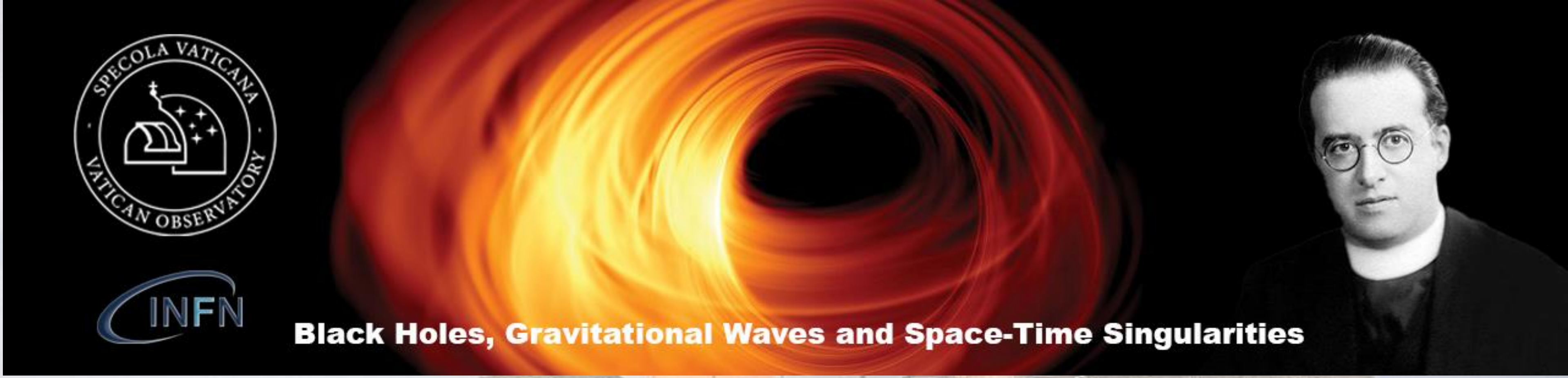

Black Holes, Gravitational Waves and Space-Time Singularities

ΛCDM: the road ahead

18 June 2024

Michael S. Turner
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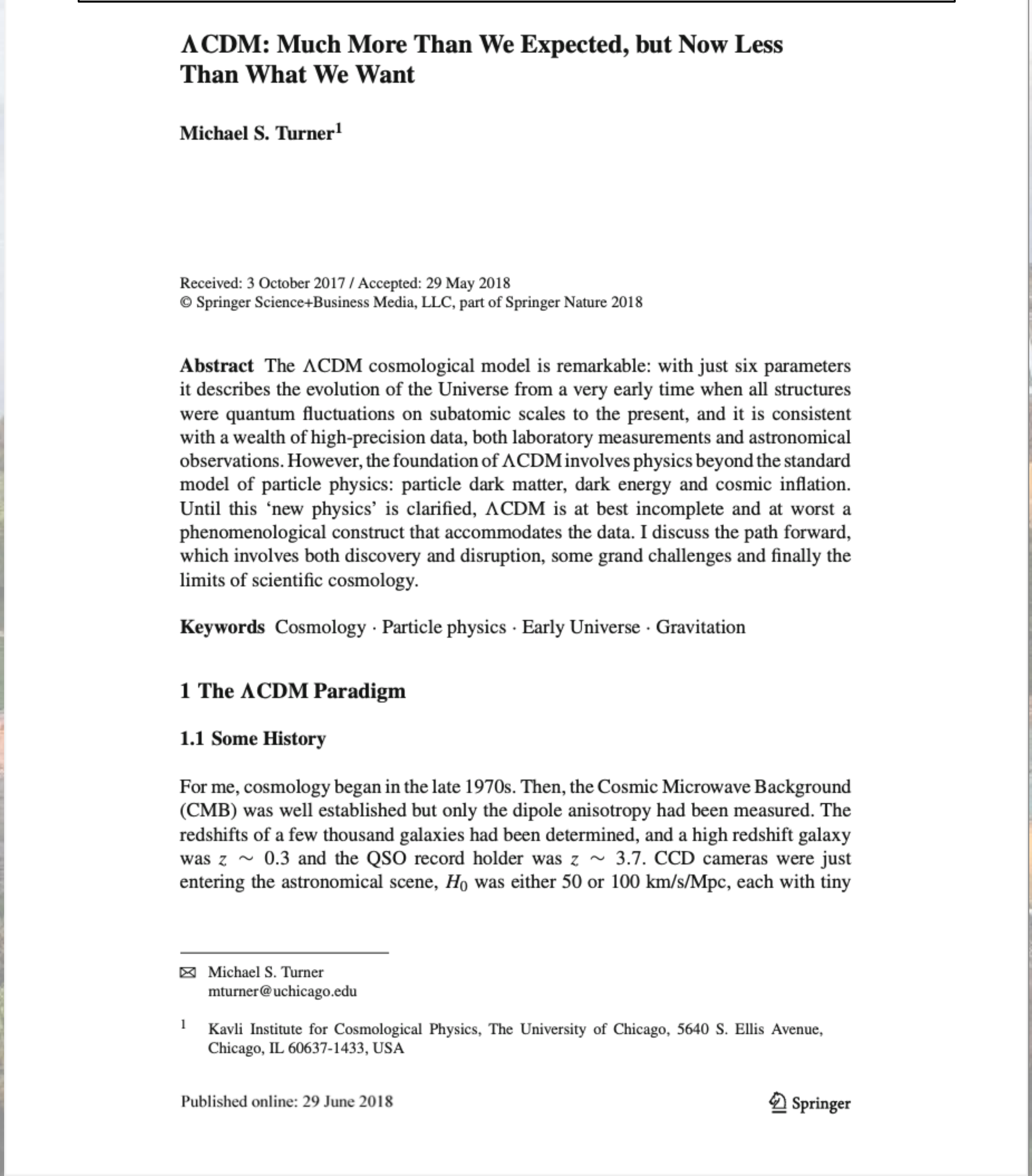
and
Kavli Institute for Cosmological Physics
University of Chicago

Lemaître 2017



ΛCDM: Much More Than We Expected, but Now Less Than What We Want

Michael S. Turner[1]

Received: 3 October 2017 / Accepted: 29 May 2018

Abstract The ΛCDM cosmological model is remarkable: with just six parameters it describes the evolution of the Universe from a very early time when all structures were quantum fluctuations on subatomic scales to the present, and it is consistent with a wealth of high-precision data, both laboratory measurements and astronomical observations. However, the foundation of ΛCDM involves physics beyond the standard model of particle physics: particle dark matter, dark energy and cosmic inflation. Until this 'new physics' is clarified, ΛCDM is at best incomplete and at worst a phenomenological construct that accommodates the data. I discuss the path forward, which involves both discovery and disruption, some grand challenges and finally the limits of scientific cosmology.

Keywords Cosmology · Particle physics · Early Universe · Gravitation

1 The ΛCDM Paradigm

1.1 Some History

For me, cosmology began in the late 1970s. Then, the Cosmic Microwave Background (CMB) was well established but only the dipole anisotropy had been measured. The redshifts of a few thousand galaxies had been determined, and a high redshift galaxy was $z \sim 0.3$ and the QSO record holder was $z \sim 3.7$. CCD cameras were just entering the astronomical scene, H_0 was either 50 or 100 km/s/Mpc, each with tiny

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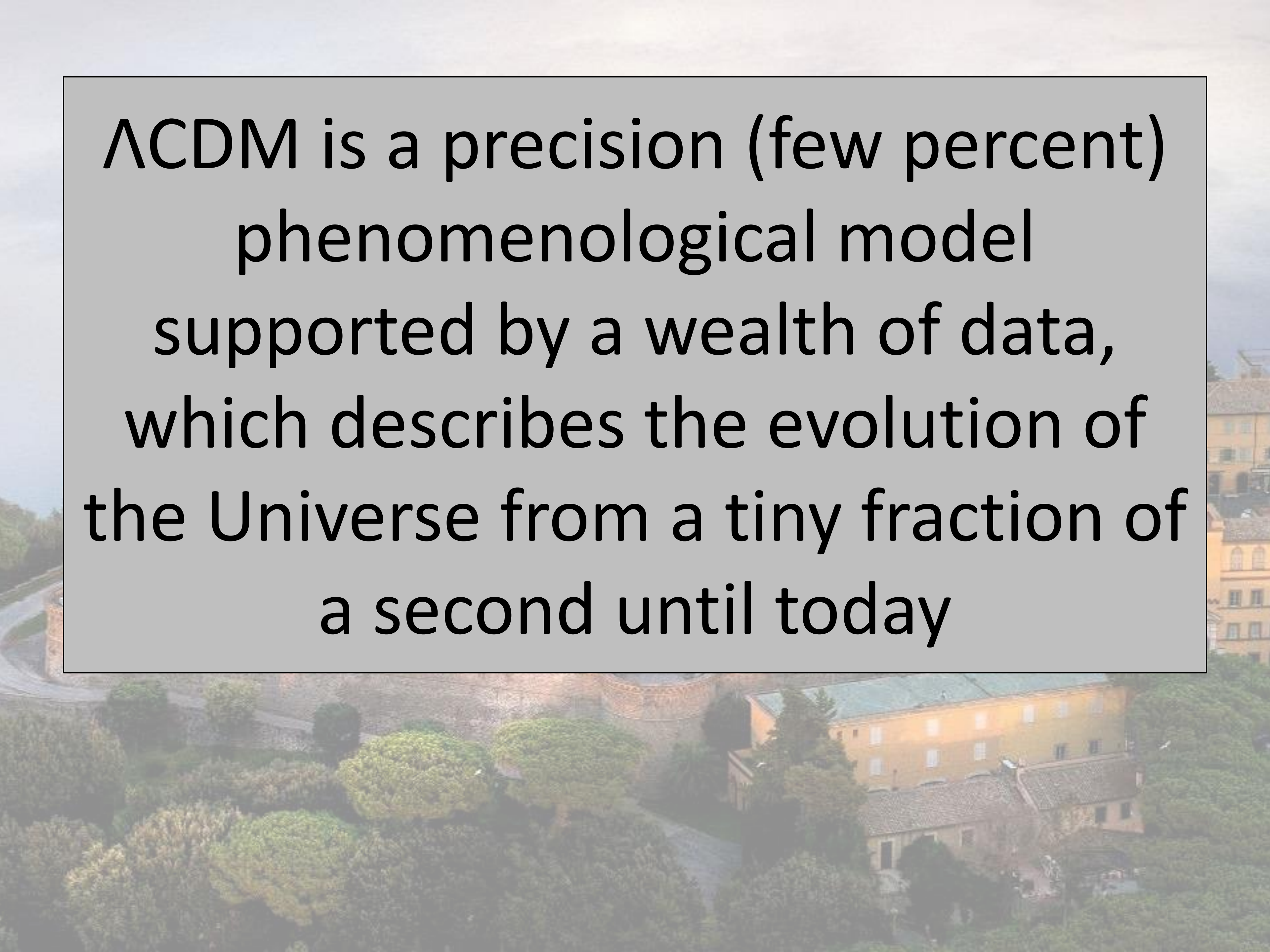

ΛCDM is a precision (few percent) phenomenological model supported by a wealth of data, which describes the evolution of the Universe from a tiny fraction of a second until today

ΛCDM in plain English

… very-early accelerated expansion driven by the potential energy of a scalar field gives rise to a very-large, smooth, spatially flat patch that becomes all that we can see today. **Quantum fluctuations** during this **inflationary** phase grow into the seeds for galaxies. The conversion of potential field energy into heat produces the quark soup that evolves a baryon asymmetry and long-lived dark matter particles. The excess of quarks over antiquarks (**baryogenesis**) becomes neutrons and protons, later some light elements and finally atoms. The gravity of the **dark matter** particles drives the formation of structure from galaxies to superclusters and a mere 5 billion years ago the repulsive gravity of **dark energy (Λ)** again drove accelerated expansion …

… a lot of new physics in that plain language

- The repulsive gravity of **Dark Energy** explains cosmic acceleration and Λ (quantum vacuum energy) is the default dark energy candidate. *What is dark energy, why now, why so small?*

- A very early burst of tremendous expansion – **Inflation** – explains our smooth, flat Universe with seeds for galaxies grown from quantum fluctuations. *Really? how?*

- The gravity of slowly-moving **Dark Matter** particles (CDM) holds all cosmic structures together. *Which particle(s)?*

- **Baryogenesis** produces an excess of matter over anti-matter and the survival of a small number of baryons today (few per billion photons). *Baryons are important; more details please!*

ΛCDM is a phenomenological model that *can* be ungraded to a fundamental model of the Universe (or not)

- Gravity and spacetime: done!, but could be improved
- Dark matter: particle in the “BSM theory”
- Inflation: inflaton in the BSM theory
- Baryogenesis: B, C and CP violation in the BSM

Can we find the BSM theory?

Cosmology will help!

A long road to precision cosmology!

ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

The Road to Precision Cosmology

Michael S. Turner[1,2]

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[2]The Kavli Foundation, Los Angeles, California

Annu. Rev. Nucl. Part. Sci. 2022. 72:1–35

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The *Annual Review of Nuclear and Particle Science* is online at nucl.annualreviews.org

https://doi.org/10.1146/annurev-nucl-111119-041046

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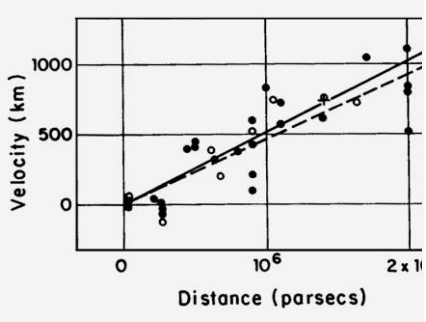
Abstract

In the past 50 years, cosmology has gone from a field known for the errors being in the exponents to a precision science. The transformation—powered by ideas, technology, a paradigm shift, and culture change—has revolutionized our understanding of the Universe, with the Lambda cold dark matter (ΛCDM) paradigm as its crowning achievement. I chronicle the journey of precision cosmology and finish with thoughts about the next cosmological paradigm.

Two exemplars for precision cosmology: CMB and Baryons



ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

The Road to Precision Cosmology

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e *Hubble Space Telescope* Key Project to
Constant*

ladore[1,2], Brad K. Gibson[3], Laura Ferrarese[4], Daniel D. Kelson[5],
', Robert C. Kennicutt, Jr.[8], Holland C. Ford[9], John A. Graham[5]

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553, Number 1

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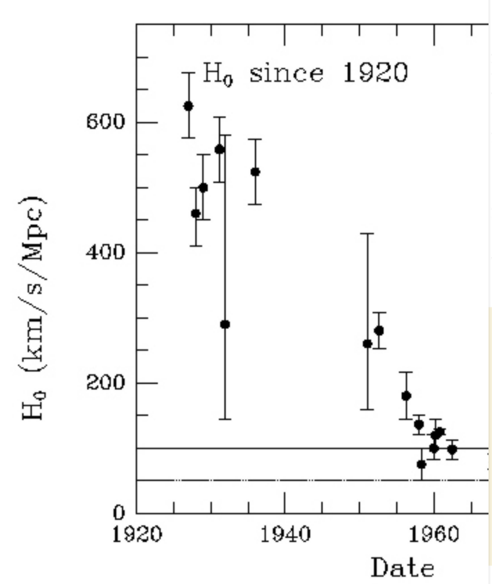
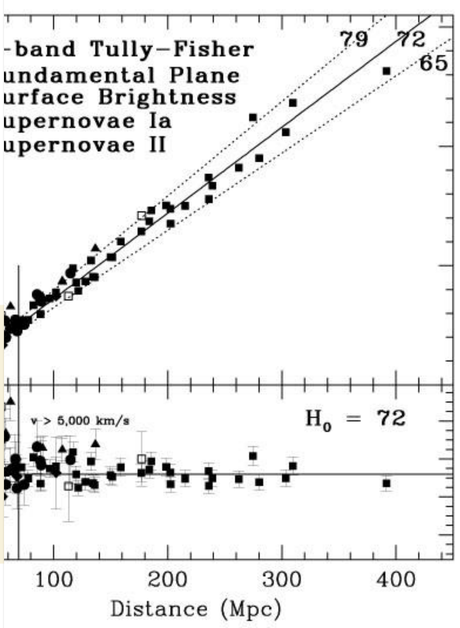
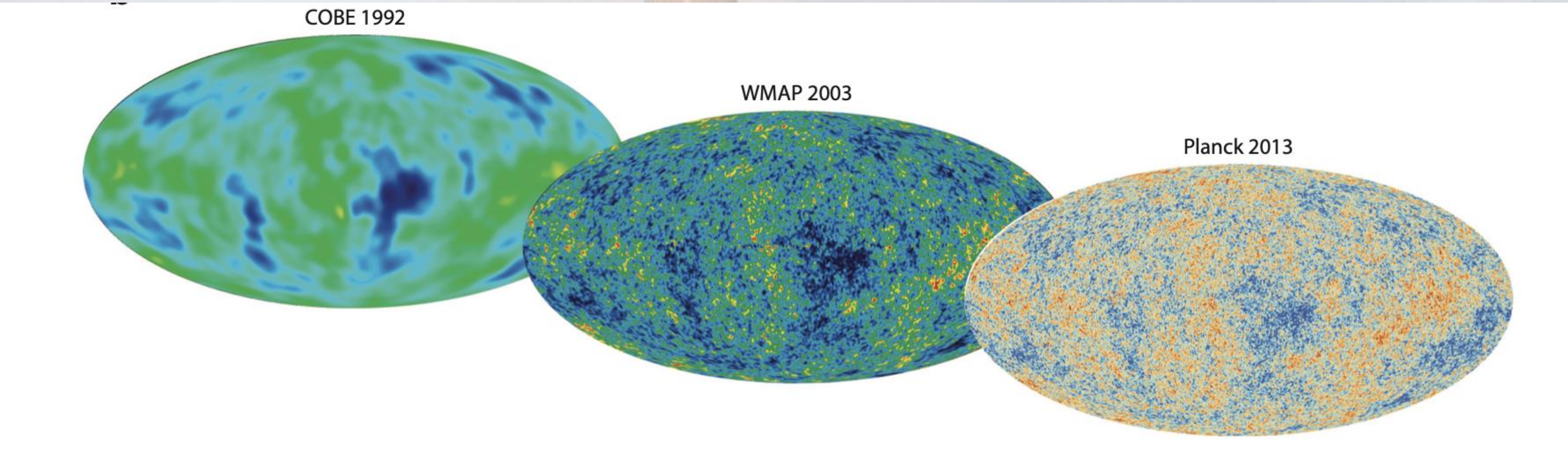




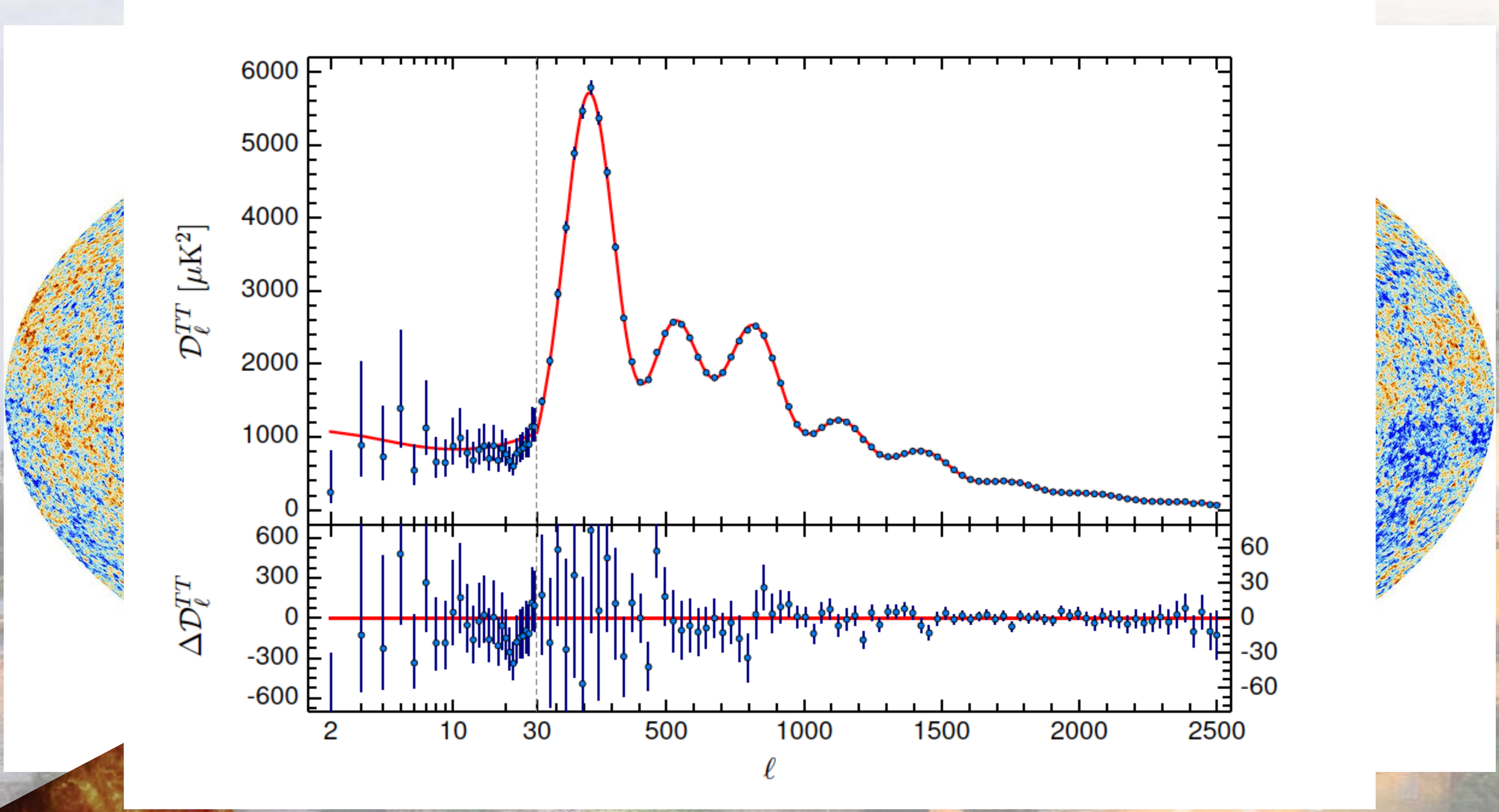


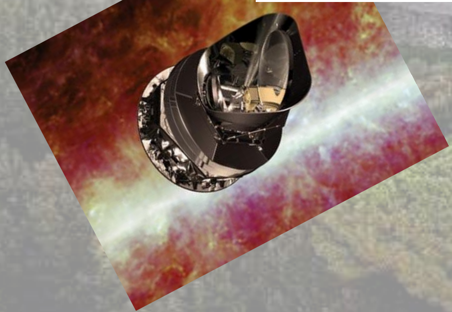
COBE 1992

WMAP 2003

Planck 2013

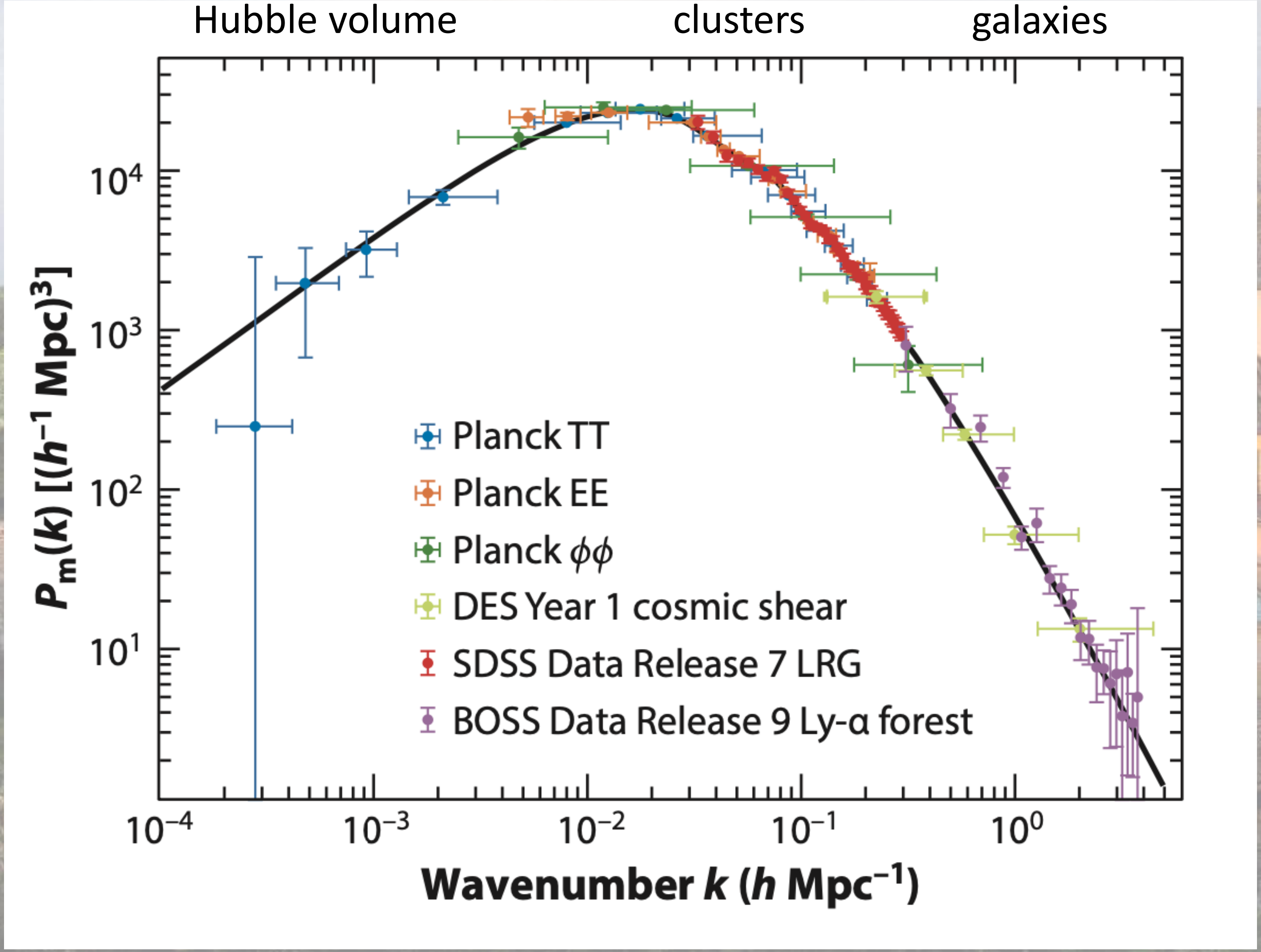
6 physical parameters





1. Baryon mass density
2. CDM mass density
3. Density perturbation amplitude
4. Tilt
5. Sound horizon
6. Optical depth

Measurements of large-scale structure agree with ΛCDM



Cosmic consistency: $\Omega_B h^2$ at <1% precision

D/H + Nuclear physics at t ~ 1 sec → $\Omega_b h^2 = 0.02166 \pm 0.00015$

CMB + Gravity driven acoustic oscillations at t = 380,000 yrs → $\Omega_b h^2 = 0.02237 \pm 0.00015$

