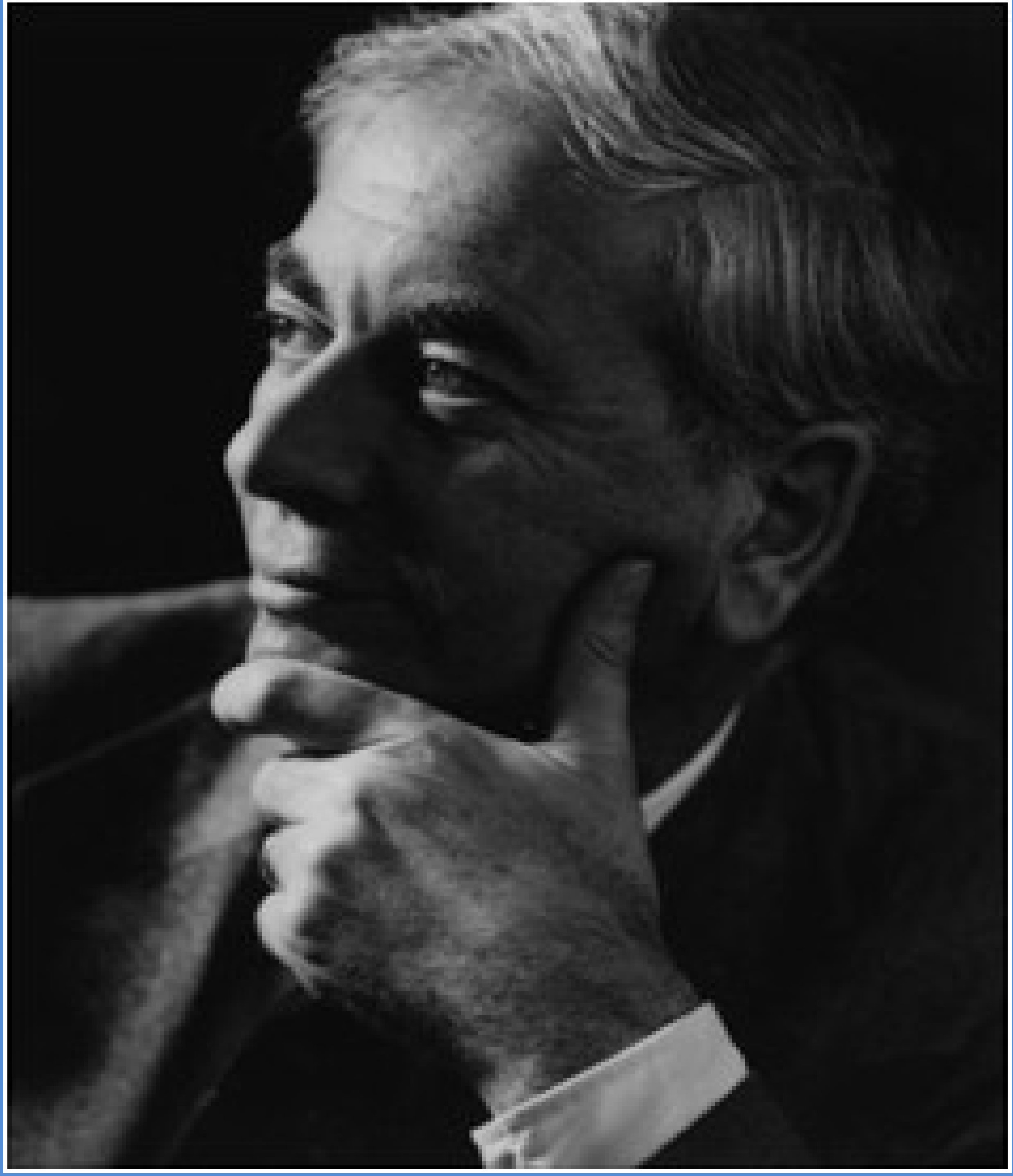
REAL AND COUNTERFACTUAL UNIVERSES

Martin Rees
Cambridge University



BEYOND THE HORIZON

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'.

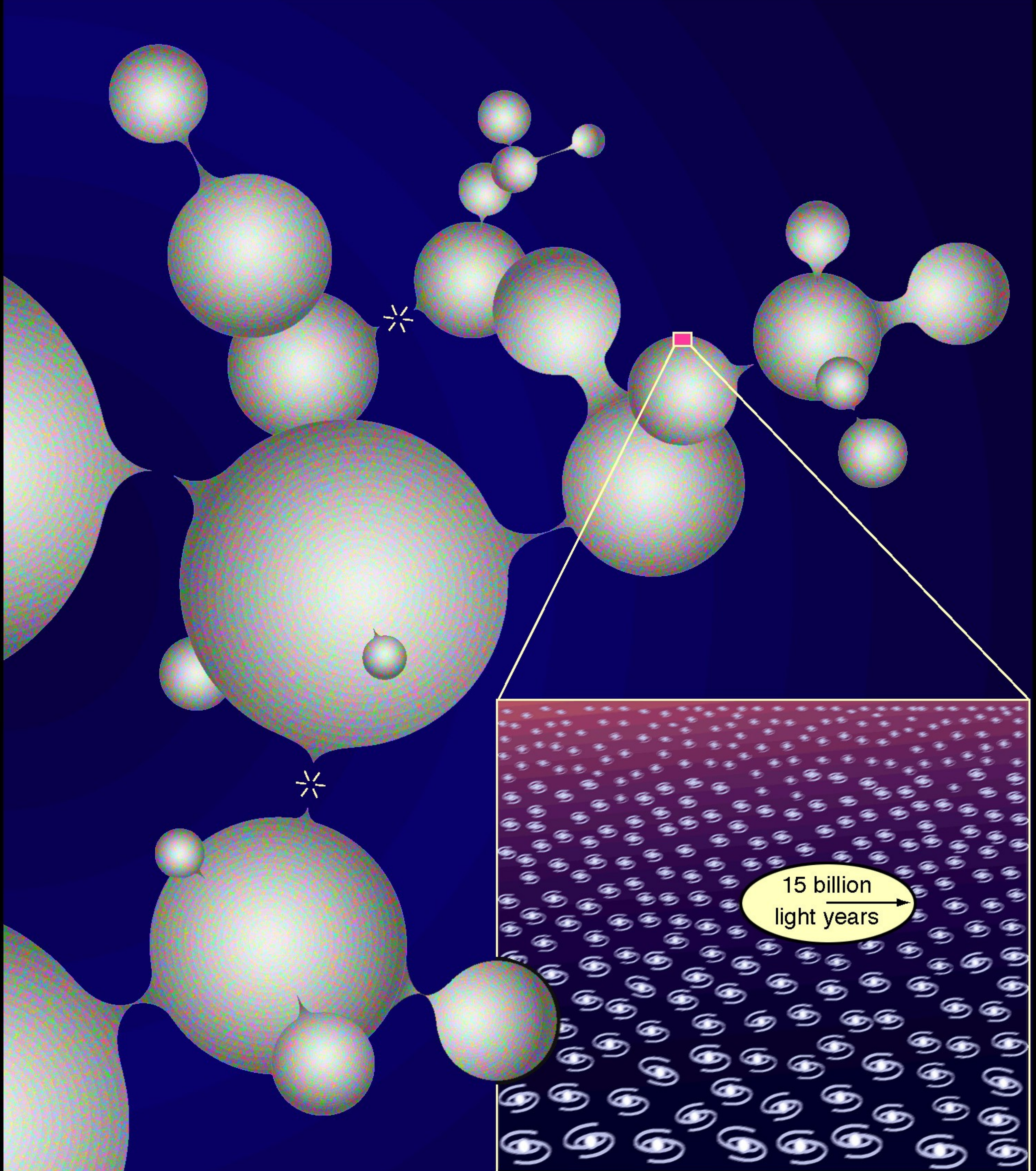
But lack of discernible gradients (in CMB or galaxy counts) across Hubble scale suggest that our universe extends for $> 10^{15}$ l.y

