The Big Picture: Long Term Evolution of Astrophysical Systems

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The Copernican Time Principle

The current cosmological epoch has no special significance.

The Copernican Time Principle

The current cosmological epoch
has no special significance.

Interesting physics processes will
continue to take place in the future,
despite decreasingly energy levels

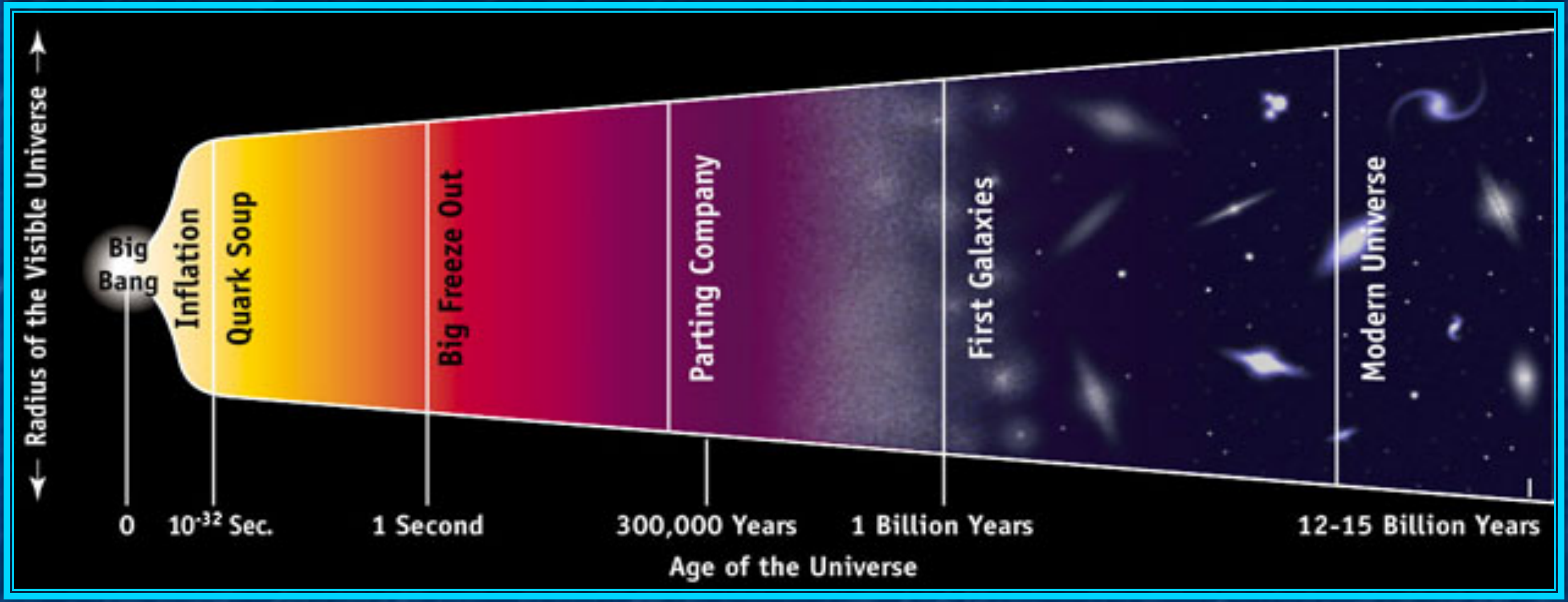
Yet Another Principle:

The cosmological future informs our understanding of astrophysics in the present day universe.

Cosmological Decade

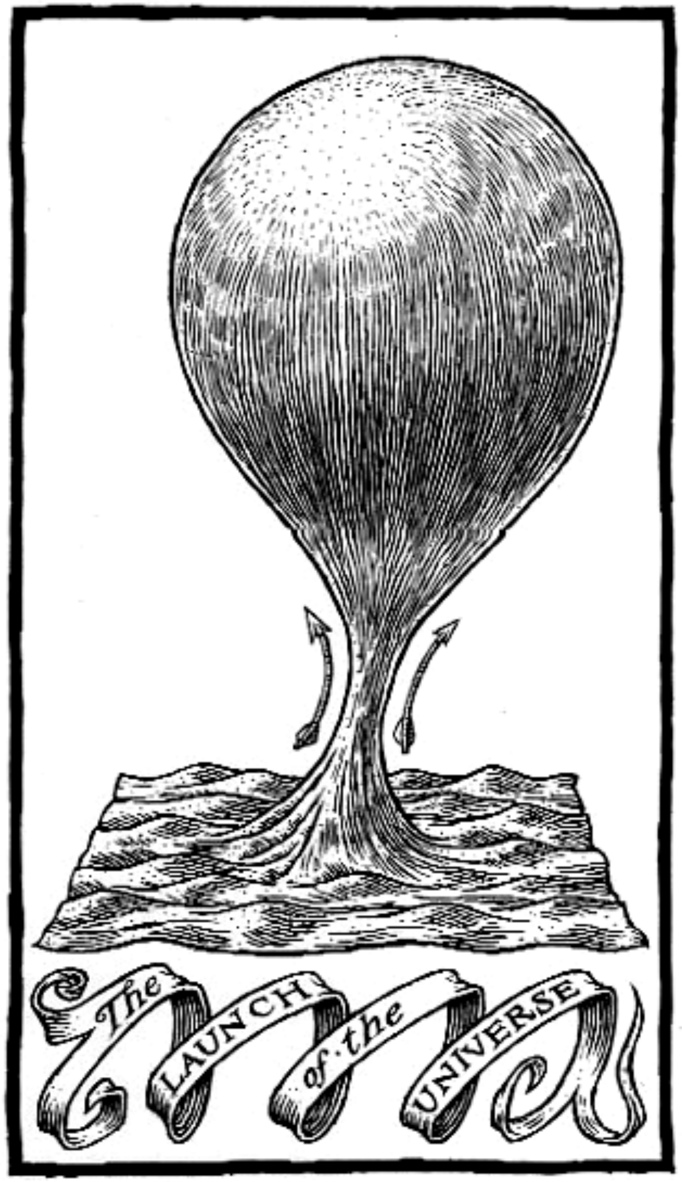
$$t = 10^{\eta}\ years$$

Cosmic Timeline

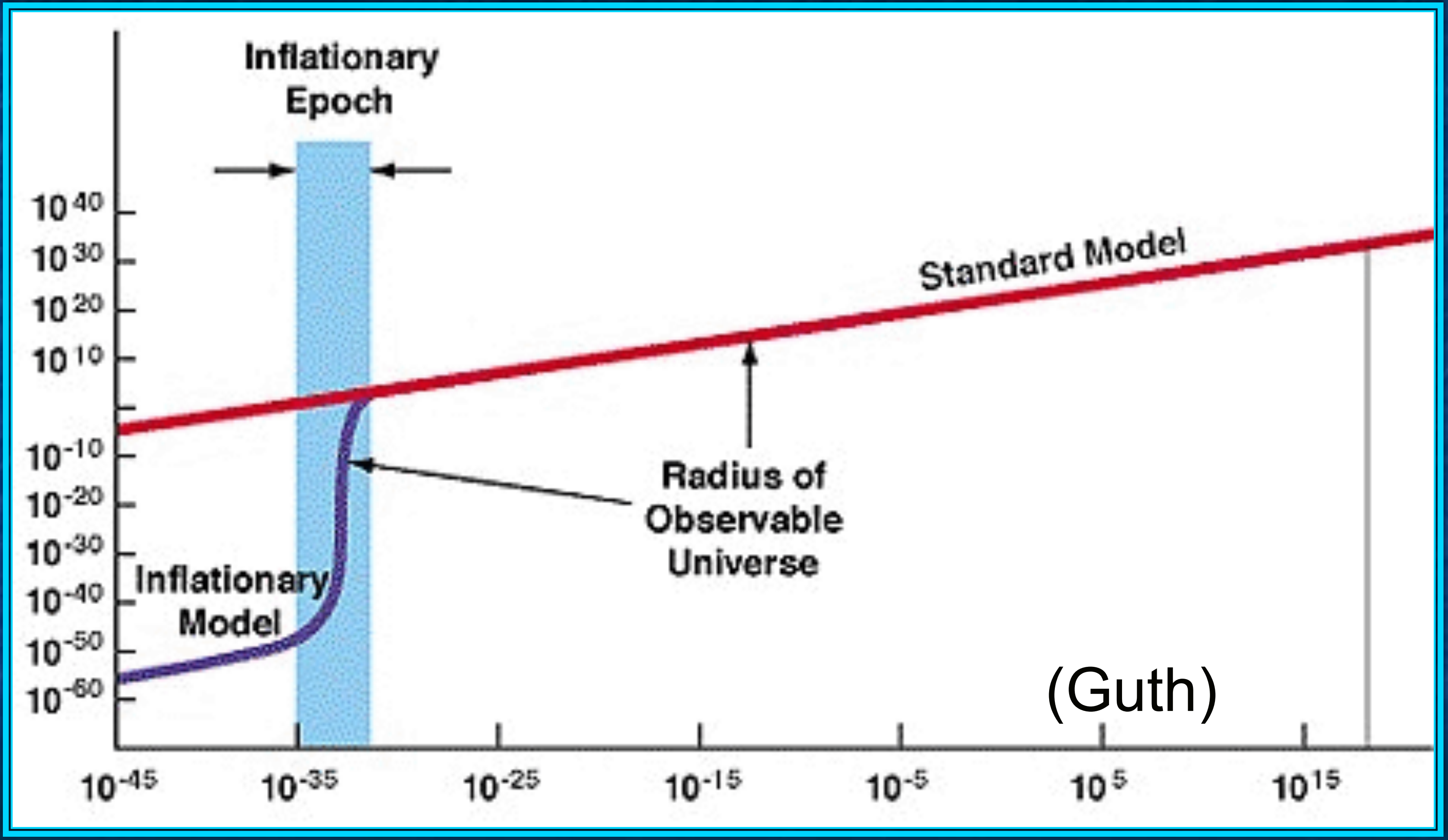


Five Ages of the Universe

Primordial Era	n < 6
Stelliferous Era	n = 6 - 14
Degenerate Era	n = 14 - 40
Black Hole Era	n = 40 - 100
Dark Era	n > 100

