The rise and fall of ΛCDM

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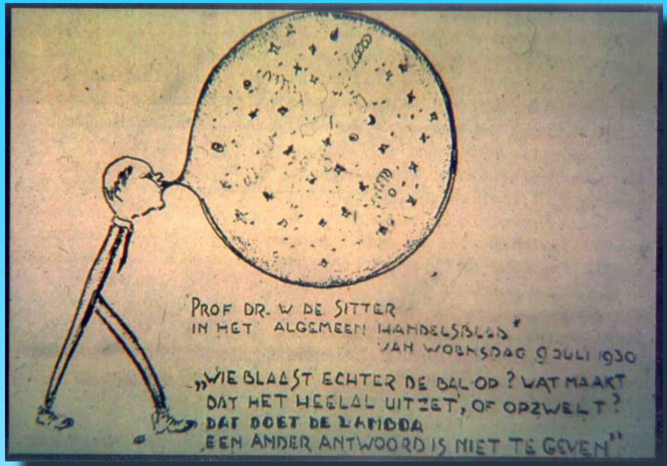
University of Durham

The standard model of cosmology



Based on 2 key ideas from the 1980s:

1. Inflation

Universe born in the wrong vacuum

→ Expands exponentially fast

→ (a) flat geometry ($\Omega_k = 0$); (b) Gaussian, adiabatic perturbations (quantum fluctuations)

2. Non-baryonic cold dark matter particles

→ Current incarnation is ΛCDM (standard model):

Cold dark matter

Cosmological constant

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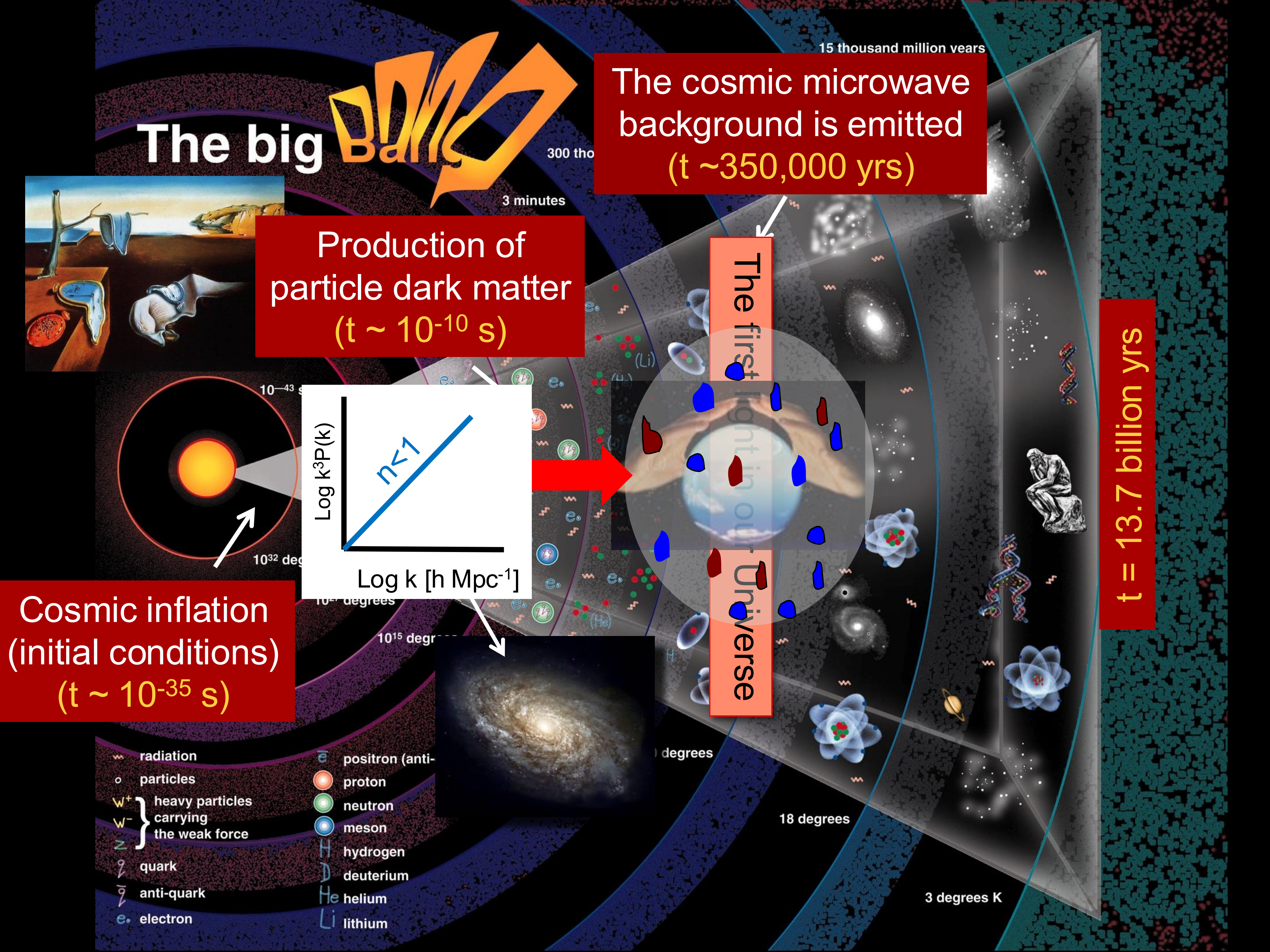
The ΛCDM model of cosmogony

Cosmological constant

Cold dark matter

- Proposed in 1980s, it is an *ab initio,* fully specified model of cosmic evolution and the formation of cosmic structure
- Has strong predictive power and can, in principle, be ruled out
- Has made a number of predictions that were subsequently tested empirically (e.g. CMB, LSS, galaxy formation)

Three Nobel Prizes in Physics since 2006



The big Bang
The cosmic microwave background is emitted
(t ~350,000 yrs)
Production of particle dark matter
(t ~ 10^-10 s)
Cosmic inflation (initial conditions)
(t ~ 10^-35 s)
The first light in our Universe
t = 13.7 billion yrs
Log k^3P(k)
Log k [h Mpc^-1]
n<1
15 thousand million years
3 minutes
3 degrees K
18 degrees
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
proton
neutron
meson
hydrogen
deuterium
helium
lithium

Non-baryonic dark matter candidates

From the early 1980s:

Type	example	mass
hot	neutrino	few tens of eV
warm	sterile ν	keV-MeV
cold	axion neutralino	10^{-5}eV - 100 GeV

The dark matter power spectrum

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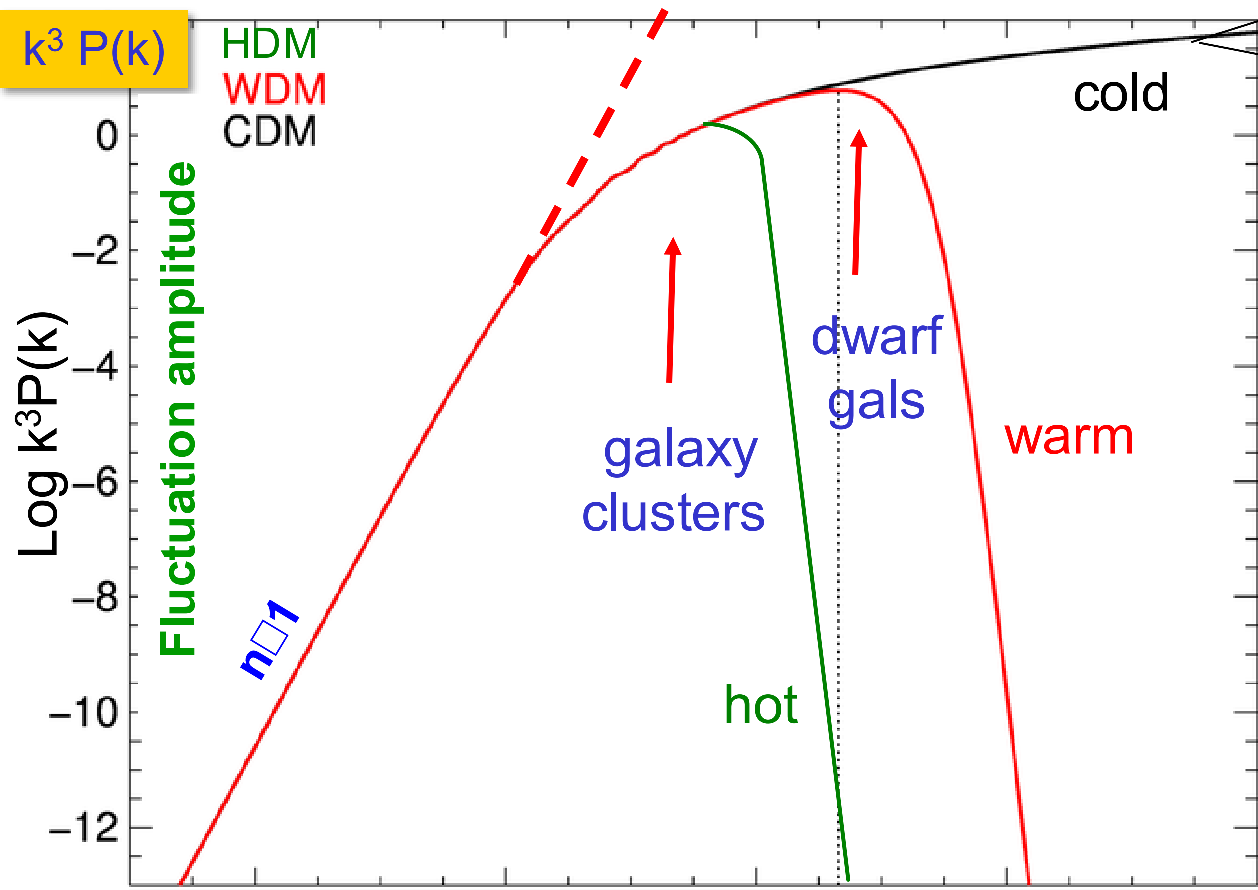
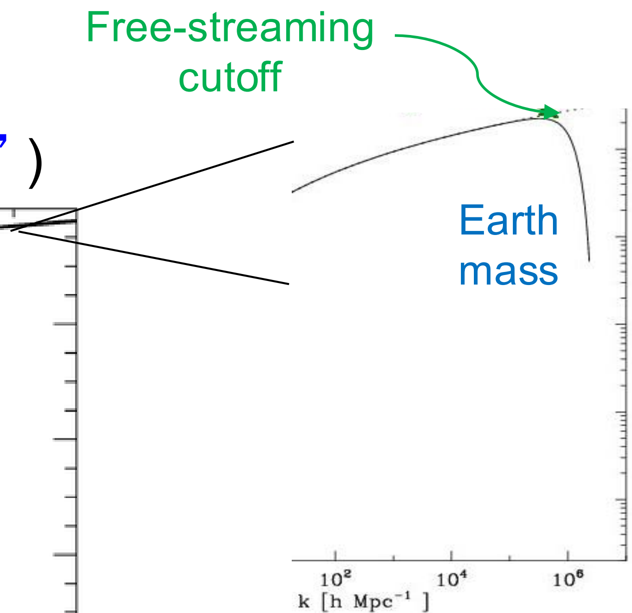
The linear power spectrum (“power per octave”)





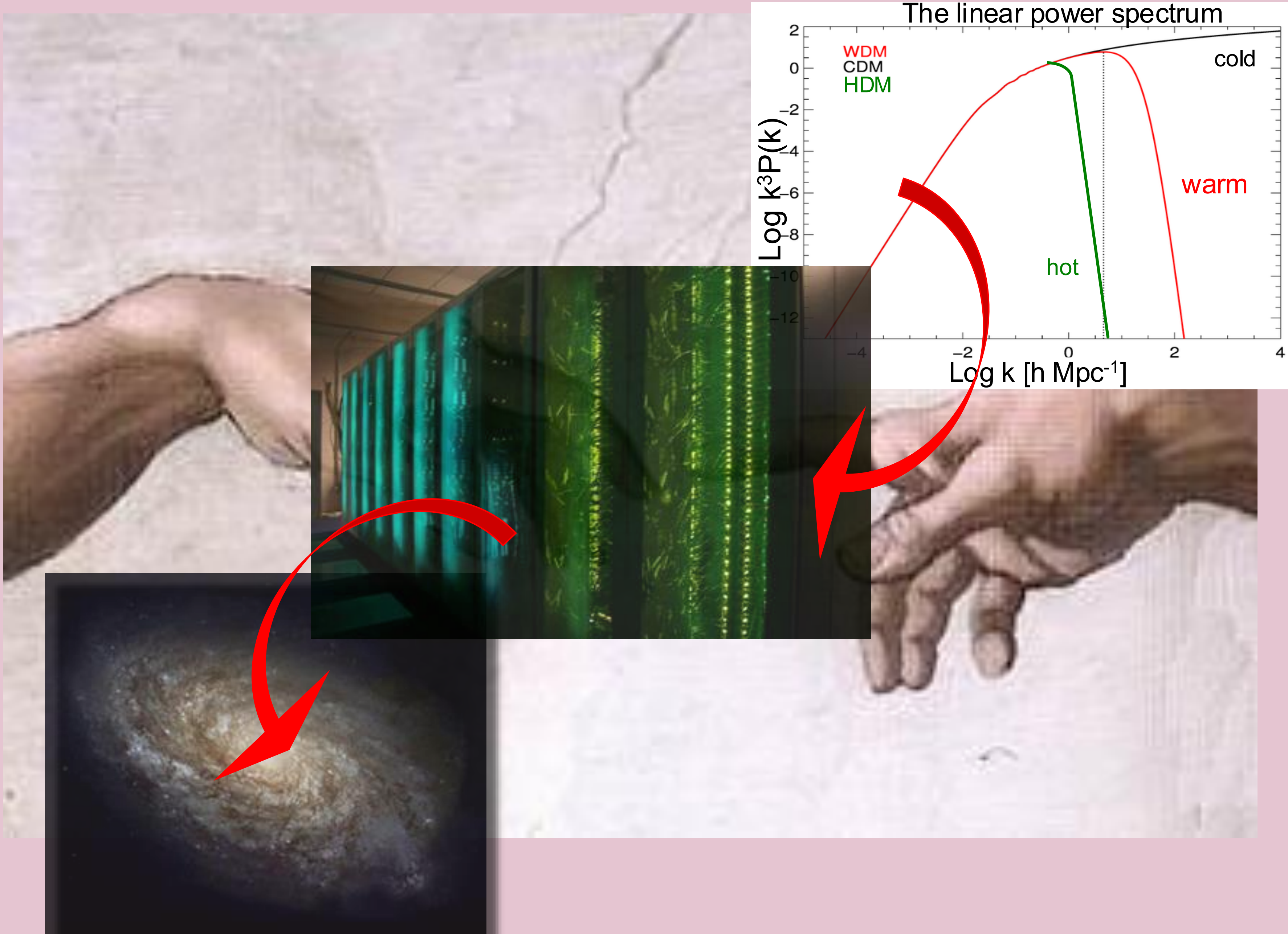
Free streaming →

$\lambda_{cut} \propto m_x^{-1}$

for a thermal relic

These possibilites can be tested with astrophysics

Non-linear evolution



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Non-linear evolution: simulations

Assumption about content of Universe → Initial conditions

Relevant equations:

Collisionless Boltzmann;

Poisson; Friedmann eqns;

Radiative hydrodynamics

Subgrid astrophysics

How to make a virtual universe

Hot dark matter

$m_\nu = 30$ ev → $\Omega_m = 1$

1981

HAS THE NEUTRINO A NON-ZERO REST MASS?*
(Tritium β-Spectrum Measurement)

V. Lubimov, E. Novikov, V. Nozik, E. Tretyakov
Institute for Theoretical and Experimental Physics, Moscow, U.S.S.R.

V. Kosik
Institute of Molecular Genetics, Moscow, U.S.S.R.

ABSTRACT

The high energy part of the β-spectrum of tritium in the v... molecule was measured with high precision by a toroidal β-spect... meter. The results give evidence for a non-zero electron anti-neutrino mass.

Fifty years ago Pauli introduced the neutrino to explain the β-spectrum shape. Pauli made the first estimate of the neutrino mass ($E_{3\,max}$ ≅ nuclei mass defect): it should be very small or maybe zero. Up to now the study of the β-spectrum shape is the most sensitive, direct method of neutrino mass measurement.

For allowed β-transitions, if $M_\nu = 0$, then $S \simeq (E-E_0)^2$. The Kurie plot is then a straight line with the only kinematic parameter being $E_k = E_0$ (total β-transition energy). If $M_\nu \neq 0$, then $S \simeq (E_0-E)\sqrt{(E_0-E)^2-M_\nu^2}$. The Kurie plot is then distorted, especially near the endpoint.

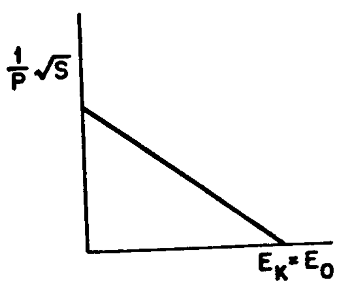


Fig. 1. Kurie plot for $M_\nu = 0$.

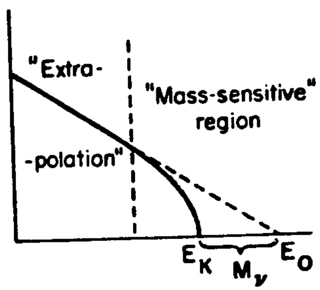
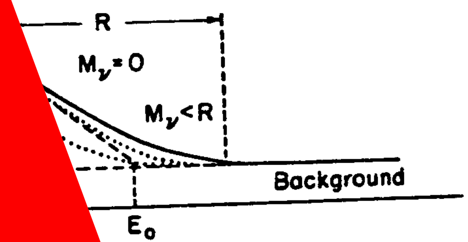


Fig. 2. Kurie plot for $M_\nu \neq 0$.

The method for the neutrino mass measurement is to obtain E_0 from the extrapolation and obtain E_k from the spectrum intercept. Then $M_\nu = E_0 - E_k$. Qualitatively, $M_\nu \neq 0$ if the β-spectrum near the end-point runs below the extrapolated curve.

*Paper presented by Oleg Egorov.

I... things are more complicated. The apparatus reso-... ...rongly affects the spectrum endpoint and rather ...e spectrum slope.



...ealistic Kurie plot.

... extrapolation. However, we are unable ..., then once again the lack of counts near the ... indicate that $M_\nu \neq 0$. If $M_\nu \lesssim R$, the changes due to ...mass and the influence of R are indistinguishable. For M_ν ...ermination the knowledge of R is compulsory. The background determines the statistical accuracy near the endpoint, i.e., in the region of the highest sensitivity to the ν mass. So: 1) R should be ∼ M_ν, 2) the smaller M_ν is, the smaller the background (∼ M_ν^2) must be and the higher the statistics (∼ M_ν^{-3}) must be. For example, suppose that for M_ν = 100 eV we need resolution R, background Q, and statistics N. If M_ν = 30 eV, to achieve the same ΔM/M they should be R/3, Q/10, and N × 30, respectively.

The shorter the β-spectrum, the less it is spread due to R (as R ∼ Δp/p = const.). A classical example is ^3H β-decay, which has 1) the smallest E_0 ∼ 18.6 keV, 2) an allowed β-transition, simple nucleus, and simple theoretical interpretation, 3) highly reduced radioactivity. The first experiments with ^3H were by S. Curran et al. (1948) and G. Hanna, B. Pontecorvo (1949). Using ^3H gas in a proportional counter, they obtained $M_\nu \leq 1$ keV. Further progress required magnetic spectrometer development. This allowed the resolution to be improved considerably, and L. Langer and R. Moffat (1952) obtained $M_\nu \leq 250$ eV. The best value was obtained by K. Bergkvist (1972): R ∼ 50 eV and $M_\nu \leq 55$ eV.

The ITEP spectrometer is of a new type: ironless, with toroidal magnetic field (E. Tretyakov, 1973). The principle of the toroidal magnetic field focusing systems was proposed by V. Vladimirsky et al. (An example is a "Horn" of ν-beams.) It turns out that a rectilinear conductor (current) has a focusing ability for particles emitted perpendicular to the rotation axis. This system has infinite periodical focusing structure. The ITEP spectrometer is based on this principle.

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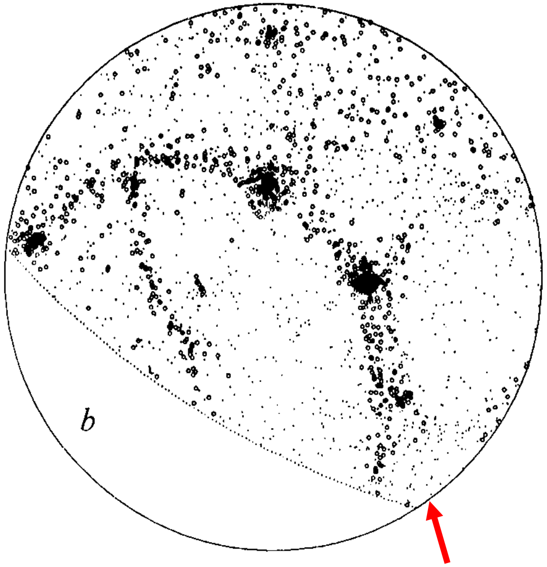
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

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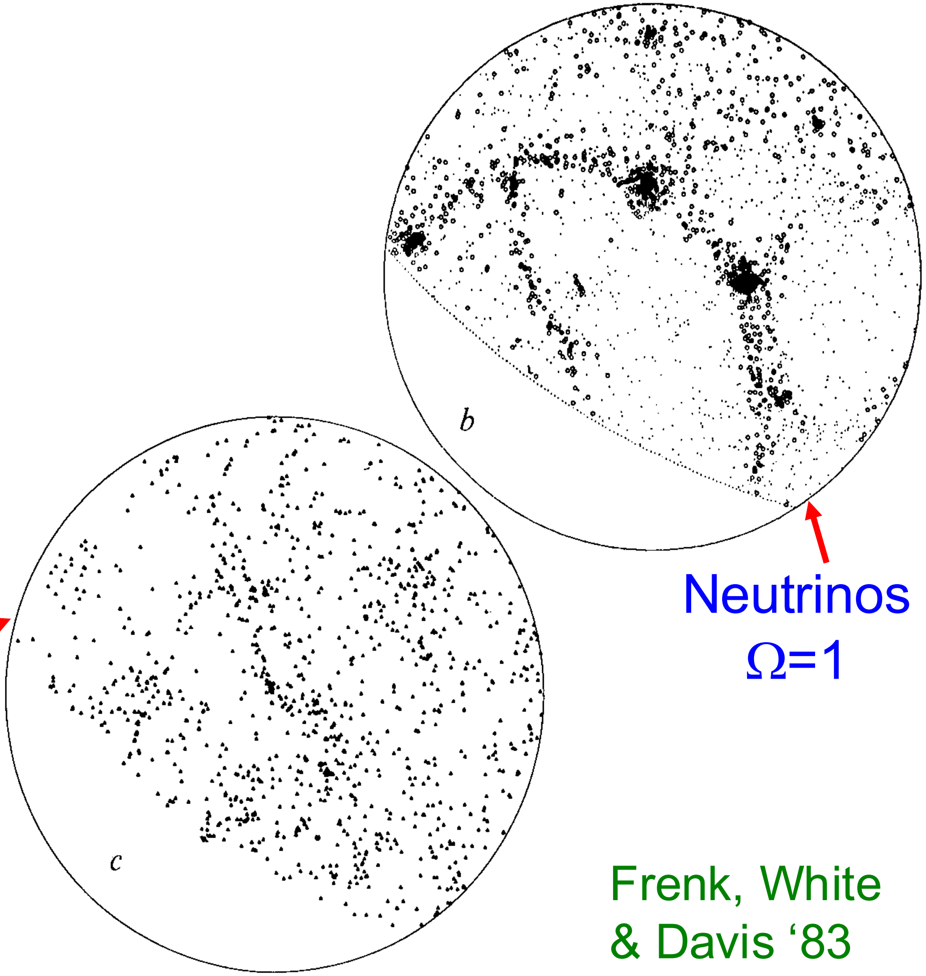
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev



