An Odyssey through our Universe

from the Big Bang to Black Holes, Unknown Dark Forces and Unseen Dimensions and Universes

John W. Harris, Yale University

Romania at CERN Symposium 2023

Bucharest University, 11 January 2023

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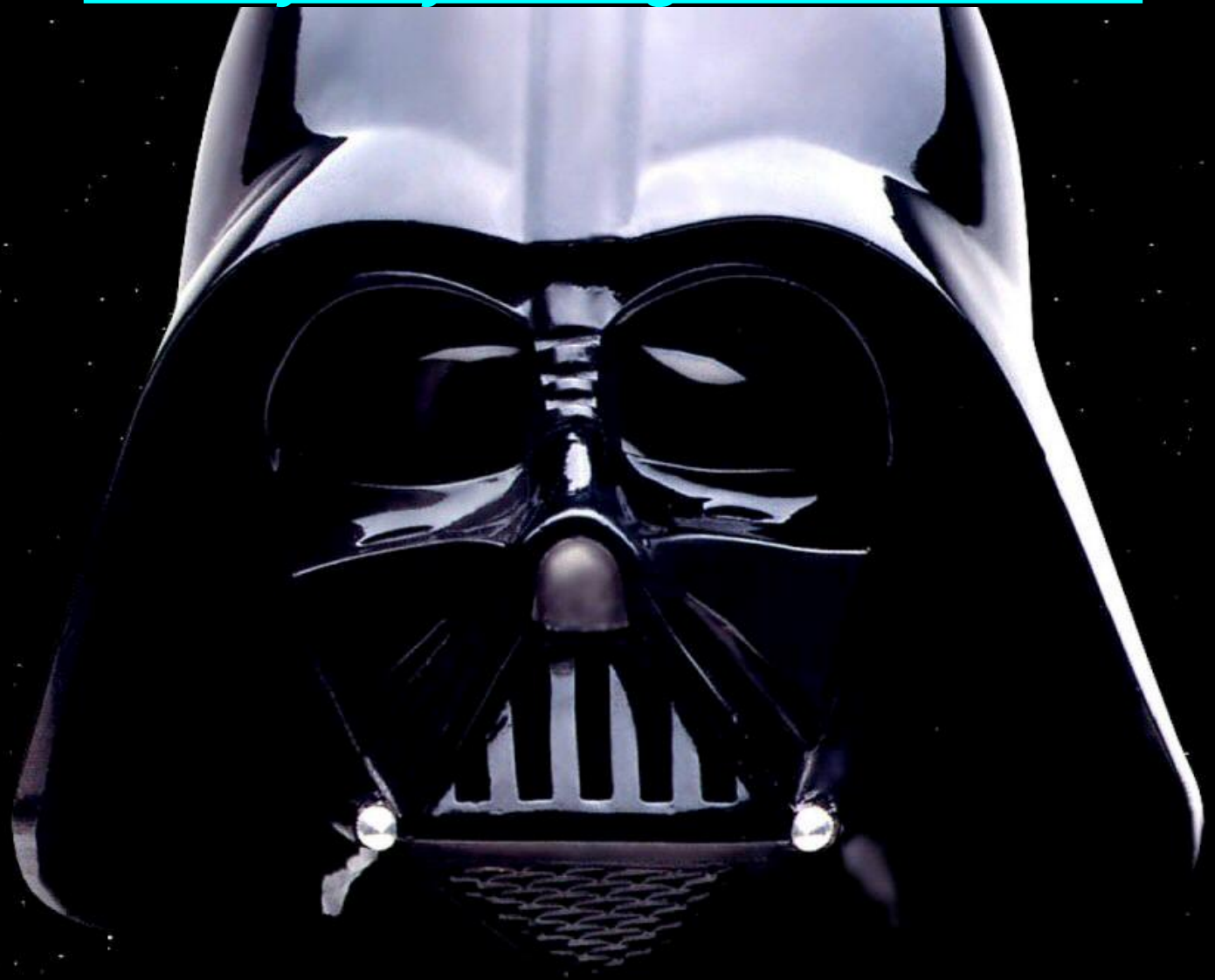
An Odyssey through our Universe



Unknown Dark Forces

An Odyssey through our Universe

"In Search of the Fourth Dimension"
Salvador Dalí

Unseen Dimensions

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An Odyssey through our Universe

"The Disintegration of the Persistence of Memory"
Salvador Dalí

and Universes

What are the BIG Questions Today?

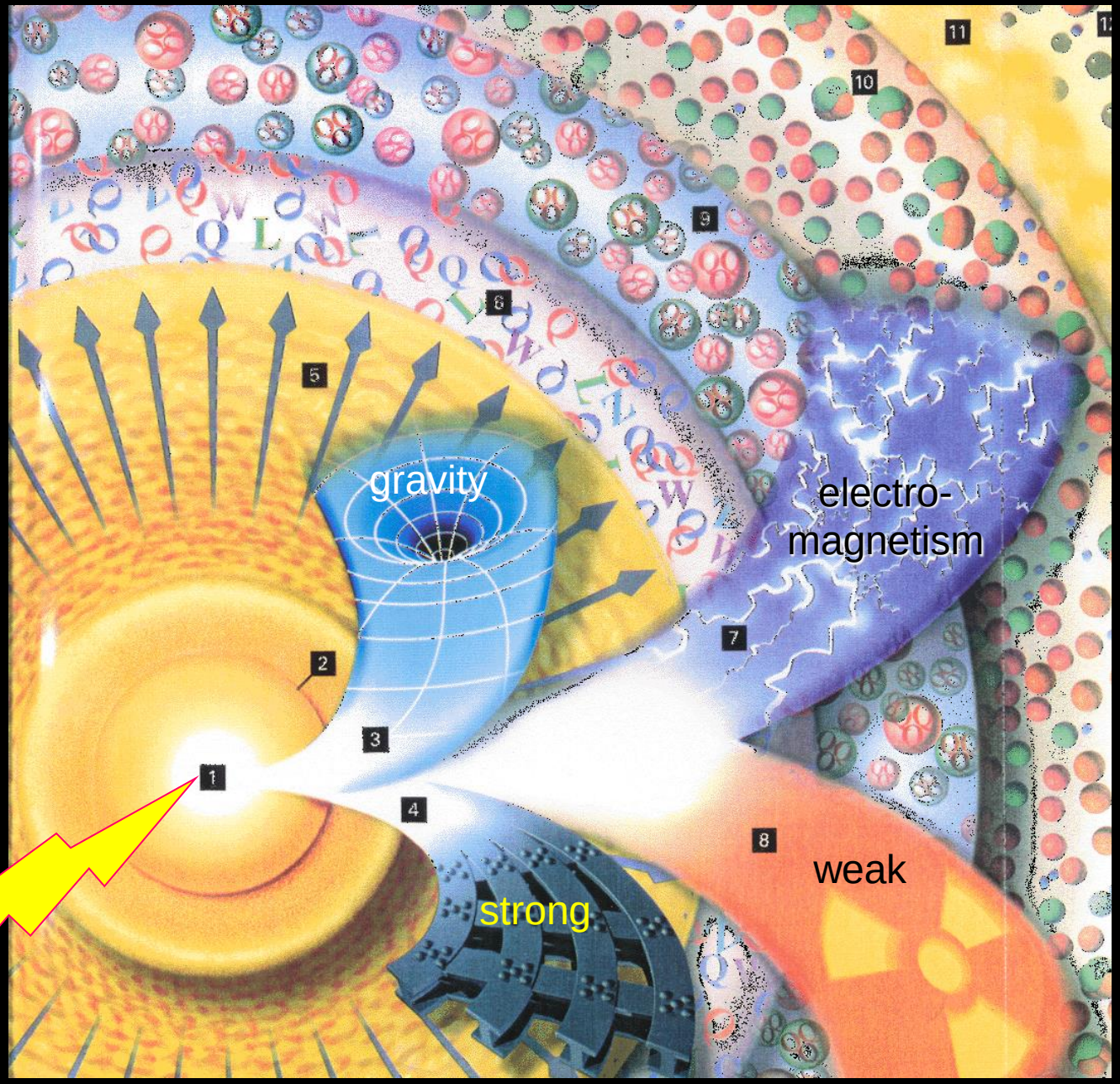
- Origin of Our Universe?
  - What happened early on? Are there other universes?
- How was Matter ever formed?
- What is Dark Matter?
- What is Dark Energy?

- Quantum Mechanics versus Gravity?
- What are Extra Dimensions and do they exist?
- ……

How Did the Universe Evolve?

How Did the Universe Evolve?

First Instant!



Courtesy: National Geographic

There was light / energy

From μ-seconds to Minutes

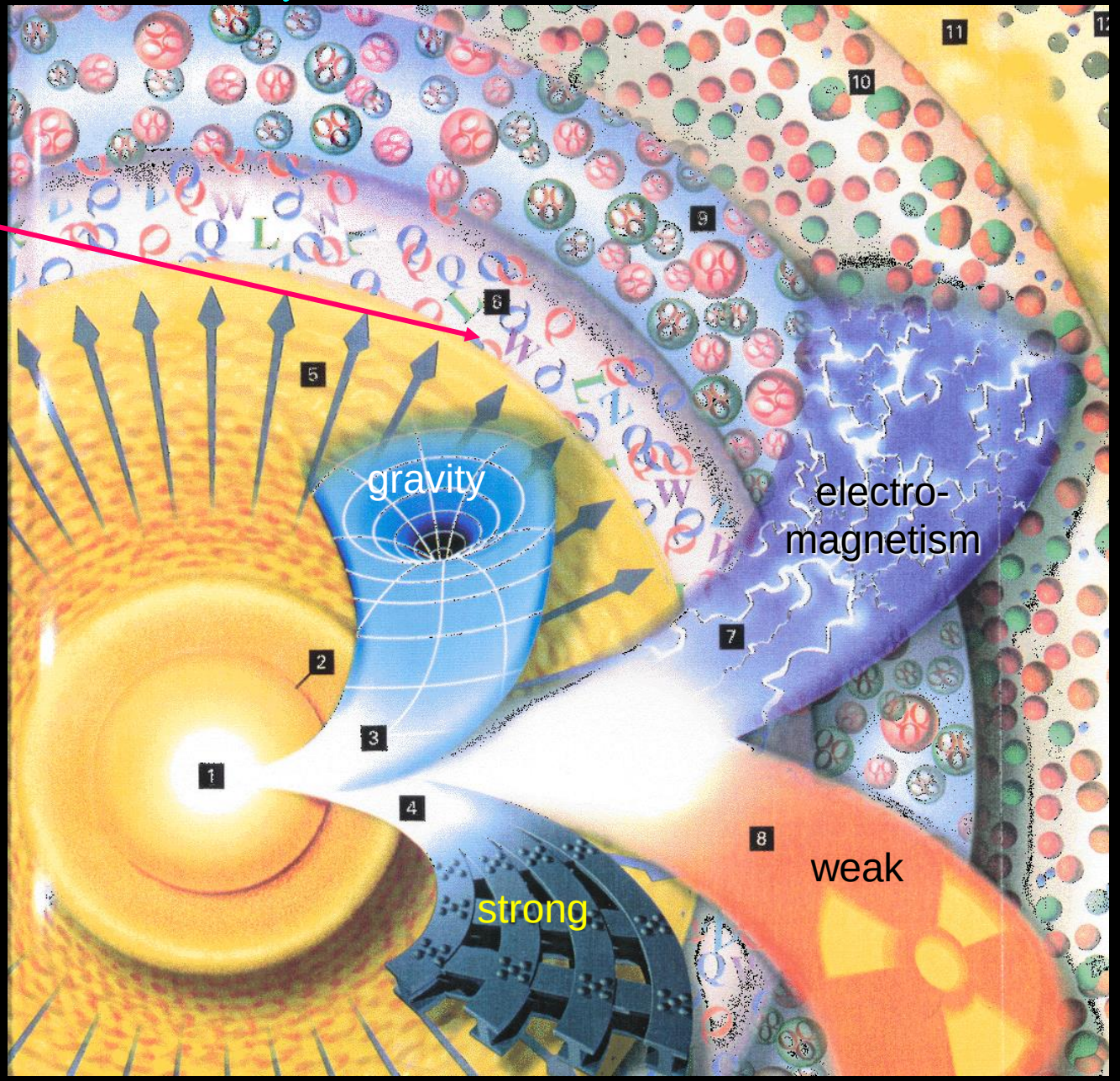
At 10 micro-seconds & 2 trillion K ‡
Quark-to-hadron* phase transition

Quark-Gluon Plasma

Rapid inflation

gravity, strong & E-W forces separate

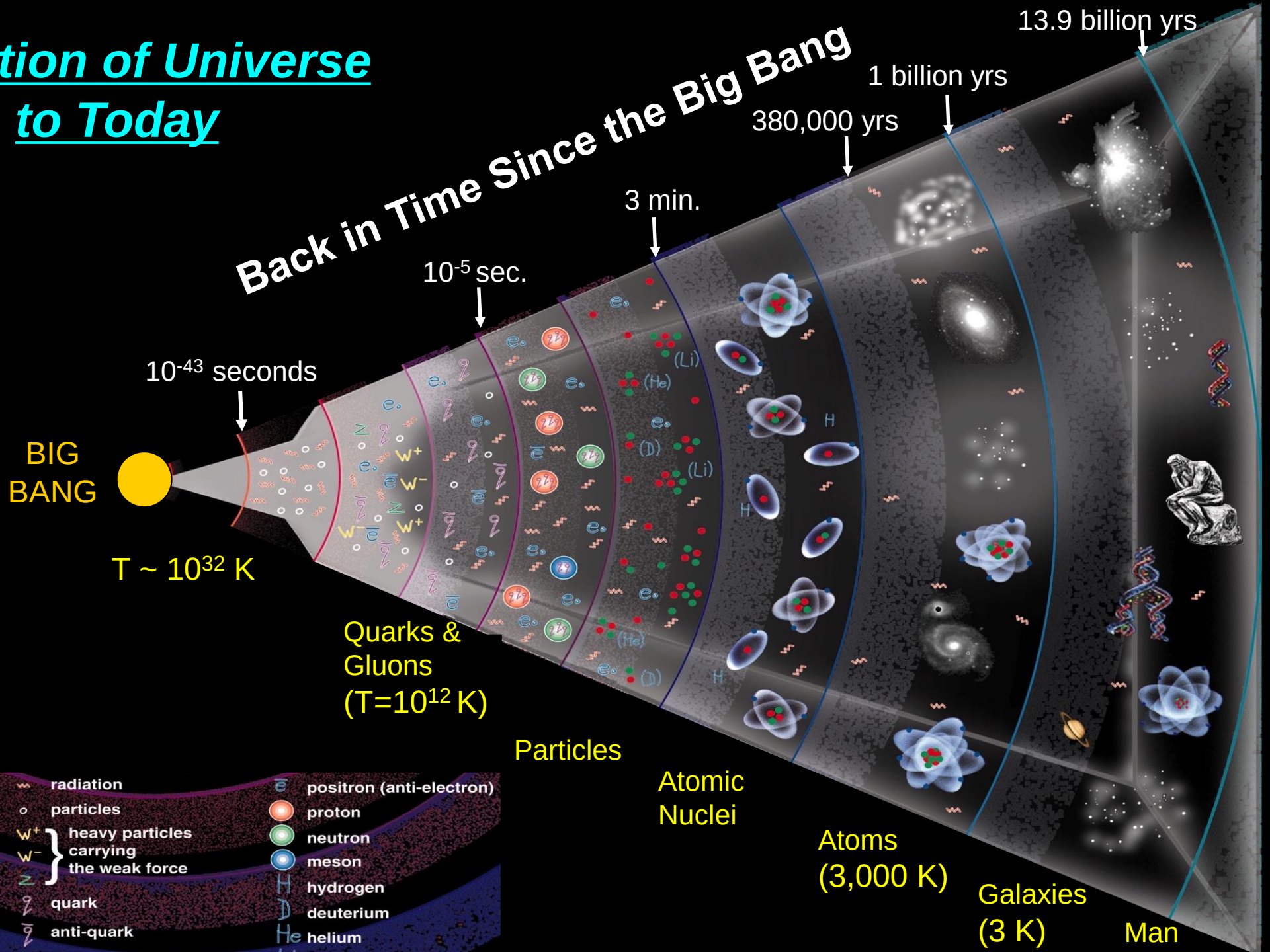
At 10^{-43} seconds, all forces were unified (acting as a single force)



