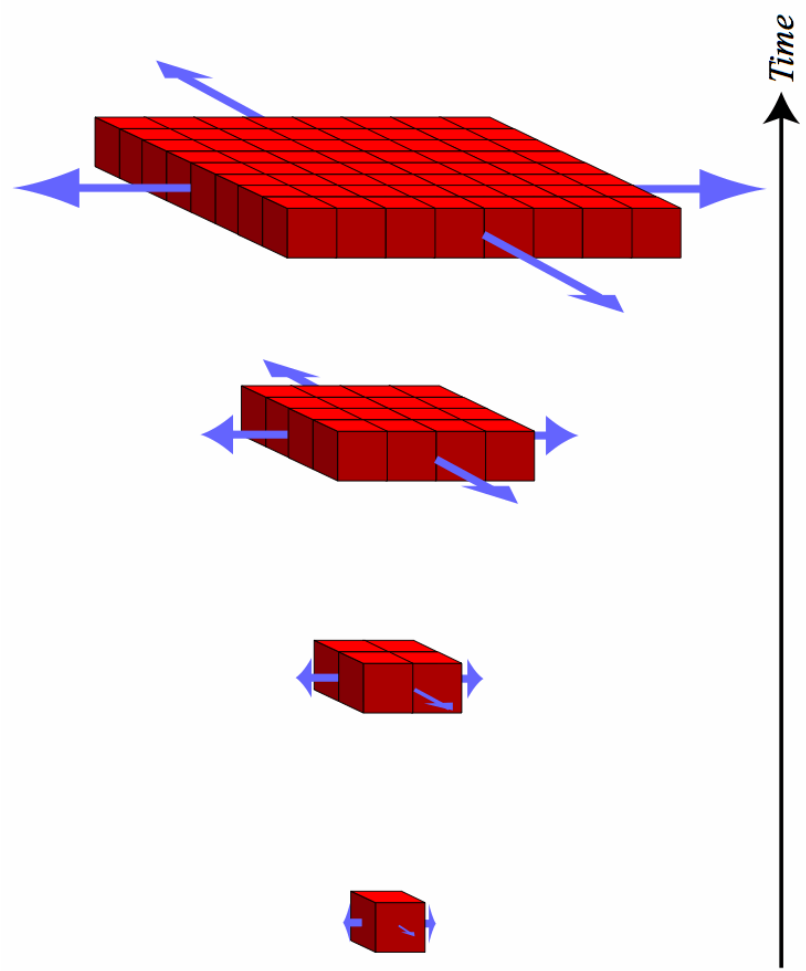
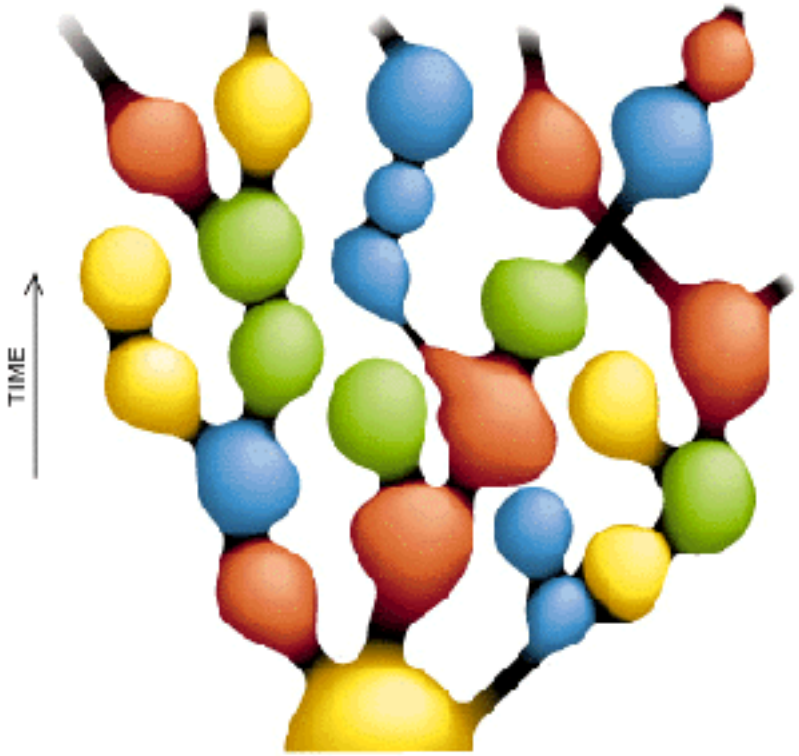
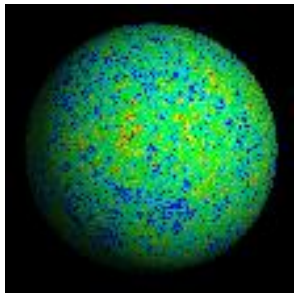
The Inflating Universe

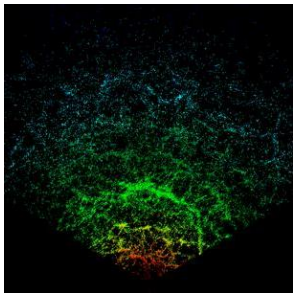




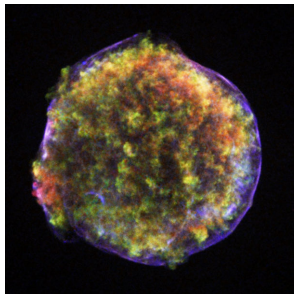
THE COSMIC SMÖRGÅSBORD



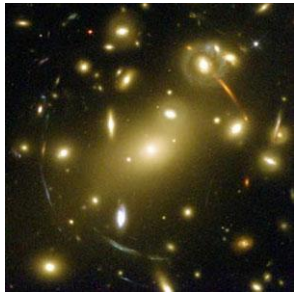
Microwave background



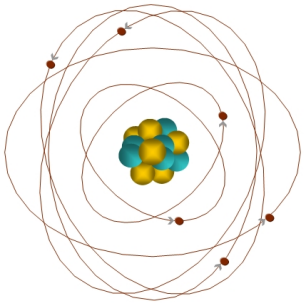
Galaxy surveys



Supernovae Ia

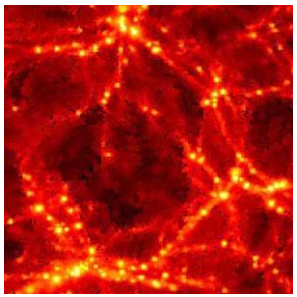


Gravitational lensing

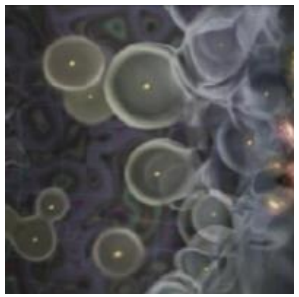


Big Bang nucleosynthesis

Galaxy clusters



Lyman α forest



Neutral hydrogen tomography

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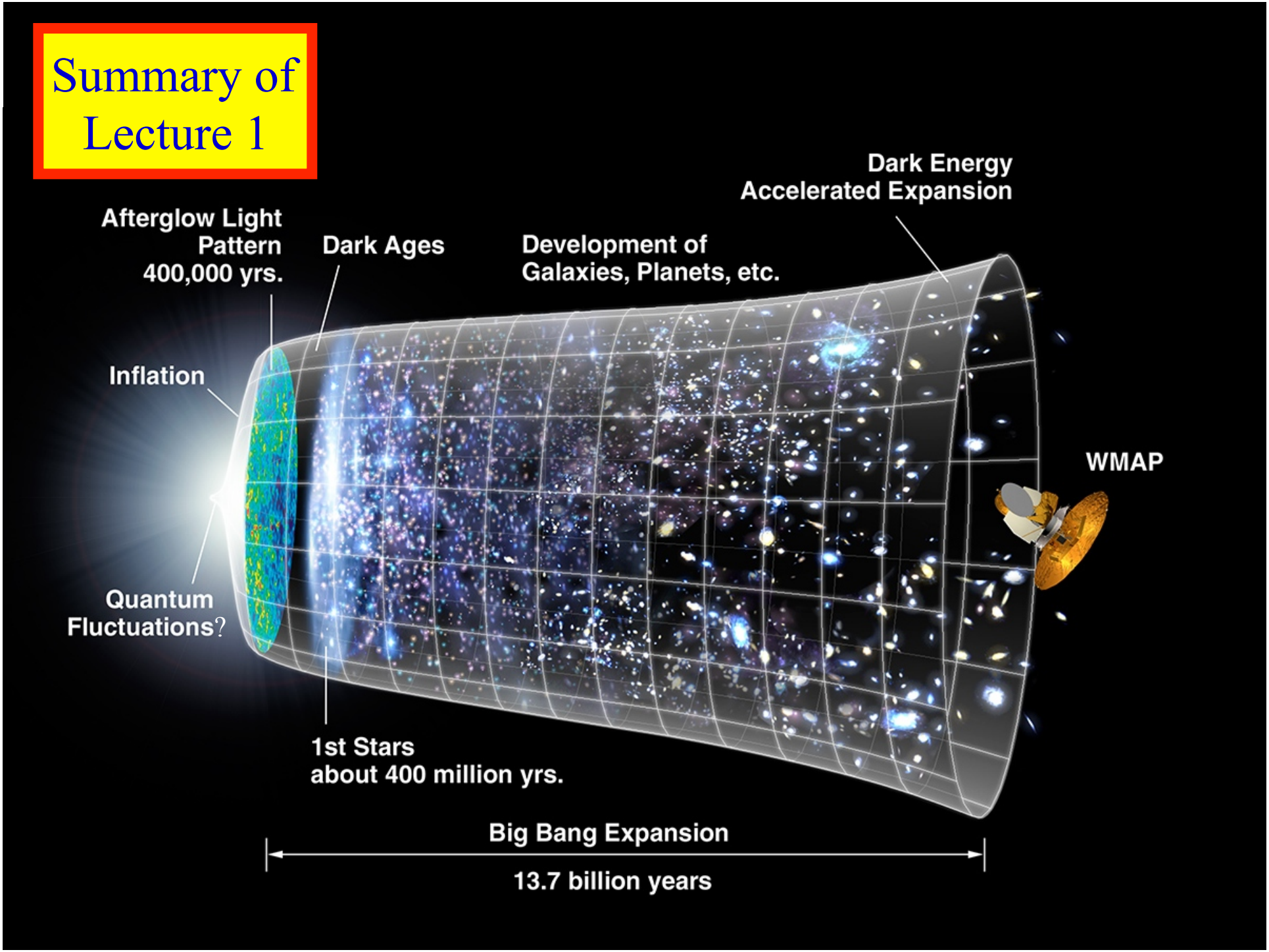
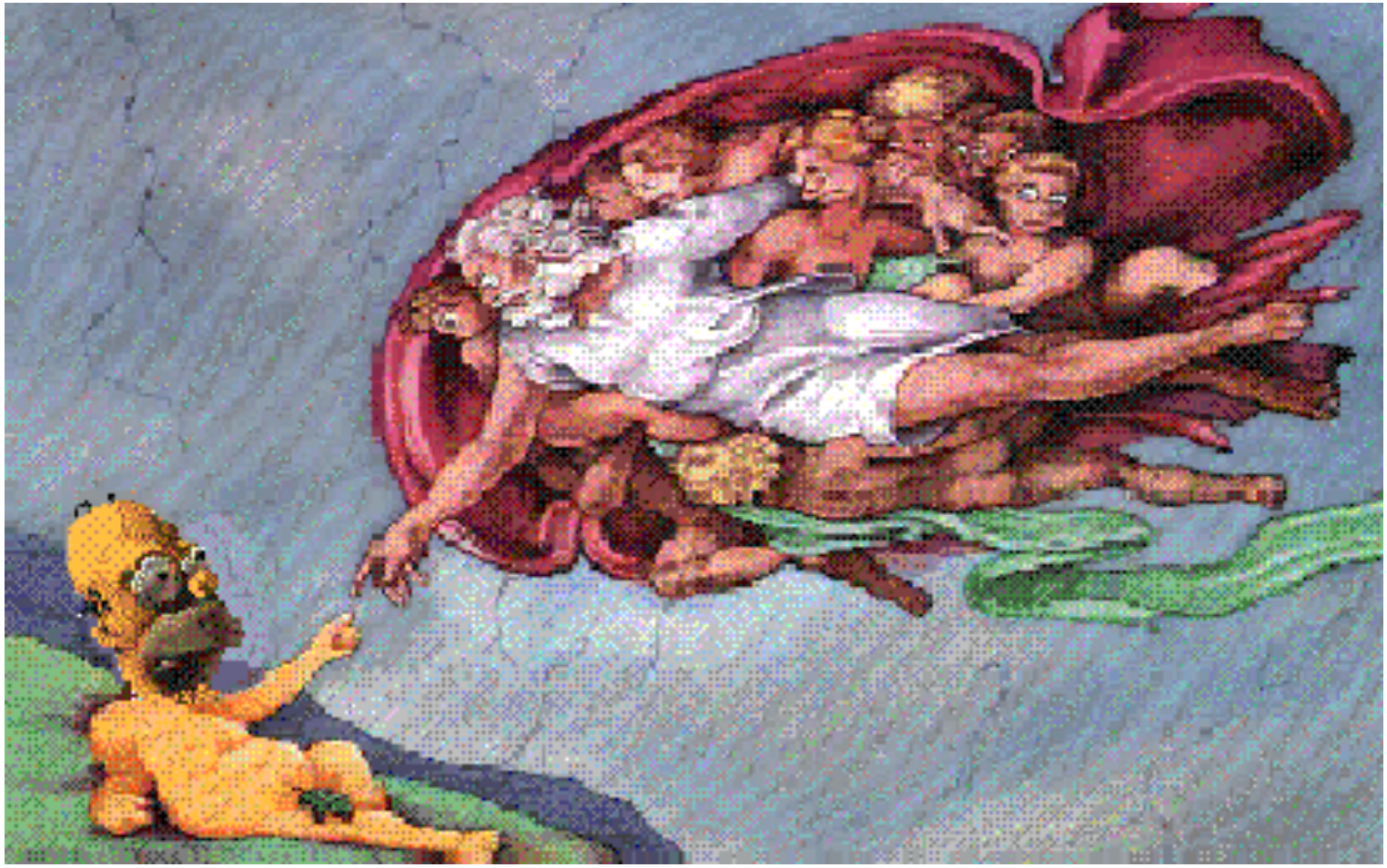
What have we learned?

Summary of Lecture 1



How did it all begin?



