Instituto de Física
Universidade de São Paulo

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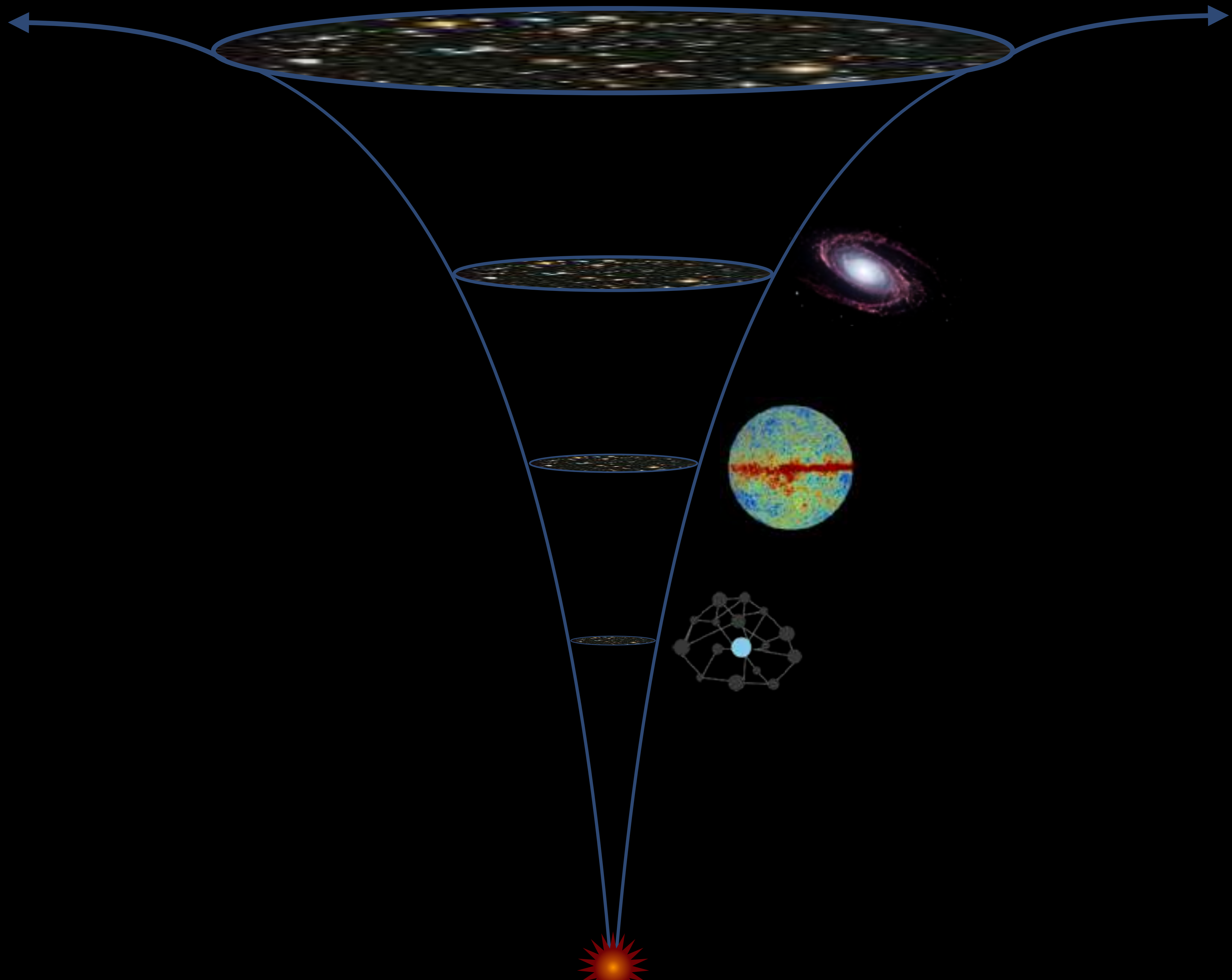
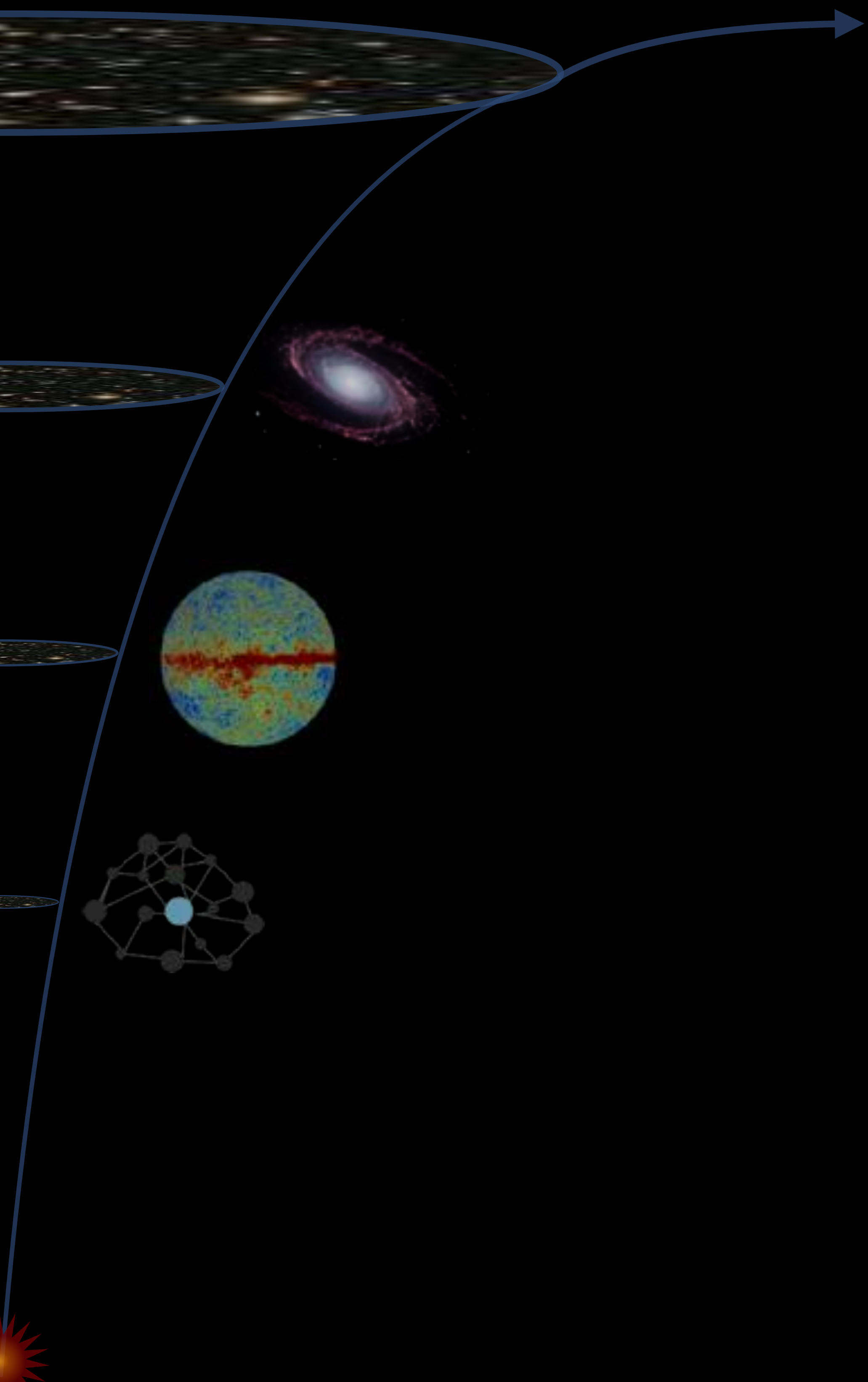
PHYSICS/USP

COSMOLOGY: FROM INFLATION TO LARGE-SCALE STRUCTURE

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



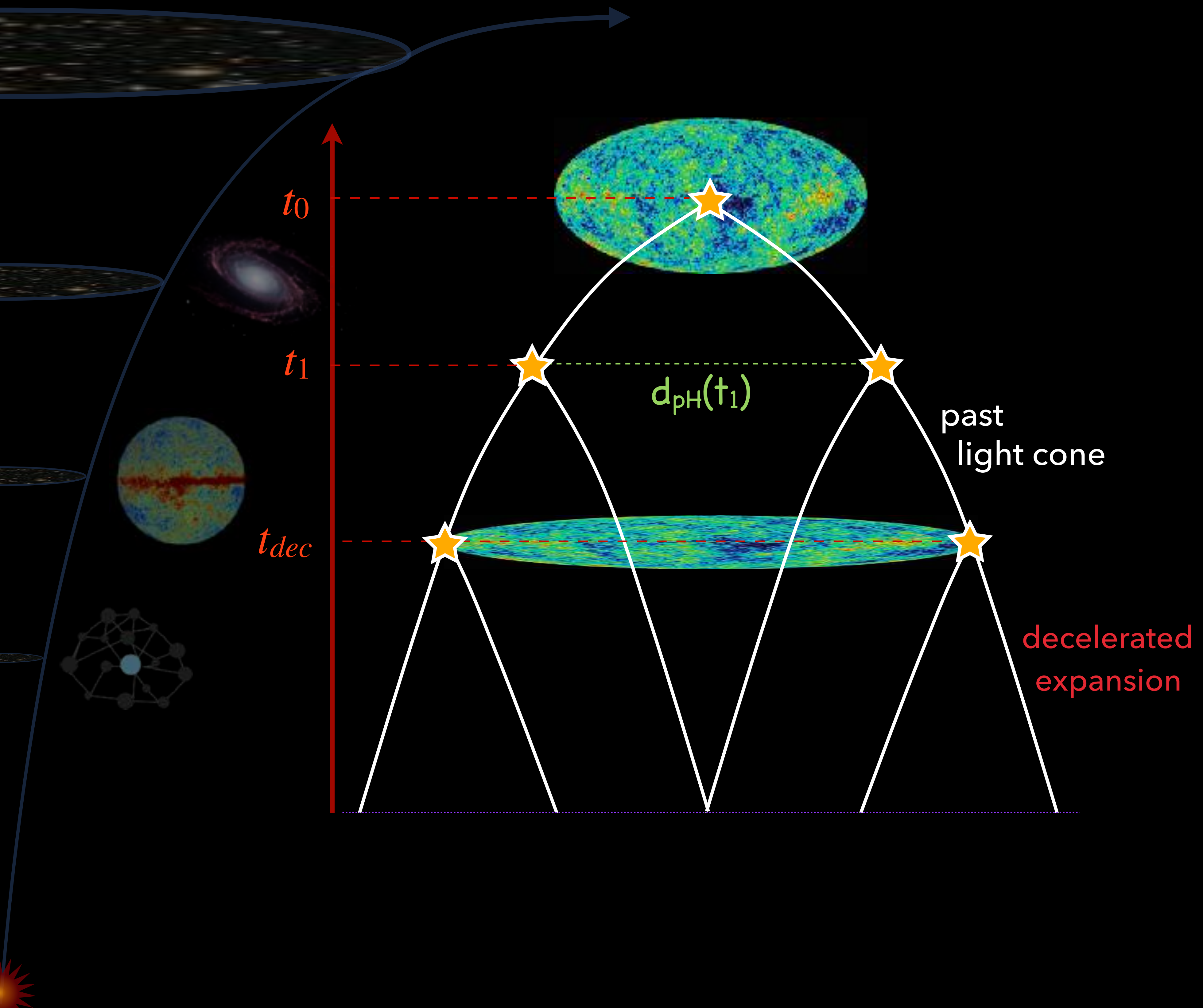
DARK ENERGY

LARGE-SCALE STRUCTURE

CMB

INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY

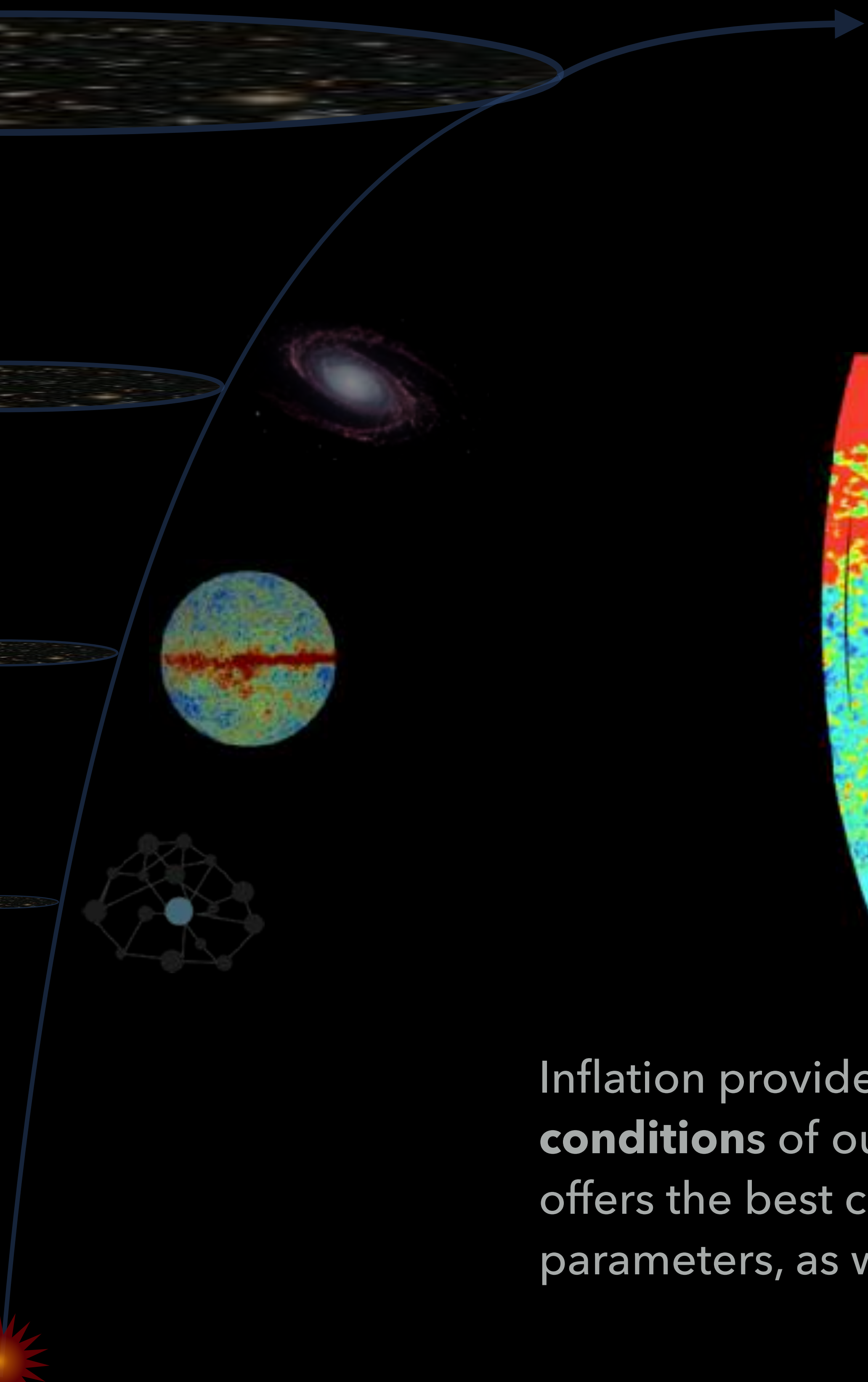
LSS

CMB

Starobinsky ’79, ’85
Mukhanov & Chibisov ’81
Guth ’82
Linde ’83, ’85
(…)

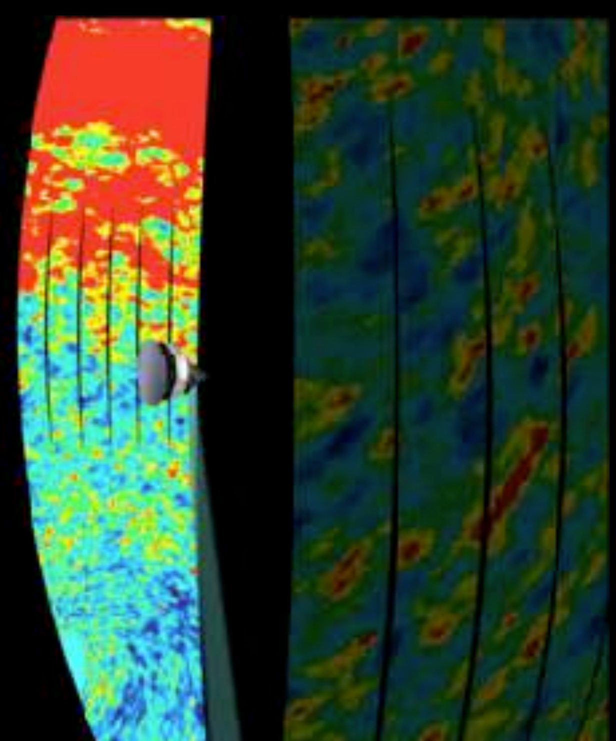
INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY

LSS



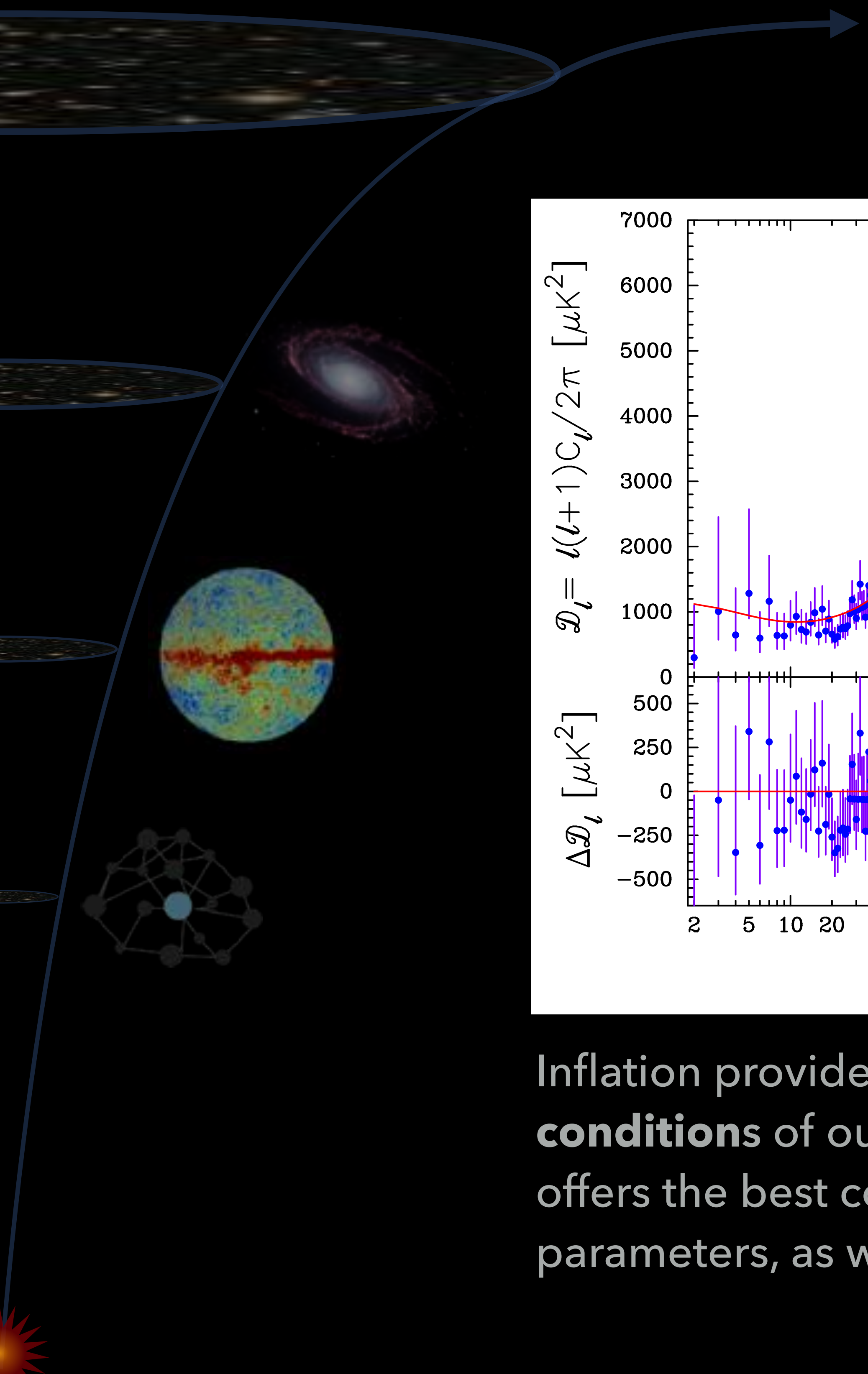
CMB

COBE '93-' 96
WMAP '06-'09
Planck '15-'18

Inflation provides our best theory for the **initial conditions** of our Universe. Presently the **CMB** offers the best constraints on many cosmological parameters, as well as inflationary models

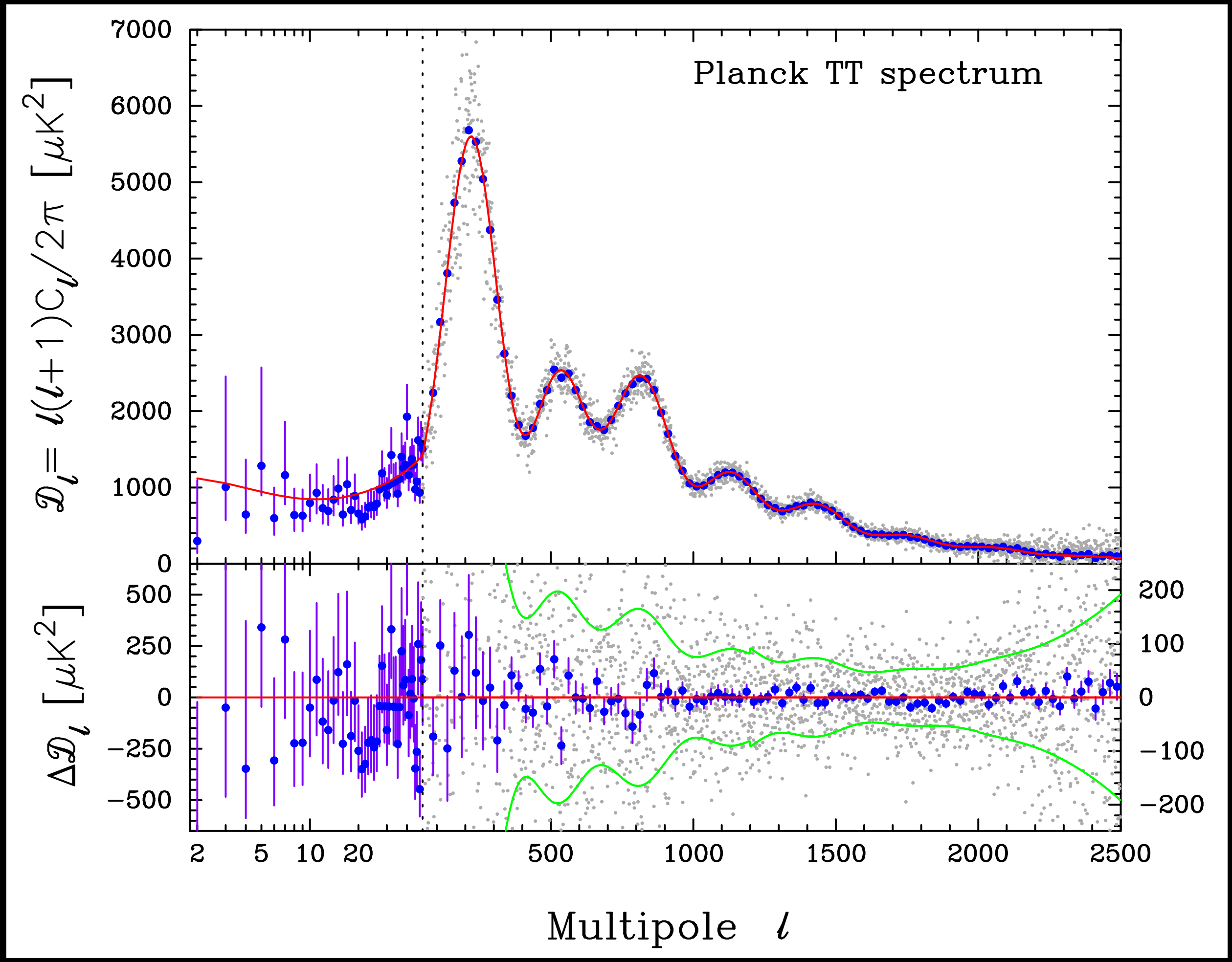
INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY

LSS



Inflation provides our best theory for the **initial conditions** of our Universe. Presently the **CMB** offers the best constraints on many cosmological parameters, as well as inflationary models

CMB

COBE '93-' 96
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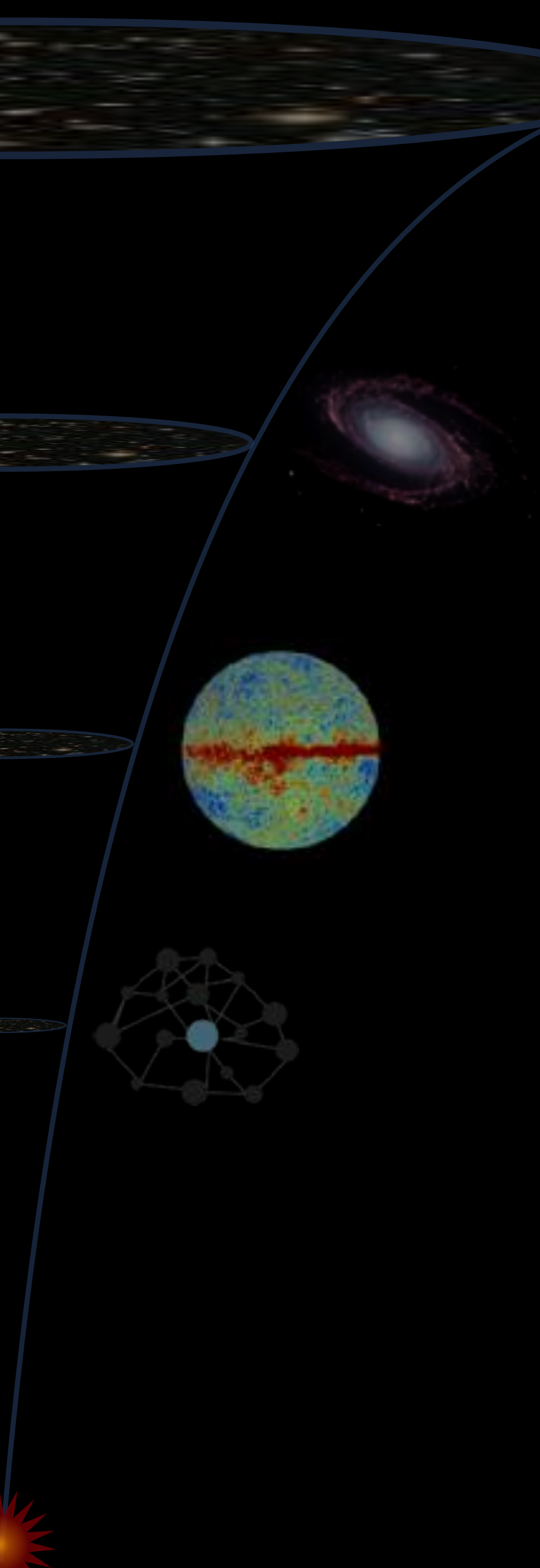
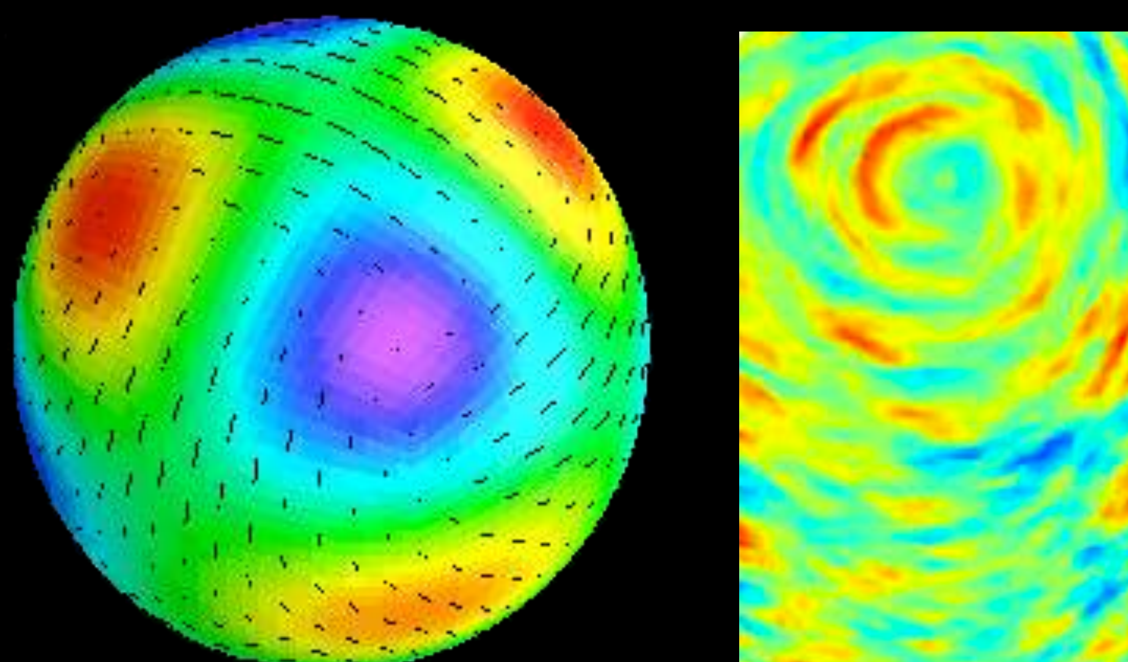
INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY

LSS



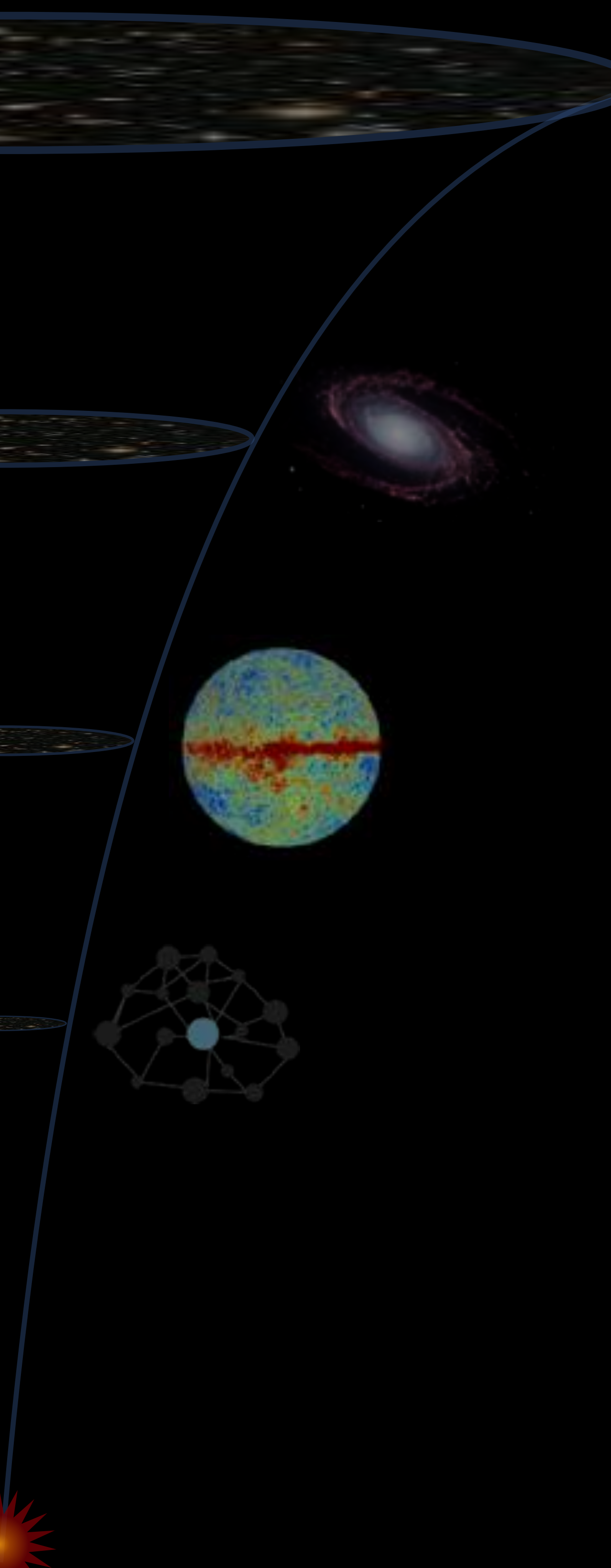
CMB

More fundamental tests of inflation depend on two signals which are very difficult to detect: ***B-mode polarization*** from GWs, and ***non-Gaussian signatures***

Seljak & Zaldarriaga ’97
Kamionkowski et al. ’97
Maldacena ‘02

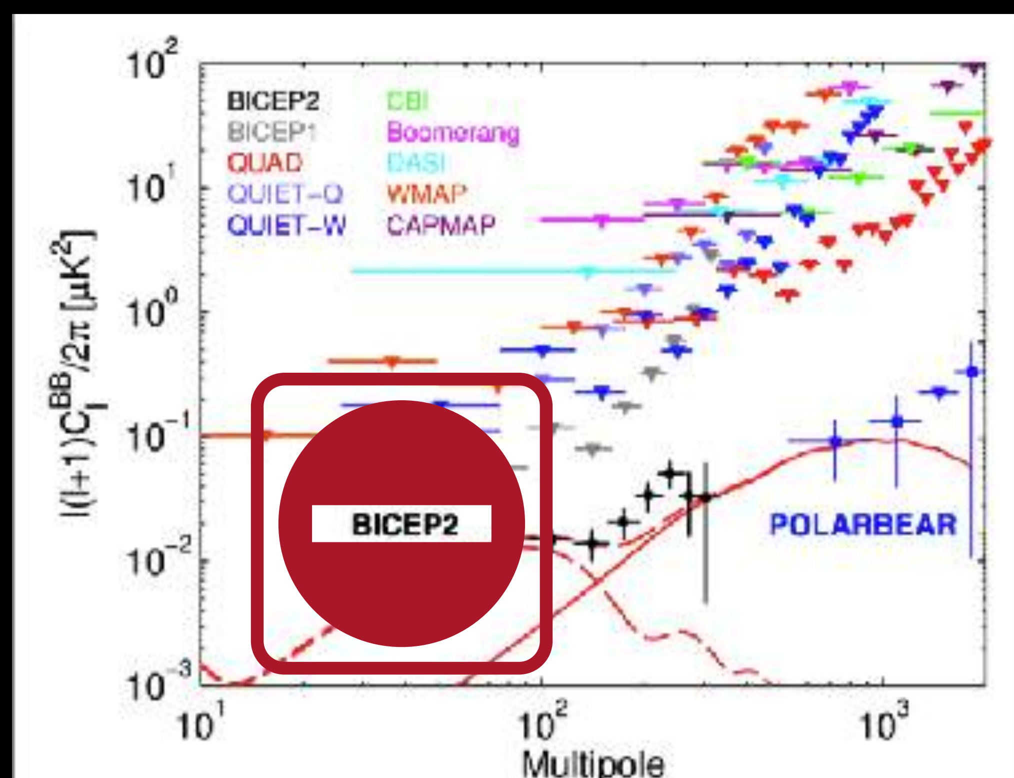
INFLATION

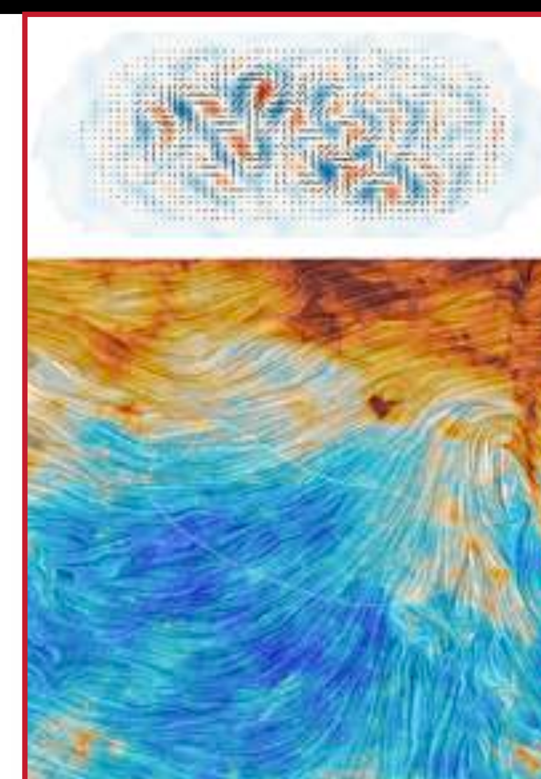
FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY

LSS





CMB

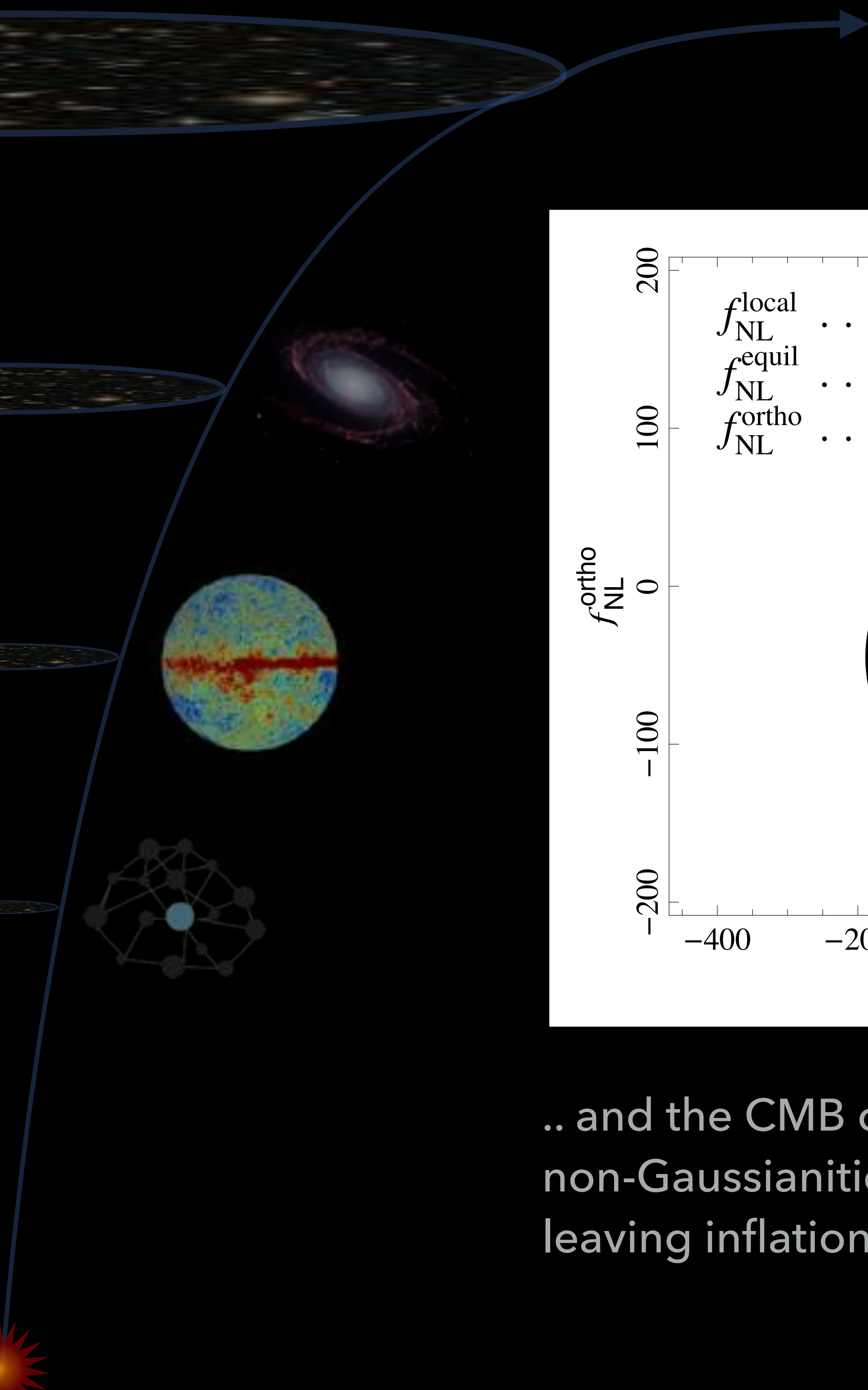
Kovac et al. ’14

Planck Collab. ’18

Initial excitement about a possible detection of B-modes from gravity waves ended in disappointment…

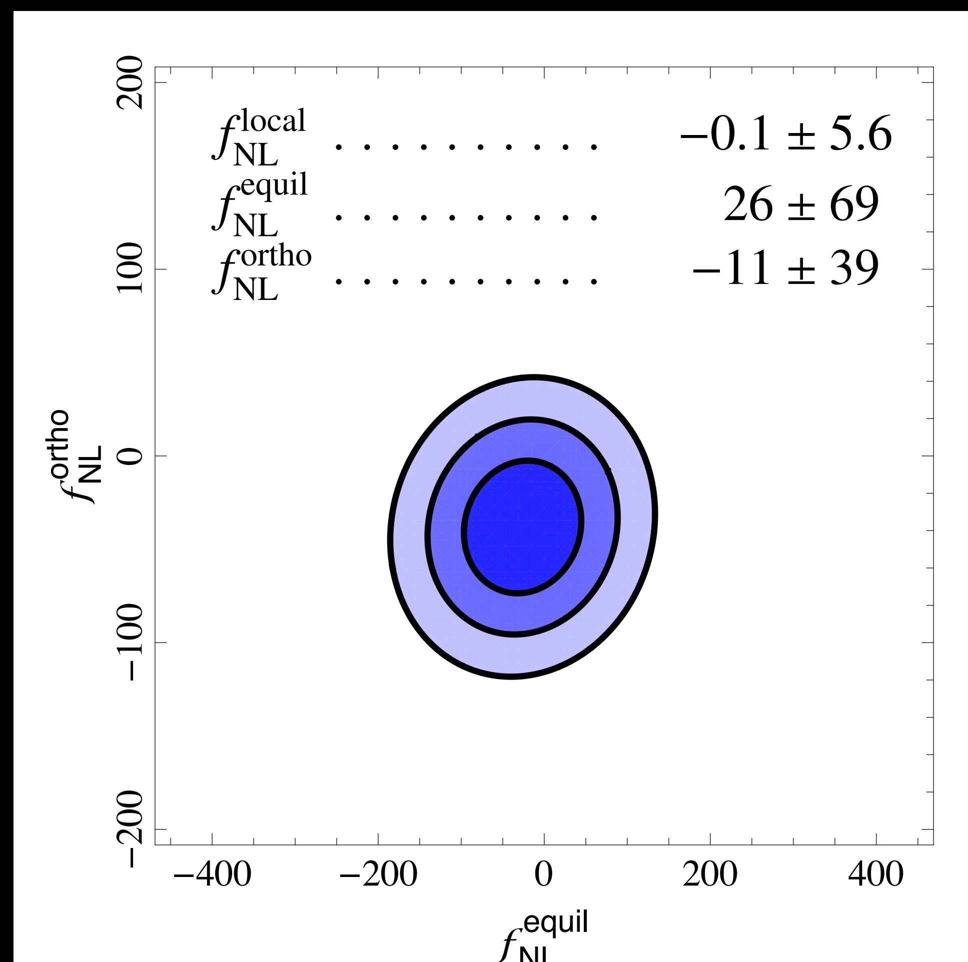
INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY

LSS



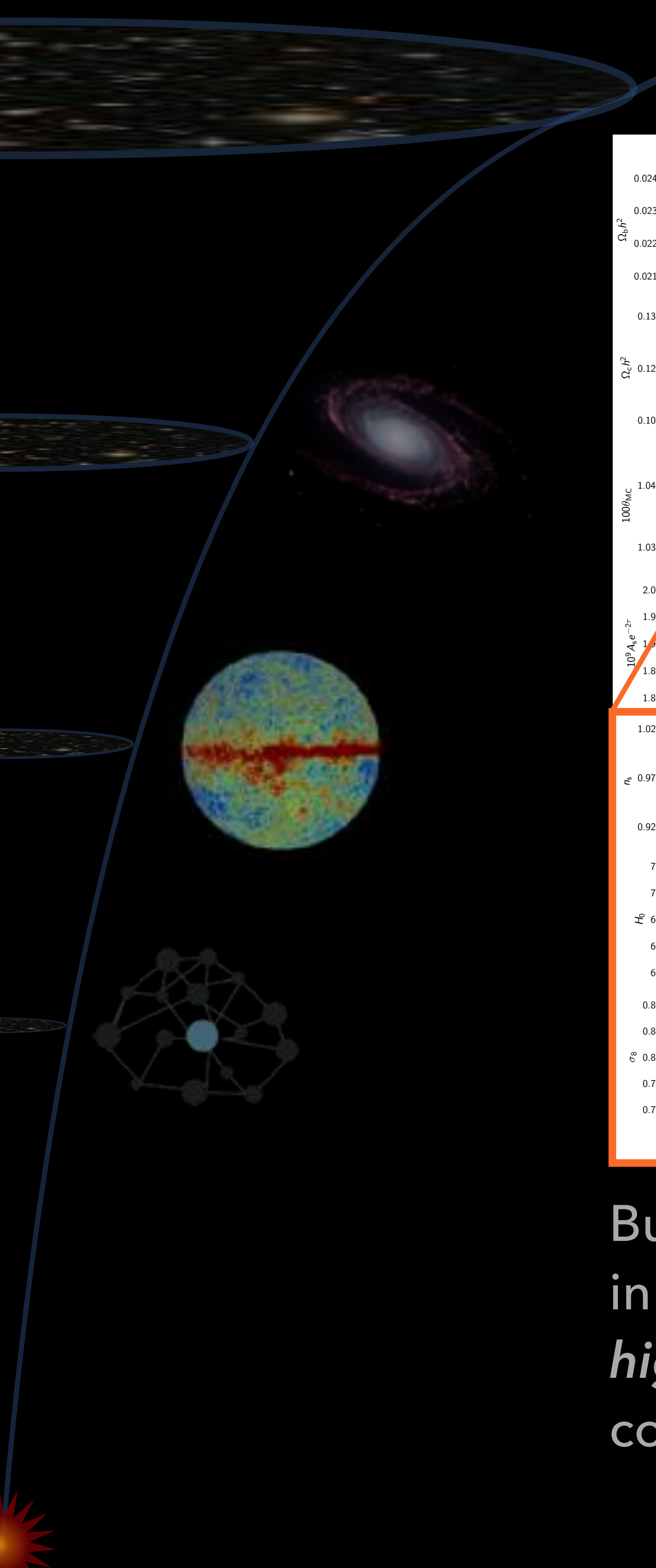
.. and the CMB constraints on primordial non-Gaussianities are still relatively weak, leaving inflation in a sort of limbo.

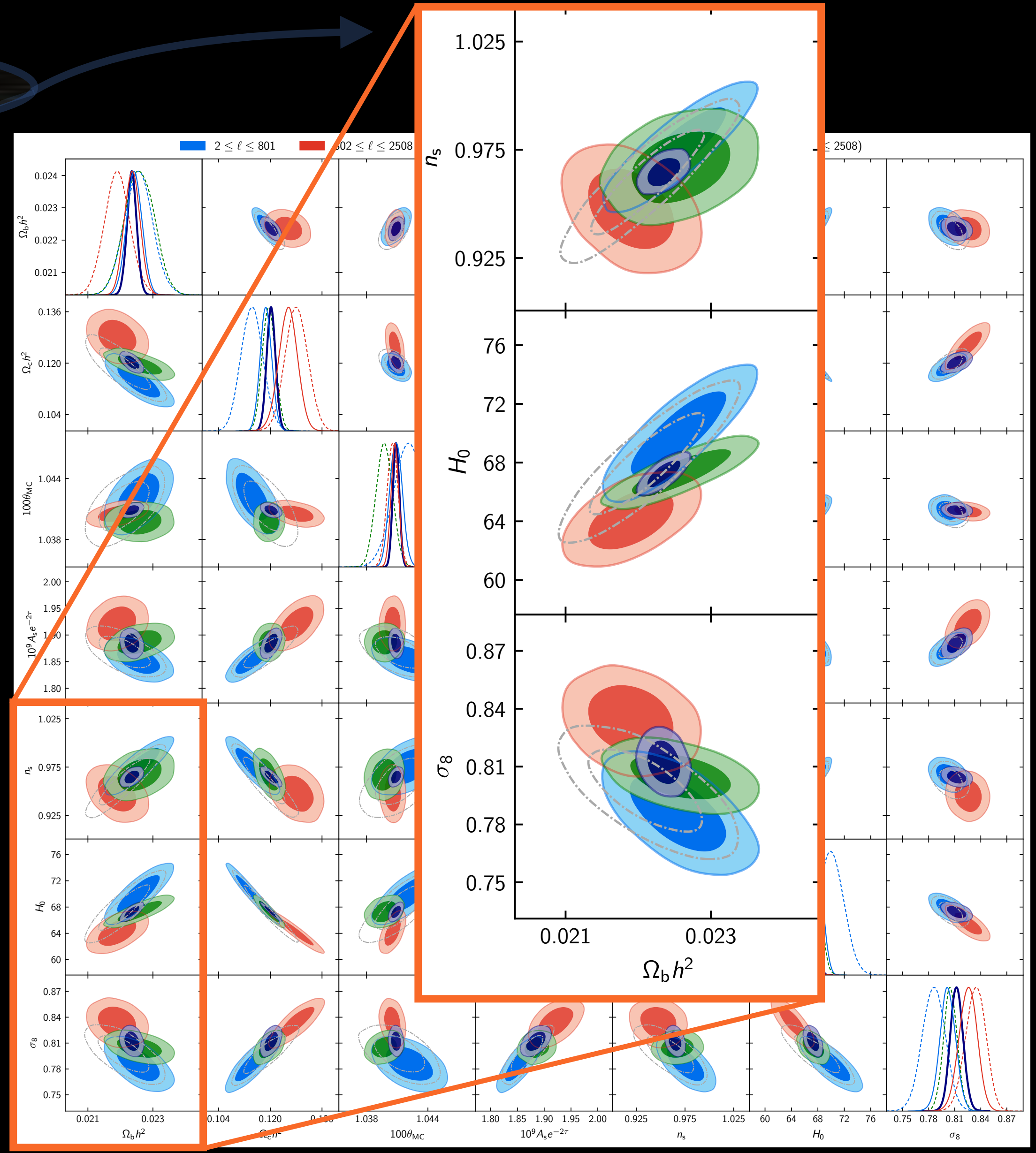
CMB

Verde et al. '00
Maldacena '02
Planck '18

INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS





DARK ENERGY

LSS

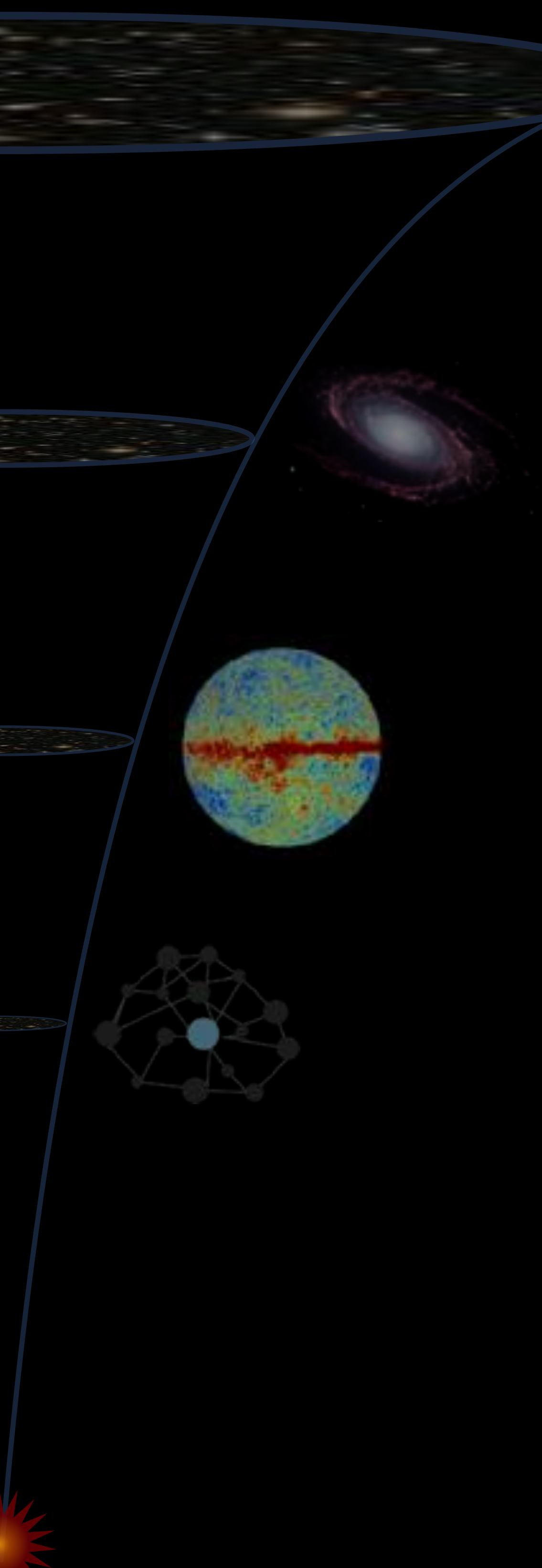
CMB

Planck Collab. '18

But more importantly, the CMB, and *Planck* in particular, imposed for the first time ***high-precision constraints*** on many cosmological parameters…

INFLATION

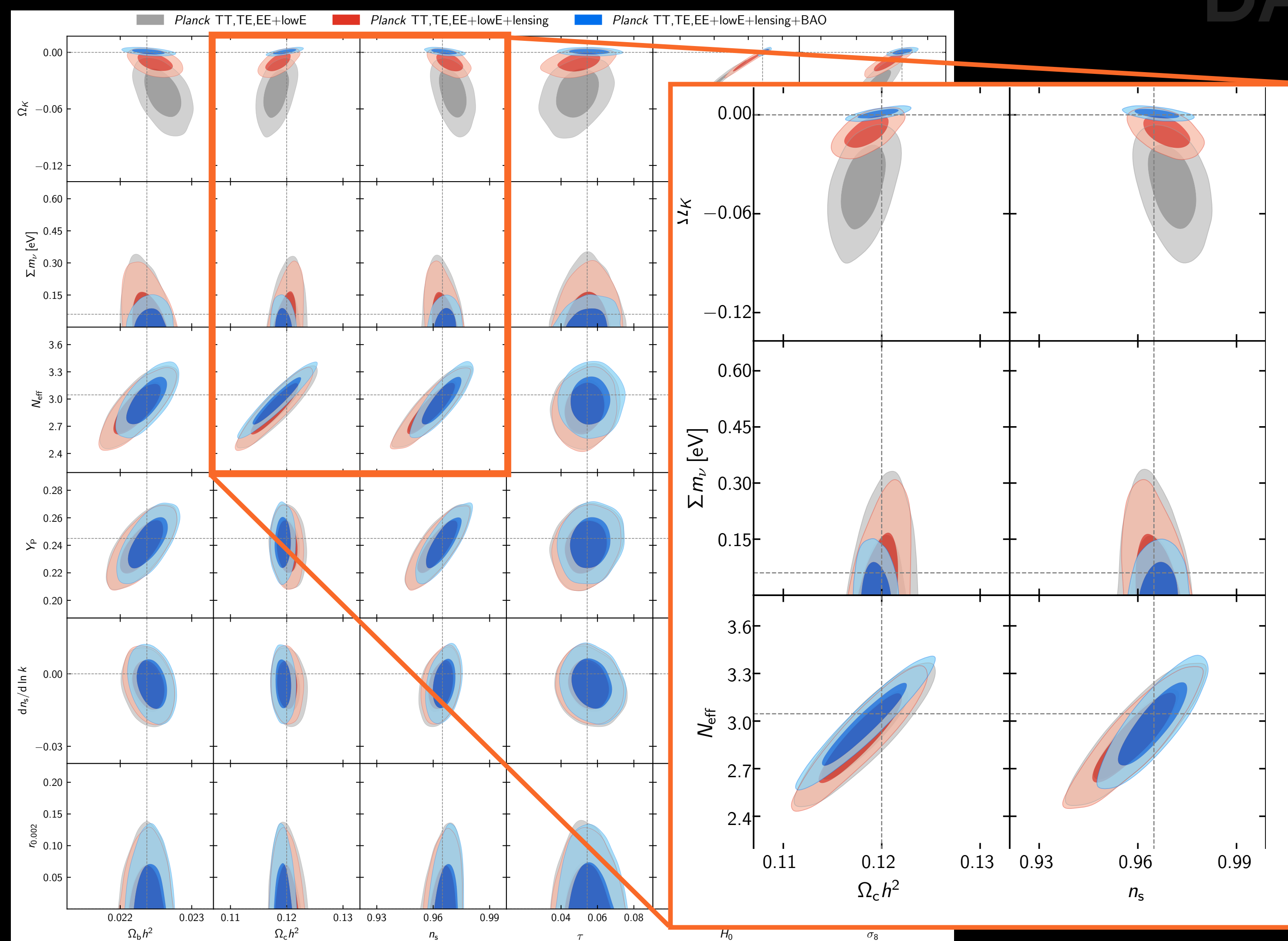
FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY

LSS

CMB

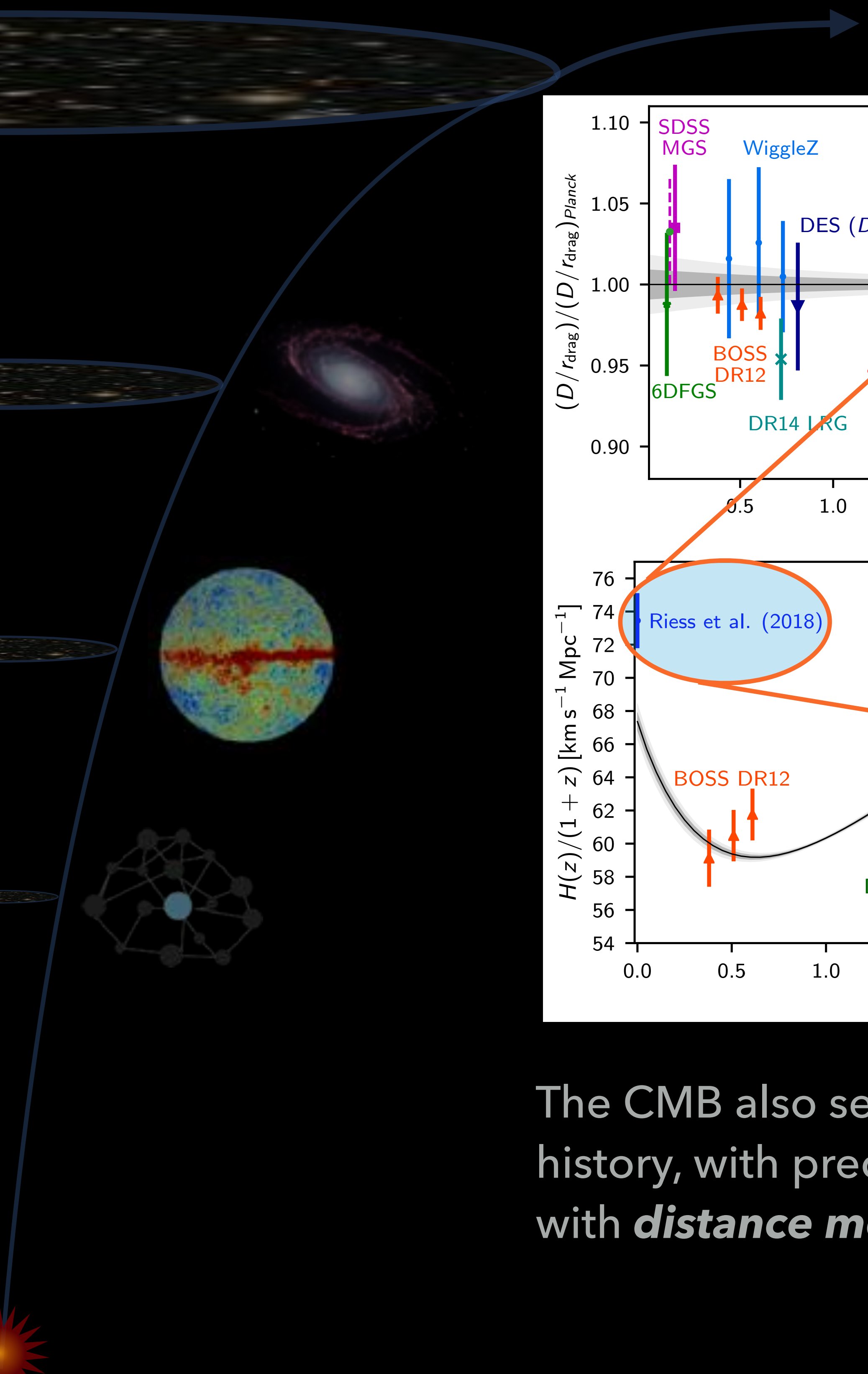


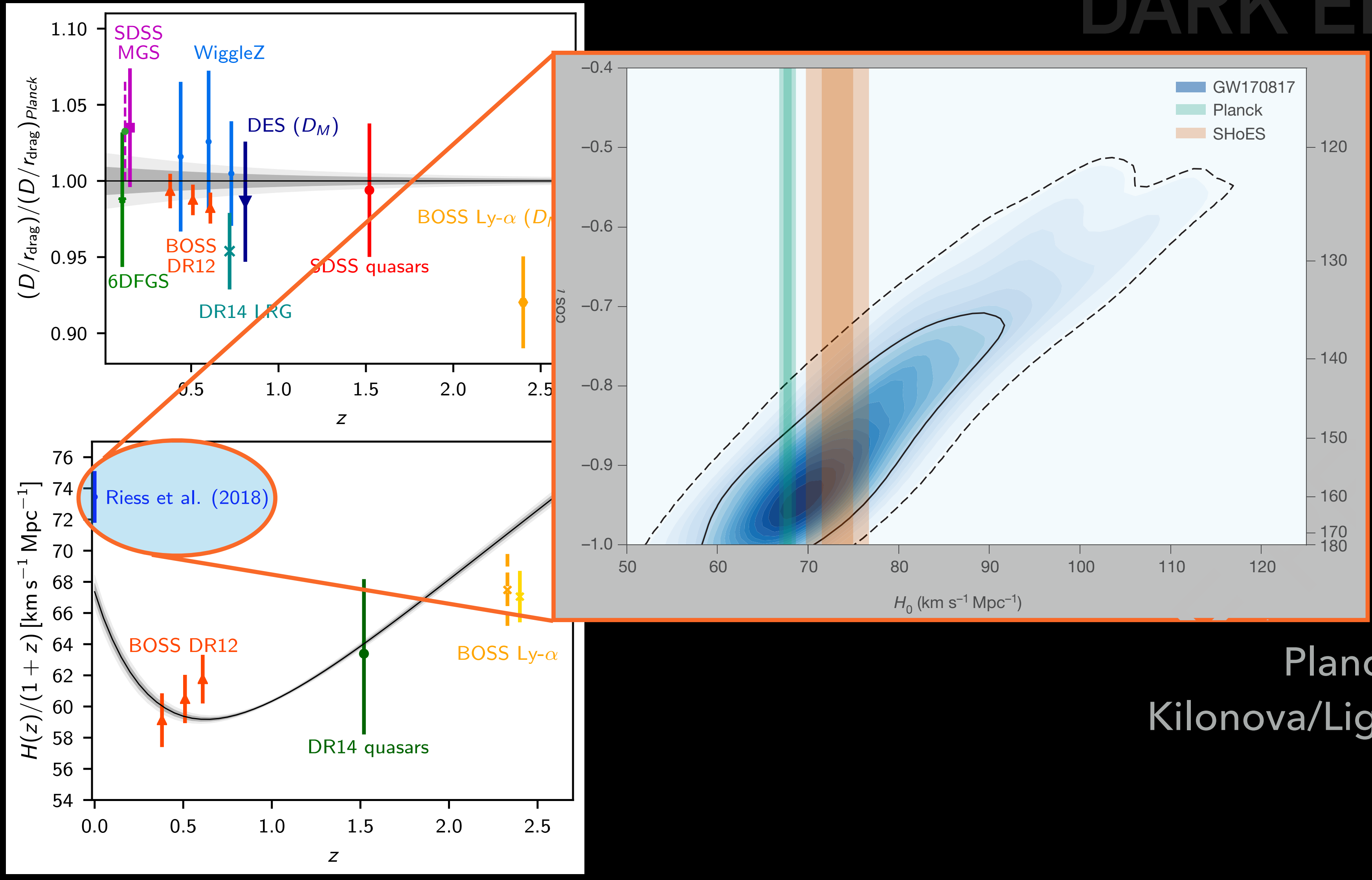
Planck Collab. '18

… as well as some fundamental physics parameters: strong evidence for *cold dark matter*, near-zero *spatial curvature*, *neutrino masses* and *effective number of relativistic d.o.f.*

INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS





DARK ENERGY

LSS

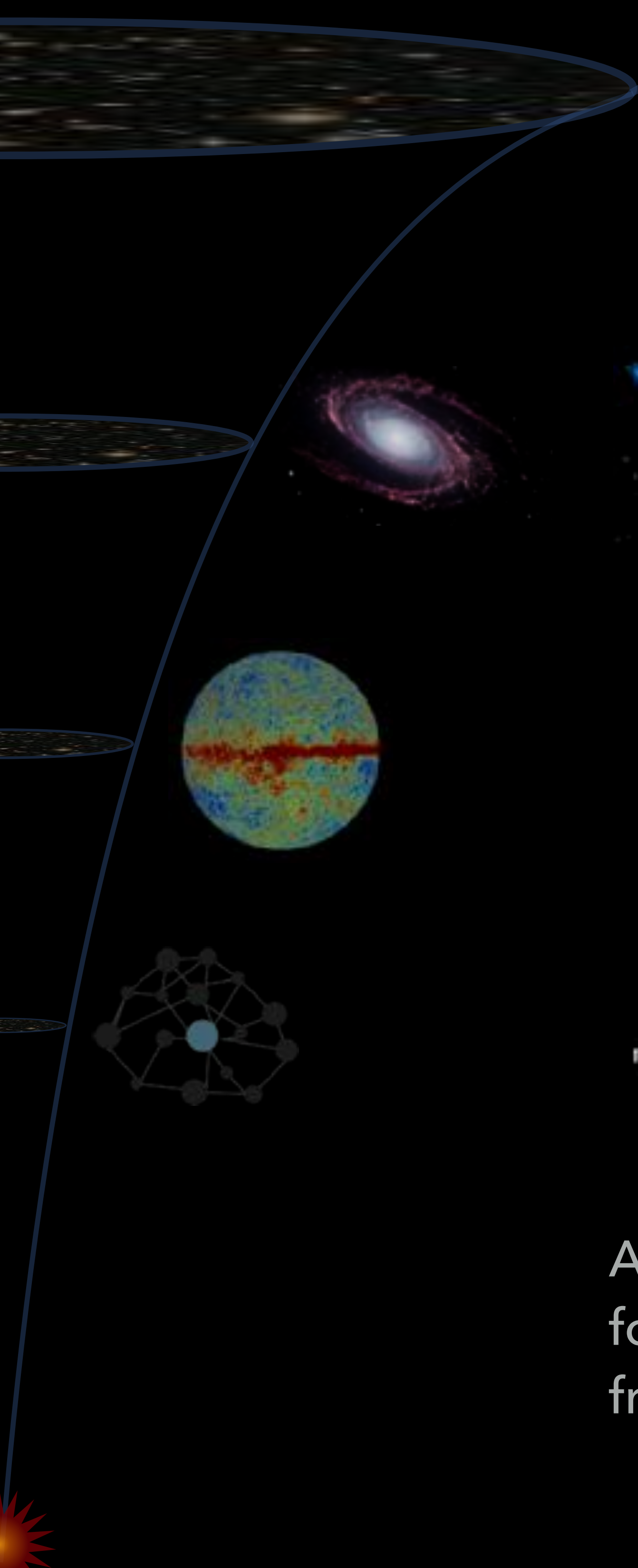
CMB

Planck Collab. '18
Kilonova/Ligo Collab. '18

The CMB also sets the stage for the expansion history, with precise predictions that can be checked with ***distance measurements*** at low redshifts

INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY

LSS

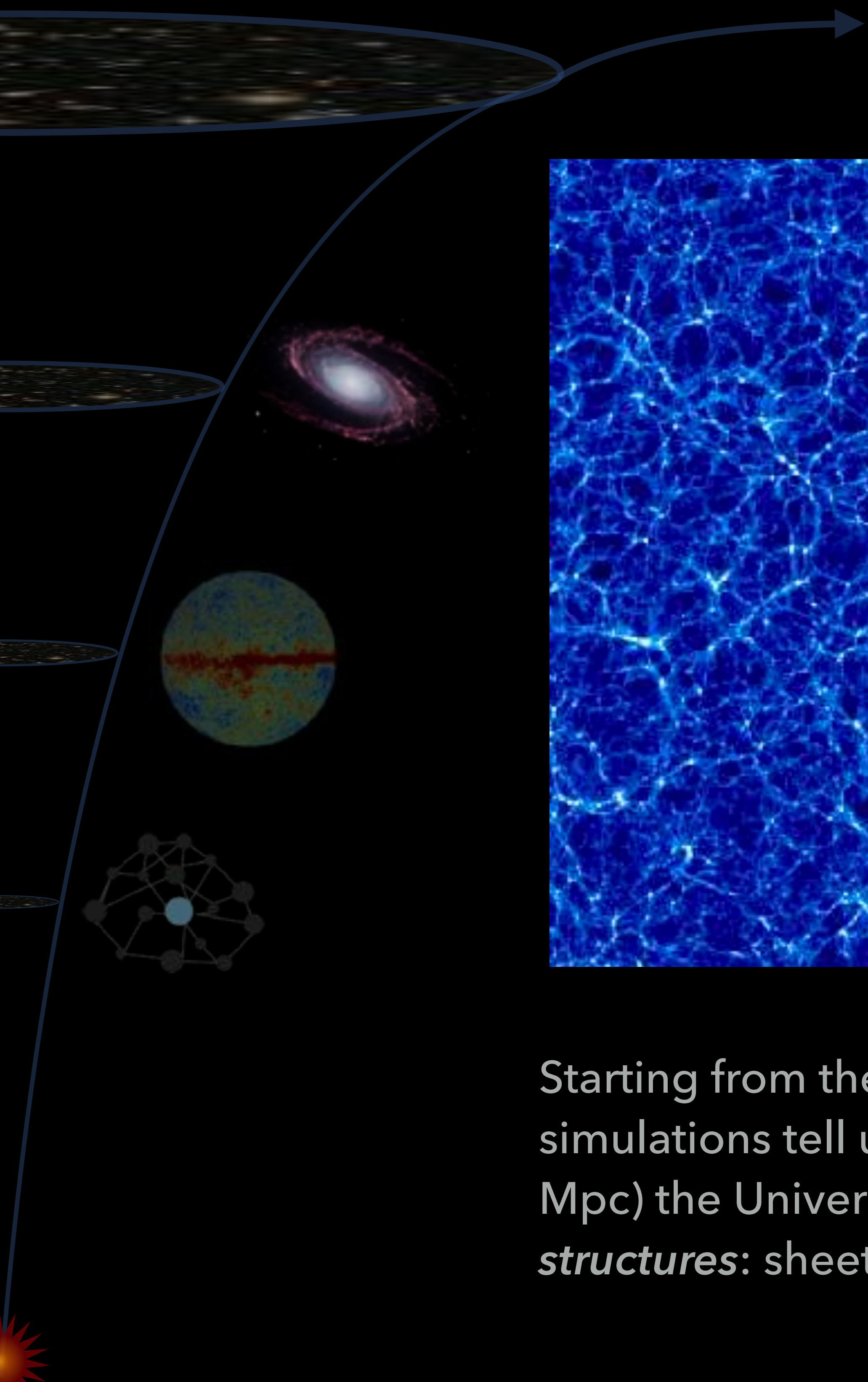
Peebles & Yu ’70
Zel’dovich ’72
…
Vogelsberger et al. ’14

CMB

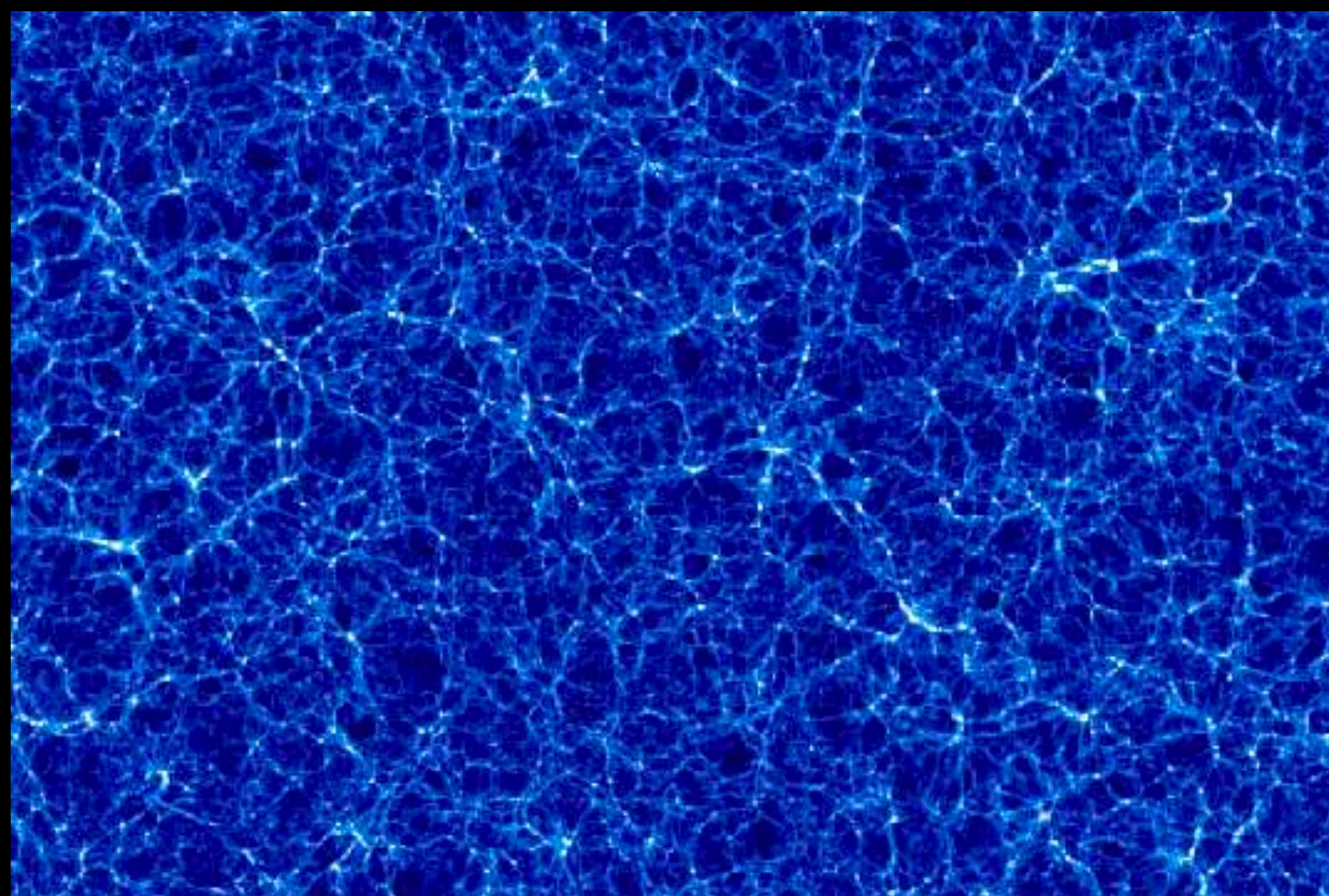
After decoupling, the *initial conditions* are set for the Universe to start *forming structures,* from dark and baryonic matter

INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY



LSS

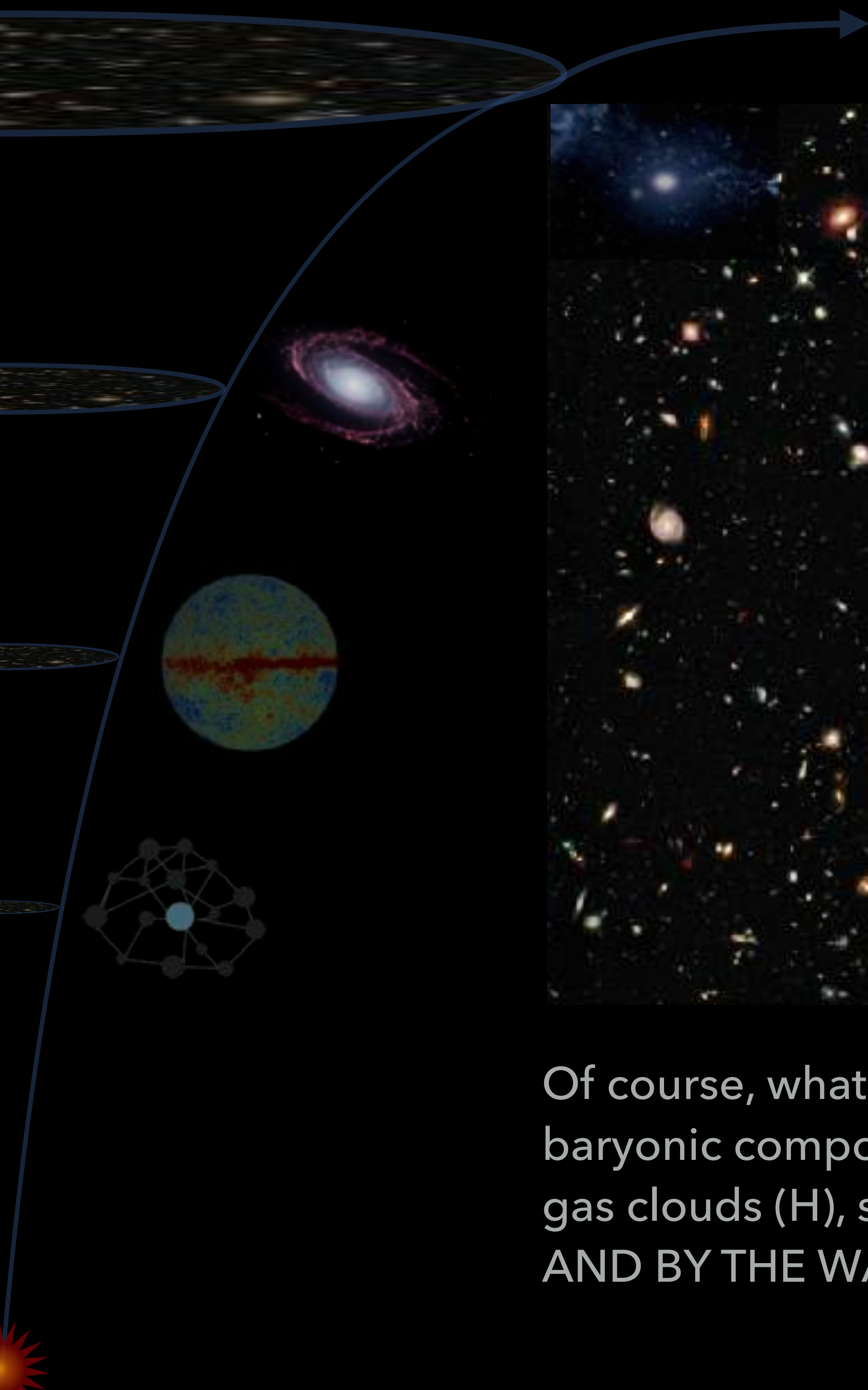
MultiDARK Collab.

CMB

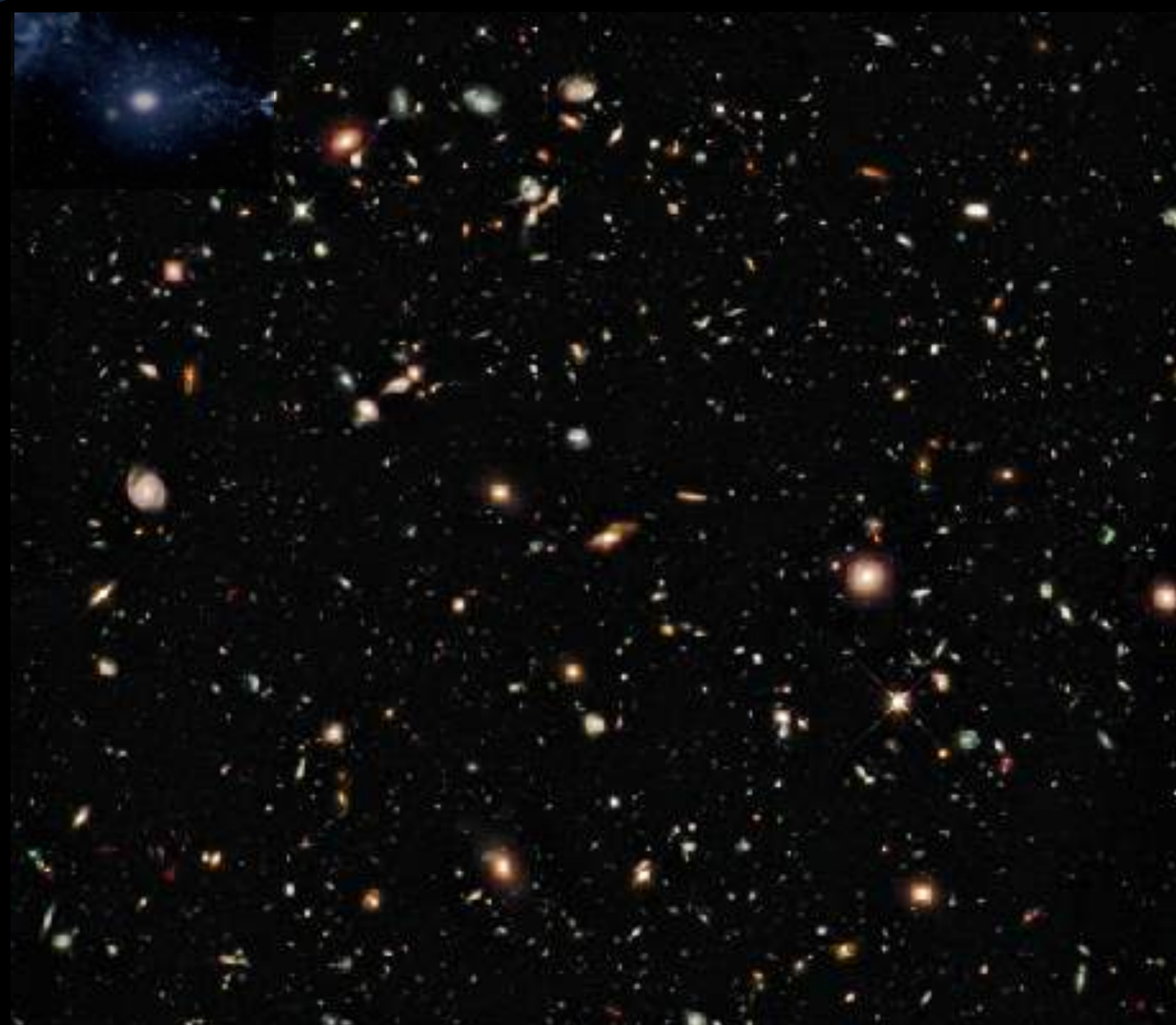
Starting from these initial conditions, N-body simulations tell us that on very large scales (>100 Mpc) the Universe should look like a ***web of structures***: sheets, filaments, nodes, halos, etc.