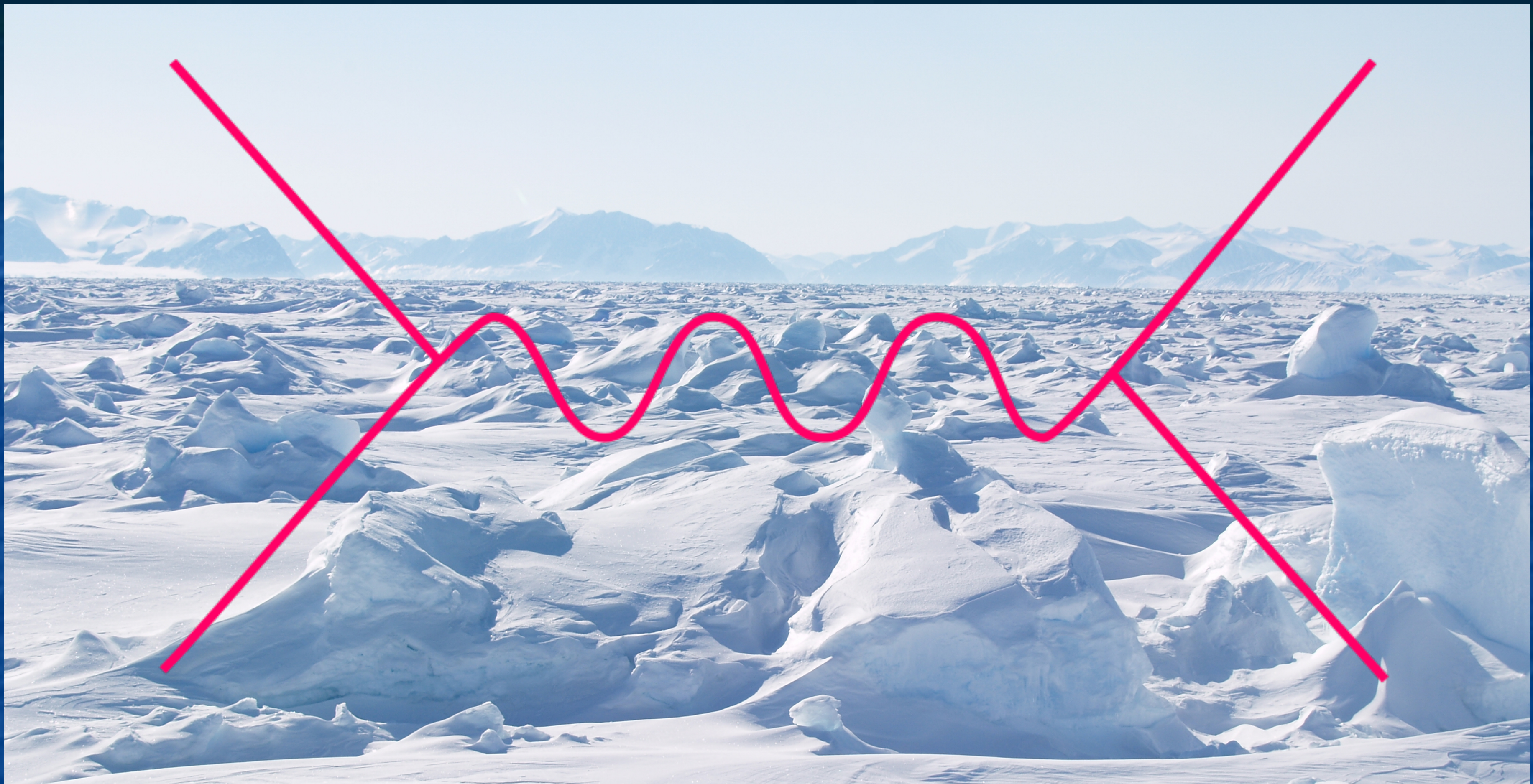

The LAUNCH of·the UNIVERSE

The Inflationary Universe



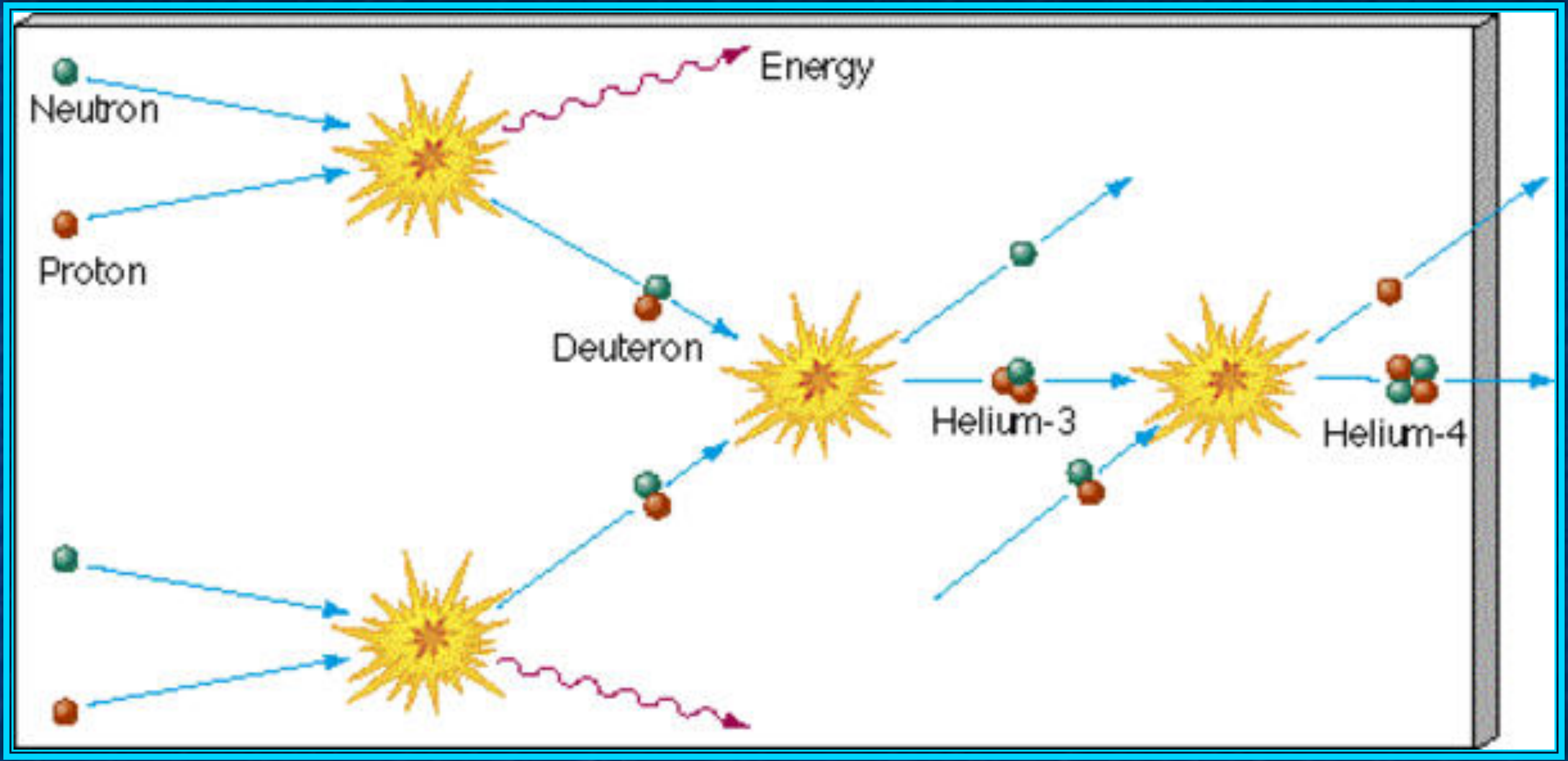
Time in seconds

Matter > Antimatter

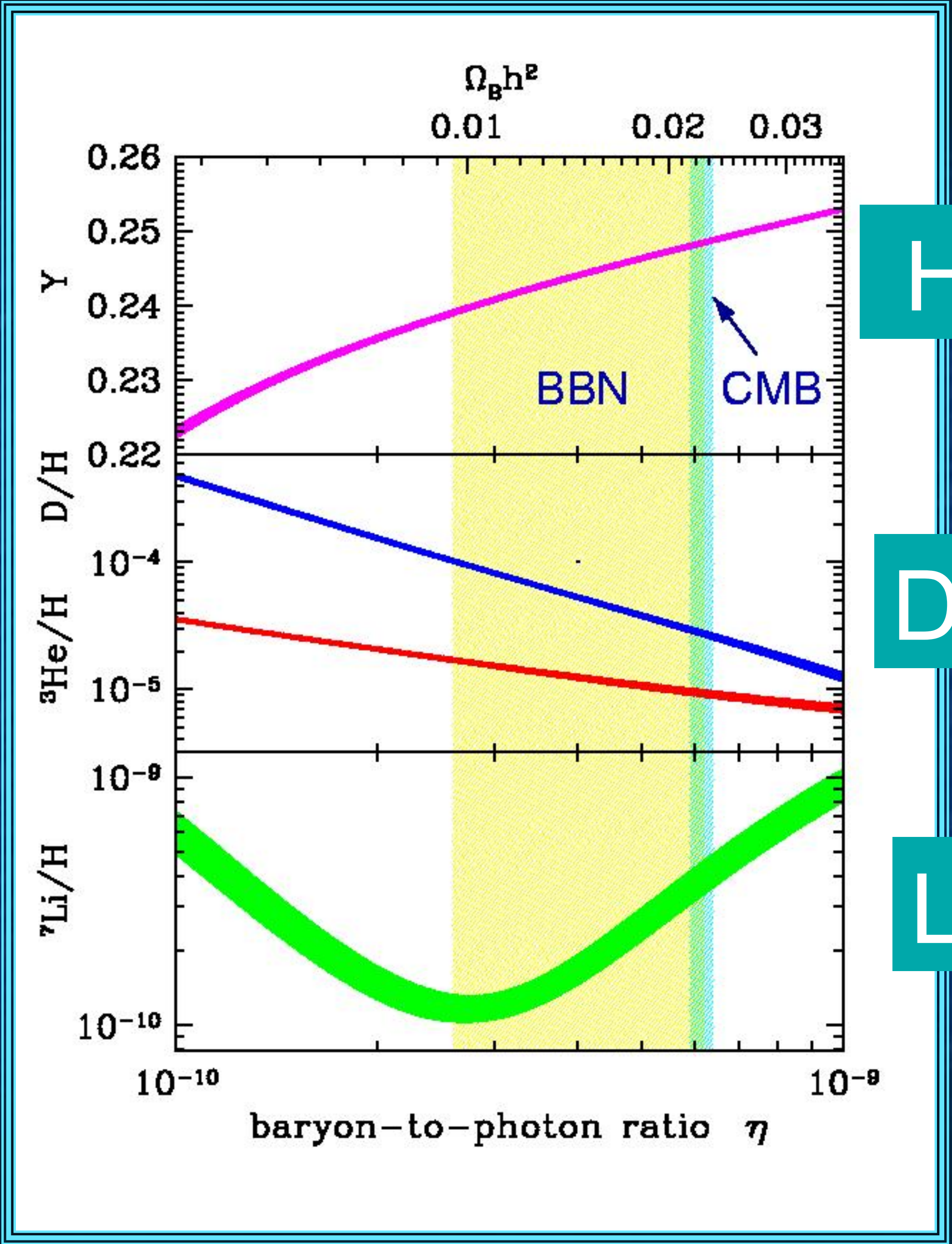


Dark matter abundance freezes before universe is 1 second old

The synthesis of light elements begins when the universe is one second old



and ends three minutes later…



Helium

Deuterium

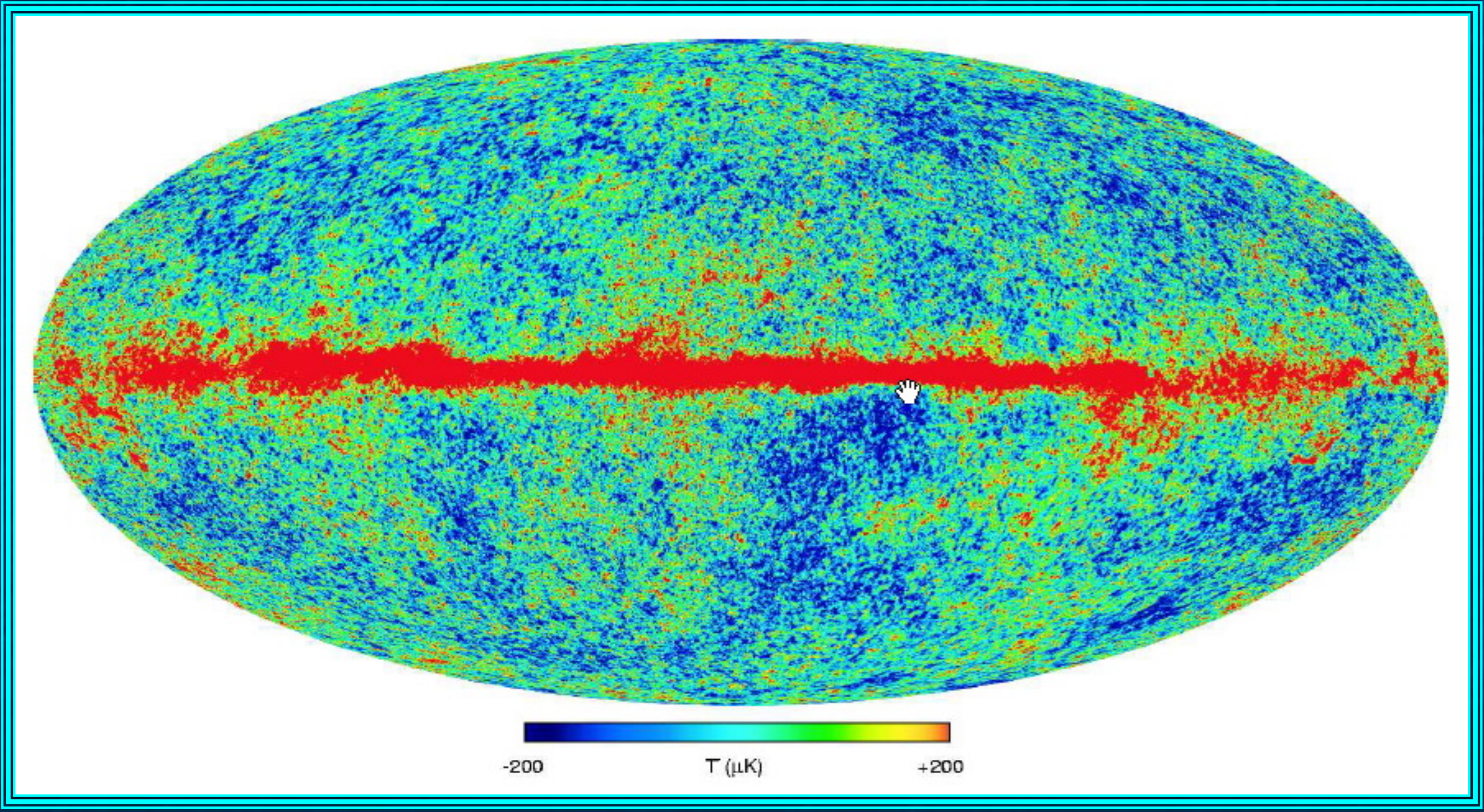
Lithium

(Schramm)

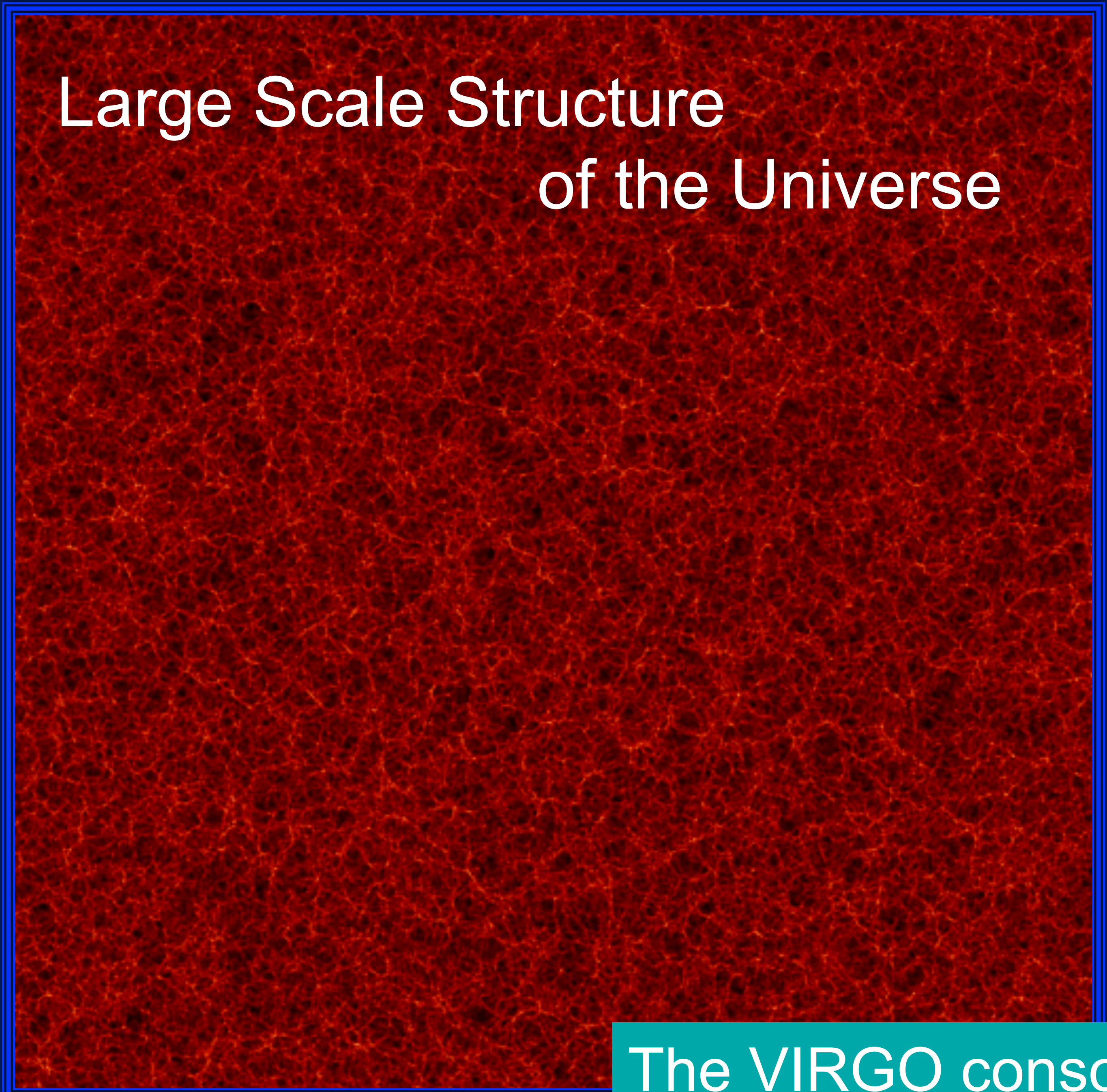
The Primordial Era

- The Big Bang
- Inflation
- Matter > Antimatter
- Quarks --- protons & neutrons
- Nuclear synthesis of the light elements
- Cosmic Microwave Background
- Universe continues to expand