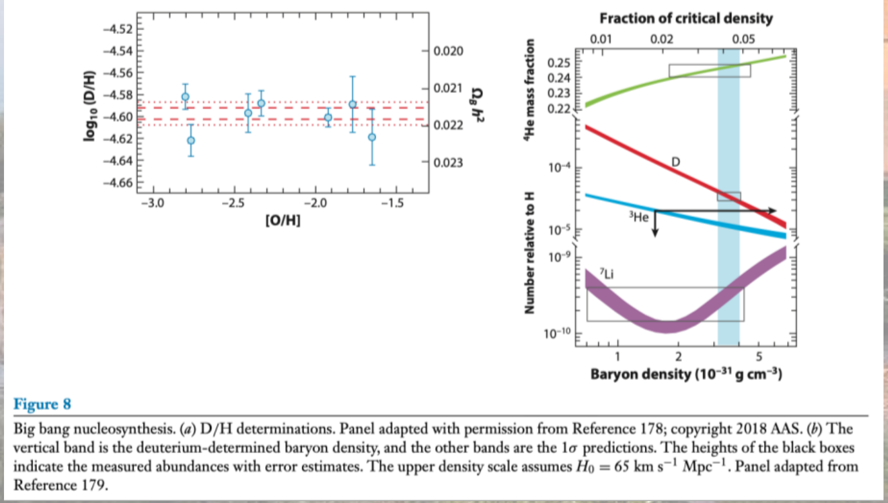
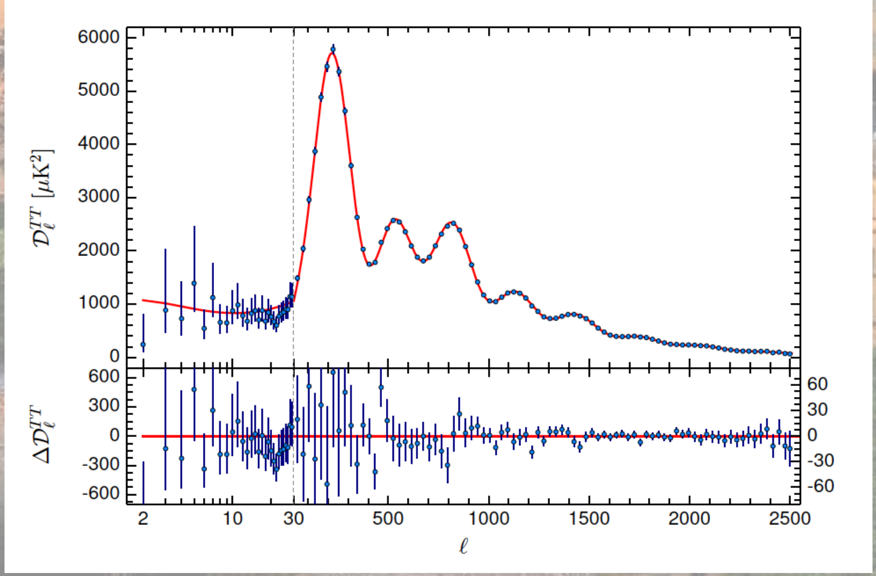
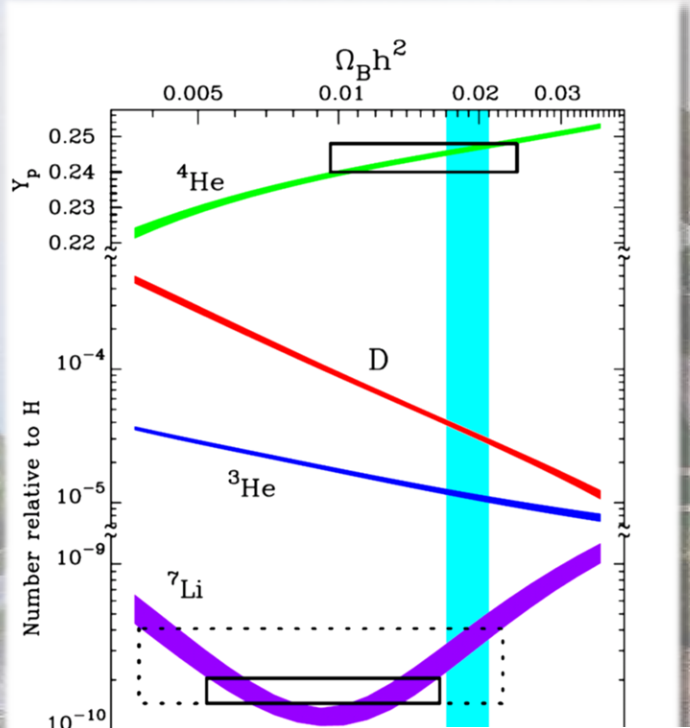


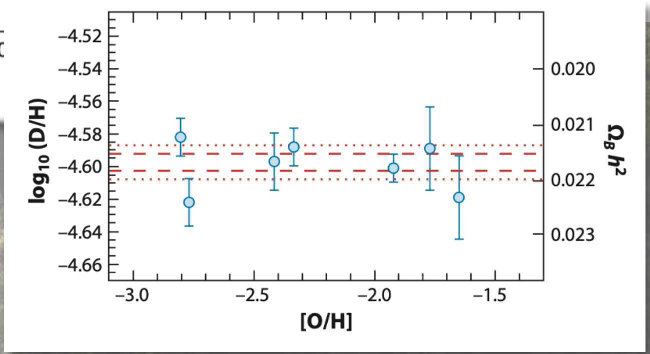
Figure 8

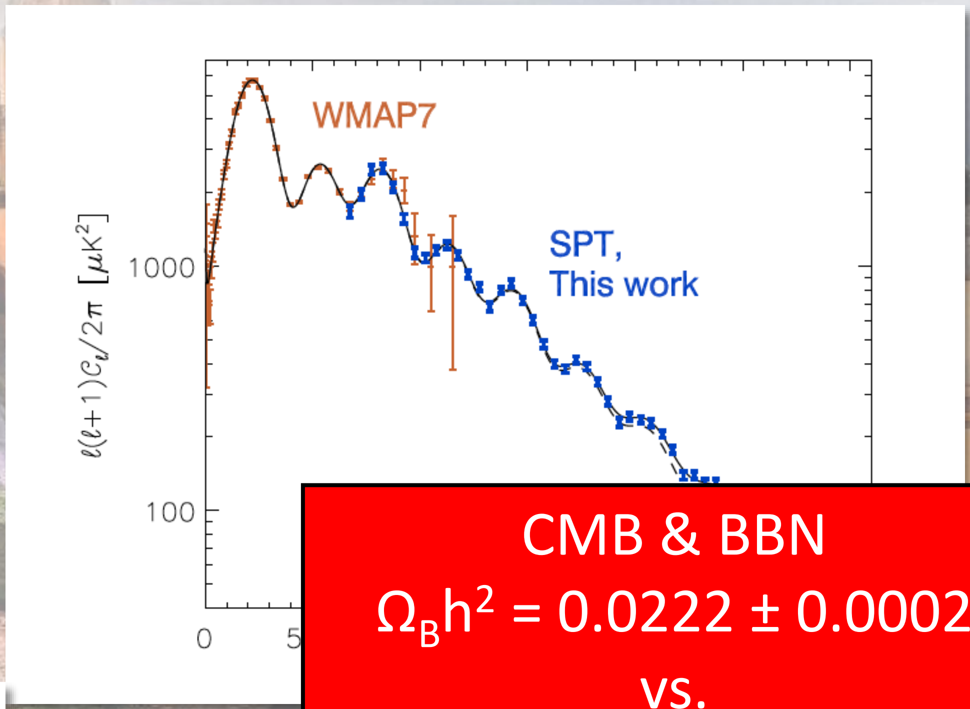
Big bang nucleosynthesis. (*a*) D/H determinations. Panel adapted with permission from Reference 178; copyright 2018 AAS. (*b*) The vertical band is the deuterium-determined baryon density, and the other bands are the 1σ predictions. The heights of the black boxes indicate the measured abundances with error estimates. The upper density scale assumes $H_0 = 65$ km s^{-1} Mpc^{-1}. Panel adapted from Reference 179.



Airtight evidence for nonbaryonic DM







CMB & BBN

$\Omega_B h^2 = 0.0222 \pm 0.0002$

vs.

CMB/SDSS/DES/DESI

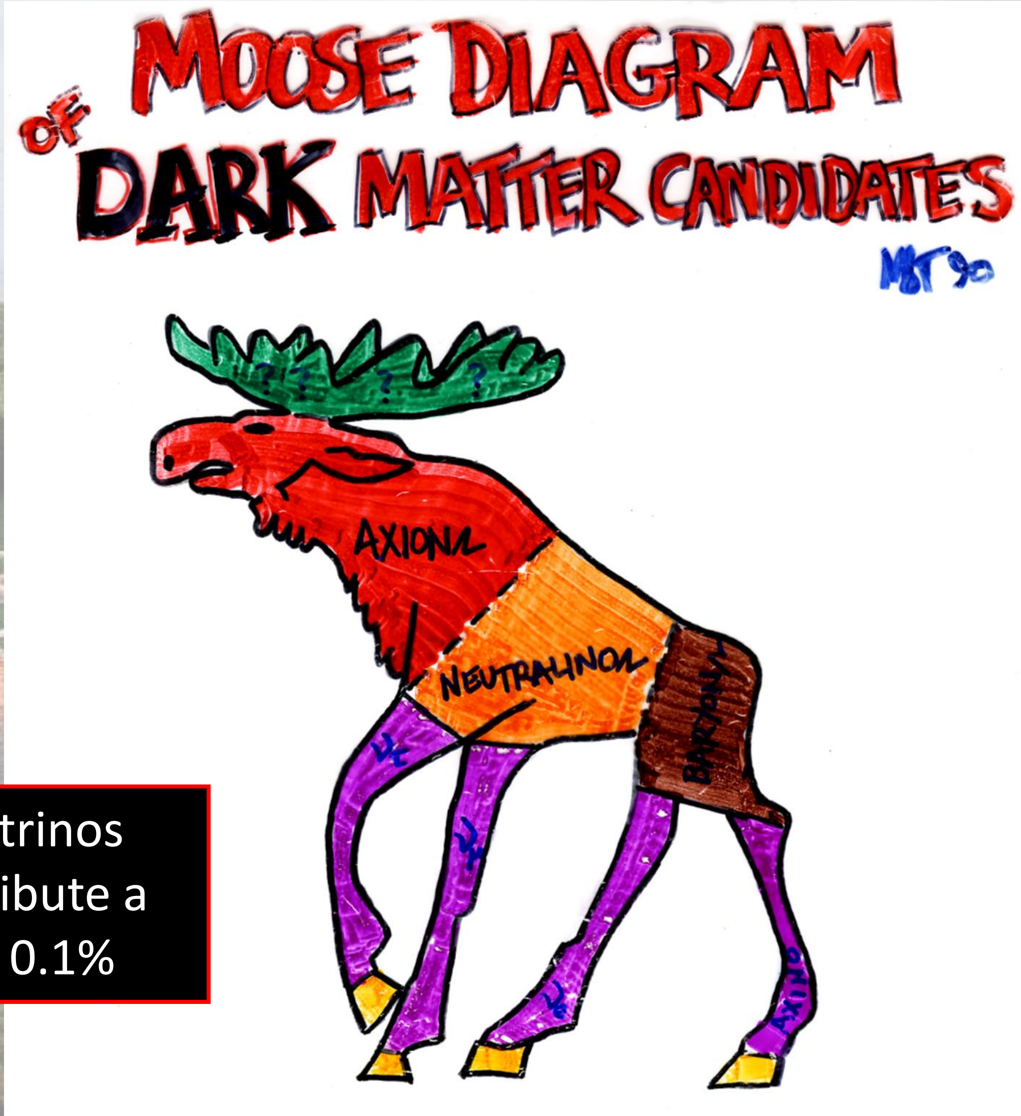
$\Omega_M h^2 = 0.143 \pm 0.001$

> 50σ discrepancy

Since “Lemaître 2017”

- ΛCDM: remains alive and well as the precision increases from a few percent to sub percent
- Dark matter: sensitive experiments, but no evidence for the DM particle & lots of ideas for candidates and detection
- Inflation: Keck/BICEP keep drilling down on the B-modes (more results soon!)
- Dark Energy: DESI (and DES 5yr) hint at something very interesting – not just Λ!
- Loose threads?
  - Hubble tension: Wendy, Licia and Adam
  - Other tensions (e.g., σ_8)
- JWST reveals the first billion years of cosmic history

DM: Circa 1990 – 2010



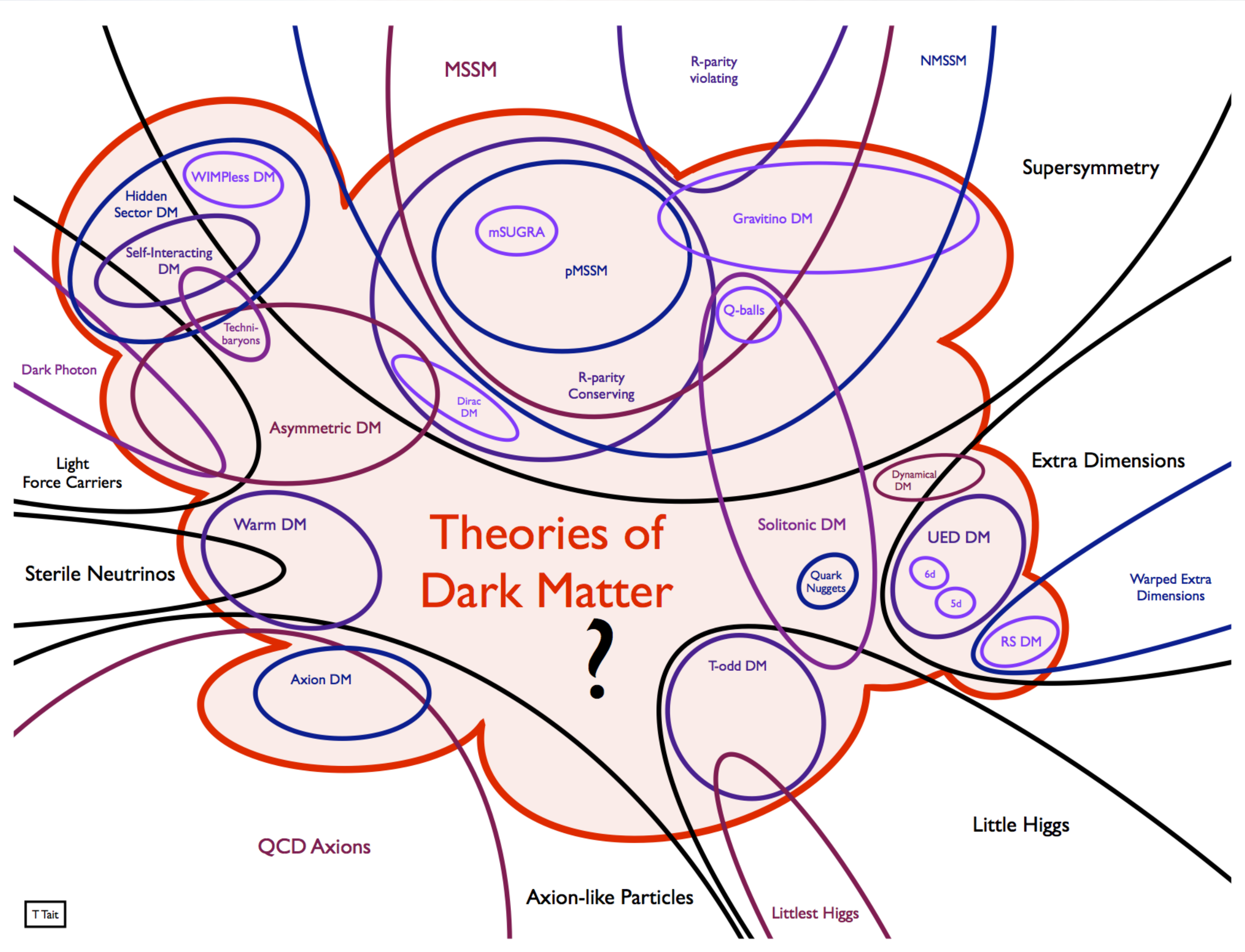
Neutrinos contribute a few 0.1%

Full Court Press!!

- Produce at LHC
- Detect particles in our halo
- Detect annihilation products

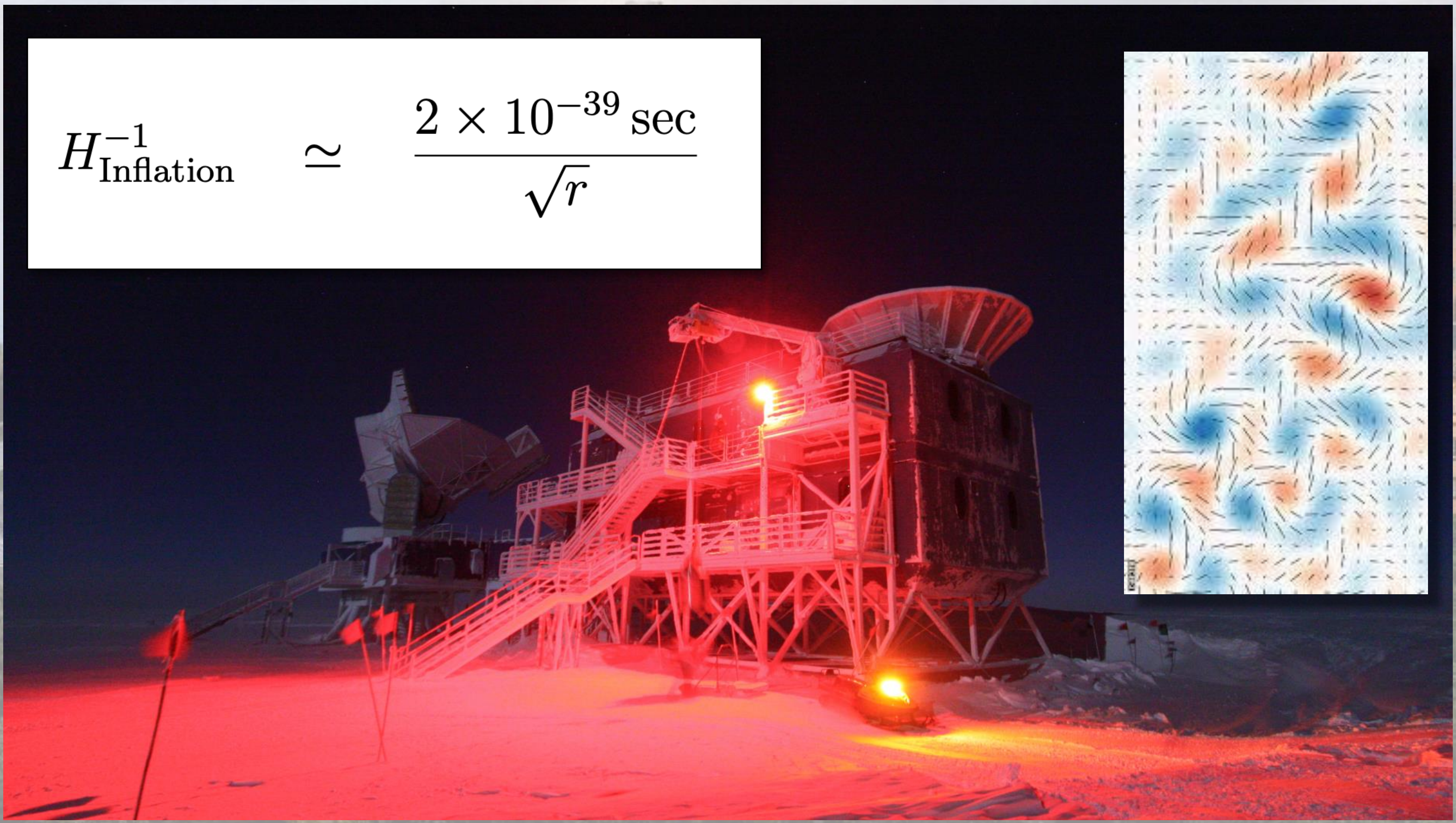
But where is the WIMP?

No lack of new ideas!



T Tait

Keck/BICEP continue to lead the way on B-modes



$$H^{-1}_{\text{Inflation}} \simeq \frac{2 \times 10^{-39}\,\text{sec}}{\sqrt{r}}$$

- 2018: r < 0.036 (95% cl), $\sigma_r = 0.009$
- 2024 or 2025: 5 years more data, more bands, more detectors & $\sigma_r = 0.005$ expected
- Simons Observatory, CMB S4?, Litebird ahead

arXiv:2203.16556v1 [astro-ph.CO] 30 Mar 2022

The Latest Constraints on Inflationary B-modes from the BICEP/Keck Telescopes

The BICEP/*Keck* Collaboration: P. A. R. Ade[a], Z. Ahmed[b], M. Amiri[c], D. Barkats[d], R. Basu Thakur[e], C. A. Bischoff[f], D. Beck[b,g], J. J. Bock[e,h], H. Boenish[d], E. Bullock[i], V. Buza[j], J. R. Cheshire IV[i], J. Connors[d], J. Cornelison[d], M. Crumrine[k], A. Cukierman[g,b], E. V. Denison[l], M. Dierickx[d], L. Duband[m], M. Eiben[d], S. Fatigoni[c], J. P. Filippini[n,o], S. Fliescher[k], C. Giannakopoulos[f], N. Goeckner-Wald[g], D. C. Goldfinger[d], J. Grayson[g], P. Grimes[d], G. Hall[k], G. Halal[g], M. Halpern[c], E. Hand[f], S. Harrison[d], S. Henderson[b], S. R. Hildebrandt[e,h], G. C. Hilton[l], J. Hubmayr[l], H. Hui[e], K. D. Irwin[g,b,l], J. Kang[g,e], K. S. Karkare[d,j], E. Karpel[g], S. Kefeli[e], S. A. Kernasovskiy[g], J. M. Kovac[d,p], C. L. Kuo[g,b], K. Lau[k,*], E. M. Leitch[j], A. Lennox[n], K. G. Megerian[h], L. Minutolo[e], L. Moncelsi[e], Y. Nakato[g], T. Namikawa[q], H. T. Nguyen[h], R. O'Brient[e,h], R. W. Ogburn IV[g,b], S. Palladino[f], M. Petroff[d], T. Prouve[m], C. Pryke[k,i], B. Racine[d,r], C. D. Reintsema[l], S. Richter[d], A. Schillaci[e], R. Schwarz[k], B. L. Schmitt[d], C. D. Sheehy[s], B. Singari[i], A. Soliman[e], T. St. Germaine[d,p], B. Steinbach[e], R. V. Sudiwala[a], G. P. Teply[e], K. L. Thompson[g,b], J. E. Tolan[g], C. Tucker[a], A. D. Turner[h], C. Umiltà[f,n], C. Vergès[d], A. G. Vieregg[t,j], A. Wandui[e], A. C. Weber[h], D. V. Wiebe[c], J. Willmert[k], C. L. Wong[d,p], W. L. K. Wu[b], H. Yang[g], K. W. Yoon[g,b], E. Young[g,b], C. Yu[g], L. Zeng[d], C. Zhang[e], and S. Zhang[e]

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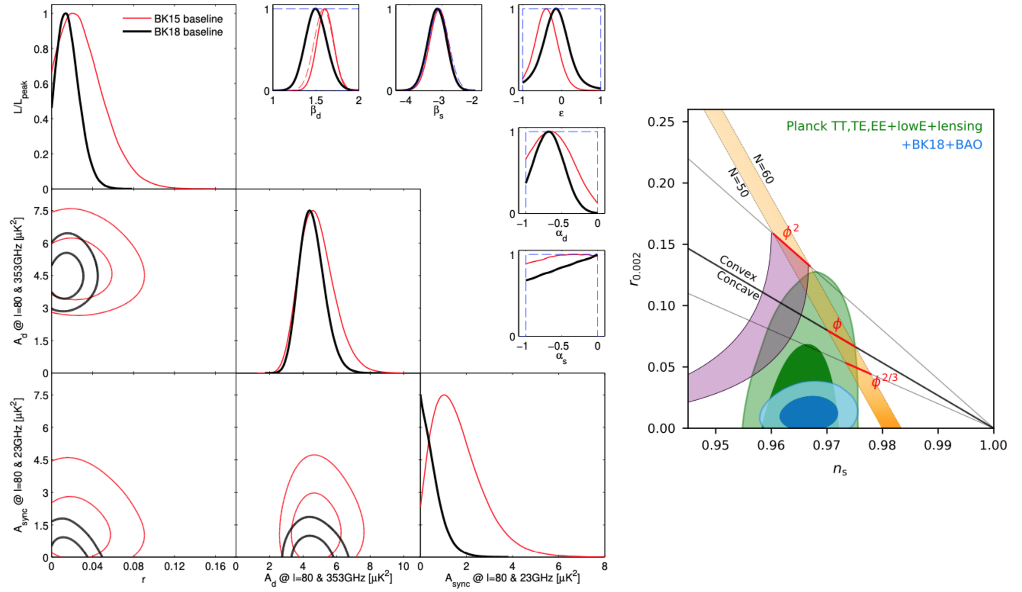


Figure 5. *Left*: `CosmoMC` likelihood results for the BICEP/*Keck* baseline model. Selected 1D and 2D marginalized posteriors are shown. The red faint curves are the results from BK15 while the black solid curves are the results of BK18. The dashed blue and red lines show priors on foreground parameters. The analysis method is the same as in BK15, except the β_d prior based on *Planck* data from other regions of the sky is removed this time due to the improved sensitivity of BK18. *Right*: Constraints in the r vs. n_s plane. The purple and orange bands are natural inflation and monomial inflation respectively. The blue contour shows the updated constraint after adding BK18 and BAO data to the *Planck* baseline analysis. The r posterior is tightened from $r_{0.05} < 0.11$ to $r_{0.05} < 0.035$ at 95% confidence.

