The End of Space and Time

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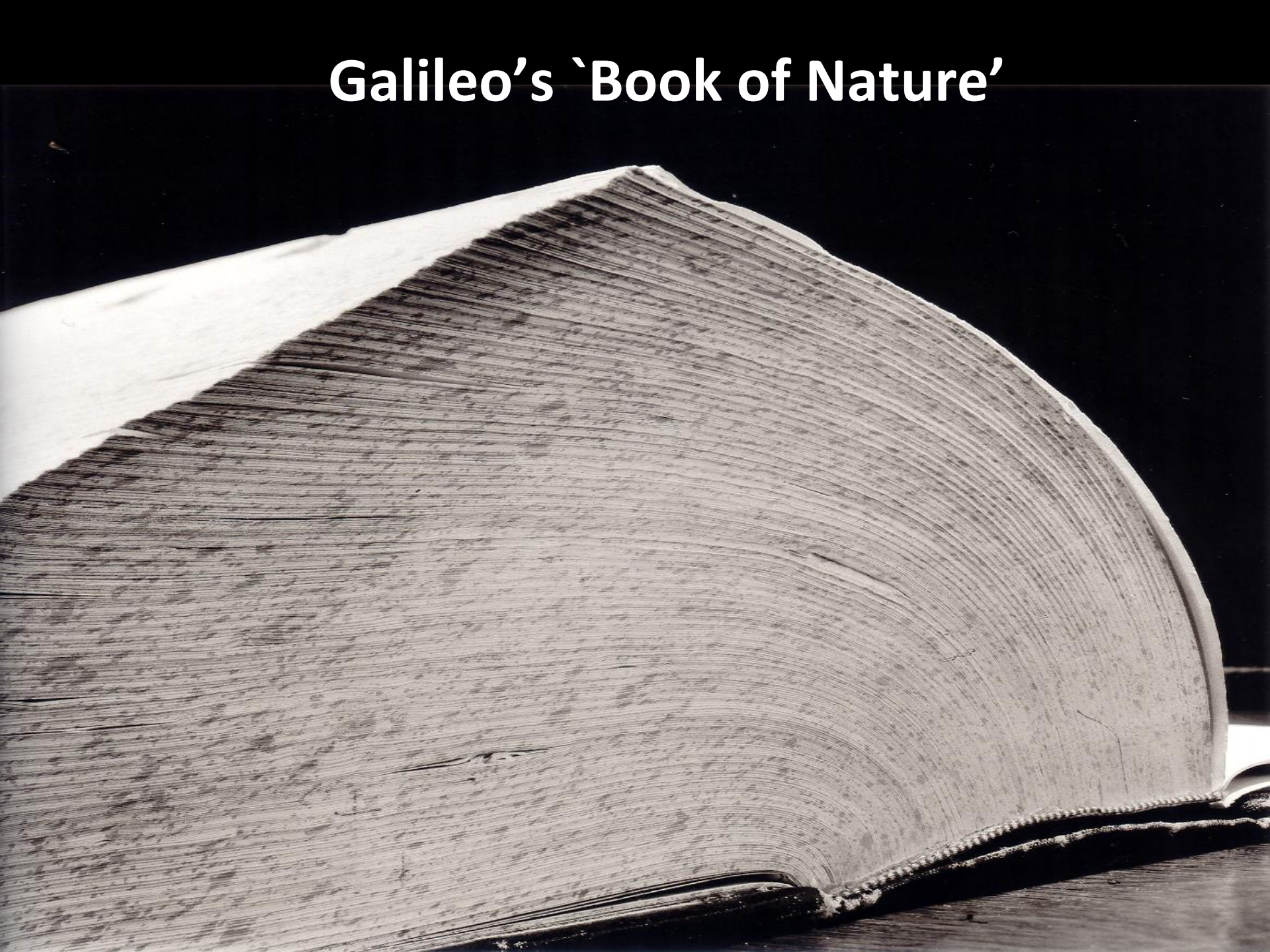
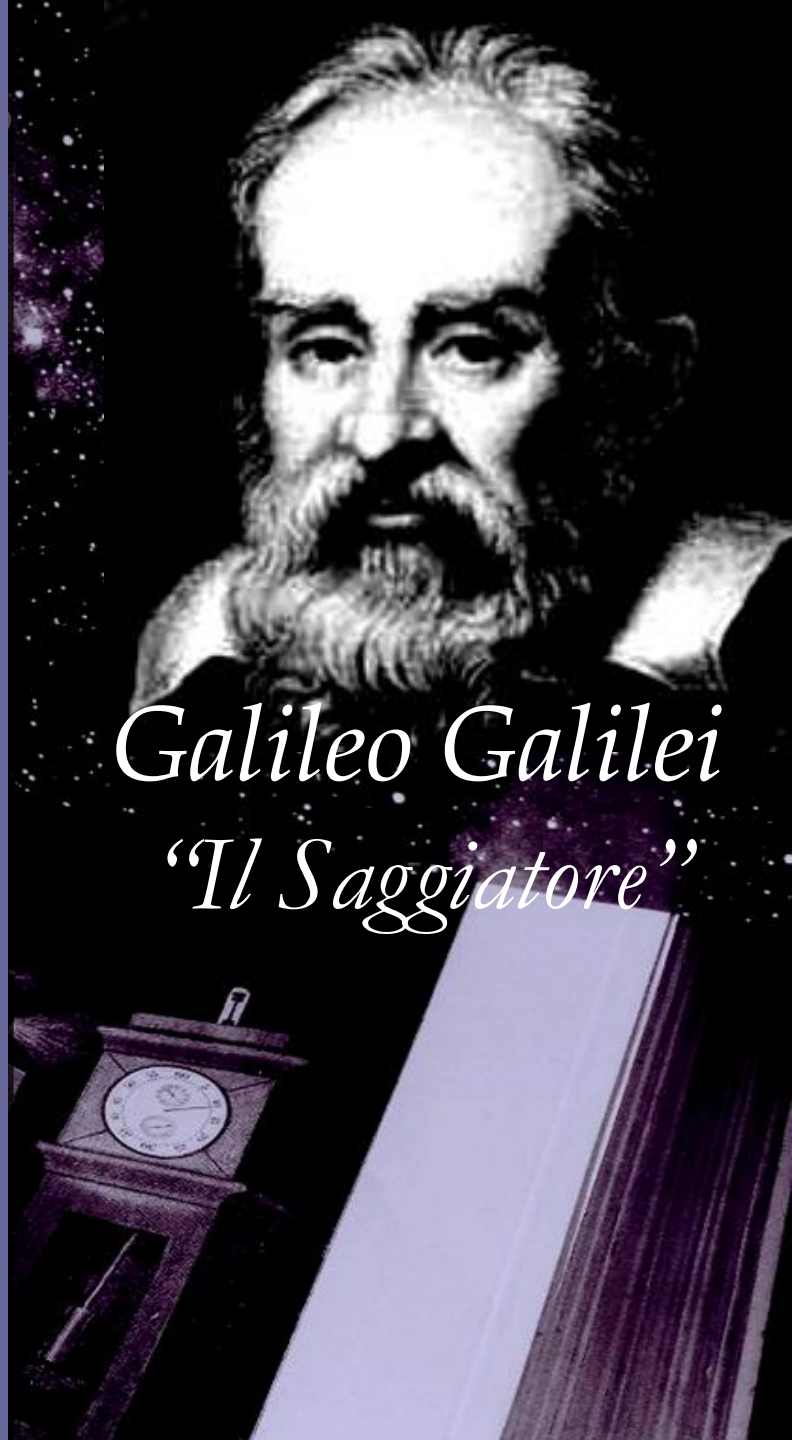
University of Amsterdam

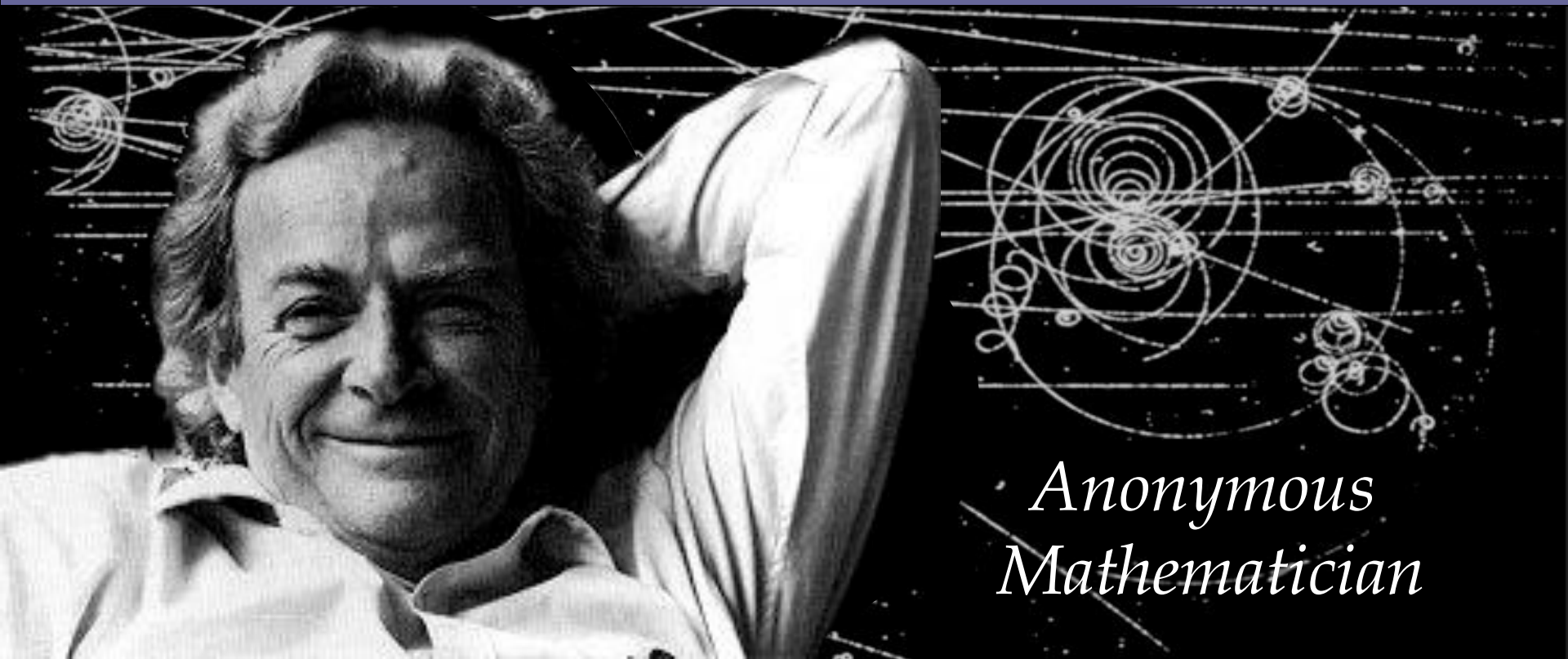
Galileo's `Book of Nature'



"The universe cannot be read until we have learned the language and become familiar with the characters in which it is written. It is written in mathematical language, and the letters are triangles, circles and other geometrical figures, without which means it is humanly impossible to comprehend a single word."

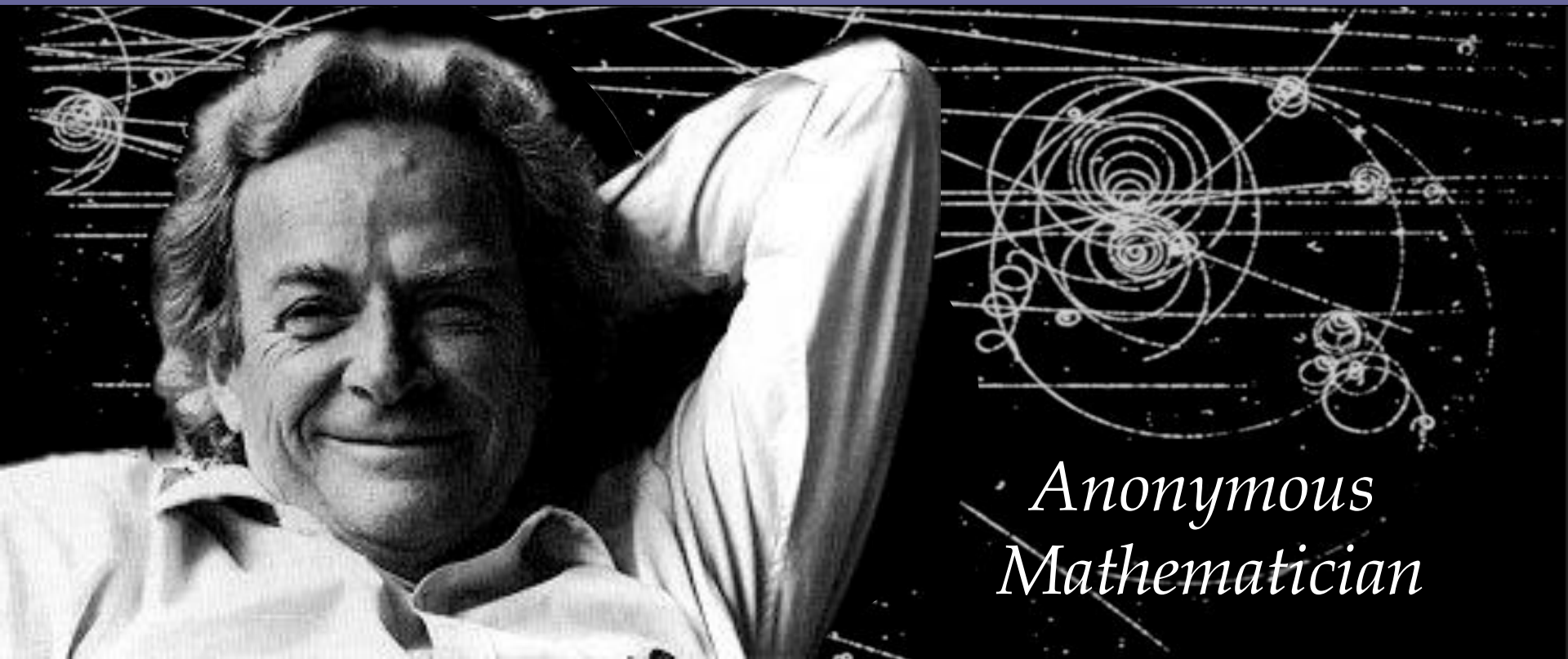


"To those who do not know mathematics it is difficult to get across a real feeling as to the beauty, the deepest beauty, of nature ... If you want to learn about nature, to appreciate nature, it is necessary to understand the language that she speaks in."



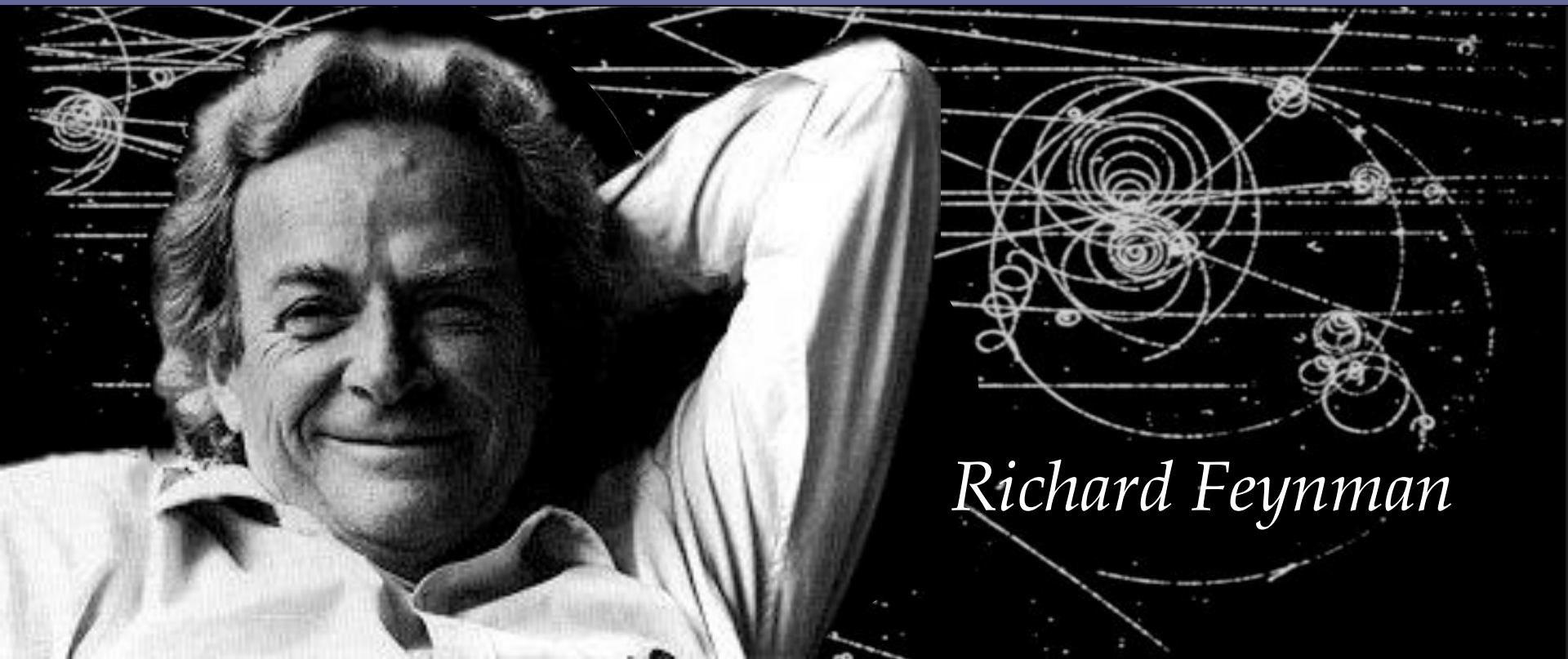
Anonymous Mathematician

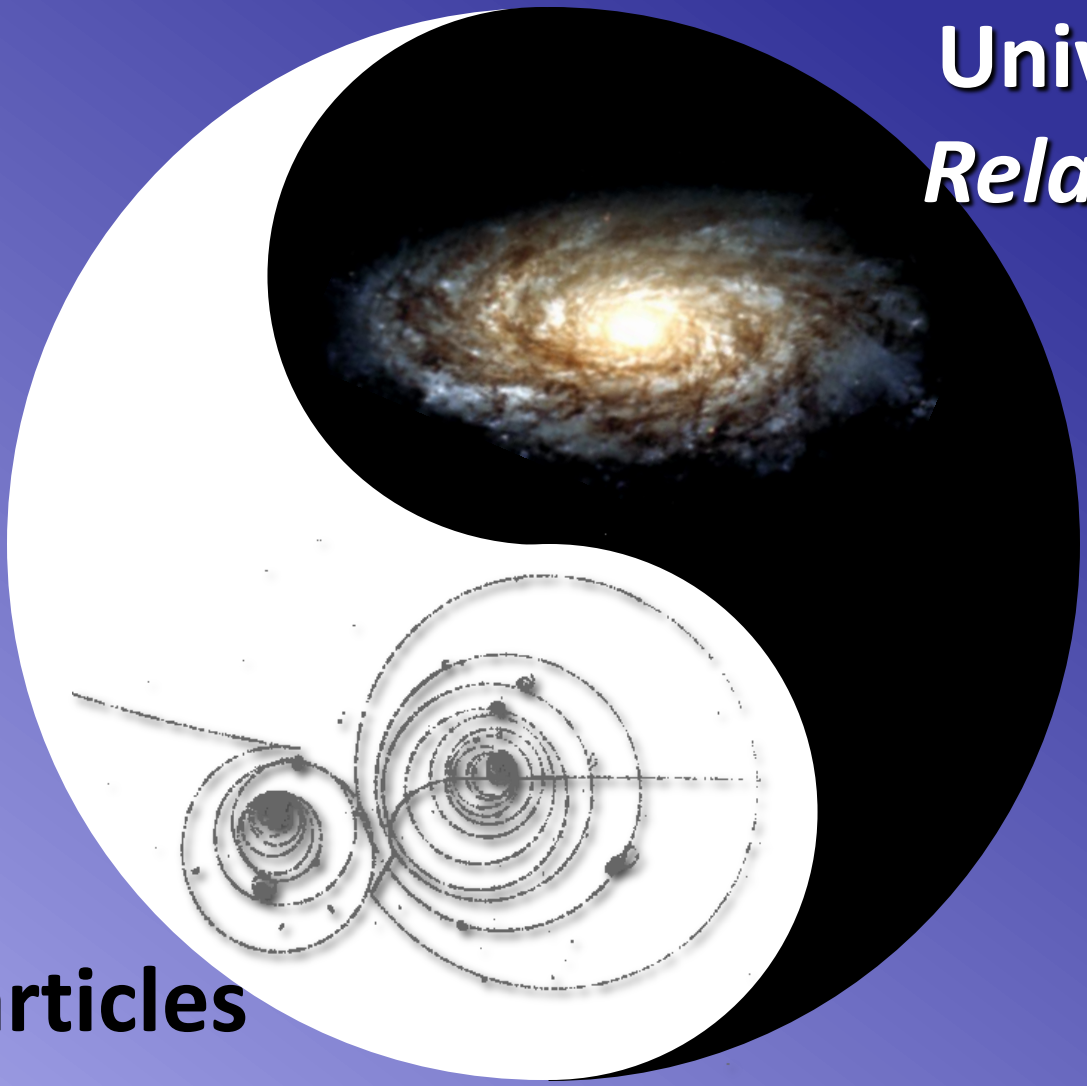
"If all mathematics,disappeared today, physics would be set back exactly one week."



Anonymous Mathematician

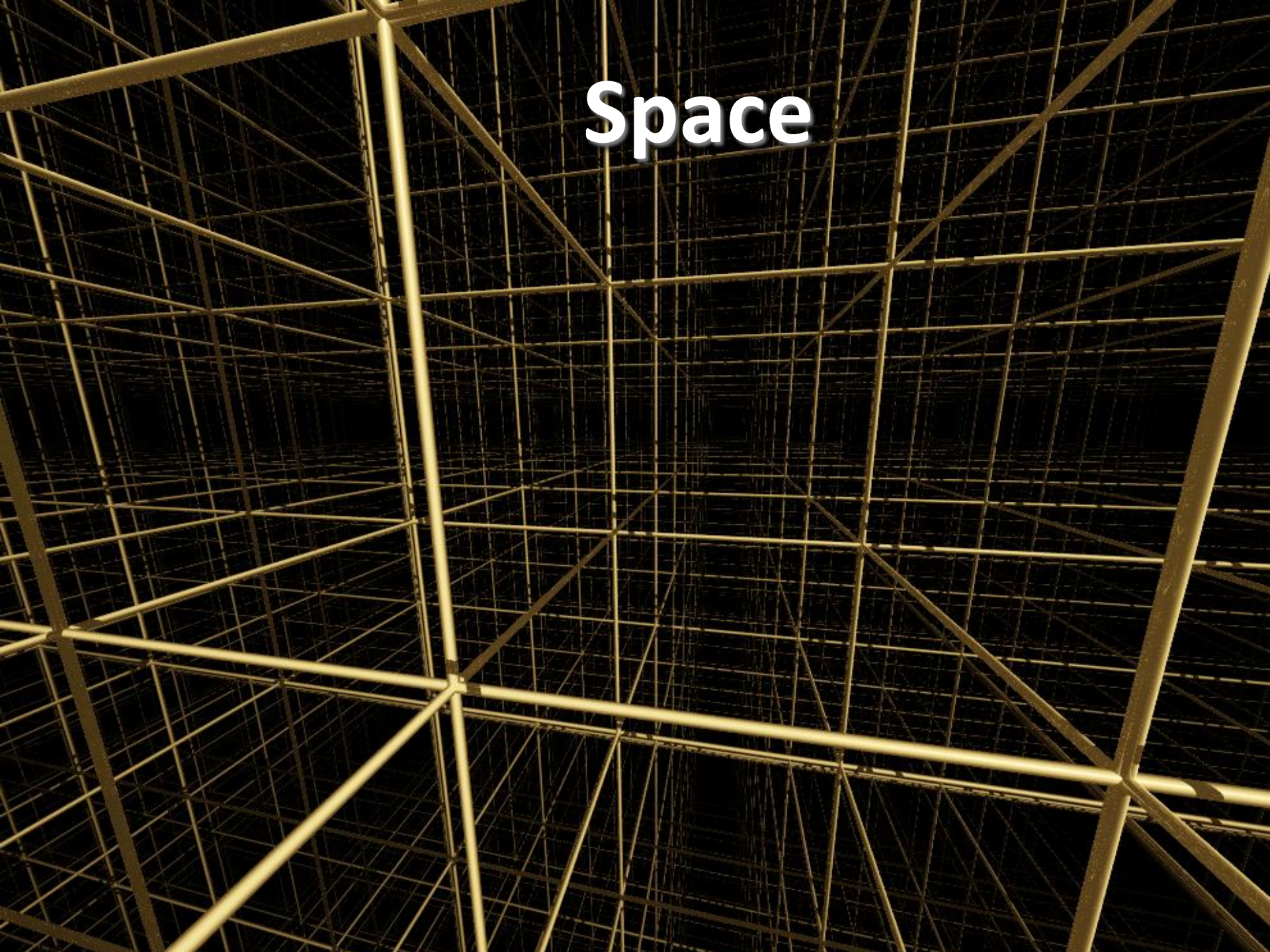
"That was the week that God created the world."

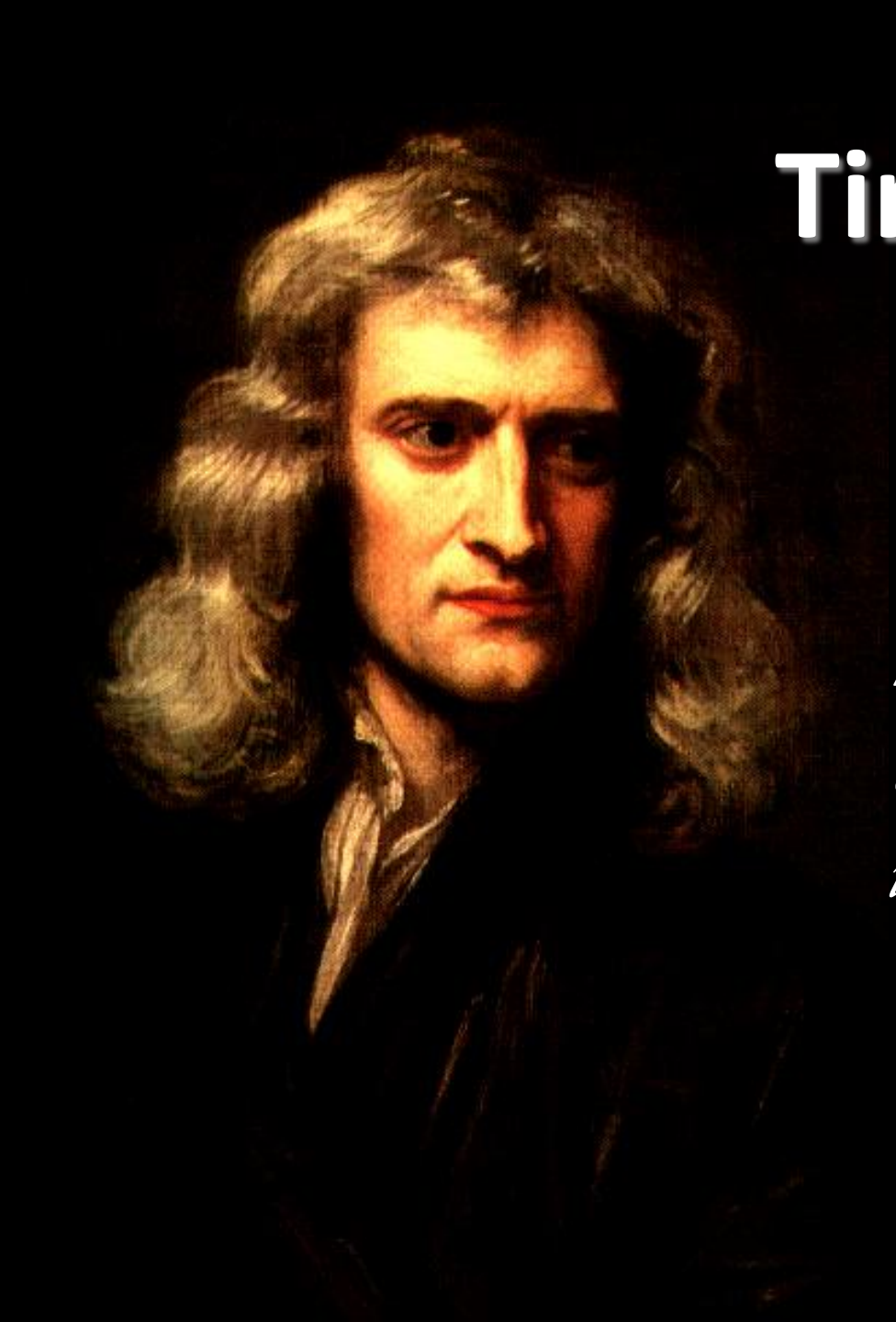




Universe
Relativity

Particles
Quantum


Space

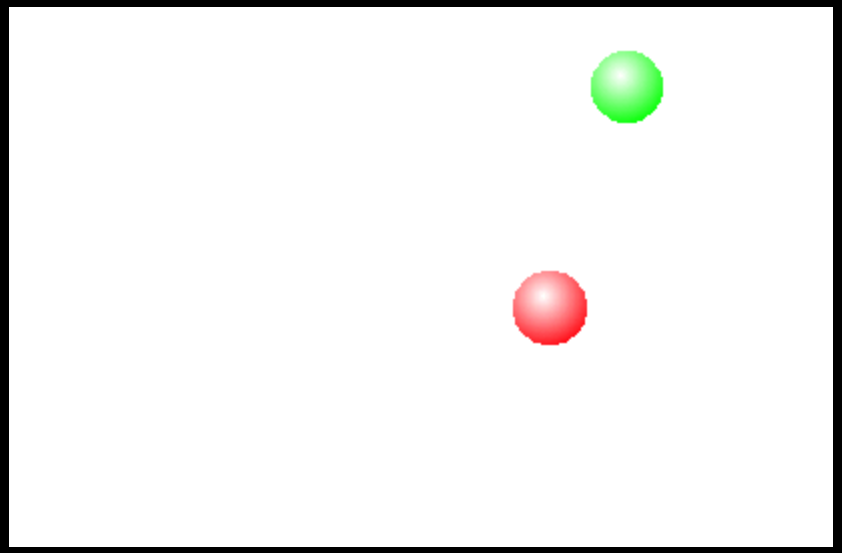


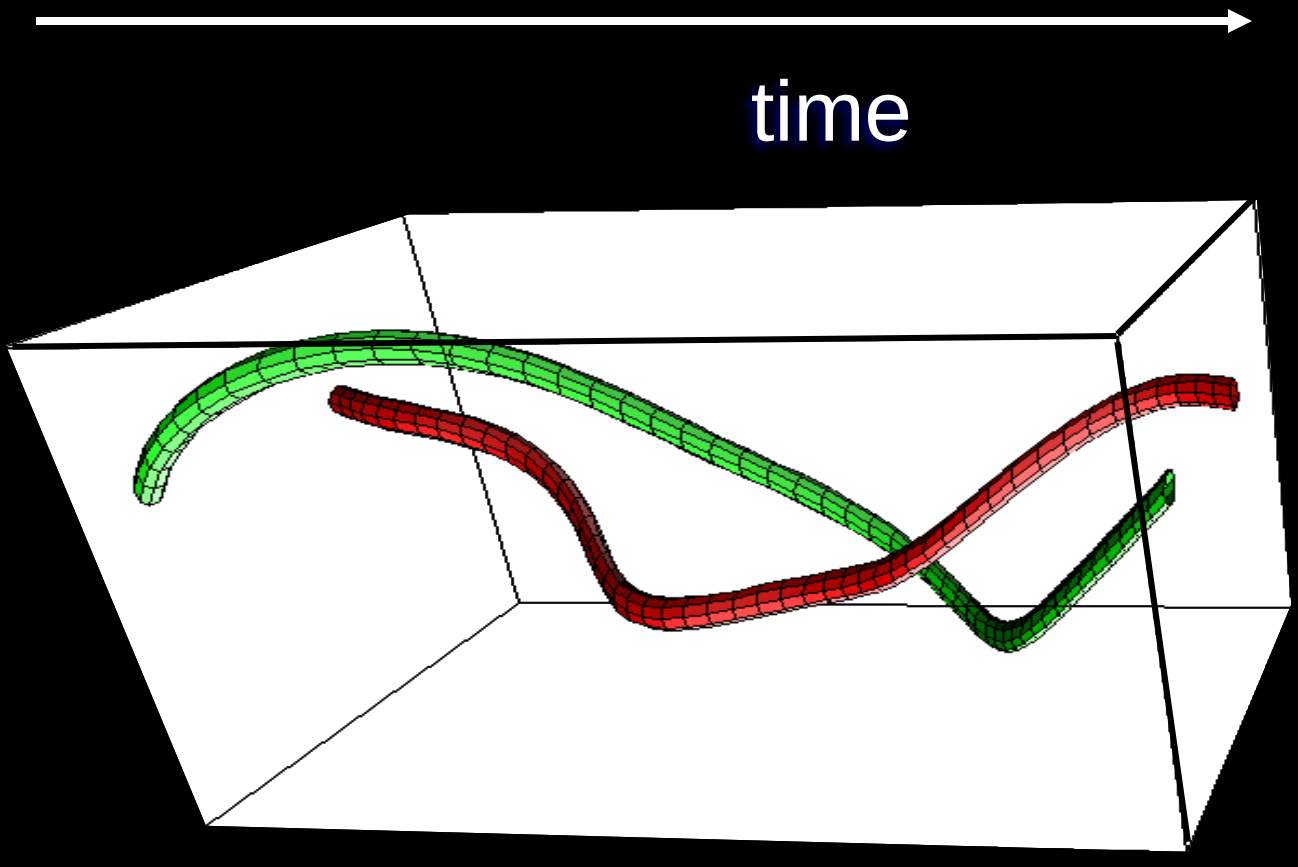
Time

"Absolute, true and mathematical time, of itself, and by its own nature, flows uniformly on, without regard to anything external."