Frenk, White & Davis ‘83

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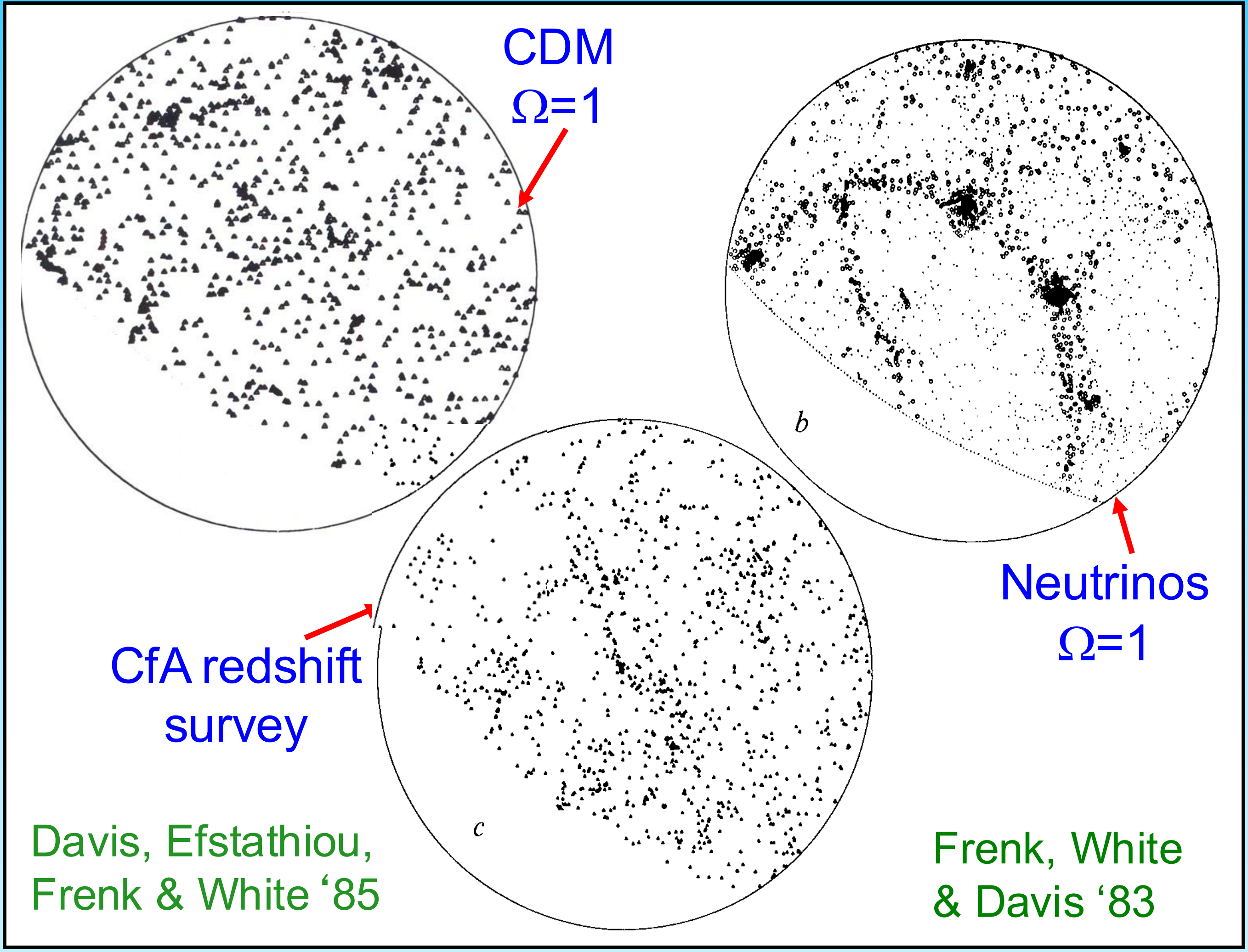
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω → m_ν<< 30 ev

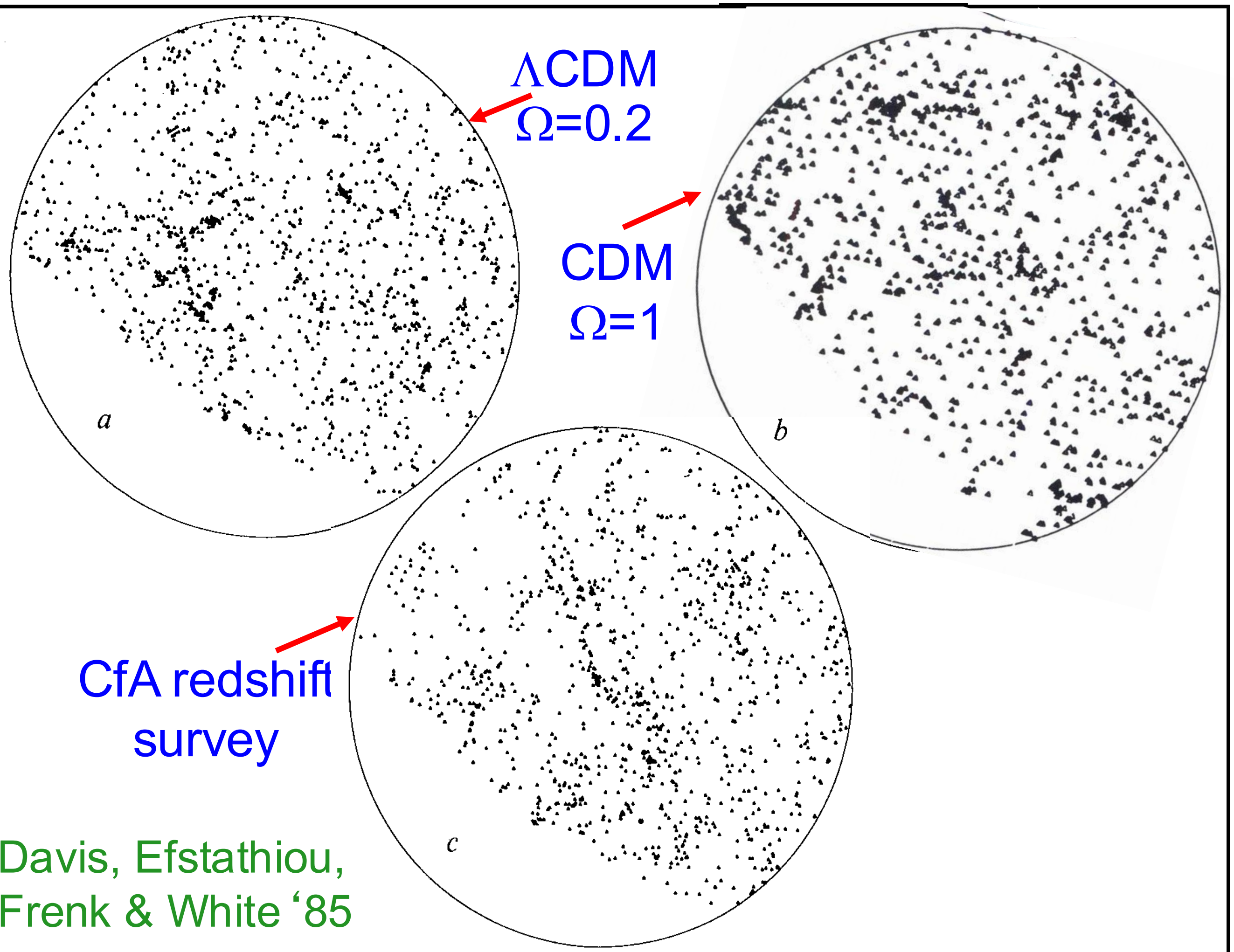
Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



Non-baryonic dark matter cosmologies

Λ was inconceivable in 1985



Davis, Efstathiou, Frenk & White '85

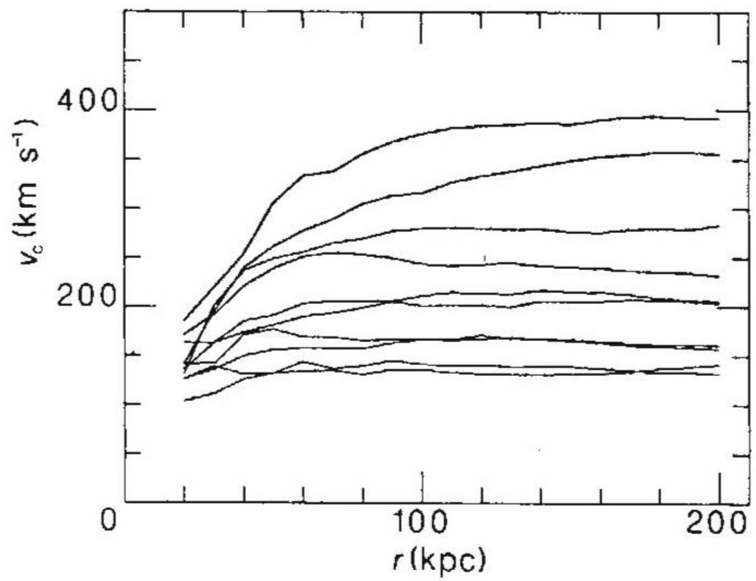
1982 – 1990: the glory days of

$\Omega_{matter} = 1$ (→ "standard CDM")

Cold dark matter, the structure of galactic haloes and the origin of the Hubble sequence

Carlos S. Frenk*, Simon D. M. White†, George Efstathiou‡ & Marc Davis§

A popular theory for galaxy formation holds that the Universe is dominated by exotic particles such as axions, photinos or gravitinos (collectively known as cold dark matter, CDM)[1–3]. This hypothesis can reconcile the aesthetically pleasing idea of a flat universe with the standard theory of primordial nucleosynthesis and with upper limits on anisotropies in the cosmic microwave background[4–6]. The resulting model is consistent with the observed dynamics of galaxy clustering only if galaxy formation is biased towards high-density regions[7,8]. We have shown that such a biased model successfully matches the distribution of galaxies on megaparsec (Mpc) scales[9]. If it is to be viable, it must also account for the structure of individual galaxies and their haloes. Here we describe a simulation of a flat CDM universe which can resolve structures of comparable scale to the luminous parts of galaxies. We find that such a universe produces objects with the abundance and characteristic properties inferred for galaxy haloes. Our results imply that merging plays an important part in galaxy formation and suggest a possible explanation for the Hubble sequence.



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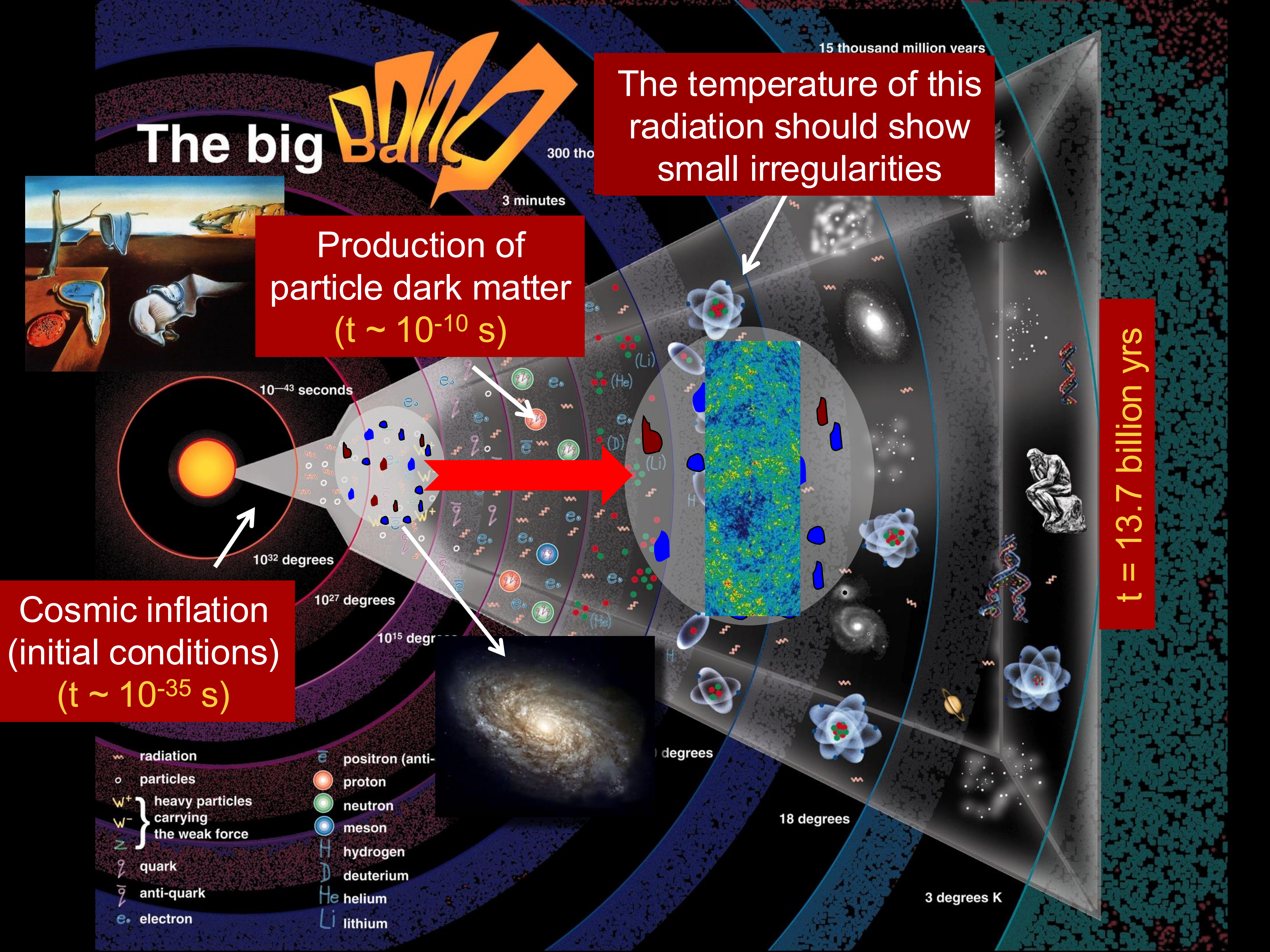
CDM rules

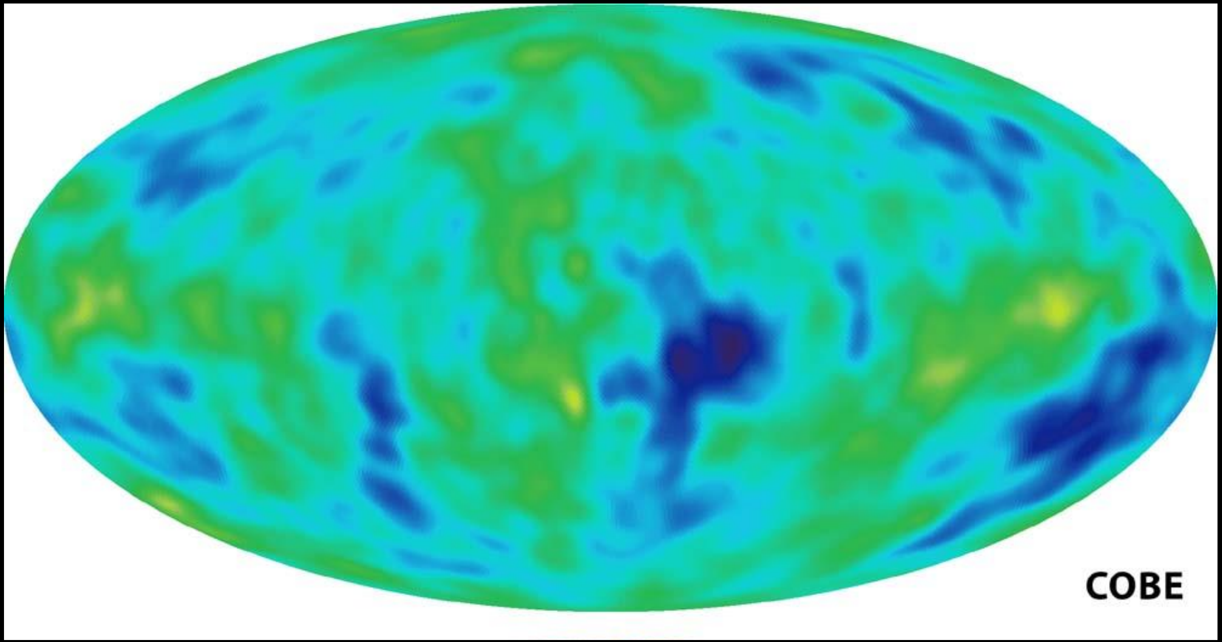
1987



The big Bang
The temperature of this radiation should show small irregularities
Production of particle dark matter
(t ~ 10^{-10} s)
Cosmic inflation (initial conditions)
(t ~ 10^{-35} s)
t = 13.7 billion yrs
15 thousand million years
300 tho
3 minutes
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degr
degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-
proton
neutron
meson
hydrogen
deuterium
helium
lithium

The CMB

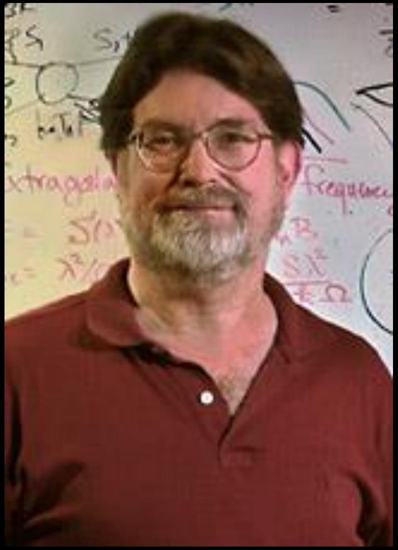
1992



COBE data consistent with Ω =1 CDM!

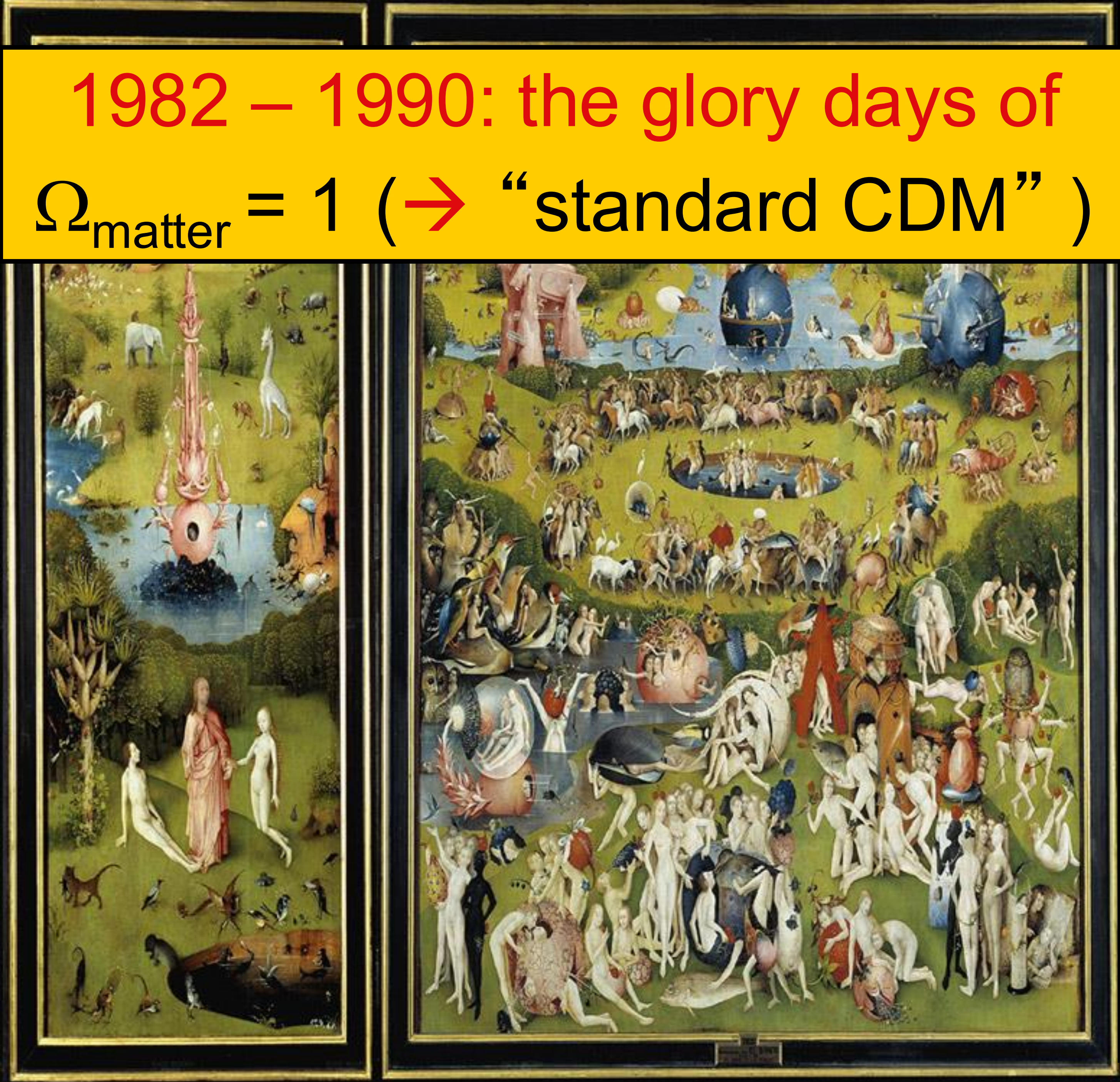
George Smoot - Nobel Prize 2006

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES



1982 – 1990: the glory days of $\Omega_{matter} = 1$ (→ "standard CDM")

What went wrong?



ΛCDM

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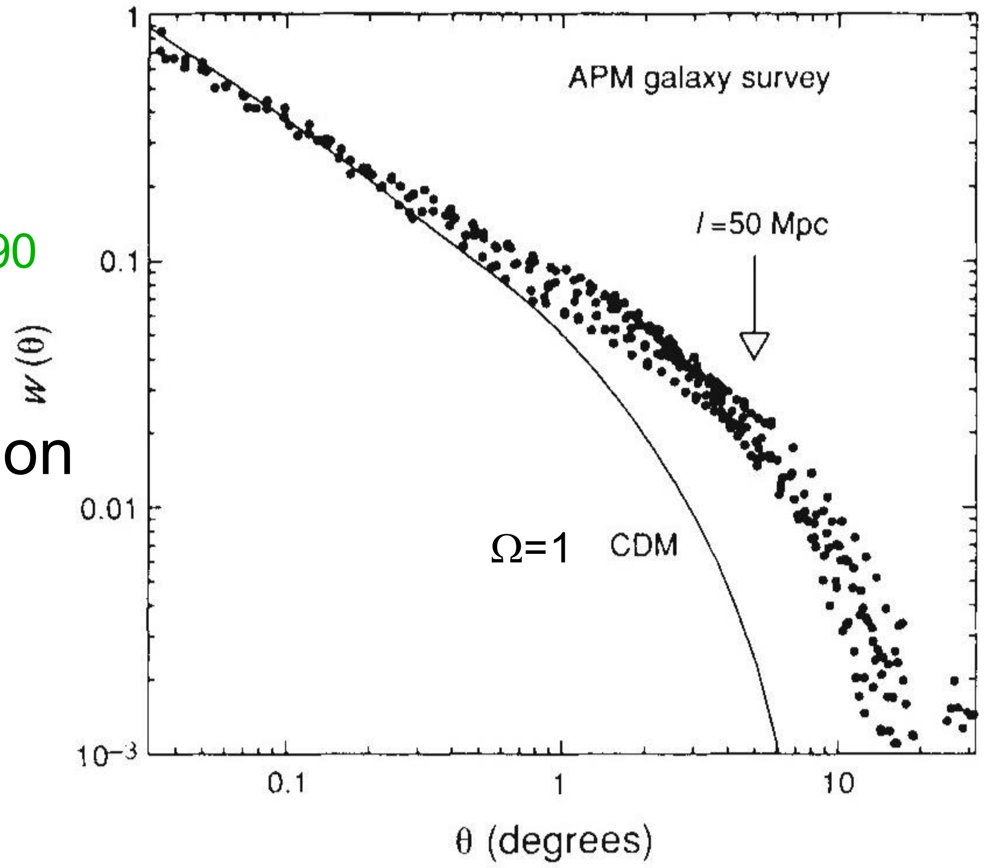
1990: Ω = 1 CDM under strain

Angular 2-pt correlation function

Maddox, Efstathiou, Sutherland & Loveday '90



Too much "power on large scales"

Possible solution: lower Ω_{matter} and add Λ to CDM (to have Ω_{tot} =1, as required by inflation) (Efstathiou et al □91)

The end of standard (Ω_{matter} =1) CDM … or why Ω_{matter} cannot be 1

White, Navarro, Evrard & Frenk -- Nature 1993

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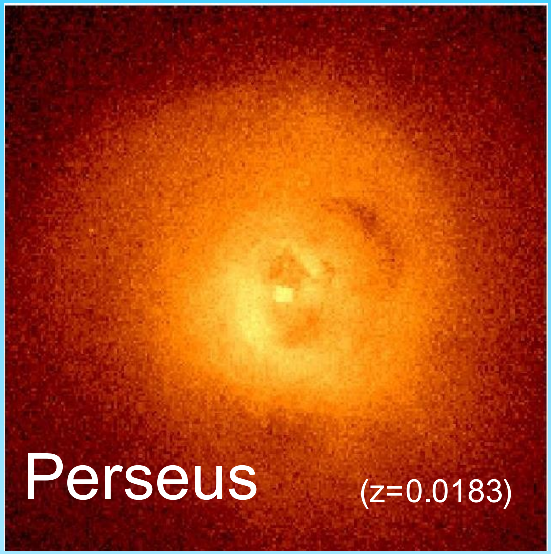
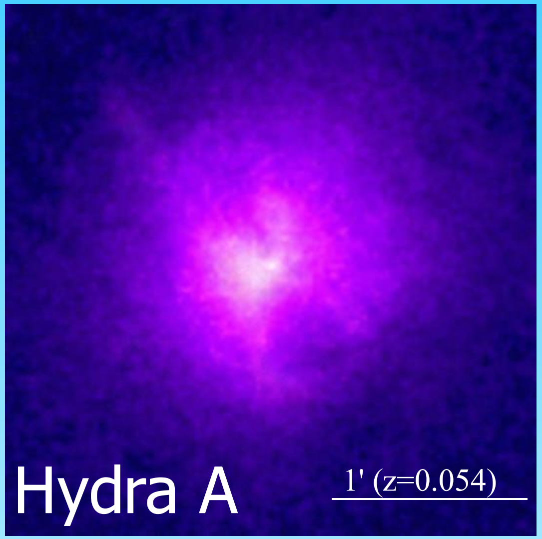
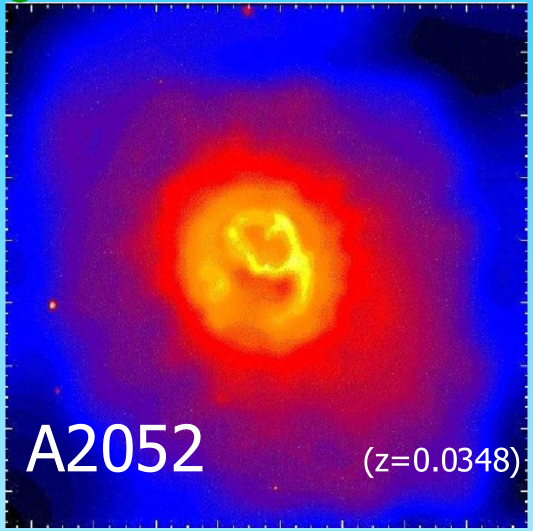
Galaxy clusters

X-ray emission from hot plasma in clusters

Images from David Buote







About 90% of baryons in clusters are in hot gas

X-rays ⇒ gas mass

Photometry ⇒ stellar mass

Gas in hydrostatic equilibrium so X-rays (or lensing) ⇒ total gravitating mass

} ⇒ Baryon fraction, f_b

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Ω from the baryon fraction in clusters

baryon fraction in clusters ≈ baryon fraction of universe

$$f_b = \frac{M_b}{M_{tot}} = \gamma \frac{\Omega_b}{\Omega_m}$$

White, Navarro, Evrard & Frenk
Nature 1993

where γ=1 if f_b is a fair sample of the universe

simulations → $\gamma = 0.9 \pm 10\%$

X-rays+lensing → $f_b = (0.060h^{-3/2} + 0.009) \pm 10\%$

BBNS, CMB → $\Omega_b h^2 = 0.019 \pm 20\%$

HST → $h = 0.7 \pm 10\%$

→ $$\Omega_m = \frac{\Omega_b \gamma}{f_b} = 0.31 \pm 0.12$$

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Ω from the baryon fraction in clusters

$$\Omega_m = \frac{\Omega_b \gamma}{f_b} = 0.31 \pm 0.12$$

White, Navarro, Evrard & Frenk
Nature 1993

Requires Λ X 0.7 to be compatible with inflation (Ω=1)

There is no theoretical basis for inferred value of Λ

A “natural” value (Planck value) is

10^{120} larger than observed !!!