JWST reveals the billion years

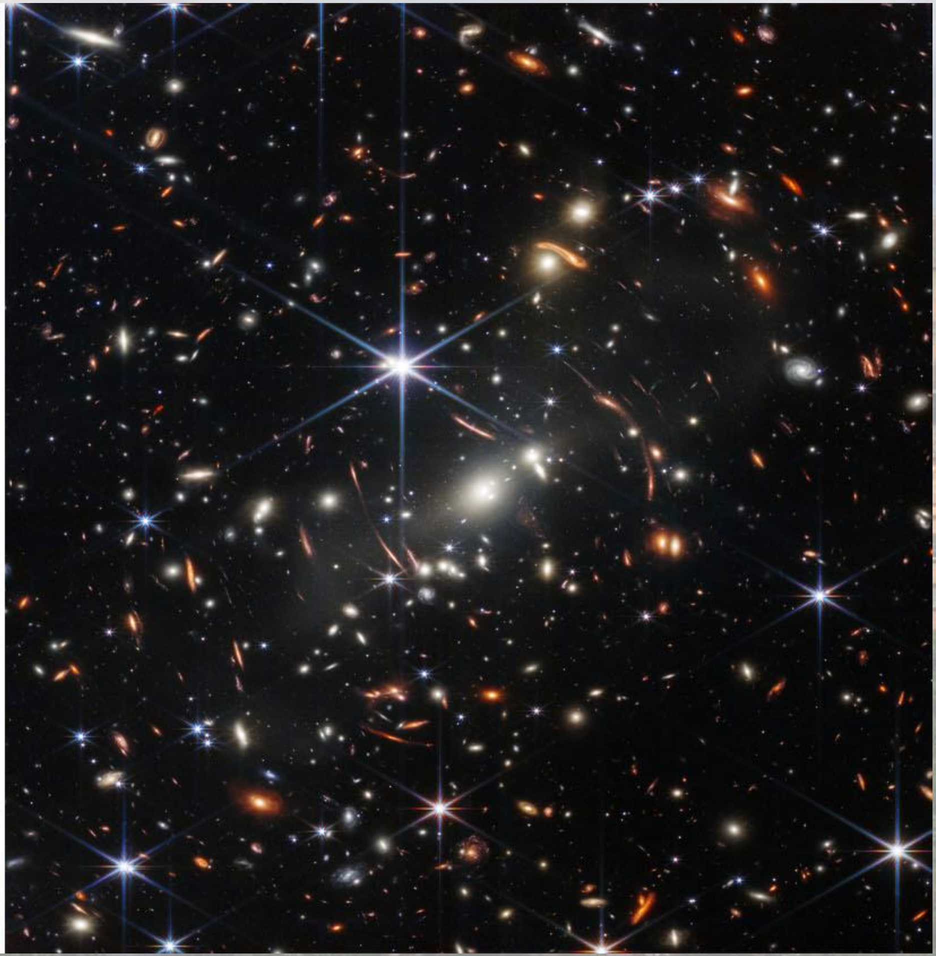
bigger aperture, IR, better site, higher resolution and SPECTRA

- "Uninhibited," bursty star formation – faster than expected
- Small, messy galaxies with lots of UV radiation beyond $z = 10$ with spectra not seen at low z
- But, hard to connect light to mass to constrain ΛCDM (don't believe everything you read!). Some lessons?
  - Early lenses reveal galactic substructure down to 10^7 solar masses (Keeley et al arXiv:2405.01620) → $m > 6$ keV
  - SMBH at $z > 4$ with masses from 4×10^5 to 8×10^7 solar masses (Maiolino et al, arXiv:230801230) -- challenge to make (need seeds?)
- New light on the distance scale (Wendy and Adam)

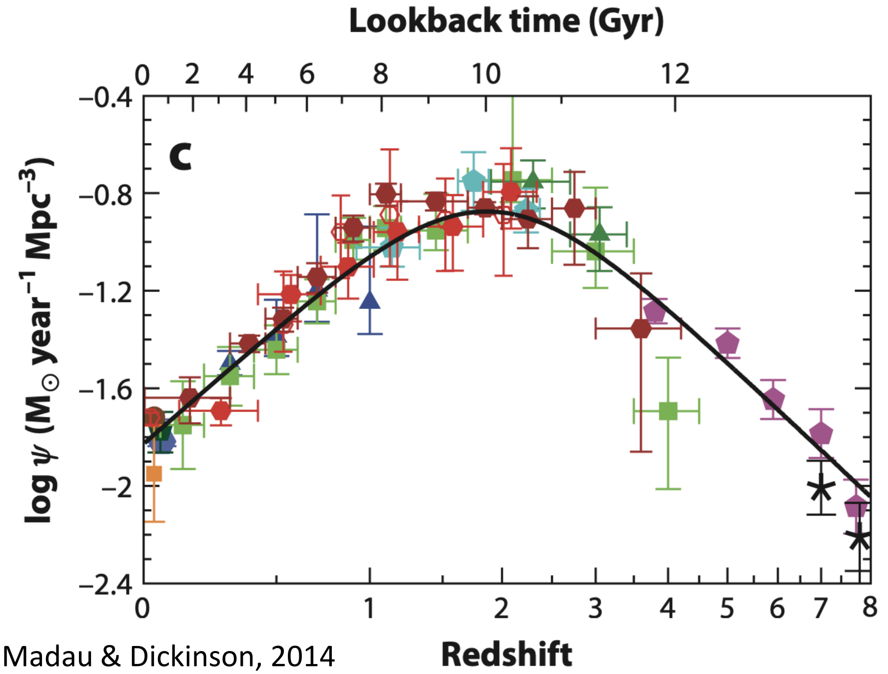
Adieu James: December 25, 2021

The power of infrared eyes!

Hubble Optical Deep Field

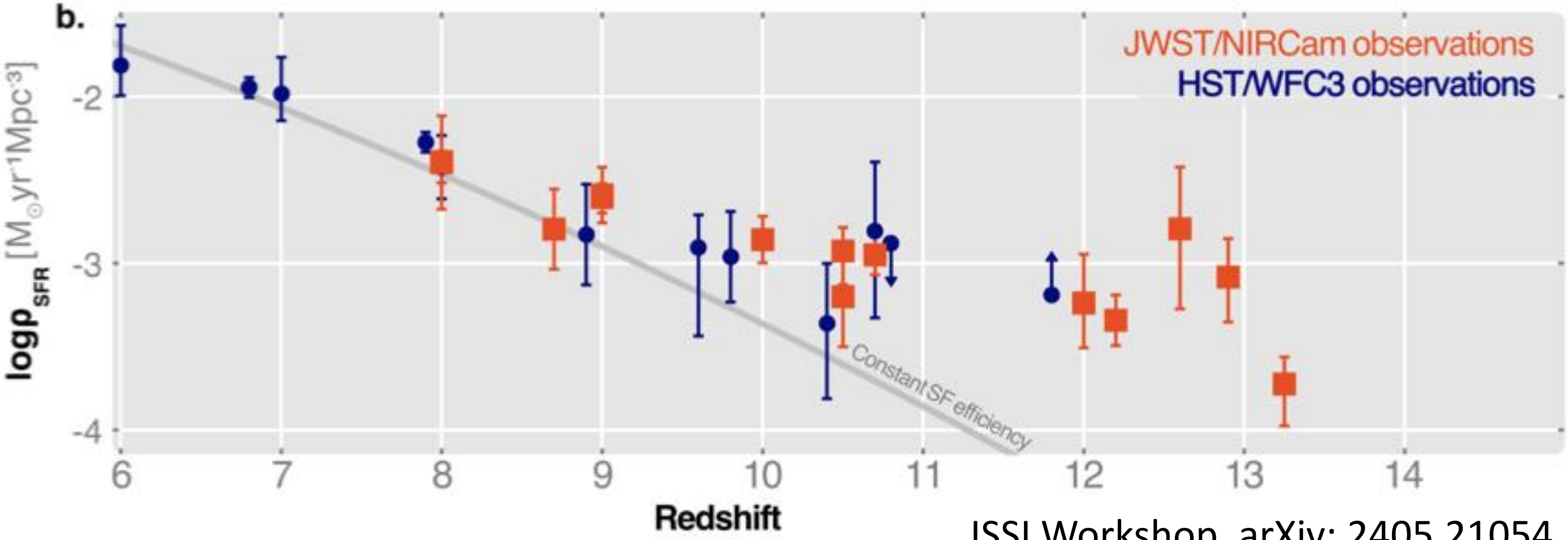


JWST NIR Deep Field



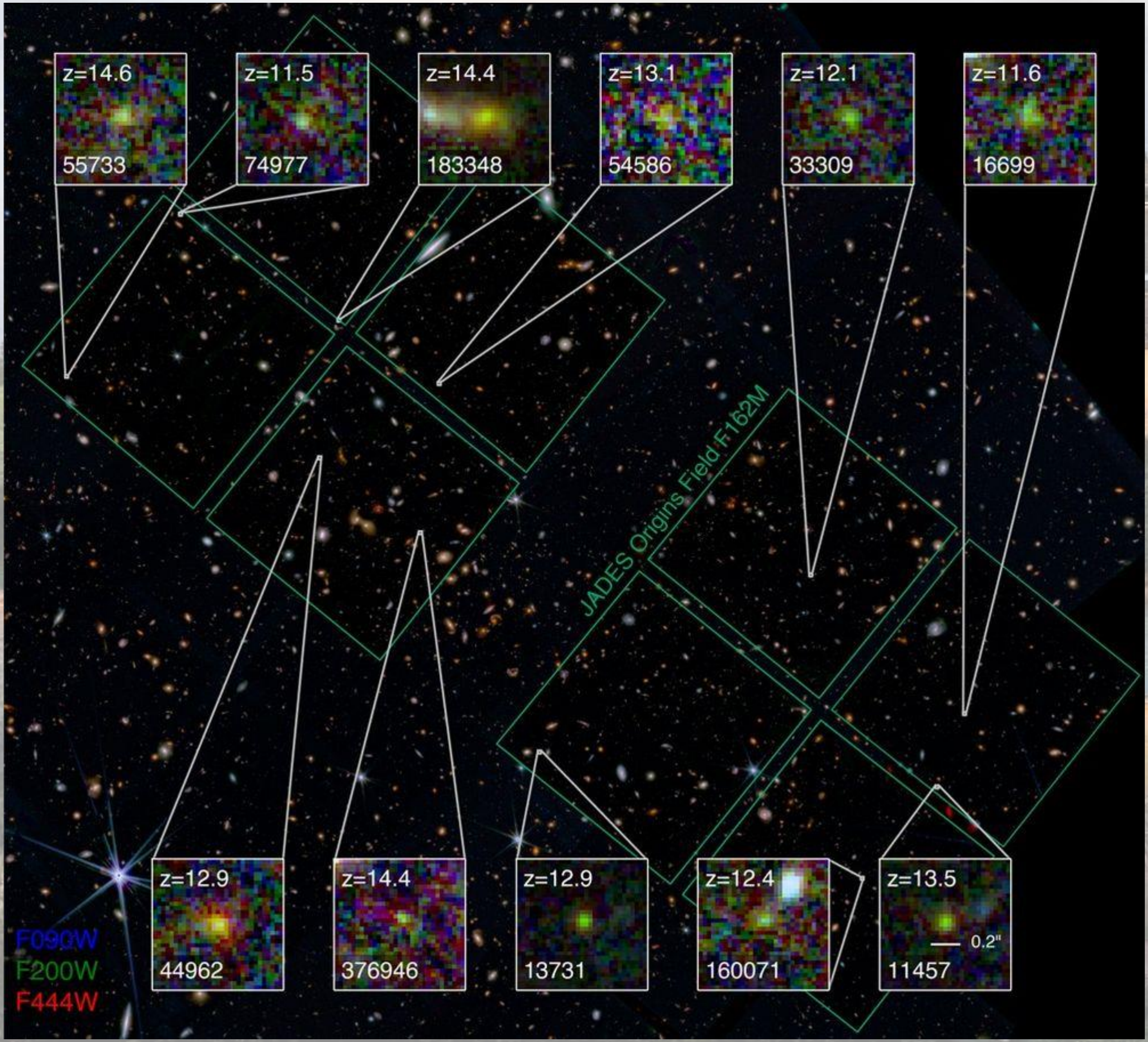
Madau & Dickinson, 2014

Lots of early, bursty and uninhibited star formation (unexpected)



ISSI Workshop, arXiv: 2405.21054

Lots of high redshift galaxies

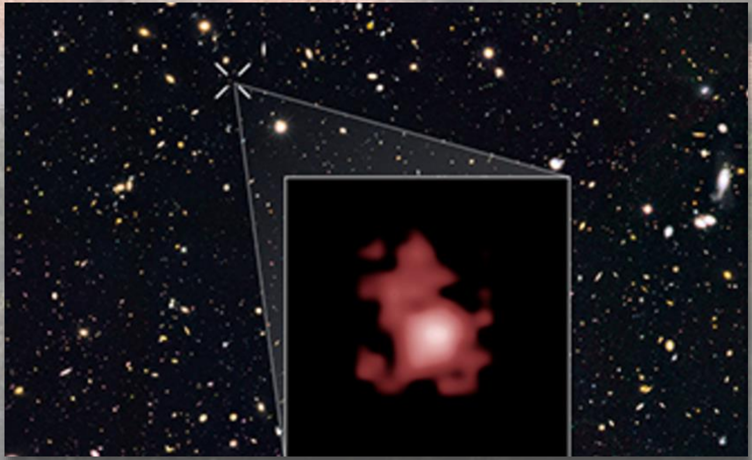


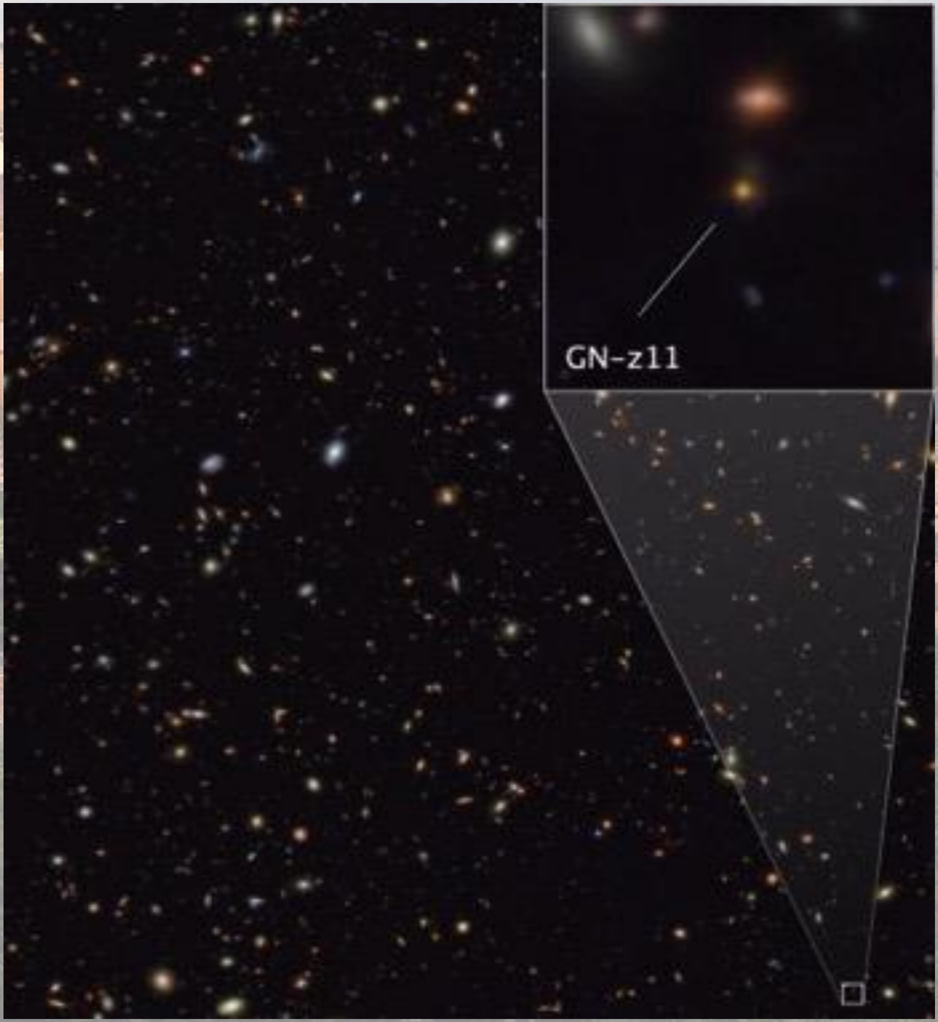
Poster child: GN-z11

found with HST (candidate z = 11 galaxy), studied with JWST

- $z = 10.60 \pm 0.0013$
- $d_C = 31.2$ Bly
- $d_L = 362$ Bly
- $d_A = 2.69$ Bly ($z = 0.25$)

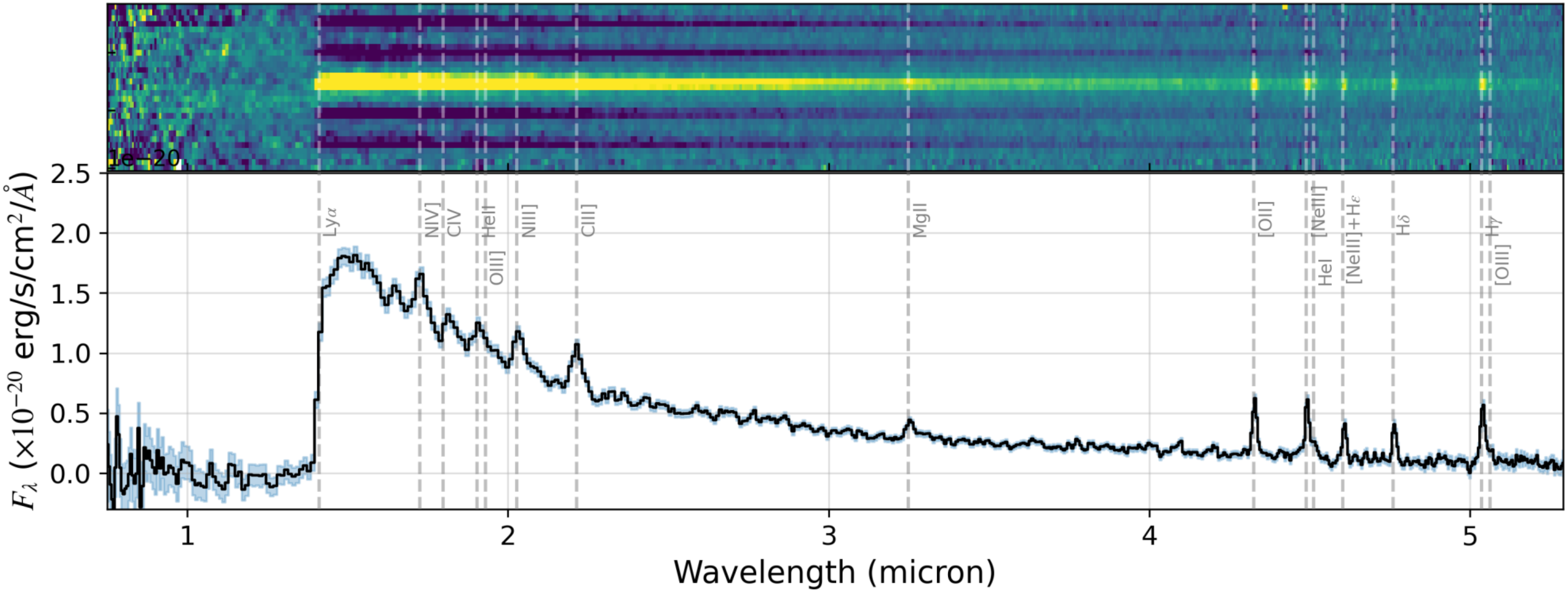
NB: $d_A = d_C/(1+z)$ and $d_L = (1+z)d_C$





GN-z11 (cont'd)

- 100 pc resolution at d_C = 32 BLy
- 10^9 solar masses in stars
- few x 10^6 solar mass BH (so big, so early)
- Look at that spectrum of a redshift 10.6 object!



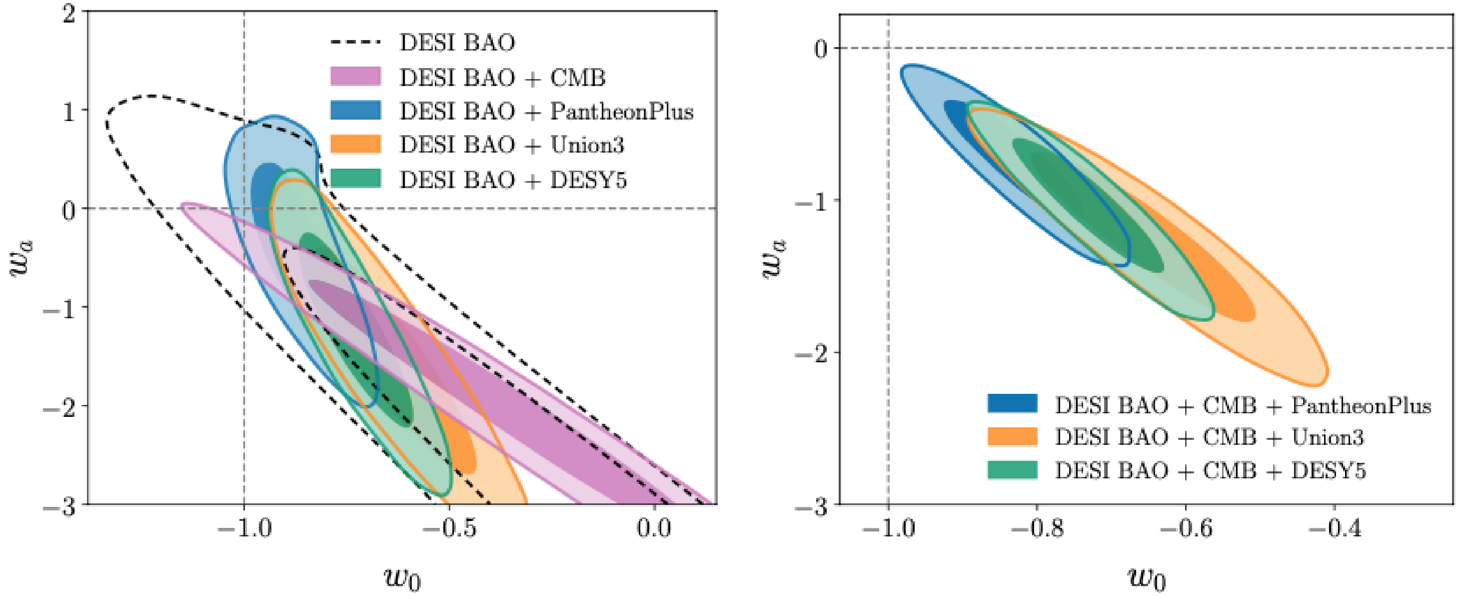
DESI (and DES 5 yr)

hints that dark energy evolves (i.e., not Λ)

- DESI year 1 alone: 20M redshifts and BAO distances to $z = 4$
- ΛCDM is a reasonable fit, but a (3-4)σ better fit is evolving dark energy $w_0 = -0.7$ and $w_a = -1$
- If the result holds up, something is going on right now AND BIG NEWS ABOUT DARK ENERGY
- Matilde de Abreu (UCLA UG) and I have looked at this: a rolling scalar field is a better fit than ΛCDM or w_0/w_a (and better motivated)

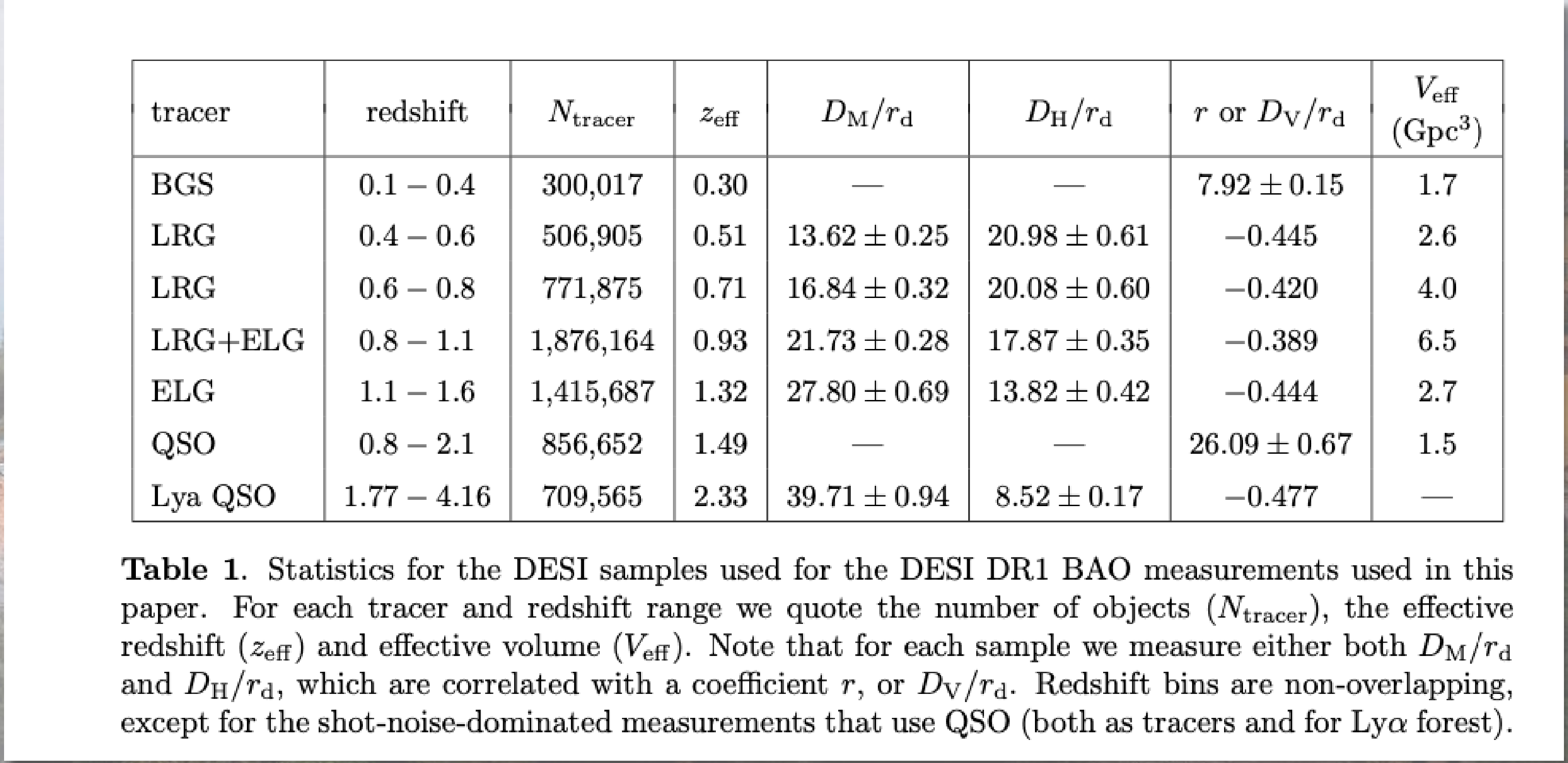
DESI fits to $w_0 w_a$ (DES 5yr similar)

NB: $w = w_0 + w_a(1-a) = w_0 + w_a z/(1+z)$



DESI BAO distances (few % precision)

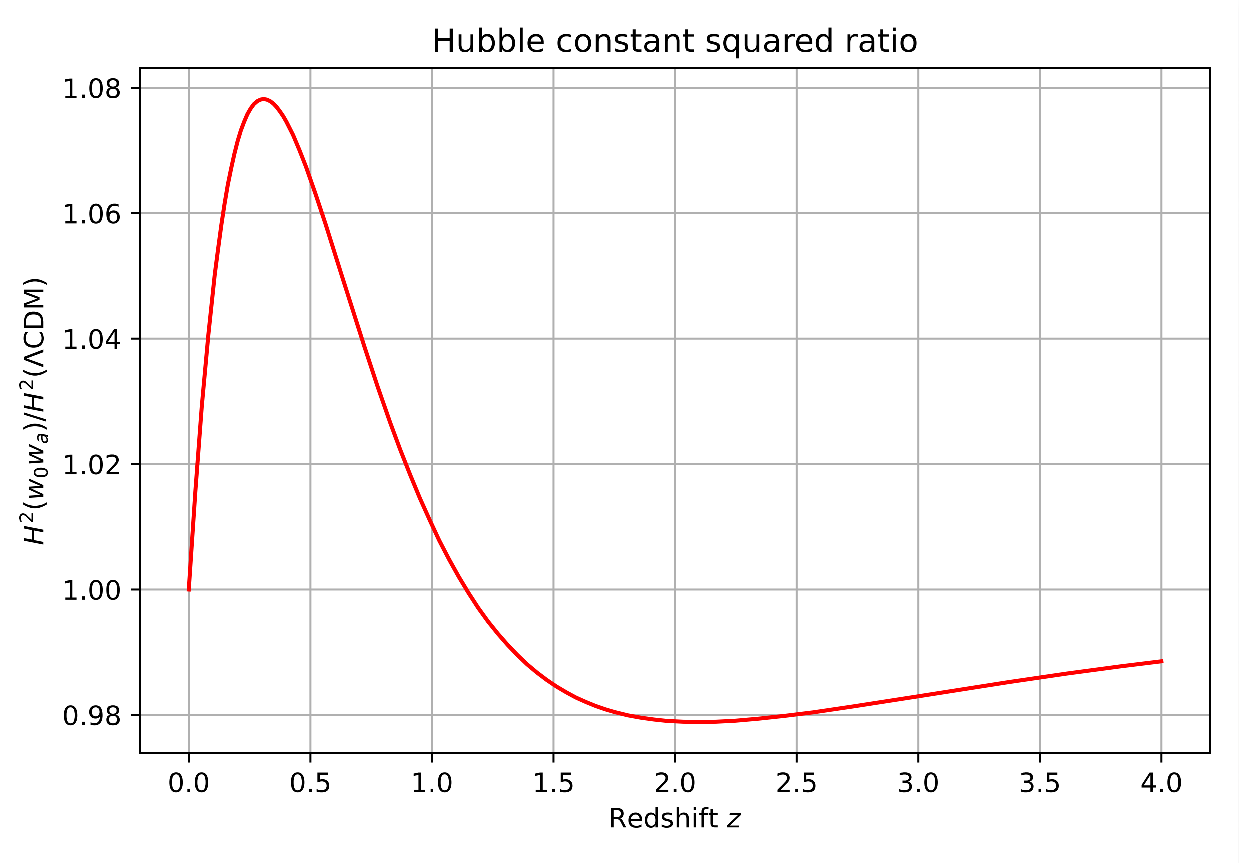
note: $D_H = \frac{1}{H(z)}$ and $D_M = \int dz/H(z) = d_C$