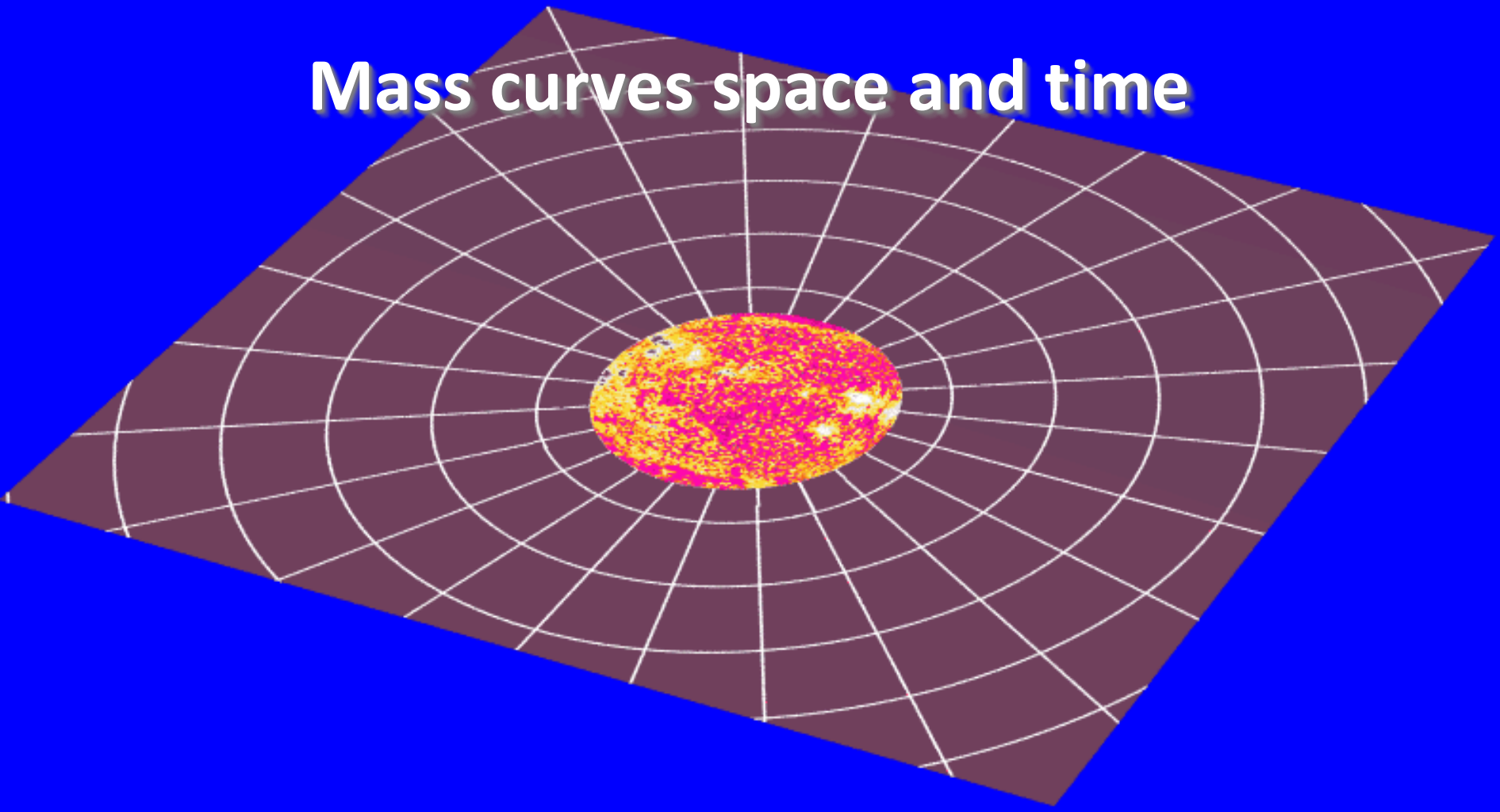
- Newton

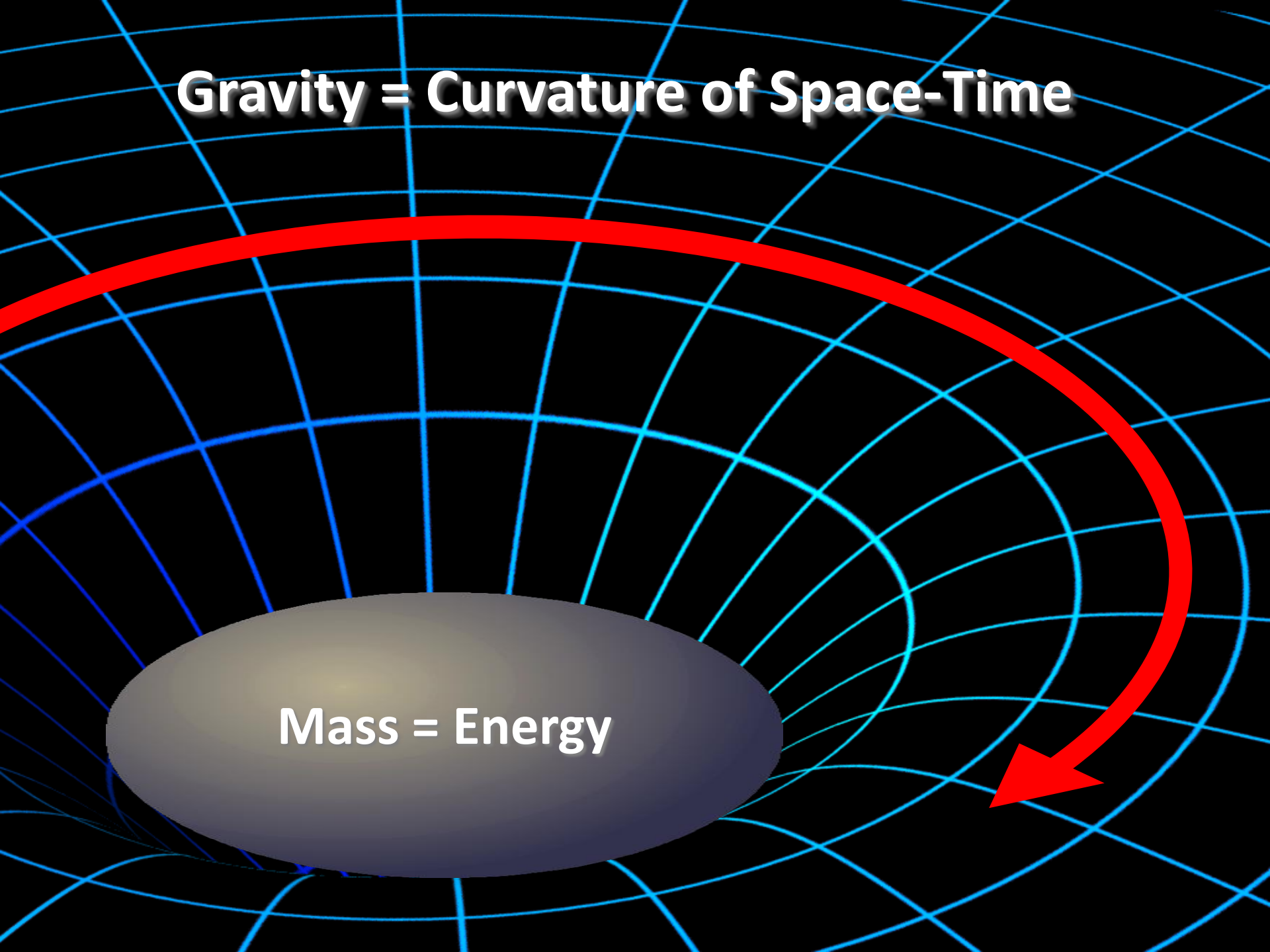
“Time is the fourth dimension”