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DEFW '92

Nature 1992

REVIEW ARTICLE

The end of cold dark matter?

M. Davis, G. Efstathiou, C. S. Frenk & S. D. M. White

The successful cold dark matter (CDM) theory for the formation of structure in the Universe has suffered recent setbacks from observational evidence suggesting that there is more large-scale structure than it can explain. This may force a fundamental revision or even abandonment of the theory, or may simply reflect a modulation of the galaxy distribution by processes associated with galaxy formation. Better understanding of galaxy formation is needed before the demise of CDM is declared.

HOW did structure in the Universe form? This question has puzzled mankind for centuries, but in the past decade some cosmologists have felt that they were close to providing an answer. What has become known as the cold dark matter (CDM) theory is an elegant construct which links many aspects of the structure we see today to physical processes which took place when the Universe was only 10^{-35} s old. Recently, observations have been reported that seem to conflict with this model (see.

tion could have originated from quantum fluctuations that were inflated to macroscopic scale. Except in circumstances that appear contrived, the fluctuations would indeed contain no characteristic scales; in technical terms, irregularities in the spatial curvature are predicted to be a gaussian random field with a scale-invariant spectrum[9-12]. For the first time cosmologists had a set of initial conditions stemming directly from fundamental, even if speculative, physics.

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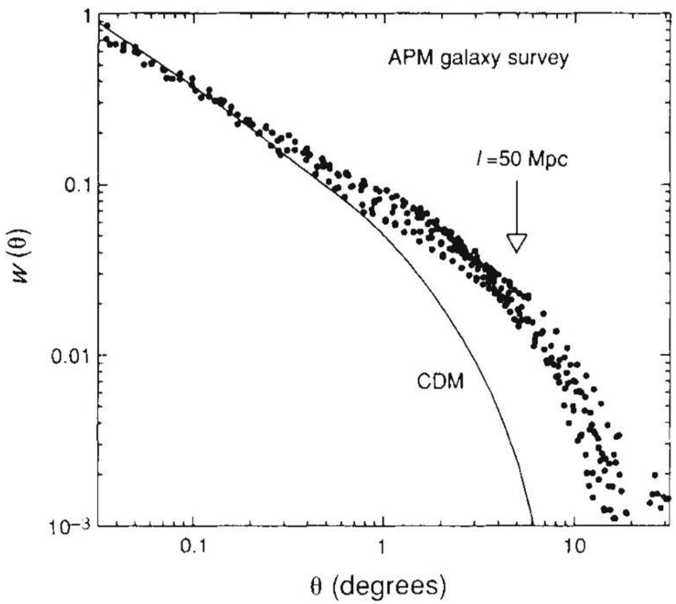
DEFW '92

Angular 2-pt correlation function



REVIEW ARTICLE

end of the range allowed by observation[55], lowering the Hubble constant still further seems an implausible way of obtaining more large-scale structure. Lowering Ω is another possibility, but without an additional ingredient such models are inconsistent both with a spatially flat universe and with present upper limits on fluctuations in the microwave background[56,57]. These problems can be avoided by appealing to a cosmological constant, because a low-density universe is spatially flat if the cosmological constant takes the value[58] $\Lambda = 3H_0^2(1-\Omega)$. With such carefully chosen parameters it is possible to construct a CDM universe that explains large-scale structure[59], is compatible with inflation and with microwave-background experiments, and is old enough to contain the oldest observed star clusters even for a present expansion rate as high as $H_0 = 80\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, the value preferred by some recent measurements[60,61]. From the point of view of a particle physicist, the value of Λ needed to work these miracles is extraordinarily small, 10^{120} times smaller than its 'natural' value[62]. Such fine tuning seems sufficiently unattractive that most cosmologists regard this solution as a long shot, preferring to think that some unknown symmetry principle requires the cosmological constant to be exactly zero.

Other possible fixes for the CDM model involve decaying particles or departures from the scale-invariant seed fluctuations predicted by simple inflationary models. For example, the pre-

(Some) evidence for dark energy

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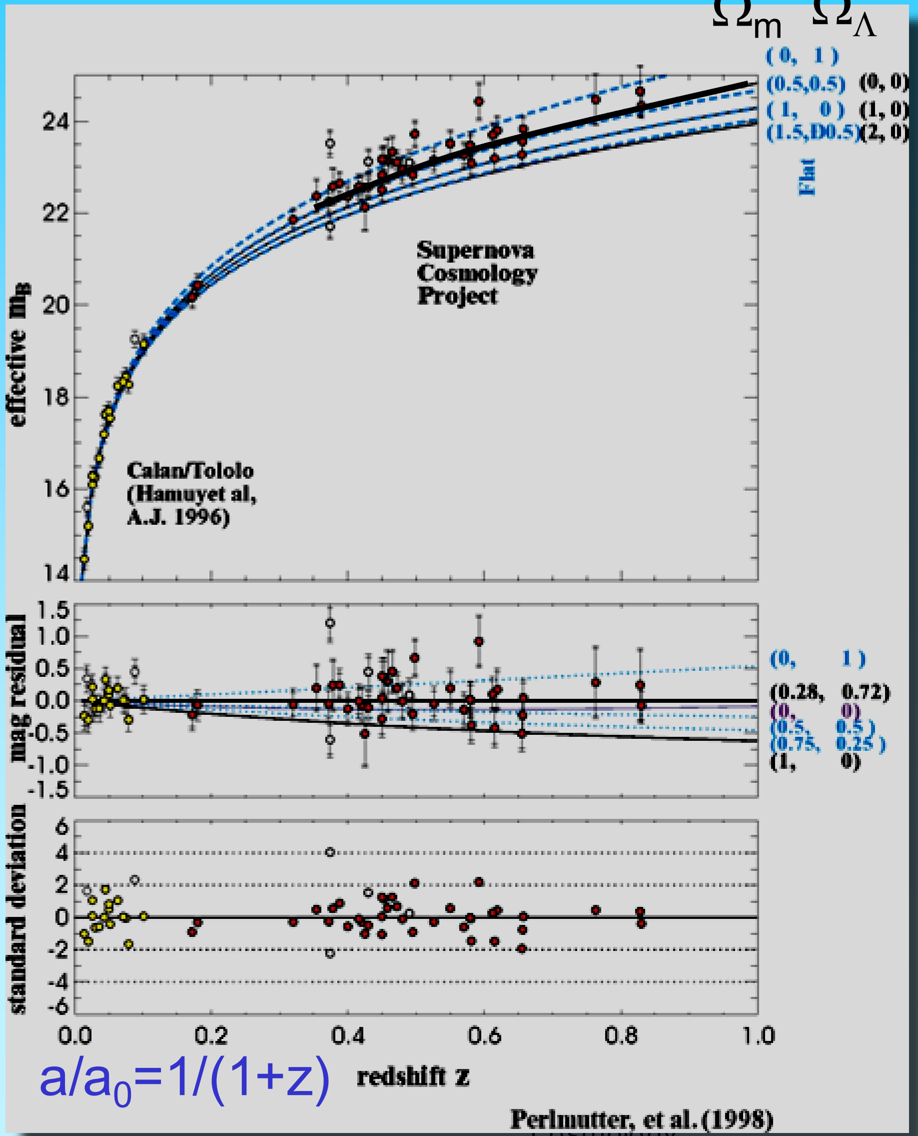
Evidence for Λ from high-z supernovae

SN type Ia (standard candles) at z~0.5 are fainter than expected even if the Universe were empty

flux

 Cosmic expansion must have been accelerating since the light was emitted



Perlmutter et al ’98; Riess et al ‘98
Schmidt et al ‘98

Cosmology

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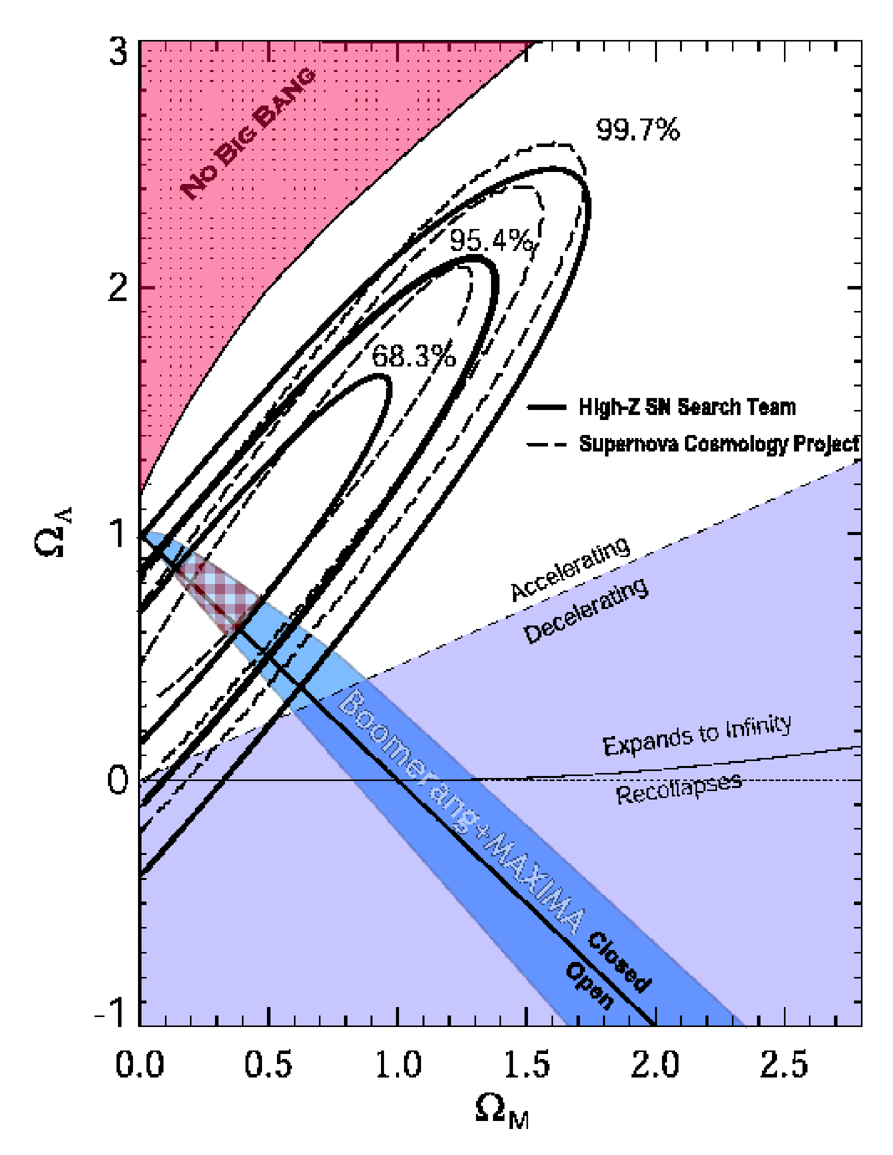
Evidence for Λ from high-z supernovae

SN type Ia (standard candles) at z~0.5 are fainter than expected even if the Universe were empty

Cosmic expansion must have been accelerating since the light was emitted



Perlmutter et al ’98; Reiss et al ‘98
Schmidt et al ‘98

Evidence for Λ from high-z supernovae

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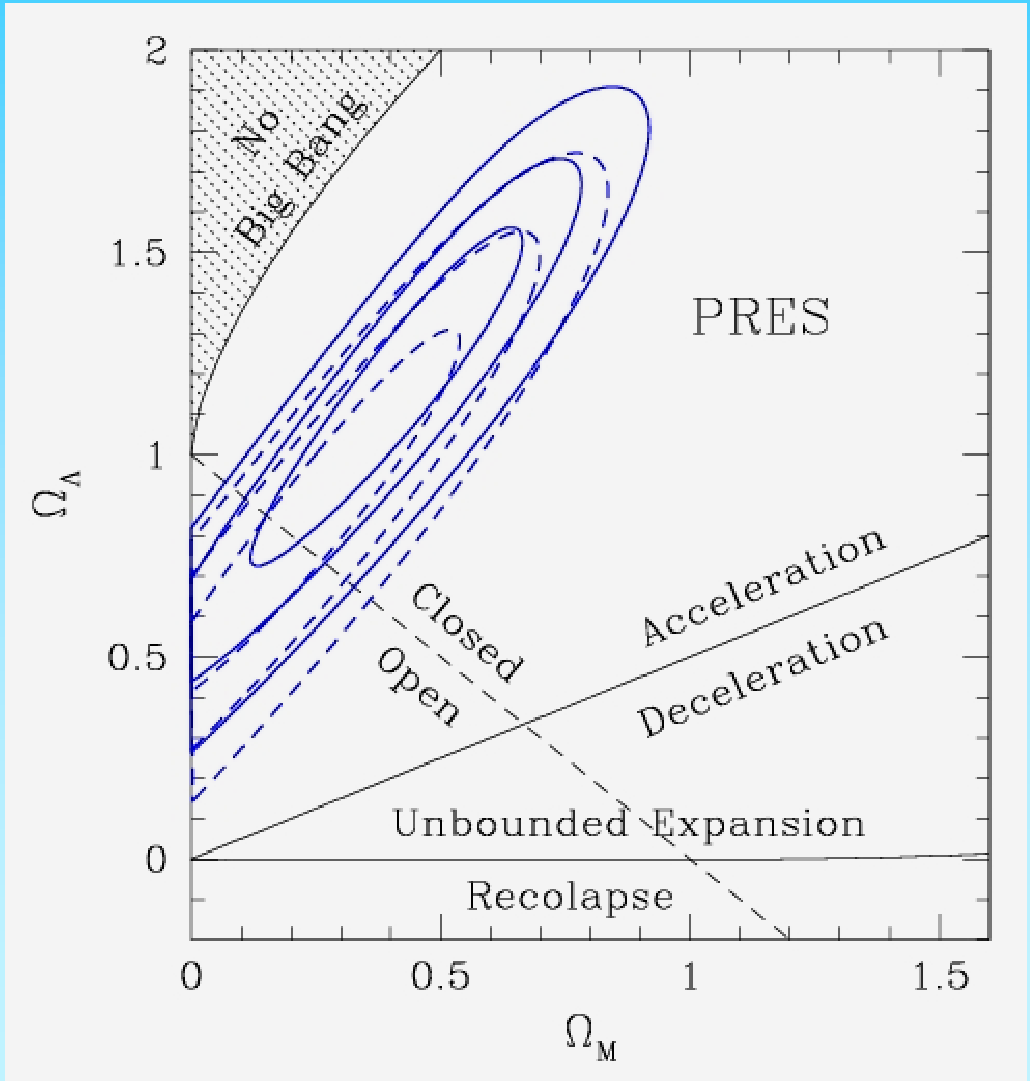
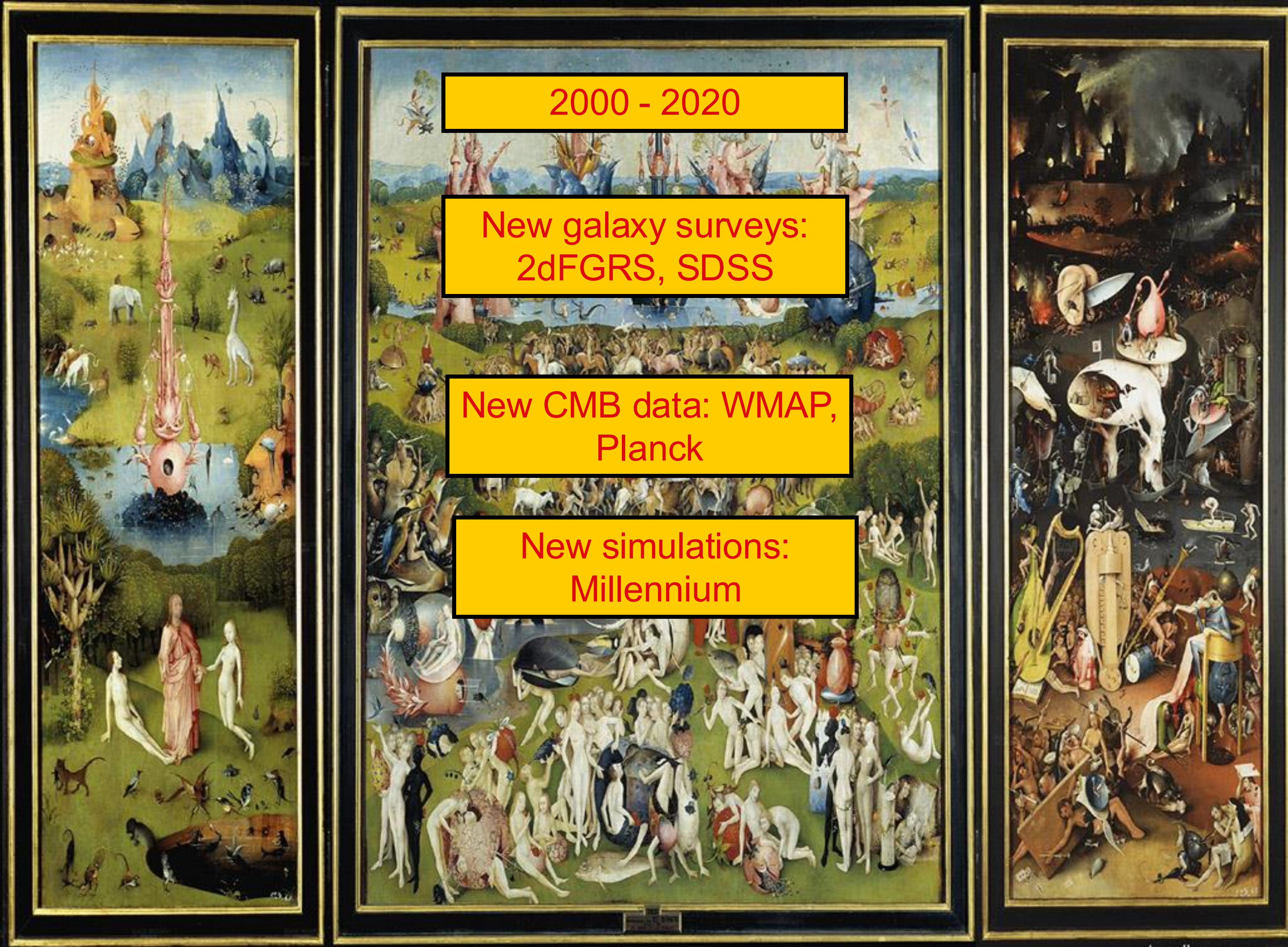
Later data ruled out $\Omega_\Lambda = 0$.



Clocchiatti et al '06


2000 - 2020
New galaxy surveys: 2dFGRS, SDSS
New CMB data: WMAP, Planck
New simulations: Millennium

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Observational tests of ΛCDM

Fundamental prediction of ΛCDM

→ Primordial power spectrum of density perturbations

+ random phases

Can test this in two regimes:

Linear regime: cosmic microwave background (z~1000)

large-scale structure (z~3 - 0)

Evolved non-linear regime: dark matter halos →

- abundance
- structure
- clustering

(z~15 – 0)

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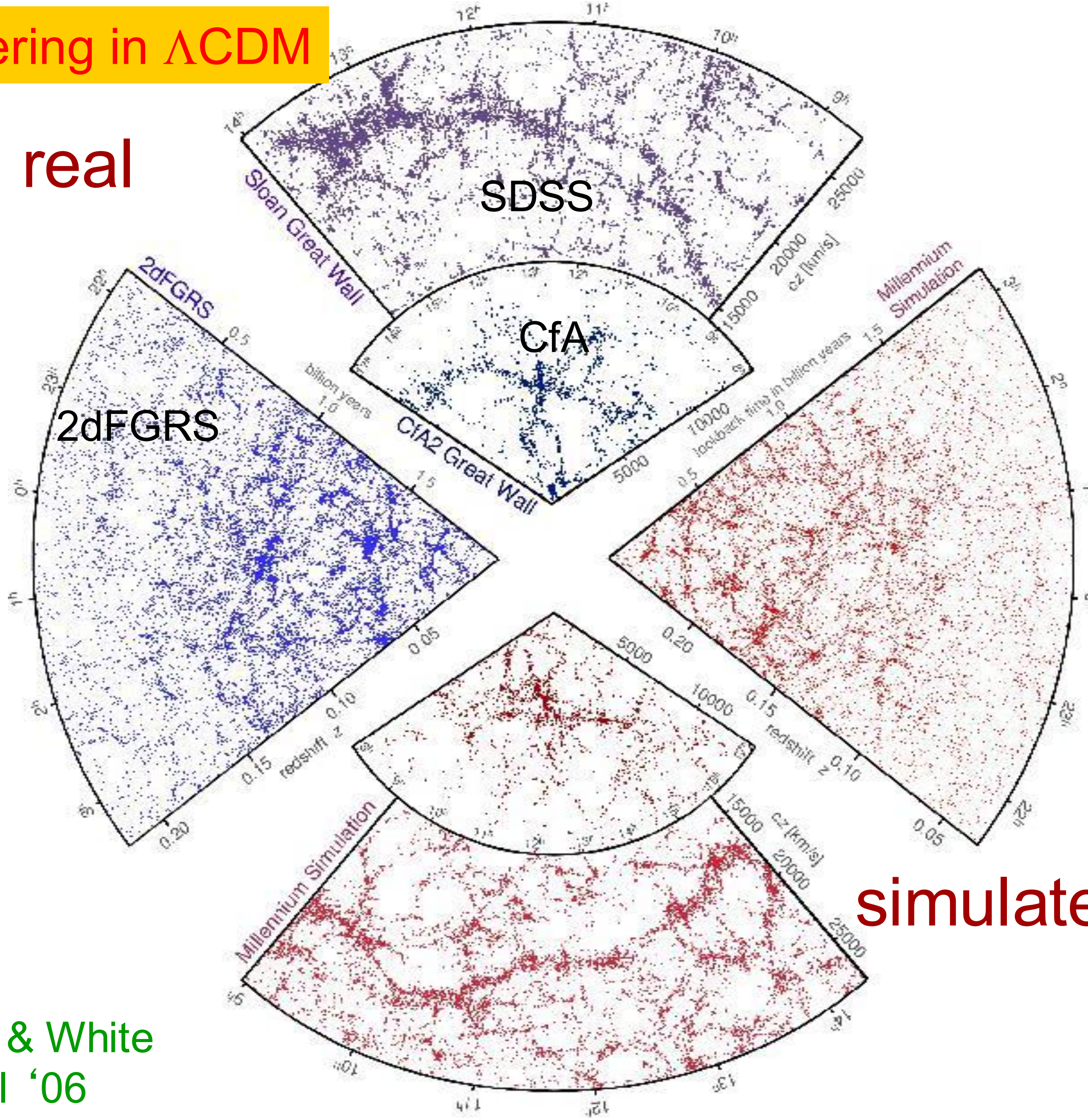
Galaxy clustering in ΛCDM