Courtesy: National Geographic

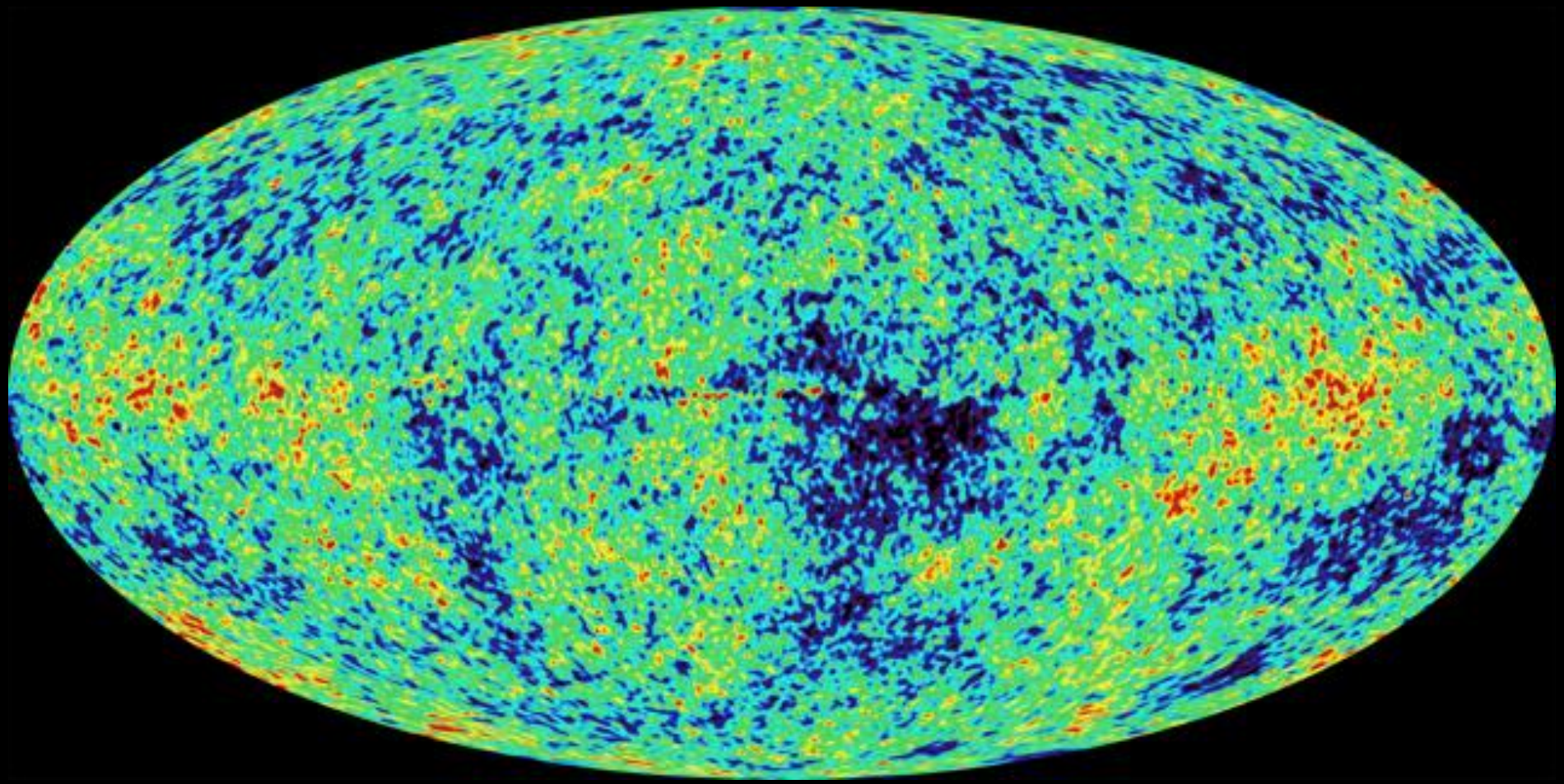
*** hadrons = nuclear particles** **‡ K = ºC + 273**

Evolution of Universe to Today



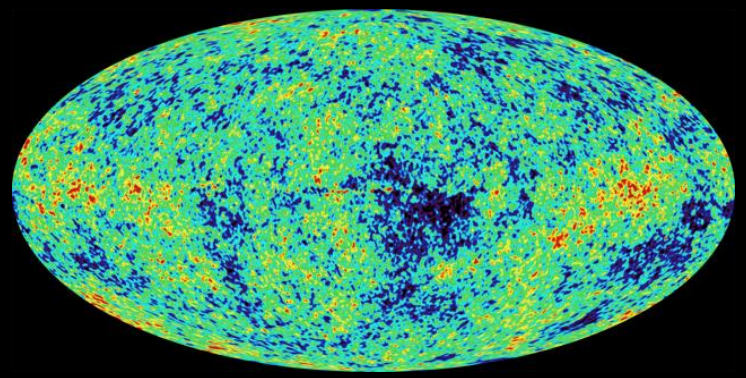
Let's Go Backward in Time
When the Universe was 380,000 Years Old

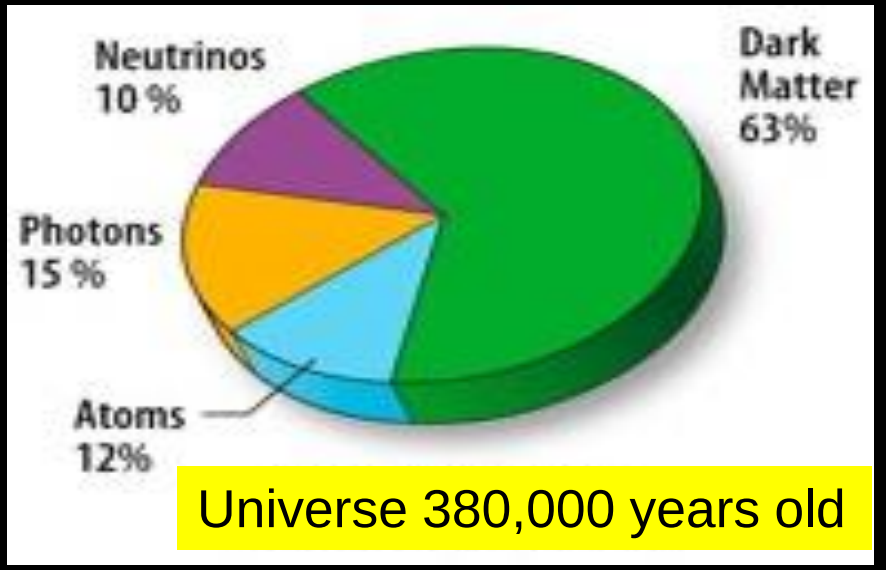
The Cosmic Microwave Background – Uniformity of Temperature of the Universe



Observed temperature differences (in color) are only ~ .0002 K

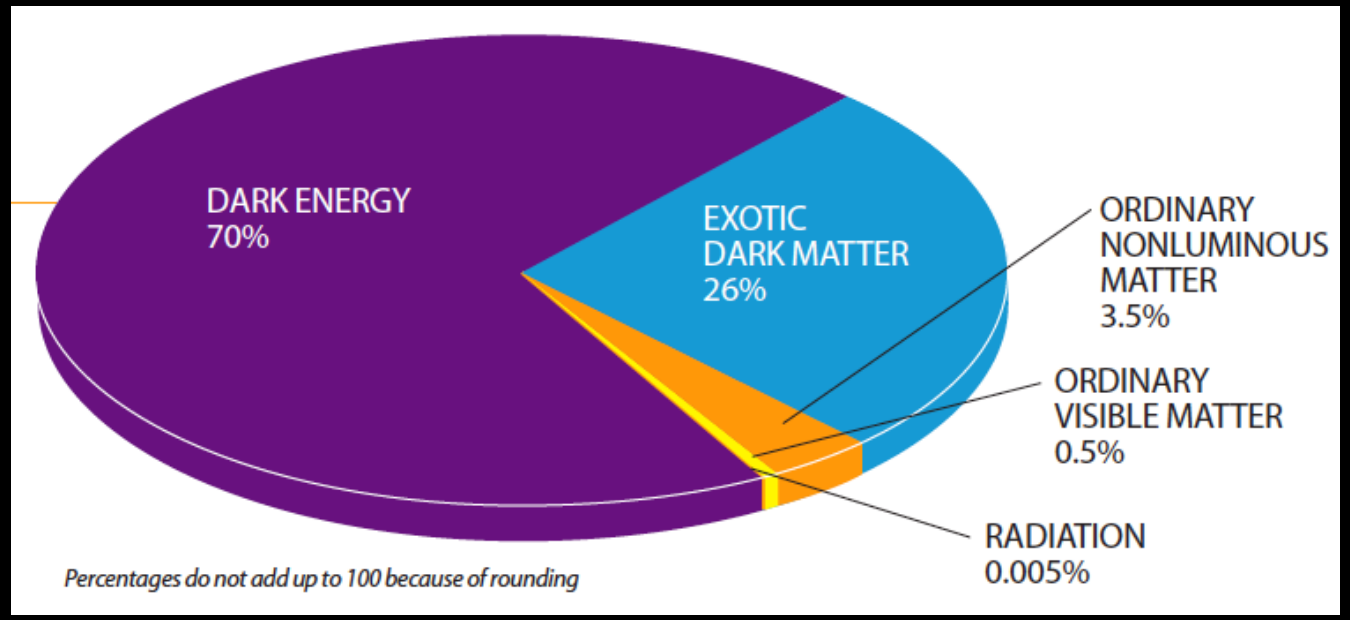
Temperature Fluctuations of the Universe





Universe 380,000 years old

Today



Dark Matter!

Evidence – visible effects on matter

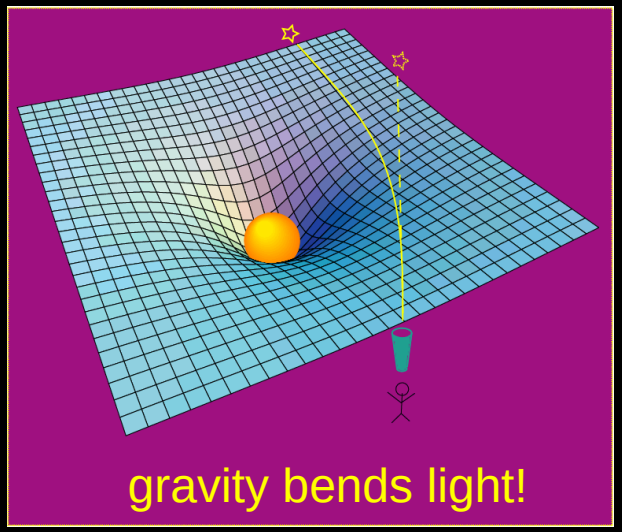
Cosmic Microwave Background Fluctuations

Over many years, evidence has mounted:

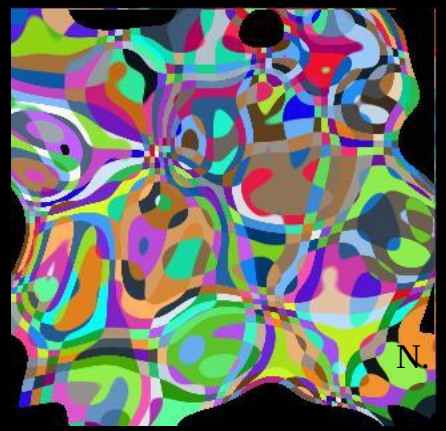
- Baryonic matter in Universe is too low!
- Motion of galaxies in clusters & odd rotation of spiral galaxies
- Large-scale structure

Gravitational Lensing →

(distortion of starlight due to unseen masses)



→



What is Dark Matter?

- Visible so far only through gravitational effects
- If exotic particles, candidates are:

  Hot Dark Matter (neutrinos) or Cold Dark Matter (a new particle - lightest super-symmetric partner)

- Top candidates:

  Weakly Interacting Massive Particle or Super-WIMP

  Mediator particles (connect dark matter with ordinary matter)

	Baryonic	WIMP	Super-WIMP
Gravity	✓	✓	✓
Electromagnetic force	✓		
Weak nuclear force	✓	✓	
Strong nuclear force	✓		
Possible dark forces		✓	✓

- We just do not know!