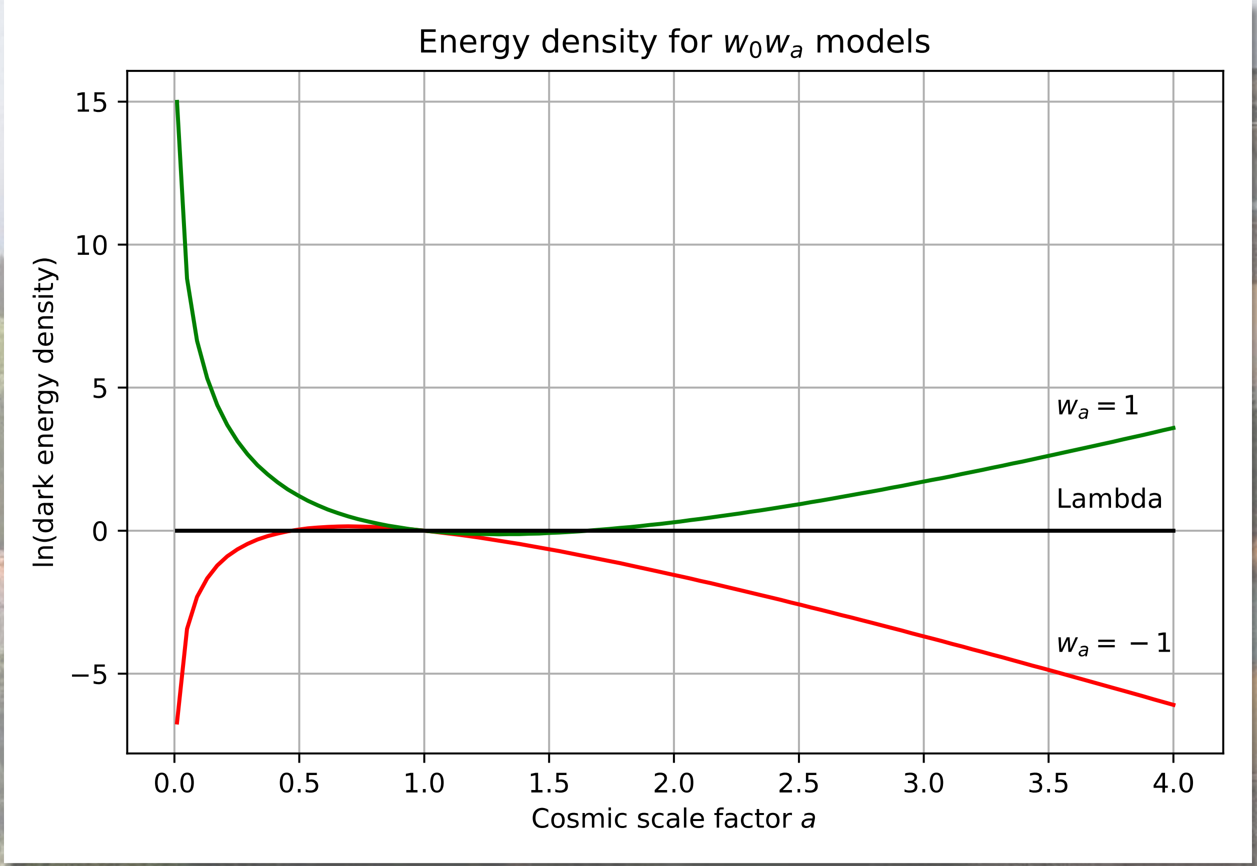
tracer	redshift	$N_{\rm tracer}$	$z_{\rm eff}$	$D_{\rm M}/r_{\rm d}$	$D_{\rm H}/r_{\rm d}$	r or $D_{\rm V}/r_{\rm d}$	$V_{\rm eff}$ (Gpc^3)
BGS	0.1 – 0.4	300,017	0.30	—	—	7.92 ± 0.15	1.7
LRG	0.4 – 0.6	506,905	0.51	13.62 ± 0.25	20.98 ± 0.61	-0.445	2.6
LRG	0.6 – 0.8	771,875	0.71	16.84 ± 0.32	20.08 ± 0.60	-0.420	4.0
LRG+ELG	0.8 – 1.1	1,876,164	0.93	21.73 ± 0.28	17.87 ± 0.35	-0.389	6.5
ELG	1.1 – 1.6	1,415,687	1.32	27.80 ± 0.69	13.82 ± 0.42	-0.444	2.7
QSO	0.8 – 2.1	856,652	1.49	—	—	26.09 ± 0.67	1.5
Lya QSO	1.77 – 4.16	709,565	2.33	39.71 ± 0.94	8.52 ± 0.17	-0.477	—

Table 1. Statistics for the DESI samples used for the DESI DR1 BAO measurements used in this paper. For each tracer and redshift range we quote the number of objects ($N_{\rm tracer}$), the effective redshift ($z_{\rm eff}$) and effective volume ($V_{\rm eff}$). Note that for each sample we measure either both $D_{\rm M}/r_{\rm d}$ and $D_{\rm H}/r_{\rm d}$, which are correlated with a coefficient r, or $D_{\rm V}/r_{\rm d}$. Redshift bins are non-overlapping, except for the shot-noise-dominated measurements that use QSO (both as tracers and for Lyα forest).

Best-fit w_0w_a model compared to ΛCDM is the Universe is giving us the @@#!?

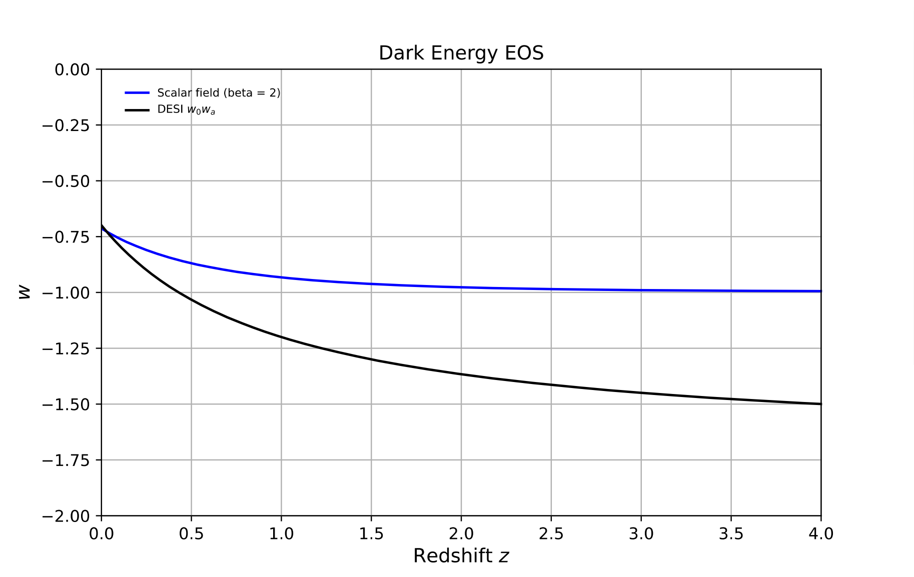


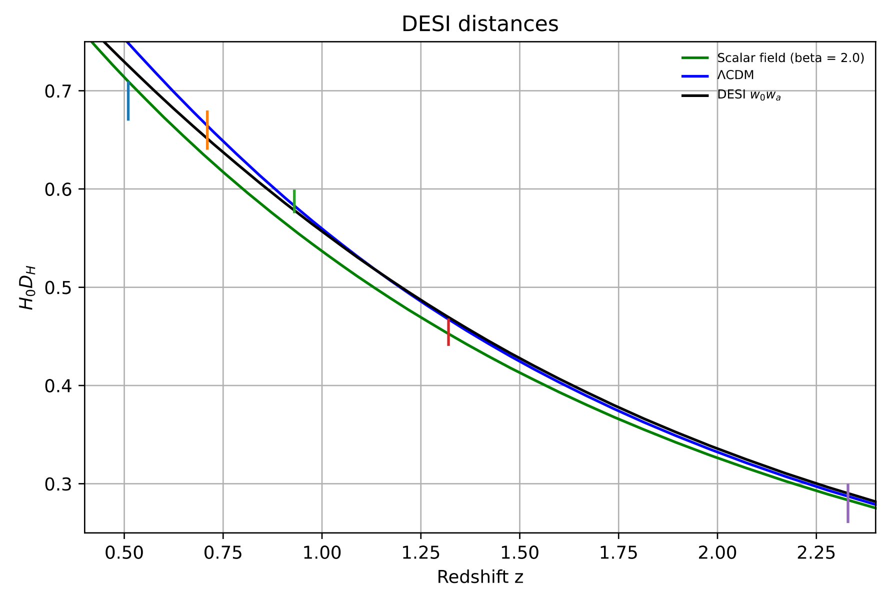
w_0w_a parameterization maybe useful, but it is unphysical



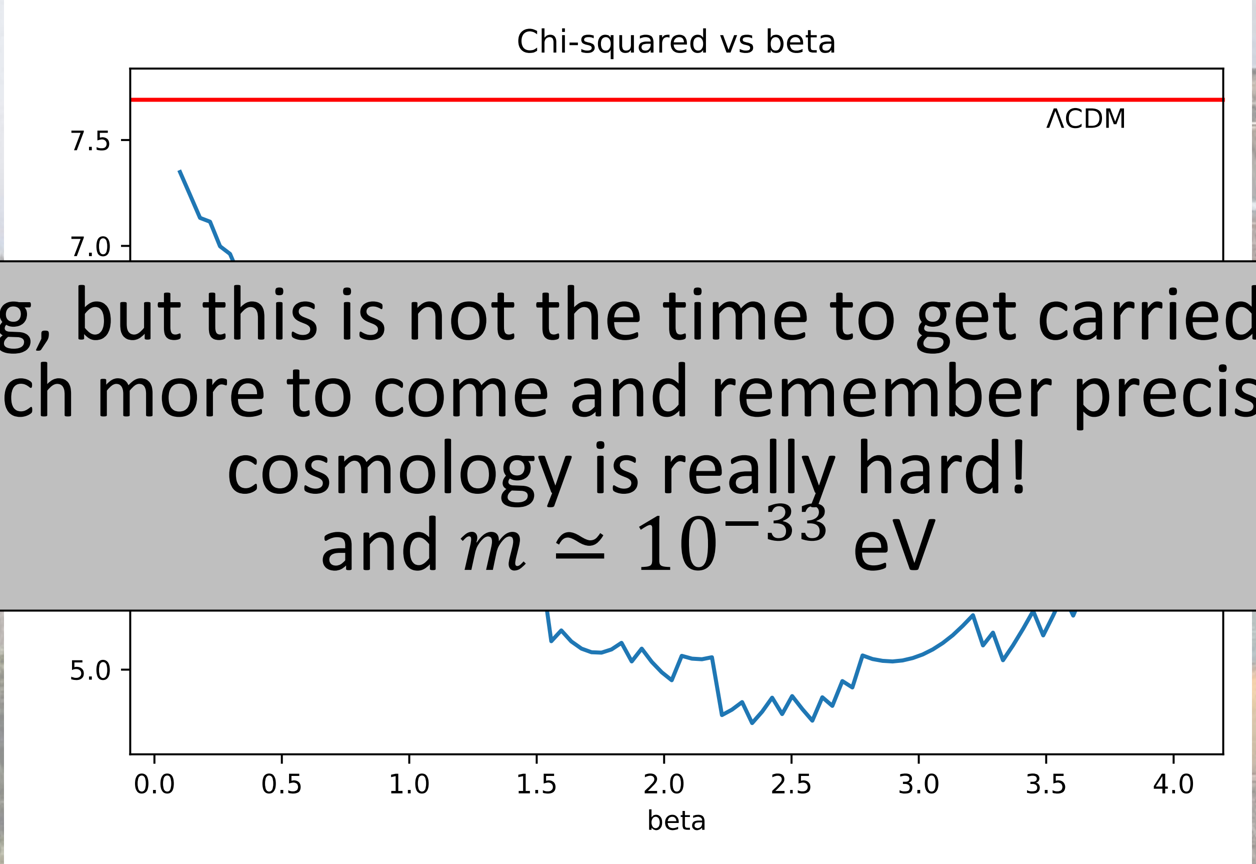
Scalar field ϕ with $V(\phi) = \frac{1}{2}m^2\phi^2$

$$\beta \equiv m^2/H_0^2$$

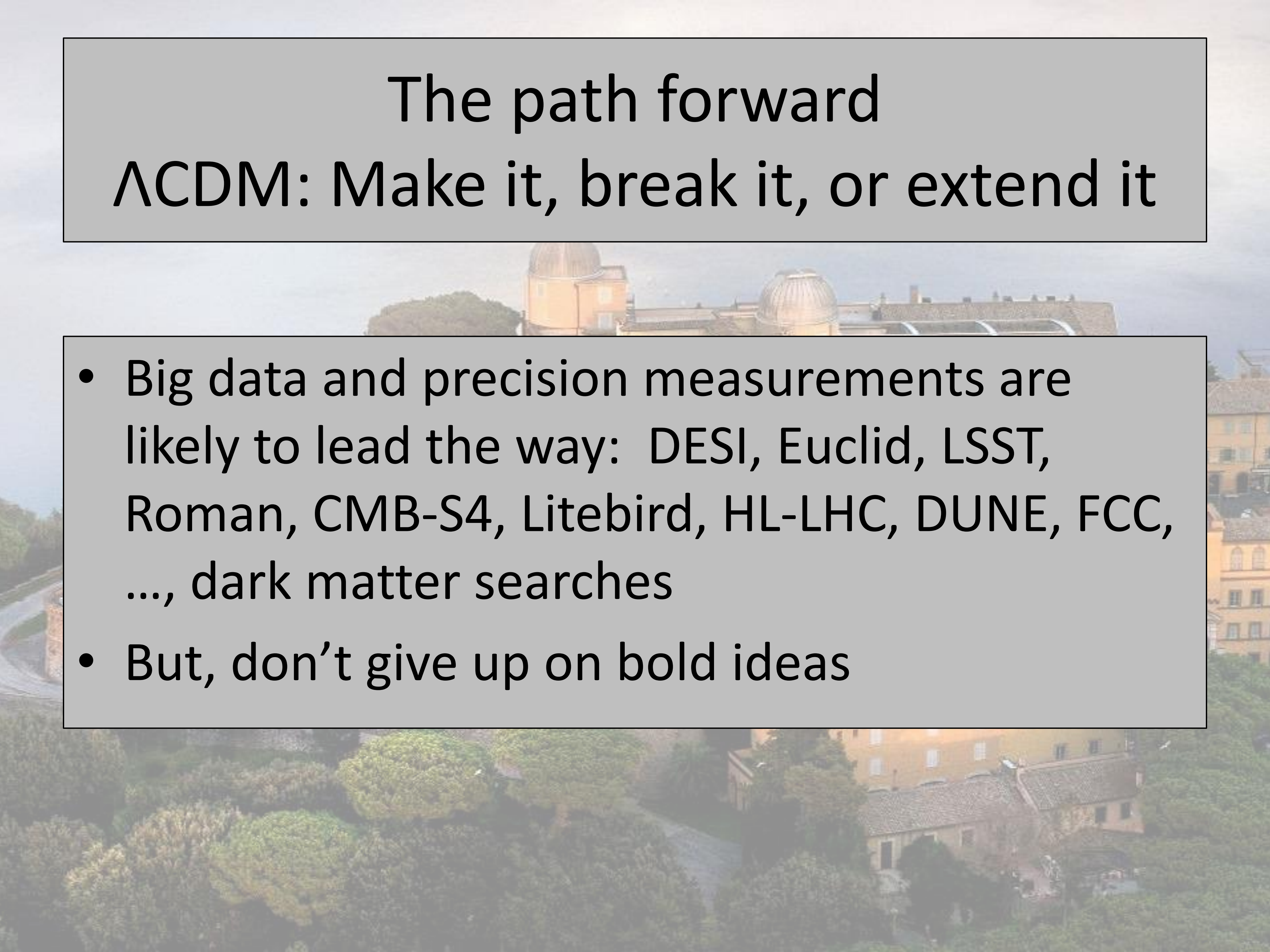




Scalar field works just as well (with one less parameter, only $\beta = m^2/H_0^2$

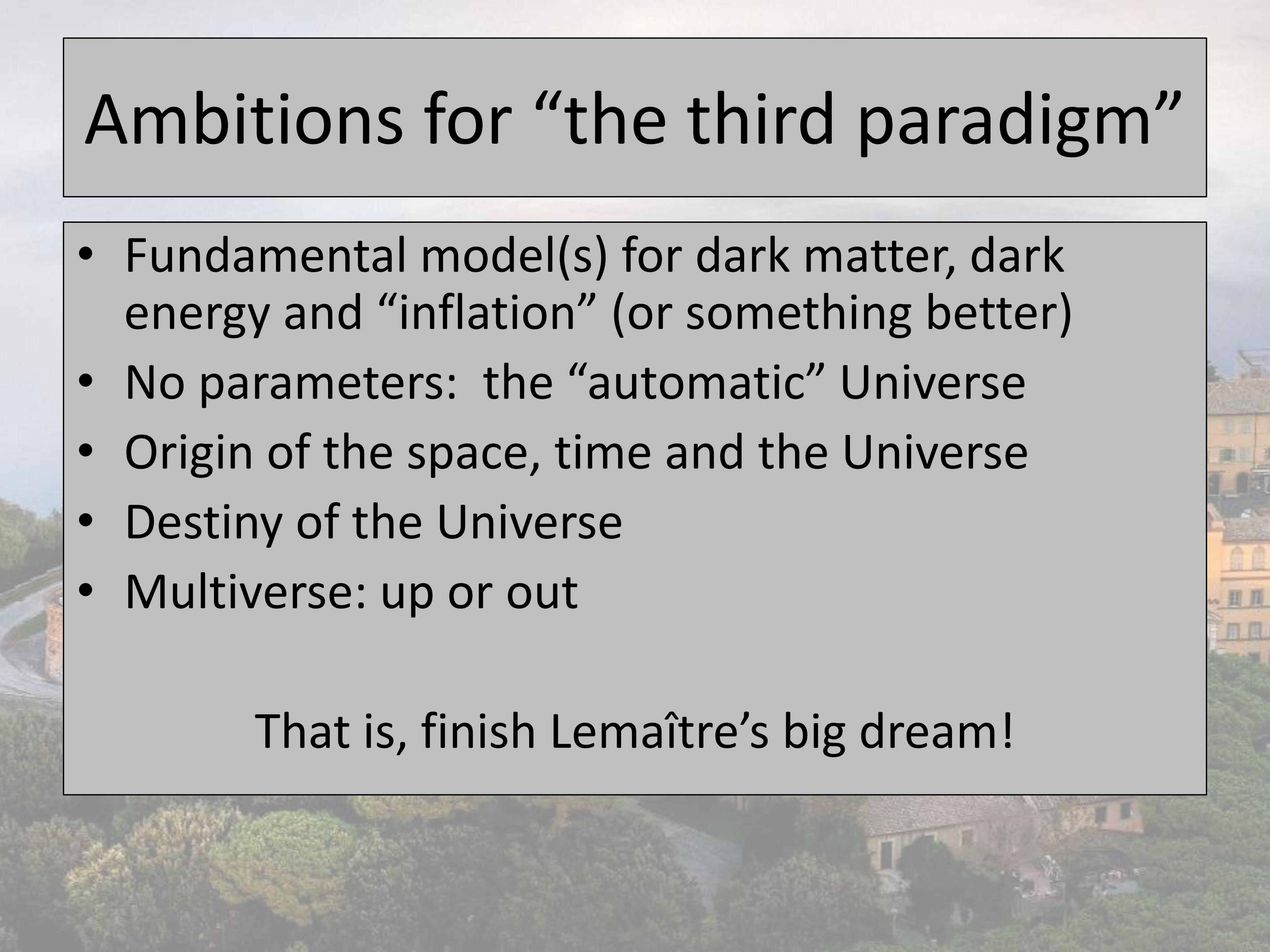


Exciting, but this is not the time to get carried away!
Much more to come and remember precision cosmology is really hard!
and $m \simeq 10^{-33}$ eV



The path forward
ΛCDM: Make it, break it, or extend it

- Big data and precision measurements are likely to lead the way: DESI, Euclid, LSST, Roman, CMB-S4, Litebird, HL-LHC, DUNE, FCC, …, dark matter searches
- But, don’t give up on bold ideas



Ambitions for “the third paradigm”

- Fundamental model(s) for dark matter, dark energy and “inflation” (or something better)
- No parameters: the “automatic” Universe
- Origin of the space, time and the Universe
- Destiny of the Universe
- Multiverse: up or out

That is, finish Lemaître’s big dream!

The grandest challenge in cosmology:
Connect big ideas with big data

Precision Cosmology!

Precision Cosmology is Hard

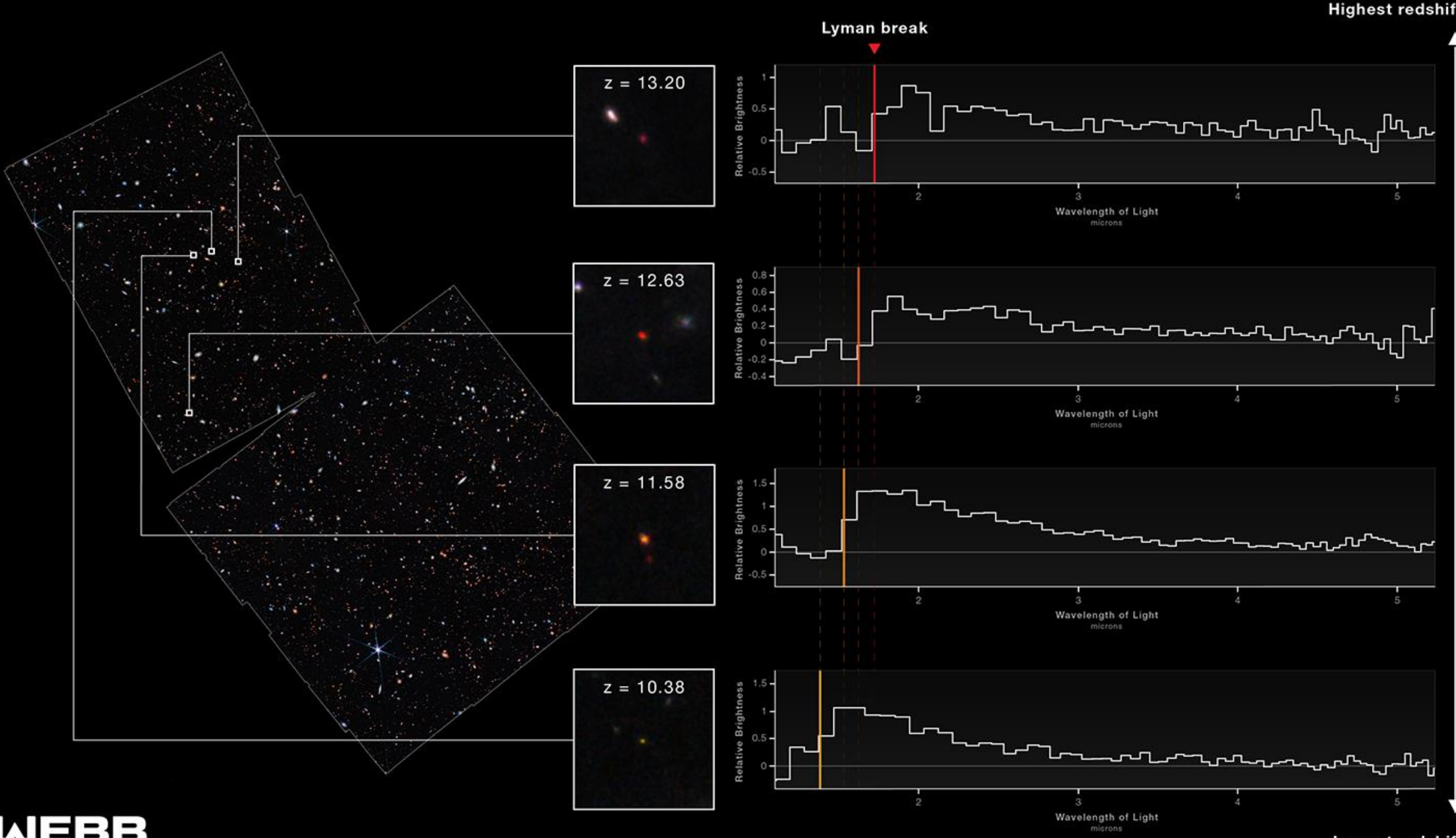
Accurate Cosmology is even Harder!