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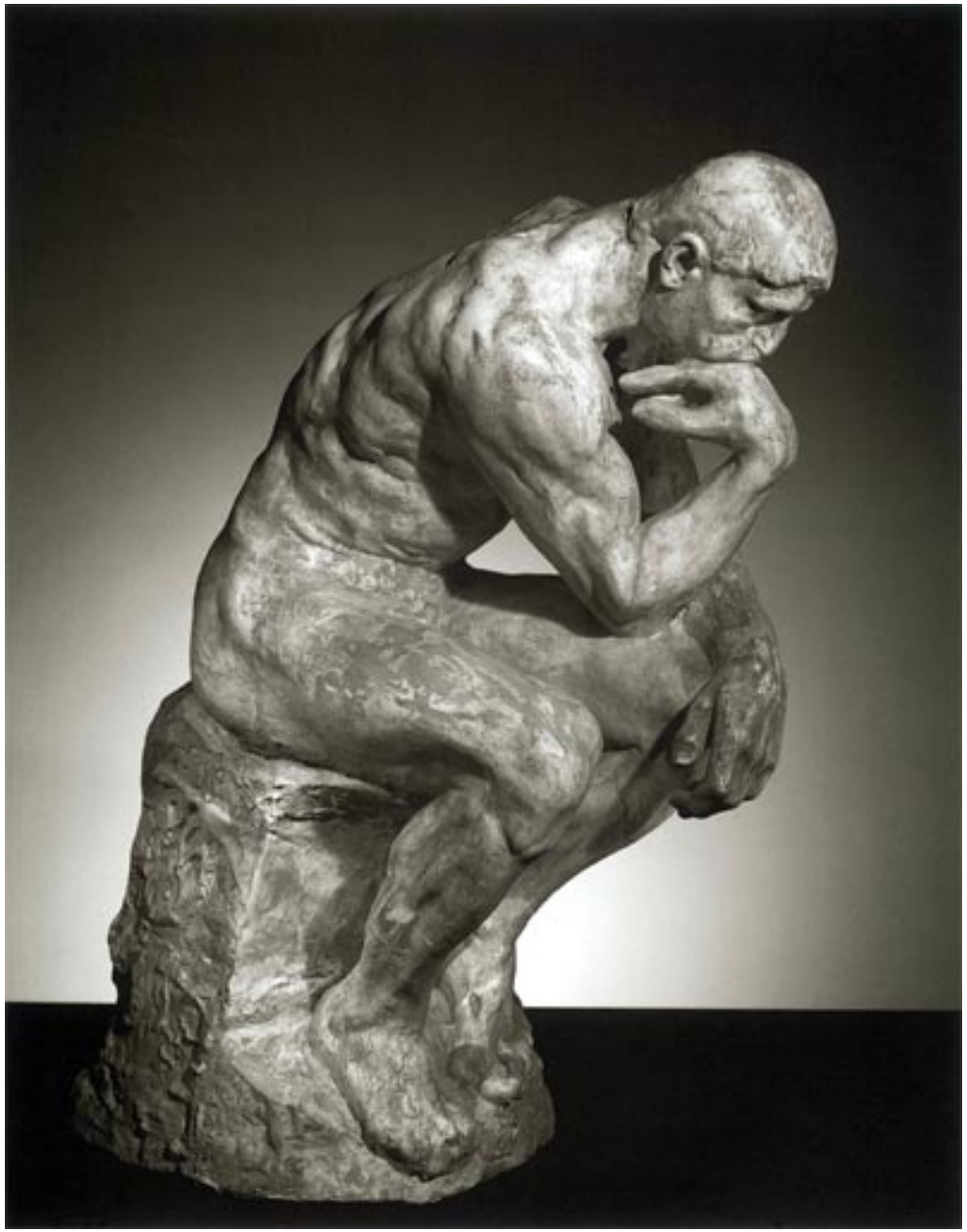
Some things to ponder…



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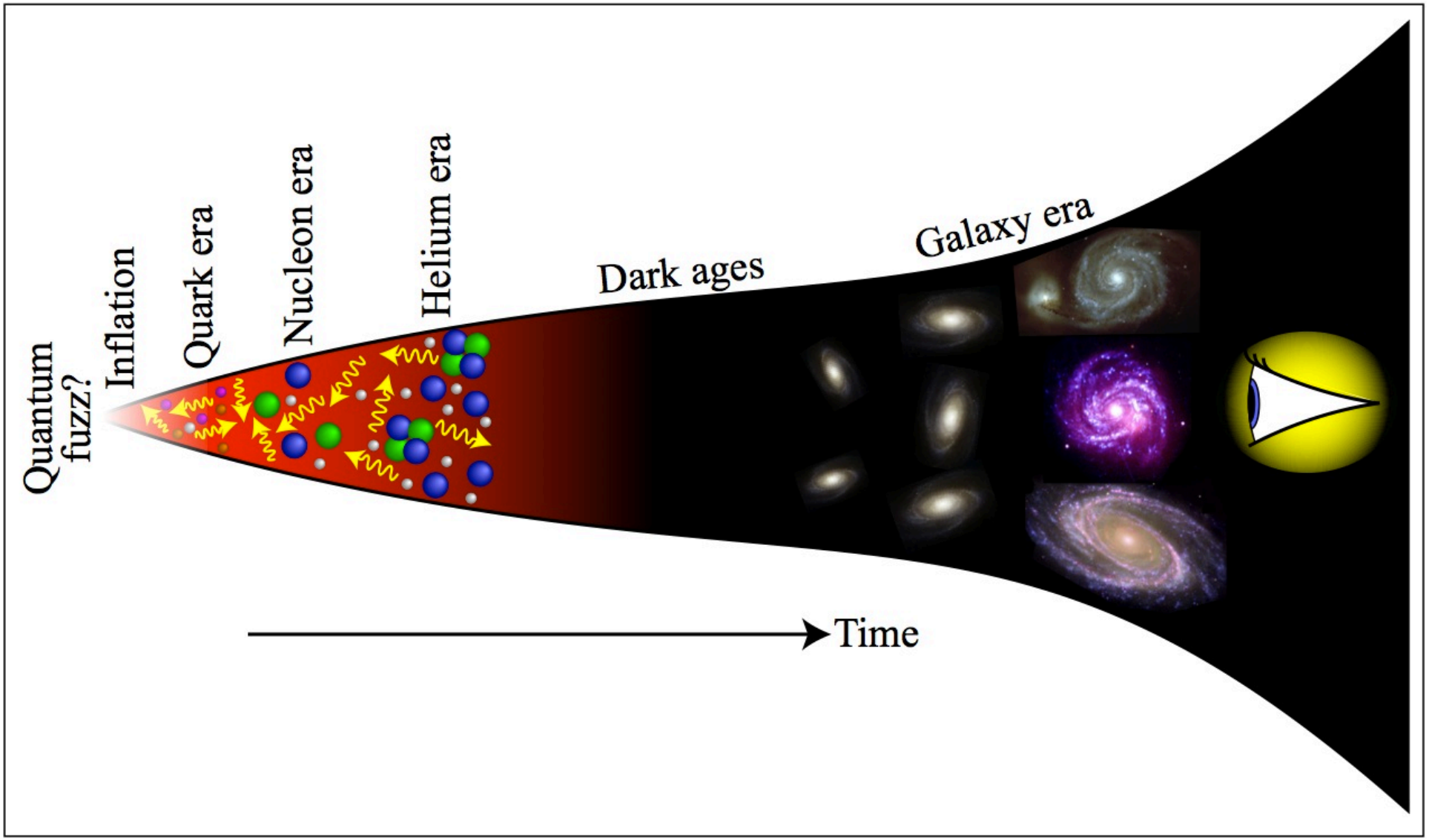
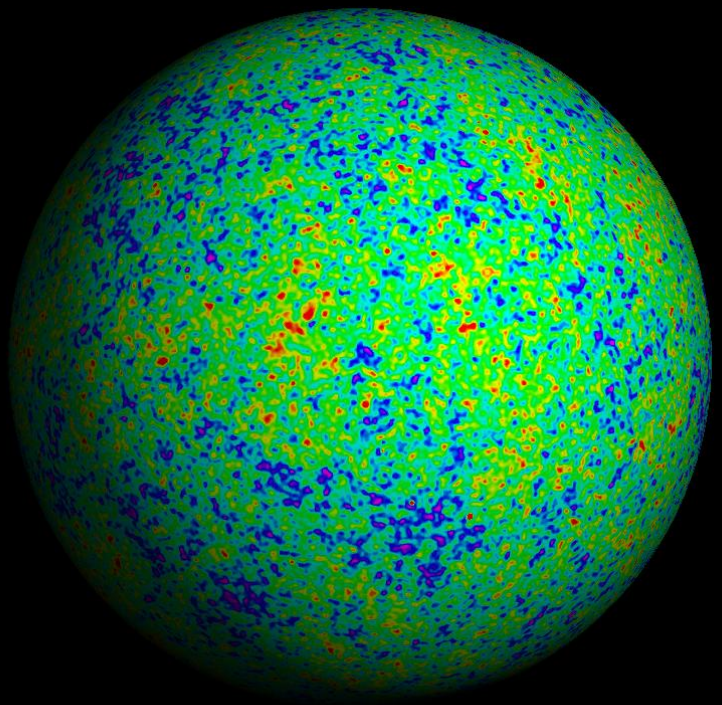
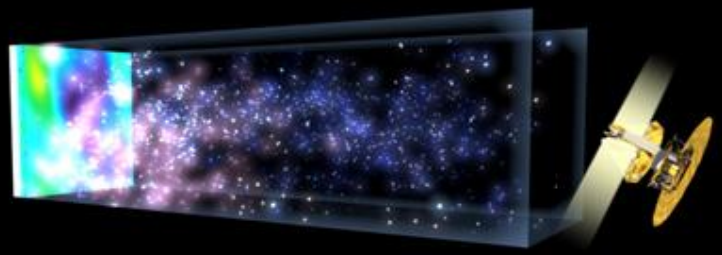
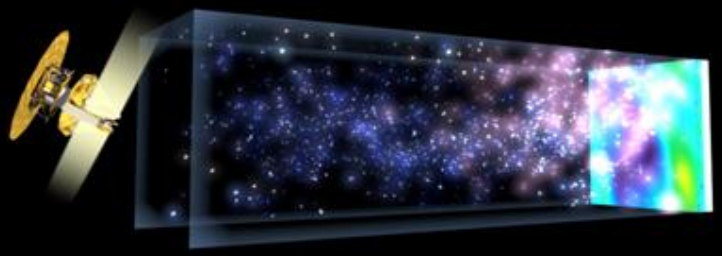
What put the "bang" into our Big Bang?



The "Horizon Problem":







How did causally disconnected regions know to bang at the same time?

The "Flatness Problem": Why was our Big Bang so "Goldilocks"?

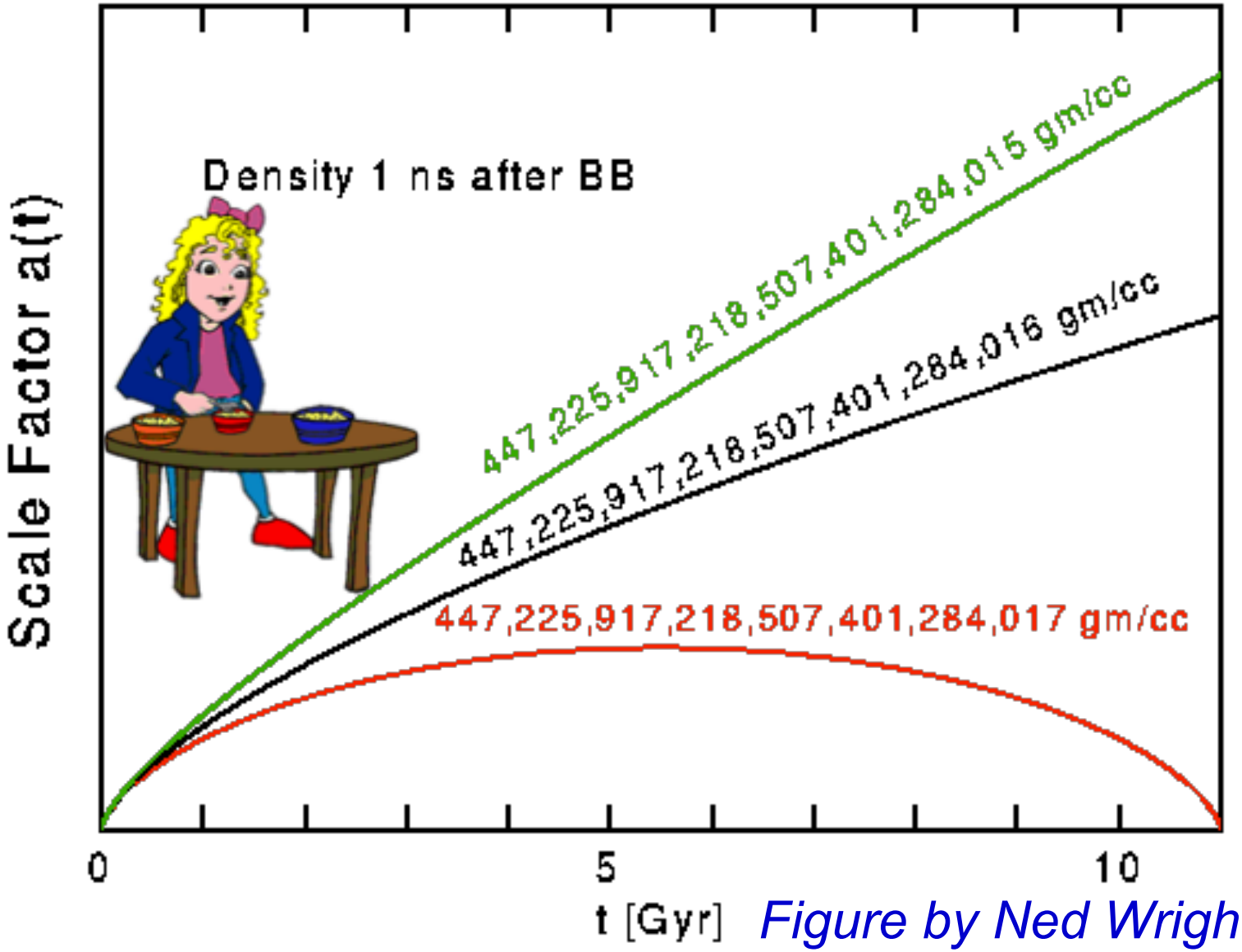


Figure by Ned Wright

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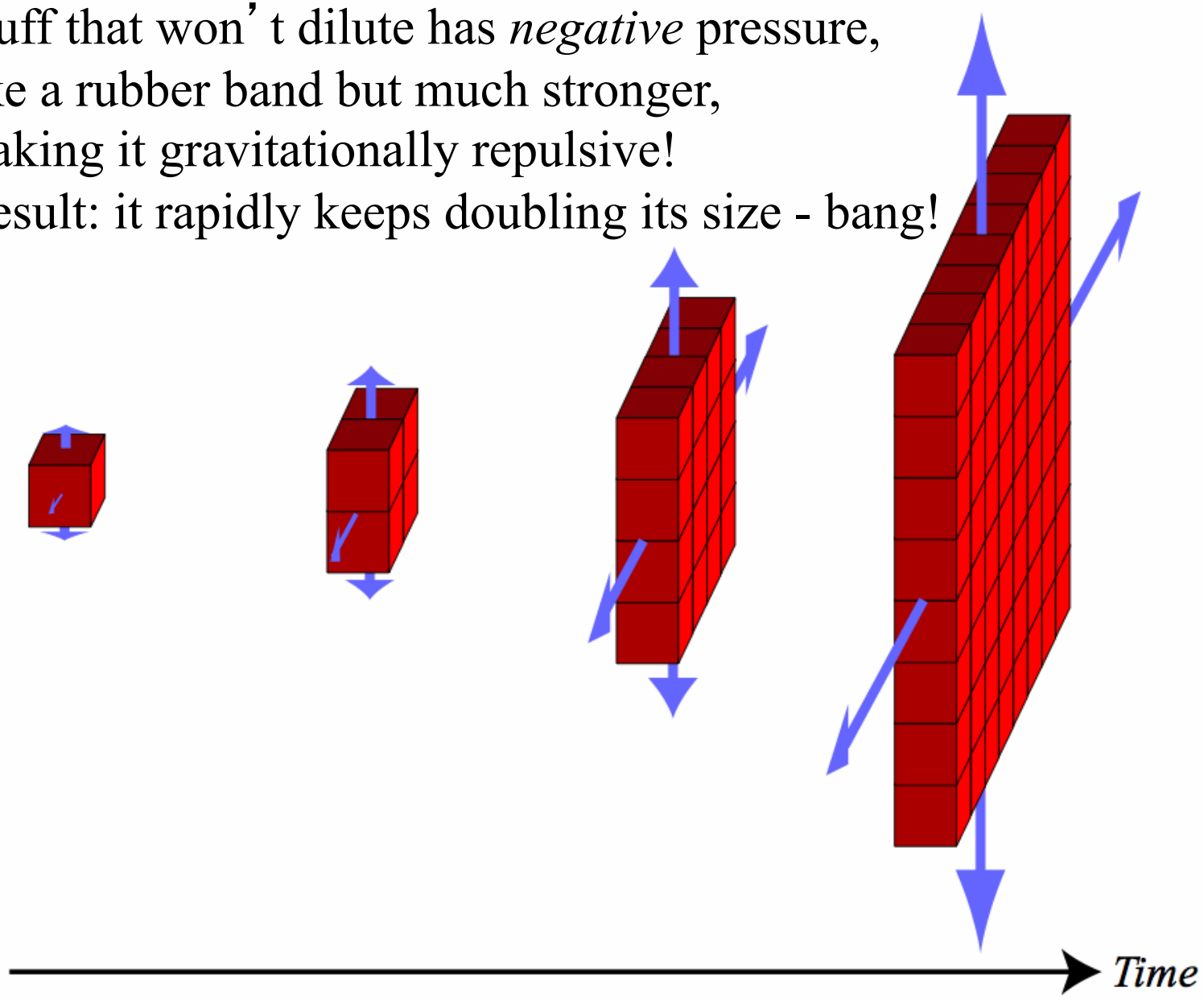
How inflation works:

- Einstein: source of gravity = density $+3p/c^2$
- Stuff that won't dilute has *negative* pressure, like a rubber band but much stronger, making it gravitationally repulsive!
- Result: it rapidly keeps doubling its size - bang!