  So, active searches ongoing:

  Large neutrino detectors (decays) underground

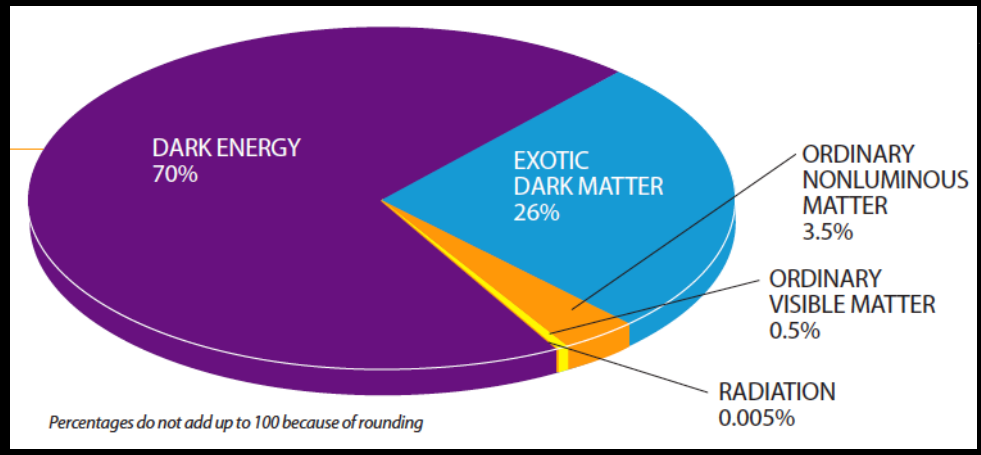
  Direct detection (interaction in detectors) & in space

  Large Hadron Collider (production and detection)

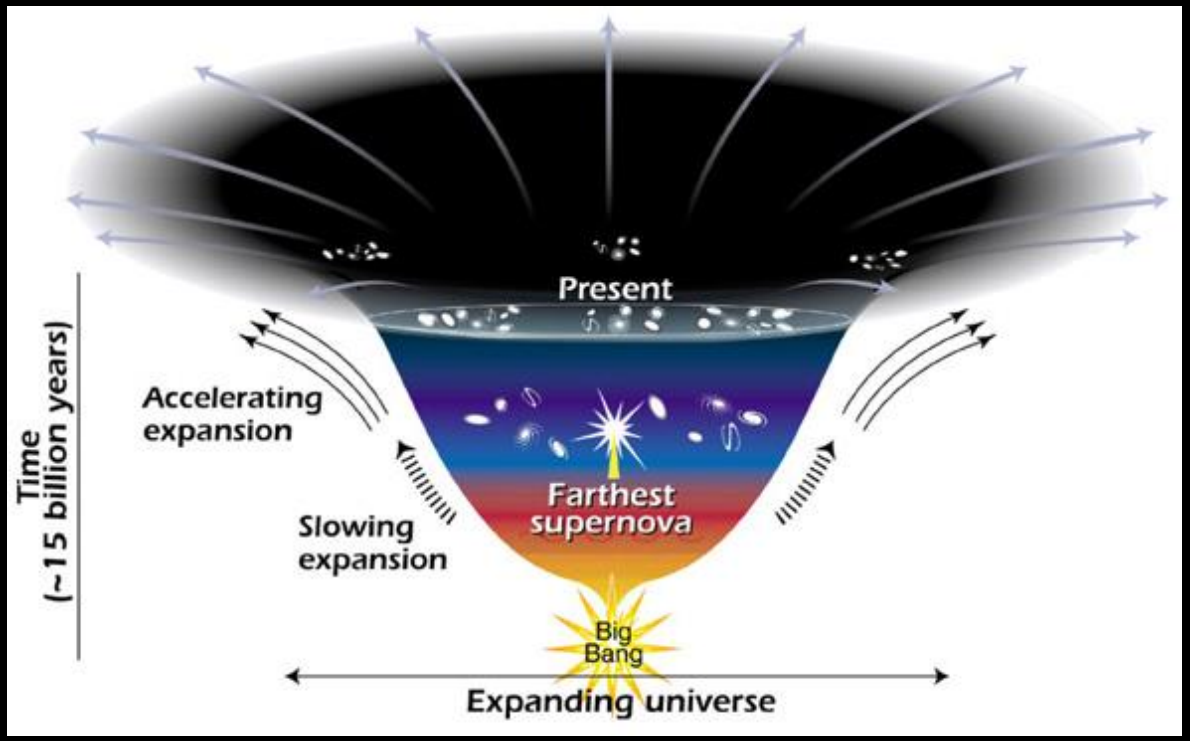
Search for new (heavier) particles, missing momentum, mediator particles, mini black holes

Evidence for Dark Energy!

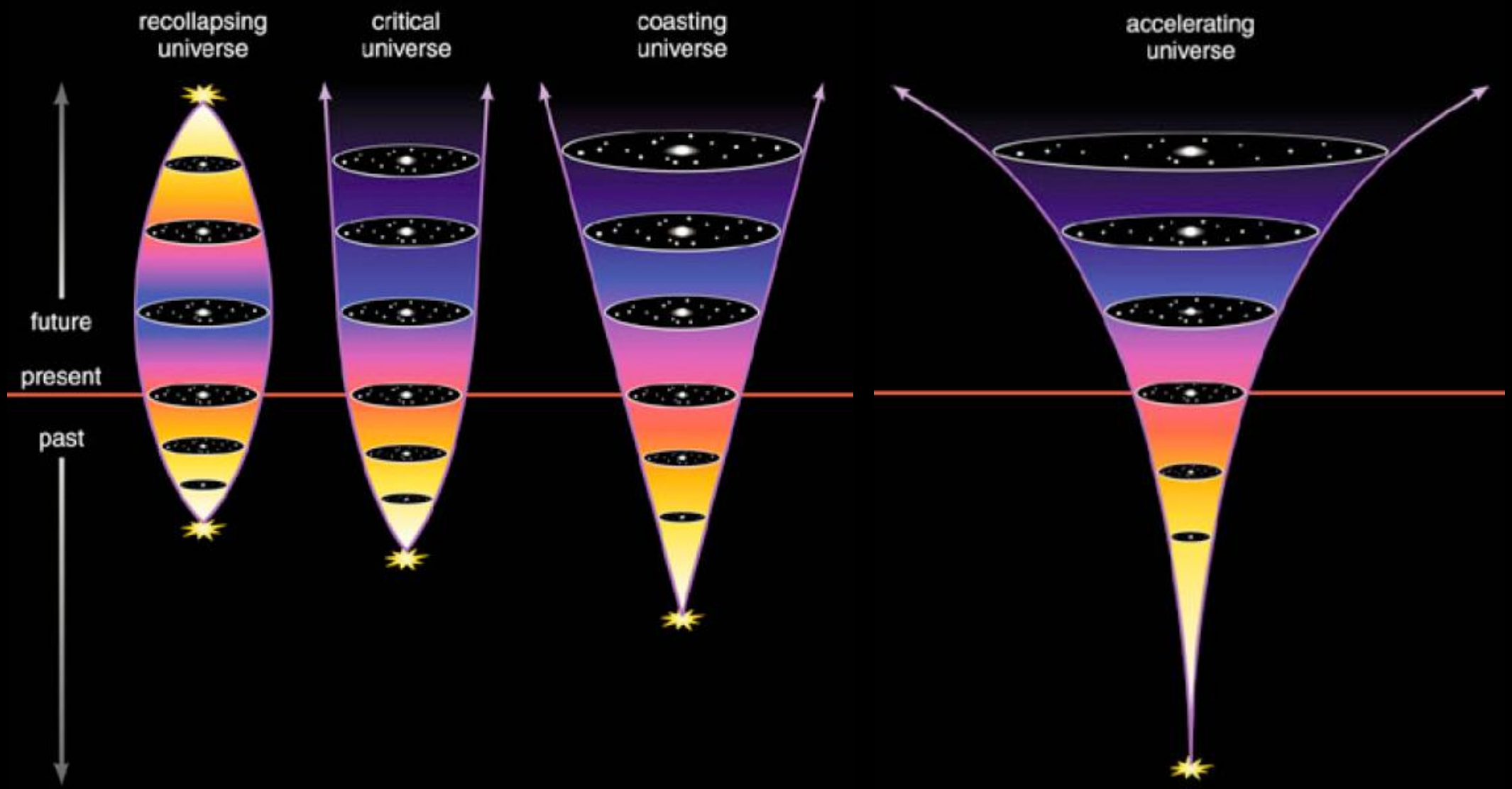
Cosmic Micro-wave Background



Large scale supernova searches



The Significance of Dark Energy for our Future



So, What is Dark Energy?

Again – we do not know!

- "Cosmological constant" in Einstein's theory of gravity?

  A property of space (empty space is not a void!).

- A "repulsive fluid" of energy filling all of space?

  Repulsive effect, opposite that of gravity!

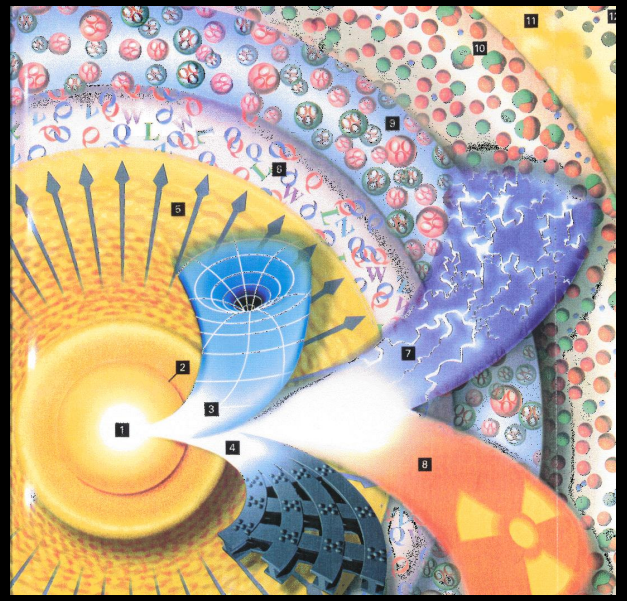
- A new type of field (with repulsive force!) creating "cosmic acceleration"?

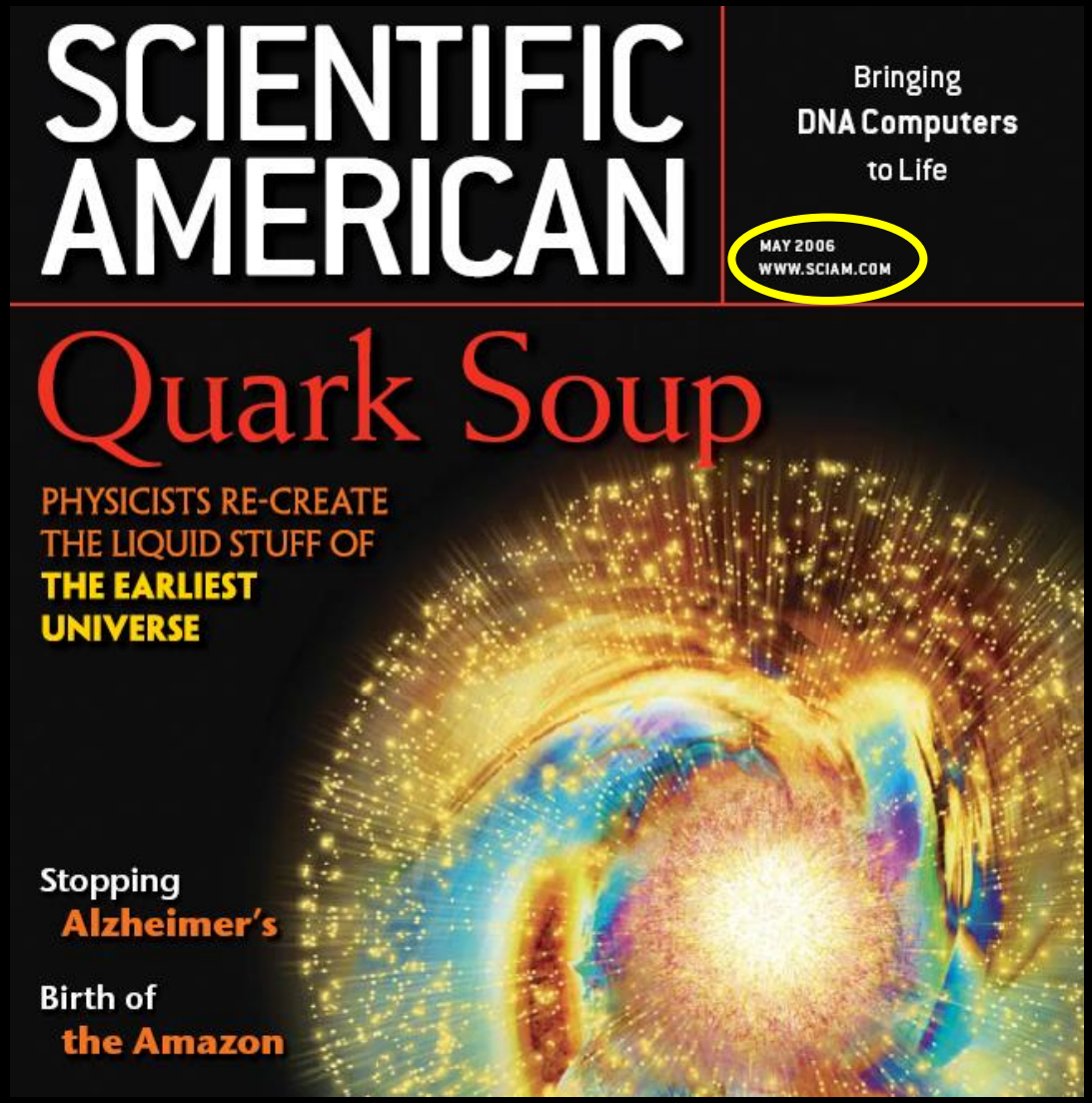
Is there a relation between Dark Energy & Dark Matter?

Either Einstein's theory of gravity is incorrect or incomplete (a new force?)

Many extra-terrestrial studies exist.

Farther Back in Time –
When the Universe Was 10 Micro-seconds Old!

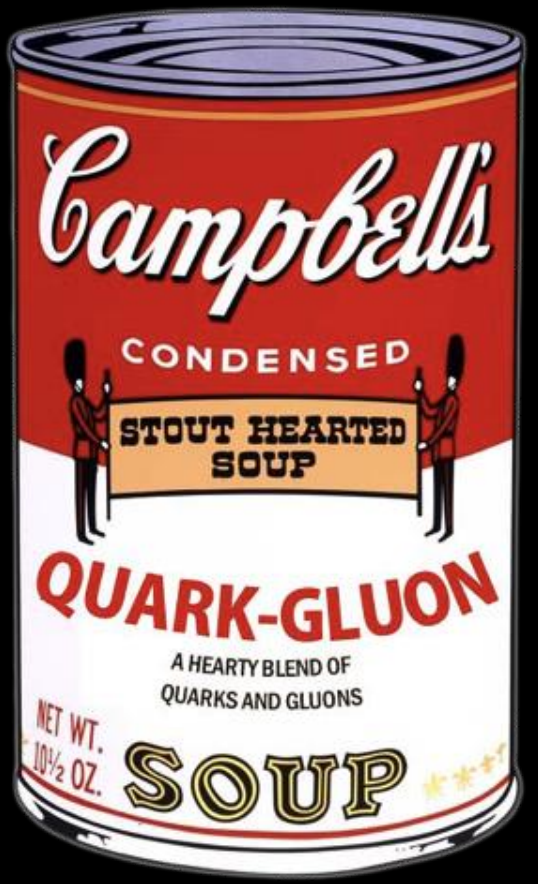




Quark-Gluon Plasma (QGP) Soup

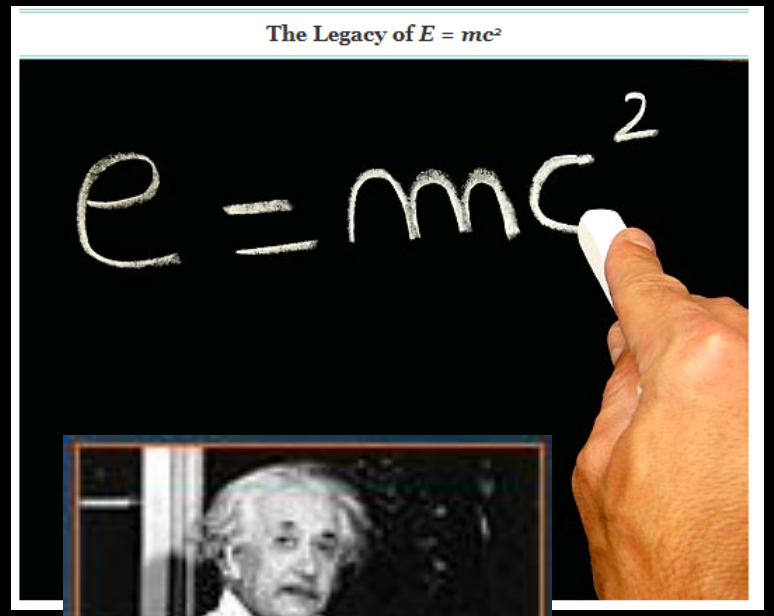
- Standard Model → predicts quark-hadron phase transition at high temperature (T)
- Cosmology → must have been a quark-hadron phase transition in early Universe
- Astrophysics → might exist in cores of dense stars or N-star or Black Hole collisions

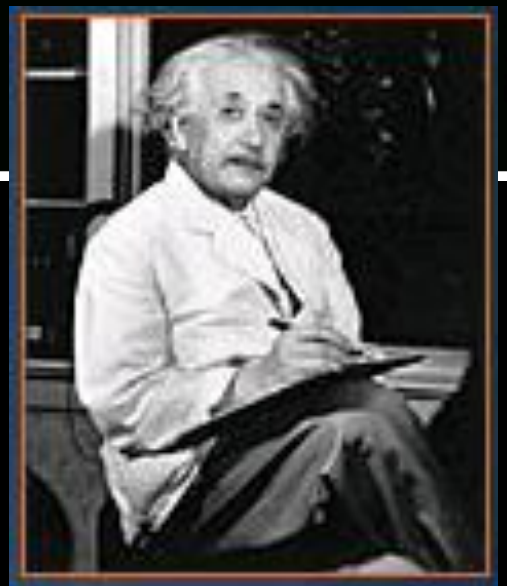
Can we make it in the lab?