INFLATION

FROM FUNDAMENTAL PHYSICS TO ASTROPHYSICS



DARK ENERGY



LSS

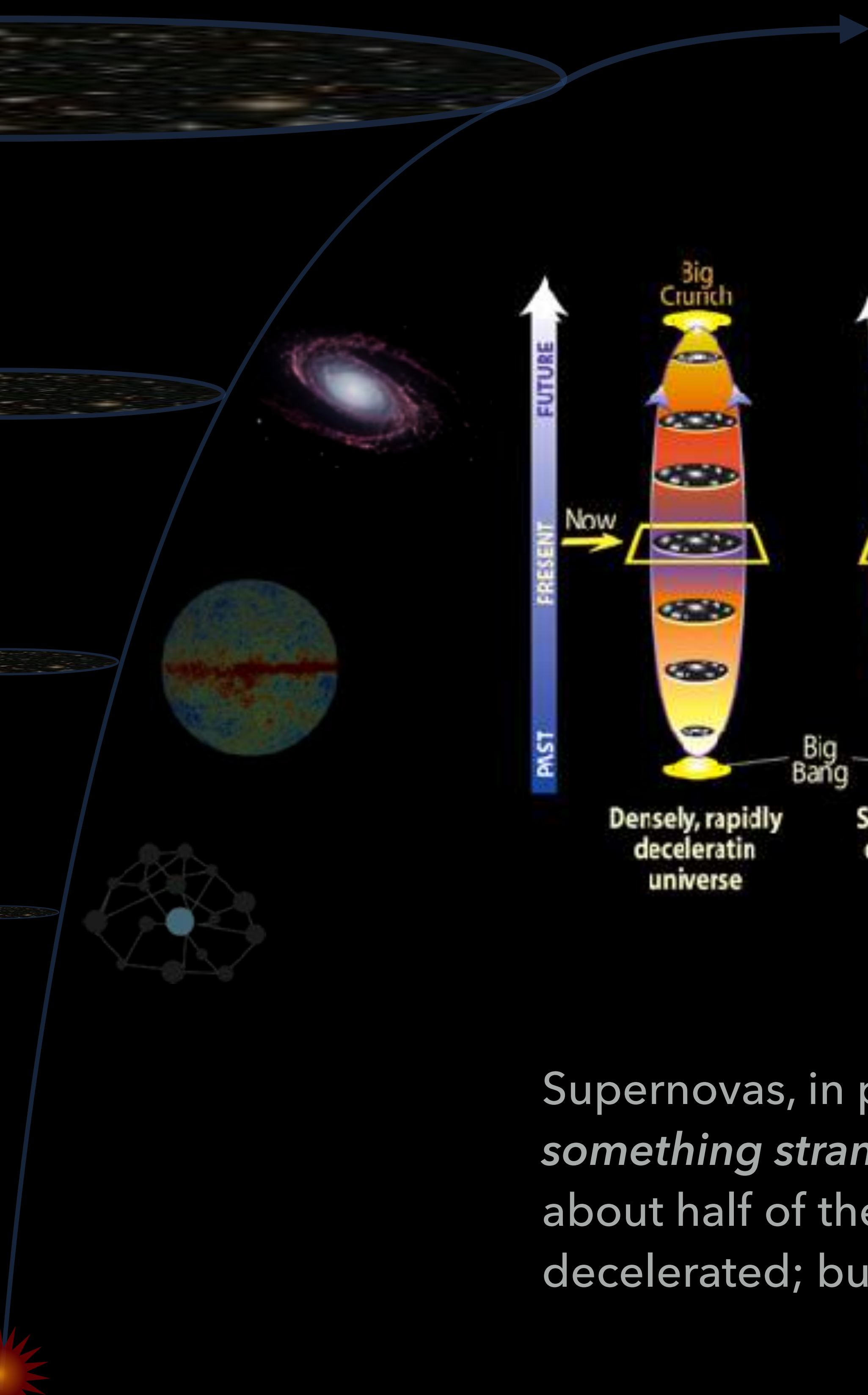
HST Deep Field

CMB

Of course, what we *actually observe* are baryonic components: galaxies, quasars, gas clouds (H), supernovas…
AND BY THE WAY…

INFLATION

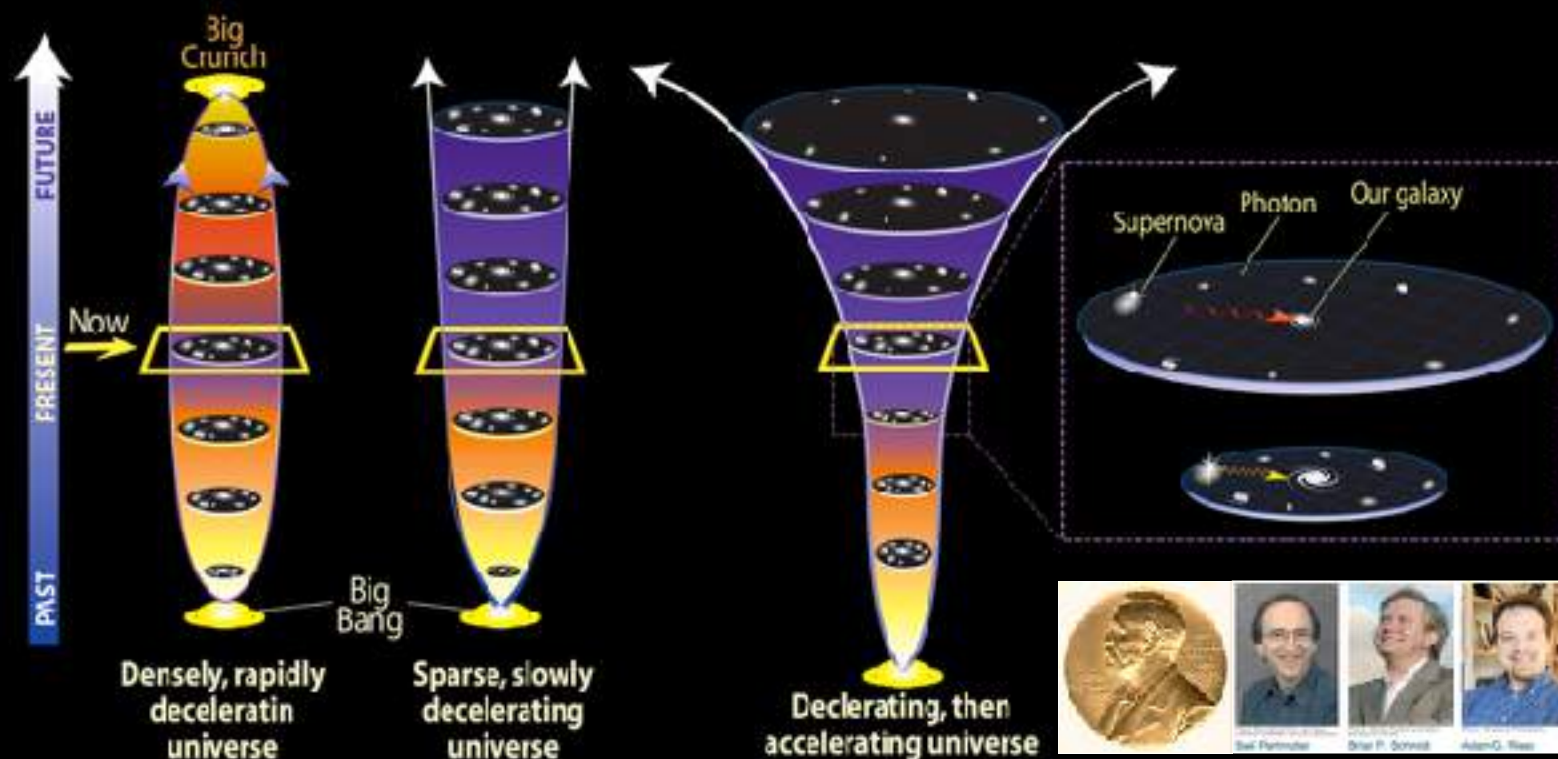
DARK ENERGY OR MODIFIED GRAVITY?



DARK ENERGY

Riess et al. '98

Perlmutter et al. '98



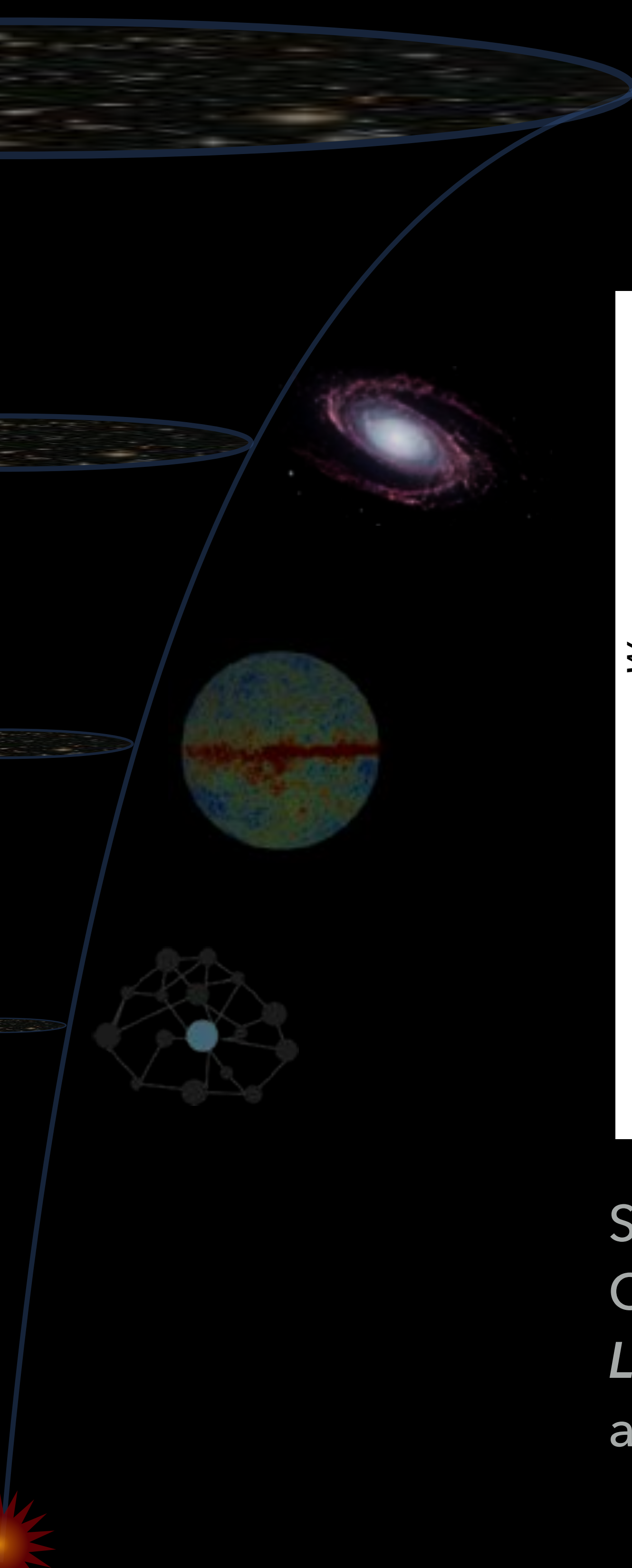
LSS

CMB

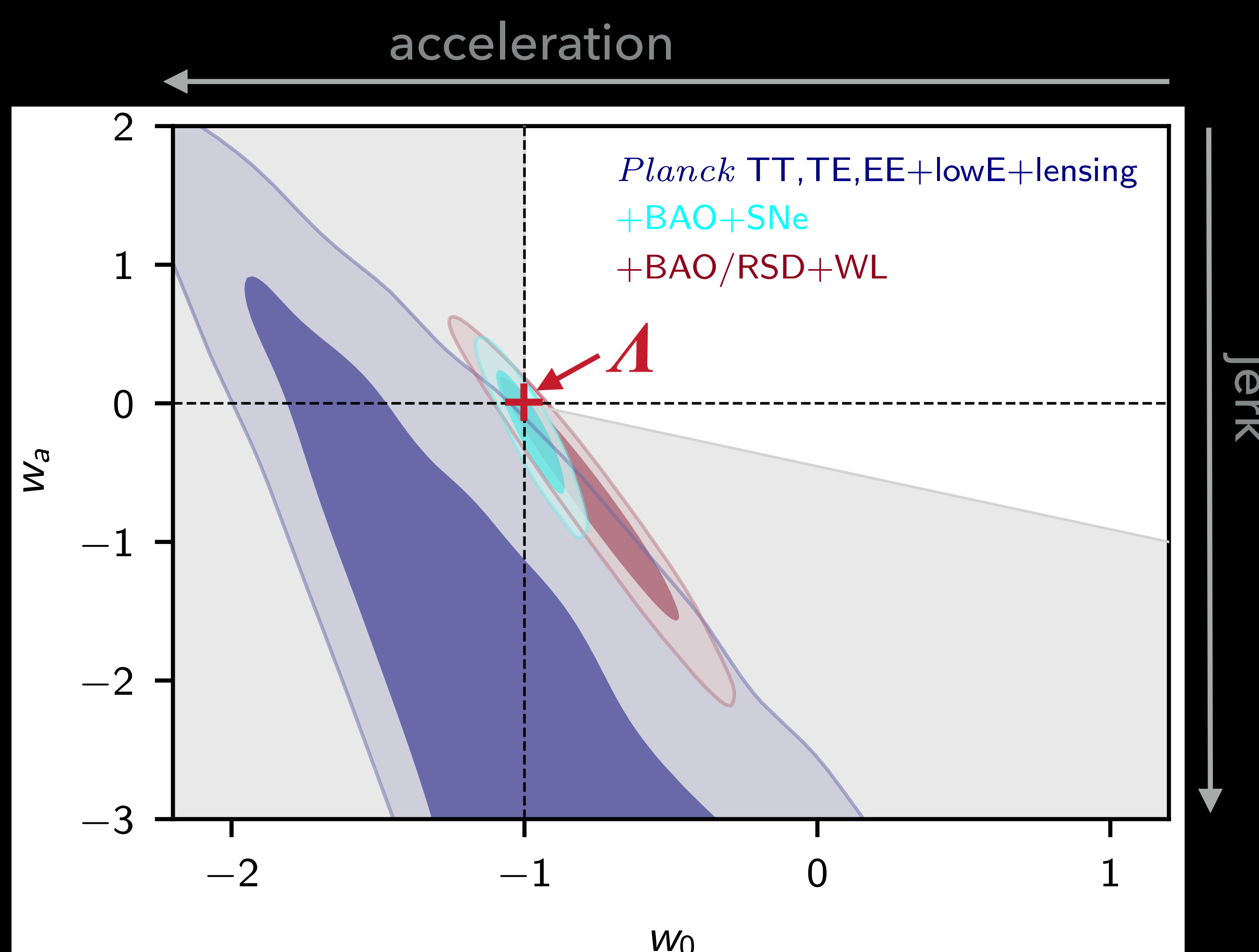
Supernovas, in particular, gave us the first hints that *something strange* was going on. Apparently, for about half of the age of the Universe, its expansion decelerated; but then, it started to *accelerate*

INFLATION

DARK ENERGY OR MODIFIED GRAVITY?



$$w = \frac{p}{\rho} = w_0 + w_a(1-a)$$



Since ***acceleration*** takes place in the late Universe, the CMB is not a powerful test. However, ***supernovas and LSS*** enable accurate phenomenology of the recent accelerated phase

DARK ENERGY

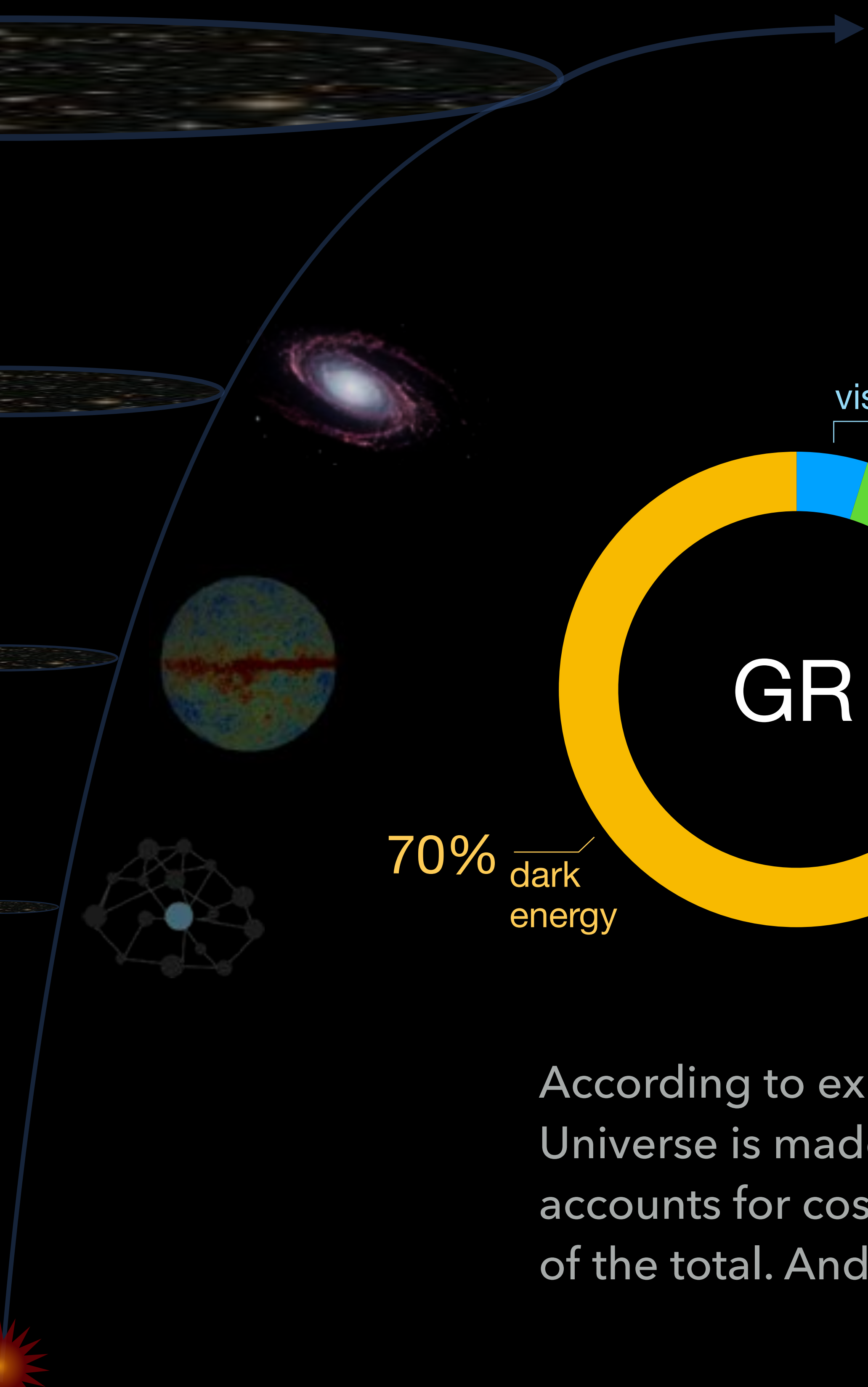
LSS

BOSS Collab. '17
Planck Collab. '18

CMB

INFLATION

DARK ENERGY OR MODIFIED GRAVITY?



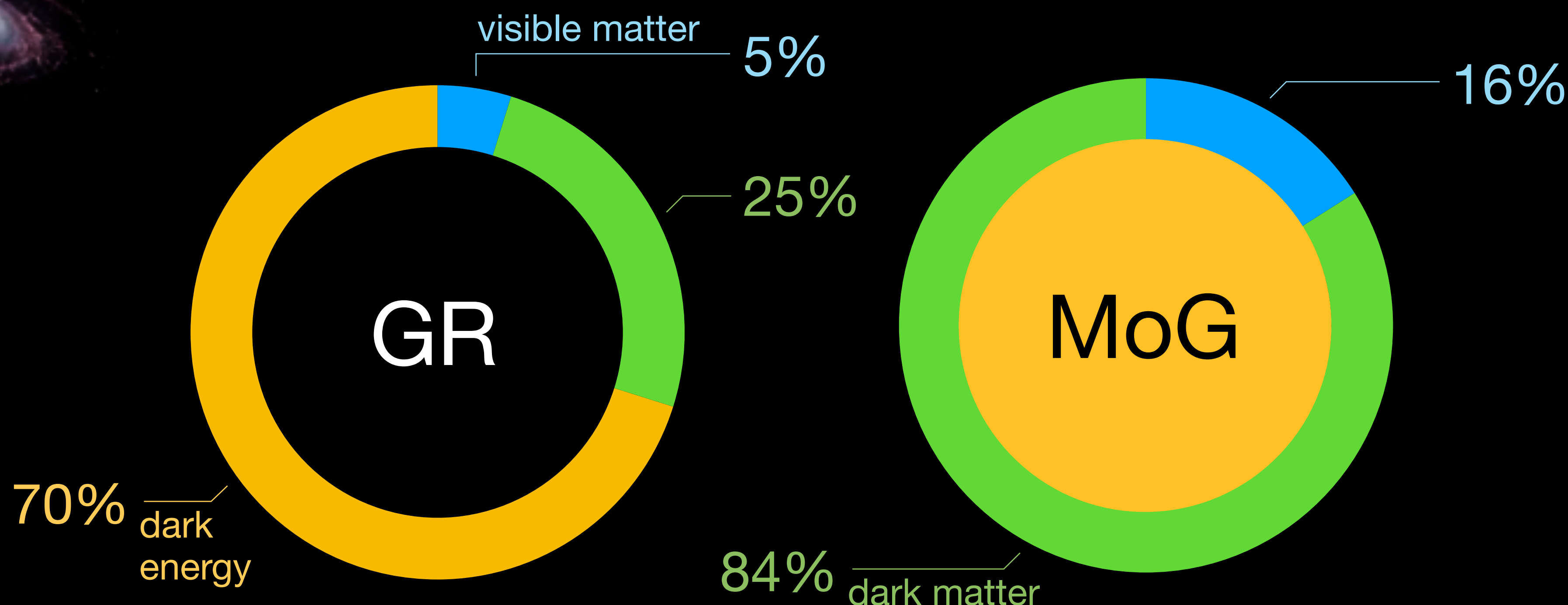
DARK ENERGY

MODIF. GRAVITY

LSS

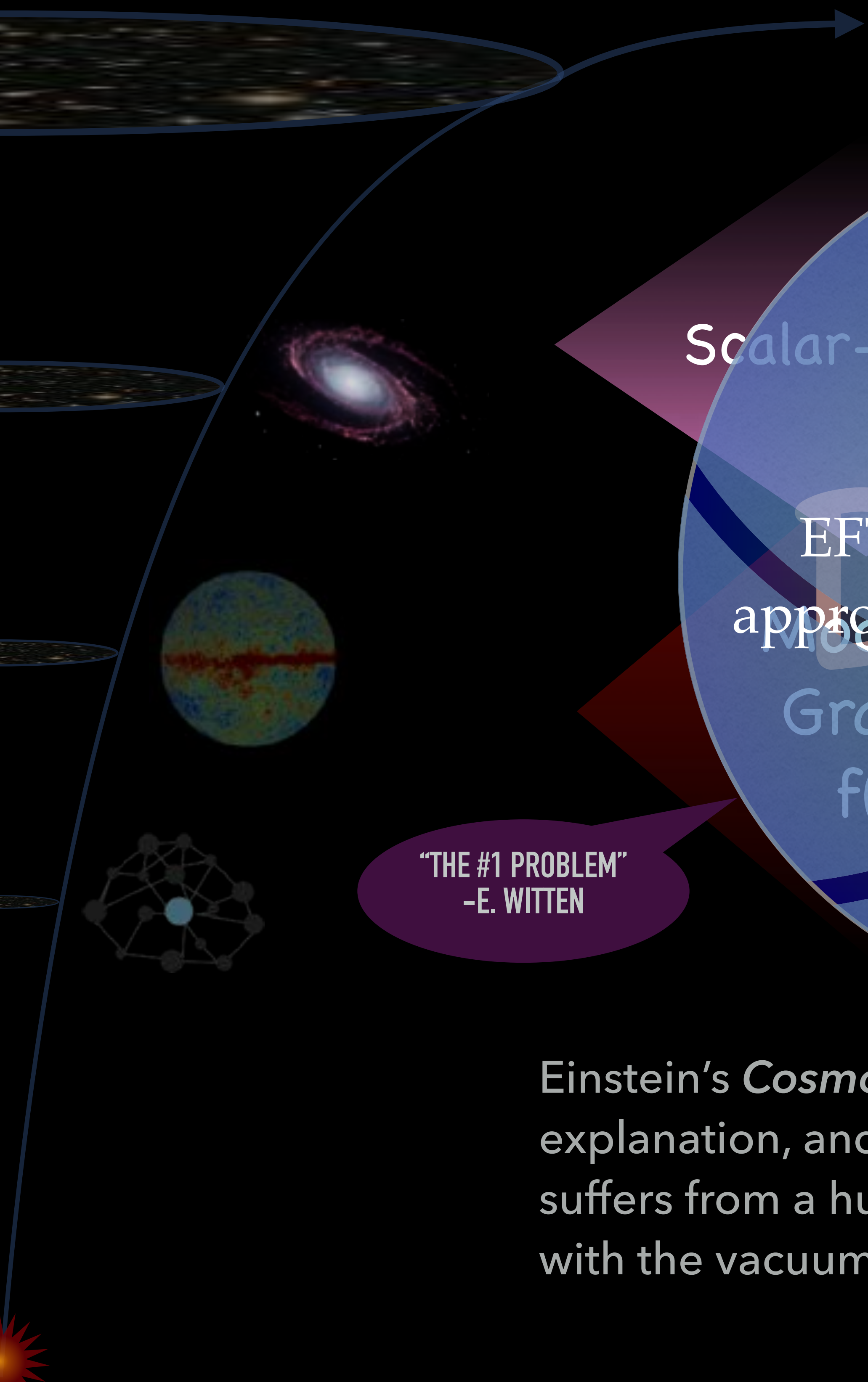
CMB

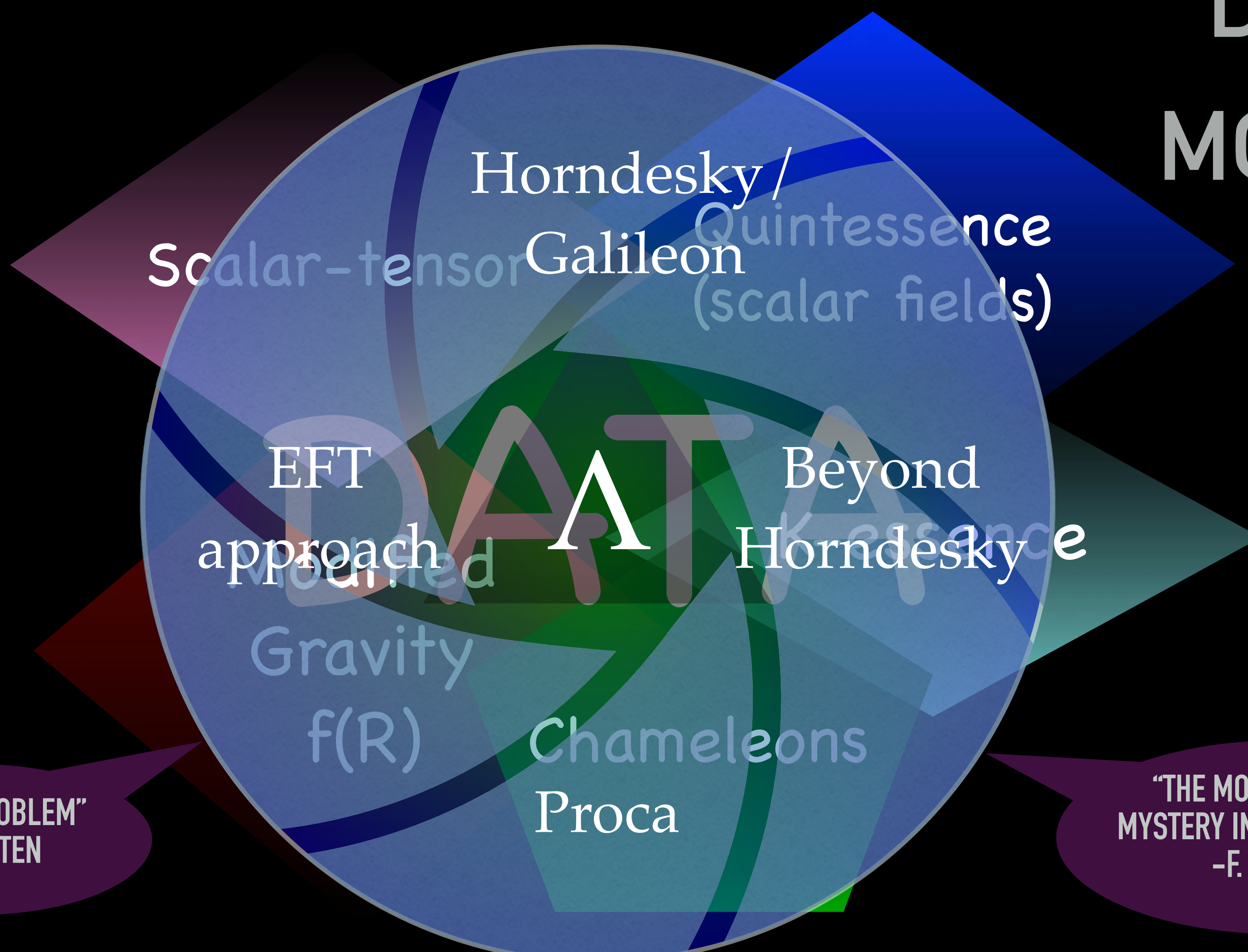
INFLATION



According to existing data, only a small fraction of our Universe is made of ***visible matter***: if ***dark energy*** accounts for cosmic acceleration, it makes up ~70% of the total. And, of course, there is still ***dark matter***…

DARK ENERGY OR MODIFIED GRAVITY?





DARK ENERGY

MODIF. GRAVITY

LSS

CMB

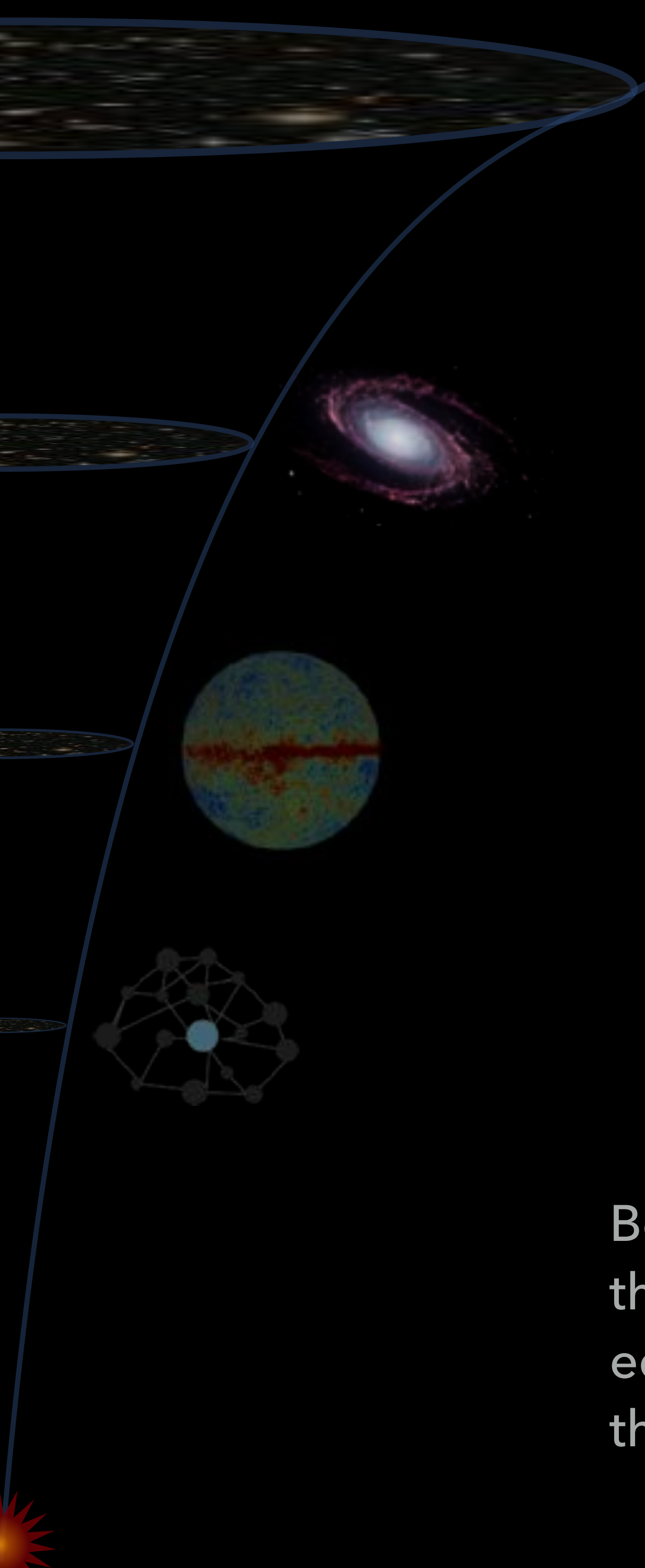
INFLATION

"THE #1 PROBLEM" -E. WITTEN

"THE MOST PROFOUND MYSTERY IN BASIC SCIENCE" -F. WILCZEK

Einstein's *Cosmological Constant (Λ)* is still the simplest explanation, and is ***consistent with all data.*** However, it suffers from a huge ***naturalness*** problem, compared with the vacuum energies arising from the SM

DARK ENERGY OR MODIFIED GRAVITY?



