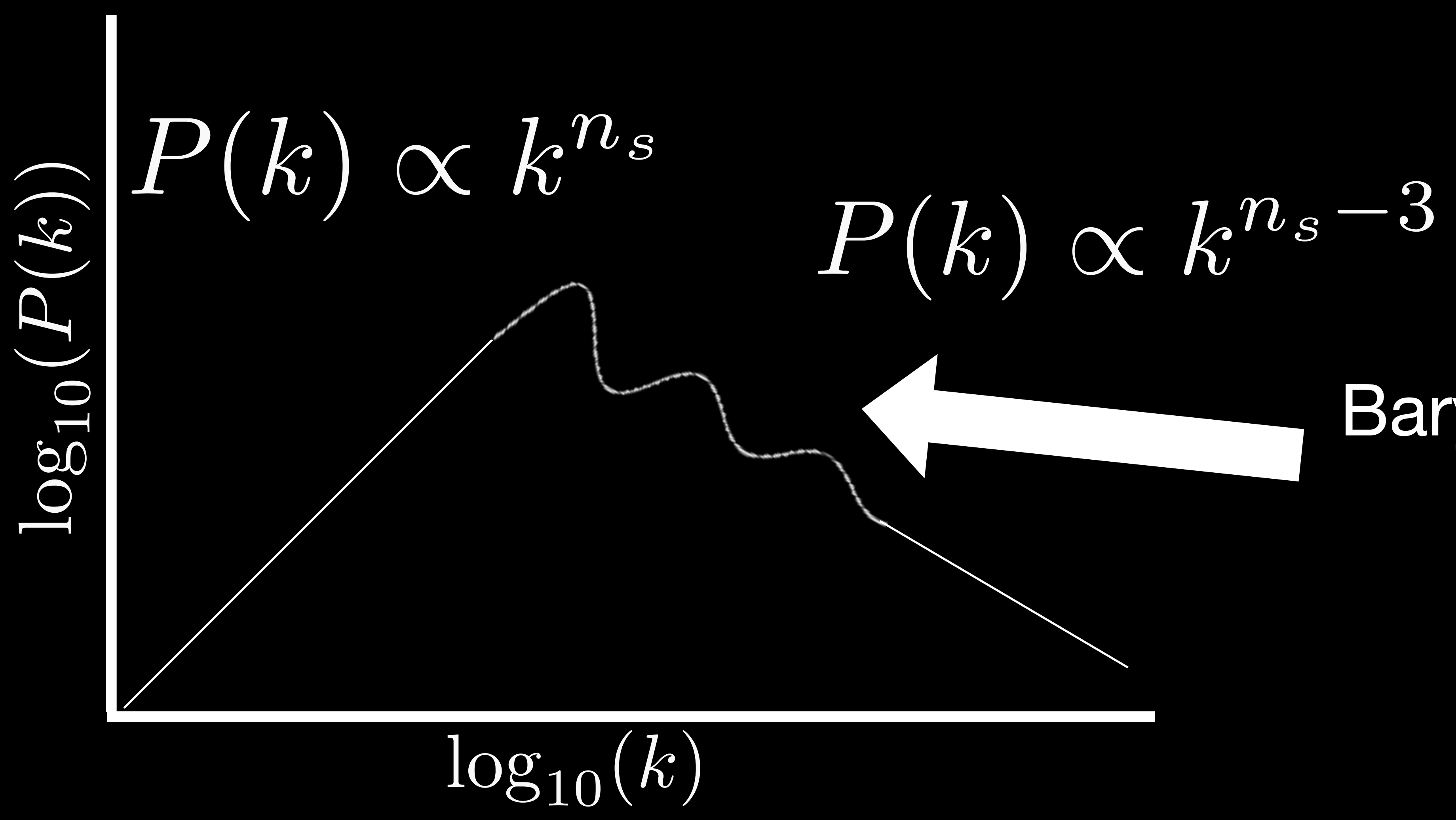
Current LSS experiment

Standard model of Cosmological Structure Formation



$$P(k) = \left\langle \delta(\vec{k})\delta^*(\vec{k}) \right\rangle$$





Baryon Acoustic Oscillation (BAO)

Simplifying the unknown physics of galaxies

- The DM halos are the sites of galaxy formation.
- They form at the peak of density fluctuation in the early universe
- The knowledge of peak statistics of Gaussian Random Field (GRF) applies (BBKS).

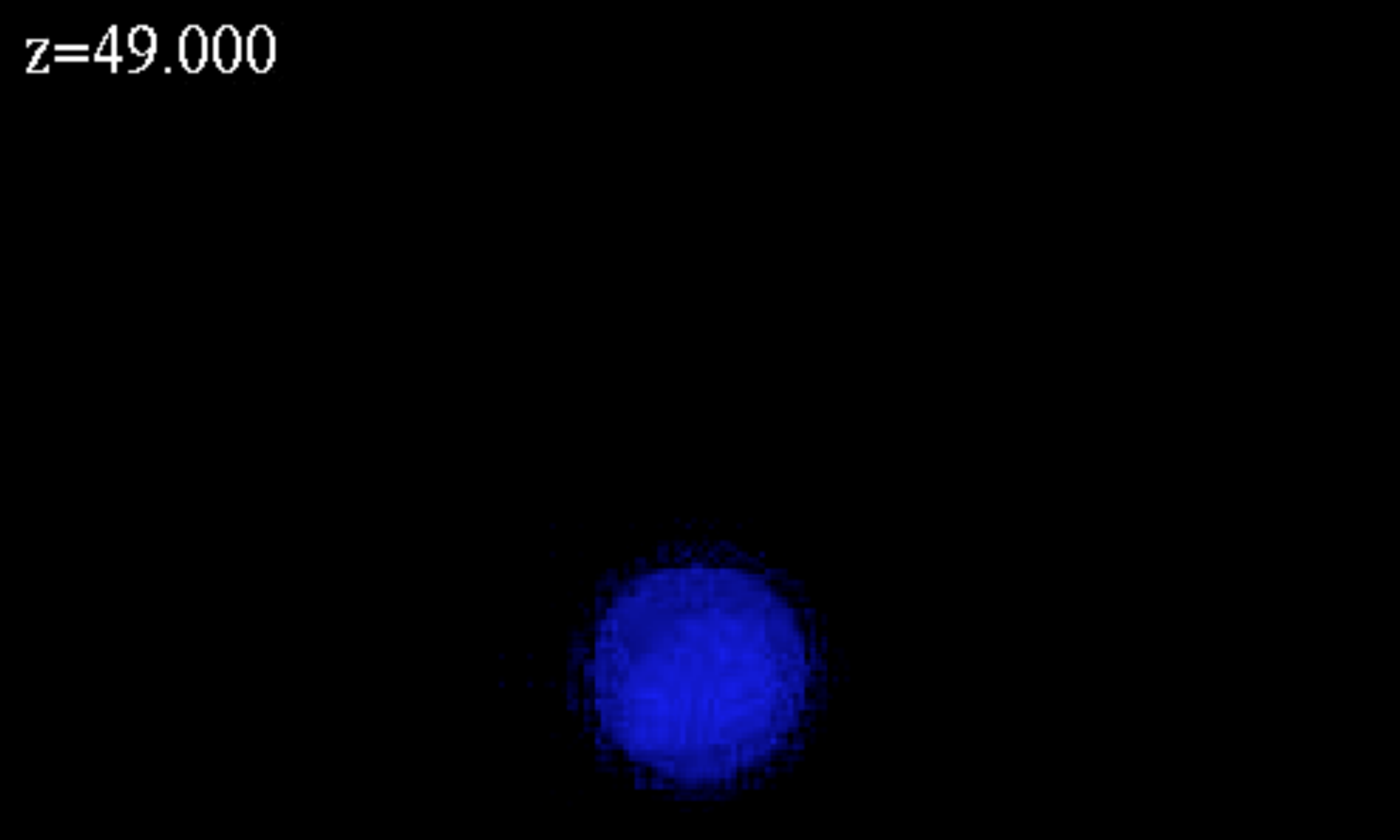
$$\delta_{\text{peak}}(k) = b(M)\delta_m(k)$$

Deviation from GRF will induce higher order terms

$$\delta_{\text{peak}}(k) = b(M, k)\delta_m(k)$$

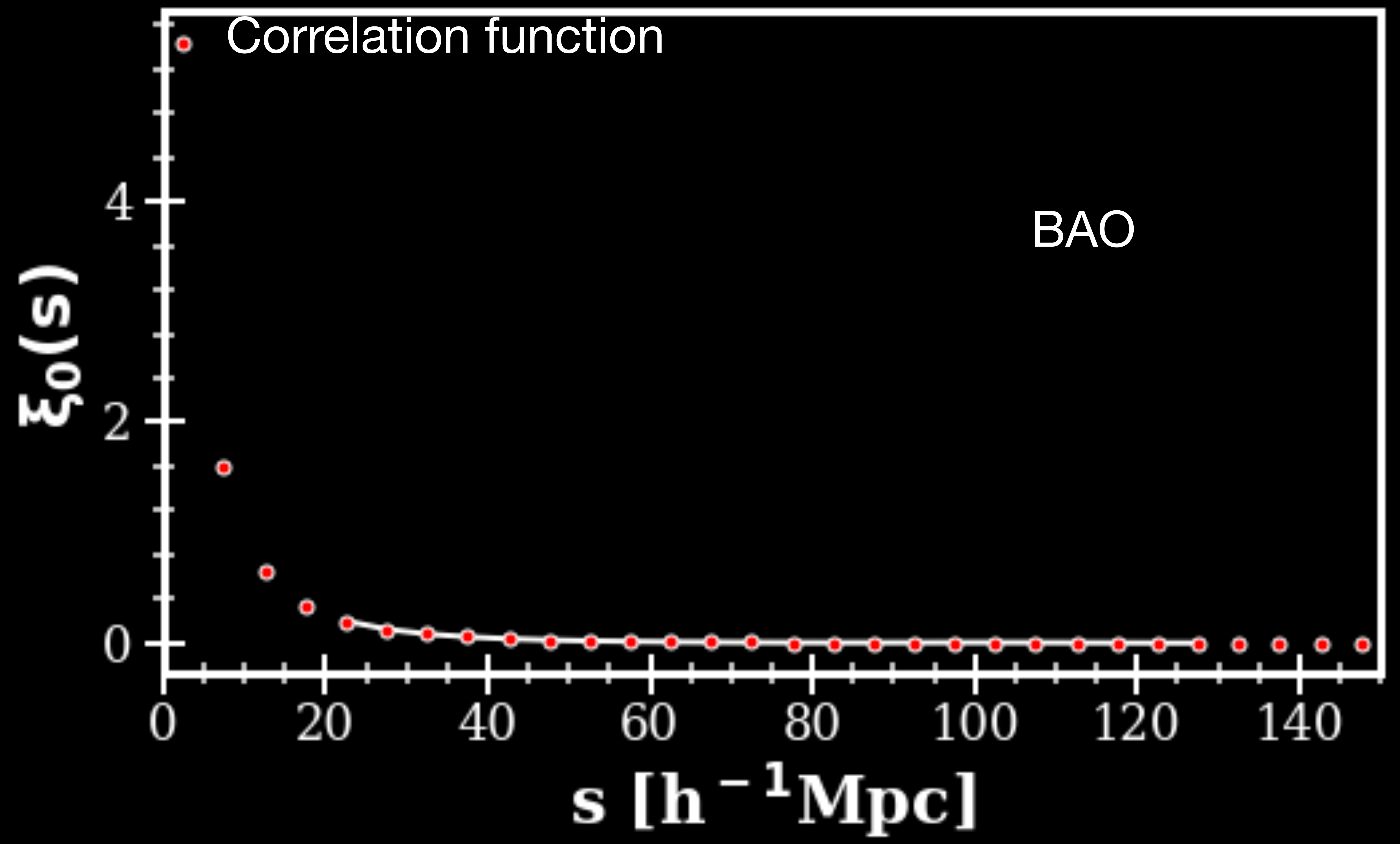
Critical to understand when is this necessary.
Degenerate with cosmology (shape of P(k)) which can be broken by weak lensing.

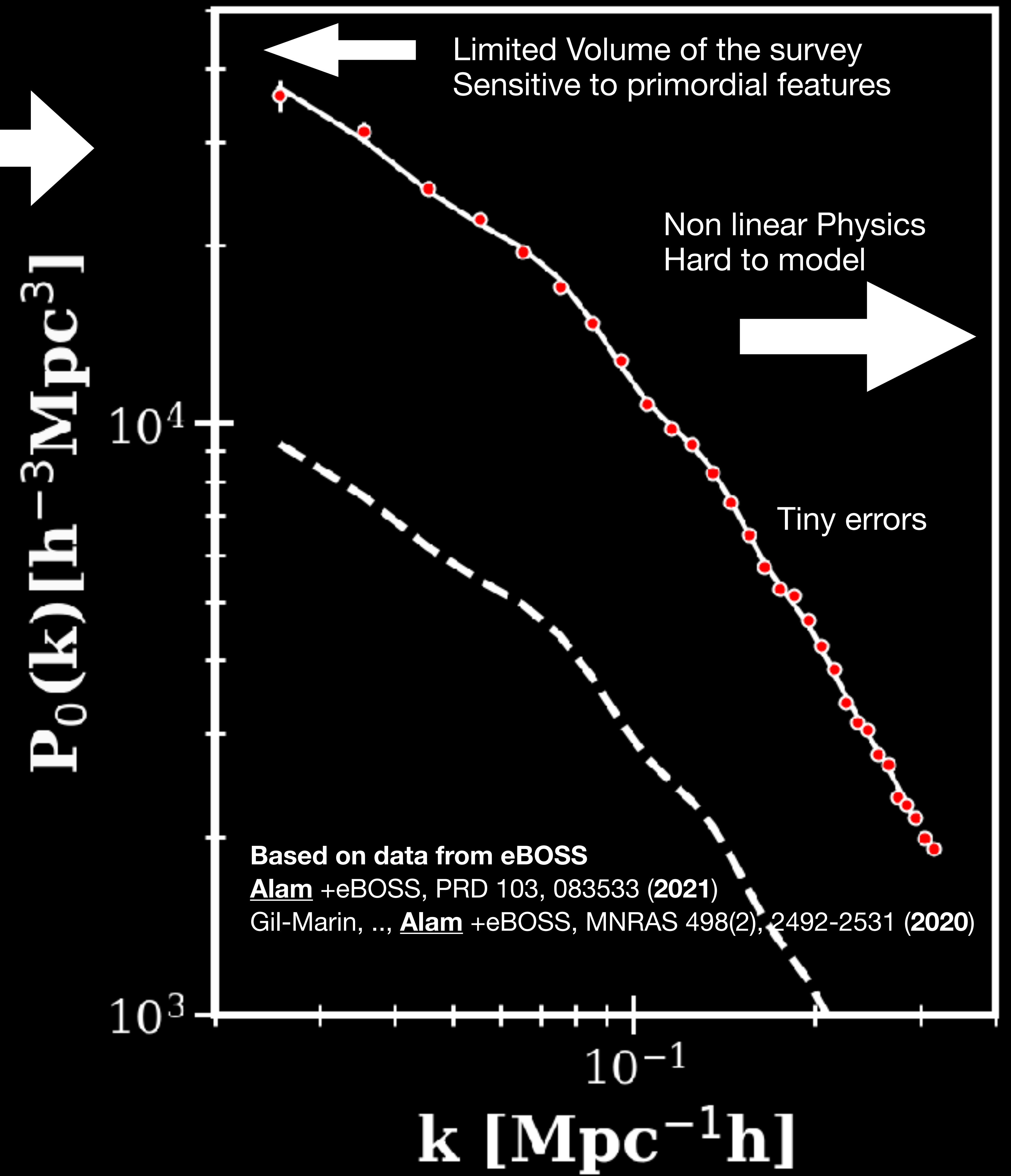
The Dark Matter Halos



Current LSS experiment

Standard model of Cosmological Structure Formation



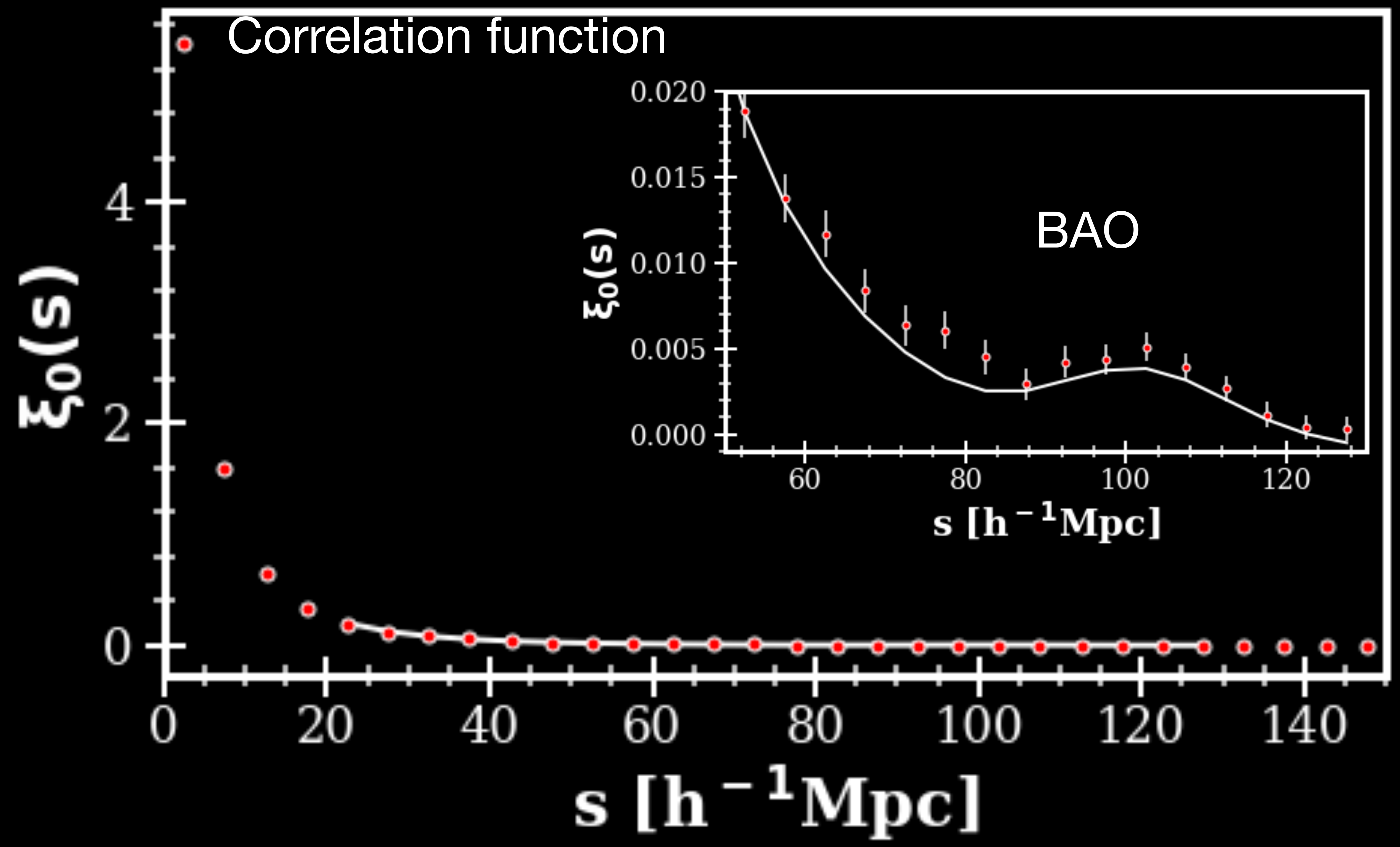


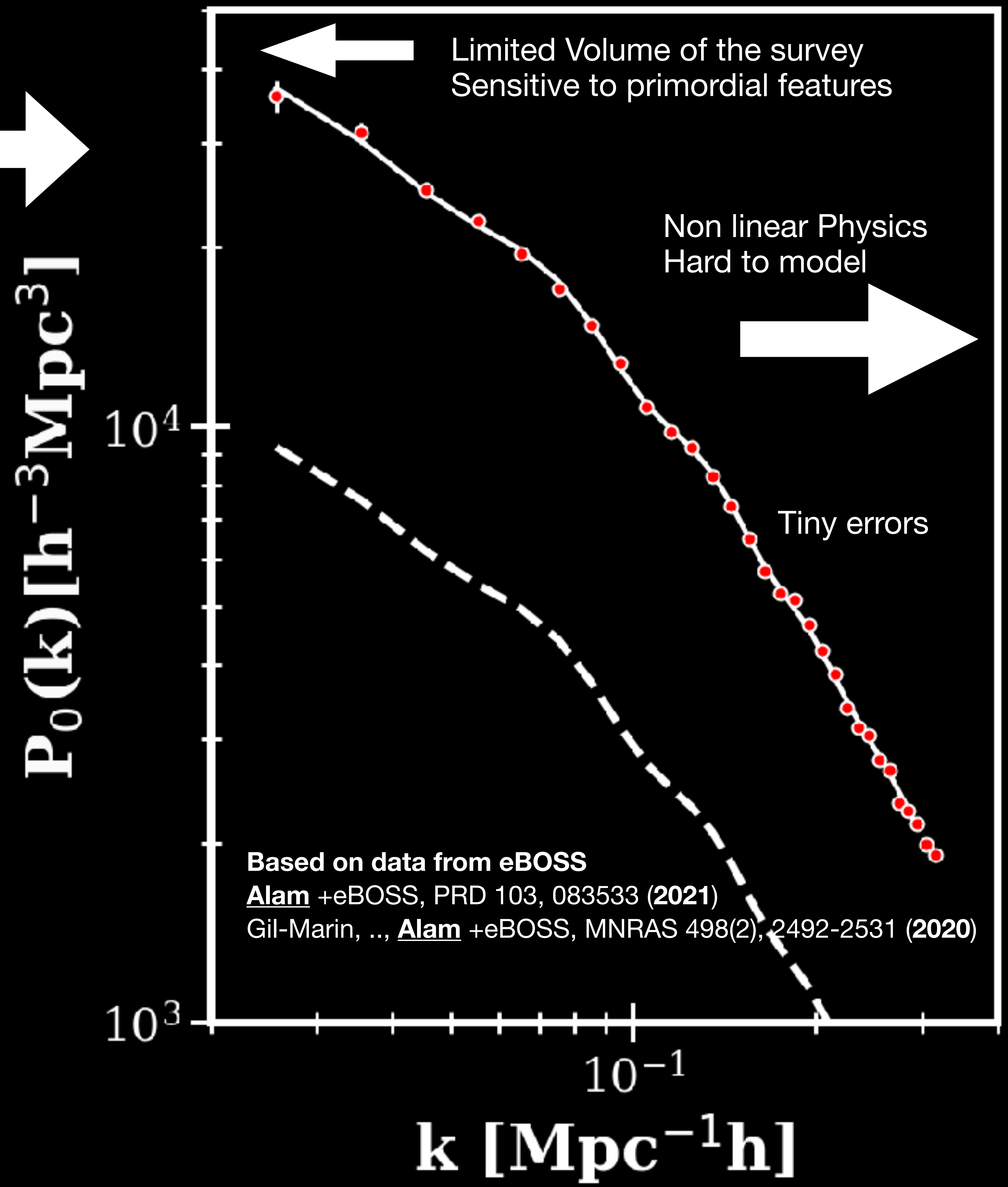
Fourier Conjugates

$$\xi(r) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle \quad \Longleftrightarrow \quad P(k) = \left\langle \delta(\vec{k})\delta^*(\vec{k}) \right\rangle$$