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Inflation solves all three problems!

- The "Bang" Problem
- The Horizon Problem
- The Flatness Problem

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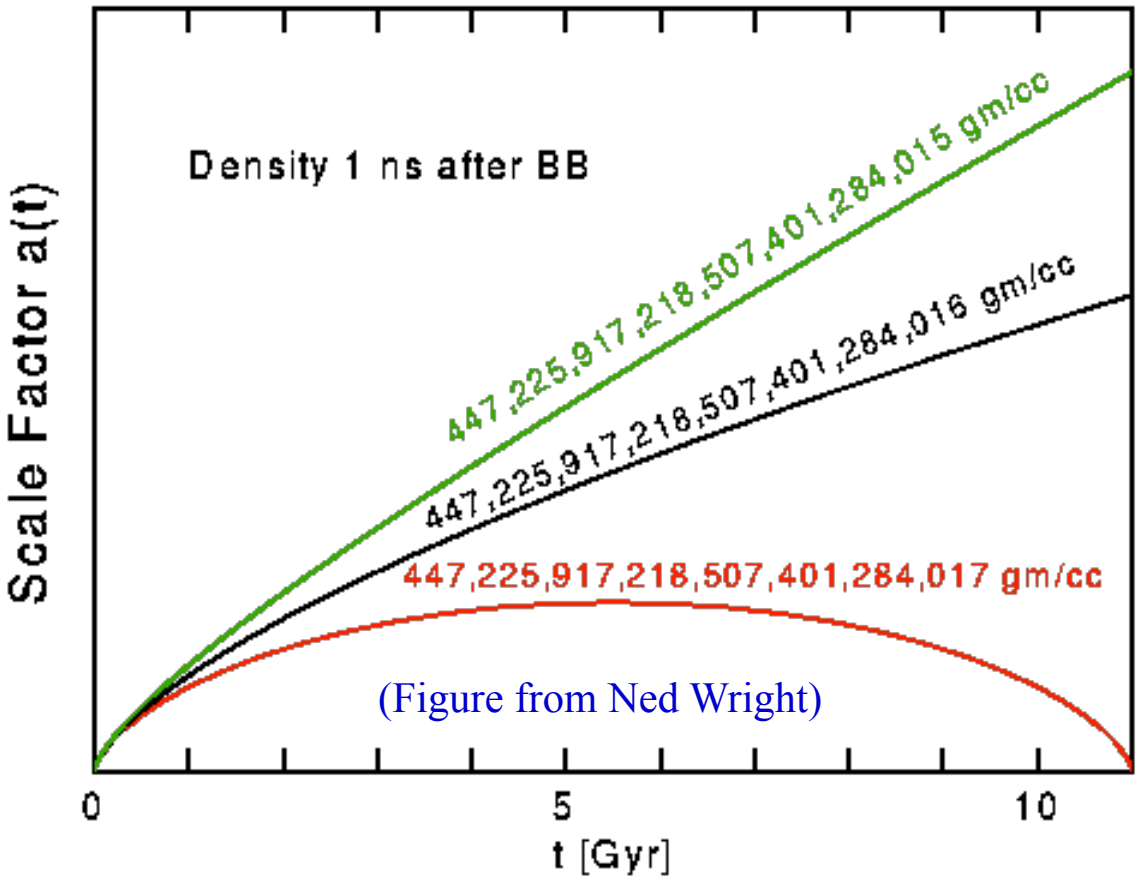
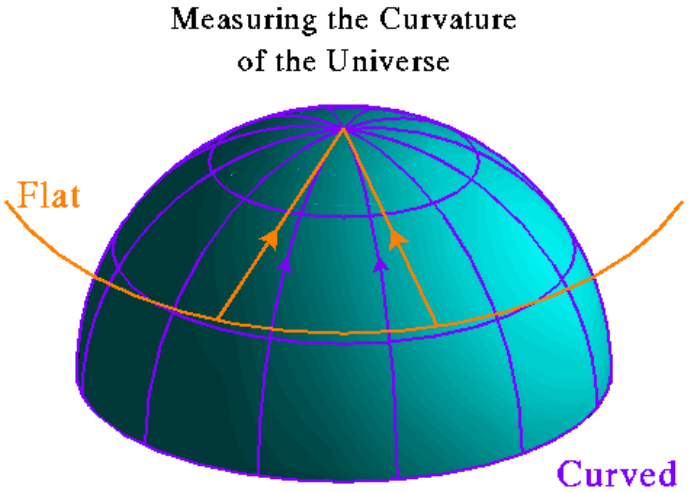
Evidence #1 for inflation:

Space is very flat

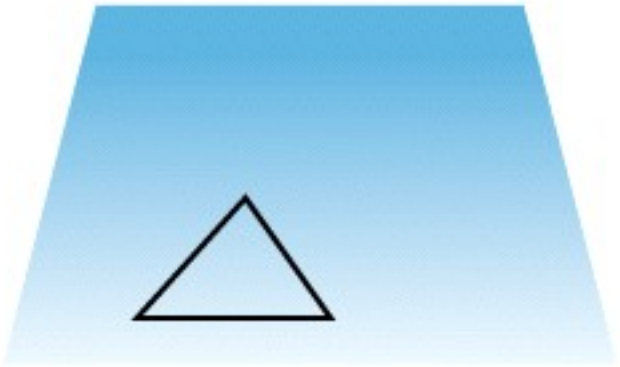


(Figure from Ned Wright)

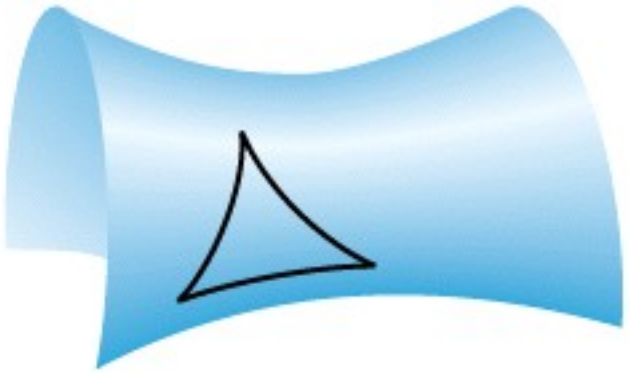


(Figure from Wayne Hu)

a Spherical space $\rho > \rho_c$



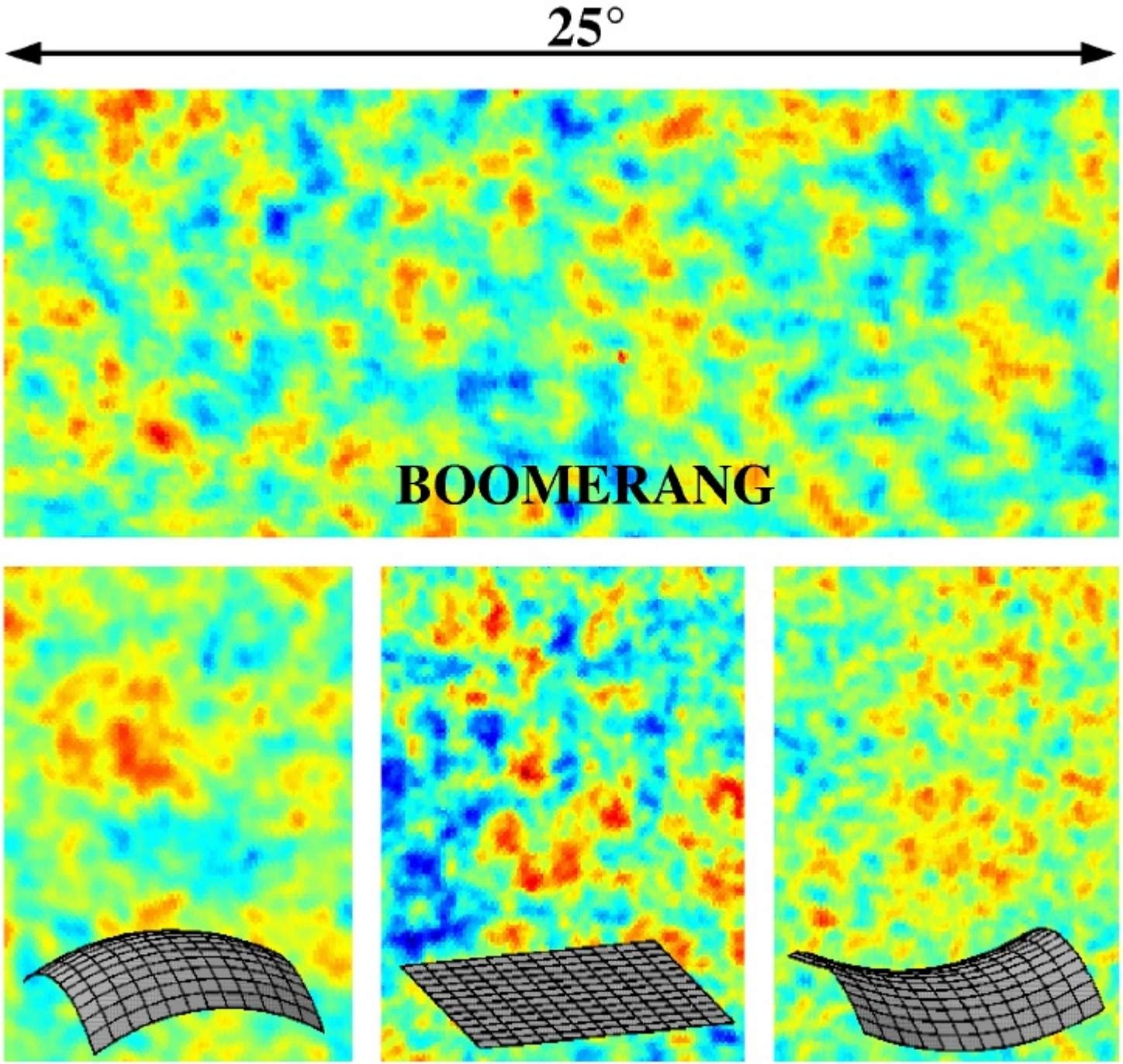
b Flat space $\rho = \rho_c$

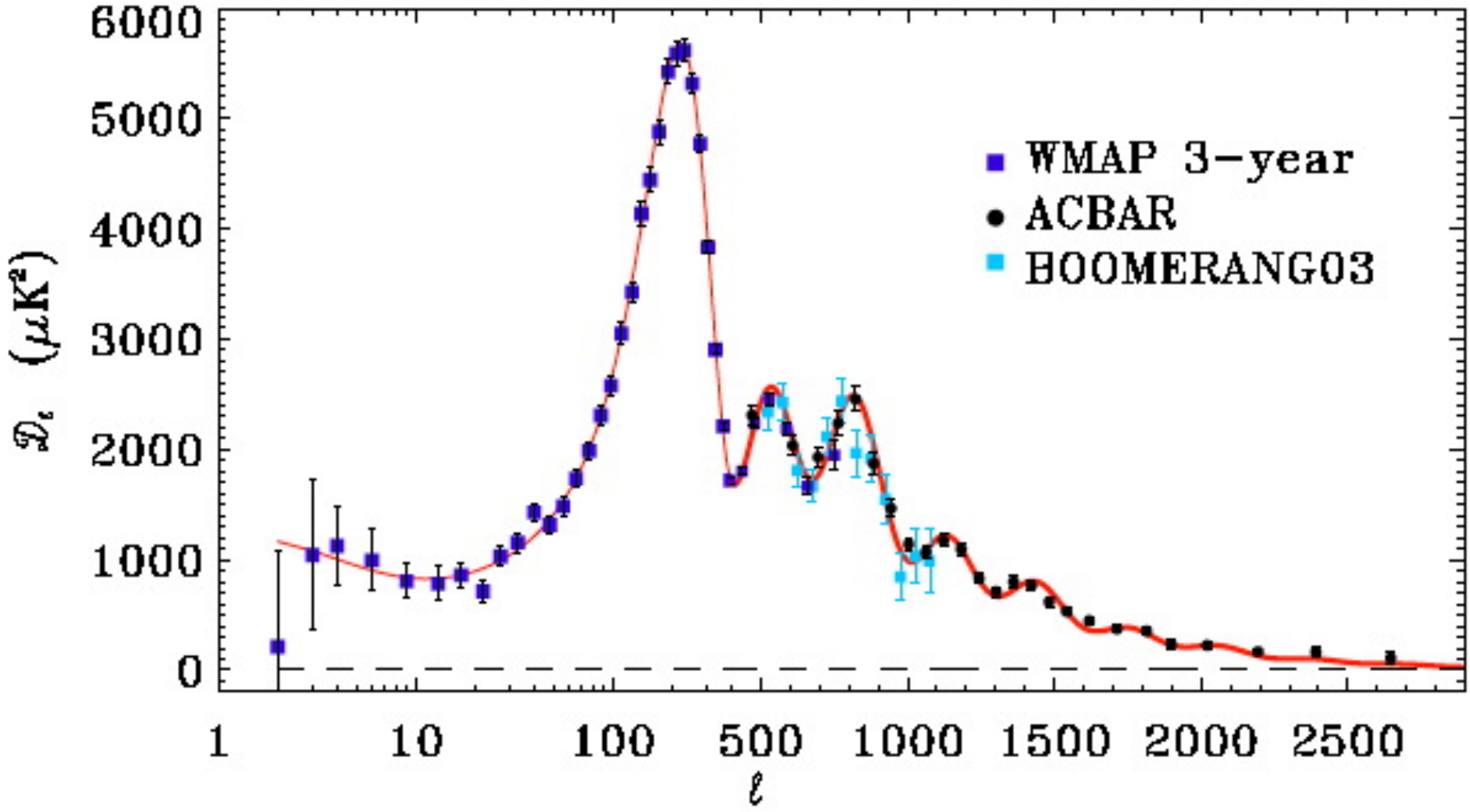


c Hyperbolical space $\rho < \rho_c$

Alan Guth

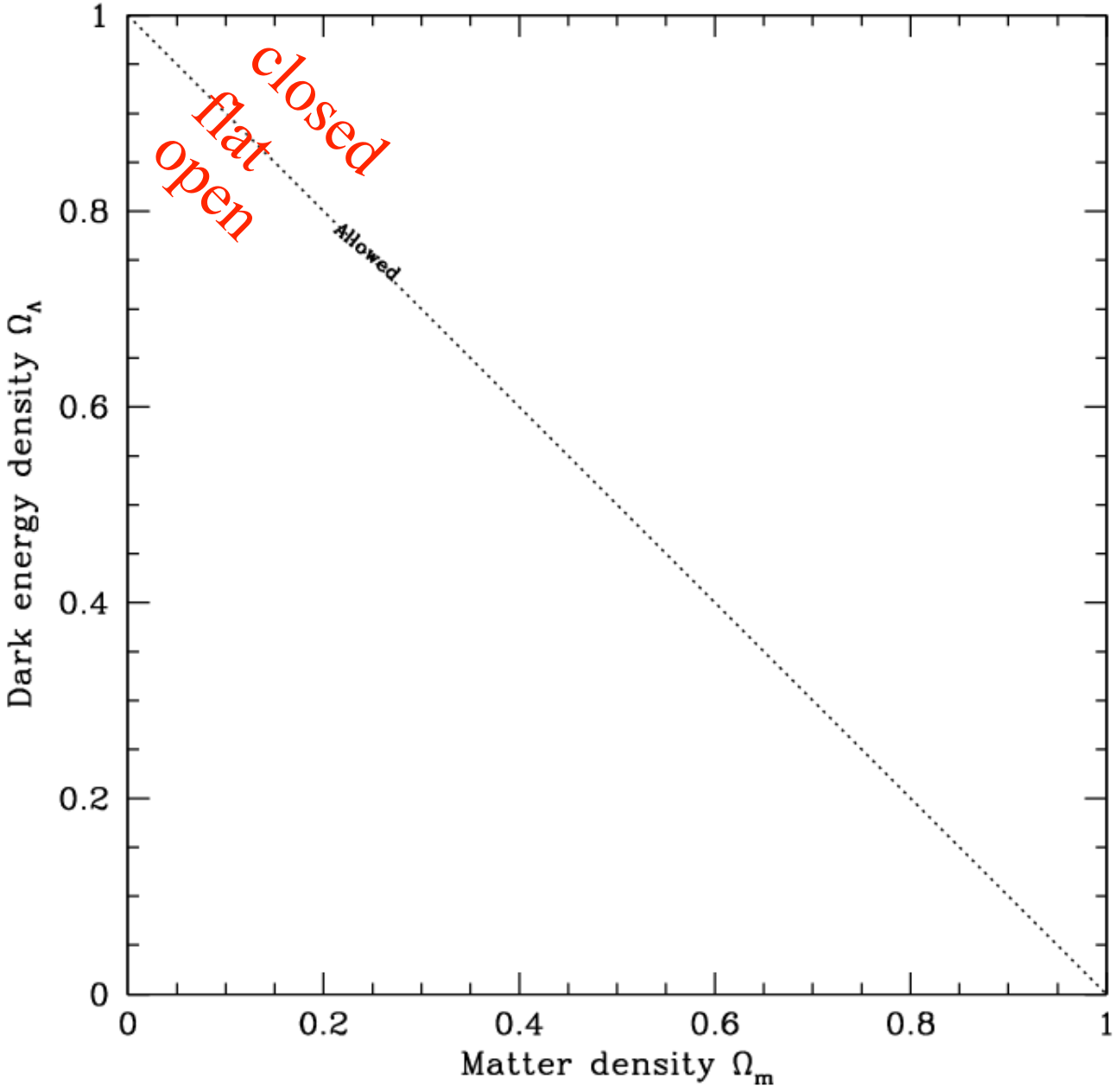
(Figure from Boomerang team)





Reichardt et al 2008, arXiv:0801.1491

How flat is space?



