A Journey Through Time & Space:

Compiling our Cosmic Inventory

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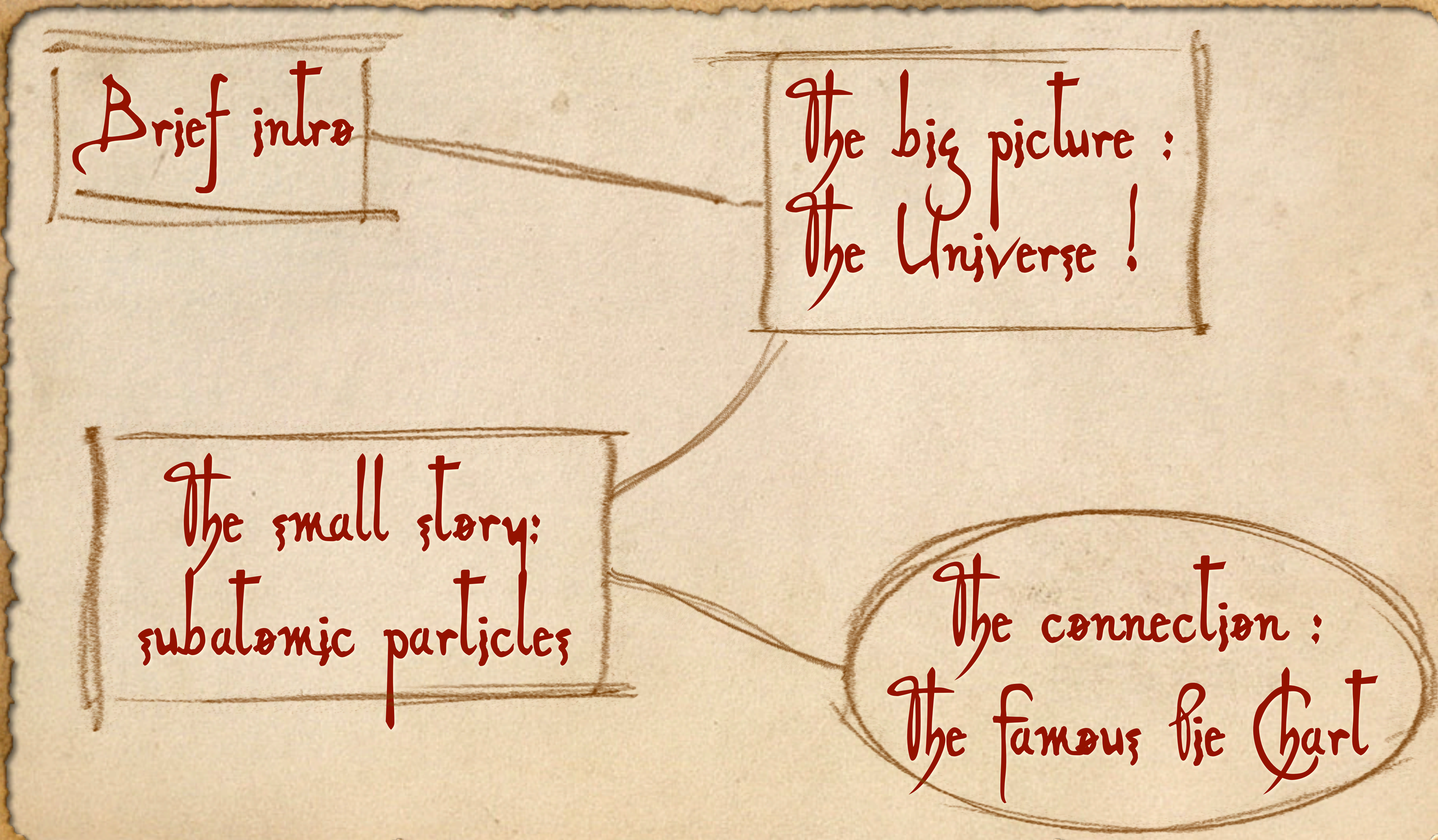
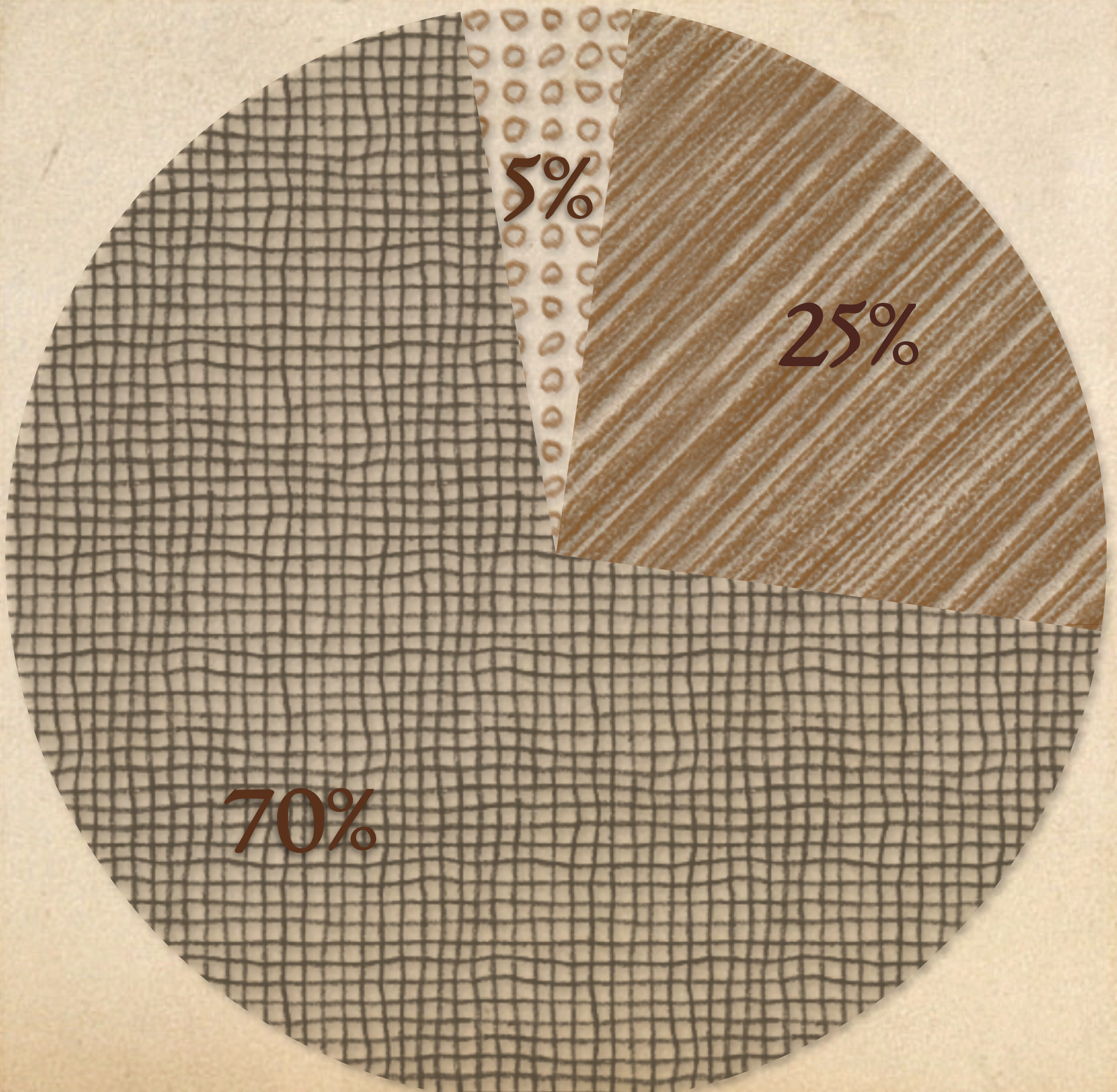
I ask you to look both ways. for the road to a knowledge of the stars leads through the atom; and important knowledge of the atom has been reached through the stars.

~Arthur Eddington

Outline of The Talk



The Famous Pie Chart



100 years in the making

Turn of the 20th Century

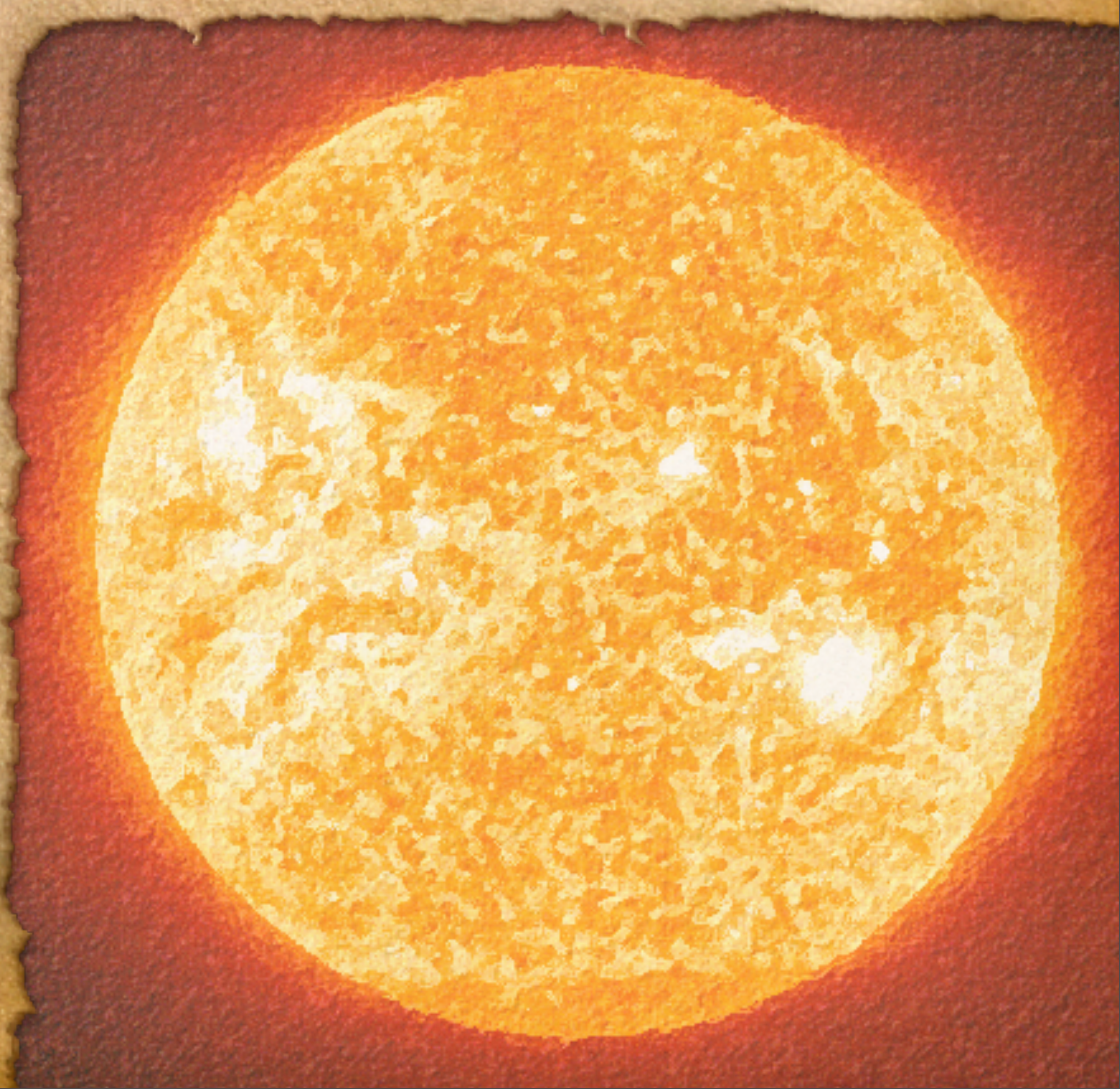
- Physics is finished !!!
- Physics is:
  - Classical mechanics & Thermodynamics
  - Electromagnetism & Newtonian gravity
- Current theory able to explain all experimental observations

  (except for a few pesky, probably irrelevant details)
- Promising young candidates (e.g. Einstein) encouraged to enter a different field

