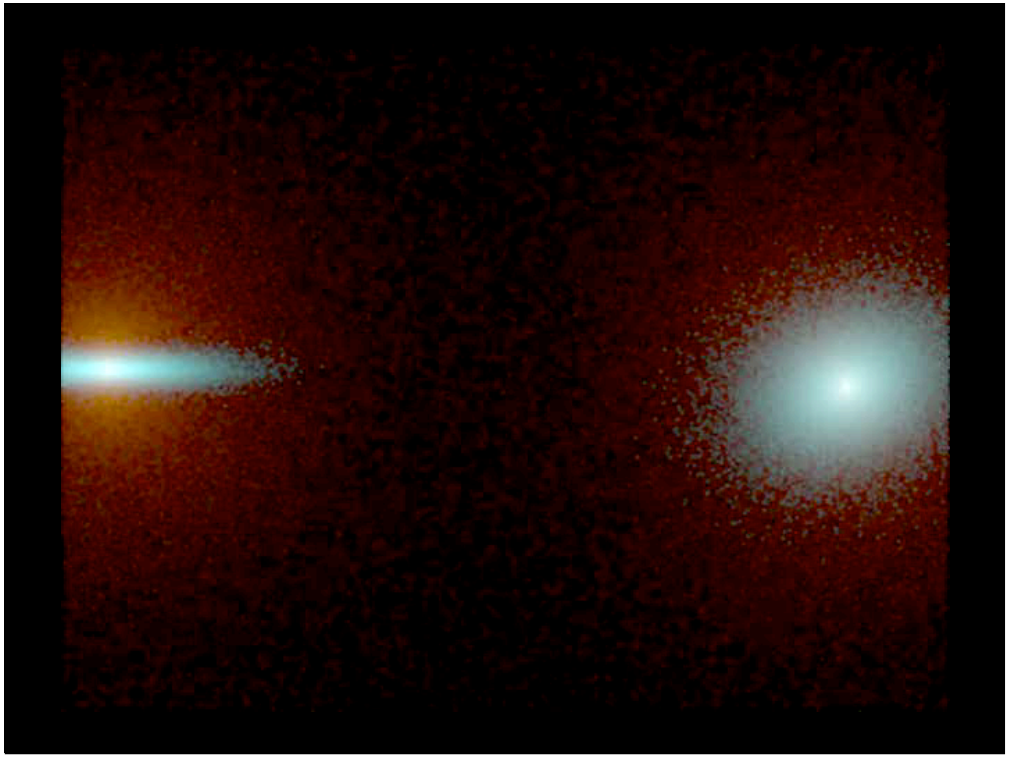
The science of the multiverse: Exploring some key parameters.

(An un-philosophical talk for philosophers)

Martin Rees

the challenges that motivate cosmologists (uncontroversial!)

- What is out there? Cosmic exploration.
- Interpreting phenomena in terms of known (and perhaps ‘new’) physics.
- How, from a ‘simple beginning’, described by a few parameters, did our Universe evolve into its present complexity (stars, planets, people)?
- *Why do the key parameters have their actual values?*
- *Can we understand, at a deeper level, why our Universe is the way it is?*

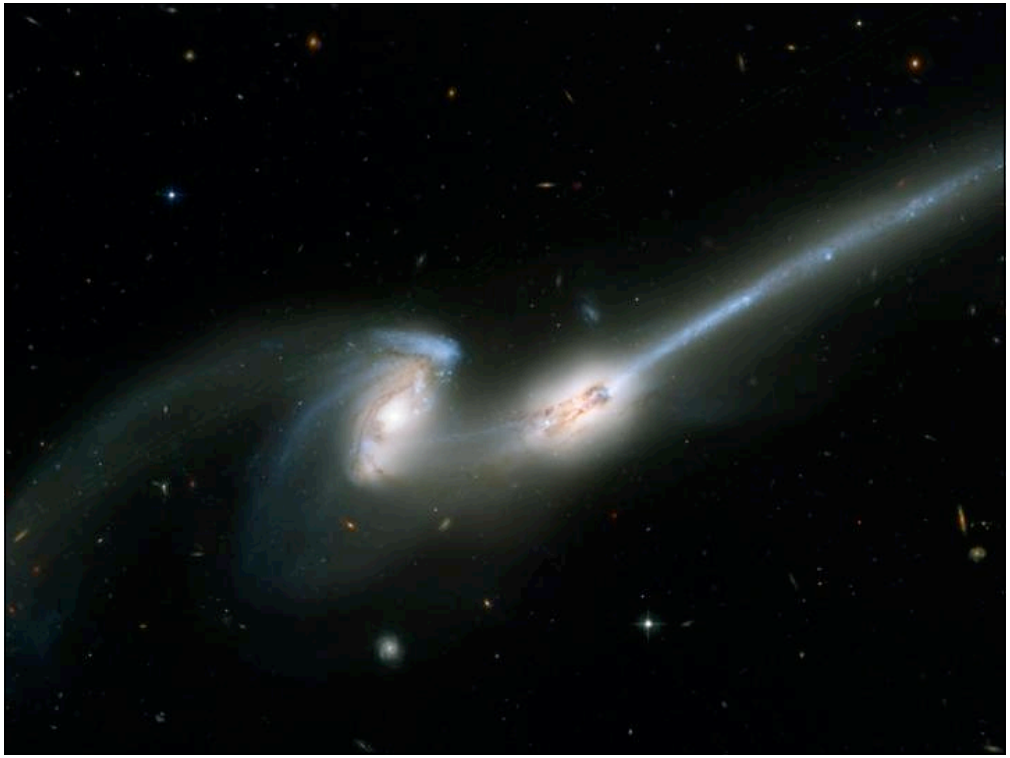


Gallaxy collision movie from the Hawaii Research web site. The red indicates the dark matter making up 80% of the mass.

It simulates the formation of the antennae galaxy collision.

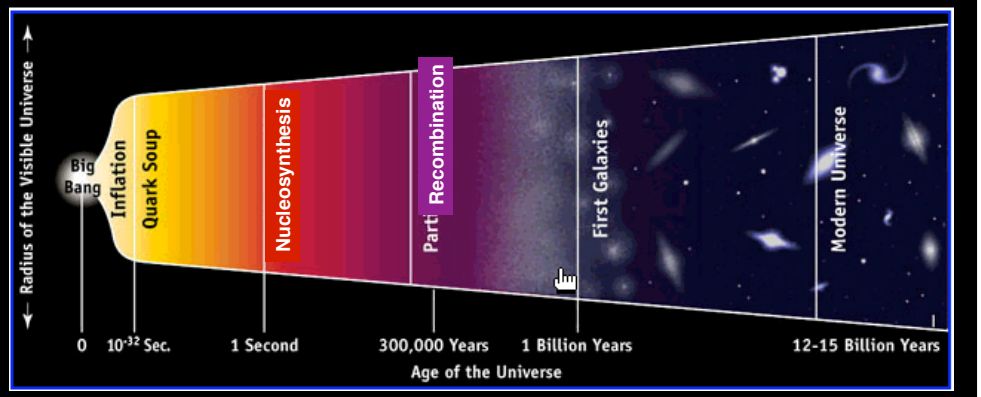
Looks like Antennae half way through

Spanning about 1000 million years



NGC4676 from HST. Galaxies undergoing collision about 160M years after closest approach.
Distnace 420Mly

Cosmic Evolution -Cartoon



Well-understood nonlinear simulations

5 WAYS TO REFUTE "HOT BIG BANG"

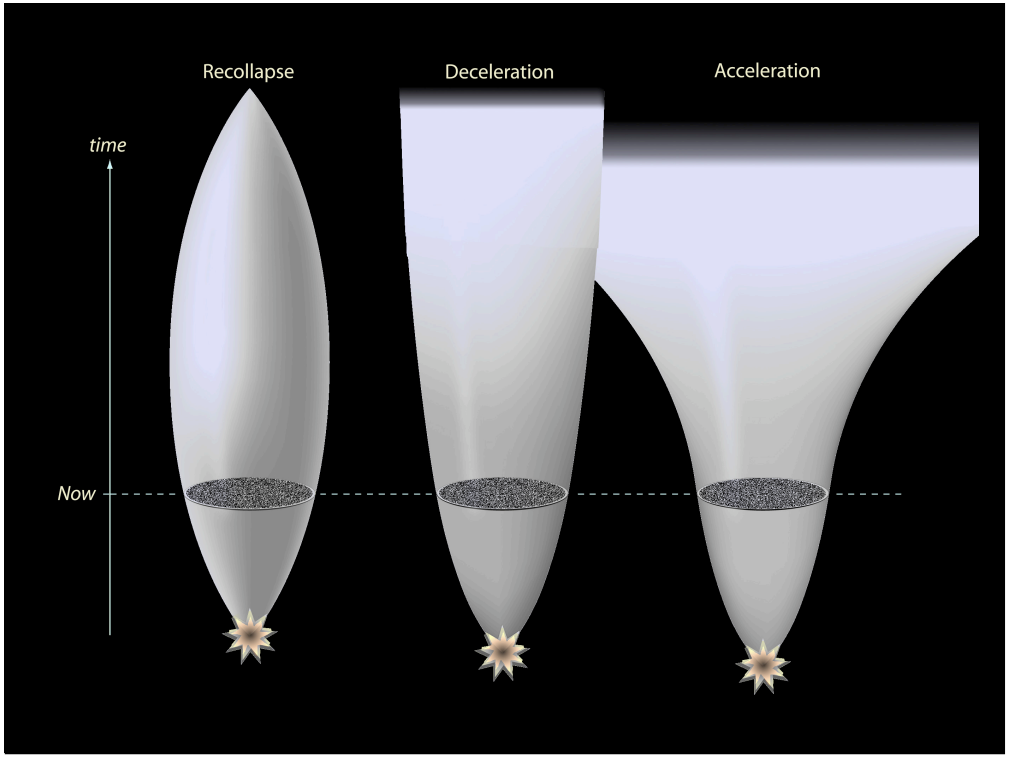
Object with $\ll$23% helium

Millimetre-wave background below prediction

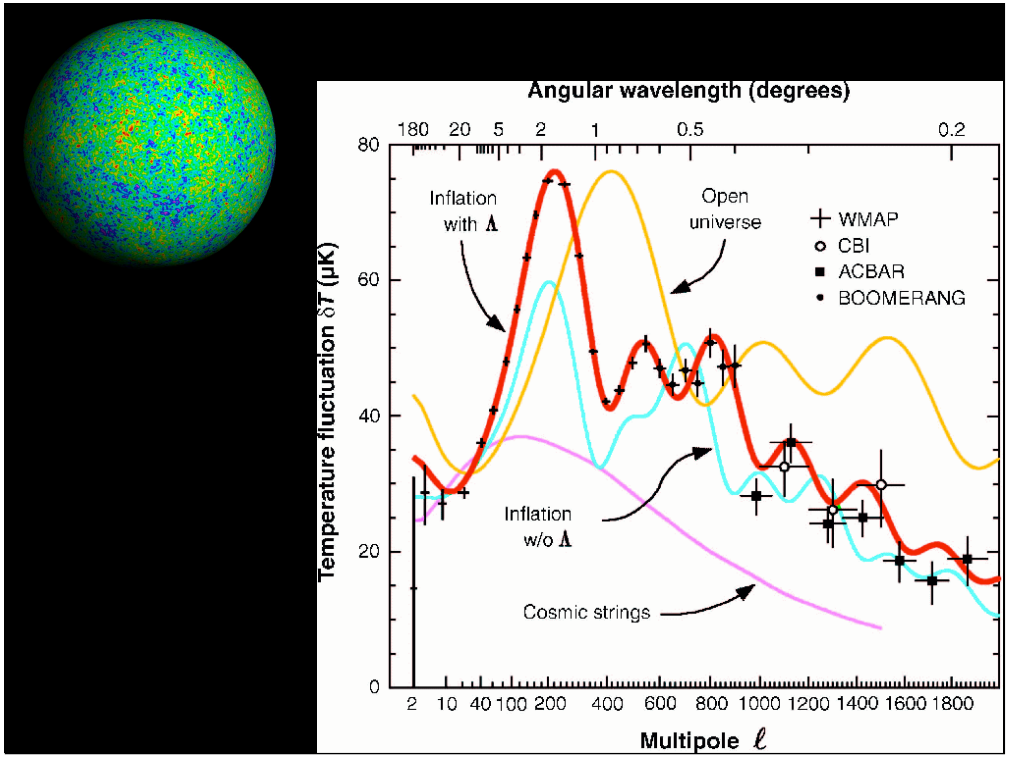
Stable neutrino with mass $100 - 10^6$ eV

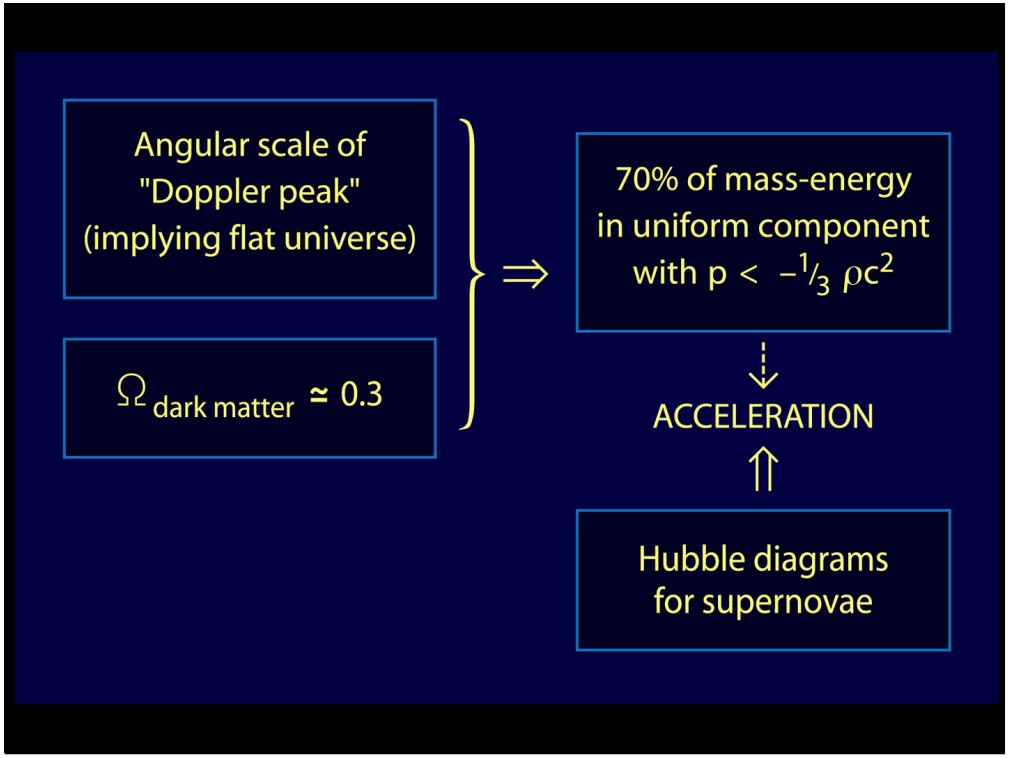
Too much deuterium to match baryon density

$\Delta T/T$ too small to account for present structure

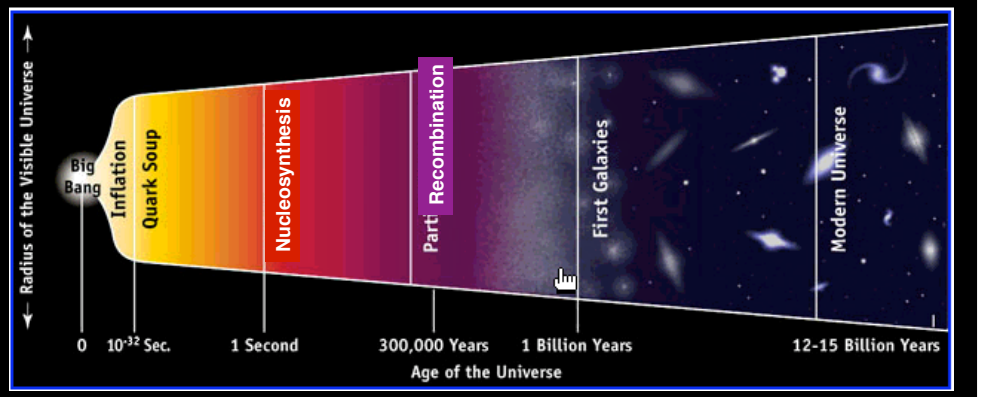

Recollapse
Deceleration
Acceleration
time
Now

Evidence for ‘flatness’ and vacuum energy


Angular wavelength (degrees)
180 20 5 2 1 0.5 0.2
Temperature fluctuation δT (μK)
80
60
40
20
0
Inflation with Λ
Open universe
WMAP
CBI
ACBAR
BOOMERANG
Inflation w/o Λ
Cosmic strings
2 10 40 100 200 400 600 800 1000 1200 1400 1600 1800
Multipole ℓ


Angular scale of
"Doppler peak"
(implying flat universe)
$\Omega_{\text{dark matter}} \simeq 0.3$
$\Rightarrow$
70% of mass-energy
in uniform component
with $p < -\frac{1}{3}\rho c^2$
ACCELERATION
Hubble diagrams
for supernovae

Cosmic Evolution -Cartoon



Well-understood nonlinear simulations

How extensive is the "physical reality" that's within the remit of science?

HOW MUCH LIES BEYOND OUR HORIZON (10^{10} l.y distant)?

Cannot be sure of anything beyond present causal horizon.

Moreover, topology could be complex or 'kaleidoscopic'.

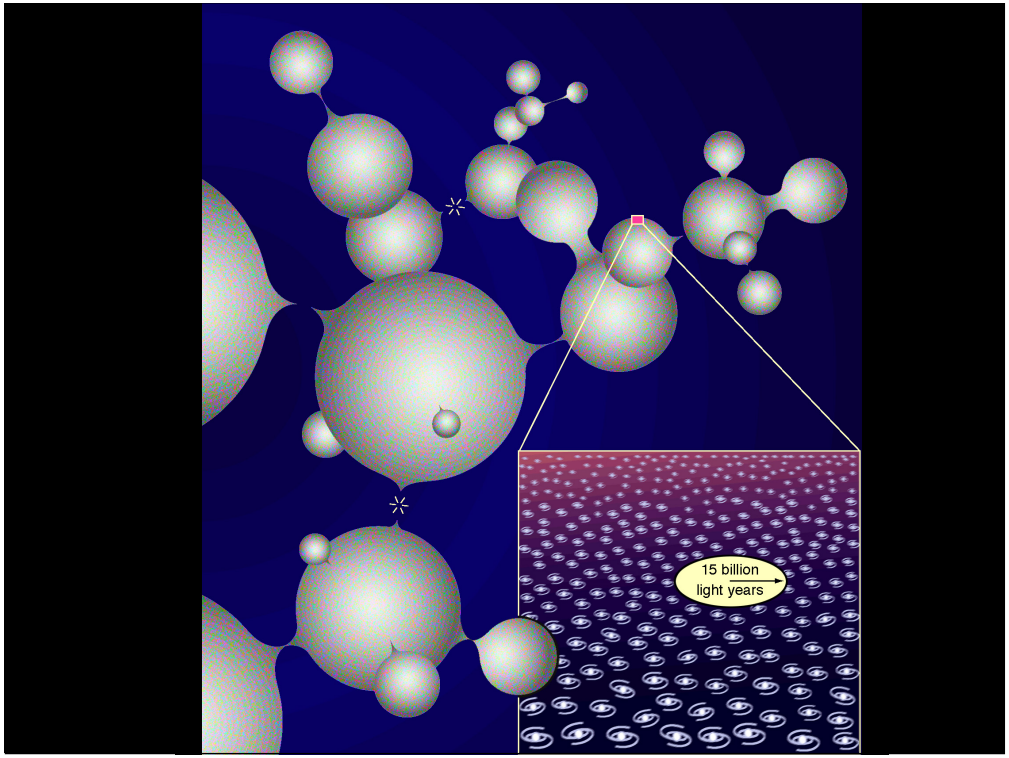
But lack of discernible gradients (in CMB or galaxy counts) across Hubble scale suggest that our universe extends for $> 10^{15}$ l.y