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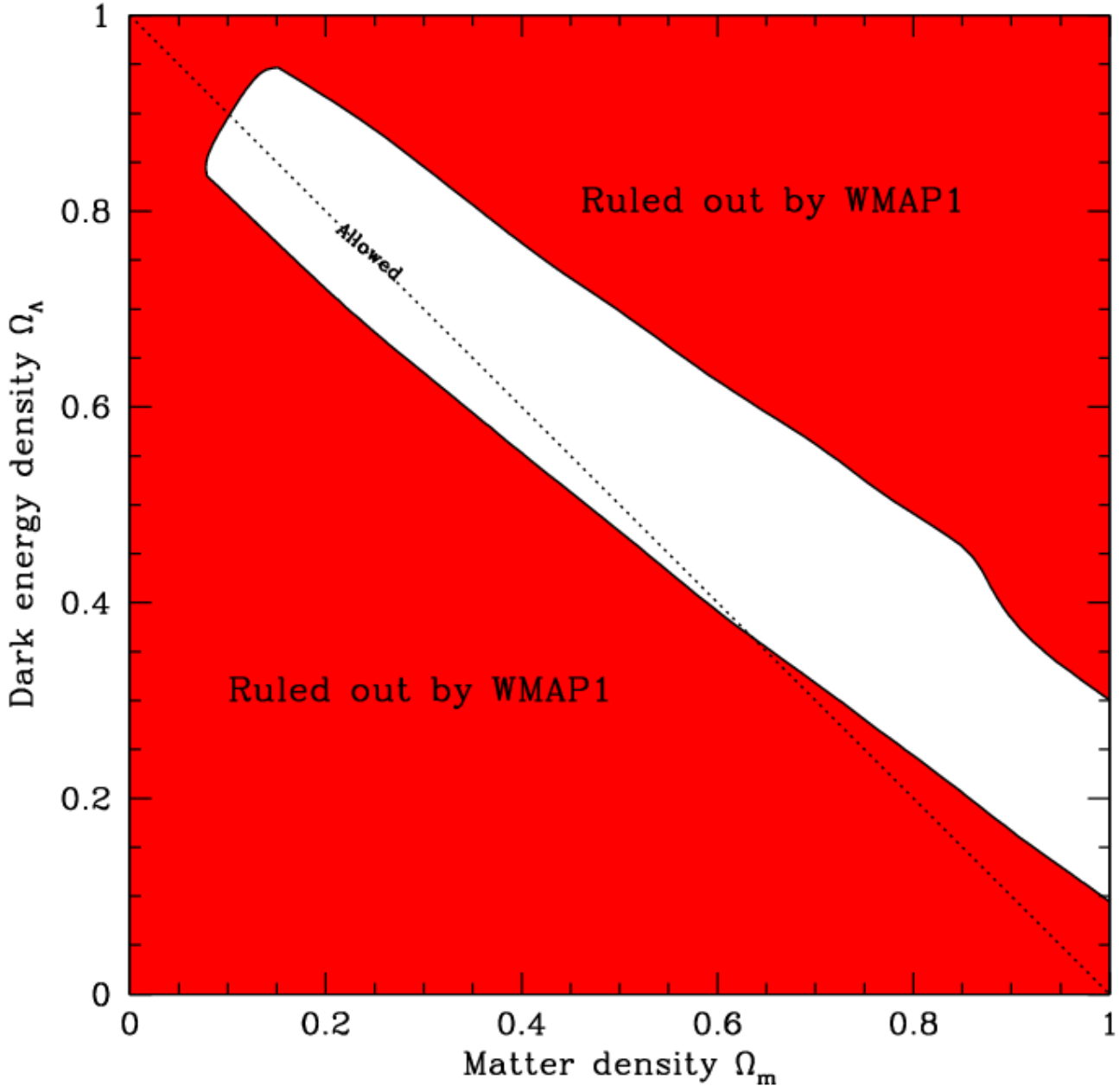
How flat is space?



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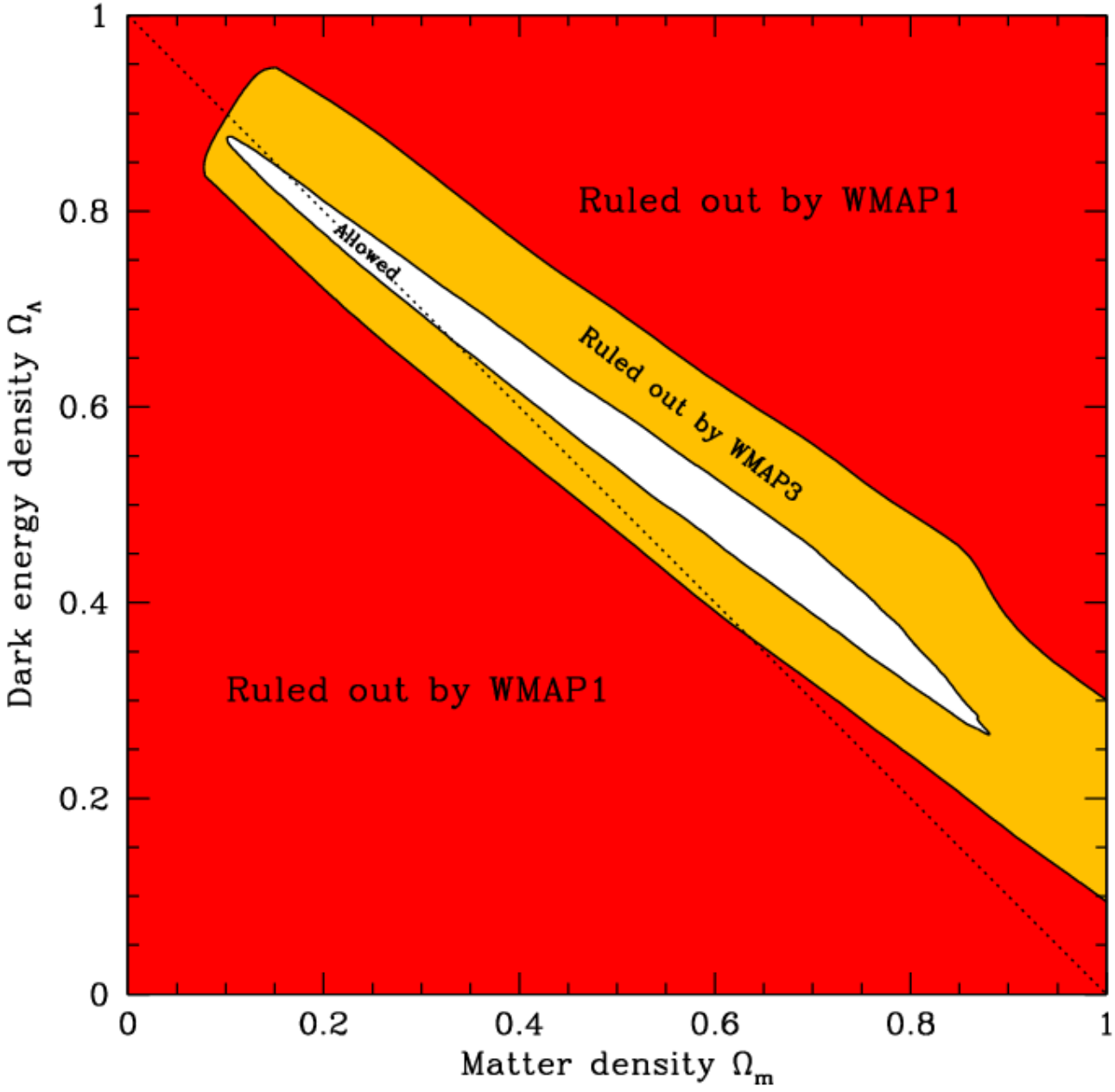
How flat is space? Somewhat.



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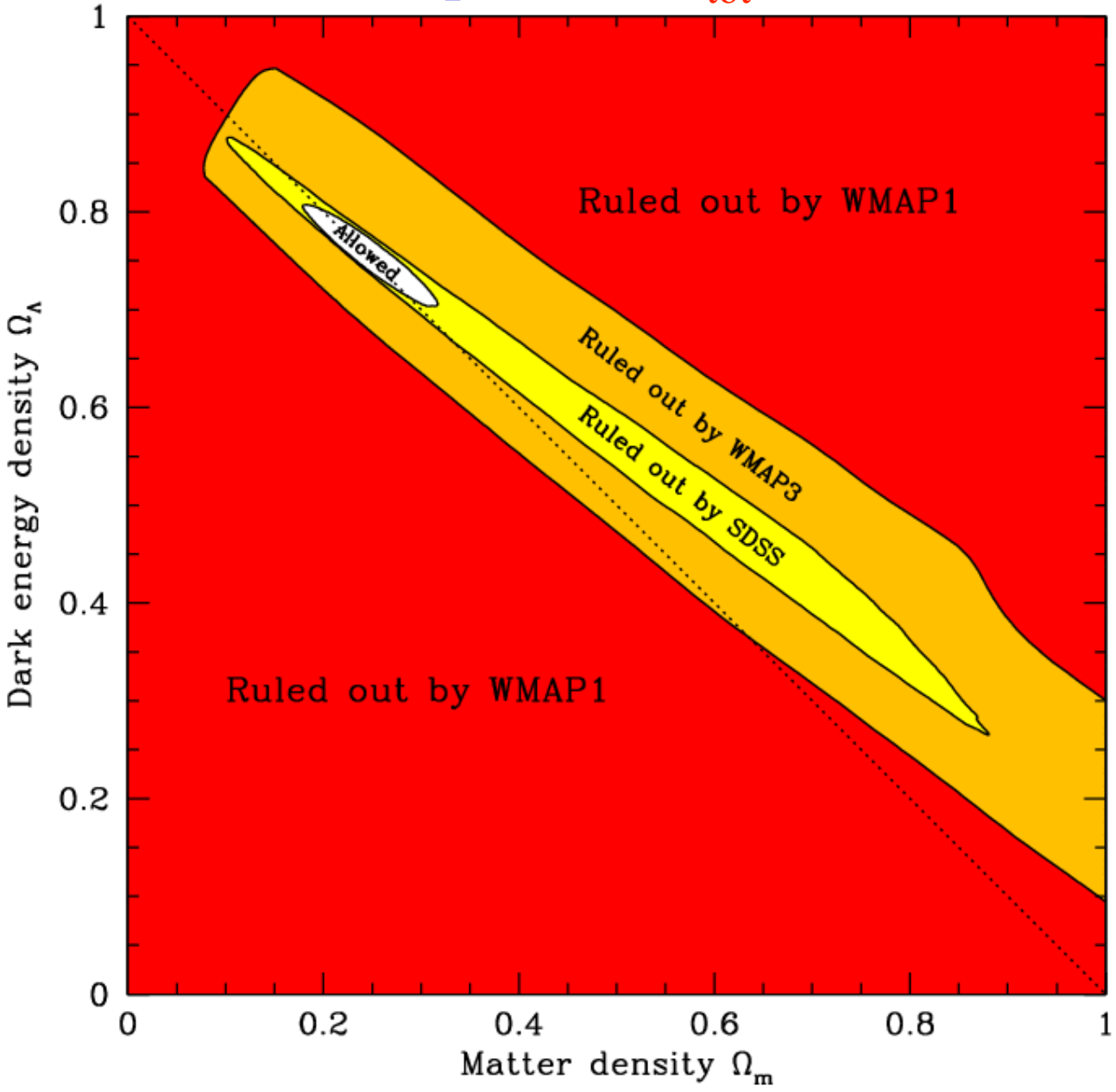
How flat is space? $\Omega_{tot}=1.003\pm0.010$



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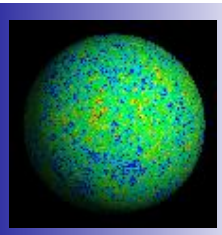
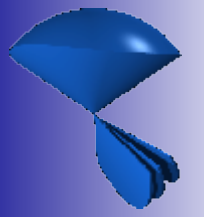
Party on!



CMB

+



LSS

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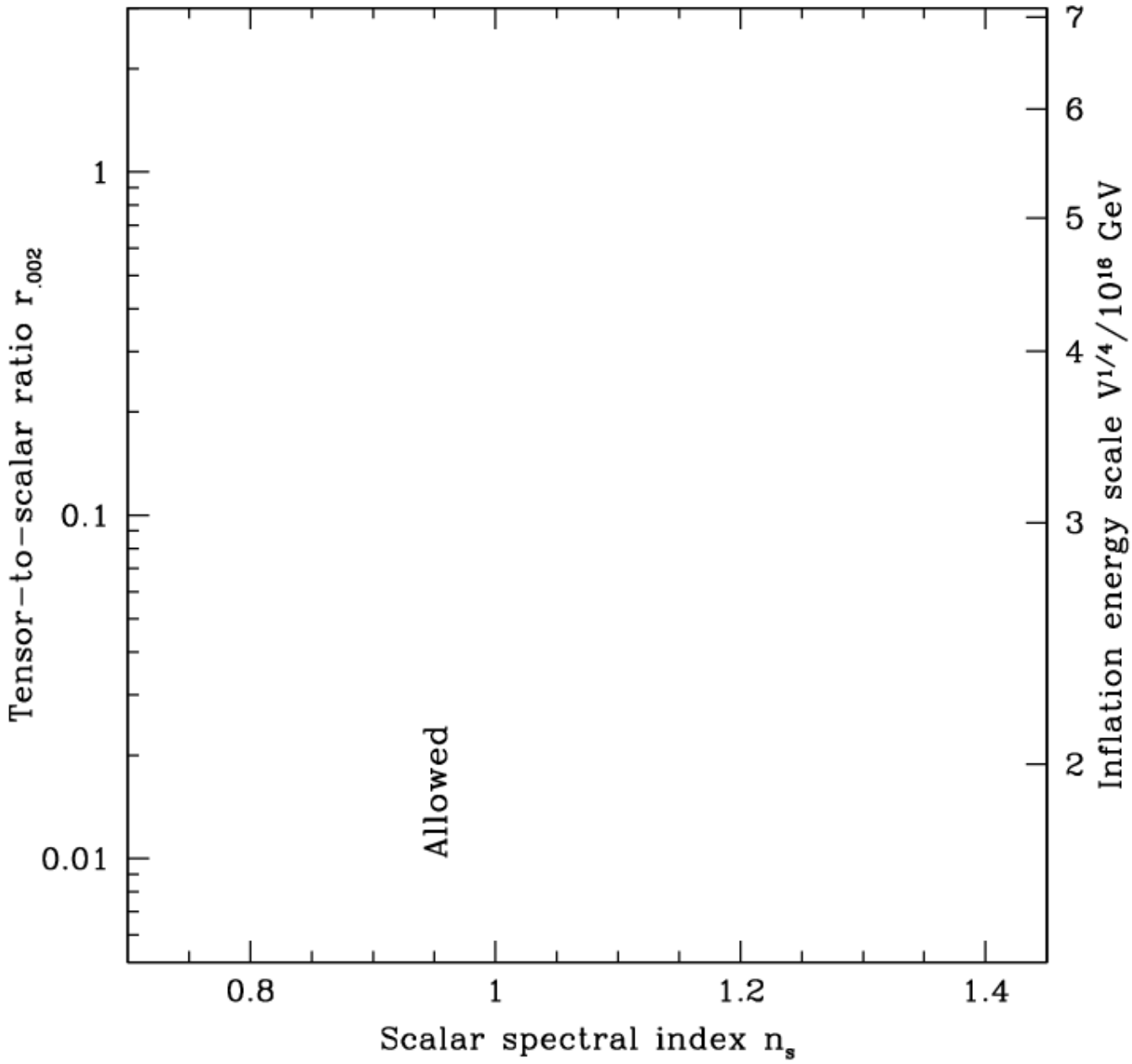
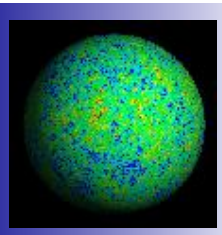
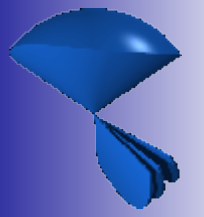