WMAP: Cosmic Background Radiation

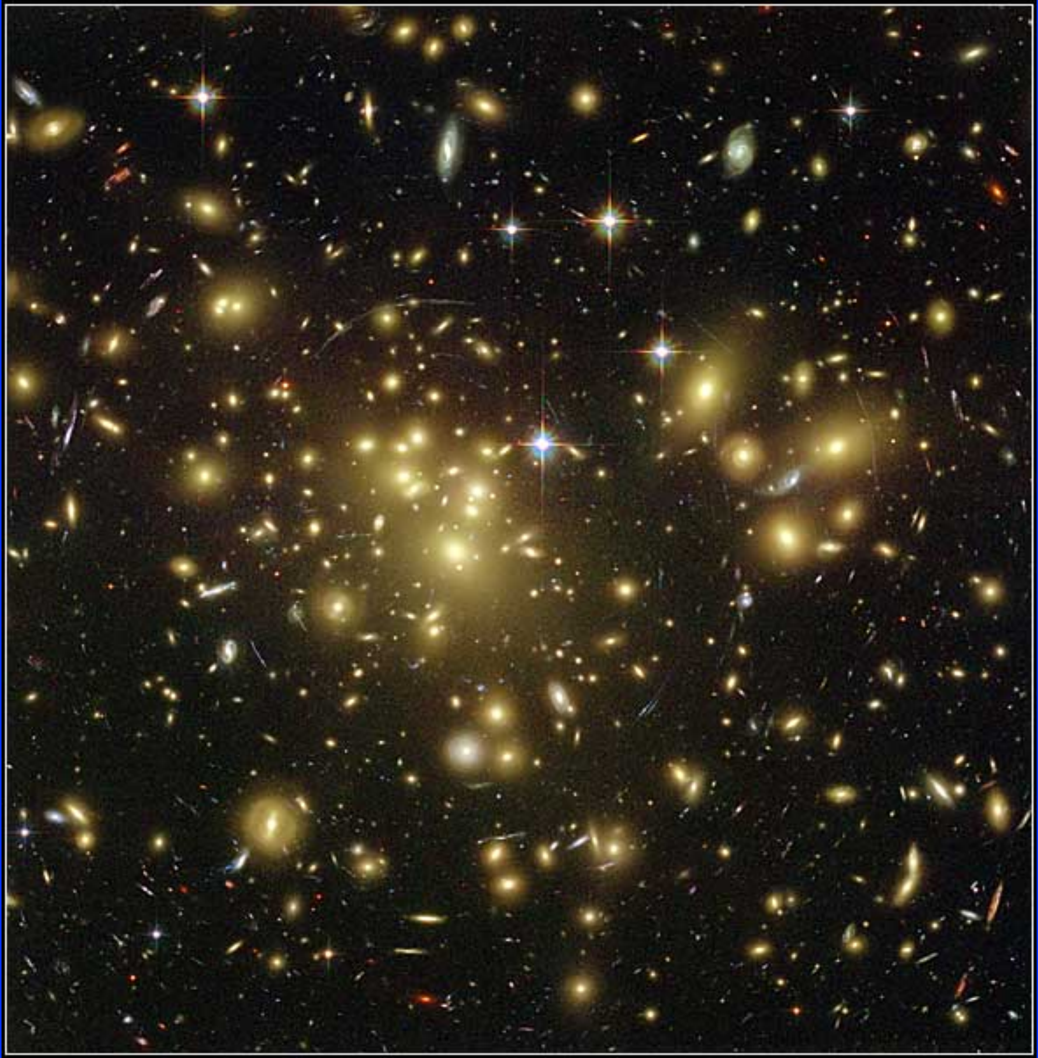


Large Scale Structure of the Universe

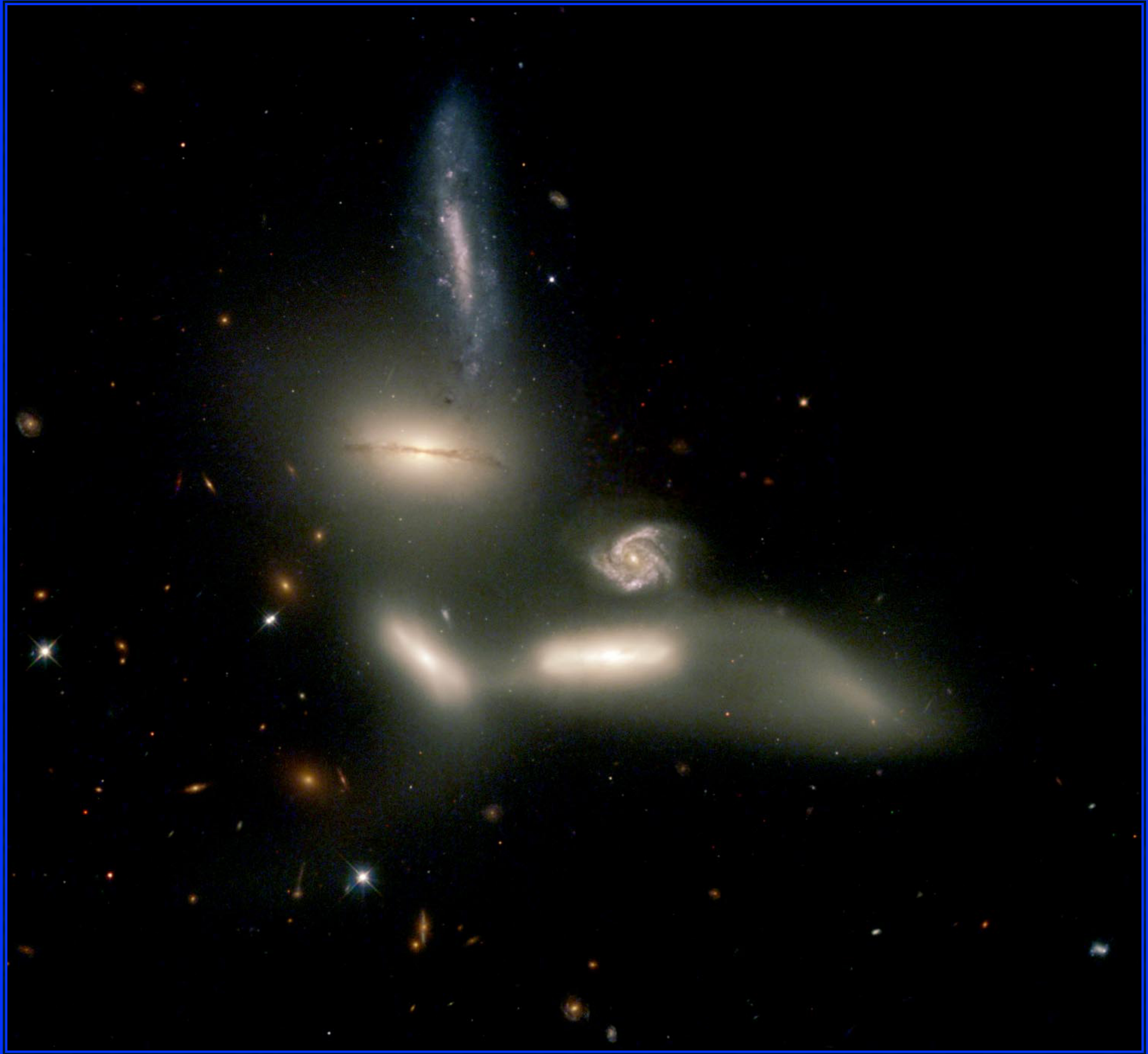


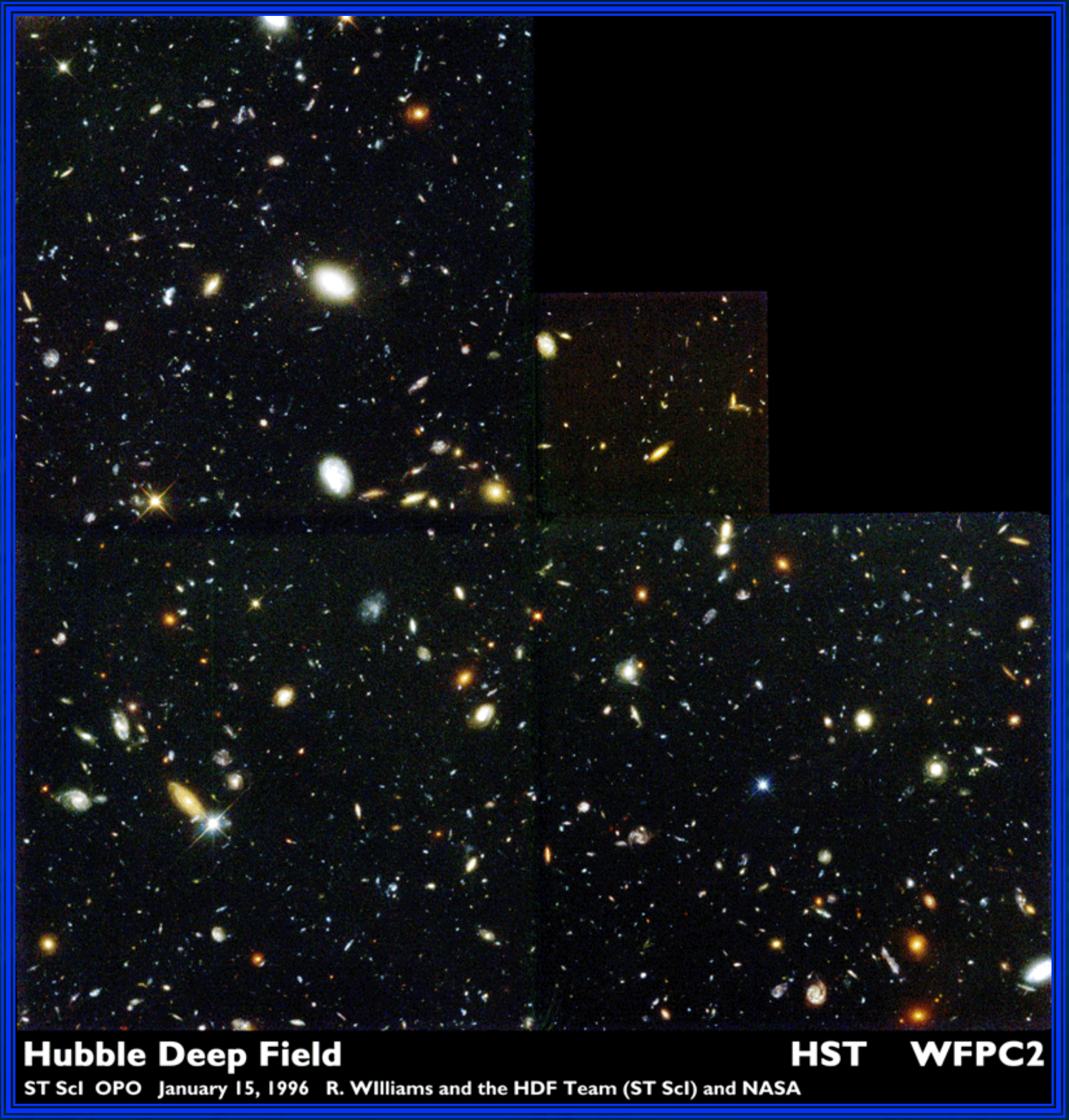
The VIRGO consortium

Galaxy Cluster Abell 1689 HST ▪ ACS



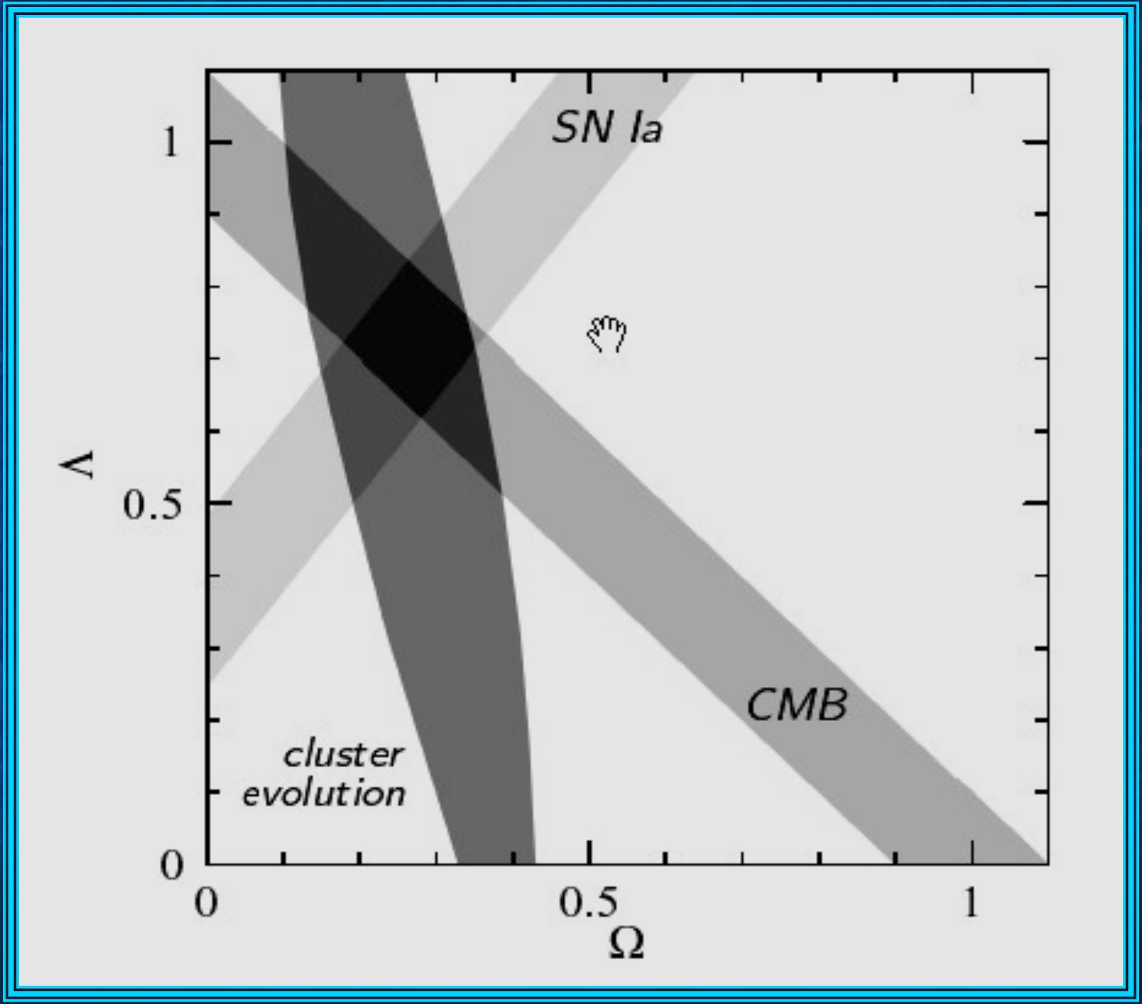
NASA, N. Benitez (JHU), T. Broadhurst (Hebrew Univ.), H. Ford (JHU), M. Clampin(STScl), G. Hartig (STScl), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA STScl-PRC03-01a

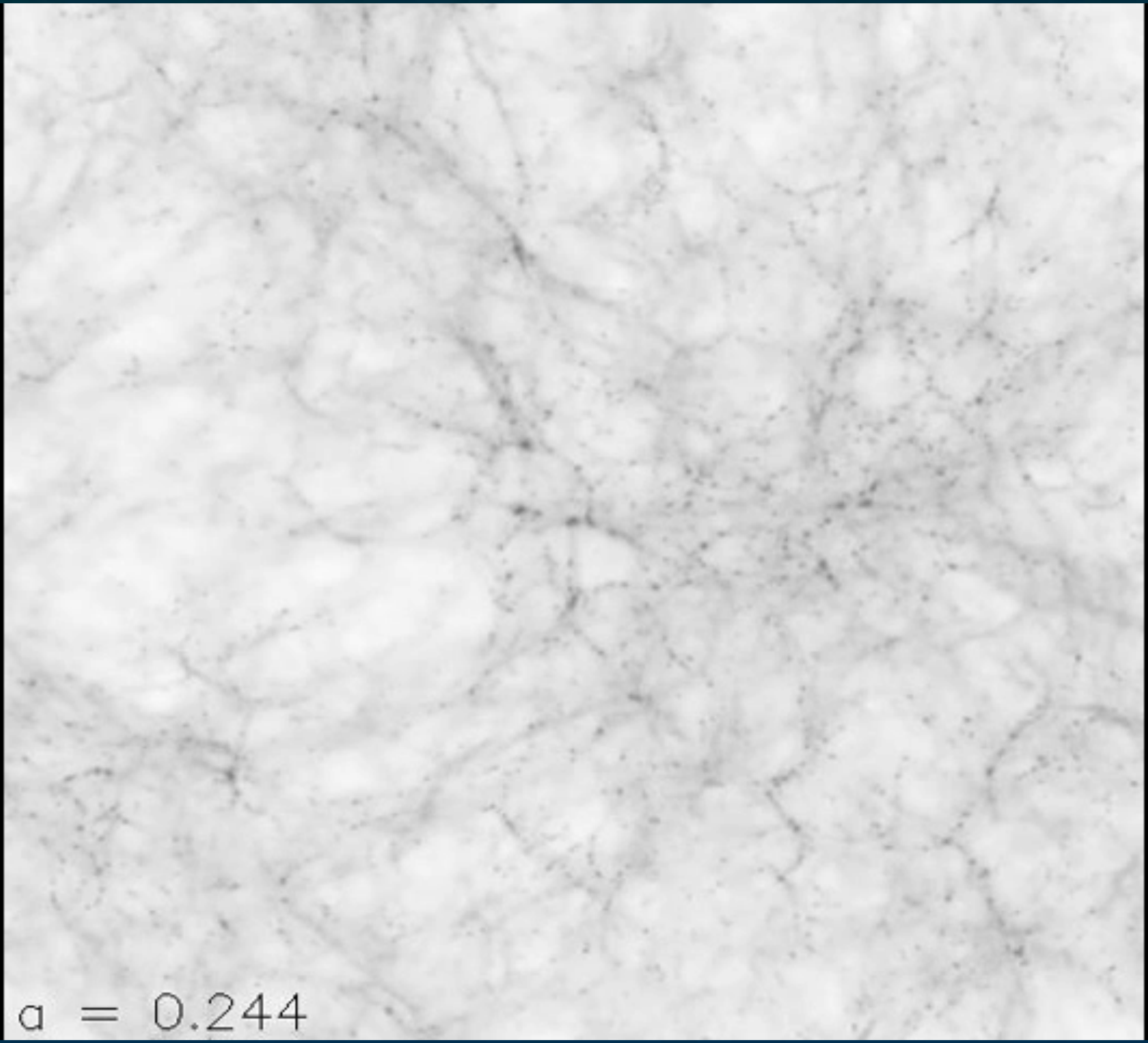



Hubble Deep Field
HST WFPC2
ST ScI OPO January 15, 1996 R. WIlliams and the HDF Team (ST ScI) and NASA

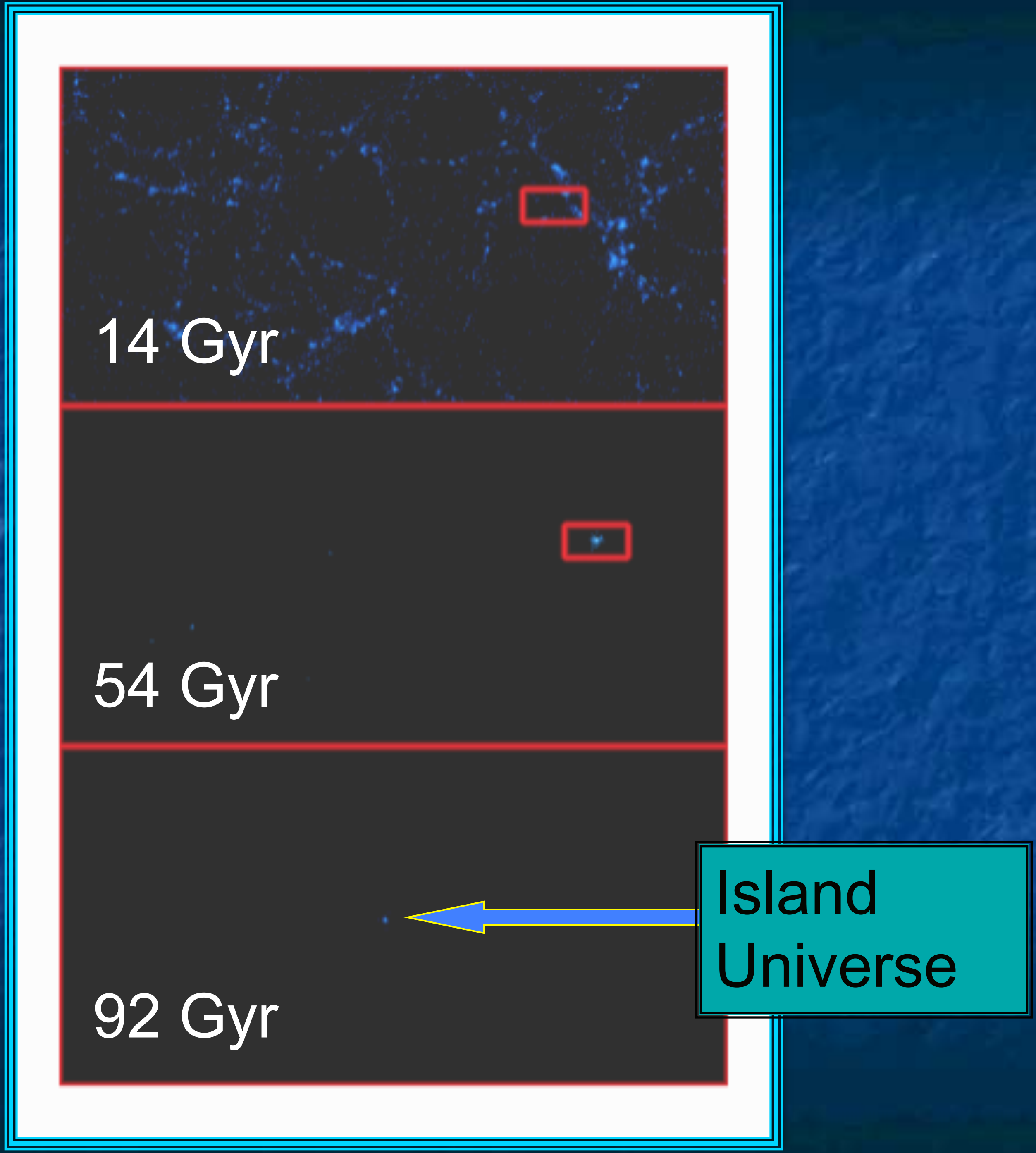
The Present Epoch

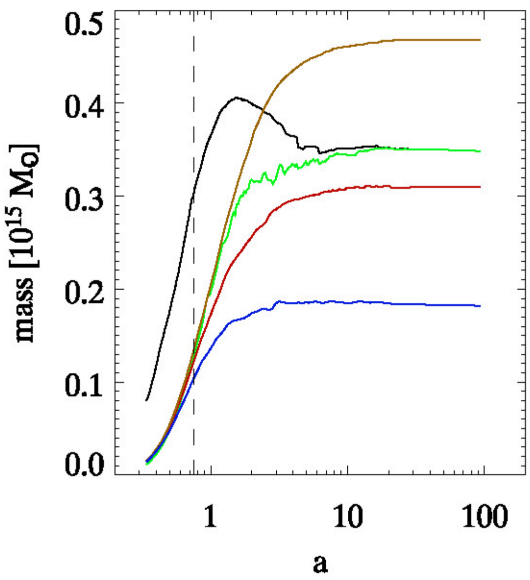
Cosmological Parameters

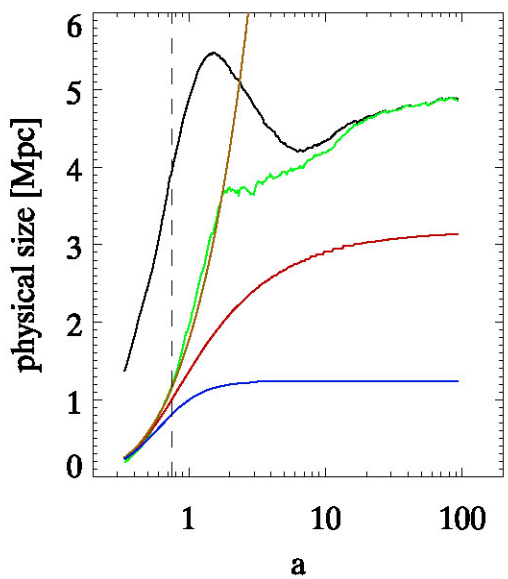


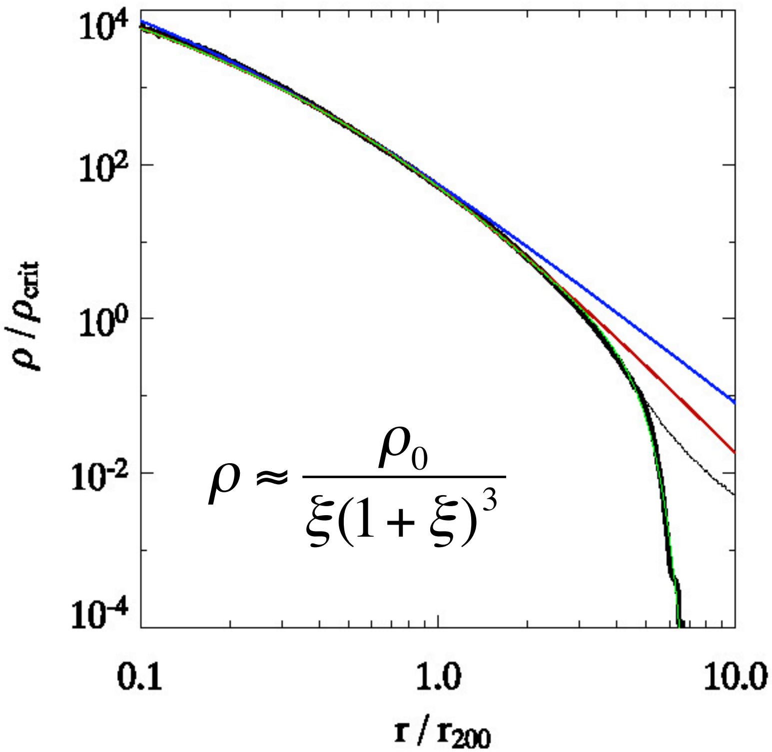


(Busha, Ketchum, Butler, Evrard, Adams)


14 Gyr
54 Gyr
92 Gyr
Island Universe





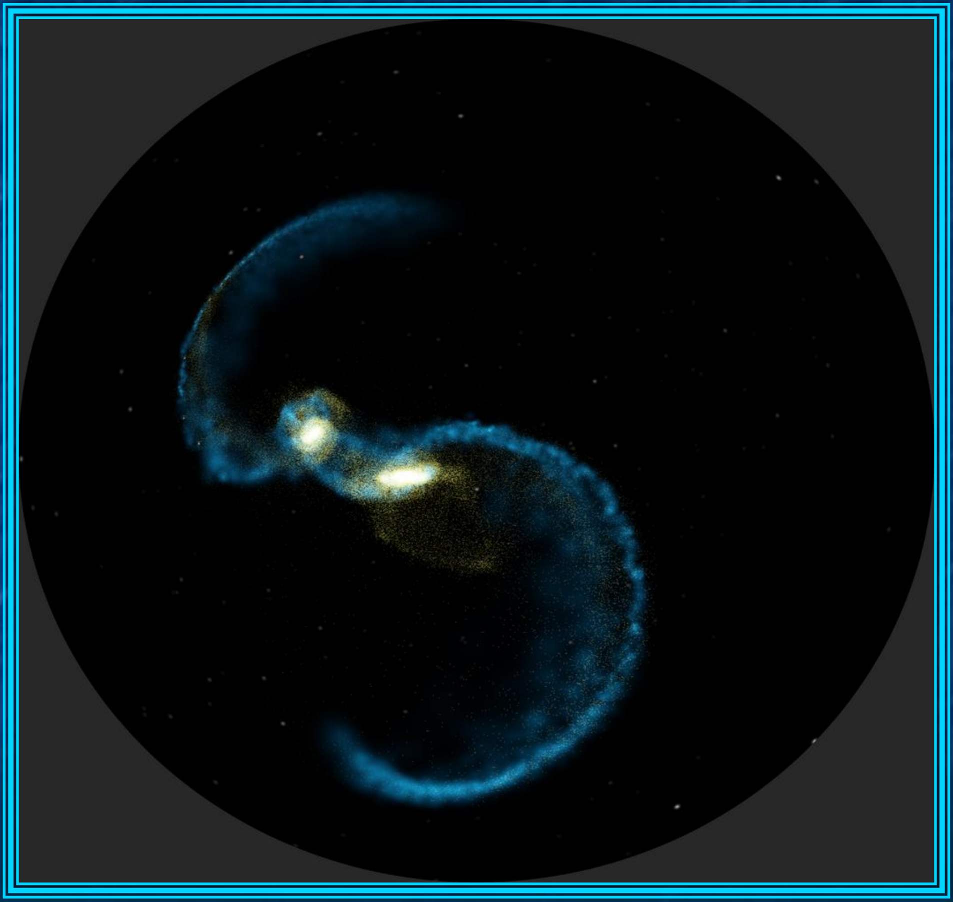


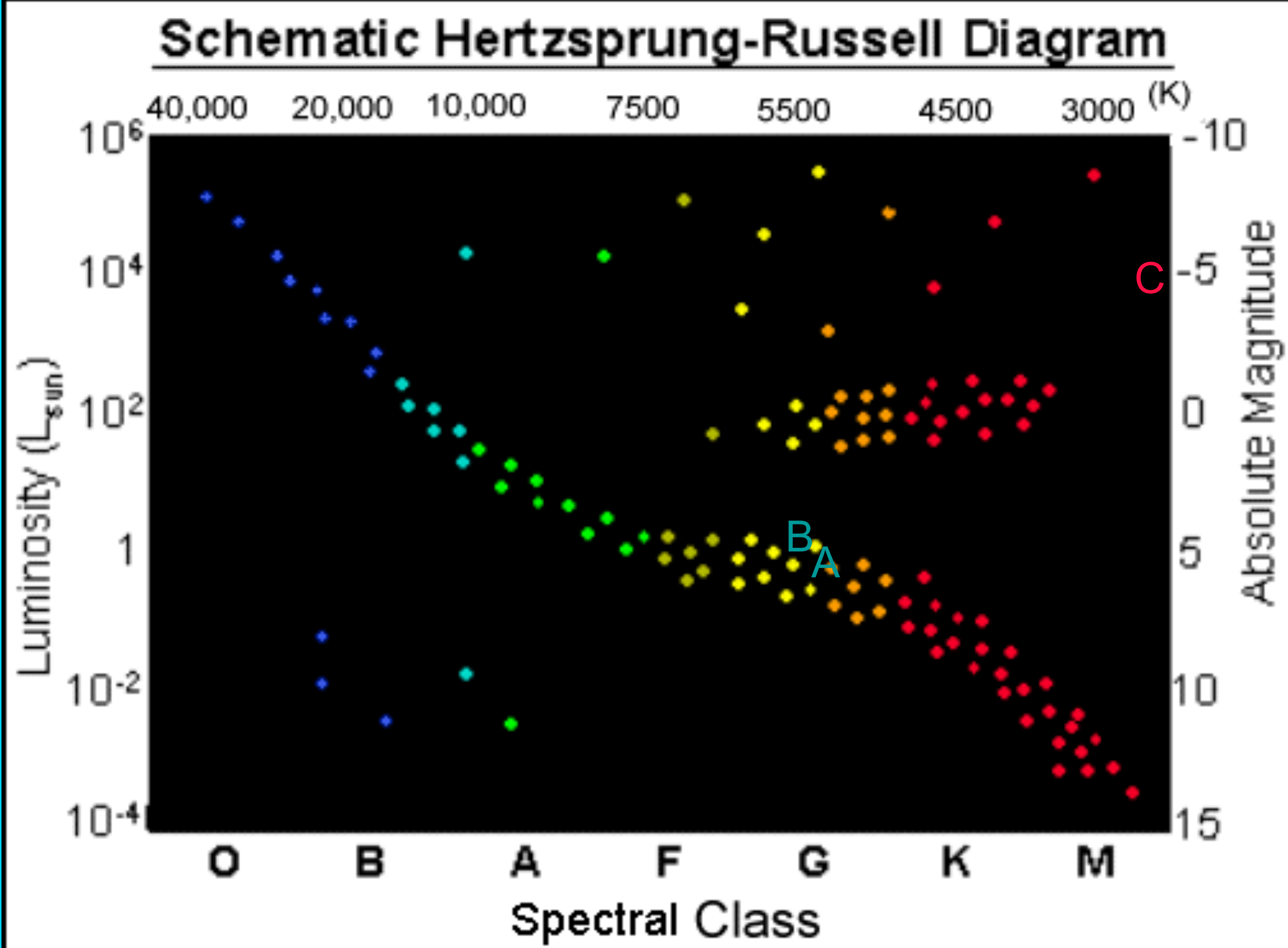
Dark matter halos approach a well-defined asymptotic form with unambiguous total mass, outer radius, density profile