$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + 8\pi G T^{E}_{\mu\nu}$$

$$\Delta G\mu\nu + G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

DARK ENERGY

MODIF. GRAVITY

LSS

CMB

SAME MATTER, DIFFERENT GRAVITY

$$\nabla^2 \Phi = \frac{16\pi G}{3}\delta\rho - \frac{1}{6}\delta R(f_R)$$

Both ***dark energy*** and ***modified gravity*** can describe the same expansion history (w/ identical Friedmann equations), but changing gravity's laws also affects the ***Poisson equation*** and the ***geodesic equations***

INFLATION

DARK ENERGY OR MODIFIED GRAVITY?

DARK ENERGY

MODIF. GRAVITY

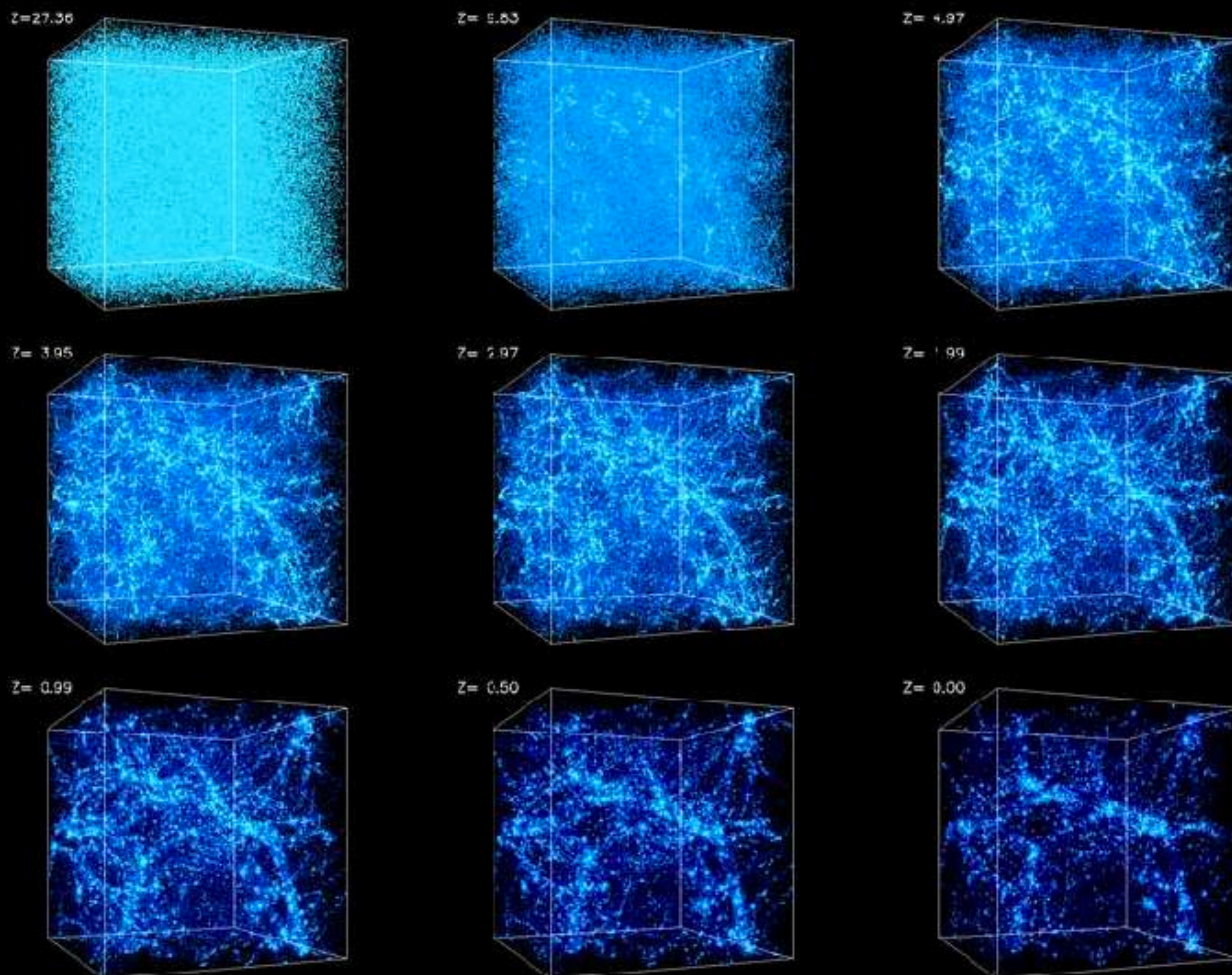
LSS

CMB

INFLATION

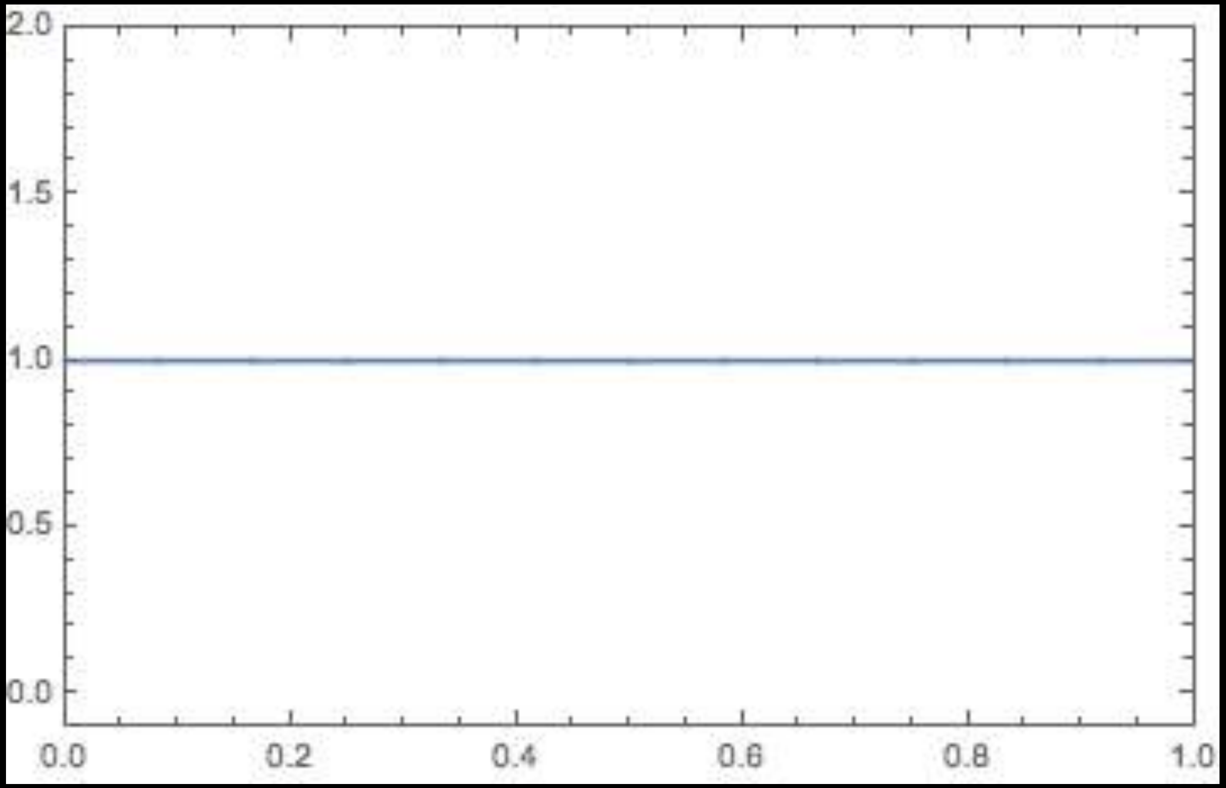
Today one of the greatest challenges in cosmology is to produce accurate *3D maps of the Universe*, where we can *measure cosmic acceleration*, *test gravity on large scales*, understand *how galaxies form and evolve*, and even *search for the influence of neutrinos*

THE VISIBLE AND THE INVISIBLE WEBS

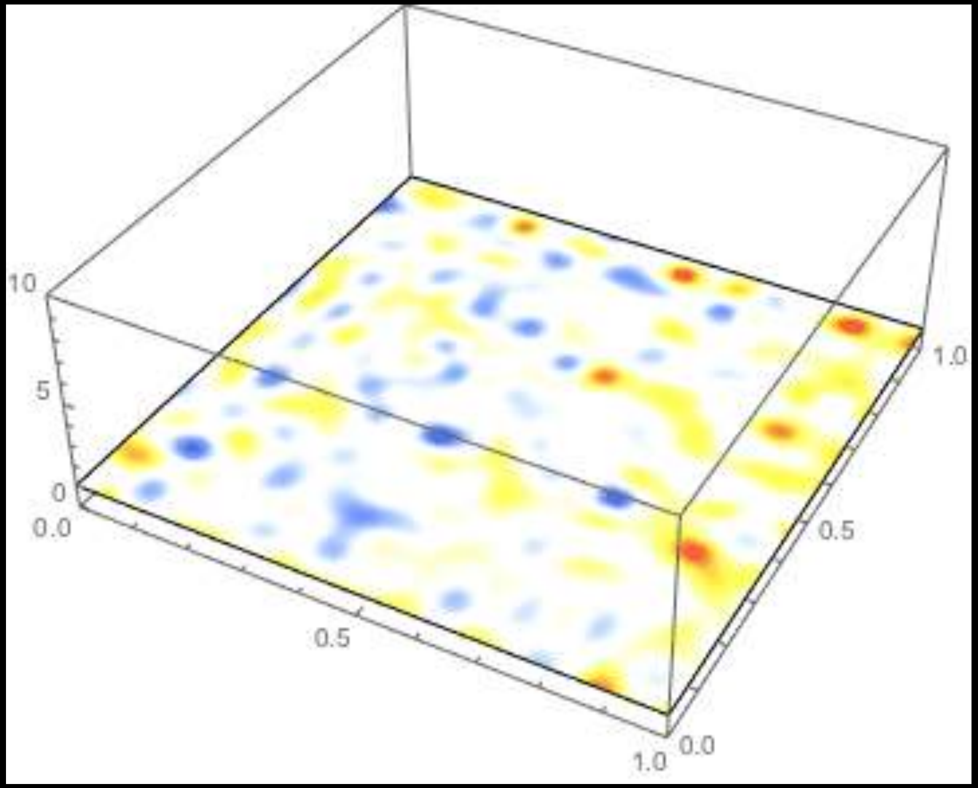


THE VISIBLE AND THE INVISIBLE WEBS

1D

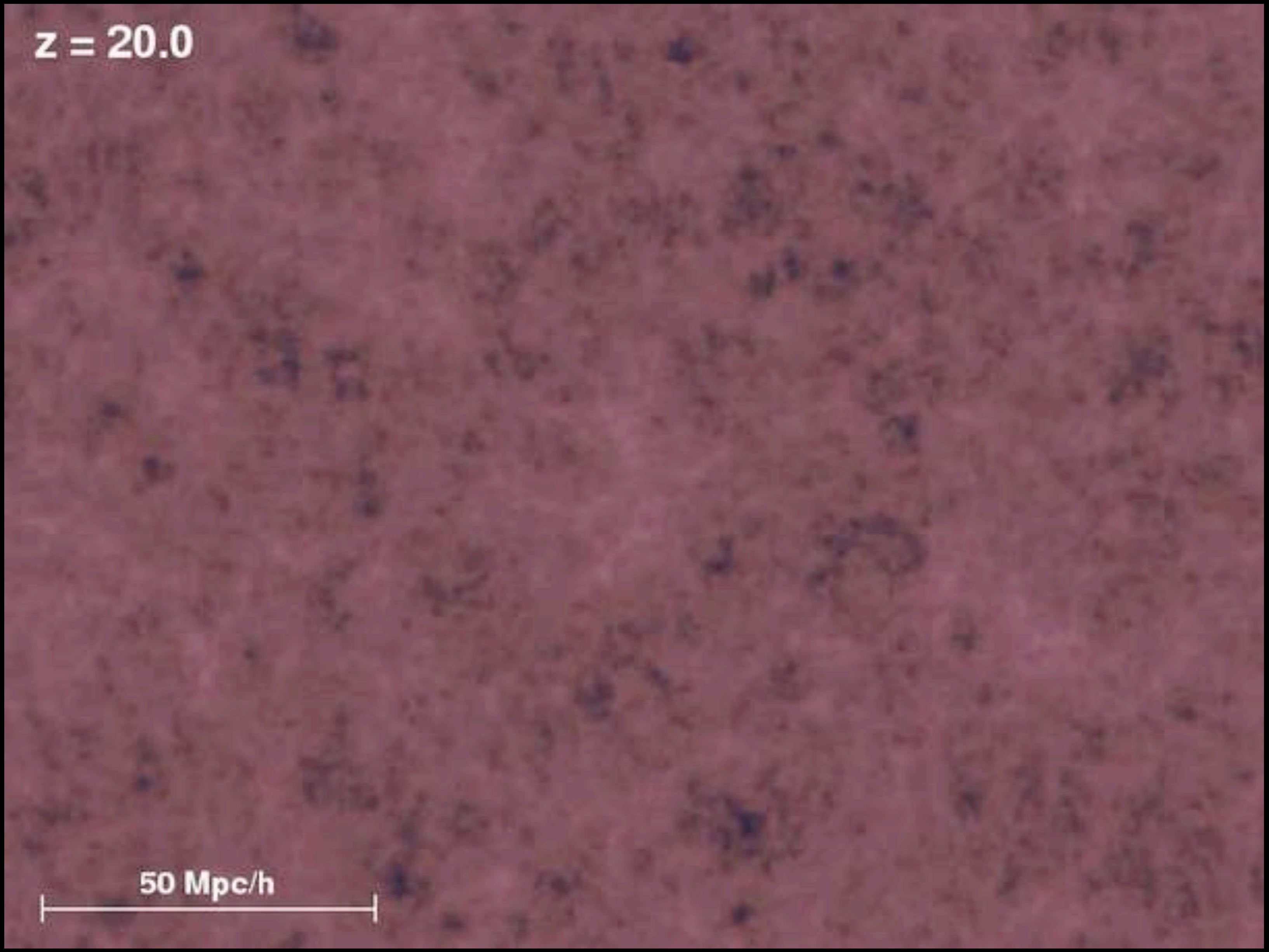


2D



Initially, density fluctuations are very small ($\delta\rho/\rho$ ~ 10^{-4}), and in this linear regime, structure formation proceeds at a moderate pace

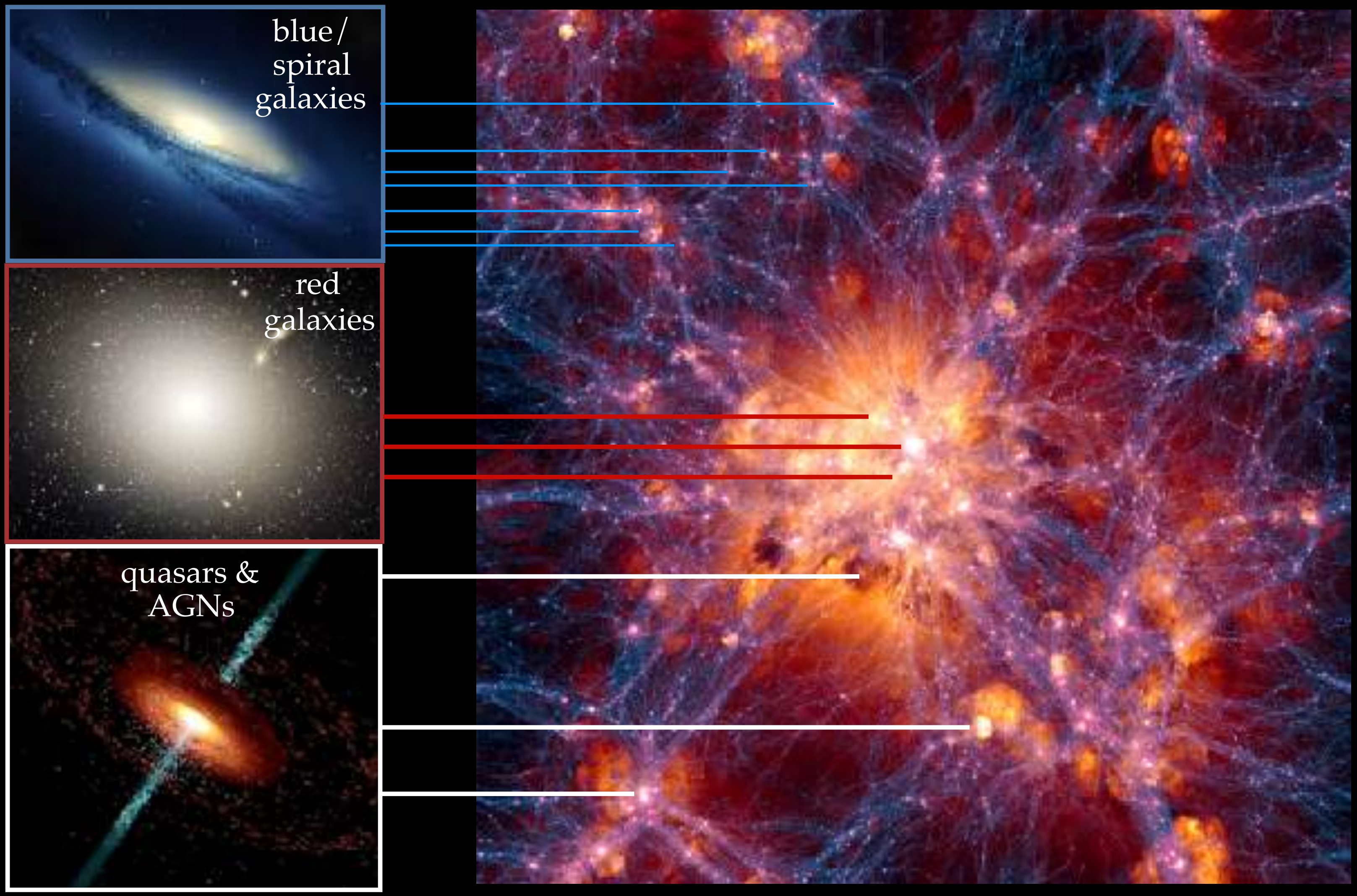
THE VISIBLE AND THE INVISIBLE WEBS



However, soon the linear regime fails to describe the growing concentration of matter in the initially overdense regions. Gravity is a relentless force ***driving inequality*** in the Universe.

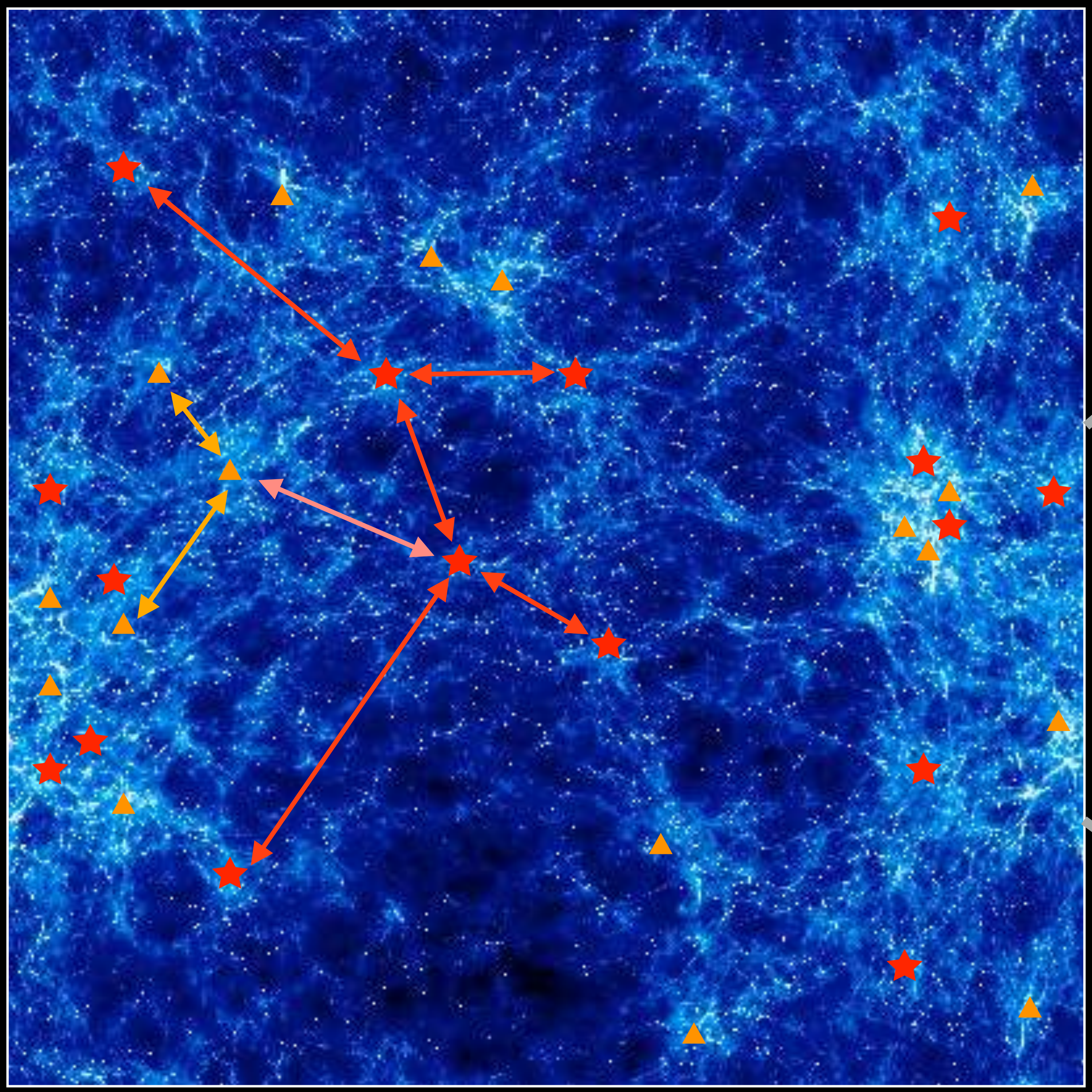
THE VISIBLE AND THE INVISIBLE WEBS

Visible v. Invisible structures

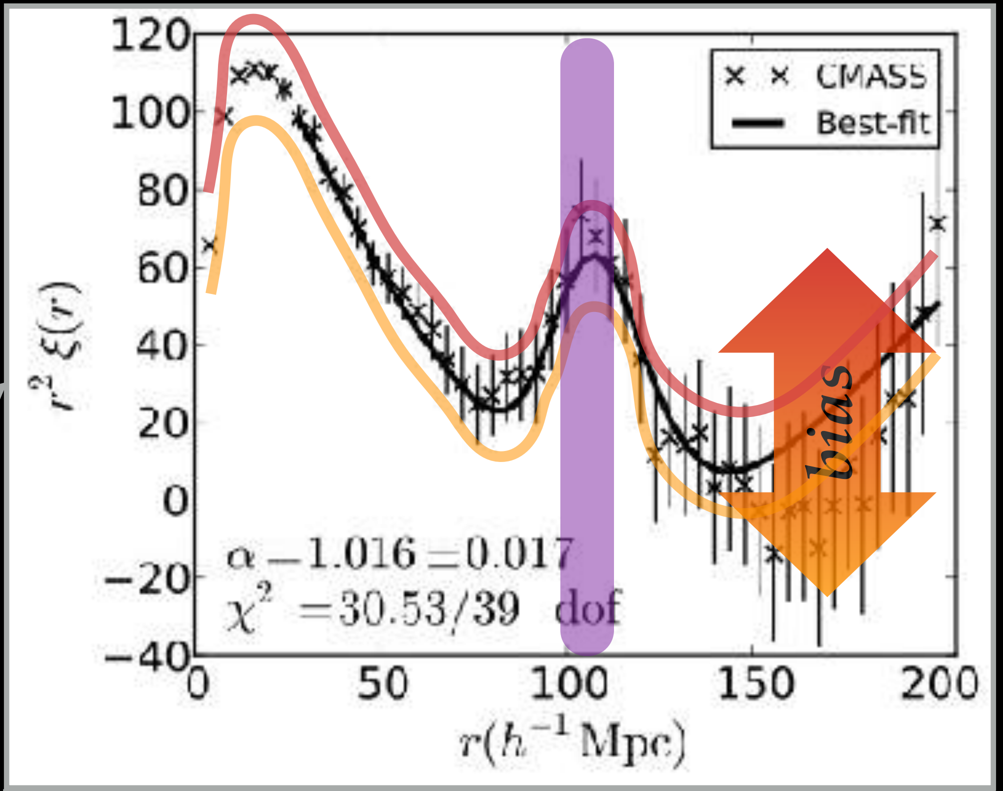


Dark matter is 5-6x more abundant than baryonic matter, therefore it often determines the gravitational wells where we also find luminous baryons– galaxies of all kinds, quasars, gas clouds, etc.