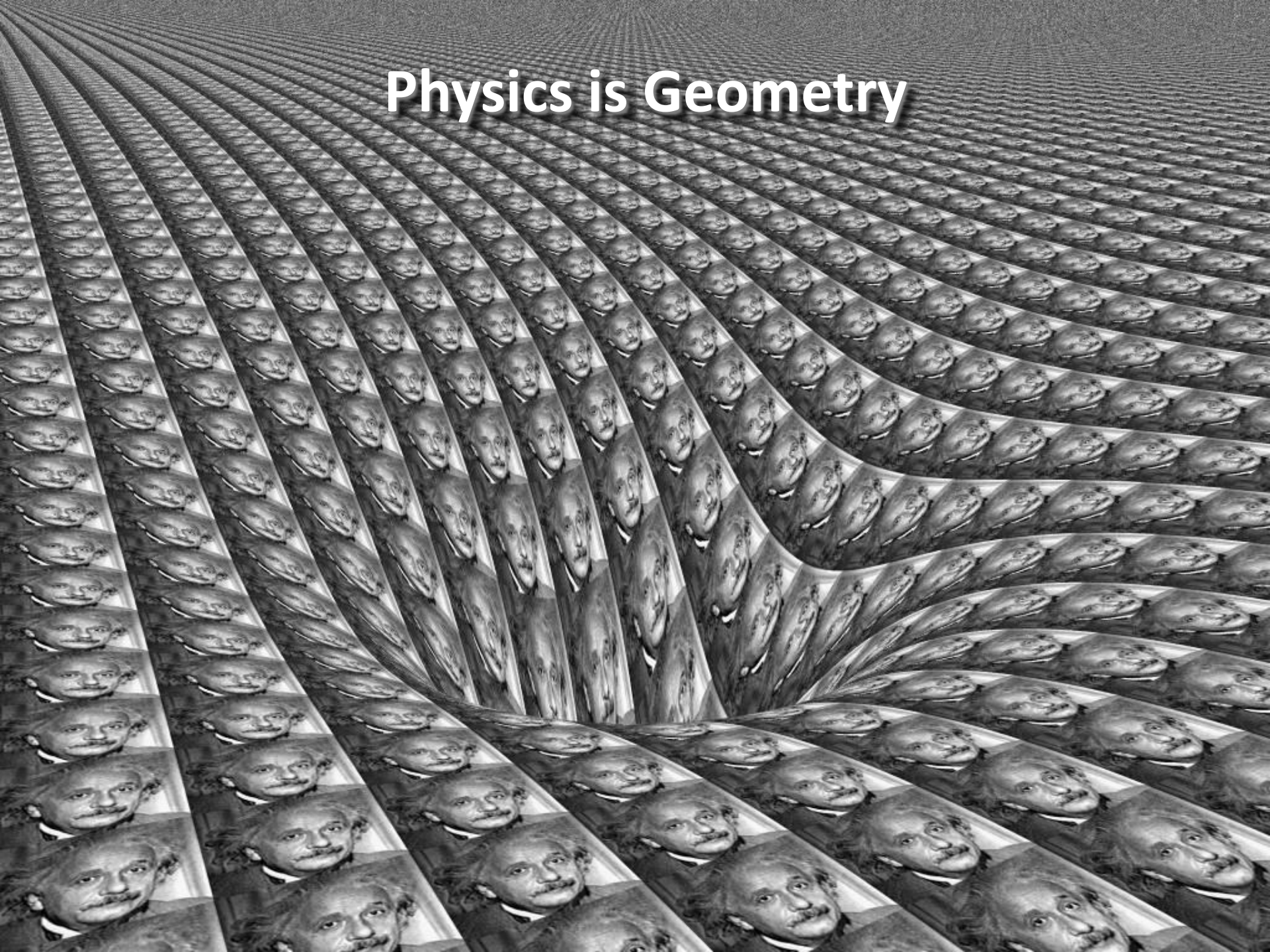

time

Mass curves space and time

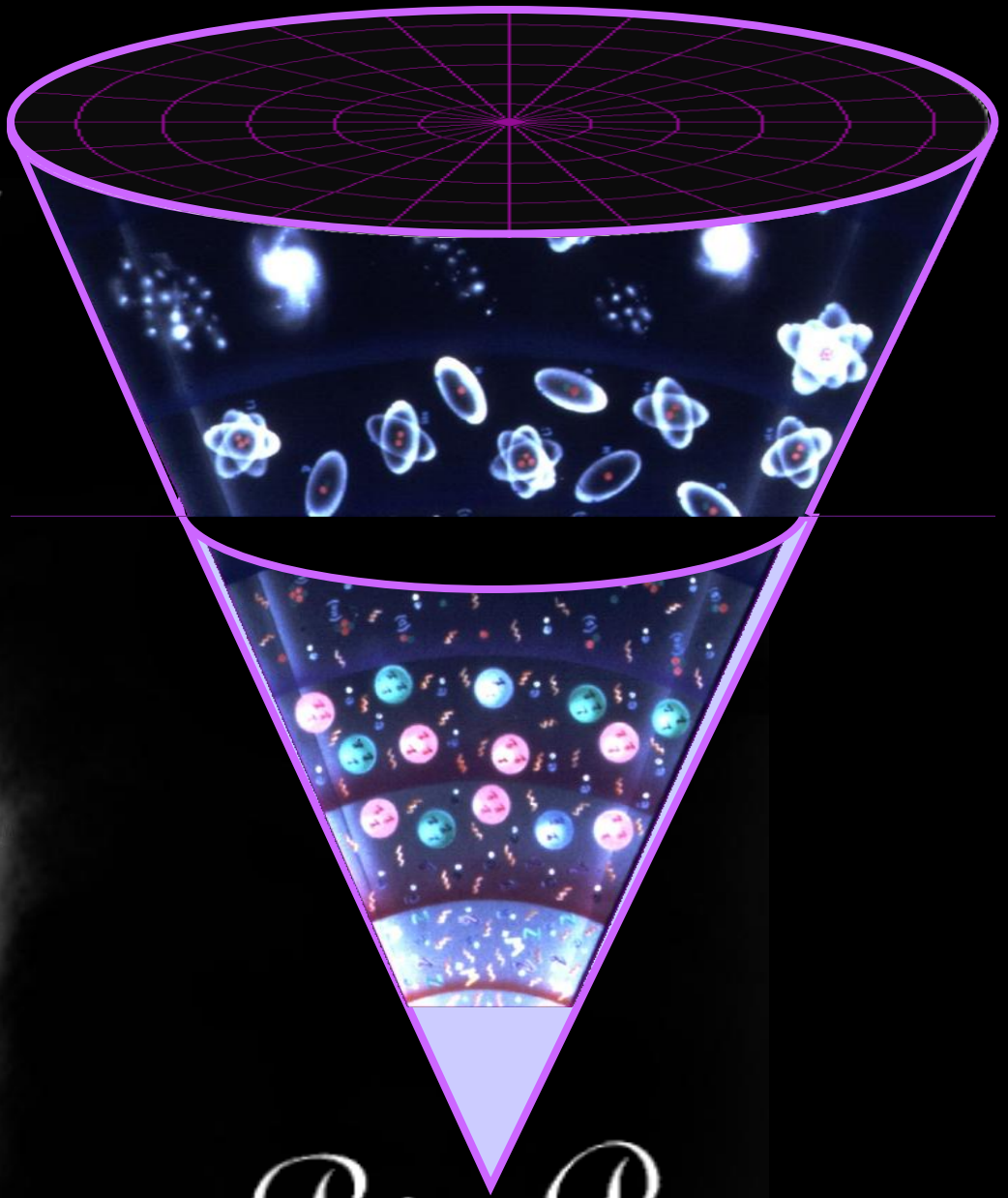



Gravity = Curvature of Space-Time
Mass = Energy

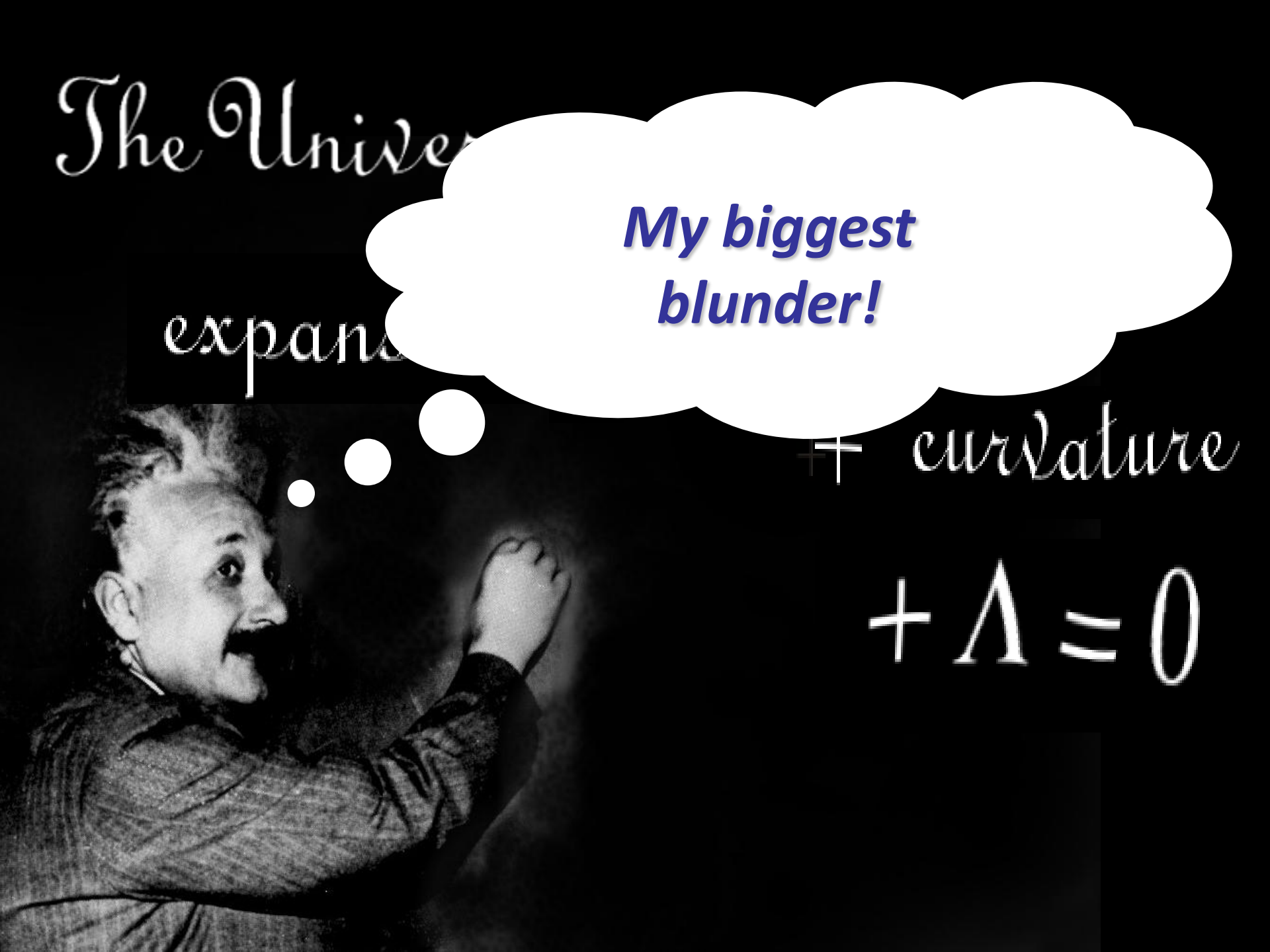
Physics is Geometry

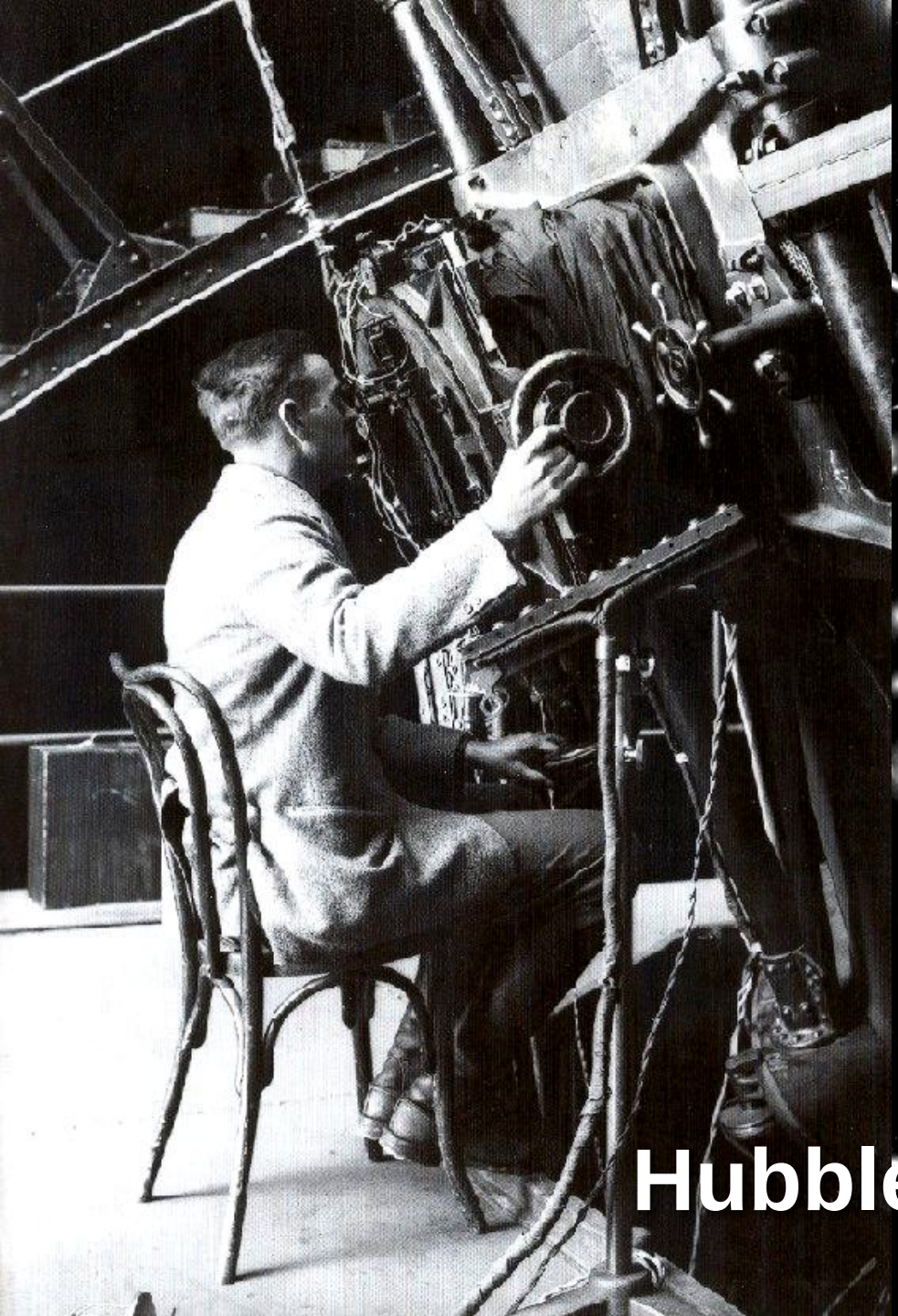


The Universe



Big Bang

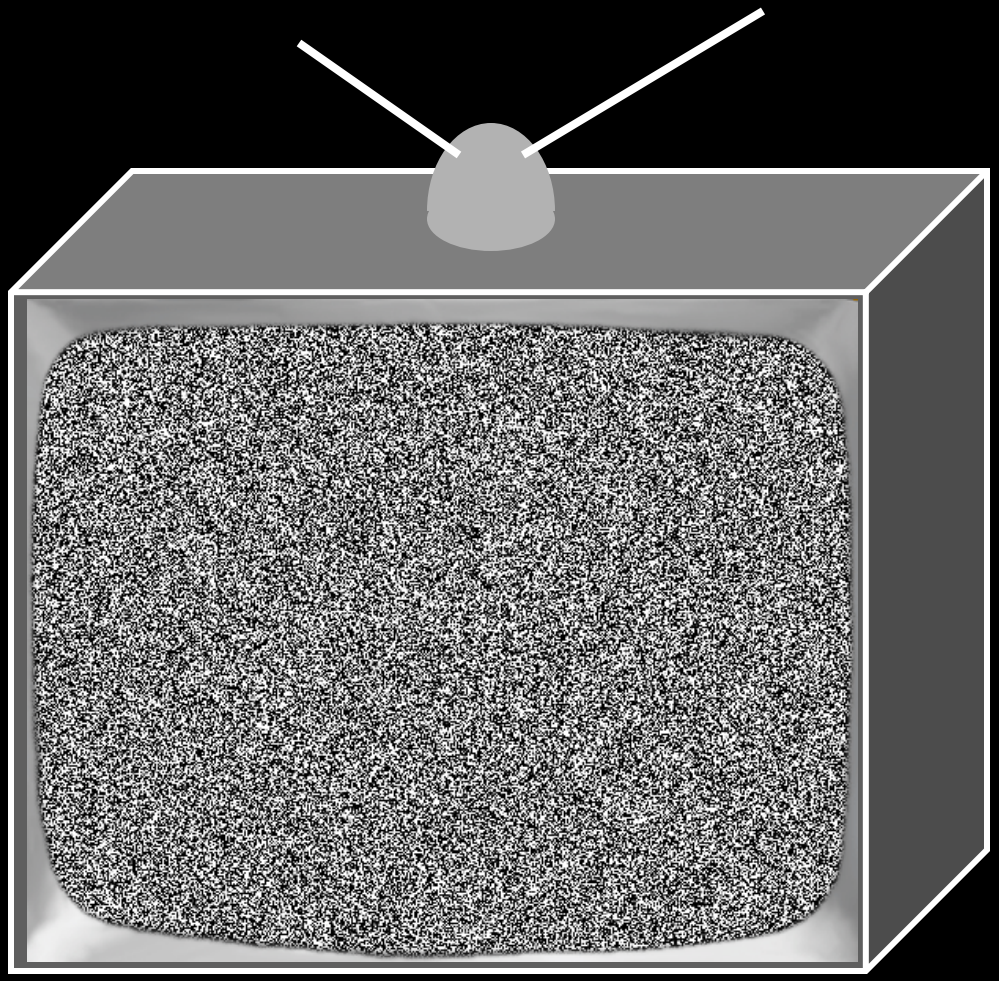

The Univer
My biggest blunder!
expans
curvature
+ Λ = 0



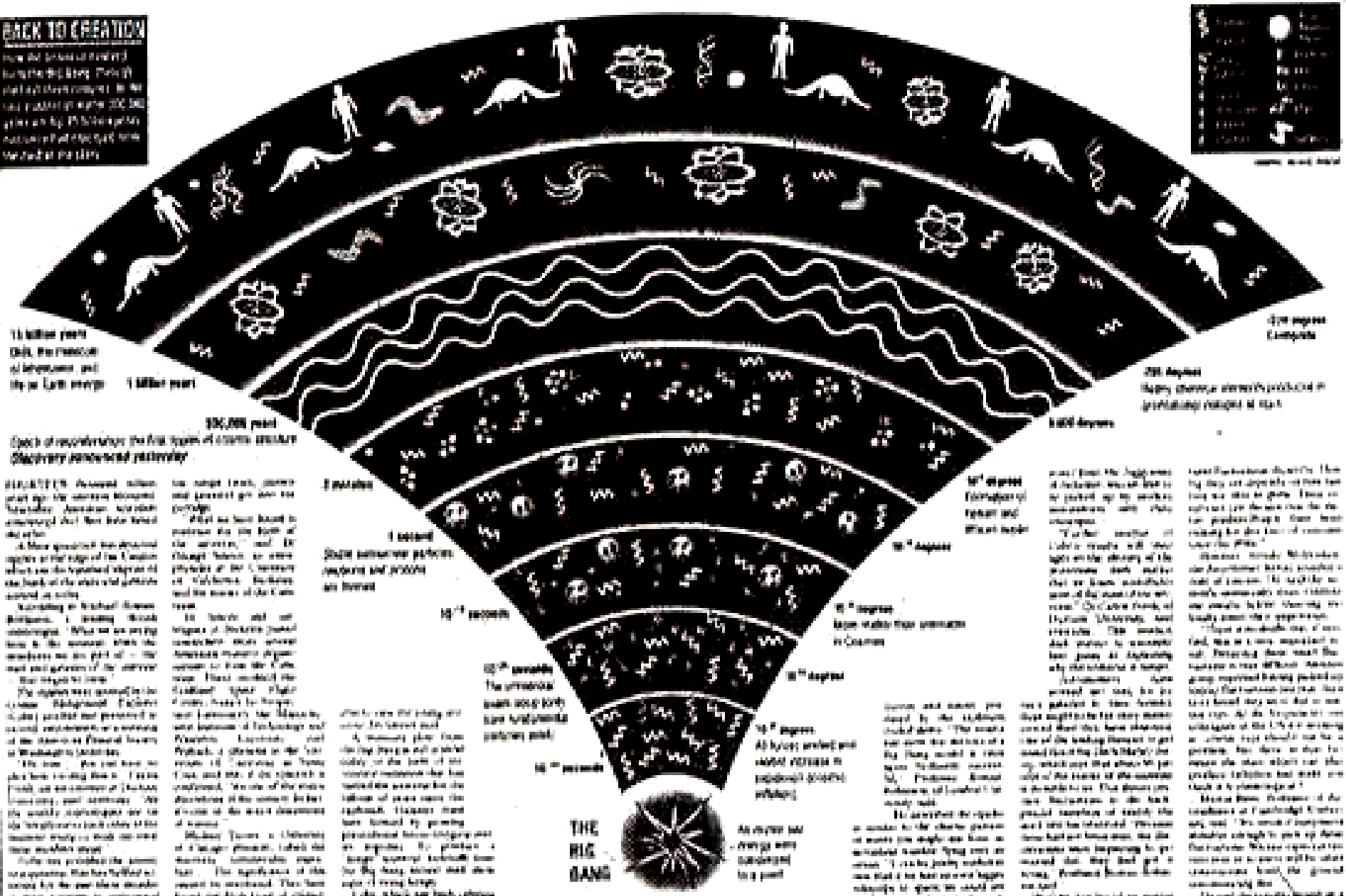
Hubble, 1929

1965: Penzias & Wilson

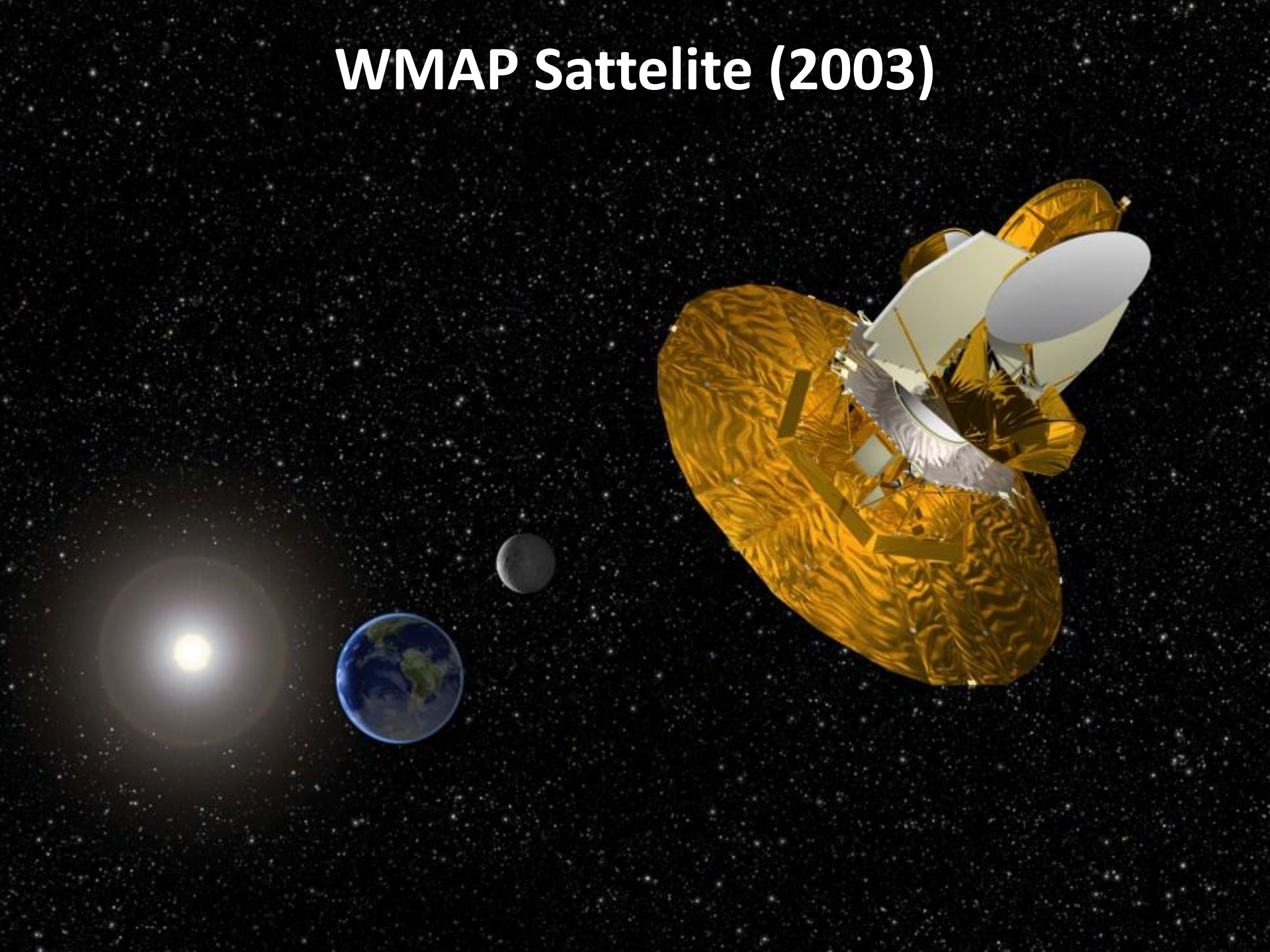
Cosmic Microwave Background



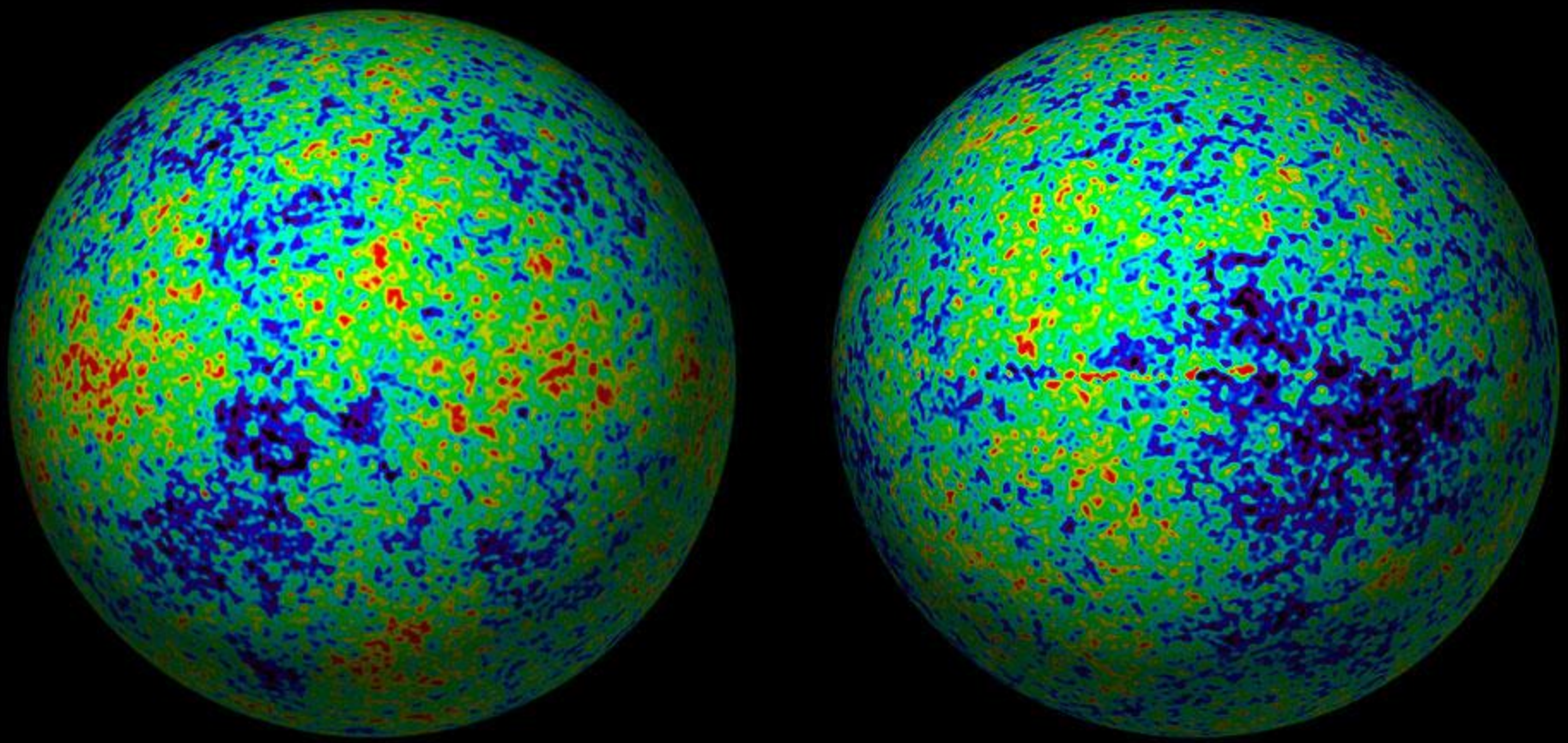
How the universe began



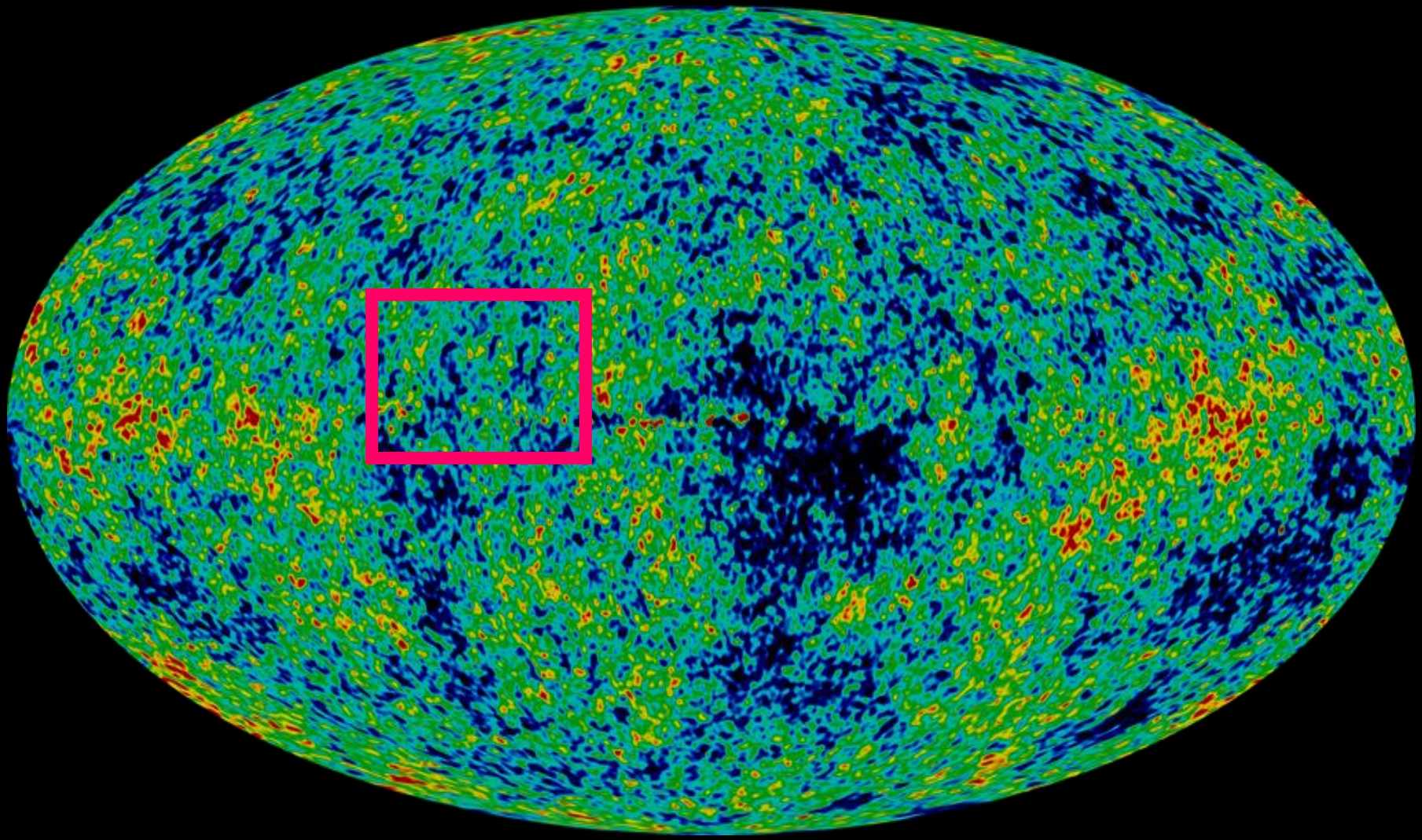
WMAP Sattelite (2003)

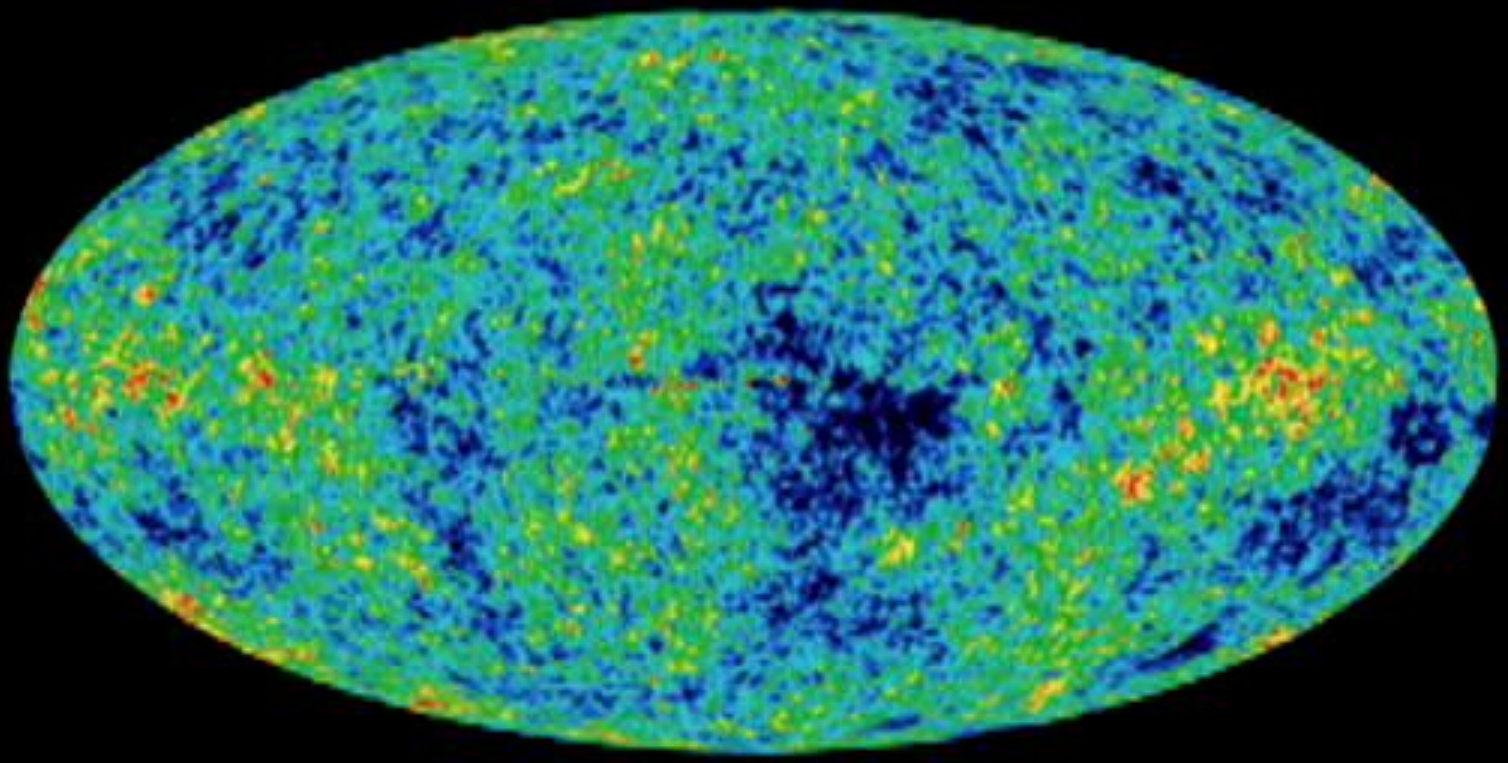


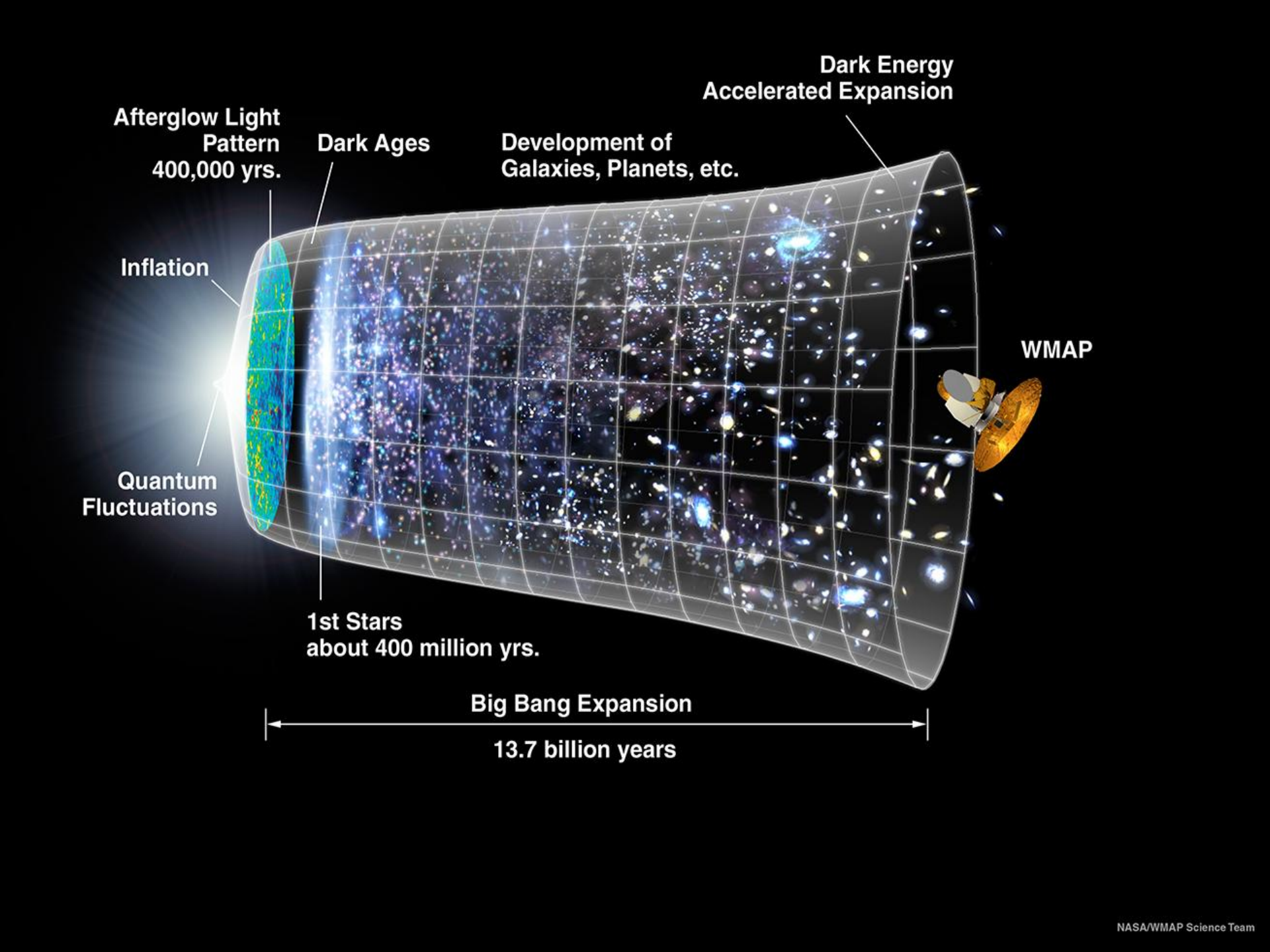
Very Early Universe

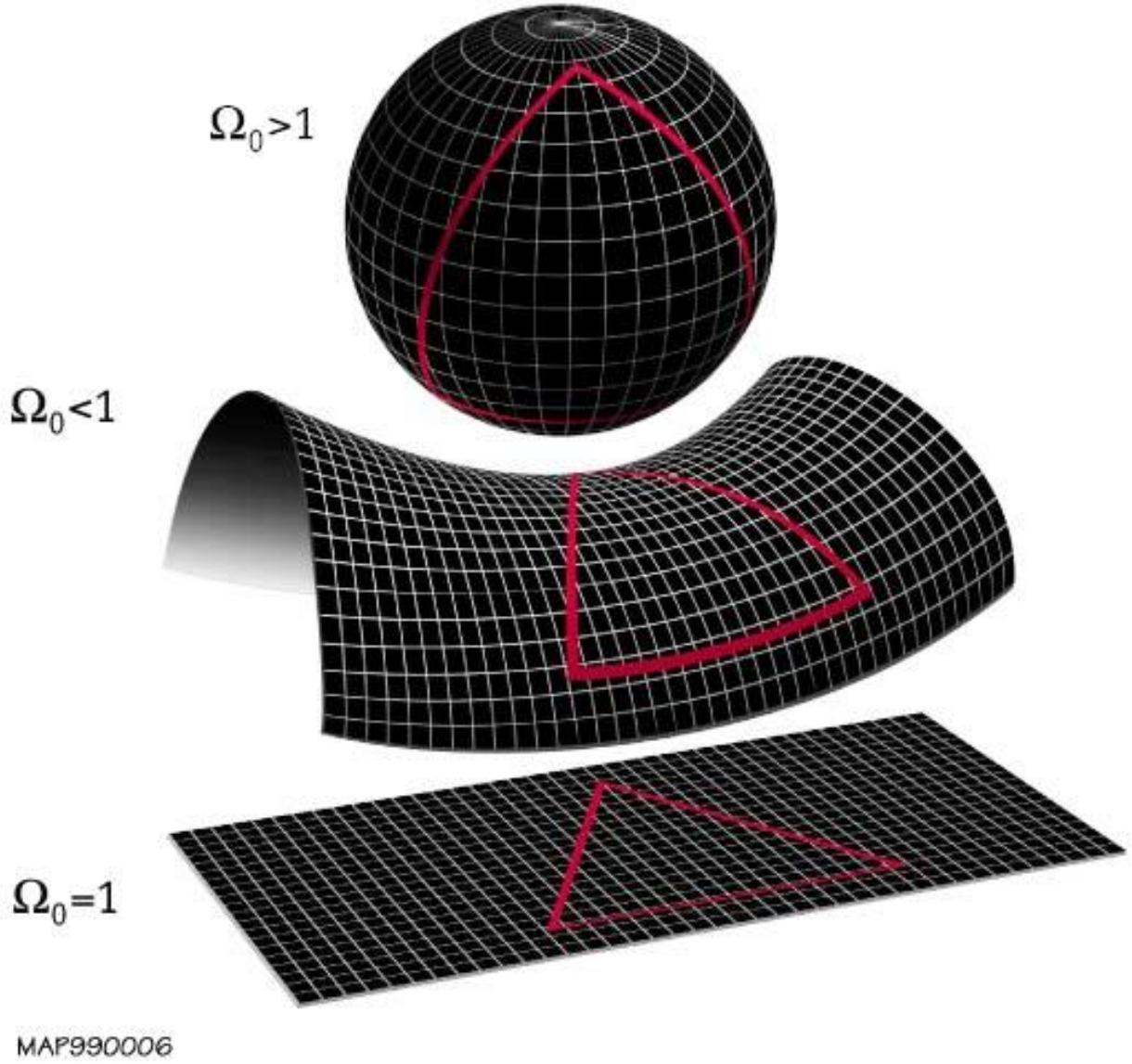


First Light, 400,000 yr after Big Bang

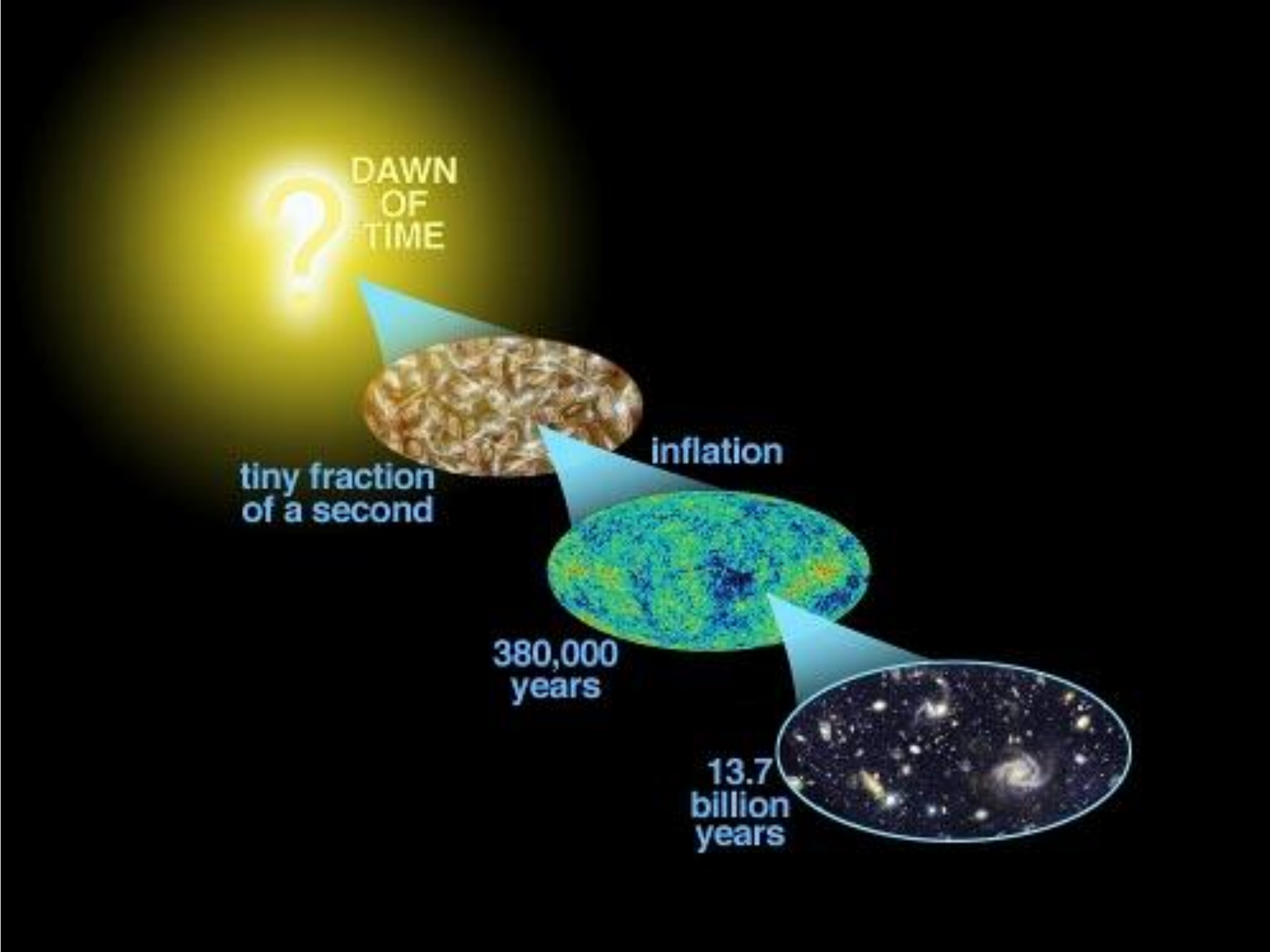





Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team



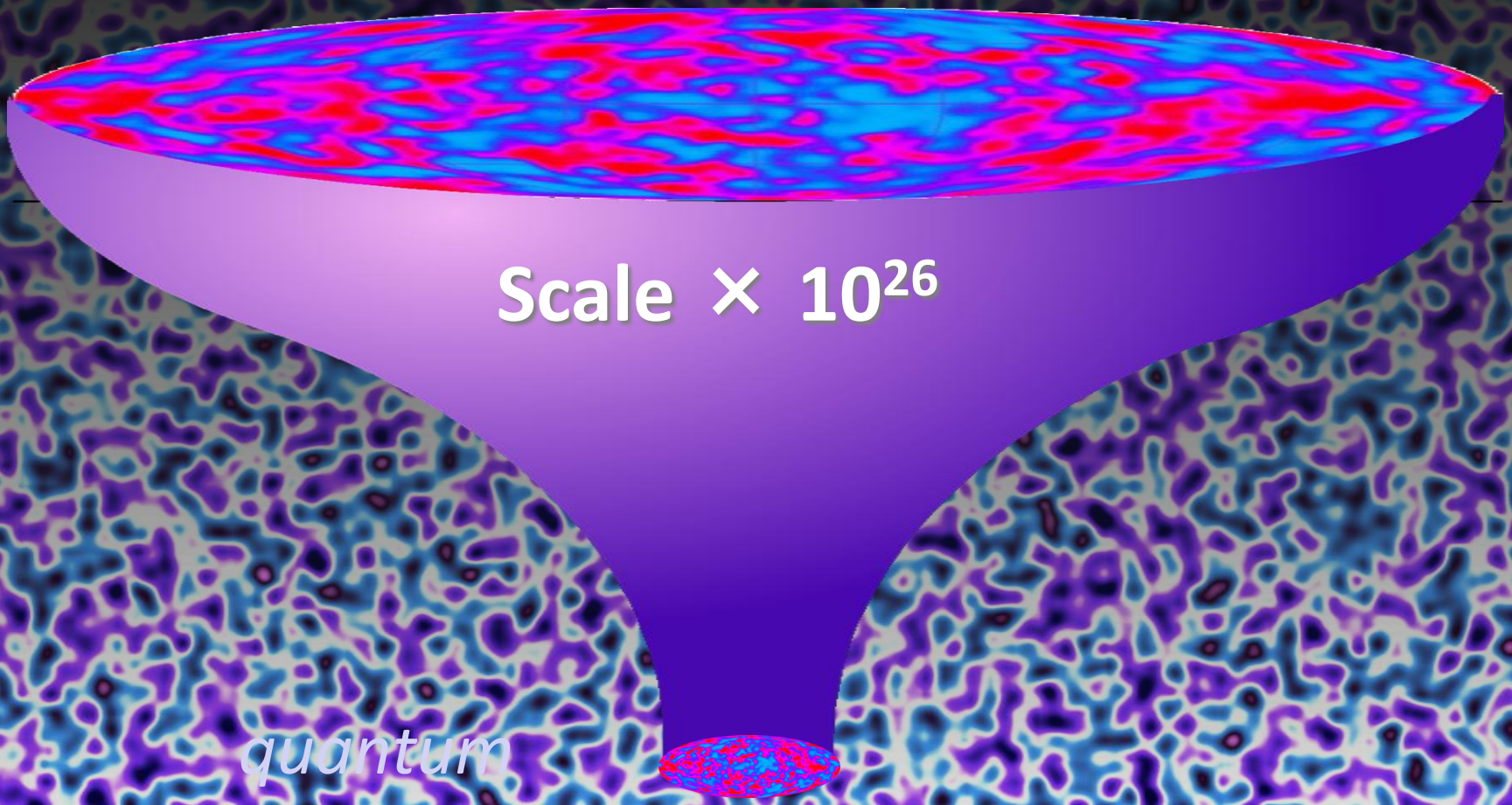
Why is the Universe
so flat, large, and full of structure?


DAWN
OF
TIME
tiny fraction
of a second
inflation
380,000
years
13.7
billion
years