CMB + LSS



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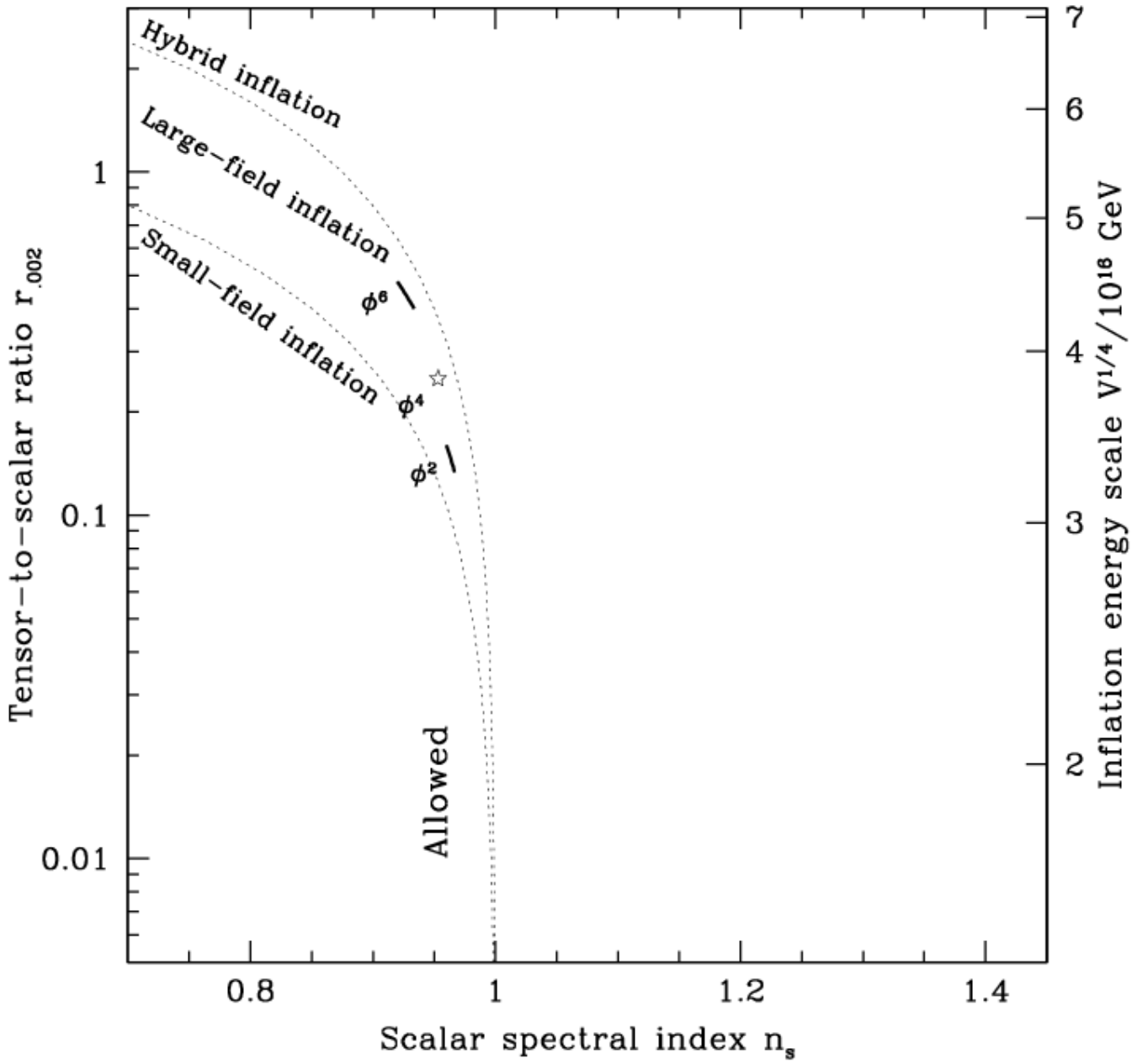

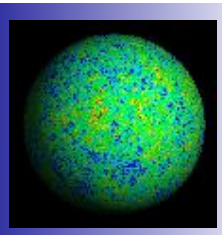

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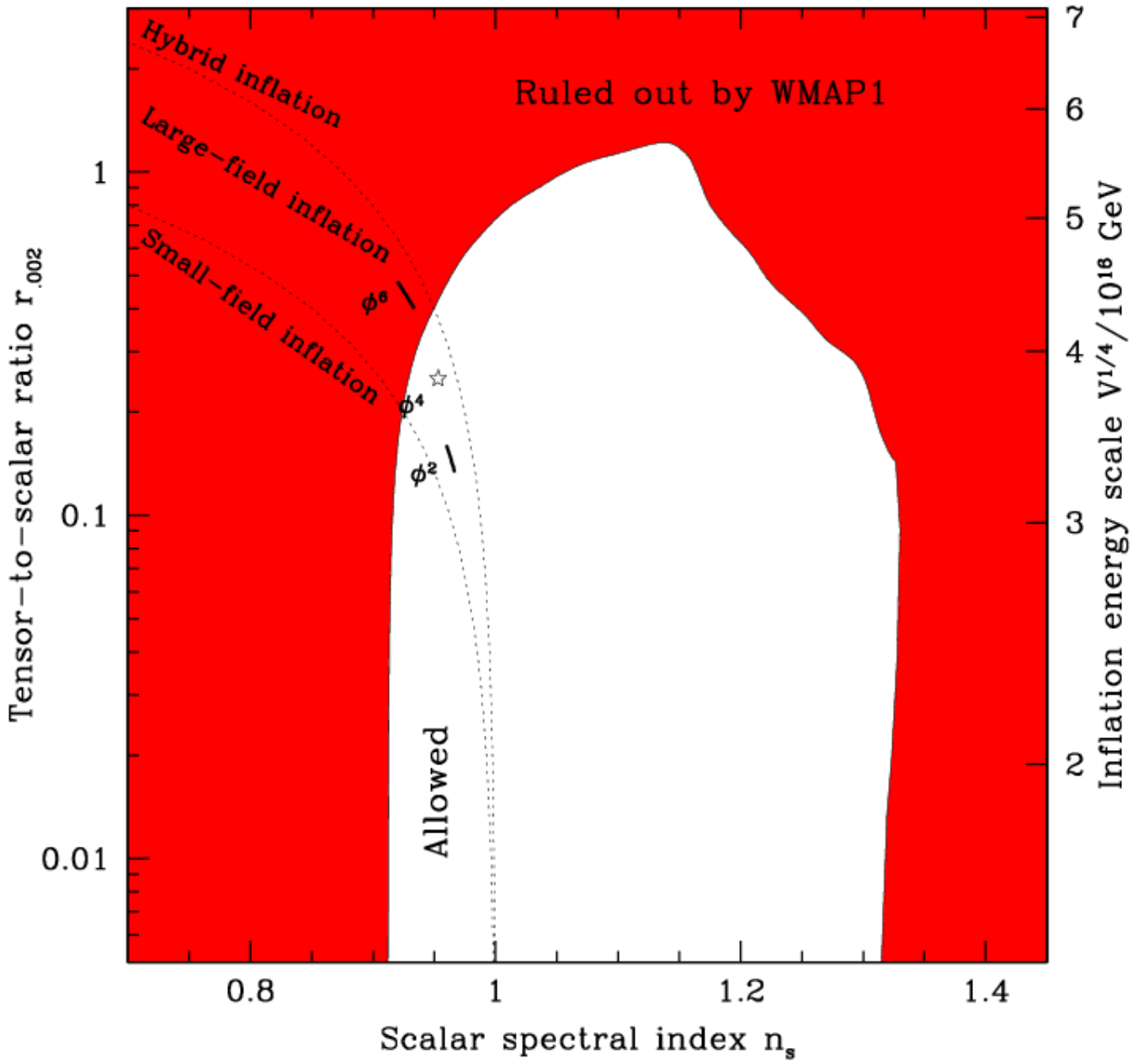

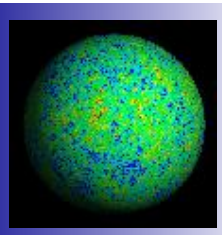

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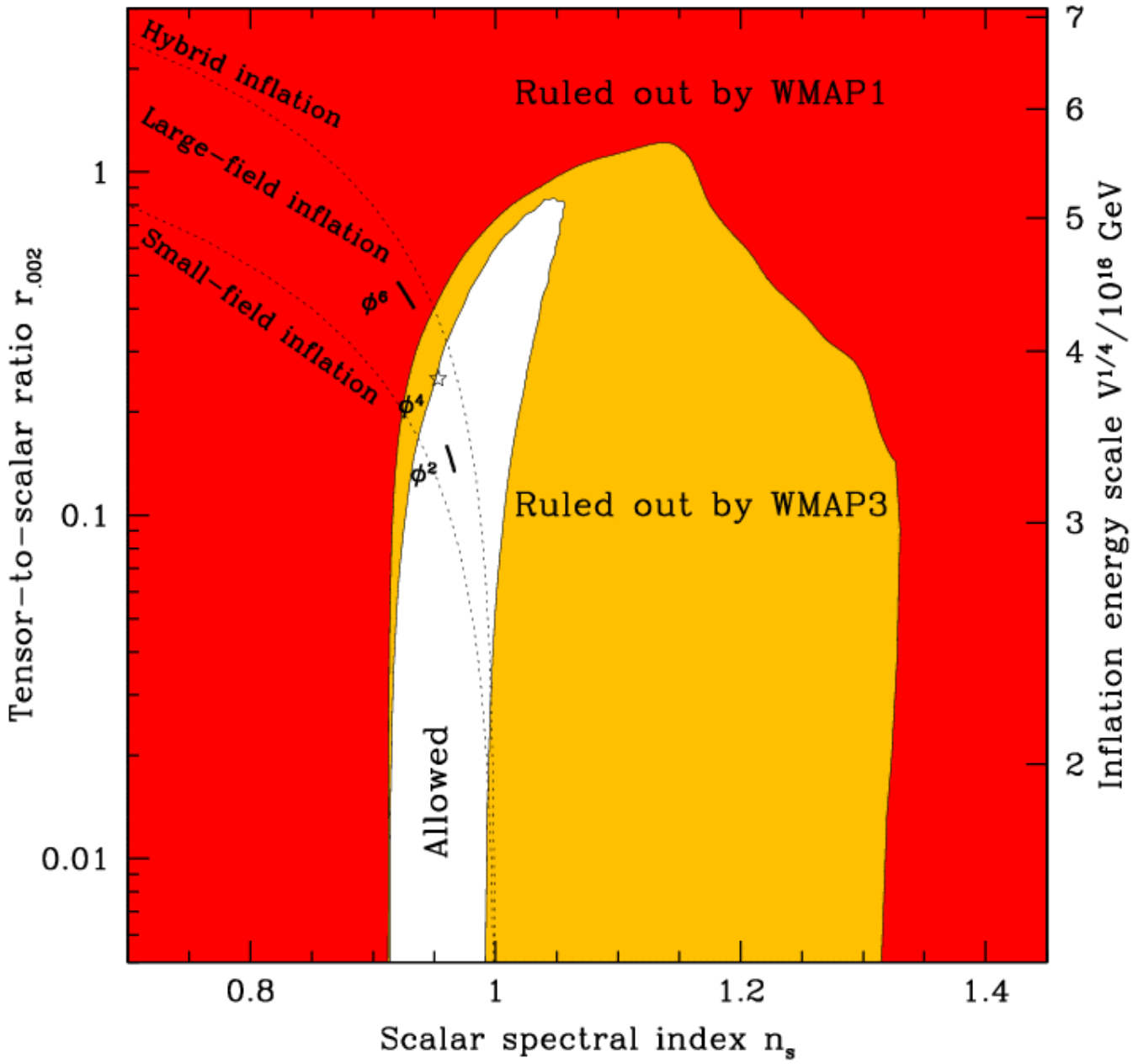

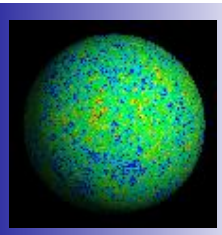

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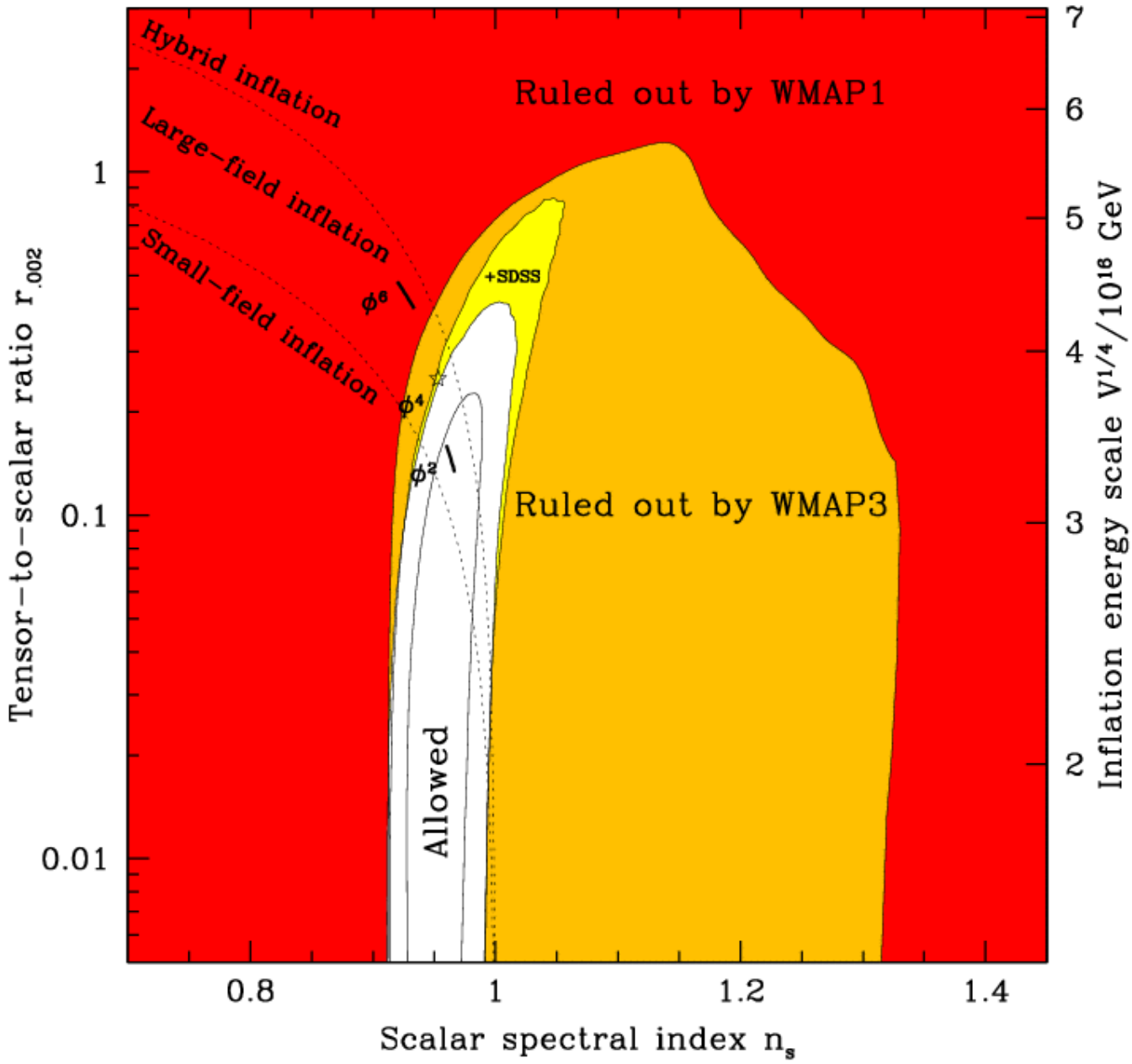