Current LSS experiment

Standard model of Cosmological Structure Formation





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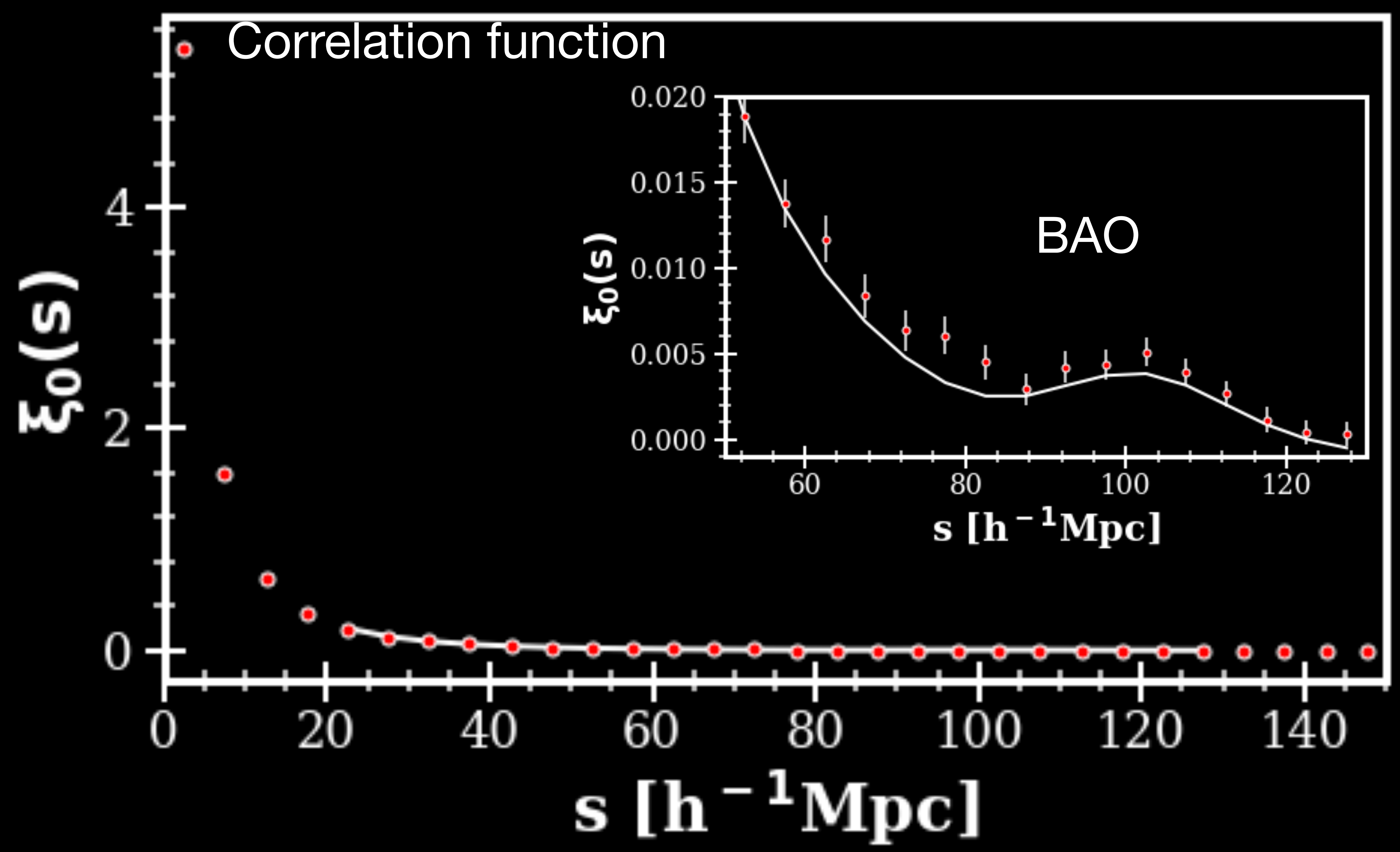
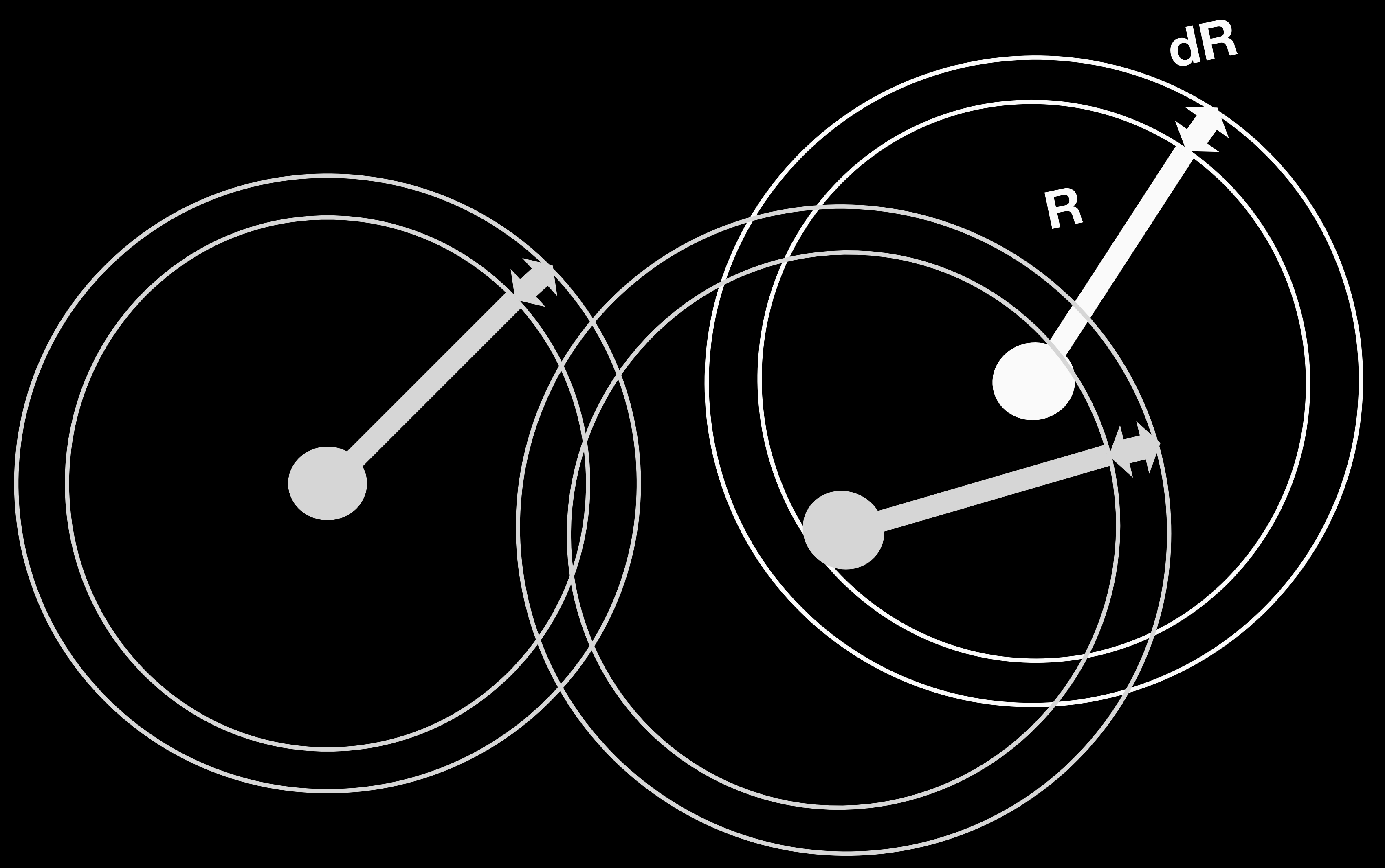
Correlation Function



Measure Correlation Function



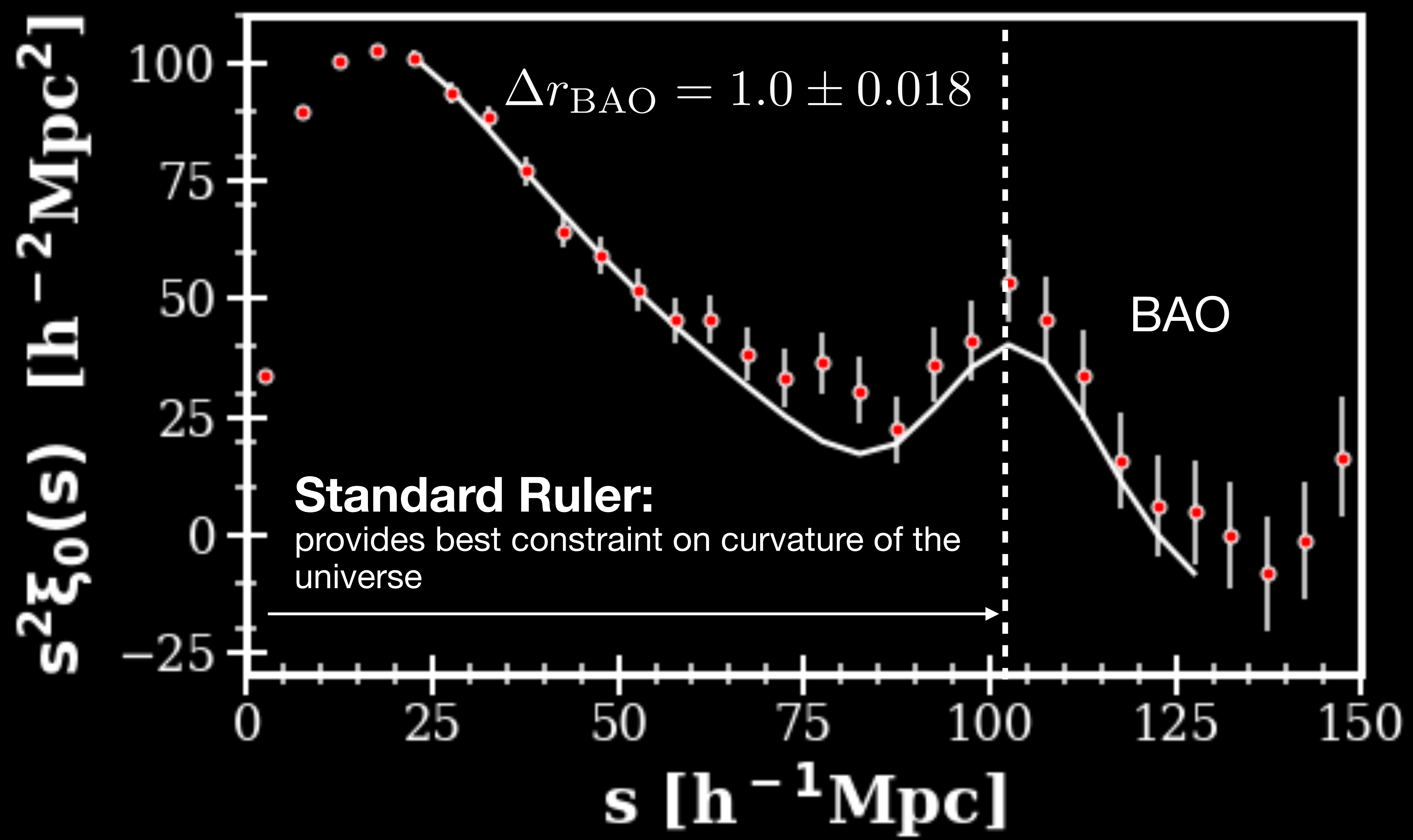
$$\xi(R) = \frac{\mathrm{npair}_{\mathrm{galaxy}}(R)}{\mathrm{npair}_{\mathrm{randoms}}(R)} - 1 \equiv \left\langle \delta(\vec{x})\delta(\vec{x}+\vec{R}) \right\rangle$$

Fourier Conjugates

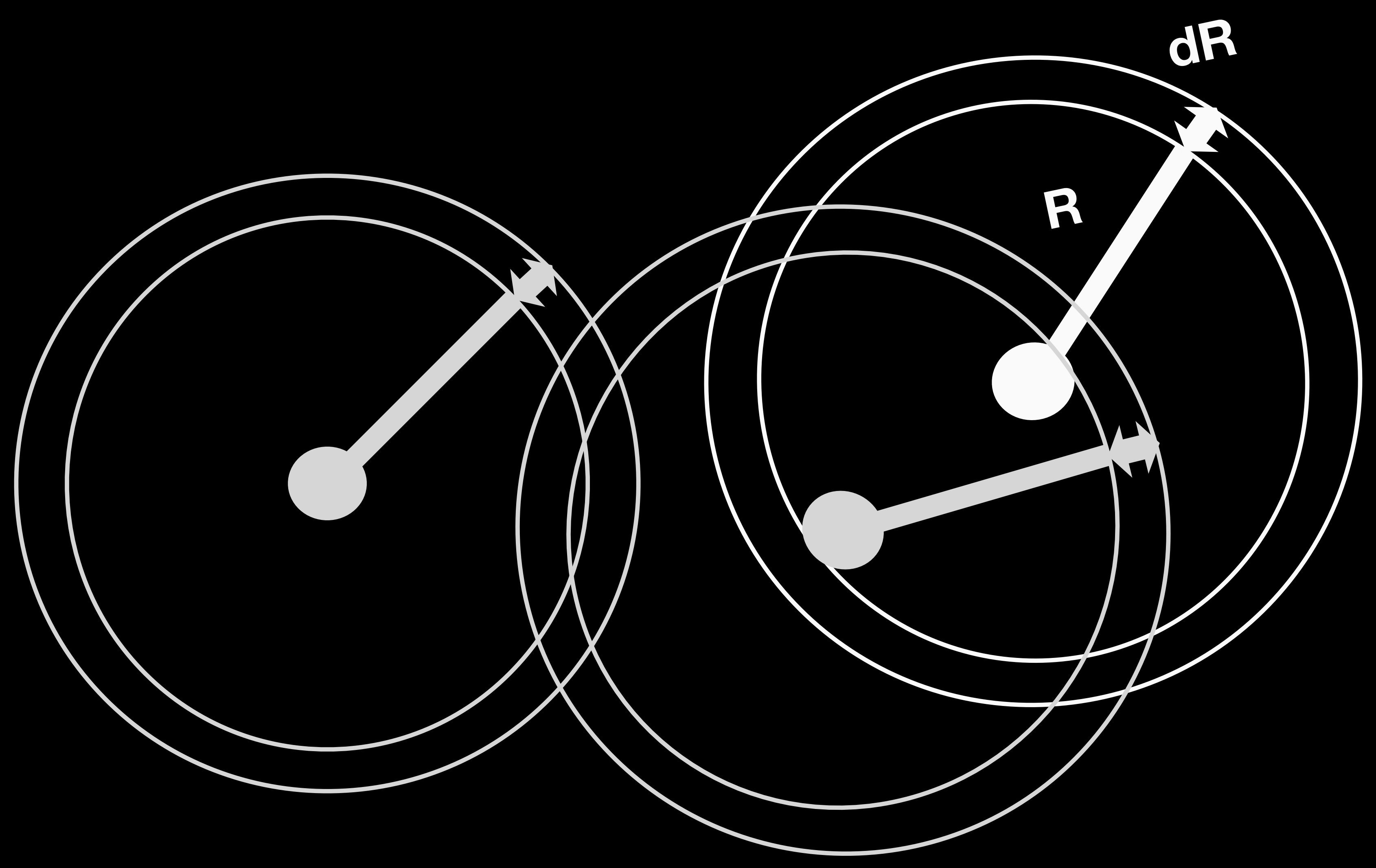
$$\xi(r) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle \quad \Longleftrightarrow \quad P(k) = \left\langle \delta(\vec{k})\delta^*(\vec{k}) \right\rangle$$

Based on data from eBOSS
Alam +eBOSS, PRD 103, 083533 (**2021**)
Gil-Marin, .., **Alam** +eBOSS, MNRAS 498(2), 2492-2531 (**2020**)

Correlation Function



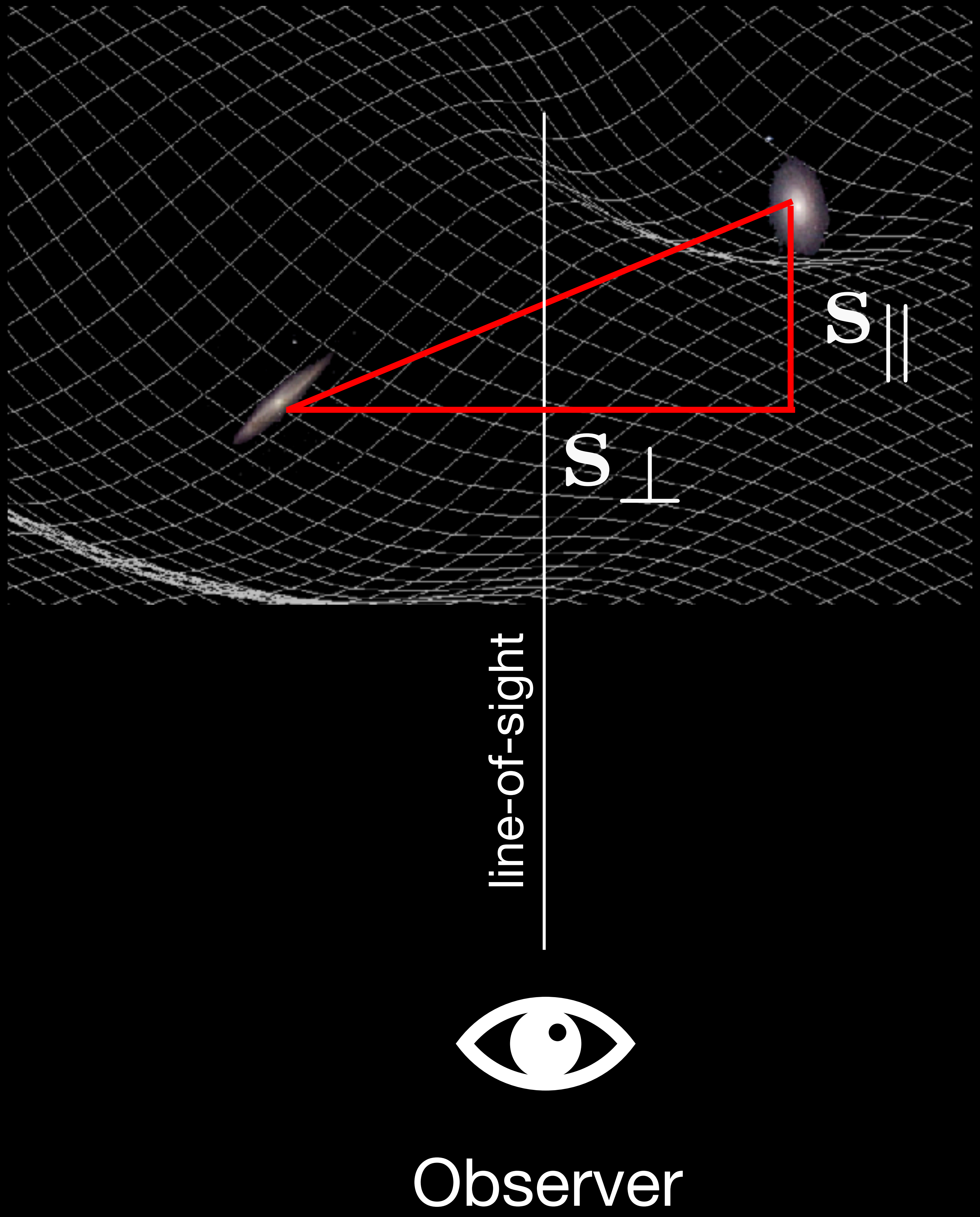
Measure Correlation Function

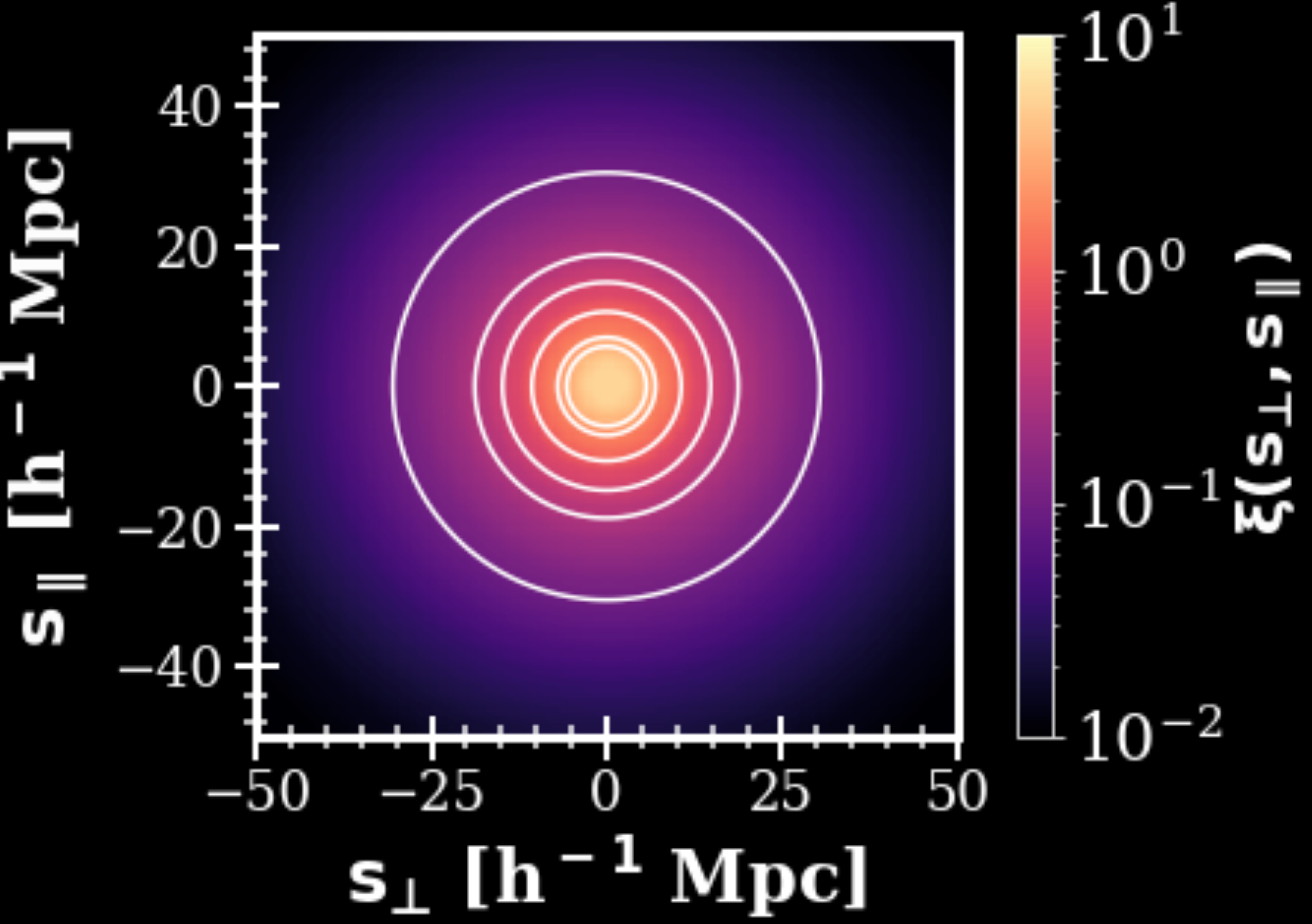


$$\xi(R) = \frac{\mathrm{npair}_{\mathrm{galaxy}}(R)}{\mathrm{npair}_{\mathrm{randoms}}(R)} - 1 \equiv \left\langle \delta(\vec{x})\delta(\vec{x}+\vec{R}) \right\rangle$$

How about isotropy?
Is the galaxy clustering consistent with isotropic universe?