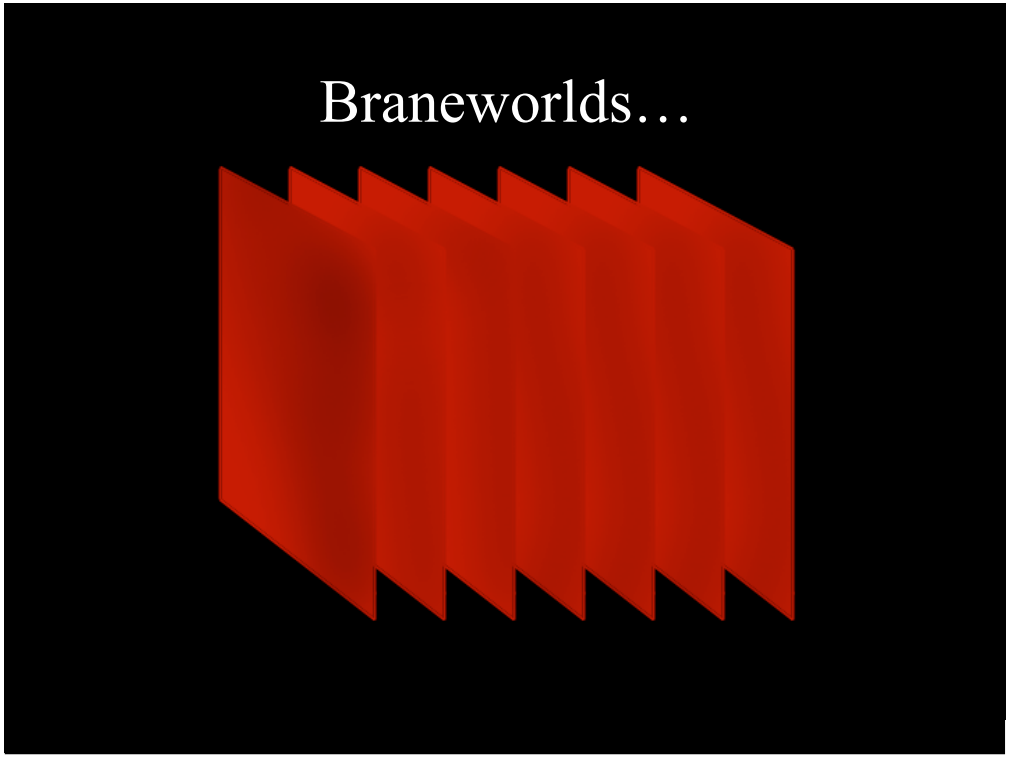
and space could extend $> 10^{100}$ l.y

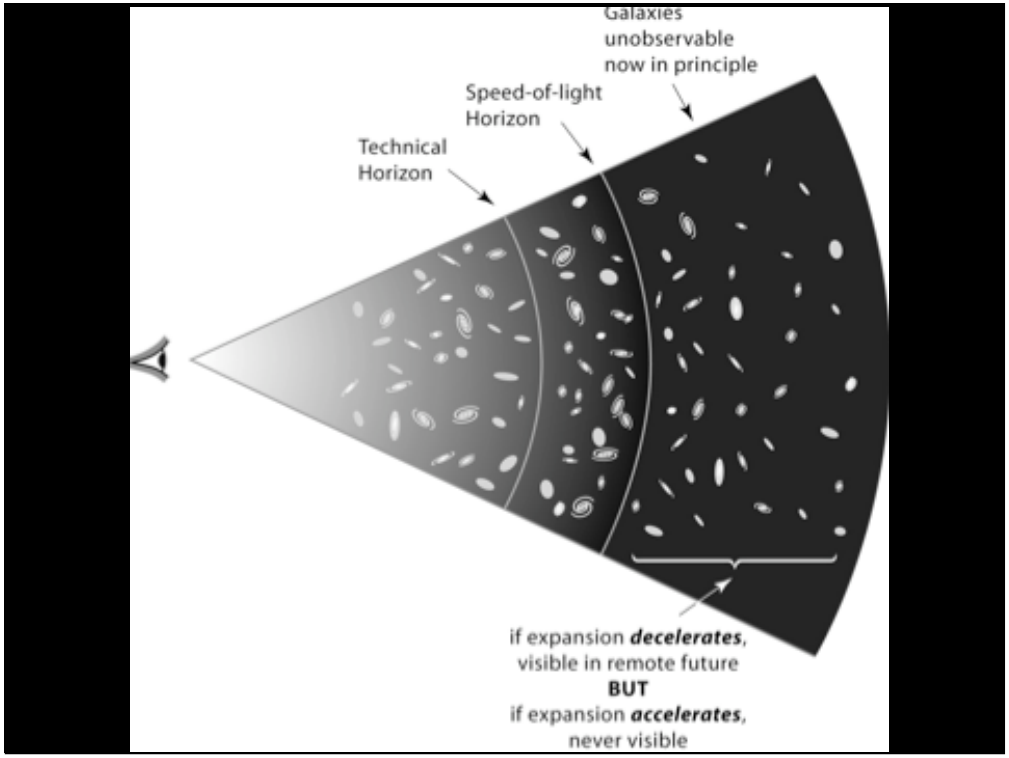
or even >>>>>>

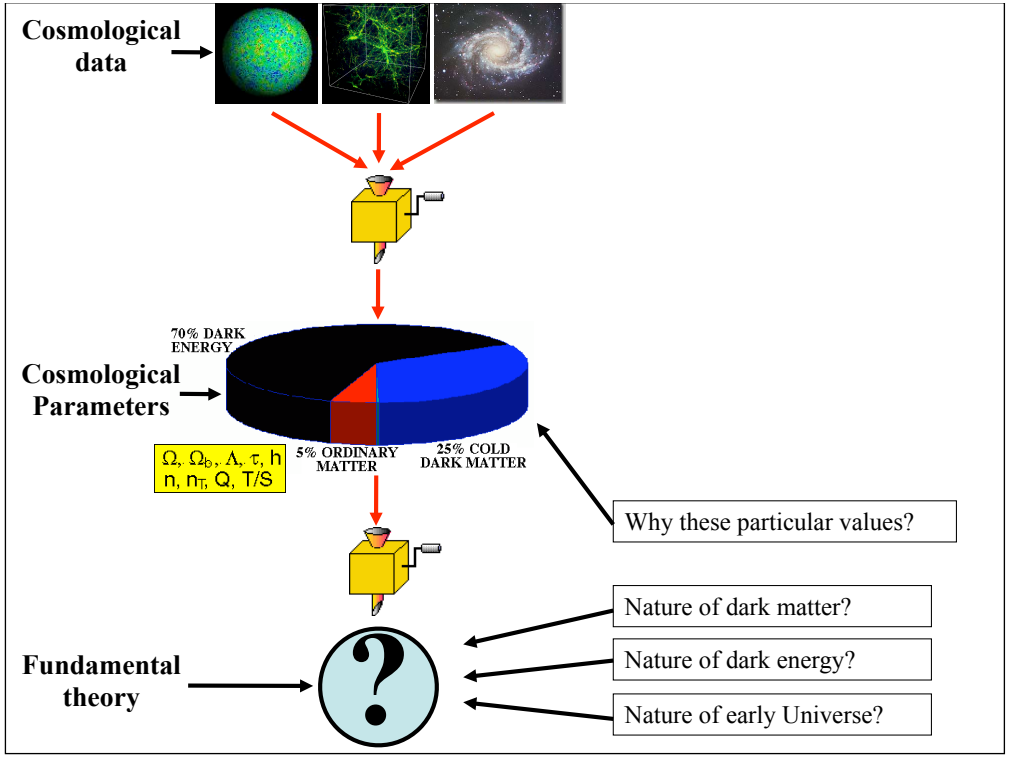
(replicas!)

Moreover, this immensity could be the aftermath of just
one big bang out of many (eternal inflation, braneworlds, etc)


15 billion
light years


Braneworlds…


Galaxies
unobservable
now in principle
Speed-of-light
Horizon
Technical
Horizon
if expansion *decelerates*,
visible in remote future
BUT
if expansion *accelerates*,
never visible


Cosmological data
70% DARK ENERGY
Cosmological Parameters
Ω, Ω_b, Λ, τ, h
n, n_T, Q, T/S
5% ORDINARY MATTER
25% COLD DARK MATTER
Why these particular values?
Nature of dark matter?
Nature of dark energy?
Nature of early Universe?
Fundamental theory
?

BASIC NUMBERS

Density of baryons, dark matter and dark energy
curvature
Q
Coupling constants, etc

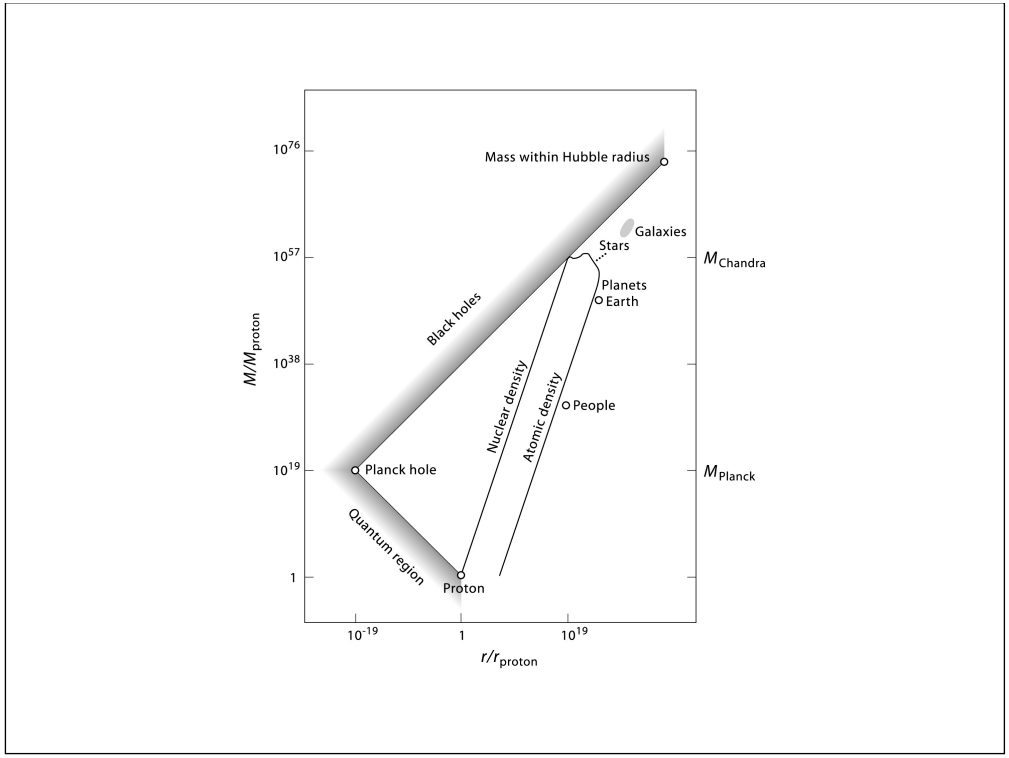
These numbers seem universal over the part of our universe that we can observe.
BUT IF THIS OBSERVED DOMAIN IS ONLY AN INFINITESIMAL FRACTION OF PHYSICAL REALITY MAYBE SOME OF THEM ARE -- IN THIS GRANDER CONTEXT -- NOT TRULY UNIVERSAL?

What part of parameter space allows interesting complexity?

(An exercise in ‘counterfactual history’ -- interesting irrespective of ‘philosophical’ preconceptions. No need to introduce the A-word)

Prerequisites for complex cosmos

- *Gravity -- but the weaker the better (At least one very large number in physics)*


10^{76}
10^{57}
10^{38}
10^{19}
1
M/M_{proton}
Mass within Hubble radius
Galaxies
Stars
Planets
Earth
People
Black holes
Nuclear density
Atomic density
Planck hole
Quantum region
Proton
$M_{Chandra}$
M_{Planck}
10^{-19}
1
10^{19}
r/r_{proton}

Prerequisites for complex cosmos

- *Gravity -- but weaker the better (at least one very large number in physics)*
- *Departures from thermodynamic equilibrium*

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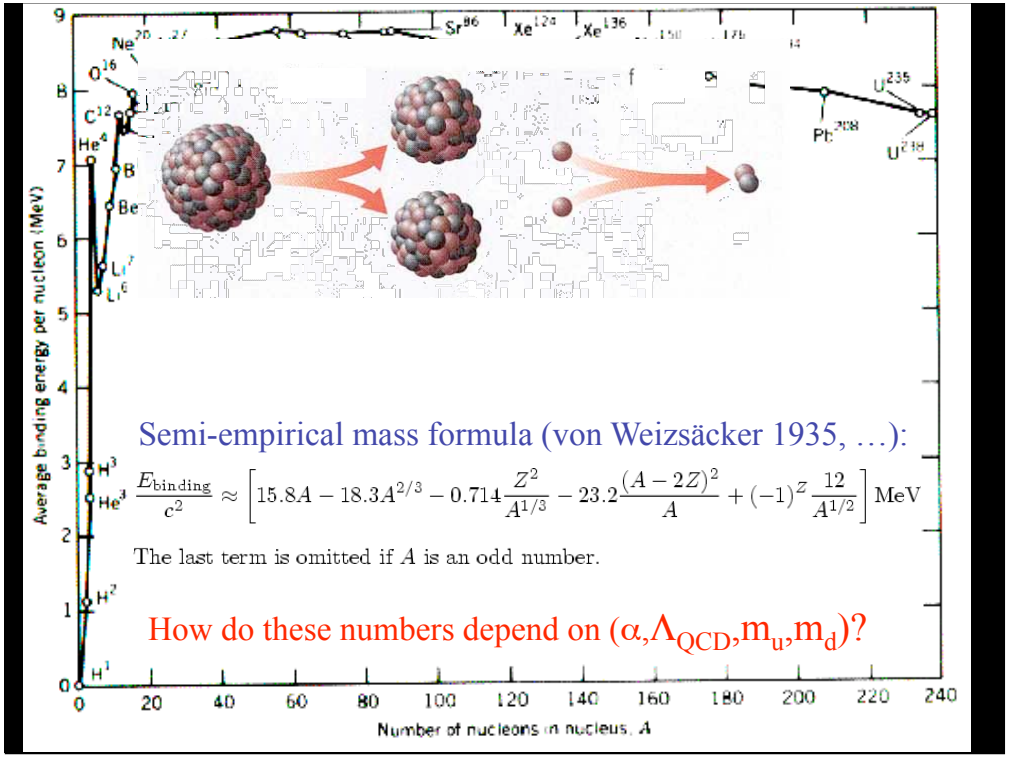
- *Non-trivial chemistry ('tuning' between nuclear and e-m forces)*



Semi-empirical mass formula (von Weizsäcker 1935, …):

$$\frac{E_{\text{binding}}}{c^2} \approx \left[15.8A - 18.3A^{2/3} - 0.714\frac{Z^2}{A^{1/3}} - 23.2\frac{(A-2Z)^2}{A} + (-1)^Z\frac{12}{A^{1/2}}\right] \text{MeV}$$

The last term is omitted if A is an odd number.

How do these numbers depend on $(\alpha, \Lambda_{QCD}, m_u, m_d)$?

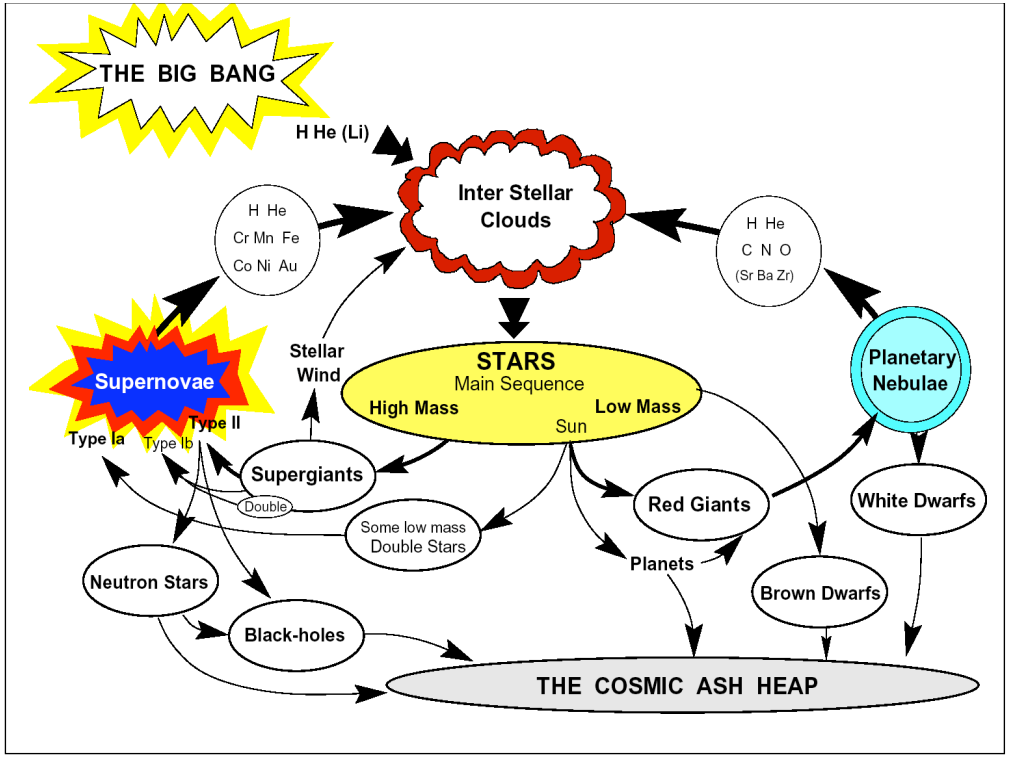
Obviously, at the present time we have more than enough to do in order to understand how the world works the way we find it. But I think ***one must have at least a modicum of curiosity about the strange dimensionless numbers that appear in physics.***

There seem to be ***two lines of attack*** on questions such as these, the ***first*** to demonstrate that the precise numerical values of the dimensionless ***numbers are all entirely necessary to the logical consistency of physics***. The ***second*** point of view is that some, if not all, of the numbers in question are fluctuations; that in ***other places of the universe their values would be different. My inclination is to favour this second point of view. On this second basis the curious placing of the levels in C^{12} and O^{16} need no longer have the appearance of astonishing accidents***. It could simply be that since creatures like ourselves depend on a balance between carbon and oxygen, we can exist only in the portions of the universe where these levels happen to be correctly placed. In other places the level in O^{16} might be a little higher, so that the addition of α-particles to C^{12} was highly resonant. In such a place oxygen would be overwhelmingly more abundant than carbon, and creatures like ourselves could not exist.

Hoyle "Galaxies, Nuclei & Quasars" 1968

Prerequisites for complex cosmos

- *Gravity -- but weaker the better (at least one very large number in physics)*
- *Departures from thermodynamic equilibrium*
- *Matter/antimatter asymmetry*
- *Non-trivial chemistry ('tuning' between nuclear and e-m forces)*
- *At least one star (and '2nd generation' stars?)*


THE BIG BANG
H He (Li)
Inter Stellar Clouds
H He
Cr Mn Fe
Co Ni Au
H He
C N O
(Sr Ba Zr)
Supernovae
Stellar Wind
STARS
Main Sequence
High Mass
Low Mass
Sun
Planetary Nebulae
Type II
Type Ia
Type Ib
Supergiants
Double
Some low mass Double Stars
Red Giants
White Dwarfs
Planets
Neutron Stars
Brown Dwarfs
Black-holes
THE COSMIC ASH HEAP

Prerequisites for complex cosmos

- *Gravity -- but weaker the better (at least one very large number in physics)*
- *Departures from thermodynamic equilibrium*
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- *Non-trivial chemistry ('tuning' between nuclear and e-m forces)*
- *At least one star (and '2nd generation' stars?)*
- *'Tuned' cosmic expansion rate*

Tests of inflation

- ‘flatness’
- Curvature fluctuations close to scale-independent (amplitude Q), but with ‘tilt’ towards large scales
- Tensor/scalar ratio of fluctuation amplitudes non-zero, and a diagnostic of physics in the inflationary era

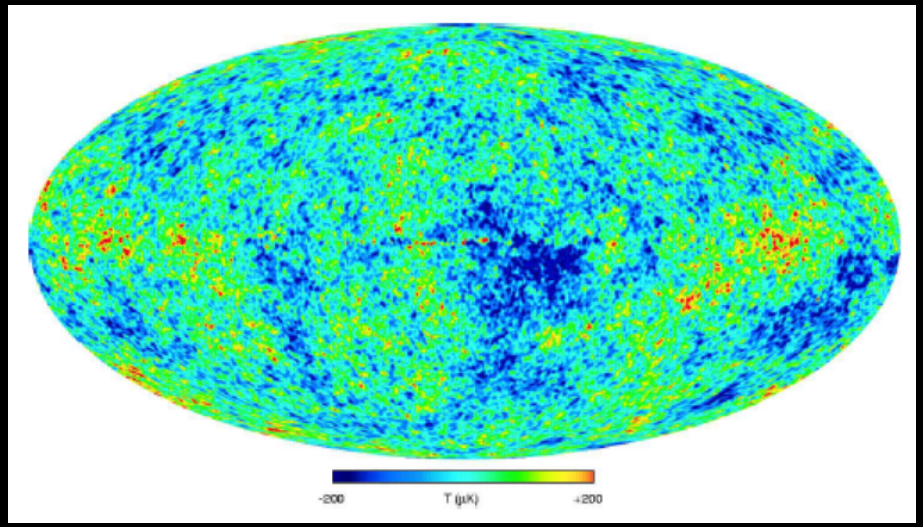
‘Fine tuning’ of lambda

(also ‘fine tuning’ of curvature, but inflation can explain that)