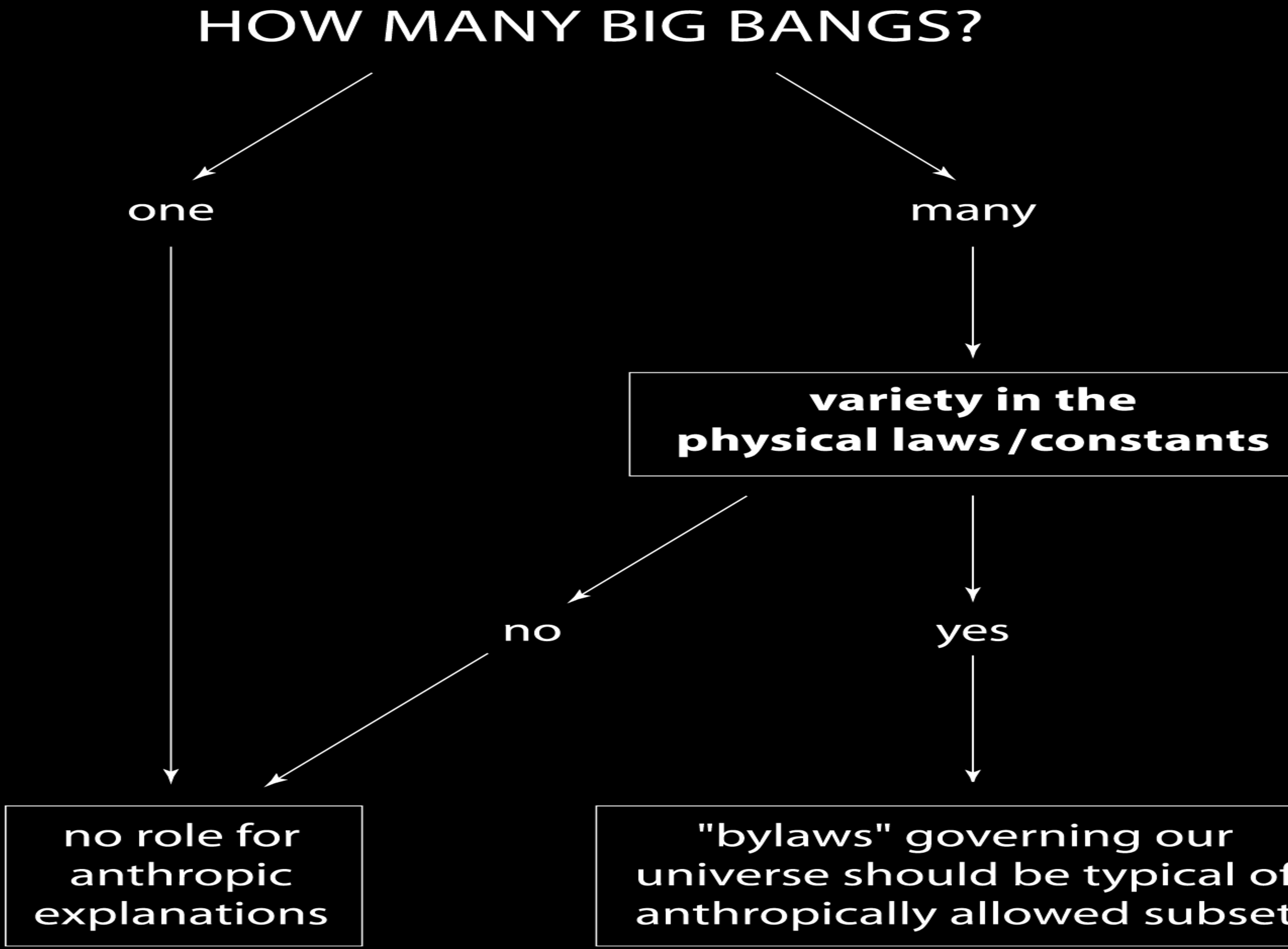
and space could extend $> 10^{100}$ l.y

or even >>>>>>

(replicas!)

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


15 billion
light years


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

What range of laws and constants allow interesting complexity?

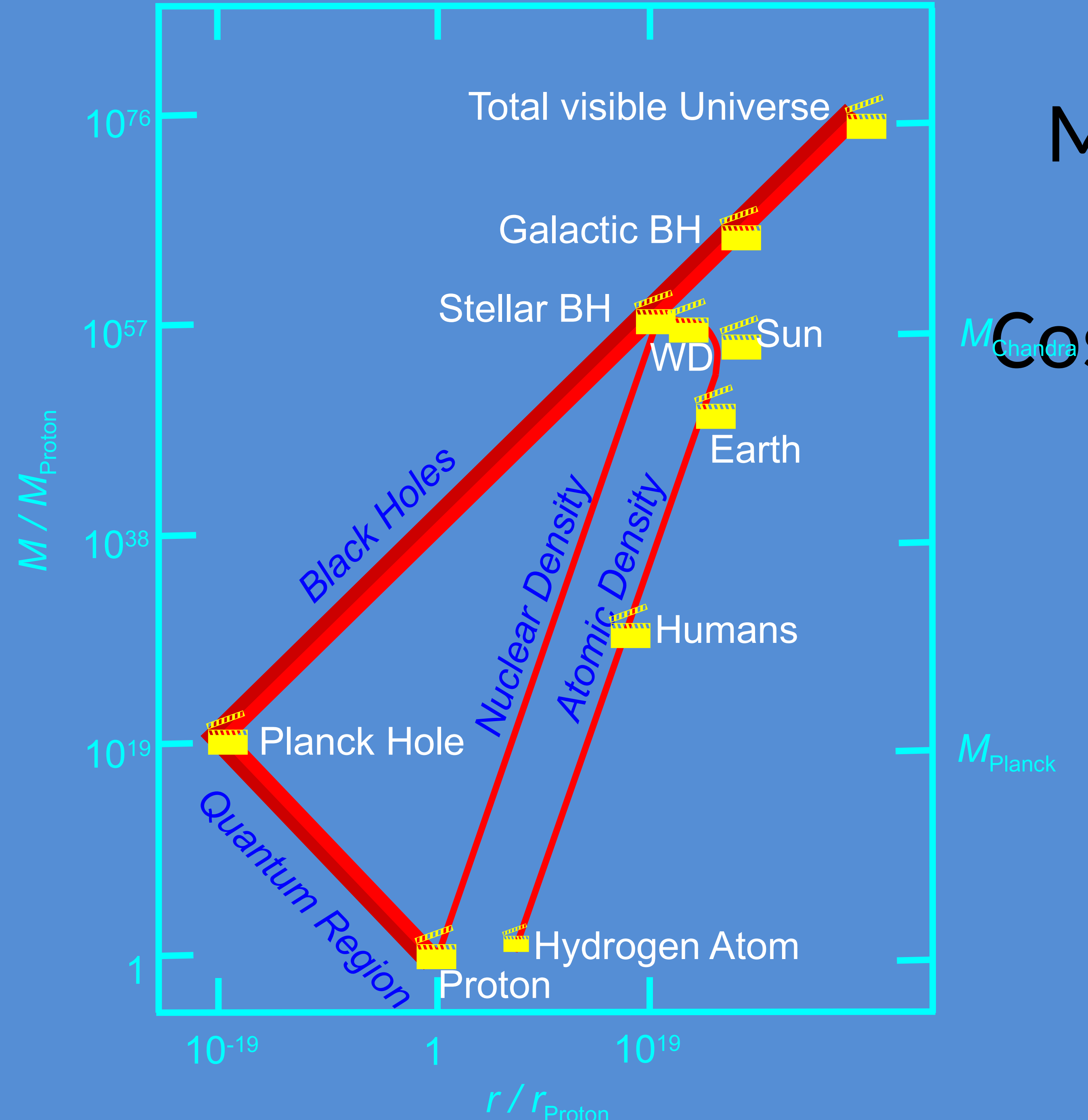
(A crucial part of the ‘anthropic programme’. But for those allergic to this it’s an exercise in ‘counterfactual history’ -- interesting irrespective of ‘philosophical’ preconceptions.)