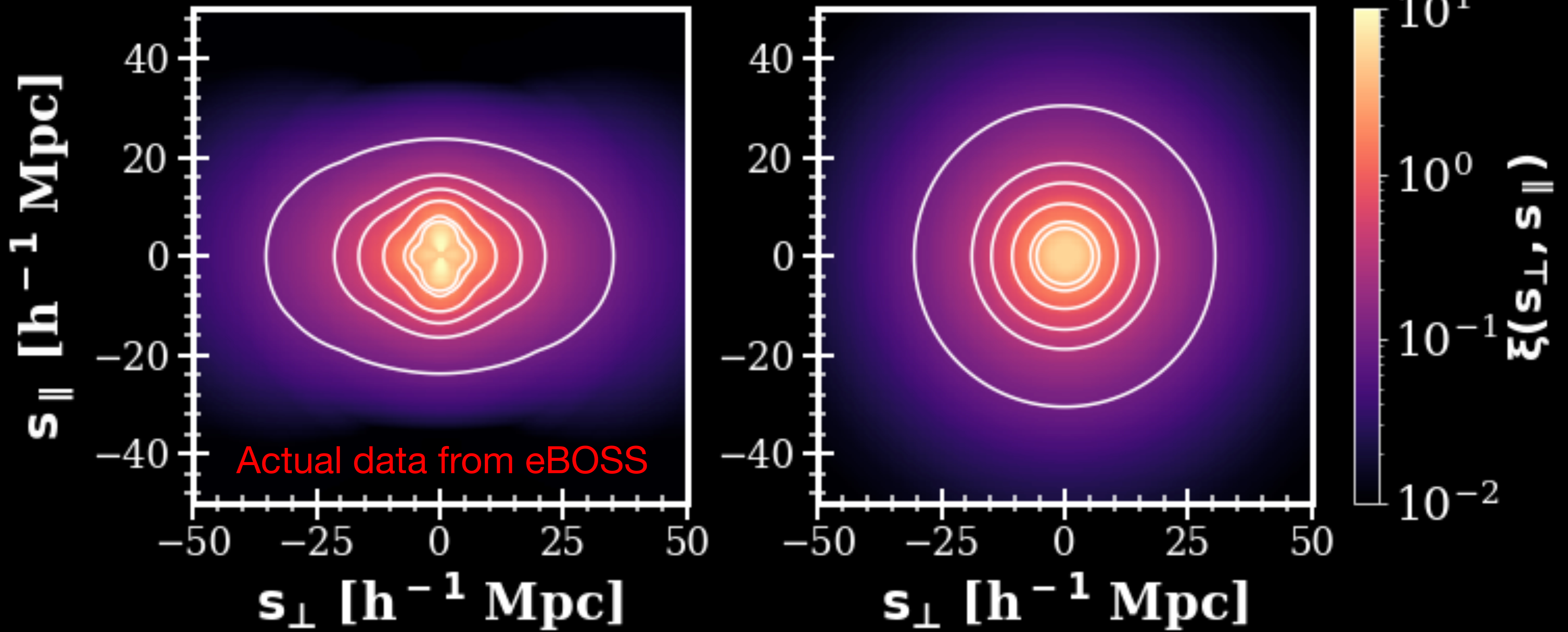
Isotropic? Correlation Function





Anisotropic? Correlation Function

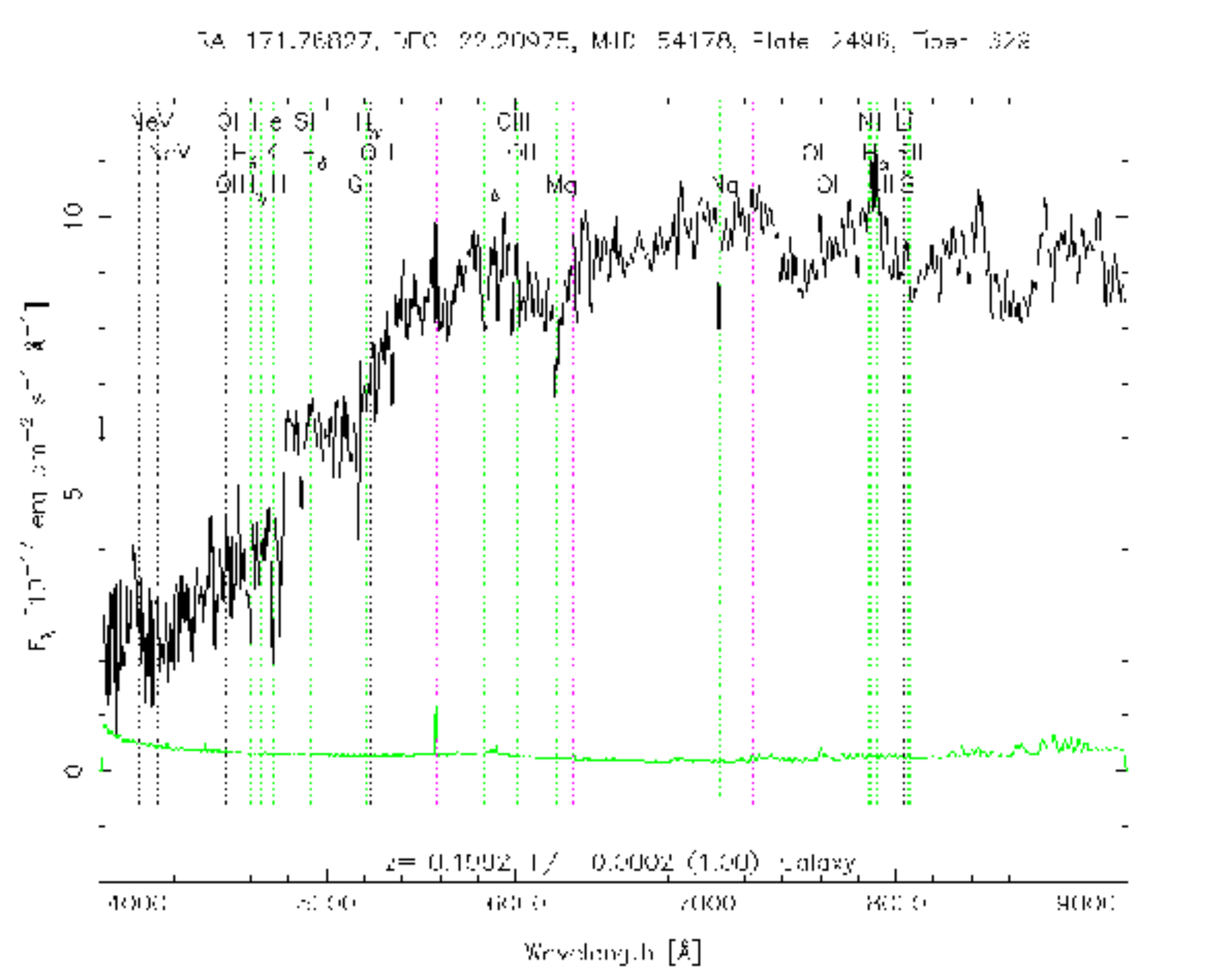
Redshift Space Distortions (RSD)



Based on data from eBOSS
Alam +eBOSS, PRD 103, 083533 (**2021**)
Bautista, .., **Alam** +eBOSS, MNRAS 500(1), 736-762 (**2021**)

Quick Intro to Galaxy Redshift experiments

- **Sloan Digital Sky Survey** (SDSS/eBOSS)
  current state of the art result (data public)
  2000-2020 (20 years of data)
  2.5 million Galaxy Spectra



$$\lambda_{\rm obs} = \frac{a_{\rm now}}{a_{\rm emit}} \lambda_{\rm emit}$$

$$z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} - 1 = \frac{a_{\rm now}}{a_{\rm emit}} - 1$$

$$\text{Distance} = \frac{c}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

Let us think about Redshift

$$z_{\rm obs} = z_{\rm cosmo} + \Delta v/c + z_g$$

$\mathcal{O}(1)$ $\quad\mathcal{O}(10^{-3})$ $\quad\mathcal{O}(10^{-4})$

$$\lambda_{\rm obs} = \frac{a_{\rm now}}{a_{\rm emit}} \lambda_{\rm emit}$$

$$z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} - 1 = \frac{a_{\rm now}}{a_{\rm emit}} - 1$$

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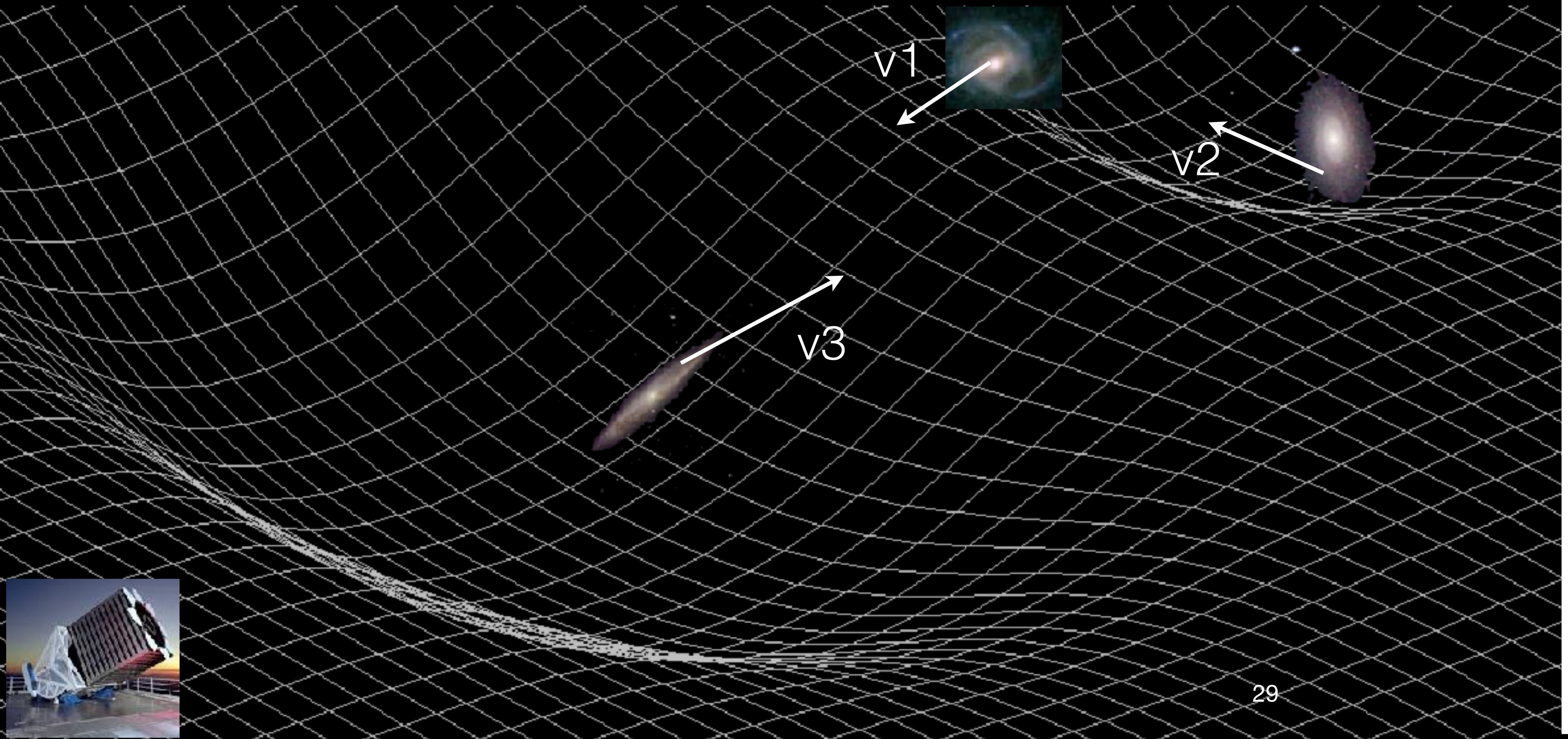

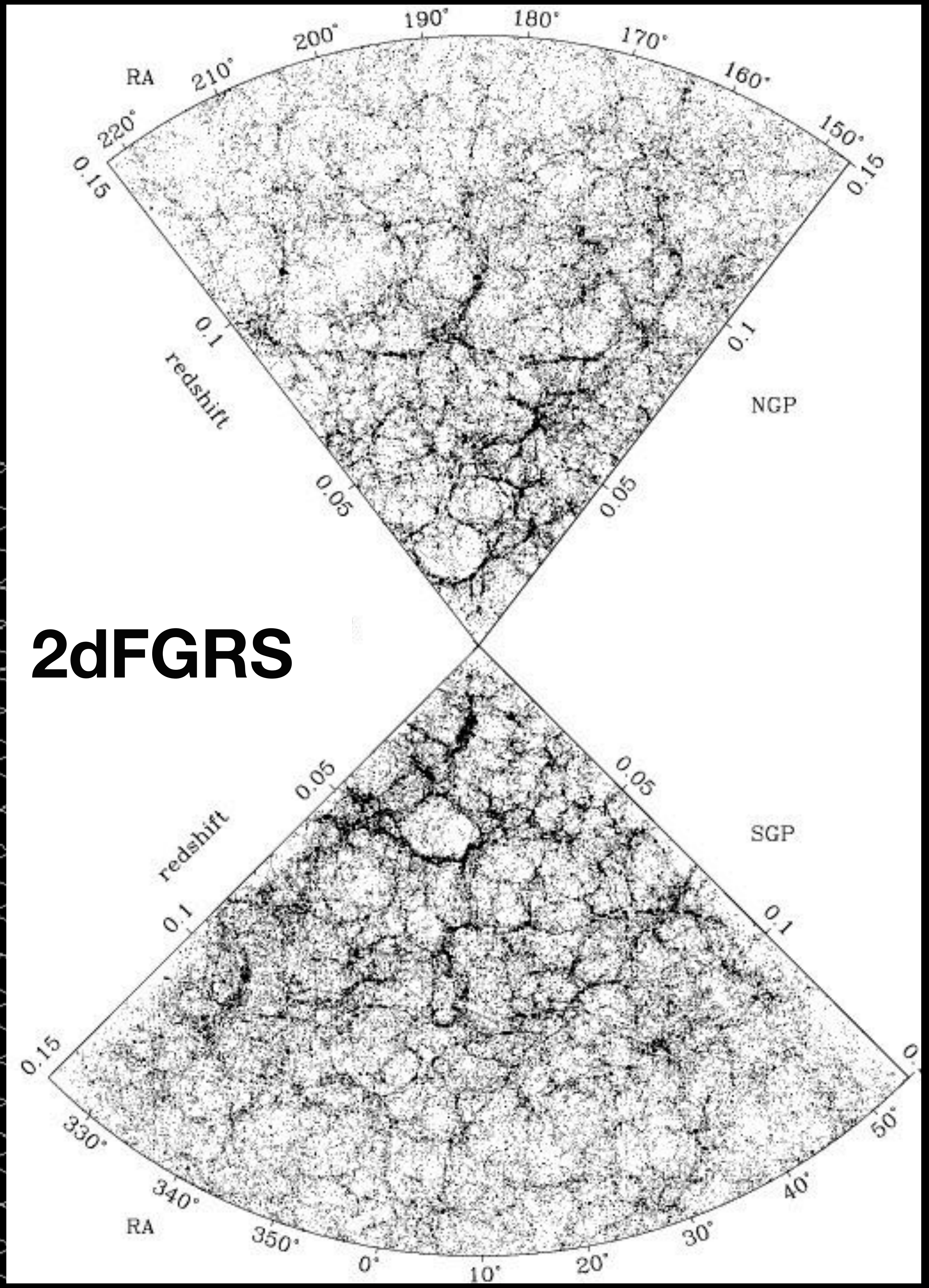

Let us think about Redshift

$$z_{\rm obs} = z_{\rm cosmo} + \Delta v/c + z_g$$

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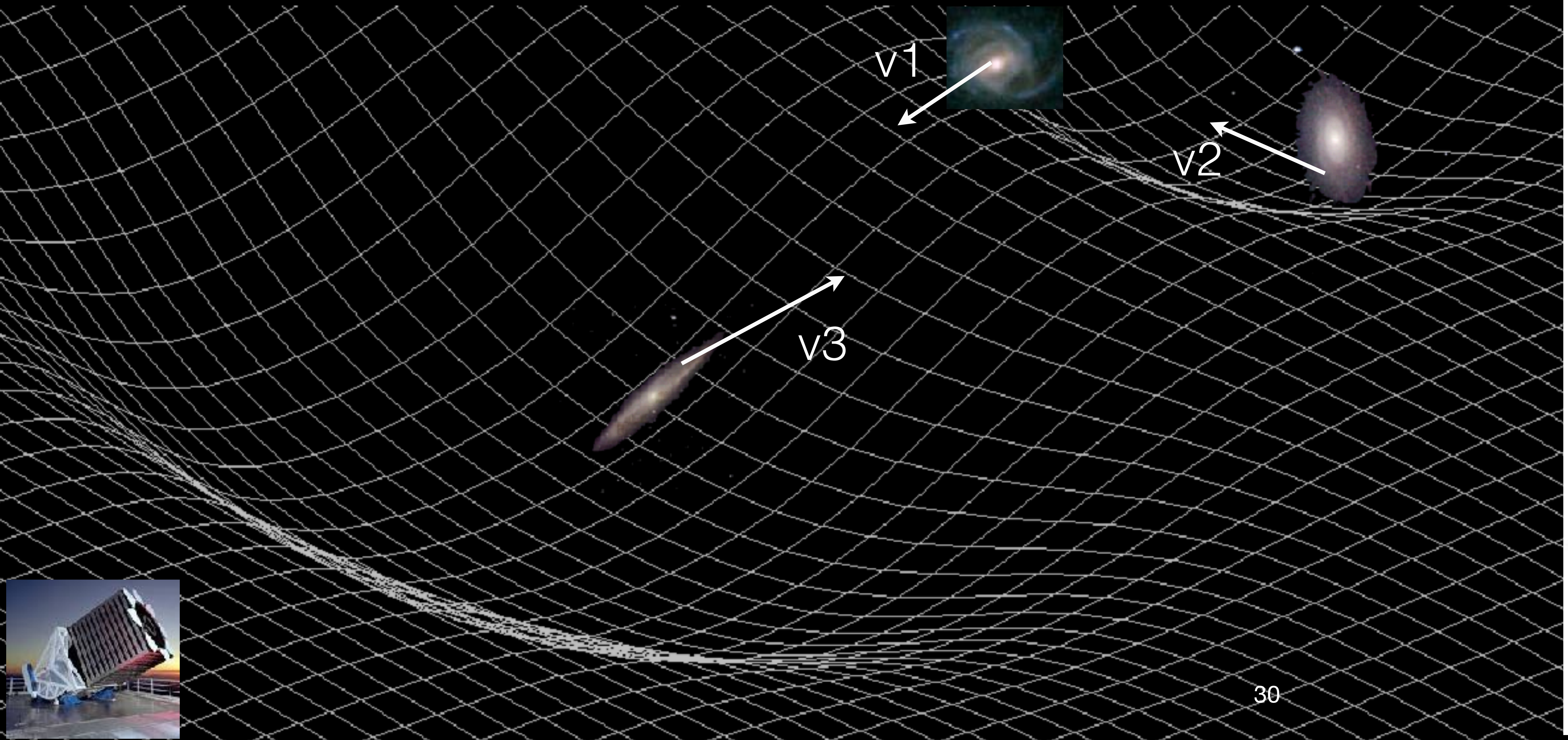
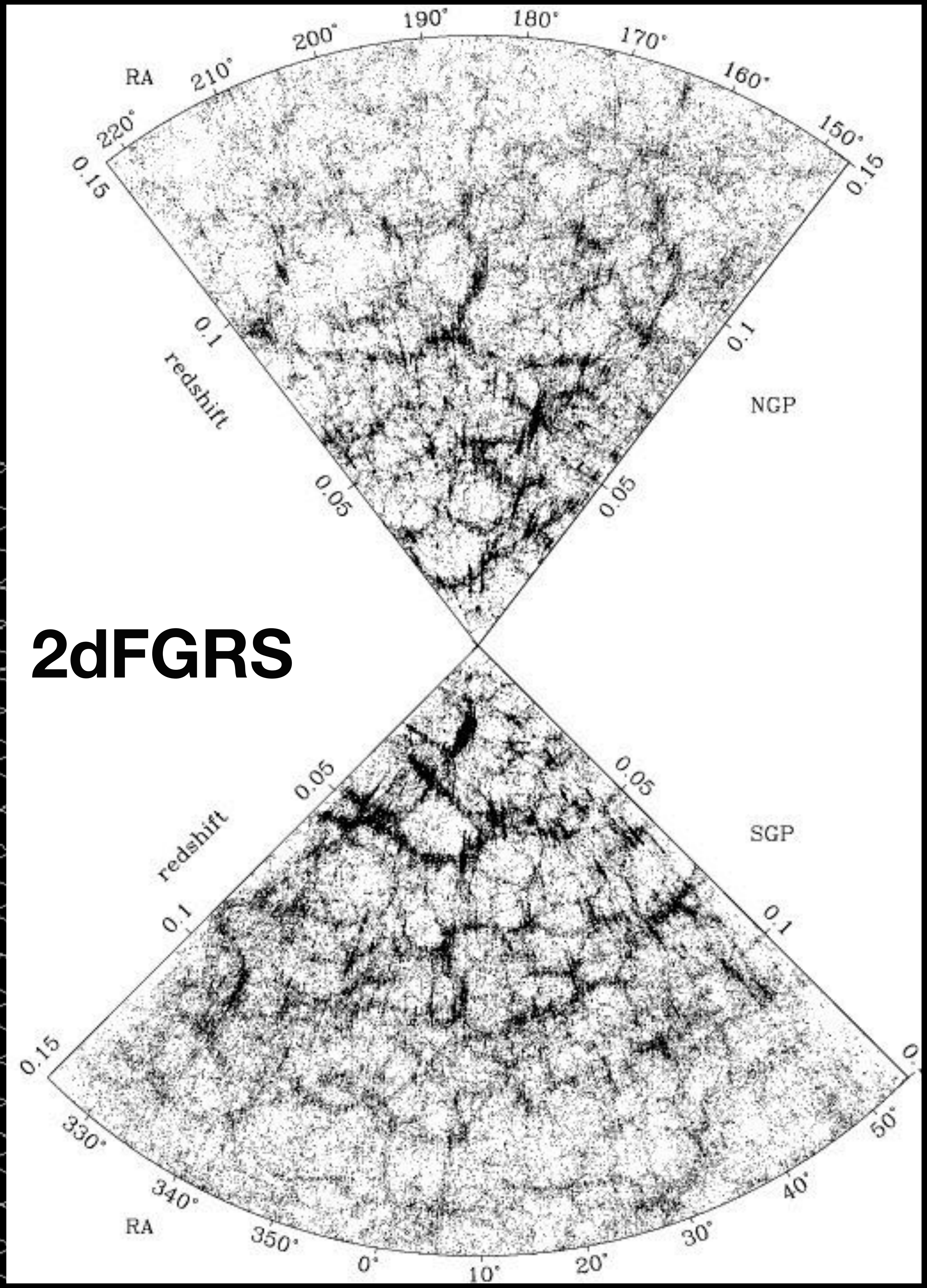
$$\lambda_{\rm obs} = \frac{a_{\rm now}}{a_{\rm emit}} \lambda_{\rm emit}$$