From The Solar System out to the Edge of the Universe

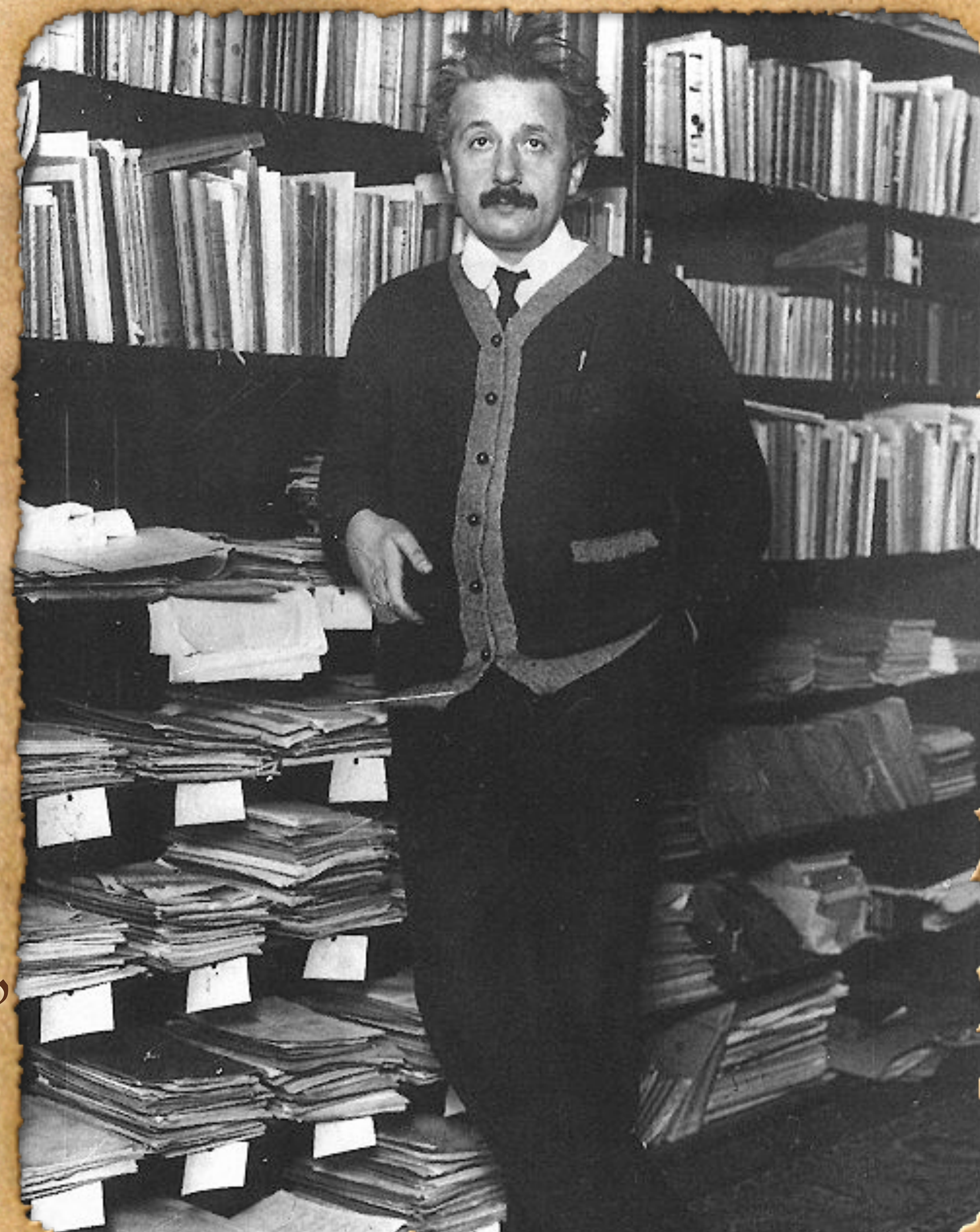
Starting at 1901 ...

- The Sun is at the center of the universe
- The Milkyway constitutes the entire universe
- Newtonian gravity can explain all astronomical observations
- The universe is unchanging !



But all that was soon to change …

- 1915 : Einstein proposed General Relativity
  - An alternative to Newton's Gravity
  - Milkyway was still the entirety of the Universe
  - Universe was still 'unchanging'
    - This "wrong" assumption, amazingly, lead to an important and correct result



… change gathers momentum …

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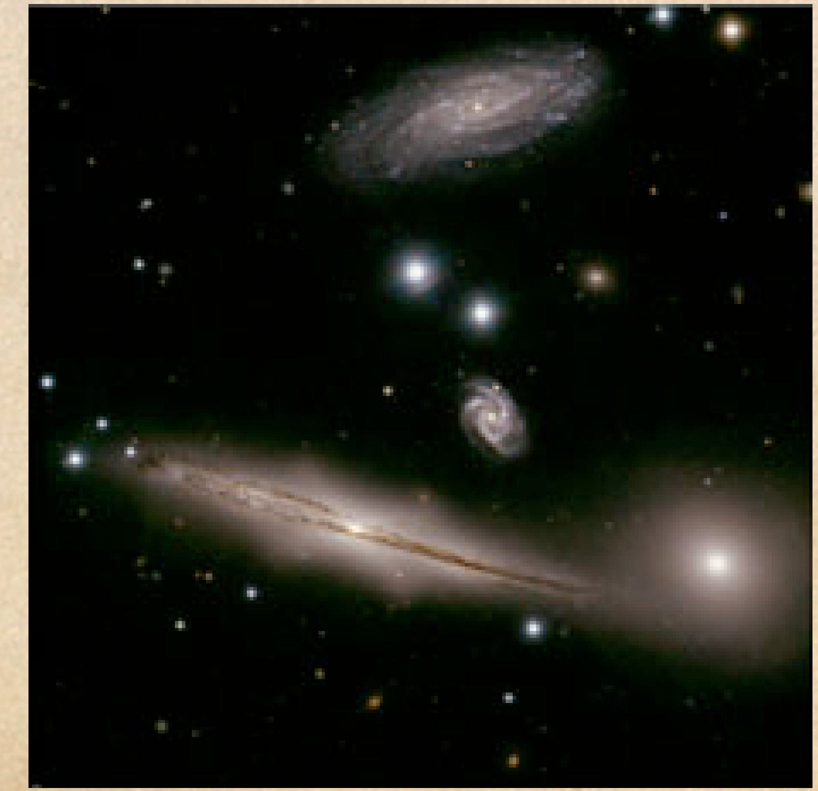

… change gathers momentum …

- 1920's : Galaxies other than Milkyway discovered !

… the last nail in the coffin of classical astrophysics !

- 1929 : Edwin Hubble discovers that the Universe is expanding !!
- The rate of expansion increases linearly with distance
- Famous Hubble law
(got a telescope named after him)

What's in a line ?

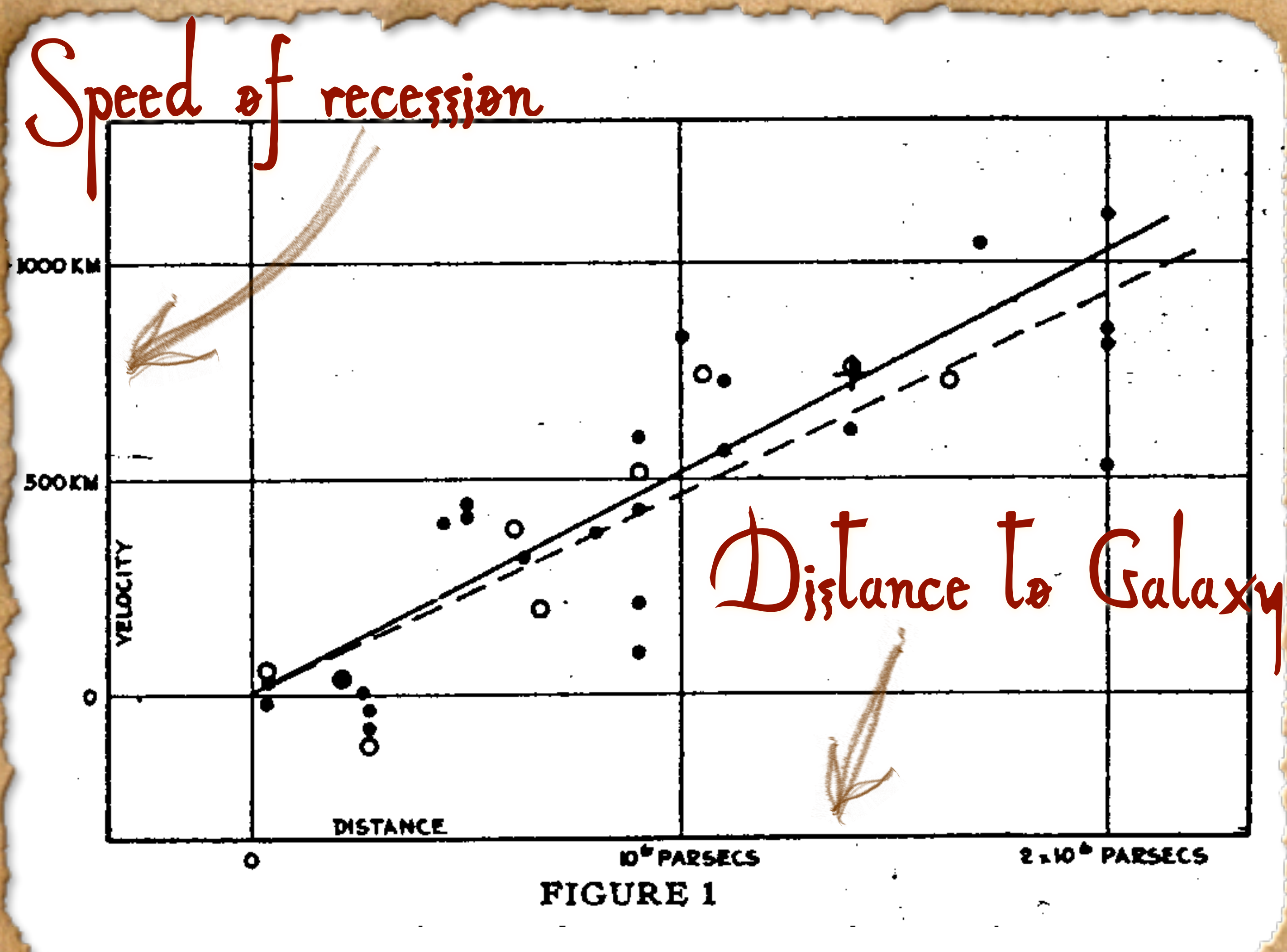

FIGURE 1

If the universe is currently expanding, it was smaller in the past. This reasoning eventually leads to the idea of the Big Bang

The expansion of universe is naturally explained by Einstein's General Relativity

The Unavoidable Equation

- General Relativity relates the shape of space to its the local content of matter and energy

$$R^{\mu}_{\nu} - \frac{1}{2} g^{\mu}_{\nu} R = \frac{8\pi G}{c^4} T^{\mu}_{\nu}$$

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Mathematical description of the geometry of space

The Matter/Energy content

The Unavoidable Equation

Newton's "G"

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That's where things stood for a while

From The Atom
On Down

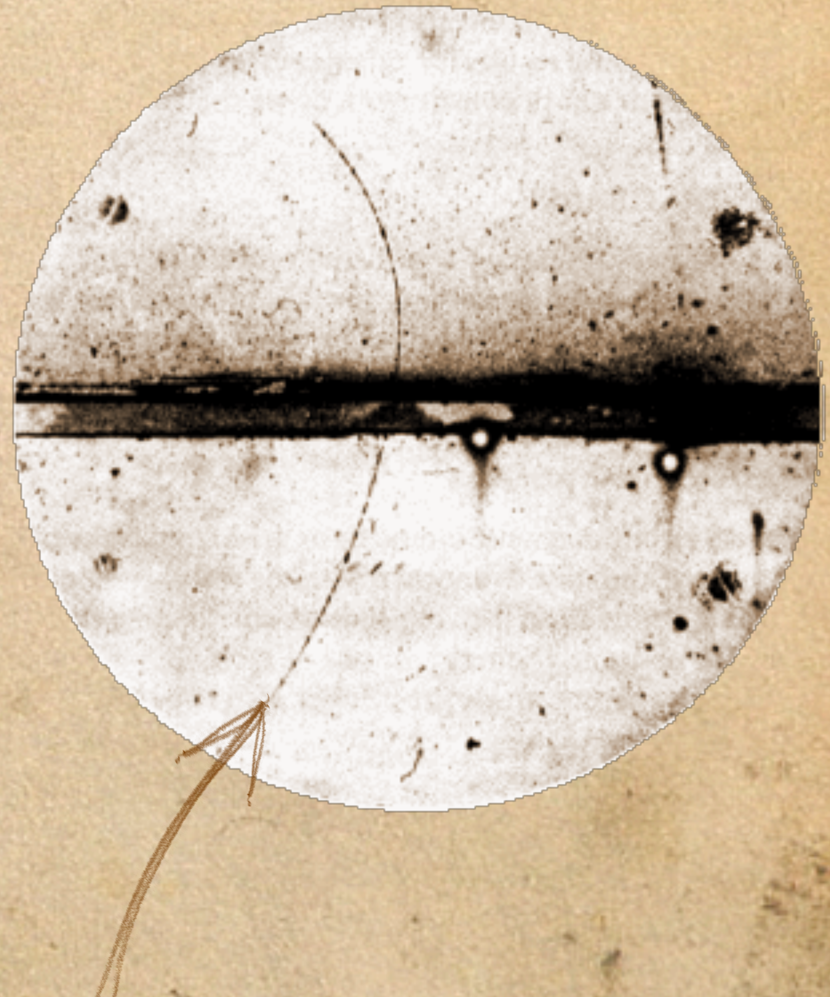
Back to 1901 …

- The "raisin pudding" model of the atom
  - Only the electron was known to exist separately
- 1911 : Rutherford discovers the nucleus
- 1919 : The proton is discovered