(+ a good check on computer models)

Different G?

What if (Gm^2 /hc) were different?

Mass versus Radius of Cosmic Objects



after Carr & Rees 1979

WHAT IS A STAR?

A self-gravitating aggregate of

$\sim \alpha_G^{-3/2}$ baryons

Where

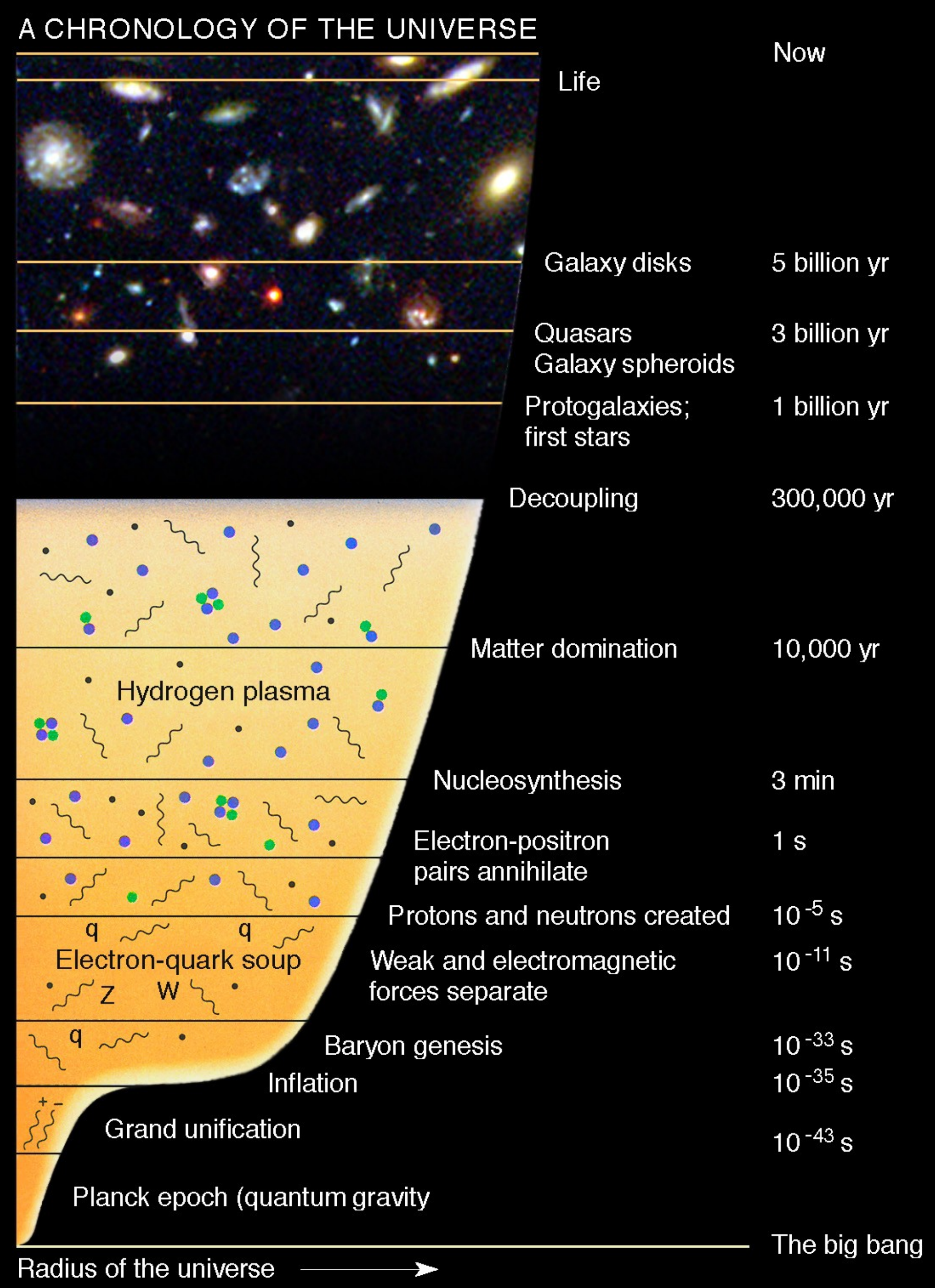
$\alpha_G = (G\, m_{proton}^2)/\hbar c$

NOTE:

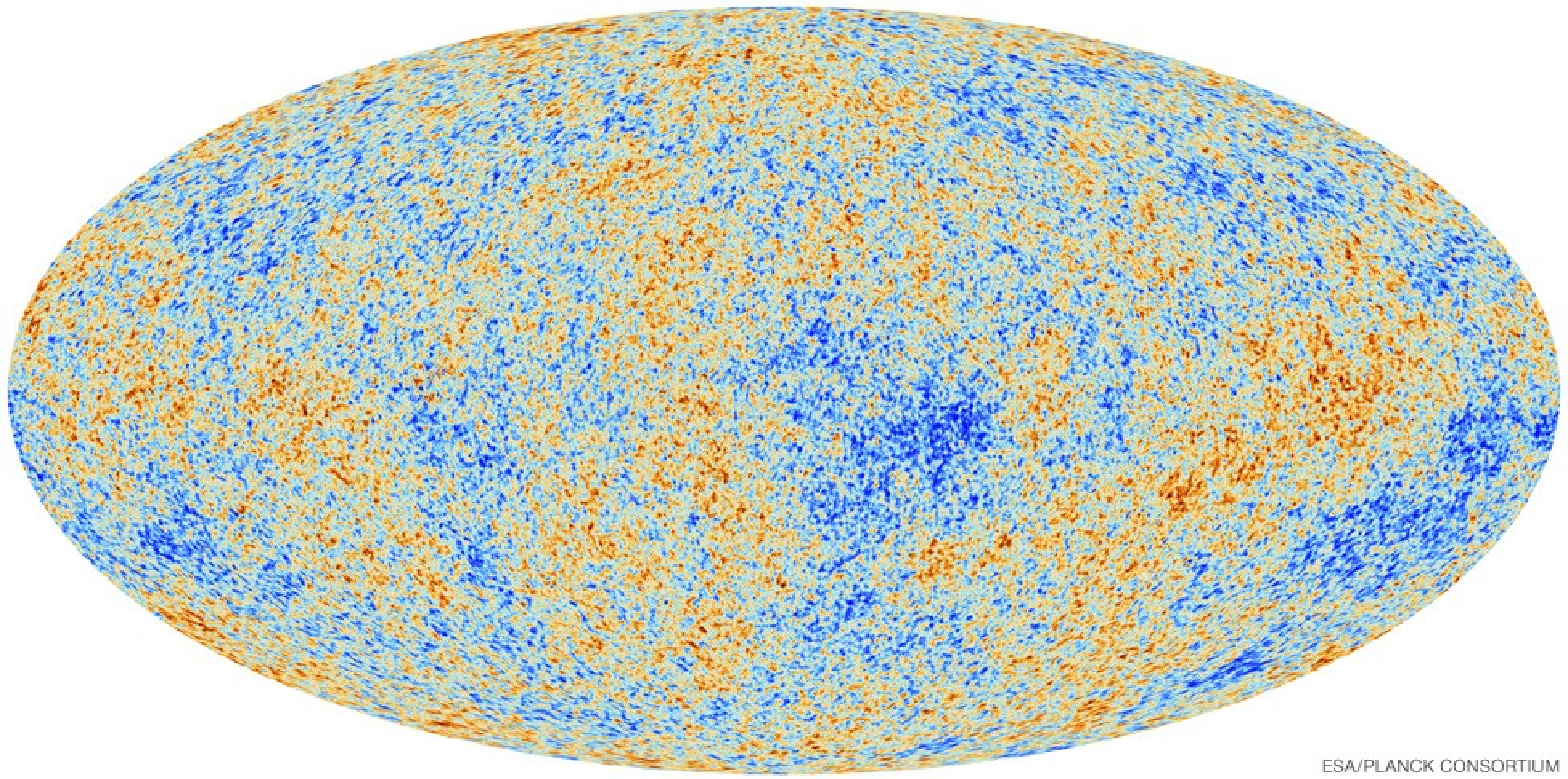
G must be weak, but is *not* 'fine-tuned' – the universe might be even more interesting if it were still weaker.