JWST ADVANCED DEEP EXTRAGALACTIC SURVEY (JADES)

WEBB SPECTRA REACH NEW MILESTONE IN REDSHIFT FRONTIER

NIRCam Imaging

NIRSpec Microshutter Array Spectroscop



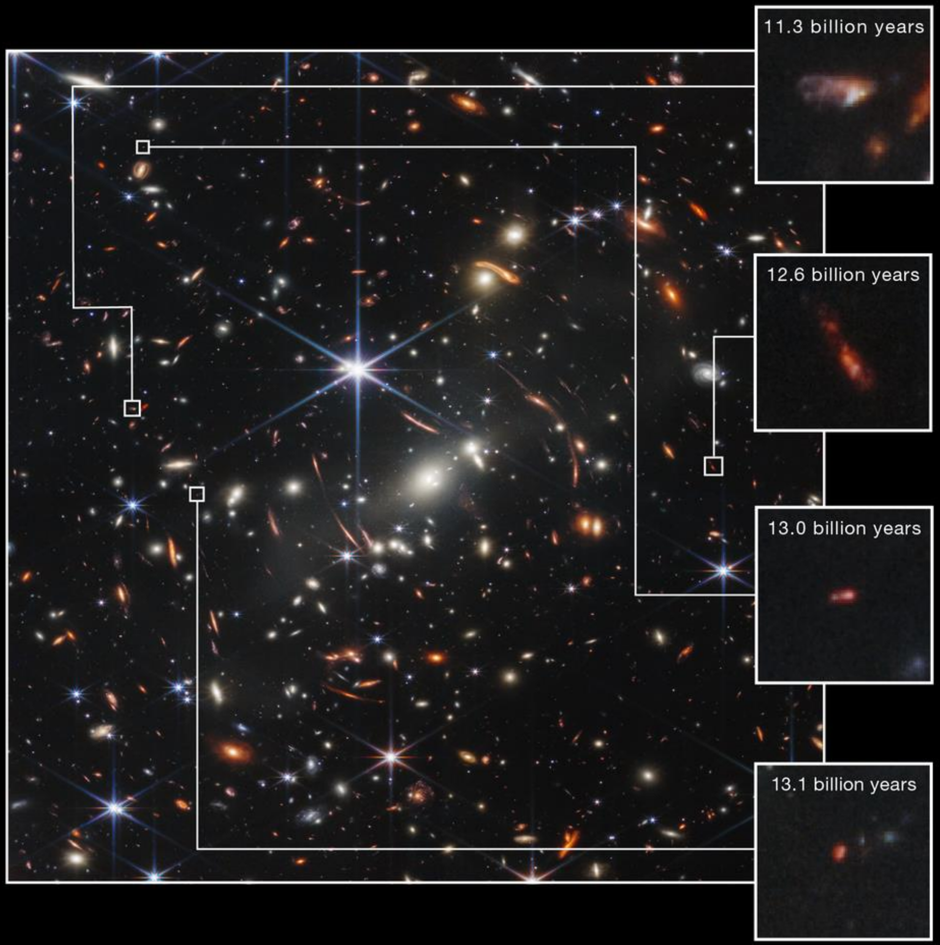
WEBB
SPACE TELESCOPE

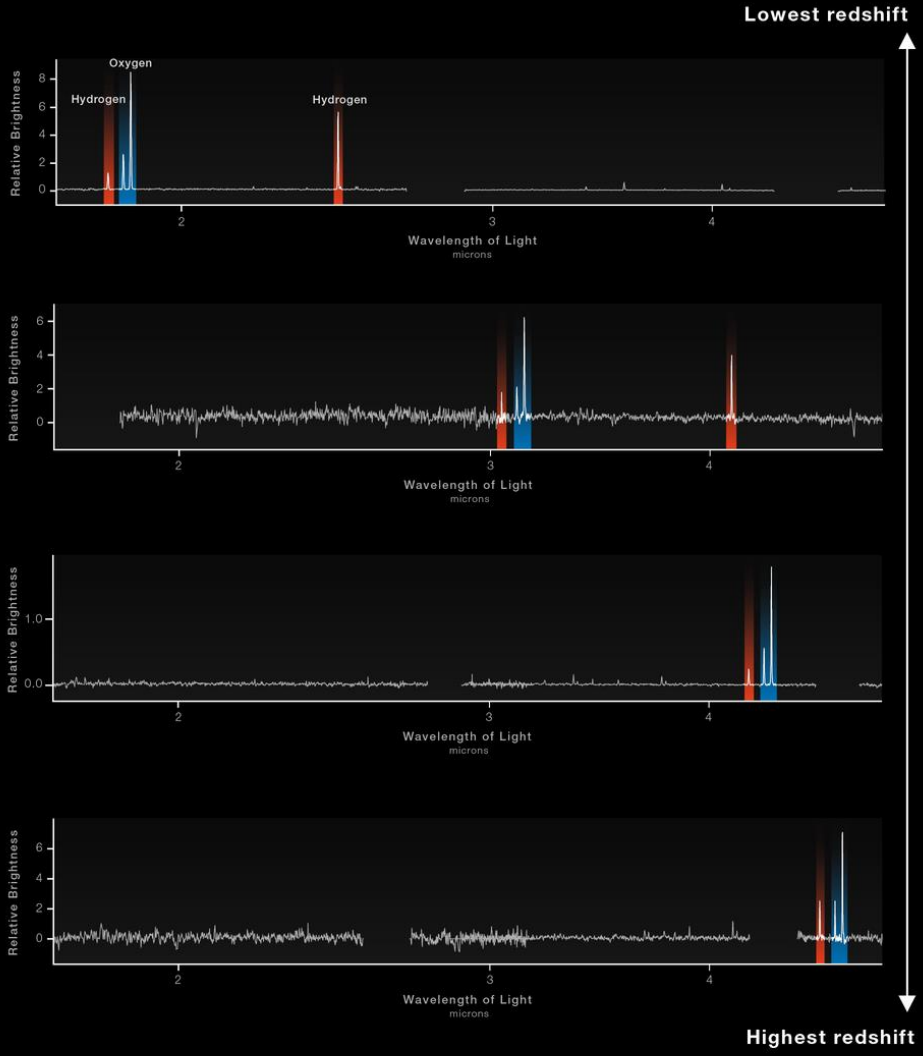
GALAXY CLUSTER SMACS 0723

WEBB SPECTRA IDENTIFY GALAXIES IN THE VERY EARLY UNIVERSE

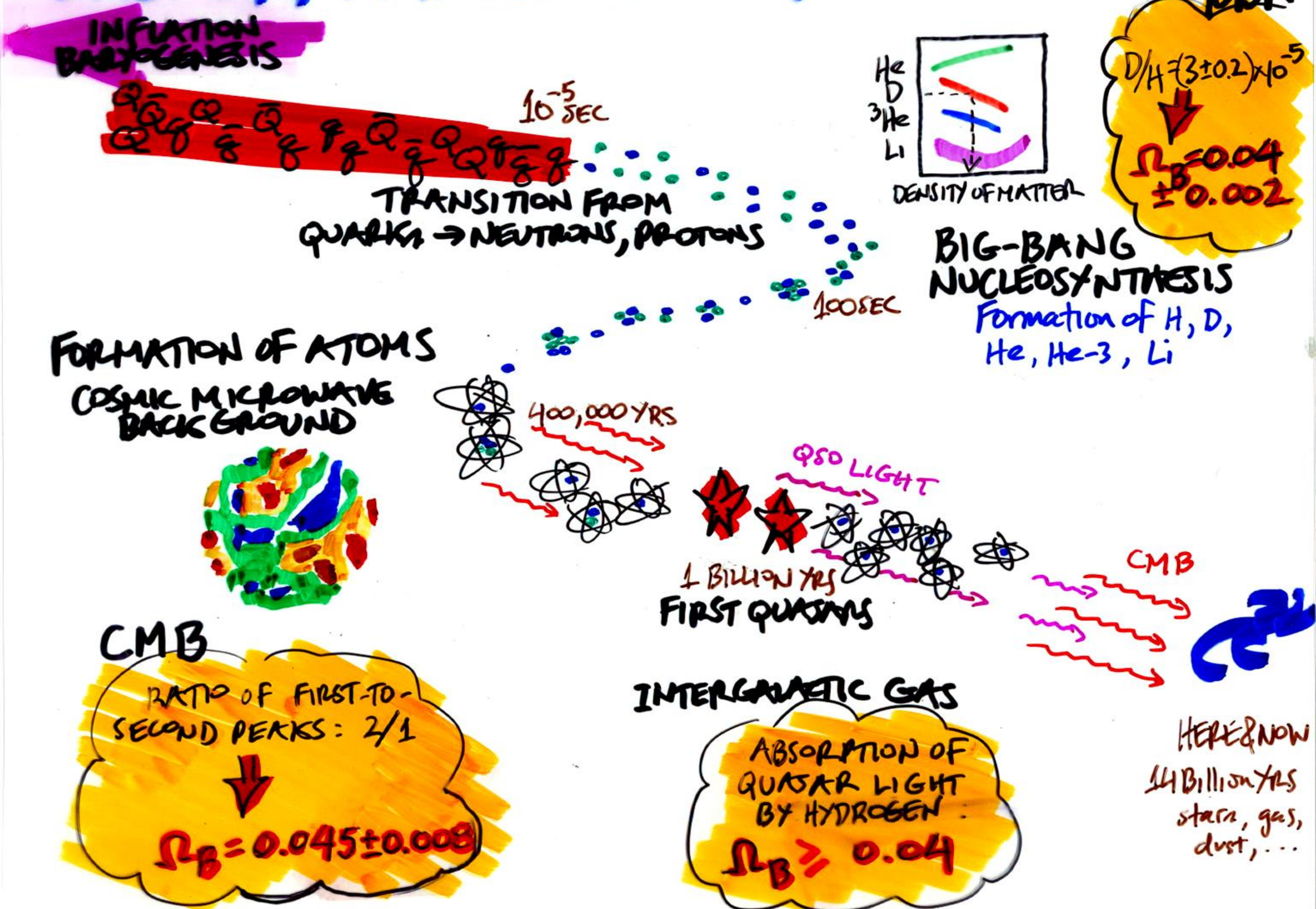
NIRCam Imaging

NIRSpec Microshutter Array Spectroscopy





ORDINARY MATTER: FROM QUARKS TO US



INFLATION BARYOGENESIS

TRANSITION FROM QUARKS → NEUTRONS, PROTONS

BBN

$D/H = (3 \pm 0.2) \times 10^{-5}$

$\Omega_B = 0.04 \pm 0.002$

BIG-BANG NUCLEOSYNTHESIS

Formation of H, D, He, He-3, Li

FORMATION OF ATOMS

COSMIC MICROWAVE BACKGROUND

FIRST QUASARS

CMB

RATIO OF FIRST-TO-SECOND PEAKS: 2/1

$\Omega_B = 0.045 \pm 0.008$

INTERGALACTIC GAS

ABSORPTION OF QUASAR LIGHT BY HYDROGEN

$\Omega_B \geq 0.04$

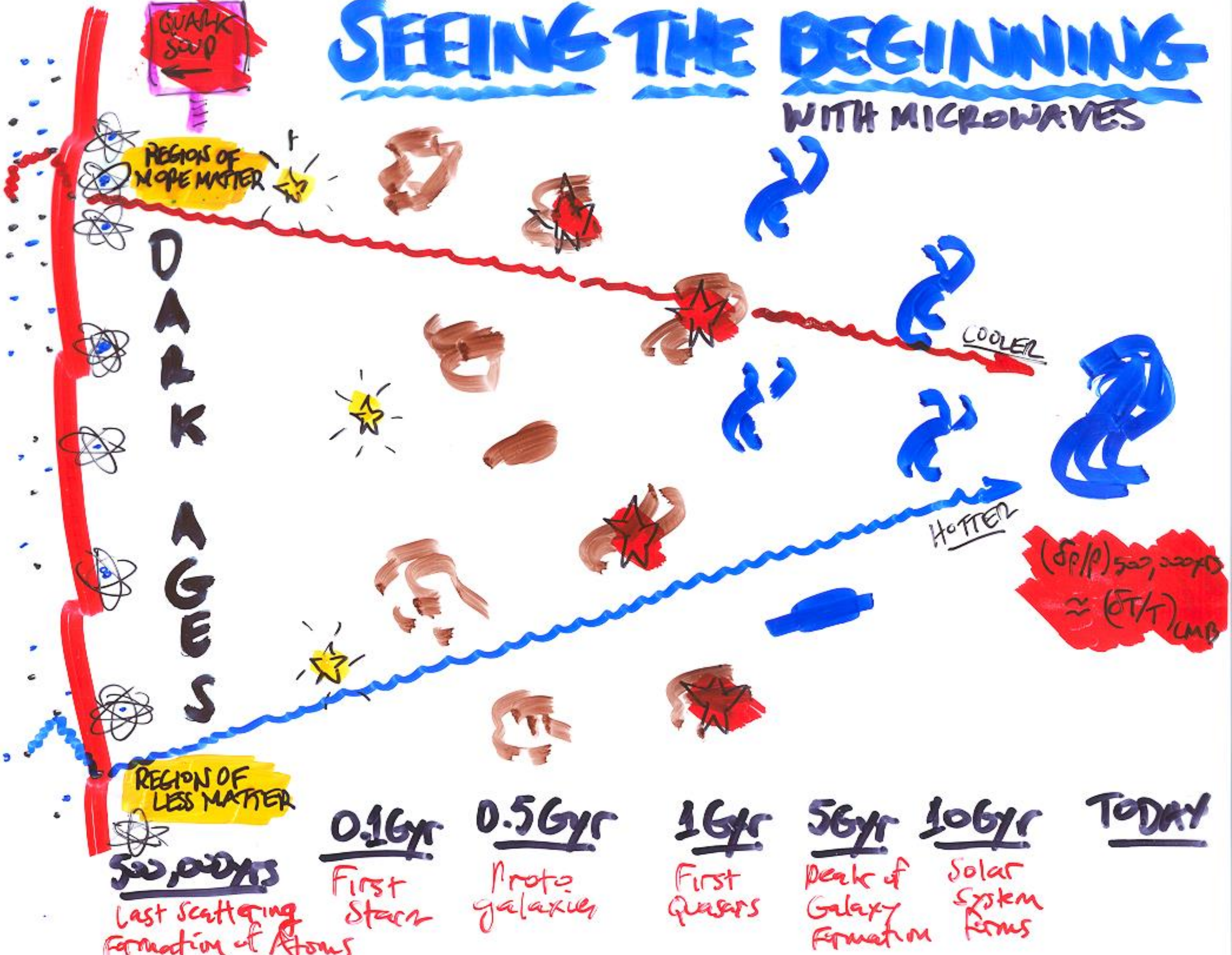
HERE&NOW

14 Billion YRS

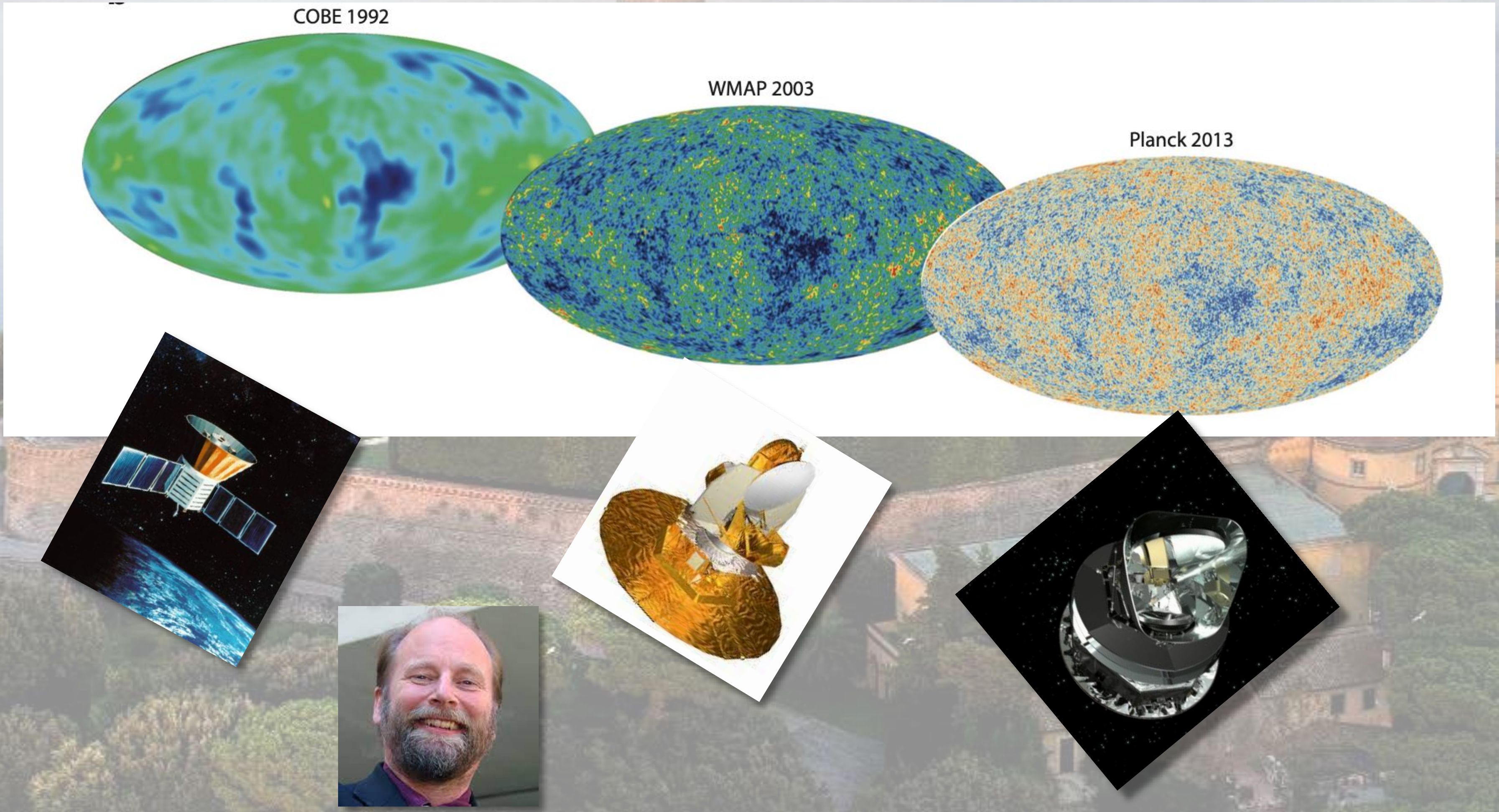
stars, gas, dust, ...

SEEING THE BEGINNING

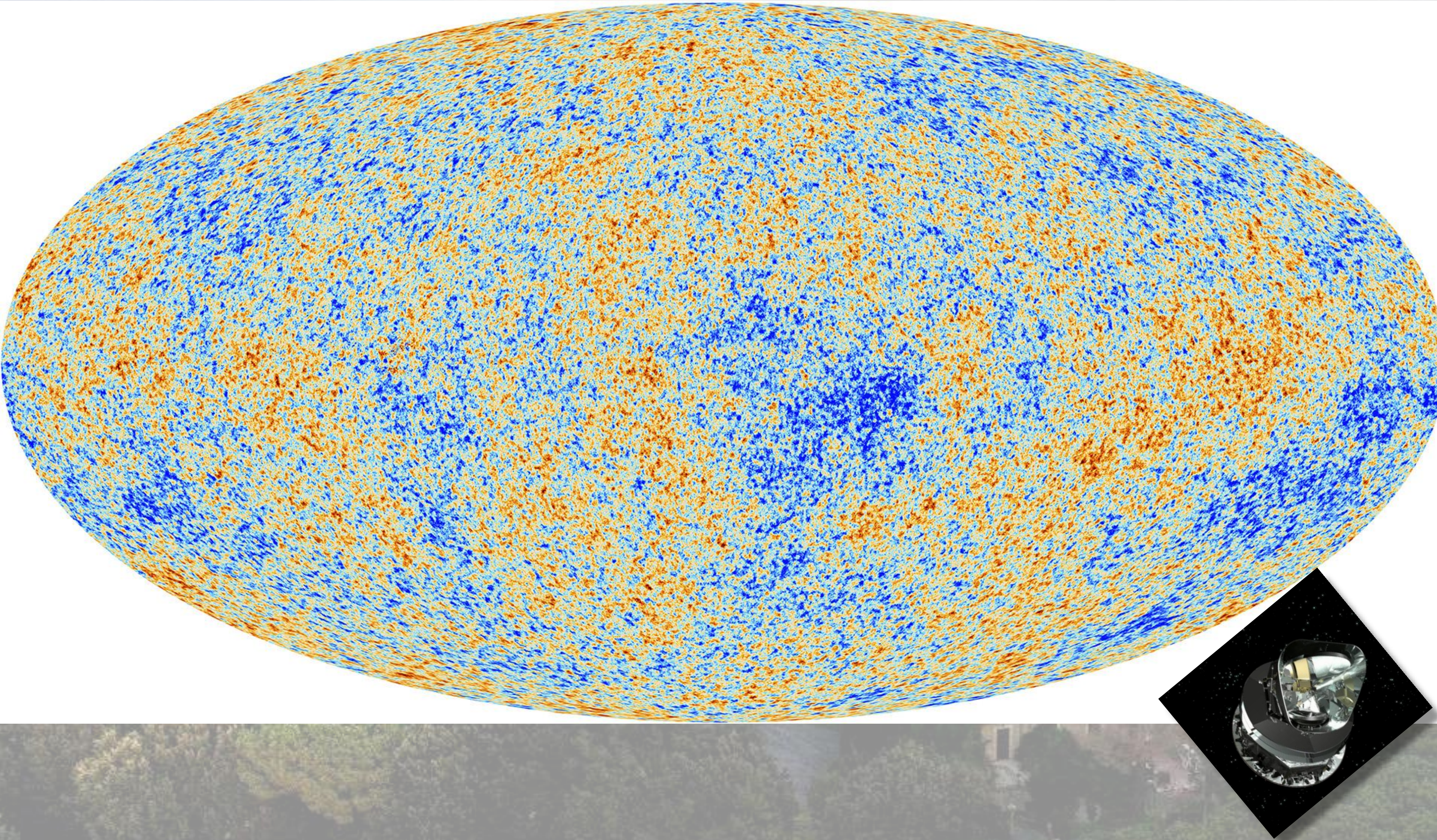
WITH MICROWAVES



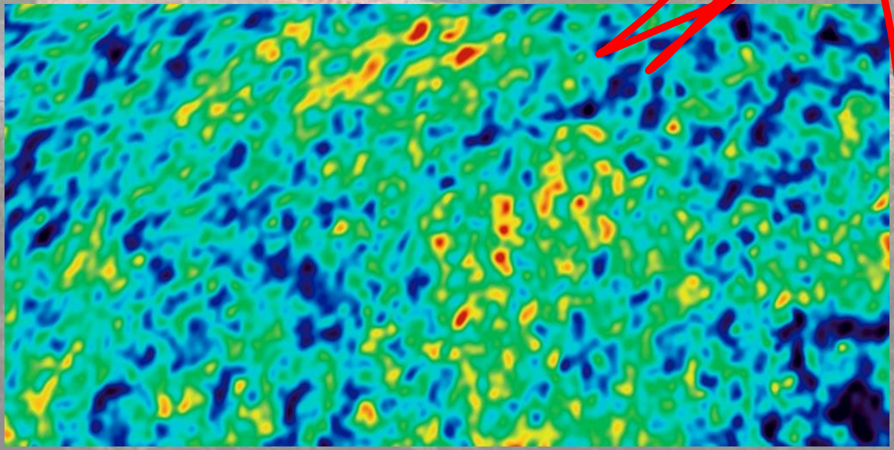
Seeing the beginning with increasing resolution and precision



The Universe at 380,000 years

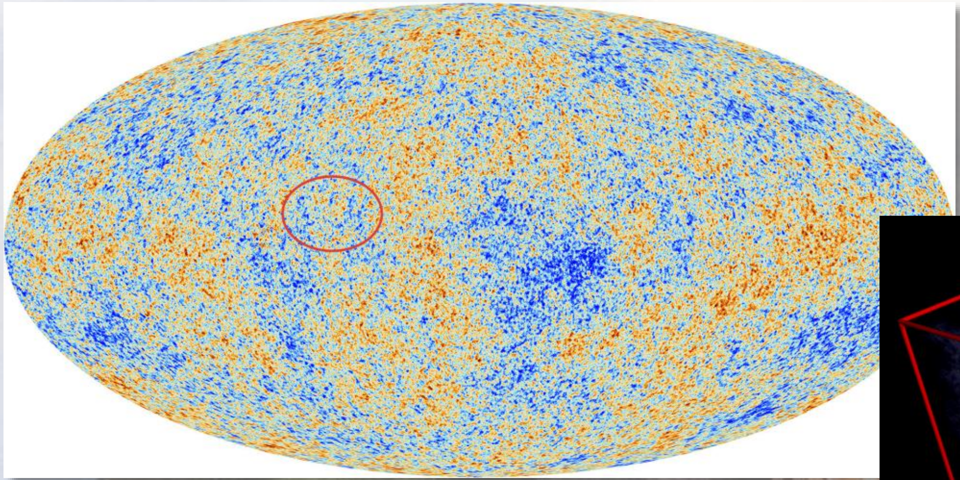


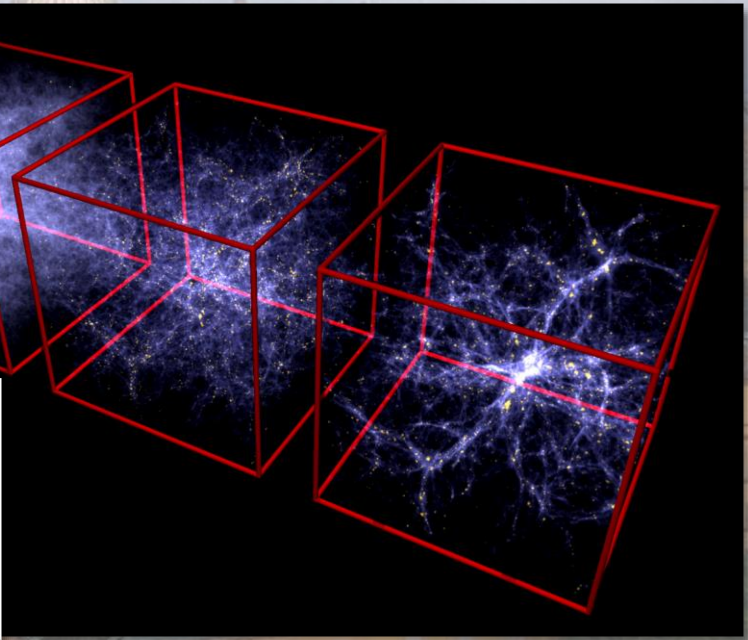
Grandest quantum connection

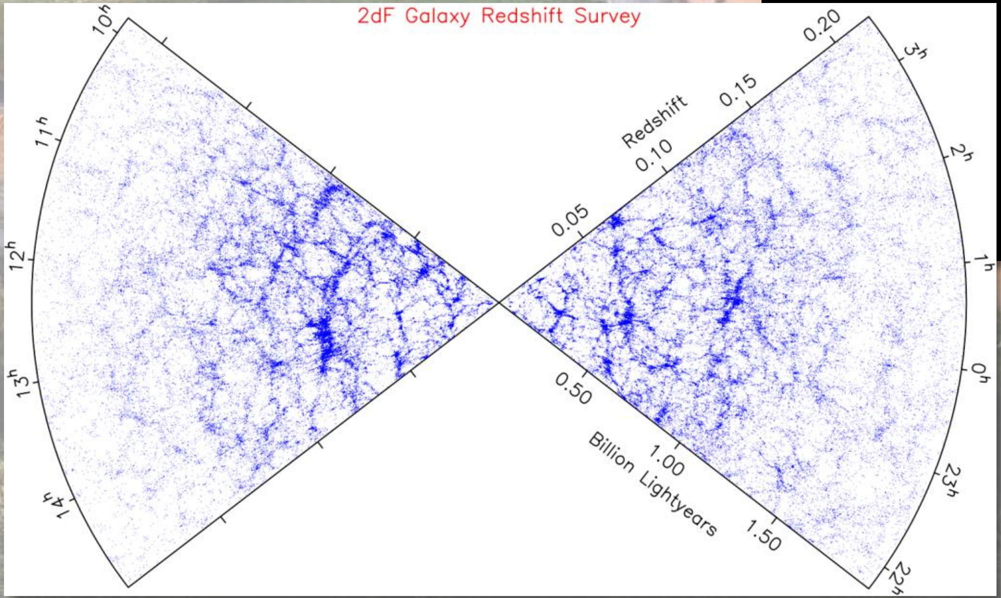


Quantum fluctuations on unimaginably small scales lead to structure on cosmic scales