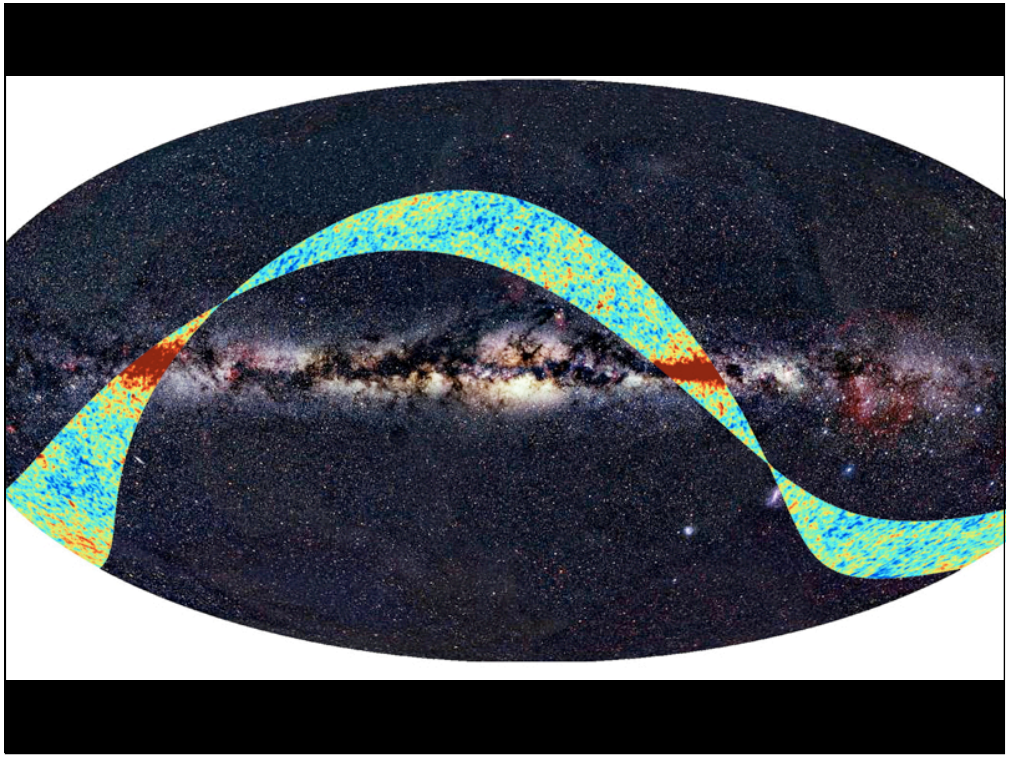
Prerequisites for complex cosmos

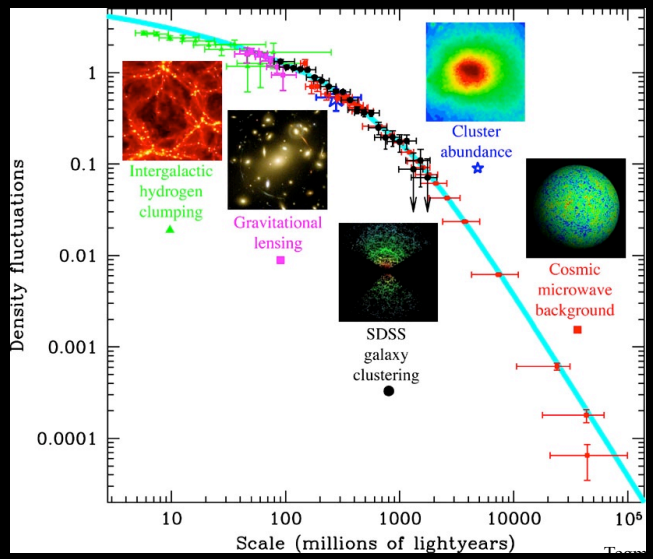
- *Gravity -- but weaker the better (at least one very large number in physics)*
- *Departures from thermodynamic equilibrium*
- *Matter/antimatter asymmetry*
- *Non-trivial chemistry ('tuning' between nuclear and e-m forces)*
- *At least one star (and '2nd generation' stars?)*
- *'Tuned' cosmic expansion rate*
- *Non-zero fluctuations in early universe*

WMAP CBR SKY



Page et al; 2003





We know the DM power spectrum very well!

A fundamental(?) number

The amplitude (Q) of fluctuations in the early universe.

FLUCTUATION AMPLITUDE

$$Q \cong 10^{-5}\left(\sim \frac{\Delta T}{T}\right)$$

→ Bound Systems* with Gravitational Binding Energy QMc^2
(Virial Velocity $Q^{1/2}c$)

Max Non-:Linear Scale

→ $Q^{1/2}$ x (Hubble Radius).

*Formation of Bound System Requires Expansion Factor of >~ Q^{-1} After System Enters Horizon.

AN ANAEMIC UNIVERSE ($Q = 10^{-6}$)

Small loosely-bound galaxies form later than in our universe; star formation is still possible, but processed material is likely to be expelled from shallow potential wells. There may be no second-generation stars containing heavy elements, and so no planetary systems at all.

If Q were significantly lower than 10^{-6}, then gas would be unable to cool with a Hubble time.*

In a Λ-dominated universe, isolated clumps could survive for an infinite time without merging into a larger scale of hierarchy. So eventually, for any $Q > 10^{-8}$, a 'star' could form – but by that time there would be merely one minihalo within the entire event horizon!

UNIVERSE WITH $Q > 10^{-3}$

Monster overdensities (up to 10^{18} $M_{\odot}$) condense out early enough that they trap the CMB radiation, and collapse as radiation-pressure-dominated hypermassive objects unable to fragment*. This leads to universe of vast holes, clustered on scales up to several percent of Hubble radius (and probably pervaded by intense 'hard' radiation).

It isn't obvious that much baryonic material would ever go into stars. (If so they would be in very compact highly bound systems.)

**This does not require pre-combination collapse. Collapse at (say)* 10^7 *years would lead to sufficient partial reionization (via strong shocks) to recouple the baryons and CMB.*

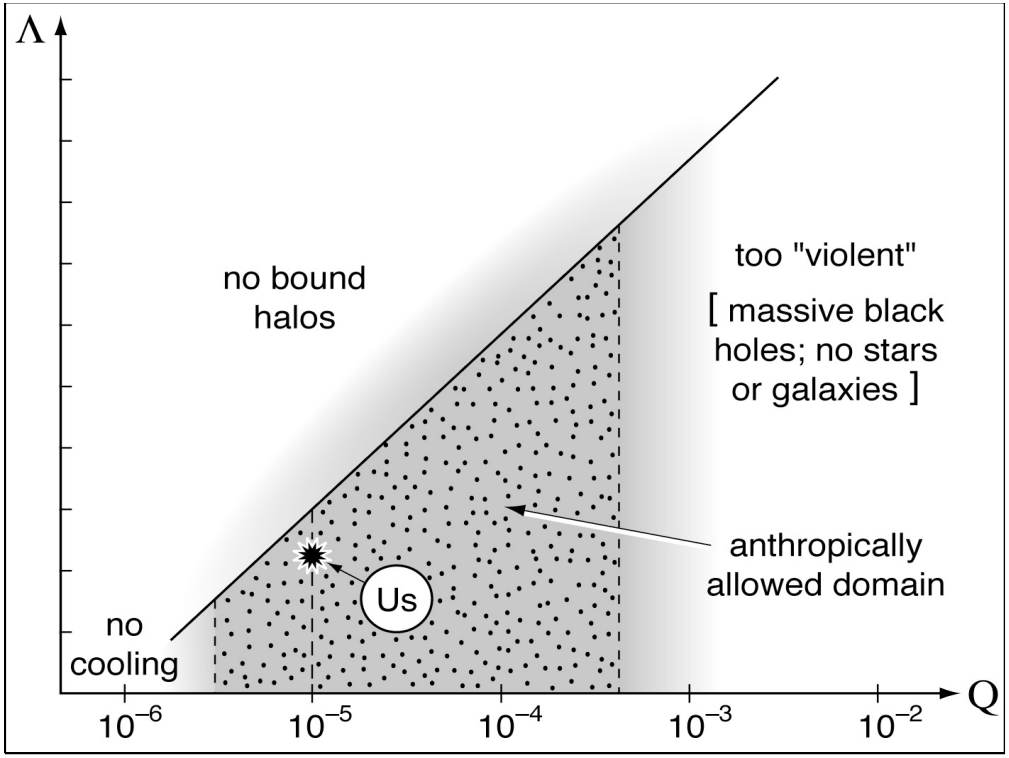
POSSIBLE UNIVERSE WITH $Q = 10^{-4}$

*perhaps more interesting than ours!

Masses $>\sim 10^{14}\ M_\odot$ condense at 3.10^8 yrs into huge disc galaxies with orbital velocity ~2000 km/sec (gas would cool efficiently via Compton cooling, leading probably to efficient star formation).

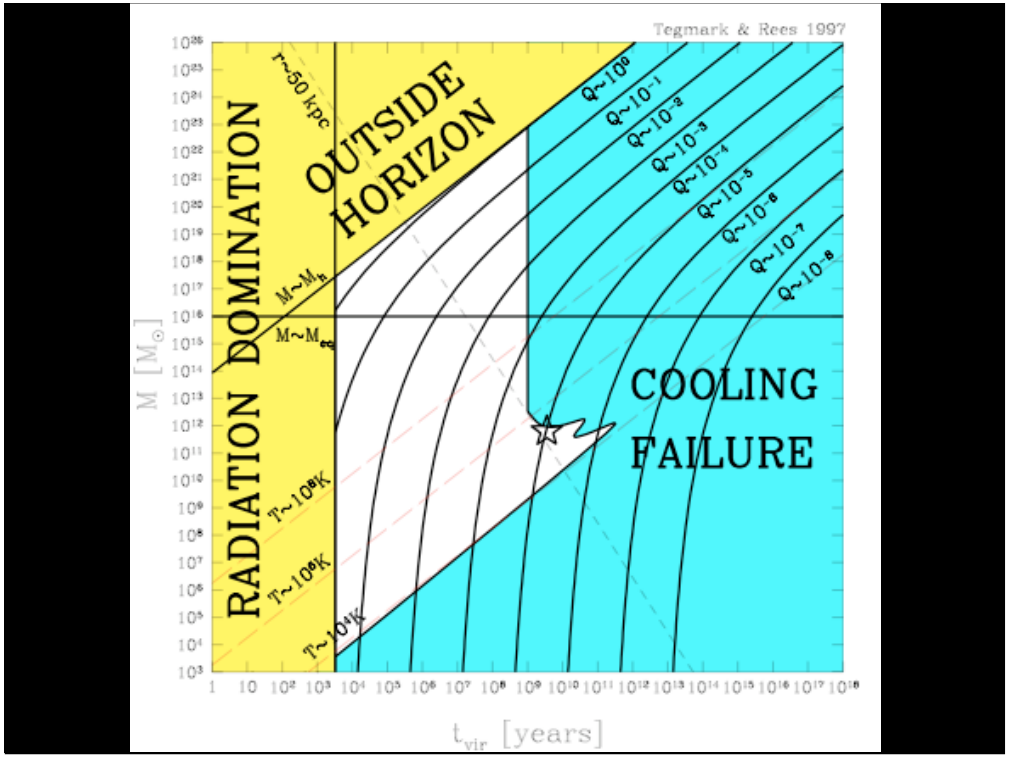
These would, after 10^{10} yrs, be in clusters of
$>\sim 10^{16}\ M_\odot$.

There would be a larger range of non-linear scales than in our actual universe. Only possible 'disfavouring' feature is that stellar systems may be too packed together to permit unperturbed planetary orbits.

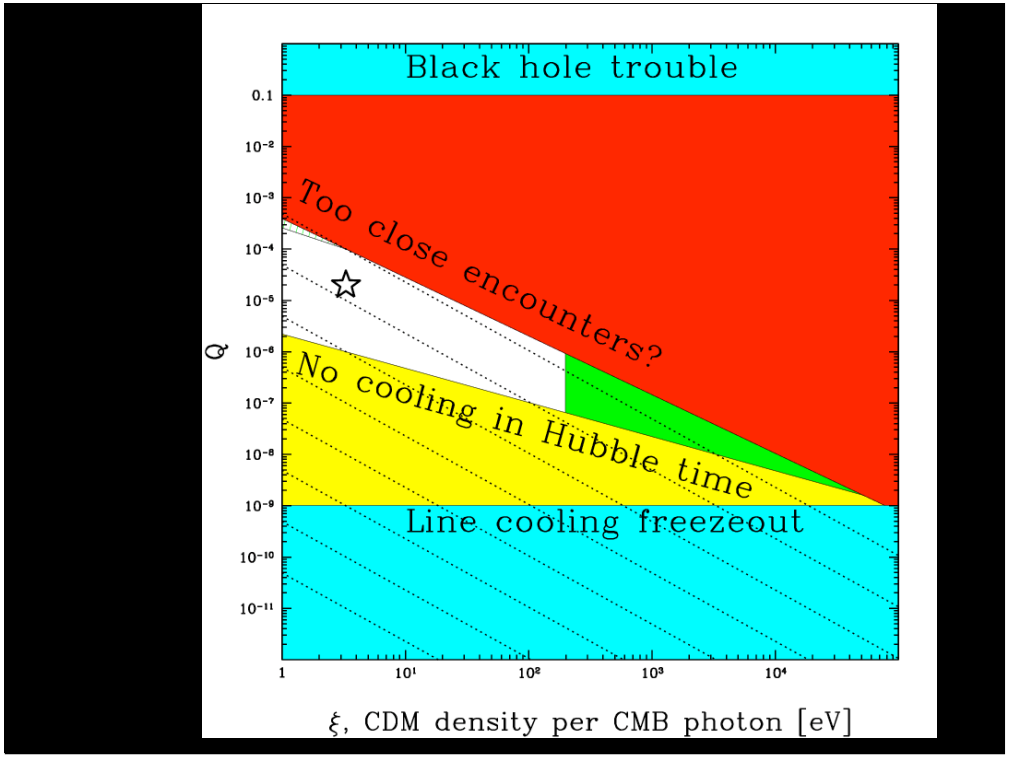

Λ
no bound
halos
too "violent"
[massive black
holes; no stars
or galaxies]
anthropically
allowed domain
Us
no
cooling
Q
10^−6
10^−5
10^−4
10^−3
10^−2

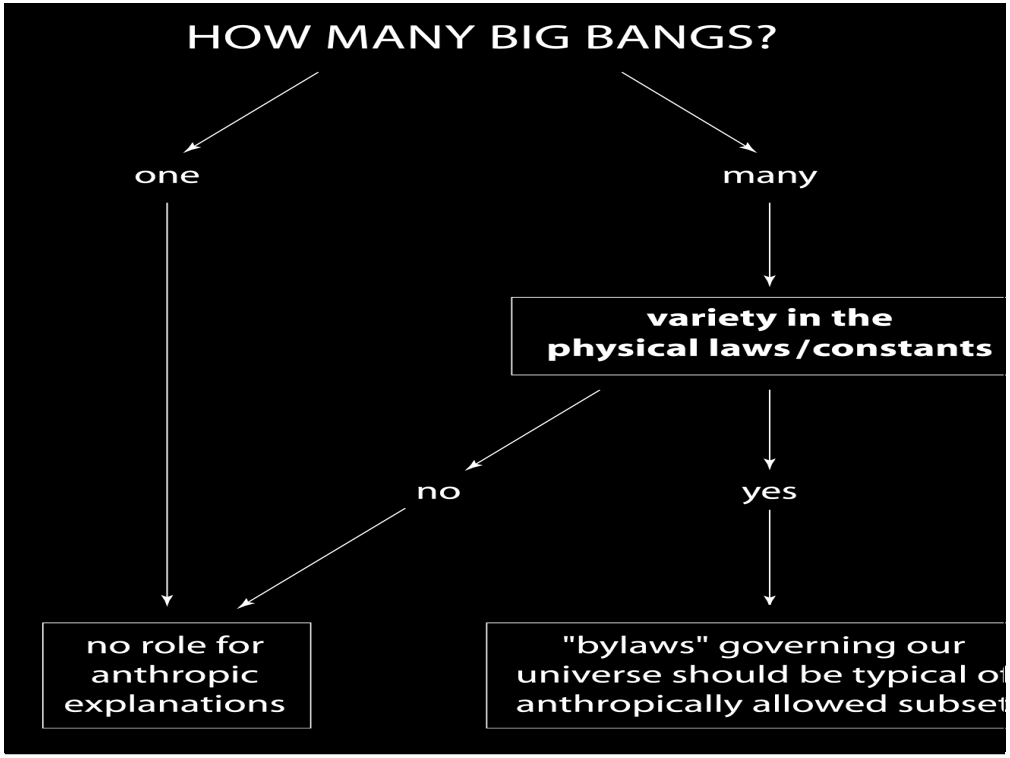
Another fundamental(?) number; dark matter mass per photon

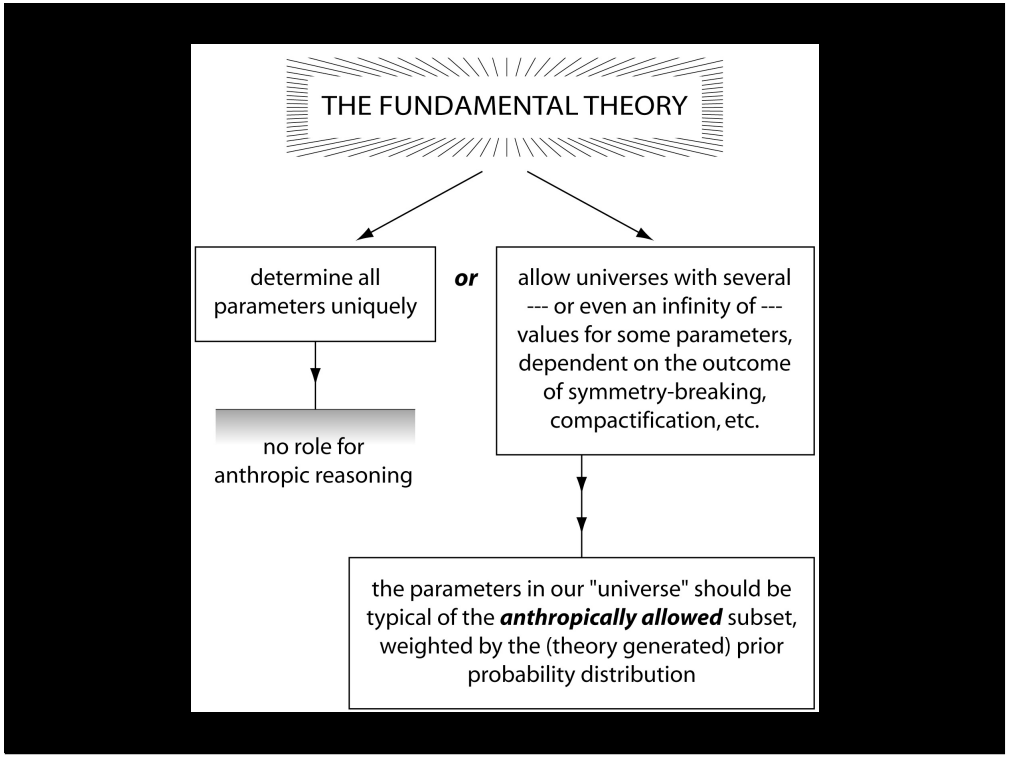
- Affects growth factor and present-day mass spectrum of CDM fluctuations for given Q
- Affects baryon/dark matter density ratio in halos
- *(If dark matter is axions, the prior distribution of this number is known).*


Tegmark & Rees 1997
OUTSIDE HORIZON
RADIATION DOMINATION
COOLING FAILURE
r~50 kpc
M~M_h
M~M_eq
T~10^8K
T~10^6K
T~10^4K
Q~10^0
Q~10^-1
Q~10^-2
Q~10^-3
Q~10^-4
Q~10^-5
Q~10^-6
Q~10^-7
Q~10^-8
M [M_⊙]
t_vir [years]

Constraint	Generally
Need nonlinear halos	$\lvert\rho_\Lambda\rvert \lesssim \rho_*$
Avoid line cooling freezeout	$Q \gtrsim \alpha^2\beta$
Primordial black hole excess	$Q \lesssim 10^{-1}$
Need cooling in Hubble time	$Q^3\xi_b^2\xi^2 \gtrsim \alpha^{-3}\ln[\alpha^{-2}]^{-16/3}\beta^4 m_p^6/125$
Avoid close encounters	
Go nonlinear after decoupling	$\xi Q \lesssim 10^{-3}\alpha^2\beta m_p$
Need equality before decoupling?	$\xi \gtrsim 0.05\alpha^2\beta m_p$
Avoid severe Silk damping	$f_b \lesssim 1/2$
Need disk instability	$f_b \gtrsim 10^2$