SO ‘STARS’ CAN EXIST FOR A WIDE RANGE OF G. BUT HOW DO *COSMOLOGICAL* MODELS DIFFER IF G IS DIFFERENT?

SCALING OF GALAXIES THE SAME AS FOR STARS



A CHRONOLOGY OF THE UNIVERSE
Now
Life
Galaxy disks
5 billion yr
Quasars
Galaxy spheroids
3 billion yr
Protogalaxies; first stars
1 billion yr
Decoupling
300,000 yr
Matter domination
10,000 yr
Hydrogen plasma
Nucleosynthesis
3 min
Electron-positron pairs annihilate
1 s
Protons and neutrons created
10 -5 s
Electron-quark soup
q
q
Z
W
Weak and electromagnetic forces separate
10 -11 s
Baryon genesis
10 -33 s
Inflation
10 -35 s
Grand unification
10 -43 s
Planck epoch (quantum gravity
The big bang
Radius of the universe


ESA/PLANCK CONSORTIUM

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 ▮▮-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!

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

**perhaps more interesting than ours!*

Masses >~ 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 >~ 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.

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.)

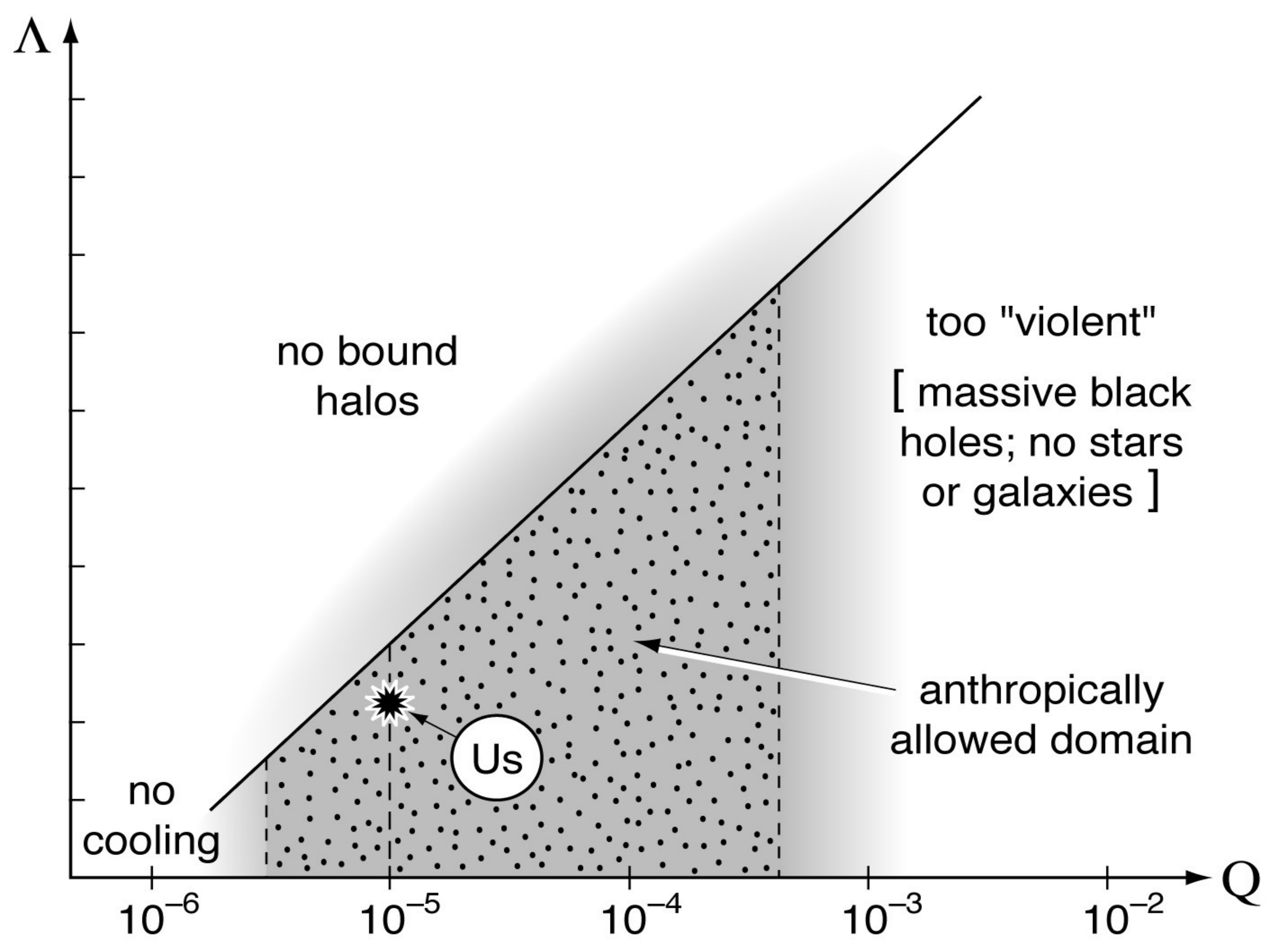
**This does not require pre-combination collapse. Collapse at (say) 10^7 years would lead to sufficient partial reionization (via strong shocks) to recouple the baryons and CMB.*

Constraints on lambda

- Positive: mustn't dominate until 'galaxies' have formed (limit is ~10 times actual value)
- Negative: mustn't cause recollapse too soon.

What if two or more parameters take non standard values?