Tracing the history from a slightly lumpy Universe to galaxies ablaze



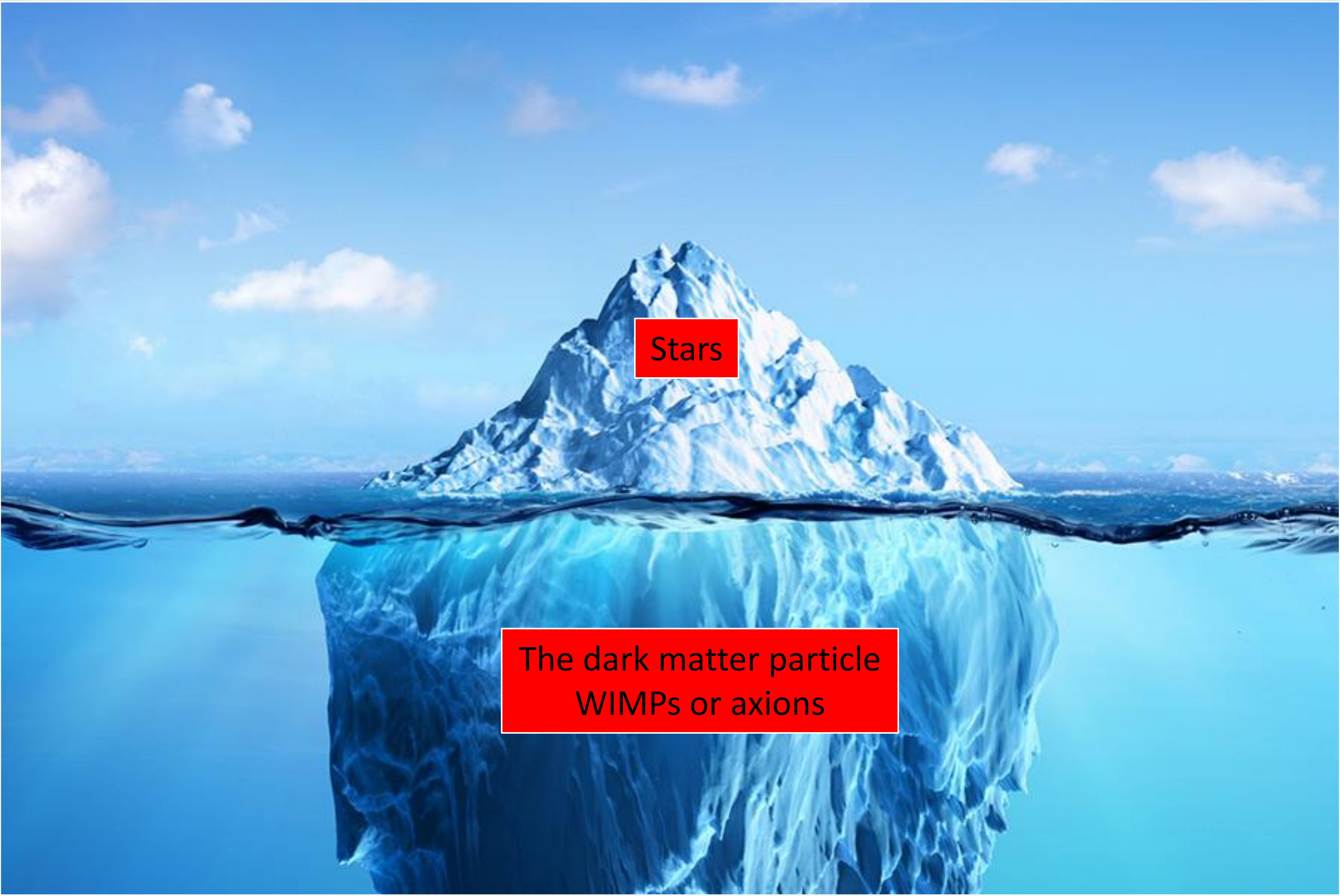




Dark Matter

- Galaxies and clusters of galaxies are held together by the gravity of dark matter
- Without the gravity of dark matter cannot make observed structure
- More diffuse (less condensed) than stellar matter
- Moves slowly (cold) and bashful (doesn’t interact much with ordinary matter)
- Not enough atoms to account for it, must be new form of matter

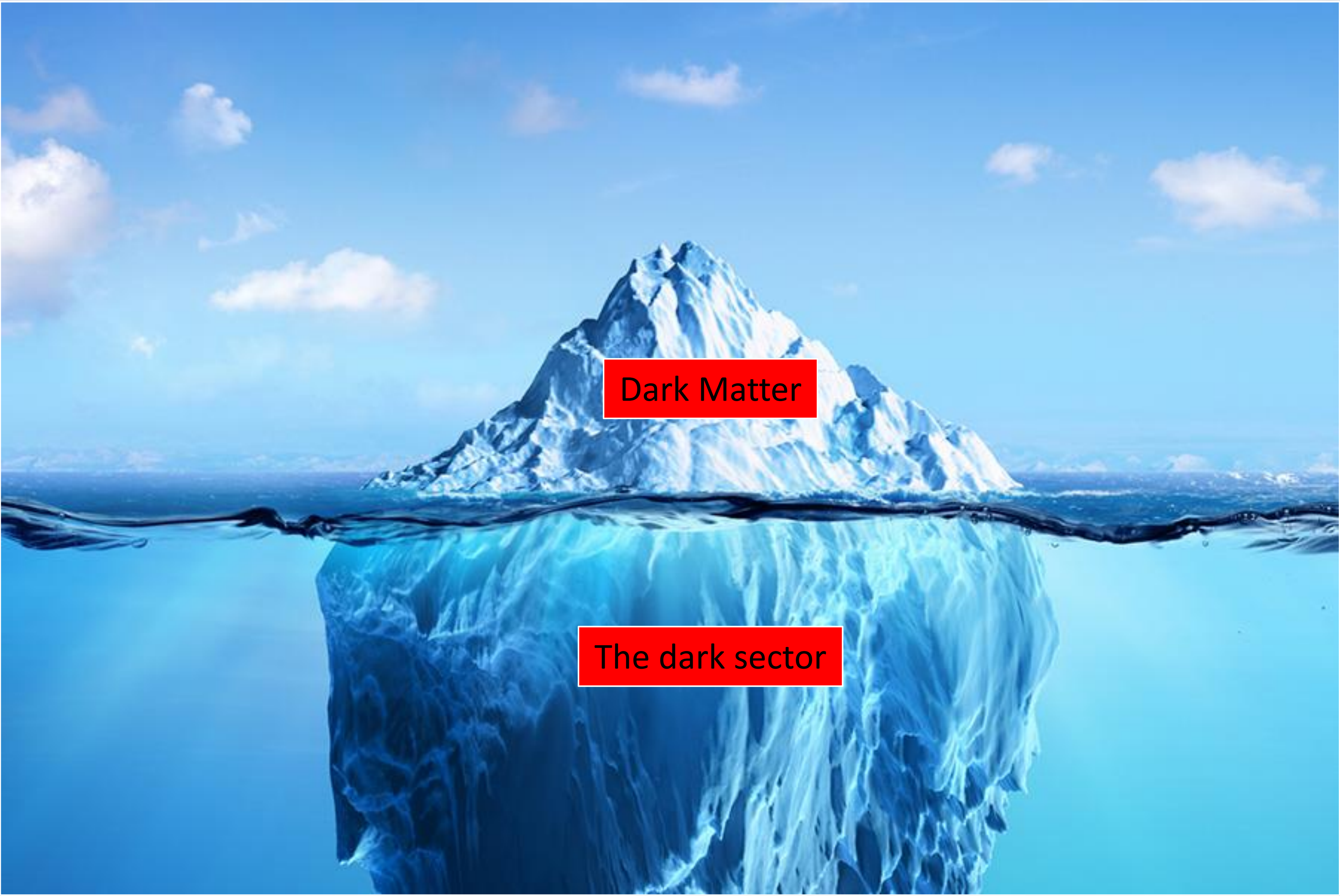
Dark Matter: this?



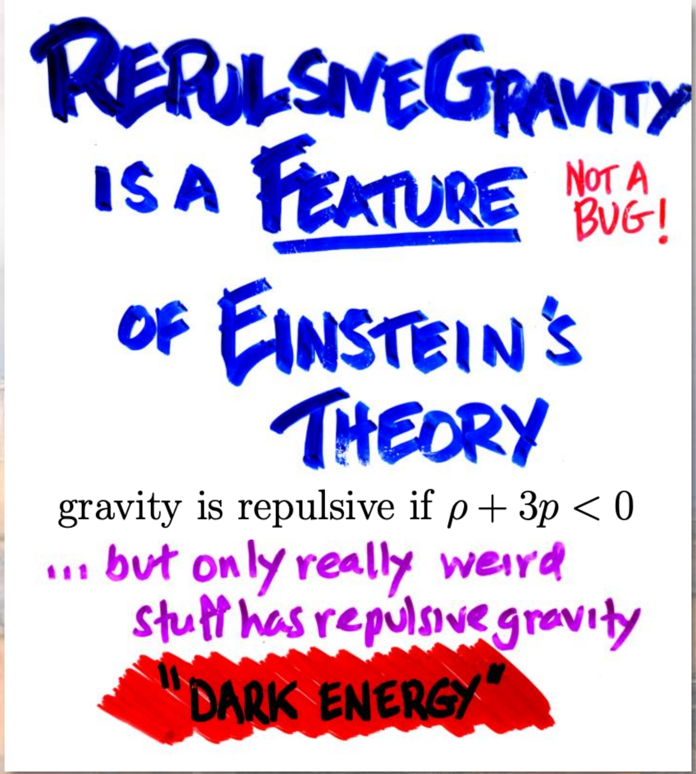
Stars

The dark matter particle
WIMPs or axions

Dark Matter: or that?



- Λ (vacuum energy) fits the date but why so small?
- Evidence of the rich vacua of string theory and the multiverse?
- Related to inflation (accelerated expansion) or something else?



REPULSIVE GRAVITY IS A FEATURE OF EINSTEIN'S THEORY

NOT A BUG!

gravity is repulsive if $\rho + 3p < 0$

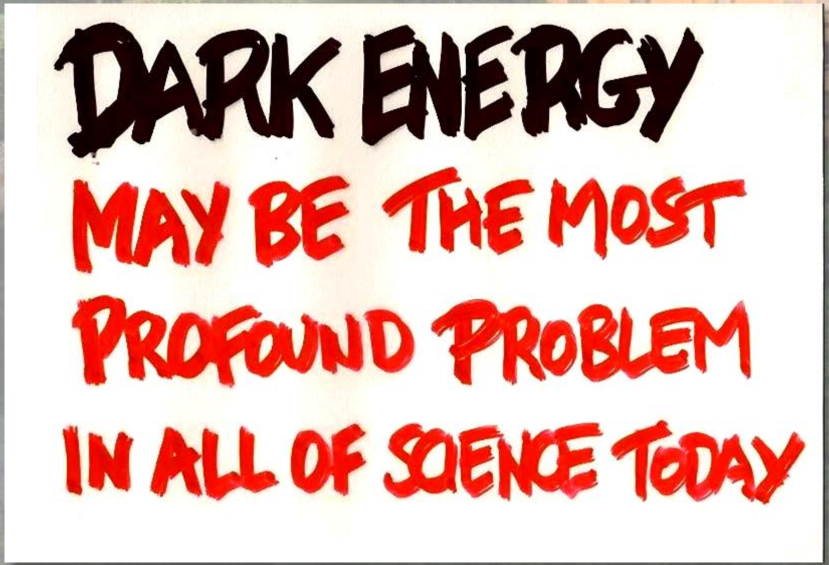
... but only really weird stuff has repulsive gravity

"DARK ENERGY"

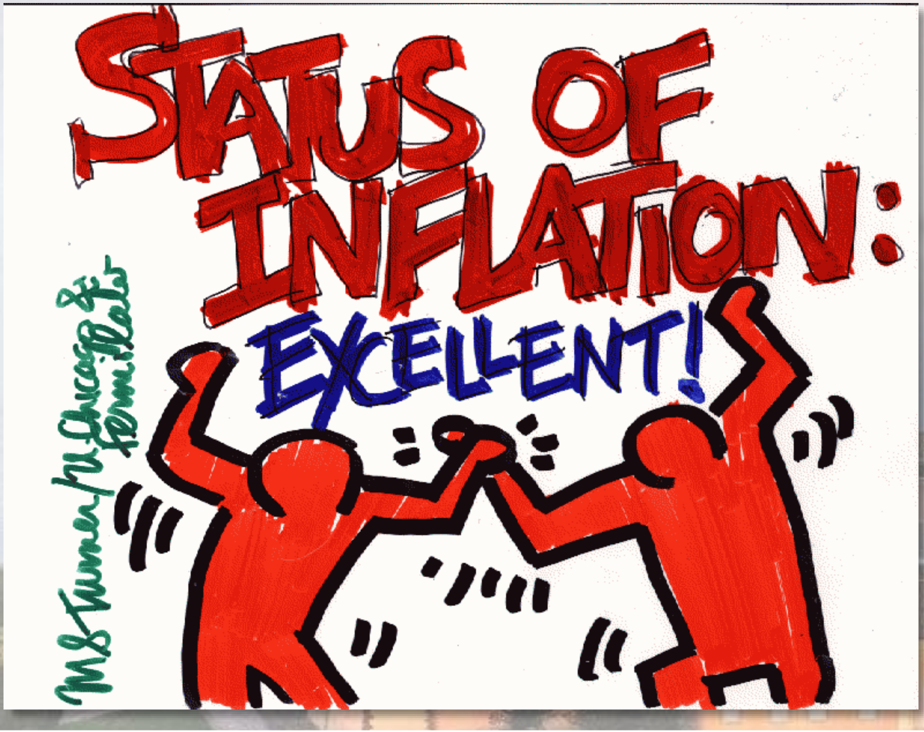
QUANTUM NOTHINGNESS HAS REPULSIVE GRAVITY!

HOW REPULSIVE?

JUST ABOUT RIGHT -- GIVE OR TAKE 10^{55}



DARK ENERGY MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY



- CMB anisotropy consistent with predictions: Gaussian, almost scale-invariant density perturbations and flat Universe, but no “standard model” or signature of “when”
- Wanted: odd-parity (B) mode of CMB polarization produced by gravitational waves

GWs and B-mode CMB polarization

n = 1

n = 0.85

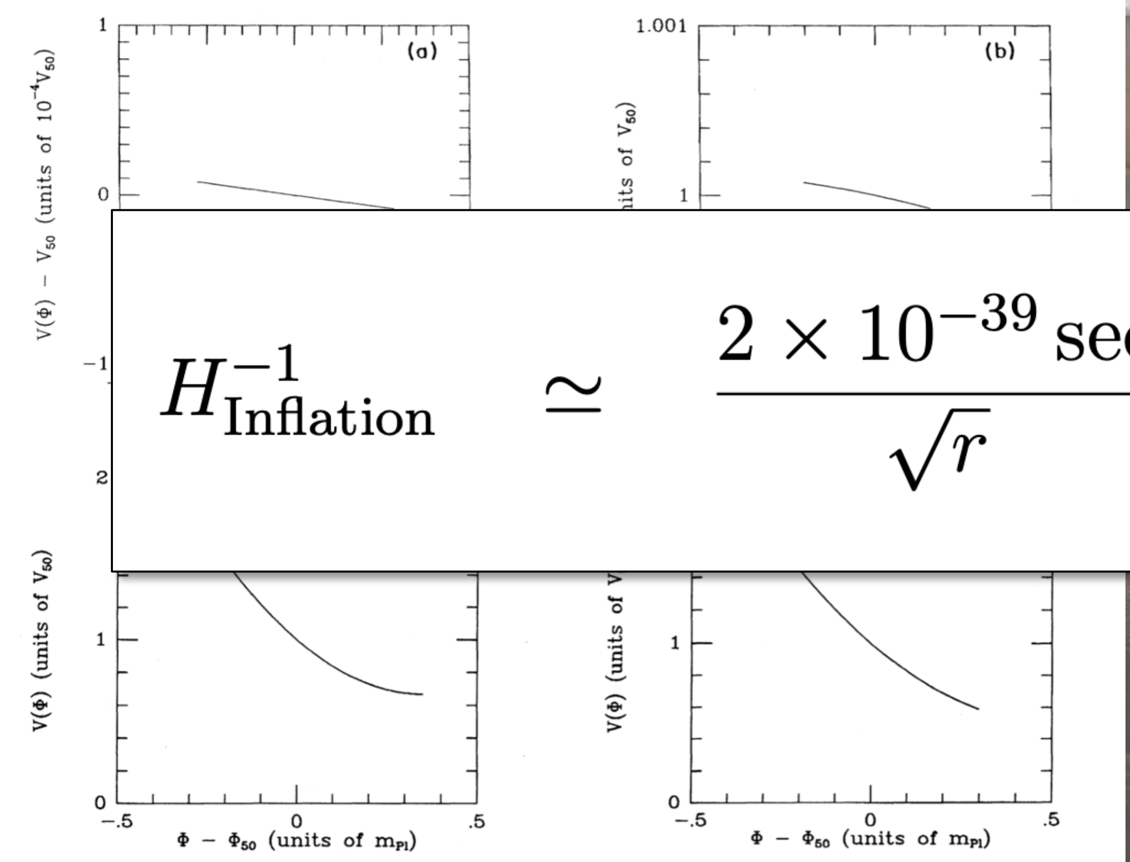
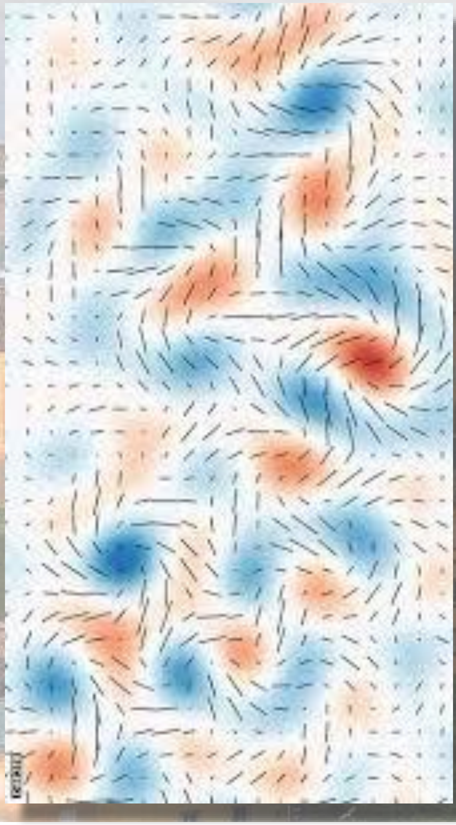


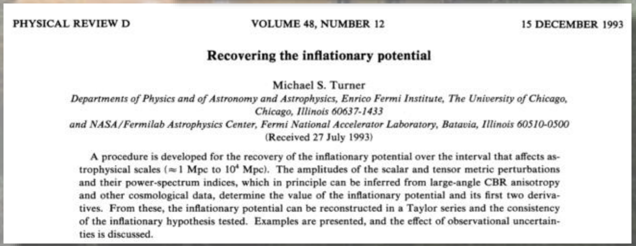
FIG. 5. The four generic inflationary potentials: (a) $n-1=-2\times10^{-6}$ and $T/S=1.4\times10^{-5}$, with the COBE DMR normalization $V_{50}^{1/4}=2.0\times10^{15}$ GeV; (b) $n=0.85$ and $T/S=1.4\times10^{-4}$, $V_{50}^{1/4}=3.6\times10^{15}$ GeV; (c) $n=1$ and $T/S=1$, $V_{50}^{1/4}=2.9\times10^{16}$ GeV; and (d) $n=0.85$ and $T/S=1$, $V_{50}^{1/4}=2.9\times10^{16}$ GeV. (a)–(d) correspond to cases (1)–(4) in the text.

$$H^{-1}_{\text{Inflation}} \simeq \frac{2\times10^{-39}\,\text{sec}}{\sqrt{r}}$$

r << 1

1





PHYSICAL REVIEW D VOLUME 48, NUMBER 12 15 DECEMBER 1993

Recovering the inflationary potential

Michael S. Turner

Departments of Physics and of Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433
and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500

(Received 27 July 1993)

A procedure is developed for the recovery of the inflationary potential over the interval that affects astrophysical scales (≈ 1 Mpc to 10^4 Mpc). The amplitudes of the scalar and tensor metric perturbations and their power-spectrum indices, which in principle can be inferred from large-angle CBR anisotropy and other cosmological data, determine the value of the inflationary potential and its first two derivatives. From these, the inflationary potential can be reconstructed in a Taylor series and the consistency of the inflationary hypothesis tested. Examples are presented, and the effect of observational uncertainties is discussed.

Hubble troubles

H_0 reined in, part one

Final Results from the *Hubble Space Telescope* Key Project to Measure the Hubble Constant*

Wendy L. Freedman[1], Barry F. Madore[1,2], Brad K. Gibson[3], Laura Ferrarese[4], Daniel D. Kelson[5], Shoko Sakai[6], Jeremy R. Mould[7], Robert C. Kennicutt, Jr.[8], Holland C. Ford[9], John A. Graham[5]

+Show full author list

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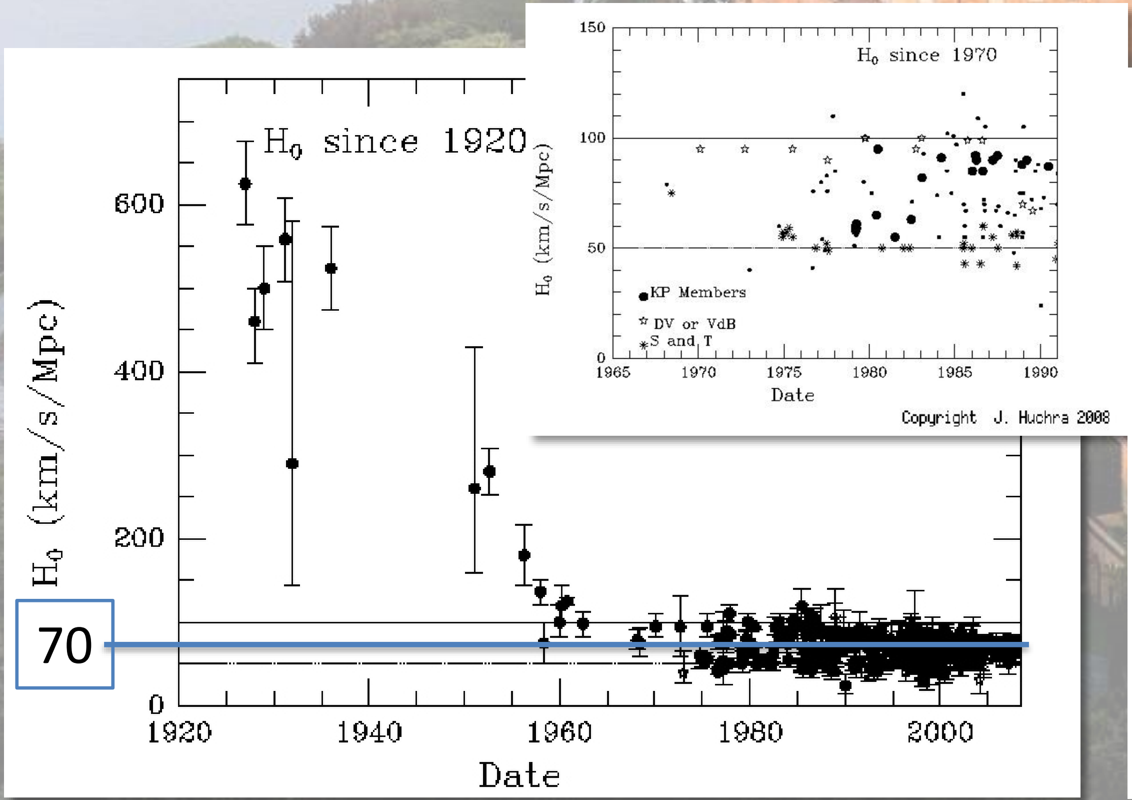
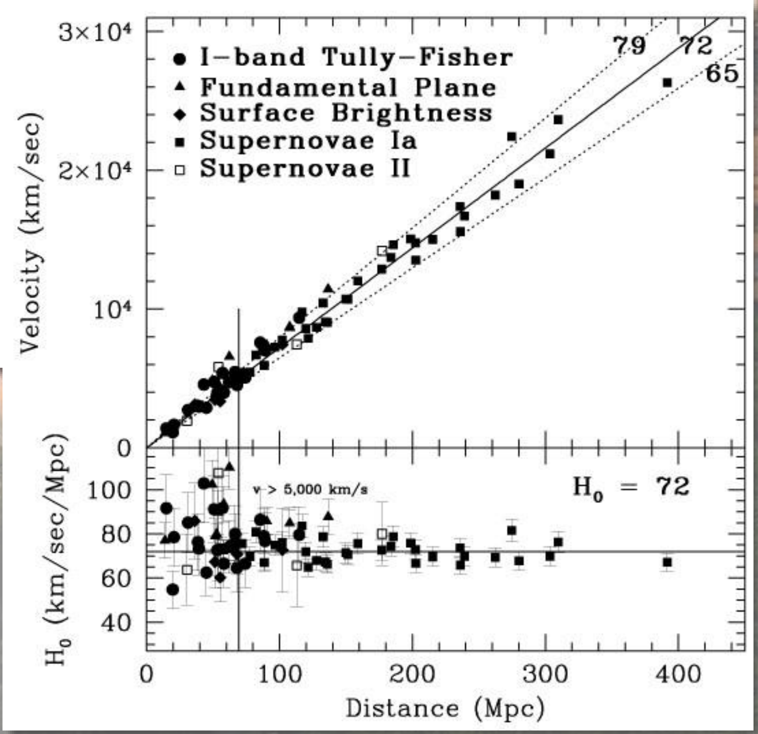
The Astrophysical Journal, Volume 553, Number 1

Citation Wendy L. Freedman *et al* 2001 *ApJ* **553** 47

H_0 = 72 ± 2 ± 6 km/s/Mpc





Hubble troubles again!

arXiv:2103.01183

"early"

"late"

- Indirect (pink): **67.5 ± 0.5** km/s/Mpc

George Efstathiou (Planck)

- Direct (cyan): **73.2 ± 1.3** km/s/Mpc

Adam Riess (SHoES)

- 5-sigma difference!