An Explosion of Particles

Particle Physics' Golden Age

- Nature had a few more particles up its sleeve
- In the 1920's/30's the development of Quantum Theory went hand in hand with the discovery of those particles



Discovery of the Positron in 1933

The Explosion Continues

- 1929 : Ernesto Lawrence builds the first particle accelerator (got two national labs named after him and a nobel prize to boot)
- Allows physicists to peek behind the nature's stage curtain
- A multitude of new subatomic particles are discovered

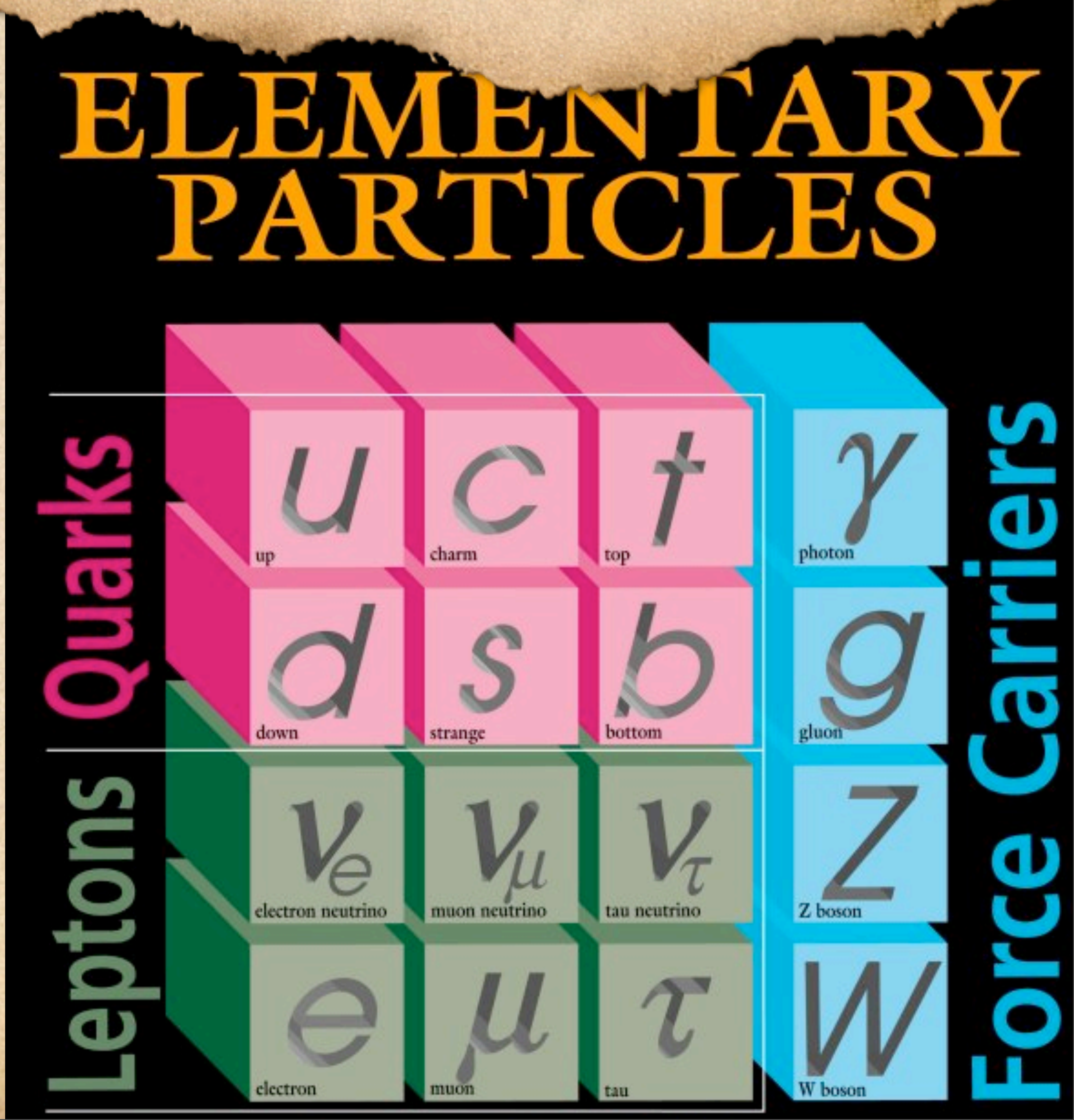
fast forward

~ 50 years

The Standard Model

- A mathematical description of all the observed fundamental particles and their interactions

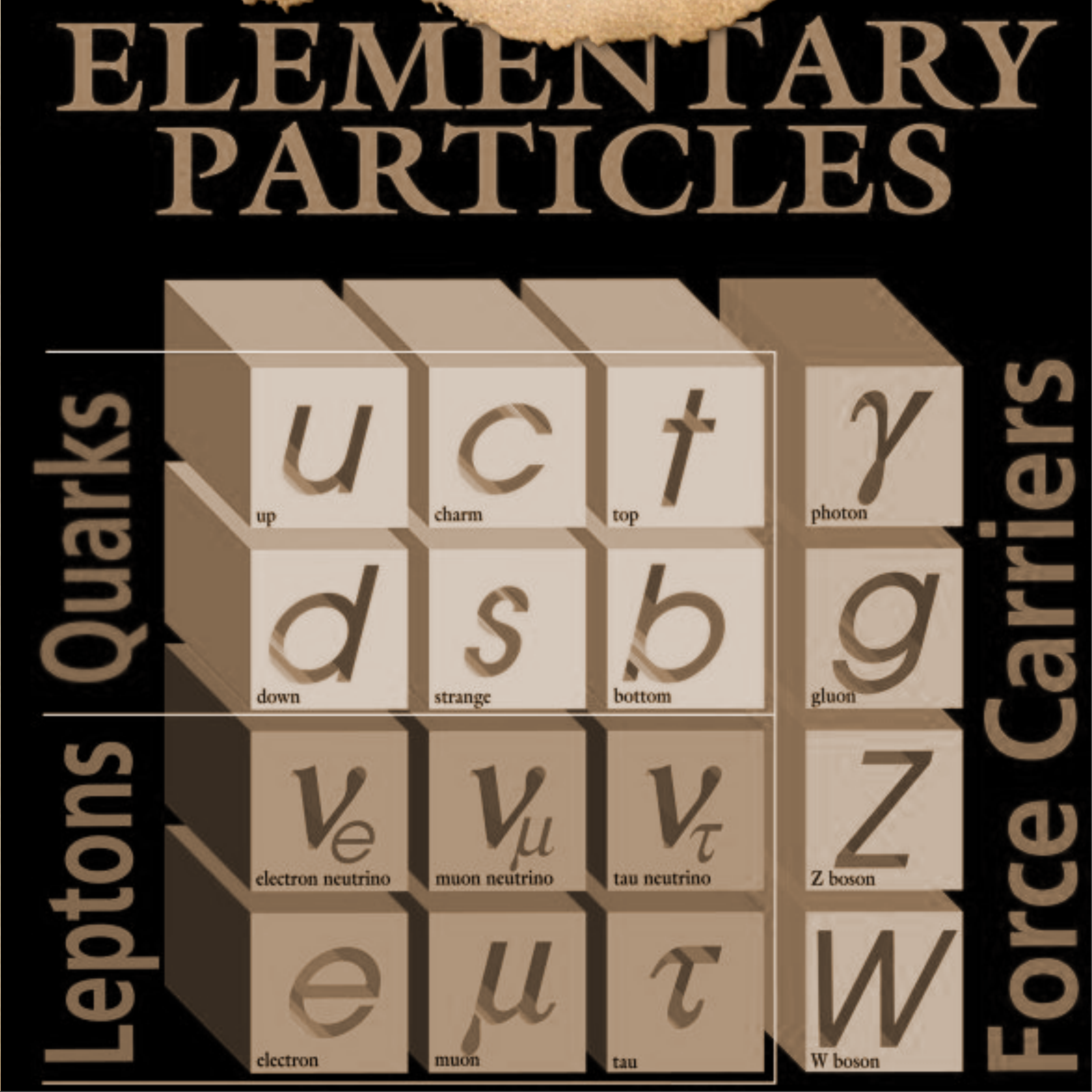
See talks by Giulia Zanderighi



The Standard Model

- A mathematical description of all the observed fundamental particles and their interactions
- A very successful theory, … BUT …

See talks by Giulia Zanderighi

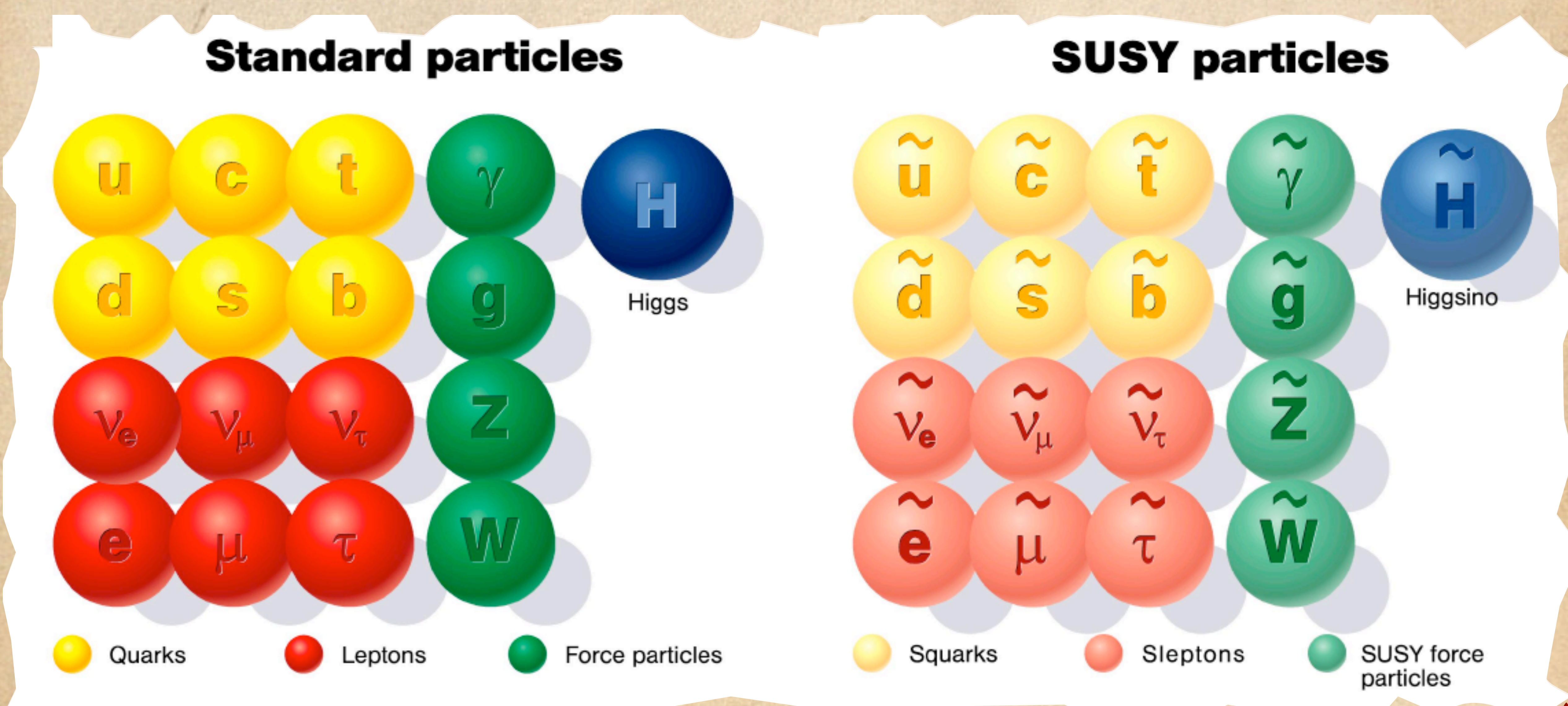


Is That Really Everything ?