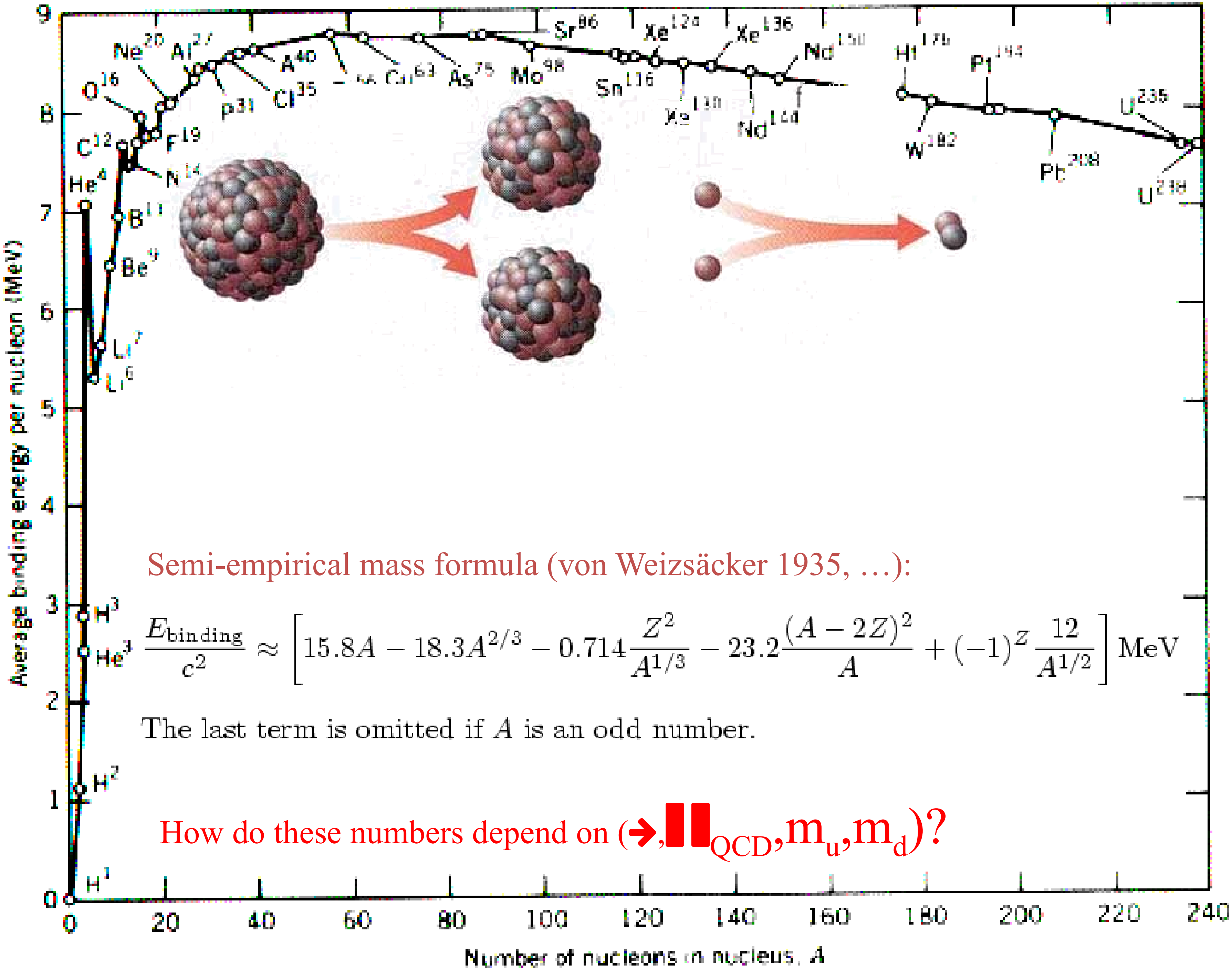
- This allows wider range for each parameter (cf extra 30 powers of 10 for lambda) *[see for instance Adams, Alexander, Grohs, and Mersini-Houghton (2017) and earlier papers by Adams and collaborators]*



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}

For higher lambda, anthropic range requires *higher* Q

For higher DM density, anthropic range allows *lower* Q

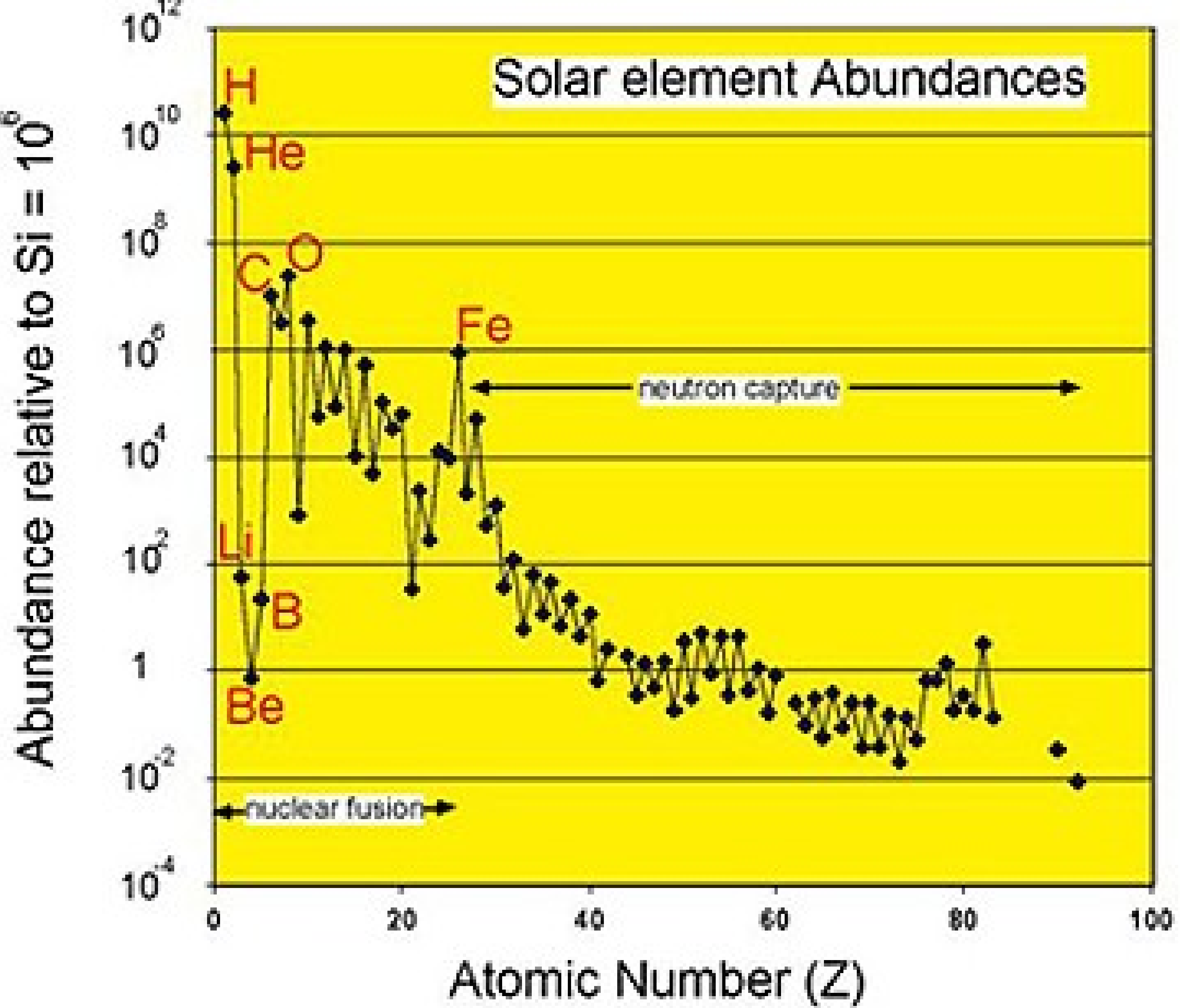


Semi-empirical mass formula (von Weizsäcker 1935, …):

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

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

How do these numbers depend on (➔,▮▮$_{QCD}$,m_u,m_d)?