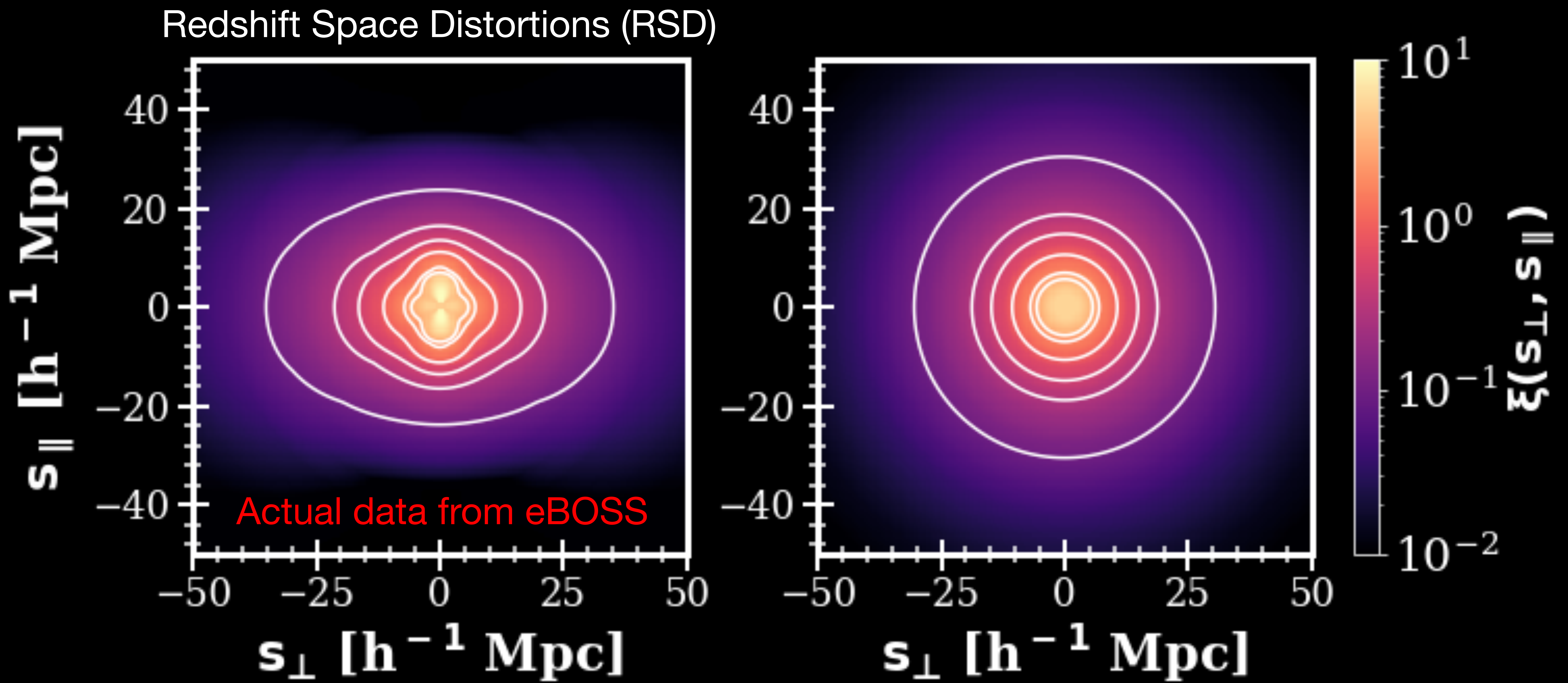
$$z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} - 1 = \frac{a_{\rm now}}{a_{\rm emit}} - 1$$

$$\text{Distance} = \frac{c}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$





Redshift Space Distortions (RSD)



Based on data from eBOSS
Alam +eBOSS, PRD 103, 083533 (**2021**)
Bautista, .., **Alam** +eBOSS, MNRAS 500(1), 736-762 (**2021**)

Redshift Space Distortion linearised

A co-ordinate transformation

$$s = r + \frac{\vec{v}\cdot\hat{r}}{aH}$$

Conservation of galaxy number density

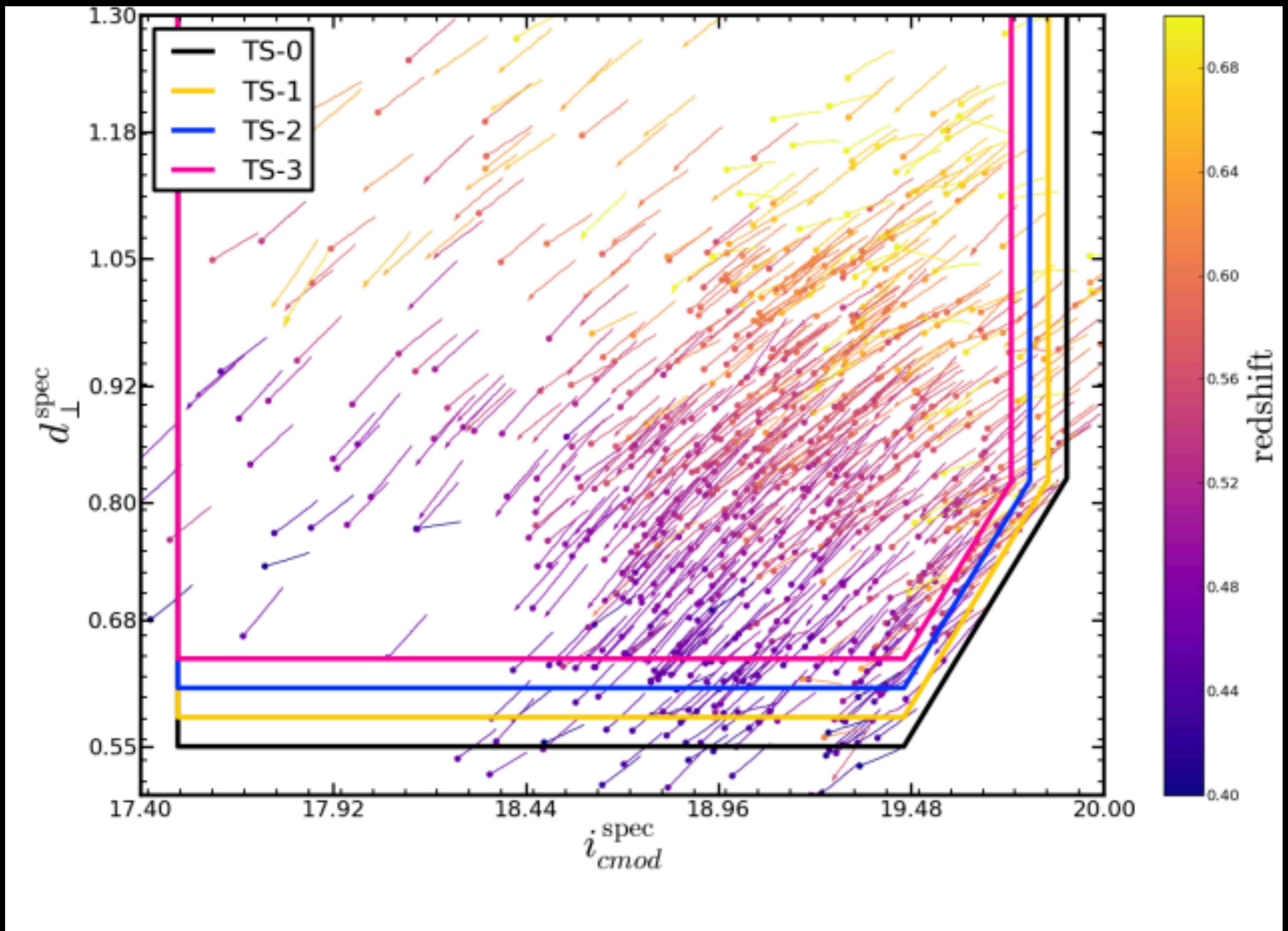
$$\rho_s d^3 s = \rho_r d^3 r$$

Relativistic beaming changes the galaxy we see in real space vs redshift space.

In real survey not strictly true.

But effect is tiny, of order 0.1% or smaller

Alam et. a.l MNRAS (2017) 471(2): 2077-2087



Redshift Space Distortion linearised

A co-ordinate transformation

$$s = r + \frac{\vec{v}\cdot\hat{r}}{aH}$$

Conservation of galaxy number

$$\rho_s d^3 s = \rho_r d^3 r$$

Over-density field

$$\delta_s = \left[b + f\mathcal{D}(r)\right]\delta_m(r)$$

RSD operator $\mathcal{D}(r) = \partial_r^2\nabla^{-2} + \left[2 + \frac{\partial \log \bar{n}(r)}{\partial \log r}\right]\frac{\partial_r}{r}\nabla^{-2}$

Consider Fourier modes

$$\delta_s(k) = (b + f(\hat{k}\cdot\hat{r})^2)\delta_m(k)$$

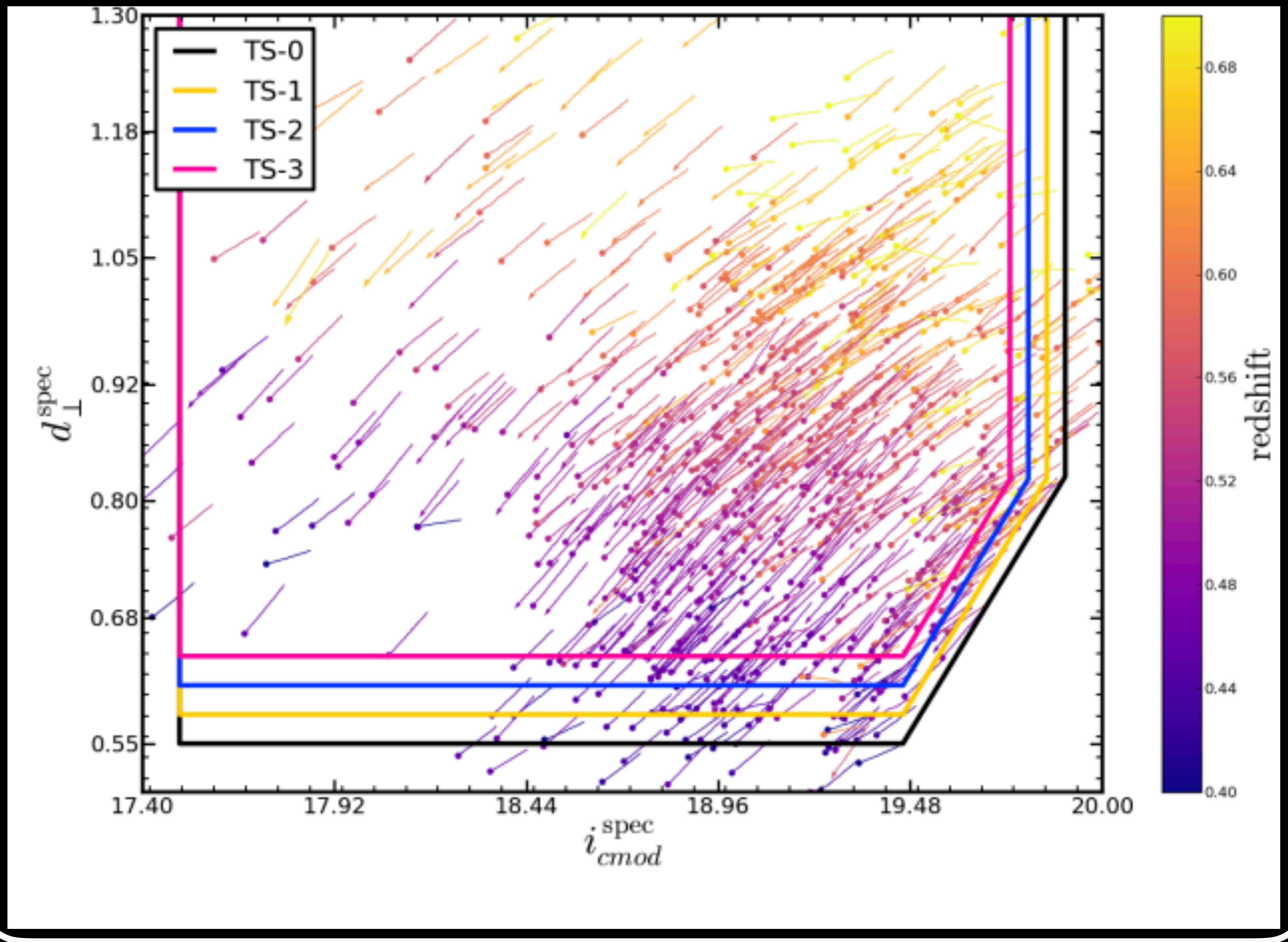
$$P_s^g(k,\mu) = P_m(k)(b + f\mu^2)^2$$

Relativistic beaming changes the galaxy we see in real space vs redshift space.

In real survey not strictly true.

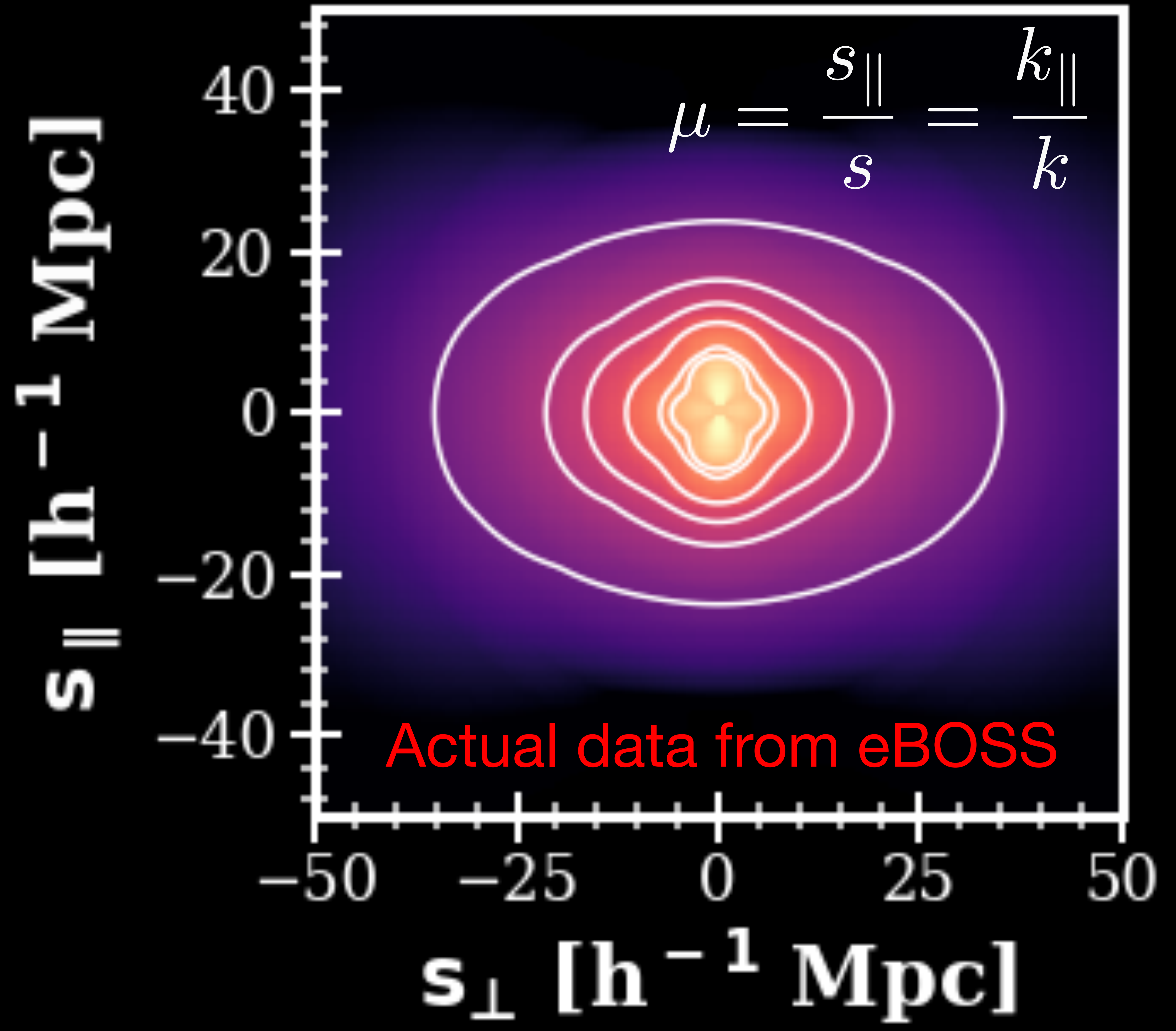
But effect is tiny, of order 0.1% or smaller

Alam et. a.l MNRAS (2017) 471(2): 2077-2087



Redshift Space Distortions (RSD)

Redshift Space Distortions (RSD)



σ_8

$$P_s^g(k,\mu) \overset{*}{=} P_m(k)(b + f\mu^2)^2$$

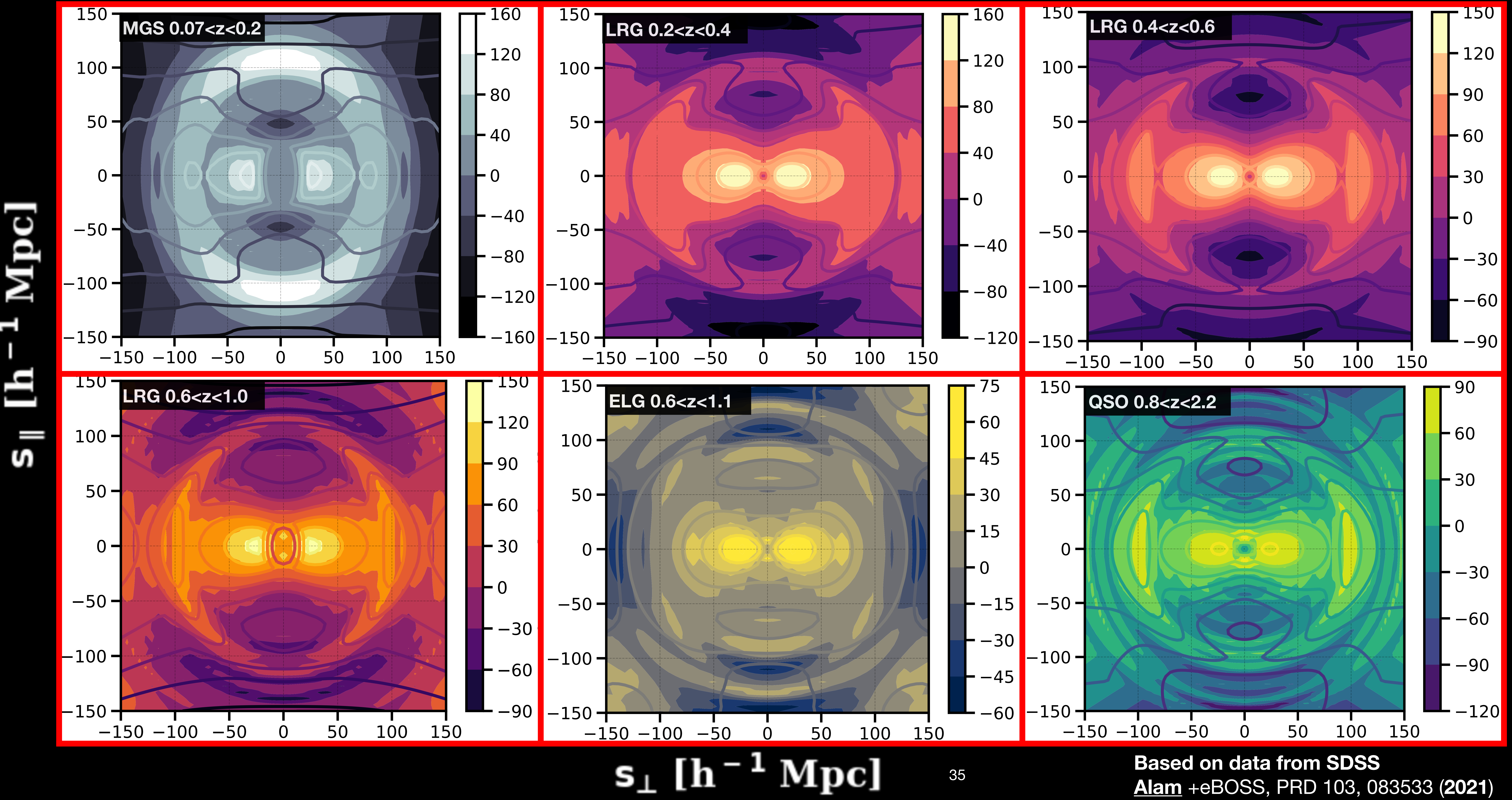
$$f_{\mathrm{gravity}}(a,k) = \frac{\partial \ln(\delta(a,k))}{\partial \ln(a)}$$ Test of gravity

$$f_{\mathrm{GR}}(a) \approx \Omega_m(a)^{0.55} \qquad \Lambda CDM$$

*Full equations are much more involved and cannot be written in such simple closed form

Wang L., Steinhardt P. J., 1998, AJ, 508, 483

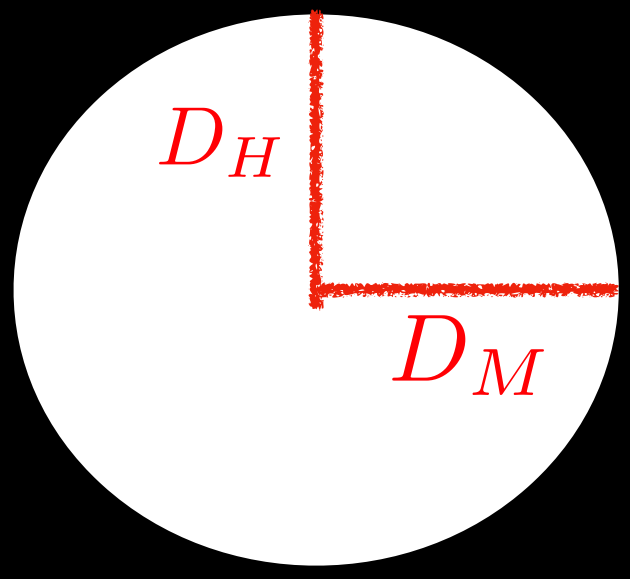
Current Status of 3d clustering measurements



Based on data from SDSS
Alam +eBOSS, PRD 103, 083533 (**2021**)