Andromeda: Our sister galaxy

Milky Way and Andromeda

Collision with Andromeda



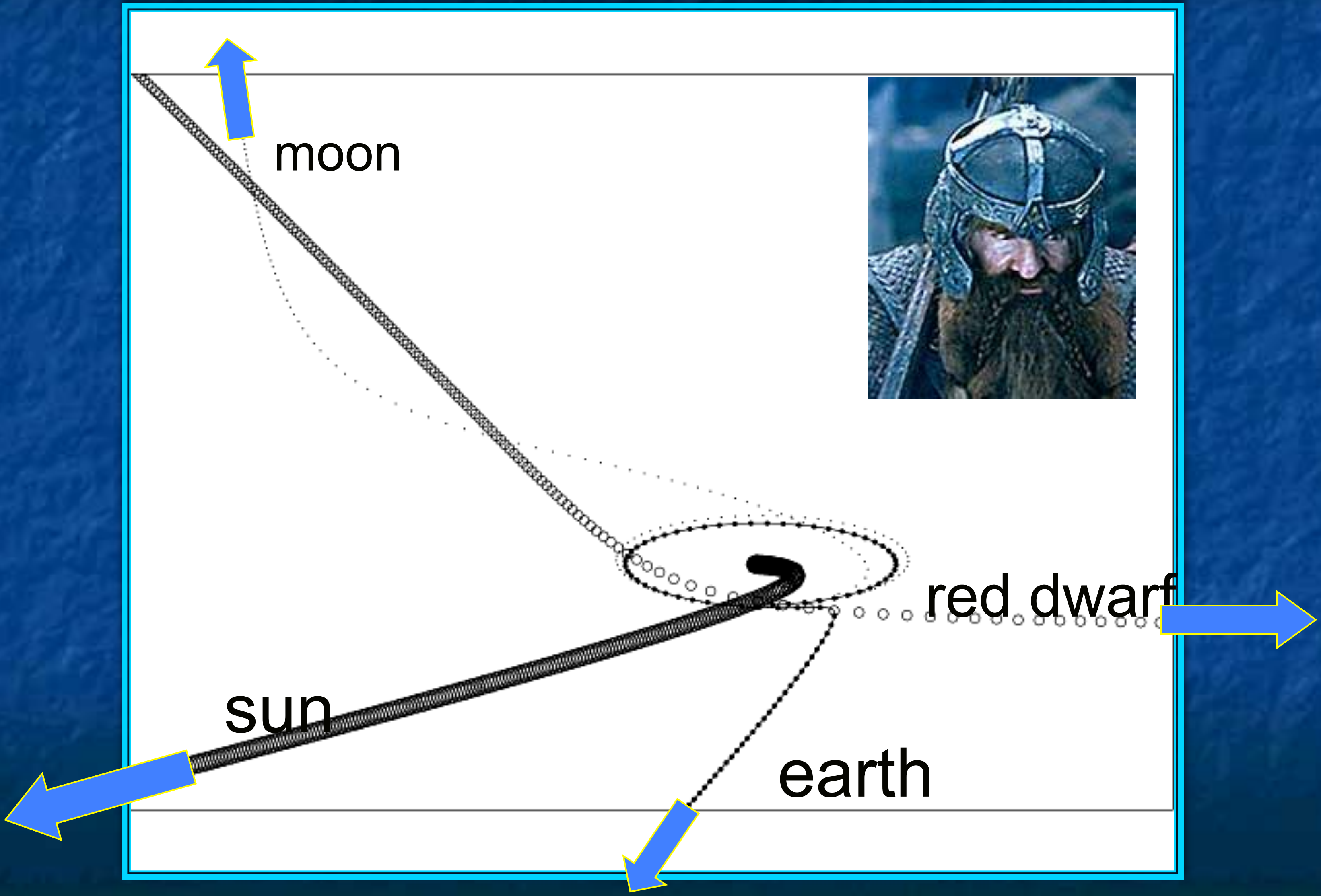


Schematic Hertzsprung-Russell Diagram
40,000
20,000
10,000
7500
5500
4500
3000
(K)
10^6
10^4
10^2
1
10^{-2}
10^{-4}
Luminosity (L_{sun})
-10
-5
0
5
10
15
Absolute Magnitude
C
B
A
O
B
A
F
G
K
M
Spectral Class

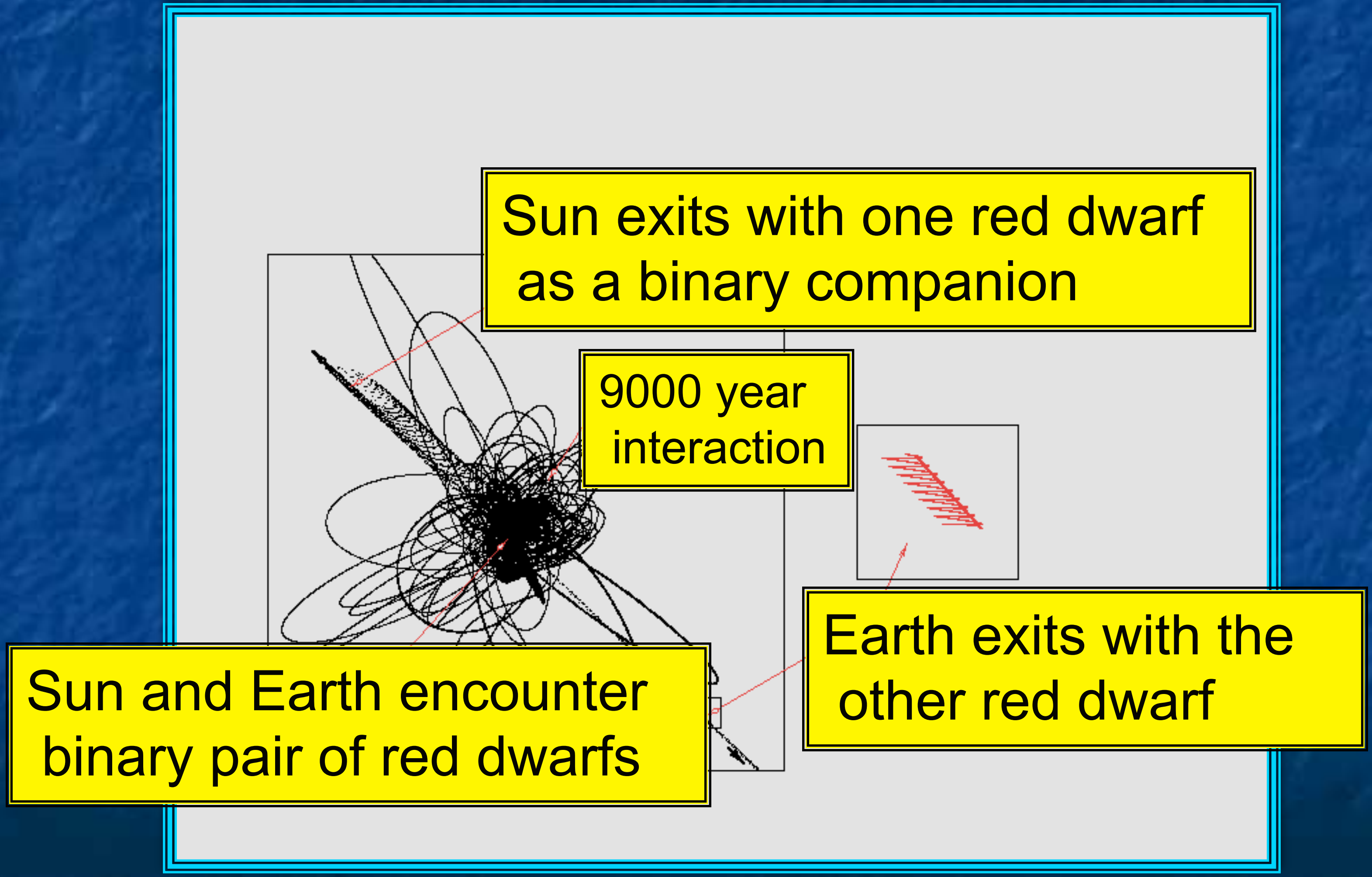
Earth swallowed by the Sun

(probably…)

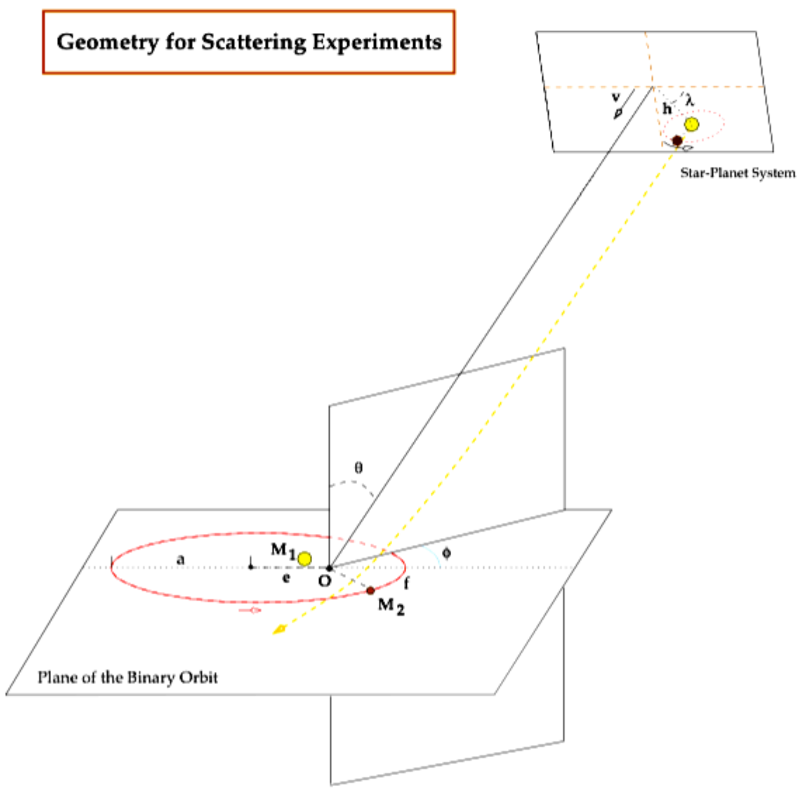
Red Dwarf saves the Earth



Red dwarf captures the Earth



Solar System Scattering



Star-Planet-Binary scattering encounters are specified by 13 parameters.

1. Parameters describing the binary orbit: m_1, m_2, e,f, a
2. Parameters describing the encounter: v, h ,ψ, θ, ϕ
3. Parameters describing a (circular) planetary orbit: r,θ_1, θ_2, θ_3

Many Parameters

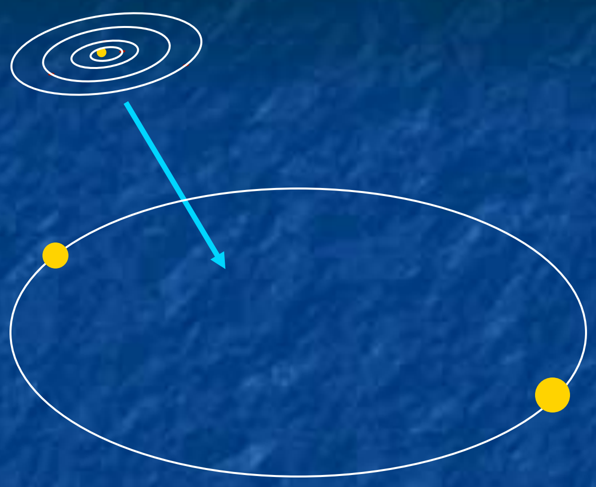
+

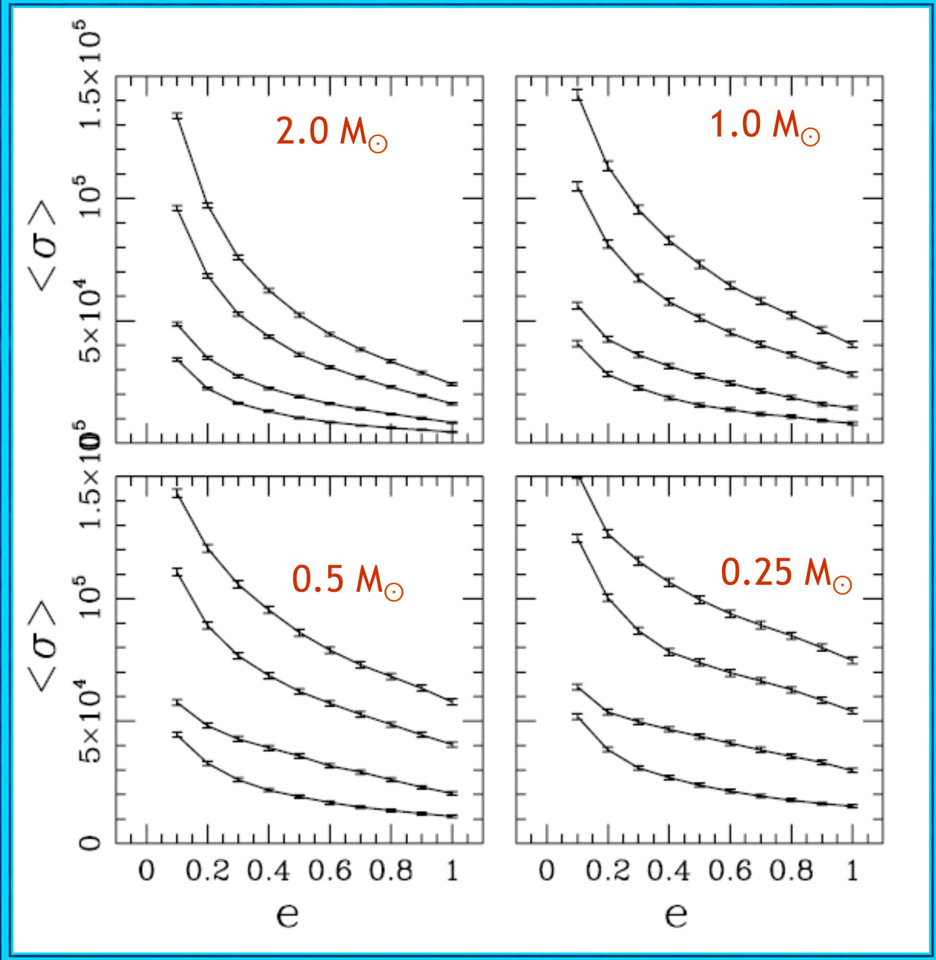
Chaotic Behavior

↓

Many Simulations
Monte Carlo
Scheme

Cross Sections vs Stellar Mass





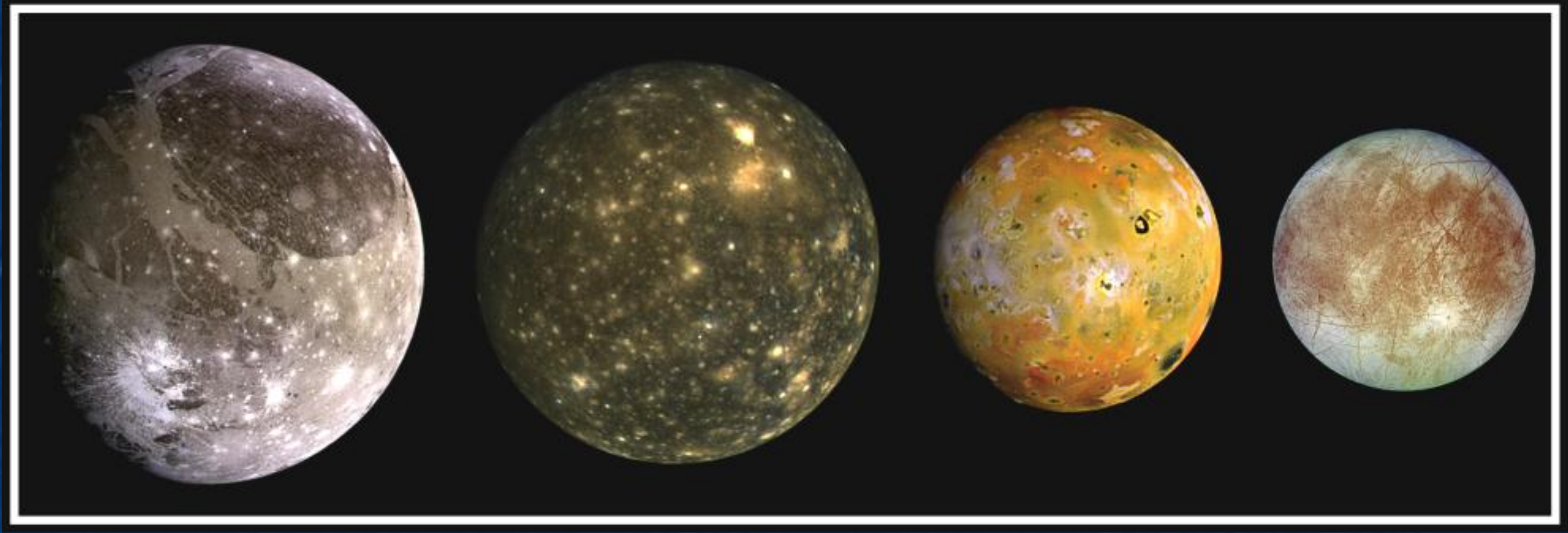
$$\langle \sigma \rangle_{ej} = C_0 \left(\frac{a_P}{AU} \right) \left(\frac{M_*}{M_{sun}} \right)^{-1/2}$$