Establish its properties at high T (and density?)

The Legacy of $E = mc^2$





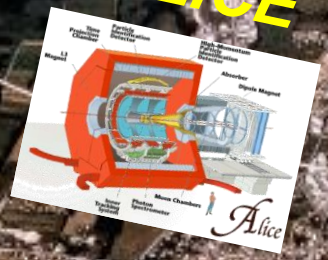
ALBERT EINSTEIN
DISCUSSING
$E = mc^2$

"It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing—a somewhat unfamiliar conception for the average mind. Furthermore, the equation $E = mc^2$, in which energy is put equal to mass, multiplied with the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy, and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned above. This was demonstrated by Cockcroft and Walton in 1932, experimentally."

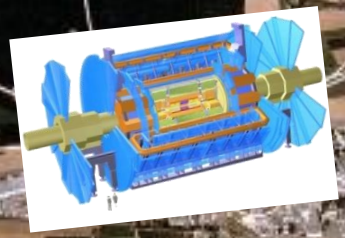
The Large Hadron Collider (LHC)

CMS

ALICE



ATLAS



The Large Hadron Collider Control Room!

Courtesy SONY Pictures

Large Hadron Collider – Built to Discover the Higgs

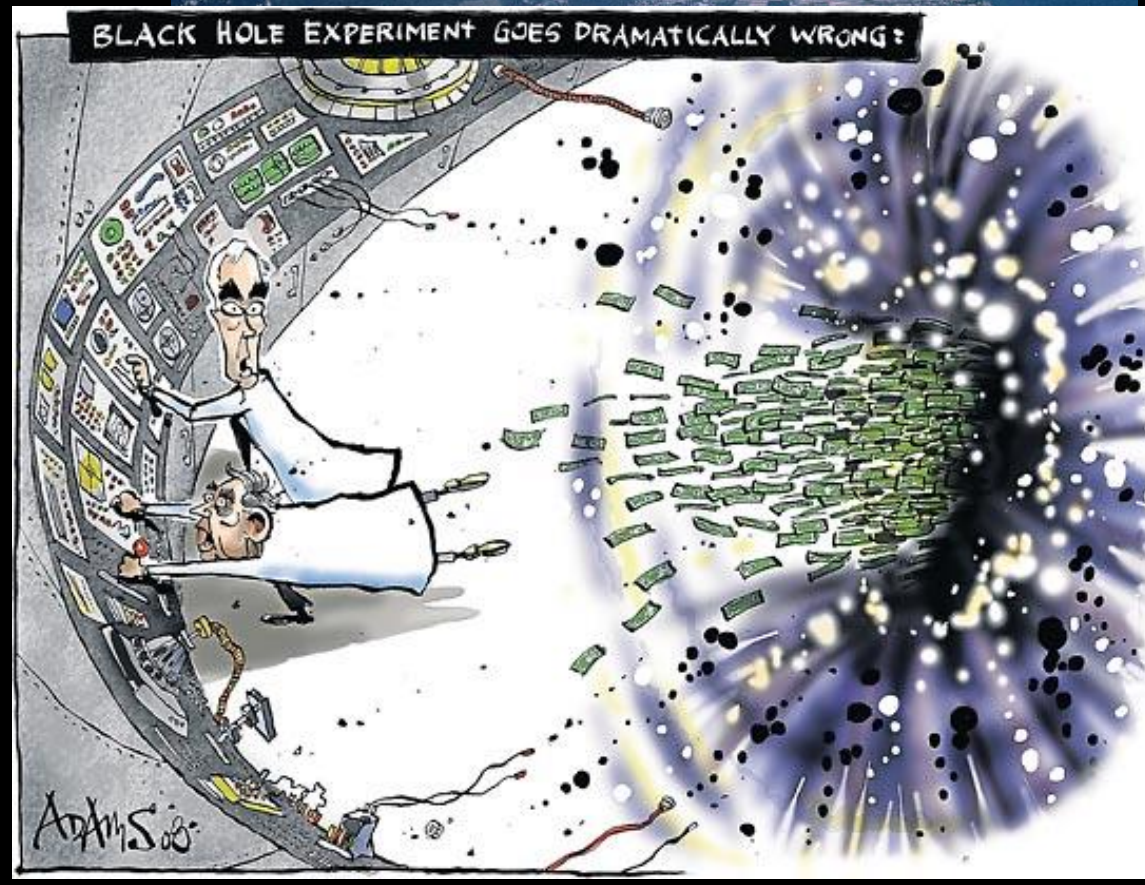
(and the Origin of Mass)

Success – Higgs Particle discovered in 2012!

LHC research also includes investigation

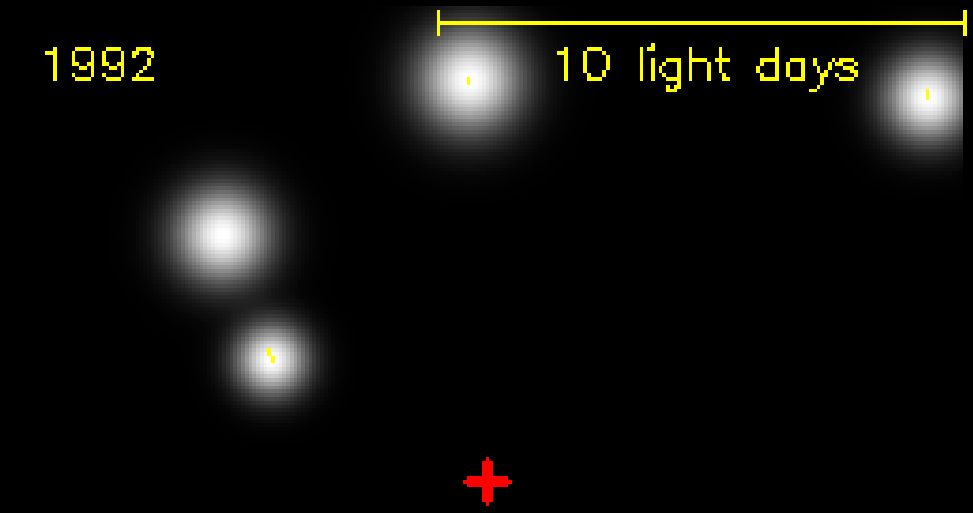
- Quark-Gluon Plasma properties
- New supersymmetric particles from early hot Universe
- Dark Matter particles
- Extra dimensions
- Mini-Black Holes

The Large Hadron Collider (LHC)



The Large Hadron Collider (LHC)

Dark Heart of Our Milky Way Galaxy!



Astronomers followed motion of stars over 14 years

- at center of our galaxy (seen from Earth).
- orbits of stars in yellow

Central Black Hole (invisible) at the red cross!

- Only motion of stars around it are visible!
- Red cross marks the position of "Sagittarius A*",
  a compact radio source (black hole).

Shown is core of our Milky Way in the constellation Sagittarius.

~ 25,000 light years away from Earth.

Finally – A Black Hole is Observed

In 2019

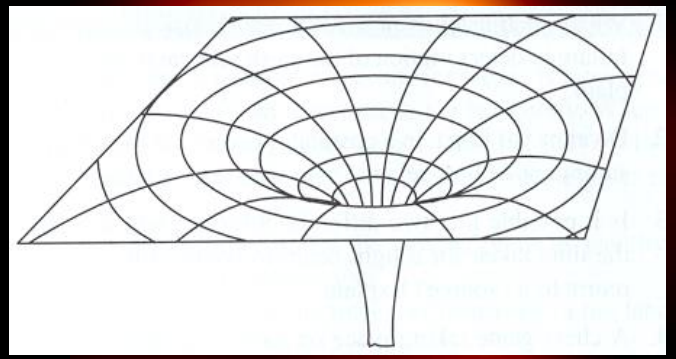
Image of the black hole at the center of galaxy M87

- outlined by emission from hot gas swirling around it from the strong gravity near its event horizon

Event Horizon telescope (2019, courtesy NASA)

Breaking News (May 12, 2022)!

Image of the black hole at the center of our Milky Way Galaxy!



At the core of our Milky Way in the constellation Sagittarius.

~ 25,000 light years away from Earth.


YOU ARE HERE

Roger Penrose, Reinhard Genzel and Andrea Ghez
2020 Nobel Prize in Physics

Penrose “for the discovery that black hole formation is a robust prediction of the general theory of relativity”, and Genzel and Ghez “for the discovery of a supermassive compact object at the centre of our galaxy”.

Heavy Ions at the LHC - So What Have We Found So Far?

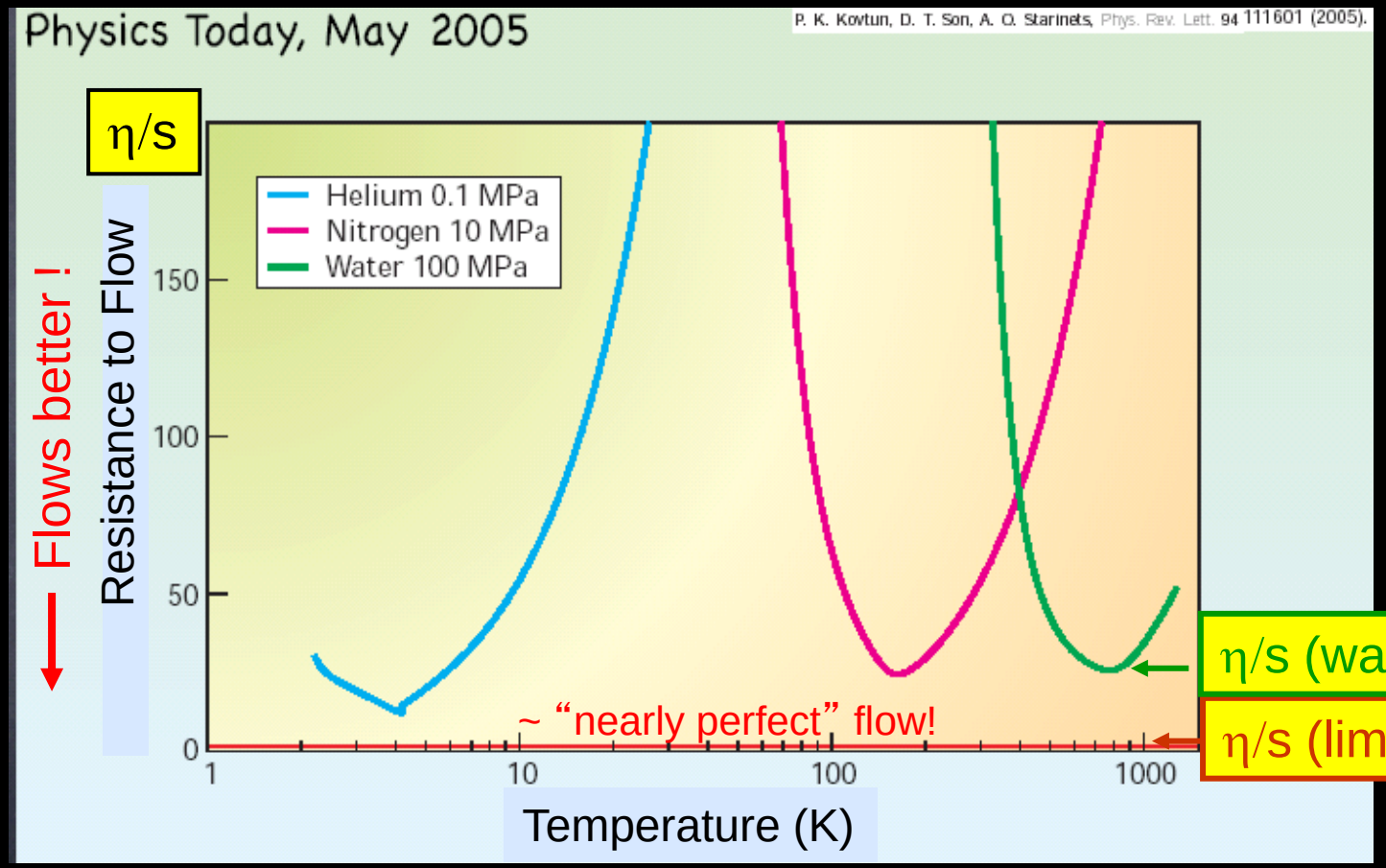
Summary of Experimental Results –

- Successfully heated matter to temperature $T > 2 \times 10^{12}$ (2,000,000,000,000) K
- More than100,000 times hotter than the core of Sun
- Hot enough to make a QGP Soup – no other form of matter we know could exist

What are its characteristics?

- It flows like a liquid, better than any we know or have made
- It behaves like an ultra-hot soup of quarks, anti-quarks (and gluons)
- It is opaque to the most energetic probes (fast quarks)

Fluids that Flow!