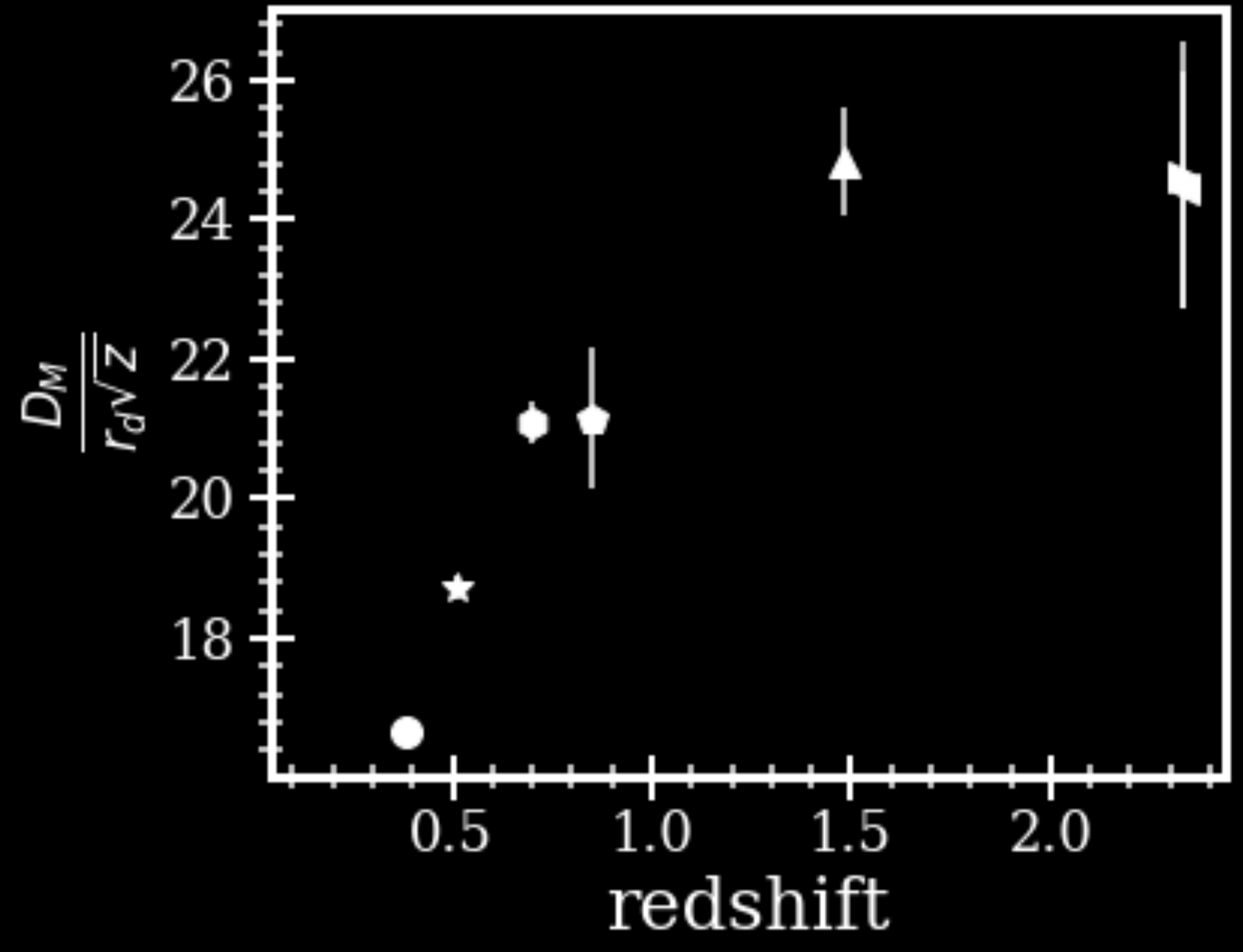
BAO constrains Geometry and RSD Growth of the Universe

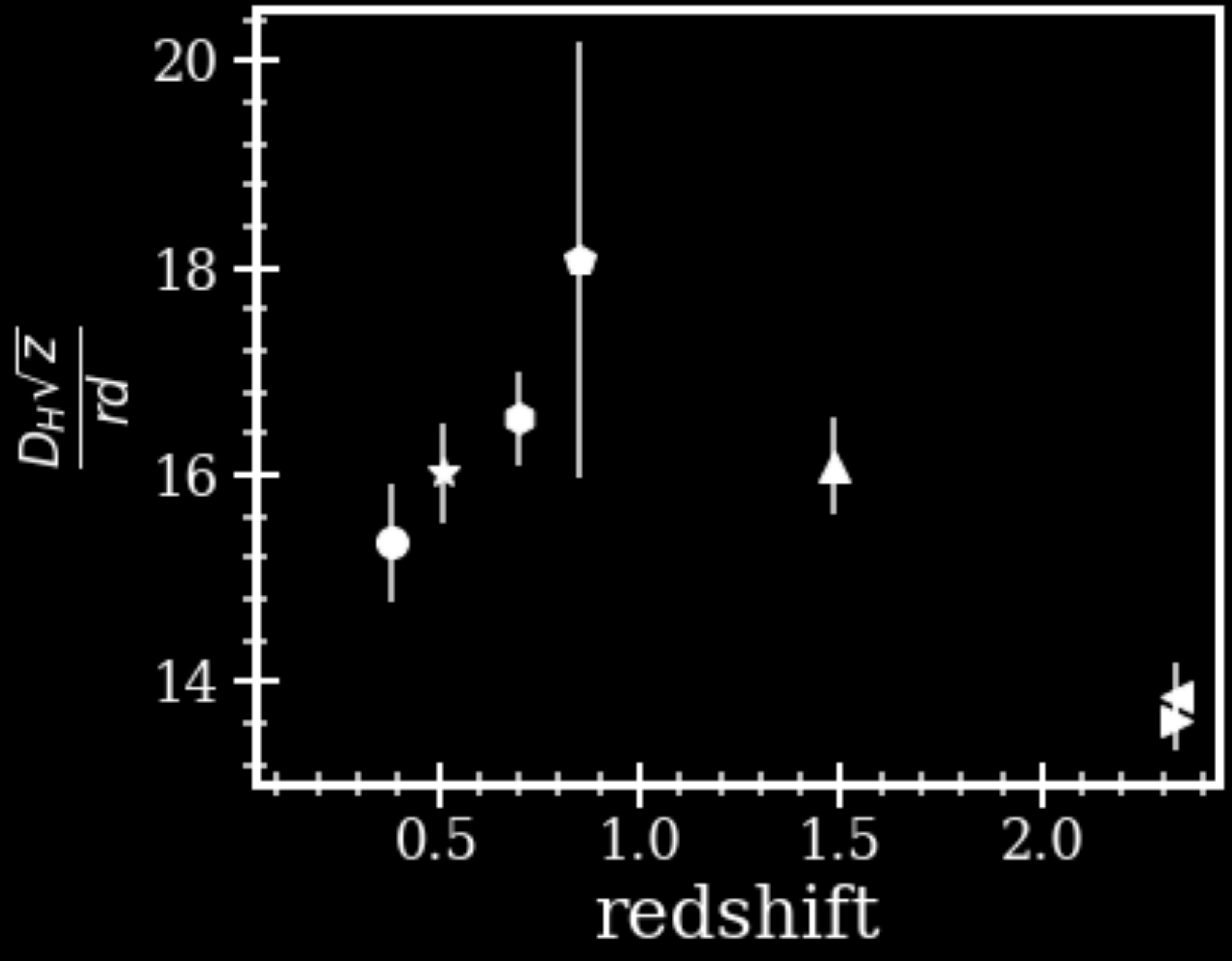
$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

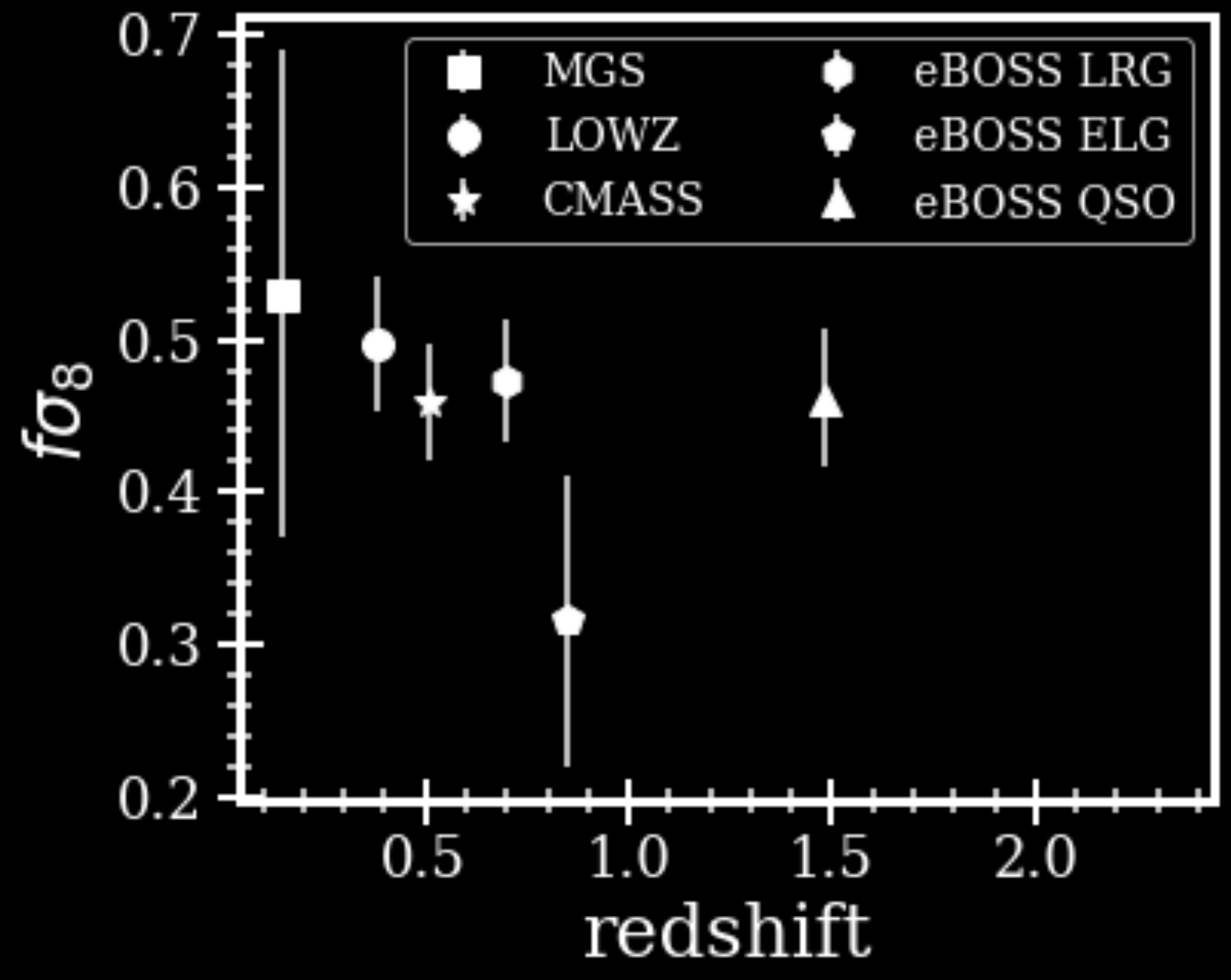


$$D_M = \frac{c}{H_0} S_k\left(\frac{D_C(z)}{c/H_0}\right)$$

$$D_H = \frac{c}{H(z)}$$







$S_k(x) = \sin(\sqrt{-\Omega_k}x)/\sqrt{-\Omega_k},\ \Omega_k < 0$

$S_k(x) = x,\ \Omega_k = 0$
$S_k(x) = \sin(\sqrt{\Omega_k}x)/\sqrt{\Omega_k},\ \Omega_k > 0$

Alam +eBOSS, PRD 103, 083533 (**2021**)

What Have we learned?

Alam +eBOSS, PRD 103, 083533 (**2021**)

Matter density, expansion rate, amplitude of fluctuation

$$\Omega_m = 0.304 \pm 0.002$$

Matter density

$$H_0 = 68.19 \pm 0.36\,\mathrm{km/s/Mpc}$$

Expansion rate of the Universe

$$\sigma_8 = 0.807 \pm 0.006$$

Current amplitude of matter power spectrum

*$\Lambda\mathrm{CDM}$

*Includes observations of CMB, SN1 and WL

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*$\Lambda\mathrm{CDM}$

Curvature of the Universe

$$\Omega_k = 0.0001 \pm 0.0017$$

*$o\Lambda\mathrm{CDM}$

*Includes observations of CMB, SN1 and WL

What Have we learned?

Alam +eBOSS, PRD 103, 083533 (2021)

Matter density, expansion rate, amplitude of fluctuation

$$\Omega_m = 0.304 \pm 0.002$$ Matter density

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*ΛCDM

Curvature of the Universe

$$\Omega_k = 0.0001 \pm 0.0017$$

*$o\Lambda$CDM

Dark Energy equation of state

- Is dark energy cosmological constant?

$$\rho \propto a^{-3(w+1)}$$

$$w = -1.02 \pm 0.03$$

*wCDM

*Includes observations of CMB, SN1 and WL

Testing Gravity

Redshift Space Distortions as a probe of gravity

$$f_{\rm gravity}(a,k) = \frac{\partial \ln(\delta(a,k))}{\partial \ln(a)}$$

Alam et. al. MNRAS 456, 3743-3756 (2016)

But the theory space is pretty large

Scalar perturbation

$$ds^2 = -a^2(\tau)\left[(1+2\Psi(\tau,\vec{x}))d\tau^2 - (1-2\Phi(\tau,\vec{x}))d\vec{x}^2\right]$$

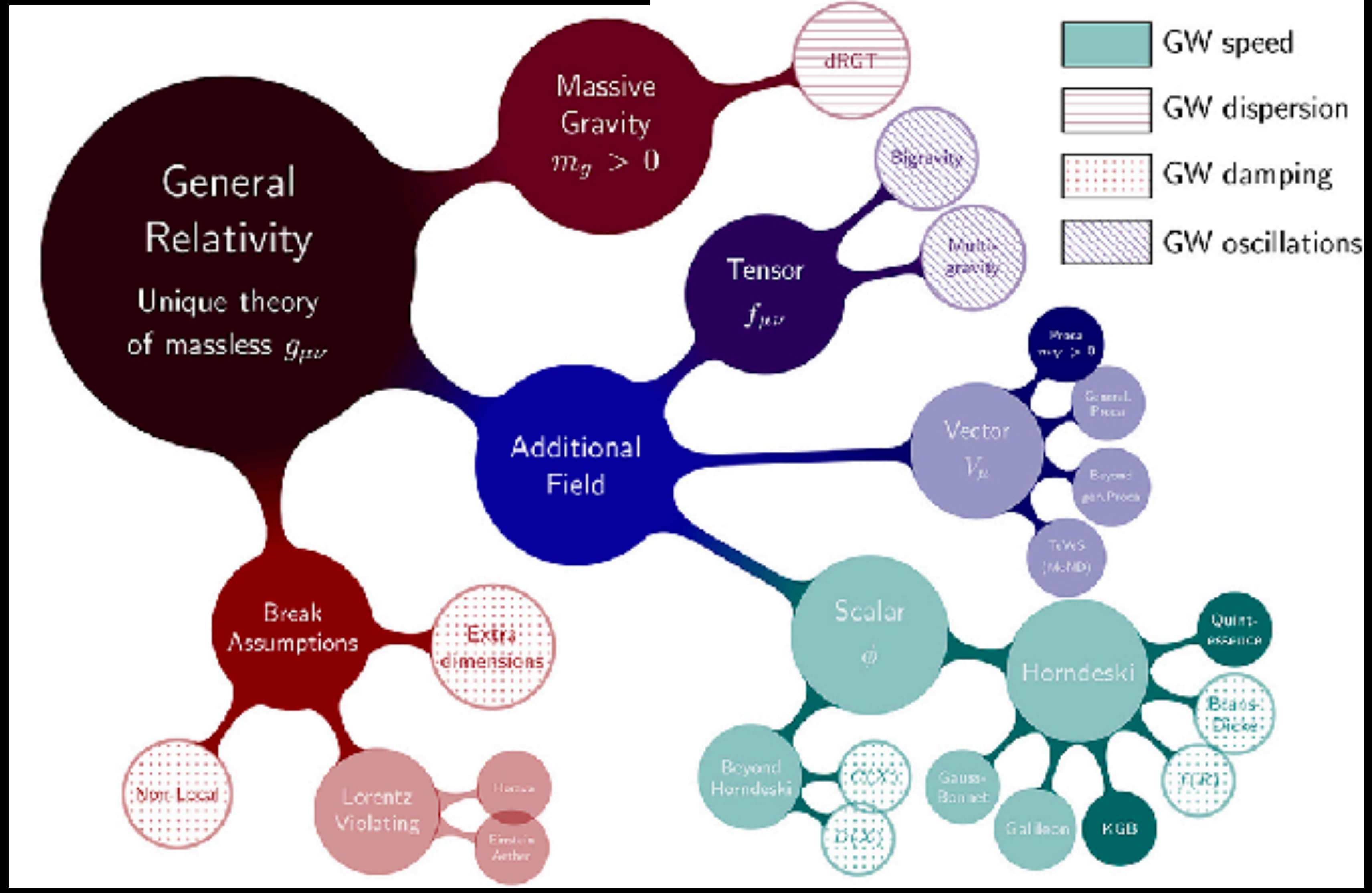
Einstein equations

$$k^2\Psi = -4\pi G a^2 \rho\delta$$ Poisson equation (Growth of structure)

$$k^2(\Psi + \Phi) = -8\pi G a^2 \rho\delta$$ Anisotropy (Propagation of light)

- General scalar degree of freedom in Modified gravity generically modifies these equations

Ezquiaga & Zumalacarregui, FASS 5 (2018) 44



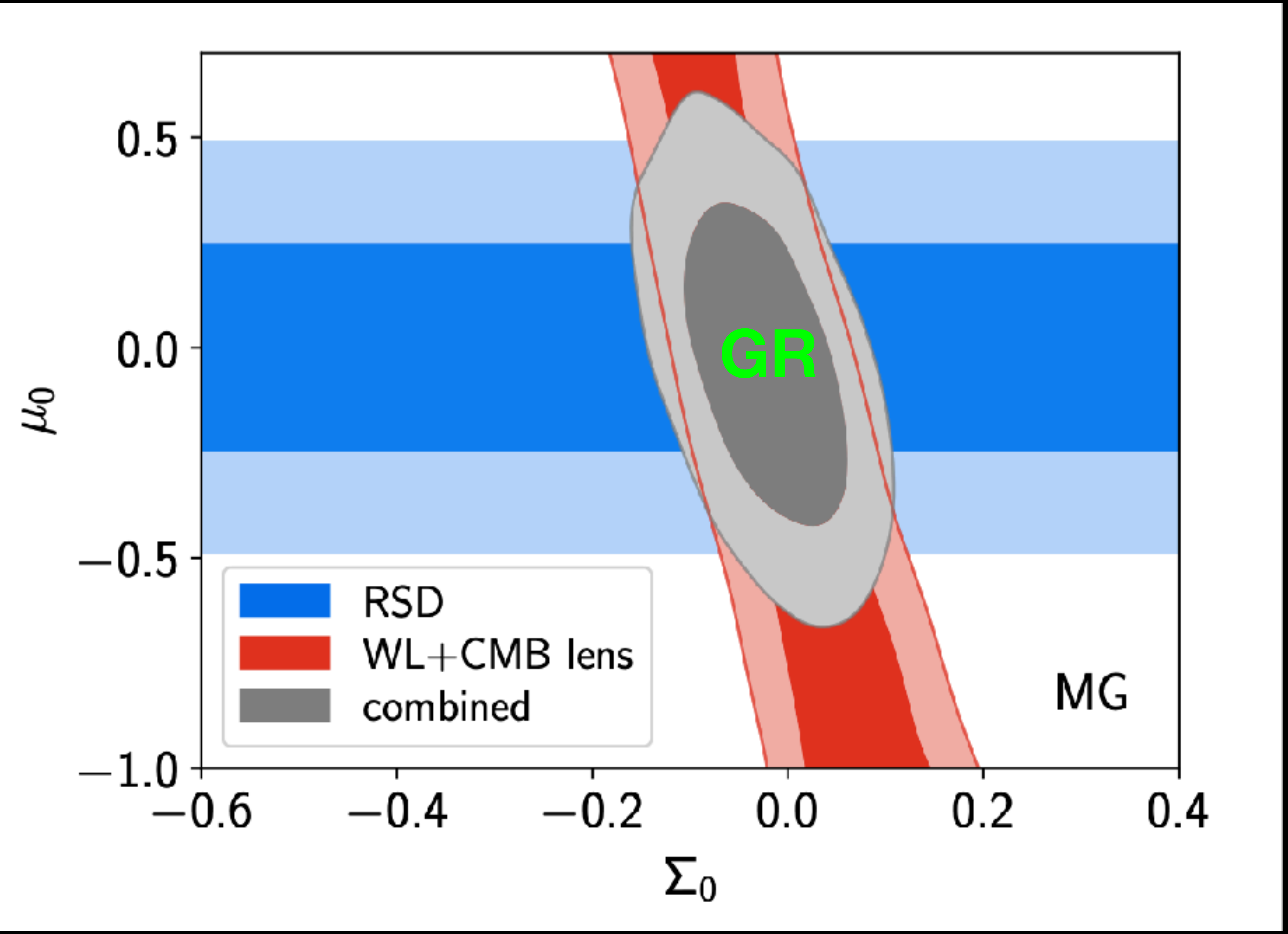
Phenomenological approach

Alam +eBOSS, PRD 103, 083533 (**2021**)

Modified Einstein equations

$$k^2\Psi = -4\pi G a^2 \rho\delta(1+\mu(a,k))$$

$$k^2(\Psi+\Phi) = -8\pi G a^2 \rho\delta(1+\Sigma(a,k))$$



Simplification due to Limited precision of data

$$\mu(a,k) = \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda(z=0)}$$

$$\Sigma(a,k) = \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda(z=0)}$$

In the future we will be able to constrain the full functional forms of the modifications

Neutrinos in Cosmology

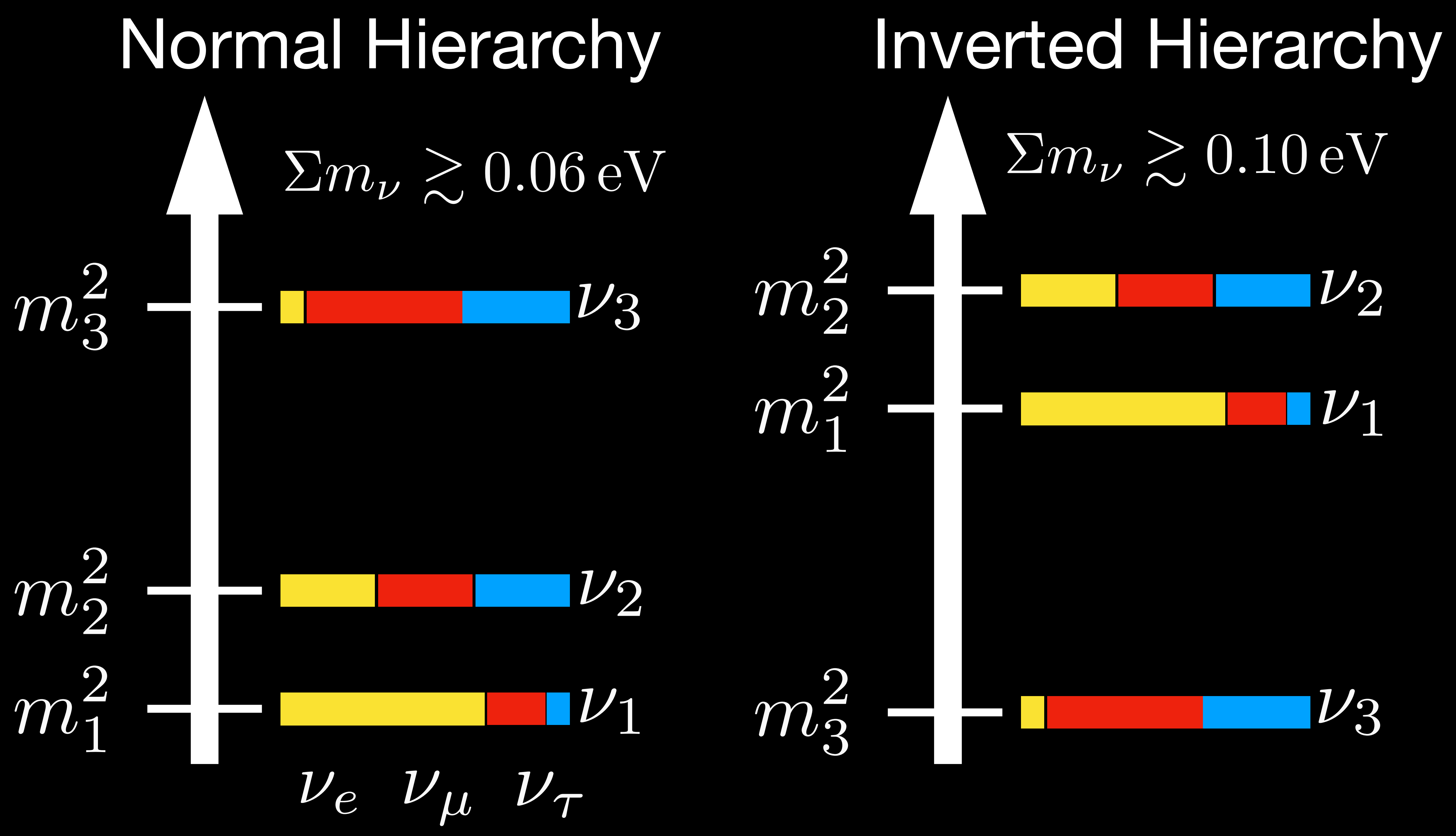
LSS can provide precise measurements of the sum of neutrino masses

Neutrino Oscillation experiments

Gonzalez-Garcia JHEP 1411:052, 2014

$$\Delta m^2_{21} = (0.0086 \pm 0.0011\mathrm{eV})^2$$ Solar

$$\Delta m^2_{3\ell} = (0.05 \pm 0.0005\mathrm{eV})^2$$ Atmospheric



Neutrinos and Cosmology : Geometry

$$\Omega_\nu = \frac{\Sigma m_\nu}{93.14 h^2 \mathrm{eV}} \qquad f_\nu = \frac{\Omega_\nu}{\Omega_m}$$

- Neutrino becomes relativistic to non-relativistic as their temperature and hence thermal velocity drops.