Cosmic Inflation

$t = 10^{-35} \sim 10^{-32}$ s

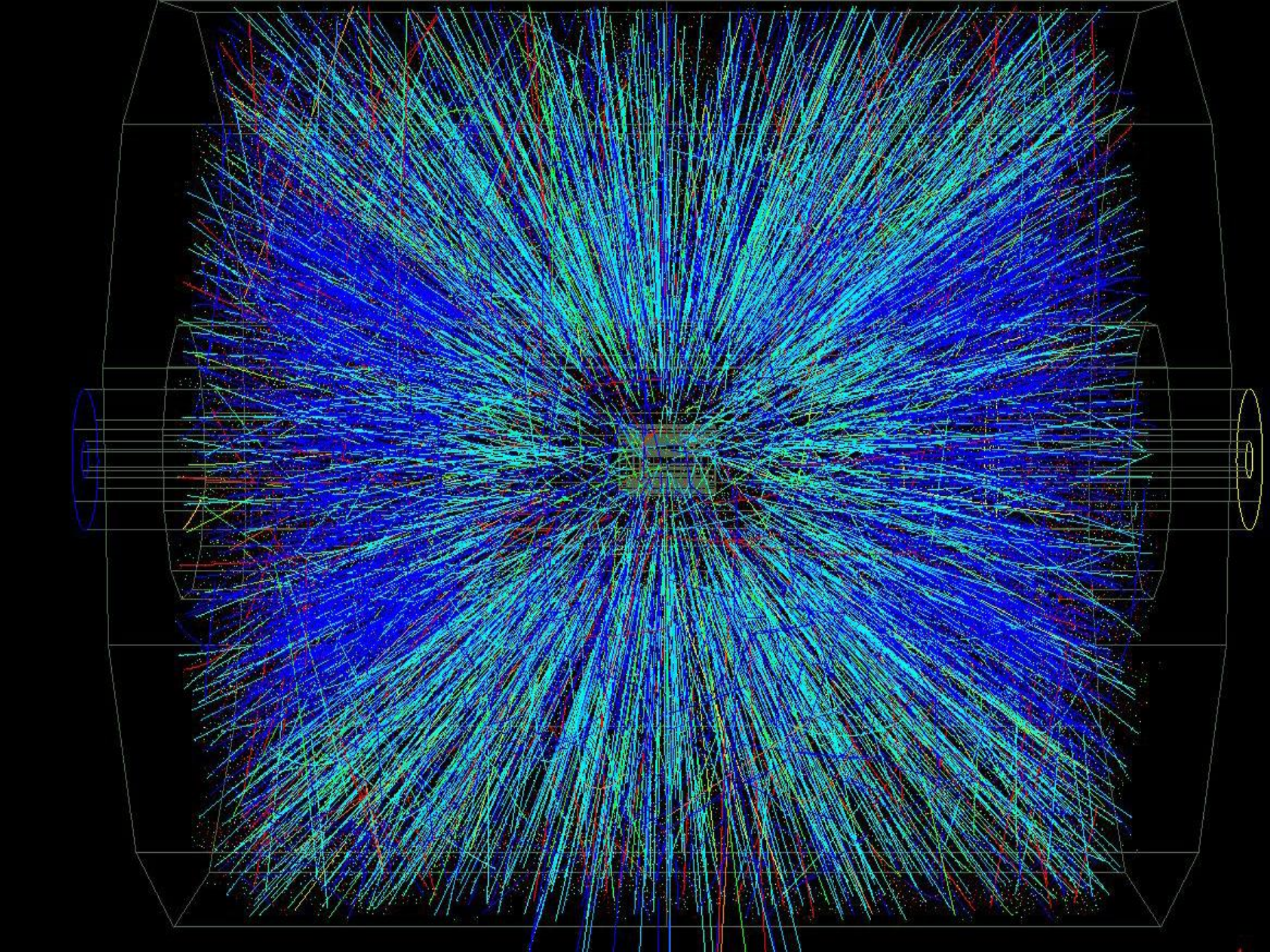
classical



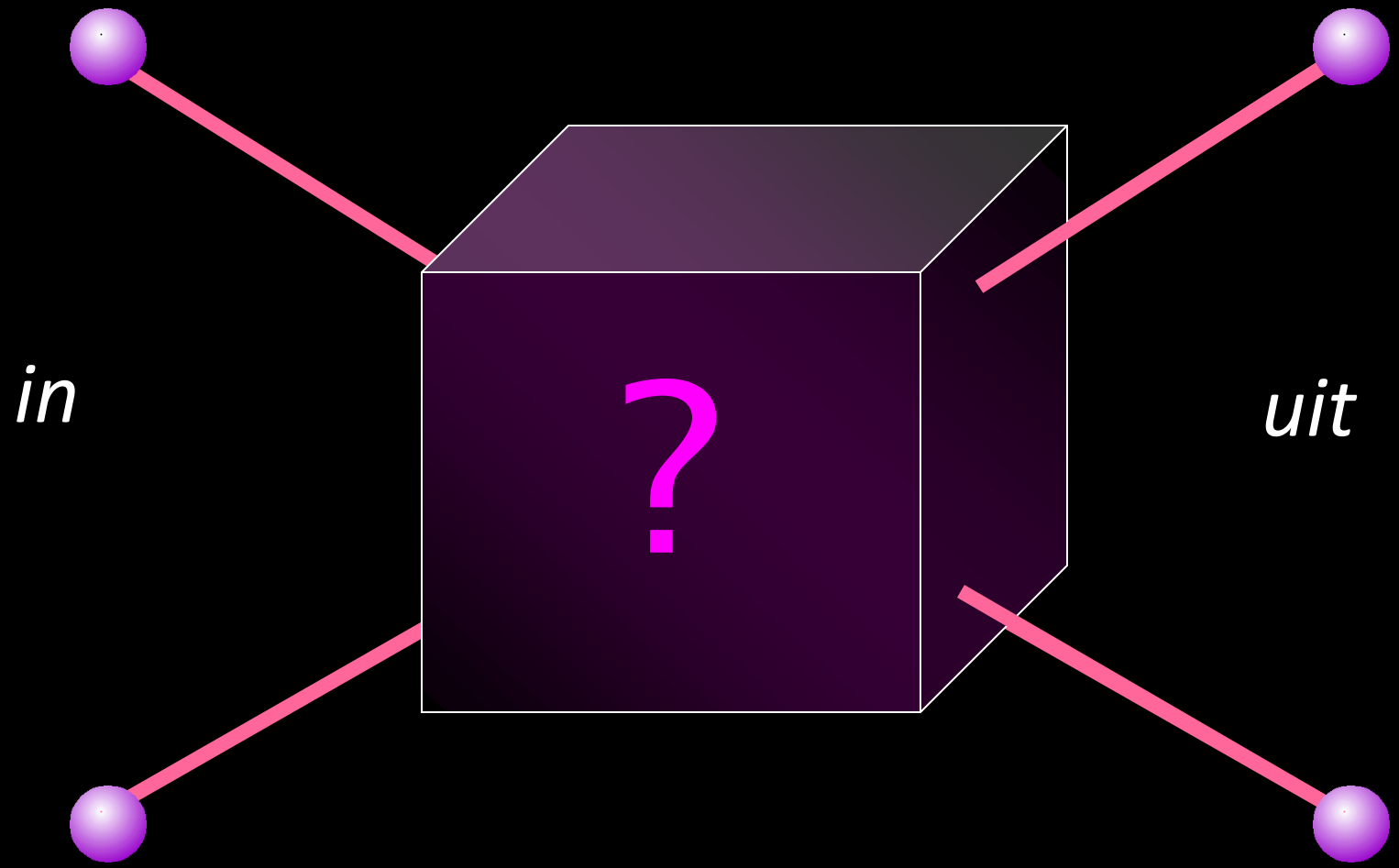
quantum

Big Bang

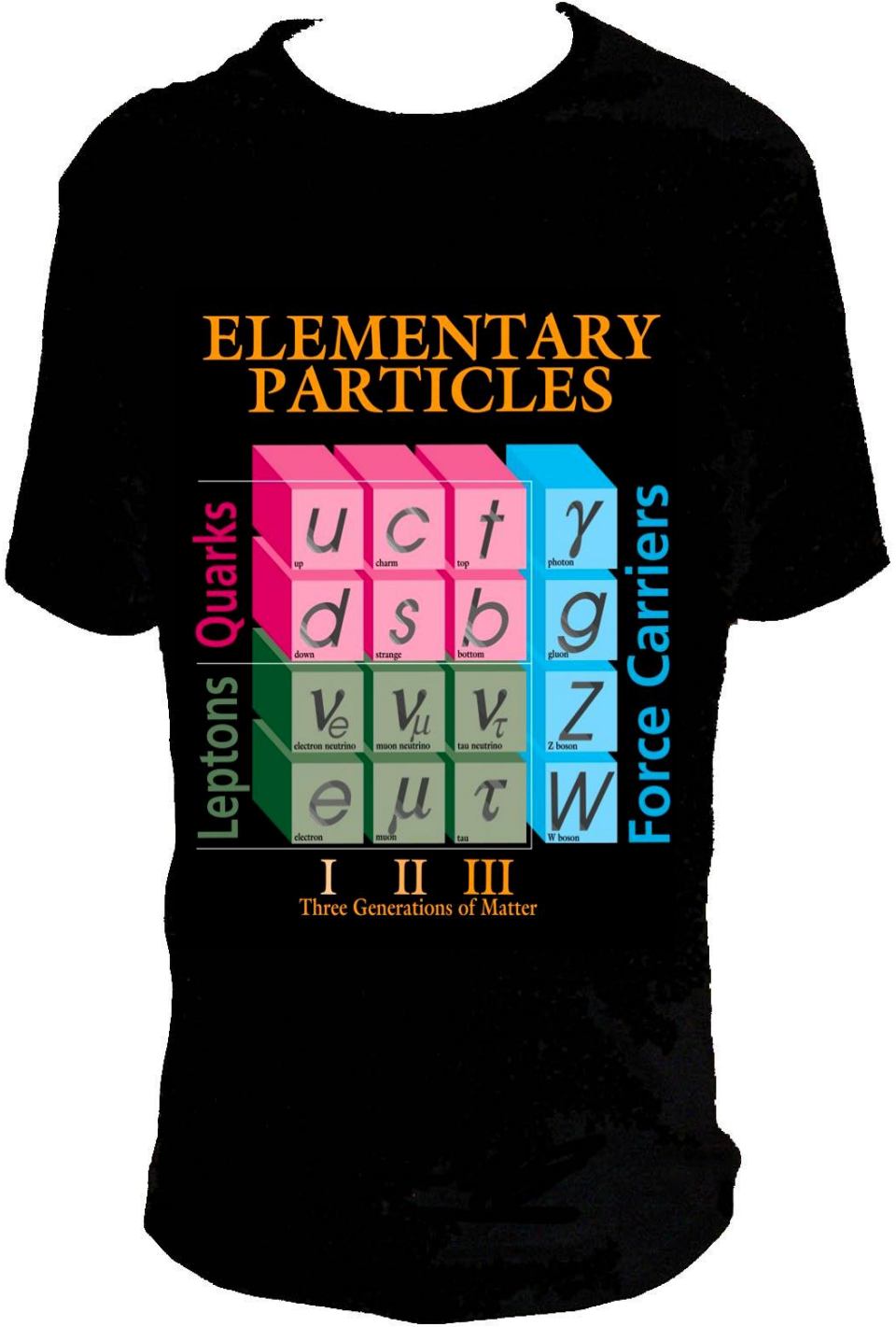
The Quantum World



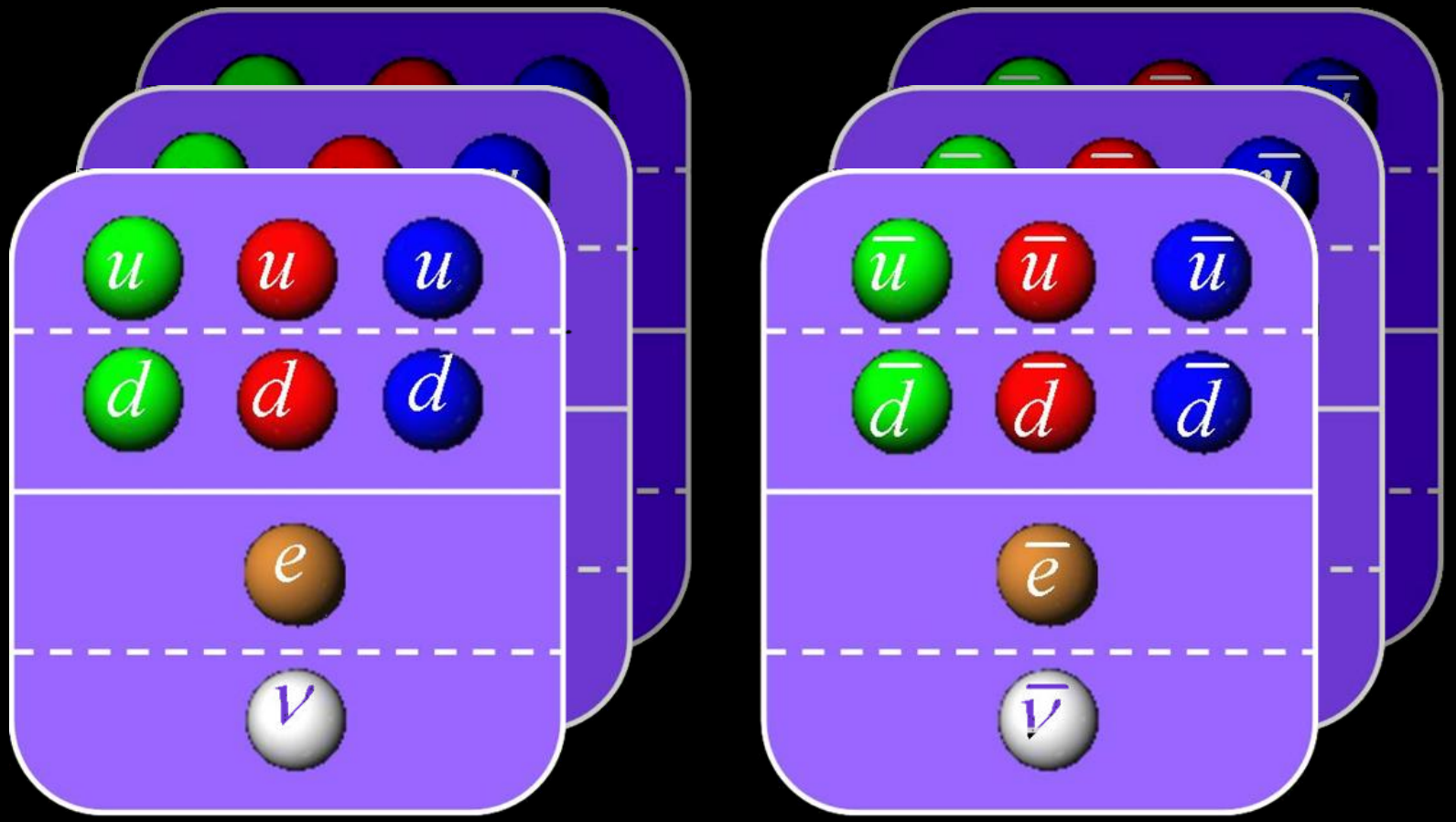
Black Box



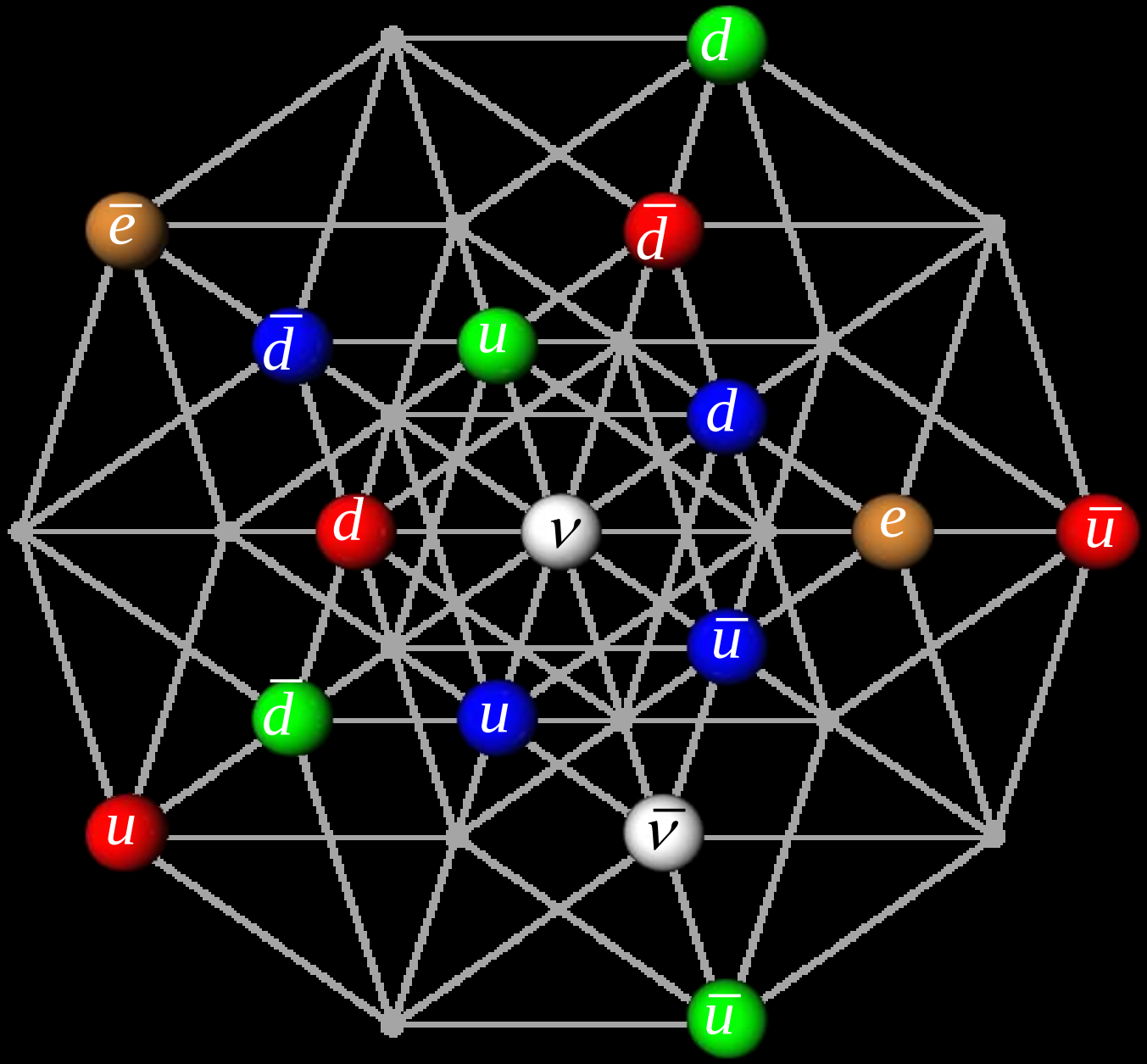
$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\nu g^a_\mu g^b_\nu g^c_\mu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{C}^a\partial^2 C^a + g_s f^{abc}\partial_\mu \bar{C}^a C^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - ig c_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w M A_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\lambda_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + X^+(\partial^2 - M^2)X^+ + X^-(\partial^2 - M^2)X^- + X^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + Y\partial^2 Y + igc_w W^+_\mu(\partial_\mu X^0 X^- - \partial_\mu X^+ X^0) + igs_w W^+_\mu(\partial_\mu Y X^- - \partial_\mu X^+ Y) + igc_w W^-_\mu(\partial_\mu X^- X^0 - \partial_\mu X^0 X^+) + igs_w W^-_\mu(\partial_\mu X^- Y - \partial_\mu Y X^+) + igc_w Z^0_\mu(\partial_\mu X^+ X^+ - \partial_\mu X^- X^-) + igs_w A_\mu(\partial_\mu X^+ X^+ - \partial_\mu X^- X^-) - \tfrac{1}{2}gM[X^+X^+H + X^-X^-H + \tfrac{1}{c_w^2}X^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[X^+X^0\phi^+ - X^-X^0\phi^-] + \tfrac{1}{2c_w}igM[X^0X^-\phi^+ - X^0X^+\phi^-] + igMs_w[X^0X^-\phi^+ - X^0X^+\phi^-] + \tfrac{1}{2}igM[X^+X^+\phi^0 - X^-X^-\phi^0]$$

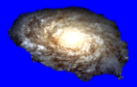


Standard Model

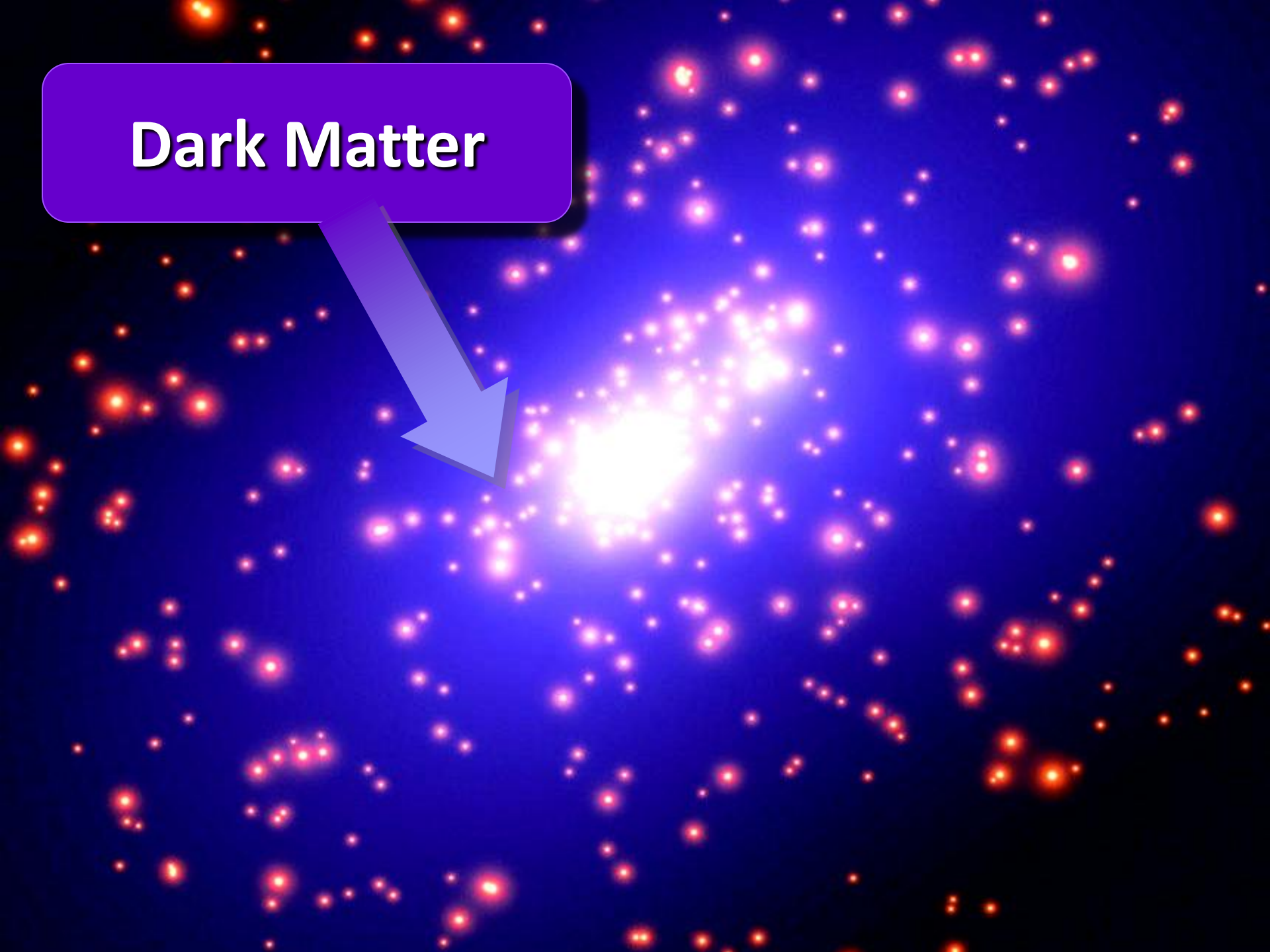


Grand Unified Theory?

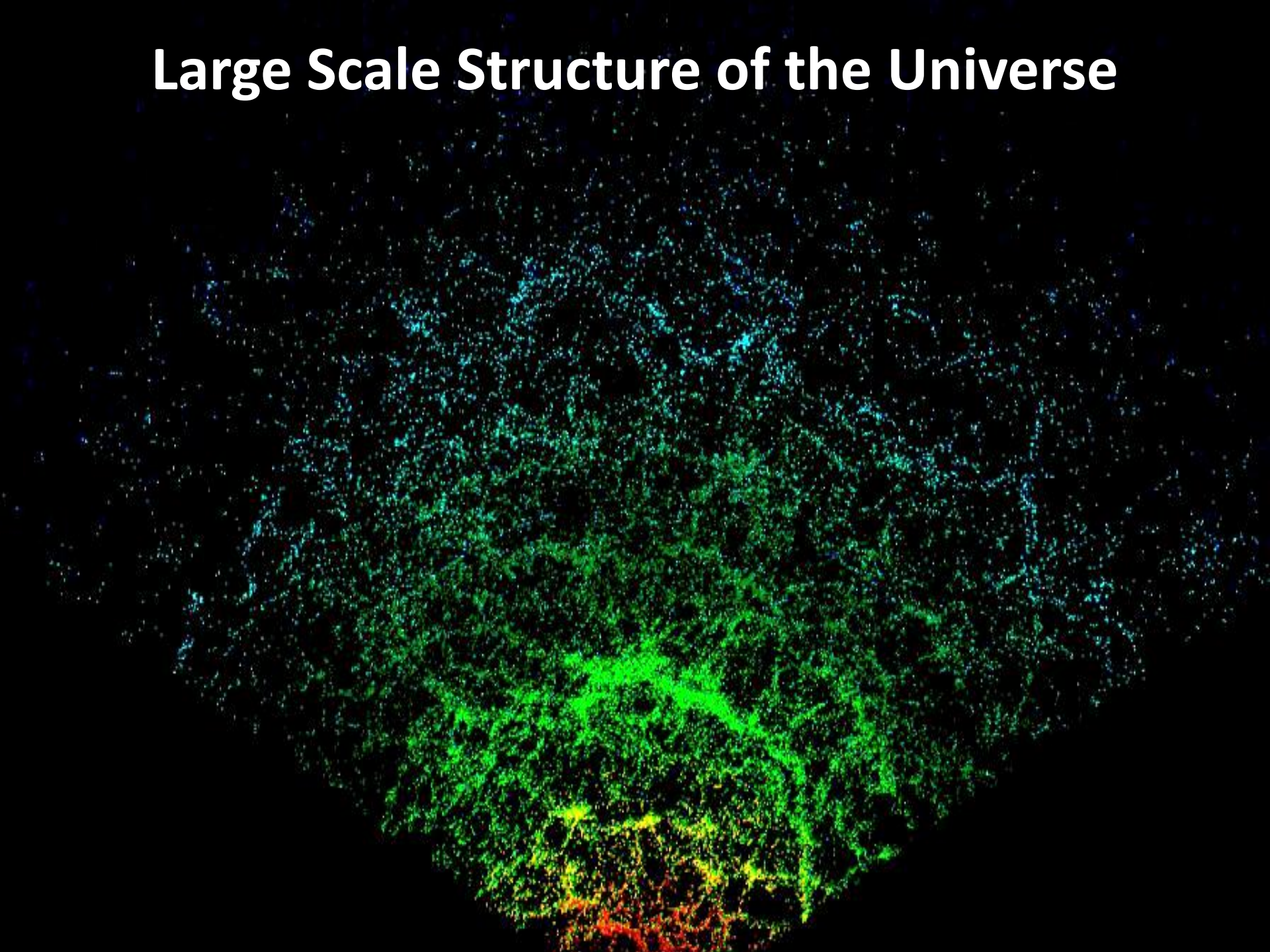


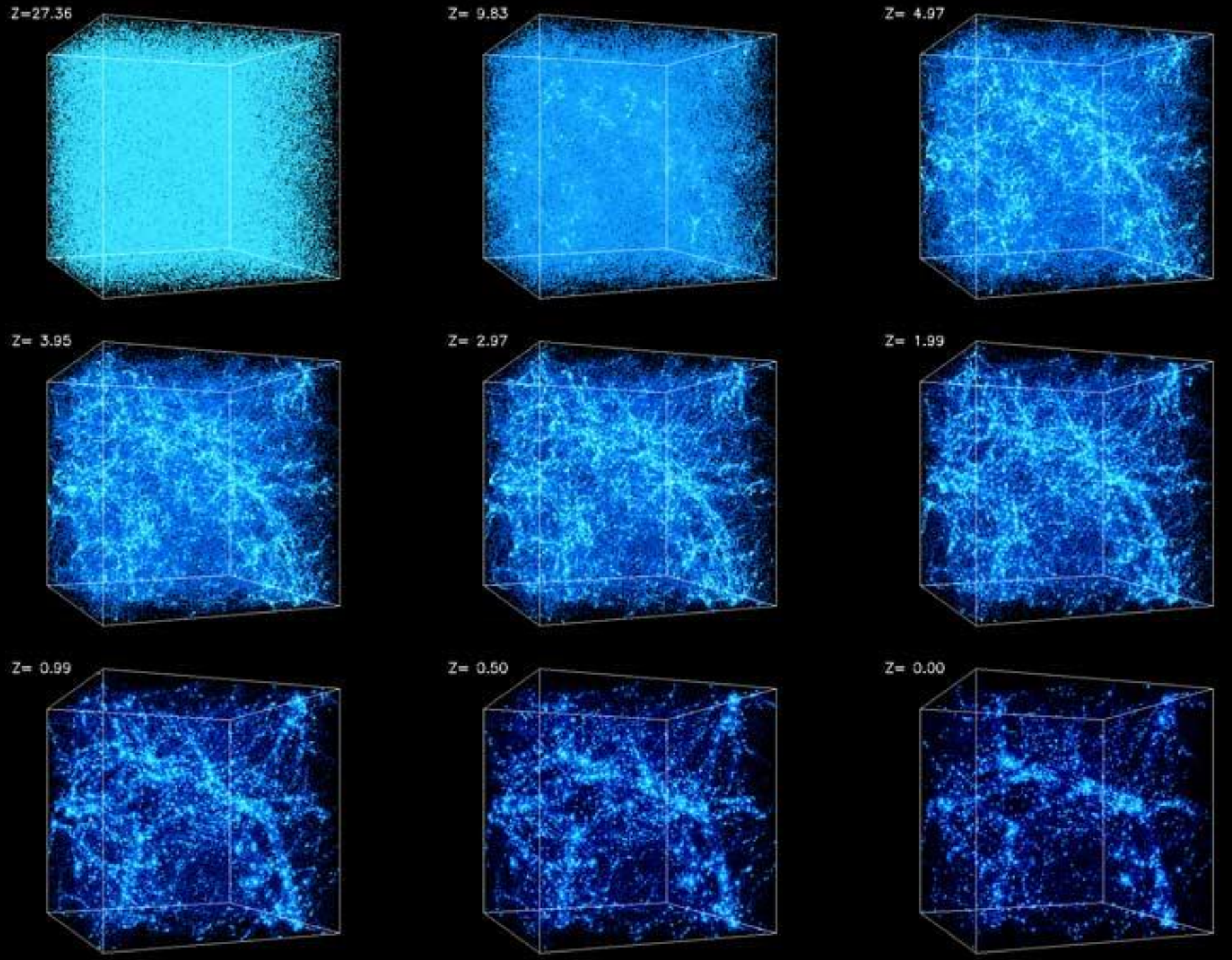


Dark Matter

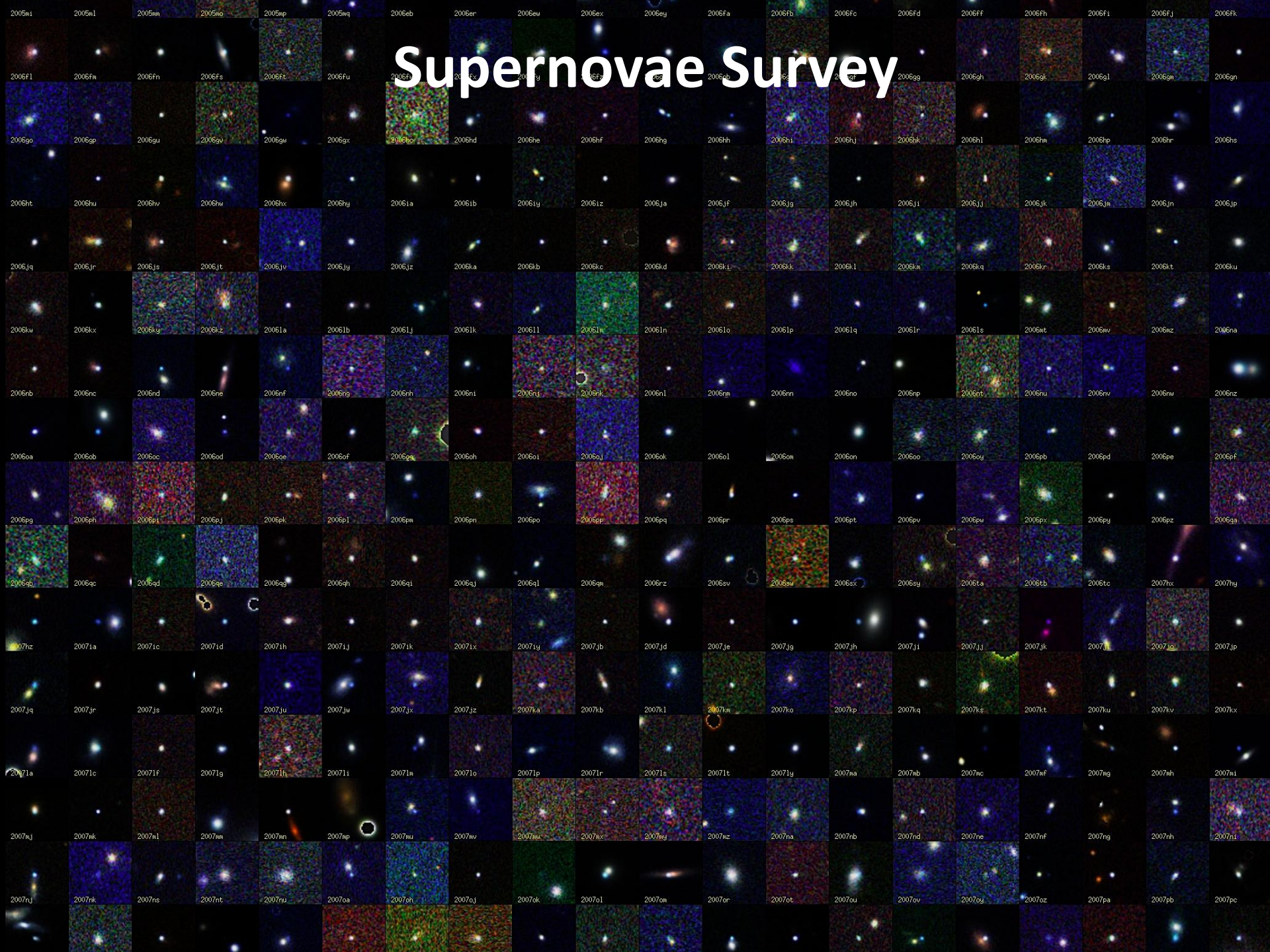

Dark Matter

Large Scale Structure of the Universe

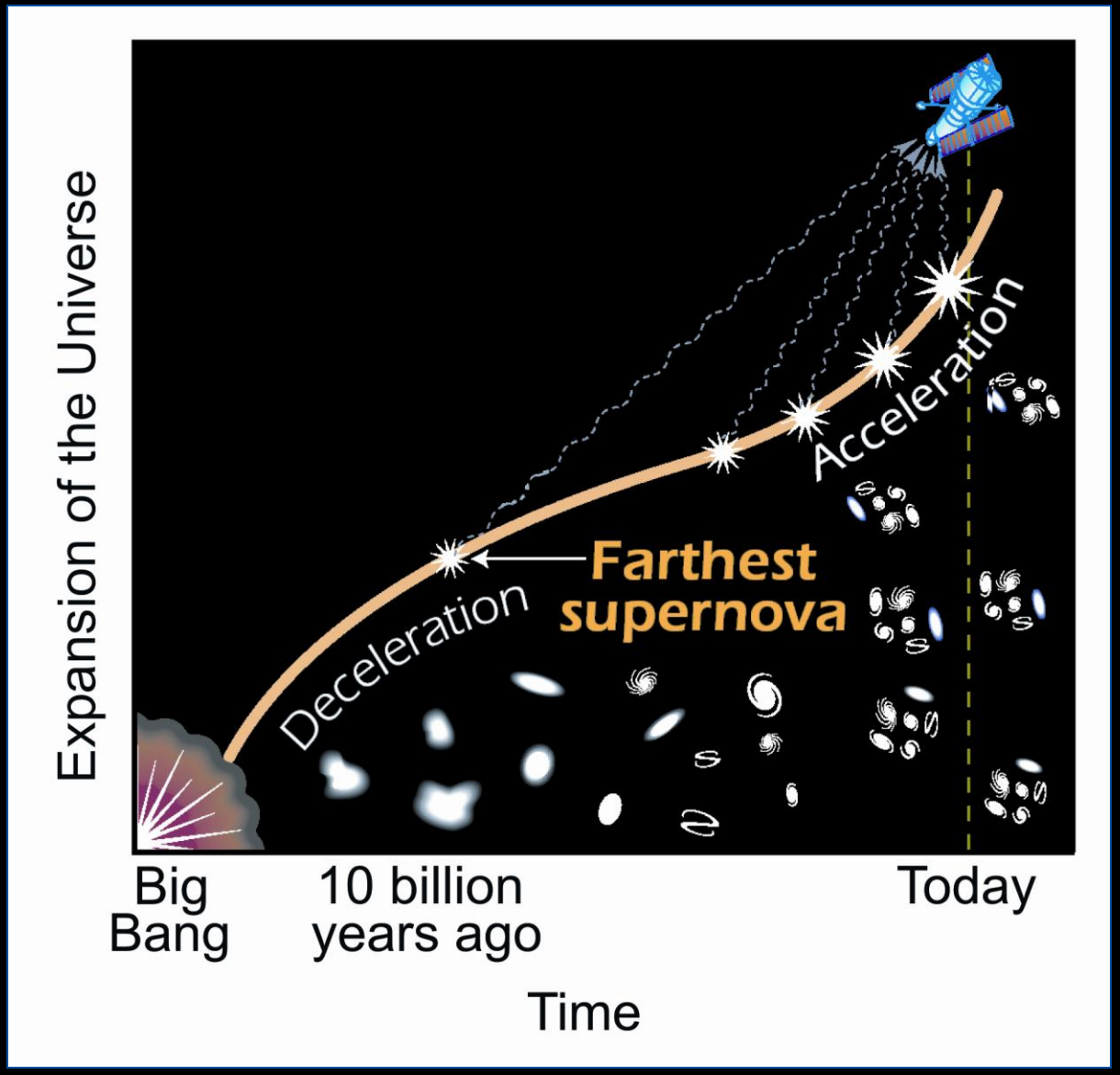



Z=27.36
Z= 9.83
Z= 4.97
Z= 3.95
Z= 2.97
Z= 1.99
Z= 0.99
Z= 0.50
Z= 0.00

Supernovae (type Ia)


Supernovae Survey

Λ > 0: Dark Energy



The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

Photo: U. Montan

Saul Perlmutter

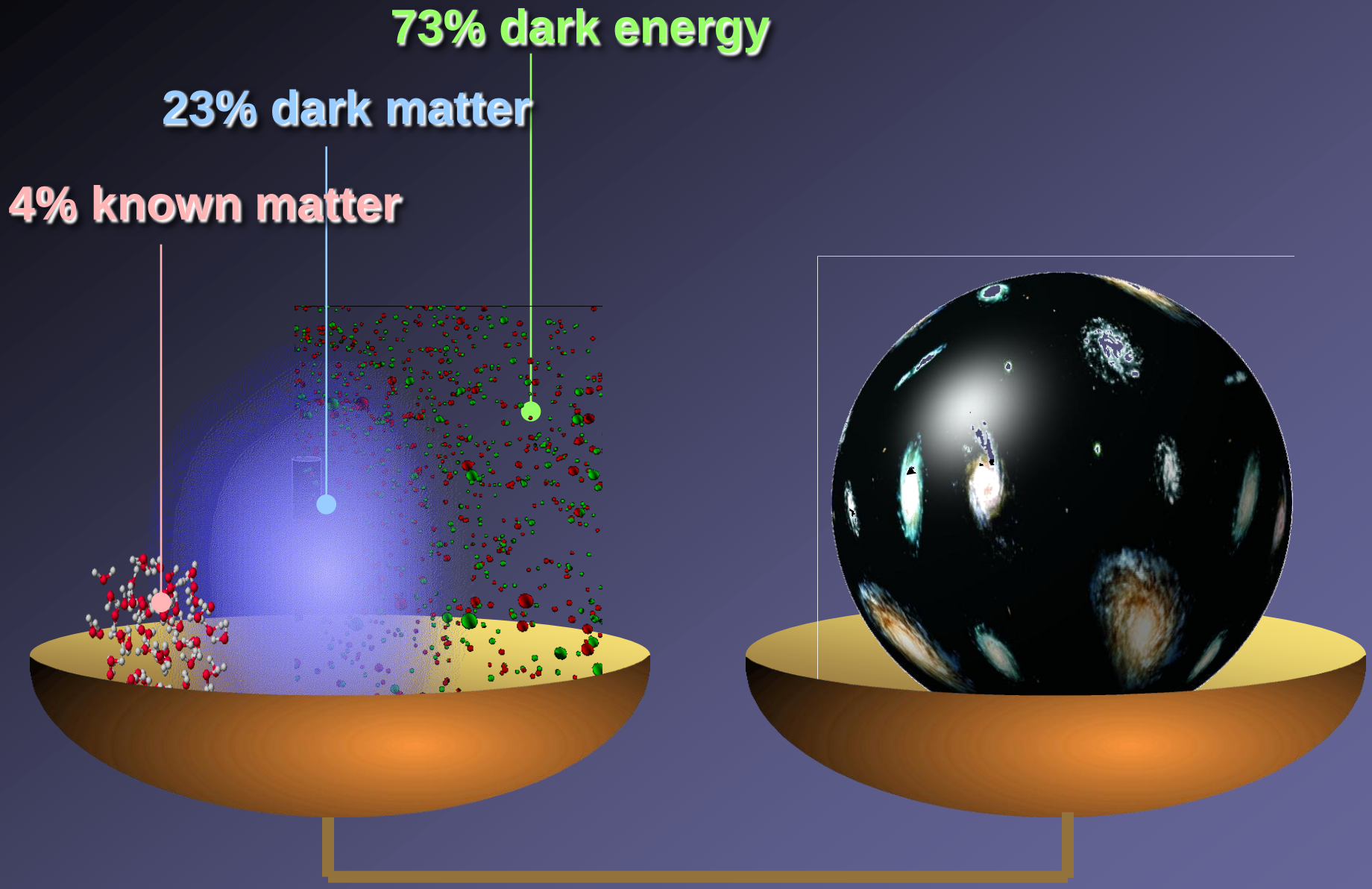
Photo: U. Montan

Brian P. Schmidt

Photo: U. Montan

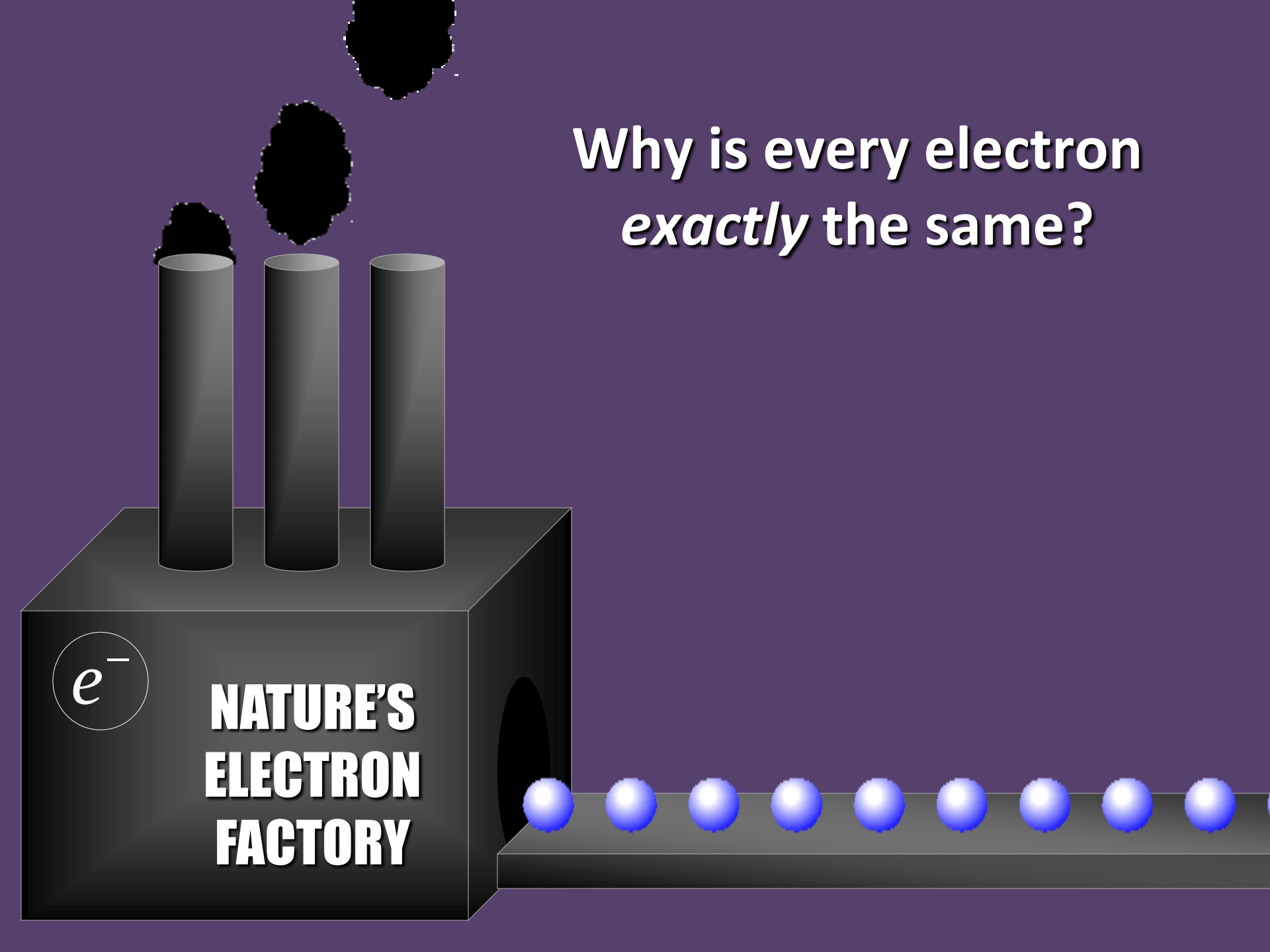
Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.