real



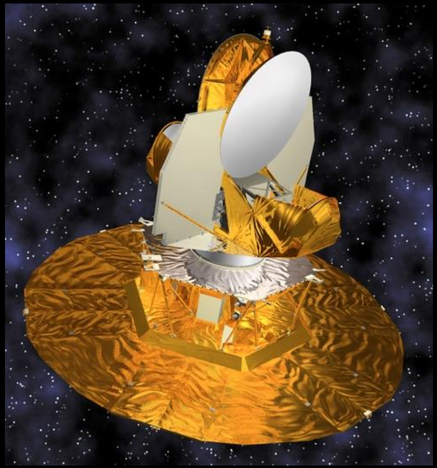
simulated

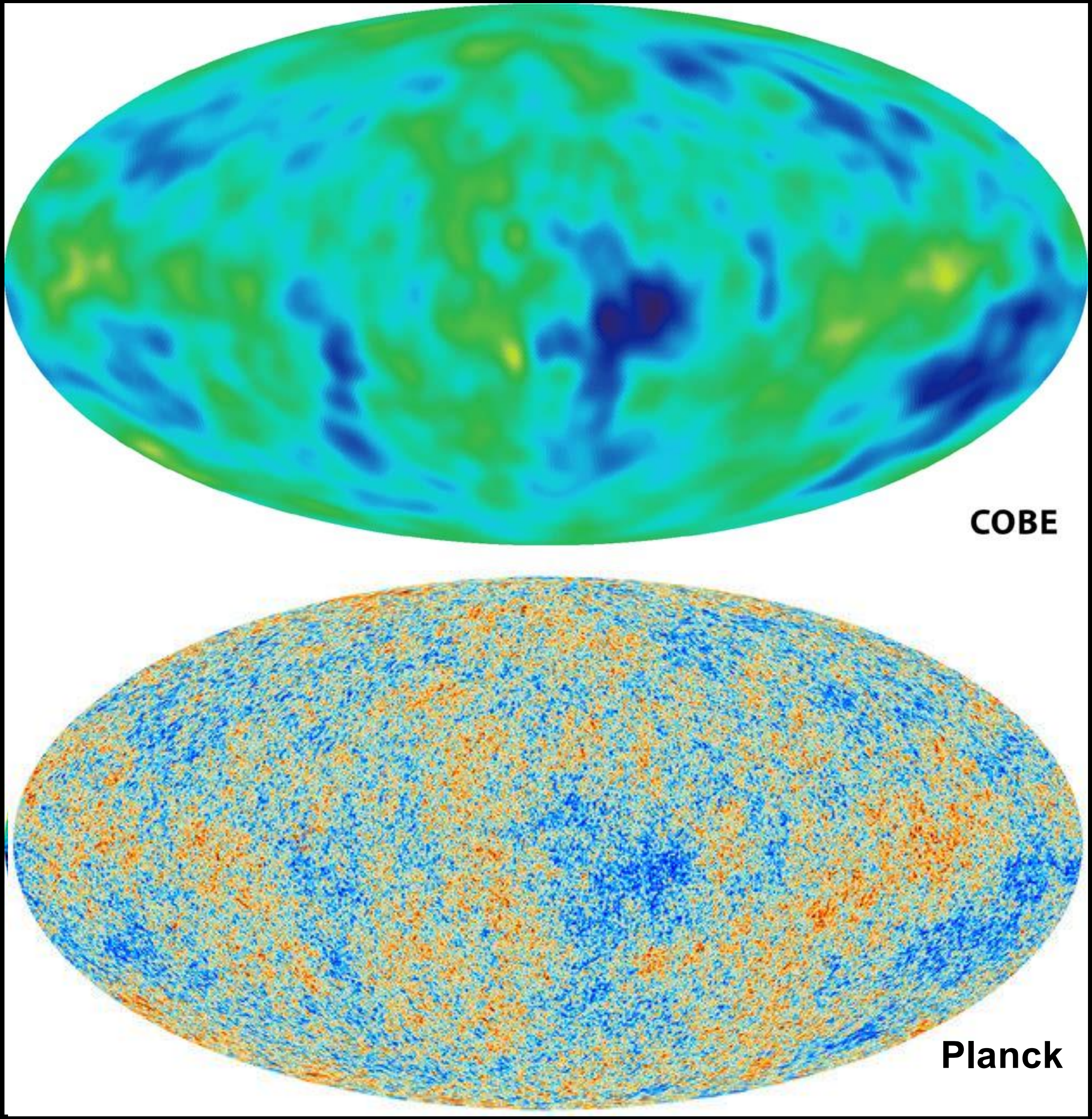
Springel, Frenk & White
Nature, April '06

The CMB

1992

2012





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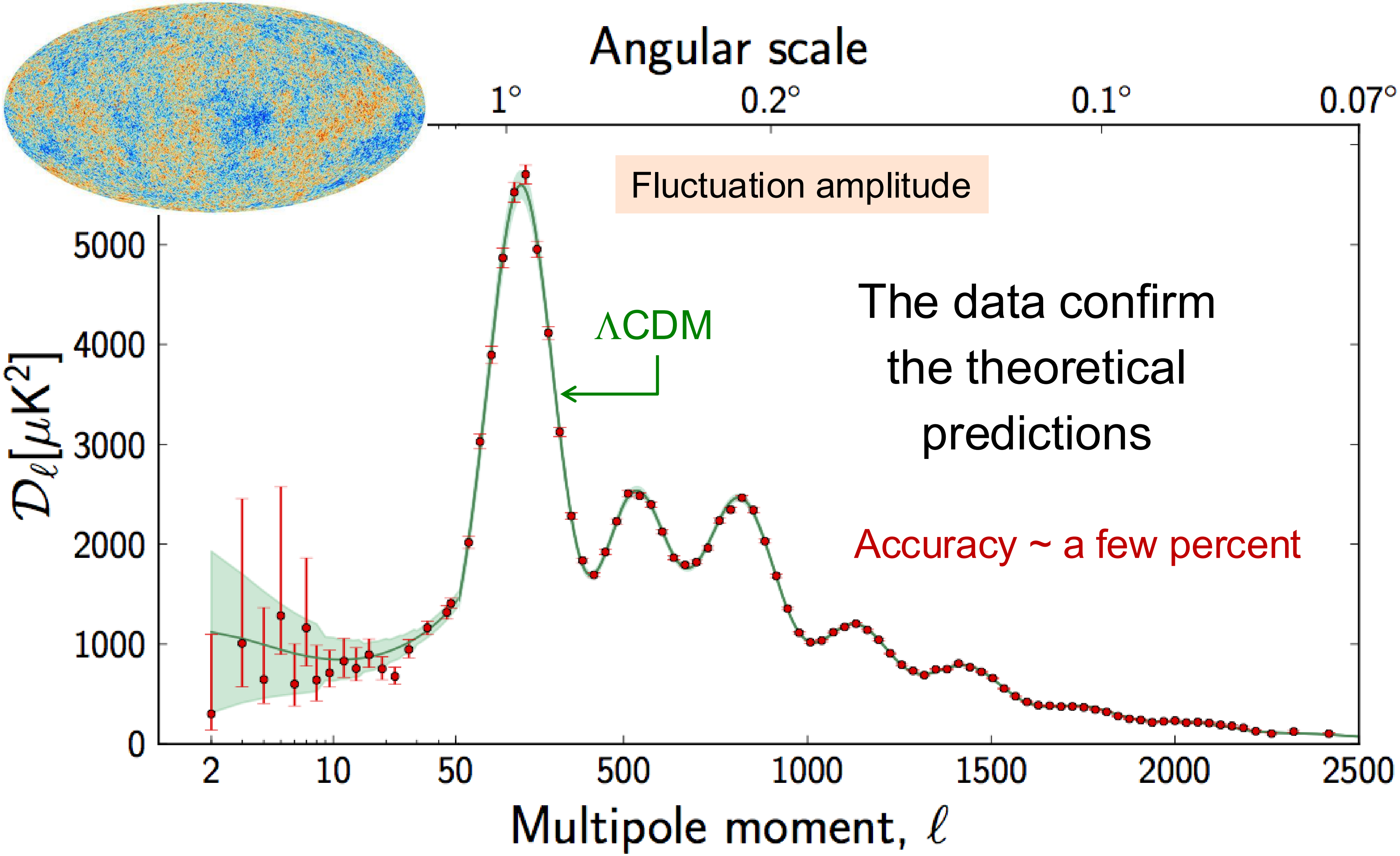
Planck: CMB temperature anisotropies

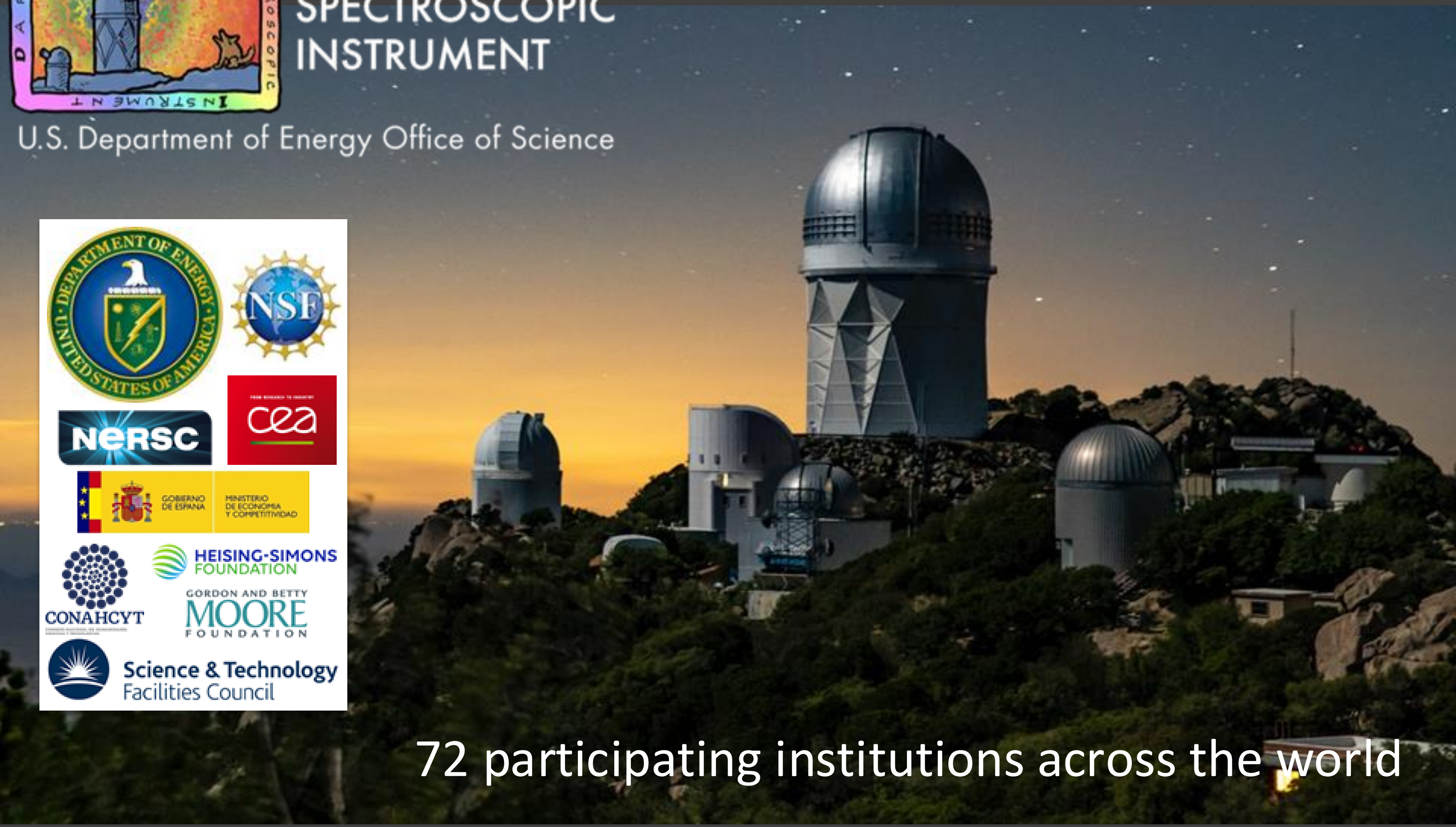


Planck coll. 2015

Tests of ΛCDM a subpercent accuracy?

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



72 participating institutions across the world

DESI in the news

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

By Dennis Overbye

April 4, 2024

Leer en español

On Thursday, astronomers who are conducting what they describe

DESI in the news

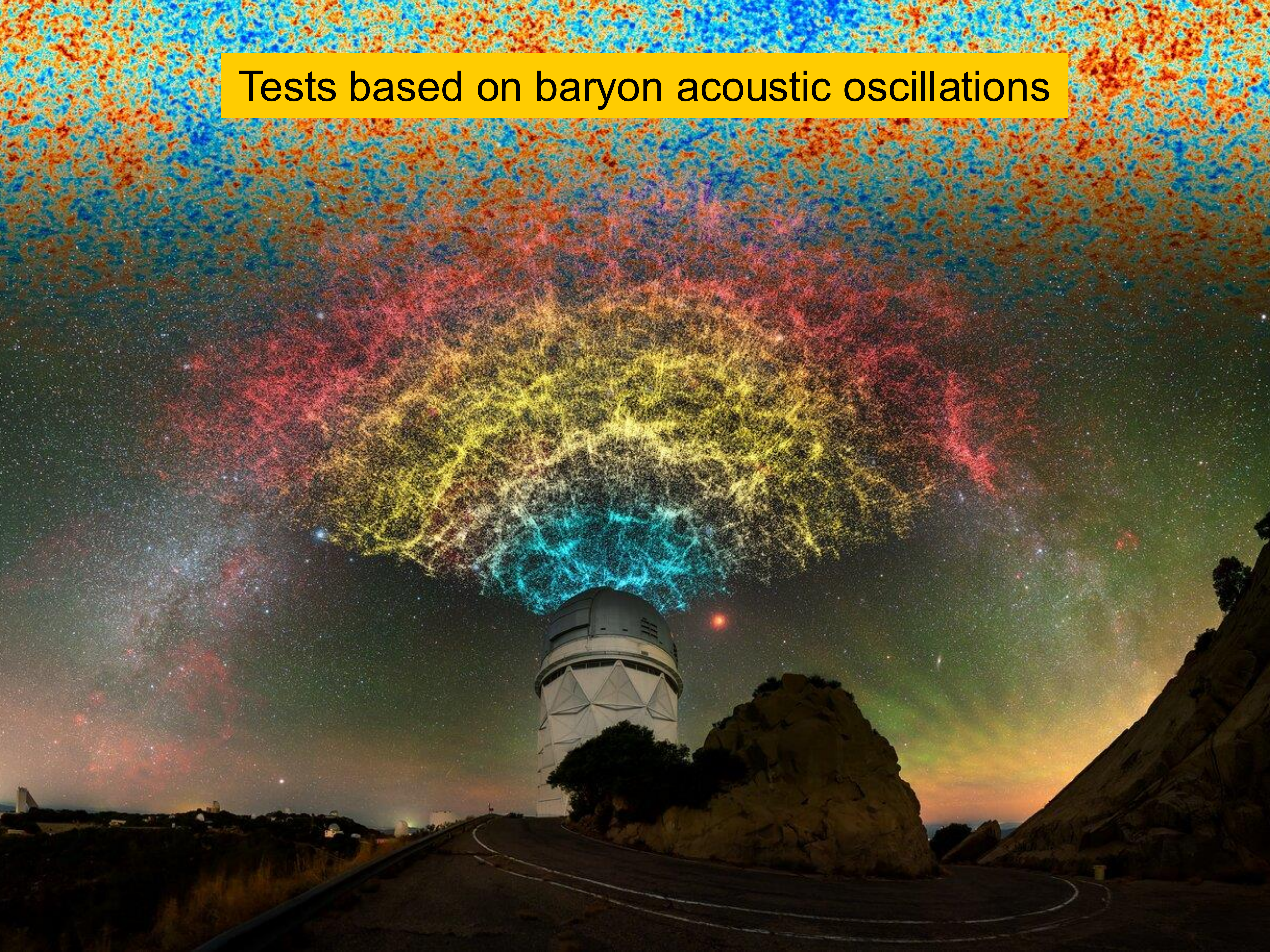
A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

discovered a major flaw in their

ic force. That could be

A neutrino mass mismatch could shake cosmology's foundations

Tests based on baryon acoustic oscillations



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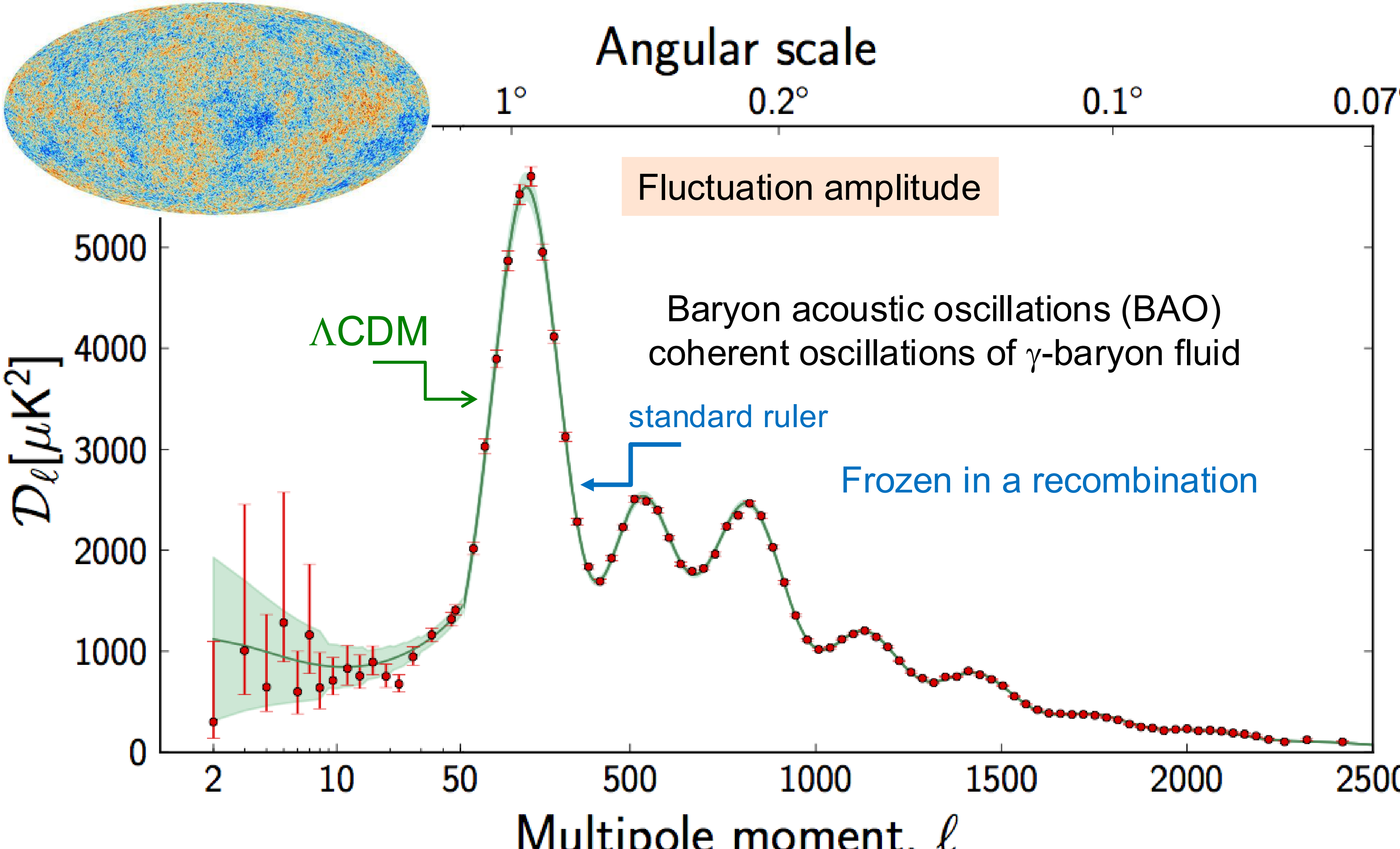
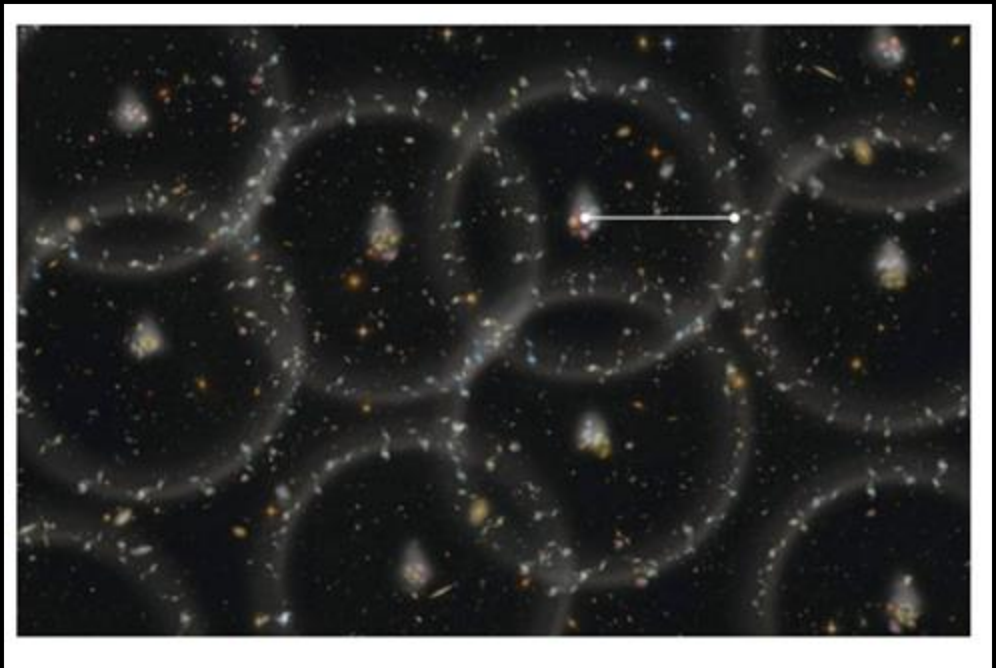
Planck: CMB temperature anisotropies

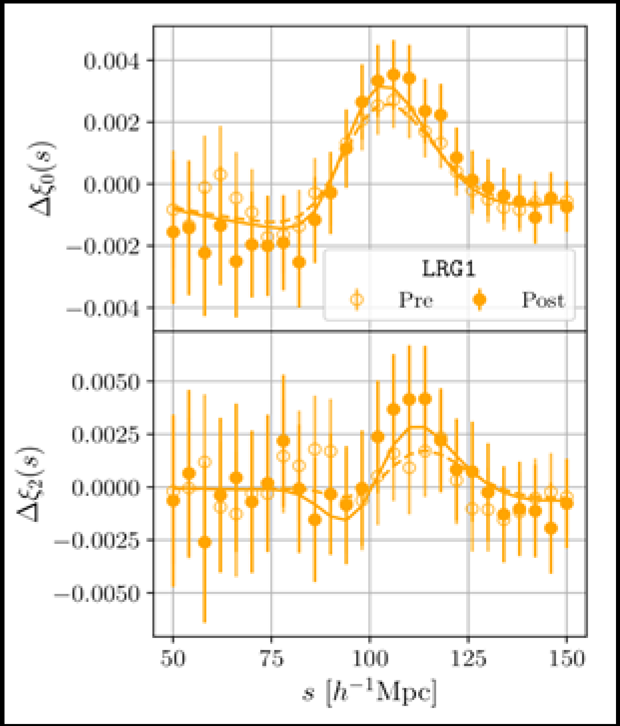


Planck coll. 2015

Baryon acoustic oscillations (BAO)

DESI already has > 30 million spectra





The scale of the oscillations (the sound horizon at z_{rec}) is determined by physics → BAO scale is standard ruler

Discovered in 2005 by 2dFGRS and SDSS

→ can measure expansion history of universe

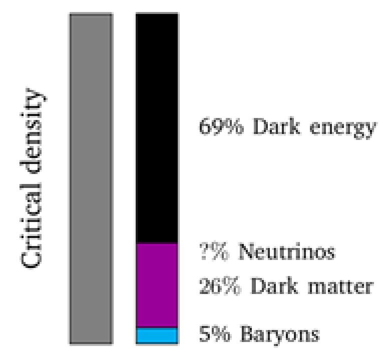
The distance-redshift relation

The distance-redshift relation depends on the energy density of various matter components, including massive neutrinos:

$$D_{\mathrm{M}}(z) = \frac{c}{H_0}\int_0^z \mathrm{d}z' \, \frac{H_0}{H(z')},$$

$$\frac{H(z)^2}{H_0^2} = \Omega_{\mathrm{r}}(1+z)^4 + \Omega_{\mathrm{m}}(1+z)^3 + \Omega_{\Lambda} + \Omega_{\nu}(z).$$

Radiation **Matter** **Dark energy** **Neutrinos**



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DESI BAO and dark energy

Dark energy has a negative pressure:

$$P = w\rho$$

Simplest case:

$$w = -1 \quad (\Lambda)$$

Introducing a time-varying equation of state:

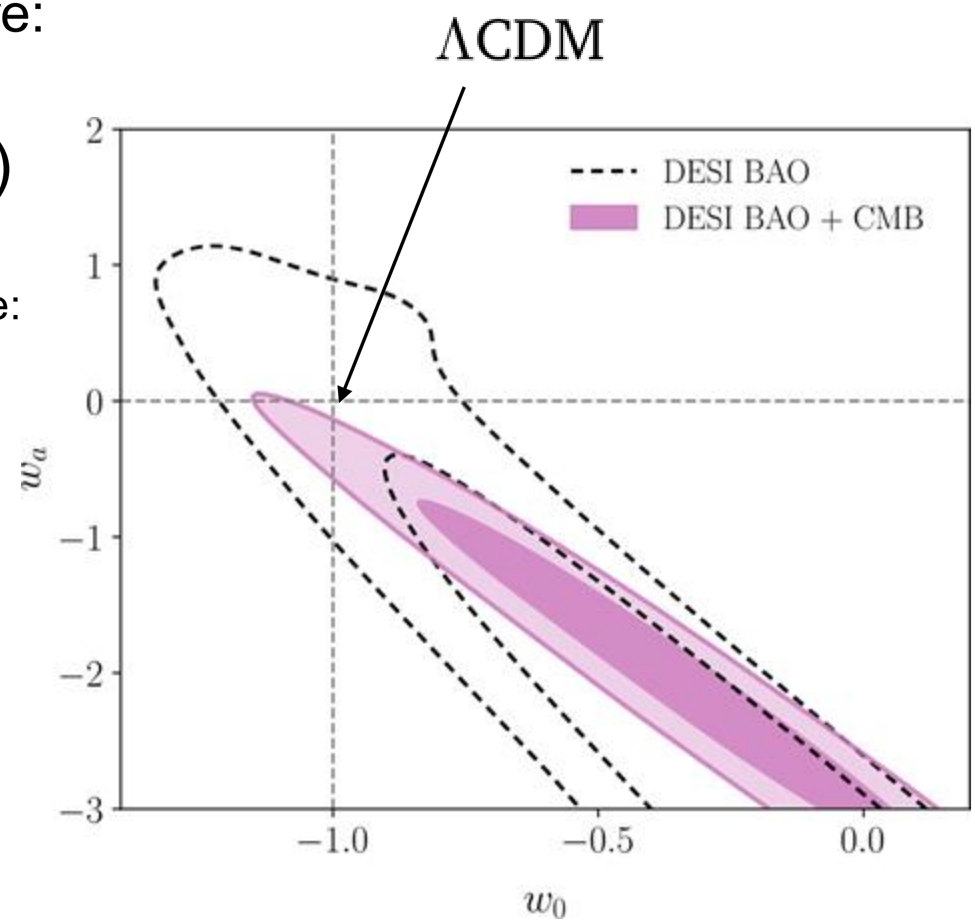
$$w(a) = w_0 + w_a(1 - a)$$

DR1 results

Preference over ΛCDM:

DESI alone: 1.5σ

DESI + CMB: 2.6σ



DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI BAO and dark energy

University of Durham

Dark energy has a negative pressure:

$$P = w\rho$$

Simplest case:

$$w = -1 \quad (\Lambda)$$

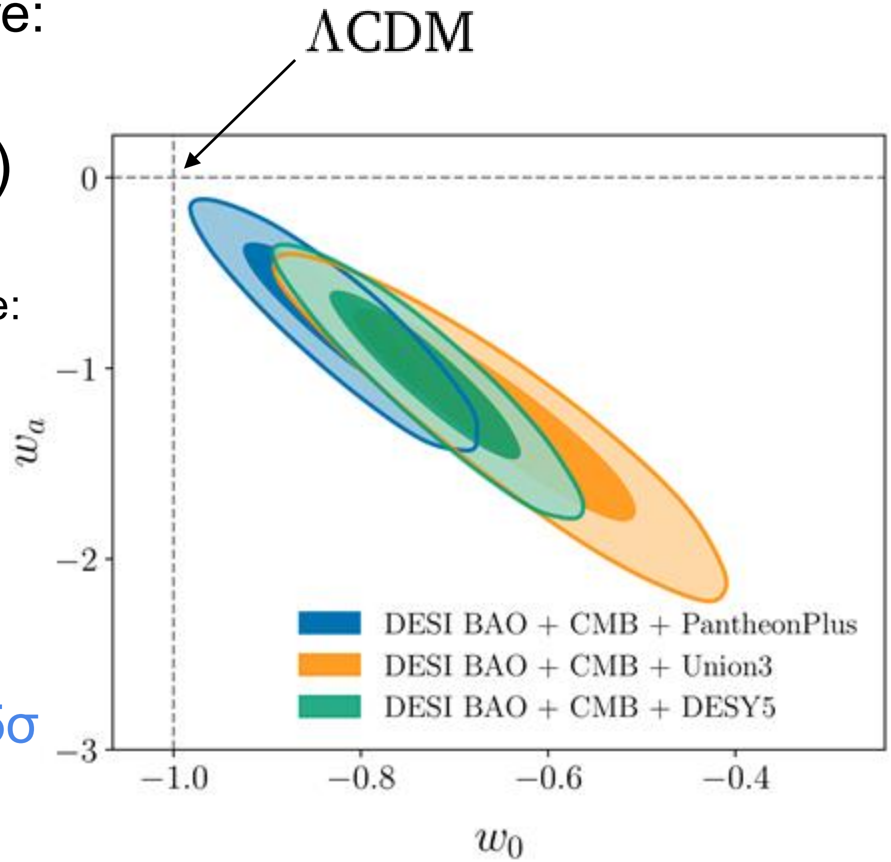
Introducing a time-varying equation of state:

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

DR1 results

Preference over ΛCDM:

DESI + CMB + PantheonPlus: 2.5σ
DESI + CMB + Union3: 3.5σ
DESI + CMB + DESY5: 3.9σ



DESI collaboration: Adame+ '24

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

Institute for Computational Cosmology

The DESI DR2 sample

We now have DR2 results (papers in April/25)

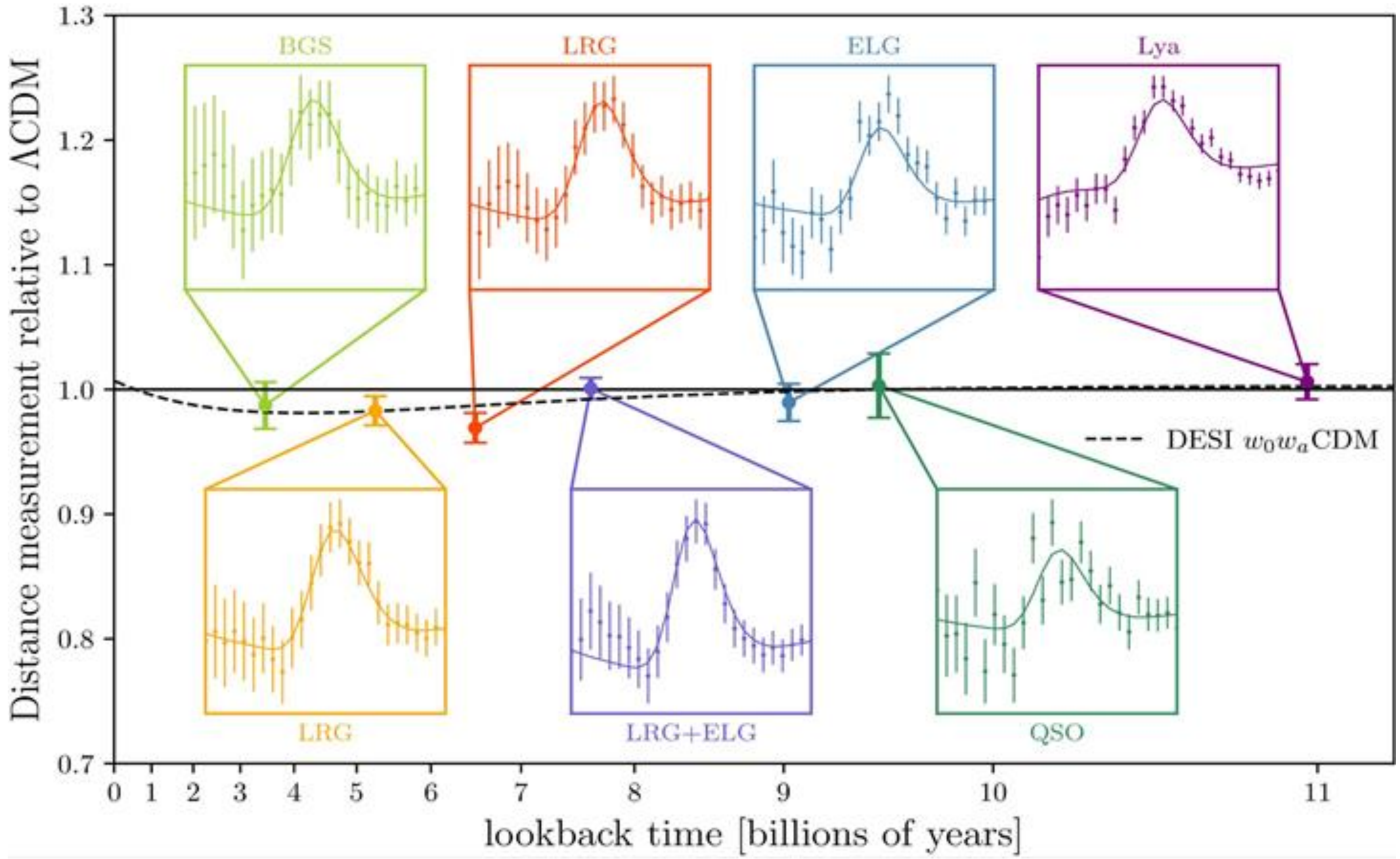
DESI observed over 30M galaxy and quasar redshifts after 3 years, 14M of which are used in the latest analysis.

This represents a factor 2.4 improvement over DR1.

Tracer	DR1	DR2
BGS	300,043	1,188,526
LRG	2,138,627	4,468,483
ELG	2,432,072	6,534,844
QSO	1,223,391	2,062,839
Total	6,094,133	14,254,692

DESI BAO measurements

University of Durham



Can measure expansion history of universe

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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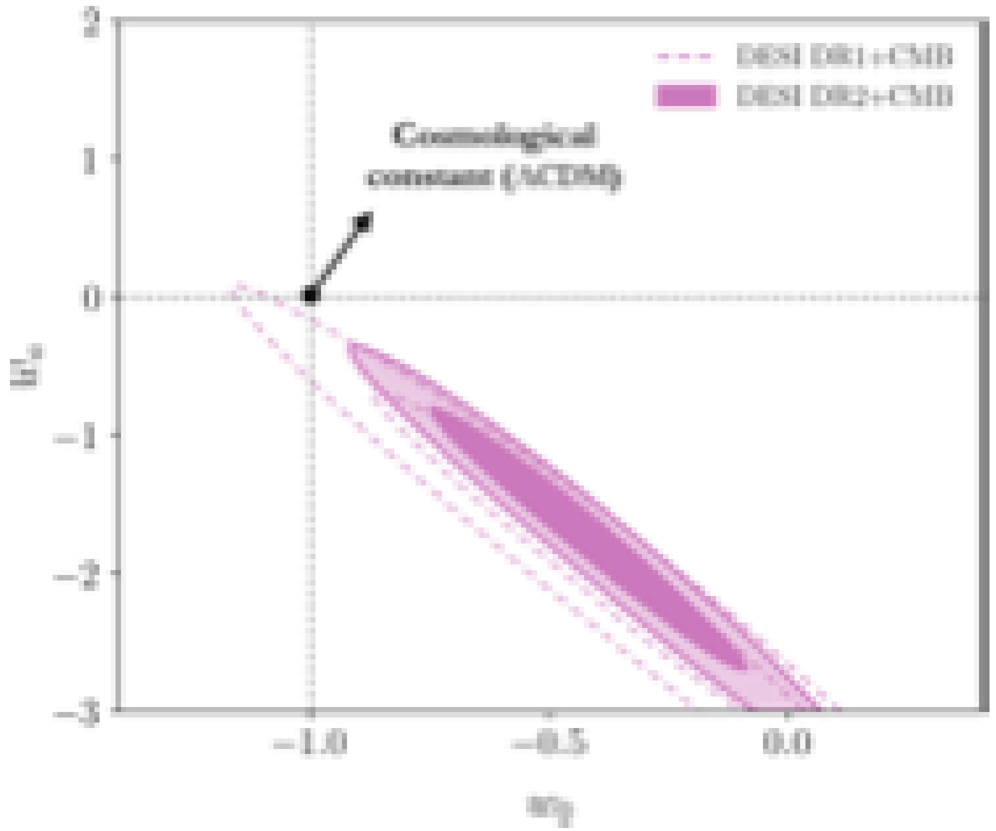
Dynamical dark energy

Combined with CMB data, there is a clear preference for $w_0 > -1$ and $w_a < 0$.

The preference for $w_0 w_a$CDM from BAO+CMB increases from 2.6σ (DR1) to 3.1σ (DR2).

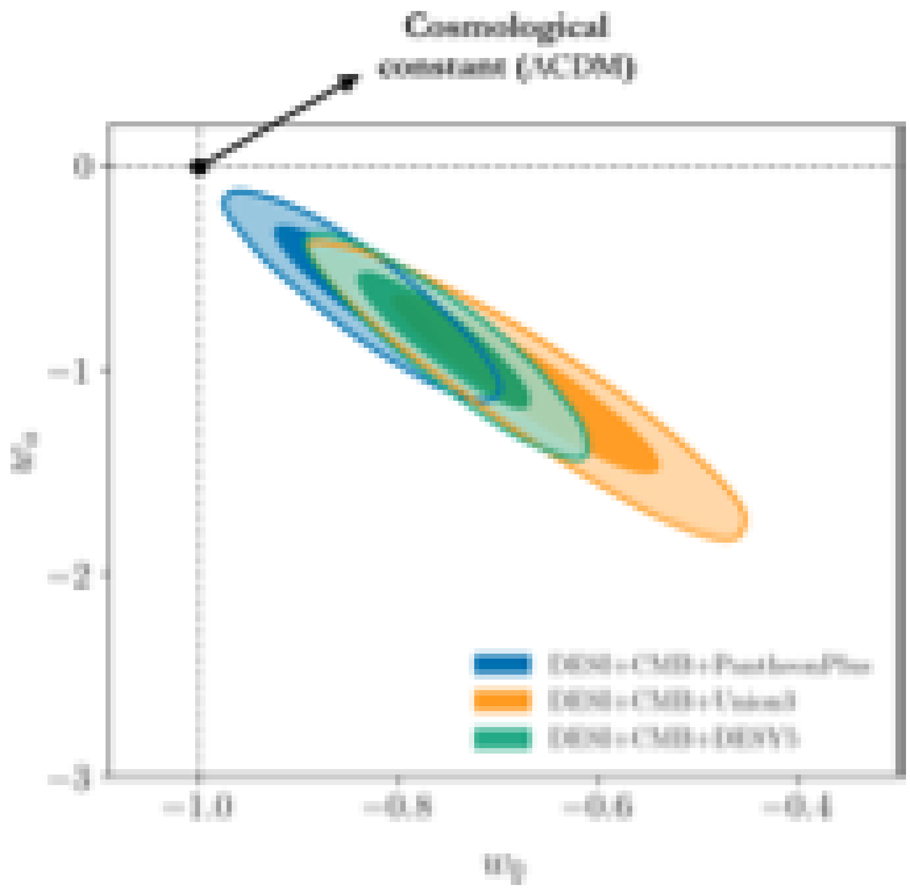


DESI collaboration: Adame+ '25

Dynamical dark energy

Significance of rejection of ΛCDM:

- DESI+CMB+Pantheon+: 2.8σ
- DESI+CMB+Union3: 3.8σ
- DESI+CMB+DESY5: 4.2σ



DESI collaboration: Adame+ ‘24

First neutrino results from DESI

The BAO scale at various z → expansion history

→ depends on the sum of neutrino masses

Standard Model Neutrinos

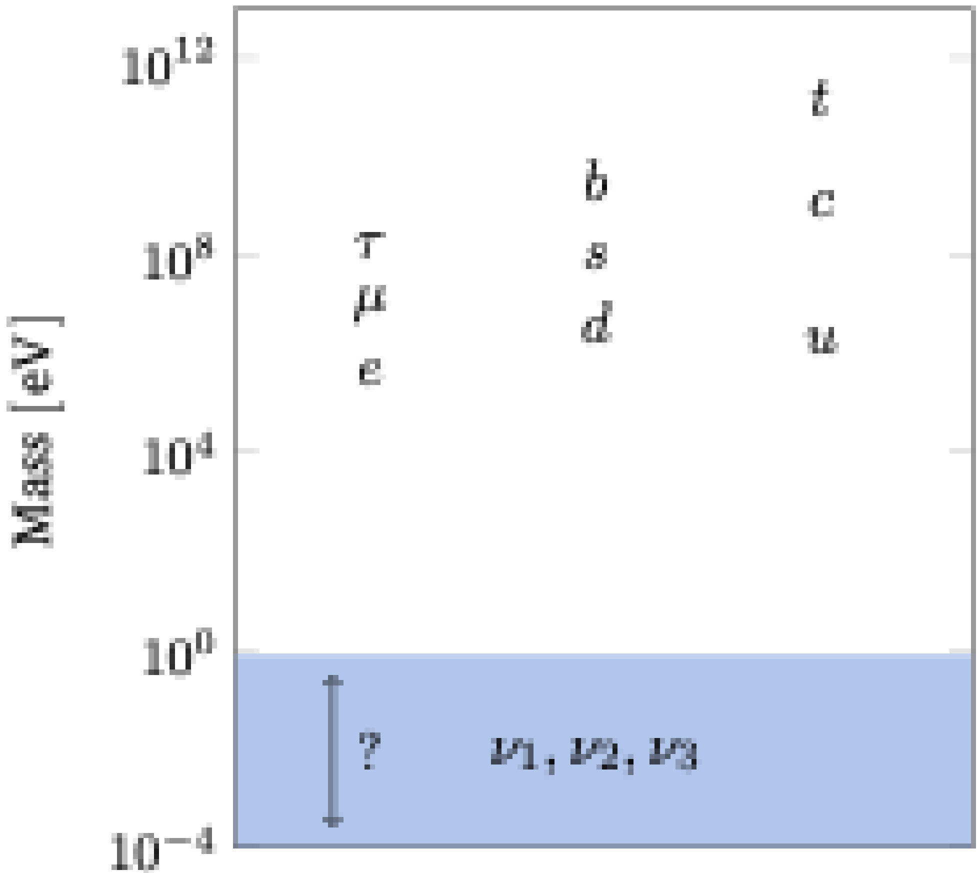
Standard Model Fermions

ν_e	ν_μ	ν_τ
e	μ	τ
u	c	t
d	s	b

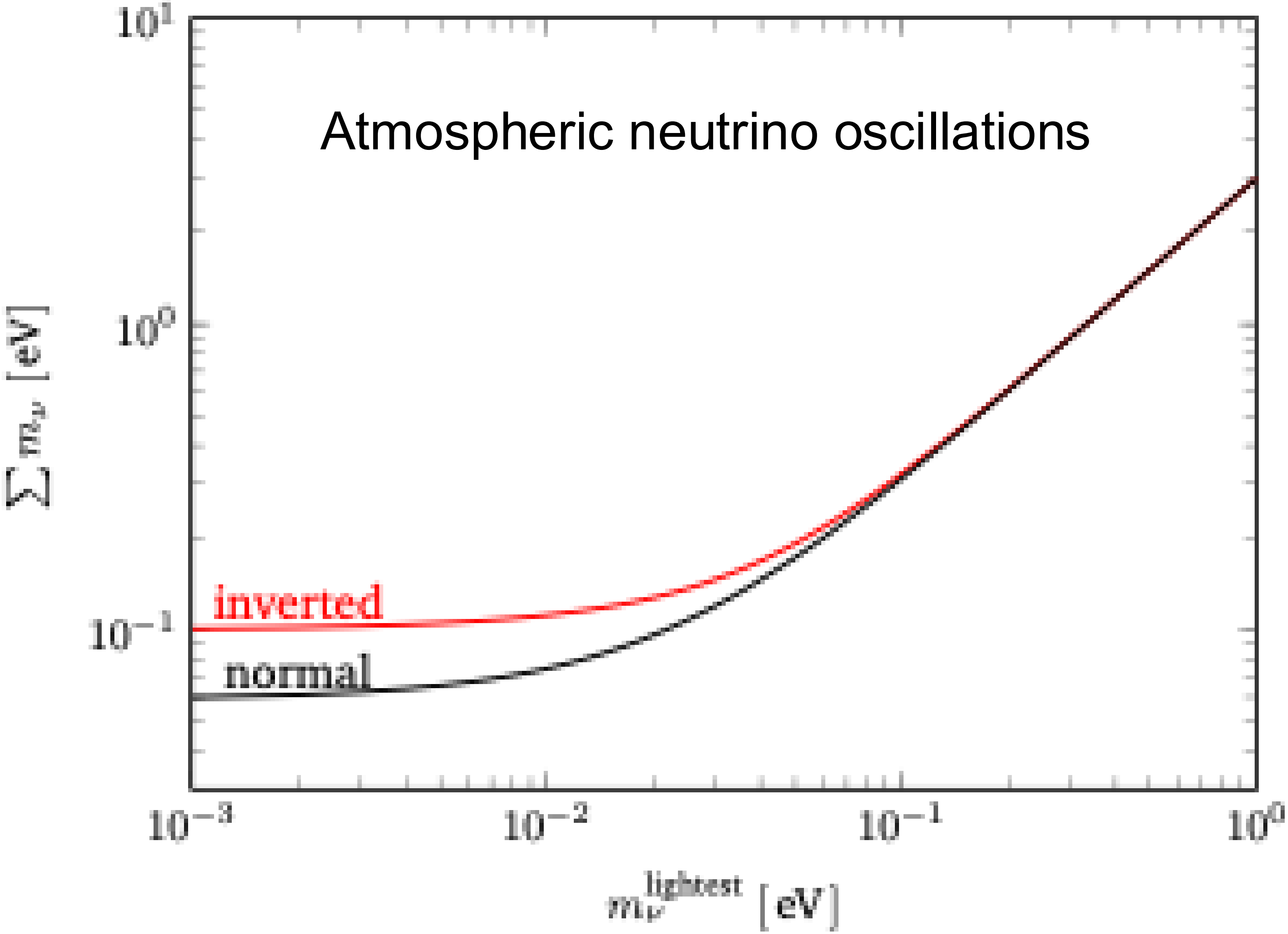
Neutrino oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix},$$

which gives us Δm_{ij}^2.