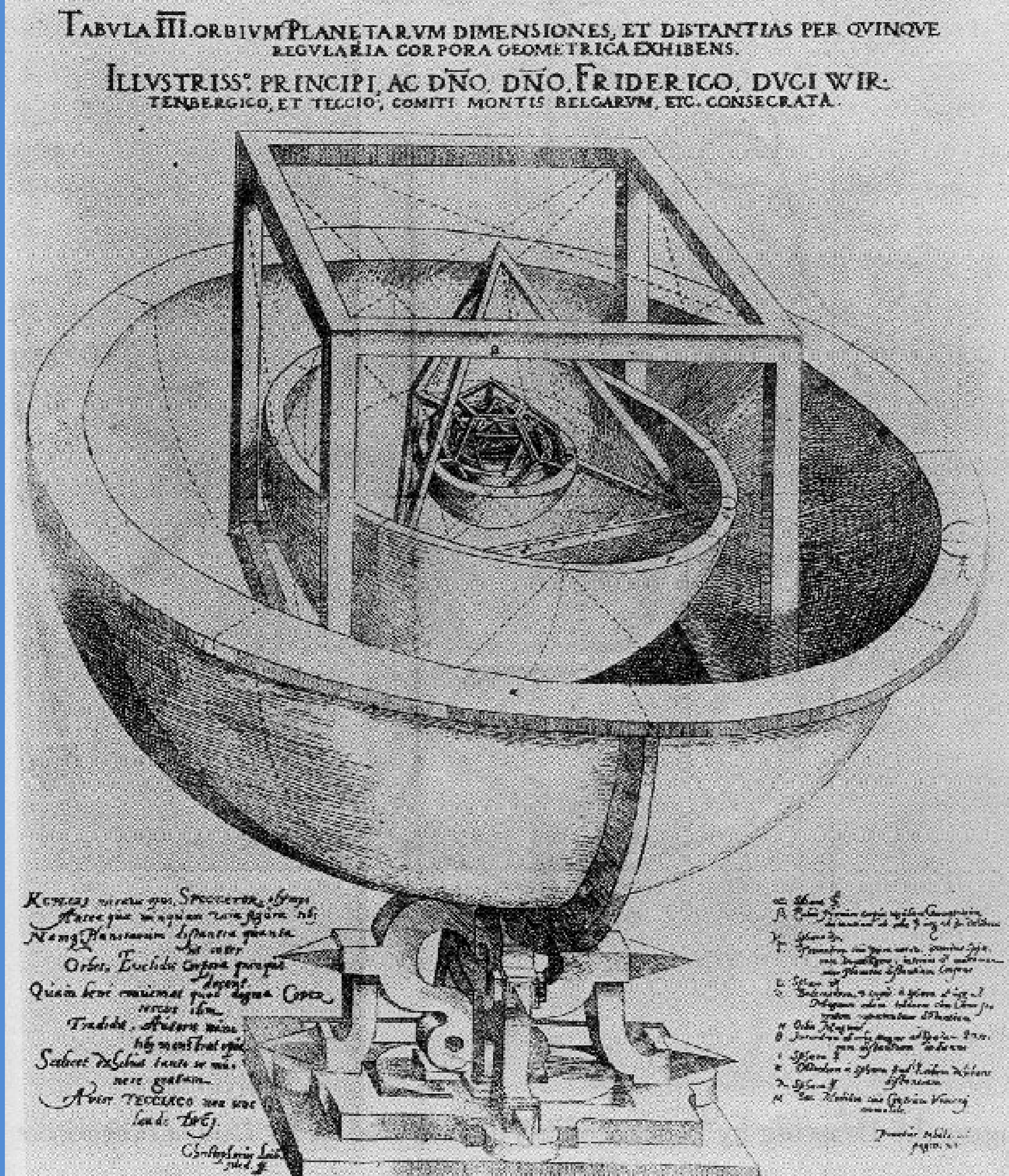


Solar element Abundances
Abundance relative to Si = 10^6
Atomic Number (Z)
H
He
Li
Be
B
C
O
Fe
neutron capture
nuclear fusion
10^{12}
10^{10}
10^8
10^6
10^4
10^2
1
10^{-2}
10^{-4}
0
20
40
60
80
100

A ‘Nuclear-free Universe’ (counterfactual!)

- *Stars undergo K-H contraction until they become white dwarfs (up to 5.6 solar masses for pure H) or black holes (higher masses)*
- *Jupiter-like planets could exist.*
- *Total radiative output <u>perhaps not much less </u>than in actual universe.*
- *BUT No chemistry, no rocky planets, no life**

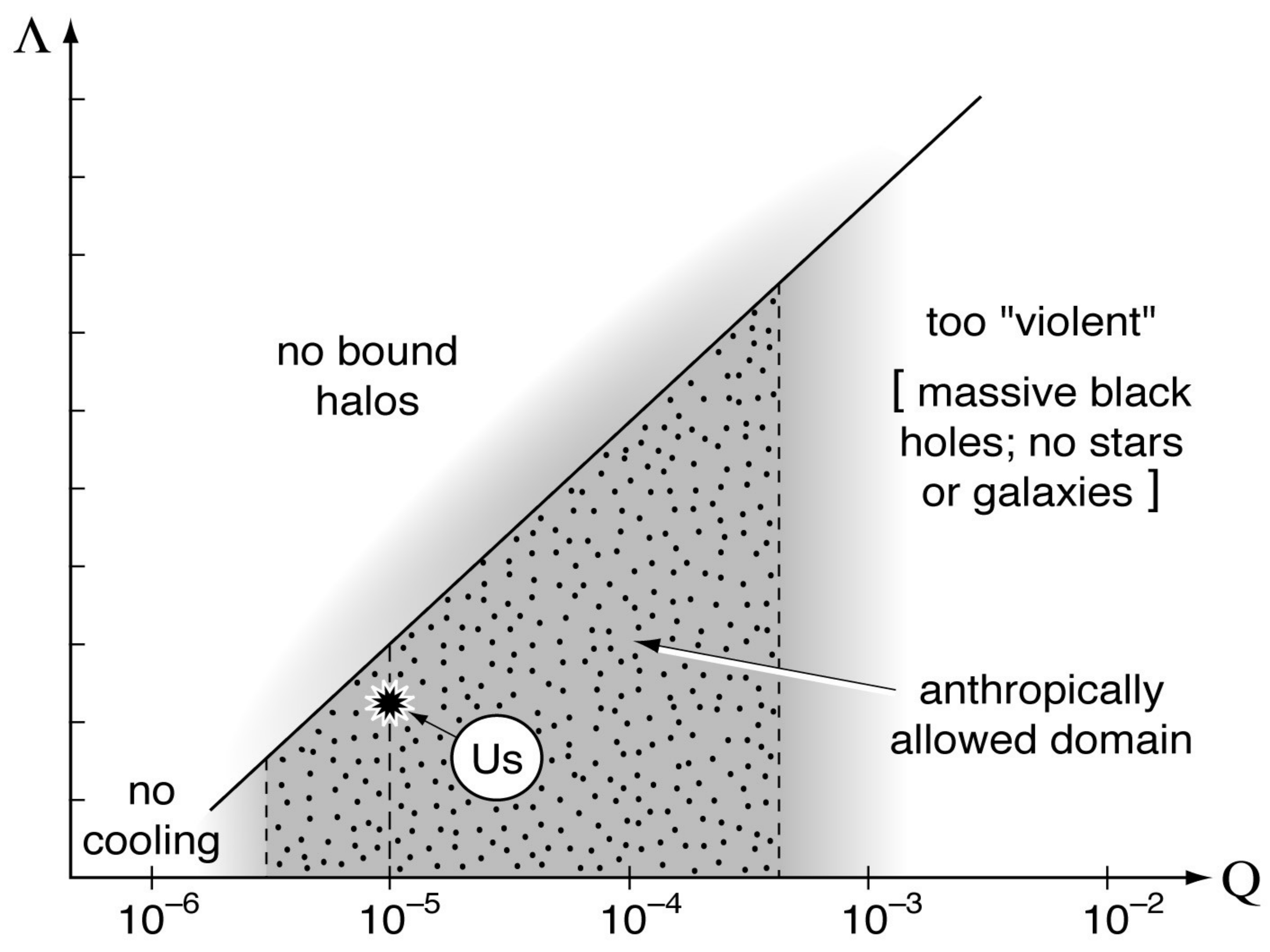
- * maybe Hoyle’s ‘Black Cloud’!