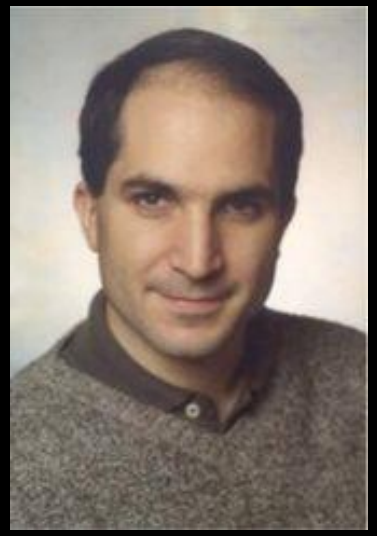


$T = 2 \times 10^{12}$ K

Quantum lower limit: $\eta/s > 1/4\pi \sim .08$ (calculated in String Theory with Black Hole in a 5th dimension)

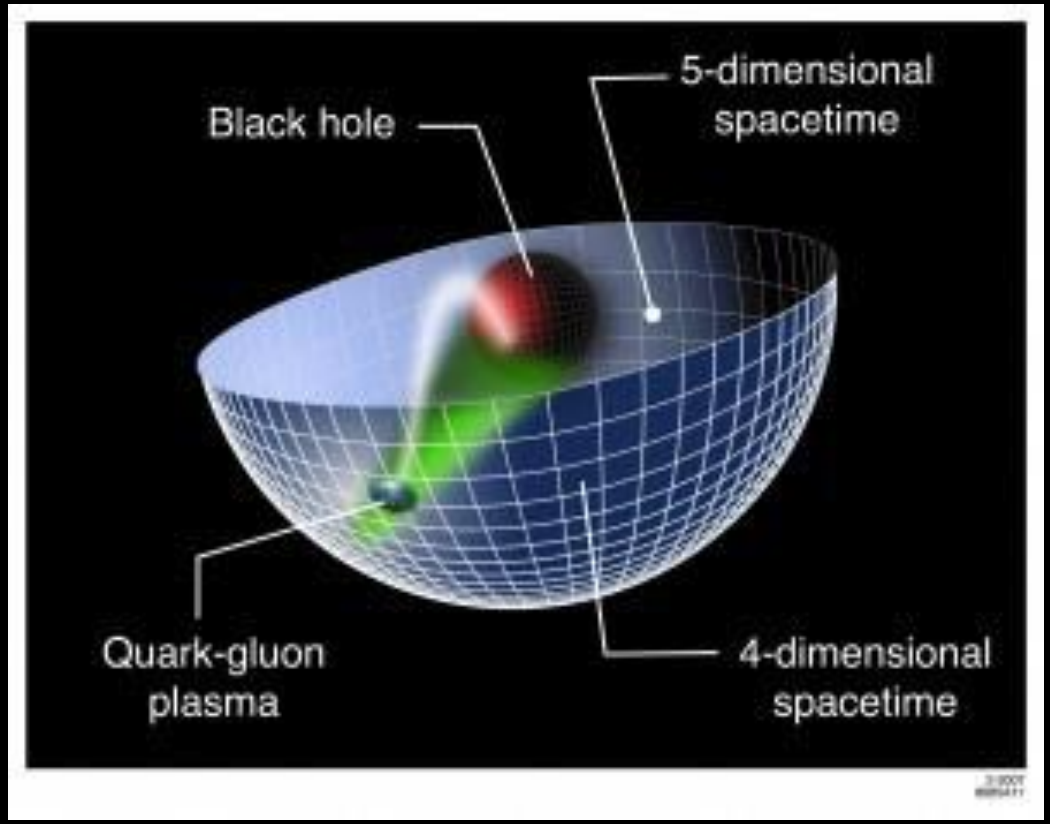
From heavy-ion data $\eta/s \sim 0.1$ near or at lower limit!

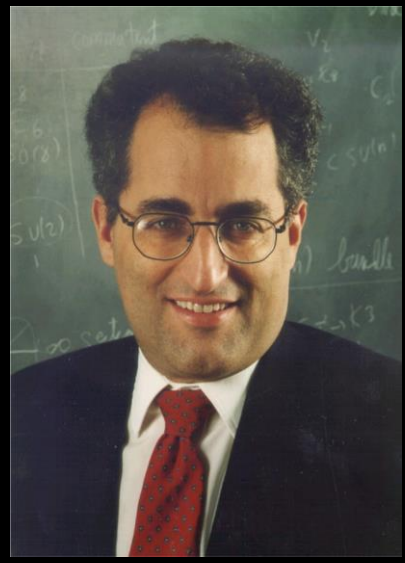
4D Representation of a 5D World



Juan Maldacena

Juan Maldacena conjectured that String Theory in a 5D universe can be painted onto our 4D boundary universe.



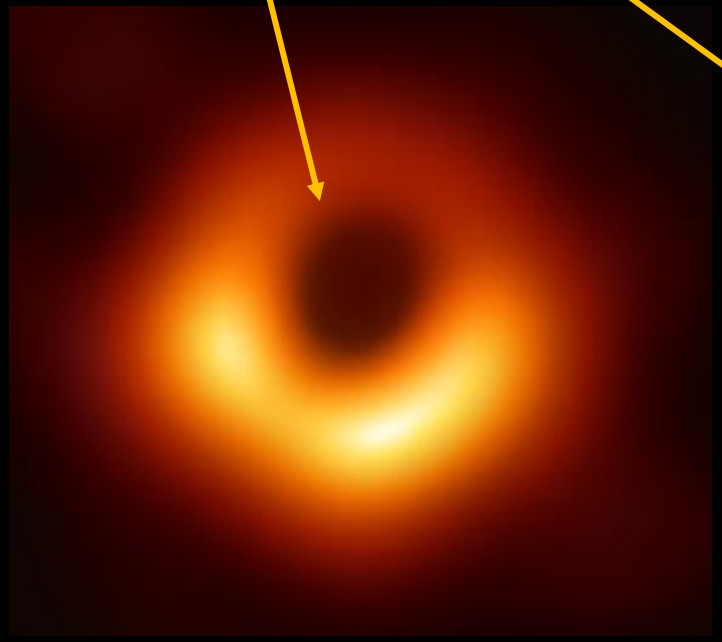


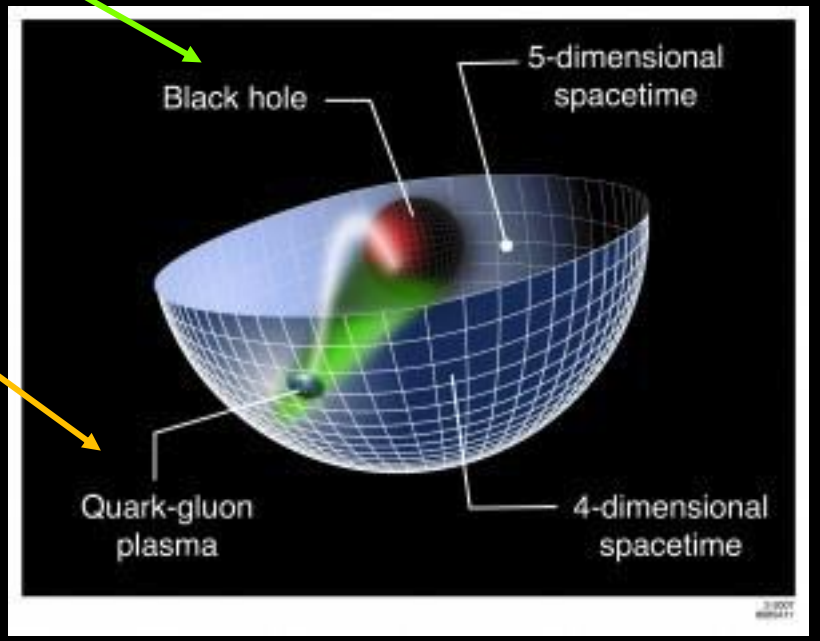
Edward Witten

Ed Witten showed that a black hole in a particular 5D space-time corresponds to a hot system of quarks & gluons (QGP) on the 4D space-time boundary.

4D Representation of a 5D World

Space-time near the event horizon of a black hole behaves like a nearly perfect liquid of quarks and gluons!



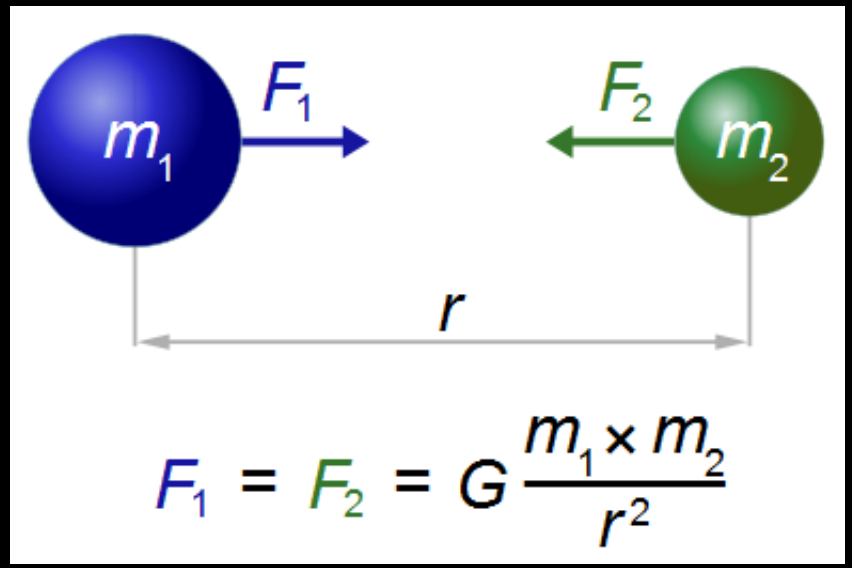


Event Horizon telescope (2019, courtesy NASA)

The String Theory discussion will continue…

Speaking of Mass – Back to Gravity for a Moment!

- Gravity - the Force We Think We Know
  - Gravitational force equation
- What we can see and feel
  - Everyday life, solar system
- What we can see but cannot imagine
  - Black Holes, Pulsars, Quasars, etc.



Gravity

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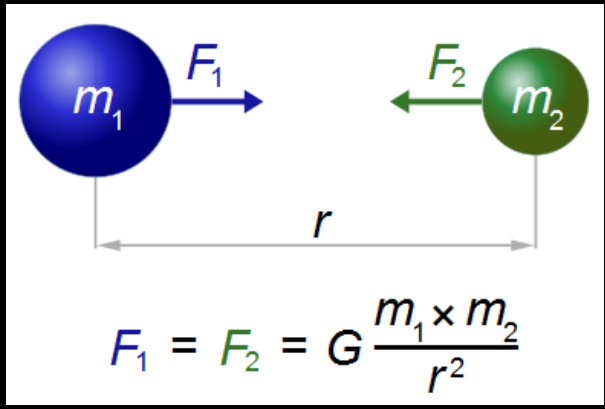


- What we cannot see
  - Gravitons (force carriers of gravity?)
- The Force We Want to Get to Know Better

Problems with Gravity –

- Have not identified force carrier!
- Instantaneous Action of Newtonian Gravity as a Force!
- There is a conflict with Quantum Mechanics on small scales!
- Purported to be resolved in String Theory & Extra Dimensions!

Recent News about Gravity – Gravitational Waves

Two Black Holes Merge – First Observed 2015

https://www.black-holes.org/gw150914

Binary Neutron Star Merger

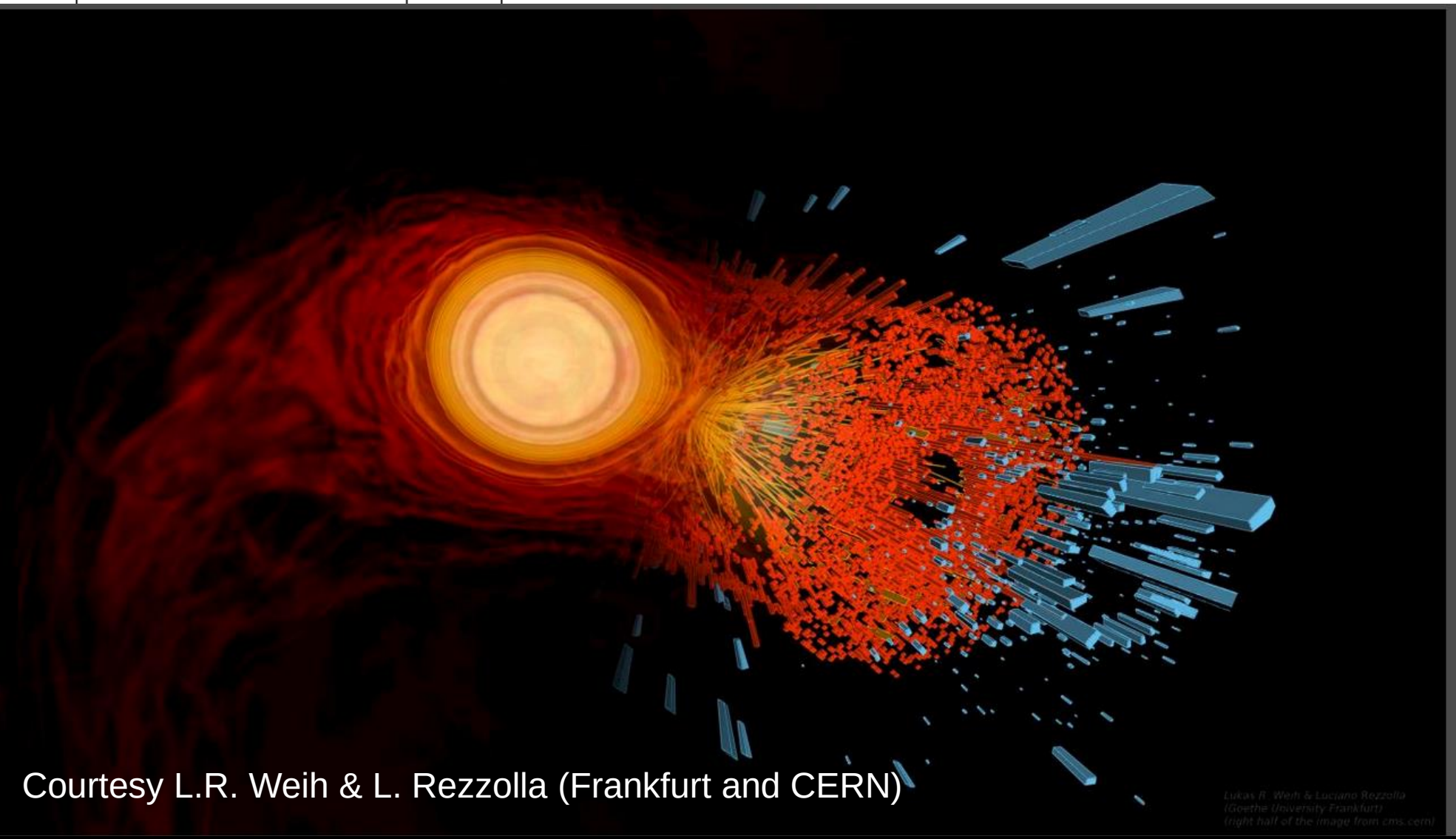
- **Play Video at: http://www.sciencemag.org/news/2017/10/merging-**

IOP Publishing

physicsworld

Gravitational waves from neutron-star mergers could reveal quark-gluon plasma

15 May 2020



Dark star crashes: the computer simulation of two merging neutron stars (left) blended with an image of heavy-ion collisions at CERN to highlight the connection of astrophysics with nuclear physics. Courtesy: Lukas R Weih and Luciano Rezzolla/Goethe University Frankfurt and CMS/CERN)

Courtesy L.R. Weih & L. Rezzolla (Frankfurt and CERN)

Gravitational waves from neutron star mergers could provide vital information for testing theories of the QGP.