where

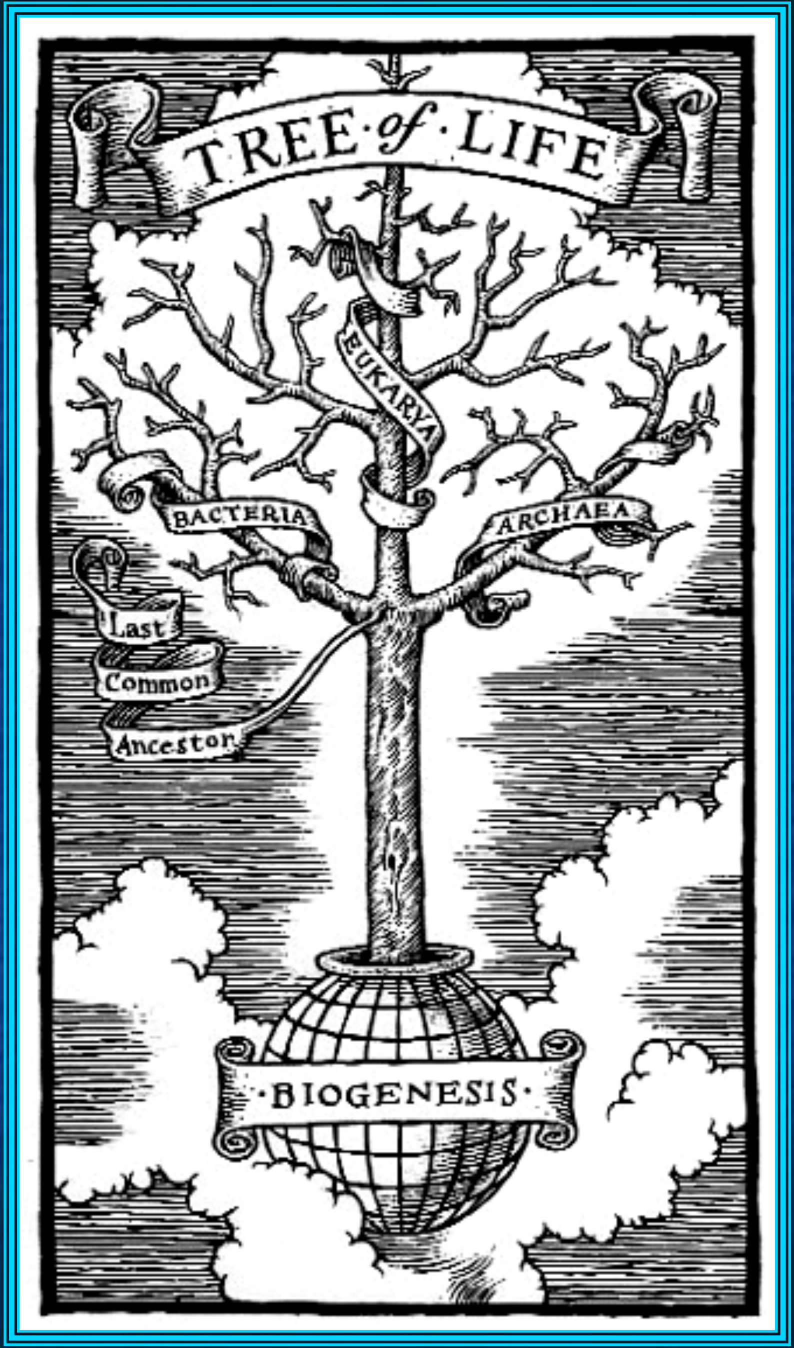
$$C_0 = 1350 \pm 160 \ \ (AU)^2$$

Galilean Satellites:

Icy worlds are easy to make



Ganymede Callisto Io Europa

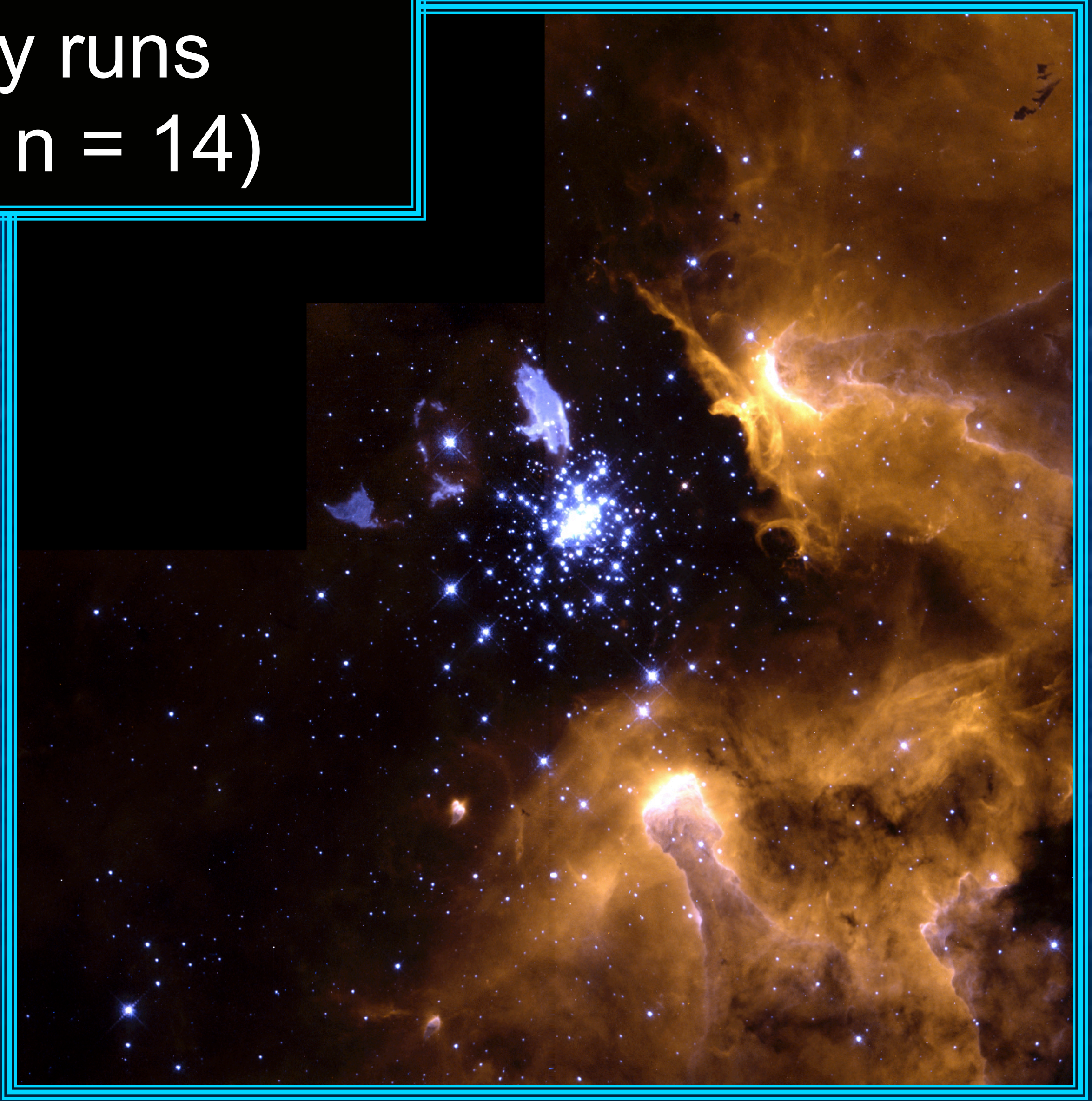


Some current data suggest that life on Earth might have originated deep underground, independent of sunlight, so that life could arise on frozen planets across the Galaxy.

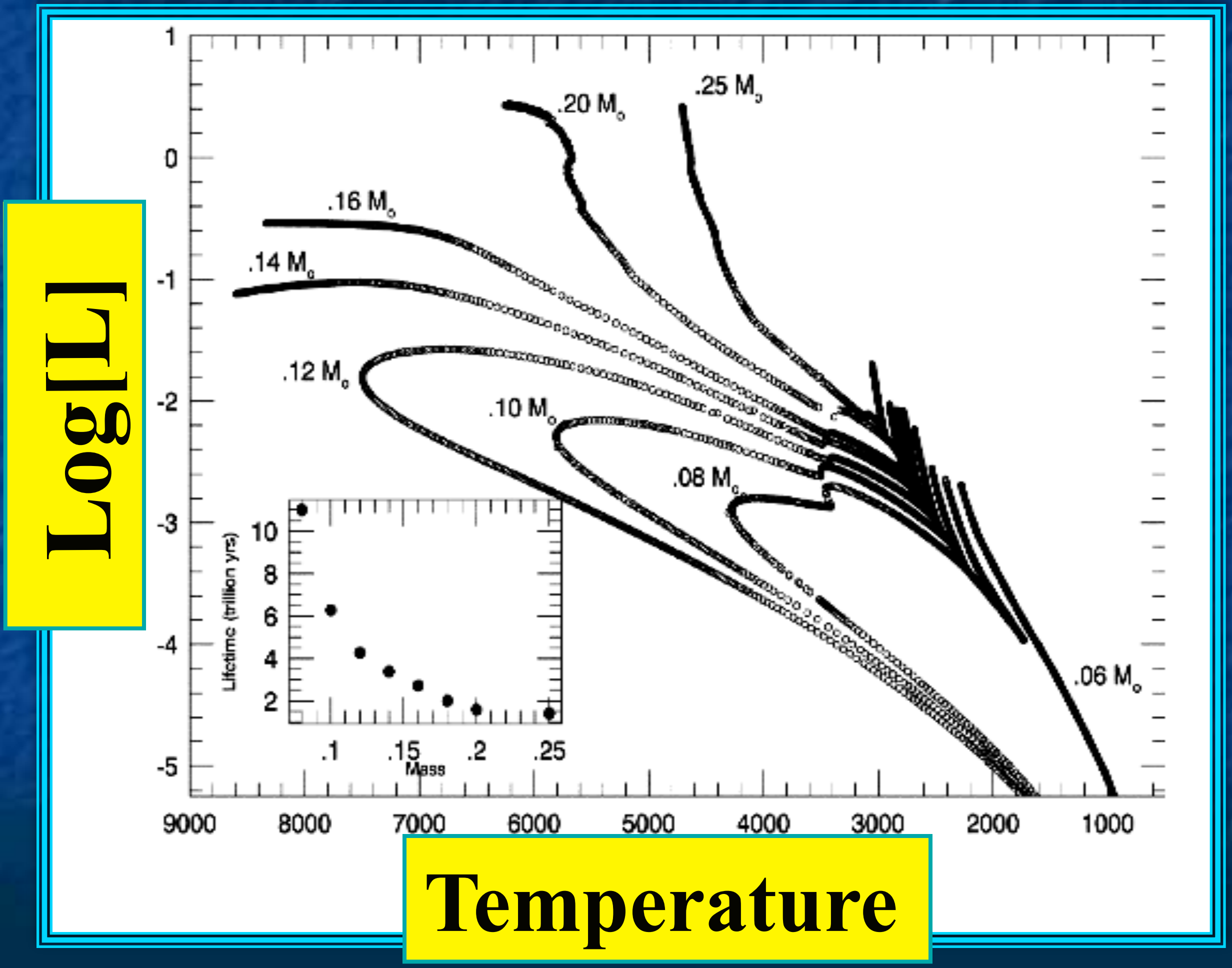
Galaxy continues to make new stars. Time scales are lengthened by:

- Recycling
- Infall onto disk
- Reduced SF rate

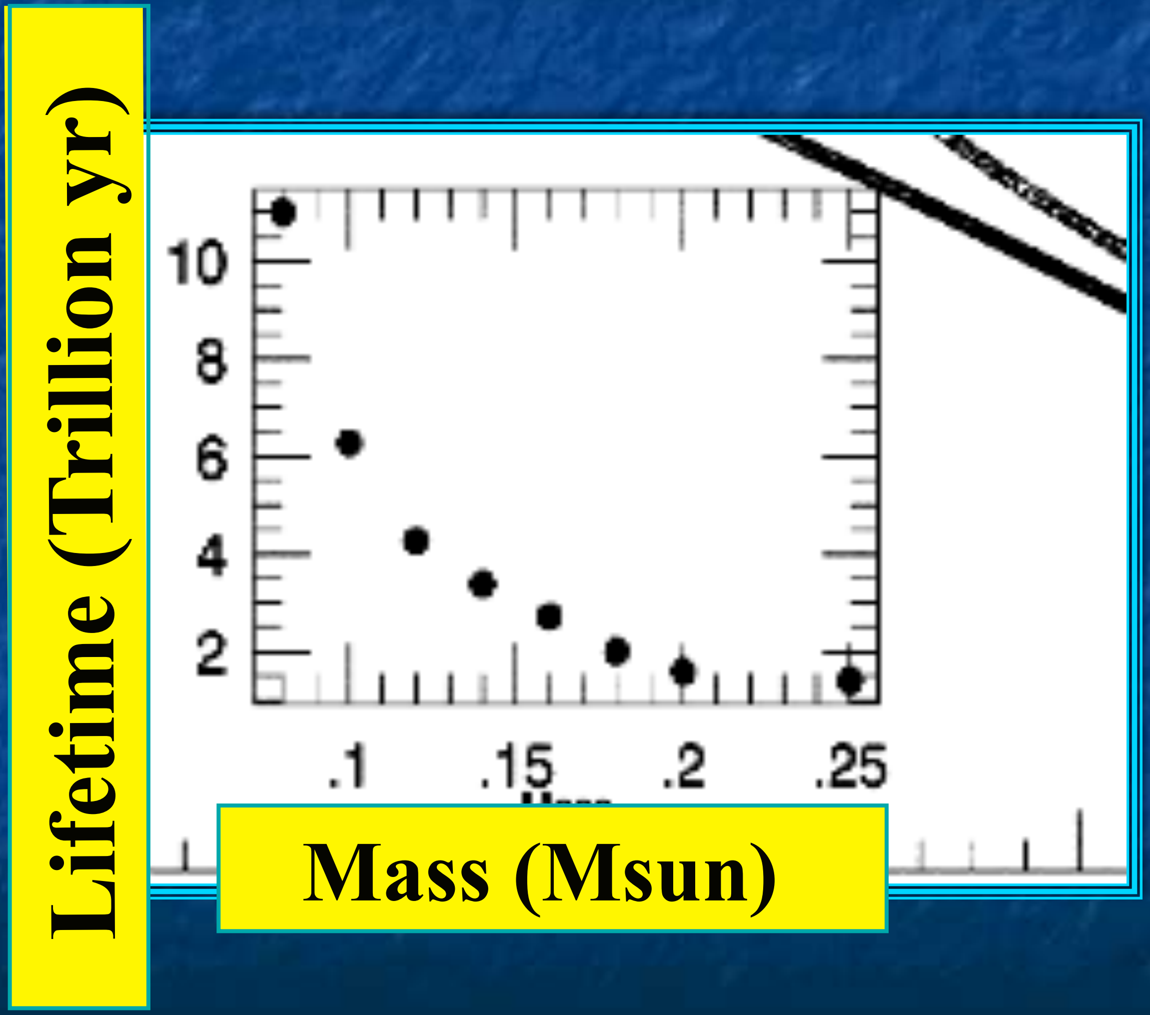
Star formation continues until the galaxy runs out of gas (at n = 14)



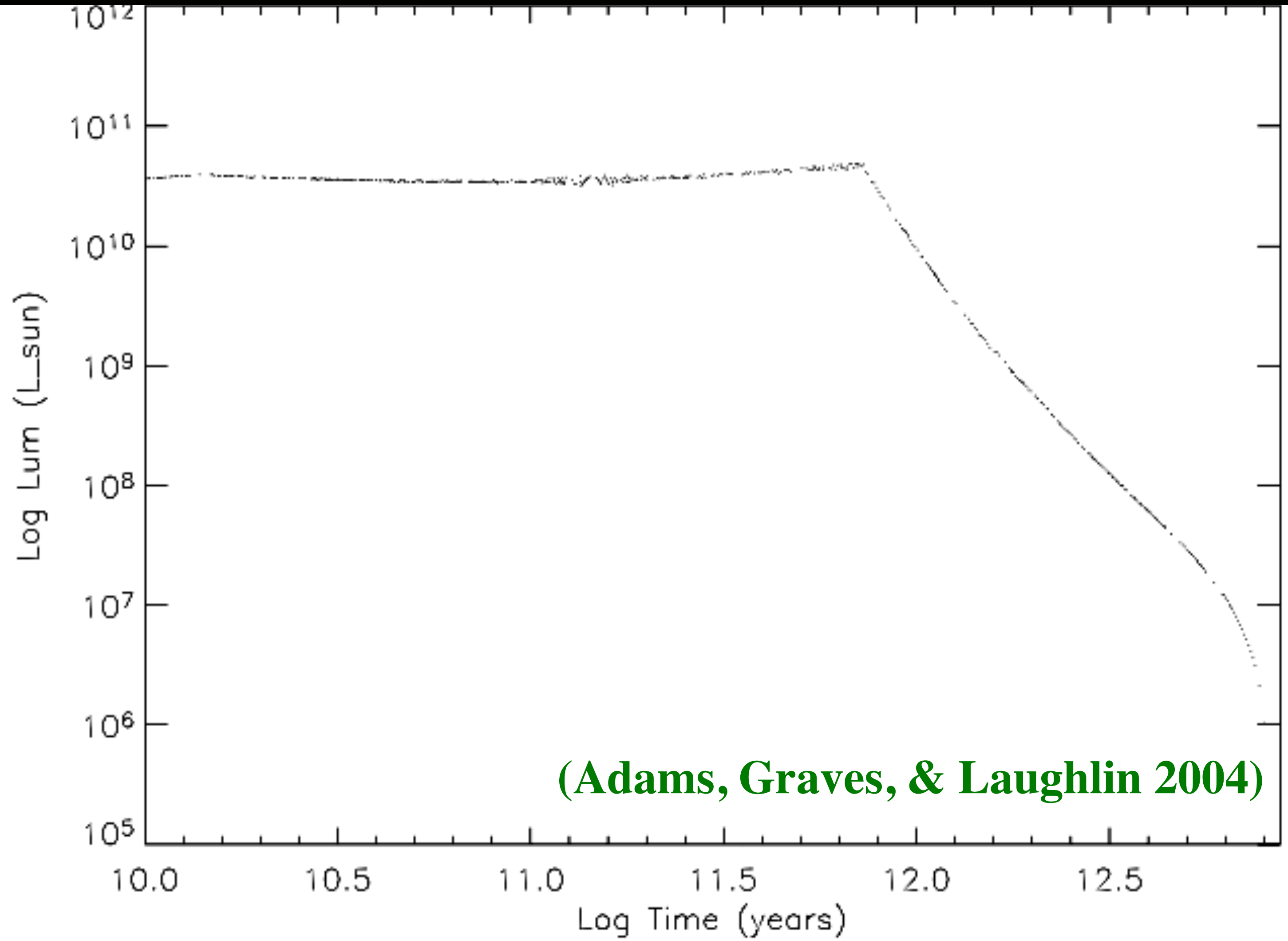
Long term Evolution of Red Dwarfs



Life Span of Red Dwarfs



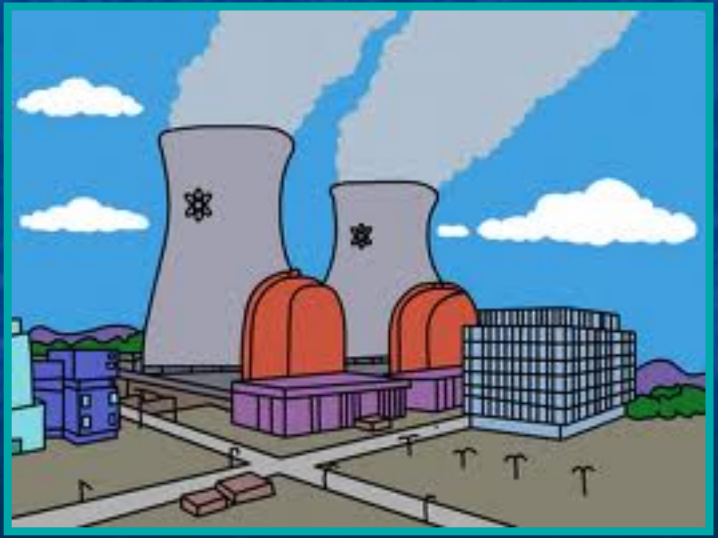
Late time light curve for Milky Way



The Stelliferous Era

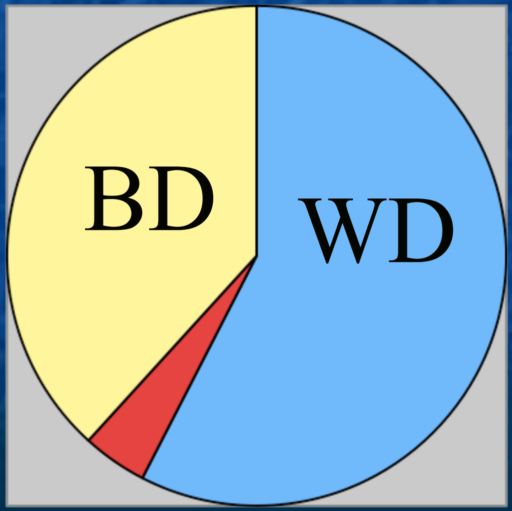
- Stars dominate energy production
- Lowest mass stars increasingly important
- Star formation and stellar evolution end near cosmological decade $n = 14$
- Future tells us why stars become red giants, why dark matter halos have their forms, how to define the mass of a galaxy, new results on orbit instabilities, dynamical scattering…