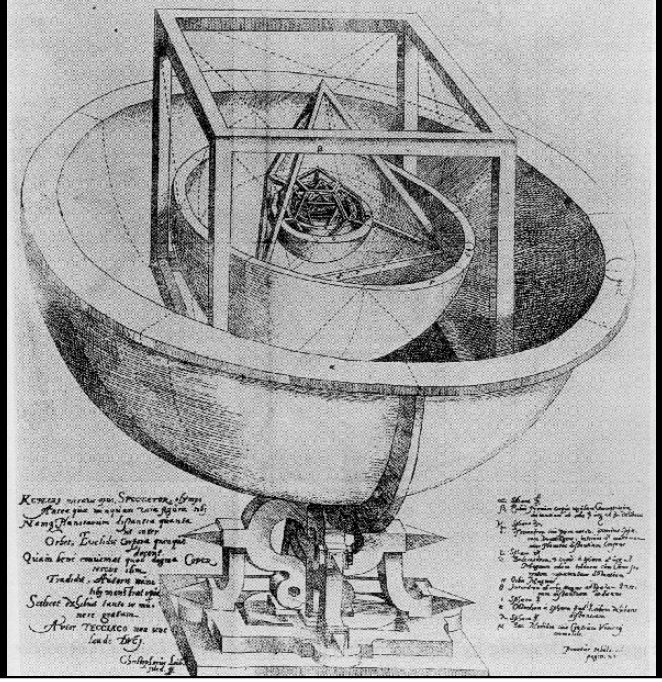

Black hole trouble
Too close encounters?
No cooling in Hubble time
Line cooling freezeout
Q
0.1
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
1
10¹
10²
10³
10⁴
ξ, CDM density per CMB photon [eV]

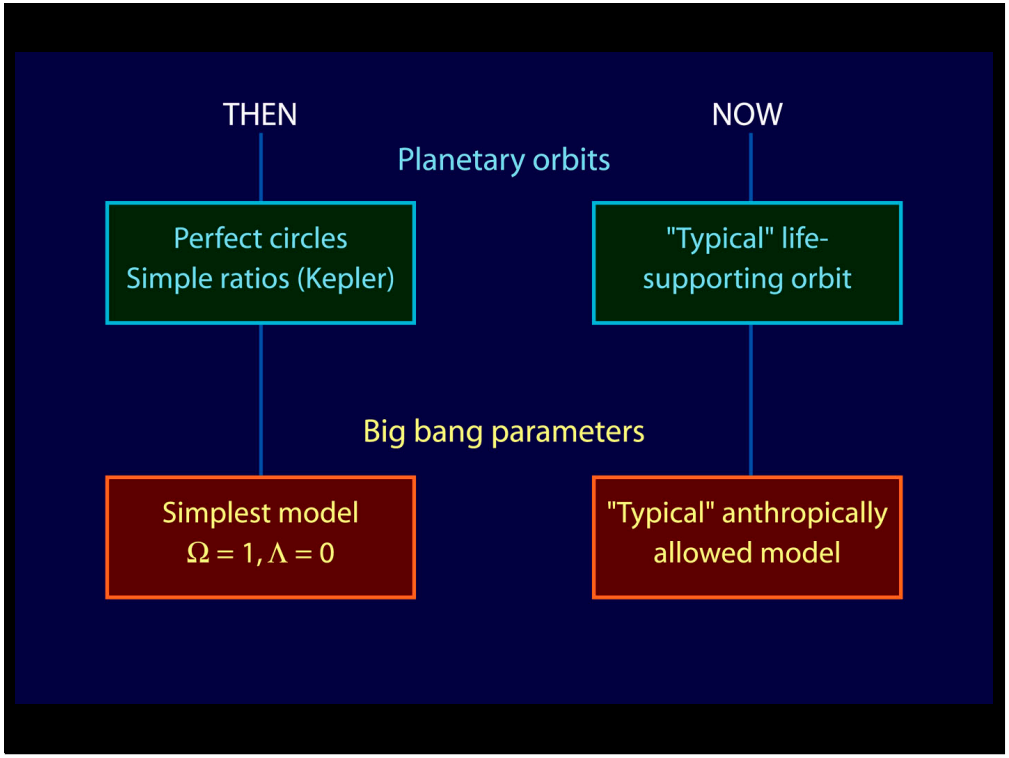

HOW MANY BIG BANGS?
one
many
variety in the physical laws /constants
no
yes
no role for anthropic explanations
"bylaws" governing our universe should be typical of anthropically allowed subset

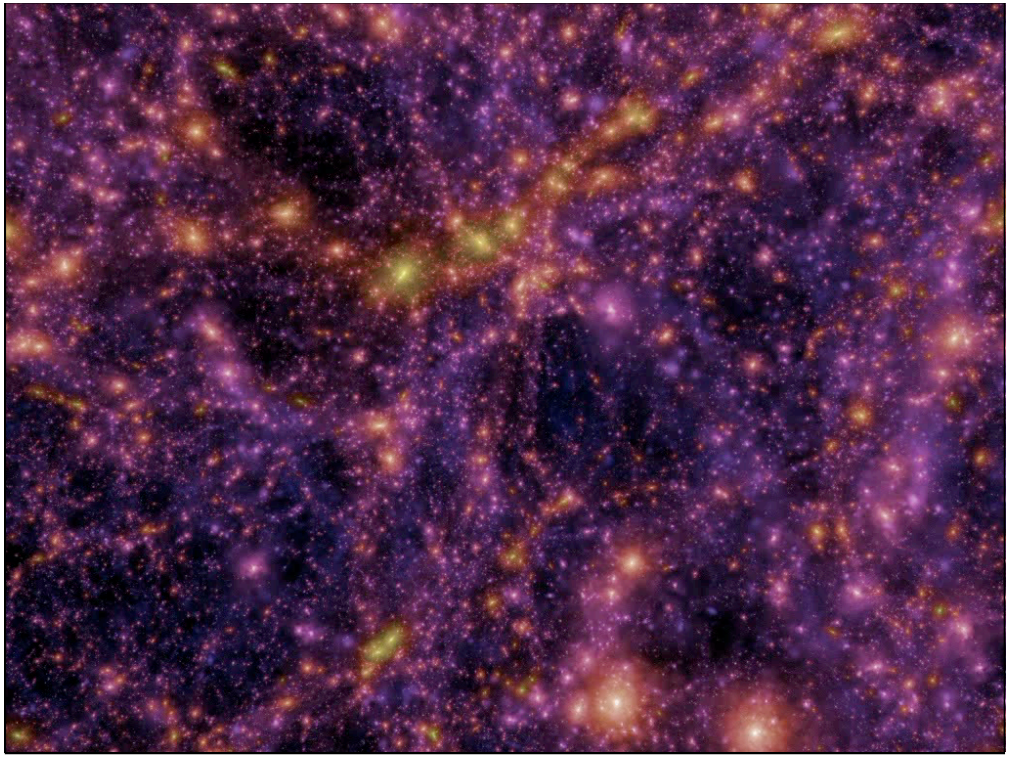

THE FUNDAMENTAL THEORY
determine all parameters uniquely
or
allow universes with several --- or even an infinity of --- values for some parameters, dependent on the outcome of symmetry-breaking, compactification, etc.
no role for anthropic reasoning
the parameters in our "universe" should be typical of the anthropically allowed subset, weighted by the (theory generated) prior probability distribution

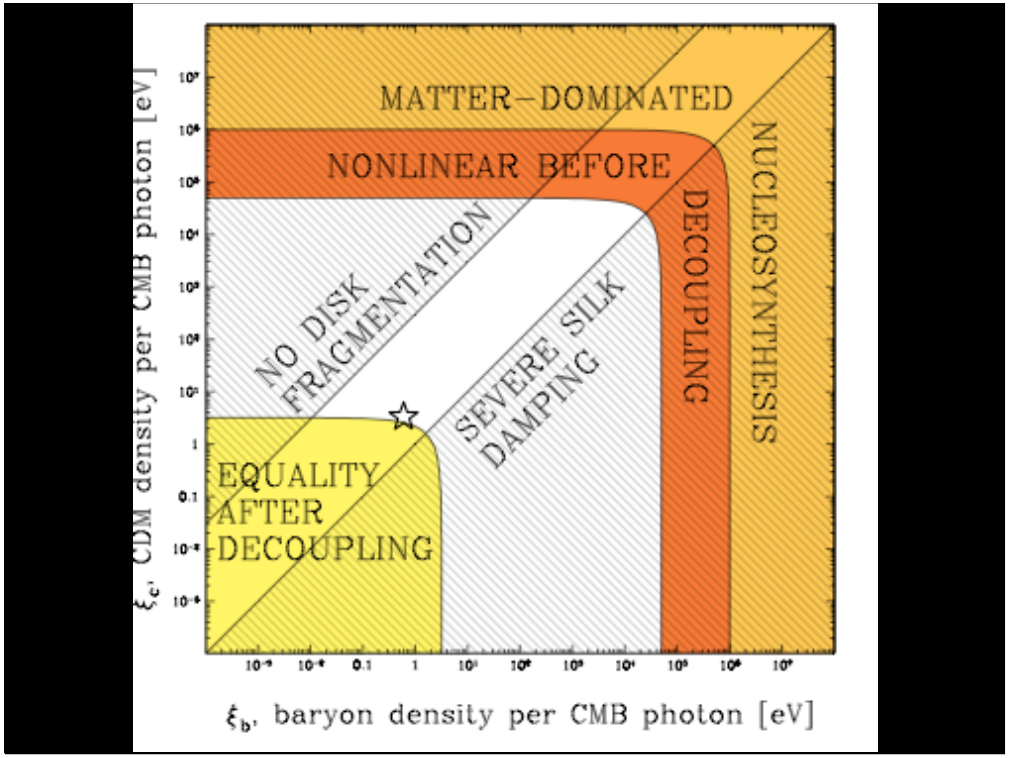
TABVLA III. ORBIVM PLANETARVM DIMENSIONES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA GEOMETRICA EXHIBENS.

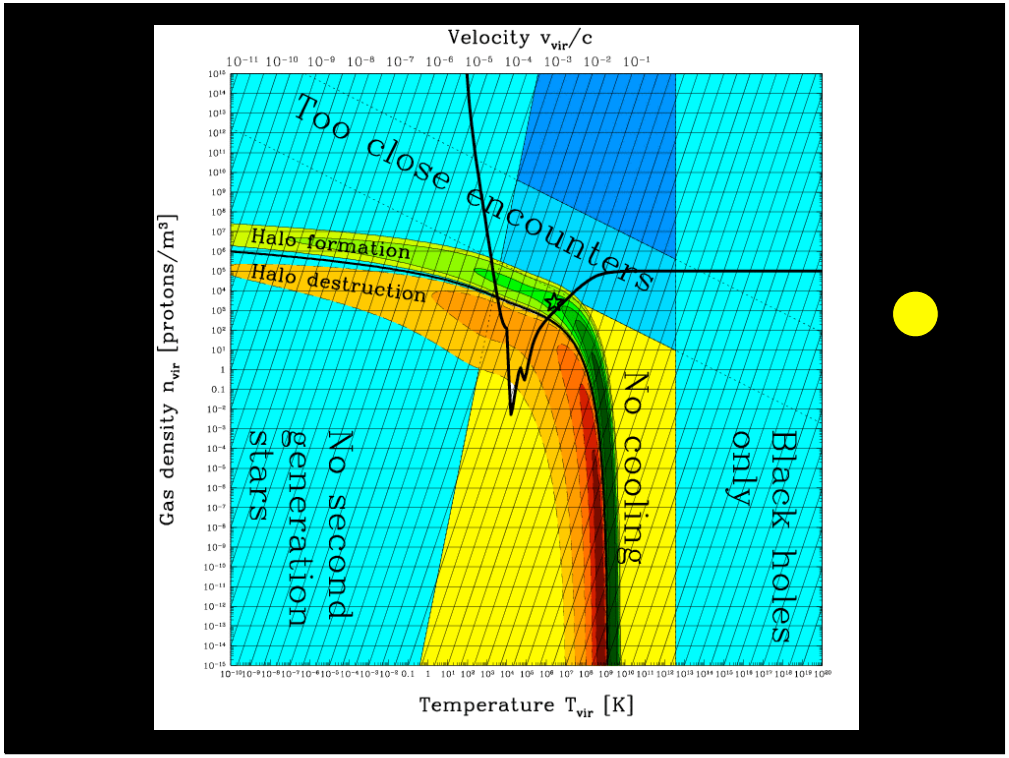
ILLVSTRISS.^MI PRINCIPI, AC DNO. DNO. FRIDERICO, DVCI WIRTENBERGICO, ET TECCIO, COMITI MONTIS BELGARVM, ETC. CONSECRATA.

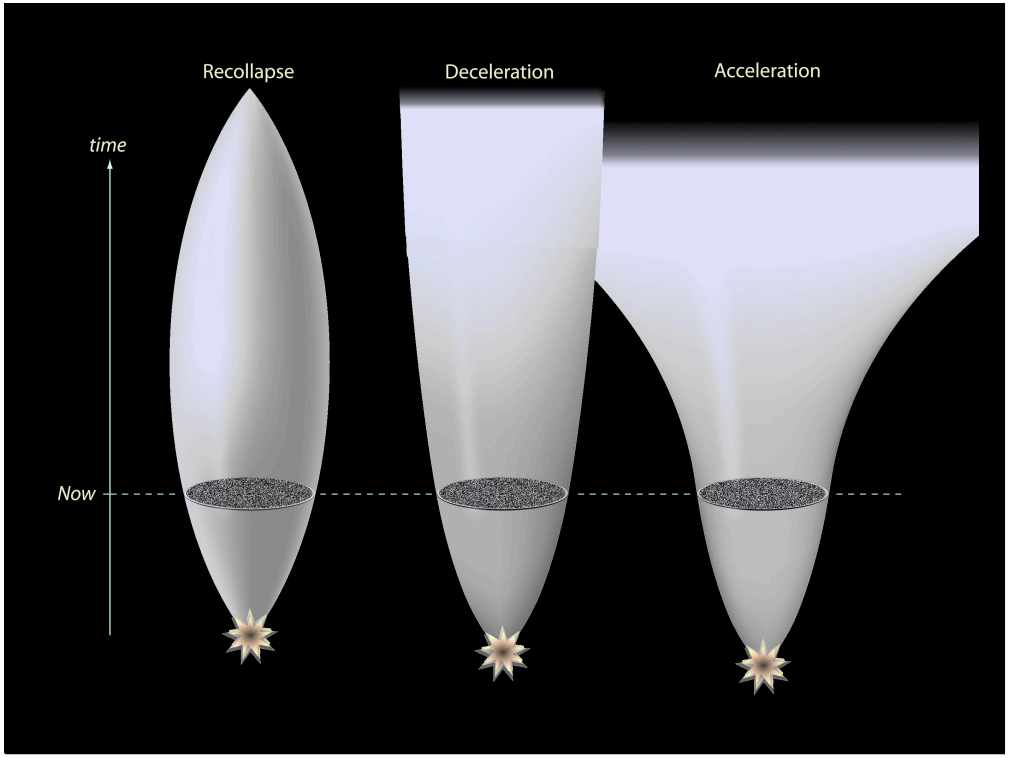


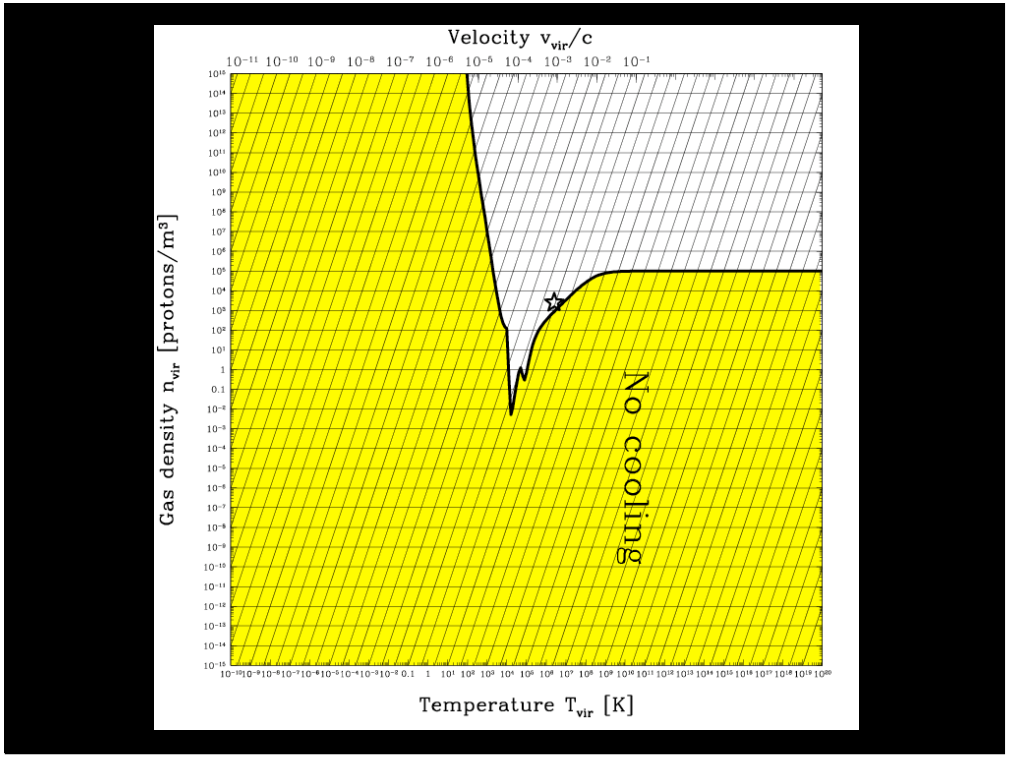

THEN
NOW
Planetary orbits
Perfect circles
Simple ratios (Kepler)
"Typical" life-supporting orbit
Big bang parameters
Simplest model
$\Omega = 1, \Lambda = 0$
"Typical" anthropically allowed model

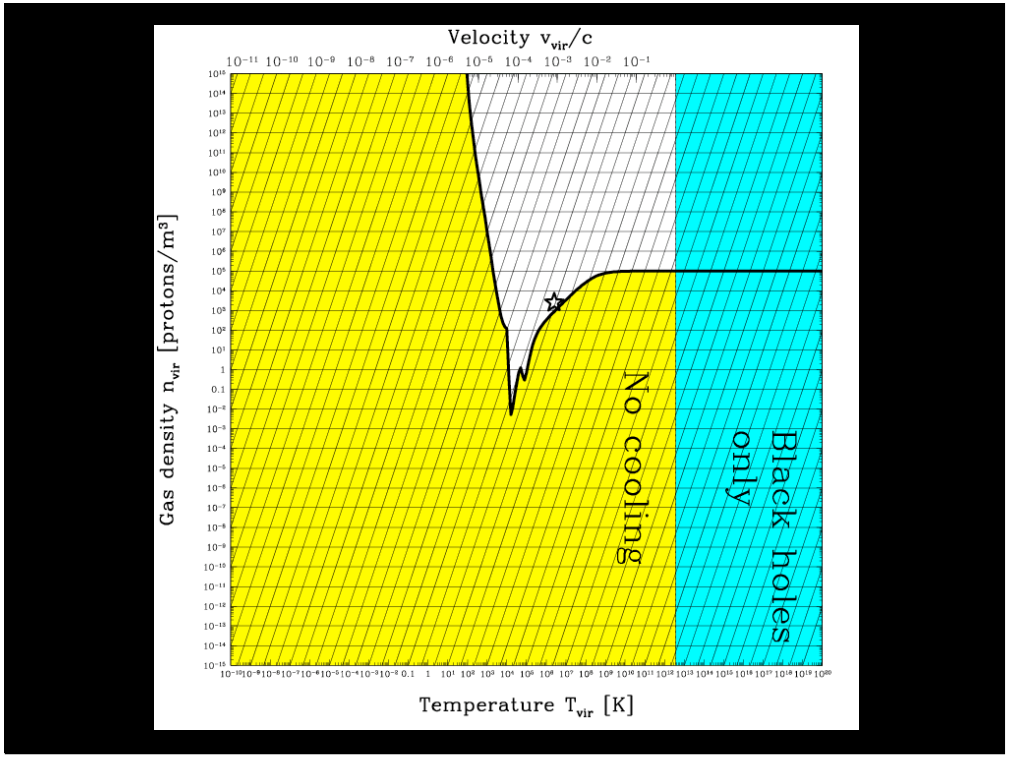


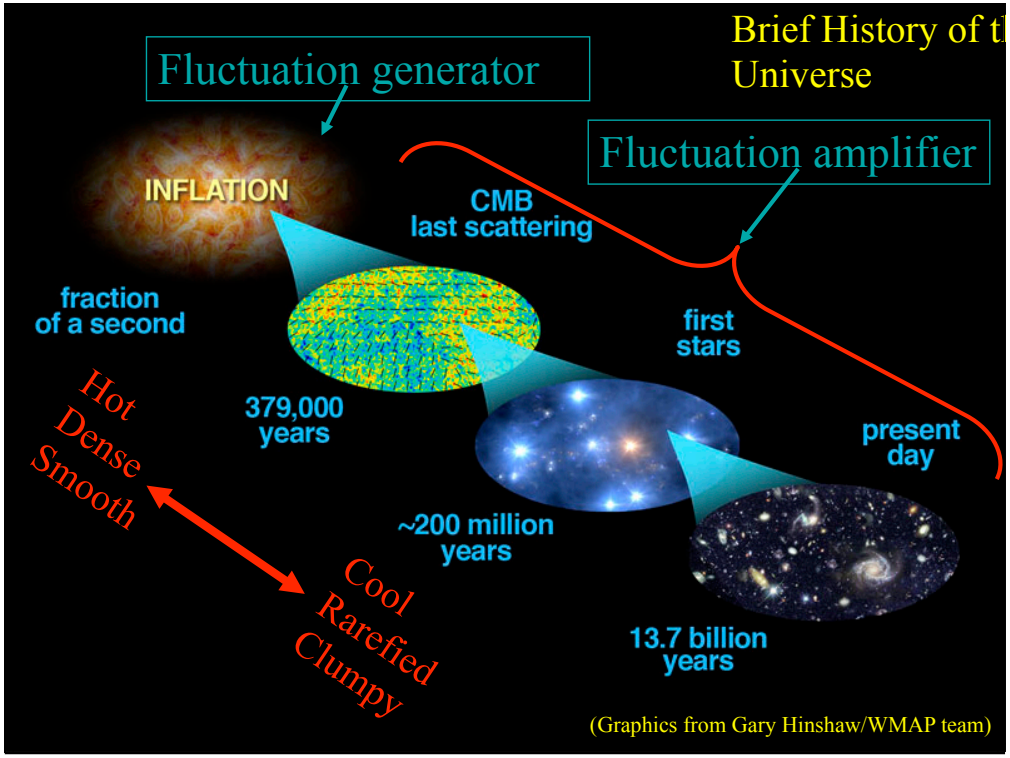

MATTER−DOMINATED
NONLINEAR BEFORE
DECOUPLING
NUCLEOSYNTHESIS
NO DISK FRAGMENTATION
SEVERE SILK DAMPING
EQUALITY AFTER DECOUPLING
ξ_c, CDM density per CMB photon [eV]
ξ_b, baryon density per CMB photon [eV]