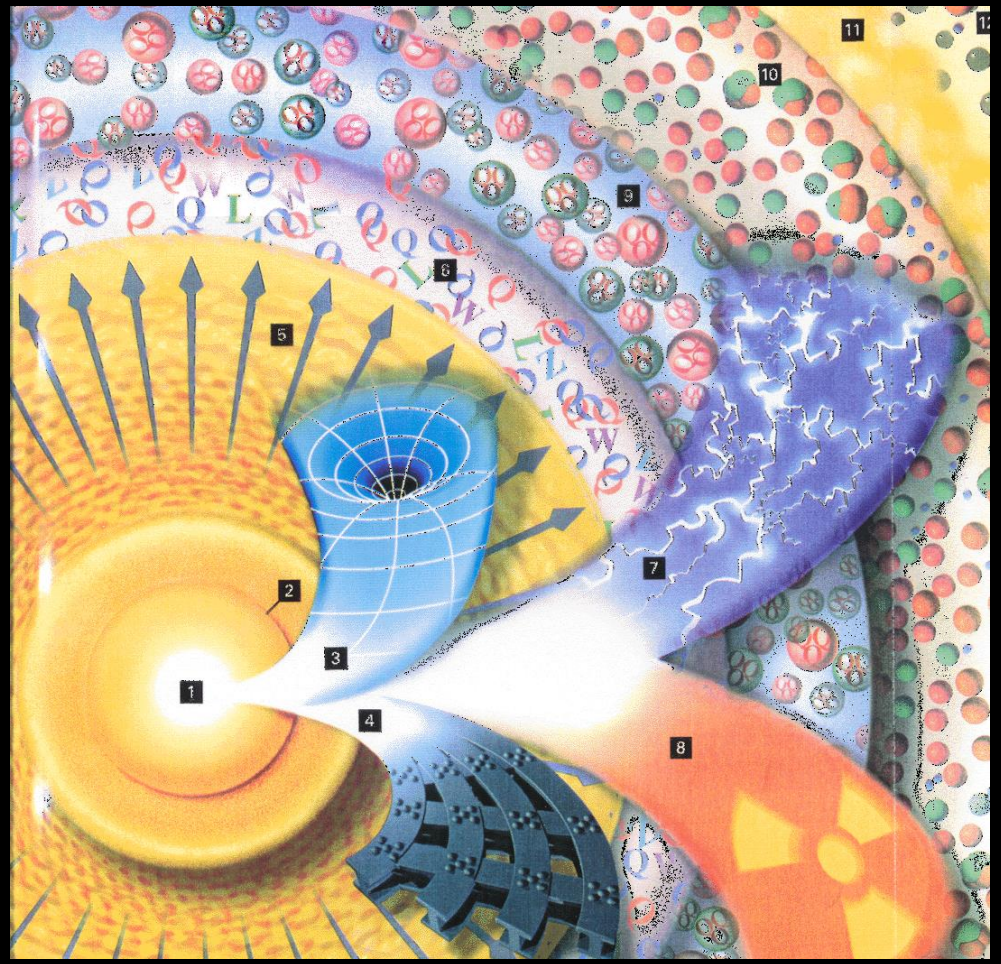
Courtesy L.R. Weih & L. Rezzolla (Frankfurt and CERN)

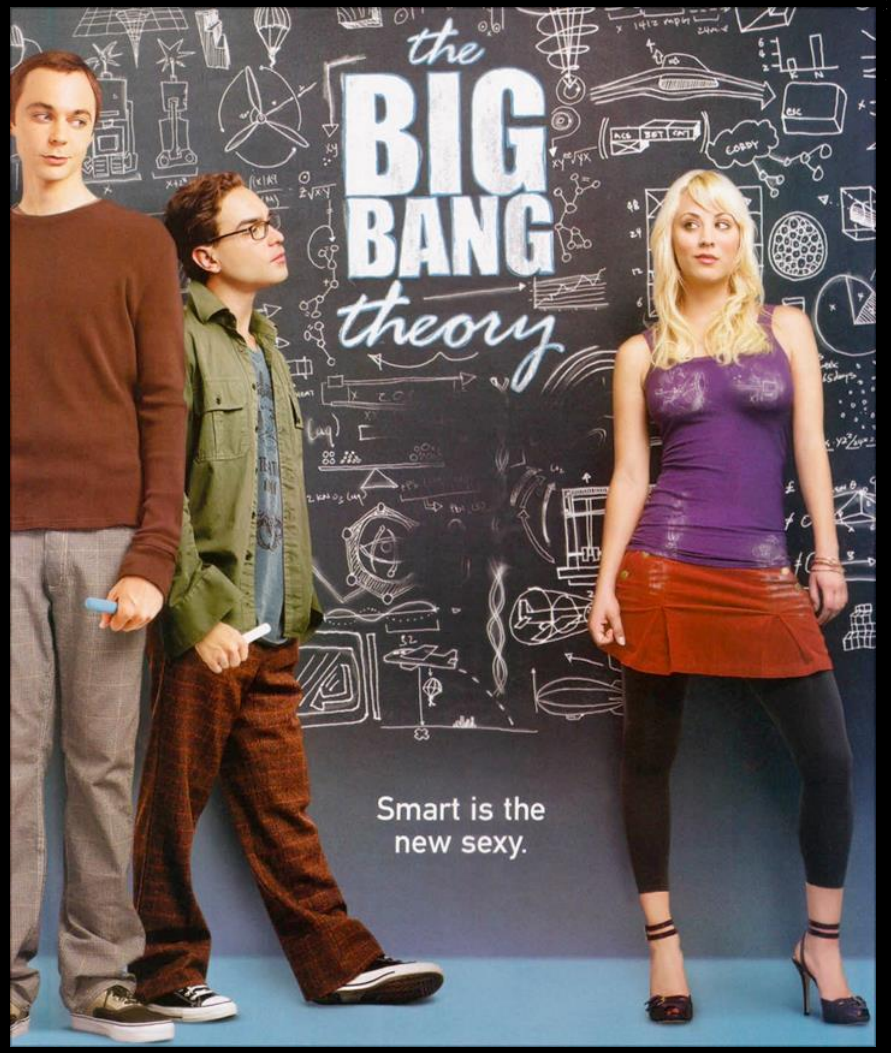
The Odyssey Continues!

- What about the Origin of Our Universe? (What happened early on…)
- What are the Properties of the Hot Quark-Gluon Soup?
- What is Dark Matter?
- What is Dark Energy?
- How Do We Resolve the Conflict between Quantum Mechanics vs Gravity?
- And What About String Theory and Extra Dimensions?
- Are there Extra Dimensions and other Universes?
- What will/can We Learn from Mergers of Binary Black Holes & Neutron Stars?
- ……

An Odyssey through our Universe

Thanks for your attention!





from the Big Bang to Black Holes, Unknown Dark Forces and Unseen Dimensions and Universes

John W. Harris, Yale University

Extra Slides

Recent Celestial Observations of Star Formation

Head-on Collision of Two Galaxies – Star Formation

Courtesy: Hubble Space Telescope / NASA

Merging of Two Galaxies – Waves of Star Formation

John W. Harris, Yale University

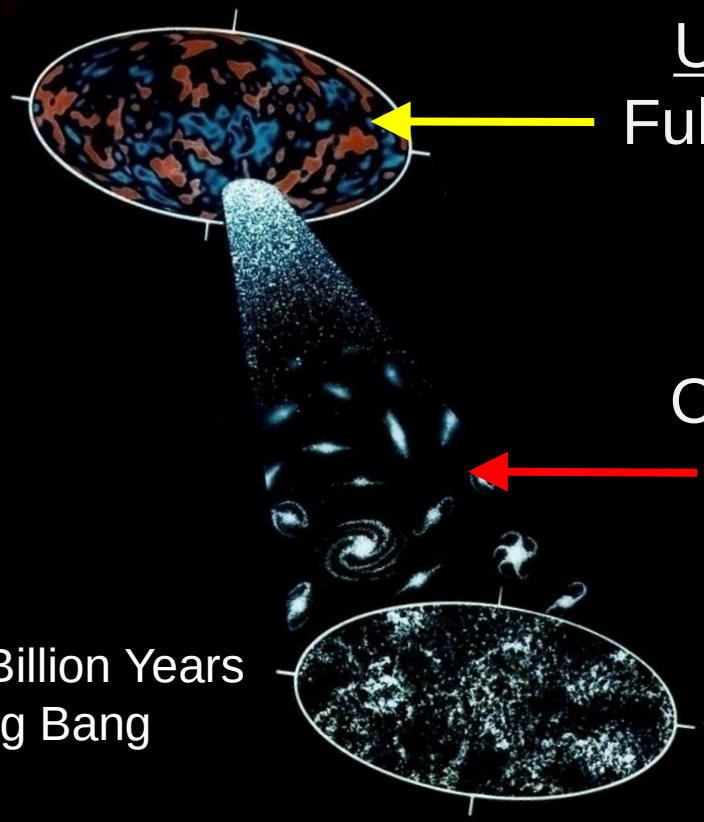
Courtesy: NSF BOIRLab/Dark Energy Survey

Merging of Two Galaxies – Waves of Star Formation

Courtesy: Hubble Space Telescope / NASA, ESA

Thanks for Your Attention!

Studying the Universe at Age 380,000 Years



Now: 13.9 Billion Years after Big Bang

Universe at Temperature T ~ 3000 K

Full of visible light (wavelength Λ ~ 1μm)

Universe expands & cools

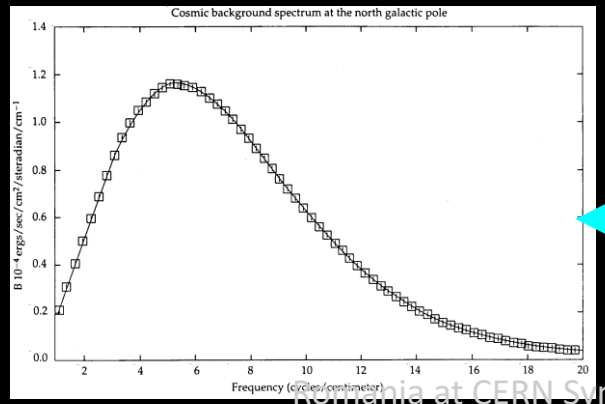
Causes light to change wavelength (red shift)

Shifts visible light to μwaves (Λ ~ 1cm)

Universe is now at T = 2.7 K

μwave radiation

Detected by satellites!



This is the

Cosmic Microwave Background (CMB) spectrum

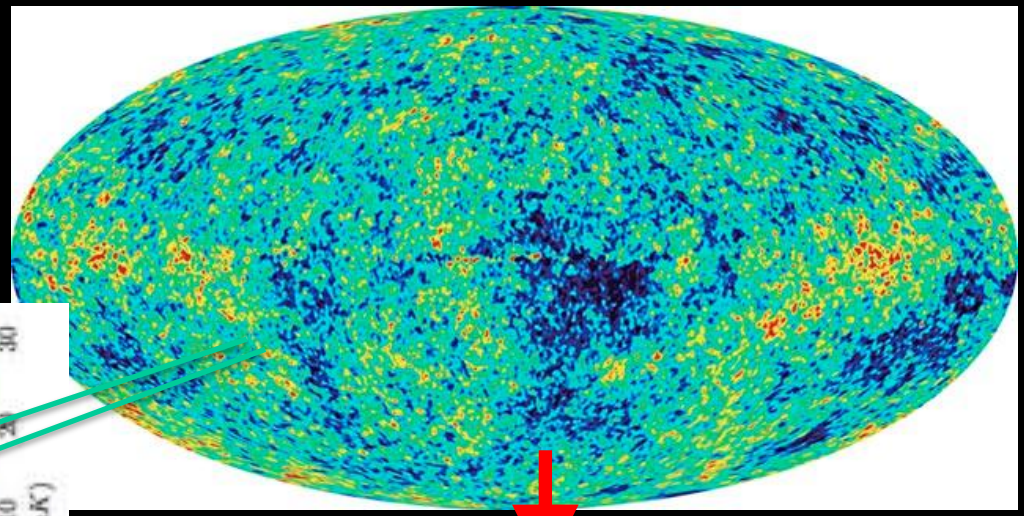
WMAP Analysis to Results

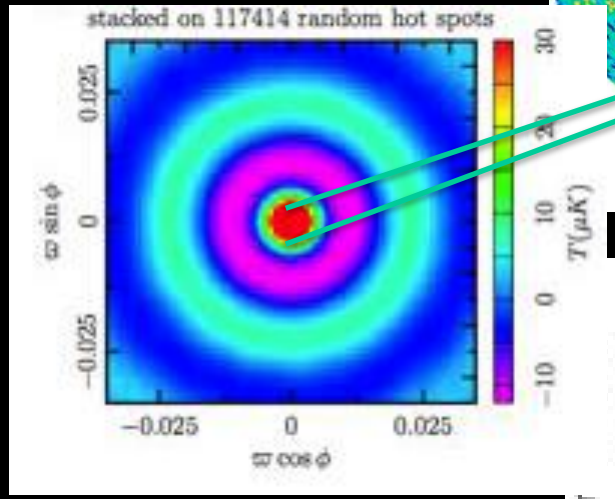
Deeper Quantification of WMAP Results

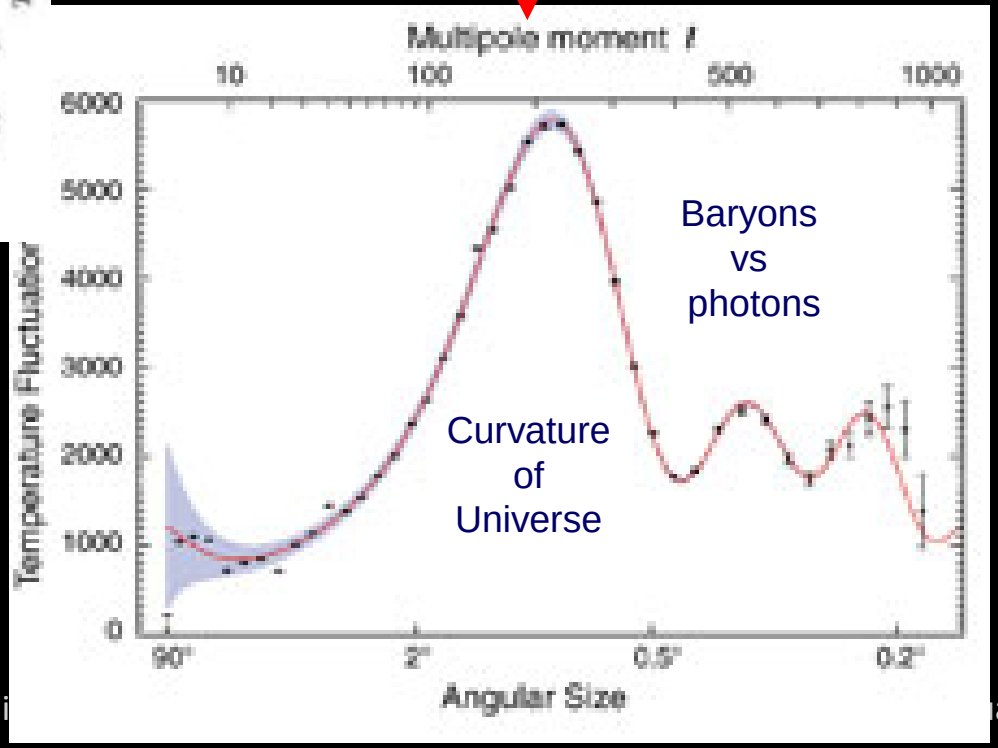
Transformation into Spherical harmonics

gives

Details of clumpiness on different size scales







What is this About 5-Dimensions?