- Probably not !!
- There are an increasing number of experimental measurements that are hard to explain by the Standard Model
- It has lots of "theoretical problems" which spurred physicists to look beyond it to a "more fundamental" theory

Supersymmetry

- An extension of the Standard Model



See Talks by R. Godbole

Consequences of Supersymmetry

- Most supersymmetric particles are too short lived to be observed in nature
- One particle, however, may be stable and potentially observable
- Such a particle would be massive, and interact rarely with 'regular' matter
- Typically referred to as a WIMP
  - Weakly Interacting Massive Particle

See talks by Richard Taillet

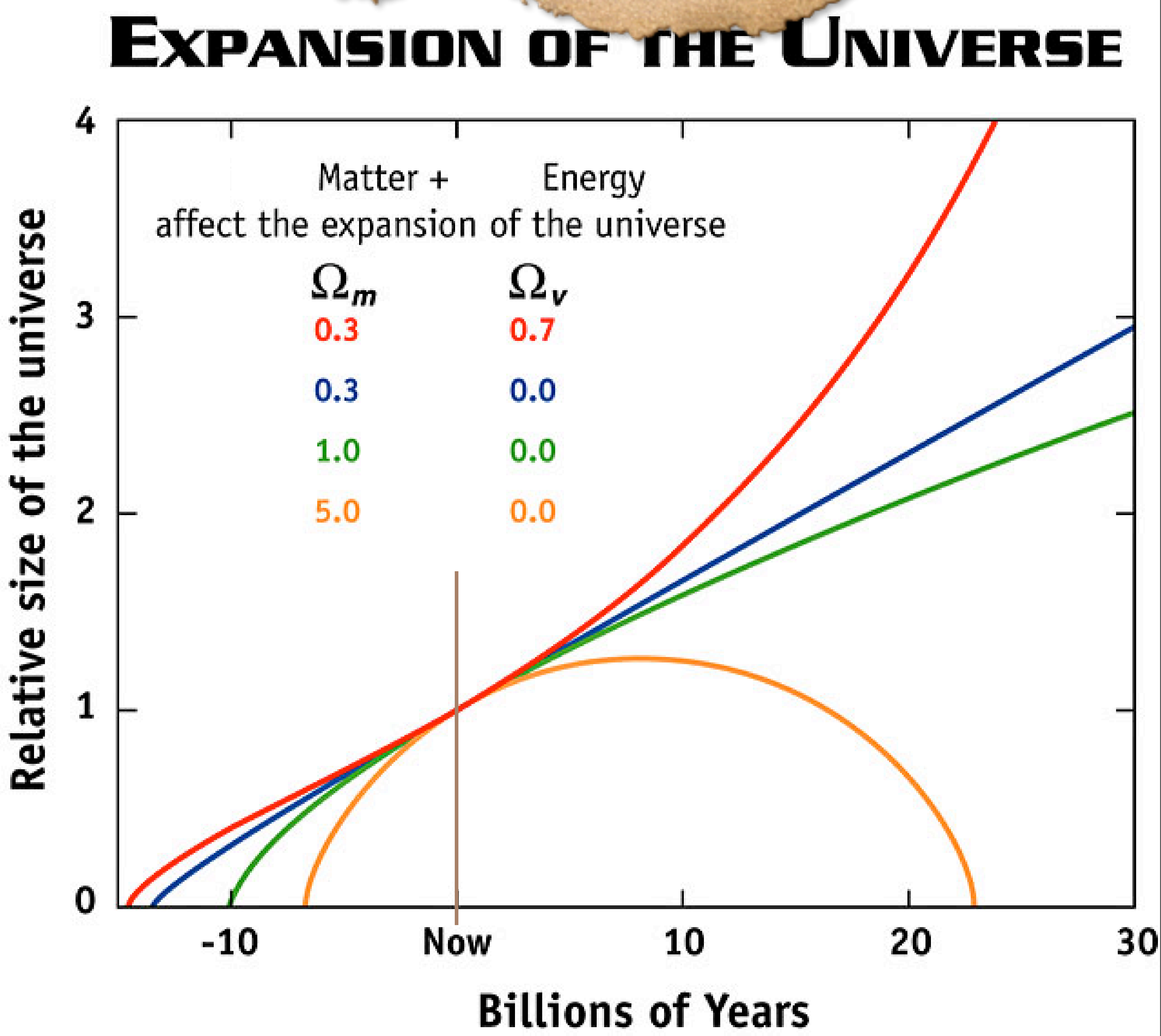
All the Ingredients at Hand

- With a particle theory such as Supersymmetry we have all the elements required to calculate T^{μ}_{ν}
- We can calculate the abundance of each particle type as a function of energy/temperature/time etc ...
- This in turn gives us the size/shape of the universe as a function of time ...

The Cosmological Souflé

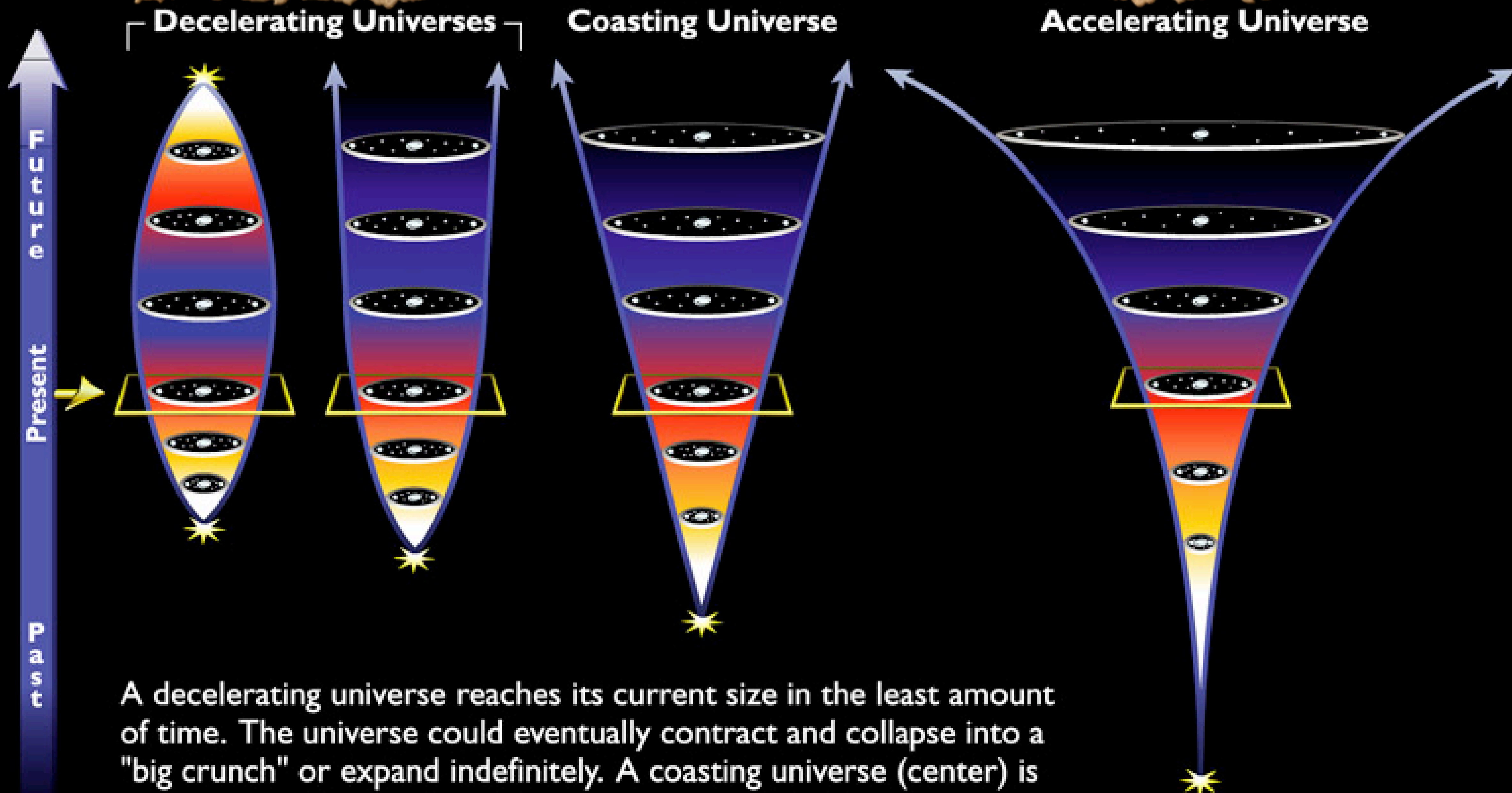
"Will it rise or will it fall ?"

- Different starting amounts of mass and energy can lead to vastly different cosmological outcomes



See talks by Laurence Perotto

The Evolution of the Universe



A decelerating universe reaches its current size in the least amount of time. The universe could eventually contract and collapse into a "big crunch" or expand indefinitely. A coasting universe (center) is older than a decelerating universe because it takes more time to reach its present size, and expands forever. An accelerating universe (right) is older still. The rate of expansion actually increases because of a repulsive force that pushes galaxies apart.

Something's Still Missing

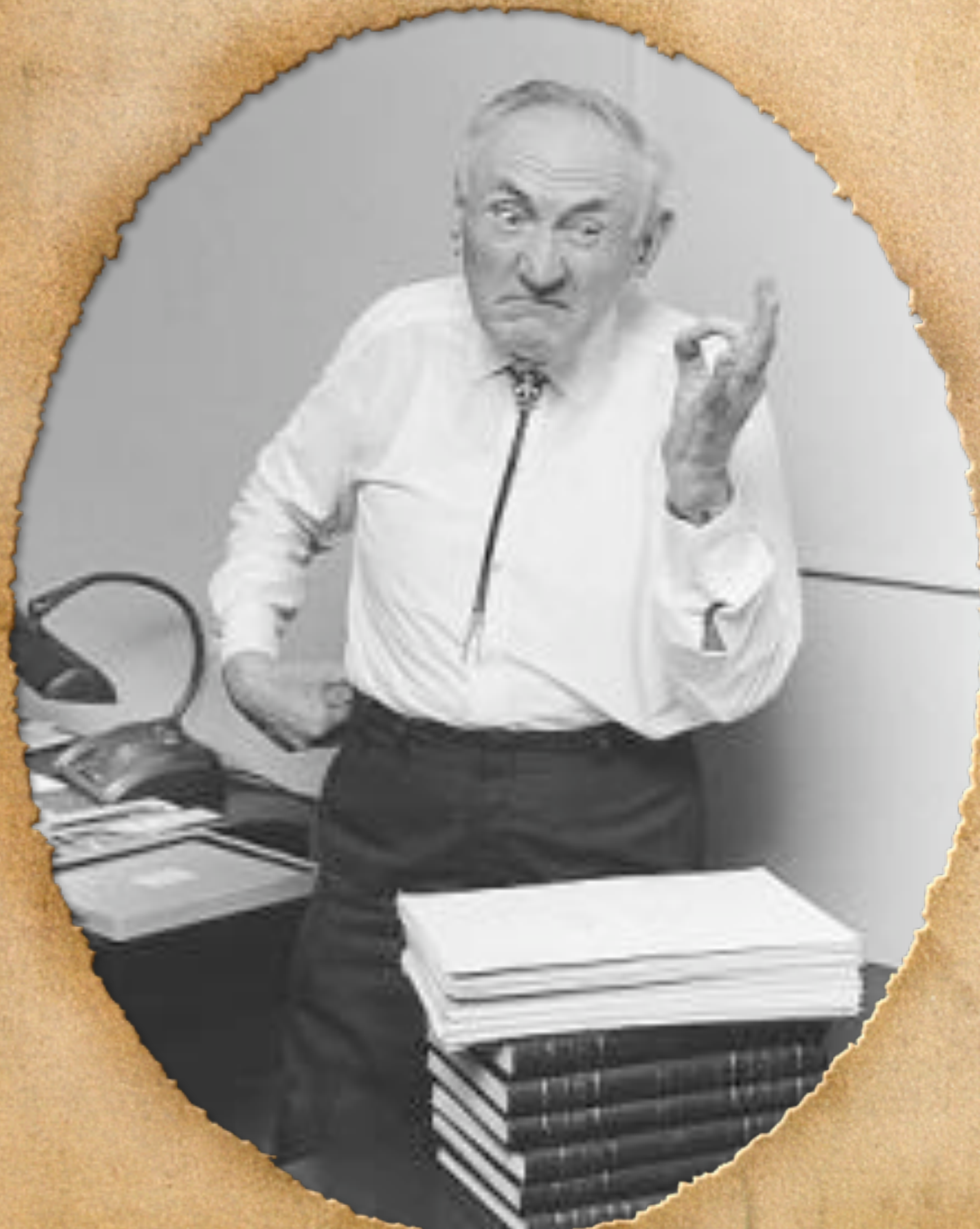
- We have in our hand a very powerful concept
- But, … it is like giving you all the directions from a chocolate cake recipe, but none of the starting amounts of ingredients
- We need some observational data

otherwise the theorists will come up with crazy ideas

Convergence of the Big and Small

(Weighing the Universe)