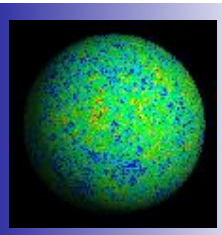

CMB

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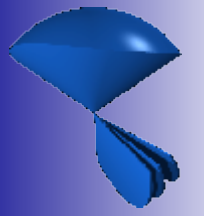

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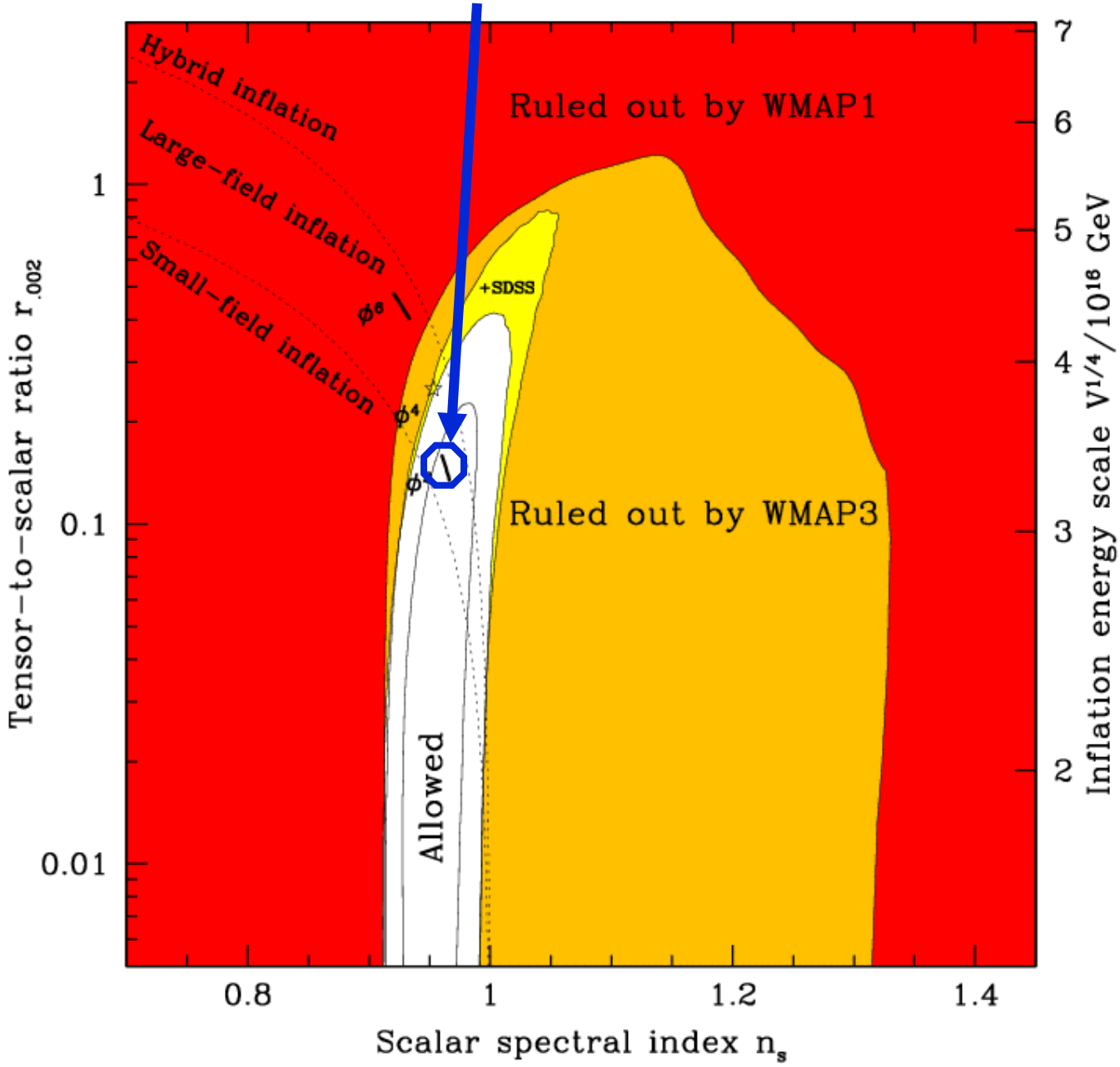
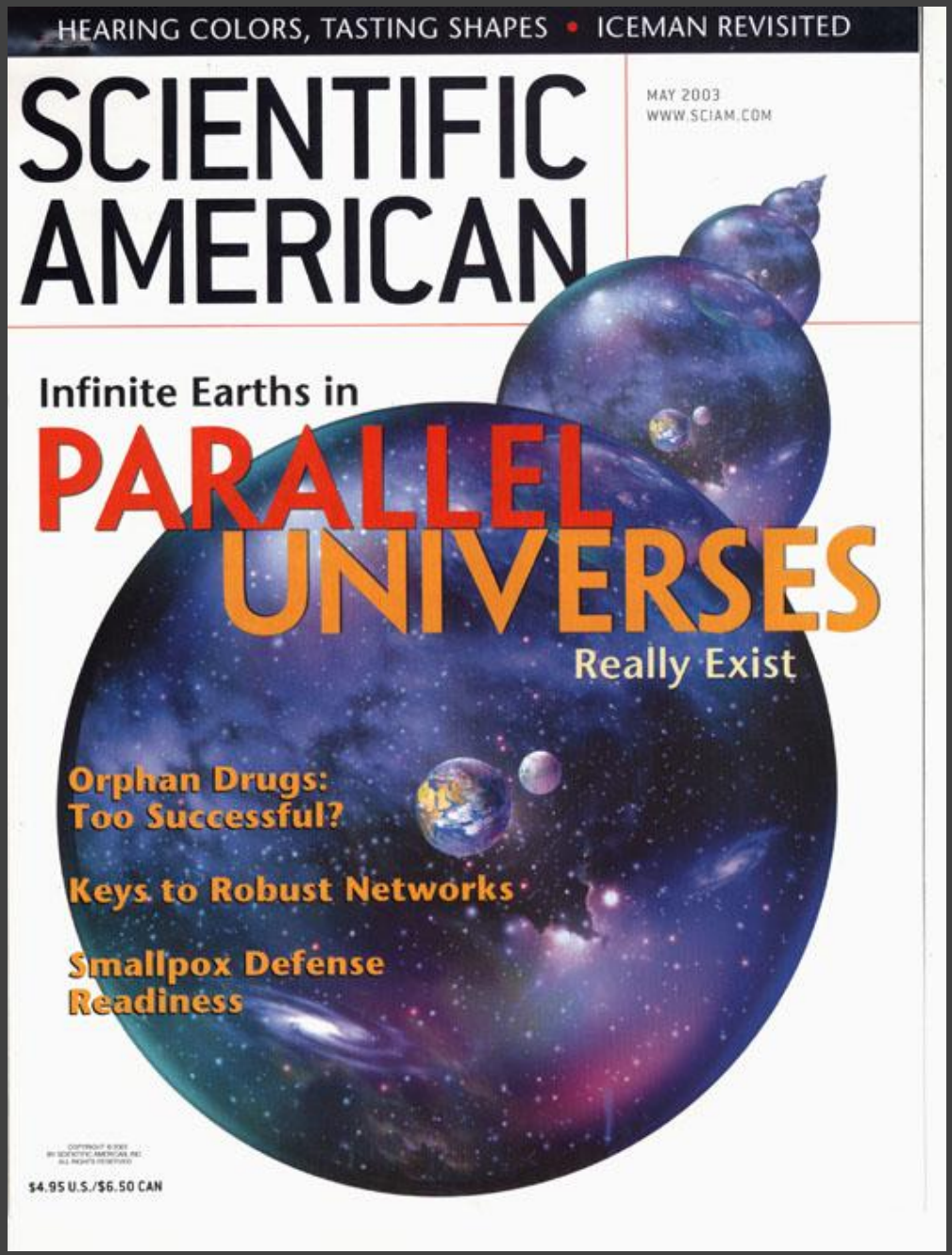
Planck + SDSS: Δn=0.008, Δr=0.012



But be careful what you wish for!

Inflation gave us more that we'd bargained for…


Parallel Universes



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ALEX VILEN
MANY WORLDS IN ONE
THE SEARCH FOR OTHER UNIVERSES
SCIENTIFIC AMERICAN
PARALLEL UNIVERSES
Michio Kaku
Bestselling Author of HYPERSPACE
Parallel Worlds
A Journey Through Creation, Higher Dimensions, and the Future of the Cosmos
NewScientist
All possible universes exist
LEONARD SUSSKIND
THE COSMIC LANDSCAPE
STRING THEORY AND THE ILLUSION OF INTELLIGENT DESIGN


This isn't science!
It's inevitable


Makes sense!
Why not?
I hate it!
AVON


Party on!

Q: Is there more that exists than we can see?

Cosmology suggests yes!

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Outline:

- The most interesting question isn't whether parallel universes exist, but whether the multiverse has 1, 2, 3 or 4 levels
- Evidence for parallel universes
- Reasons to like/dislike multiverses

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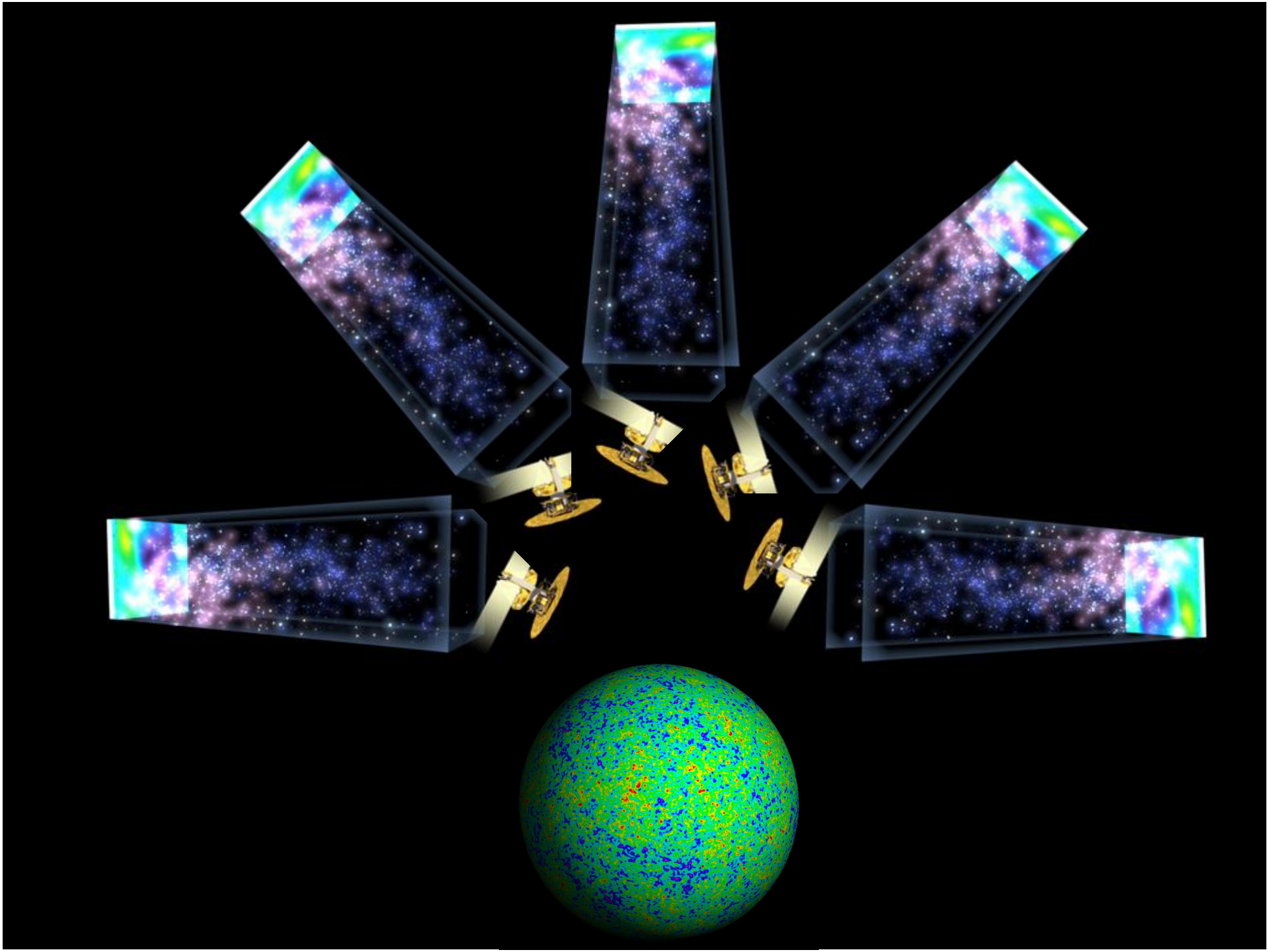
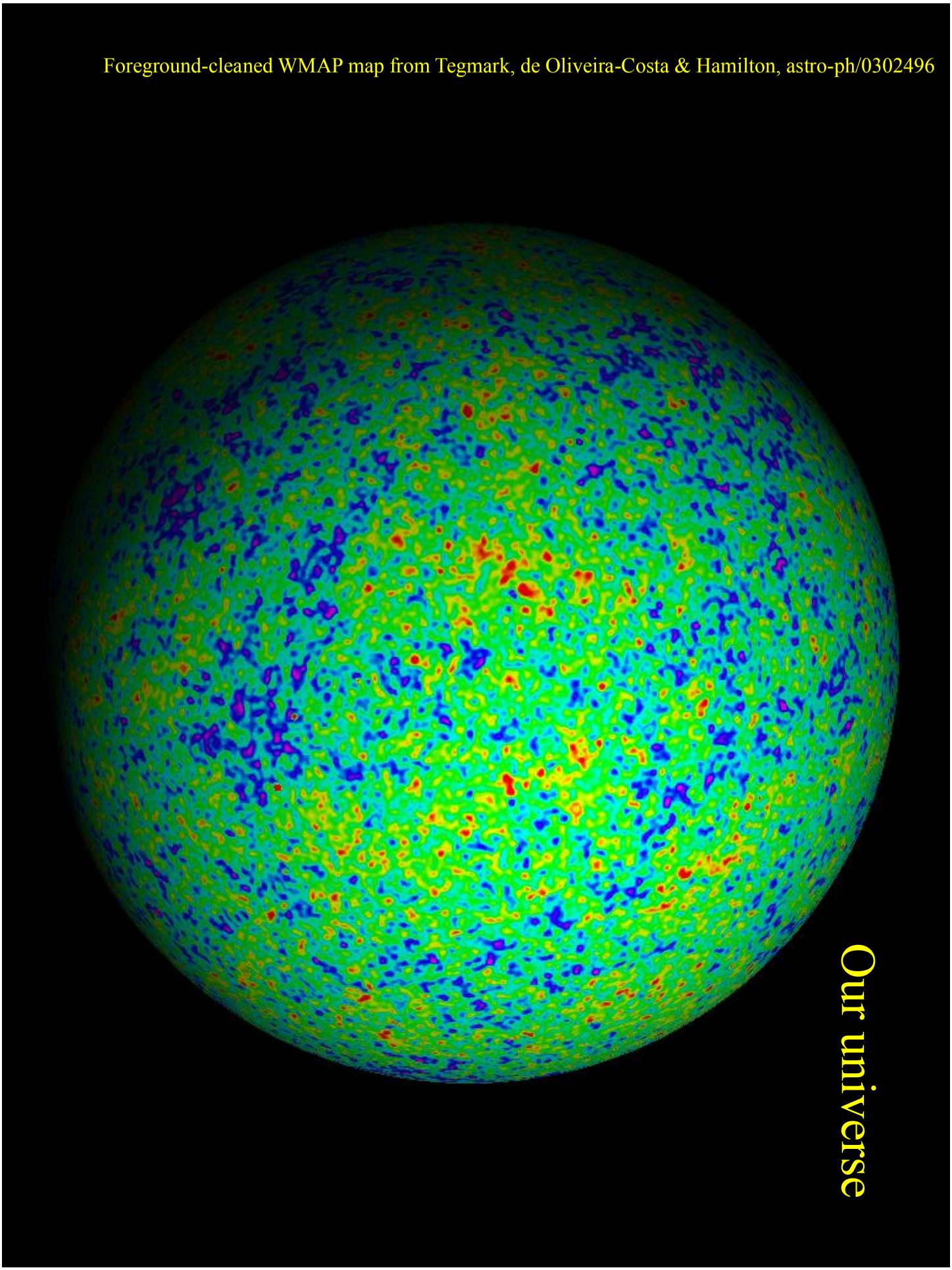
What do we mean by *our* universe?