Neutrino Mass Constraints

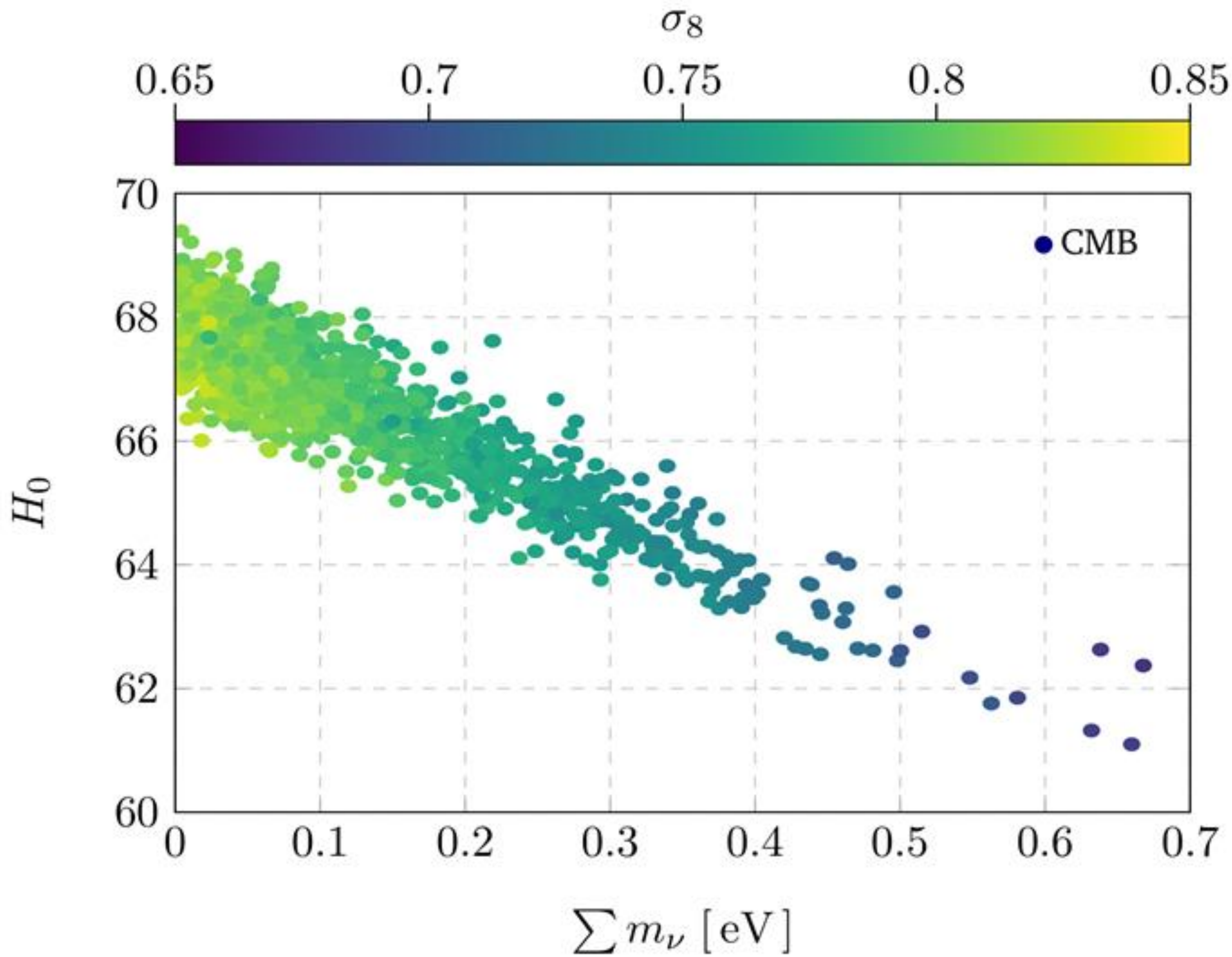


Constraints on sum of ν masses

From CMB:

assuming ΛCDM

$$\sum m_\nu < 0.21\,\mathrm{eV}$$



Constraints on sum of ν masses

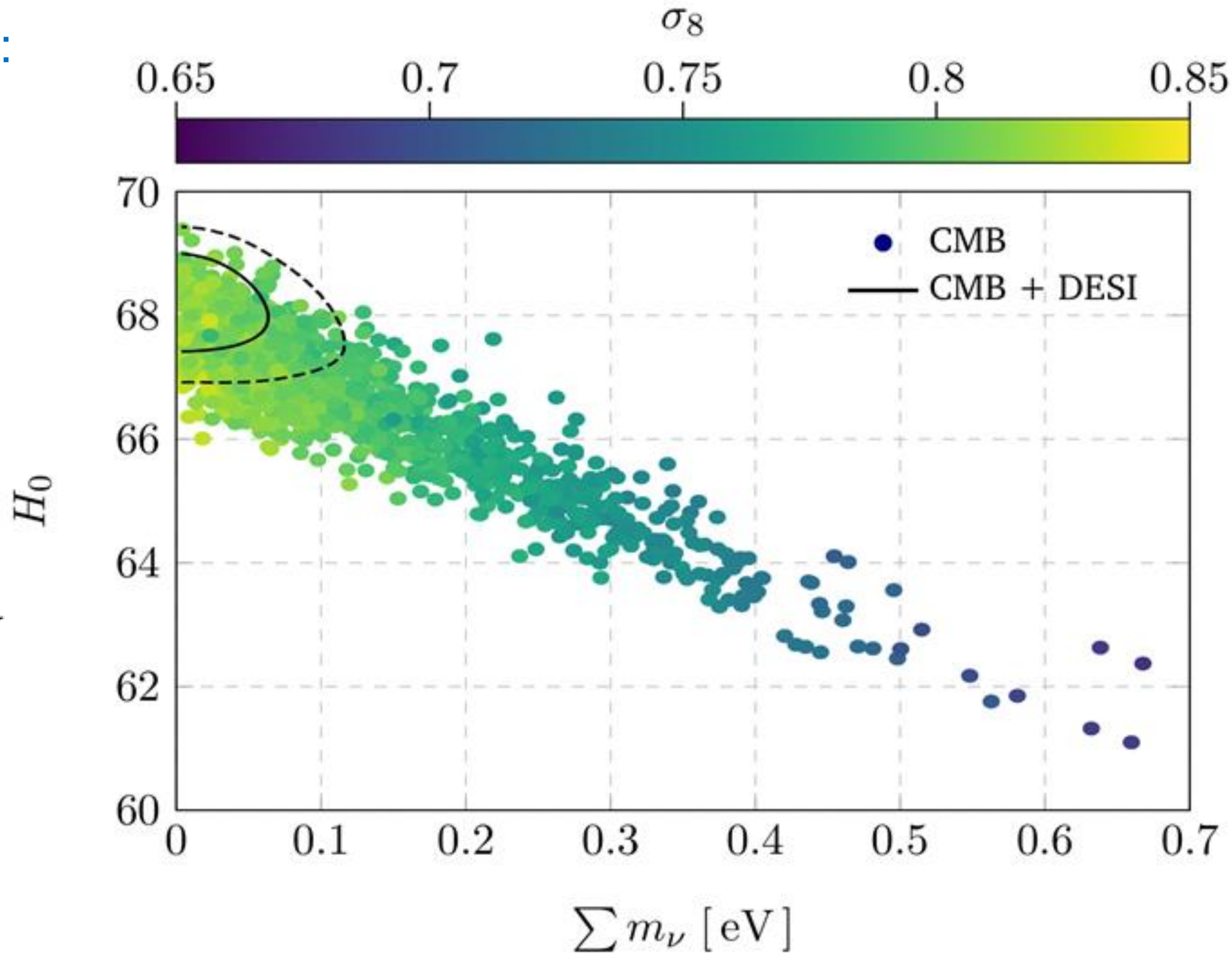
From CMB + DESI:

assuming ΛCDM

$$\sum m_\nu < 0.072\,\mathrm{eV}$$

From atmospheric ν oscillations

$$\sum m_\nu > 0.060\ \mathrm{eV}$$



Constraints on sum of ν masses

From CMB:

$$\sum m_\nu < 0.21\,\mathrm{eV}$$

From CMB + DESI BAO:

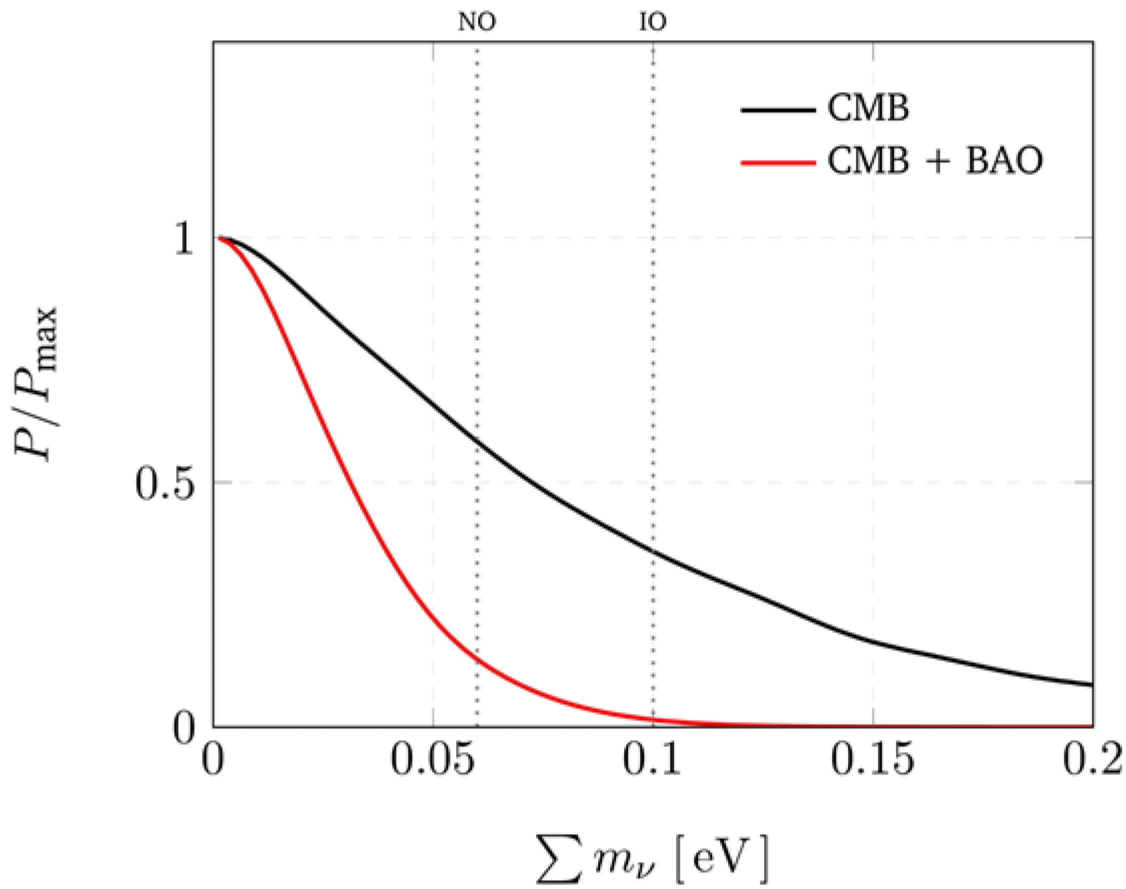
$$\sum m_\nu < 0.072\,\mathrm{eV}$$

(Both at 95%)

(Prior $\Sigma\, m_\nu > 0$)

Posterior distribution peaks at 0

Posterior distribution of ν masses in ΛCDM



Constraints on sum of ν masses

Relax the prior: introduce an effective neutrino mass, $\Sigma m_{\nu,\text{eff}}$, that coincides with the physical Σm_ν for $\Sigma m_{\nu,\text{eff}} > 0$ and extend to negative values in data space

Elbers, CSF, Jenkins, Li & Pascoli '24

Any evidence for negative values should be interpreted as a signature of unidentified systematic errors or possibly of new physics which may be unrelated to neutrinos

See also:
eBOSS Collaboration (2021; 2007.08991)
Craig et al. (2024; 2405.00836)

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Constraints on sum of ν masses

In ΛCDM, posterior peaks at $\Sigma m_{\nu,\,eff} < 0$

Inconsistent with ν oscillations at 2.6σ

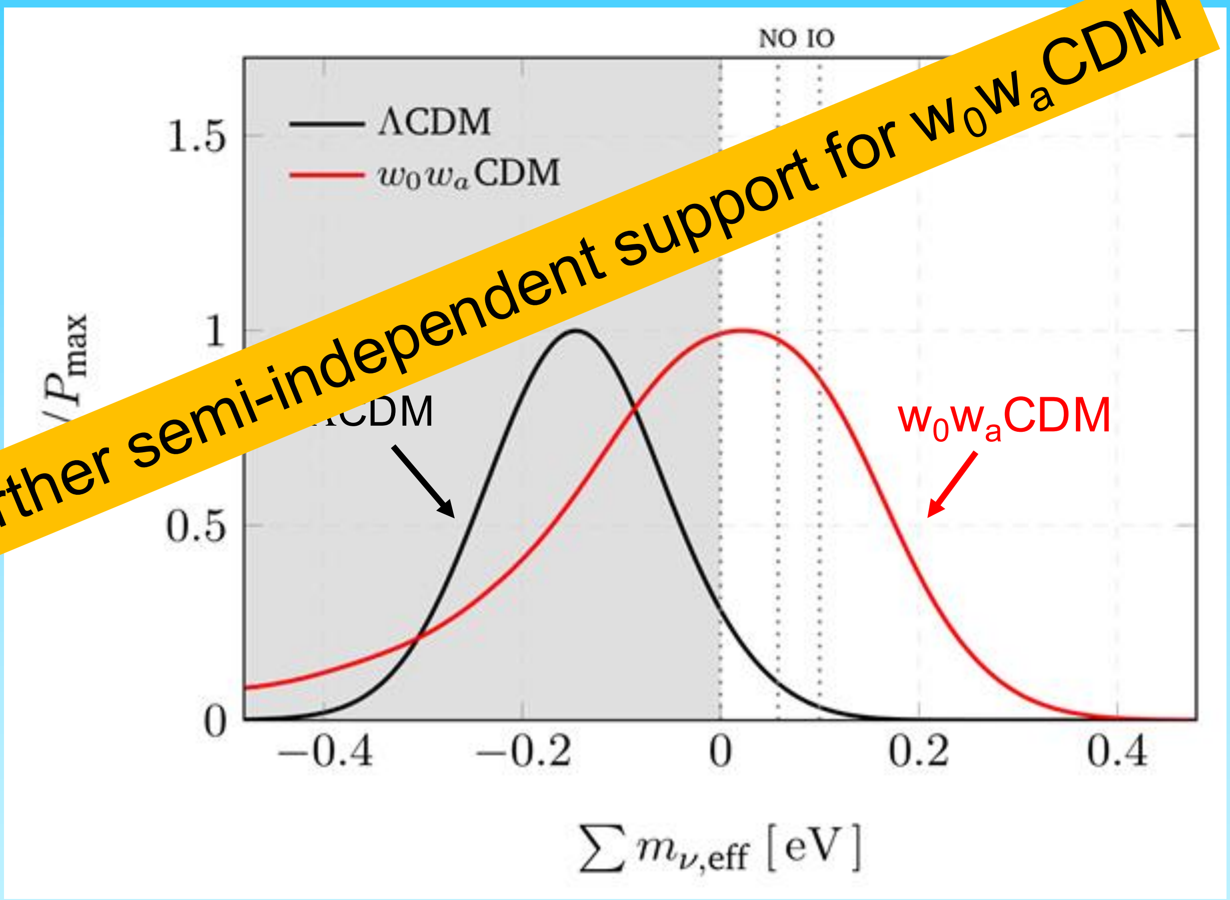
In w_0w_aCDM posterior peaks at $\Sigma m_{\nu,\,eff} > 0$

In w_0w_a CDM, bound on physical neutrino mass Σm_ν <0.195 eV

Consistent with ν oscillations

Posterior distribution of ν masses

Further semi-independent support for w_0w_aCDM



Elbers, CSF + ‘24

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Observational tests of ΛCDM

Fundamental prediction of ΛCDM

→ Primordial power spectrum of density perturbations

+ random phases

Can test this in two regimes:

Linear regime: cosmic microwave background (z~1000)

large-scale structure (z~3 - 0)

Evolved non-linear regime:

Depends v. weakly on Λ;
Test of CDM!

dark matter halos →

- abundance (z~15 – 0)
- structure
- clustering

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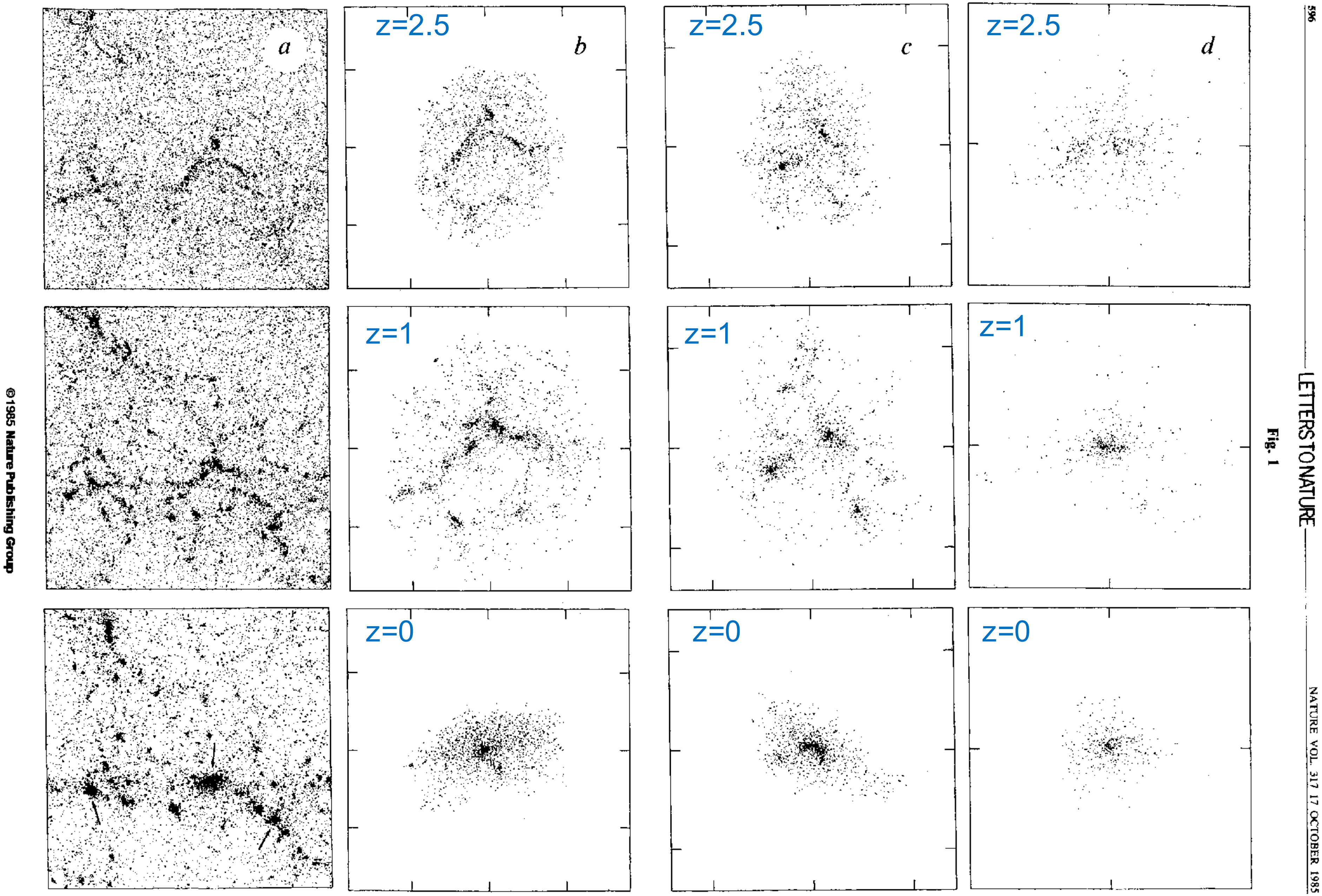
The small-scale “crisis” of ΛCDM

Four problems:

		“Solved” in:	
1.	“Missing satellites”	2002	baryon effects
2.	“Too-big-to-fail”	2015	baryon effects
3.	“Core-cusp”	1996	baryon effects
4.	“Plane of satellites”	2023	→ Cosmic web + statistics

5. Galaxies at z > 10 discovered by JWST

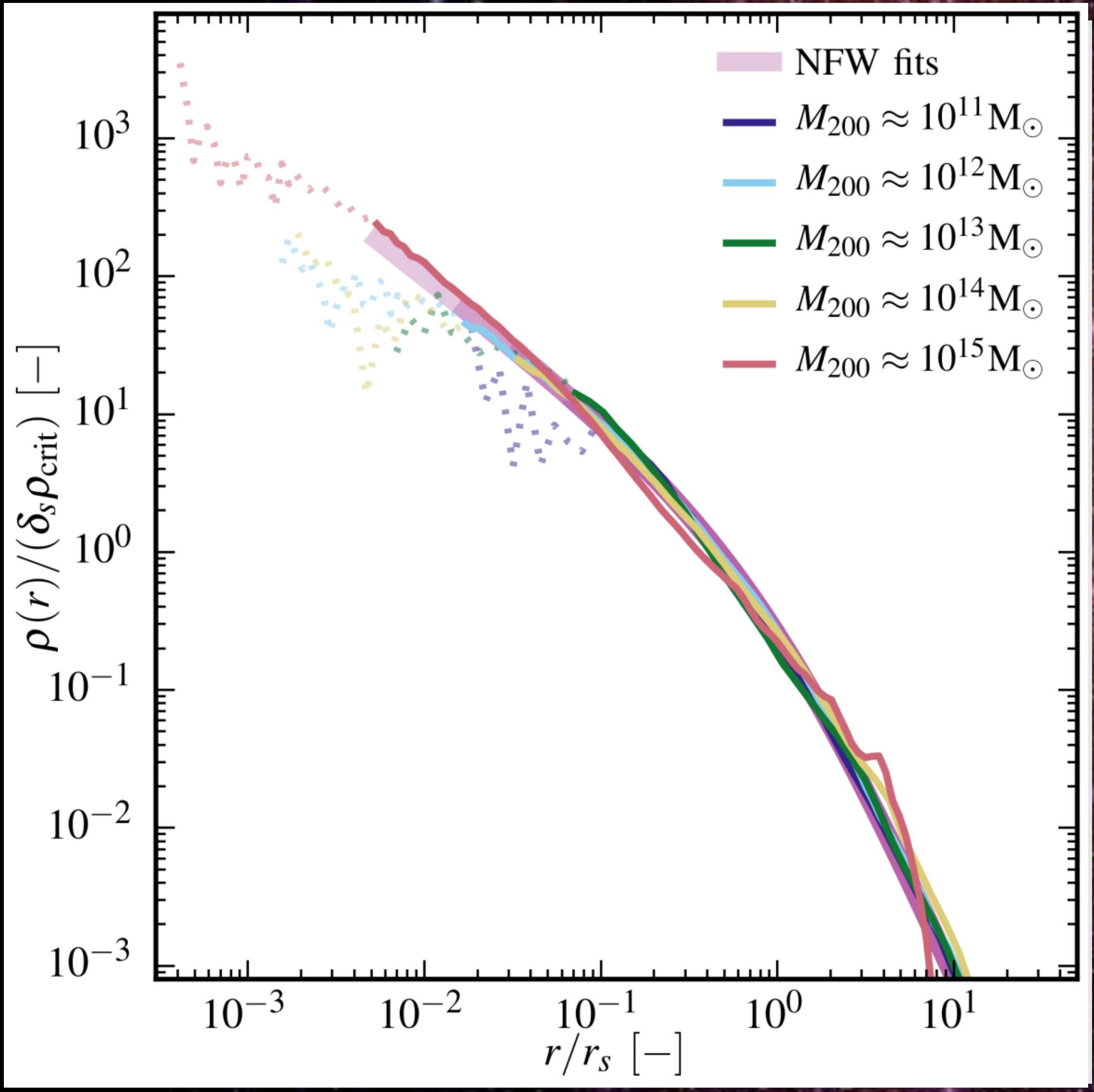
Formation of CDM halos



Frenk et al 1985

The density profile of cold dark matter halos

Navarro, Frenk & White '96



Shape of halo profiles ~independent of halo mass & cosmological parameters

Density profiles are "cuspy" – no `core' near the centre

Fitted by simple formula:

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White '97)

More massive halos and halos that form earlier have higher densities (bigger δ)

CDM

We now know:

→ the internal structure of halos of all mass

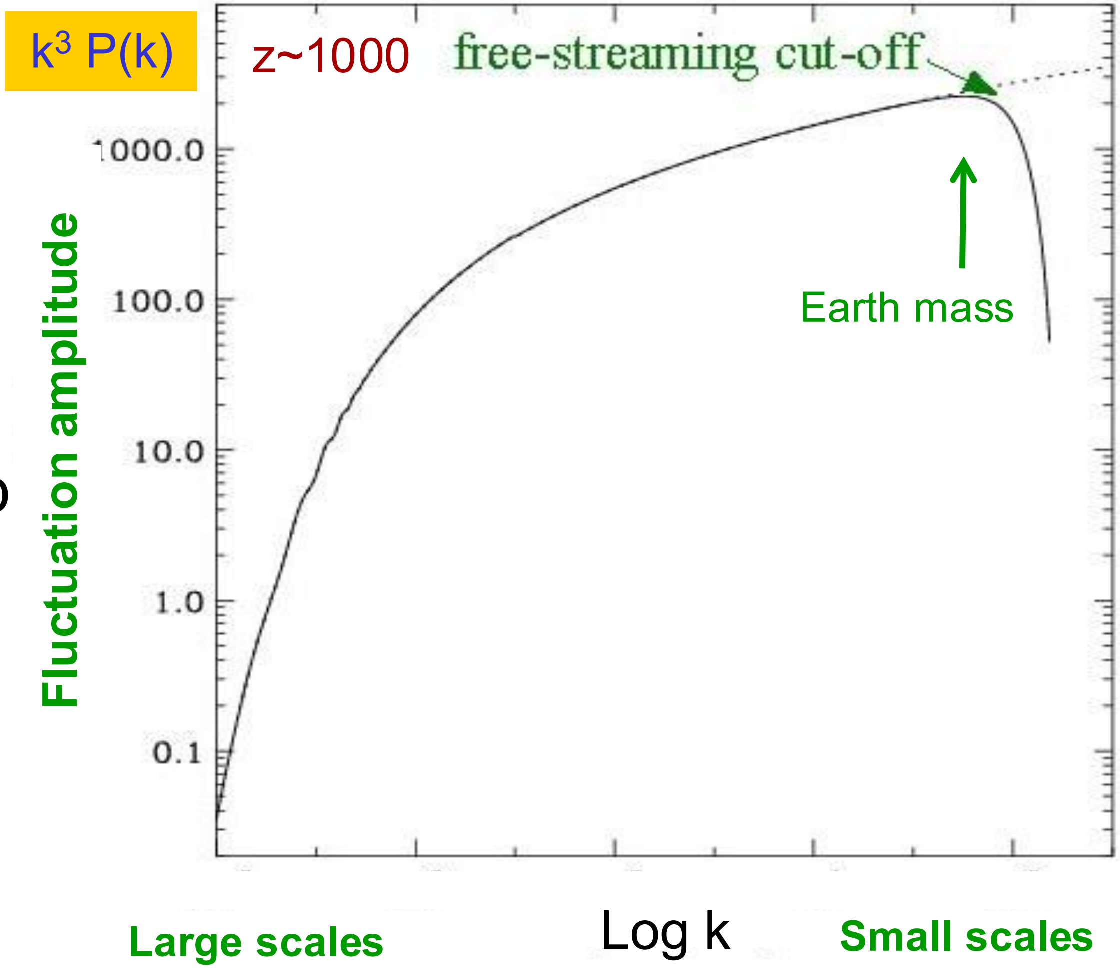
→ halo mass function down to cutoff mas

The cold dark matter power spectrum

The linear power spectrum ("power per octave")