Weight of the Universe

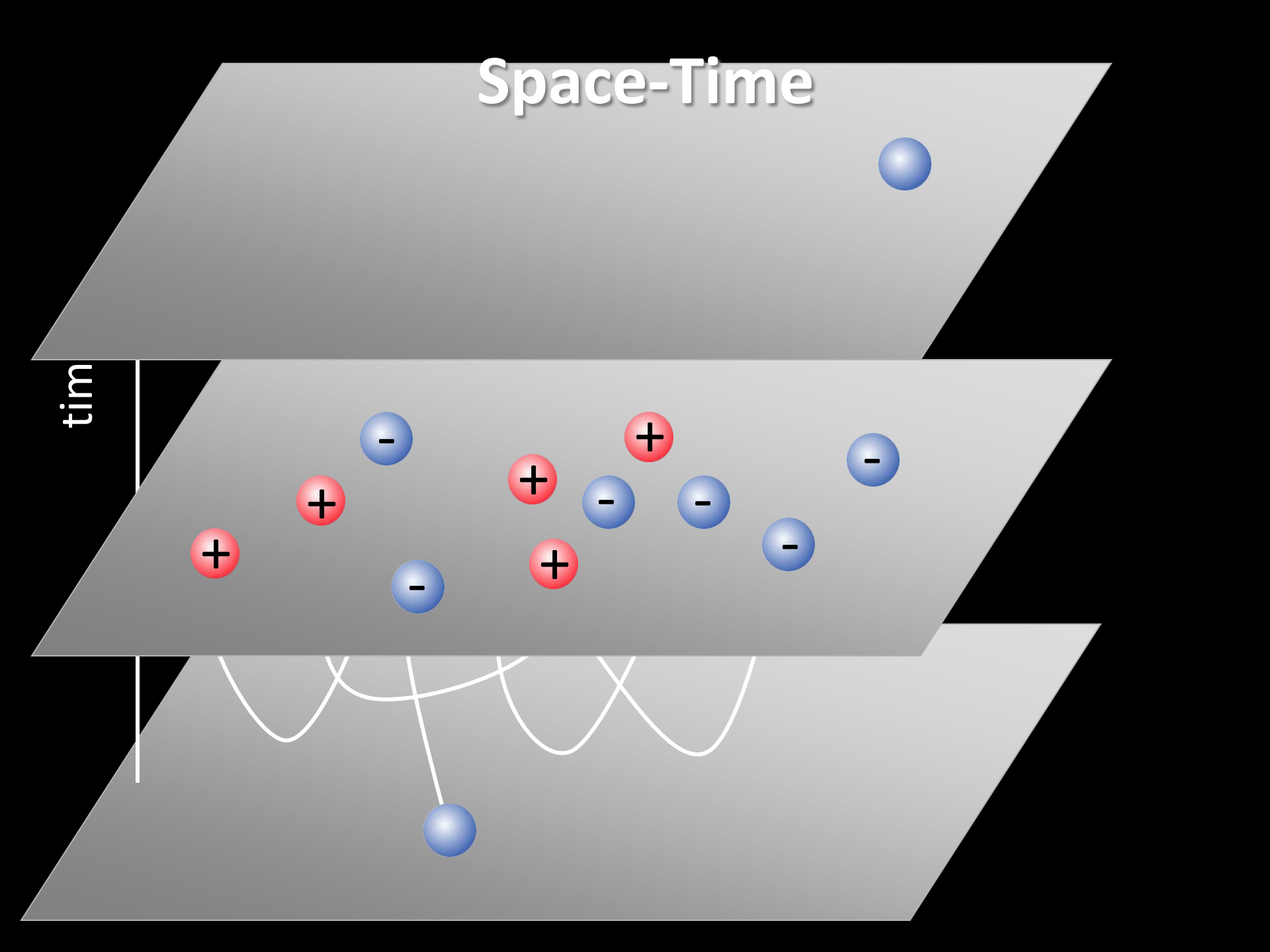

A
B
C
Cete
D
Hœc est horrenda caribdis
F
Xij. P.
300. pedum
HEGALANDIA
terra nobilium
Fisca
Horum piscium
Egge
Hasenag
Gallea peregrina
Ostrasiord
Gullesiord
Sandver
Quedesiord
Rollen
Trondanes
Langanes
Duuanes
Andanes
Rost
Scongen
Lasot
Gamblavik
Nygavik
Vast


Why is every electron *exactly* the same?
e^-
NATURE'S ELECTRON FACTORY

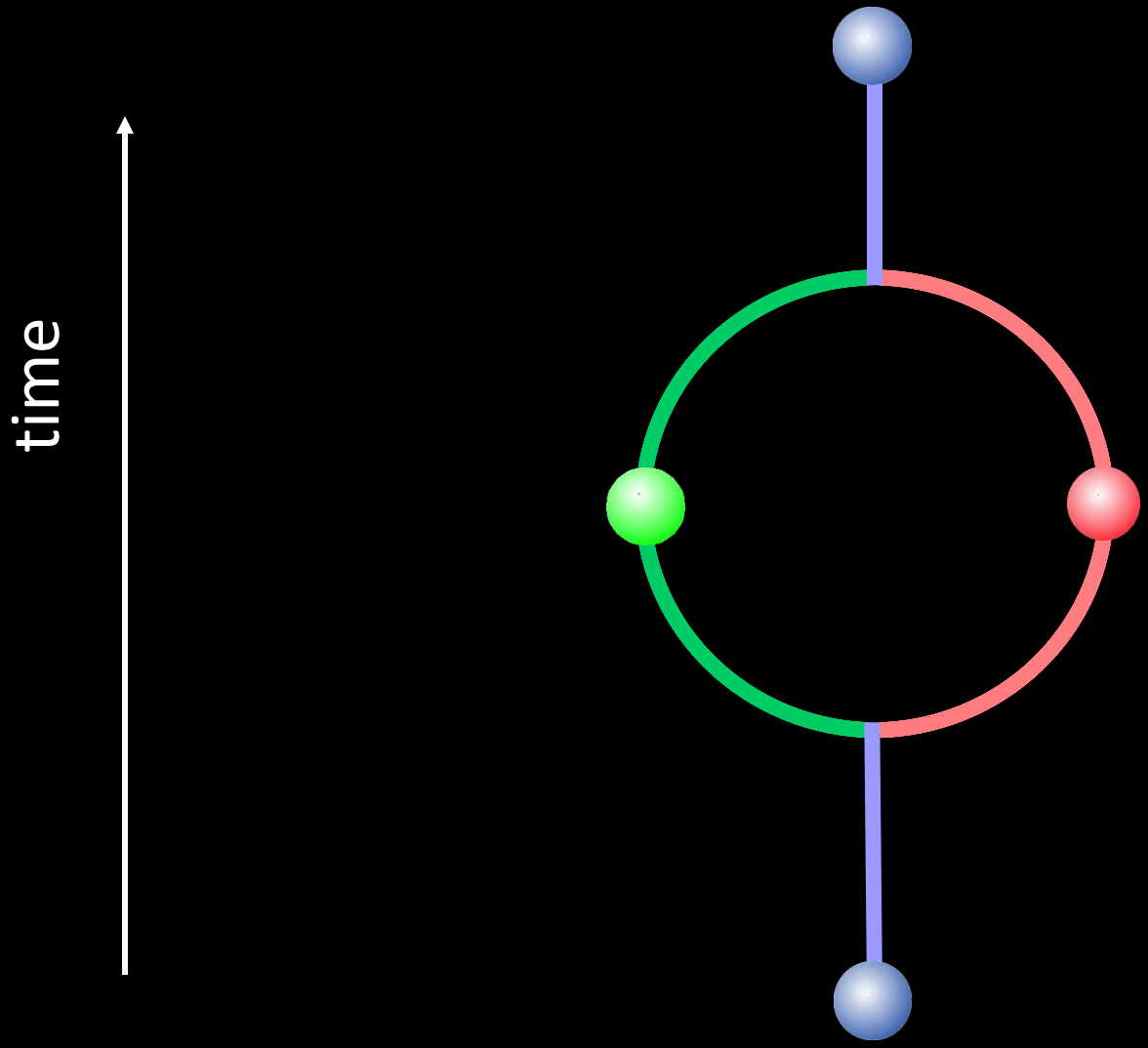
John Wheeler

There is only one electron in the universe!