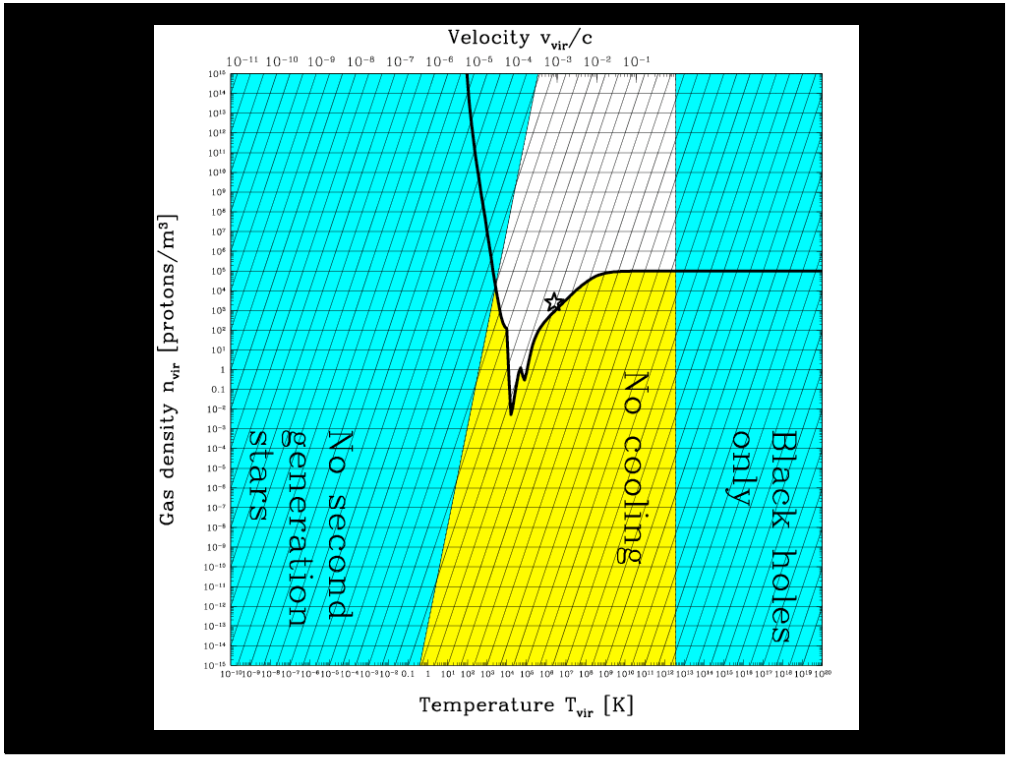

Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
Too close encounters
Halo formation
Halo destruction
No second generation stars
No cooling
Black holes only

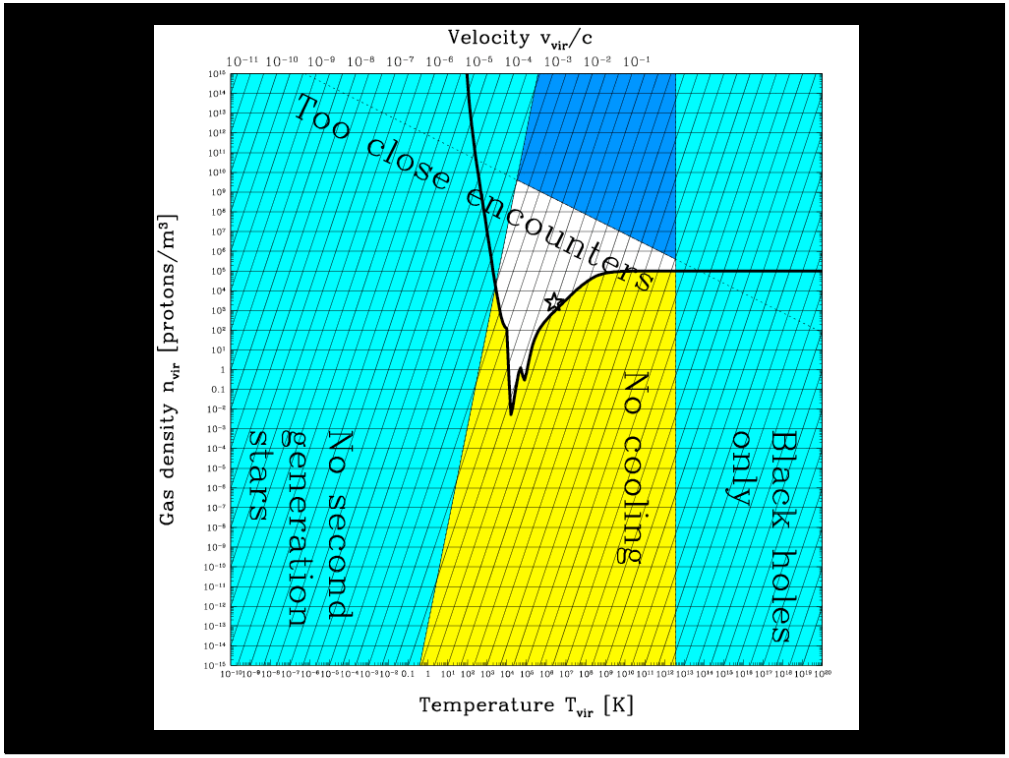

Recollapse
Deceleration
Acceleration
time
Now

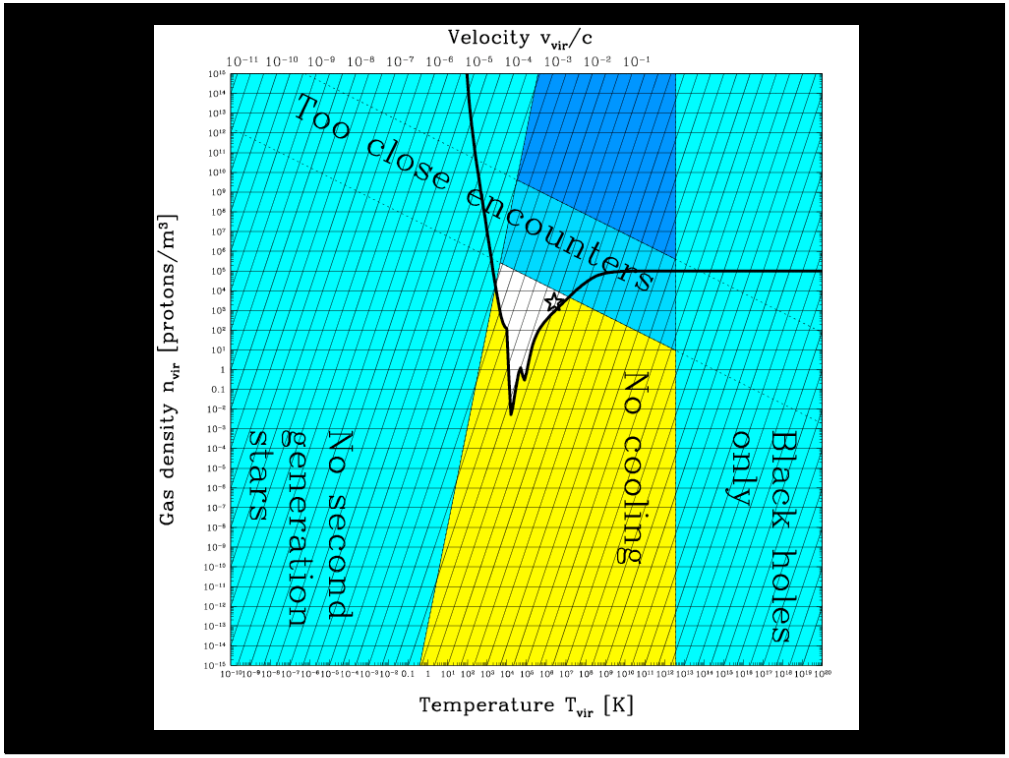

Velocity v_{vir}/c
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
Gas density n_{vir} [protons/m^3]
No cooling
Temperature T_{vir} [K]

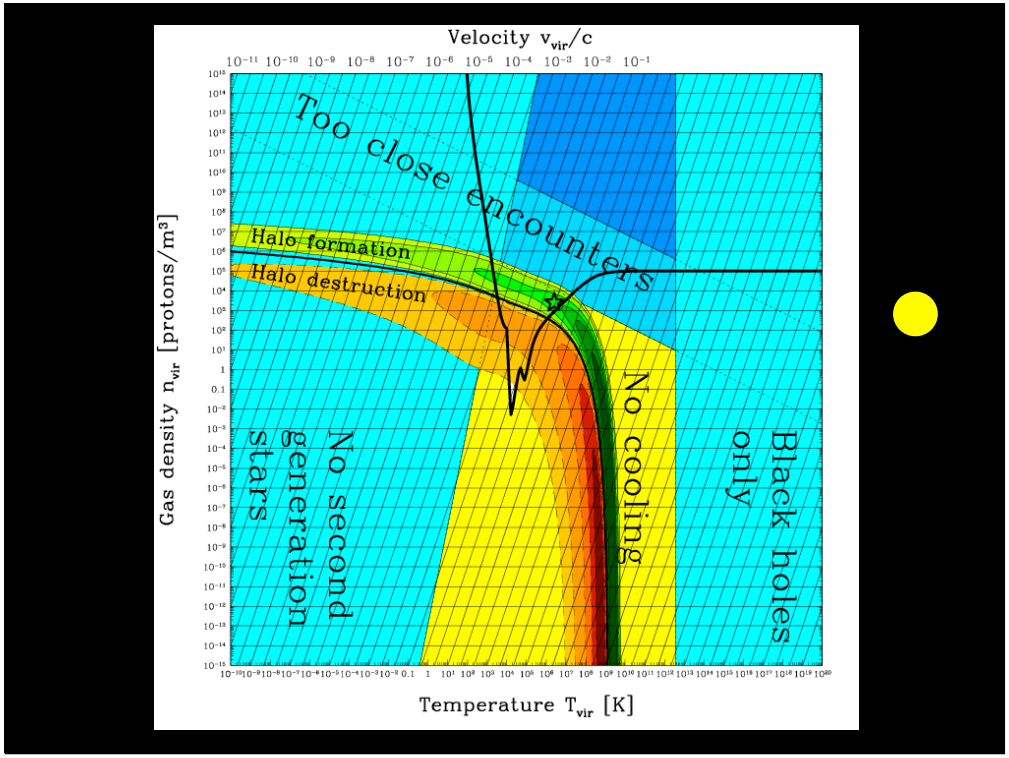

Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
No cooling
Black holes only

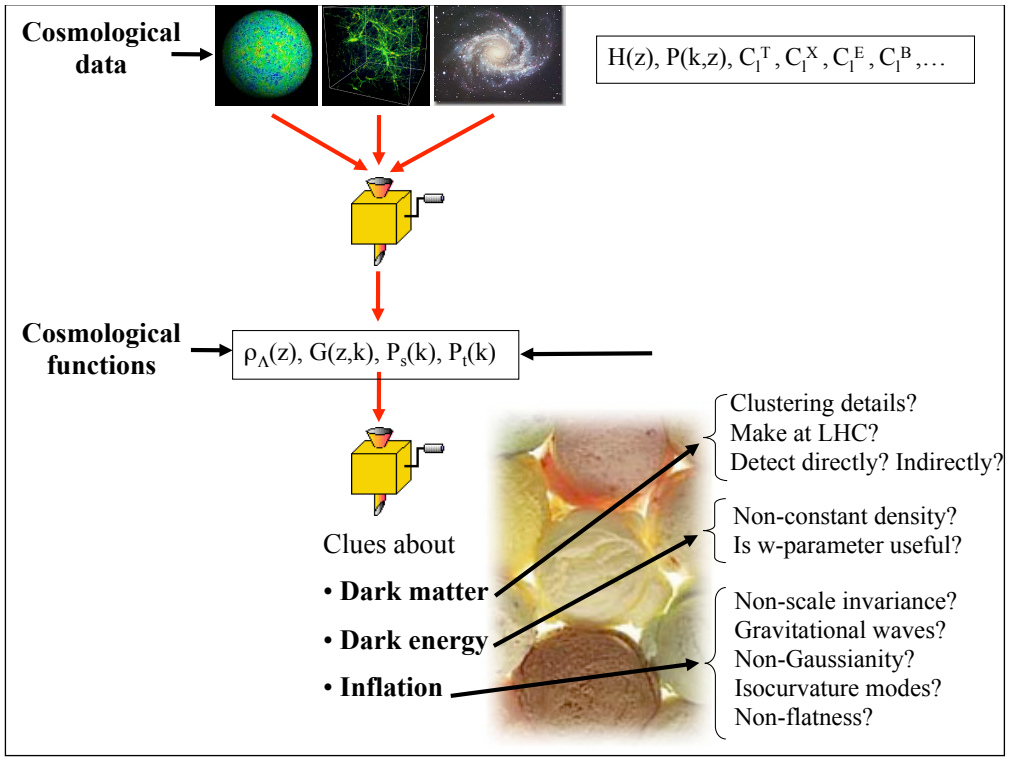

Brief History of t
Universe
Fluctuation generator
Fluctuation amplifier
INFLATION
CMB
last scattering
fraction
of a second
first
stars
379,000
years
present
day
Hot
Dense
Smooth
~200 million
years
Cool
Rarefied
Clumpy
13.7 billion
years
(Graphics from Gary Hinshaw/WMAP team)

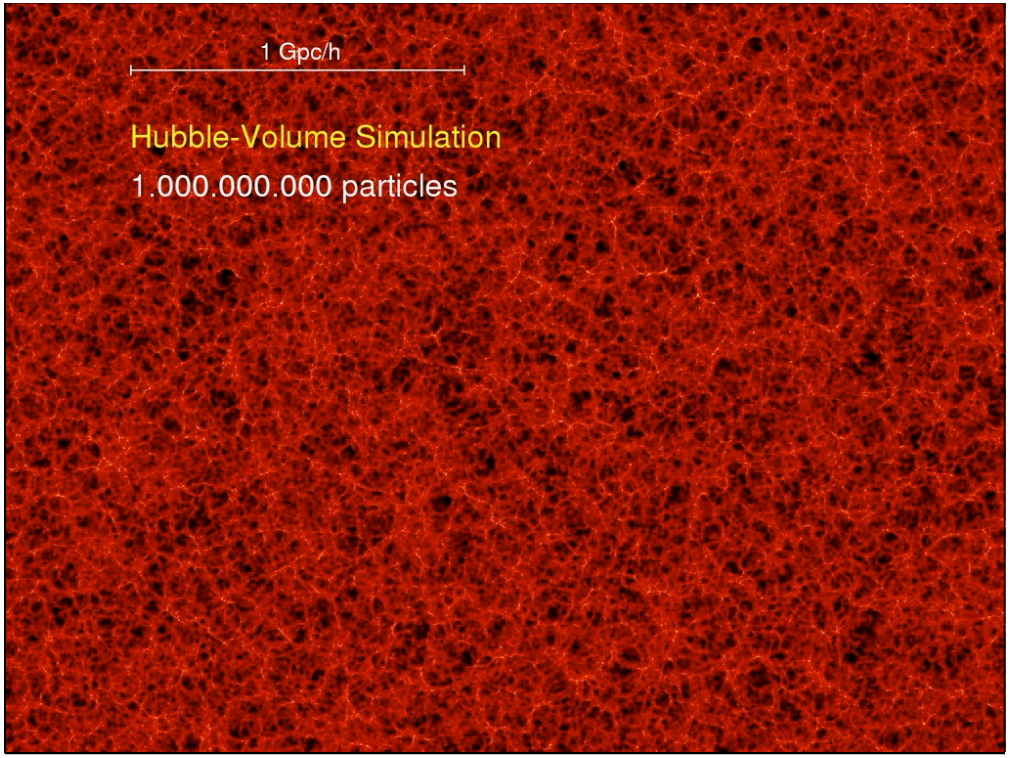

Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
No second generation stars
No cooling
Black holes only


Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
Too close encounters
No second generation stars
No cooling
Black holes only


Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
Too close encounters
No second generation stars
No cooling
Black holes only

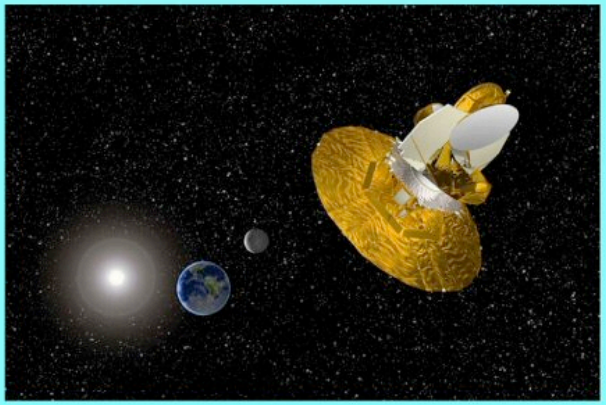

Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
Too close encounters
Halo formation
Halo destruction
No second generation stars
No cooling
Black holes only

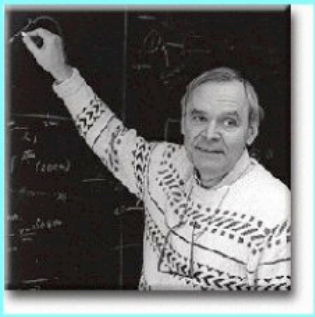

Cosmological data
H(z), P(k,z), C_l^T, C_l^X, C_l^E, C_l^B,…
Cosmological functions
$\rho_\Lambda(z)$, G(z,k), $P_s(k)$, $P_t(k)$
Clues about
• Dark matter
• Dark energy
• Inflation
Clustering details?
Make at LHC?
Detect directly? Indirectly?
Non-constant density?
Is w-parameter useful?
Non-scale invariance?
Gravitational waves?
Non-Gaussianity?
Isocurvature modes?
Non-flatness?