TABVLA III. ORBIVM PLANETARVM DIMENSIONES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA GEOMETRICA EXHIBENS.
ILLVSTRISS. PRINCIPI, AC DNO. DNO. FRIDERICO, DVCI WIRTENBERGICO, ET TECCIO, COMITI MONTIS BELGARVM, ETC. CONSECRATA.

IS THE EXISTENCE OF A MULTIVERSE (eg ETERNAL INFLATION) A SCIENTIFIC QUESTION?

YES

But it will remain speculation unless/until we have a theory that describes an inflationary phase, *and has gained credibility by accounting for phenomena in the range of observations and experiment*.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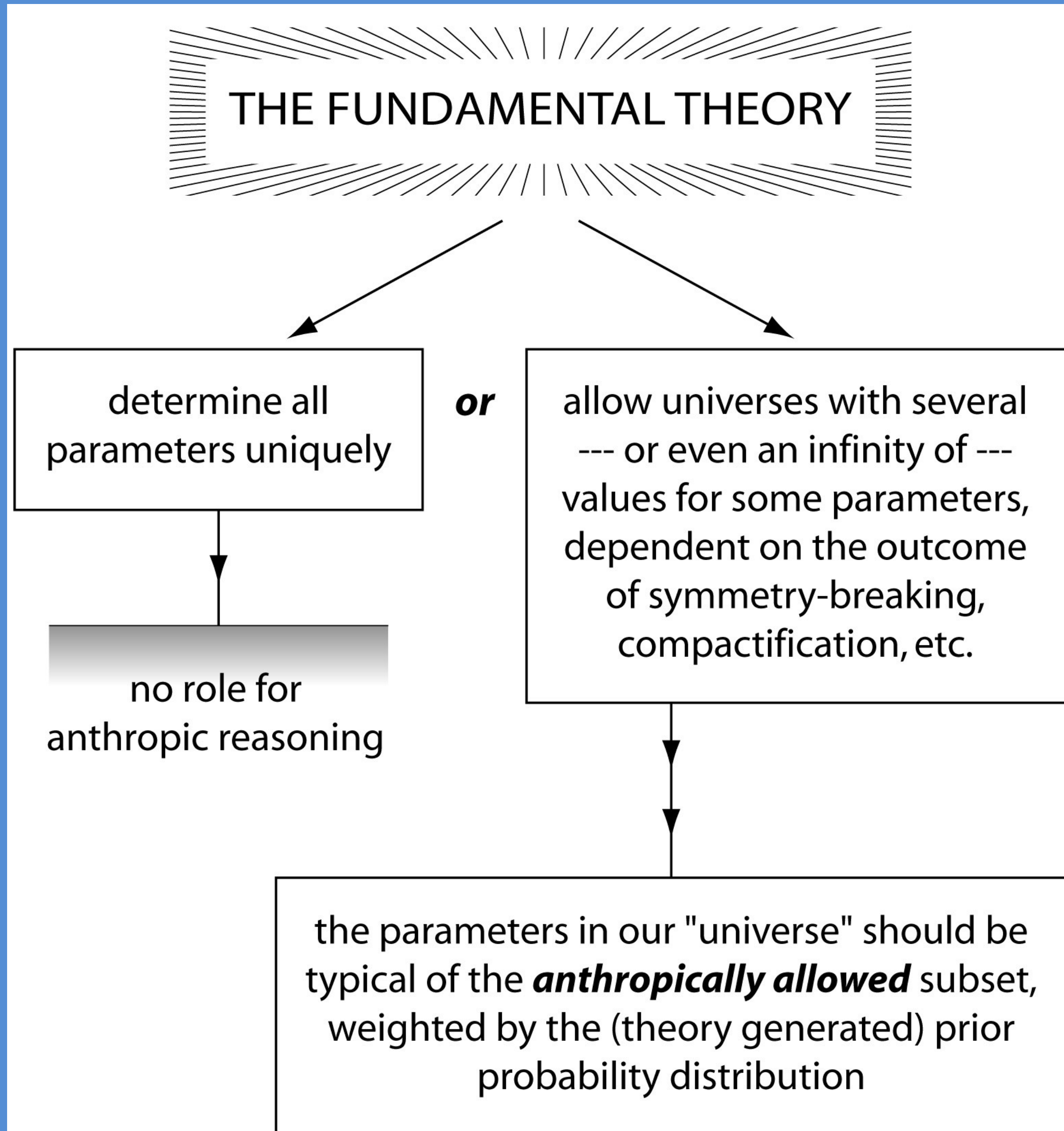
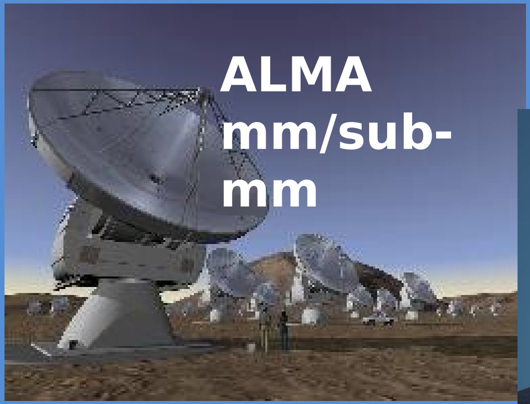
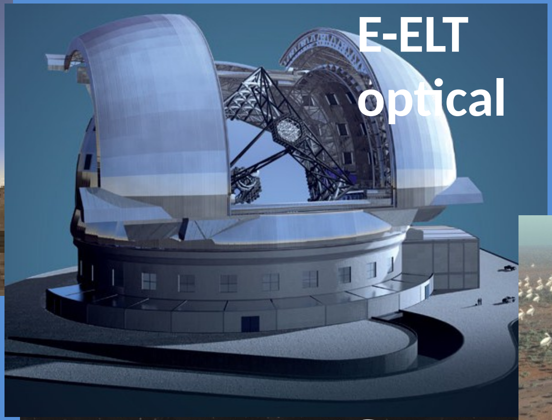
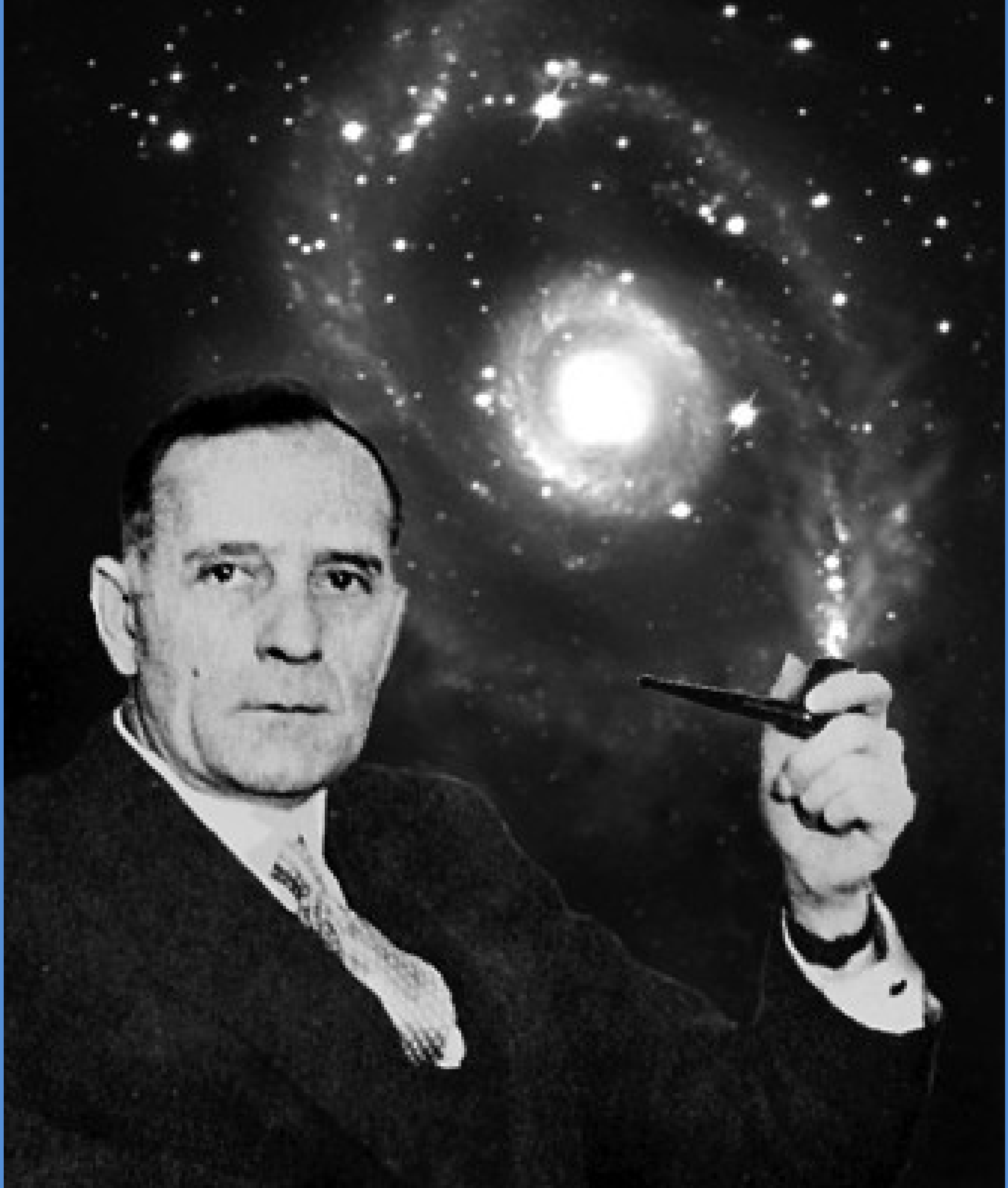