“New physics”

- The two discrepant measurements could both could be right if ΛCDM is wrong!
- New ingredient(s) to ΛCDM
  - Early dark energy
  - Extra radiation
  - None compelling yet

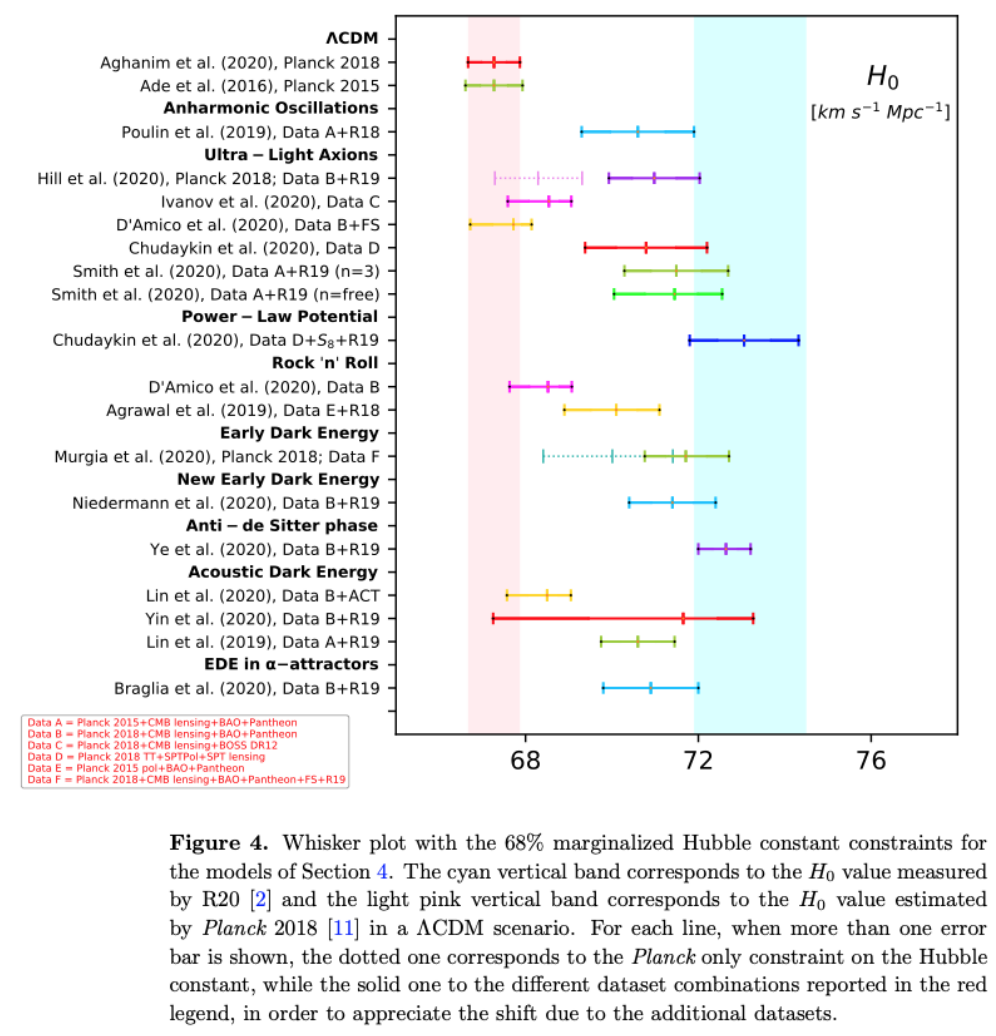
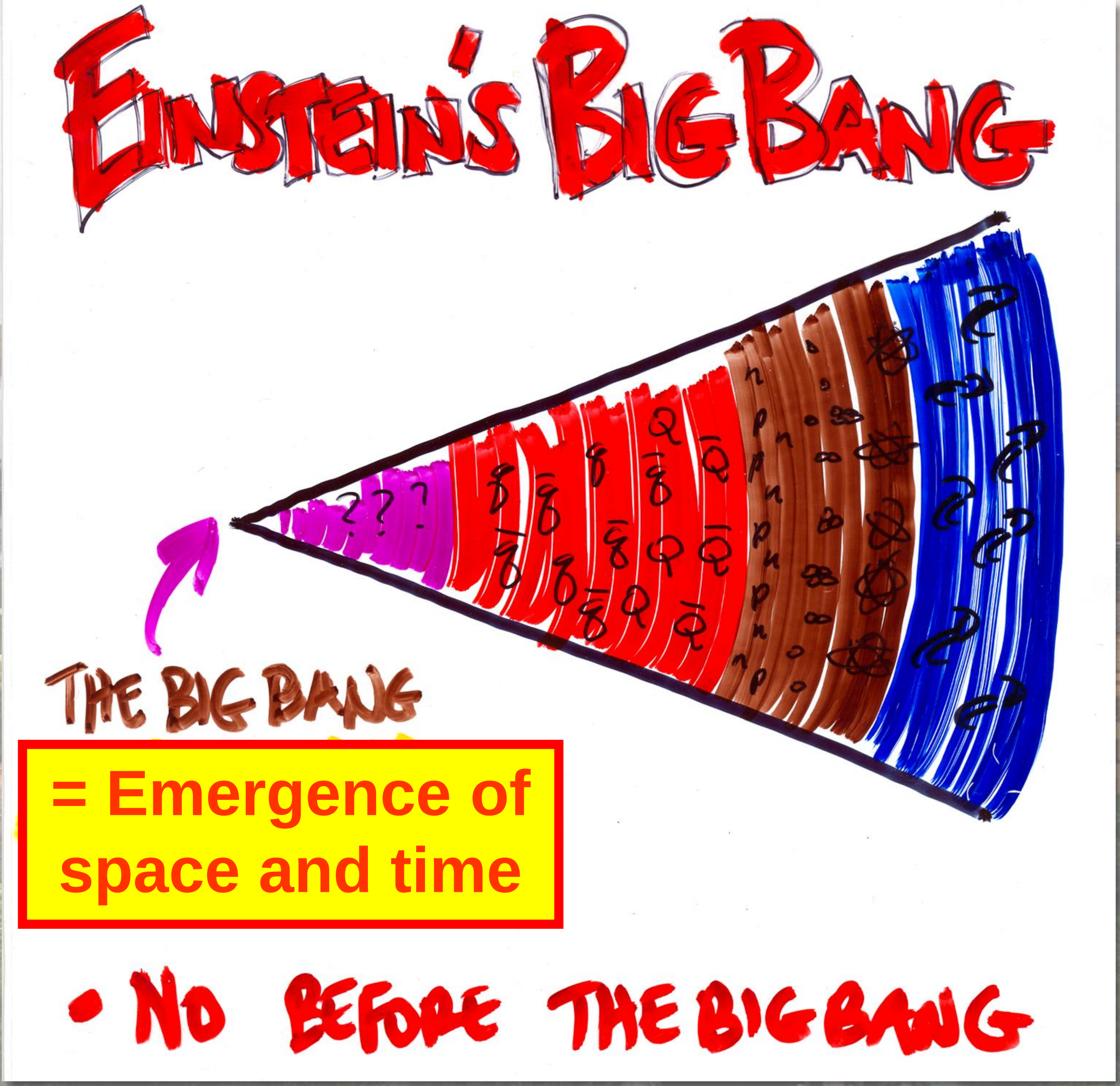


Figure 4. Whisker plot with the 68% marginalized Hubble constant constraints for the models of Section 4. The cyan vertical band corresponds to the H_0 value measured by R20 [2] and the light pink vertical band corresponds to the H_0 value estimated by *Planck* 2018 [11] in a ΛCDM scenario. For each line, when more than one error bar is shown, the dotted one corresponds to the *Planck* only constraint on the Hubble constant, while the solid one to the different dataset combinations reported in the red legend, in order to appreciate the shift due to the additional datasets.

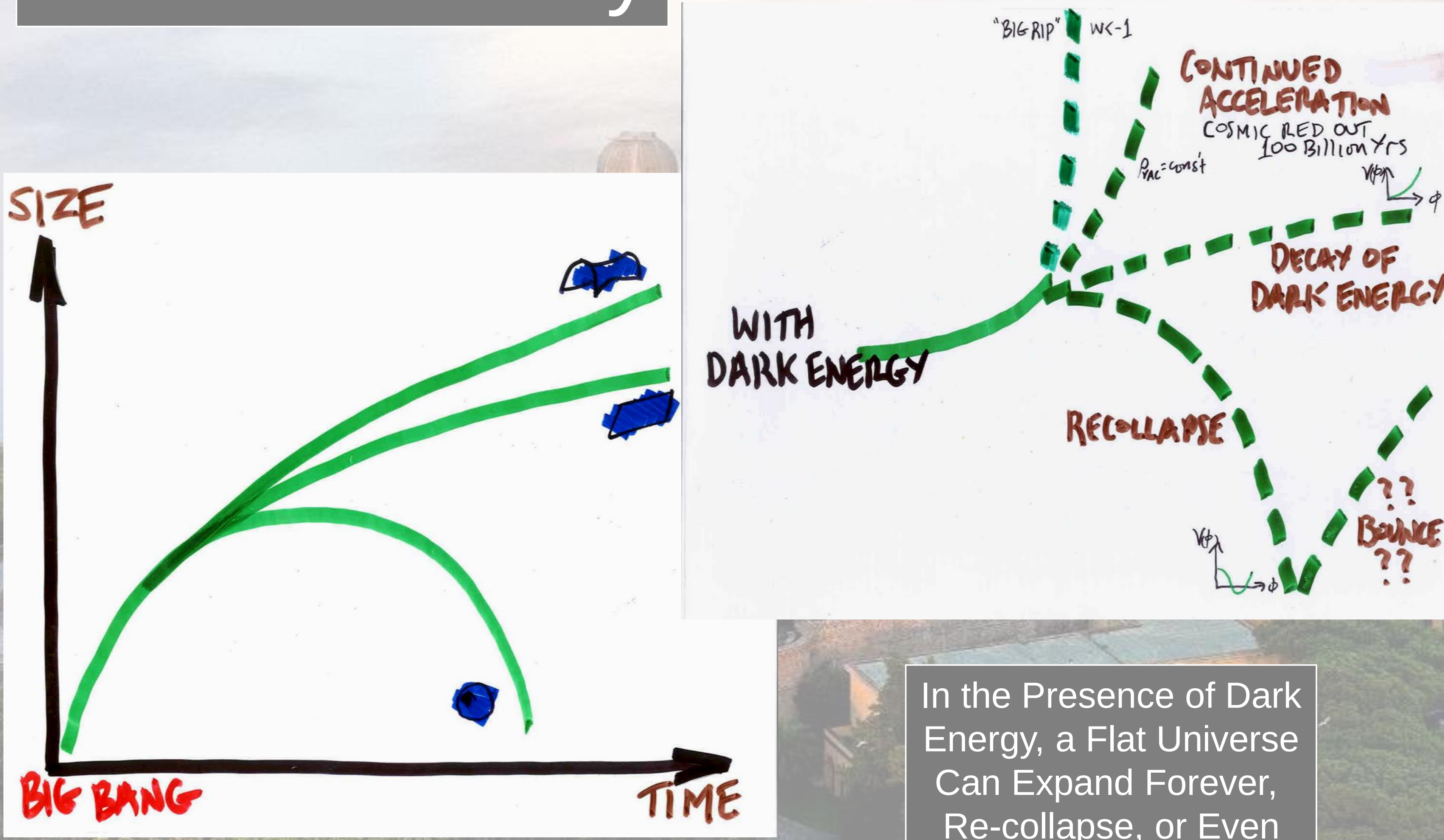
Or one or both measurements could be wrong or NEW PHYSICS! Big mystery; stay tuned!

Einstein got the right answer for the wrong reason?



= Emergence of space and time

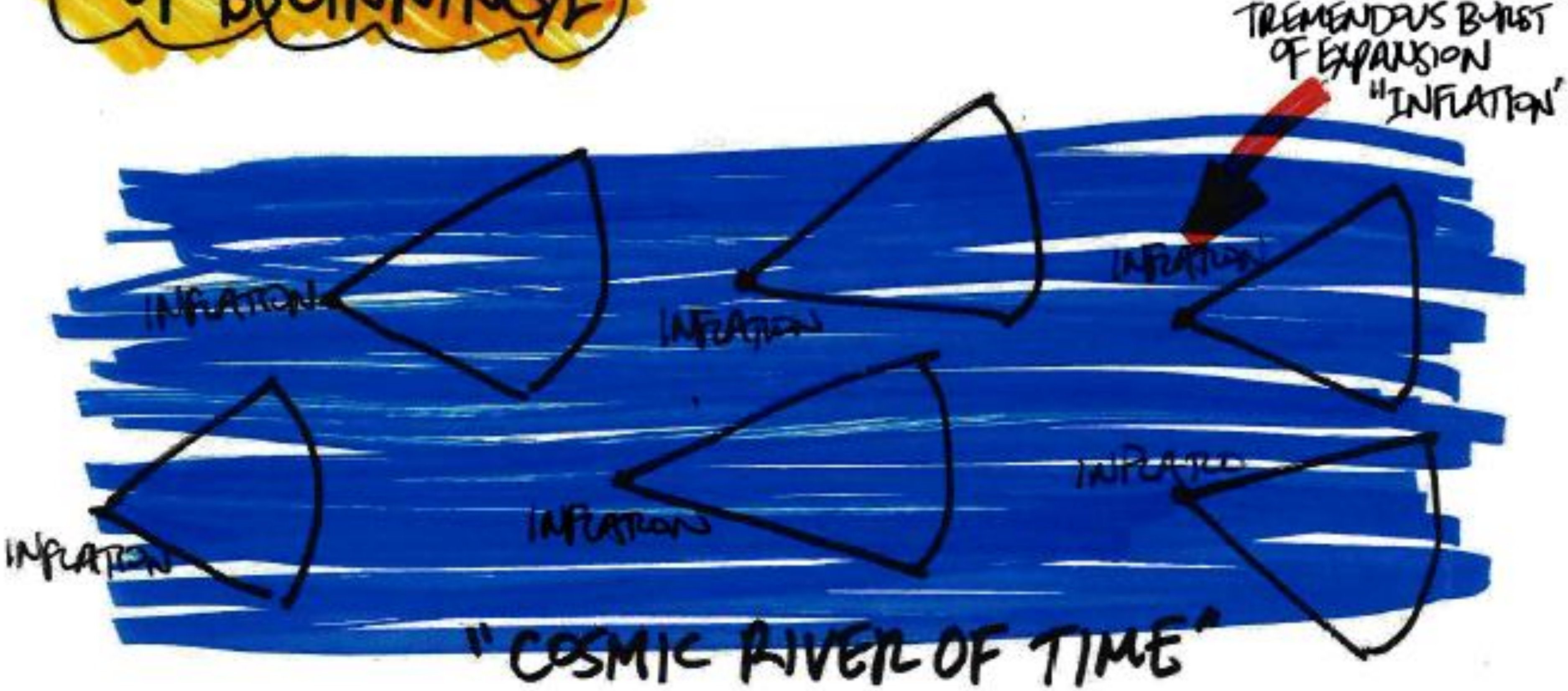
Cosmic Destiny



In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!

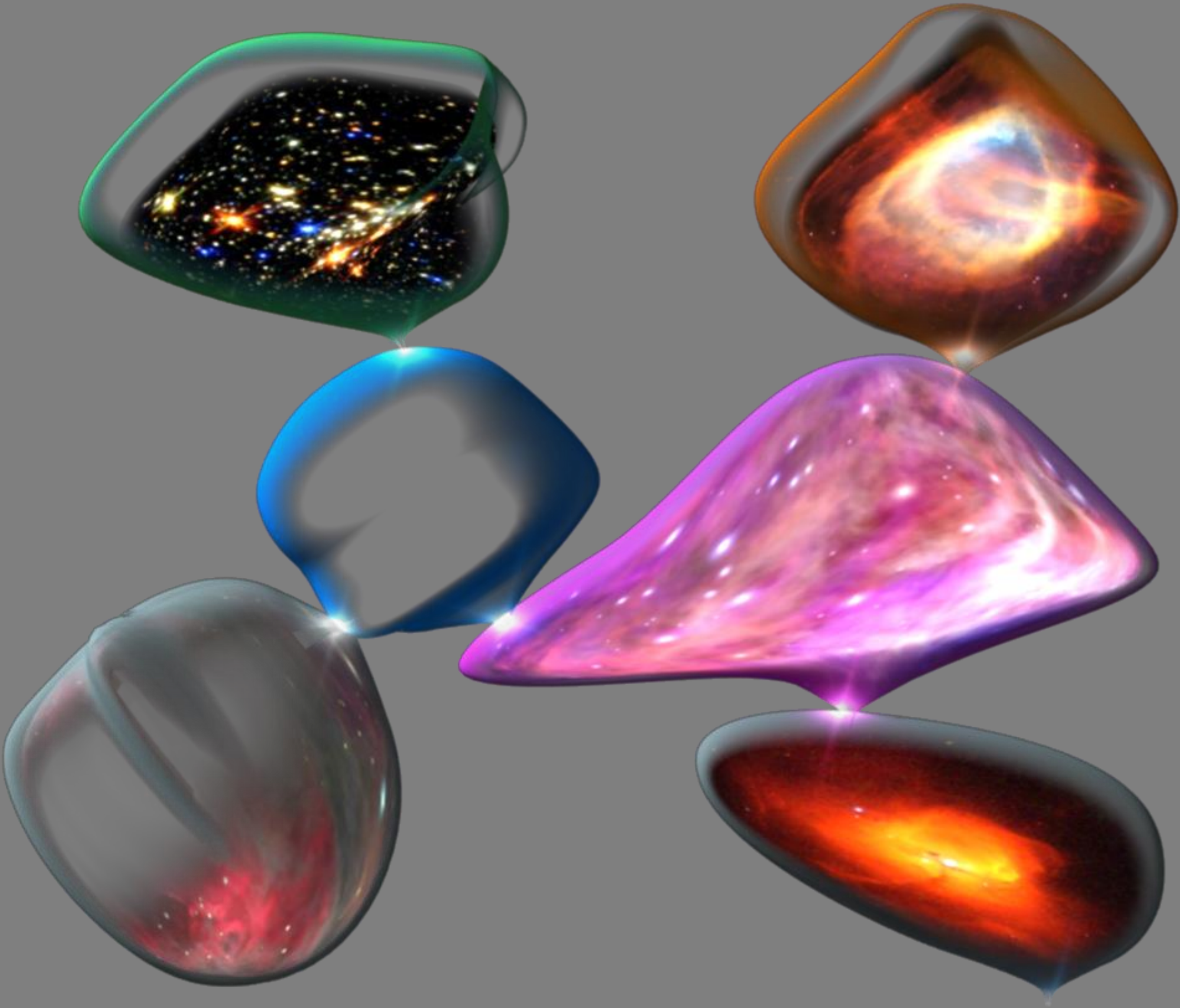
INFLATIONARY MULTIVERSE

INFINITE NUMBER OF BEGINNINGS

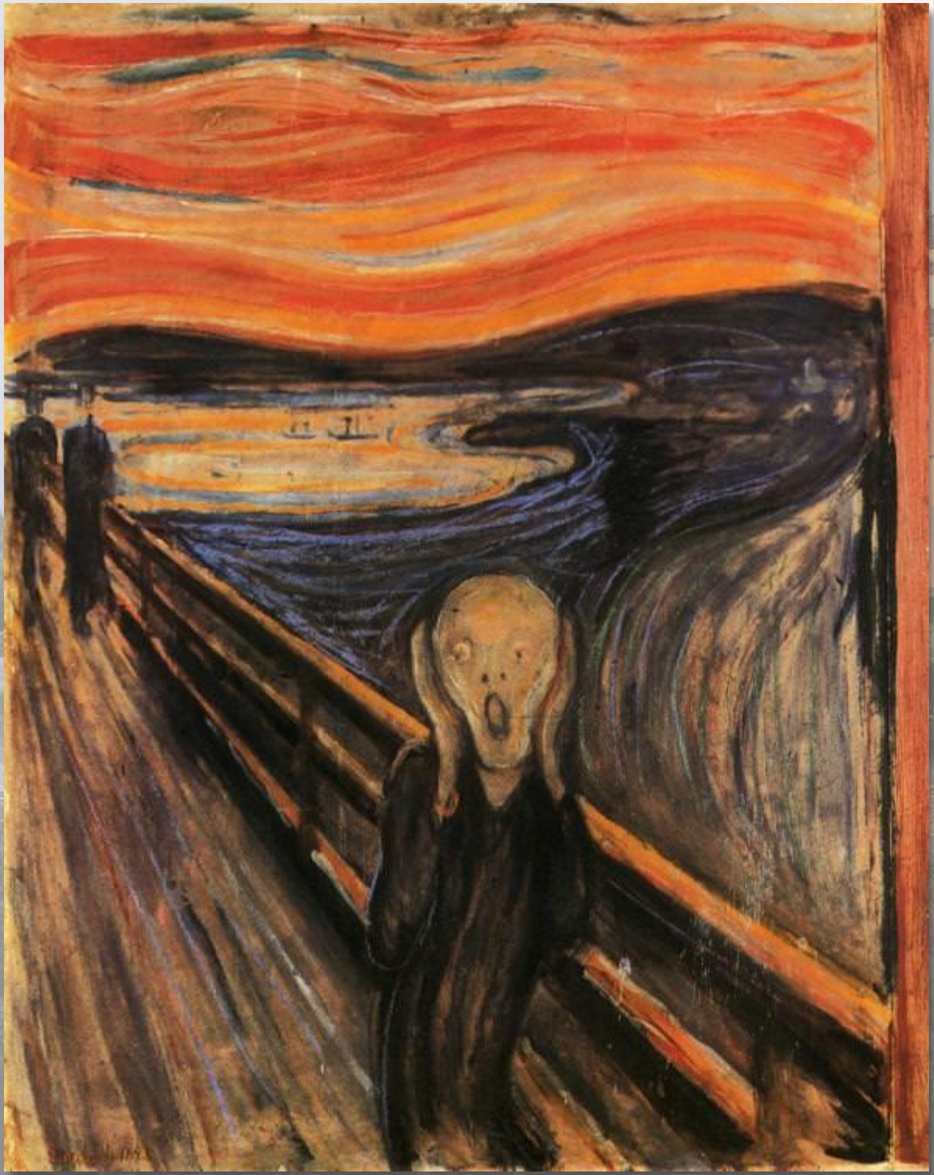


"COSMIC RIVER OF TIME"

The multiverse



What to do about the multiverse



- Most important "discovery" since Copernicus?
- But is it science? (not testable – yet)

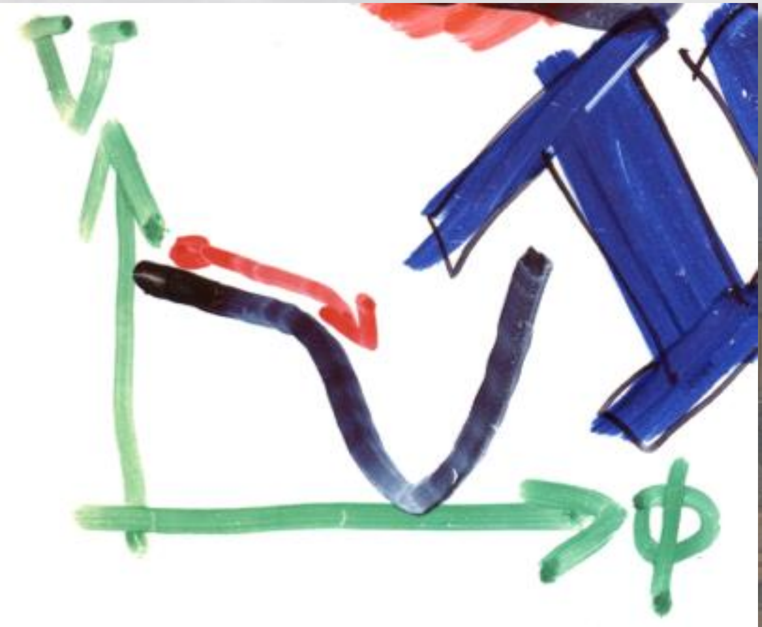
My aspiration: zero numbers

once given the ”laws of physics”

- Laws of physics (not initial conditions or parameters) determine the present large-scale features of the Universe and statistical properties (climate not weather)
- Agnostic to the uniqueness of “TOE”, the “watchmaker,” and to the existence of a multiverse/“ensembiverse”
- Successes:
  - Big bang nucleosynthesis (no need to specify initial chemical abundances; nuclear physics + expansion determines the primordial mix)
- Partial successes:
  - Baryogenesis (no need to specify initial baryon asymmetry or large entropy per baryon; baryon number + C/CP violation + expansion determine the outcome)
  - Structure formation (once the initial homogeneity is specified, gravity + expansion and hydro determine the outcome)

Learning from/testing inflation

- Inflation: essential part of automatic Universe (reduces sensitivity to initial state). Tie descriptive Planck parameters (A_S, n_s, $dn_s/d\ln k$, r, n_T) to theory parameters

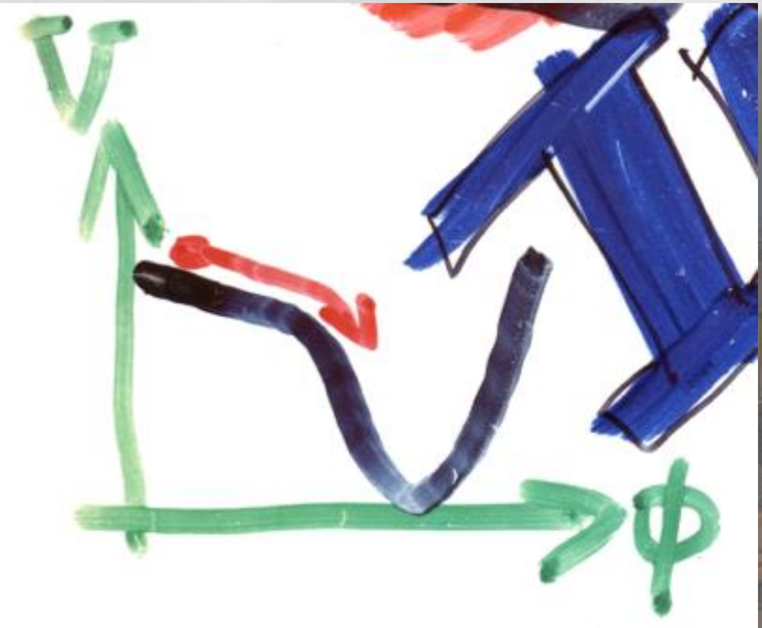


$$
\begin{aligned}
P(k) &= \frac{1024\pi^3}{75}\,\frac{k}{H_0^4}\,\frac{V_*^3}{{m_{\rm Pl}}^6 V_*'^2}\left(\frac{k}{k_*}\right)^{n-1} T^2(k) \\
n-1 &= -\frac{1}{8\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 + \frac{m_{\rm Pl}}{4\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)' \\
\frac{dn}{d\ln k} &= -\frac{1}{32\pi^2}\left(\frac{{m_{\rm Pl}}^3 V_*'''}{V_*}\right)\left(\frac{m_{\rm Pl}V_*'}{V_*}\right) \\
&\qquad + \frac{1}{8\pi^2}\left(\frac{{m_{\rm Pl}}^2 V_*''}{V_*}\right)\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 - \frac{3}{32\pi^2}\left(m_{\rm Pl}\frac{V_*'}{V_*}\right)^4 \\
T(q) &= \frac{\ln\left(1+2.34q\right)/2.34q}{\left[1+3.89q+(16.1q)^2+(5.46q)^3+(6.71q)^4\right]^{1/4}},
\end{aligned}
$$

$$
\begin{aligned}
P_T(k) &\equiv \langle |h_k|^2\rangle = \frac{8}{3\pi}\,\frac{V_*}{{m_{\rm Pl}}^4}\left(\frac{k}{k_*}\right)^{n_T-3} T_T^2(k) \\
n_T &= -\frac{1}{8\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 \\
\frac{dn_T}{d\ln k} &= \frac{1}{32\pi^2}\left(\frac{{m_{\rm Pl}}^2 V''}{V}\right)\left(\frac{m_{\rm Pl}V'}{V}\right)^2 - \frac{1}{32\pi^2}\left(\frac{m_{\rm Pl}V'}{V}\right)^4 = -n_T[(n-1)-n_T] \\
T_T(k) &\simeq \left[1+\frac{4}{3}\frac{k}{k_{\rm EQ}}+\frac{5}{2}\left(\frac{k}{k_{\rm EQ}}\right)^2\right]^{1/2},
\end{aligned}
$$

Learning from/testing inflation

- Inflation: essential part of automatic Universe (reduces sensitivity to initial state). Tie descriptive Planck parameters (A_S, n_s, $dn_s/d\ln k$, r, n_T) to theory parameters



$$
\begin{aligned}
P(k) &= \frac{1024\pi^3}{75}\,\frac{k}{H_0^4}\,\frac{V_*^3}{{m_{\rm Pl}}^6 {V_*'}^2}\left(\frac{k}{k_*}\right)^{n-1} T^2(k) \\
n-1 &= -\frac{1}{8\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 + \frac{m_{\rm Pl}}{4\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)' \\
\frac{dn}{d\ln k} &= -\frac{1}{32\pi^2}\left(\frac{{m_{\rm Pl}}^3 V_*'''}{V_*}\right)\left(\frac{m_{\rm Pl}V_*'}{V_*}\right) \\
&\qquad + \frac{1}{8\pi^2}\left(\frac{{m_{\rm Pl}}^2 V_*''}{V_*}\right)\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 - \frac{3}{32\pi^2}\left(m_{\rm Pl}\frac{V_*'}{V_*}\right)^4 \\
T(q) &= \frac{\ln\left(1+2.34q\right)/2.34q}{\left[1+3.89q+(16.1q)^2+(5.46q)^3+(6.71q)^4\right]^{1/4}},
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$$
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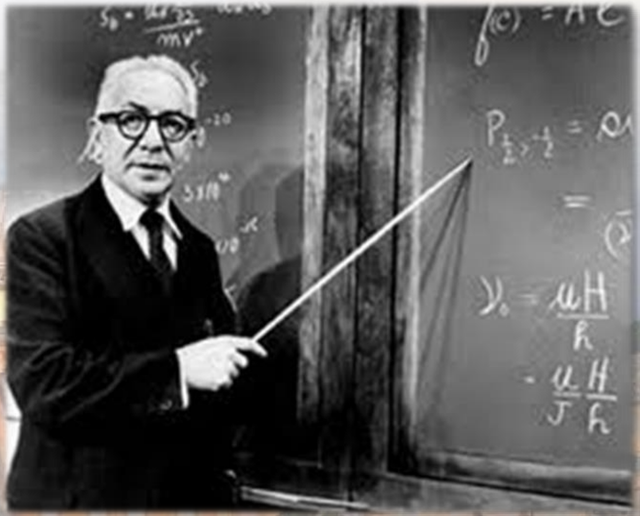
n_T &= -\frac{1}{8\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 \\
\frac{dn_T}{d\ln k} &= \frac{1}{32\pi^2}\left(\frac{{m_{\rm Pl}}^2 V''}{V}\right)\left(\frac{m_{\rm Pl}V'}{V}\right)^2 - \frac{1}{32\pi^2}\left(\frac{m_{\rm Pl}V'}{V}\right)^4 = -n_T[(n-1)-n_T] \\
T_T(k) &\simeq \left[1+\frac{4}{3}\frac{k}{k_{\rm EQ}}+\frac{5}{2}\left(\frac{k}{k_{\rm EQ}}\right)^2\right]^{1/2},
\end{aligned}
$$

What could possibly go wrong

- Initial conditions might matter
  - Axion dark matter
  - Penrose: it is all about the initial singularity
- Universe is often just beyond the reach of our biggest ideas and most powerful instruments
  - No TOE or too many missing pieces

A very complicated Universe

- Atoms : Democritus to 1964
- + photons: 1964
- + neutrinos (e, μ): 1967
- + exotic dark matter: 1981
- + CDM: 1983/4
- + massive neutrinos: 1998
- + dark energy: 1998
- + τ neutrino: 2000
- Done? Not likely!
- Why is $\Omega_{CDM}/\Omega_B \approx 5$?