1 Gpc/h
Hubble-Volume Simulation
1.000.000.000 particles

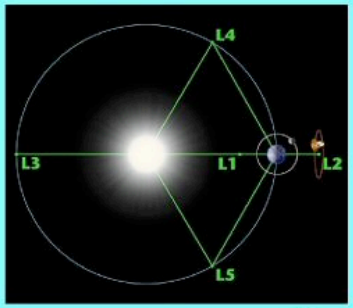
WMAP: Wilkinson Microwave Anisotropy Probe

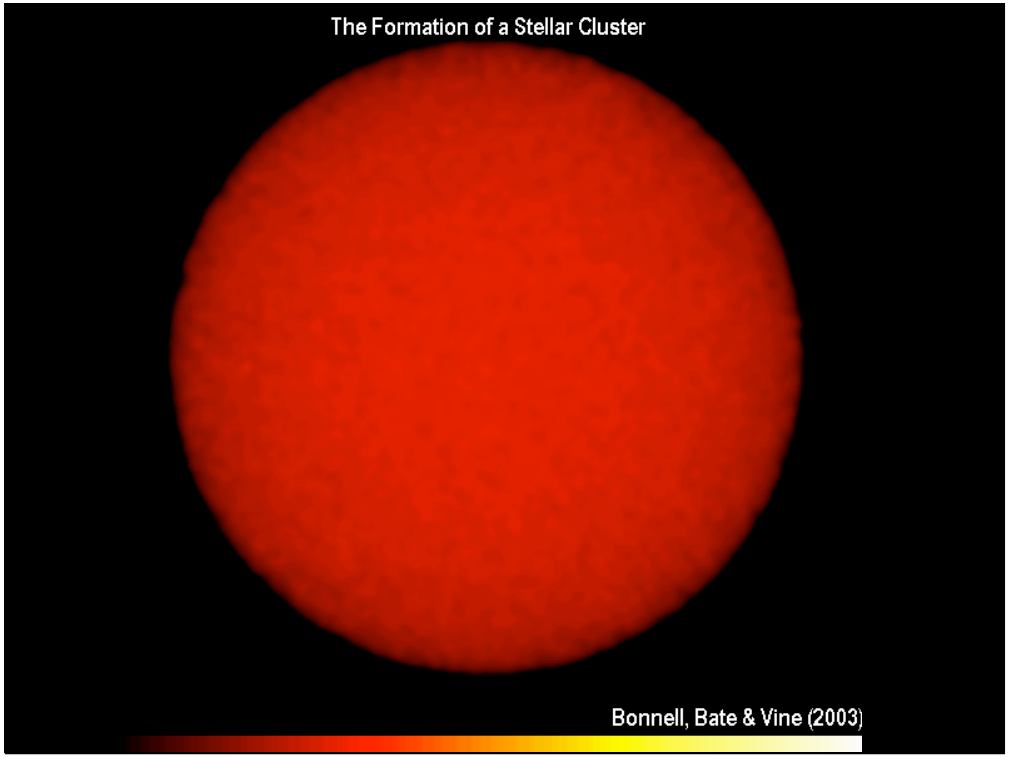
Images courtesy of NASA/WMAP Science Team





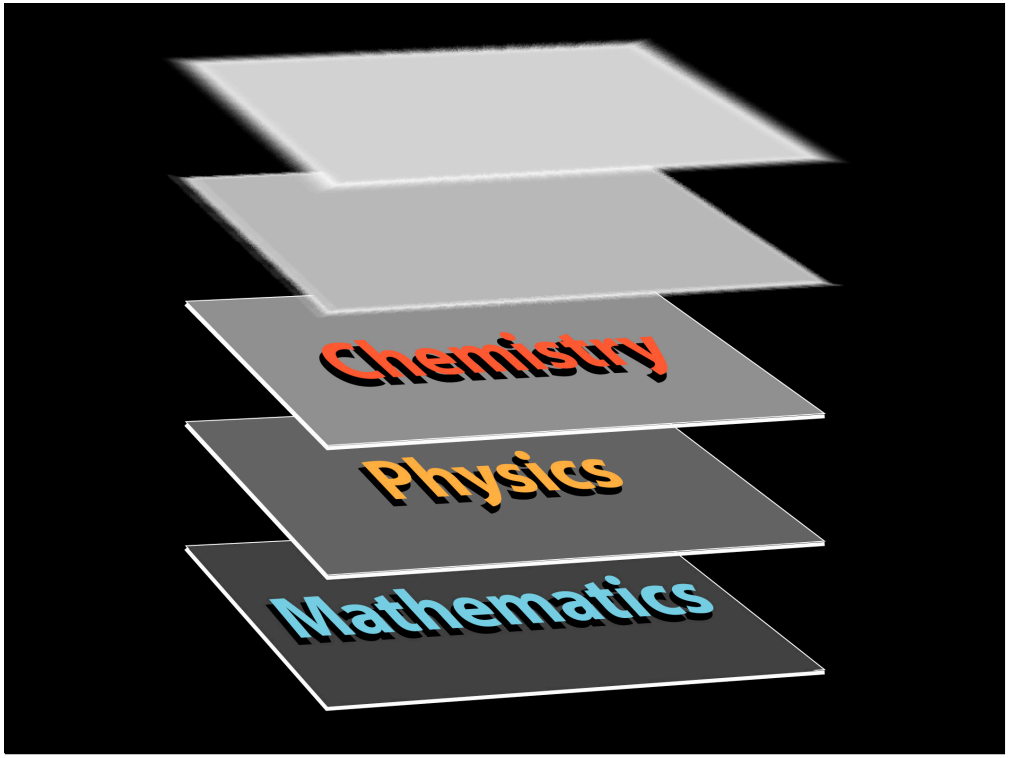
David T. Wilkinson

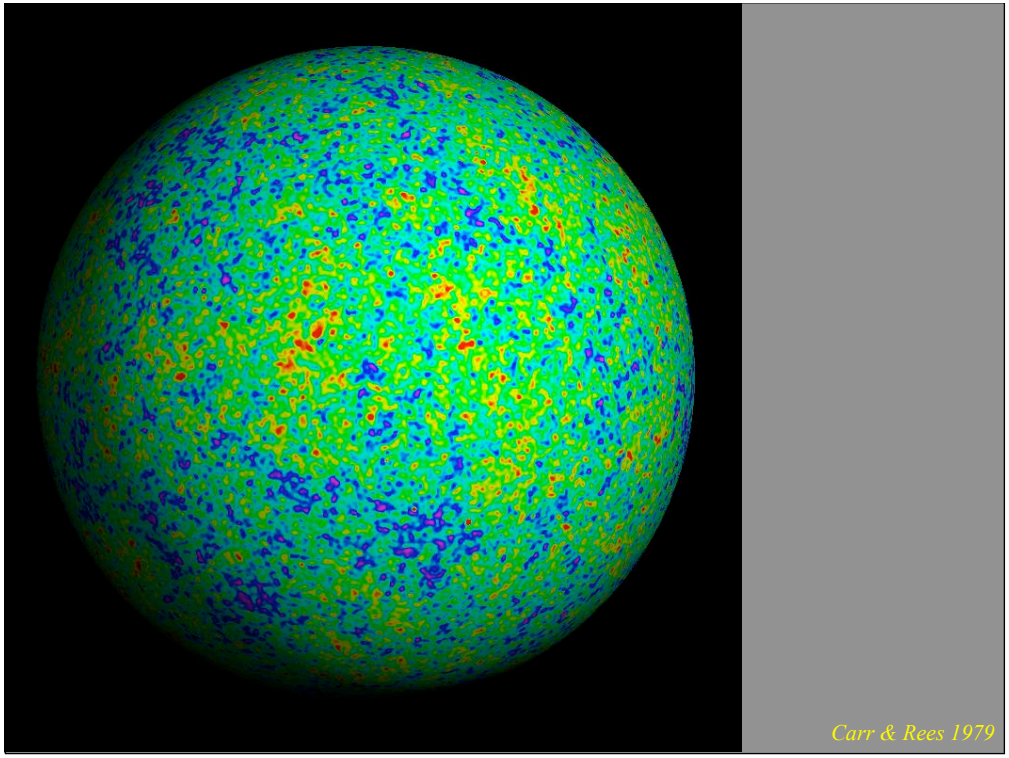




Ian Bonnell, St Andrews. Simulation of 1000 solar mass cloud 0.5 parsec in diameter, collapsing under gravity. It forms 419 stars varying in mass from 0.1 to 30 solar mass

Takes place in 500 000 years.


Chemistry
Physics
Mathematics

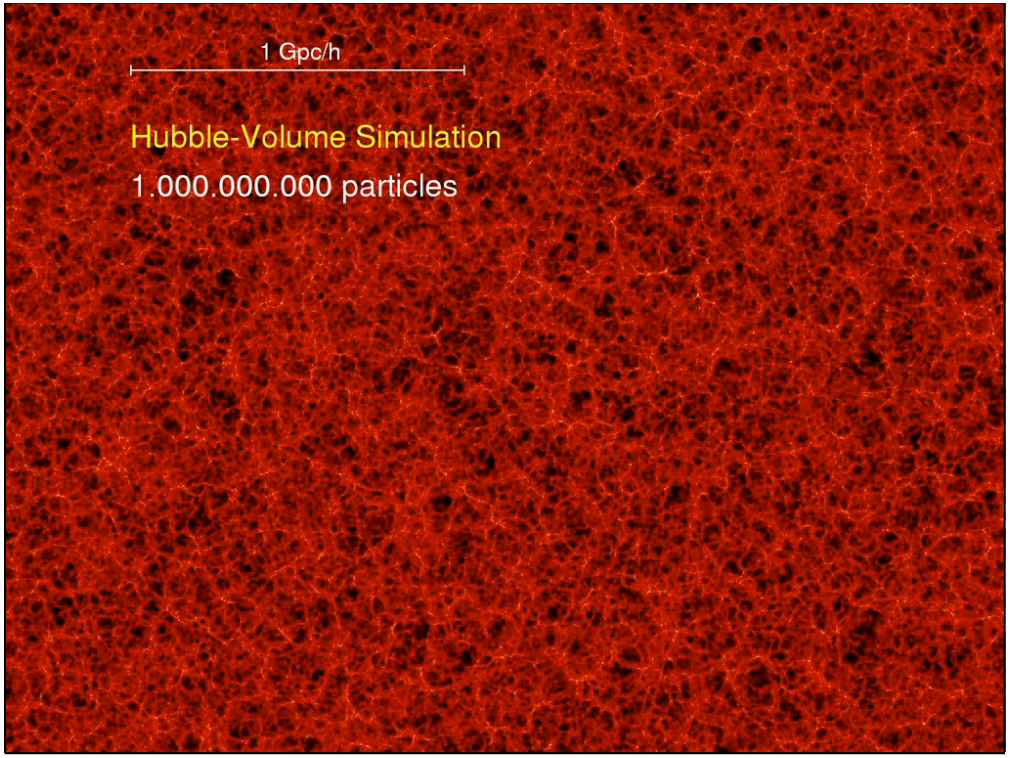

Carr & Rees 1979

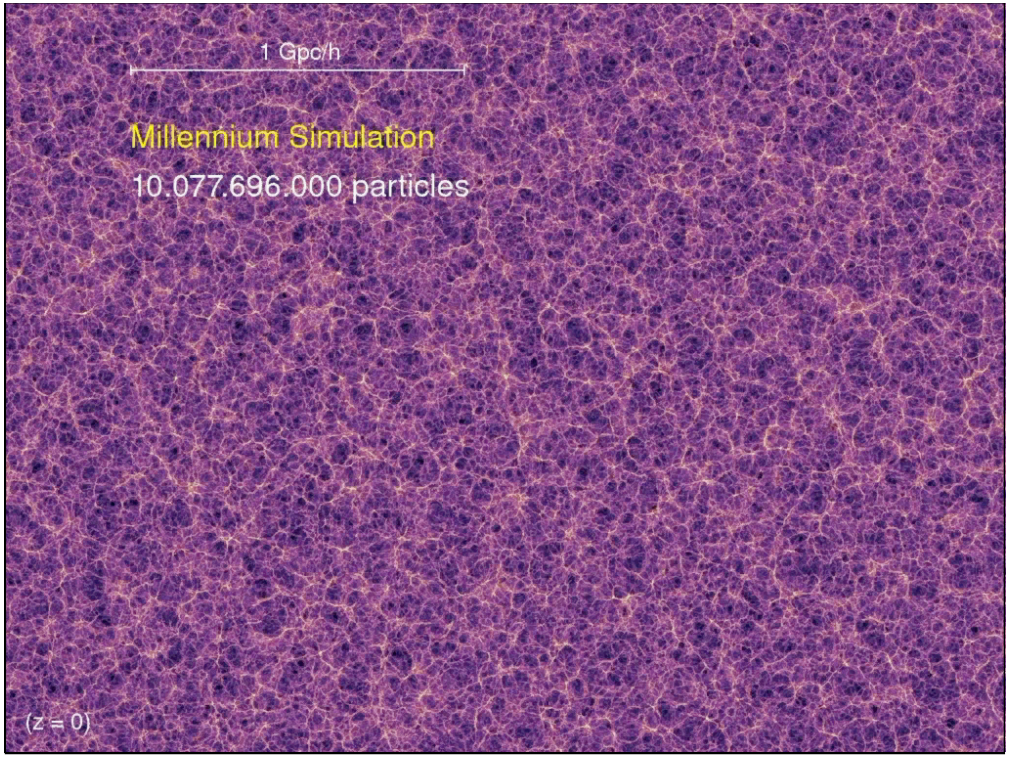
Just six numbers

Six constants of nature whose values must lie in an 'anthropic' range for life to emerge

1.	D = 3	The number of spatial dimensions
2.	G/E = 10^{-36}	The ratio of gravitational to electrostatic force
3.	S = 0.007	A measure of the strong force that binds nuclei
4.	Ω_{Total} = 1	The density of matter/energy in space
5.	Q= 0.00001	The scale of fluctuations in the microwave background
6.	Ω_{Λ}= 0.7	Omega lambda, a measure of the vacuum energy of the universe

- Coincidence?
- Consequence?
- Multiverse?


1 Gpc/h
Hubble-Volume Simulation
1.000.000.000 particles


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

Calculations of the primal "cooking" of the chemical elements predict

Hydrogen

Helium

Lithium

etc, correctly!

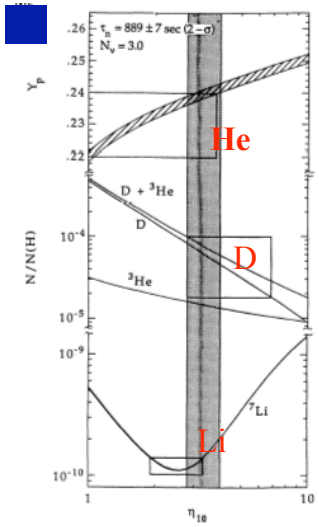
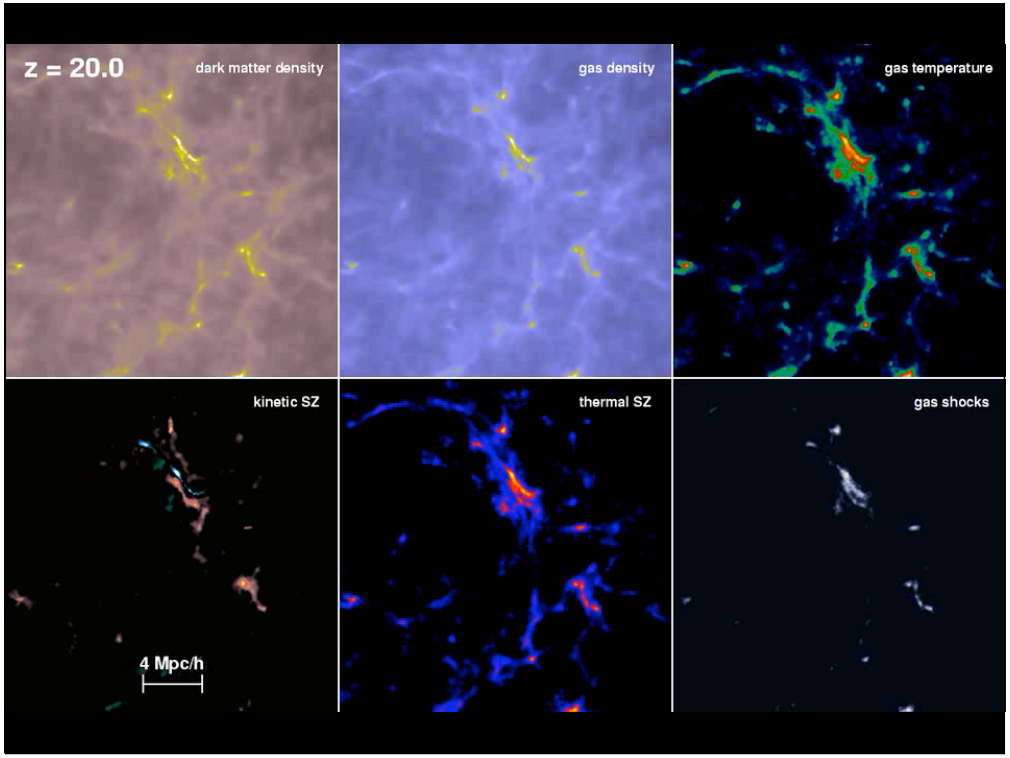
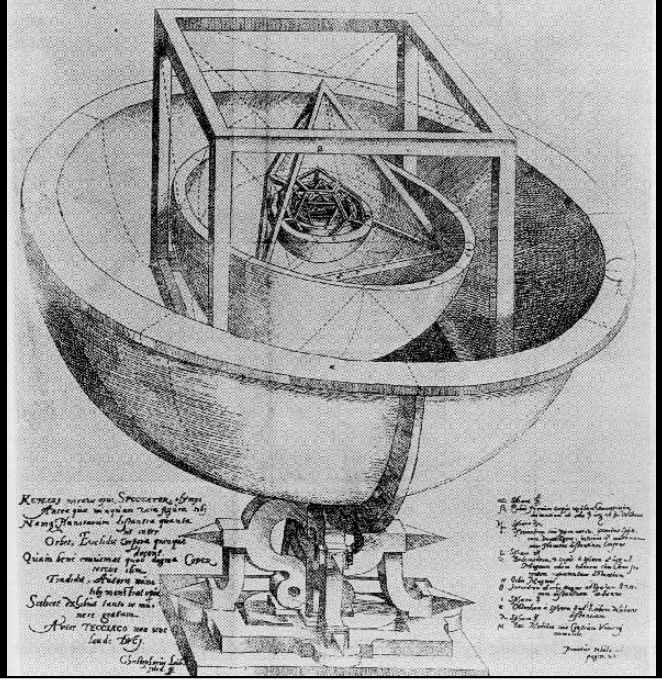


FIG. 13.—Predicted abundances (by number) of D, ^{3}He, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $882 \leq \tau_n \leq 896$ s. The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of η consistent with the observations.


z = 20.0
dark matter density
gas density
gas temperature
kinetic SZ
thermal SZ
gas shocks
4 Mpc/h

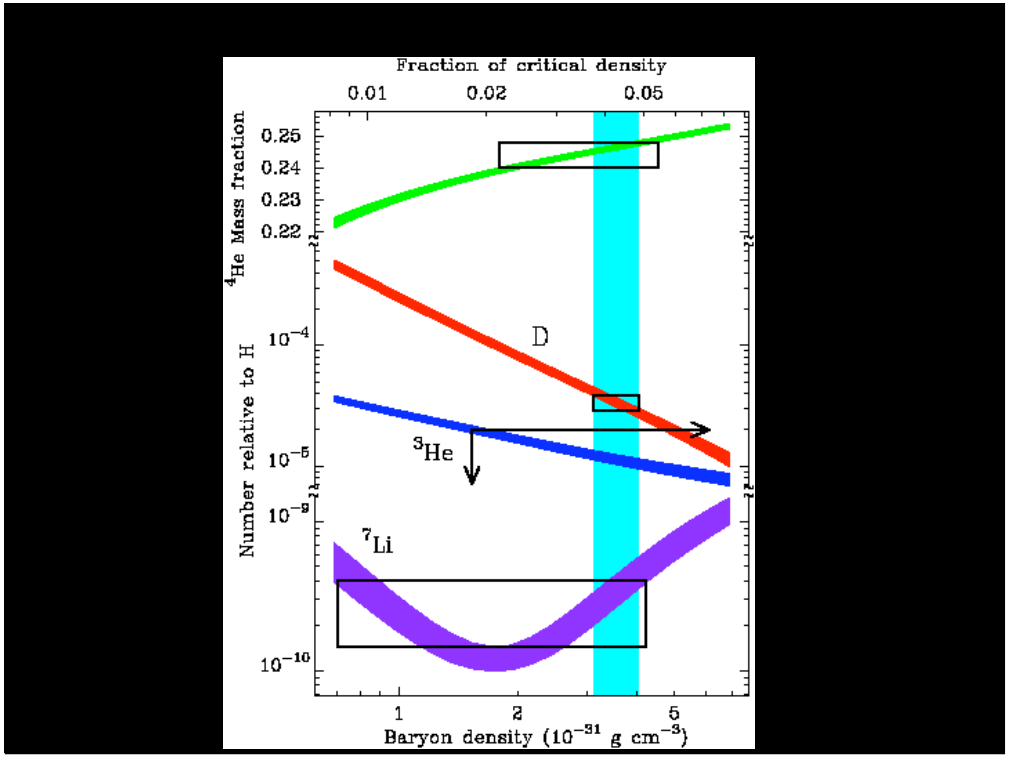
TABVLA III. ORBIVM PLANETARVM DIMENSIONES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA GEOMETRICA EXHIBENS.

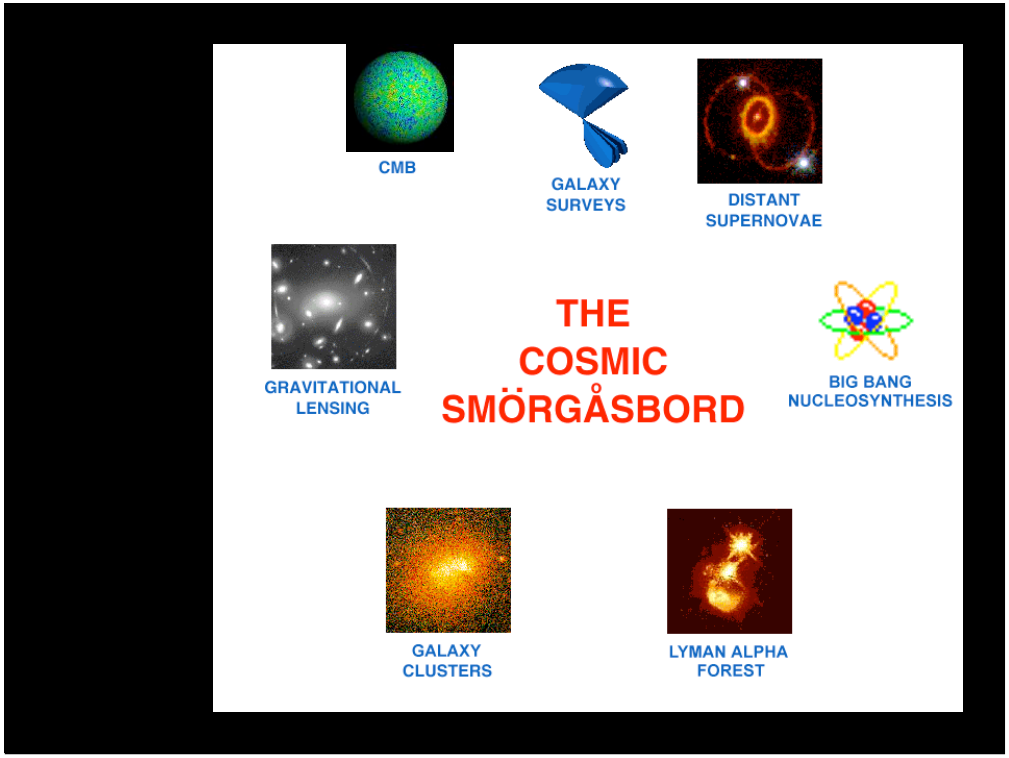
ILLVSTRISS.^MI PRINCIPI, AC DNO. DNO. FRIDERICO, DVCI WIRTENBERGICO, ET TECCIO, COMITI MONTIS BELGARVM, ETC. CONSECRATA.