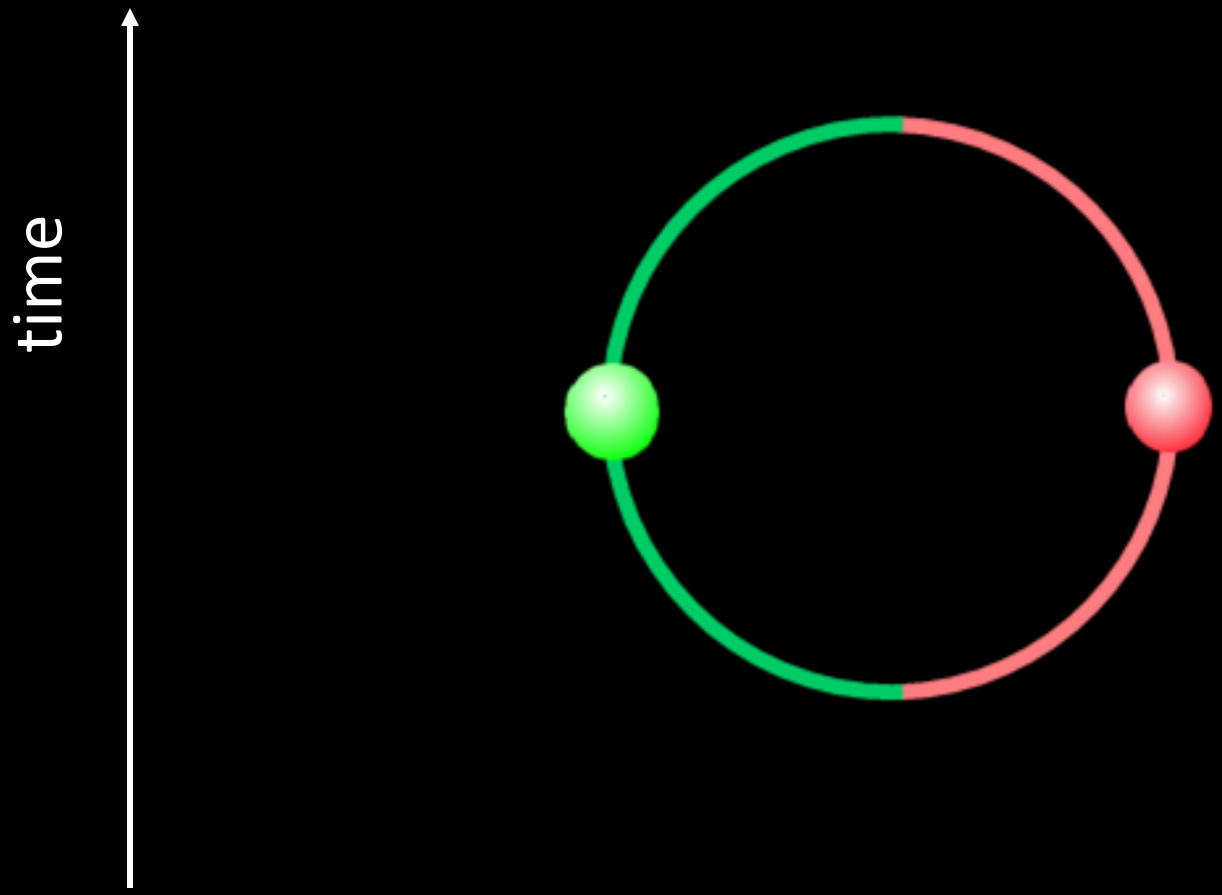
Richard Feynman


Space-Time
tim

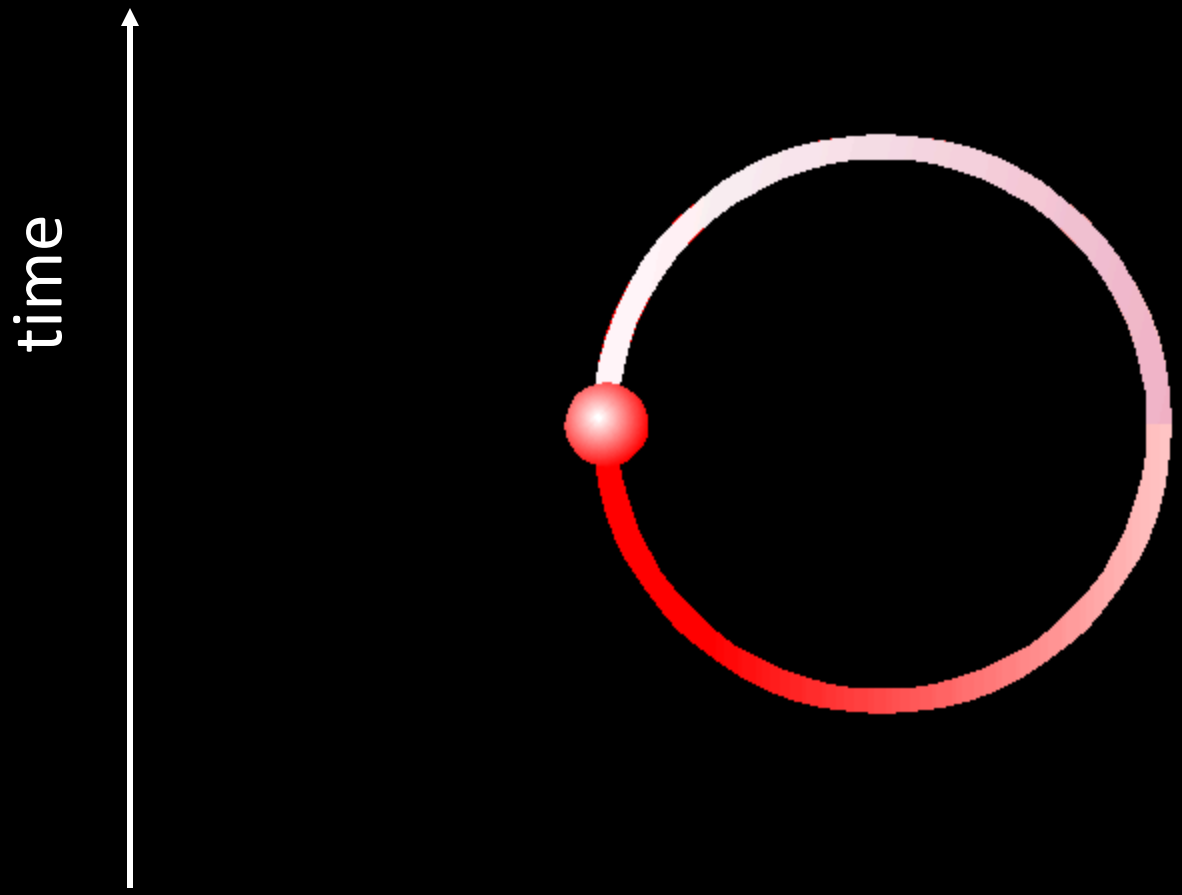
Virtual Particles

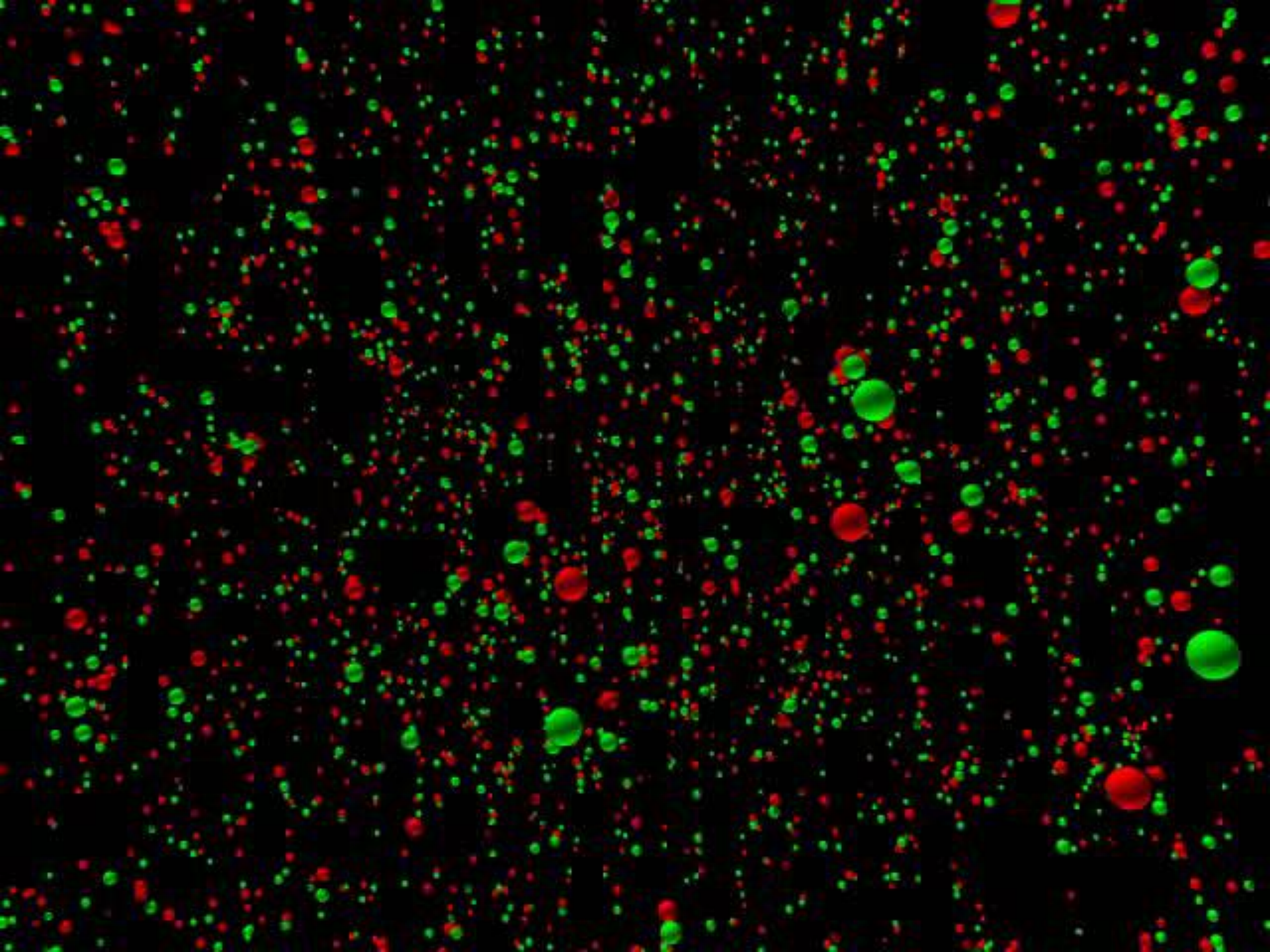


Vacuum Fluctuations

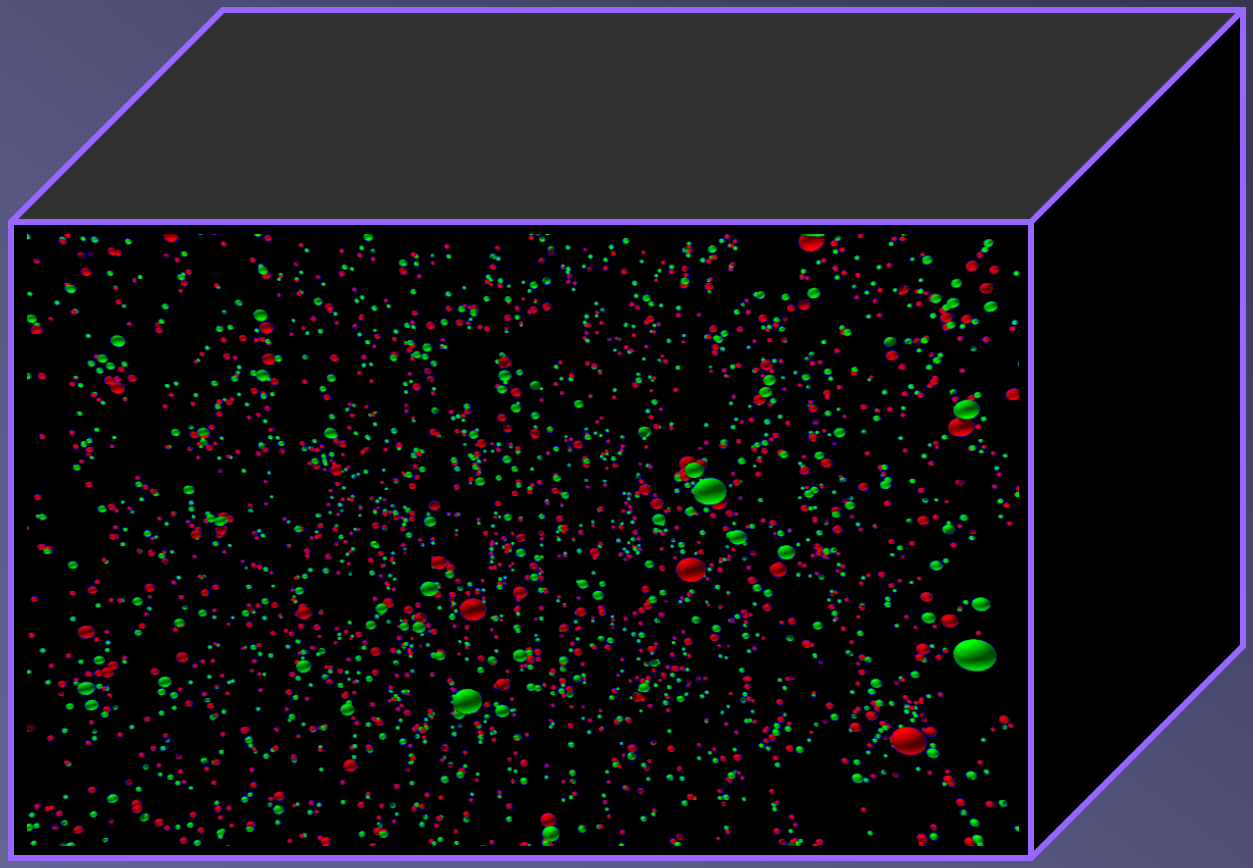


Vacuum Fluctuations

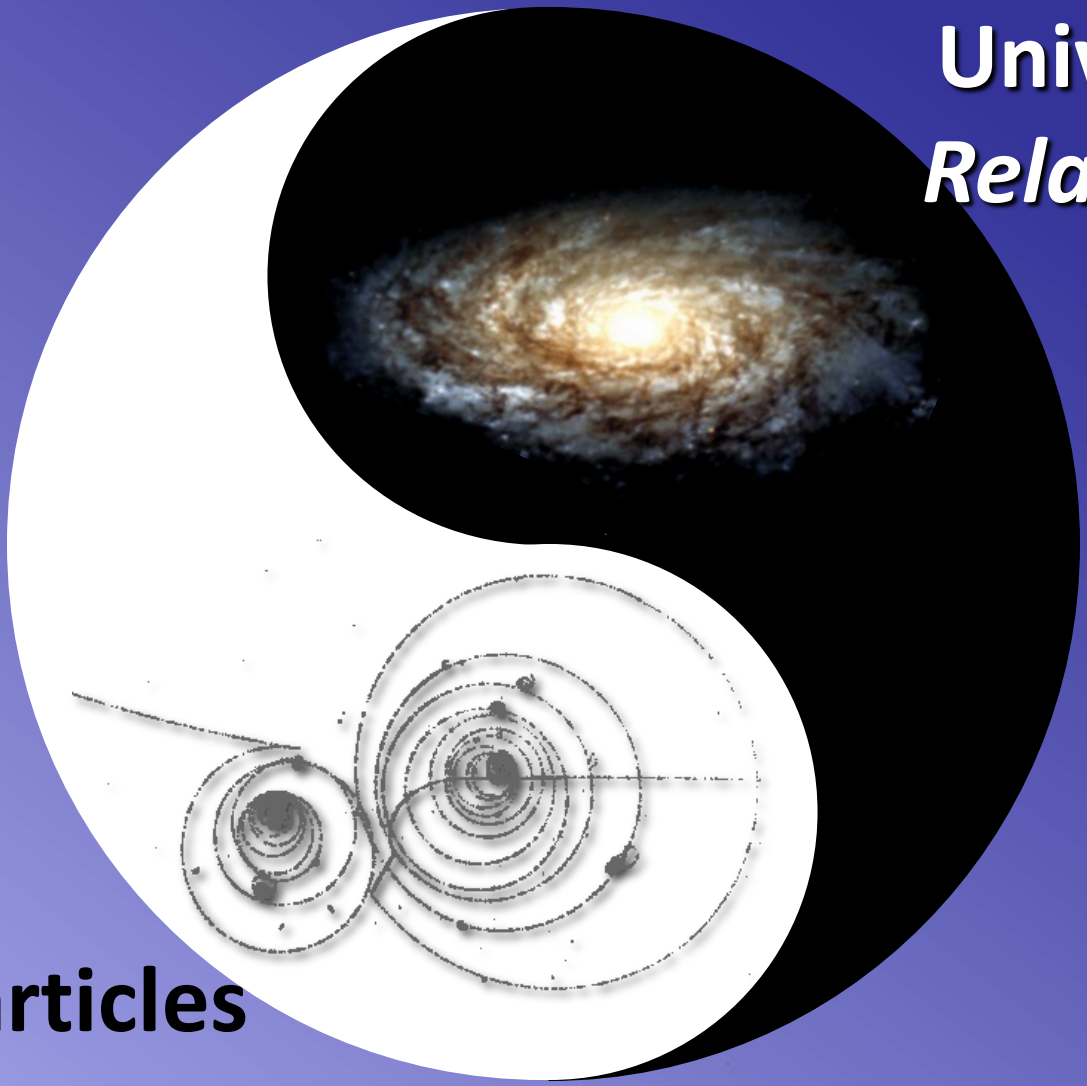




Dark Energy

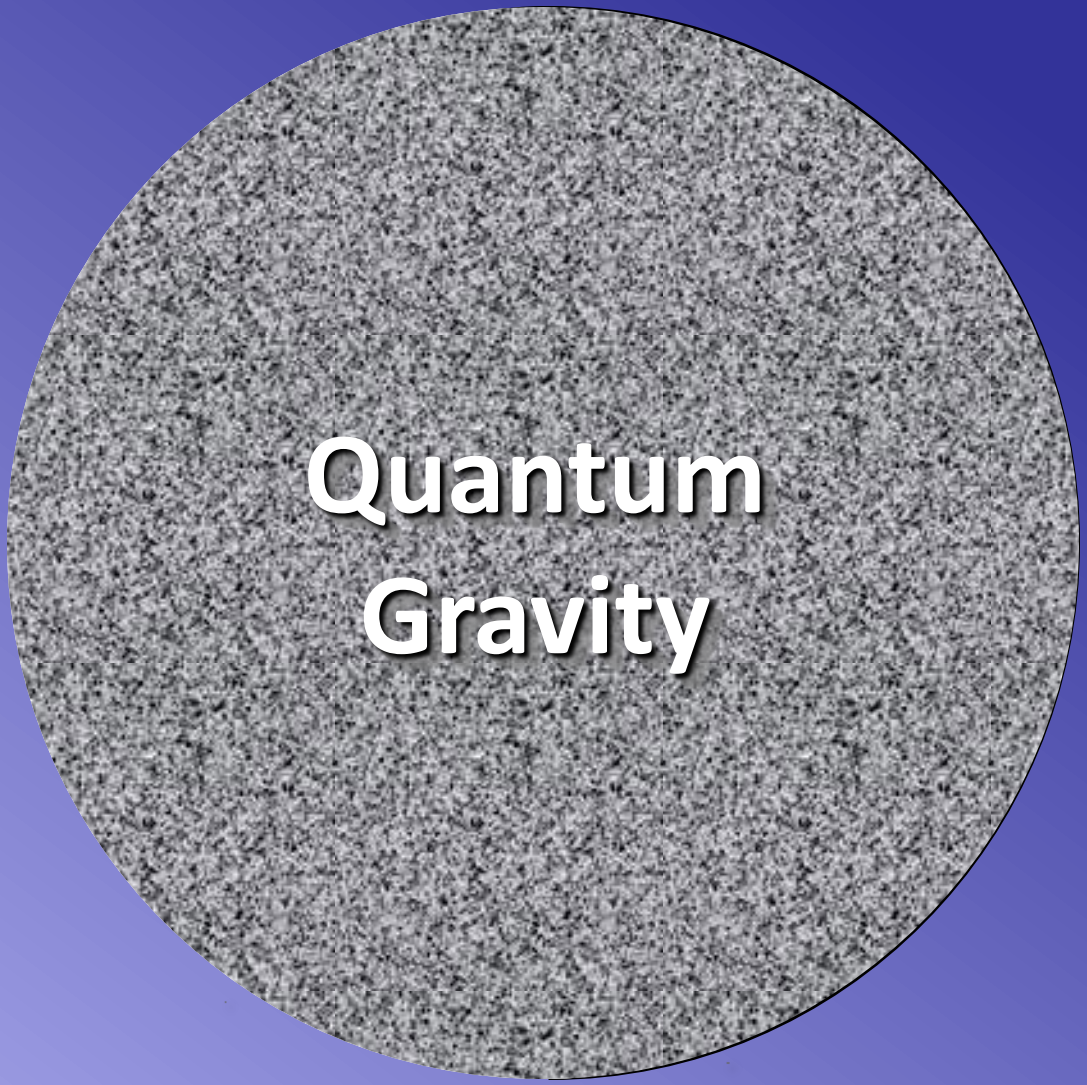


Quantum Space Time

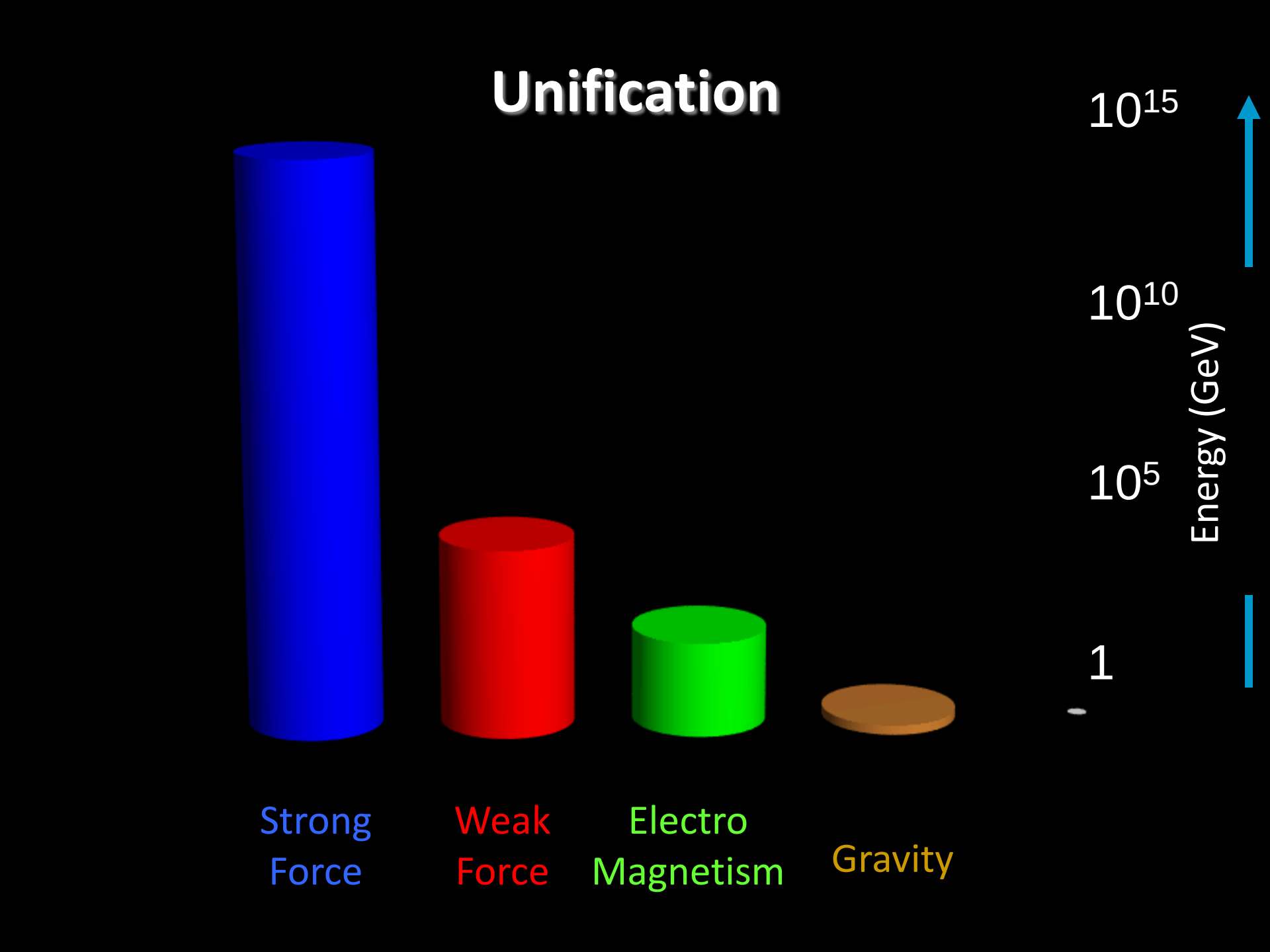


Universe
Relativity

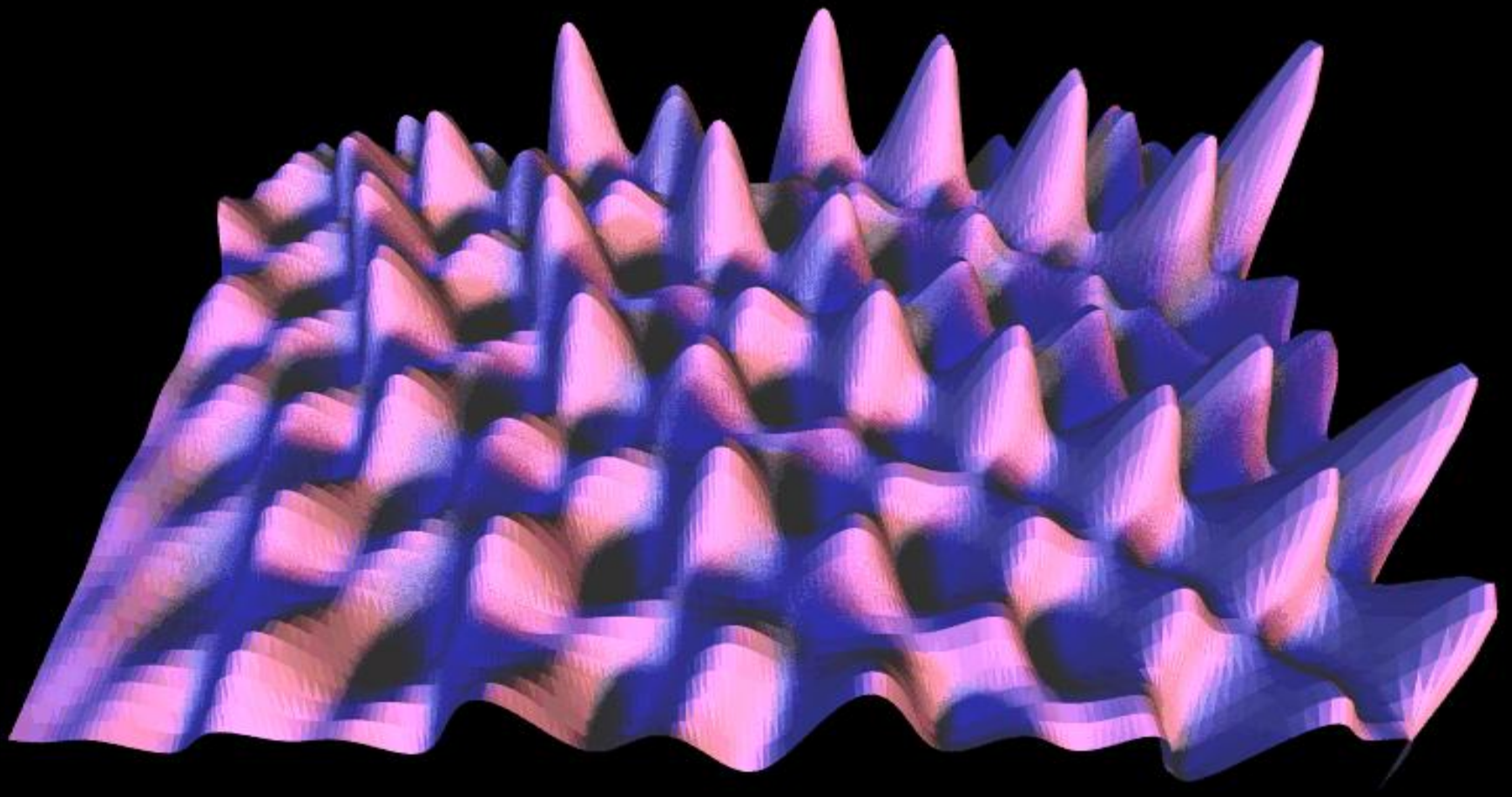
Particles
Quantum


Quantum
Gravity

Unification

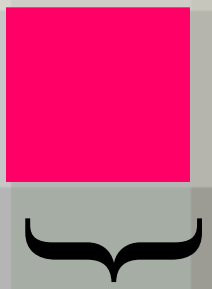


Space Time Foam



Planck length 10^{-35} m

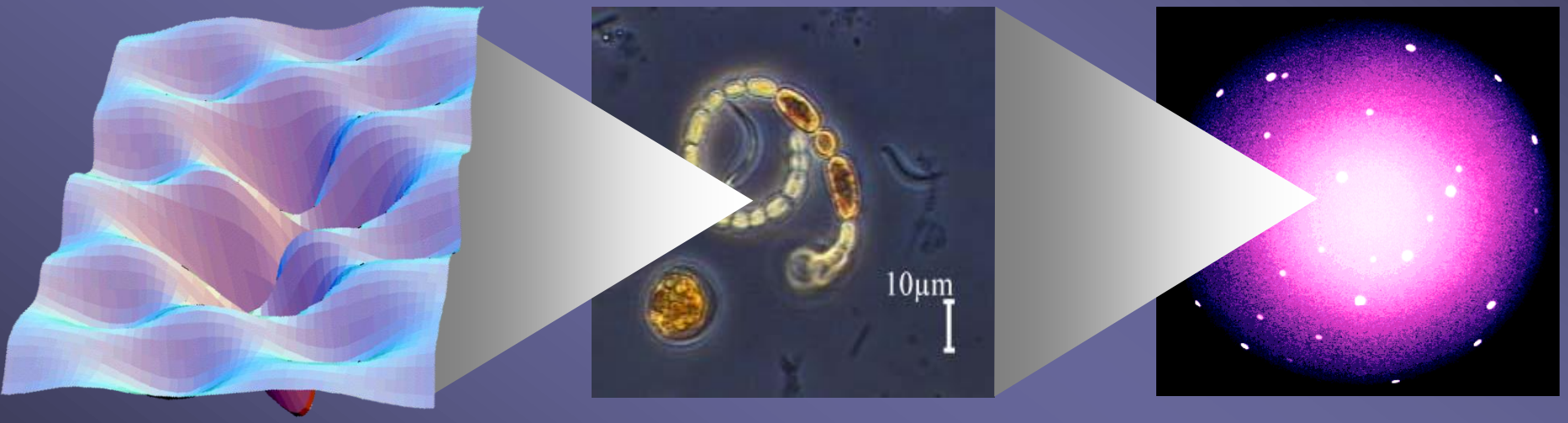

Max Planck



Planck length

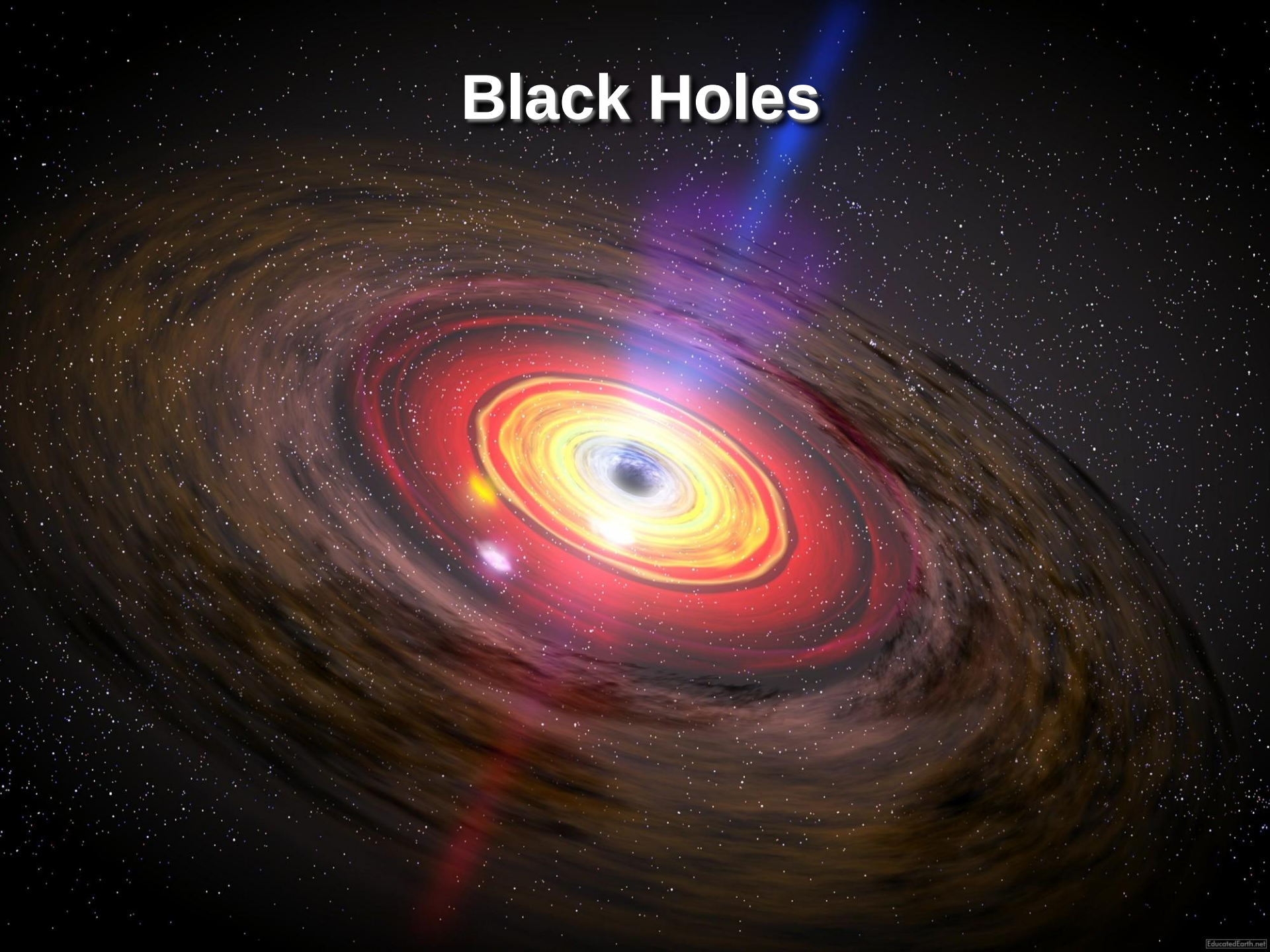
Hierarchy of Scales

$10^{-35}\,m$ $10^{-5}\,m$ $10^{25}\,m$

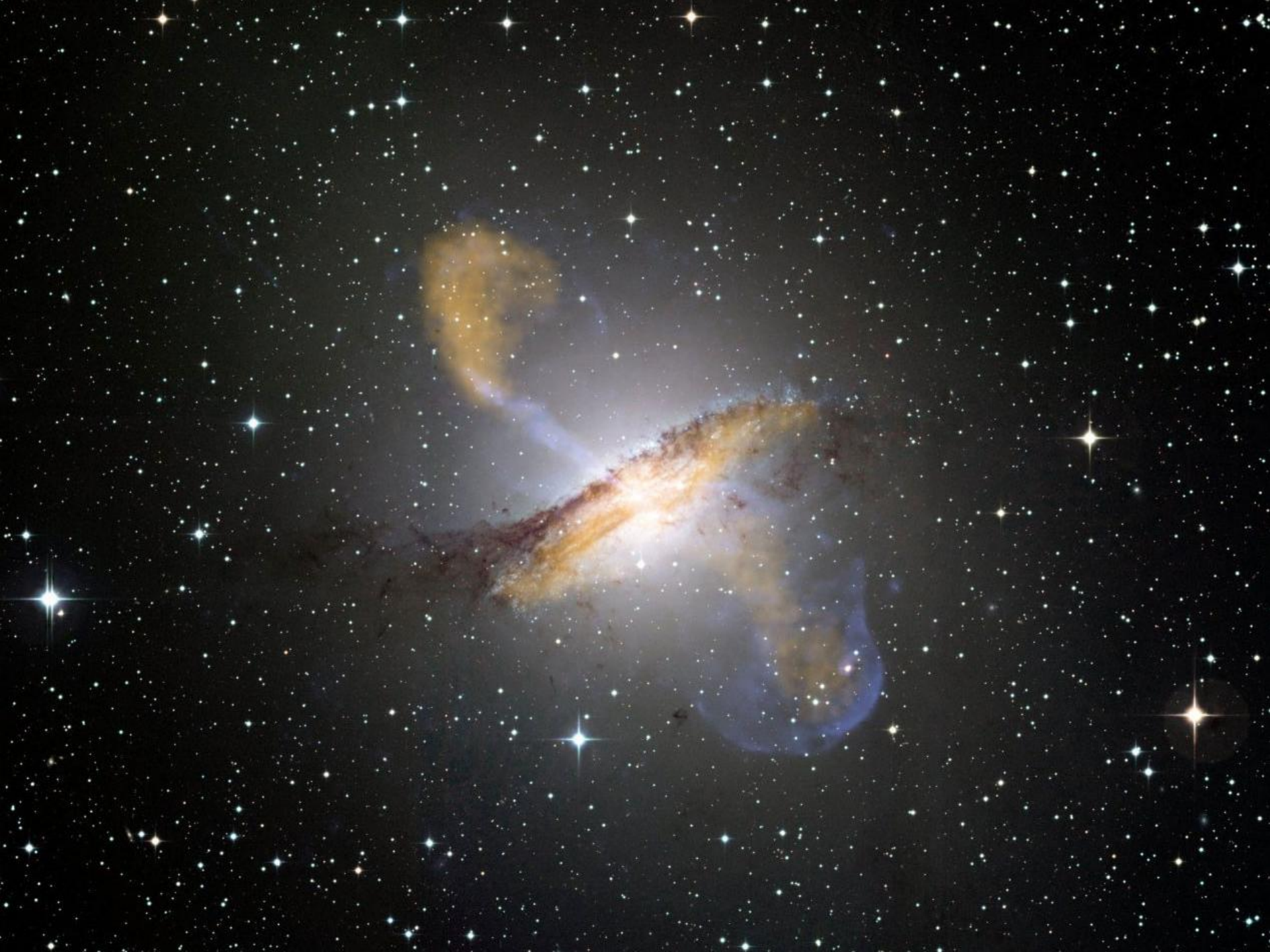


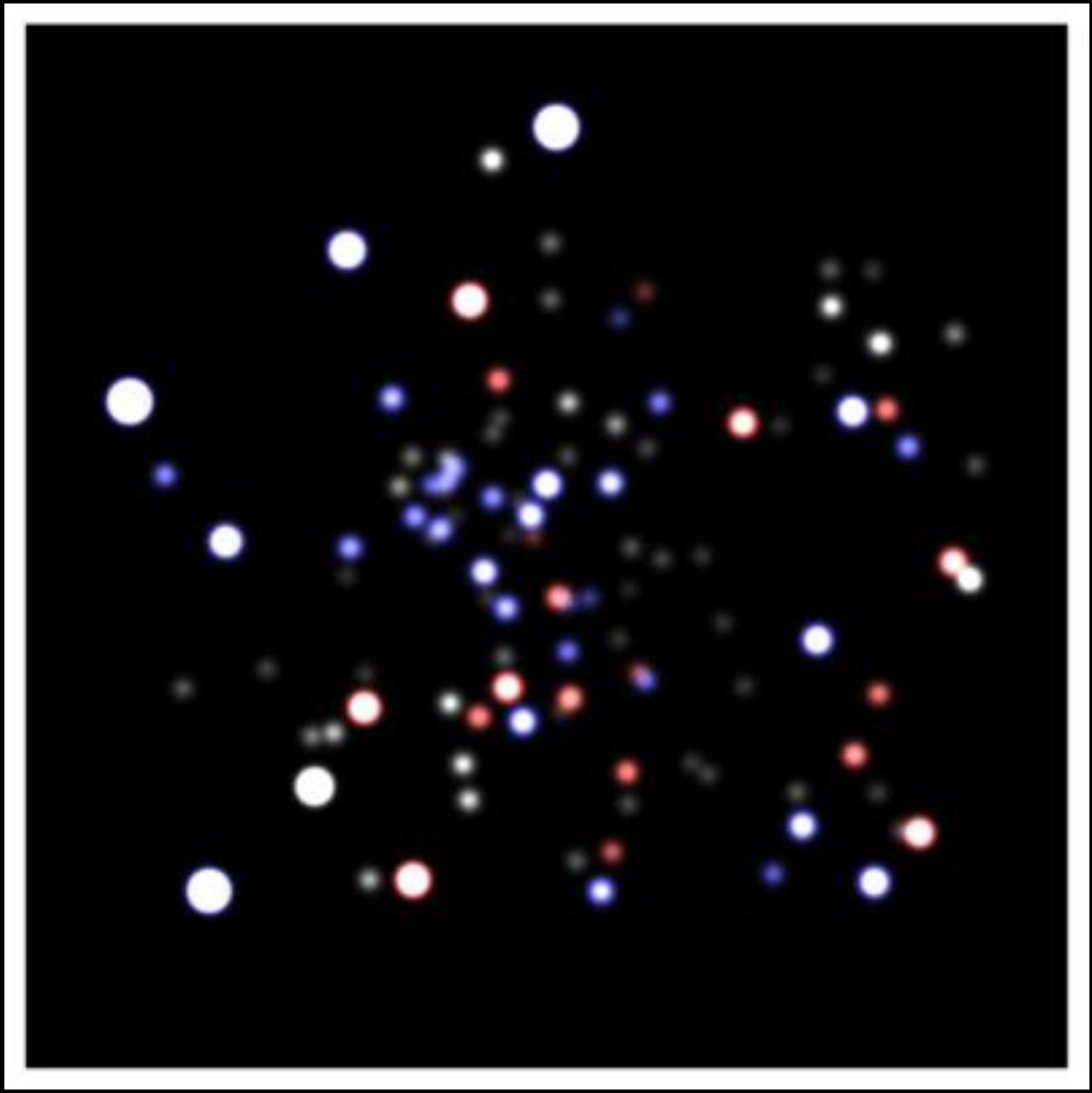
Planck Scale **“Life”** **Hubble Scale**

Black Holes

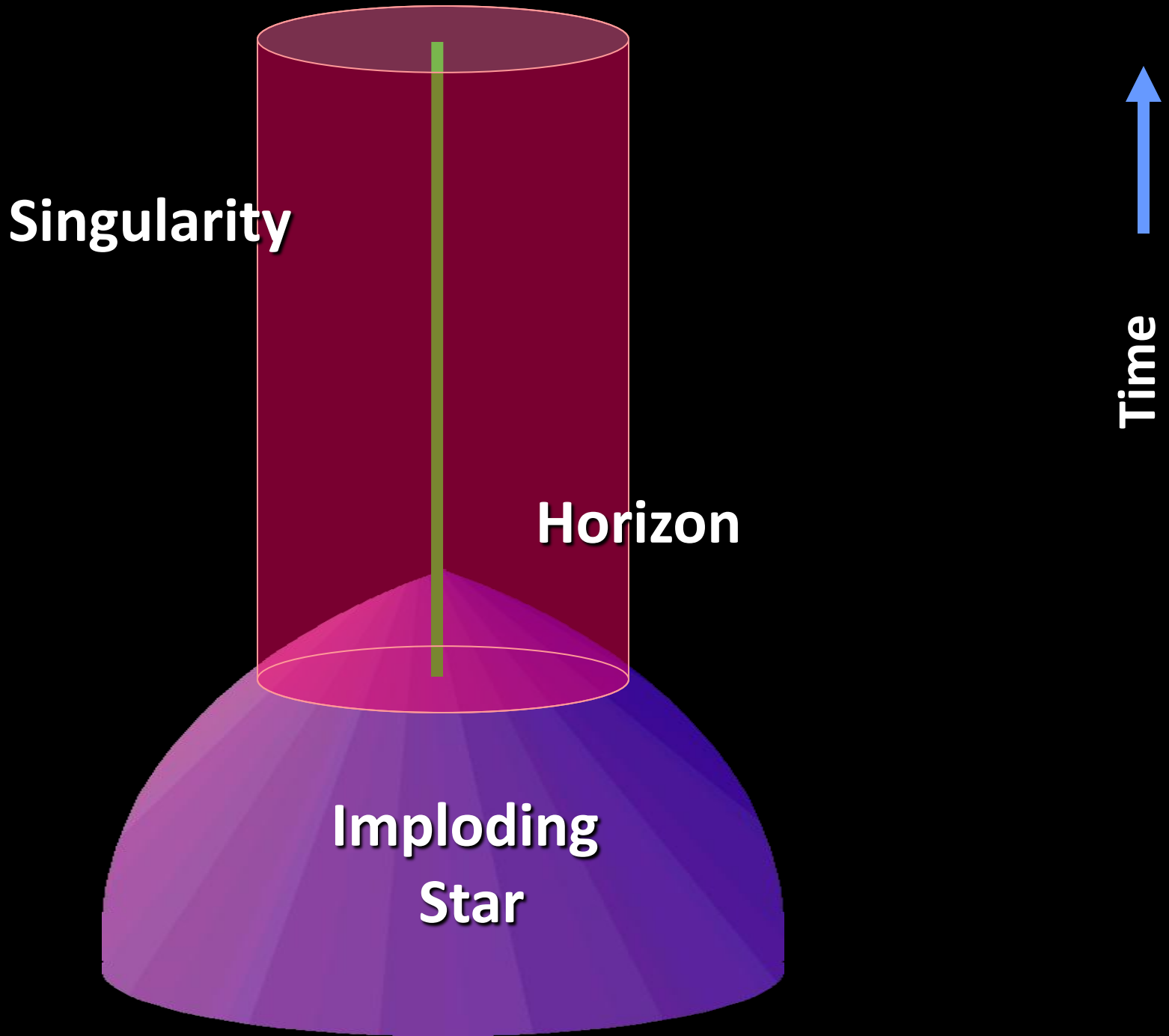


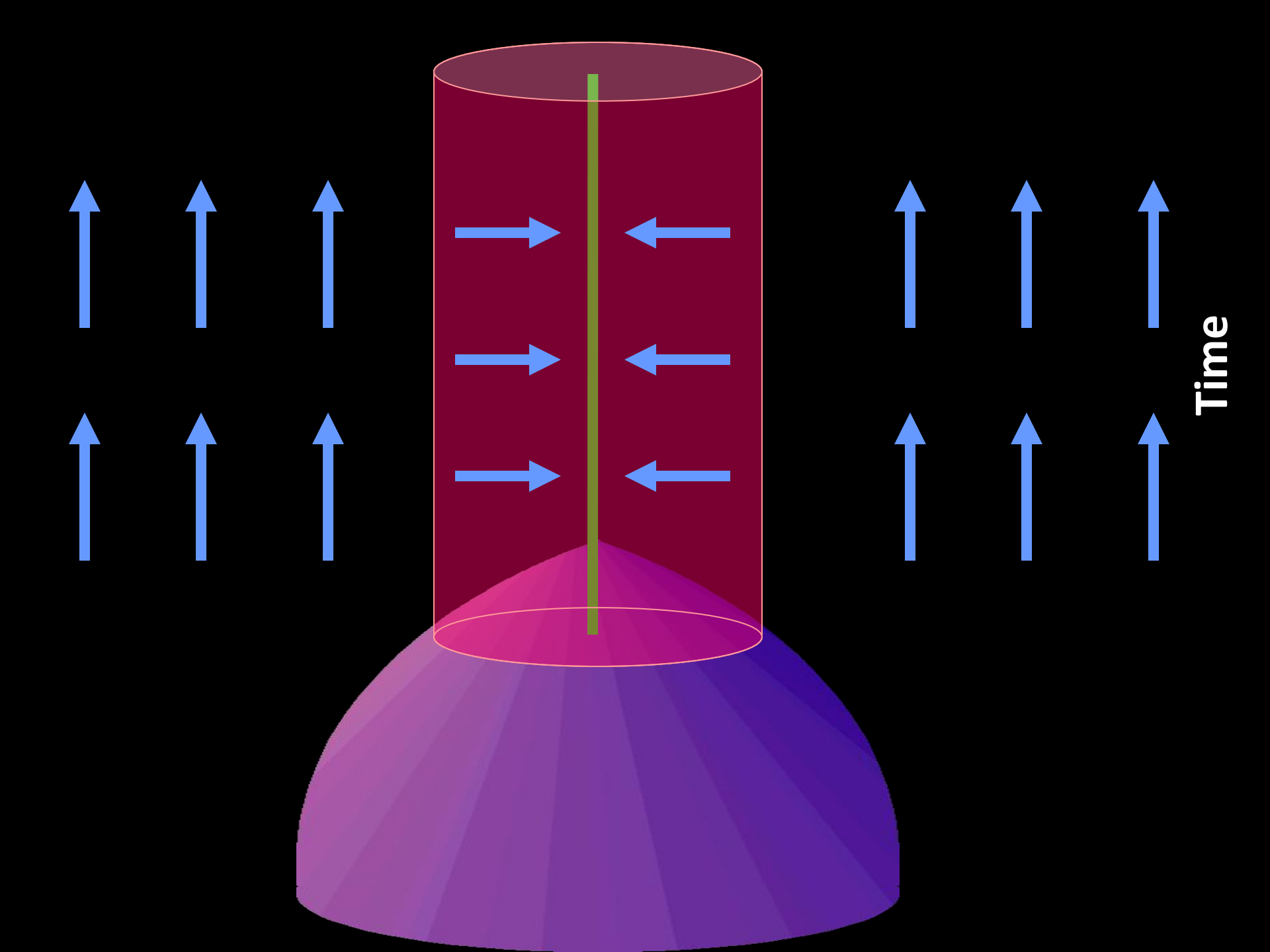
Galactic Black Hole
Million of Suns





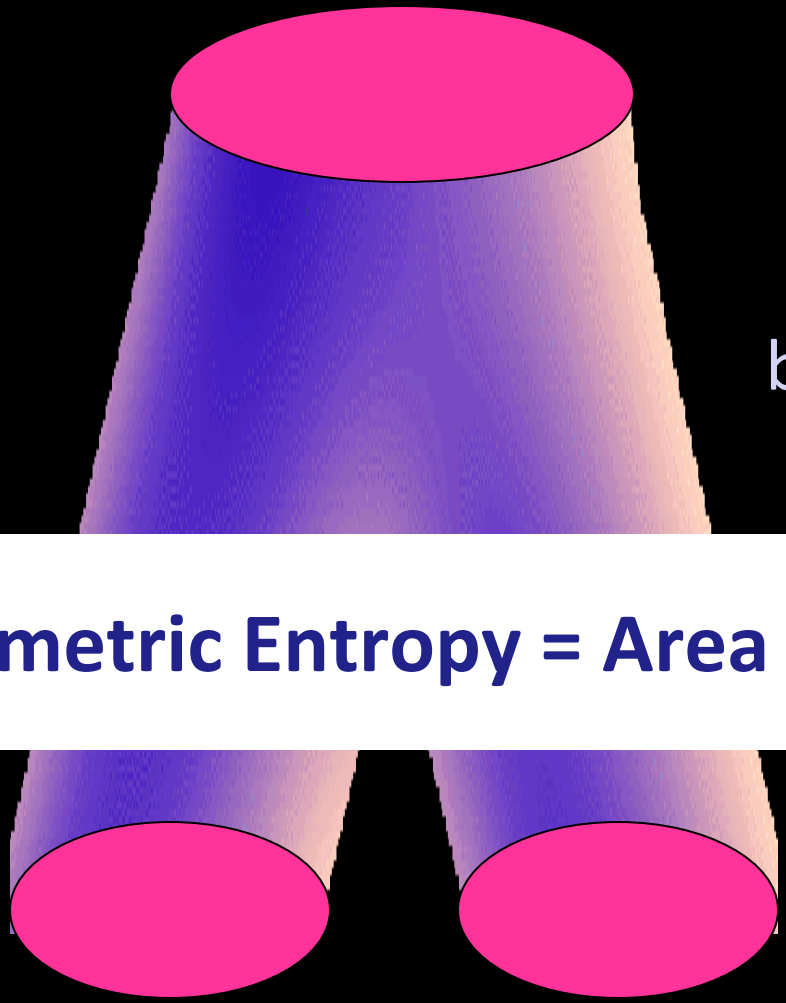
Center of the Galaxy


Singularity
Horizon
Imploding
Star
Time


Time

2nd Law Black Hole Thermodynamics

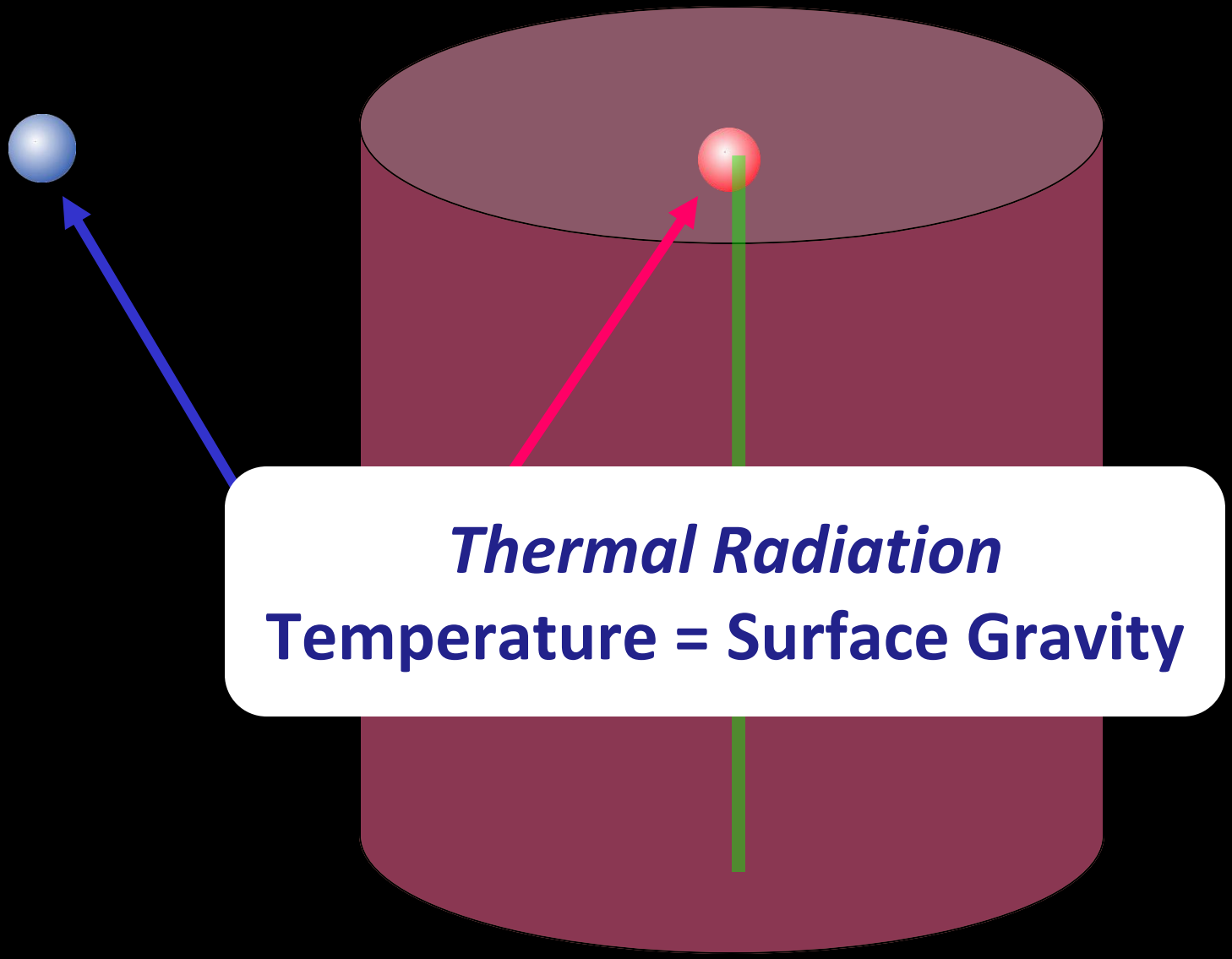
$$A \geq A_1 + A_2$$



black hole merger

Geometric Entropy = Area Horizon

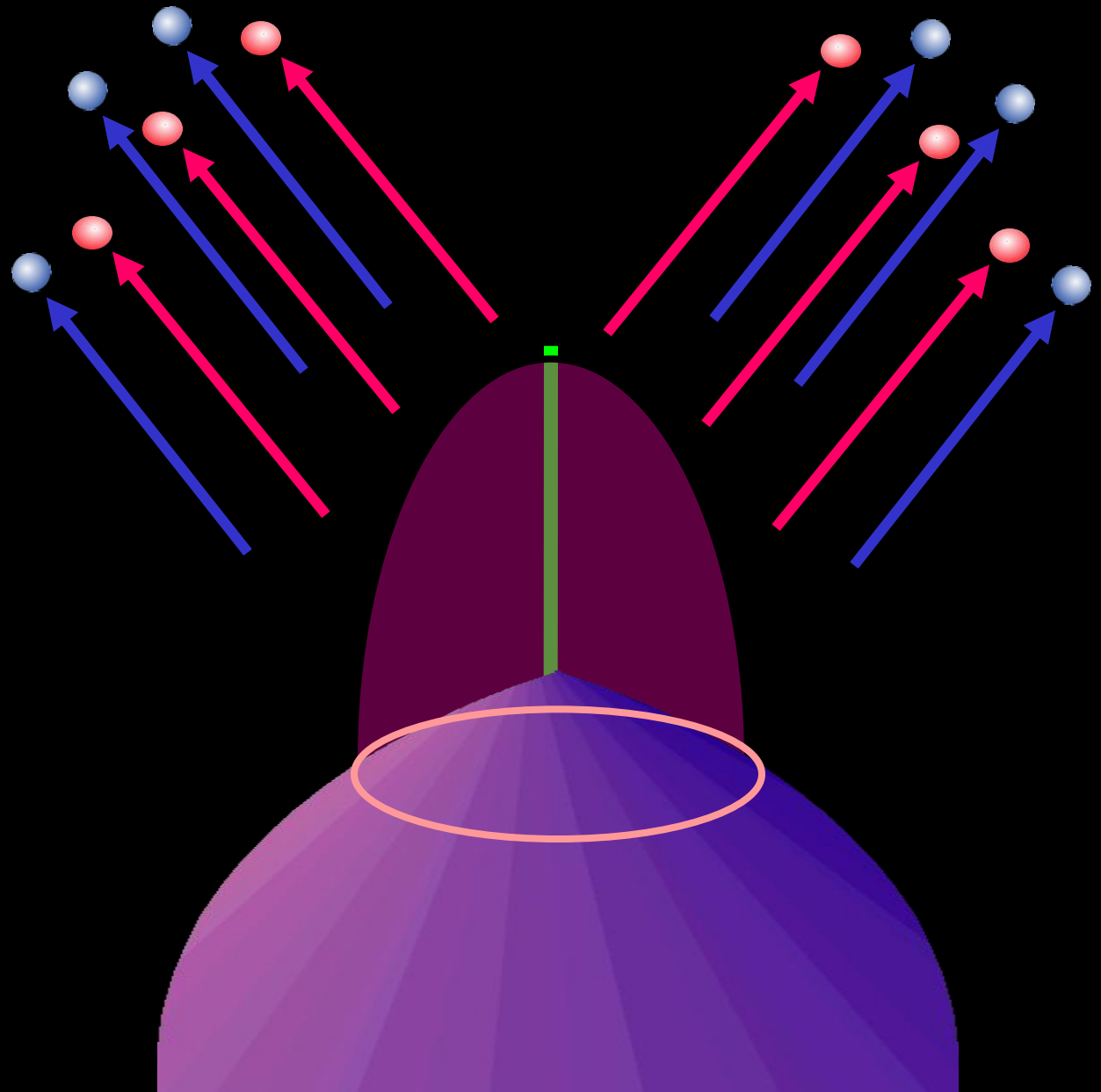
Hawking Radiation



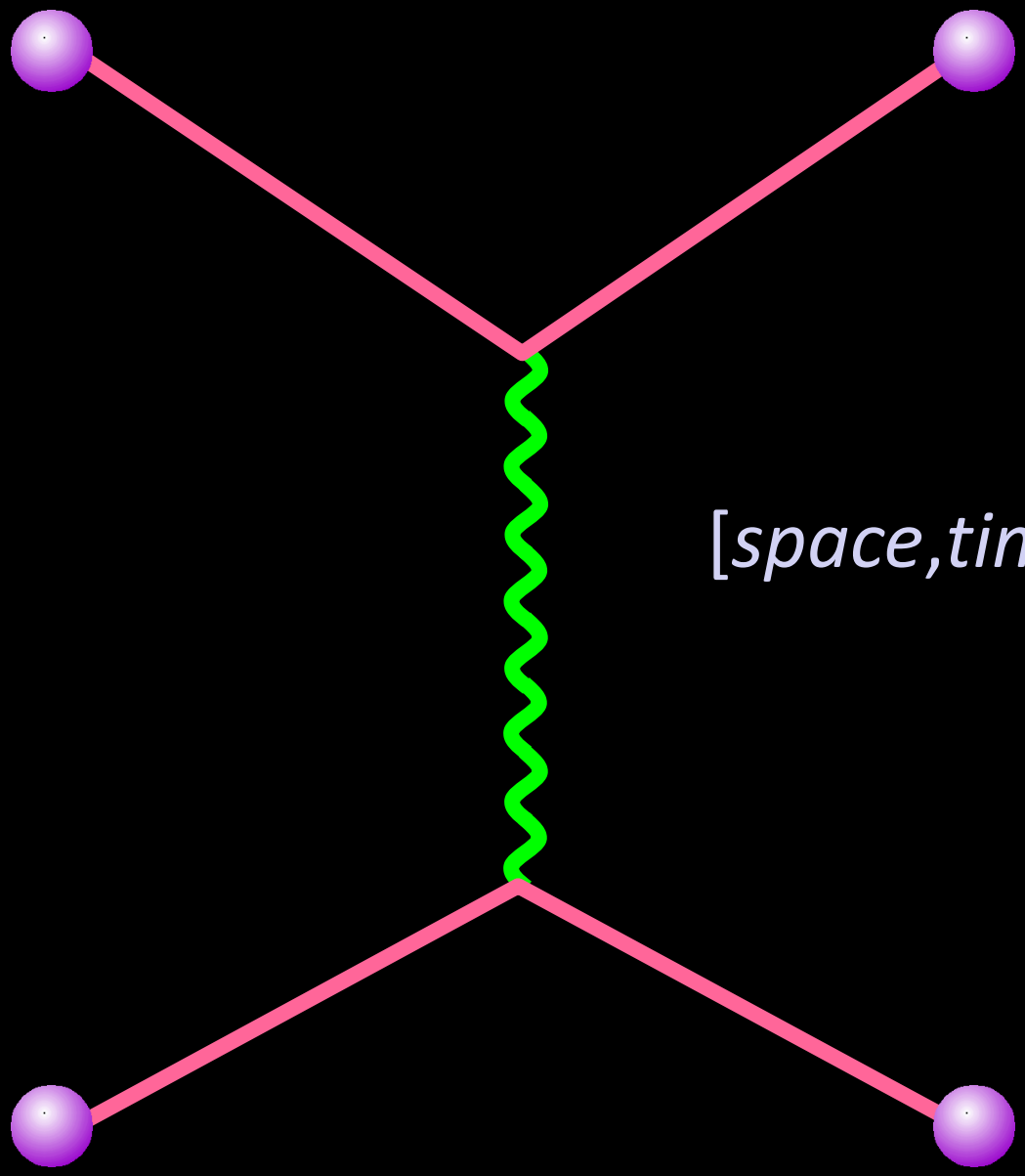
Thermal Radiation

Temperature = Surface Gravity

“Evaporating” Black Holes



Quantum Black Hole ≈ Instable Particle



[*space*,*time*] ≠ 0

“It from bit”