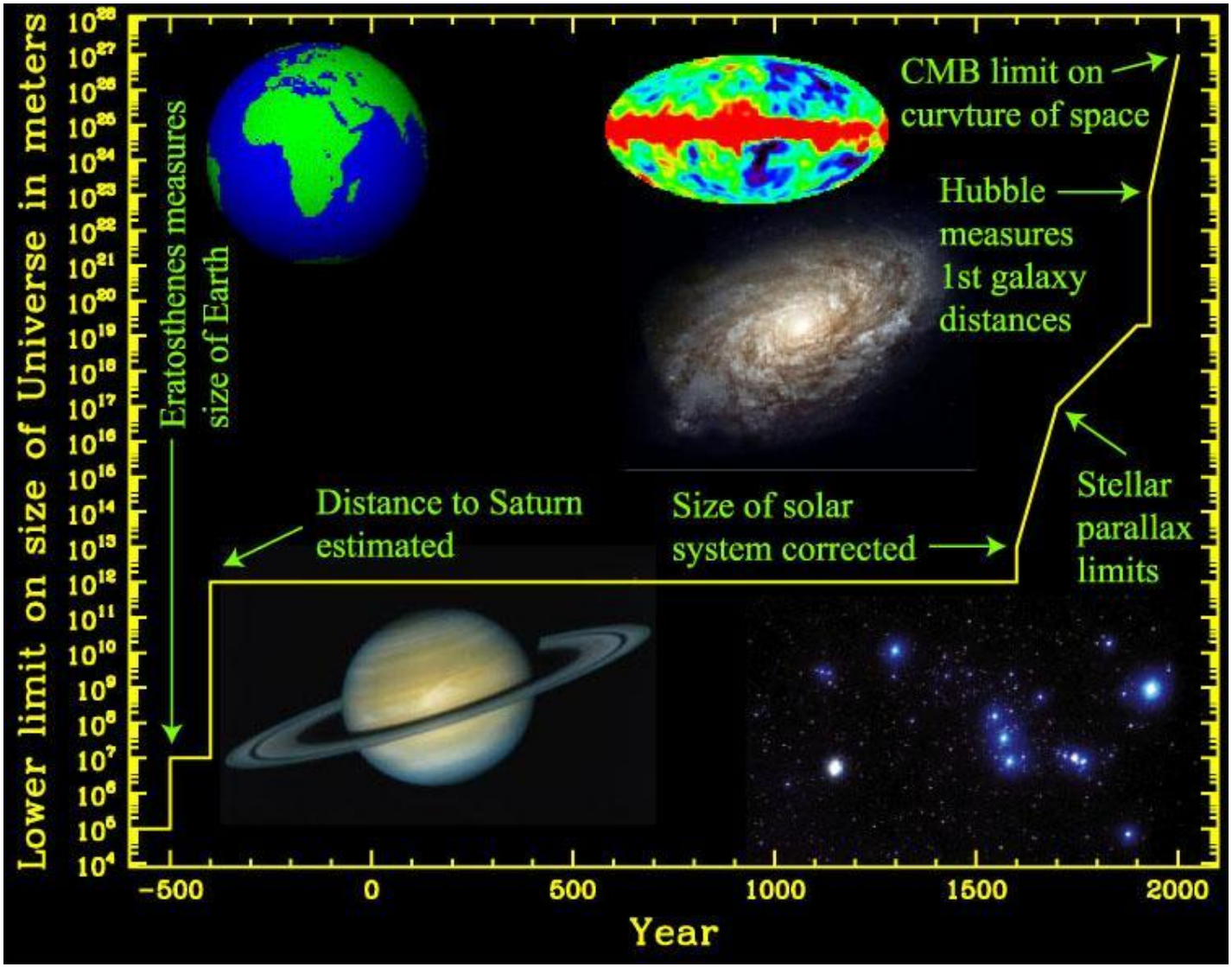
Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496



Our universe

Level I

How big is our space?



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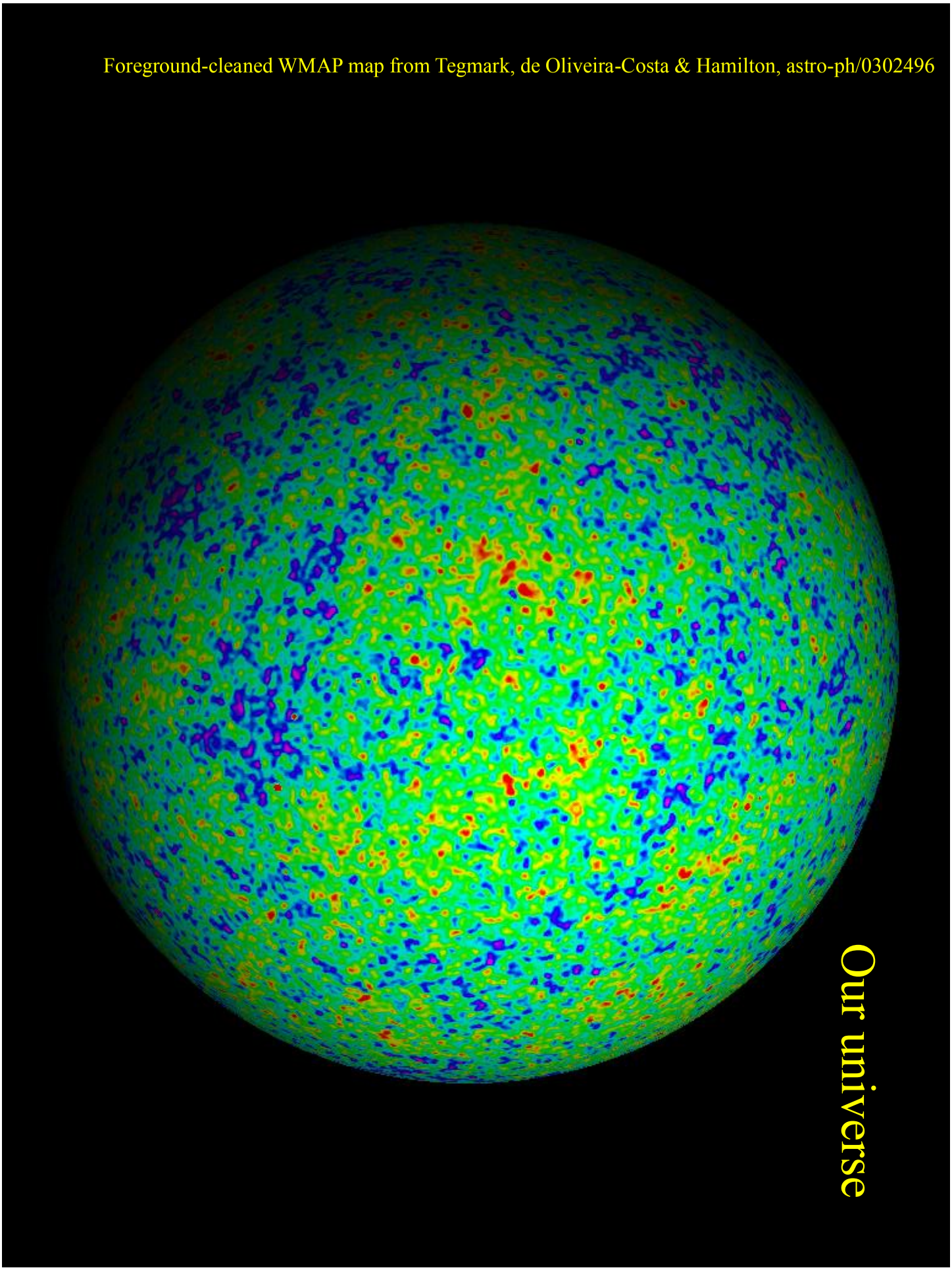

Our universe

Inflation generically predicts that space isn't just huge, but truly infinite!

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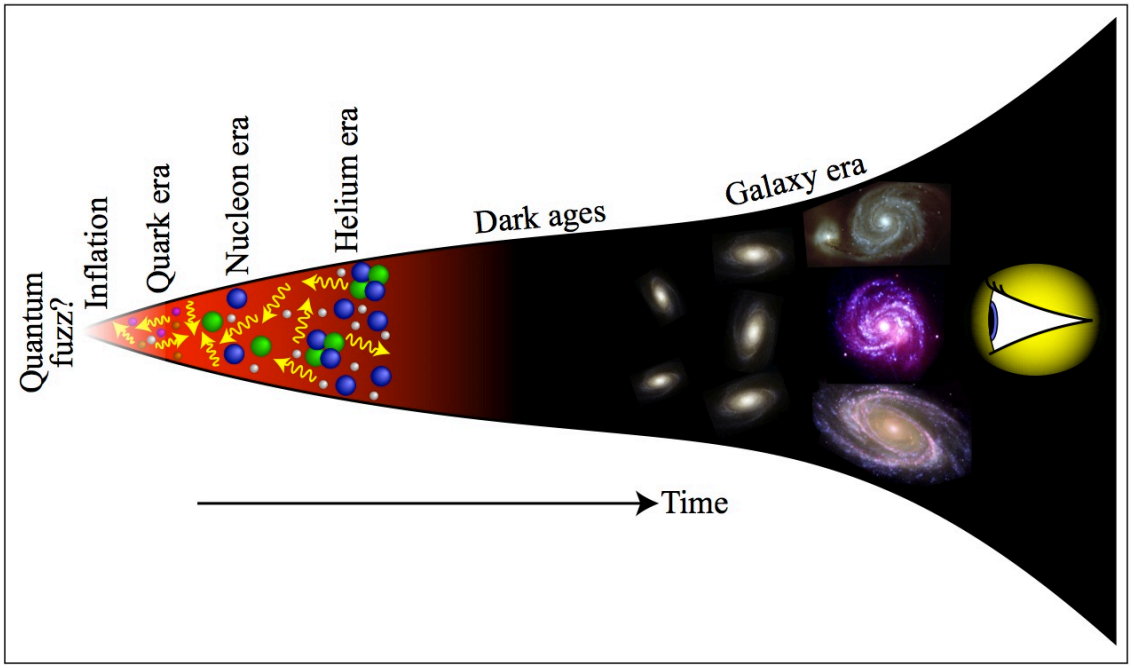
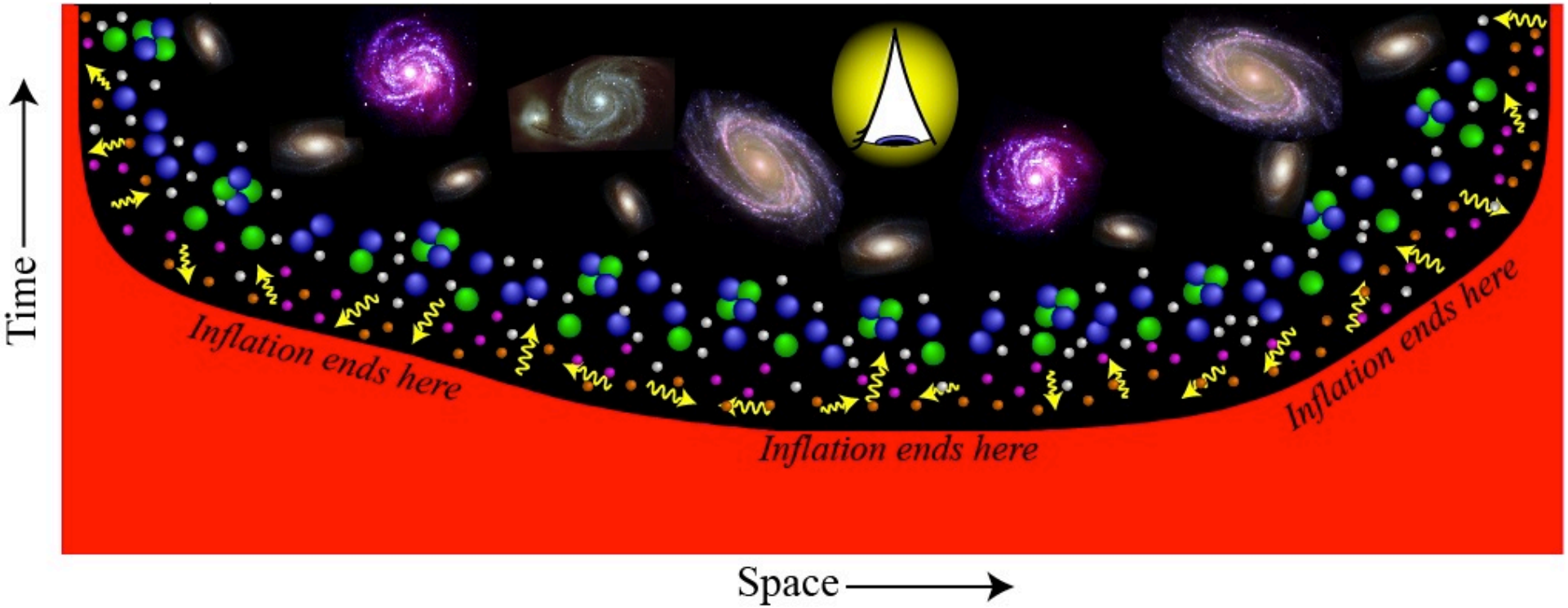
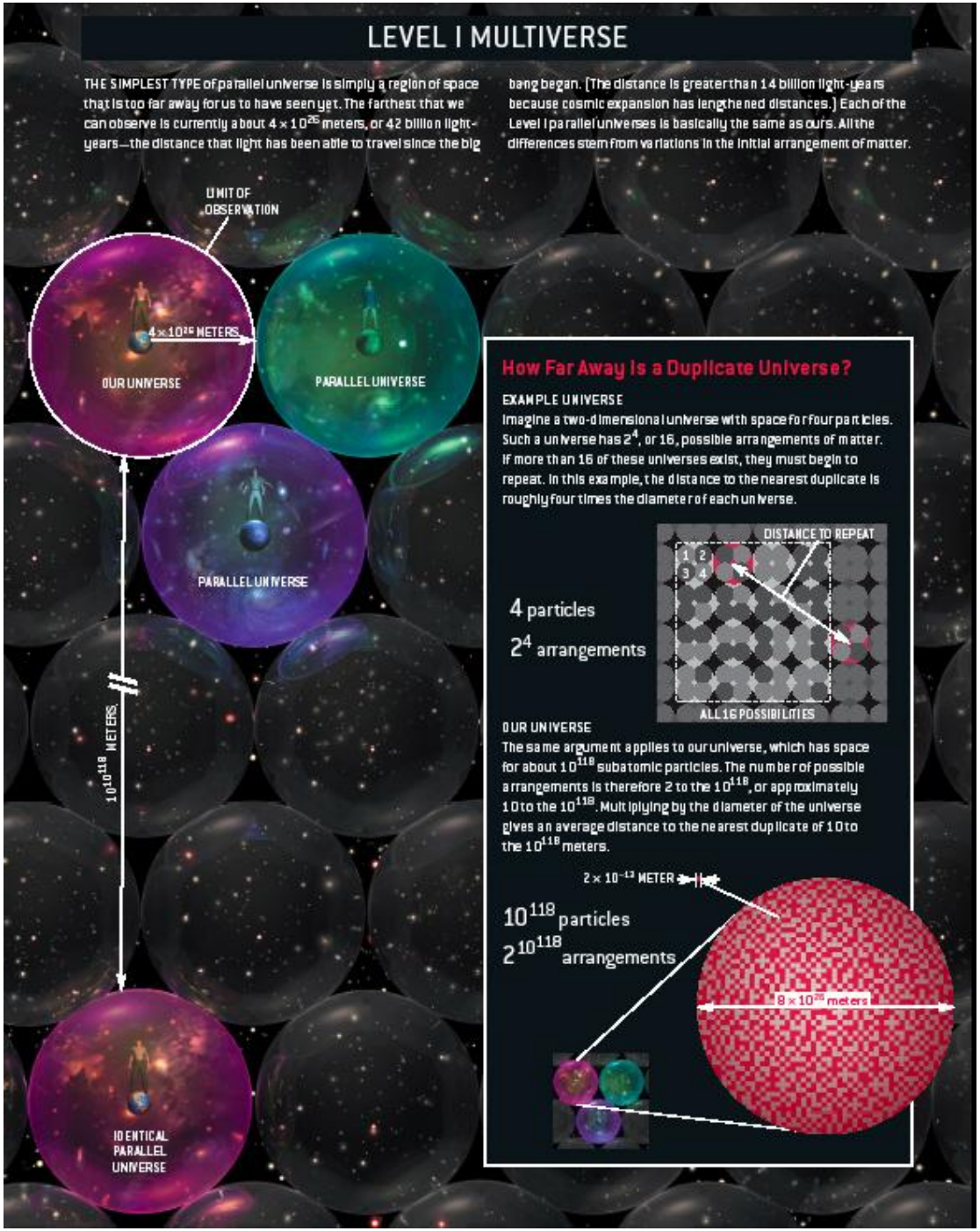
How to make an infinite space inside a finite volume