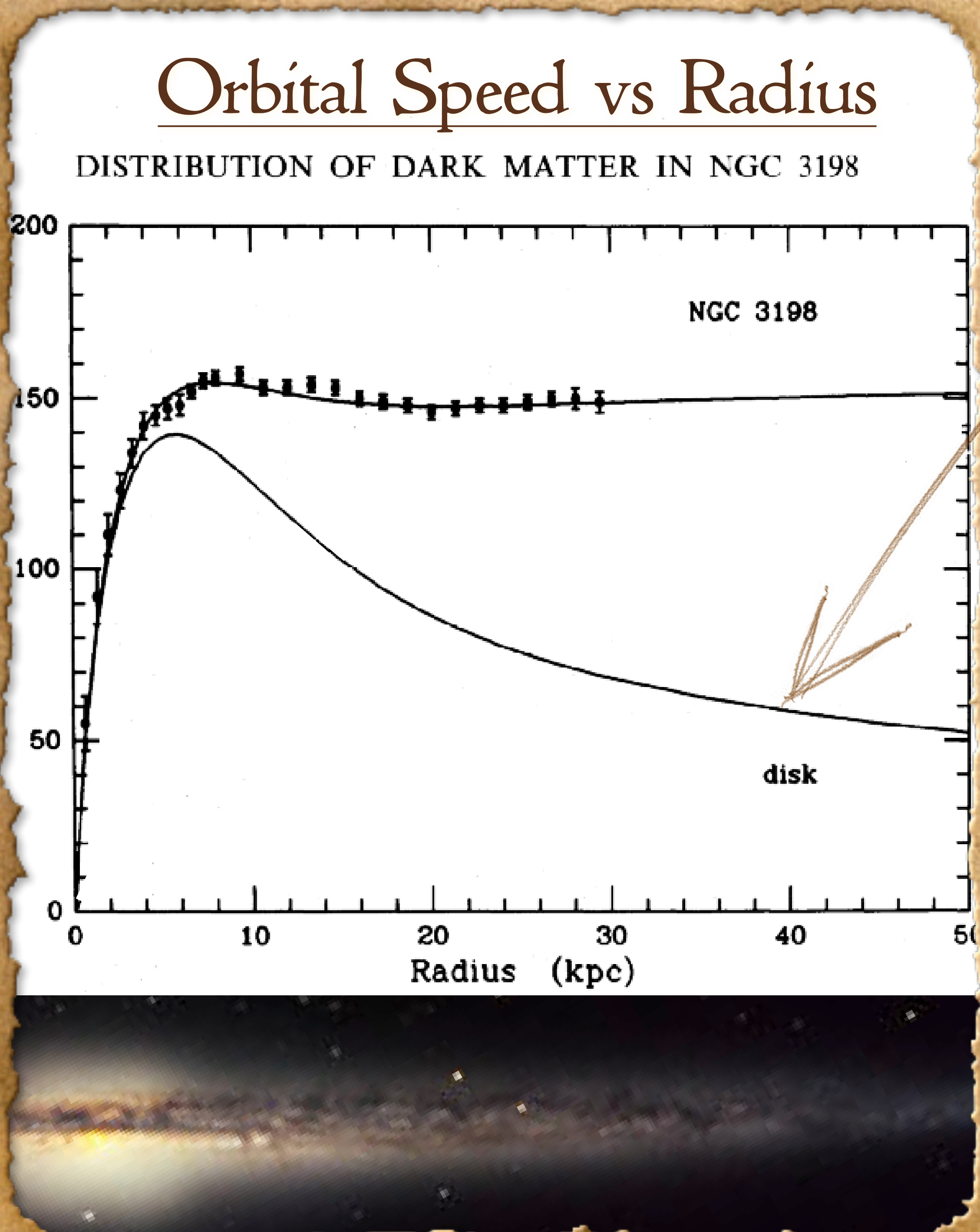
The Visible Universe
"Why there is too much Gravity"



- As early as the 1930's there was some evidence the the amount of luminous matter (i.e. stars) is not sufficient to account for the observed gravitational effects
  - However, the significance of the results was not fully appreciated for several decades.

The Case For More Gravity

"Galactic Rotation Curves"



- The orbital speed of stars around the galactic center can be easily calculated
- The mass of stars is < 10% of that required to produce the observed speed

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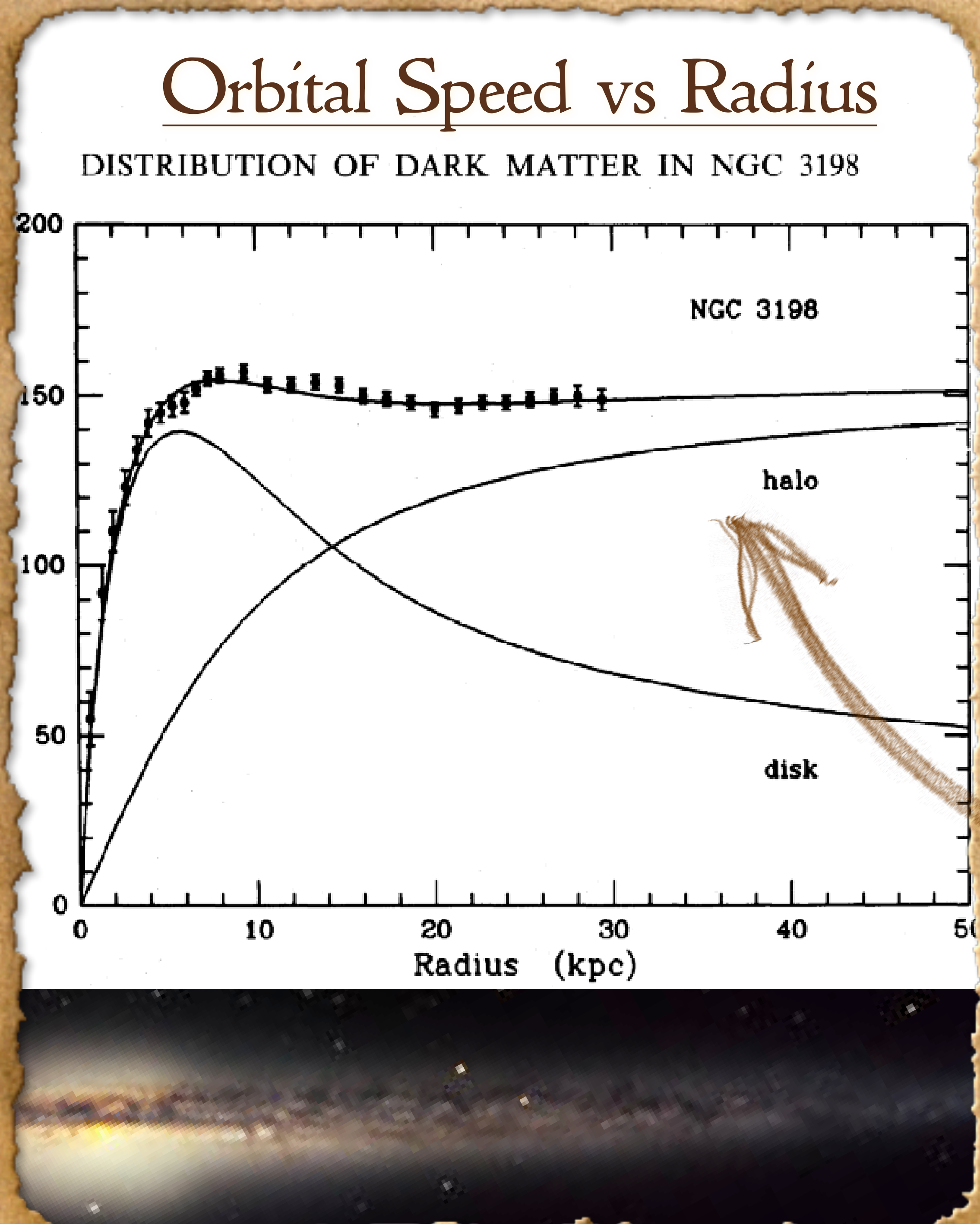
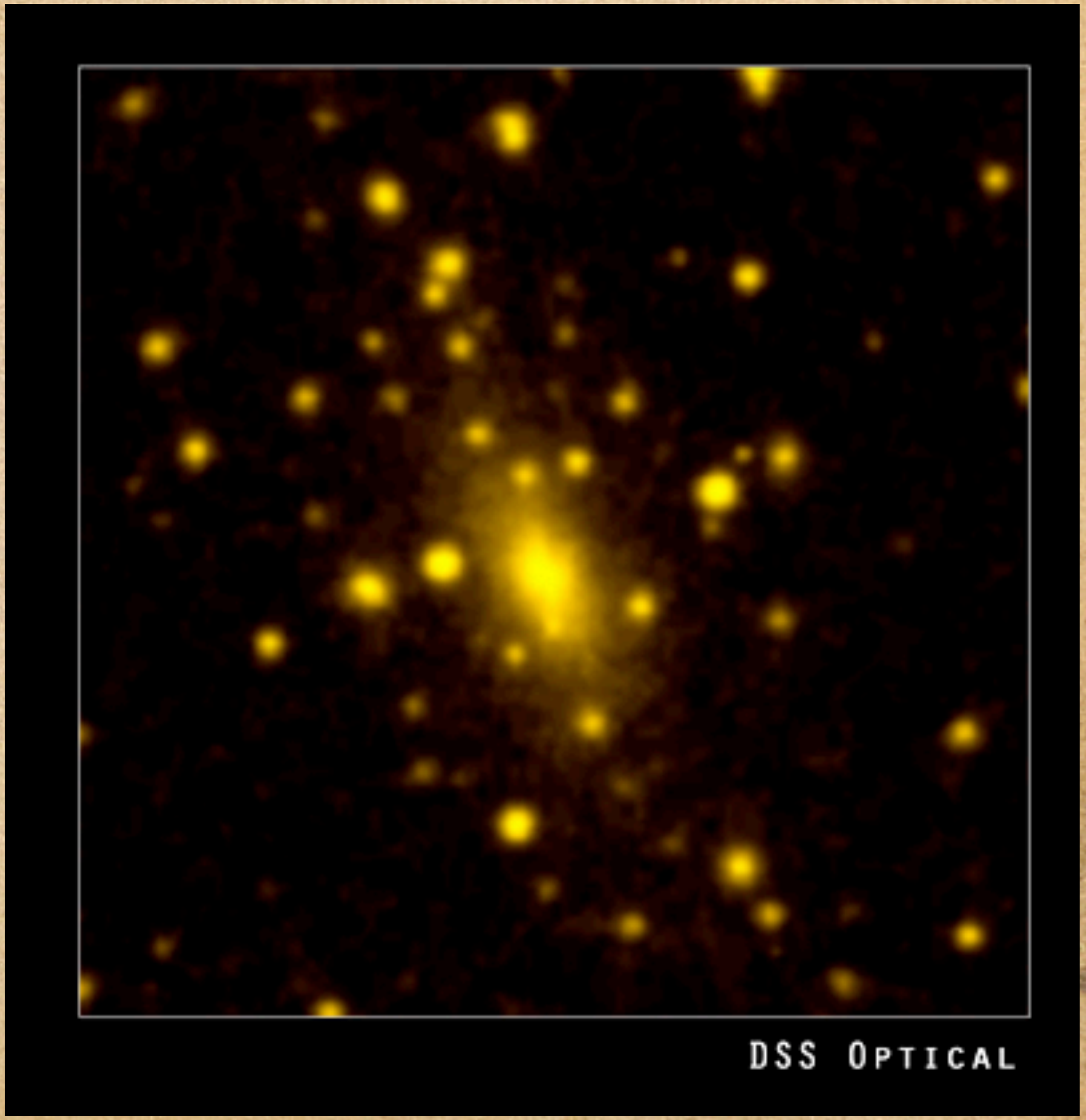


- The orbital speed of stars around the galactic center can be easily calculated
- The mass of stars is < 10% of that required to produce the observed speed
- Could there be some additional "invisible" mass ?