Geometric Entropy

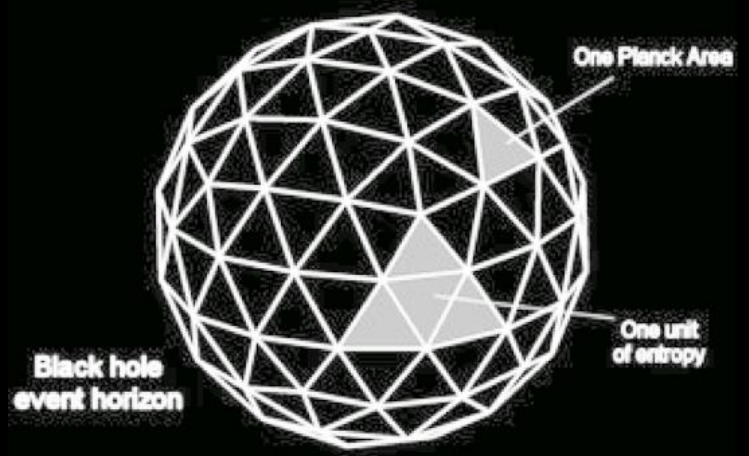
S = ¼ Area Horizon

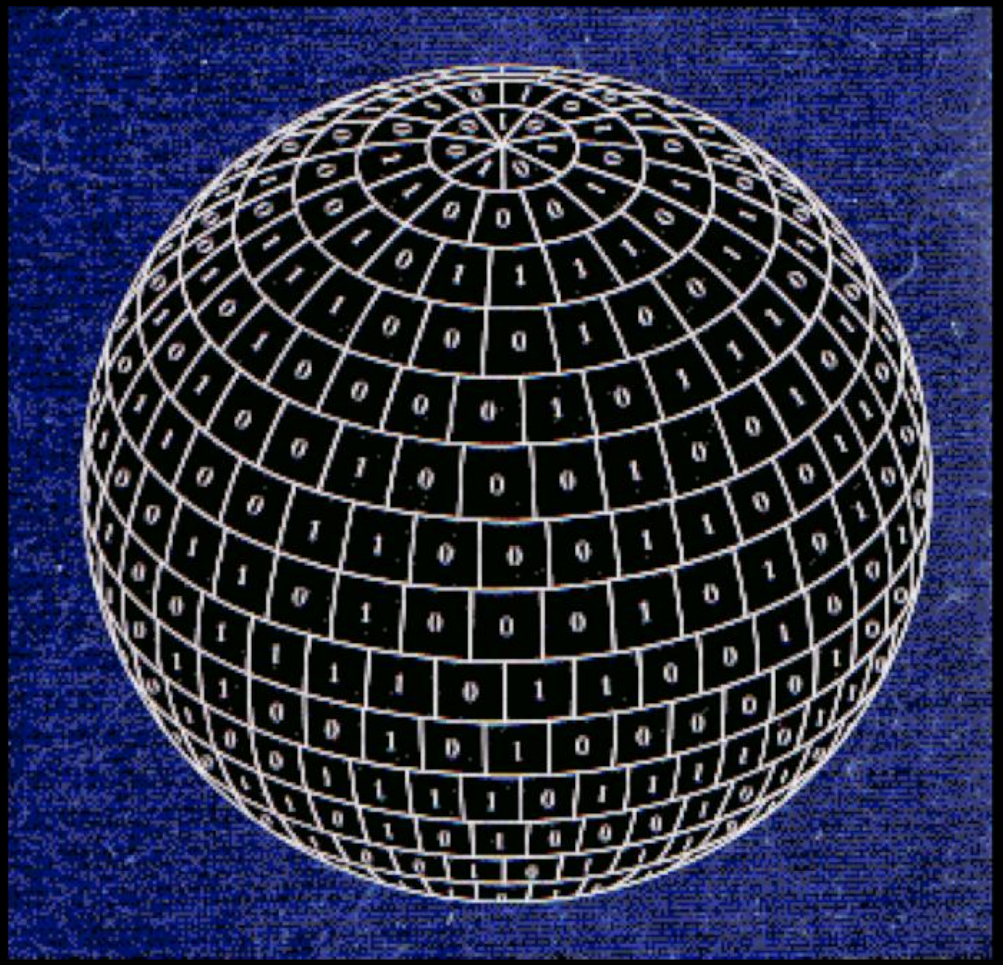
= log(# quantum states)

$1\ \text{bit}/\ell^2_{Planck}$

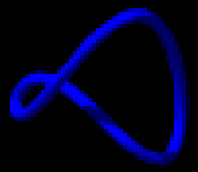
The Holographic principle

The information associated with a certain part of space may be (heuristically) represented as bits on the surface surrounding it.

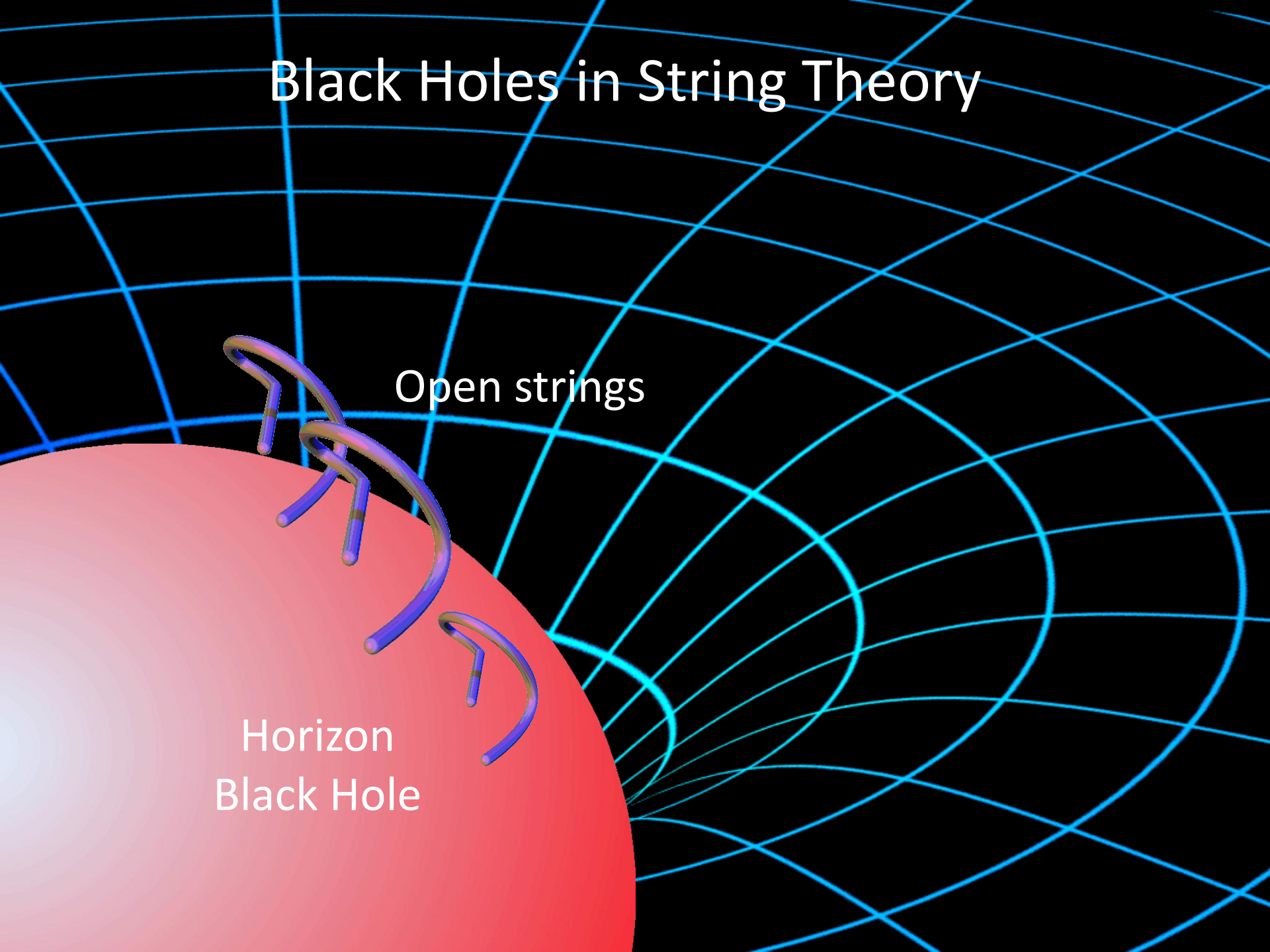




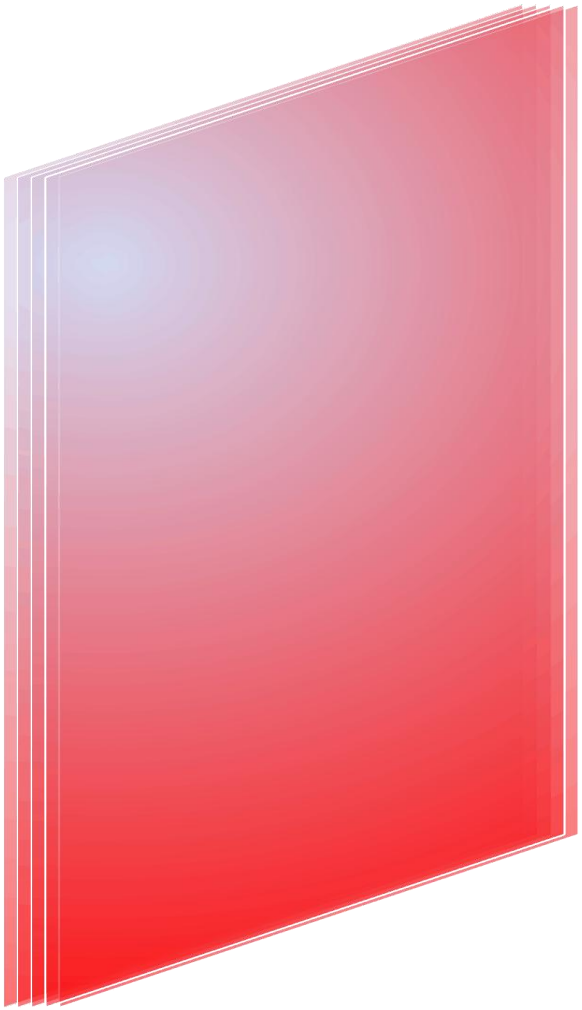
String Theory



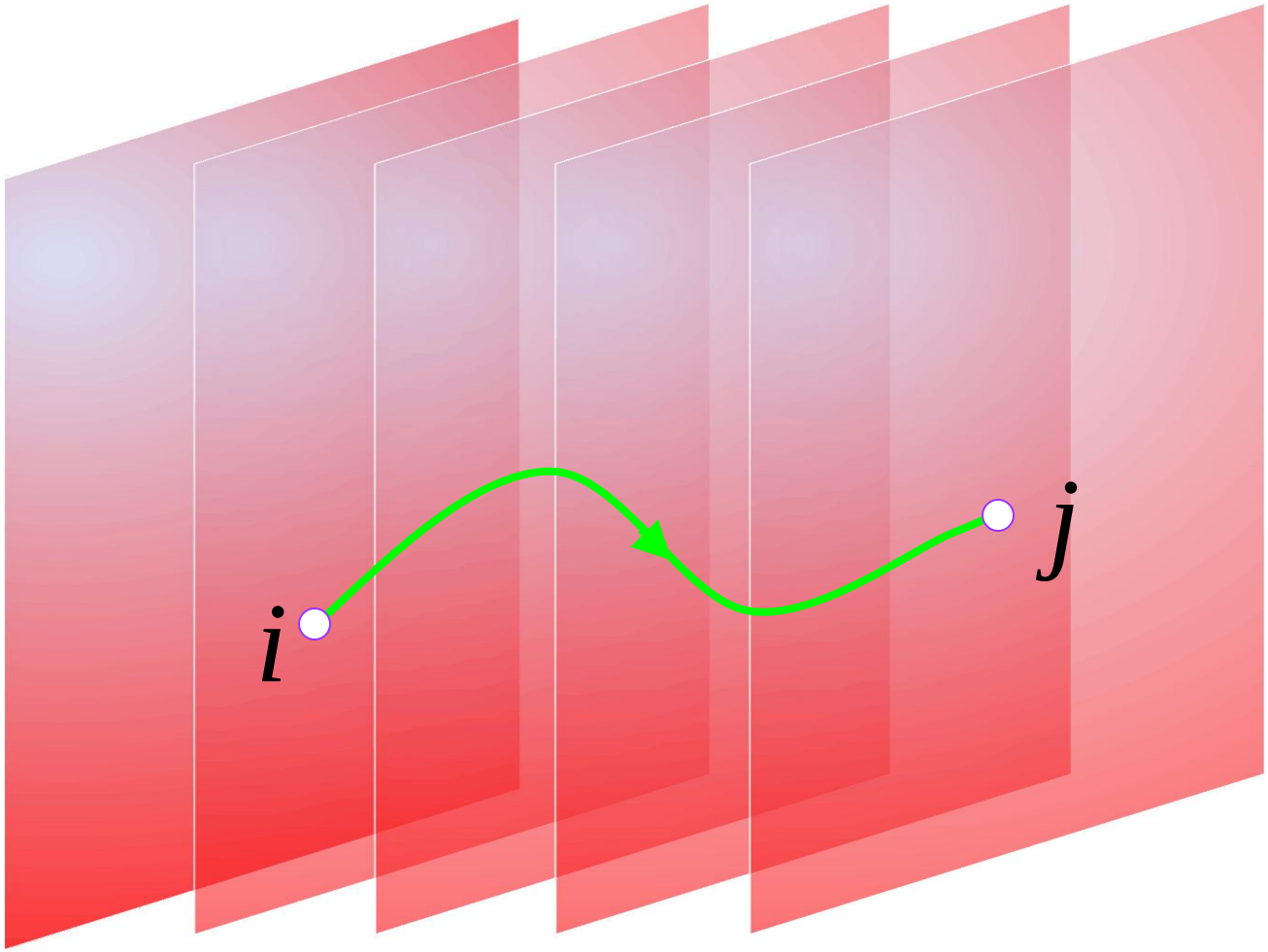
Black Holes in String Theory



Open Strings: Yang-Mills Gauge Theory



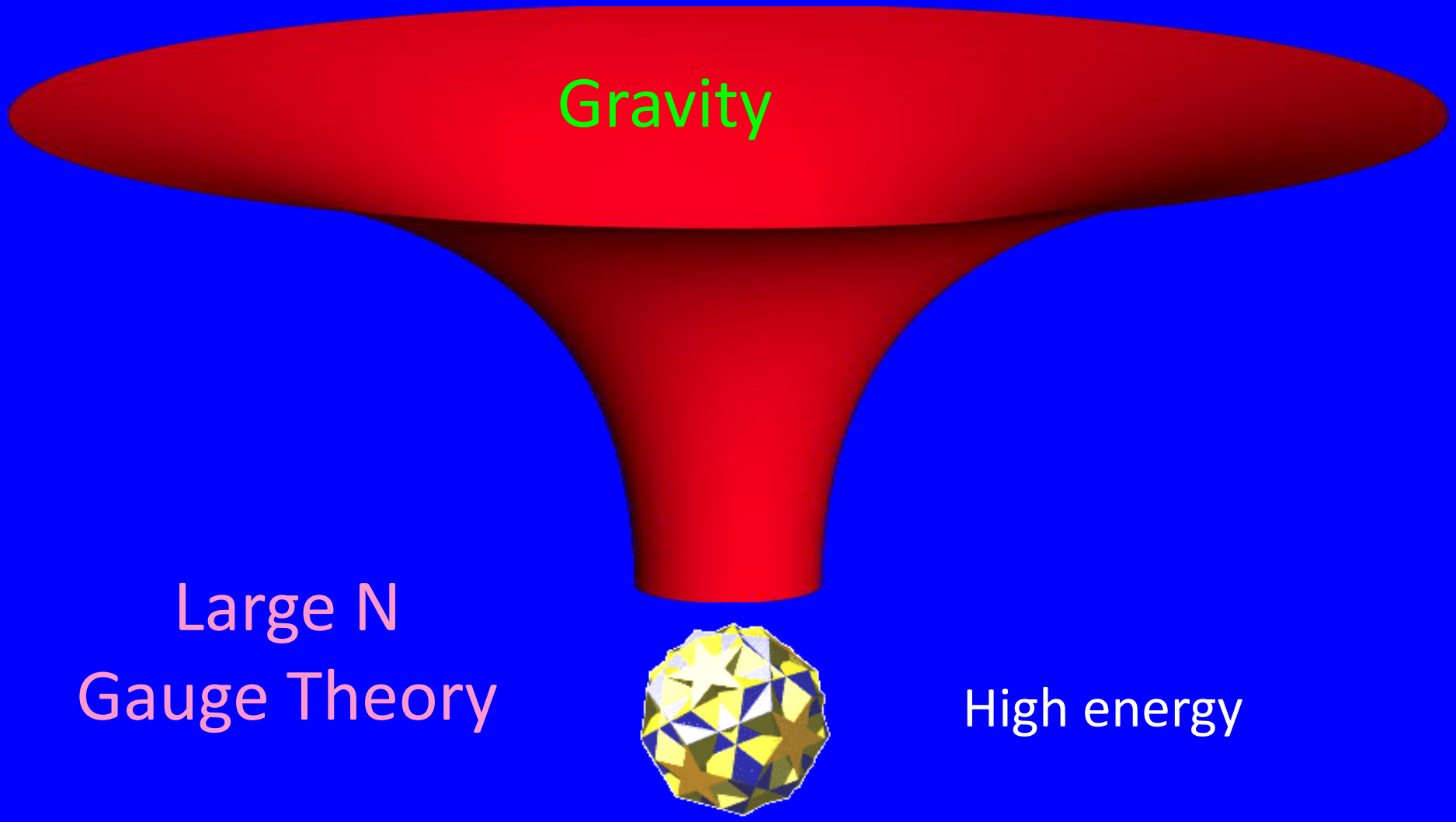
Open Strings: Yang-Mills Gauge Theory



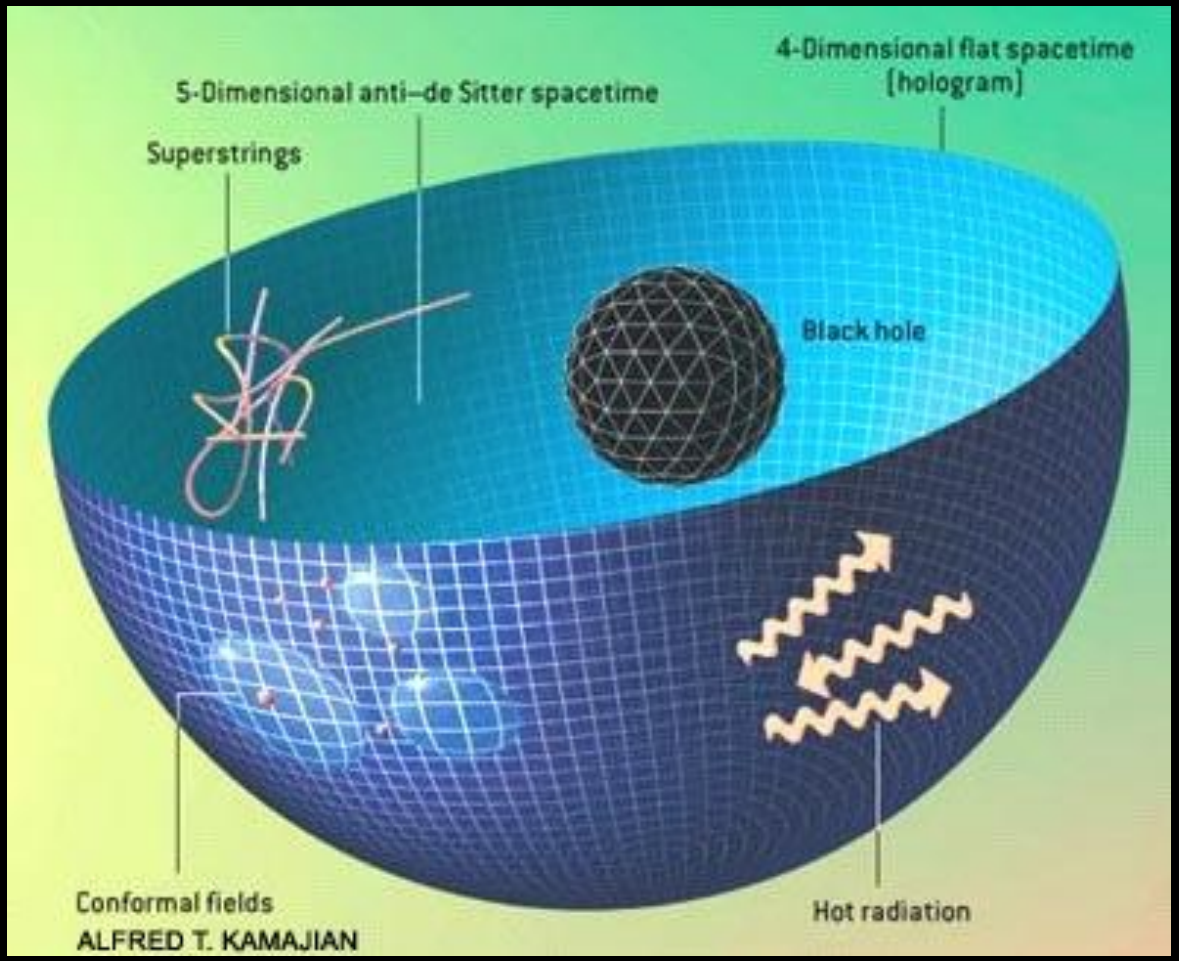
$N \times N$ matrix of strings A_{ij}

Geometry is "Emergent"

Low energy



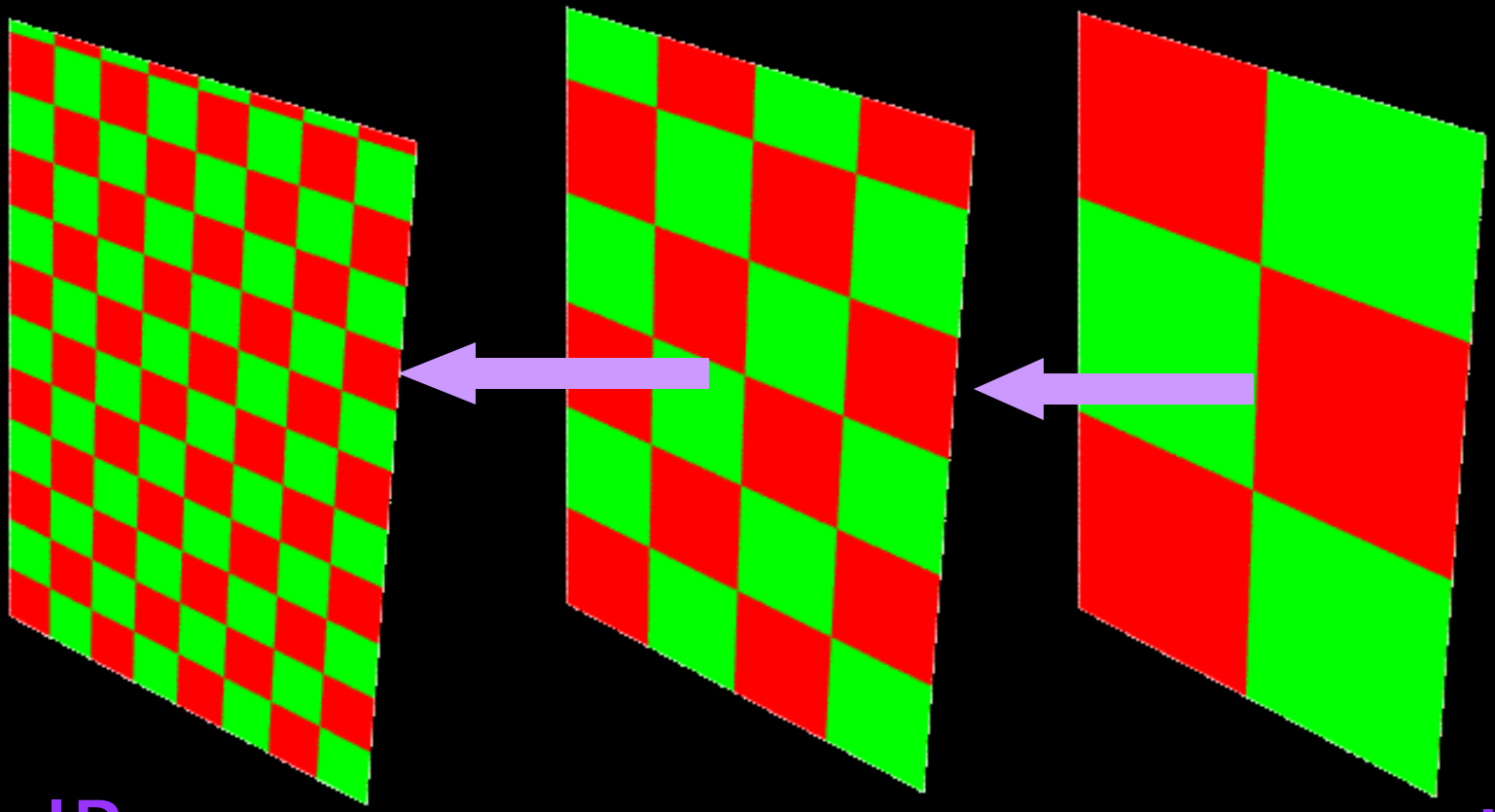
ADS/CFT Correspondence



Equivalence between field theory on the "boundary" and gravity in the "bulk"