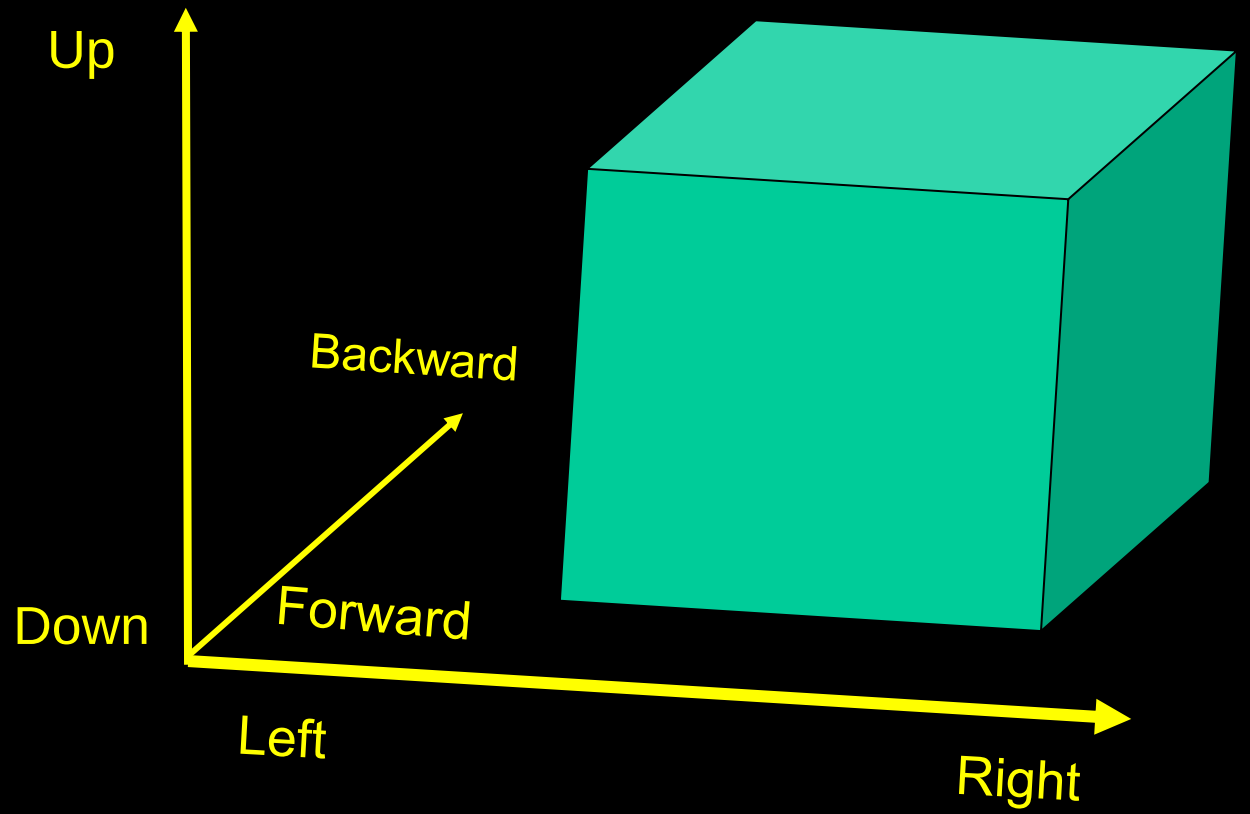
What the bleep?

A Black Hole in the 5th dimension? Explain……..

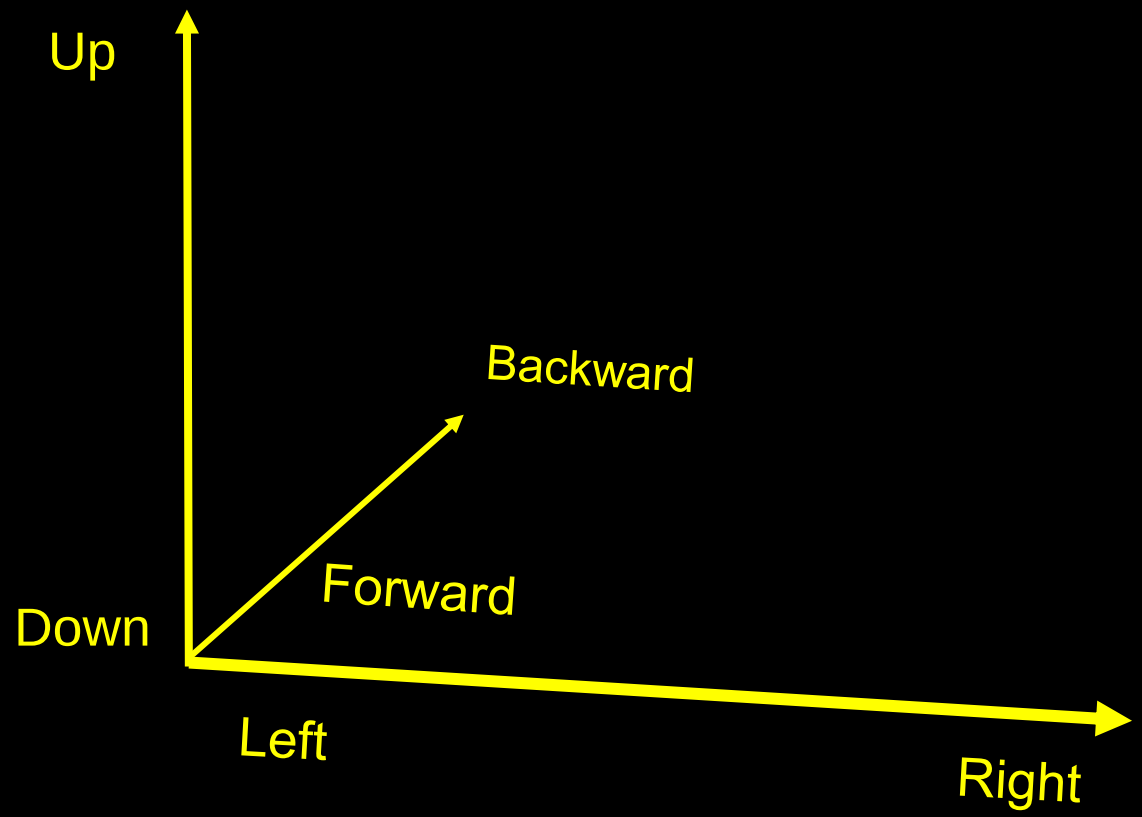
What's a Black Hole? ✓

What's this about 5D?

What's this about 5D?
We all know we live in 3 dimensions!

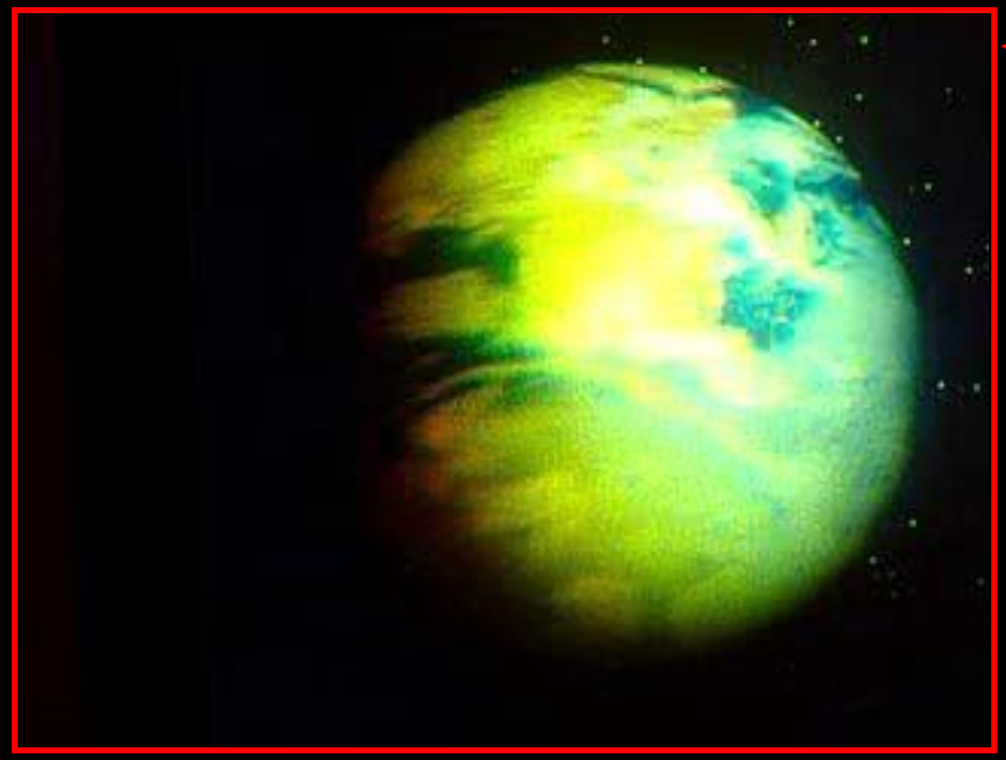


But do we?



Take 3D space + TIME! → It takes 4 dimensions to describe the world we live in!

2D Holograms



on a 2D Flat Film

Up

Down

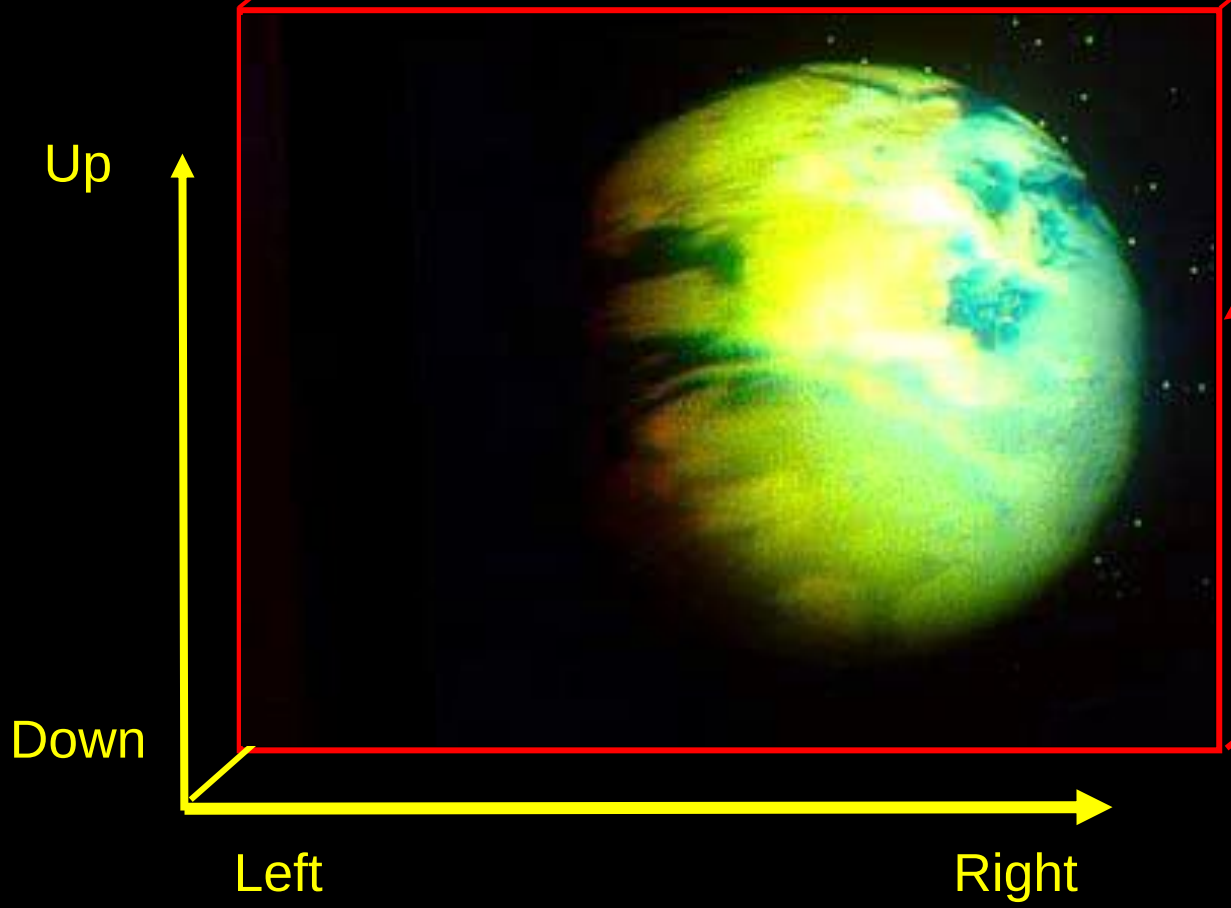
Left

Right

is encoded a
3D World!

For simplicity – let's consider only the 3 spatial dimensions!