- Free-streaming scale when non-relativistic

$$k_{nr} \approx 0.018 \Omega_m^{1/2} \sqrt{\frac{m_\nu}{1\mathrm{eV}}}\, h\mathrm{Mpc}^{-1}$$

- Radiation matter equality with neutrino

$$\rho_b(a_{\mathrm{eq}}) + \rho_c(a_{\mathrm{eq}}) = \rho_\gamma(a_{eq}) + \rho_\nu(a_{\mathrm{eq}})$$

- Changing sound horizon

$$r_d = \int_{z_{\mathrm{eq}}}^{\infty} \frac{c_s}{H(z)} dz$$

$$\left(\frac{H}{H_0}\right)^2 = \Omega_m a^{-3} + (\Omega_\gamma + \Omega_\nu) a^{-4} + \Omega_\Lambda$$

- This will affect BAO measurements

$$D_M / r_d \qquad D_H / r_d$$

*Neutrinos also affect He abundance (BBN) in the universe. But I will not discuss it in this talk for brevity.

Neutrinos and Cosmology : Growth

$$\Omega_\nu = \frac{\Sigma m_\nu}{93.14 h^2 \mathrm{eV}} \qquad f_\nu = \frac{\Omega_\nu}{\Omega_m}$$

- CDM growth with neutrino

$$\ddot{\delta}_m + 2\frac{\dot{a}}{a}\dot{\delta}_m = 4\pi G \rho_0 (1 - f_\nu)\delta_m$$

$$\delta_m \propto a^{1-\frac{3}{5}f_\nu}$$

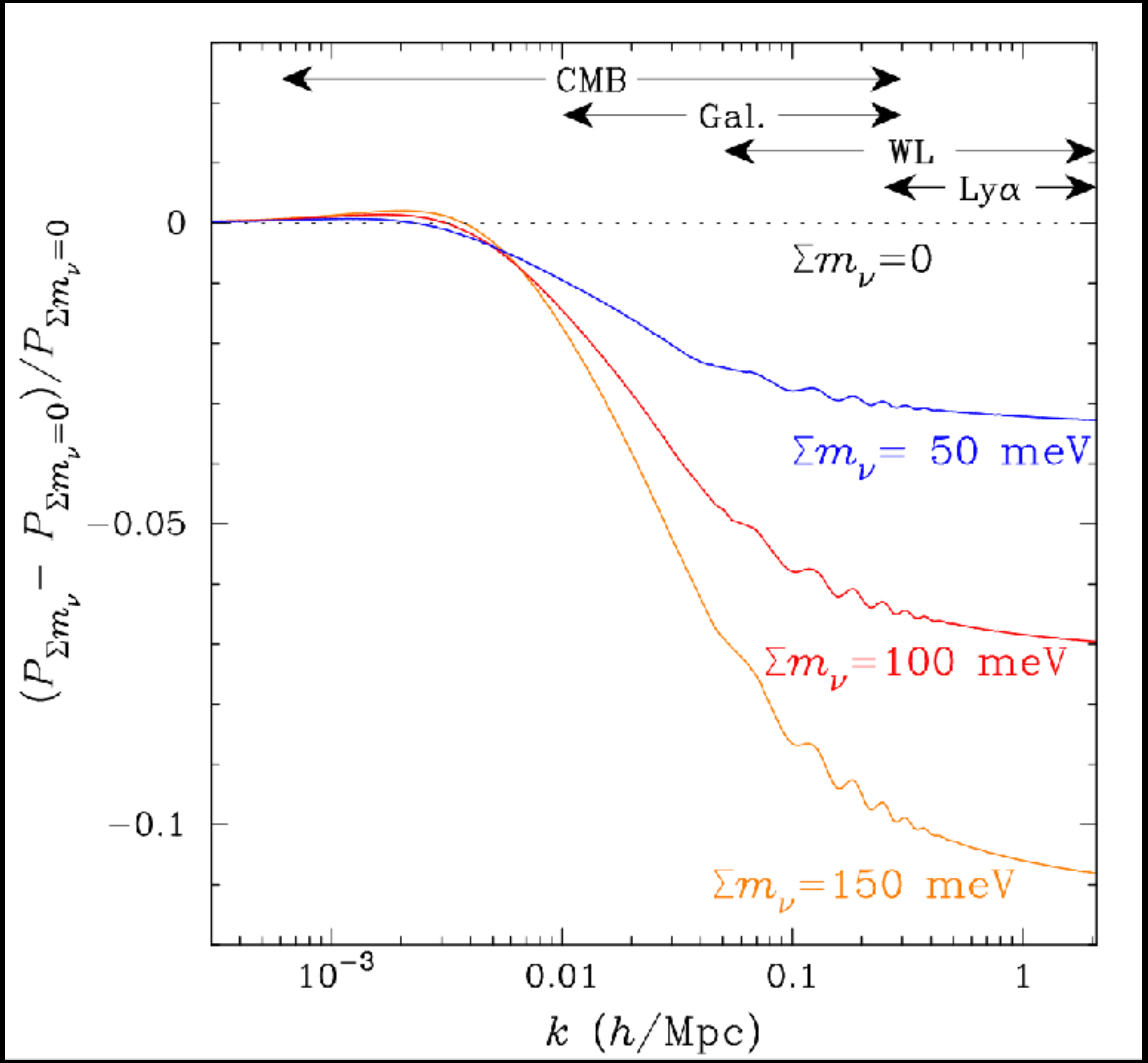
- Effect in matter power spectrum

$$P(k) = \langle \delta_c^* \delta_c \rangle \ , \ k < k_{nr}$$

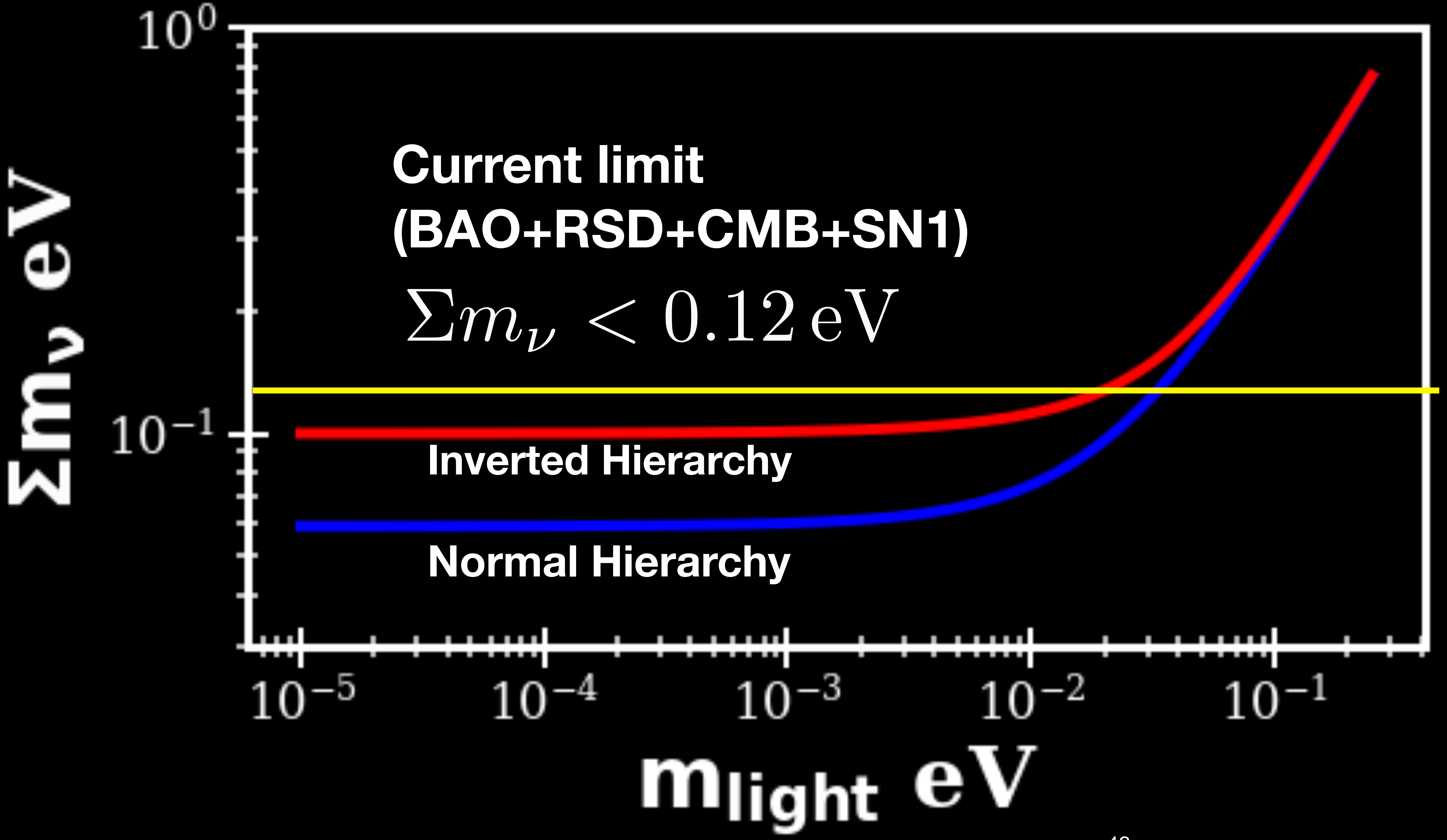
$$P(k) = (1 - f_\nu)^2 \langle \delta_c^* \delta_c \rangle \ , \ k \gg k_{nr}$$

- Redshift Space Distortions

$$f = ((1 - f_\nu)\Omega_m)^{0.55}$$



Current limit on Neutrino mass



Inverted vs Normal?

Cosmology is fortunate?

$\Sigma m_\nu^{\mathrm{true}} < 0.07\,\mathrm{eV}\,?$

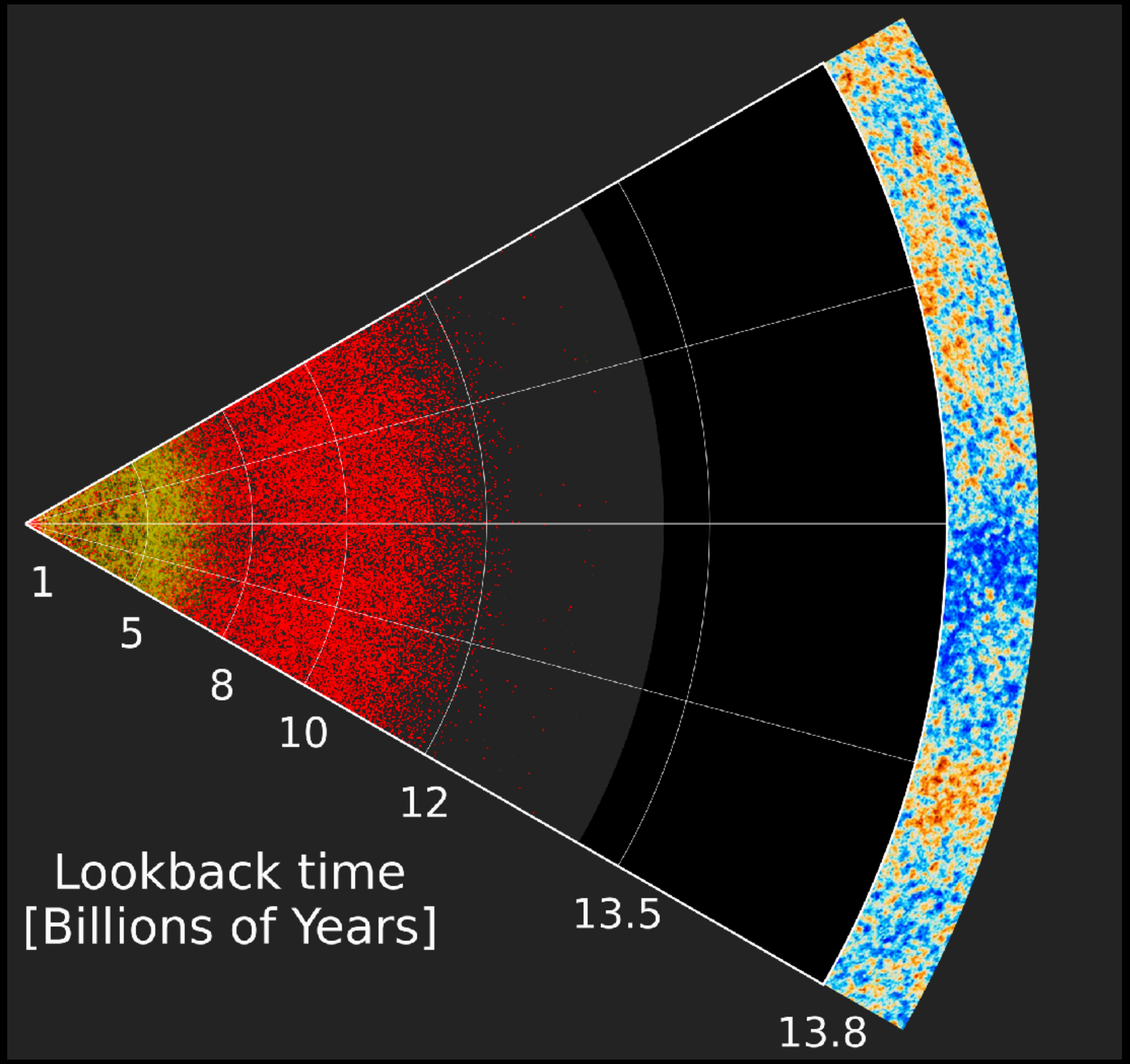
Model dependent?

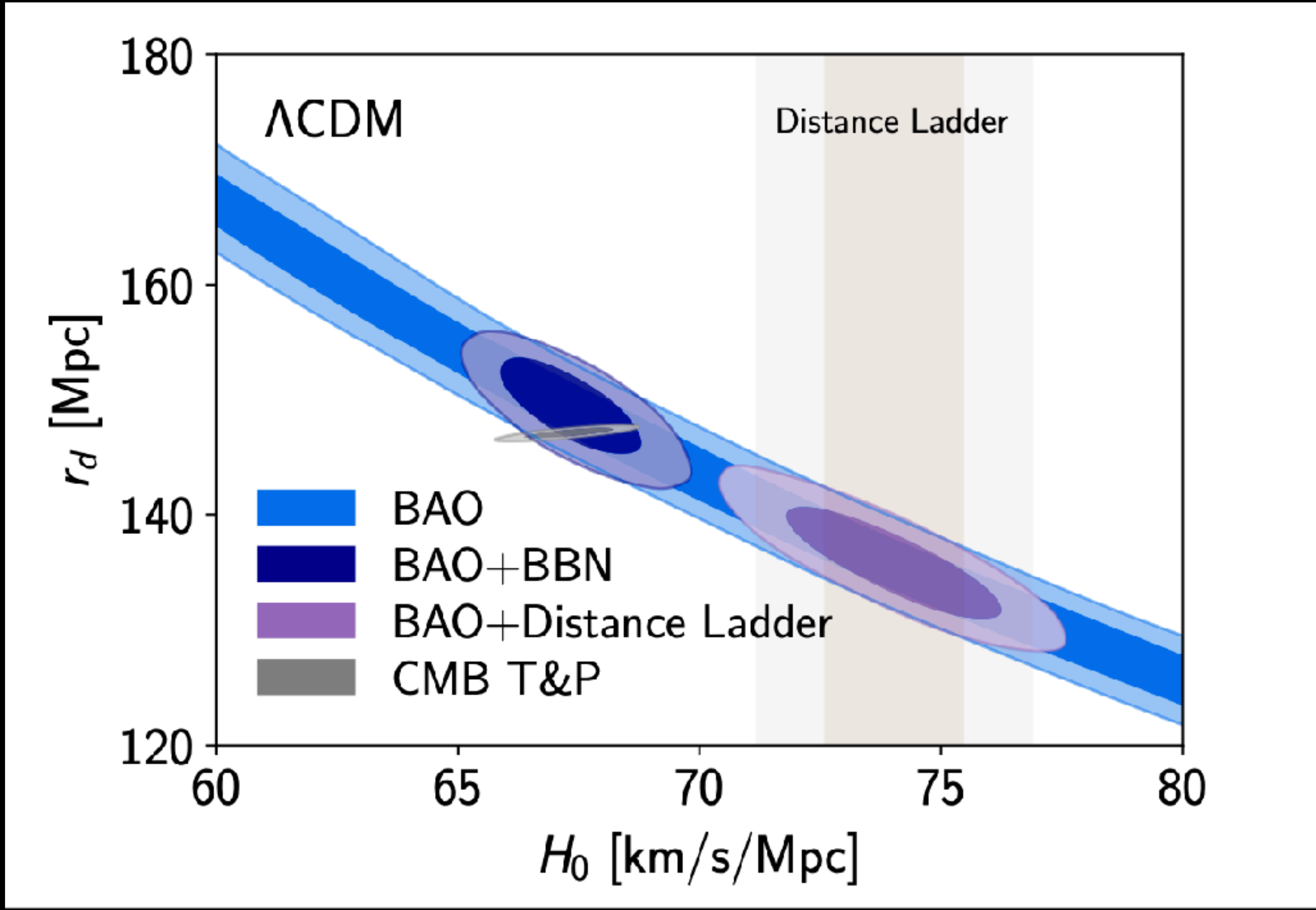
$\Sigma m_\nu < 0.16\,\mathrm{eV}$ for $\nu w\Lambda\mathrm{CDM}$

Alam +eBOSS, PRD 103, 083533 (**2021**)