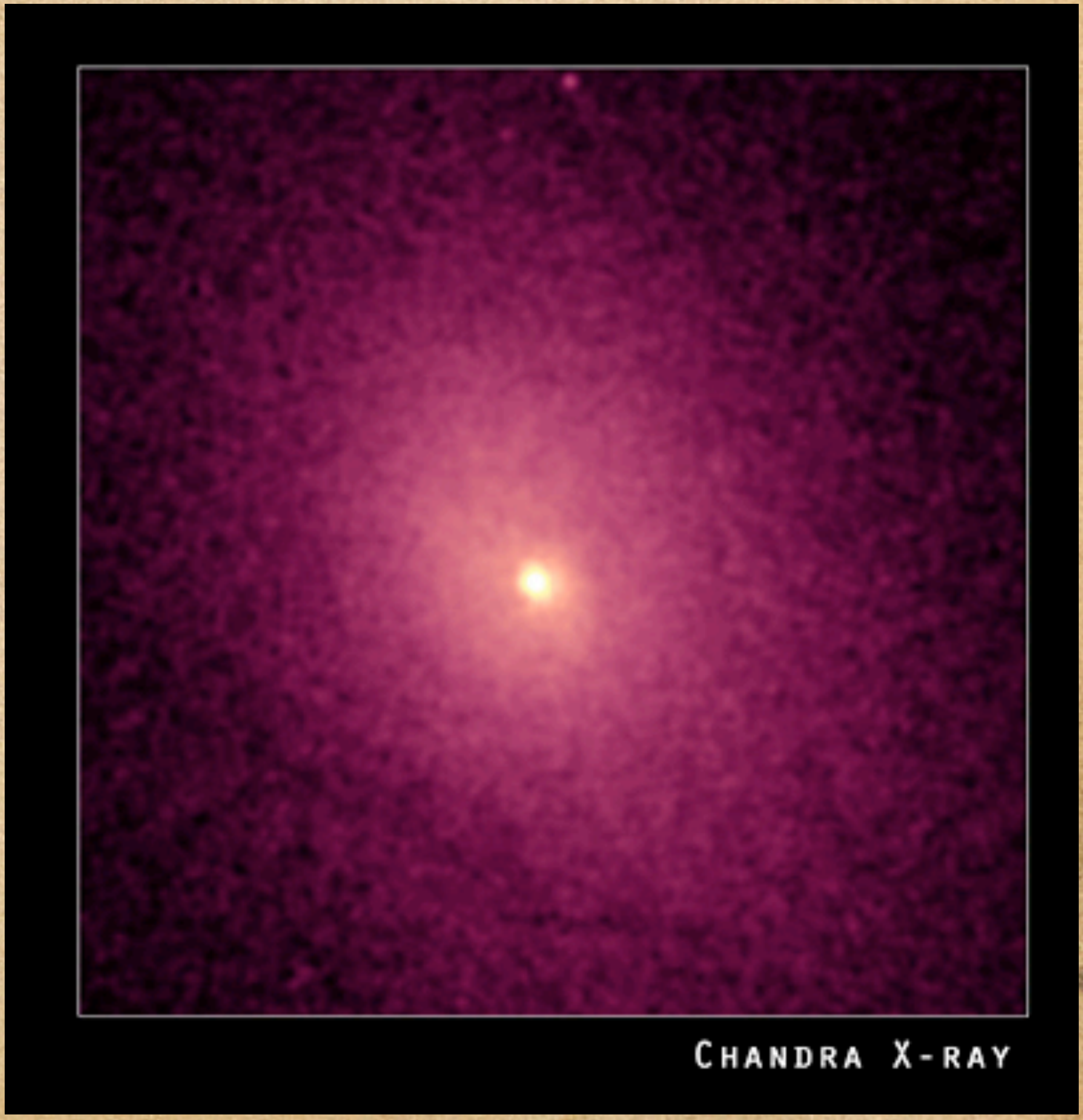
Is the Invisible Mass Truly Invisible ?

- So far, we have only established that it is not in the form of burning stars
- Could interstellar gas provide the missing mass ?



Is the Invisible Mass Truly Invisible ?

- So far, we have only established that it is not in the form of burning stars
- Could interstellar gas provide the missing mass ?
- Interstellar gas is "visible" in x-ray emissions
  - More than 5x as much mass as the stars, ... but still not enough



Gravity On The Largest Scale

"Lenses in the sky"

- General Relativity states that light is deflected by gravity
  - Mass can act as a lens
  - The "coke bottle" effect
- The amount of mass can be determined from the observed distortion

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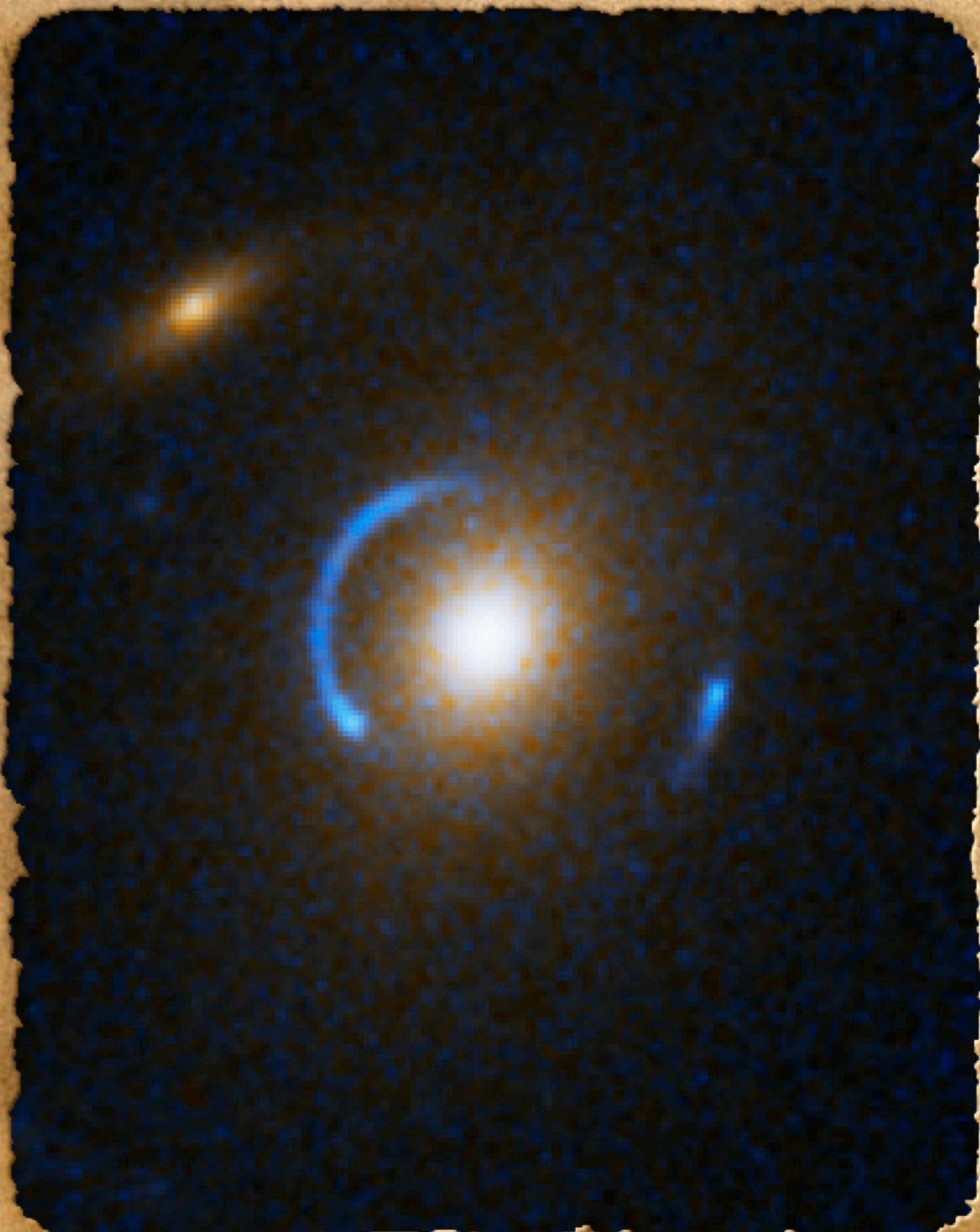

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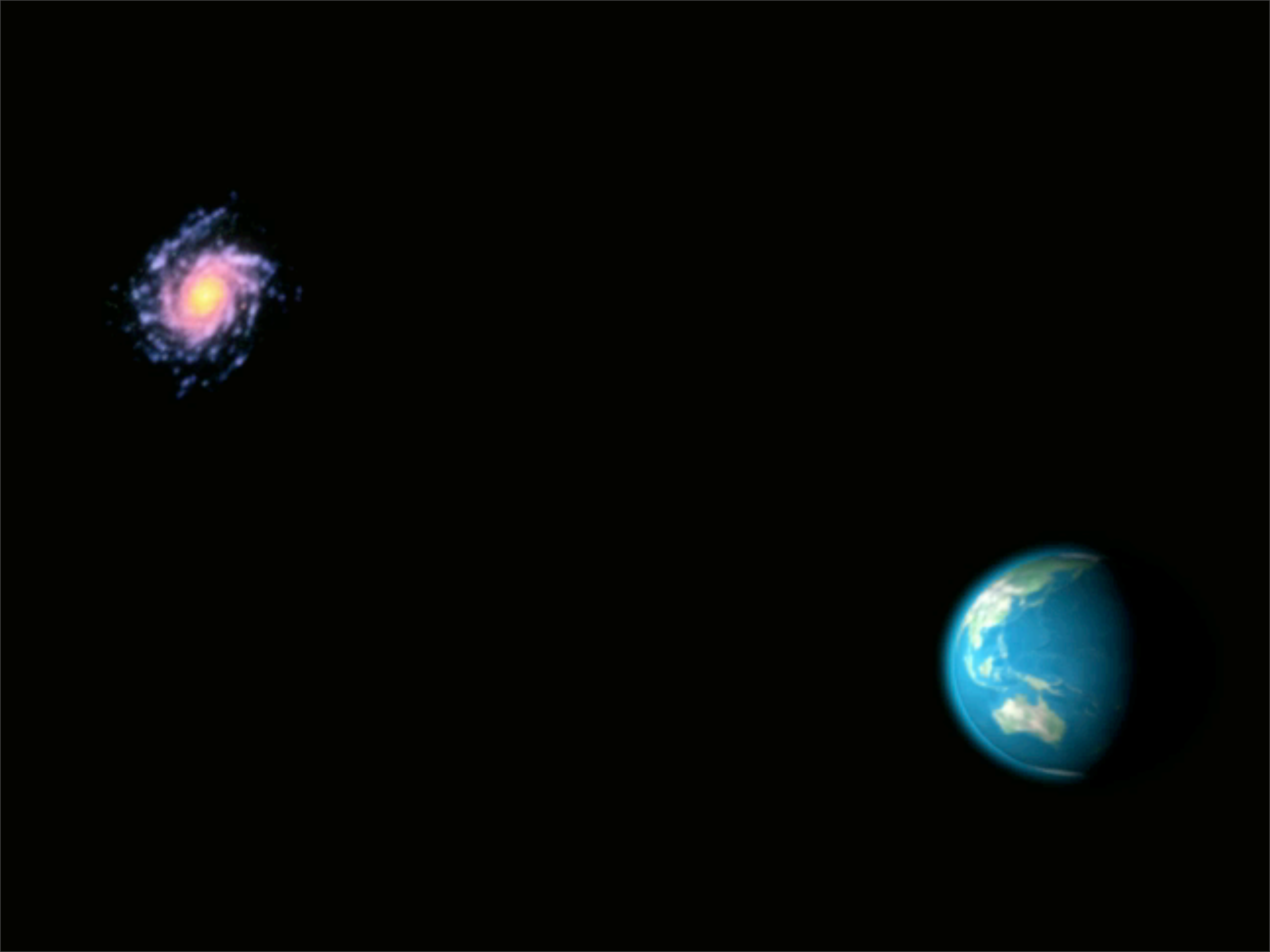
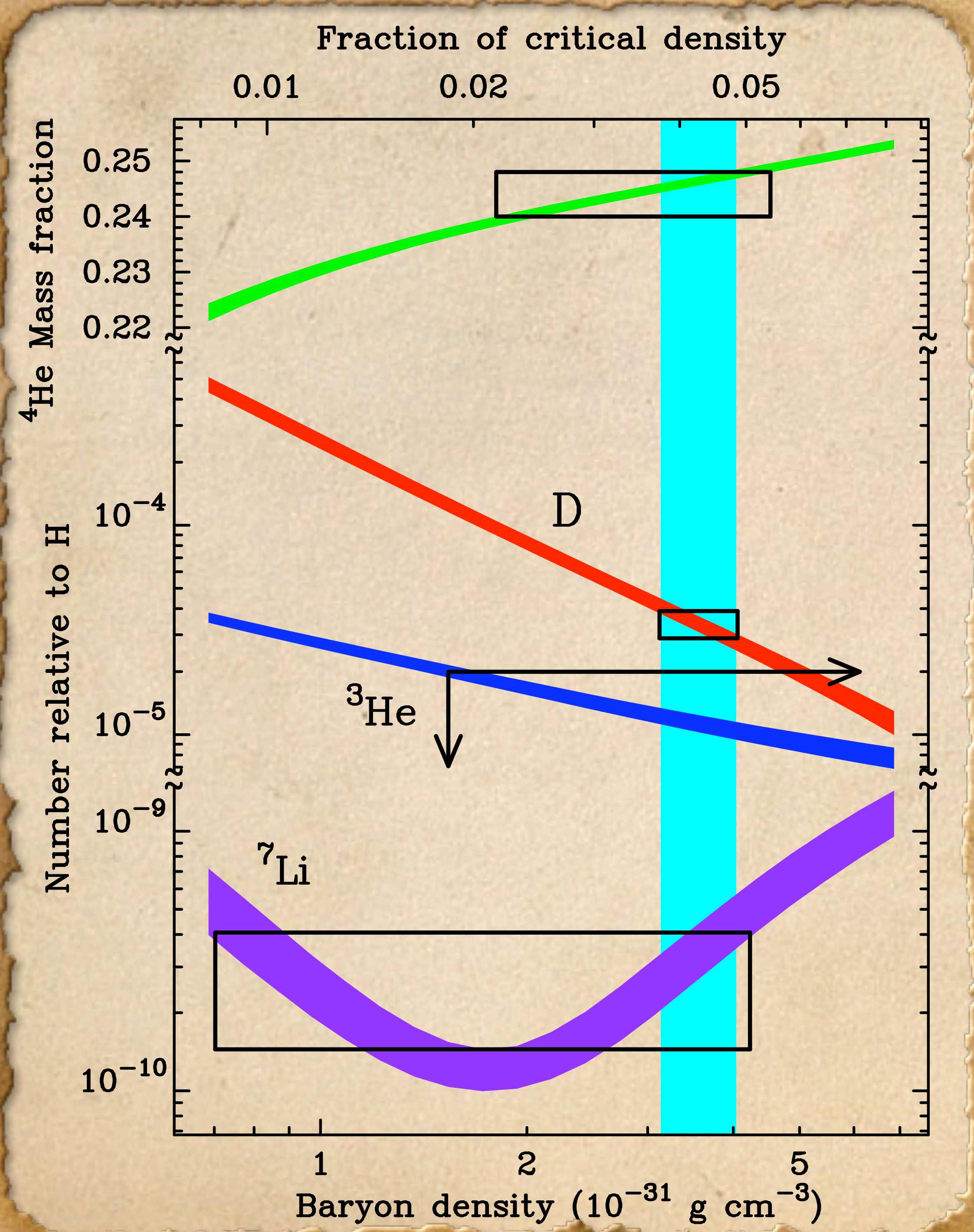