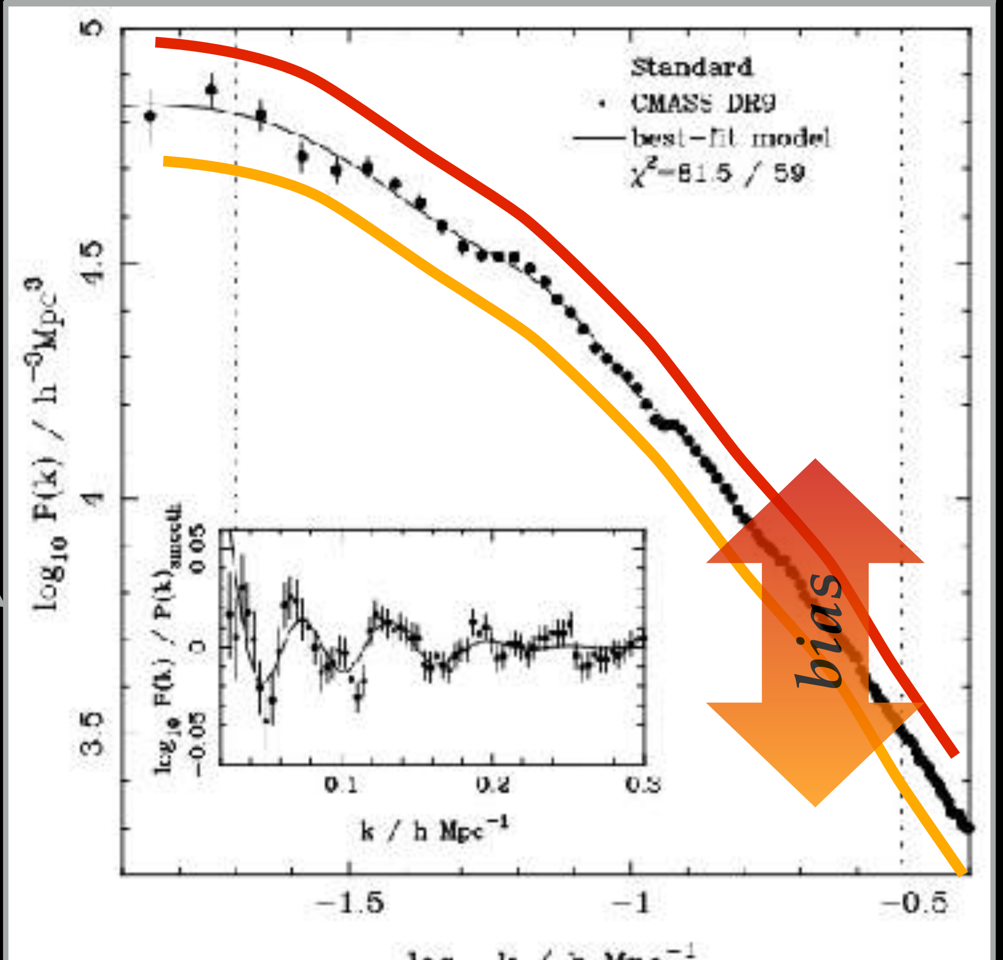
THE CLUSTERING OF MATTER



Clustering in position space



Clustering in Fourier space

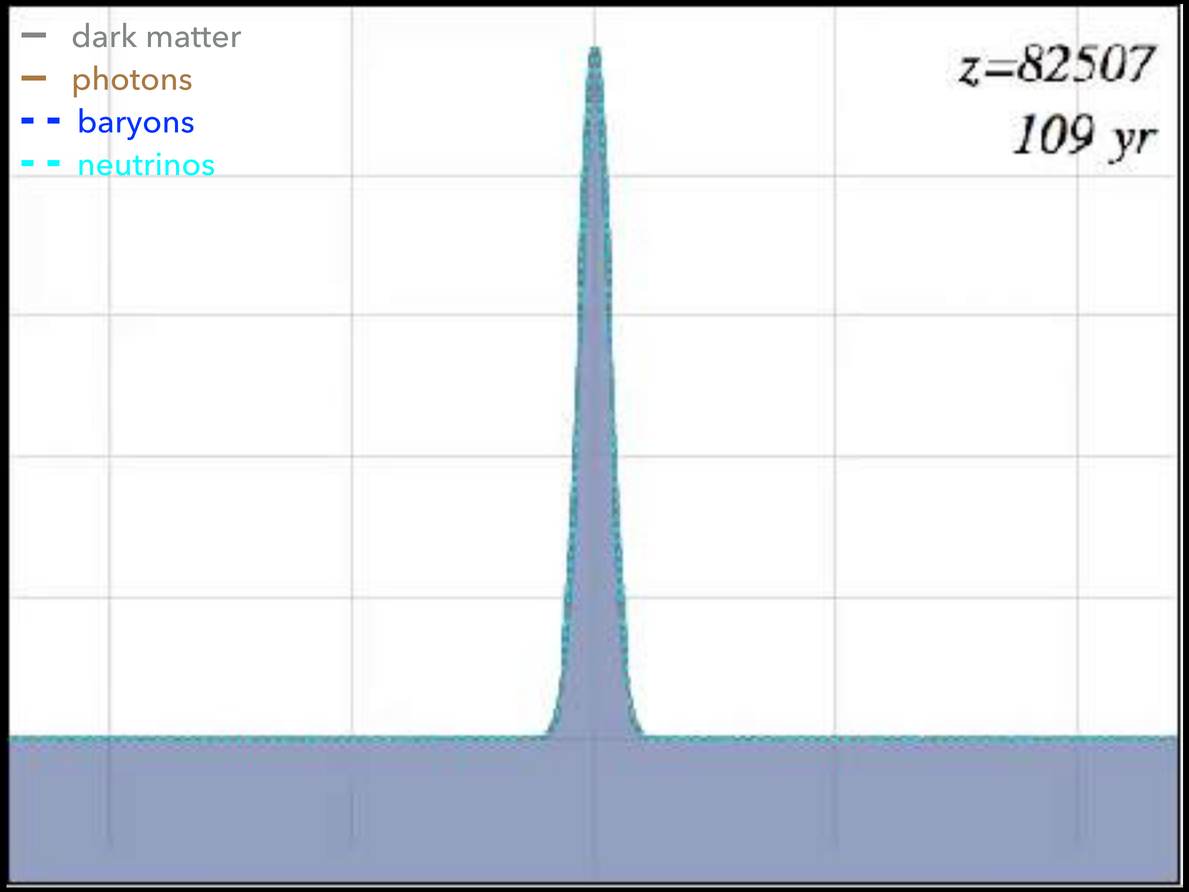


BOSS, Sánchez et al. 2017

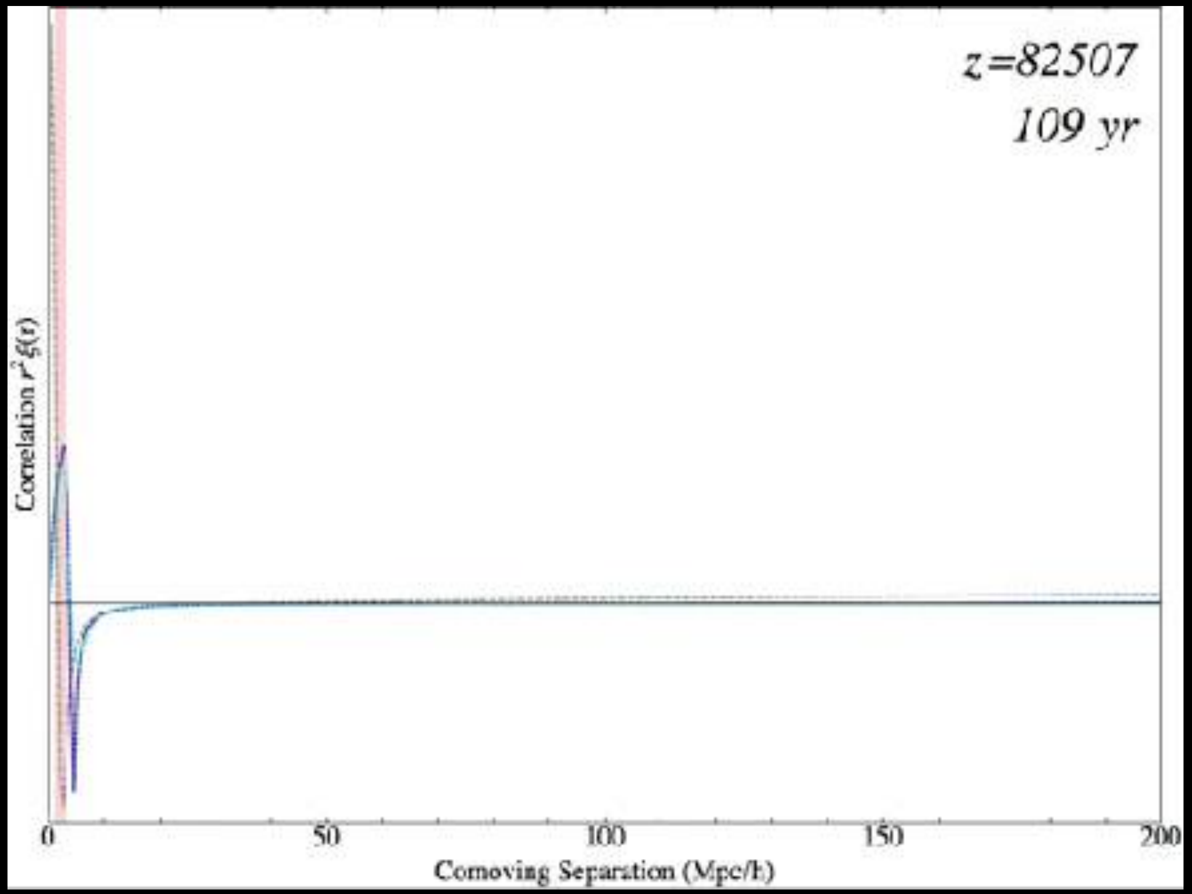
Galaxies serve as *tracers* of the dense regions of the Universe, where we find more matter. Although their *absolute* positions are irrelevant, their *relative positions* tells us about *clustering*

ECHOS FROM THE PAST

single density peak



correlation function



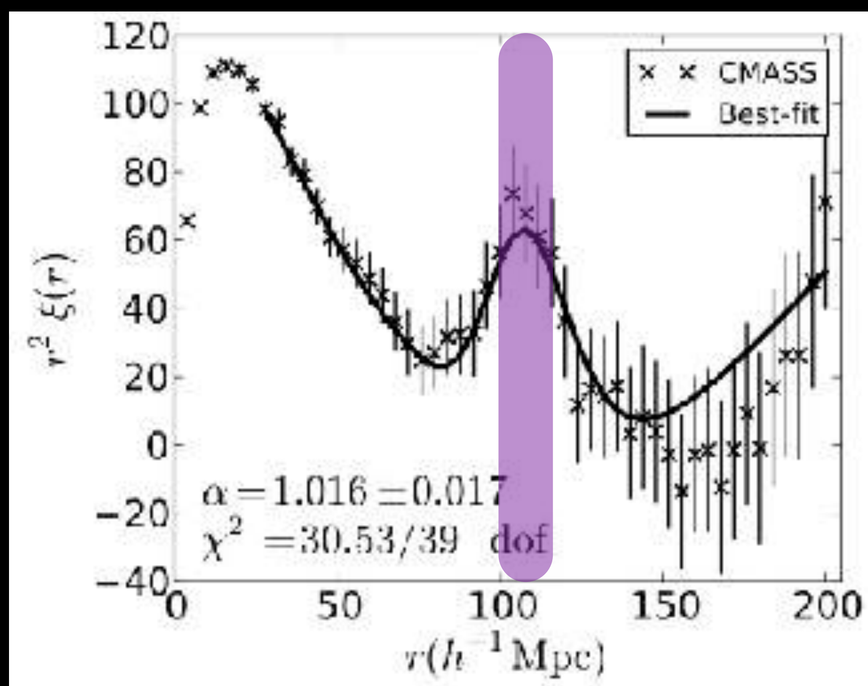
D. Eisenstein

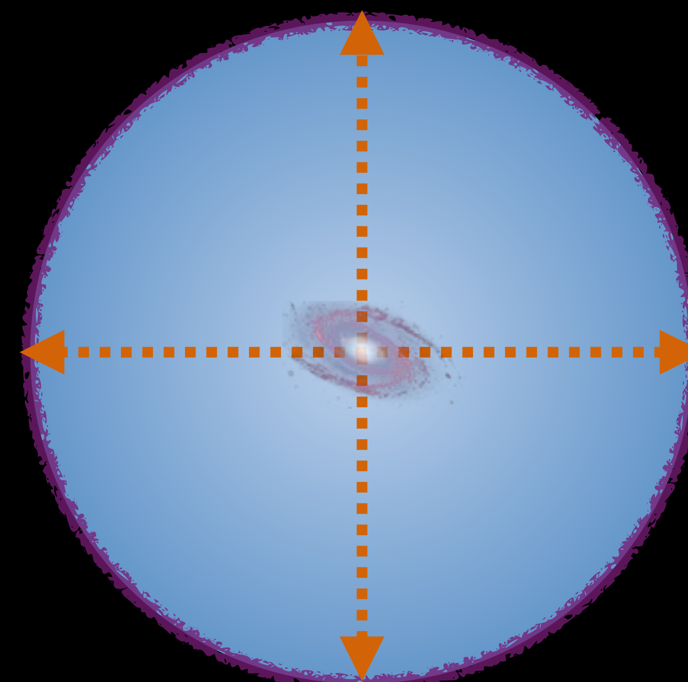
The feature in the correlation function at $r \sim 105\ h^{-1}$ Mpc arises from the ***acoustic horizon*** for the photon-baryon fluid during recombination (decoupling), at ***z~1100***.

In Fourier and Harmonic Space this translates into oscillations, hence the name: *Baryon Acoustic Oscillations (BAOs)*

OBSERVING THE BARYON ACOUSTIC OSCILLATIONS

$$\Delta r = \frac{c}{H(z)} \Delta z$$



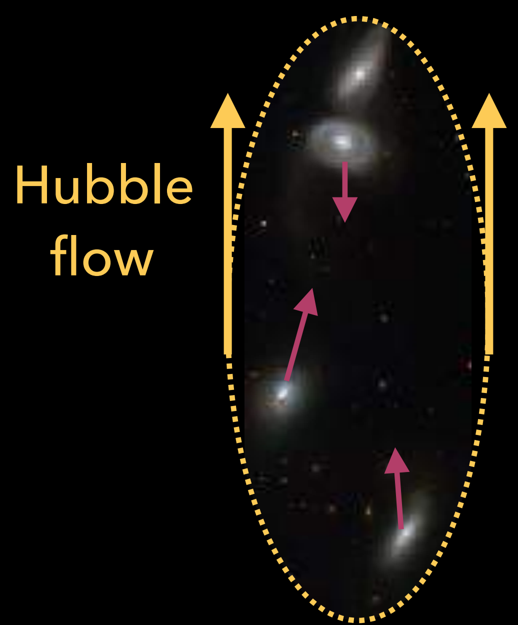


$$\Delta r = d_A\, \Delta\theta$$

BAOs are a statistical standard ruler: we expect *extra clustering* on scales L_{BAO}=(147.7±0.7) Mpc .

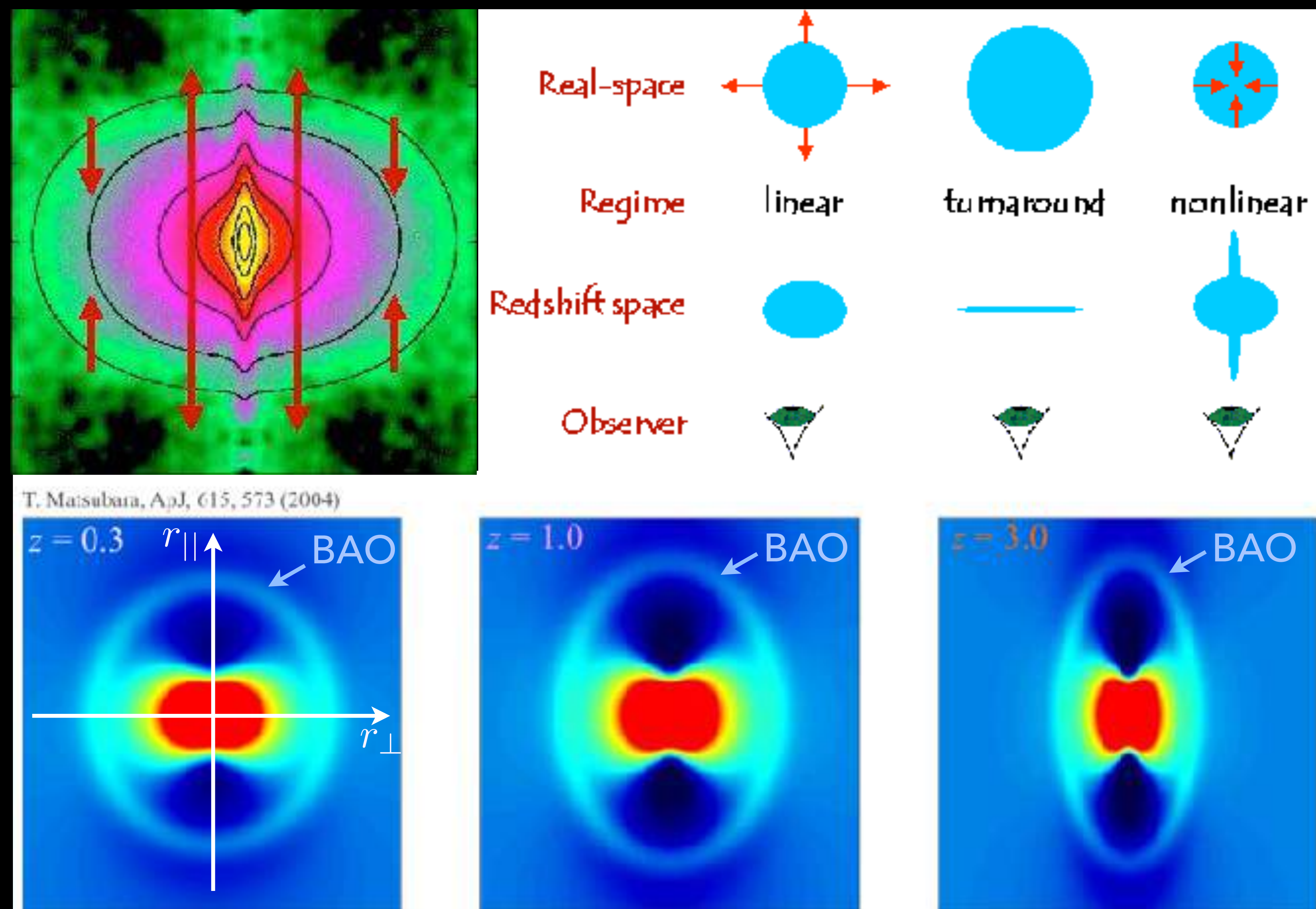
Planck 2018

REDSHIFT-SPACE DISTORTIONS



$$\xi(r) \rightarrow \xi_{obs}(r_\perp, r_{||})$$

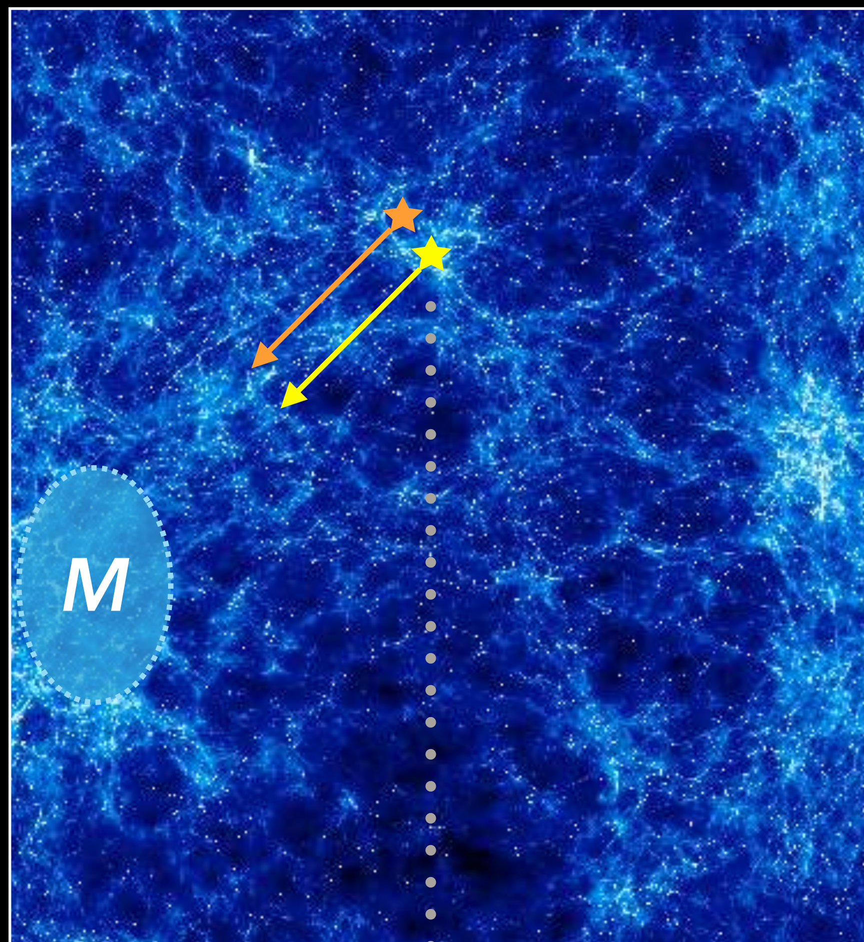
N. Kaiser 1984

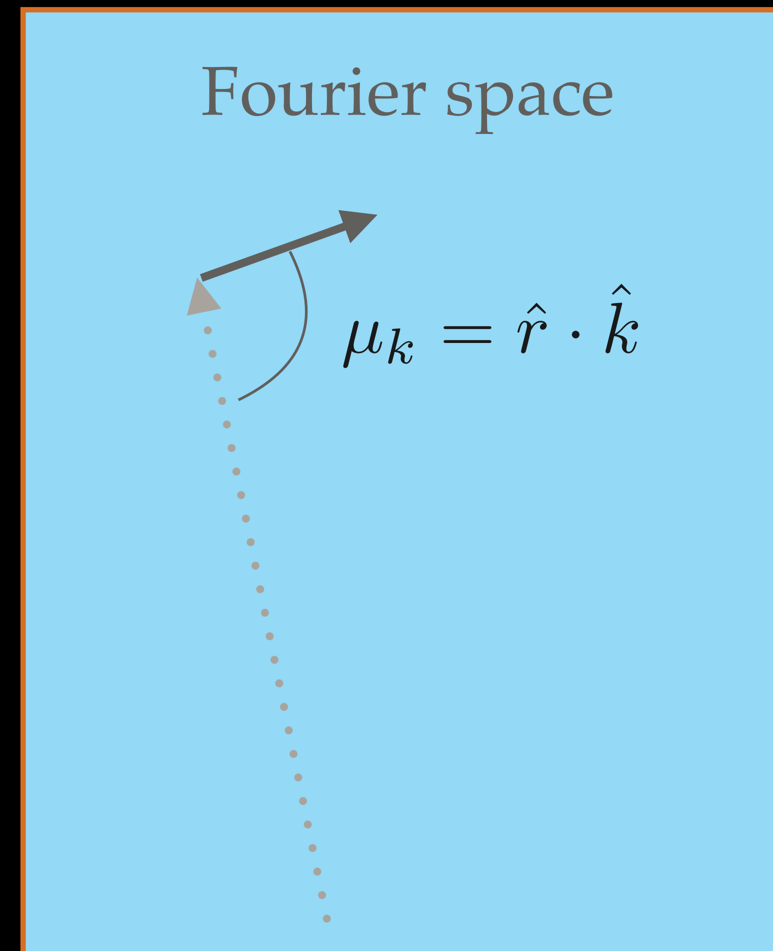


The *radial positions* to distant galaxies are inferred from their *redshifts*. Hence, we cannot distinguish between the Hubble flow and the peculiar velocities

This is the origin of the *redshift-space distortions* (RSDs) in the 2-pt correlation function and power spectrum, which become *anisotropic*

STRUCTURE FORMATION AND THE EQUIVALENCE PRINCIPLE



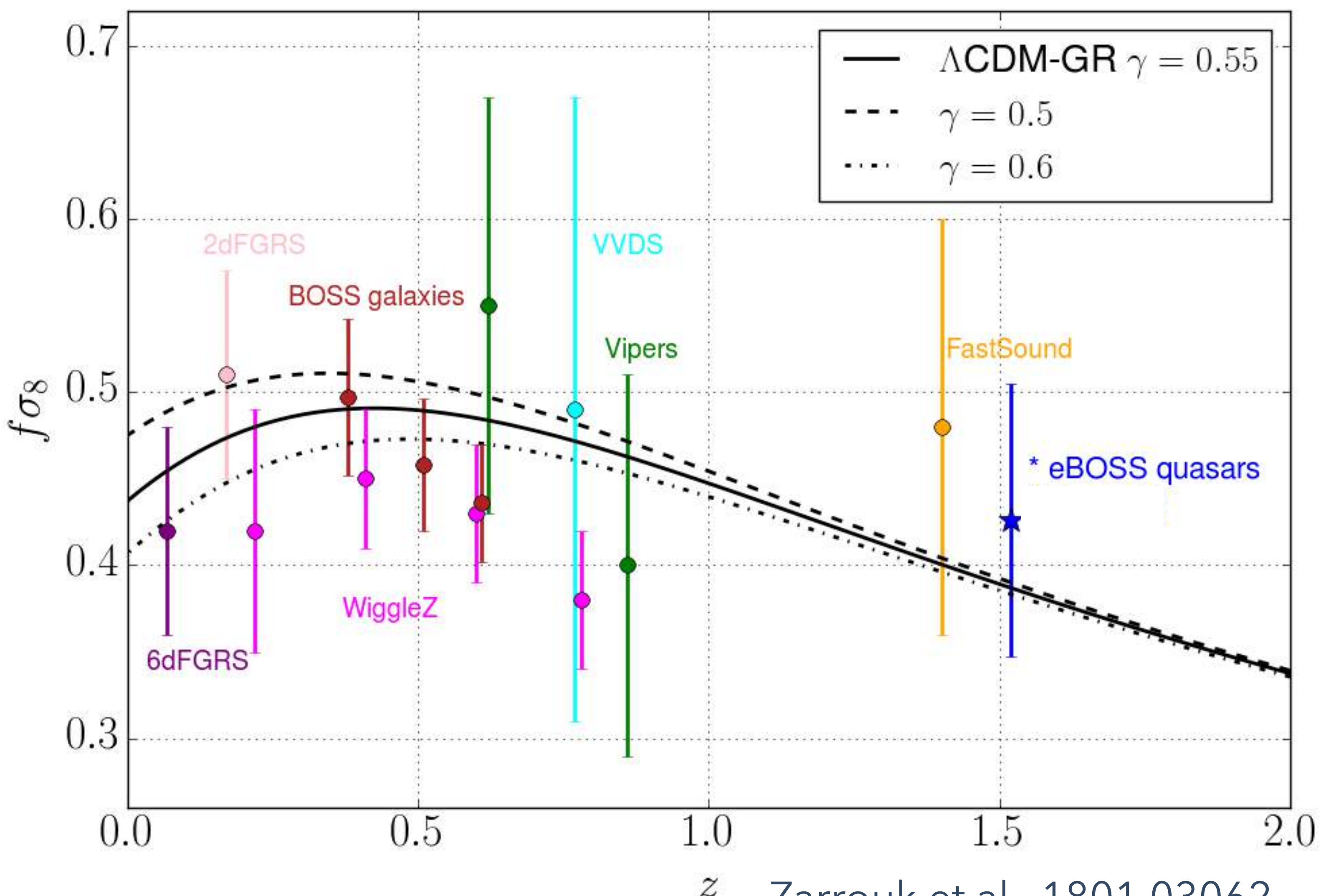


The ***velocity field*** reflects the gravitational force in an ***unbiased*** way

$$P_g(k) \simeq \left(b_g + \underline{f \mu_k^2}\right)^2 P_m(k)$$

N. Kaiser '87
Guzzo et al. '04
Percival & White '09
Raccanelli et al. '13
+

STRUCTURE FORMATION AND THE EQUIVALENCE PRINCIPLE



Zarrouk et al., 1801.03062

Peculiar velocities, RSDs

➠ matter growth rate f

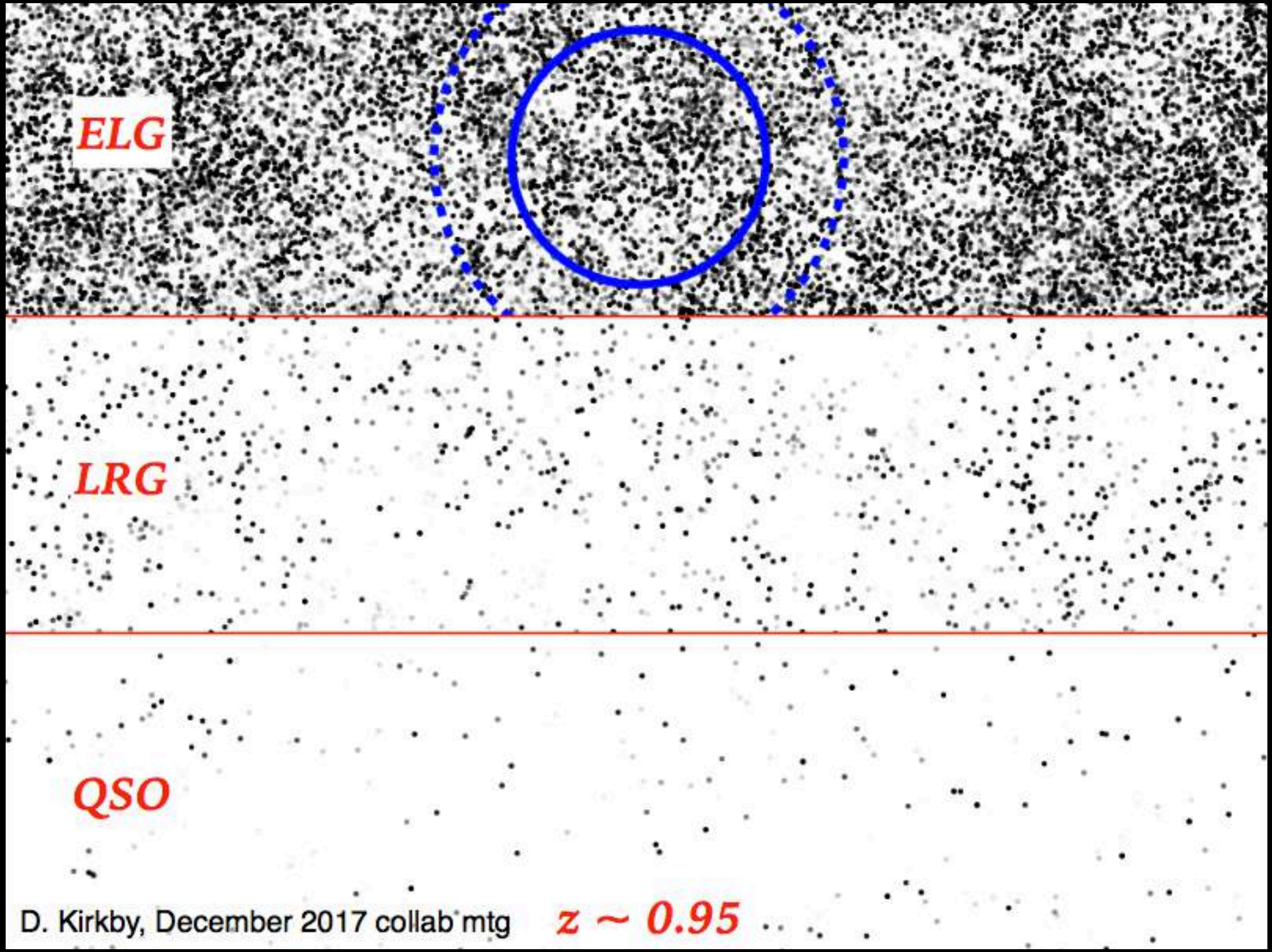
$$f = \frac{d\ln G}{d\ln a} \simeq \Omega_m^\gamma$$

$$P_g(k) \simeq \left(b_g + f\mu_k^2\right)^2 P_m(k)$$

$$= (\underline{b_g\sigma_8} + \underline{f\sigma_8}\,\mu_k^2)^2 \frac{P_m(k)}{\sigma_8^2}$$