Inconsistencies and Large Scale Structure

Hubble tension

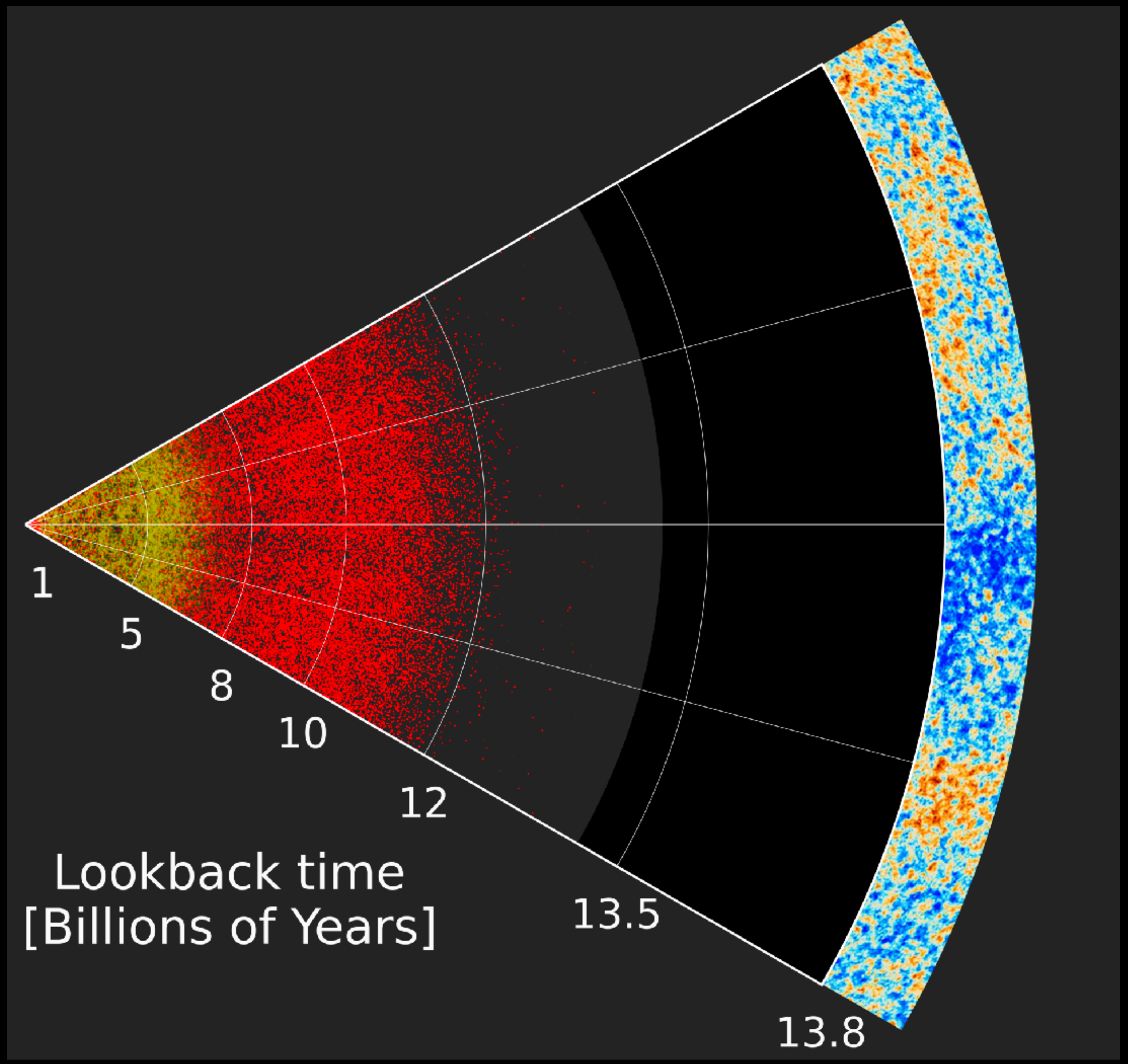


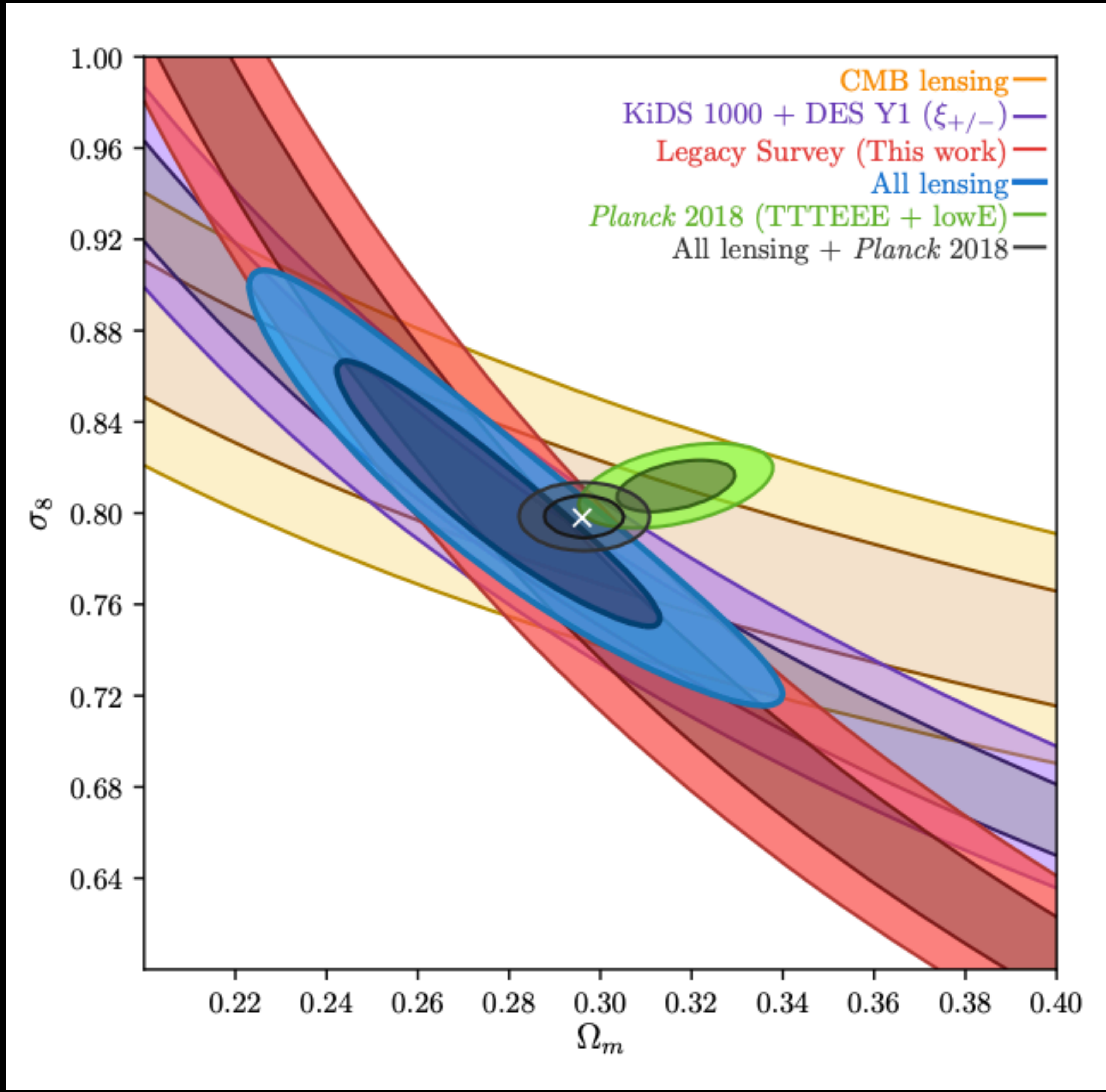


Alam +eBOSS, PRD 103, 083533 (**2021**)

Inconsistencies and Large Scale Structure

Sigma 8 tension





New Physics?
Systematics?

Hang, **Alam** et. al. MNRAS 501, 1481-1498 (2021)

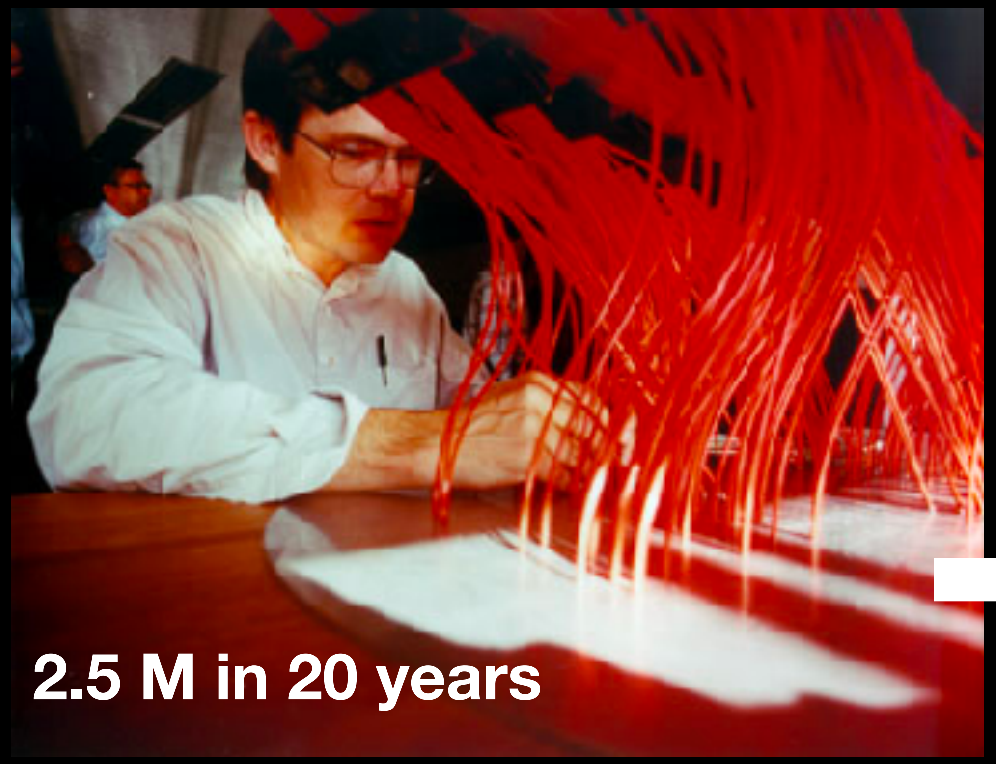
Future of LSS
(Major progress in Next 5 years)

Dark Energy Spectroscopy Instrument (DESI)

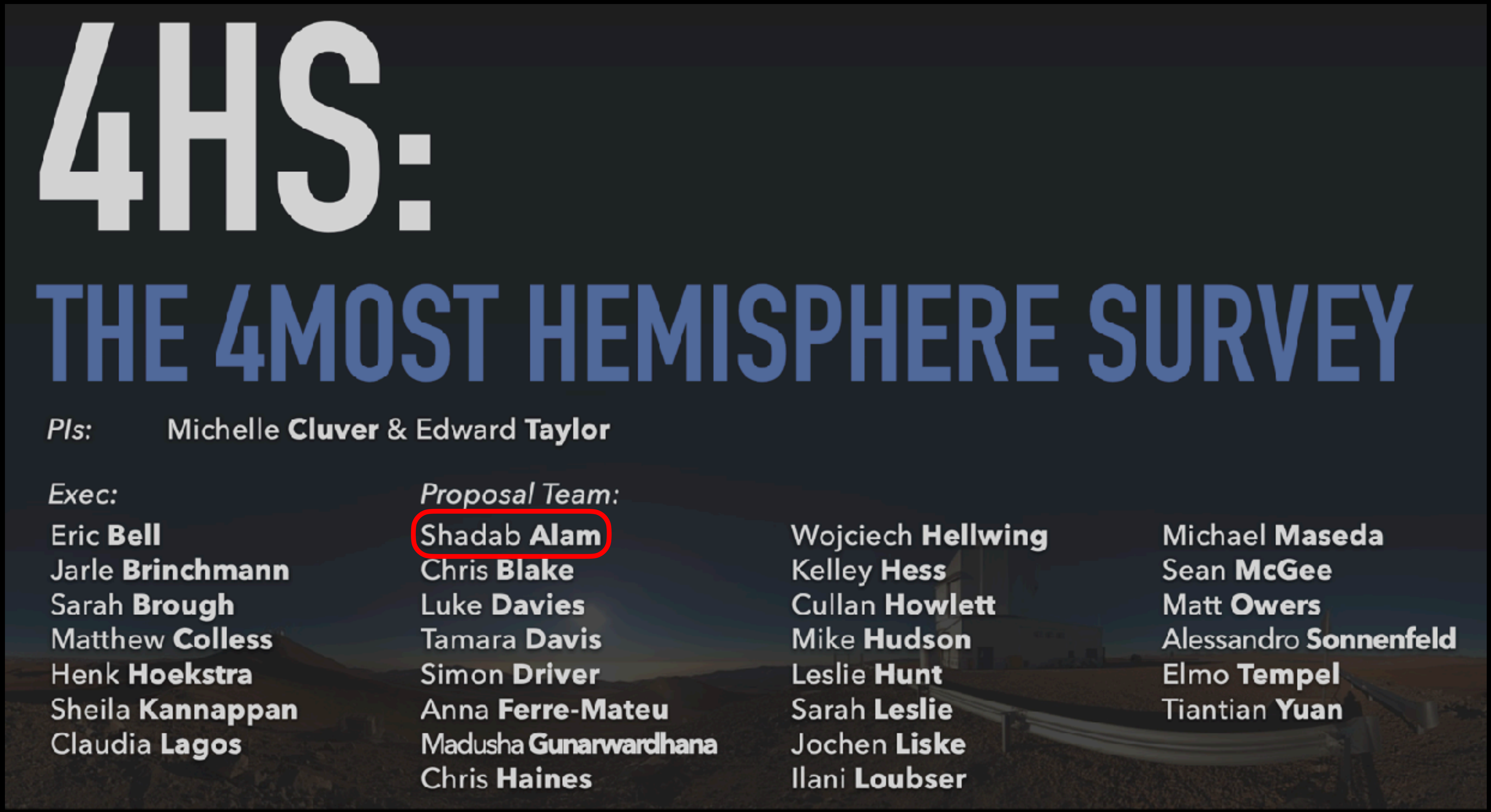
Ongoing from 2021-2026 (5 year program), overall cost~150 M $

- 2021-2026 (5 years, Ongoing since May 2021)
- Instrument performs excellently (Survey Validation Completed-April 2021)
- **40 million** Galaxy Spectra by the end of 5 years

SDSS focal plane: HUMAN



DESI focal plane: 5000 ROBOTS



A spectroscopic redshift survey targeting $z<0.15$ galaxies covering 20,000 sq deg of sky.

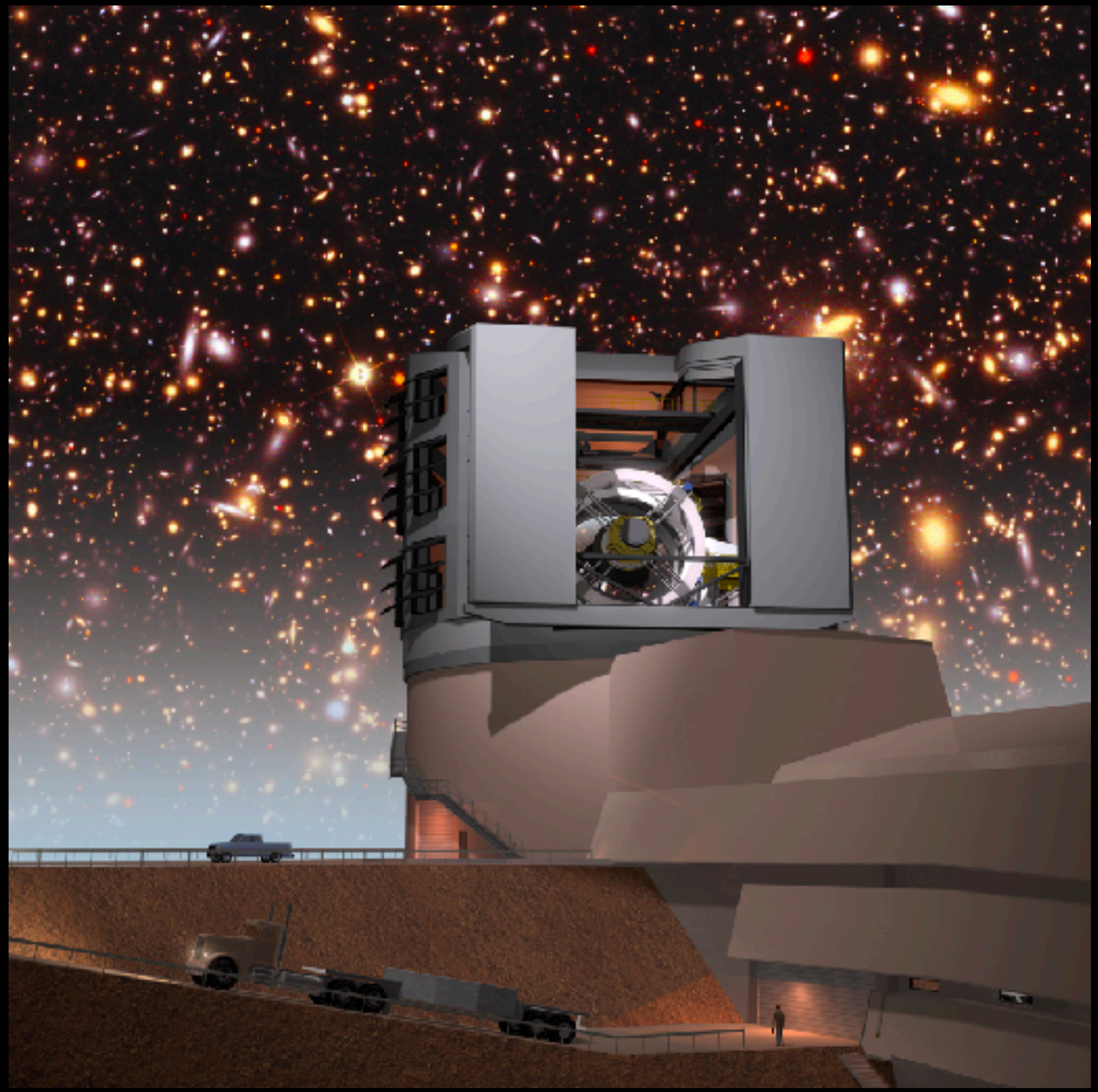
Part of 4MOST, starting by late 2024

- Establish the local benchmark for galaxy/AGN demographic in the era of LSST/EUCLID/SKA.
- Test gravity in the local Universe
- Provides an excellent resource for gravitational wave counter-part studies.
- Many more science case of interest. Potentially shed light on aspects of Hubble tension.

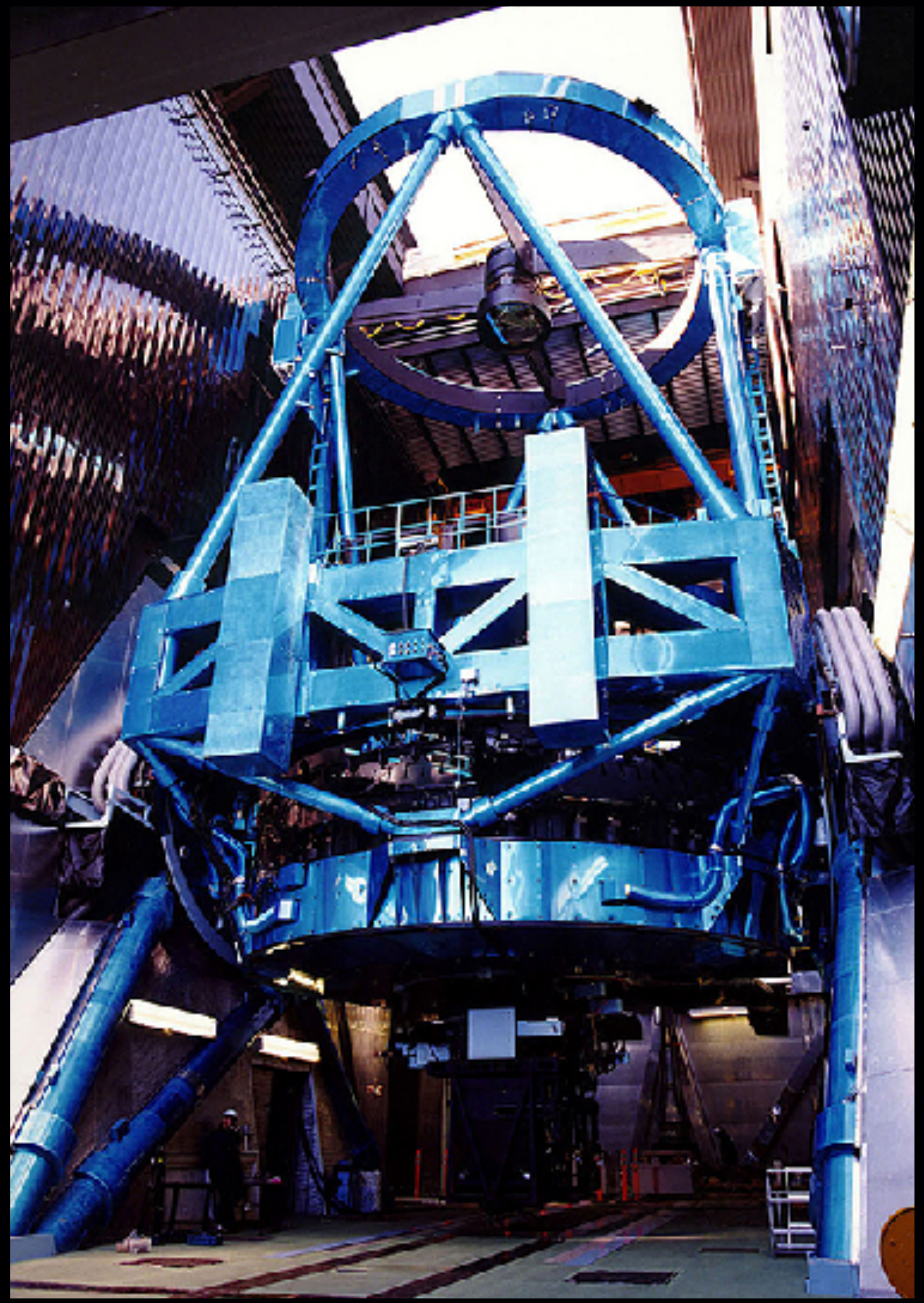
Many more LSS surveys in next 10 years

The **precision of measurements** is certain to improve dramatically. **Theoretical models** needs to improve equally to be able to use the statistical power of experiments.

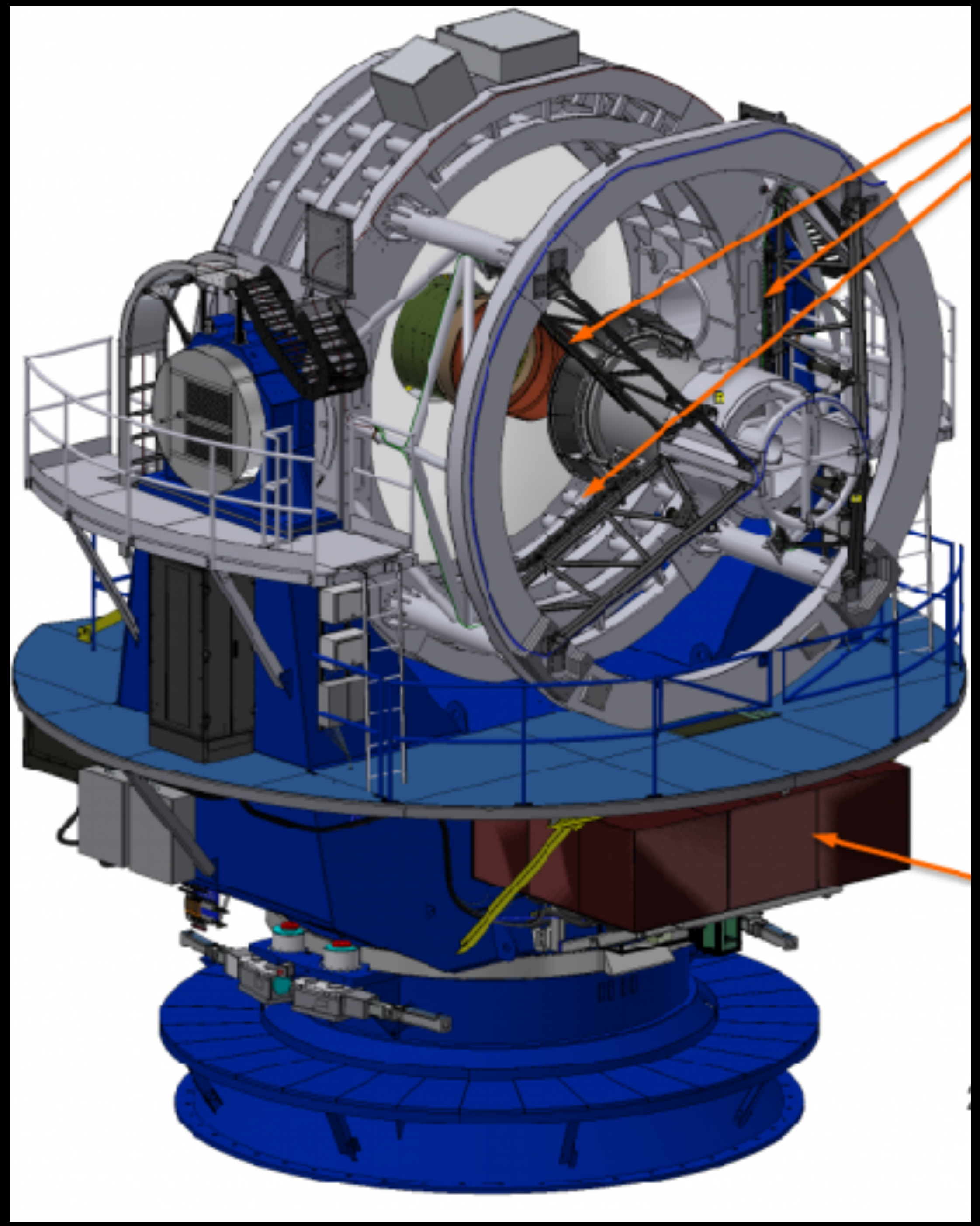
LSST: Photometric survey



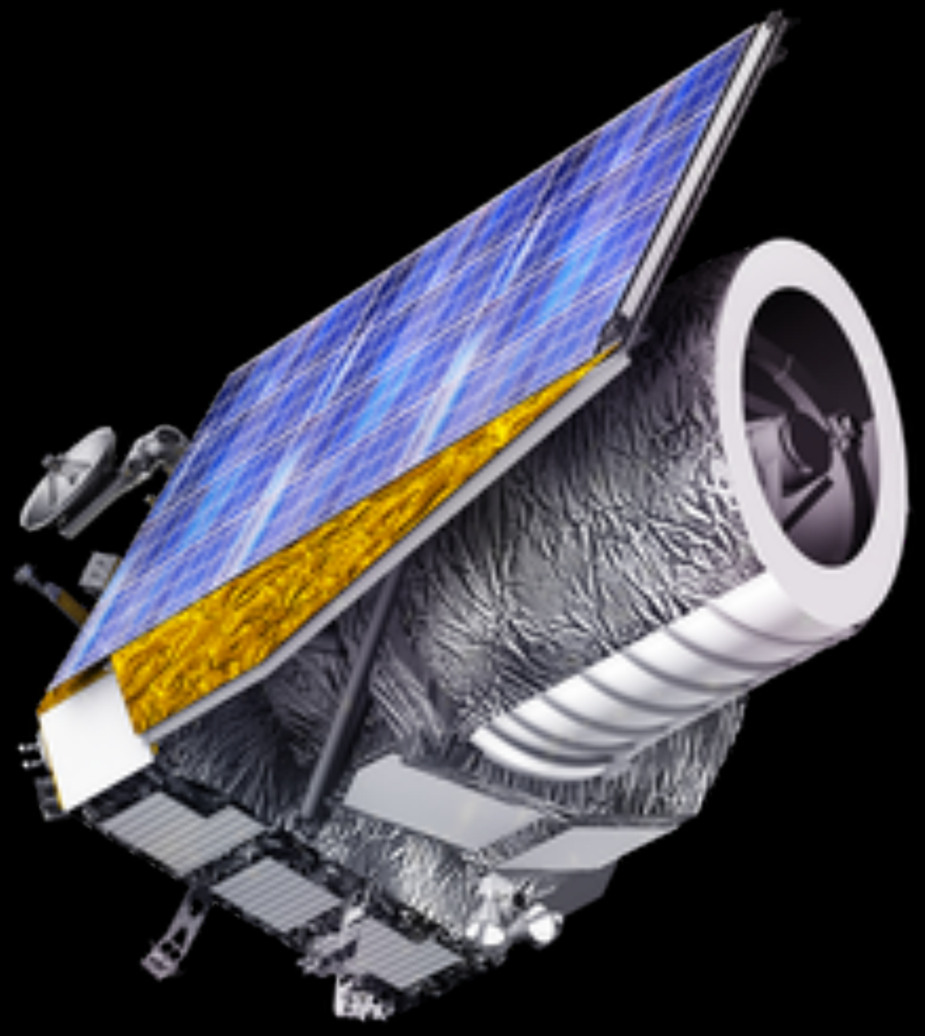
PFS: Subaru 8m



4MOST: VISTA 4m



EUCLID: 1.2m
Space mission



Some Possibilities in Next 5 years

- We might find that **Dark Energy** is not constant.