Nuclear physics determines how stellar evolution takes place, and sets the cosmic abundance of the elements, as well as the inventory of the Degenerate Era…

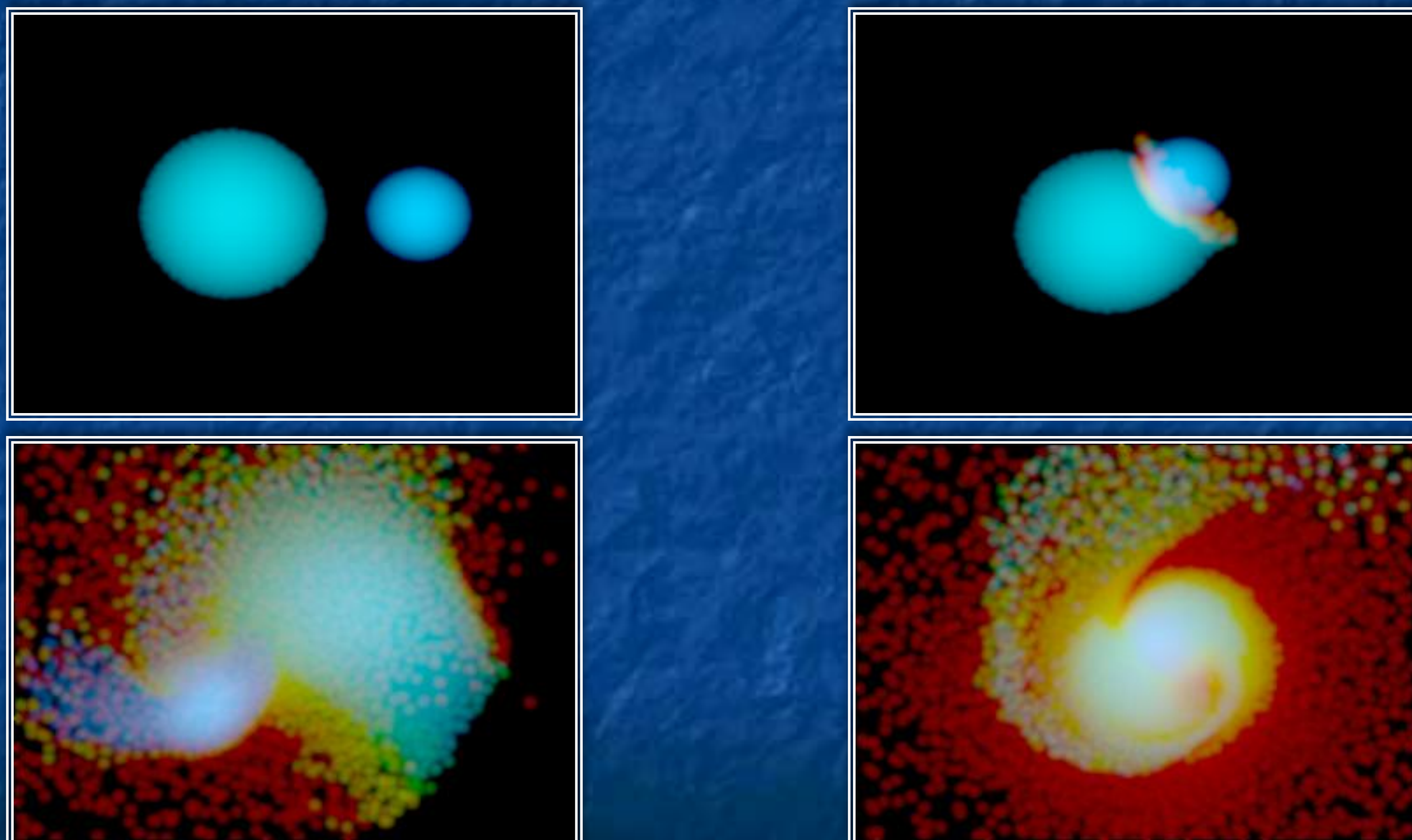


Inventory of Degenerate Era

- Brown dwarfs (from brown dwarfs)
- White dwarfs (from most stars, M=0.08-8)
- Neutron stars (from massive stars M > 8)
- Stellar Black Holes (from largest stars)

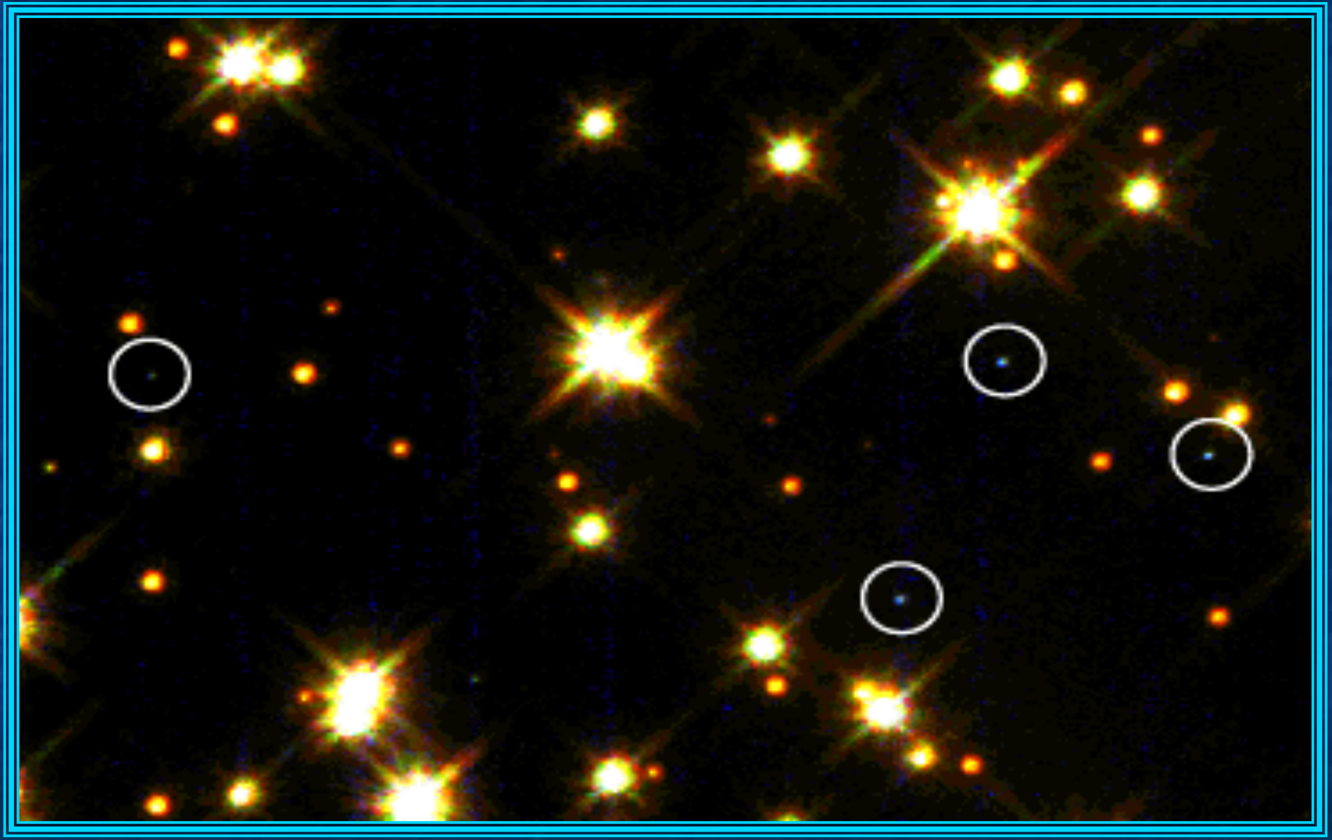


Brown Dwarf Collisions



J. Barnes

White Dwarfs of Degenerate Era Accrete Dark Matter Particles



Power = quadrillions of watts

Dynamical Relaxation of the Galaxy

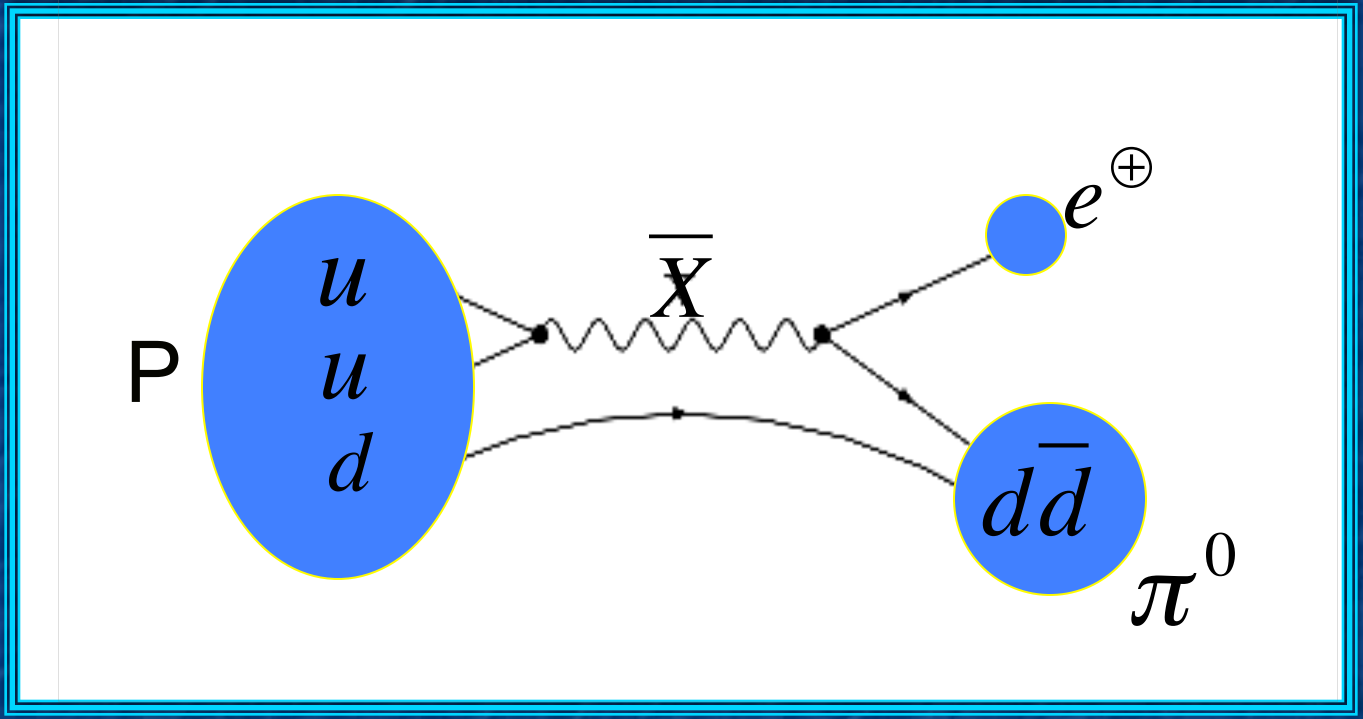
- Stellar scattering changes the structure of the galaxy over time
- Spiral disk becomes extended and diffuse
- Most stars are lost, but a few fall to center

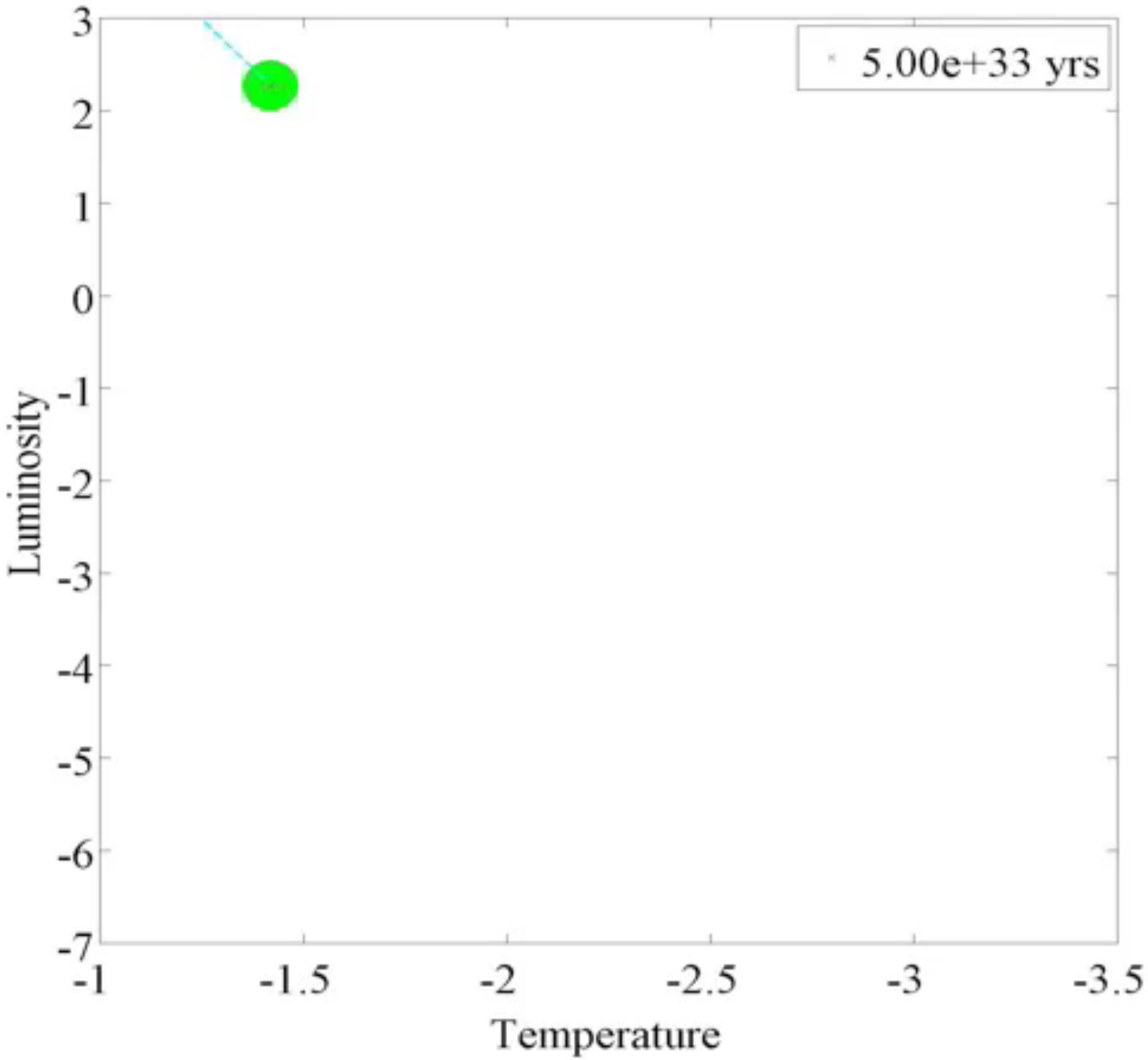
Time scale = 20 cosmological decades

Proton Decay

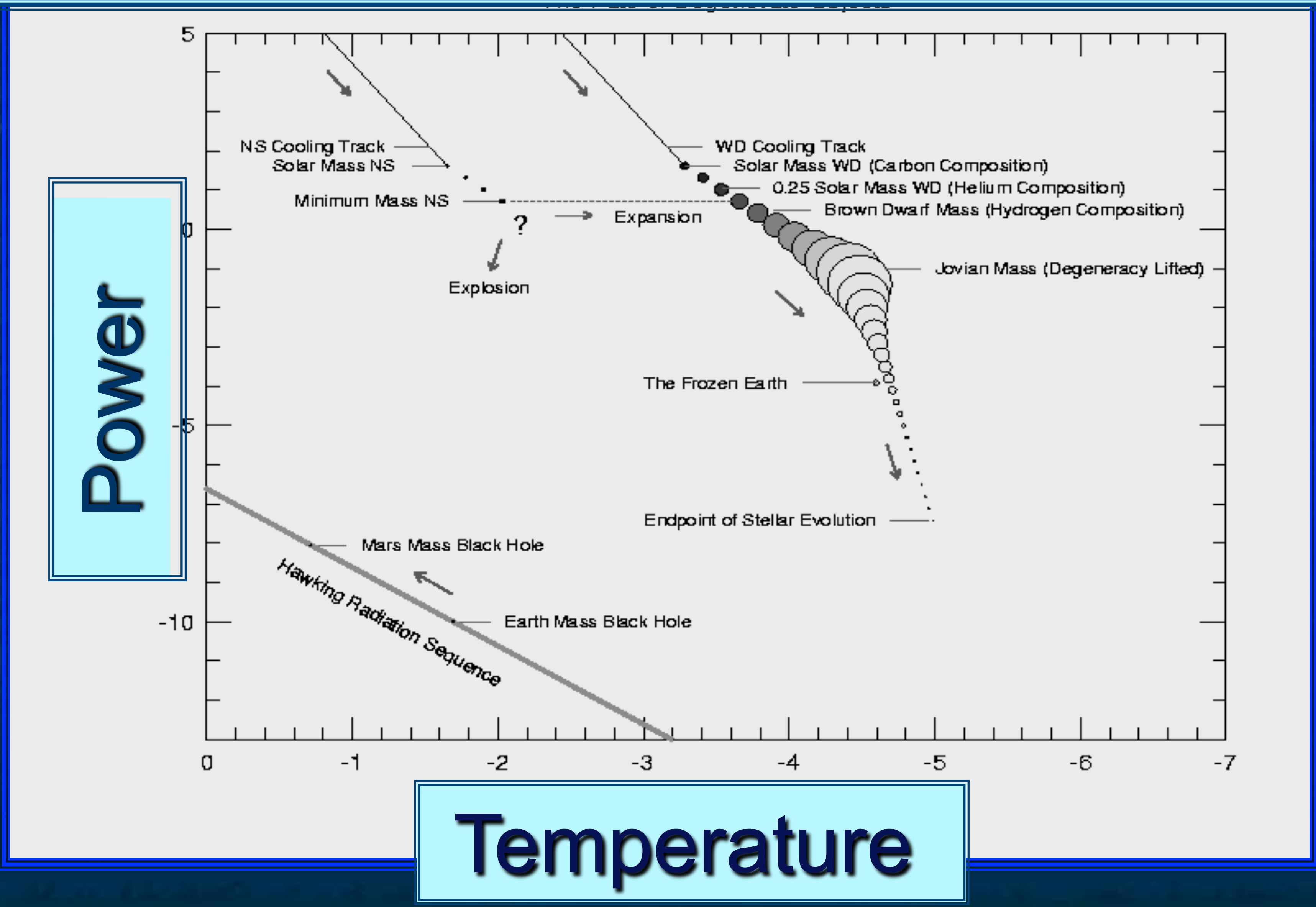
- Many possible channels
- Lifetime is recklessly uncertain
- Experiments show that $n > 33$-34
- Theory implies that $n < 45$
- Changes the universe more dramatically than any other process in our future history