Assumes a 100GeV wimp

Green et al '04



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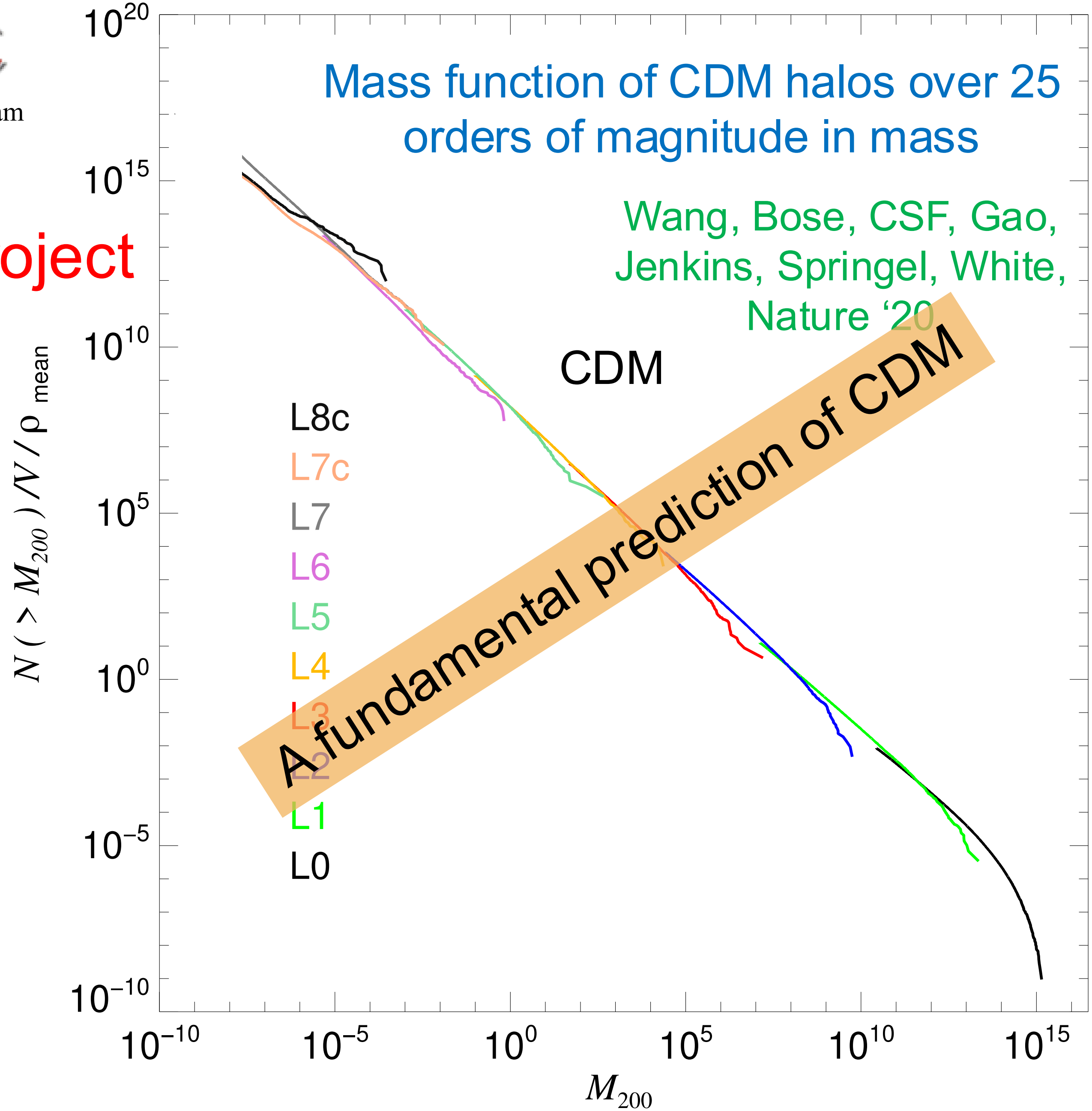
The VVV project



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A galaxy formation primer

In which halos do galaxy form?

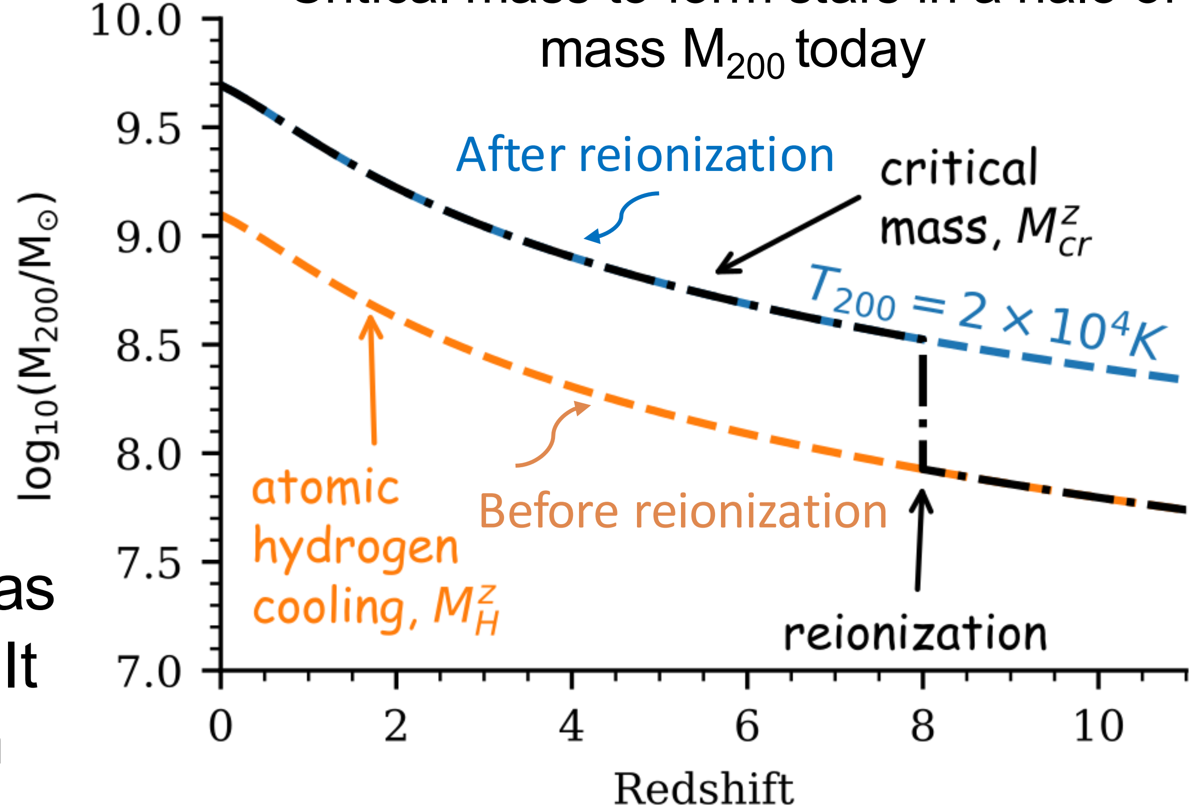
1. Before reionization, stars can only form if atomic H cooling is effective: → T>7000 K

$$M_H^z \sim (4\times10^7\ M_\odot)\left(\frac{1+z}{11}\right)^{-3/2}$$

2. After H reionization, gas is heated to T=2x10^4 K. It can only cool and form stars in halos with:

$T_{vir} > T_{IGM} = 2\times10^4$ K

Critical mass to form stars in a halo of mass M_{200} today



Benitez-Llambay & CSF '20

See also Efstathiou '82, Thoul & Weinberg '95

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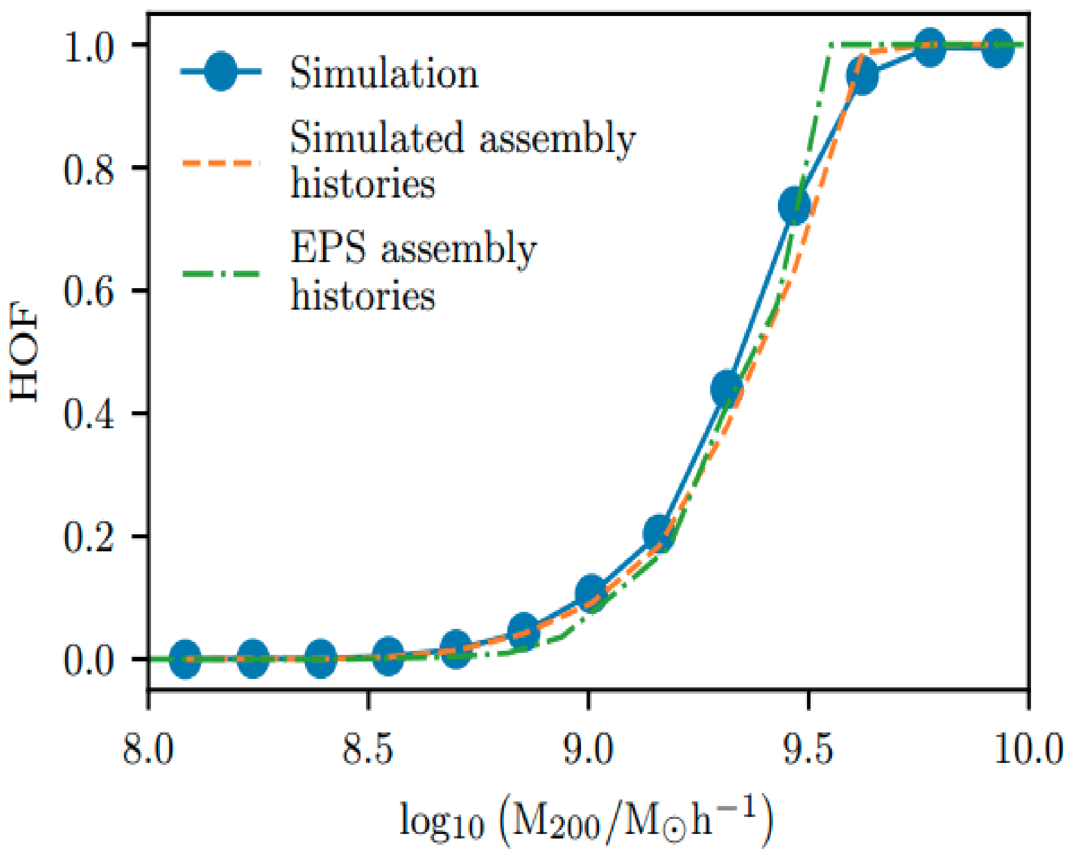
A galaxy formation primer

Halo Occupation Fraction (HOF): fraction of halos of a given mass today that host a galaxy

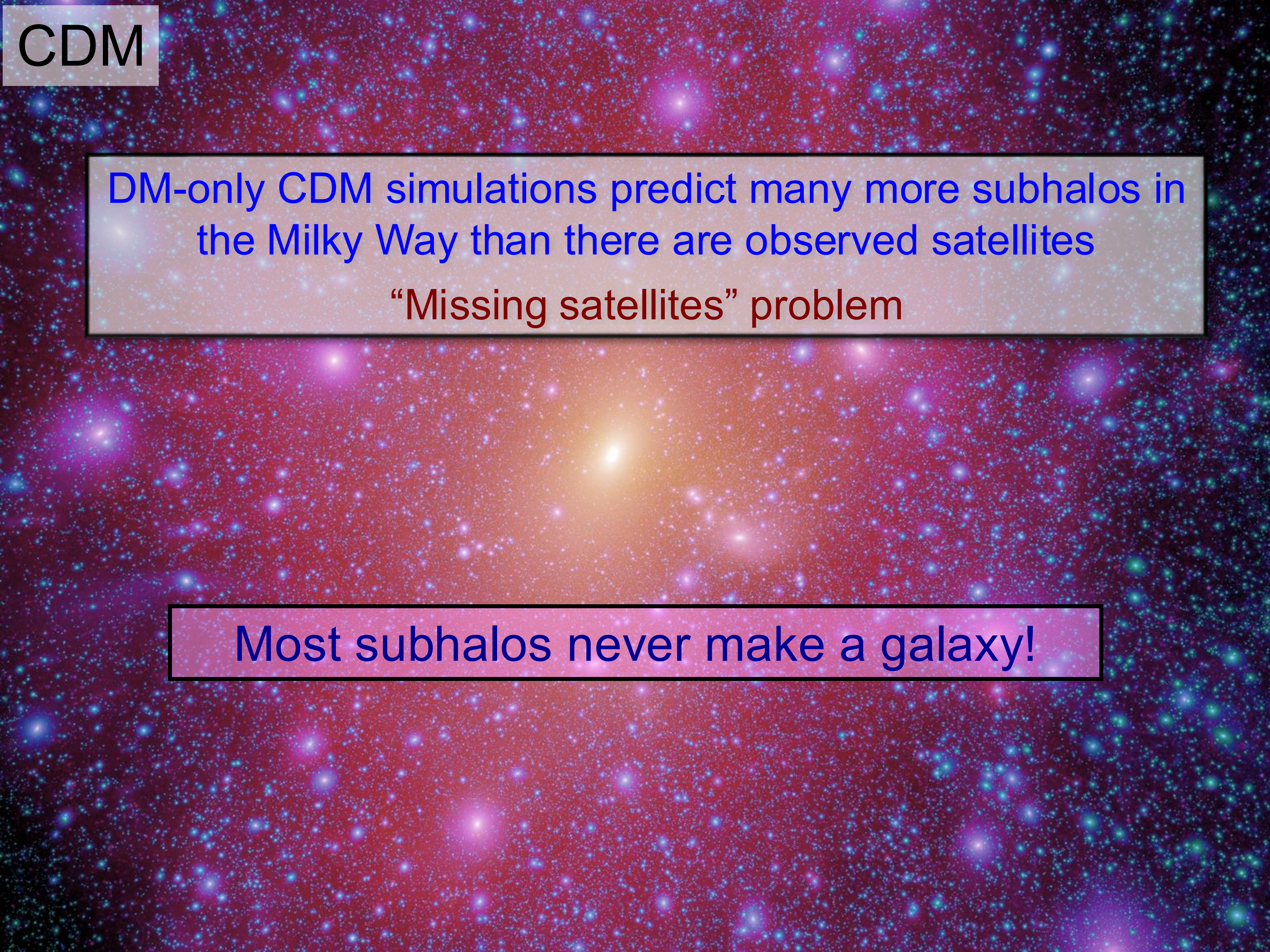
Benitez-Llambay & CSF ‘20

fraction of halos that host a galaxy



$M>3\times10^9 M_o$
→ visible

$M<3\times10^8 M_o$
→ dark


CDM
DM-only CDM simulations predict many more subhalos in the Milky Way than there are observed satellites
“Missing satellites” problem
Most subhalos never make a galaxy!

The small-scale "crisis" of ΛCDM

University of Durham

Four problems:

		"Solved" in:	
1.	"Missing satellites"	2002	baryon effects
2.	"Too-big-to-fail"	2015	baryon effects
3.	"Core-cusp"	1996	baryon effects
4.	"Plane of satellites"	2023	→ Cosmic web + statistics

5. Galaxies at z > 10 discovered by JWST

University of Durham

JWST galaxies at z= 8 -15

The Complete CEERS Early Universe Galaxy Sample: A Surprisingly Slow Evolution of the Space Density of Bright Galaxies at $z \sim 8.5$–14.5

Steven L. Finkelstein,[1] Gene C. K. Leung,[2] Micaela B. Bagley,[1] Mark Dickinson,[3] Henry C. Ferguson,[4] Casey Papovich,[5,6] Hollis B. Akins,[7] Pablo Arrabal Haro,[3] Romeel Davé,[8,9] Avishai Dekel,[10] Jeyhan S. Kartaltepe,[11] Dale D. Kocevski,[12] Anton M. Koekemoer,[13] Nor Pirzkal,[14] Rachel S. Somerville,[15] L. Y. Aaron Yung,[16,13,*] Ricardo O. Amorín,[17,18] Bren E. Backhaus,[19] Peter Behroozi,[20,21] Laura Bisigello,[22,23] Volker Bromm,[1] Caitlin M. Casey,[1] Óscar A. Chávez Ortiz,[1] Yingjie Cheng,[24] Katherine Chworowsky,[1,†] Nikko J. Cleri,[5,6] M. C. Cooper,[25] Kelcey Davis,[19] Alexander de la Vega,[26] David Elbaz,[27] Maximilien Franco,[1] Adriano Fontana,[28] Seiji Fujimoto,[29,30] Mauro Giavalisco,[24] Norman A. Grogin,[4] Benne W. Holwerda,[31] Marc Huertas-Company,[32,33,34] Michaela Hirschmann,[35] Kartheik G. Iyer,[36] Shardha Jogee,[1] Intae Jung,[37] Rebecca L. Larson,[38,39] Ray A. Lucas,[40] Bahram Mobasher,[26] Alexa M. Morales,[41] Caroline V. Morley,[42] Sagnick Mukherjee,[43] Pablo G. Pérez-González,[44] Swara Ravindranath,[45,46] Giulia Rodighiero,[47,48] Melanie J. Rowland,[49] Sandro Tacchella,[50,51] Anthony J. Taylor,[1] Jonathan R. Trump,[19] and Stephen M. Wilkins[52,53]

ABSTRACT

We present a sample of 88 candidate $z \sim 8.5$–14.5 galaxies selected from the completed NIRCam imaging from the Cosmic Evolution Early Release Science (CEERS) survey. These data cover ~90 arcmin^2 (10 NIRCam pointings) in six broad-band and one medium-band imaging filter. With this sample we confirm at higher confidence early *JWST* conclusions that bright galaxies in this epoch are more abundant than predicted by most theoretical models. We construct the rest-frame ultraviolet

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JWST galaxies at z= 8 -15

arXiv:2211.05792v2 [astro-ph.GA] 4 Nov 2023

CEERS Key Paper I: An Early Look into the First 500 Myr of Galaxy Formation with *JWST*

Steven L. Finkelstein,[1] Micaela B. Bagley,[1] Henry C. Ferguson,[2] Stephen M. Wilkins,[3,4] Jeyhan S. Kartaltepe,[5] Casey Papovich,[6,7] L. Y. Aaron Yung,[8,*] Pablo Arrabal Haro,[9] Peter Behroozi,[10,11] Mark Dickinson,[9] Dale D. Kocevski,[12] Anton M. Koekemoer,[13] Rebecca L. Larson,[14,1] Aurélien Le Bail,[15] Alexa M. Morales,[1] Pablo G. Pérez-González,[16] Denis Burgarella,[17] Romeel Davé,[18,19] Michaela Hirschmann,[20,21] Rachel S. Somerville,[22] Stijn Wuyts,[23] Volker Bromm,[1] Caitlin M. Casey,[1] Adriano Fontana,[24] Seiji Fujimoto,[1,25,26,†] Jonathan P. Gardner,[27] Mauro Giavalisco,[28] Andrea Grazian,[29] Norman A. Grogin,[2] Nimish P. Hathi,[2] Taylor A. Hutchison,[8,*] Saurabh W. Jha,[30] Shardha Jogee,[1] Lisa J. Kewley,[31] Allison Kirkpatrick,[32] Arianna S. Long,[1,†] Jennifer M. Lotz,[33] Laura Pentericci,[24]

ABSTRACT

We present an investigation into the first 500 Myr of galaxy evolution from the Cosmic Evolution Early Release Science (CEERS) survey. CEERS, one of 13 *JWST* ERS programs, targets galaxy formation $z \sim 0.5$ to $z > 10$ using several imaging and spectroscopic modes. We make use of the first epoch of CEERS NIRCam imaging, spanning 35.5 sq. arcmin, to search for candidate galaxies at $z > 9$. Following a detailed data reduction process implementing several custom steps to produce high-quality reduced images, we perform multi-band photometry across seven NIRCam broad and medium-band (and six *Hubble* broadband) filters focusing on robust colors and accurate total fluxes. We measure photometric redshifts and devise a robust set of selection criteria to identify a sample of 26 galaxy candidates at $z \sim 9$–16. These objects are compact with a median half-light radius of ∼0.5 kpc. We present an early estimate of the $z \sim 11$ rest-frame ultraviolet (UV) luminosity function, finding that the number density of galaxies at $M_{UV} \sim -20$ appears to evolve very little from $z \sim 9$ to $z \sim 11$. We also find that the abundance (surface density [arcmin^{-2}]) of our candidates exceeds nearly all theoretical predictions. We explore potential implications, including that at $z > 10$ star formation may

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JWST galaxies at z= 8 -15

A population of red candidate massive galaxies ~600 Myr after the Big Bang

Ivo Labbé[1], Pieter van Dokkum[2], Erica Nelson[3], Rachel Bezanson[4], Katherine A. Suess[5,6], Joel Leja[7,8,9], Gabriel Brammer[10], Katherine Whitaker[10,11], Elijah Mathews[7,8,9], Mauro Stefanon[12,13], Bingjie Wang[7,8,9]

Galaxies with stellar masses as high as ~ 10^{11} solar masses have been identified[1–3] out to redshifts z ~ 6, approximately one billion years after the Big Bang. It has been difficult to find massive galaxies at even earlier times, as the Balmer break region, which is needed for accurate mass estimates, is redshifted to wavelengths beyond 2.5 μm. Here we make use of the 1-5 μm coverage of the *JWST* early release observations to search for intrinsically red galaxies in the first ≈ 750 million years of cosmic history. In the survey area, we find six candidate massive galaxies (stellar mass > 10^{10} solar masses) at 7.4 ≤ z ≤ 9.1, 500–700 Myr after the Big Bang, including one galaxy with a possible stellar mass of ~10^{11} solar masses. If verified with spectroscopy, the stellar mass density in massive galaxies would be much higher than anticipated from previous studies based on rest-frame ultraviolet-selected samples.

issue is that these stellar mass densities are difficult to realize in a standard LCDM cosmology, as pointed out by several recent studies.[31,32] Our fiducial mass densities push against the limit set by the number of available baryons in the most massive dark matter halos.

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Galaxies at z= 6 – 8

THE IMPOSSIBLY EARLY GALAXY PROBLEM

Charles. L. Steinhardt [1,2], Peter Capak[1,2], Dan Masters[1,2], Josh S. Speagle[3,2,4]

Draft version June 12, 2018

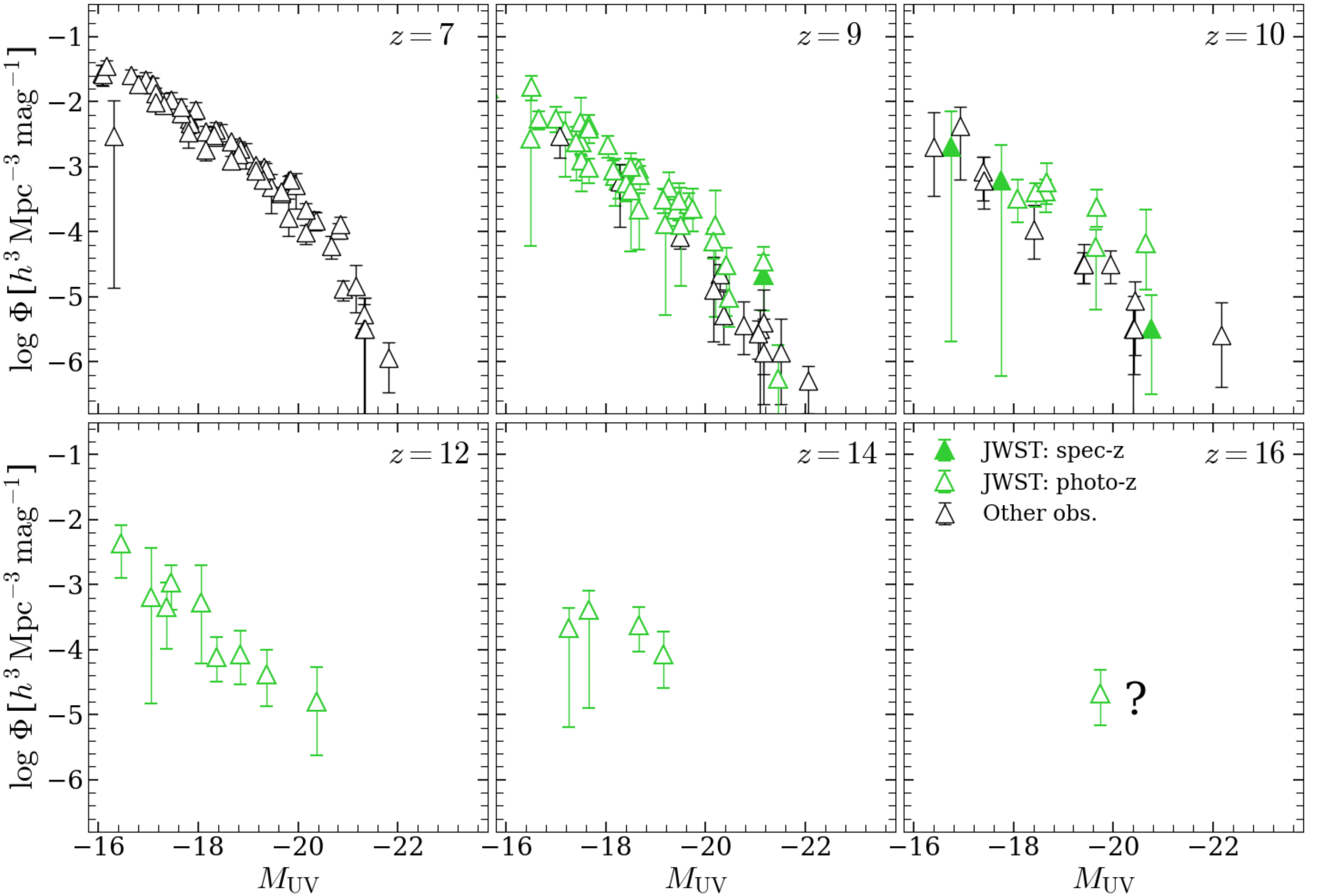
arXiv:1506.01377v2 [astro-ph.GA] 8 Apr 2016

ABSTRACT

The current hierarchical merging paradigm and ΛCDM predict that the $z \sim 4-8$ universe should be a time in which the most massive galaxies are transitioning from their initial halo assembly to the later baryonic evolution seen in star-forming galaxies and quasars. However, no evidence of this transition has been found in many high redshift galaxy surveys including CFHTLS, CANDELS and SPLASH, the first studies to probe the high-mass end at these redshifts. Indeed, if halo mass to stellar mass ratios estimated at lower-redshift continue to $z \sim 6-8$, CANDELS and SPLASH report several orders of magnitude more $M \sim 10^{12-13} M_{\odot}$ halos than are possible to have formed by those redshifts, implying these massive galaxies formed impossibly early. We consider various systematics in the stellar synthesis models used to estimate physical parameters and possible galaxy formation scenarios in an effort to reconcile observation with theory. Although known uncertainties can greatly reduce the disparity between recent observations and cold dark matter merger simulations, even taking the most conservative view of the observations, there remains considerable tension with current theory.