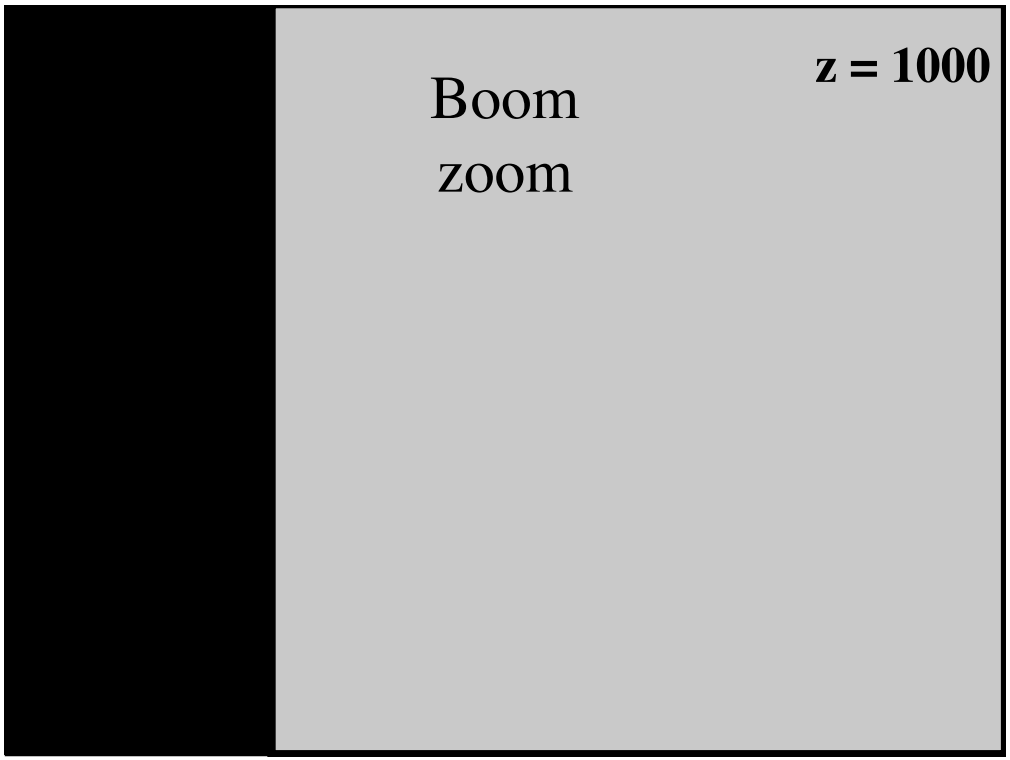


the challenge

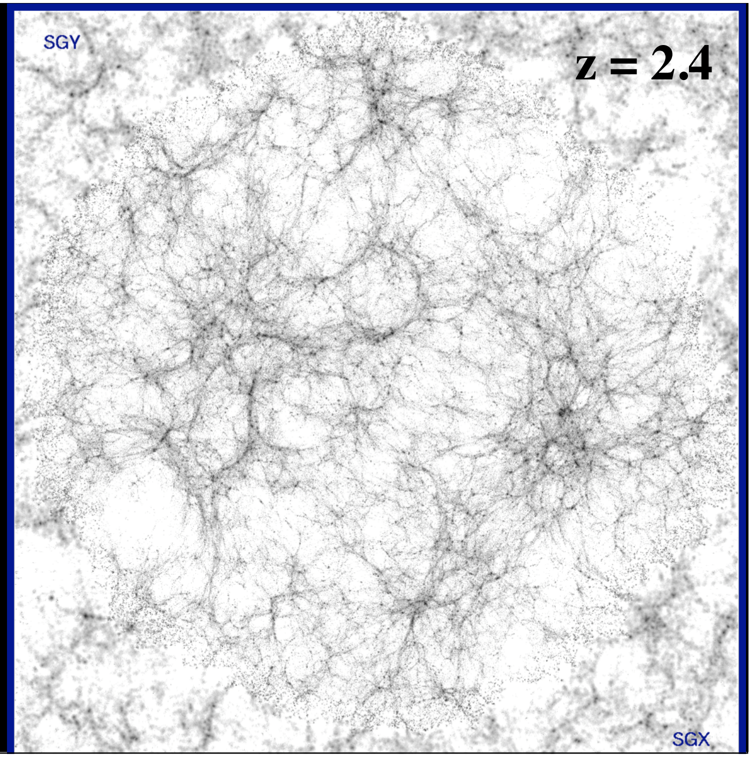
- How, from a ‘beginning’ described by a few parameters, did our Universe evolve into its present complexity?
- Can we understand, at a deeper level, why our Universe is the way it is?

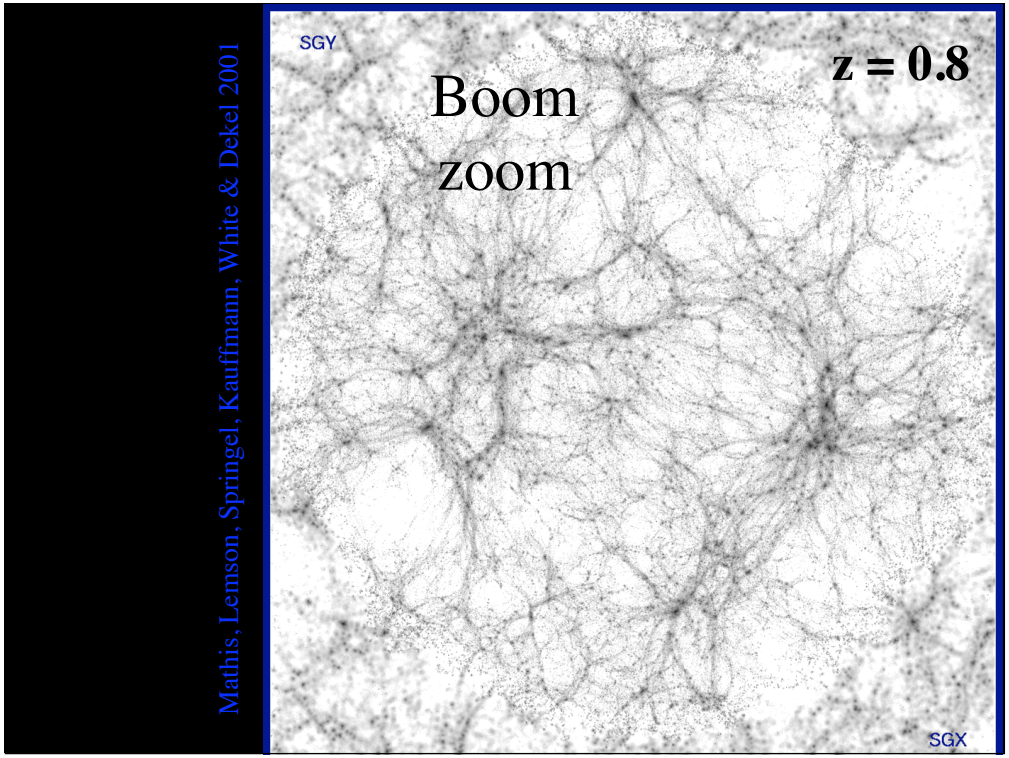

Fraction of critical density
0.01
0.02
0.05
^{4}He Mass fraction
0.25
0.24
0.23
0.22
Number relative to H
10^{-4}
10^{-5}
10^{-9}
10^{-10}
D
^{3}He
^{7}Li
1
2
5
Baryon density (10^{-31} g cm^{-3})

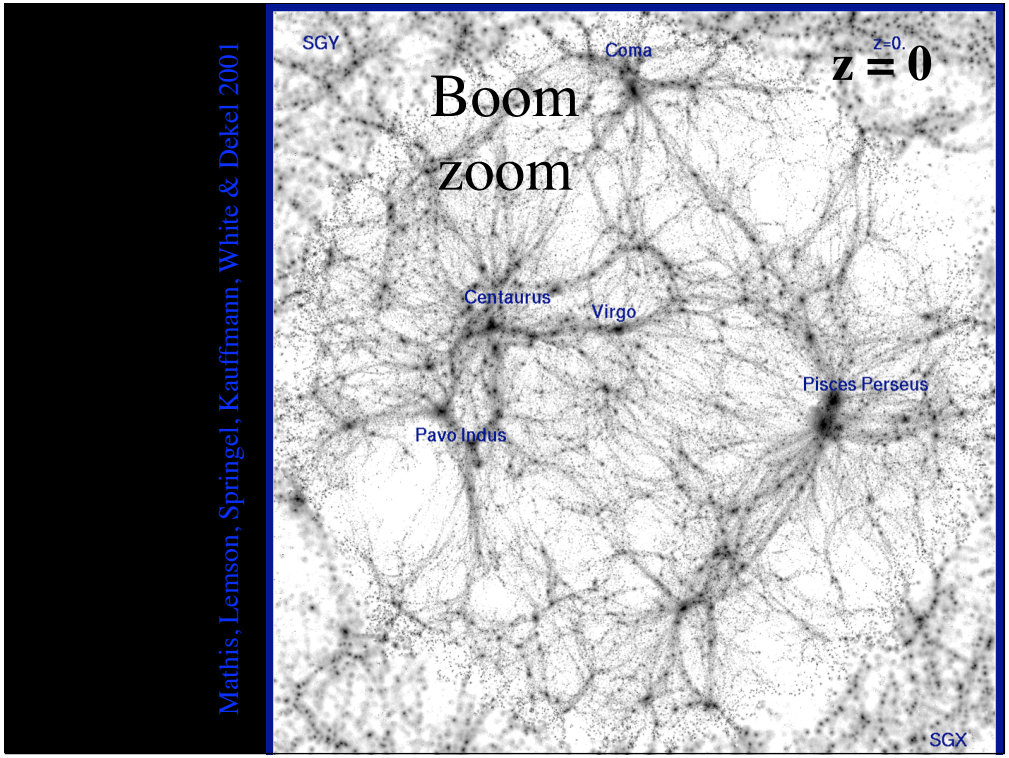

CMB
GALAXY SURVEYS
DISTANT SUPERNOVAE
GRAVITATIONAL LENSING
THE COSMIC SMÖRGÅSBORD
BIG BANG NUCLEOSYNTHESIS
GALAXY CLUSTERS
LYMAN ALPHA FOREST

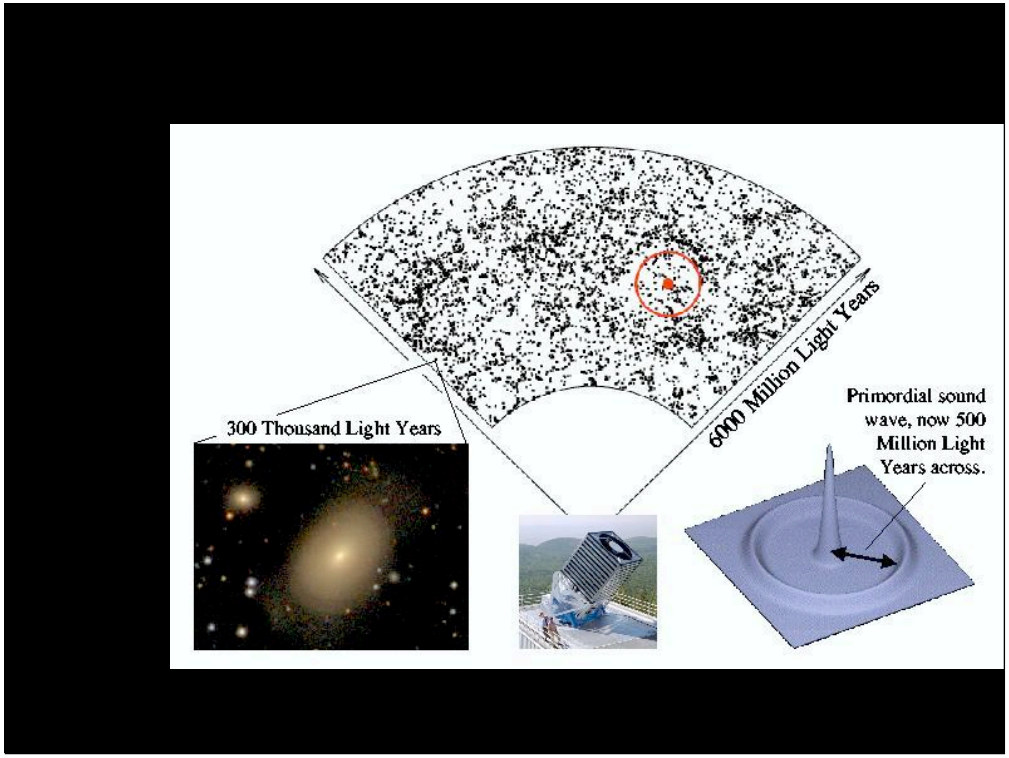

Boom
zoom
z = 1000

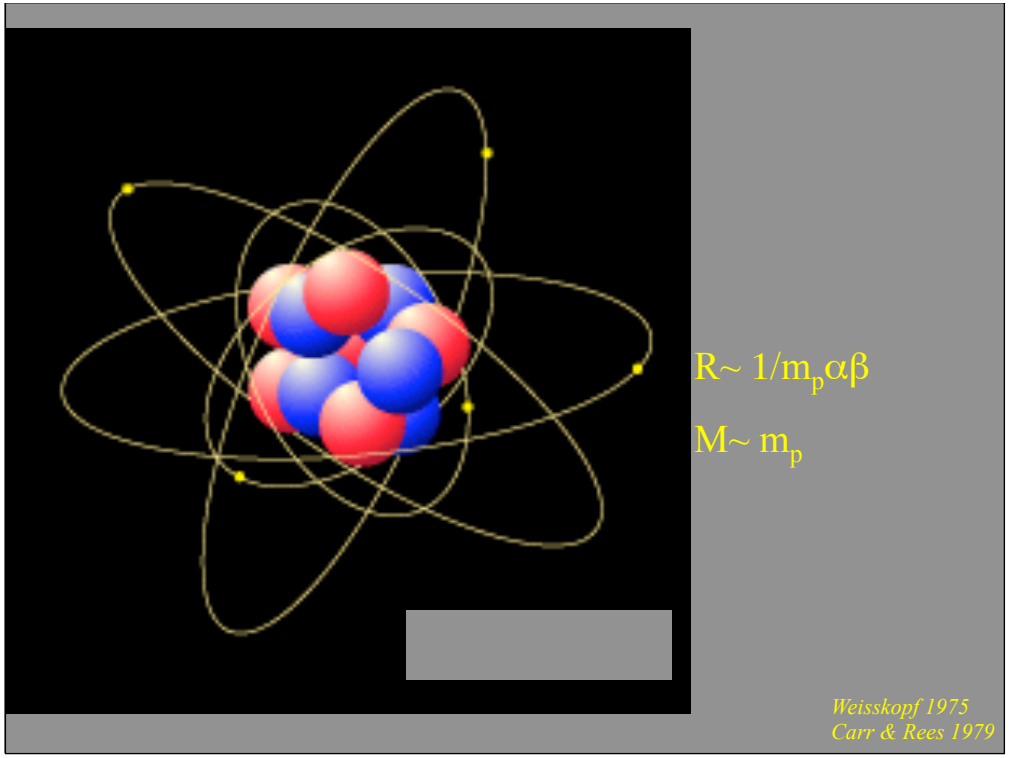
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001

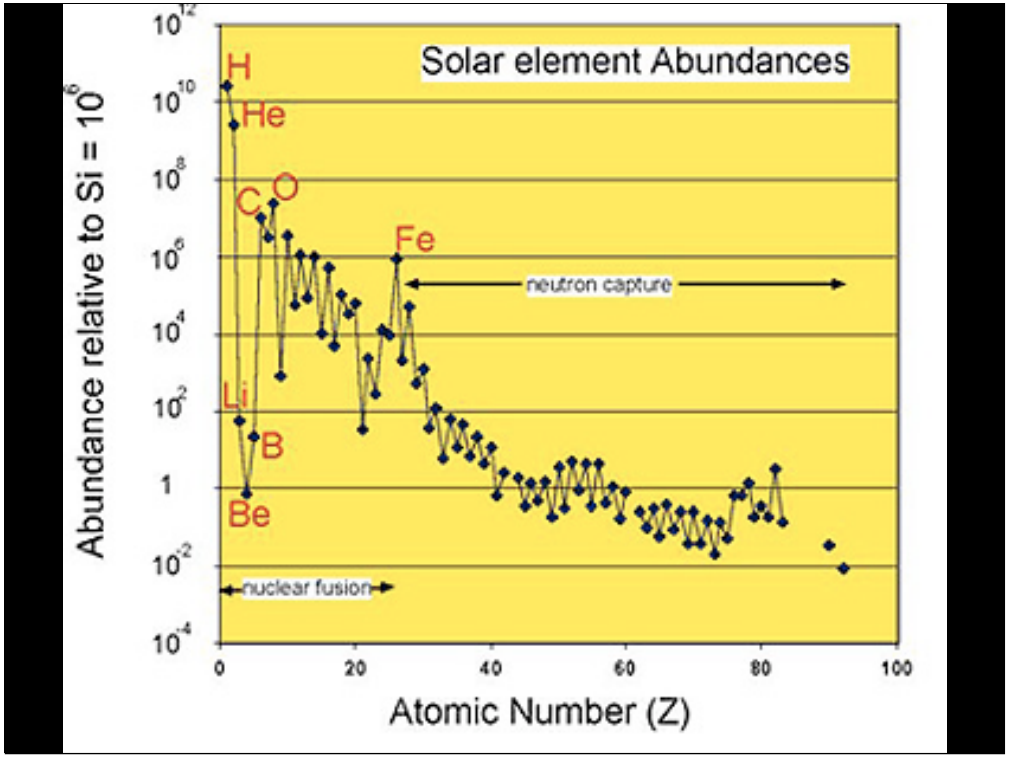


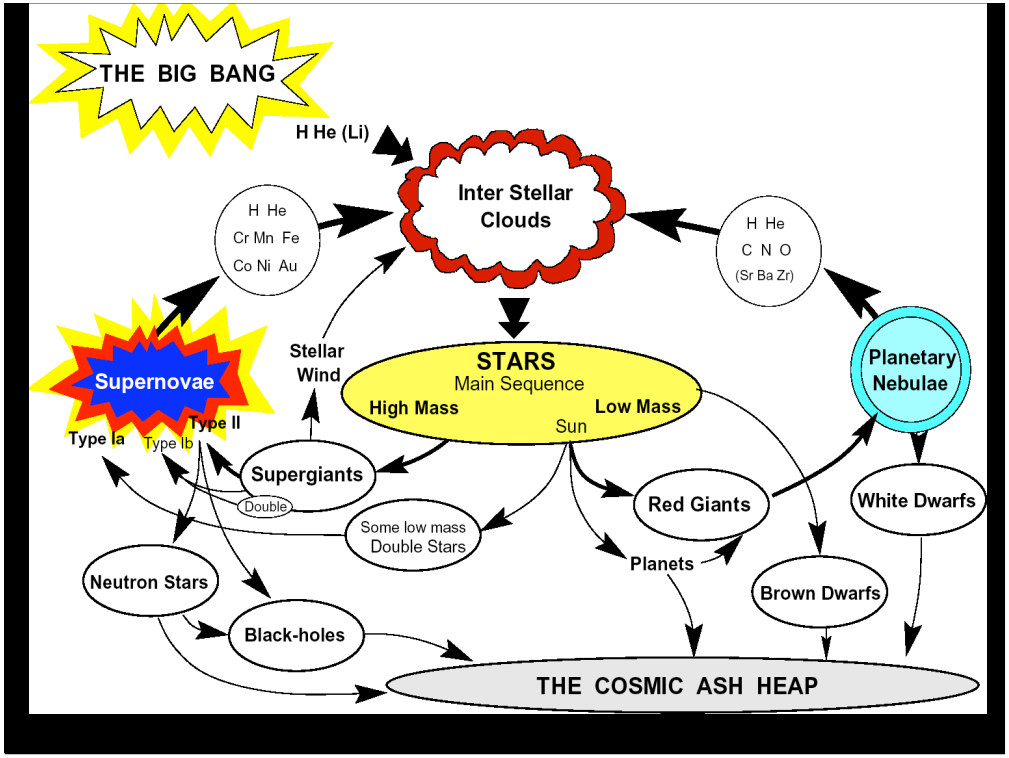

Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001
SGY
Boom
zoom
z = 0.8
SGX