THE FUNDAMENTAL THEORY
determine all parameters uniquely
or
allow universes with several --- or even an infinity of --- values for some parameters, dependent on the outcome of symmetry-breaking, compactification, etc.
no role for anthropic reasoning
the parameters in our "universe" should be typical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

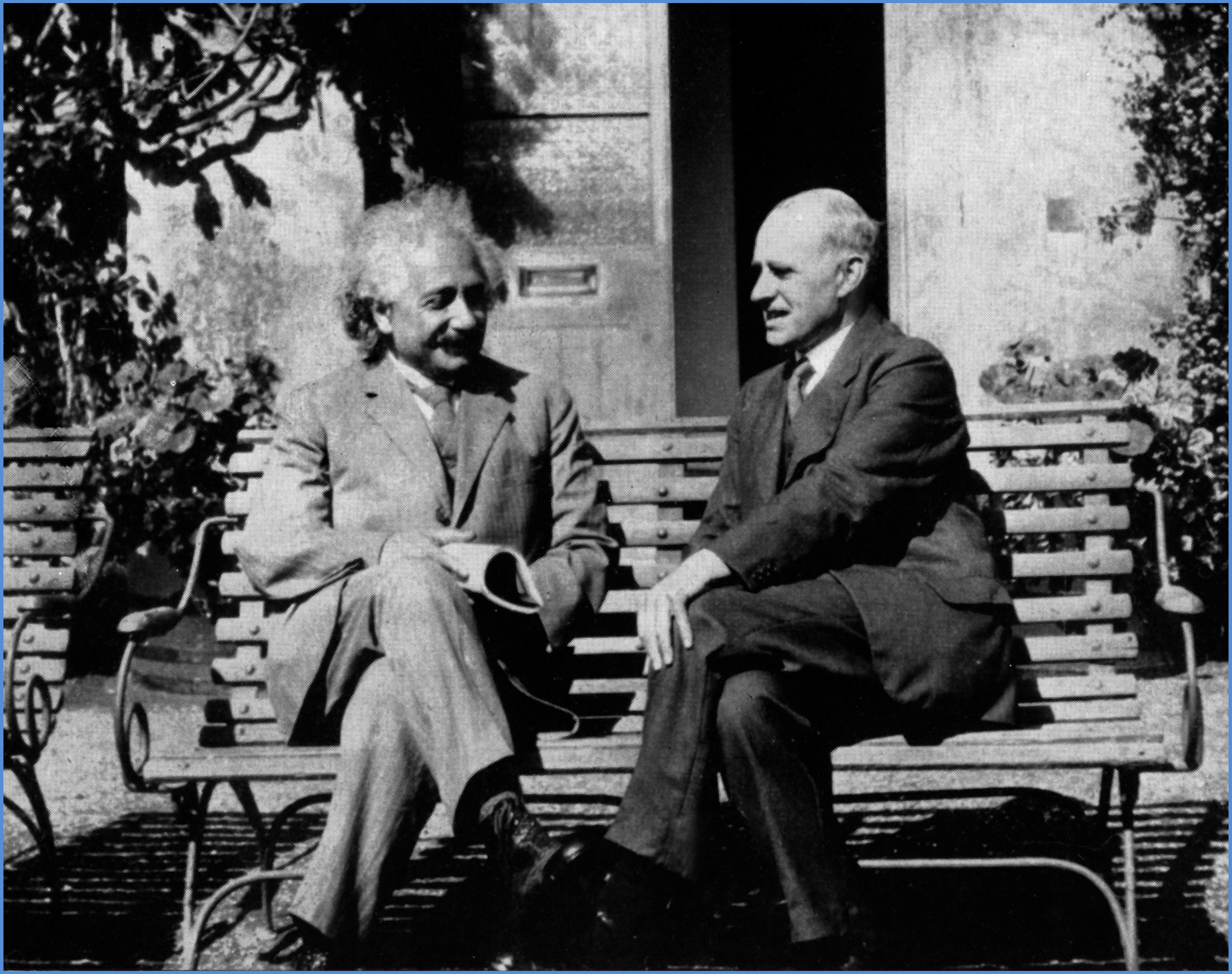
Great Observatories for the coming decades







"David believes in multiple universes—all of them lousy."



WHY DO ASTRONOMY?

- 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 the key properties of our cosmos in any ‘deeper’ way?

Progress in computer simulation

N-body and gas dynamics in expanding universe

Strong-field general relativity
(black hole mergers and recoil)

Relativistic MHD
(jets, etc)

3-D Supernova explosions

Plasma microphysics
(shocks, magnetospheres, and particle acceleration)