Proton decay channel




5.00e+33 yrs
Luminosity
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-1
-1.5
-2
-2.5
-3
-3.5
Temperature

Fate of Degenerate Objects



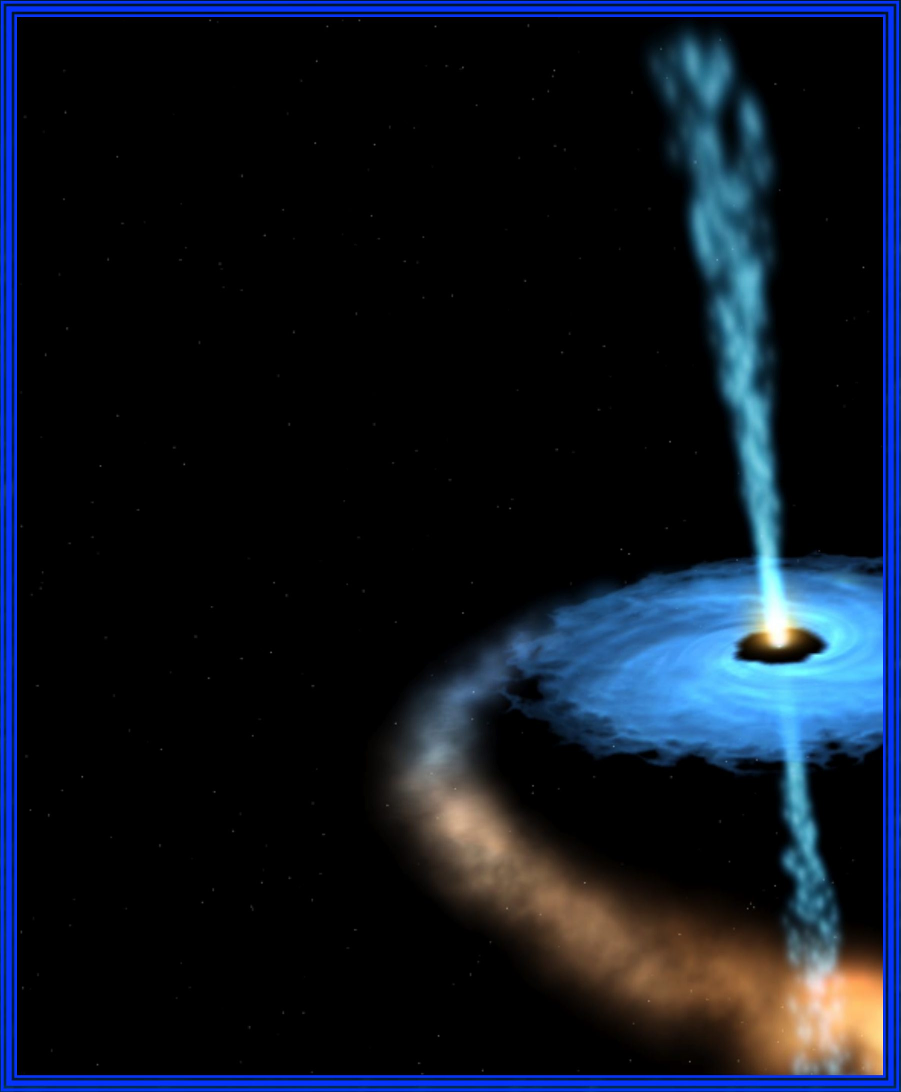
The Degenerate Era

- Inventory includes Brown Dwarfs, White Dwarfs, Neutron Stars, and Black Holes
- Star formation through brown dwarf collisions
- White dwarfs capture dark matter particles
- Galaxy relaxes dynamically
- Black holes accrete stars, gas, and grow
- ***Era ends when Protons decay at cosmological decade $n = 40$***

Every galaxy has a

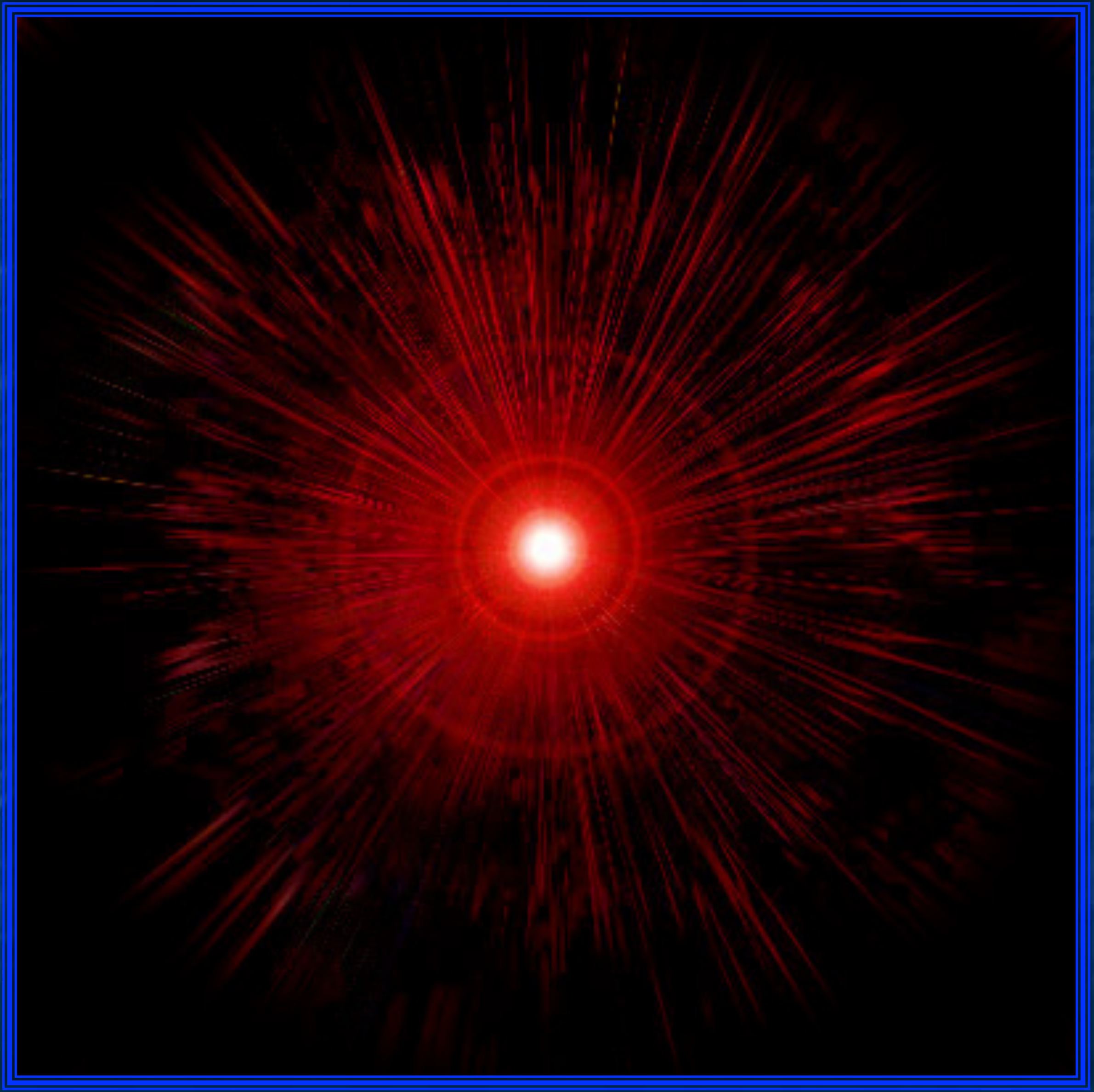
SUPERMASSIVE

black hole
anchoring its center

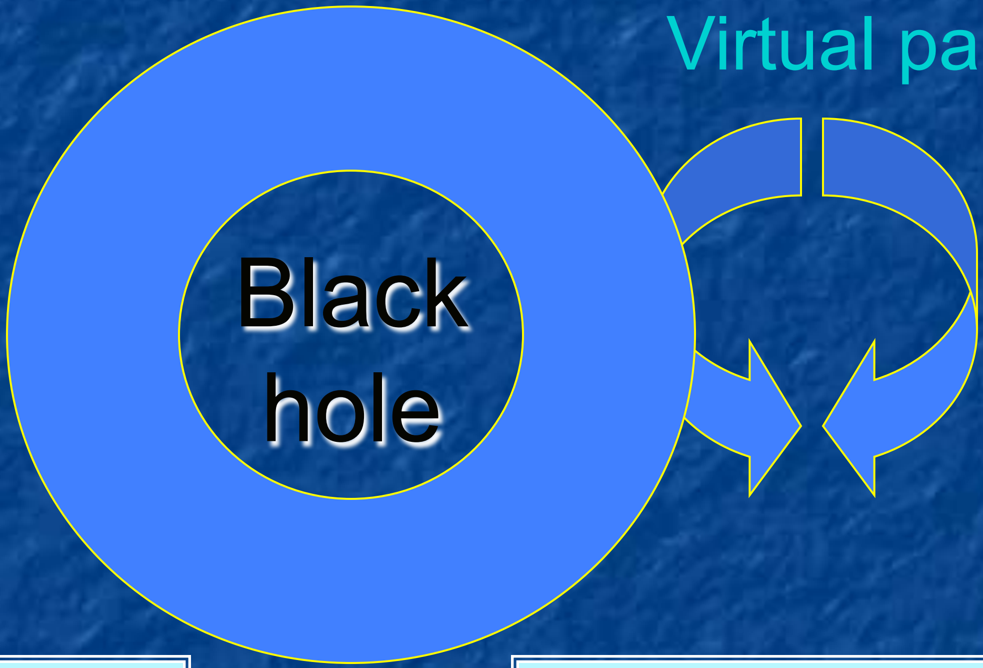


M_{bh} = millions to
billions of Suns

Every galaxy produces about one million stellar mass black holes



Hawking Radiation



$$\lambda \approx GM \approx R_s$$

$$T_H = 1/(8\pi GM)$$

$$\tau = 10^{65}\, yr \,\left[M / M_o \right]^3$$

The Black Hole Era

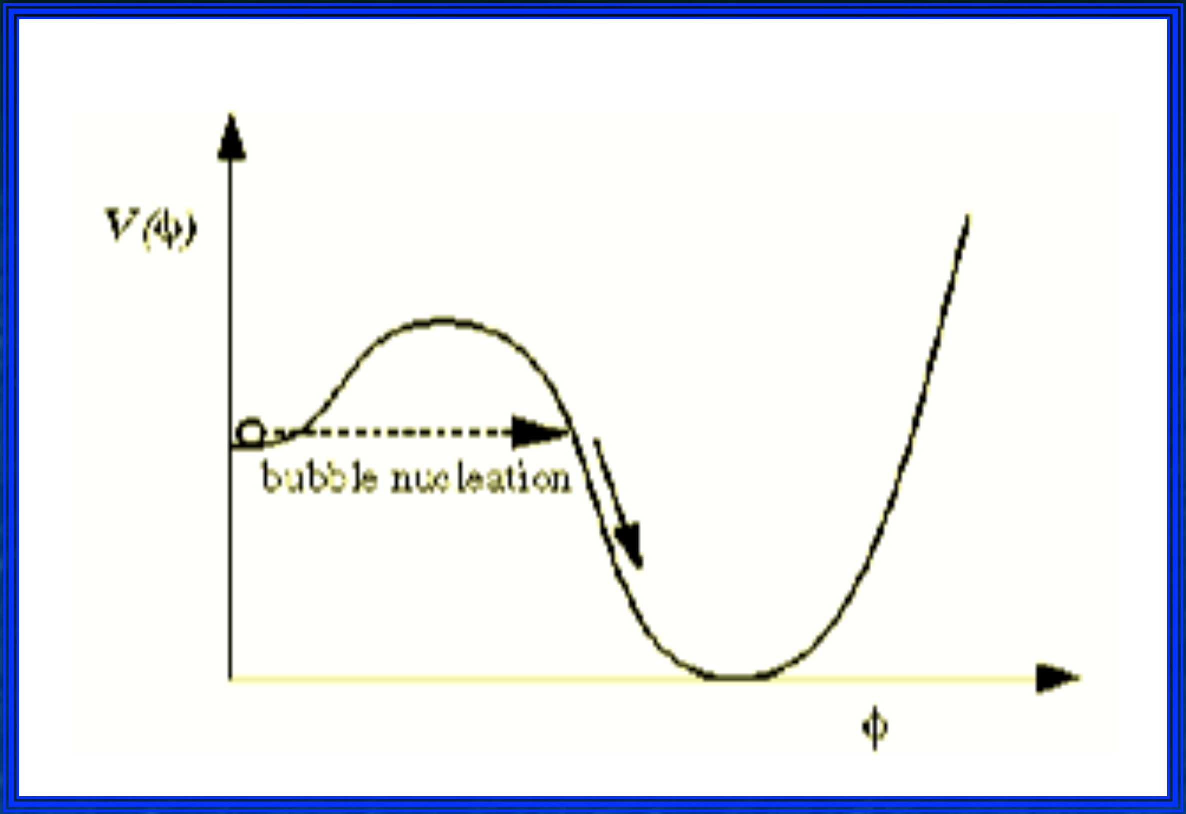
- Black holes are brightest stellar objects
- Generation of energy via Hawking radiation
- Every galaxy contributes one supermassive and about one million stellar black holes
- Black hole lifetime is mass dependent:

One solar mass:	n=65
Million solar mass:	n=83
Galactic mass:	n=98
Horizon mass:	n=131