The matter growth rate (f) is partly degenerate with galaxy bias (b_g), and both are degenerate with the amplitude of the power spectrum (σ_8)

THERE ARE MANY TRACERS OF LARGE-SCALE STRUCTURE…



THERE ARE MANY TRACERS OF LARGE-SCALE STRUCTURE…

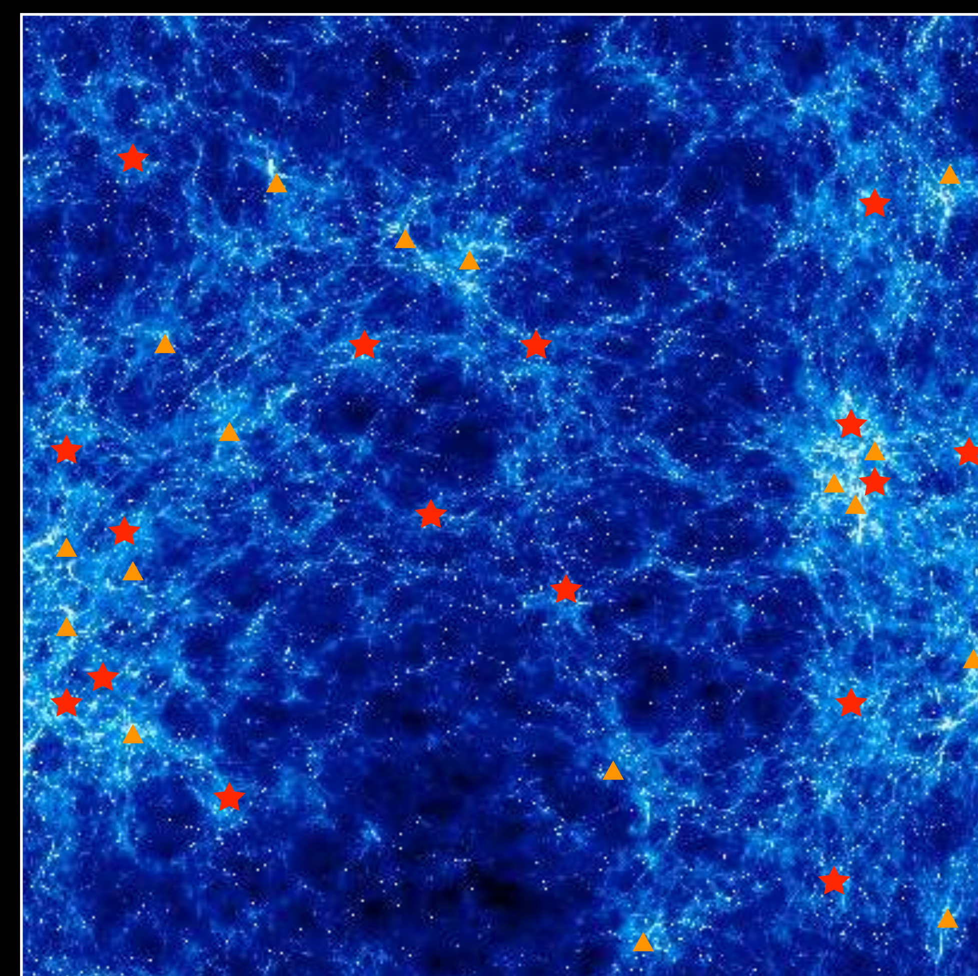
By contrasting the clustering of many ***tracers of large-scale structure*** we can ***beat cosmic variance***, and measure some parameters with high accuracy:

$$P_1 = (b_1 + f\mu_k^2) P_m(k;z)$$

$$P_2 = (b_2 + f\mu_k^2) P_m(k;z)$$

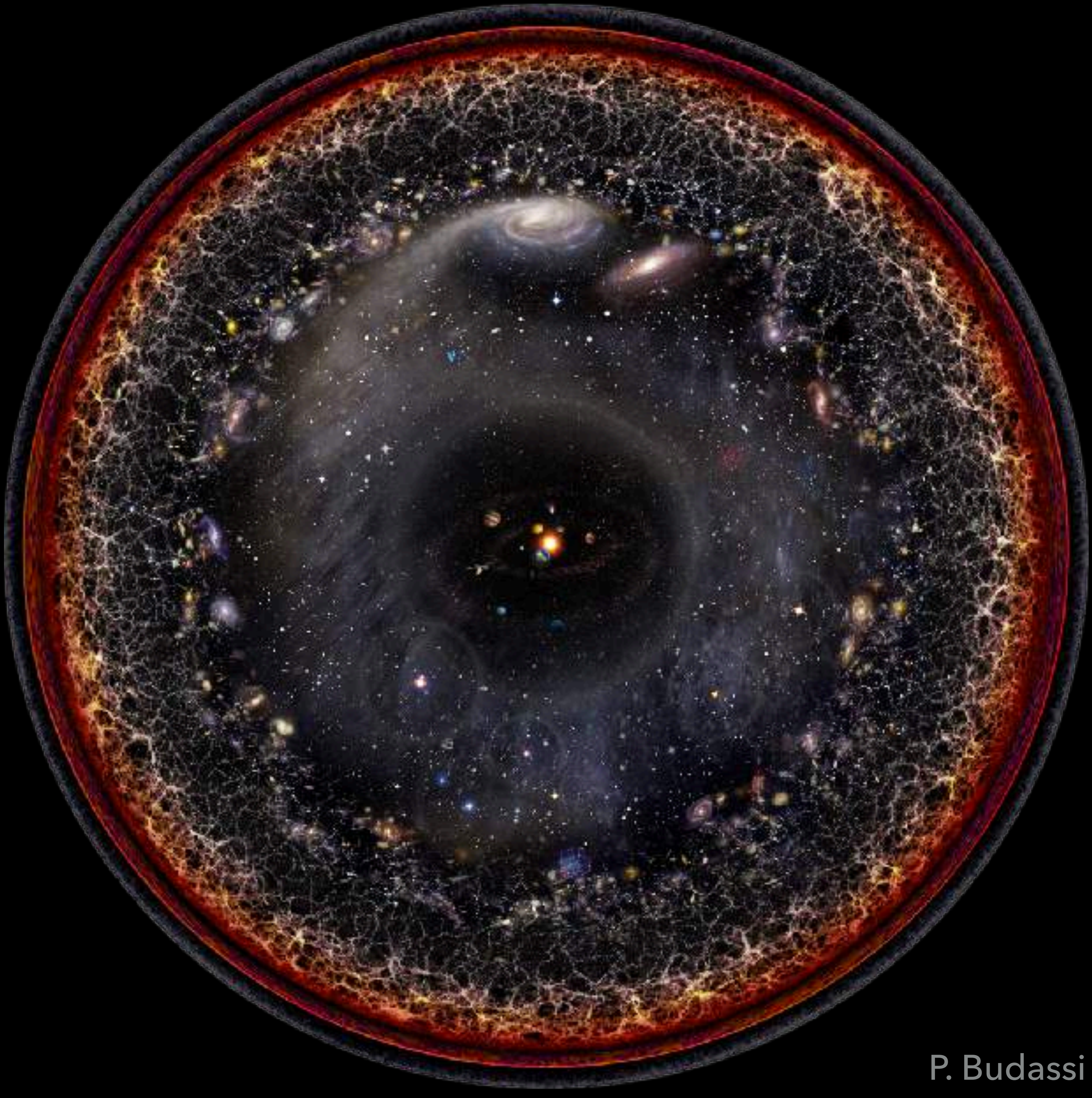
$$\frac{P_1}{P_2} = \frac{(b_1 + f\mu_k^2)}{(b_2 + f\mu_k^2)}$$

The key is ***high numbers*** of distinct types of tracers: red galaxies, blue galaxies, emission-line galaxies, quasars, neutral H regions (21cm); DM halos; …



Seljak '08 , Gil-Marín et al. '11
R.A. '12 , R.A. & Leonard '13
R.A. Secco & Loureiro '16
Bull et al. ' 16 , Fonseca et al. '16

THE OBSERVABLE UNIVERSE

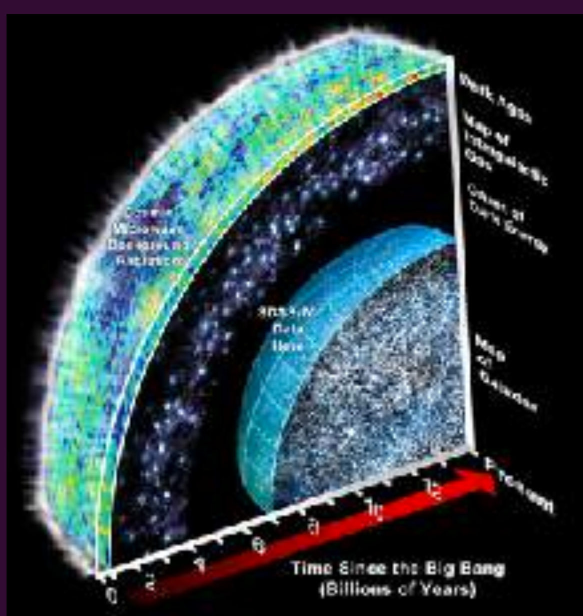


P. Budassi

SURVEYS: PAST, PRESENT AND FUTURE

Recent past and near future

SDSS



✔

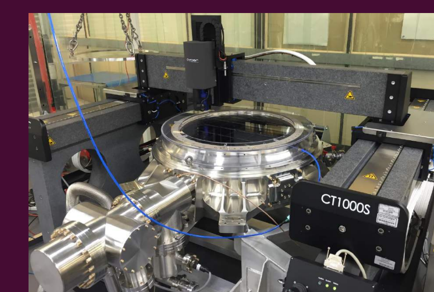
DES

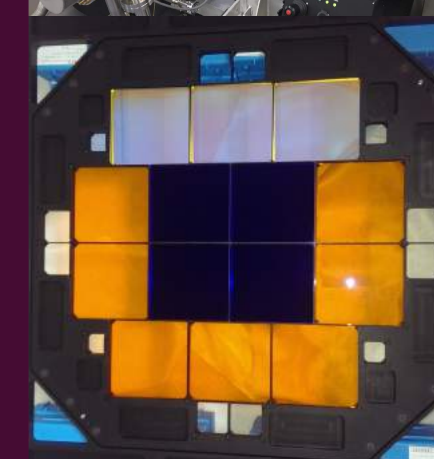
✔

SuMIRe

Prime Focus Spectrograph

J-PAS



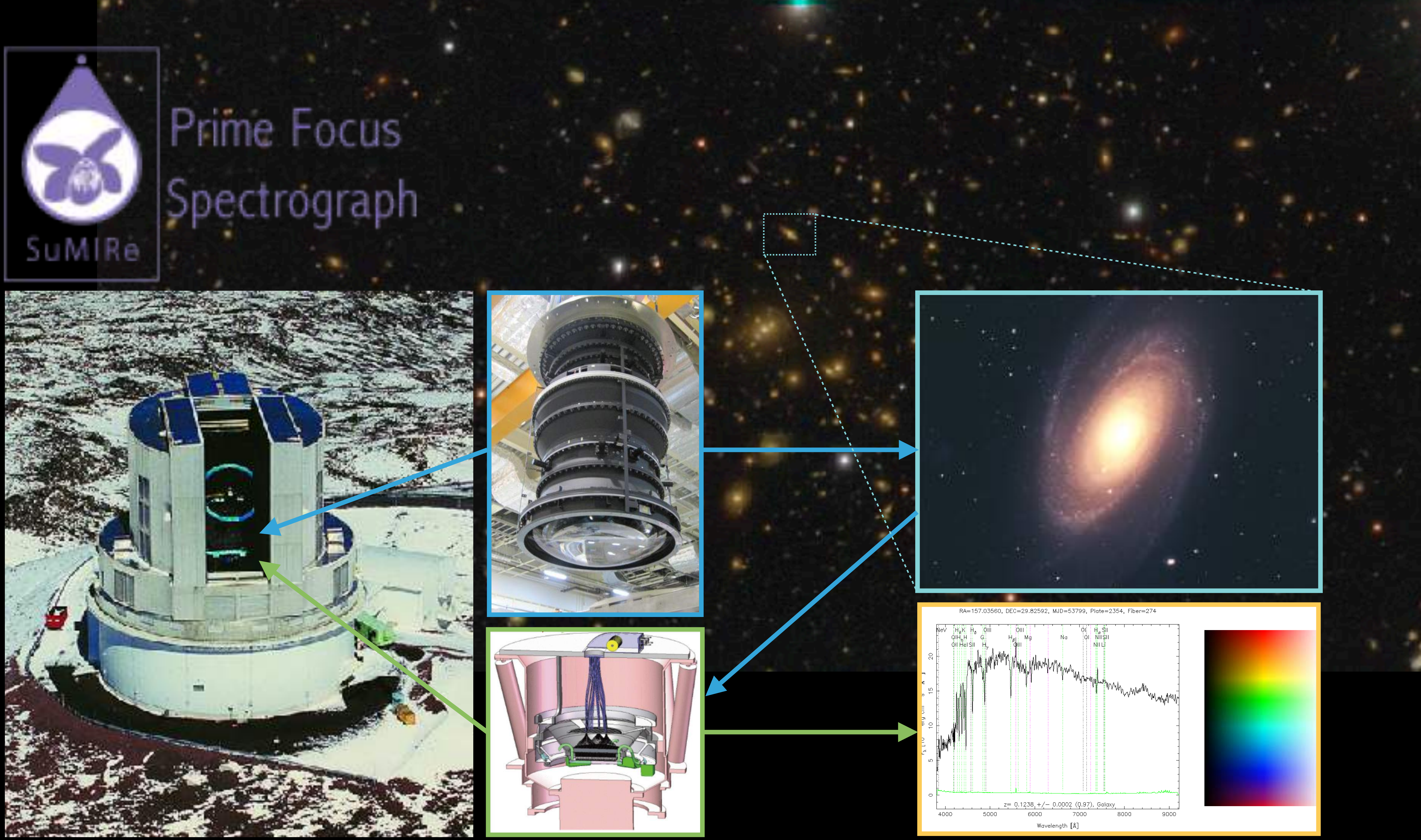


Surveys of the future

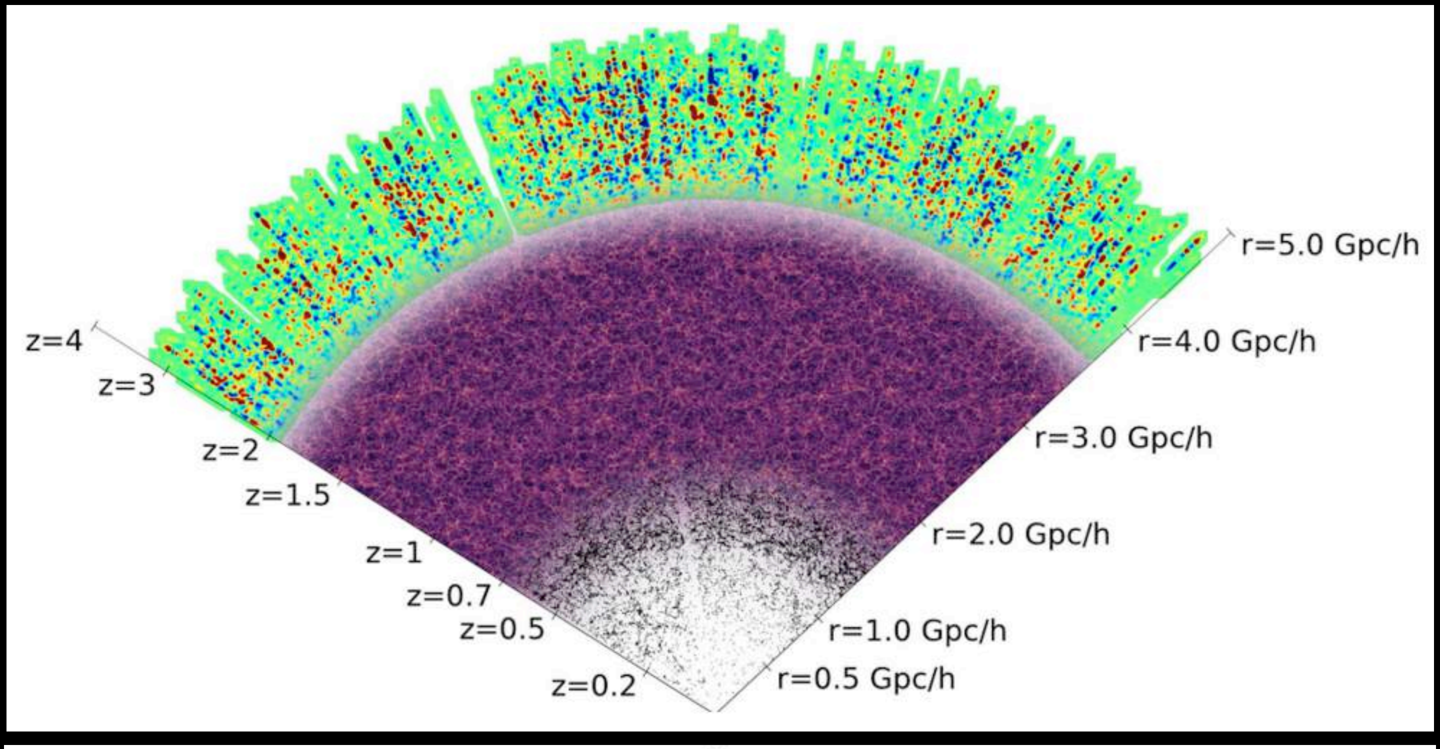
DESI

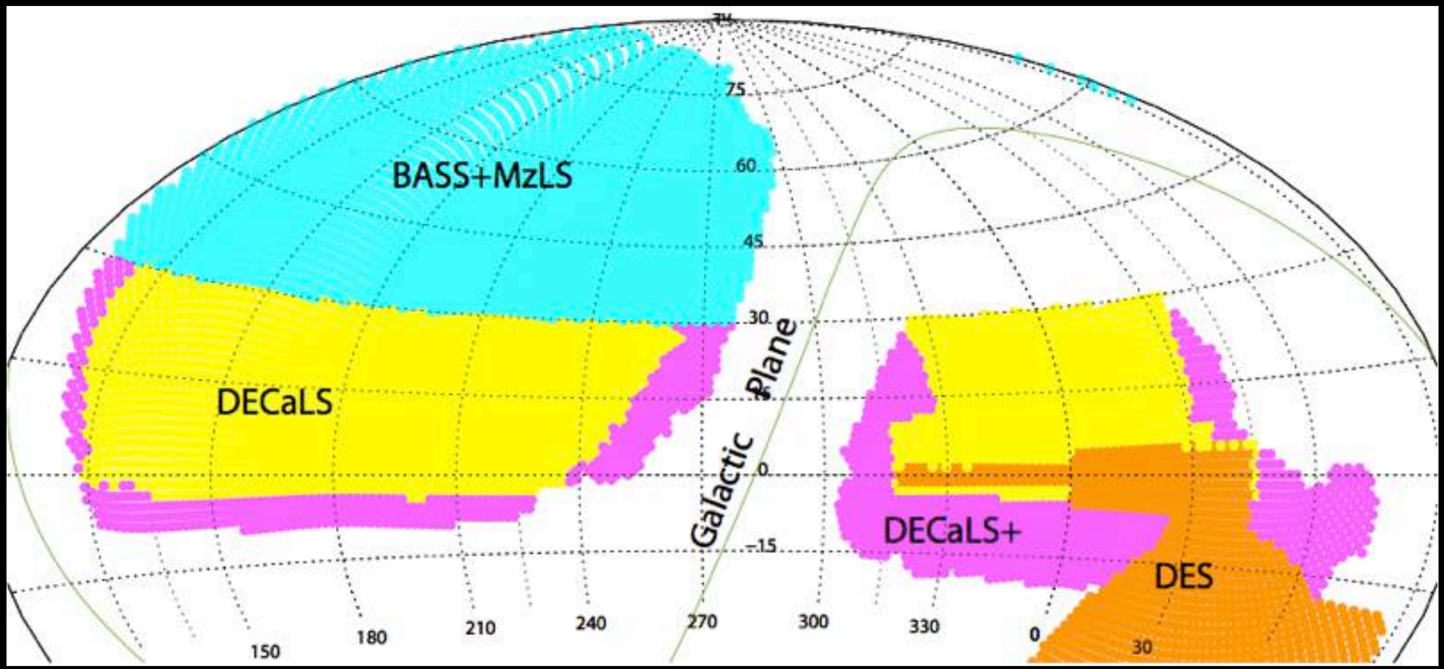
euclid

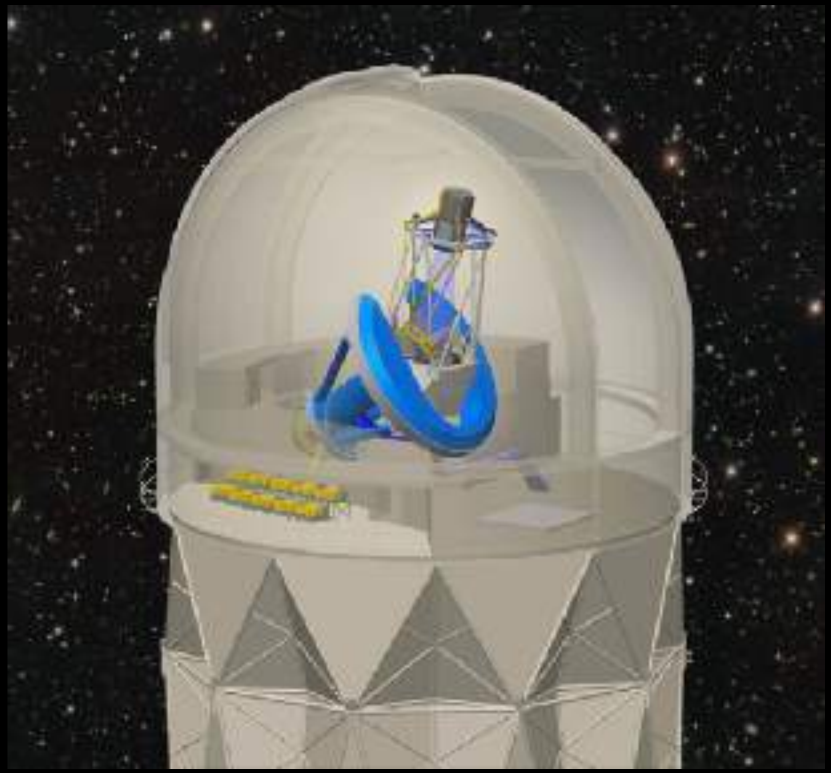
PFS: PRIME FOCUS SPECTROGRAPH



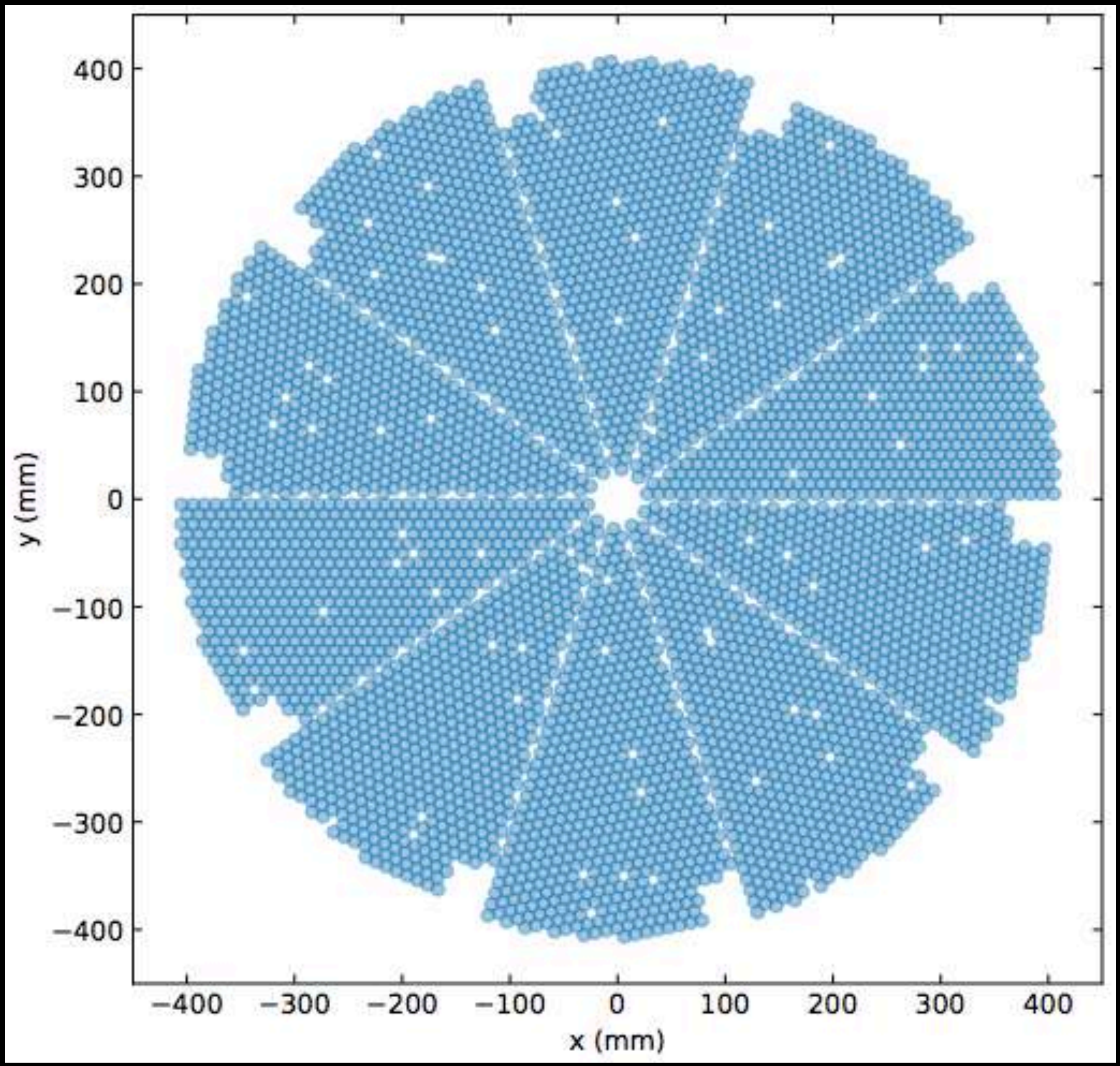
DESI: DARK ENERGY SPECTROSCOPIC INSTRUMENT

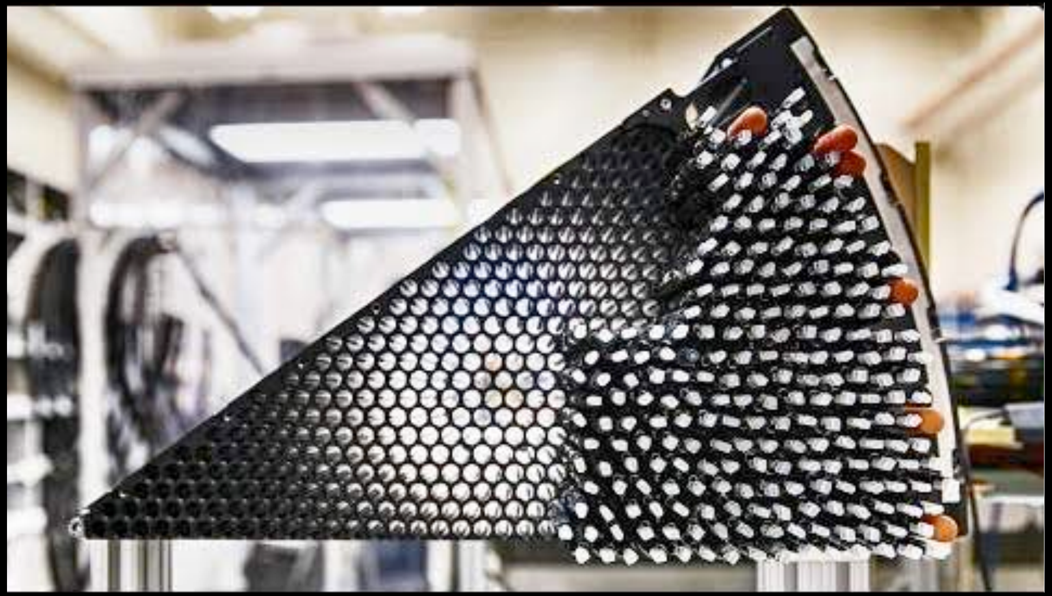






FIBER SPECTROGRAPHS (. . . , PFS, DESI, WEAVE, 4MOST)





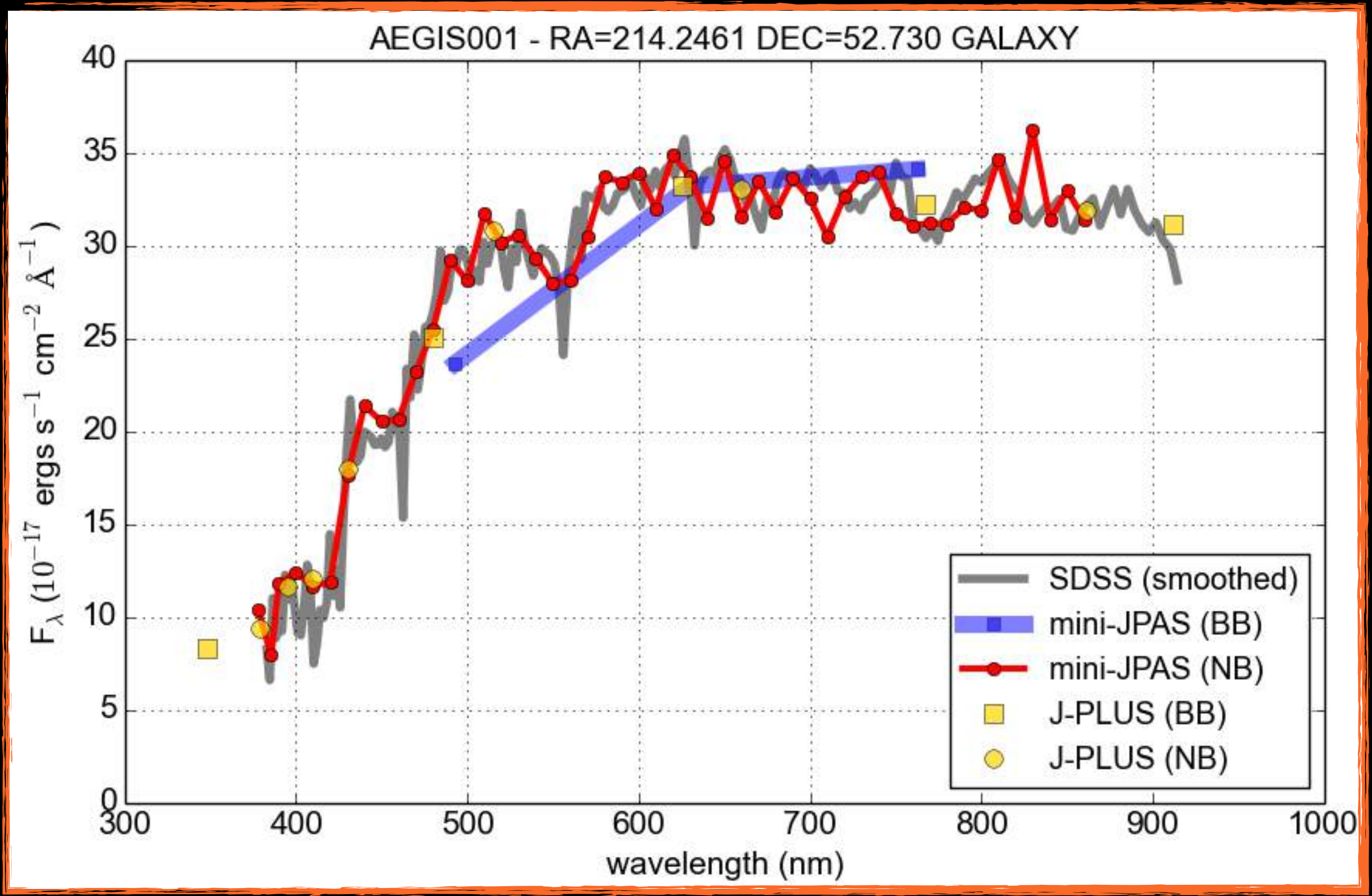
J-PAS (FIRST LIGHT: FEW MONTHS!)