"Imagine" our World as a 3D Hologram

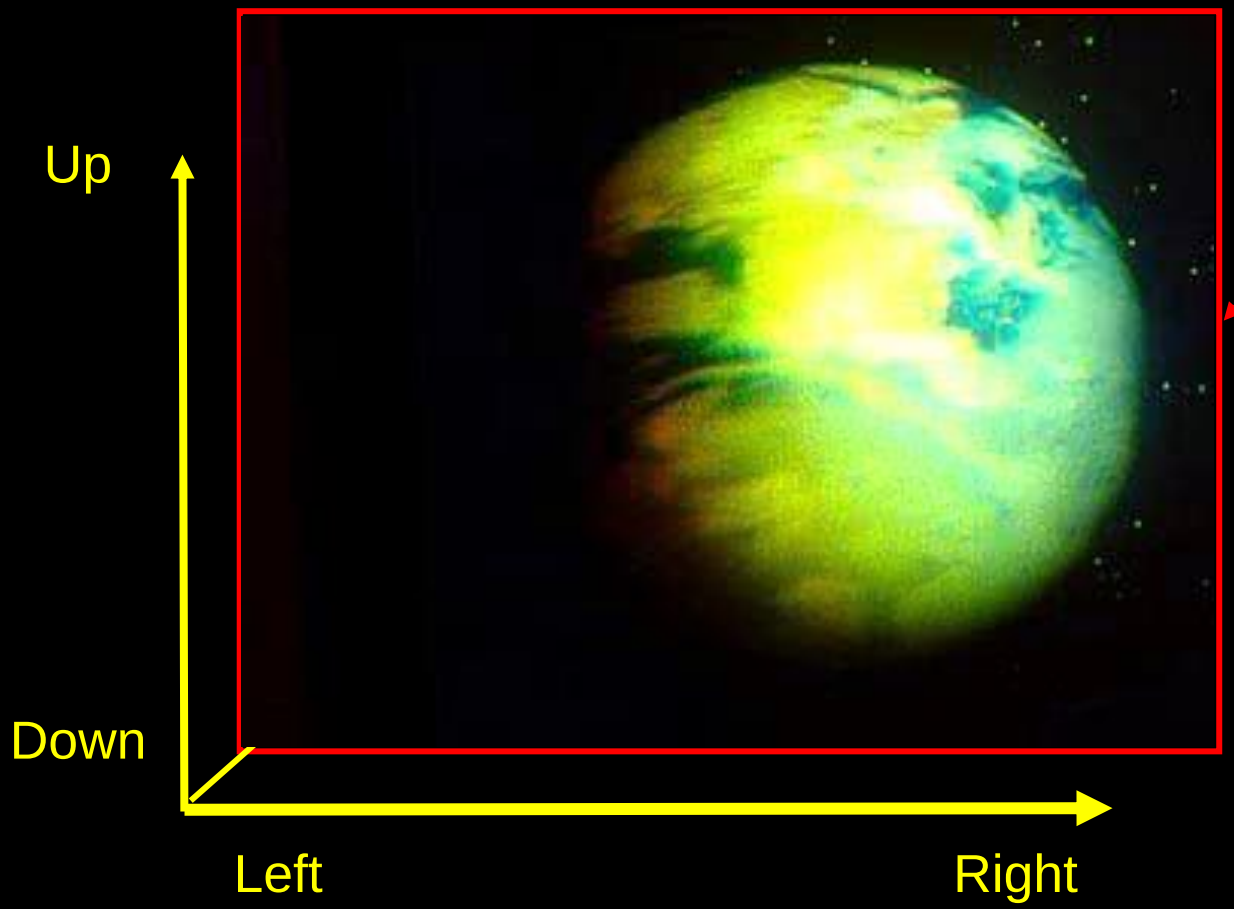


Imagine we live on a 3D hologram

Can a 4D World be "painted" onto our 3D surface?

For simplicity – let's consider only 3 spatial dimensions!

Now – Take into Account the Time Dimension



We live in
3D space + time
on a
4D surface

Now consider also the time dimension since we live in 4D!

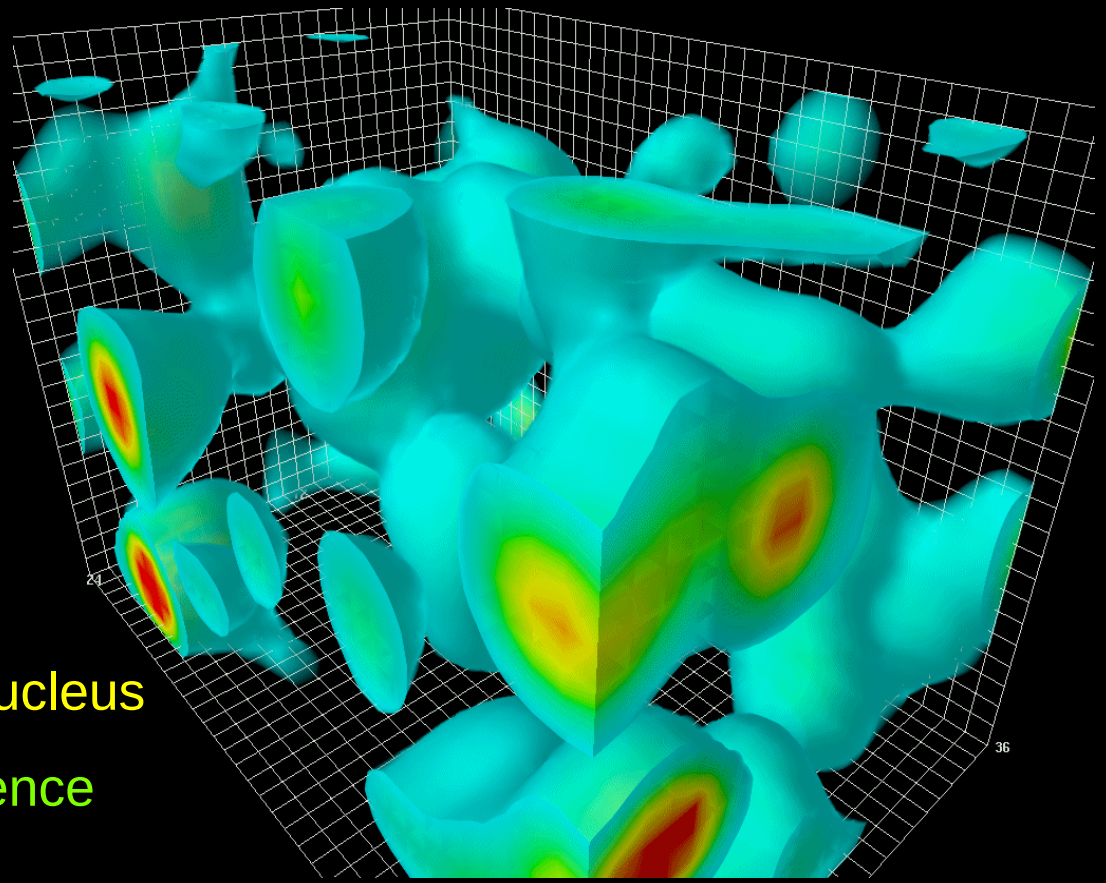
In which
a 5D World can
be encoded!

Gravity versus Quantum Mechanics

In Quantum Mechanics – Empty Space Is Not a Void!

The vacuum of space on the scale of the size of the nucleus

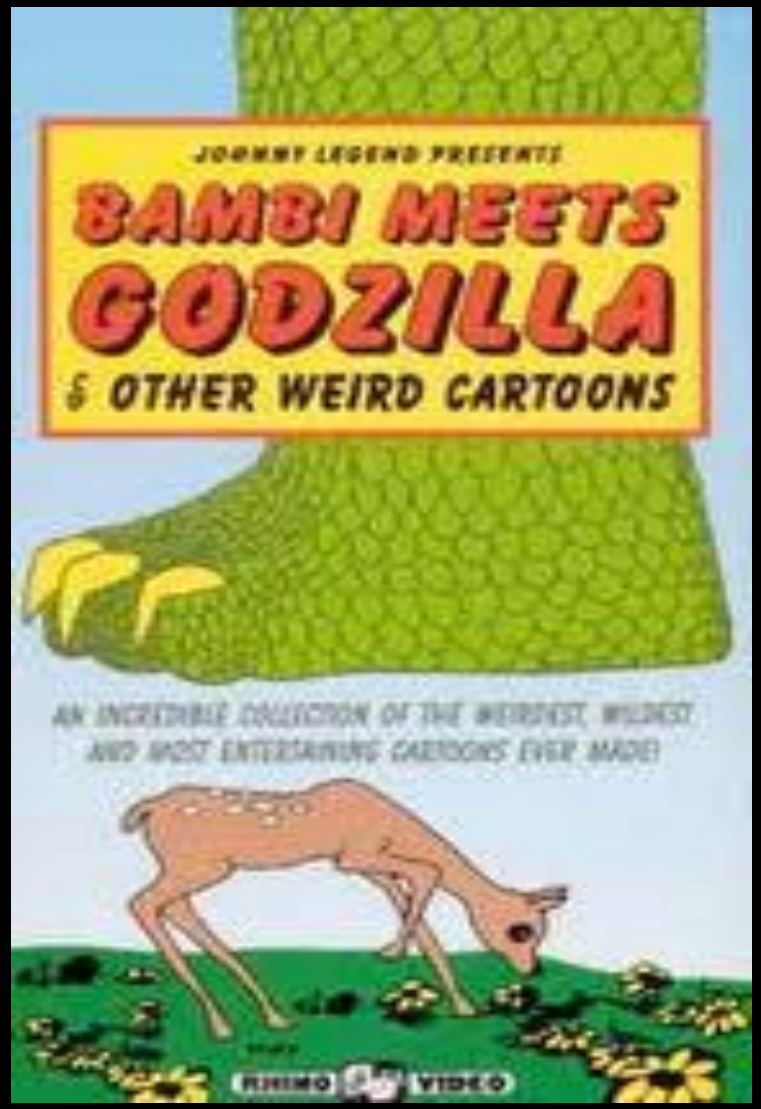
quarks and gluons come into and out of existence

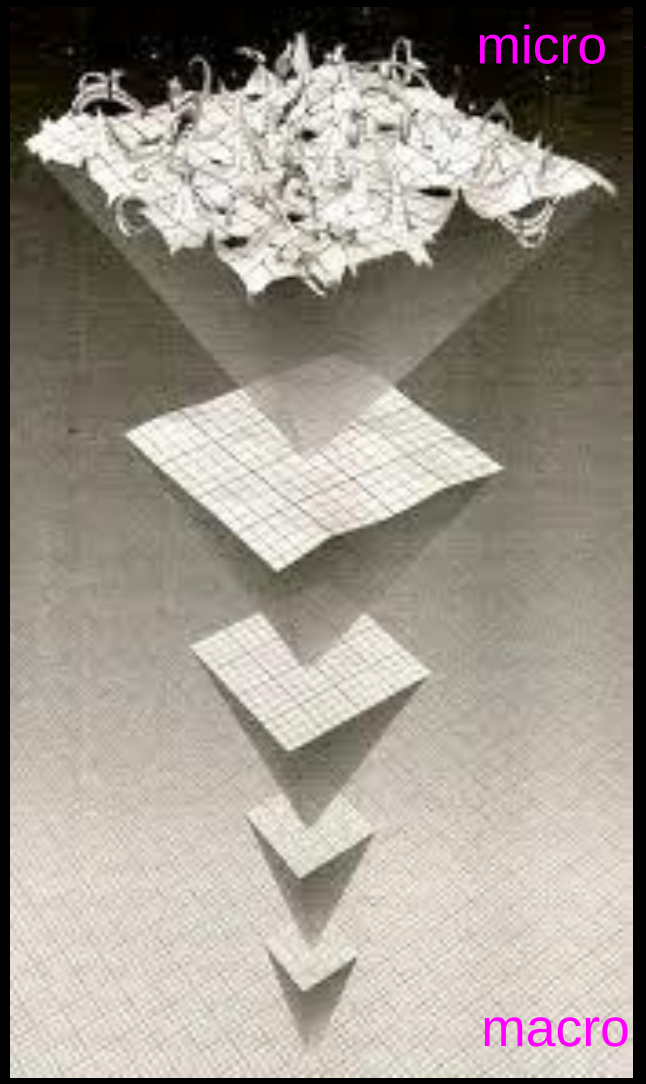


Lattice Quantum-based dynamical vacuum visualization
Adelaide Group

Gravity vs Quantum Mechanics – Cosmic Conflict!

Conflict with Quantum Mechanics on small scales!

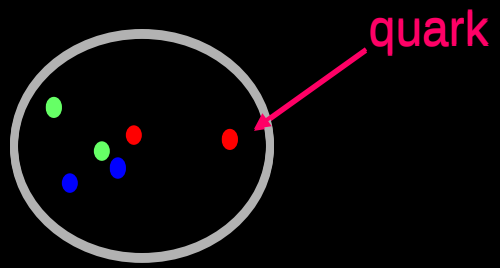




How to Make Quark Soup!

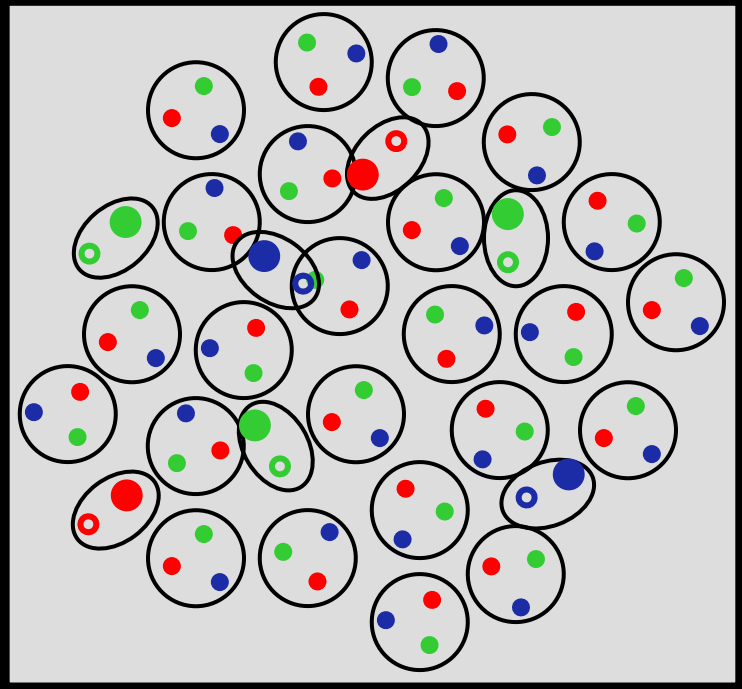
Strong – Nuclear Force

"confines" quarks and gluons to be in particles



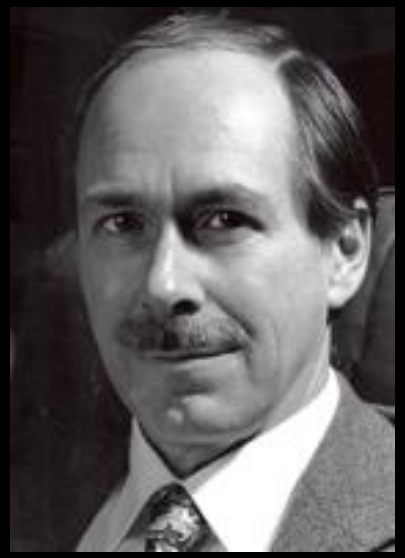
• Compress or Heat Nuclei in high energy nuclear collisions

→ *Quark-Gluon Soup !*



Quark-Gluon Soup
(quarks are confined)

4D Representation of a 5D World



Gerhard t' Hooft
Nobel Prize, 1999

Known as the Holographic Principle
(co-founders t' Hooft and Susskind)

Universe can be described as a 5D system

- has 4D volume and extends in time

equivalent to 4+1 or 5D space-time.

"Father of String Theory"

If this Holographic Principle holds - a difficult calculation on the 4D boundary,
[such as the behavior of quarks and gluons in our world]
could be traded for an easier calculation in 5D.