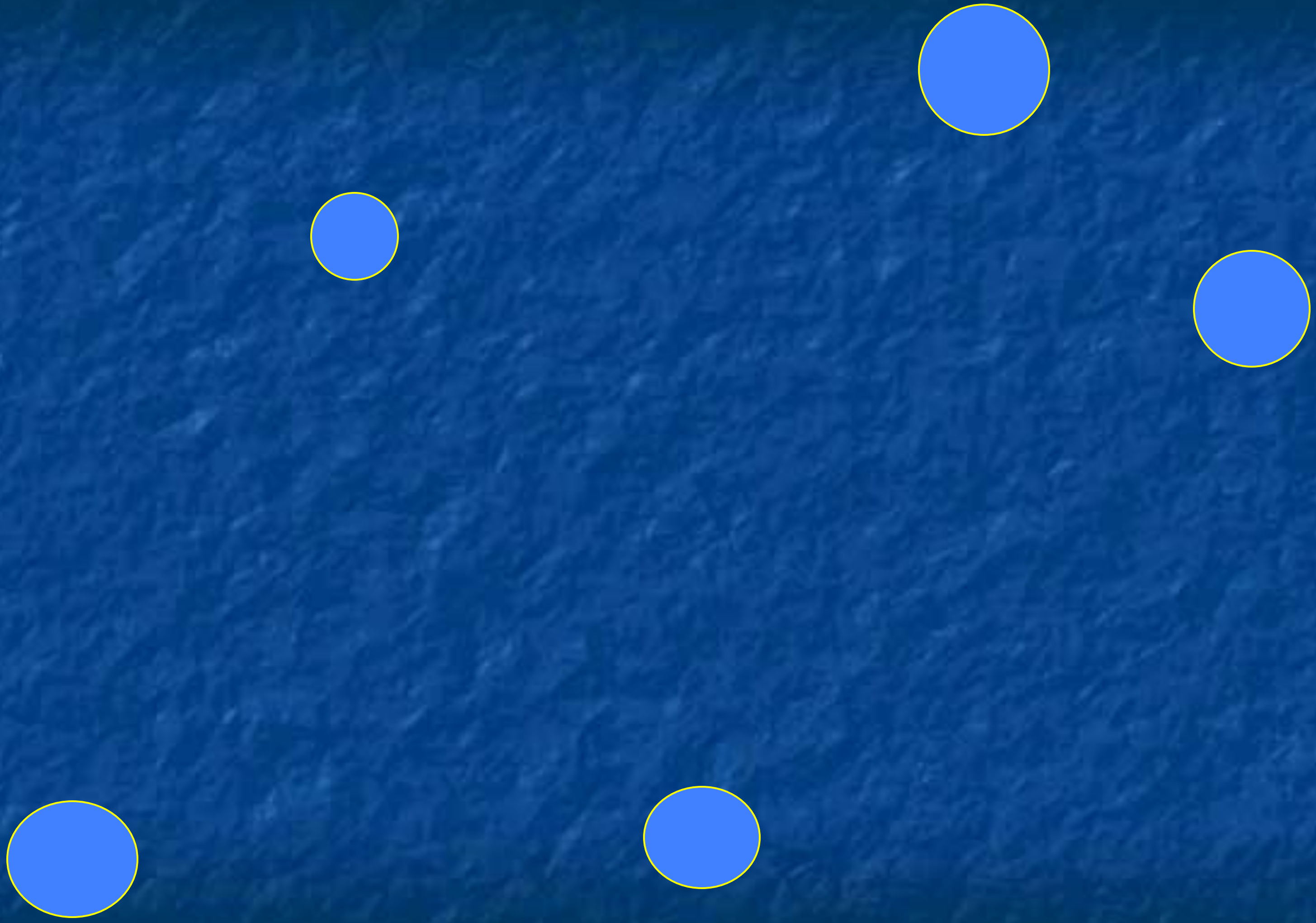
$$t_T \propto M_{bh}^3$$

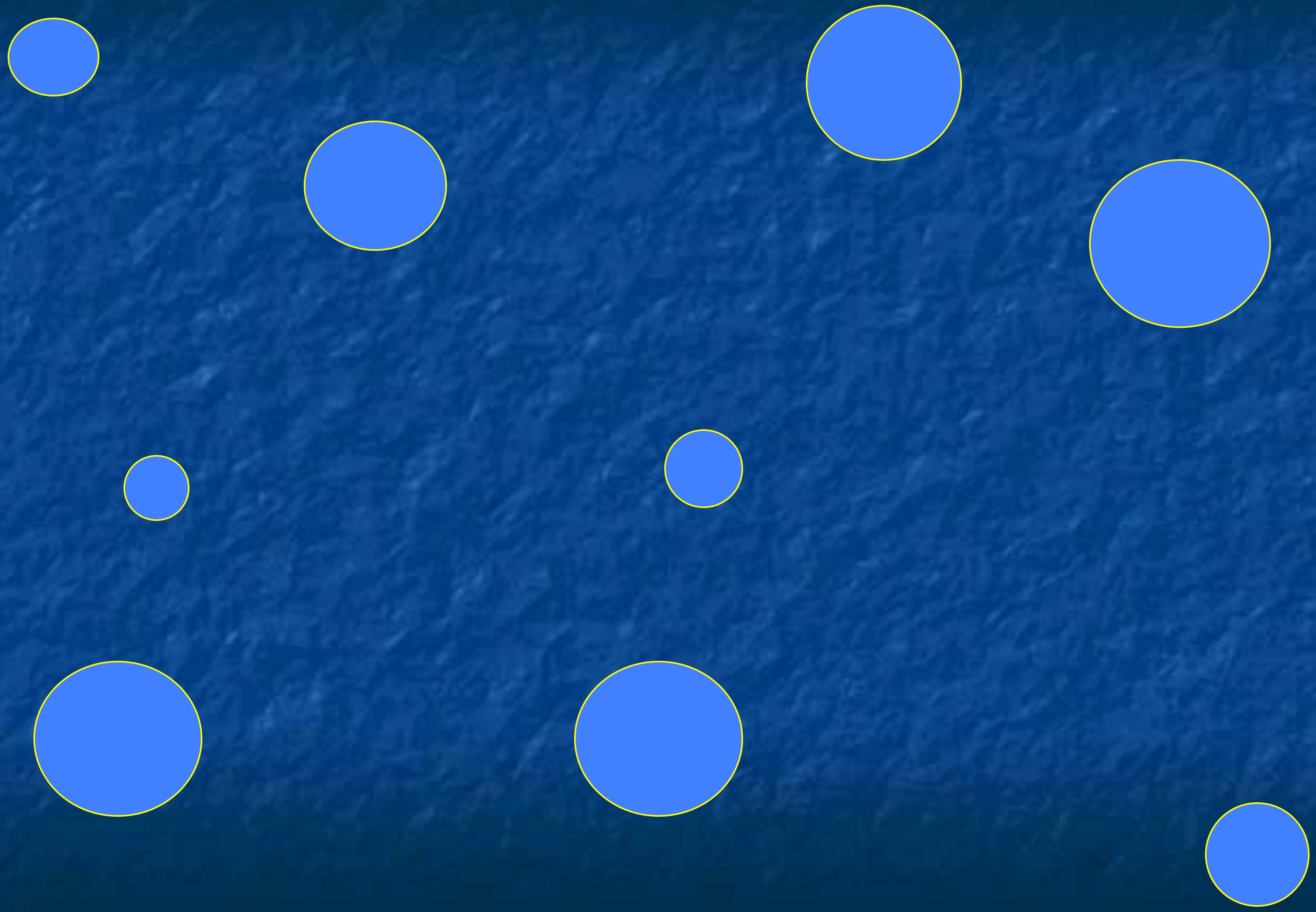
The Dark Era

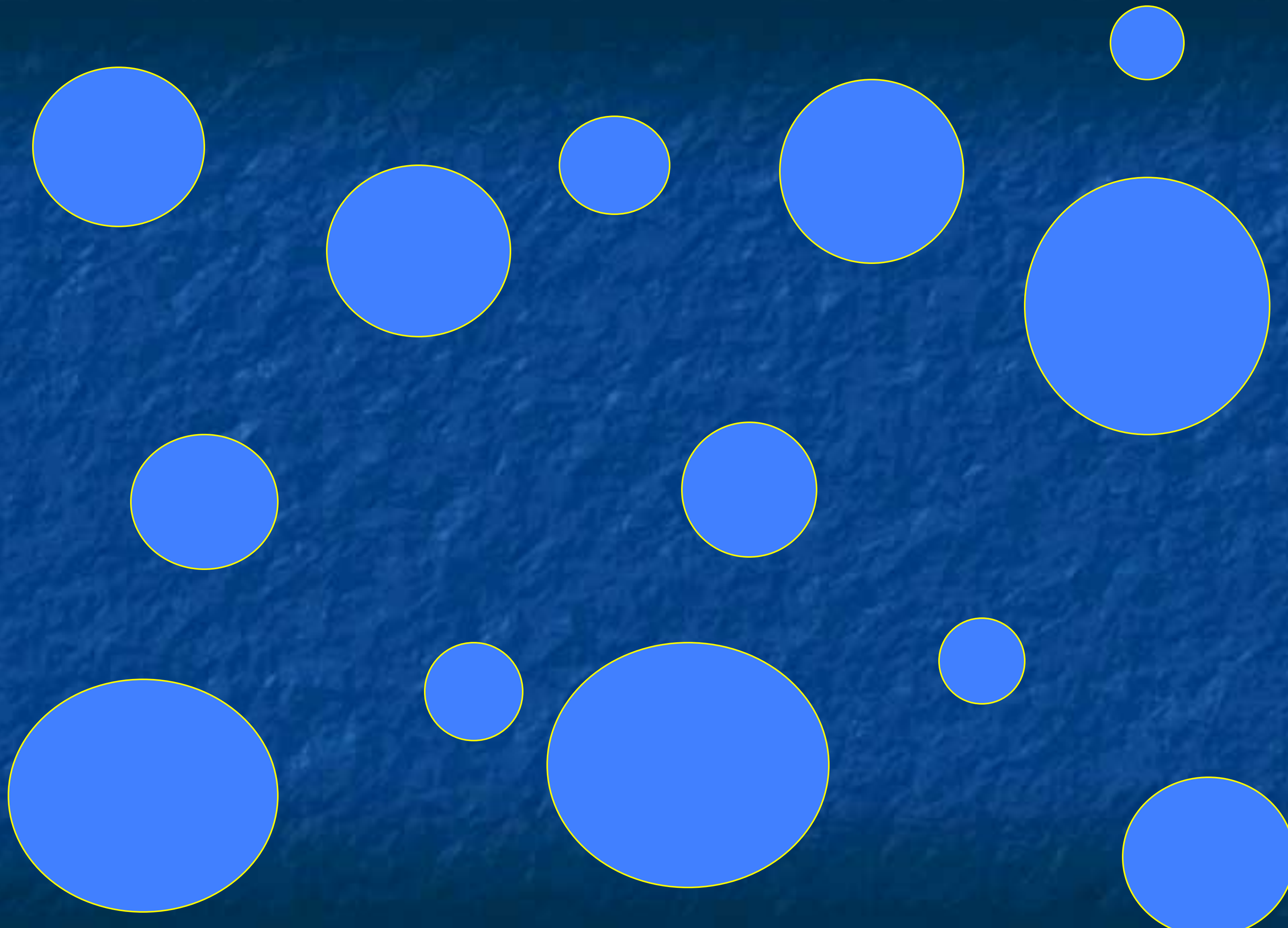
- No stellar objects of any kind
- Inventory of elementary particles: electrons, positrons, neutrinos, & photons
- Positronium formation and decay
- Low level annihilation

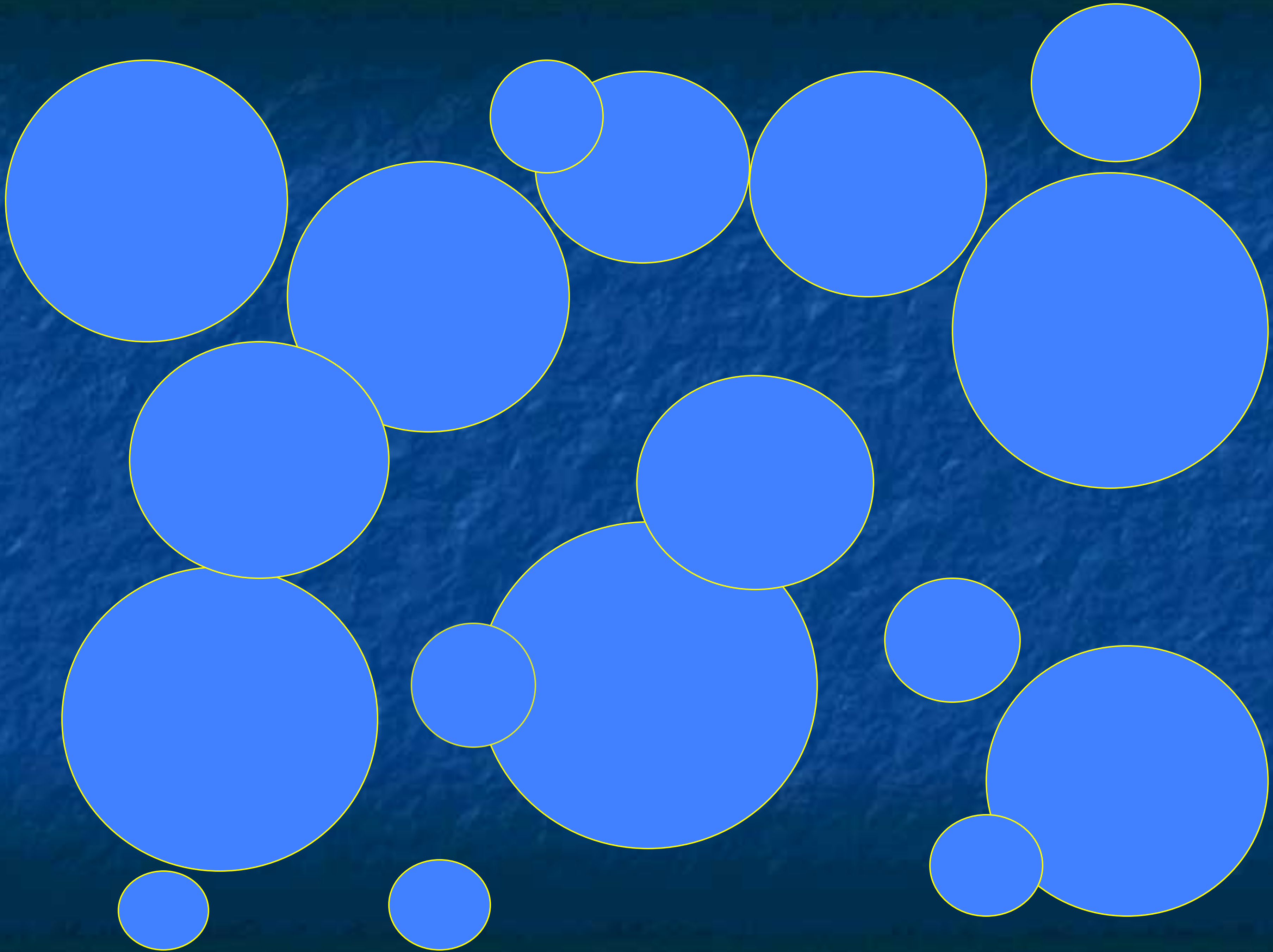


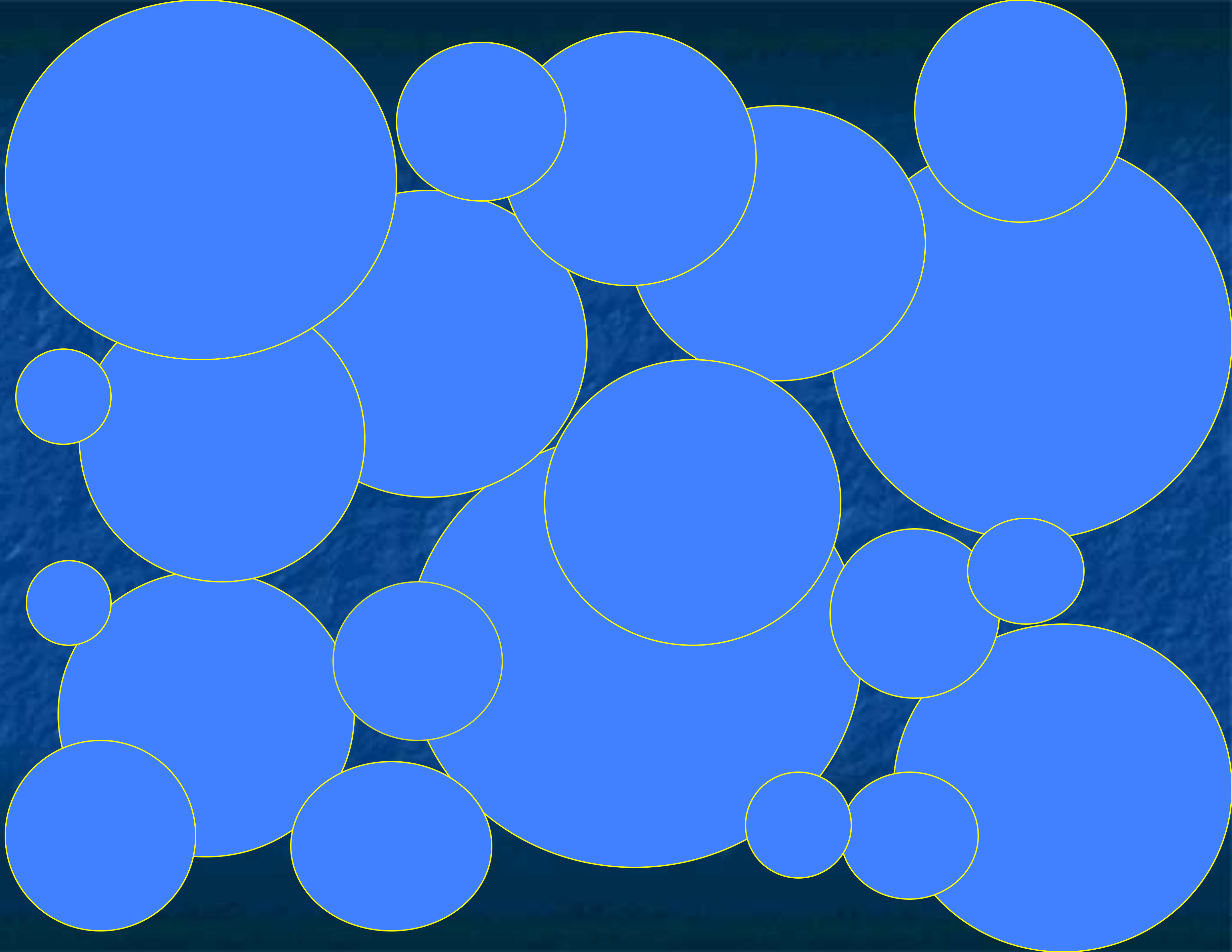
The Cosmos could experience a Future Phase Transition

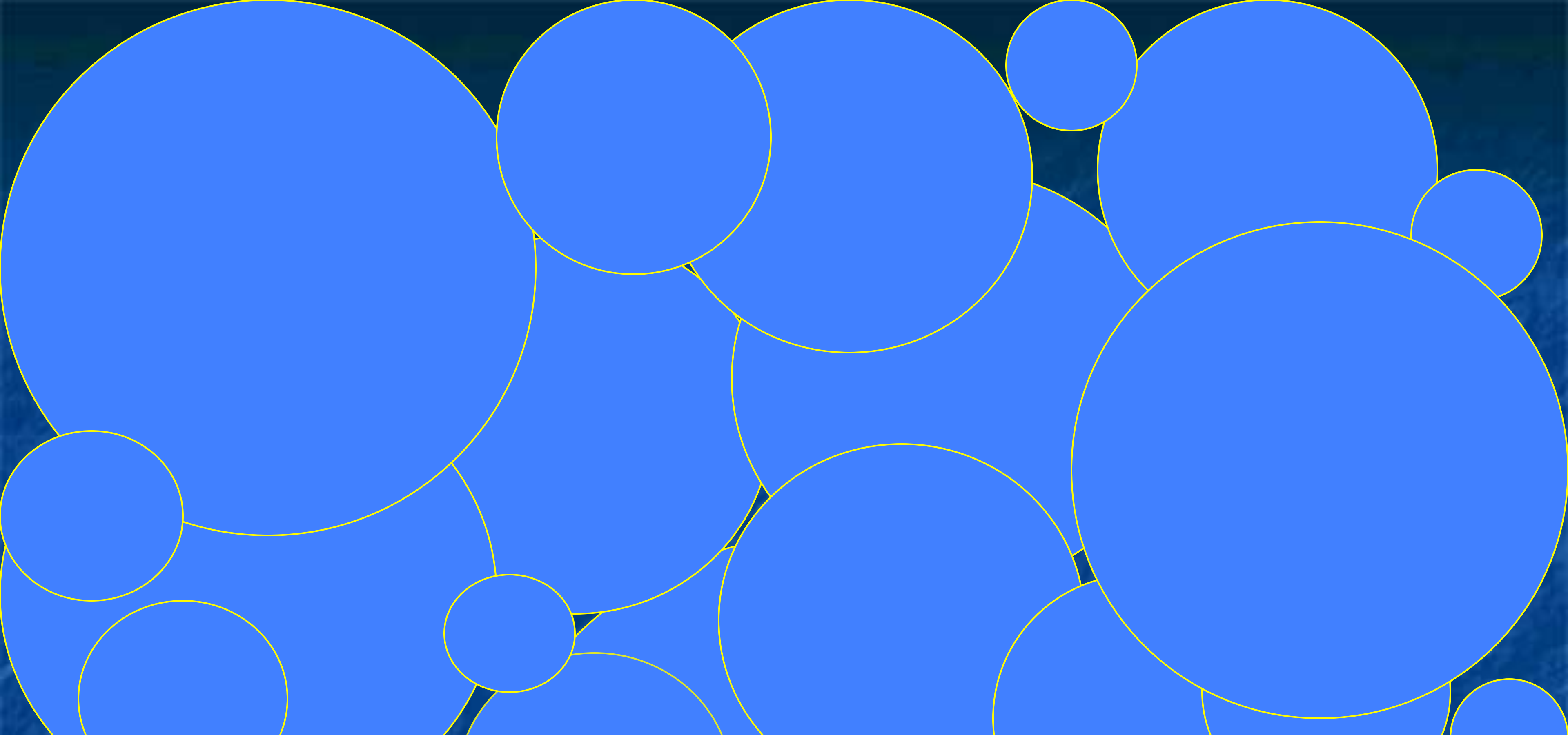






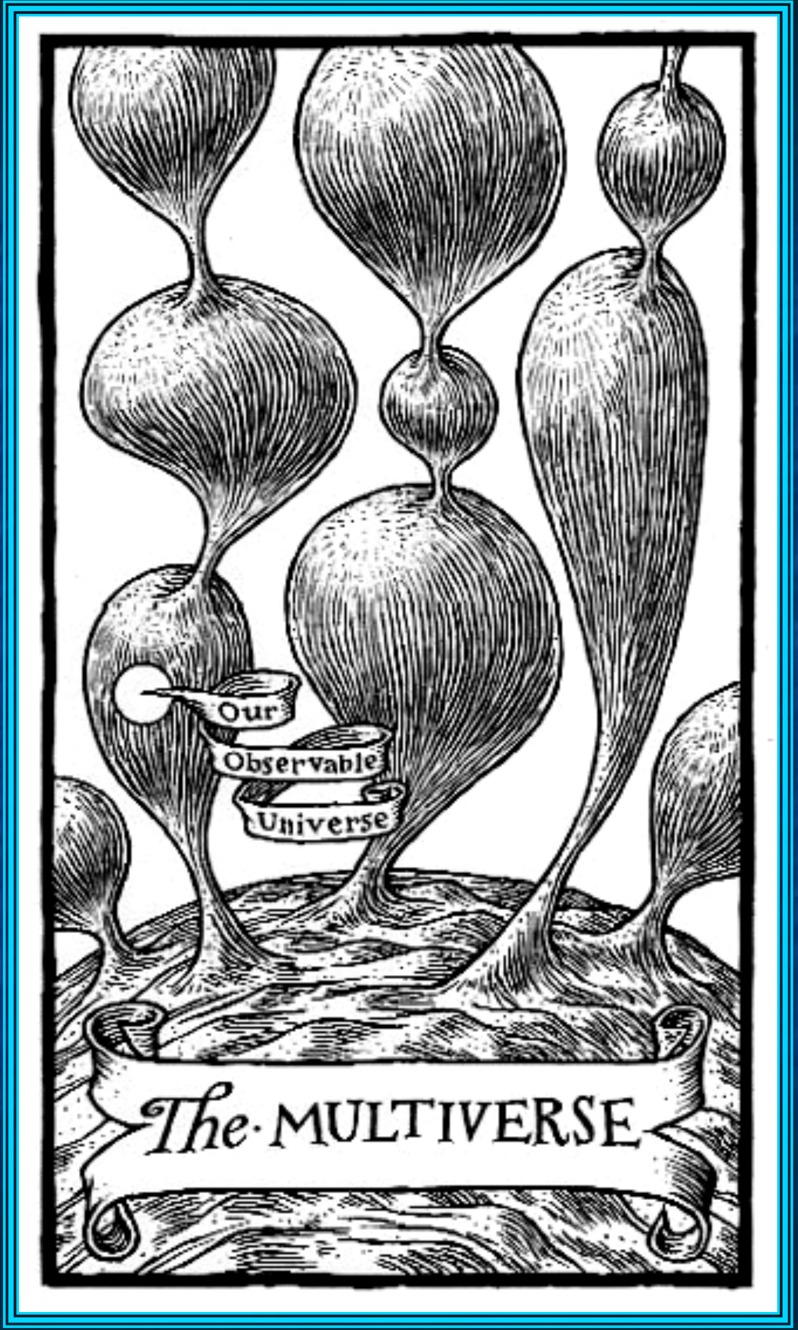






As the phase transition proceeds, the laws of physics could change, and the universe gets a new start

As our own universe experiences its time-line, other parts of the global space-time (other universes) can live through their own lifetimes, as part of a cosmic archipelago sometimes called the MULTIVERSE.



Summary

- Our current understanding of the laws of physics and astrophysics allow us to construct a working picture of the future.
- Studying physical processes of the future provides insight into current astrophysical problems, e.g., the reason for red giants, structure of dark matter halos, dynamical scattering problems, defining the masses of galaxies, etc.

Disclaimer

- As one journeys deeper into future time, projections necessarily become more uncertain (this talk stops at n = 100).
- As we learn more about the fundamental laws of physics, or if the laws change with cosmological time, corrections (both large and small) to this timeline must be made.