Big Bang Nucleosynthesis
"The ultimate limit on baryons"



- Given
  1. Our "particle theory" recipe
  2. Measured amount of light elements
- We can determine the total amount of "ordinary matter" (baryons) in all its forms
- It is still insufficient to account for observed gravitational effects

Enter Dark Matter

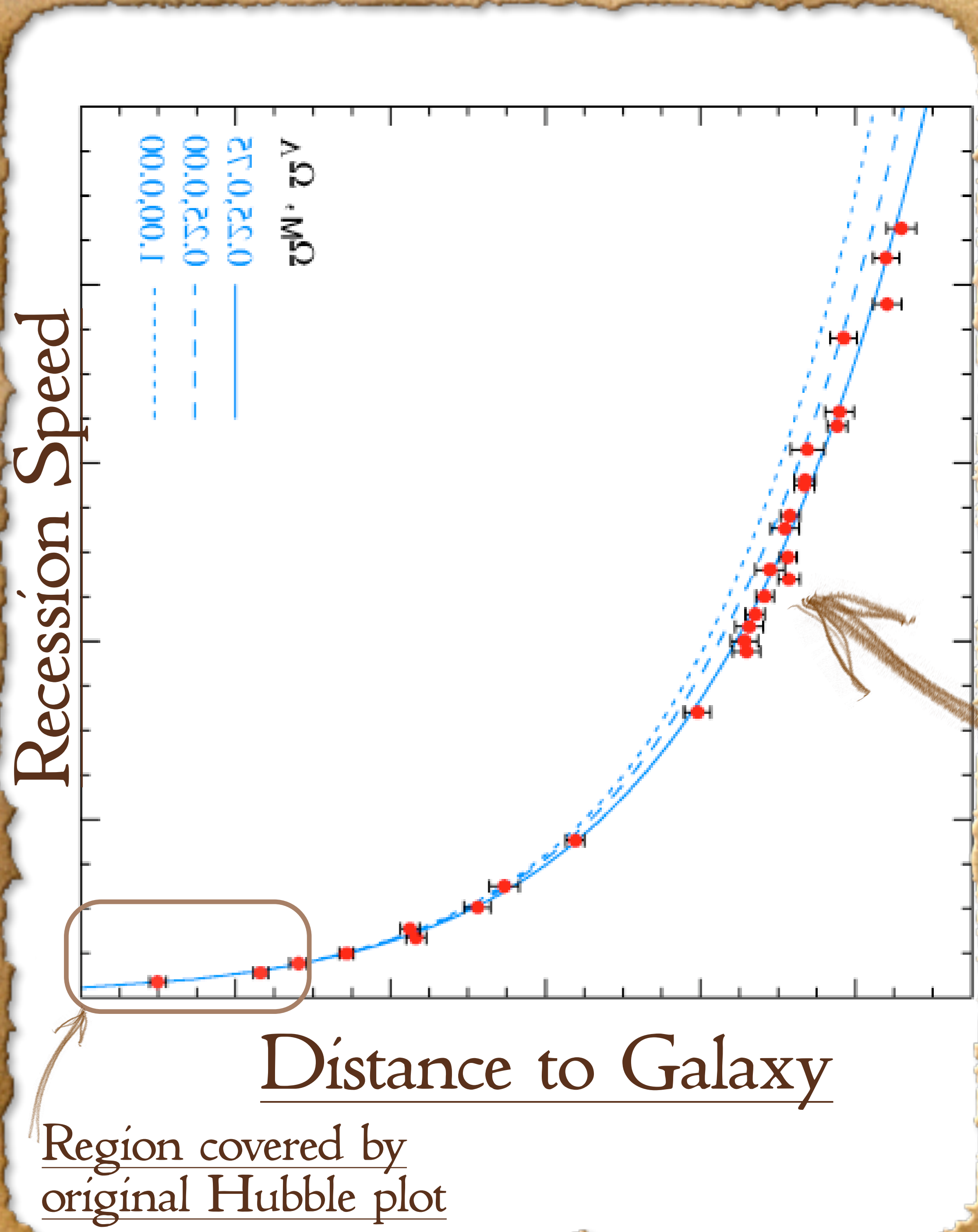
- **Dark** : Historical name based on lack of emission in the optical band
- **Matter** : Has gravity
- There are several "theoretical" candidates for this Dark Matter,
  - The Supersymmetric WIMP is one

Looking for Dark Matter In Our Back Yard

Cryogenic Dark Matter Search

- Several experiments are searching for direct evidence of Dark Matter here on Earth by looking for extremely rare interactions within their detectors

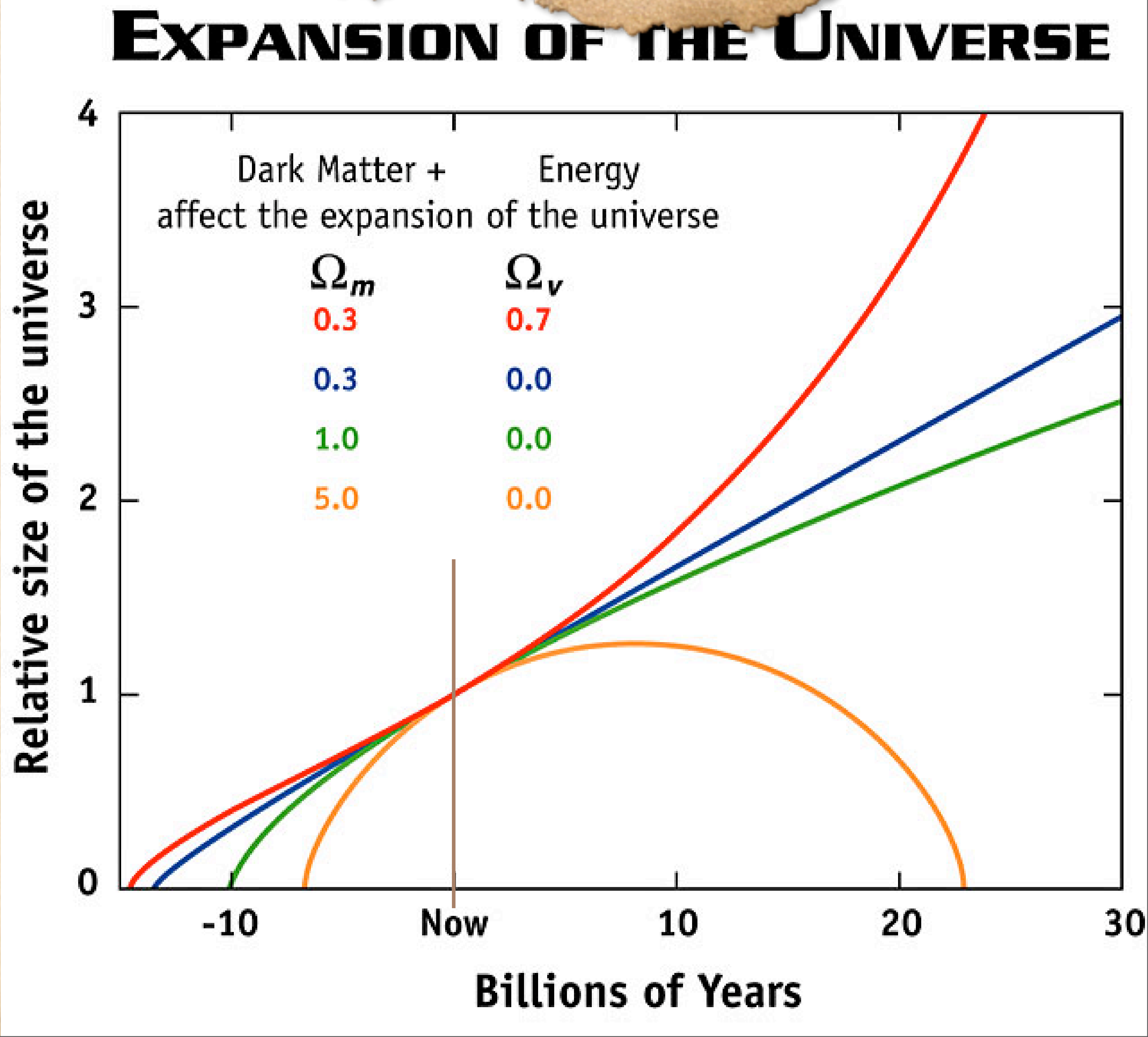
Accelerated Expansion
"The Massive Galactic Exodus"



- Redo the Hubble measurement on a much larger scale
- Distant galaxies showing an additional acceleration away from us
- Indicative of the presence of a "repulsive" anti-gravity effect

Remember The Souflé

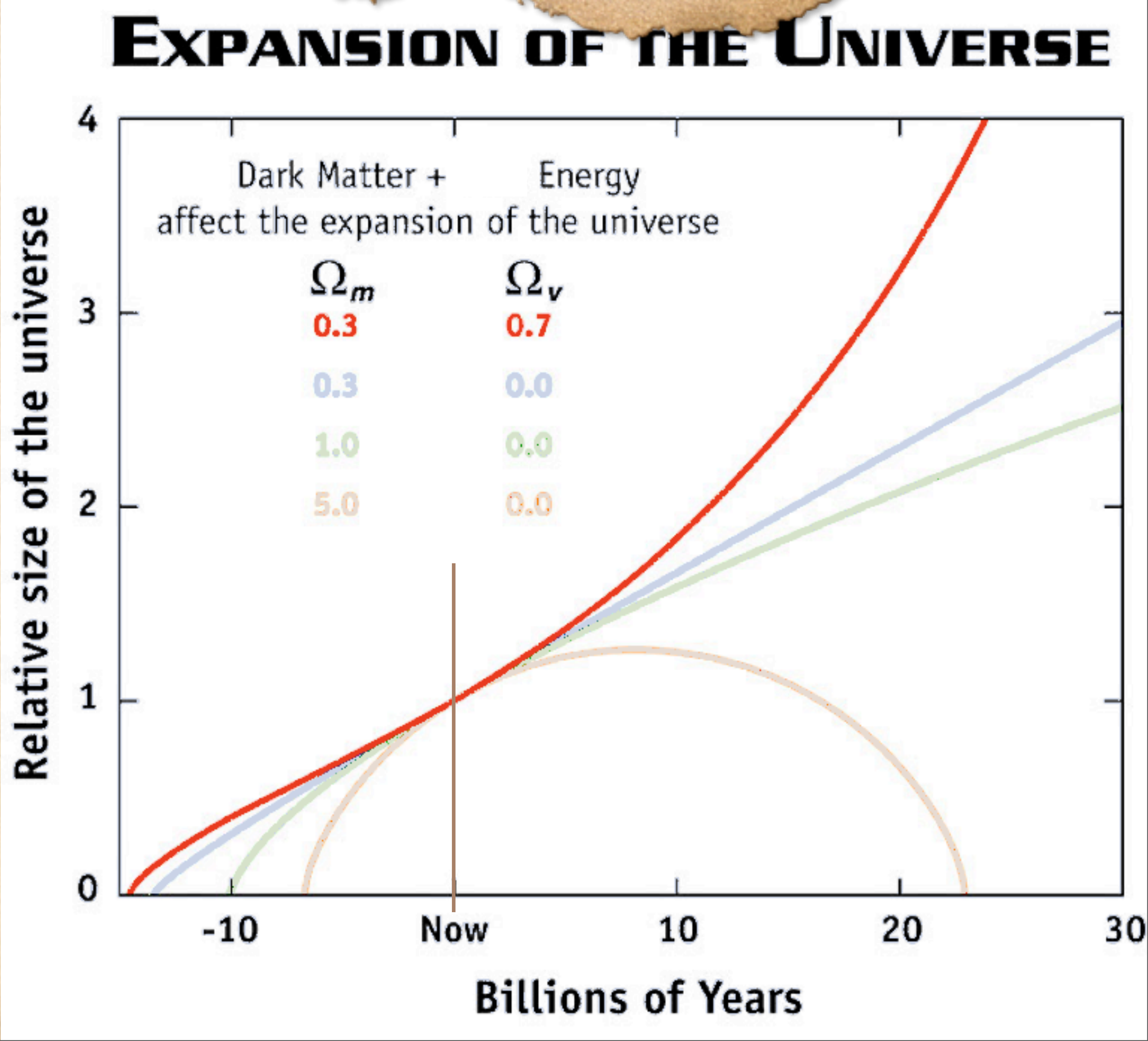
"It is Rising !"