Subject headings: galaxies: evolution

JWST galaxies at z=7-16



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JWST galaxies at z=15

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 474, 2352–2372 (2018)
Advance Access publication 2017 November 13

doi:10.1093/mnras/stx2897

2018

Predictions for deep galaxy surveys with *JWST* from ΛCDM

William I. Cowley,[1,2★] Carlton M. Baugh,[1] Shaun Cole,[1] Carlos S. Frenk[1] and Cedric G. Lacey[1]

[1] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[2] *Kapteyn Astronomical Institute, University of Groningen, PO Box 800, NL-9700 AV Groningen, the Netherlands*

GALFORM applied to Milennium XXL N-body simulation

→ Has enough resolution and volume!

Galform calibration

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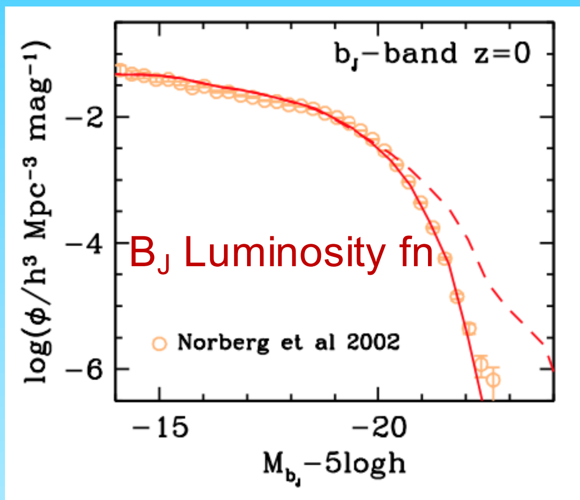
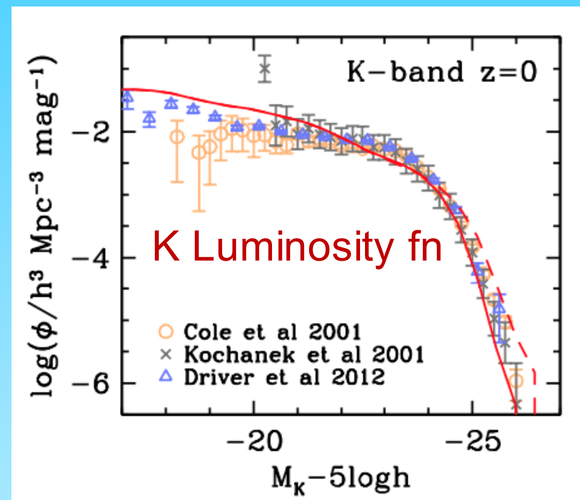
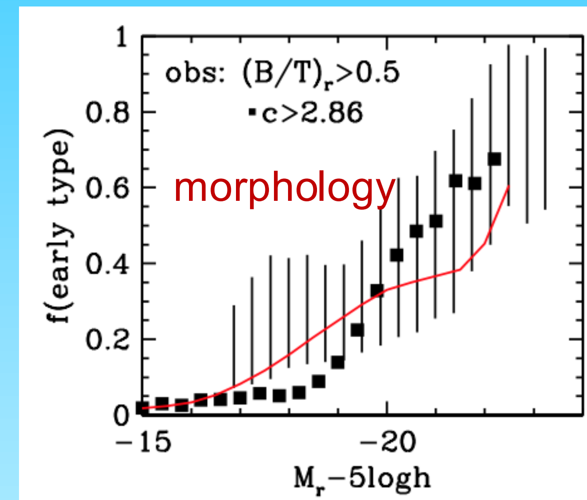
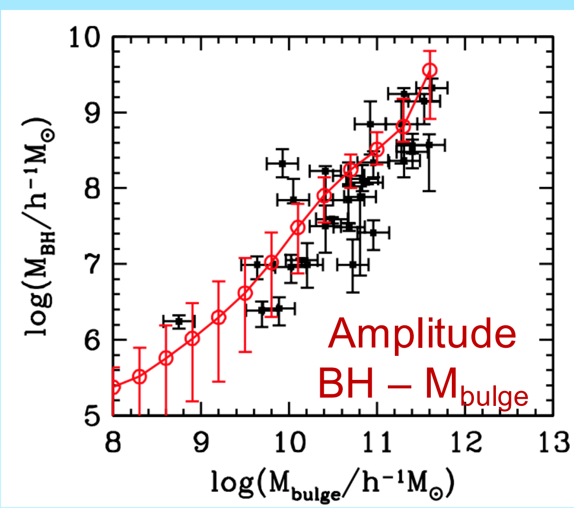
Philosophy (since 1994) → fix model parameters by matching subset of z=0 basic data

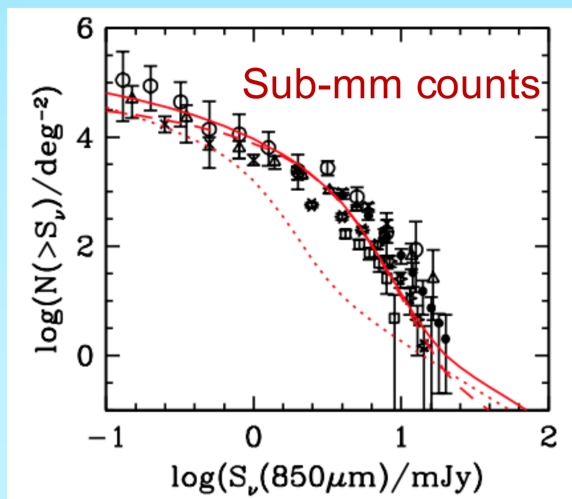
Cole et al '00
Lacey et al '16

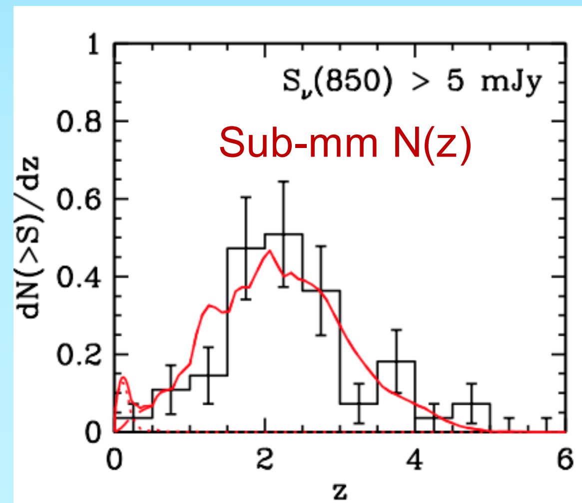












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GALFORM calibration

"The model can also explain the observed galaxy number counts at 850 μm, but only if we assume a top-heavy initial mass function for the stars formed in bursts"

Baugh et al. 05

(Only small fraction of today's stars form with top-heavy IMF)

Monthly Notices of the Royal Astronomical Society

Can the faint submillimetre galaxies be explained in the Λ cold dark matter model? FREE

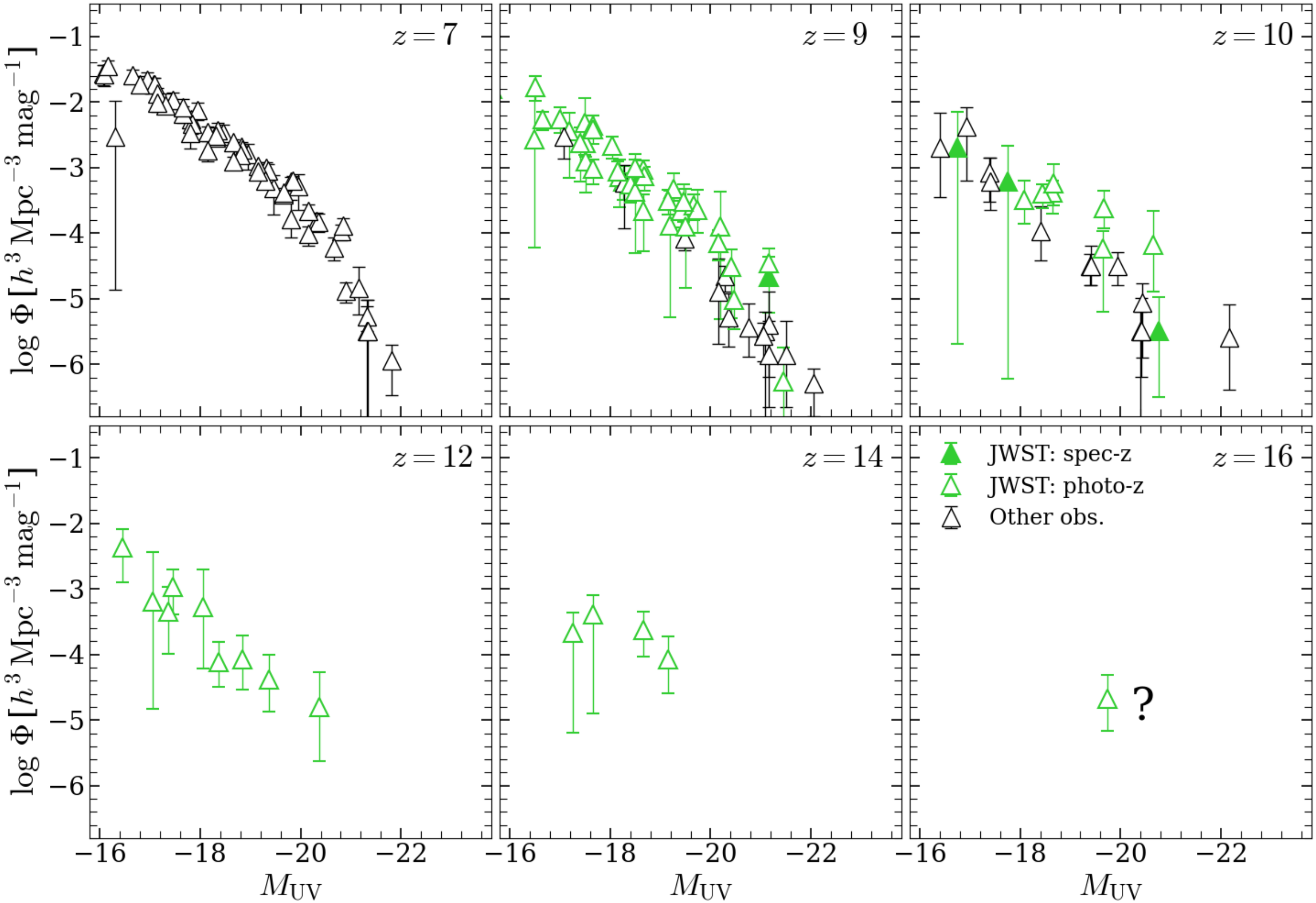
2005

C. M. Baugh, C. G. Lacey, C. S. Frenk, G. L. Granato, L. Silva, A. Bressan, A. J. Benson, S. Cole

Abstract

We present predictions for the abundance of submillimetre galaxies (SMGs) and Lyman-break galaxies (LBGs) in the Λ cold dark matter cosmology. A key feature of our model is the self-consistent calculation of the absorption and emission of radiation by dust. The new model successfully matches the LBG luminosity function, as well as reproducing the properties of the local galaxy population in the optical and infrared. The model can also explain the observed galaxy number counts at 850 μm, but only if we assume a top-heavy initial mass function for the stars formed in bursts. The predicted redshift distribution of SMGs depends relatively little on their flux over the range 1–10 mJy, with a median value of $z \approx 2.0$ at a flux of 5 mJy, in good agreement with the recent measurement by Chapman et al. The counts of SMGs are predicted to be dominated by ongoing starbursts. However, in the model these bursts are responsible for making only a few per cent of the stellar mass locked up in massive ellipticals at the present day.

JWST galaxies at z=7-16



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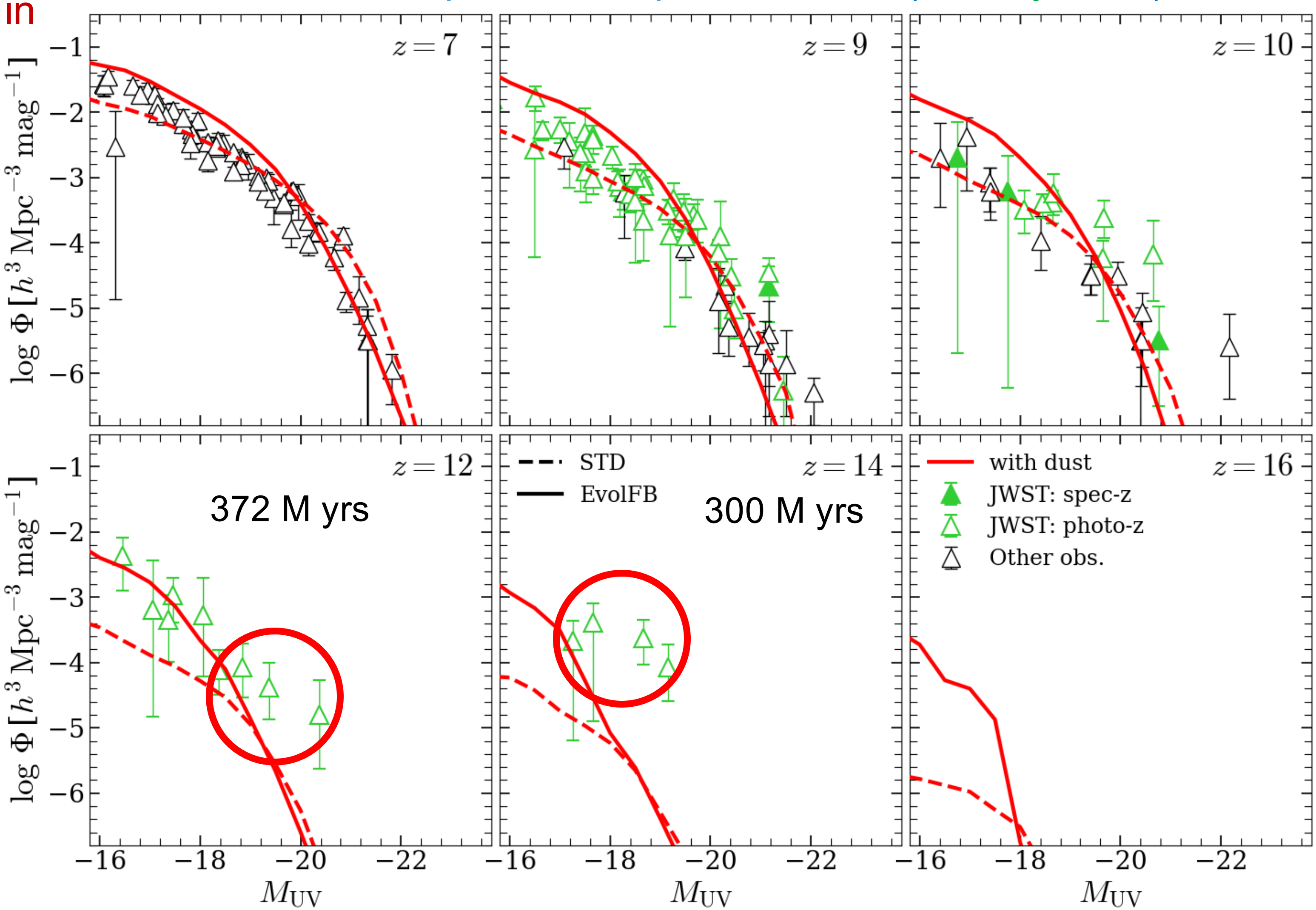
JWST galaxies at z=7-16

Key – top heavy IMF in bursts

Theoretical predictions precede data (Cowley + '18)



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JWST galaxies at z=7-16

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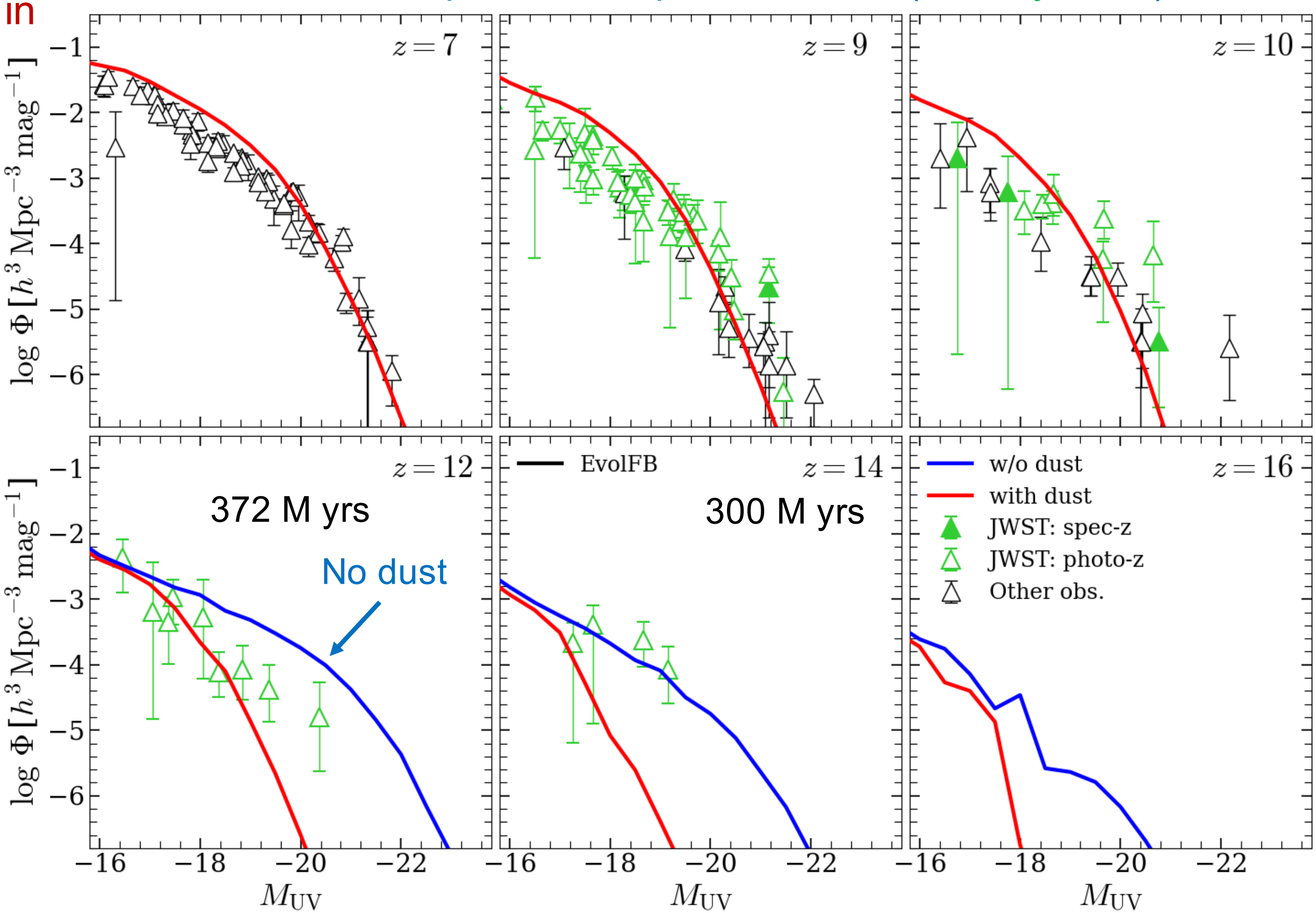
Theoretical predictions precede data (Cowley + '18)



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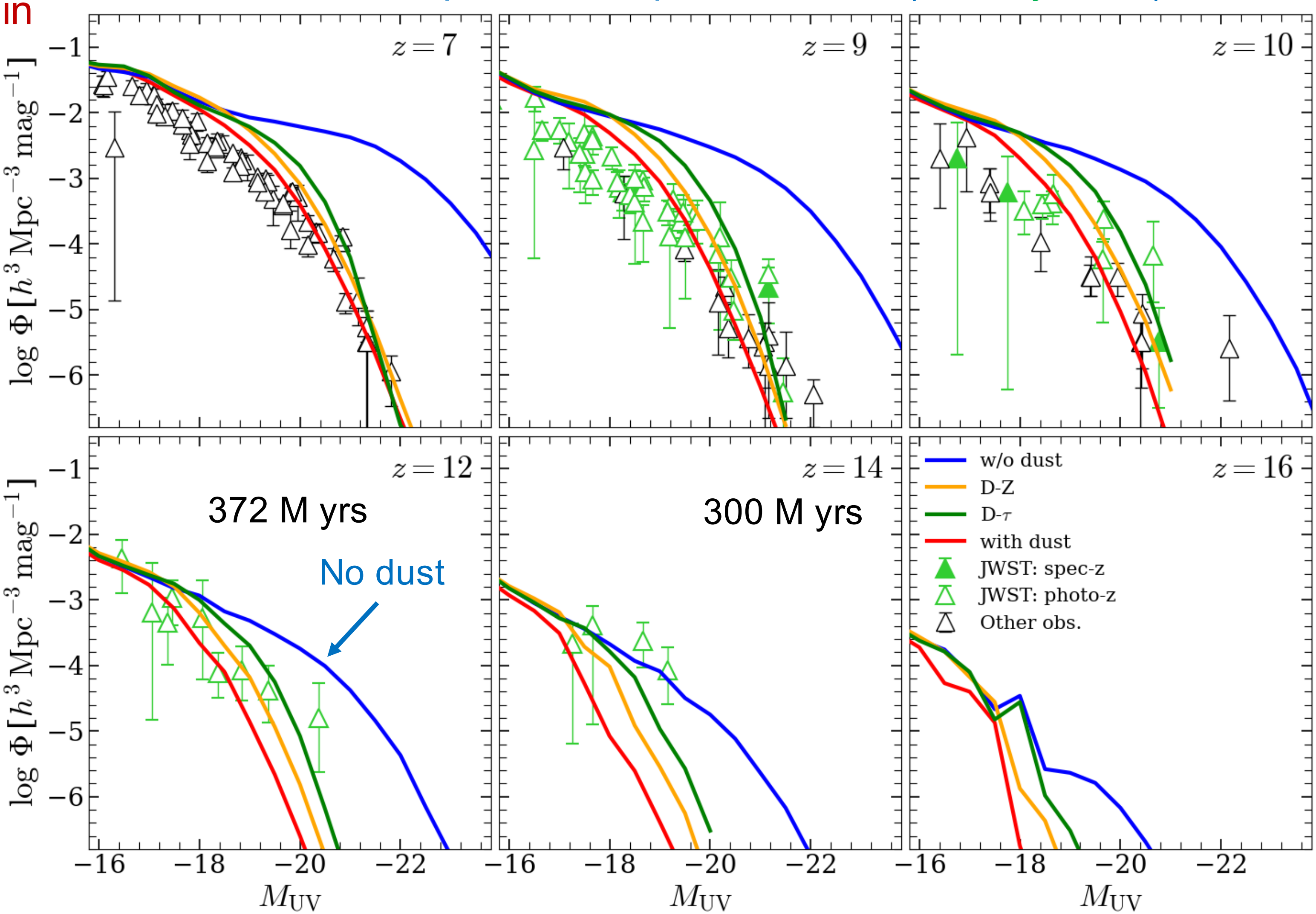

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The small-scale “crisis” of ΛCDM

Four problems:

	“Solved” in:	
1. “Missing satellites”	2002	baryon effects
2. “Too-big-to-fail”	2015	baryon effects
3. “Core-cusp”	1996	baryon effects
4. “Plane of satellites”	2023	→ Cosmic web + statistics

5. Galaxies at z > 10 discovered by JWST

→ As previously predicted by ΛCDM

Conclusions

Large scales

- Great precision of DESI BAO → ΛCDM ruled out at $(3.1 - 4.2)\sigma$; an evolving DE model (w_0w_aCDM) is favoured

- DESI BAO limit on ν masses: $\Sigma m_\nu < 0.195$ eV for w_0w_aCDM

Small scales

- Abundance of JWST galaxies at $z<14$ → as predicted in CDM