  Ongoing experiment: $\sigma_w = 1\,\%$ (Next 5 years, Alam+DESI; arXiv:1611.00036)

  New angle in the dark energy understanding.

- We will know sum of neutrino mass and possibly Hierarchy.

  Ongoing experiment: $\sigma_{\Sigma m_\nu} = 0.02\,\mathrm{eV}$ (Next 5 years, Alam+DESI; arXiv:1611.00036)

  Neutrino experiments will be able to achieve more with the help of LSS.

- We may find signature of Beyond GR effects.

  Ongoing experiment: $\sigma_G/G = 0.6\,\%$ (Next 5 years, Alam+DESI; arXiv:1611.00036)

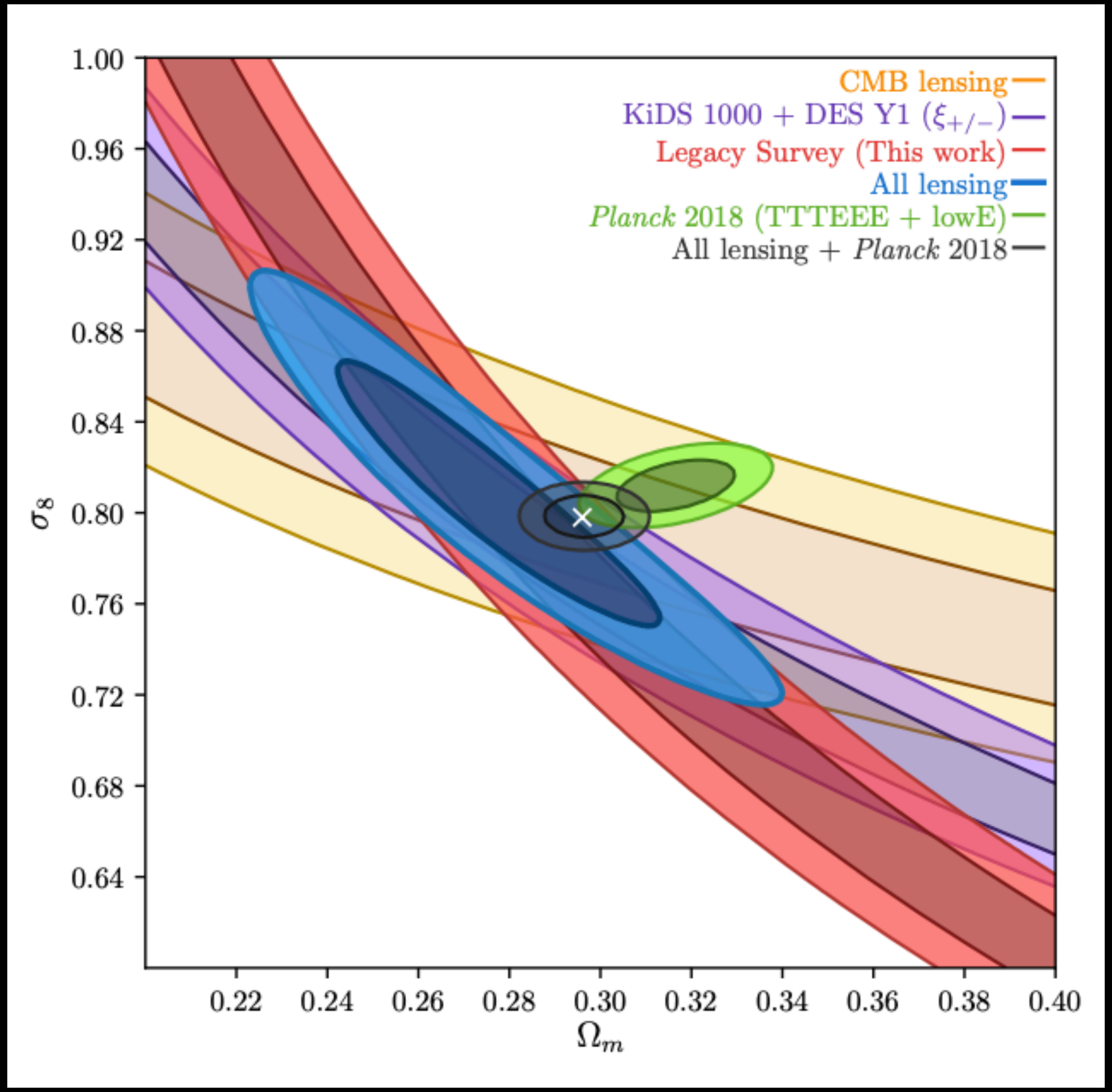
  May provide a puzzle for theorist to ponder upon for decades.

- All of the above only using redshift but we will have full optical spectra for 40 Millions galaxies and QSOs.

  Hidden physics beyond imagination?

End thoughts

- LSS plays an important role in shaping our understanding of the Universe
- Next 10 years optical galaxy surveys will dominate the field.
- In 20 year time scale, radio surveys such as Square Kilometre Array (SKA) will be the frontier.
- Robust Interpretation of these experiments will be a challenge for Cosmologist.
- We might be at a critical time where multiple signatures of new hidden physics will be revealed.



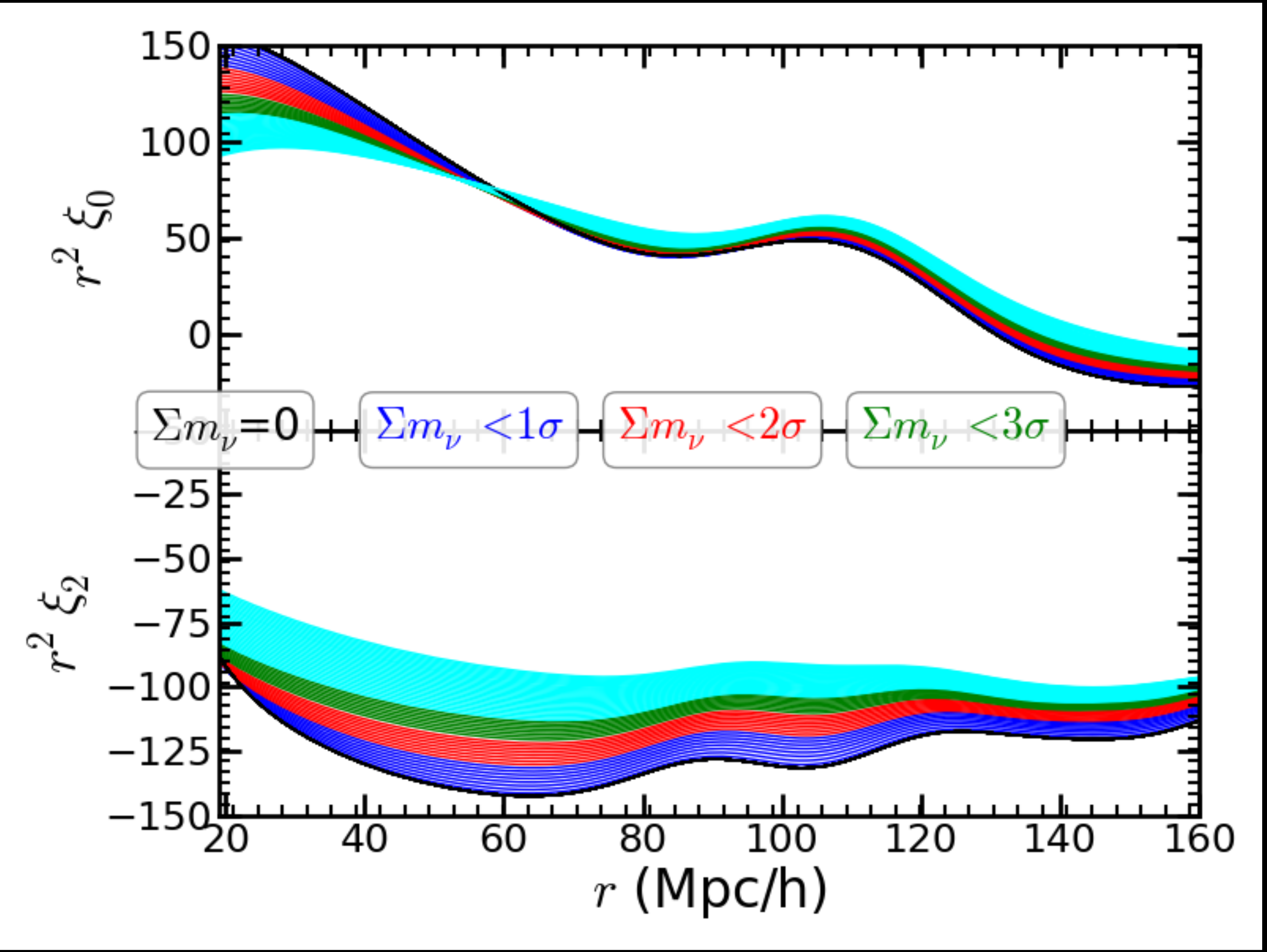
Thank You

Current limit on Neutrino mass

- Measurement of BAO scale as the function of redshift give geometrical probe of Neutrino mass along with CMB
- Measurement of RSD constrain neutrino mass by its impact on growth of structure

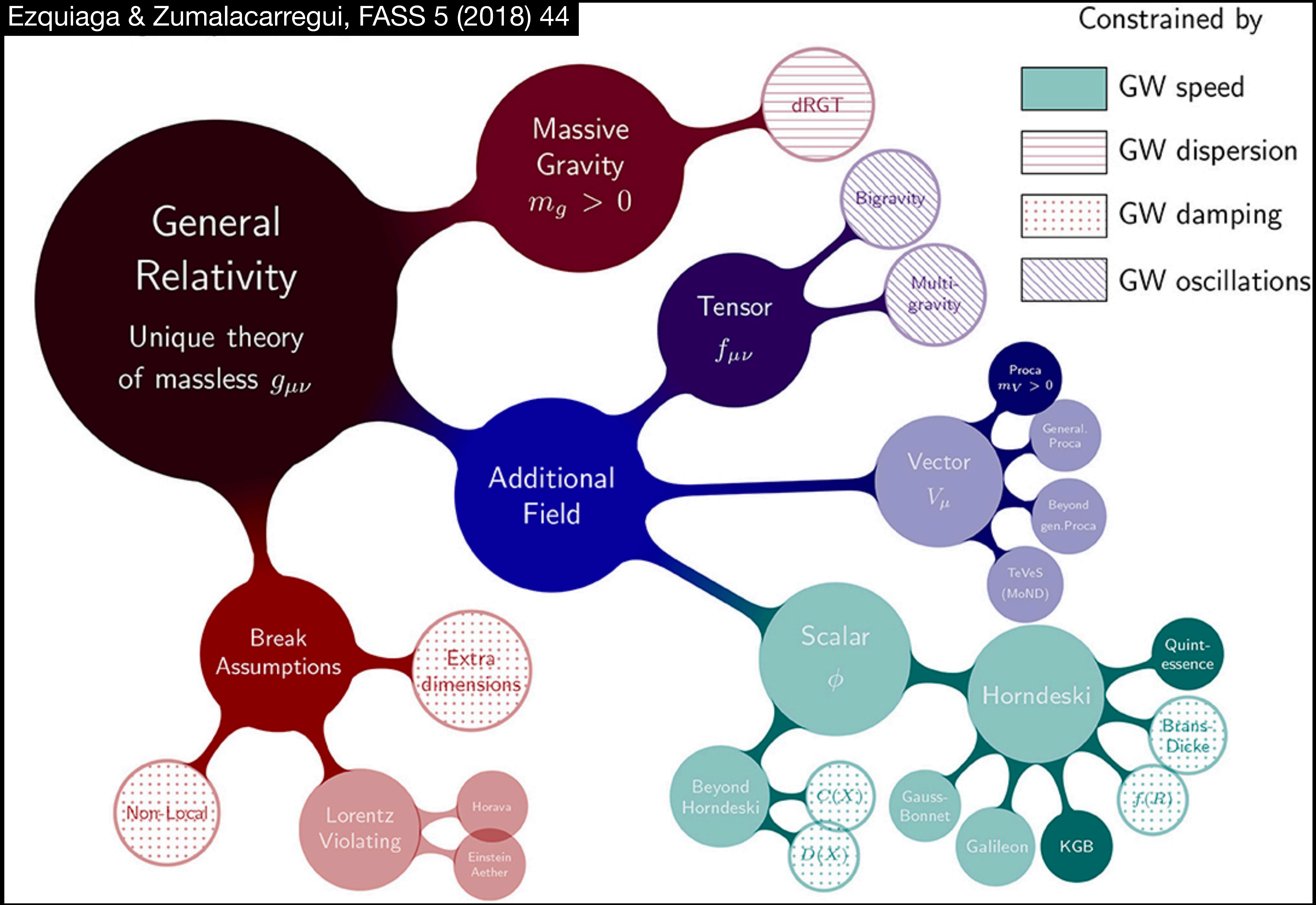
$$\Sigma m_\nu < 0.12\,\mathrm{ev}$$

Alam +eBOSS, PRD 103, 083533 (**2021**)



Tests of Gravity theories

Ezquiaga & Zumalacarregui, FASS 5 (2018) 44



Einstein-Hilbert action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R$$

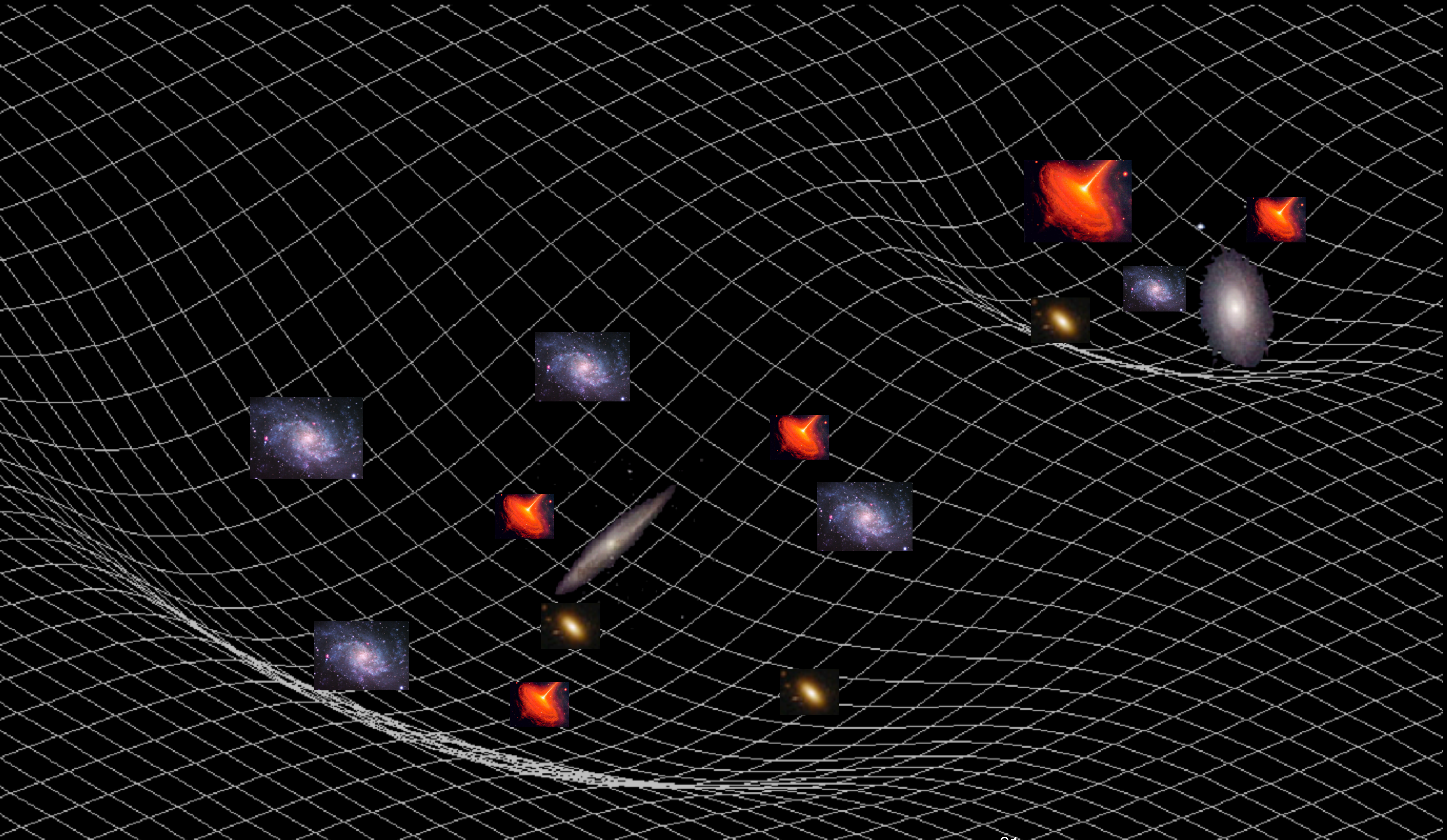
a) Pullen, **Alam**, Ho, MNRAS 449, 4326 (2015)
b) **Alam** et. al. MNRAS 453, 1754 (2015)
c) **Alam** et. al. MNRAS 456, 3743-3756 (2016)
d) Pullen, **Alam**, Ho MNRAS 460, 4098-4109 (2016)
e) Satpathy, **Alam** et. al. MNRAS 469, 1369-1382 (2017)
f) **Alam** et. al. MNRAS 465, 4853-4865 (2017)
g) Singh, **Alam** et. al. MNRAS 482, 785-806 (2019)
h) Hang, **Alam** et. al. MNRAS 501, 1481-1498 (2021)

General Relativistic effects

Gravitational Redshift: Test of equivalence principle

a) **Alam** et. al. MNRAS (2017) 470 (3): 2822-2833
b) **Alam** et. a.l MNRAS (2017) 471(2): 2077-2087
c) Zhu, **Alam**, et. al. MNRAS (2017) 471(2): 2345-2356

Constraining Physics of galaxies and the role of Black-Holes in shaping the Universe



Emission Line Galaxies
Young with active star formation

Luminous Red Galaxies
Massive with low star formation

Active Galactic Nuclei
Active supermassive black-holes

a) **Alam** et. al. MNRAS 483, 4501-4517 (2019)
b) **Alam** et. al. MNRAS 497, 581-595 (2020)
c) **Alam** et. al. MNRAS 503, 59-76 (2021)
d) **Alam** et. al. MNRAS 504, 857-870 (2021)
e) **Alam** et. al. MNRAS 504, 4667-4686 (2021)

Summary of Relativistic perturbation theory

Perturbed Einstein Field Equation

$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu} + \Lambda \delta g_{\mu\nu}$$

Spatially flat FRW metric

$$ds^2 = a^2 \eta_{\mu\nu} dx\mu dx^\nu$$

Conformal Friedman equations

$$\mathcal{H}^2 = \frac{1}{3} a^2 (8\pi G \rho + \Lambda)$$

$$\dot{\mathcal{H}} = \frac{1}{6} a^2 \left[2\Lambda - 8\pi G(\rho + 3P)\right]$$

- Evolution is adiabatic for super-horizon scale
- CDM (only interact gravitationally) perturbation grows logarithmically until matter-radiation equality. After grows with scale factor (a).
- Baryons and Radiation undergo acoustic oscillations for modes that enter the sound horizon till decoupling.
- Baryons fall into CDM potential wells after decoupling.
- Dark Energy domination slows down growth of density perturbations.

What Have we learned?

Alam +eBOSS, PRD 103, 083533 (**2021**)

Matter density, expansion rate, amplitude of fluctuation

- Precision measurements of the three main quantities governing the evolution of the universe is the very first step in reducing the theory landscape.

$\Omega_m = 0.304 \pm 0.002$ — Fraction of energy density in matter

$H_0 = 68.19 \pm 0.36\,\mathrm{km/s/Mpc}$ — Expansion rate of the Universe

$\sigma_8 = 0.807 \pm 0.006$ — Current amplitude of matter power spectrum

*ΛCDM

Curvature of the Universe

- Geometry of the universe fundamental importance. Also most inflationary models predicts geometry close to zero.

$\Omega_k = 0.0001 \pm 0.0017$ *$o\Lambda$CDM

Dark Energy equation of state

- Is dark energy cosmological constant?

$$\rho \propto a^{-3(w+1)}$$

$w = -1.02 \pm 0.03$ *wCDM

*Includes observations of CMB, SN1 and WL