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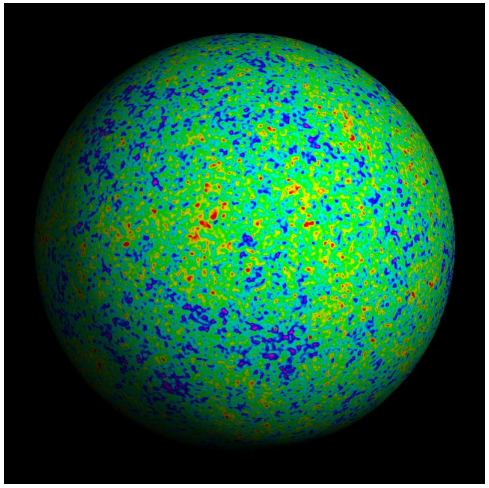
Multiverse level I: other Hubble volumes beyond our cosmic horizon



Giordano Bruno (executed 1600)
Ellis & Brundrit 1979, Q.J.R. Astr. Soc. 20, 37
Garriga & Vilenkin 2001, Phys.Rev. D64, 043511

Features:

- Same (effective) laws of physics
- Different initial conditions

For our flat "concordance" cosmological model:

- Size of our Hubble volume ~ 10^{26}m,
- Closest copy of you ~ $10^{10^{29}}$m
- Closest 100 lightyear bubble like ours ~ $10^{10^{91}}$m
- Closest Hubble volume like ours ~ $10^{10^{118}}$m

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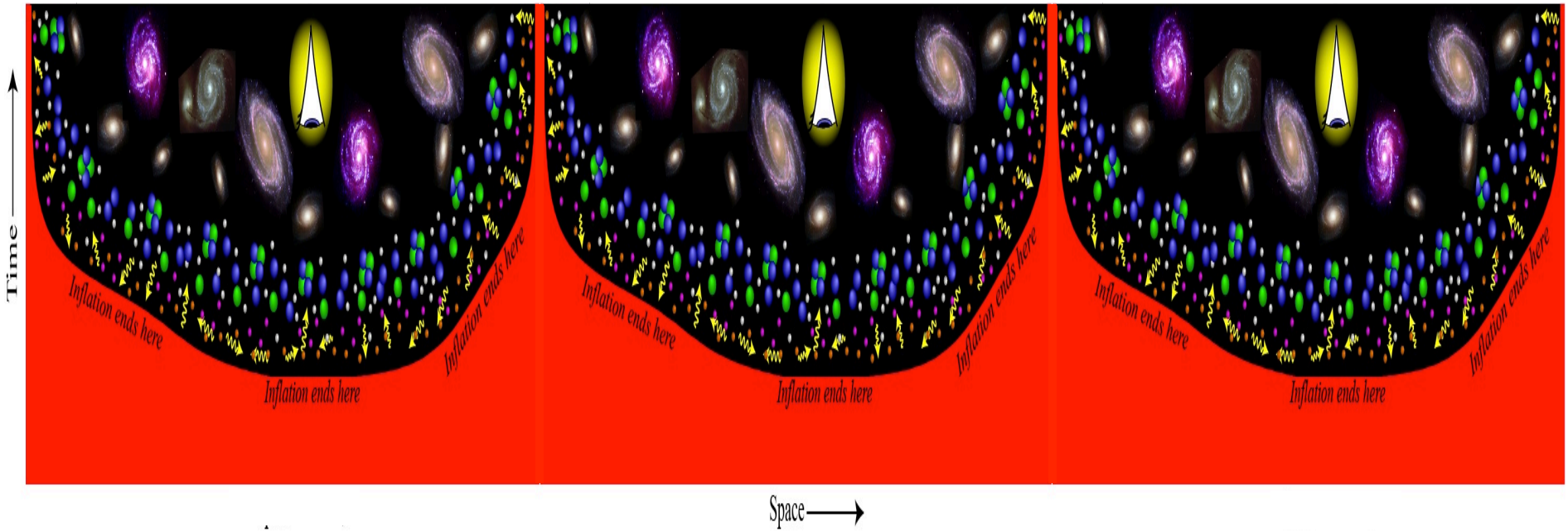
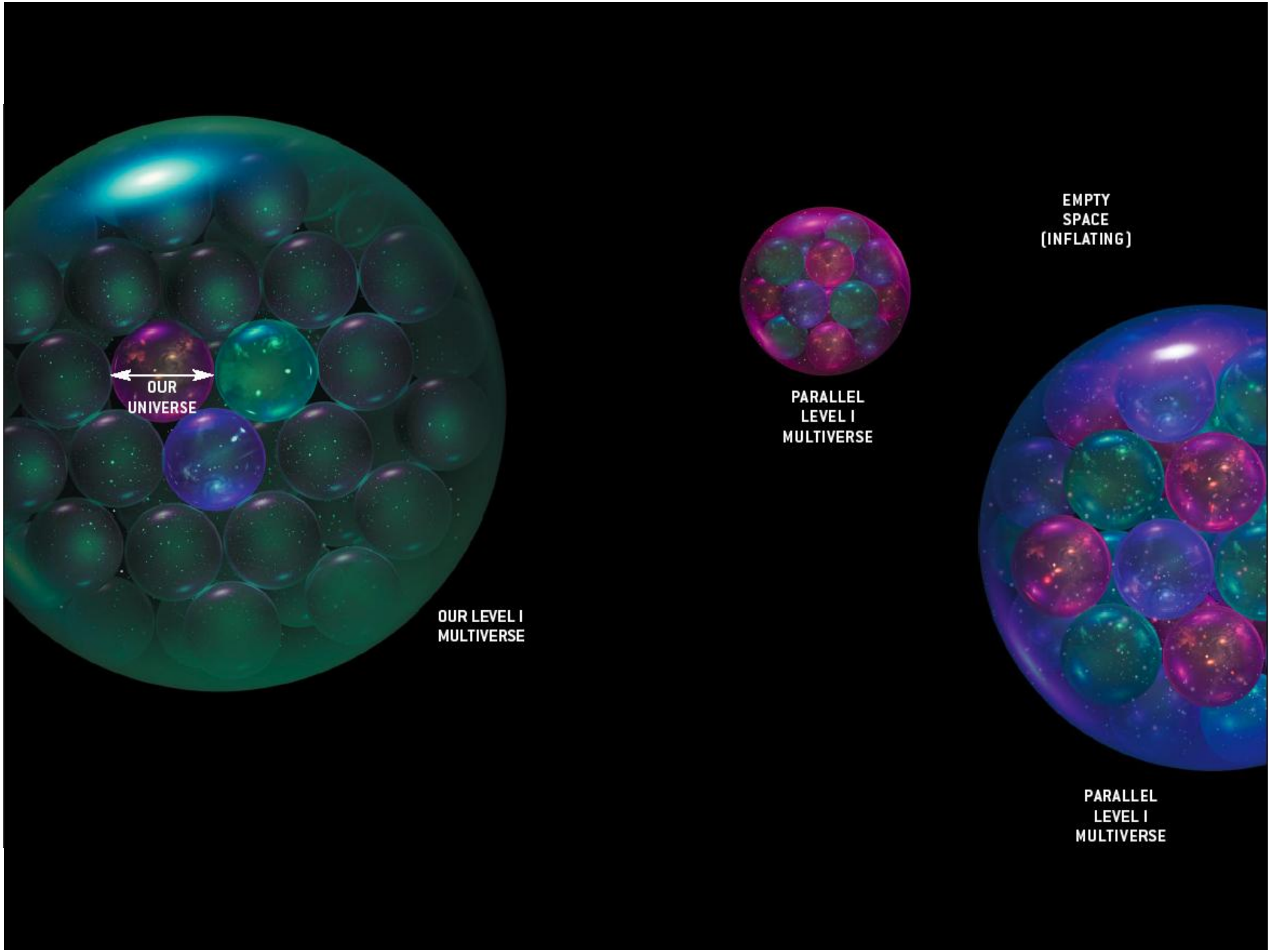
Level II

Level II Multiverse




OUR
UNIVERSE
OUR LEVEL I
MULTIVERSE
PARALLEL
LEVEL I
MULTIVERSE
EMPTY
SPACE
(INFLATING)
PARALLEL
LEVEL I
MULTIVERSE

Why these values?

Standard model parameters:

Particle physics

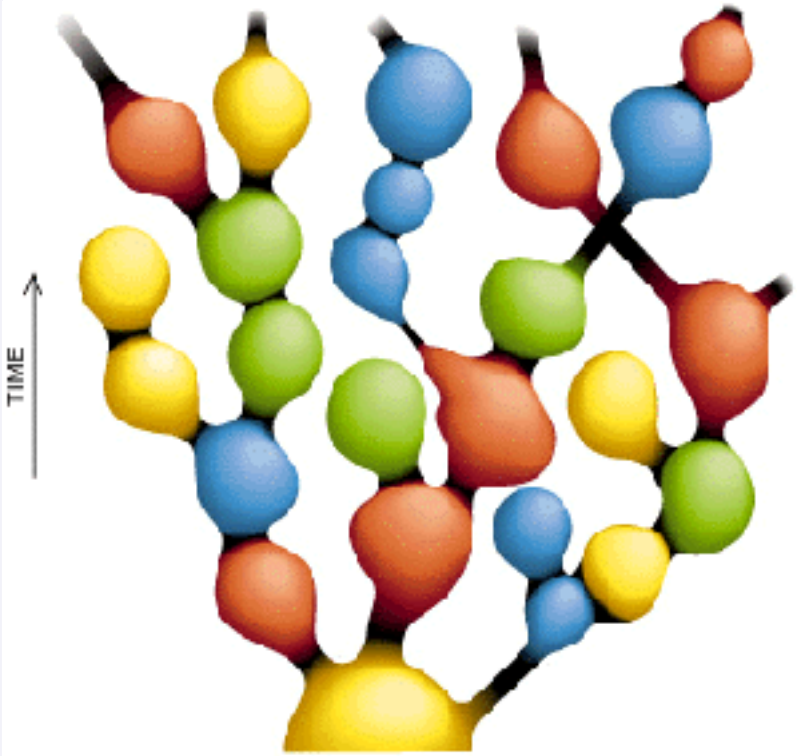
Cosmology

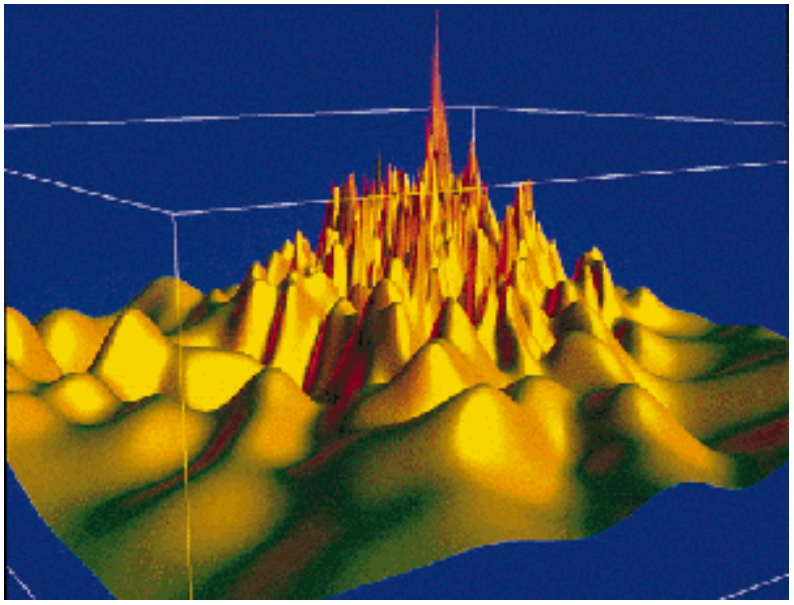
Parameter	Meaning	Measured value
g	Weak coupling constant at m_Z	0.6520 ± 0.0001
θ_W	Weinberg angle	0.48290 ± 0.00005
g_s	Strong coupling constant at m_Z	1.221 ± 0.022
μ^2	Quadratic Higgs coefficient	$\sim -10^{-33}$
λ	Quartic Higgs coefficient	$\sim 1?$
G_e	Electron Yukawa coupling	2.94×10^{-6}
G_μ	Muon Yukawa coupling	0.000607
G_τ	Tauon Yukawa coupling	0.0102156233
G_u	Up quark Yukawa coupling	0.000016 ± 0.000007
G_d	Down quark Yukawa coupling	0.00003 ± 0.00002
G_c	Charm quark Yukawa coupling	0.0072 ± 0.0006
G_s	Strange quark Yukawa coupling	0.0006 ± 0.0002
G_t	Top quark Yukawa coupling	1.002 ± 0.029
G_b	Bottom quark Yukawa coupling	0.026 ± 0.003
$\sin\theta_{12}$	Quark CKM matrix angle	0.2243 ± 0.0016
$\sin\theta_{23}$	Quark CKM matrix angle	0.0413 ± 0.0015
$\sin\theta_{13}$	Quark CKM matrix angle	0.0037 ± 0.0005
δ_{13}	Quark CKM matrix phase	1.05 ± 0.24
$\theta_{\rm qcd}$	CP-violating QCD vacuum phase	$< 10^{-9}$
G_{ν_e}	Electron neutrino Yukawa coupling	$< 1.7 \times 10^{-11}$
G_{ν_μ}	Muon neutrino Yukawa coupling	$< 1.1 \times 10^{-6}$
G_{ν_τ}	Tau neutrino Yukawa coupling	< 0.10
$\sin\theta'_{12}$	Neutrino MNS matrix angle	0.55 ± 0.06
$\sin 2\theta'_{23}$	Neutrino MNS matrix angle	≥ 0.94
$\sin\theta'_{13}$	Neutrino MNS matrix angle	≤ 0.22
δ'_{13}	Neutrino MNS matrix phase	?
ρ_Λ	Dark energy density	$(1.25 \pm 0.25) \times 10^{-123}$
$\xi_{\rm b}$	Baryon mass per photon $\rho_{\rm b}/n_\gamma$	$(0.50 \pm 0.03) \times 10^{-28}$
$\xi_{\rm c}$	Cold dark matter mass per photon $\rho_{\rm c}/n_\gamma$	$(2.5 \pm 0.2) \times 10^{-28}$
ξ_ν	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11}\sum m_{\nu_i}$	$< 0.9 \times 10^{-28}$
Q	Scalar fluctuation amplitude δ_H on horizon	$(2.0 \pm 0.2) \times 10^{-5}$
$n_{\rm s}$	Scalar spectral index	0.98 ± 0.02

$C = \hbar = G = k_b = q_e = 1$

MT, Aguirre, Rees & Wilczek 2005

Multiverse level 2: other post-inflationary regions





(Pics from Andrei Linde)

Features:

- Perhaps different *effective* laws of physics (physical constants, particles, symmetrics, dimensionality)
- Perhaps even uncountably infinite

(Compare a literally parallel Universe; living on another brane)

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DO ANY OF THESE QUESTIONS CONFUSE YOU?

1. What is the Universe expanding into?
2. How can stuff be more than 14 billion light years away when the Universe is only 14 billion light years old?
3. Where in space did the Big Bang explosion happen?
4. Did the Big Bang happen at a single point?
5. How could a the Big Bang create an infinite space in a finite time?
6. How could space not be infinite?
7. If the Universe is only 10 billion years old, how can we see objects that are now 30 billion light years away?
8. Don't galaxies receeding faster than c violate relativity theory?
9. Are galaxies really moving away from us, or is space just expanding?
10. Is the Milky Way expanding?
11. Do we have evidence for a Big Bang singularity?
12. What came before the Big Bang?
13. Should I feel insignificant?