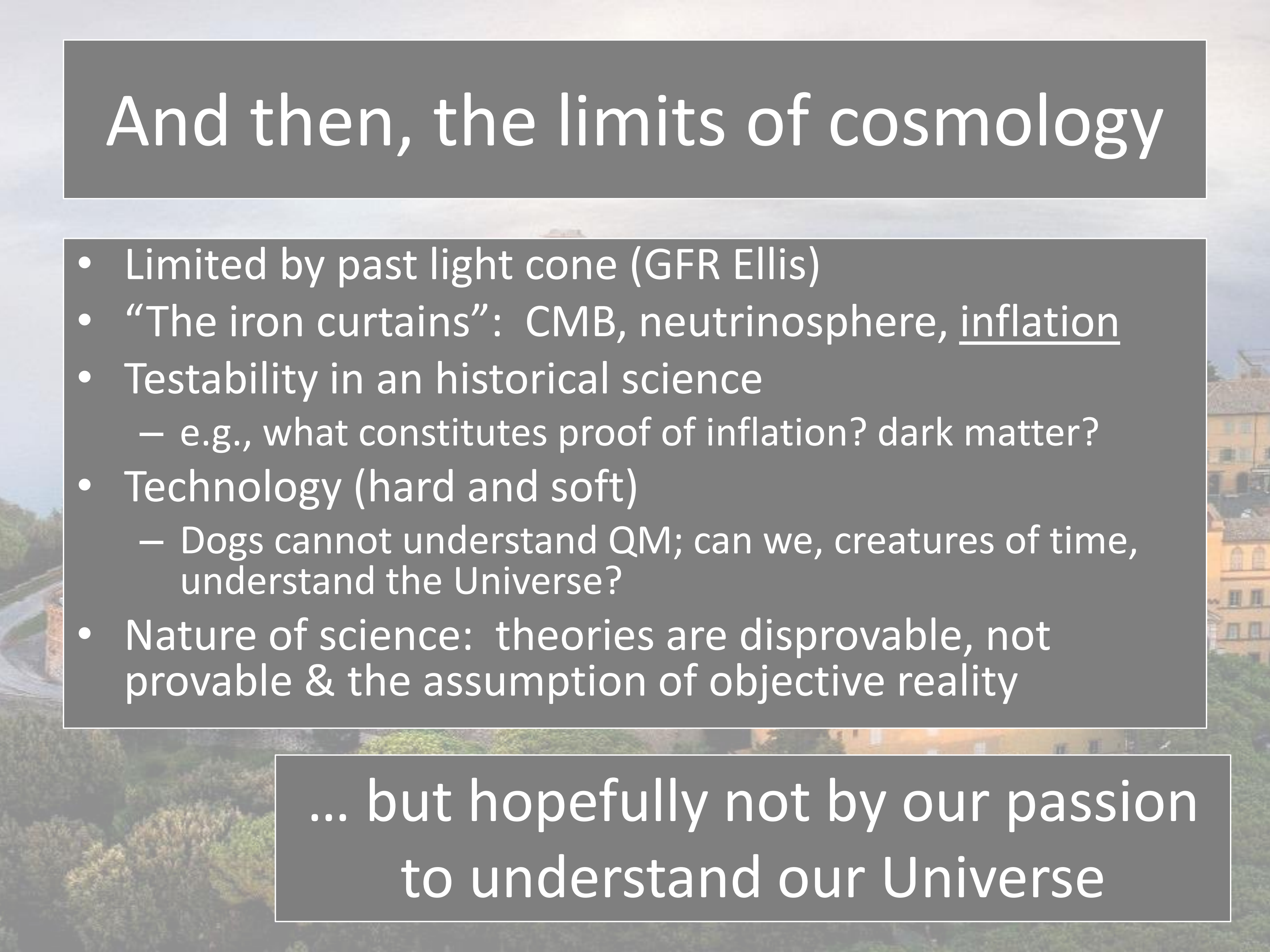


I.I. Rabi
Who ordered that?

How much room for more:

- UR: ~$0.2\rho_{CMB}$
- NR: ~$0.1\rho_{crit}$
- Other leftovers: ??

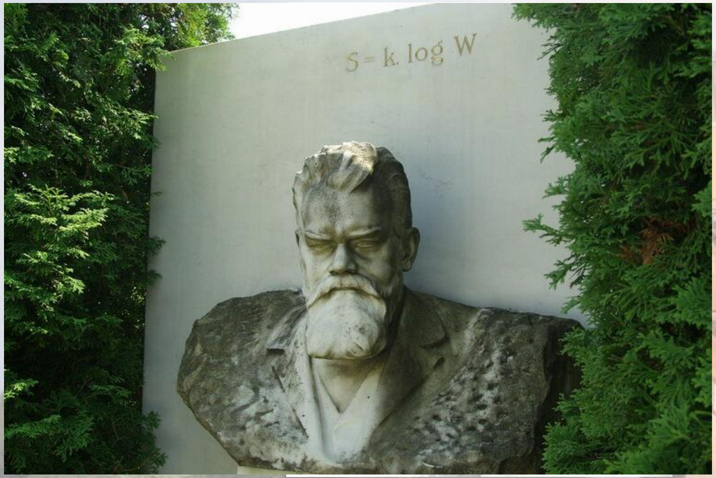
And then, the limits of cosmology



- Limited by past light cone (GFR Ellis)
- “The iron curtains”: CMB, neutrinosphere, inflation
- Testability in an historical science
  - e.g., what constitutes proof of inflation? dark matter?
- Technology (hard and soft)
  - Dogs cannot understand QM; can we, creatures of time, understand the Universe?
- Nature of science: theories are disprovable, not provable & the assumption of objective reality

… but hopefully not by our passion to understand our Universe

Boltzmann brain



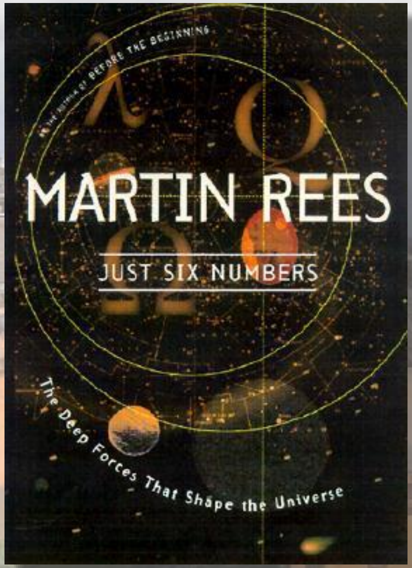
The Boltzmann brain argument suggests that it is more likely for a single brain to spontaneously and briefly form in a void (complete with a false memory of having existed in our universe) than it is for the universe to have come about as the result of a random fluctuation in a universe in thermal equilibrium. It was first proposed as a reductio ad absurdum response to Ludwig Boltzmann's early explanation for the low-entropy state of our universe.

Murray Gell-Mann: 0 numbers

There is a unique Theory Of Everything (the TOE) – a string theory – and the rest is "weather"*

*paraphrasing here, he said environmental science

Lord Rees of Ludlow: just 6 numbers



BY THE AUTHOR OF BEFORE THE BEGINNING

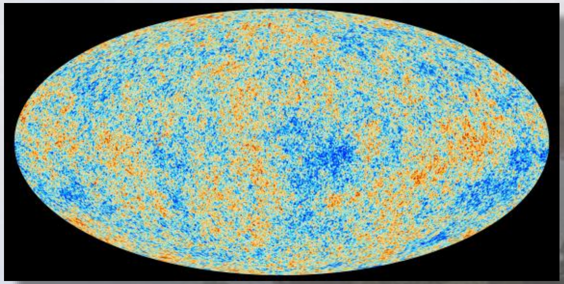
MARTIN REES

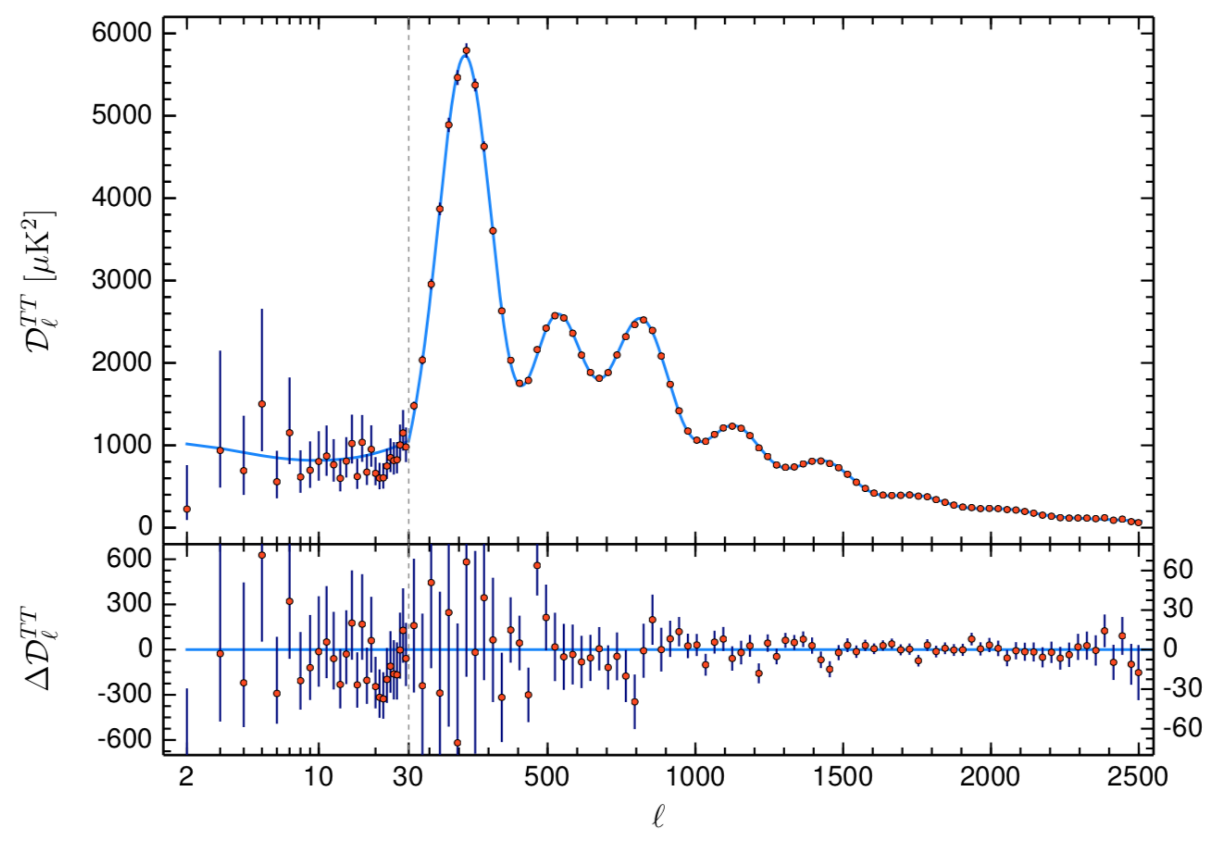
JUST SIX NUMBERS

The Deep Forces That Shape the Universe

1. 3 dimensions of space
2. Weak gravity = 10^{-36} x EM
3. Energy release in 4 H → He is $0.007mc^2$
4. Flat Universe
5. Small Λ
6. Density perturbations: $Q = 10^{-5}$

ΛCDM 6 numbers: new version of q_0/H_0?

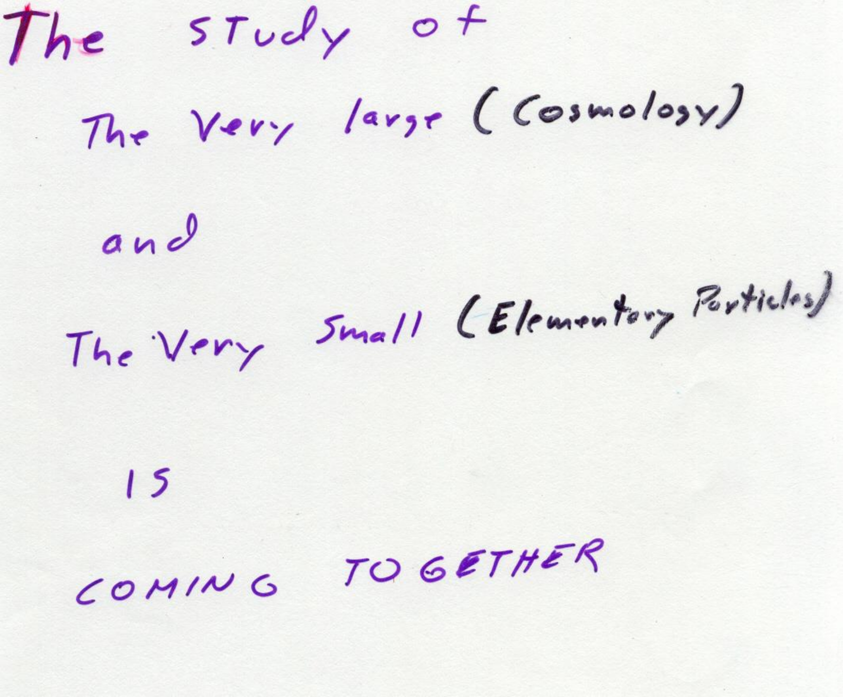




1. Baryon density
2. Matter density
3. Density perturbation amplitude
4. Tilt
5. Sound horizon
6. Optical depth

Ideas from particle physics

The coming together of the very big and the very small



The study of

The very large (Cosmology)

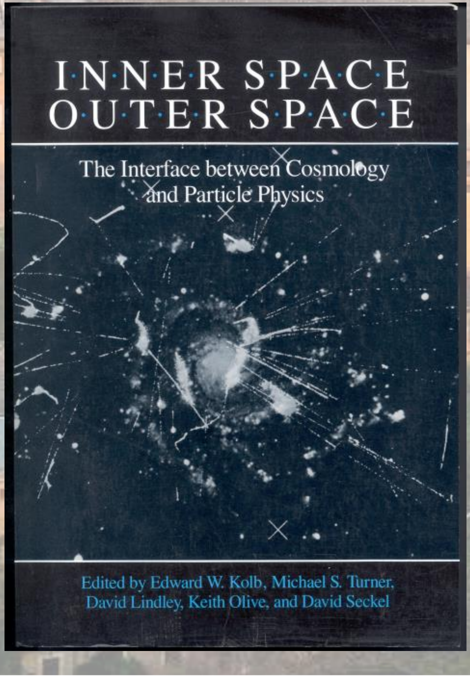
and

The Very Small (Elementary Particles)

IS

COMING TOGETHER

David Schramm circa 1980



INNER SPACE
OUTER SPACE

The Interface between Cosmology and Particle Physics

Edited by Edward W. Kolb, Michael S. Turner, David Lindley, Keith Olive, and David Seckel

Fermilab Symposium May 1984

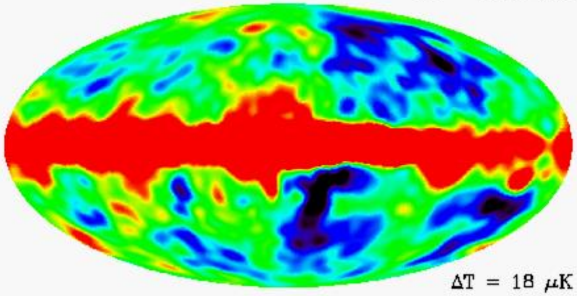
★ "RIPPLES" IN THE MICROWAVE ECHO

TEMPERATURE VARIATION ≈ 30 μK

→ EVIDENCE FOR "PRIMEVAL LUMPINESS" THAT SEEDED STRUCTURE (STARS, GALAXIES, CLUSTERS OF GALAXIES, SUPERCLUSTERS VOIDS, WALLS, ...)

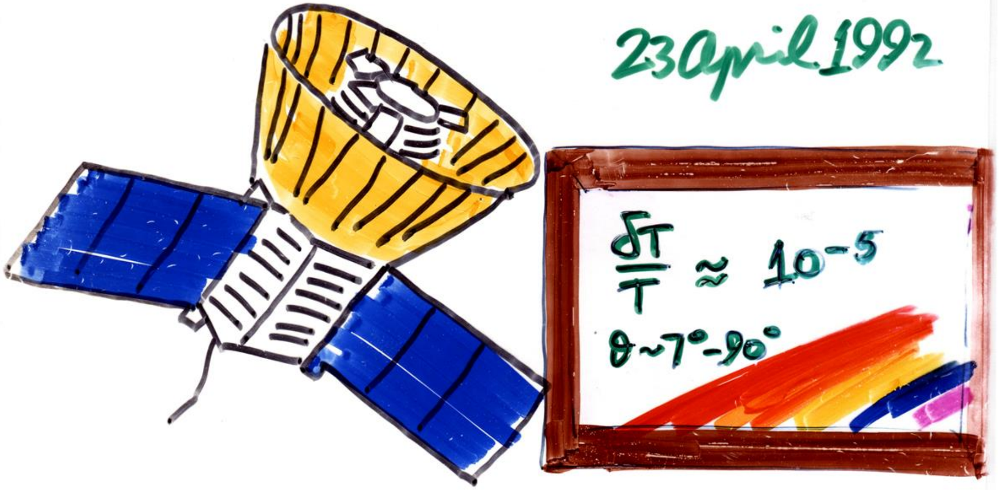
S. HAWKING: "GREATEST DISCOVERY OF ALL TIME"

ONLY A SLIGHT OVERSTATEMENT



COBE

23 April 1992

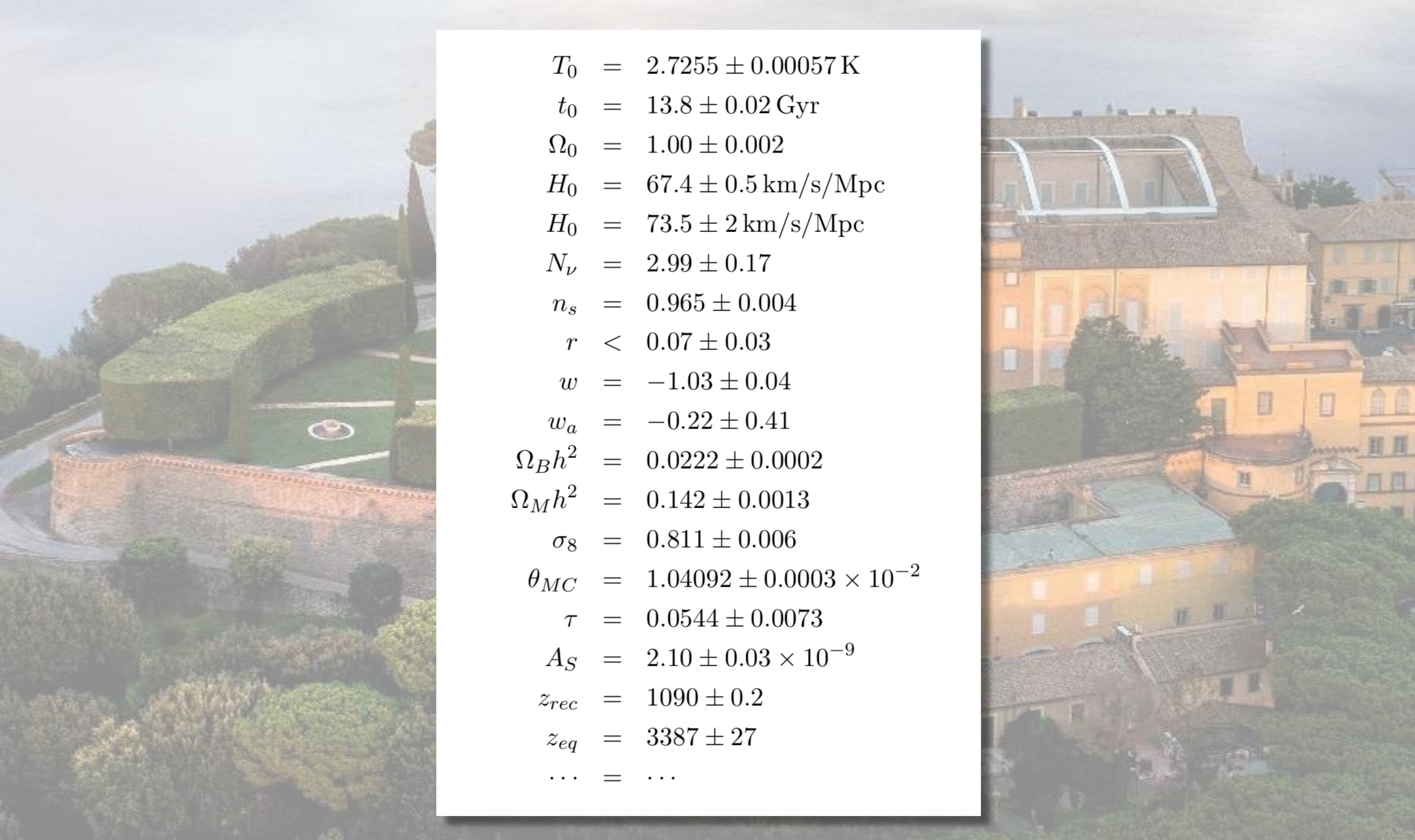


$\frac{\delta T}{T} \approx 10^{-5}$

$\theta \sim 7° - 90°$

WOW!

Era of Precision Cosmology (plenty of well measured numbers)



$$
\begin{aligned}
T_0 &= 2.7255 \pm 0.00057\,\mathrm{K} \\
t_0 &= 13.8 \pm 0.02\,\mathrm{Gyr} \\
\Omega_0 &= 1.00 \pm 0.002 \\
H_0 &= 67.4 \pm 0.5\,\mathrm{km/s/Mpc} \\
H_0 &= 73.5 \pm 2\,\mathrm{km/s/Mpc} \\
N_\nu &= 2.99 \pm 0.17 \\
n_s &= 0.965 \pm 0.004 \\
r &< 0.07 \pm 0.03 \\
w &= -1.03 \pm 0.04 \\
w_a &= -0.22 \pm 0.41 \\
\Omega_B h^2 &= 0.0222 \pm 0.0002 \\
\Omega_M h^2 &= 0.142 \pm 0.0013 \\
\sigma_8 &= 0.811 \pm 0.006 \\
\theta_{MC} &= 1.04092 \pm 0.0003 \times 10^{-2} \\
\tau &= 0.0544 \pm 0.0073 \\
A_S &= 2.10 \pm 0.03 \times 10^{-9} \\
z_{rec} &= 1090 \pm 0.2 \\
z_{eq} &= 3387 \pm 27 \\
\cdots &= \cdots
\end{aligned}
$$

INFLATION SCORECARD

PREDICTIONS	WMAP NOW	GRADE	GOAL
FLAT UNIVERSE			
★ $\Omega_0 = 1.000$	1.02 ± 0.02 $\Omega_0 = 1.03 \pm 0.03$	++*	±0.001
	* FOR DOING IT THE HARD WAY		
DENSITY PERTS FROM QM FLUC			
★ ADIABATIC	≥3 ACOUSTIC PEAKS	+	≥7
★ NEARLY SCALE-INVARIANT $(n-1) \sim \mathcal{O}(\pm 0.1)$	0.93 ± 0.03 $n = 1.05 \pm 0.09$	+	±0.001
★ NEARLY POWER-LAW $dn/d\ln k \sim \pm 10^{-3}$	−0.03 ± 0.02 $dn/d\ln k = -0.02 \pm 0.04$	✓	$\pm 10^{-3}$
★ GAUSSIAN	NO EVIDENCE AGAINST	✓	
→ **CDM**	"HAS MUCH OF THE TRUTH"	++	
GRAV WAVES FROM QM METRIC FLUC		?	
★ $T/S \gtrsim 10^{-3}$ (??)	$T/S \lesssim \mathcal{O}(1)$		$10^{-3}/10^{-4}$
★ NEARLY SCALE INVARIANT $n_T = -\frac{1}{5} T/S$	0.71 (95% cl)		±0.03