Holography

Emergent Space Dimension



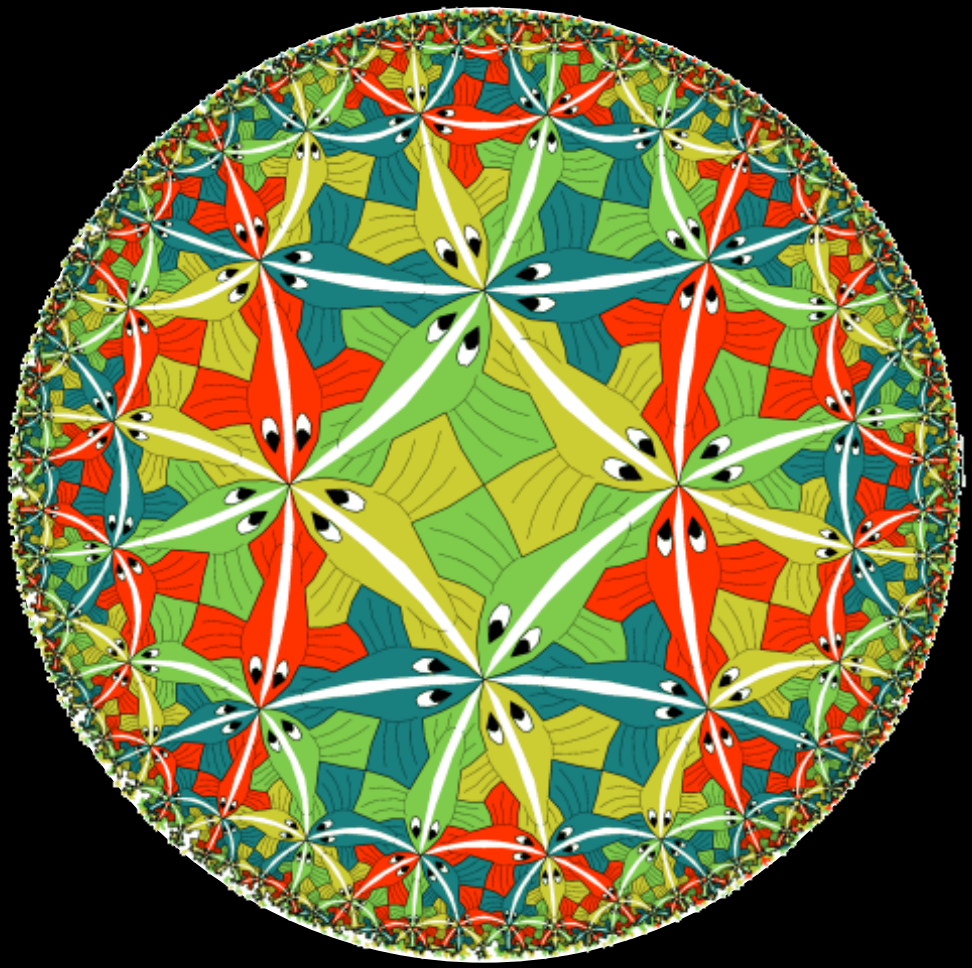
IR

UV

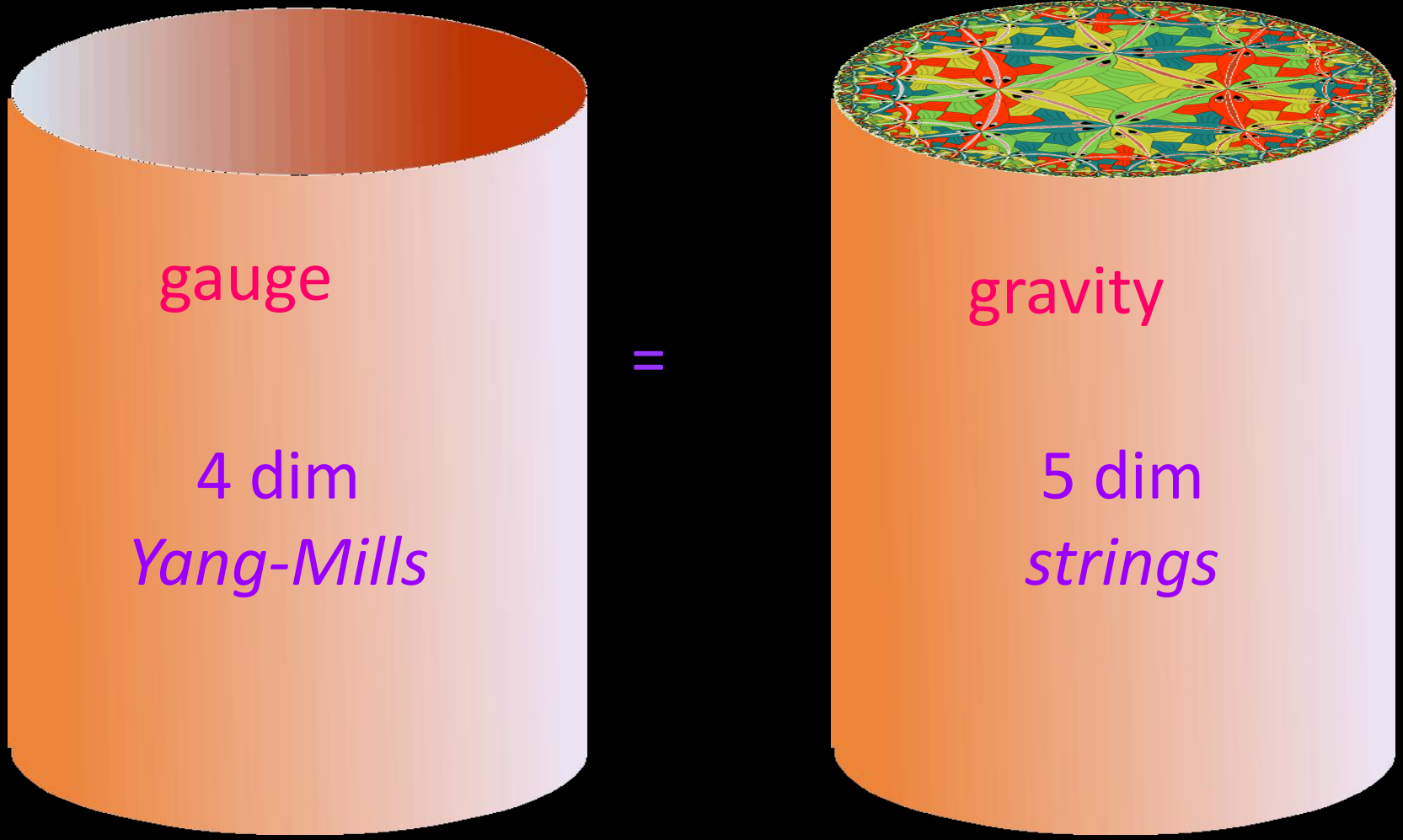
radial distance = energy scale

Renormalization Group Flow

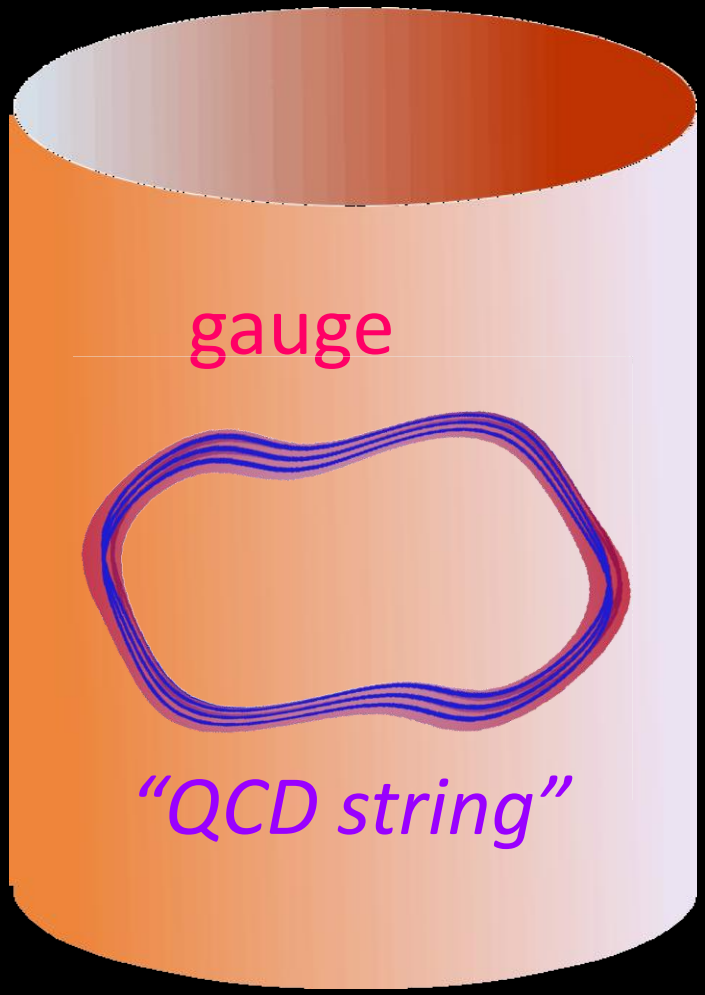
Strings in Anti-de Sitter Space



Gauge/Gravity Duality



Strings



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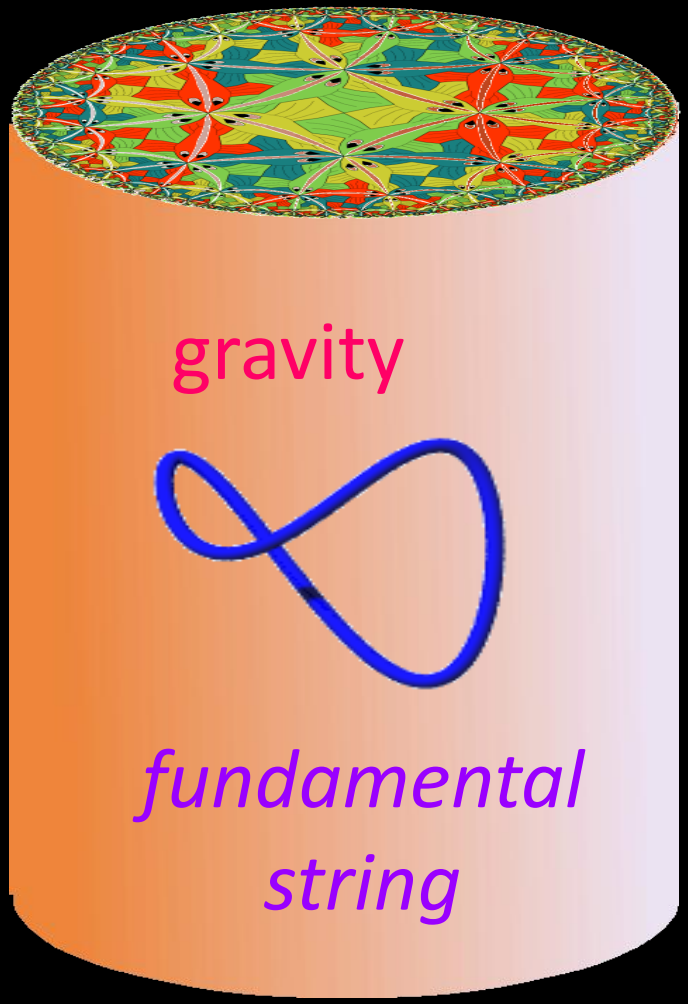
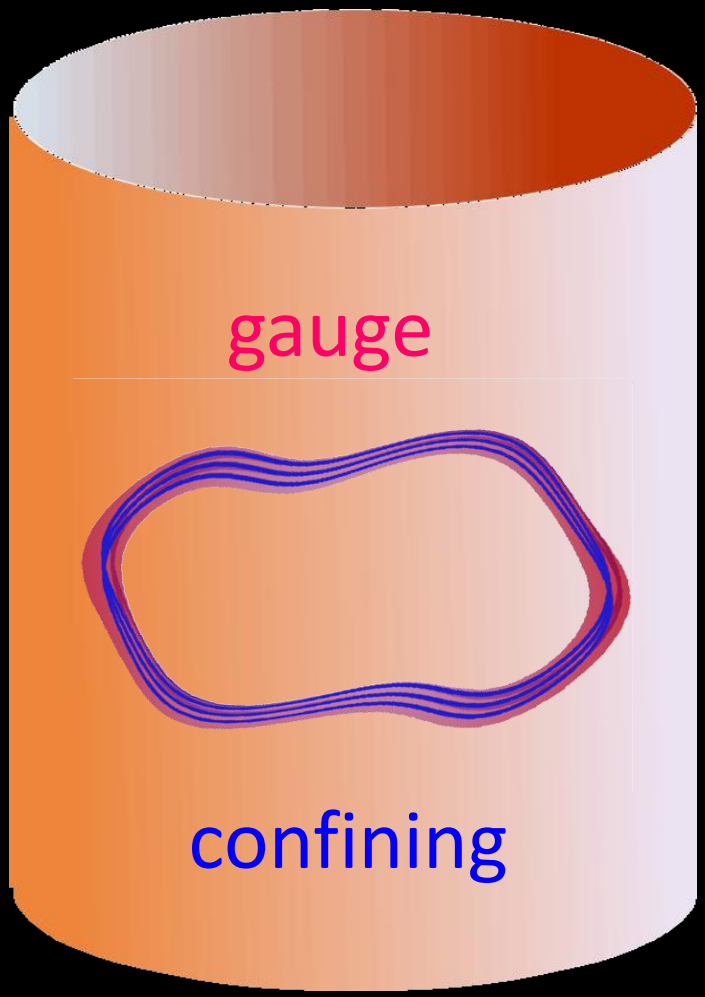


Low Temperature



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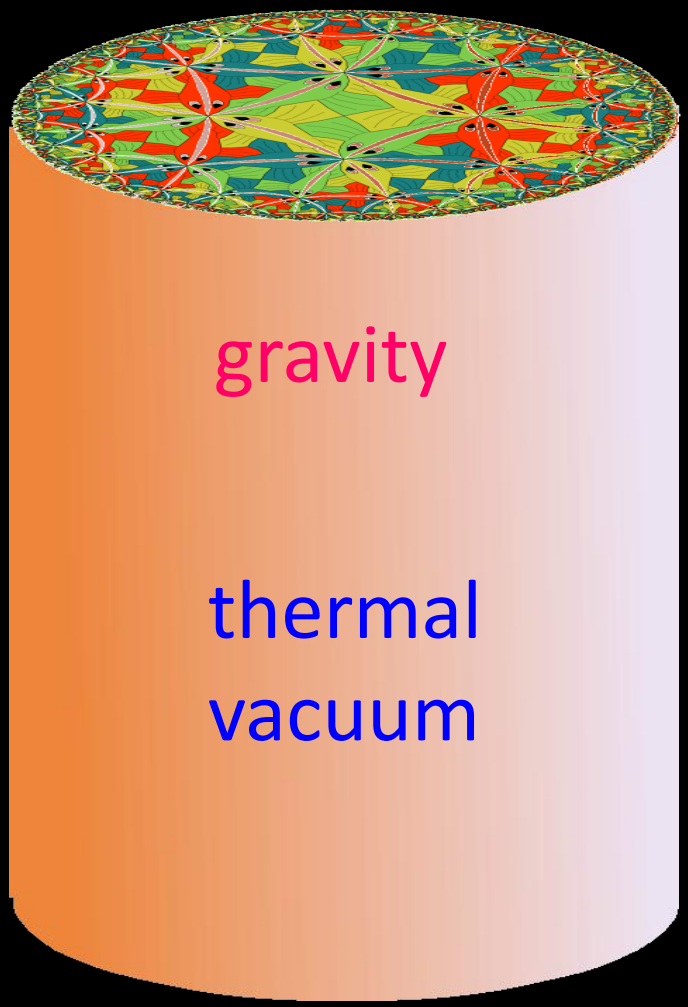
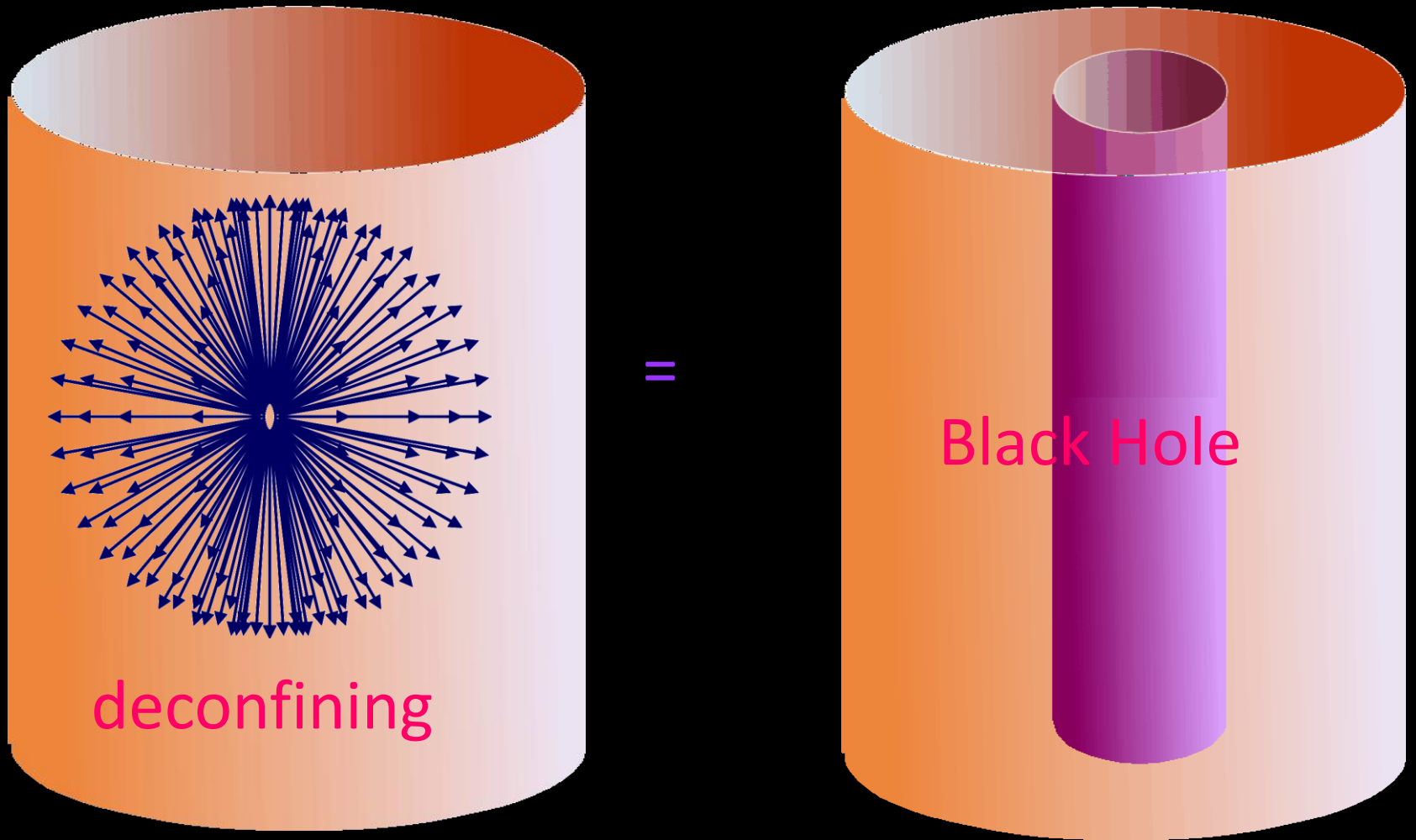
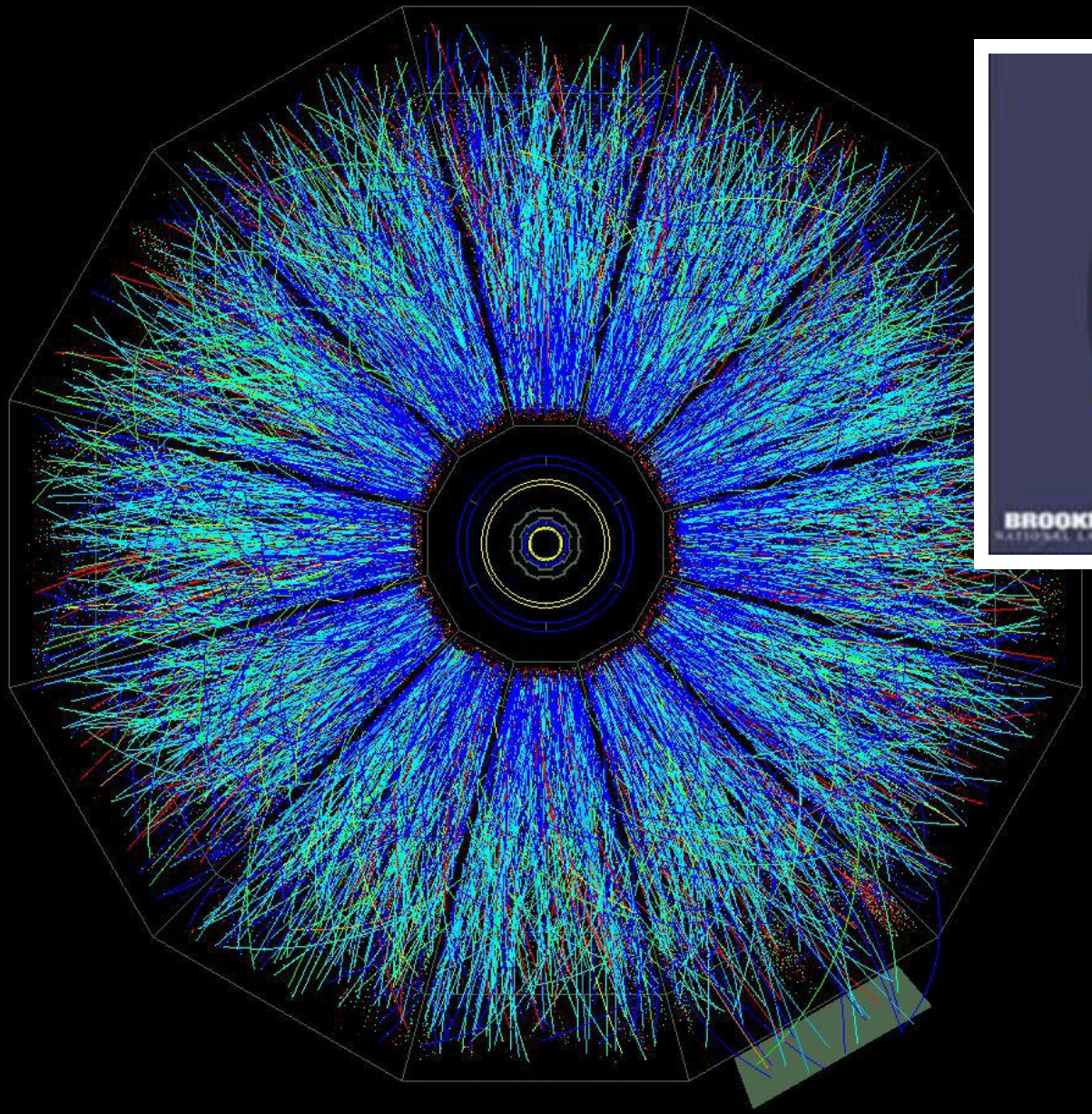
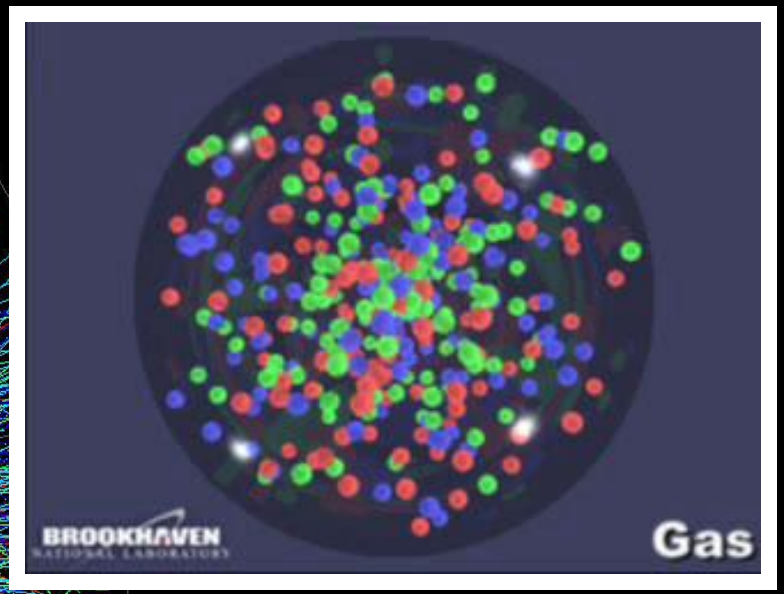


High Temperature



Black Holes at Accelerators?

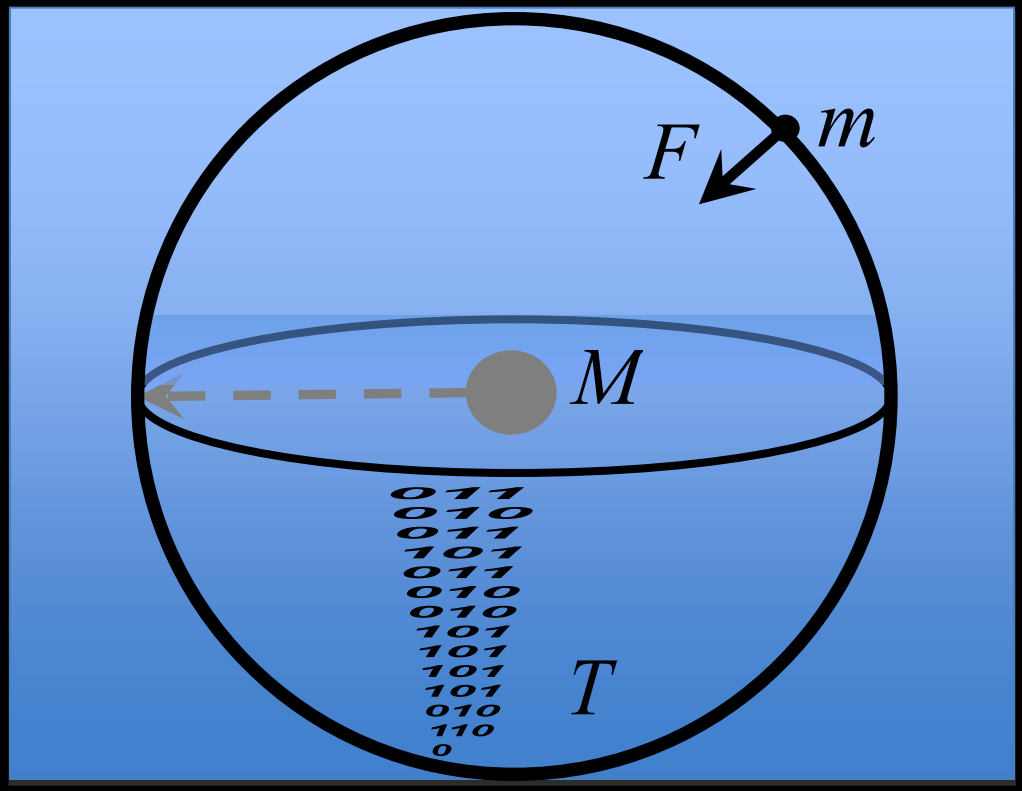




Quark Gluon Plasma

Erik Verlinde (2009)

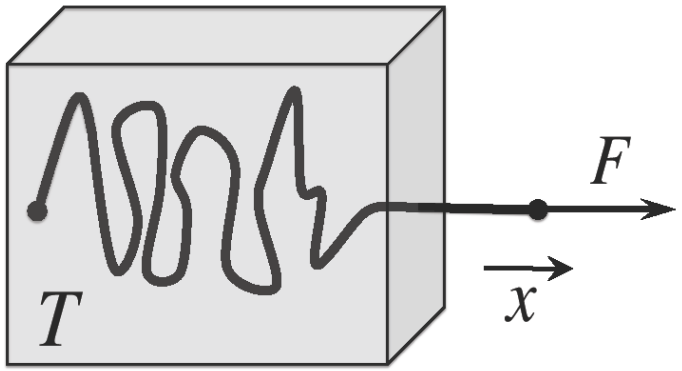
Gravity as an Entropic Force



$$F\Delta x = T\Delta S$$

Entropic force of thermodynamics

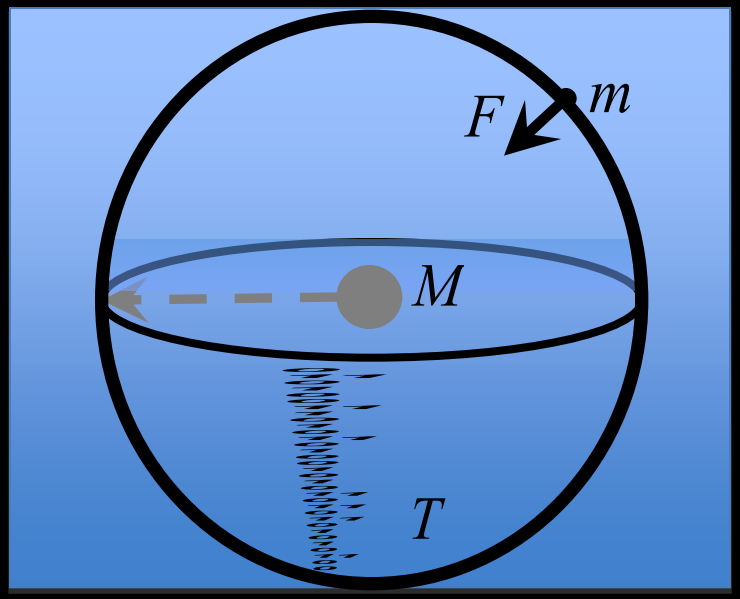
$$F\Delta x = T\Delta S$$



Polymer molecule

Entropic force due to the tendency for entropy to increase

“Derivation” of Newton’s Laws



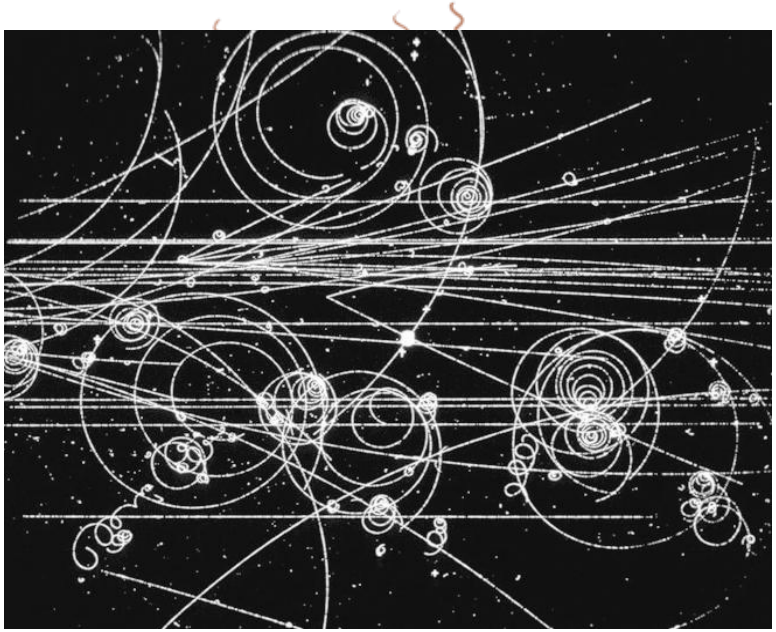
$$F\Delta x = T\Delta S$$

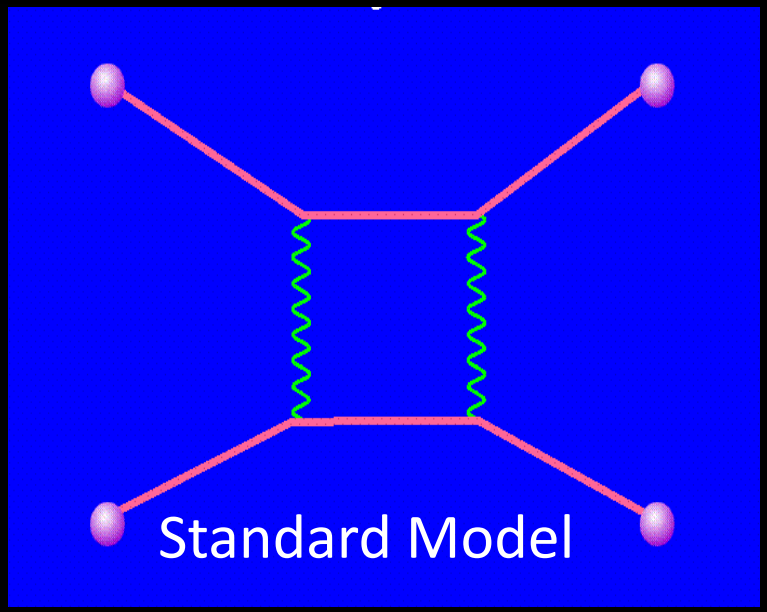
$$\Delta S = \frac{2\pi kc}{\hbar} m\Delta x$$

$$T = \frac{\hbar}{2\pi ck} a$$

$$F = ma$$

Reduction

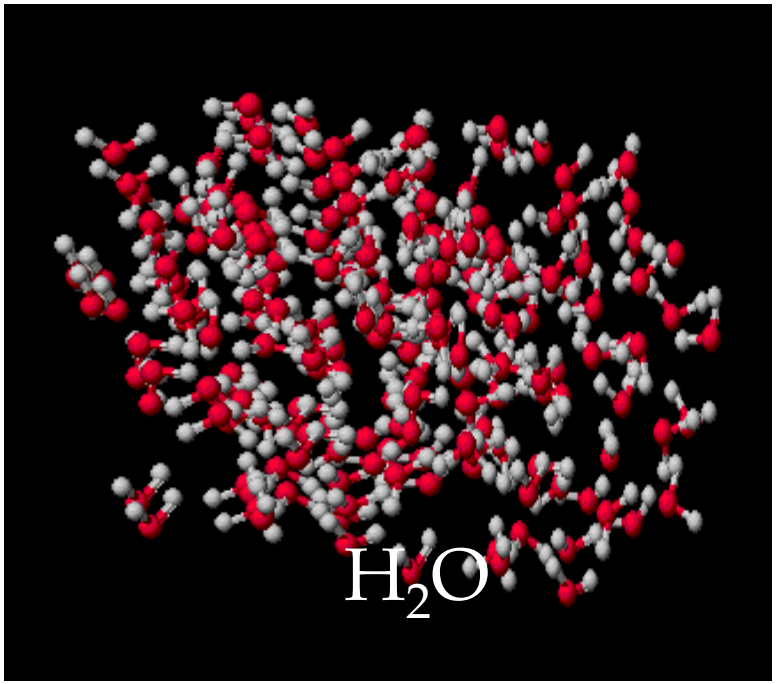




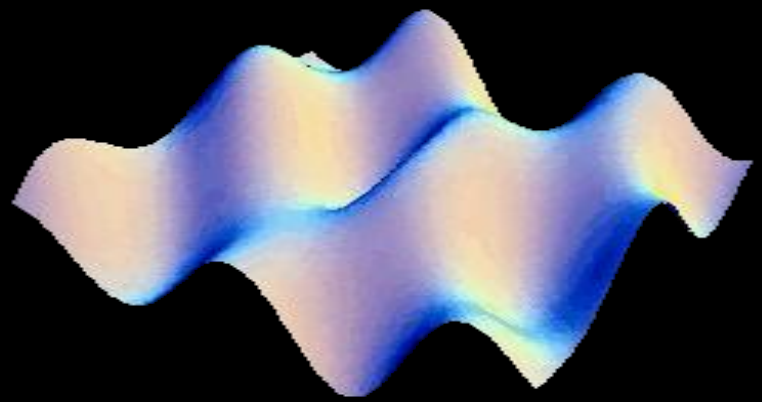
Garbage

Beauty

Emergence

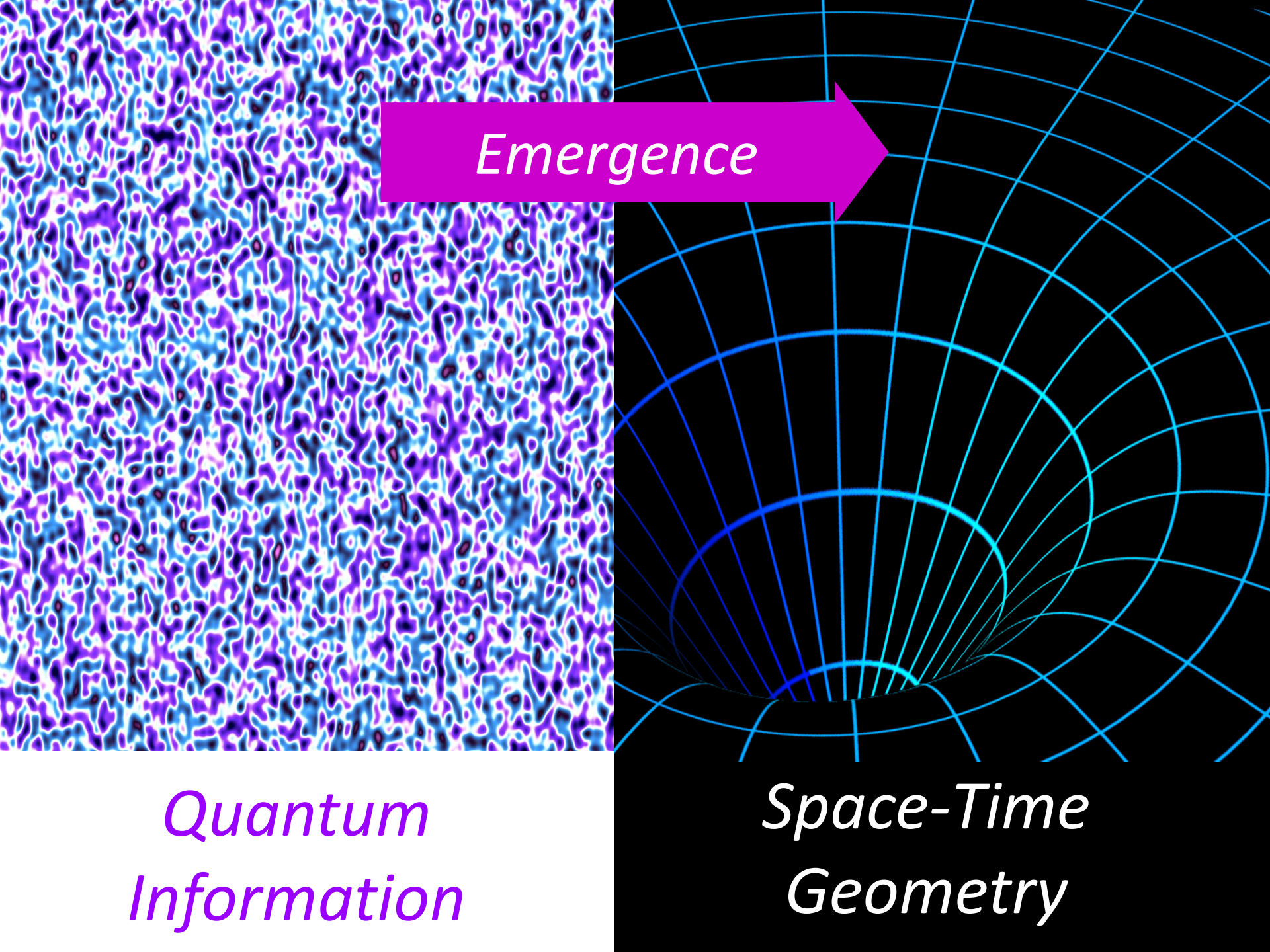


Garbage



Navier-Stokes
Hydrodynamics

Beauty


Emergence
Quantum Information
Space-Time Geometry