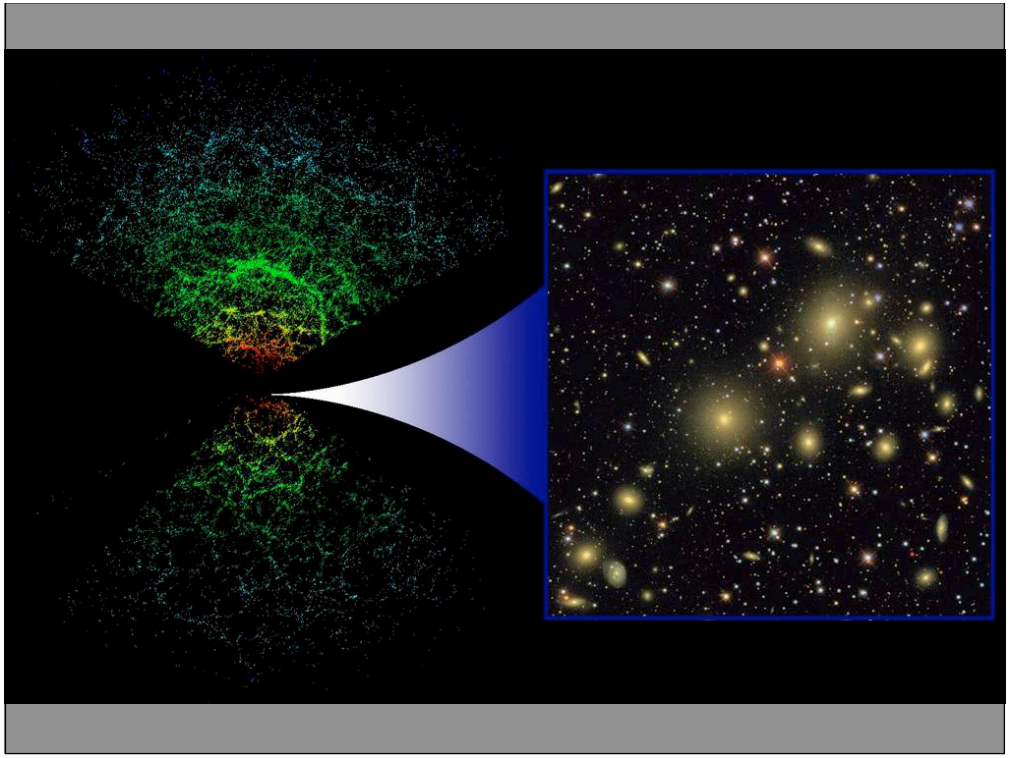

Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001
SGY
Coma
z=0.
z = 0
Boom
zoom
Centaurus
Virgo
Pisces Perseus
Pavo Indus
SGX

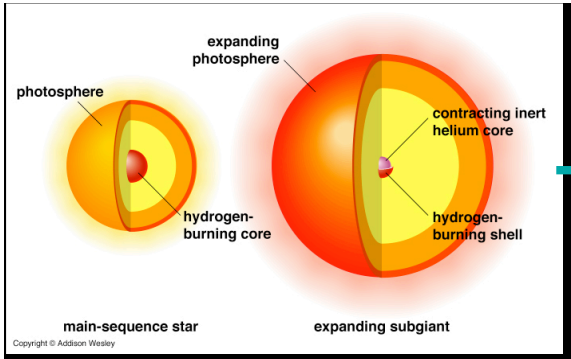

6000 Million Light Years
300 Thousand Light Years
Primordial sound wave, now 500 Million Light Years across.


$R \sim 1/m_p \alpha\beta$
$M \sim m_p$
Weisskopf 1975
Carr & Rees 1979


Solar element Abundances
Abundance relative to Si = 10^6
Atomic Number (Z)
H
He
C
O
Fe
Li
B
Be
neutron capture
nuclear fusion
10^12
10^10
10^8
10^6
10^4
10^2
1
10^-2
10^-4
0
20
40
60
80
100


THE BIG BANG
H He (Li)
Inter Stellar Clouds
H He
Cr Mn Fe
Co Ni Au
H He
C N O
(Sr Ba Zr)
Supernovae
Stellar Wind
STARS
Main Sequence
High Mass
Low Mass
Sun
Planetary Nebulae
Type II
Type Ia
Type Ib
Supergiants
Double
Some low mass Double Stars
Red Giants
White Dwarfs
Planets
Neutron Stars
Brown Dwarfs
Black-holes
THE COSMIC ASH HEAP

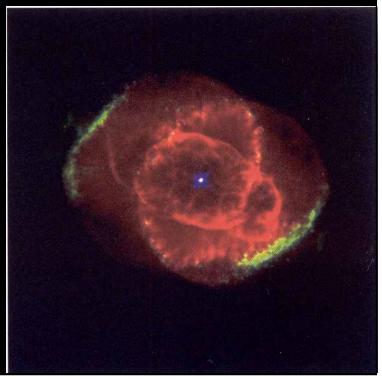




$\alpha + \alpha \rightarrow {}^{8}\mathrm{Be}$

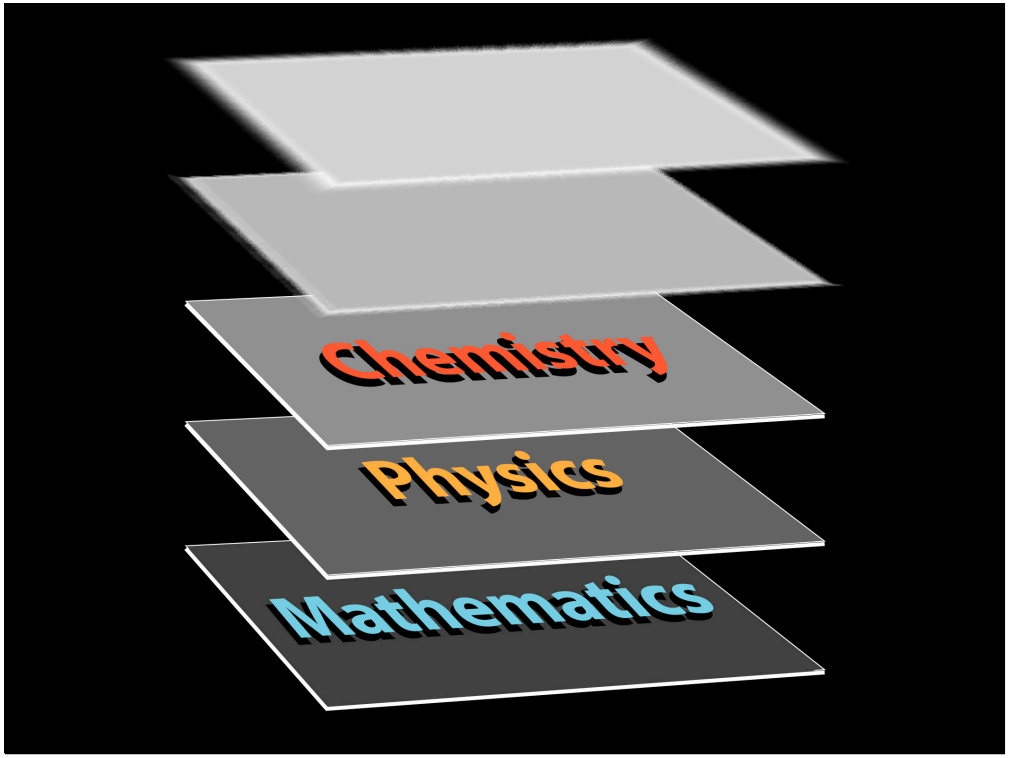
${}^{8}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C}$

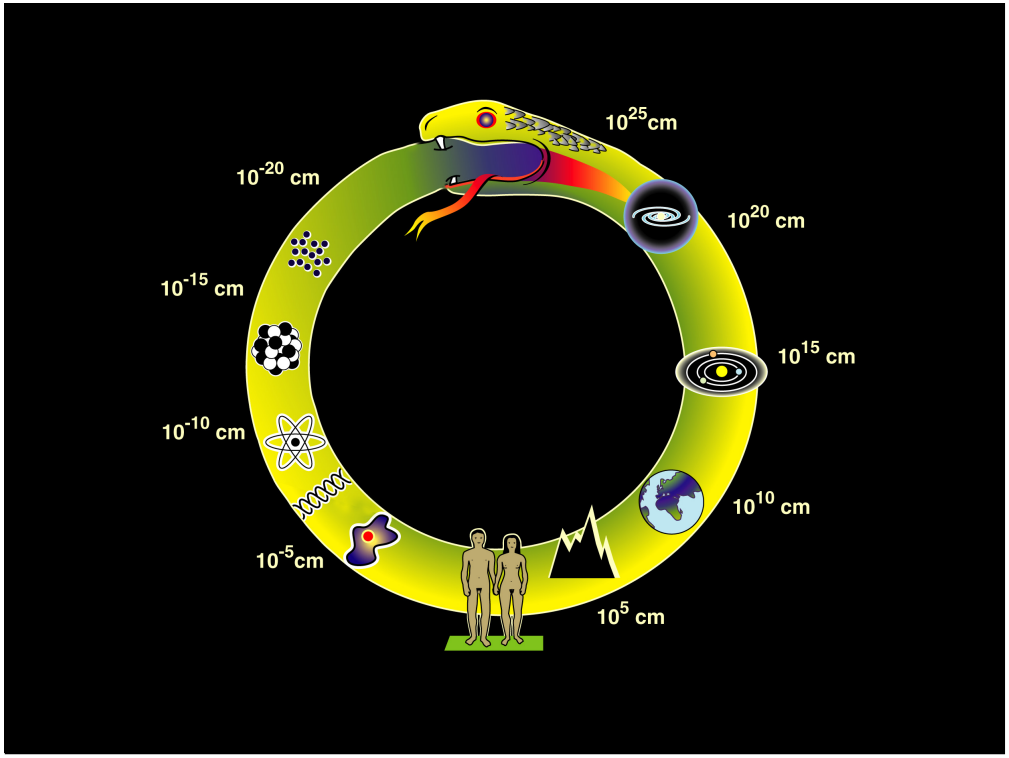
${}^{12}\mathrm{C} + \alpha \rightarrow {}^{16}\mathrm{O}$

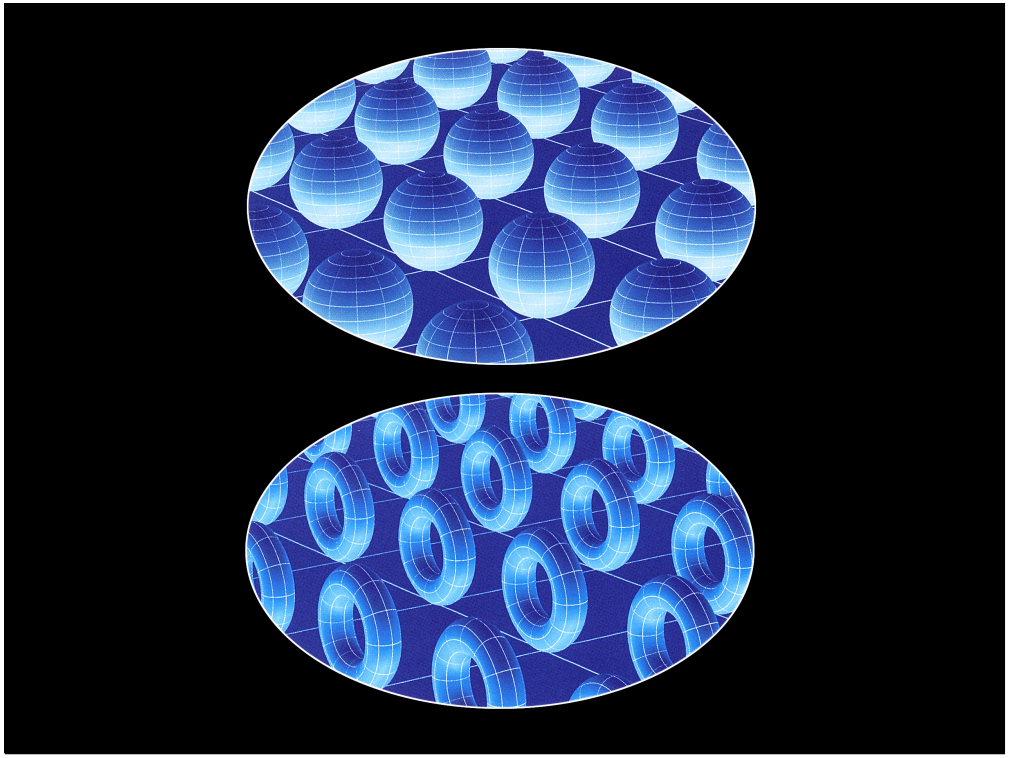


the challenges

- What is out there? Cosmic exploration.
- Interpreting phenomena in terms of known (and perhaps ‘new’) physics.
- How, from a ‘simple beginning’, did our Universe evolve into its present complexity (stars, planets, people)?
- Can we understand, at a deeper level, why our Universe is the way it is?


Chemistry
Physics
Mathematics


10^{25}cm
10^{20} cm
10^{15} cm
10^{10} cm
10^{5} cm
10^{-5}cm
10^{-10} cm
10^{-15} cm
10^{-20} cm



FLUCTUATION AMPLITUDE

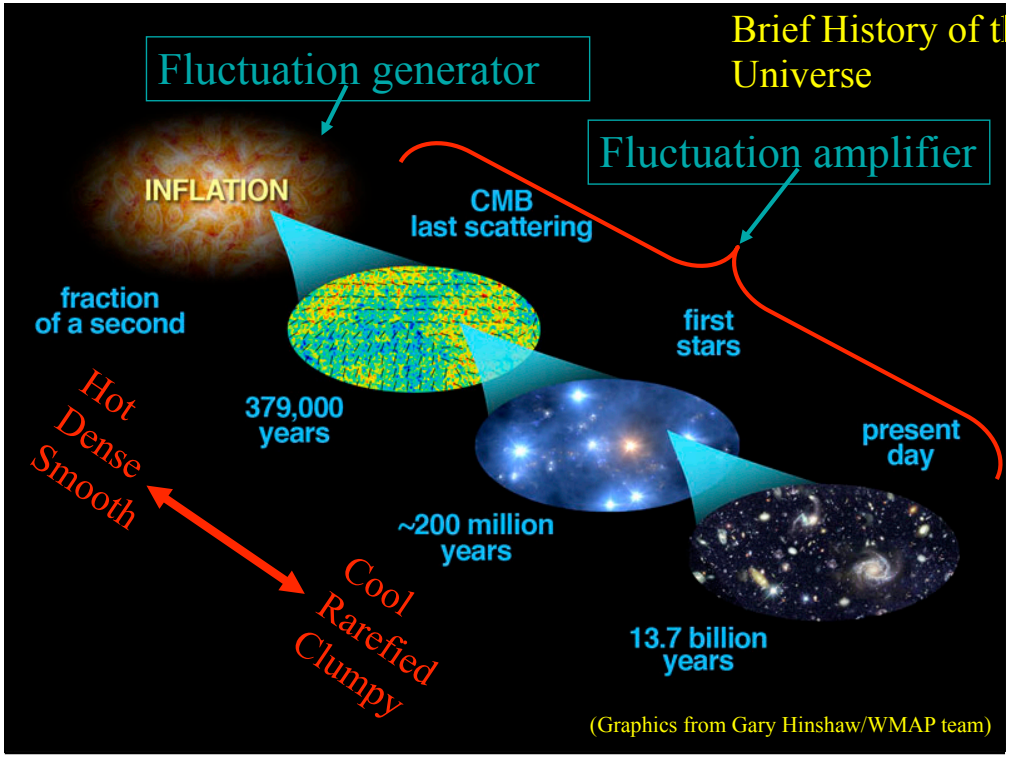
$$Q \cong 10^{-5}\left(\sim \frac{\Delta T}{T}\right)_{j}$$

→ Bound Systems* with Gravitational Binding Energy QMc^2
(Virial Velocity $Q^{1/2}c$)

Max Non-:Linear Scale

→ $Q^{1/2}$ x (Hubble Radius).

*Formation of Bound System Requires Expansion Factor of >~ Q^{-1} After System Enters Horizon.


Brief History of t
Universe
Fluctuation generator
Fluctuation amplifier
INFLATION
CMB
last scattering
fraction
of a second
first
stars
379,000
years
present
day
Hot
Dense
Smooth
~200 million
years
Cool
Rarefied
Clumpy
13.7 billion
years
(Graphics from Gary Hinshaw/WMAP team)

Calculations of the primal "cooking" of the chemical elements predict

Hydrogen

Helium

Lithium

etc, correctly!

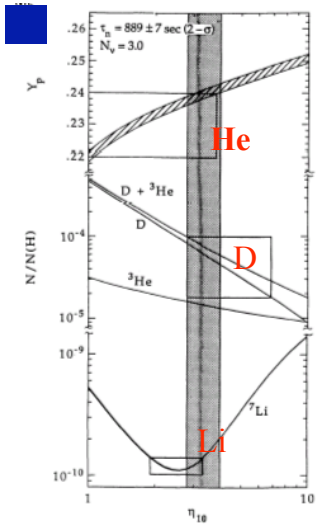


FIG. 13.—Predicted abundances (by number) of D, ^{3}He, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $882 \leq \tau_n \leq 896$ s. The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of η consistent with the observations.

Just six numbers

Six constants of nature whose values must lie in an 'anthropic' range for life to emerge

1.	D = 3	The number of spatial dimensions
2.	G/E = 10^{-36}	The ratio of gravitational to electrostatic force
3.	S = 0.007	A measure of the strong force that binds nuclei
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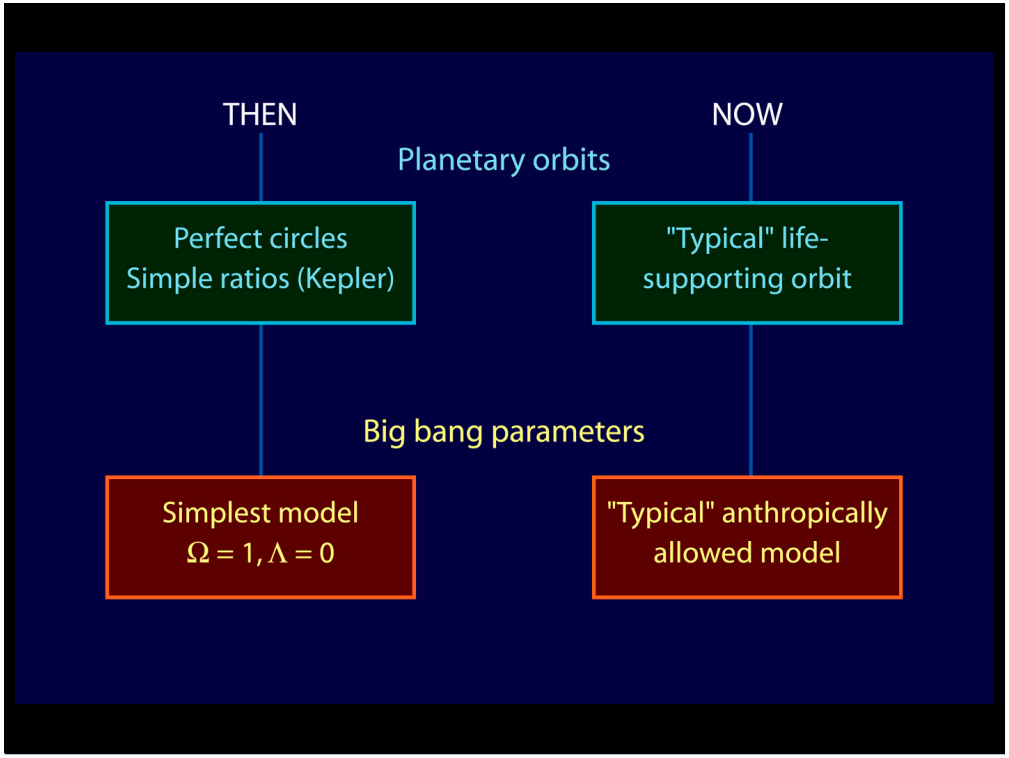
6.	Ω_{Λ}= 0.7	Omega lambda, a measure of the vacuum energy of the universe

- Coincidence?
- Consequence?
- Multiverse?


THEN
NOW
Planetary orbits
Perfect circles
Simple ratios (Kepler)
"Typical" life-supporting orbit
Big bang parameters
Simplest model
$\Omega = 1, \Lambda = 0$
"Typical" anthropically allowed model

TABVLA III. ORBIVM PLANETARVM DIMENSIONES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA GEOMETRICA EXHIBENS.

ILLVSTRISS.^MI PRINCIPI, AC DNO. DNO. FRIDERICO, DVCI WIRTENBERGICO, ET TECCIO, COMITI MONTIS BELGARVM, ETC. CONSECRATA.