J-PAS: IMAGING MEETS SPECTROSCOPY

No spectra: ***pseudo*****spectra**

imaging in 54 narrow-band filters (+BBs)

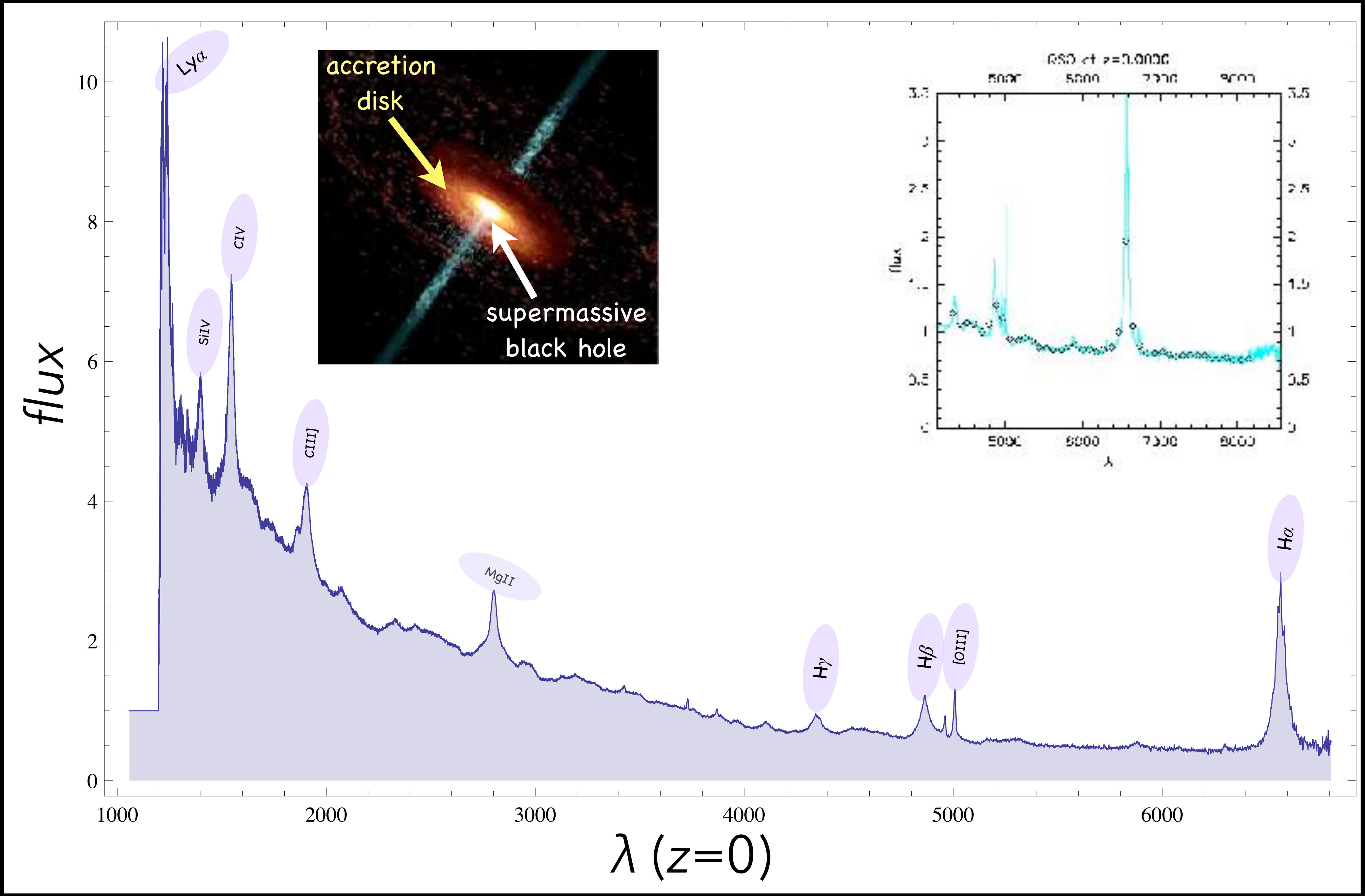
➩ **everything to r<~23**



- ➩ Dark energy/MoG
- ➩ Galaxy evolution
- ➩ LSS (BAOs & RSDs)
- ➩ Supernovas
- ➩ Clusters
- ➩ QSOs

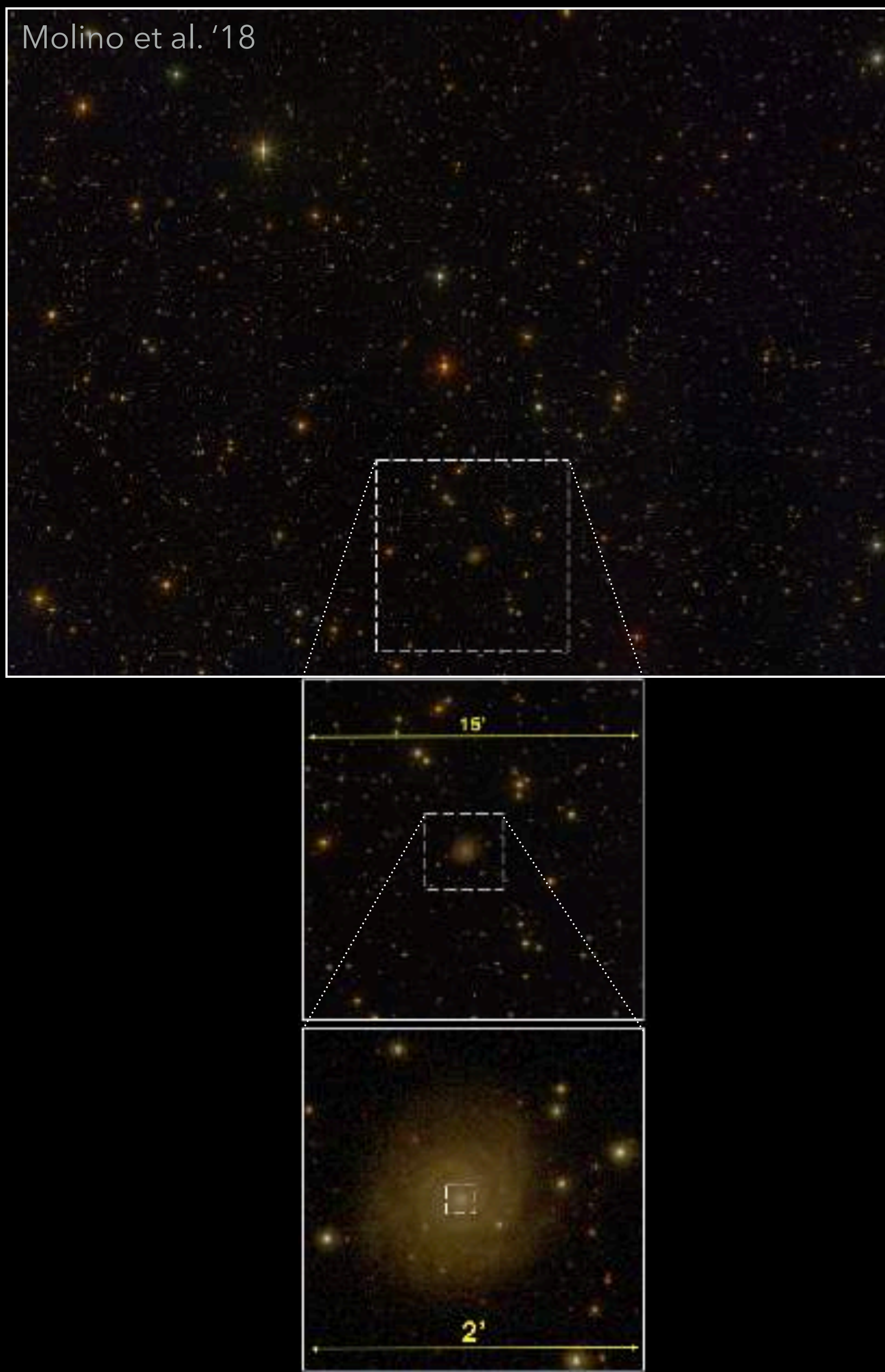
Benítez et al. '09, '14
R.A. et al. '11, …
http://j-pas.org

J-PAS: QUASARS AS SEEN BY 54 NARROW-BAND FILTERS



R.A. et al. '11

J-PAS: MASSIVE, BILLION-OBJECT SURVEY



~10^5 objects/degree^2

Huge challenge – even with 56 narrow-band filters

- ***Classical*** techniques (e.g., template matching)
- Machine learning (collab. with Comp. Sc. Depts.)

J-PAS: fully probabilistic catalogs

OBJ (RA , DEC):

→ p(star)
 → p(A)
 → p(B)
 …

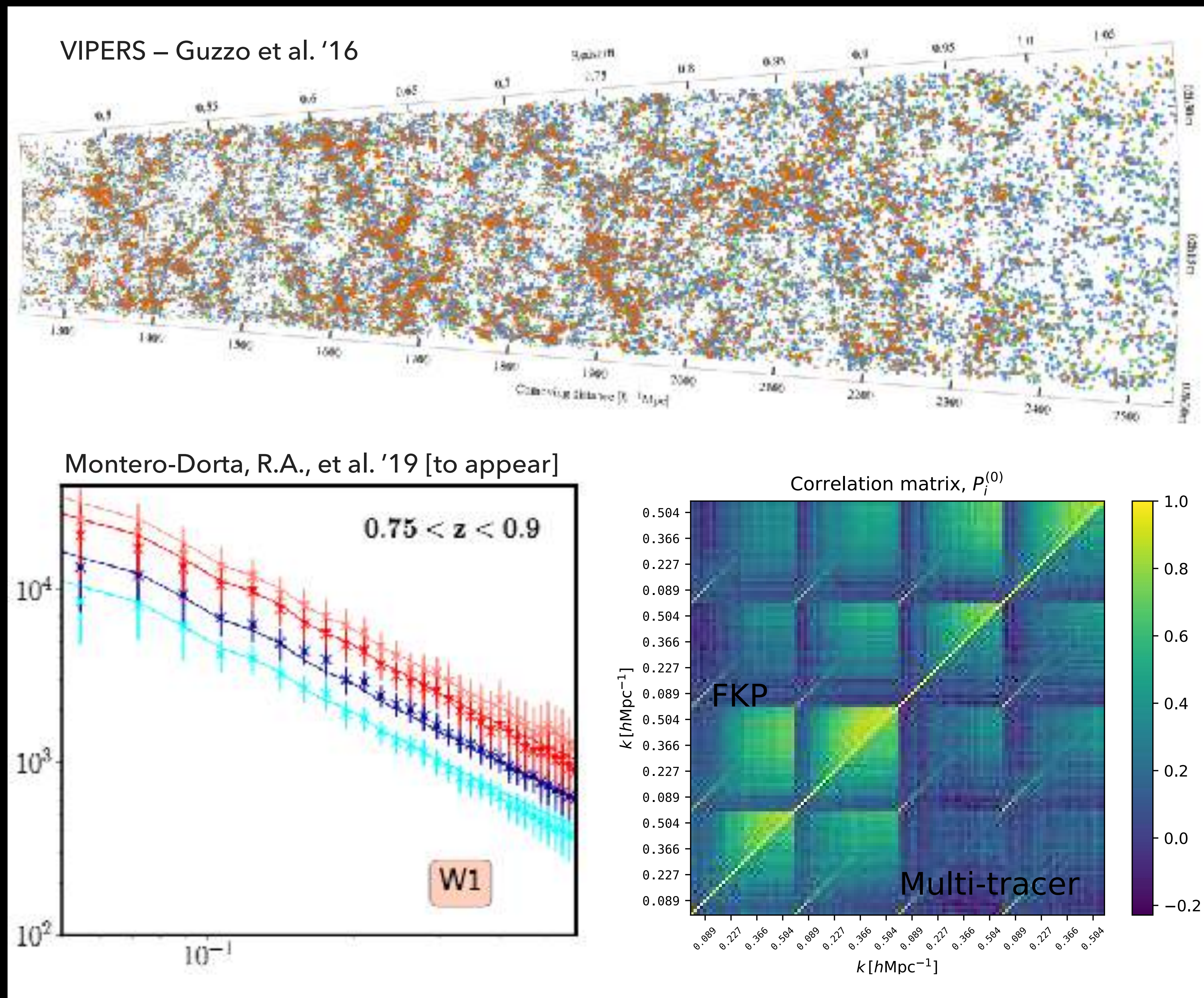
→ p(gal)
 → p(S0) → p(z|S0)
 → p(E0) → p(z|E0)
 …

→ p(qso)
 → p(Q) → p(z|Q)

→ p(junk)

NEW DATA, NEW TOOLS

Optimal methods to combine all galaxies, QSOs, halos etc.

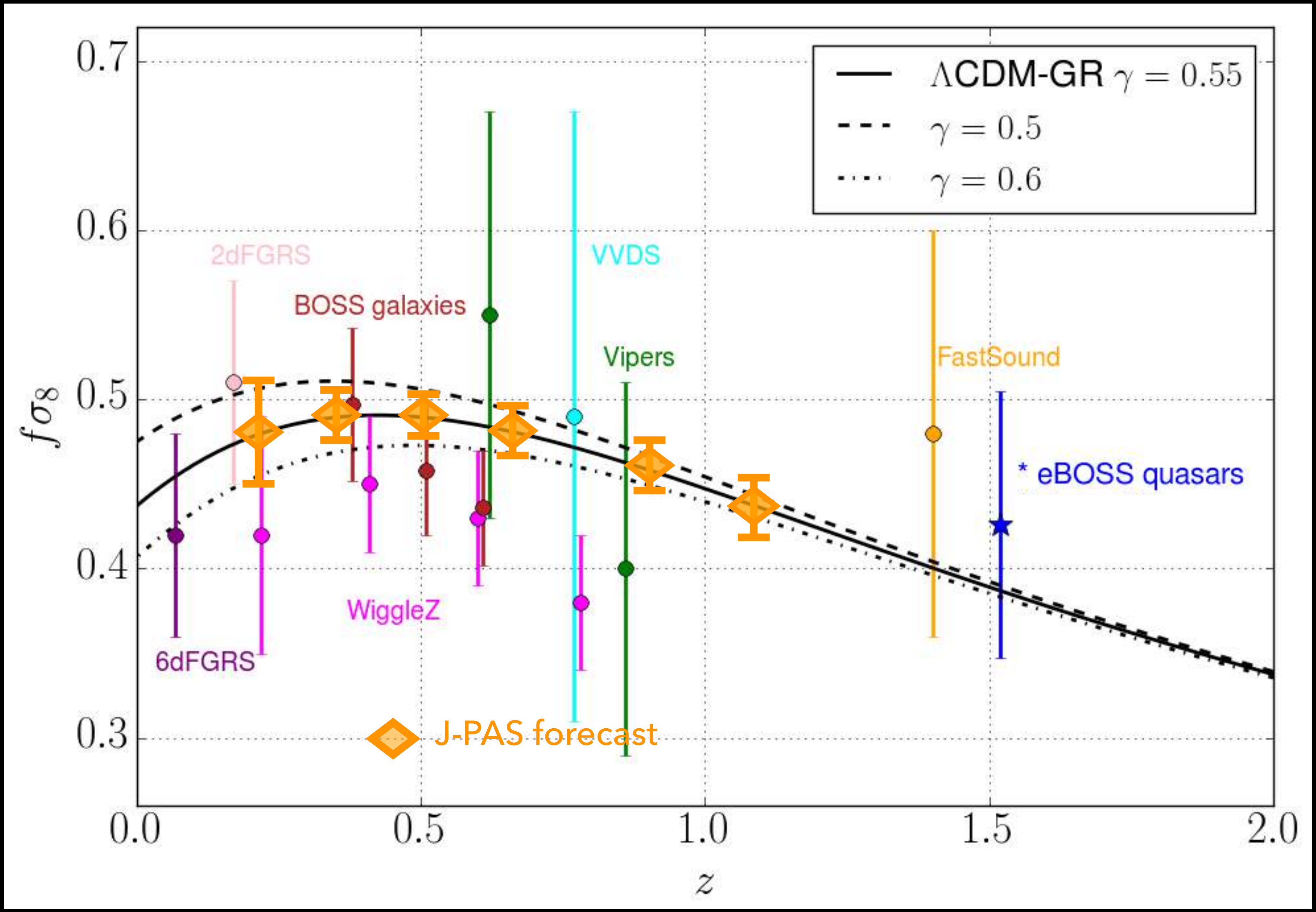


R.A., Secco & Loureiro '16

Sato-Polito, Montero-Dorta, **R.A.**, Prada & Klypin '18

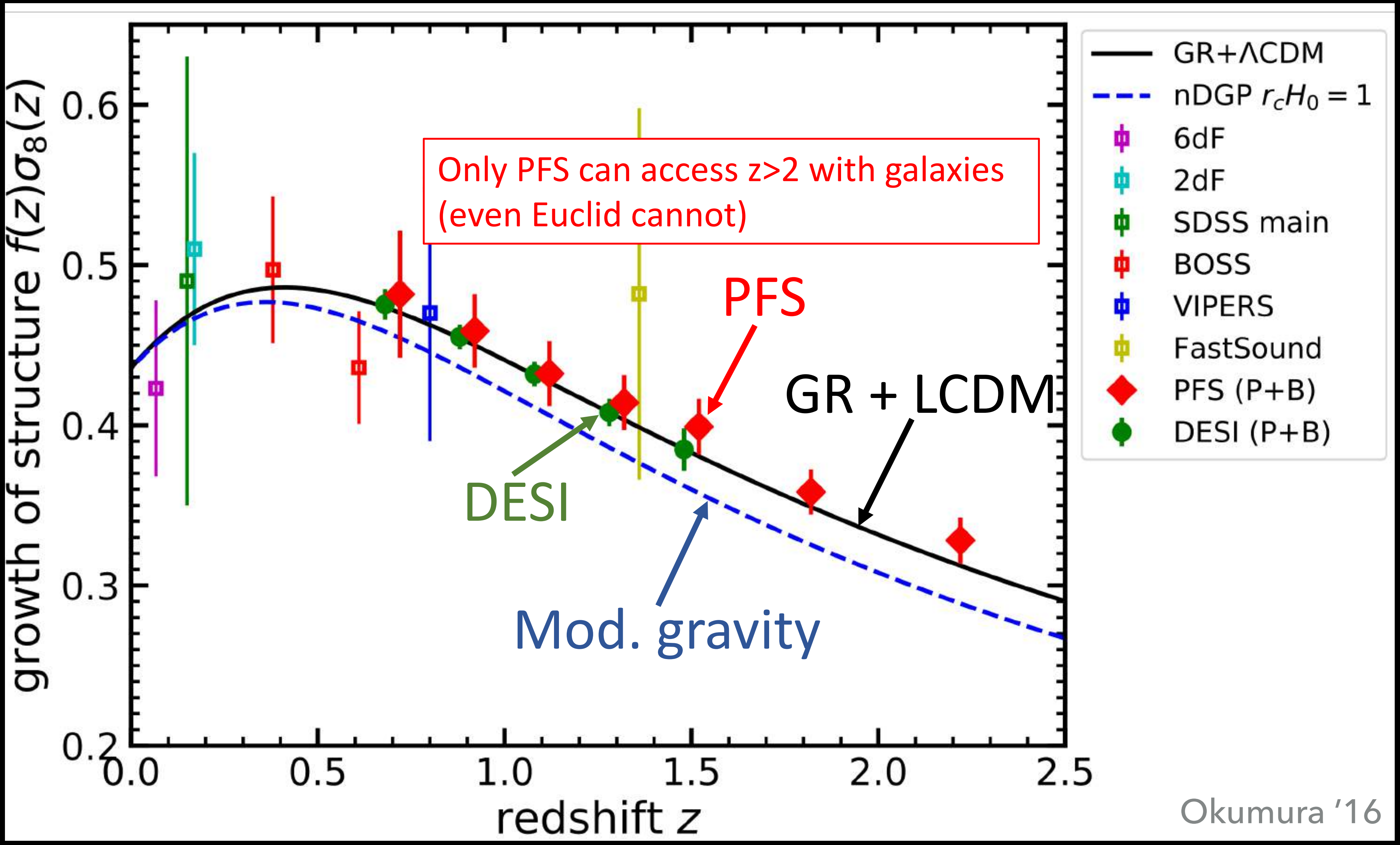
Montero-Dorta, **R.A.**, Granett, Guzzo et al., to appear '19

J-PAS: FORECASTS ON GR V. MODIFIED GRAVITY

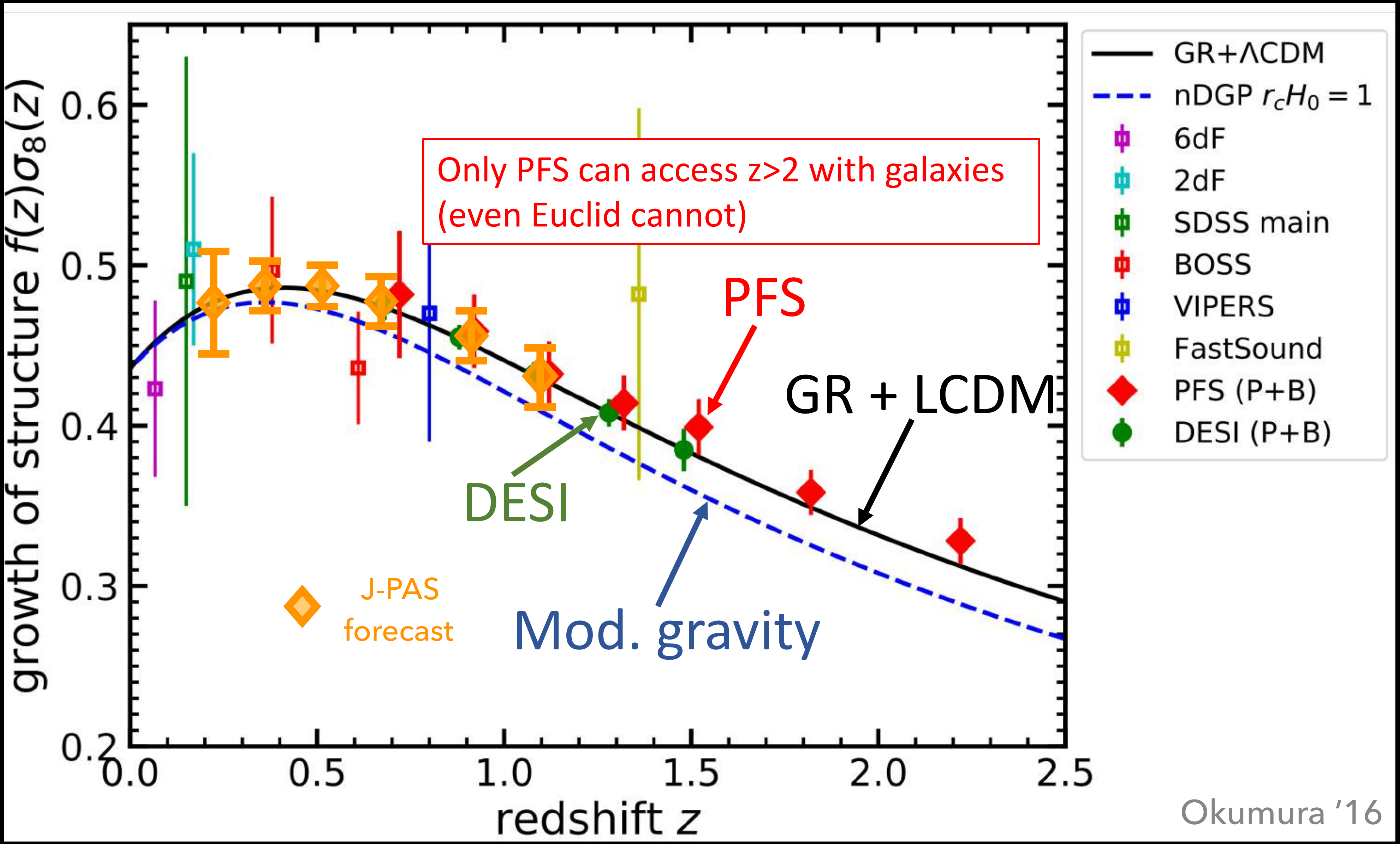


J-PAS Collab. '19 [Aparício-Villega, Maroto, R.A. et al.]

J-PAS: FORECASTS ON GR V. MODIFIED GRAVITY



J-PAS: FORECASTS ON GR V. MODIFIED GRAVITY



J-PAS Collab. '19 [Aparício-Villega, Maroto, R.A. et al.]

LARGE-SCALE STRUCTURE MEETS FUNDAMENTAL PHYSICS

- ✦ Cosmic acceleration is a ***fundamental challenge***: either dark energy or modified gravity will shake the foundations of physics
- ✦ Surveys targeting cosmic acceleration or inflation are also superb tools to understand galaxy formation
- ✦ 3D maps of the Universe are **progressing fast**: by combining optical, IR and 21cm, by ~2030 we will have mapped ~2/3 of the volume of the observable Universe!