Remember The Souflé

"It is Rising !"

- Observations (within the last 5 years) now tell us that we are on the red curve
- The means that Dark and Baryonic matter are not the whole story
- Something else is needed

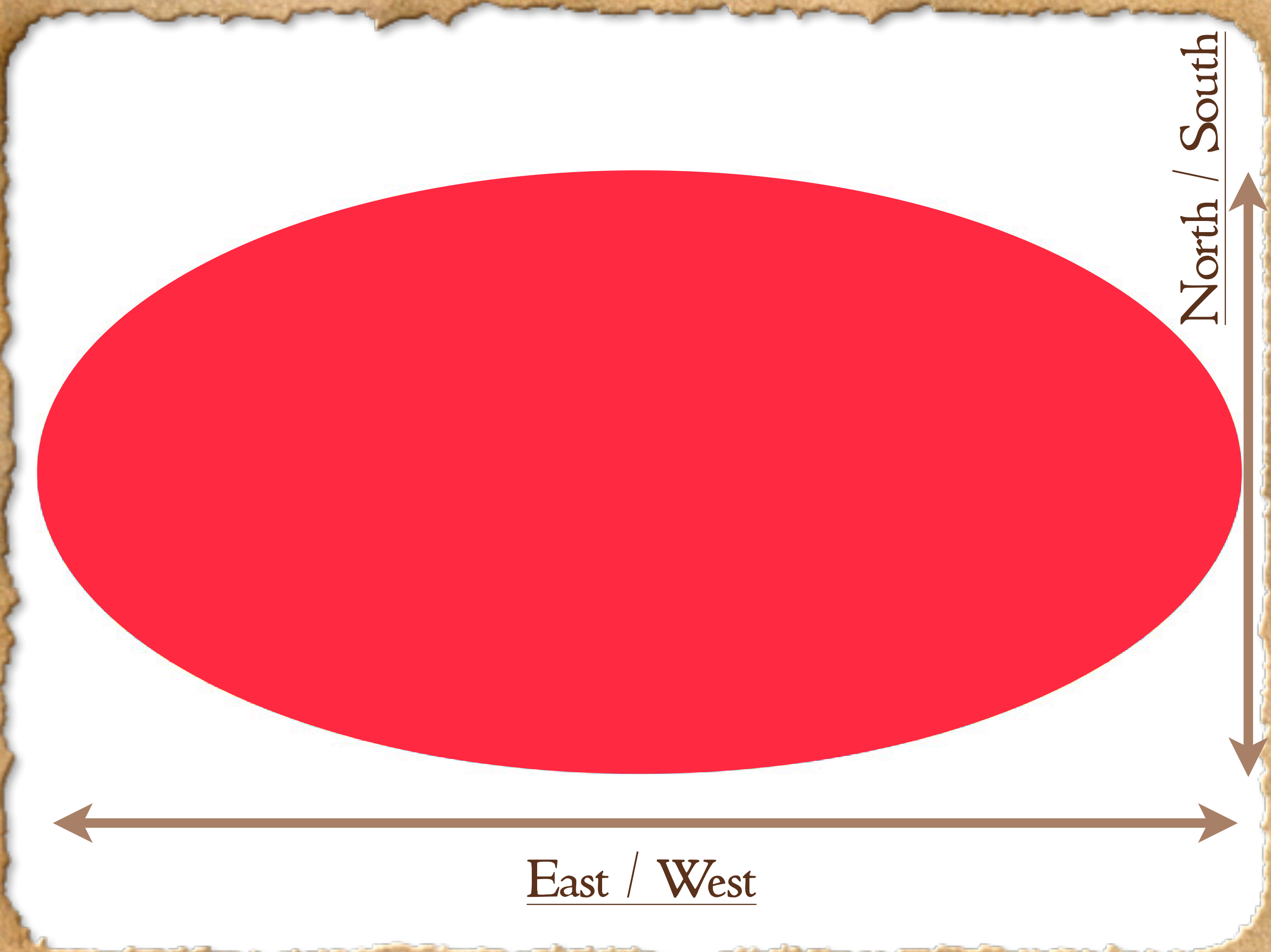


The Masked Actor

"What is Dark Energy"

- Observations at the largest distance scales indicate the presence of a third major player on the scene that is neither Baryons nor Dark Matter
- This player acts to push things apart
  - i.e. looks like anti-gravity
- Within General Relativity a uniform energy field would have that effect

The Case For Energy
"Cosmic Bubbles"



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(received a nobel prize in 1978)

See talks by Laurence Perotto

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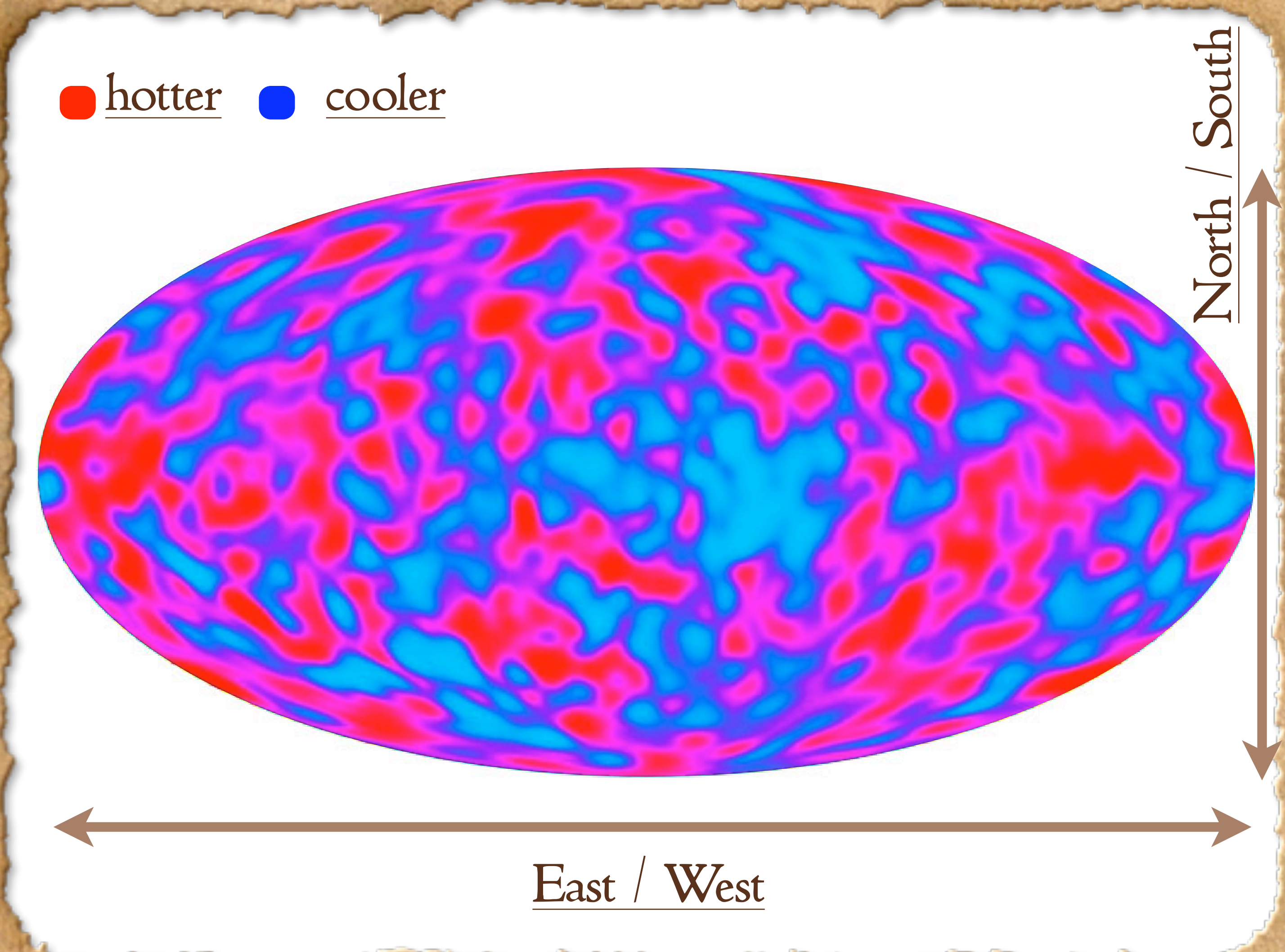

- Big Bang remnant - 2.728 K temperature everywhere we look (received a nobel prize in 1978)
- Tiny fluctuations in temperature due to density bubbles at the beginning : 2.728 K ± 0.00002 K (received a nobel prize in 2006)

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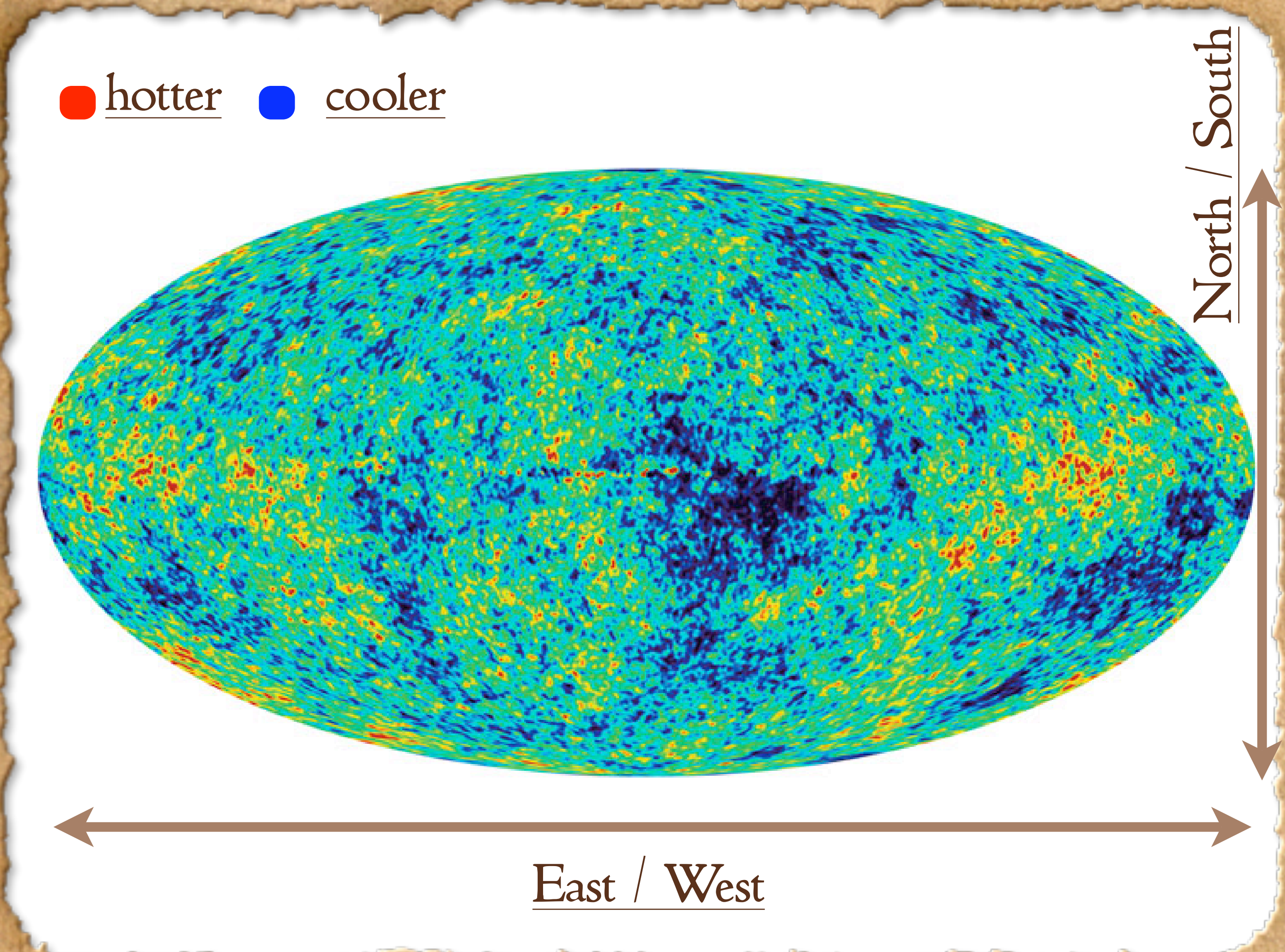


- Big Bang remnant - 2.728 K temperature everywhere we look (received a nobel prize in 1978)
- Tiny fluctuations in temperature due to density bubbles at the beginning : 2.728 K ± 0.00002 K (received a nobel prize in 2006)
- Size of bubbles tells us the how much matter/energy is in the universe (will likely receive a nobel prize in the future)

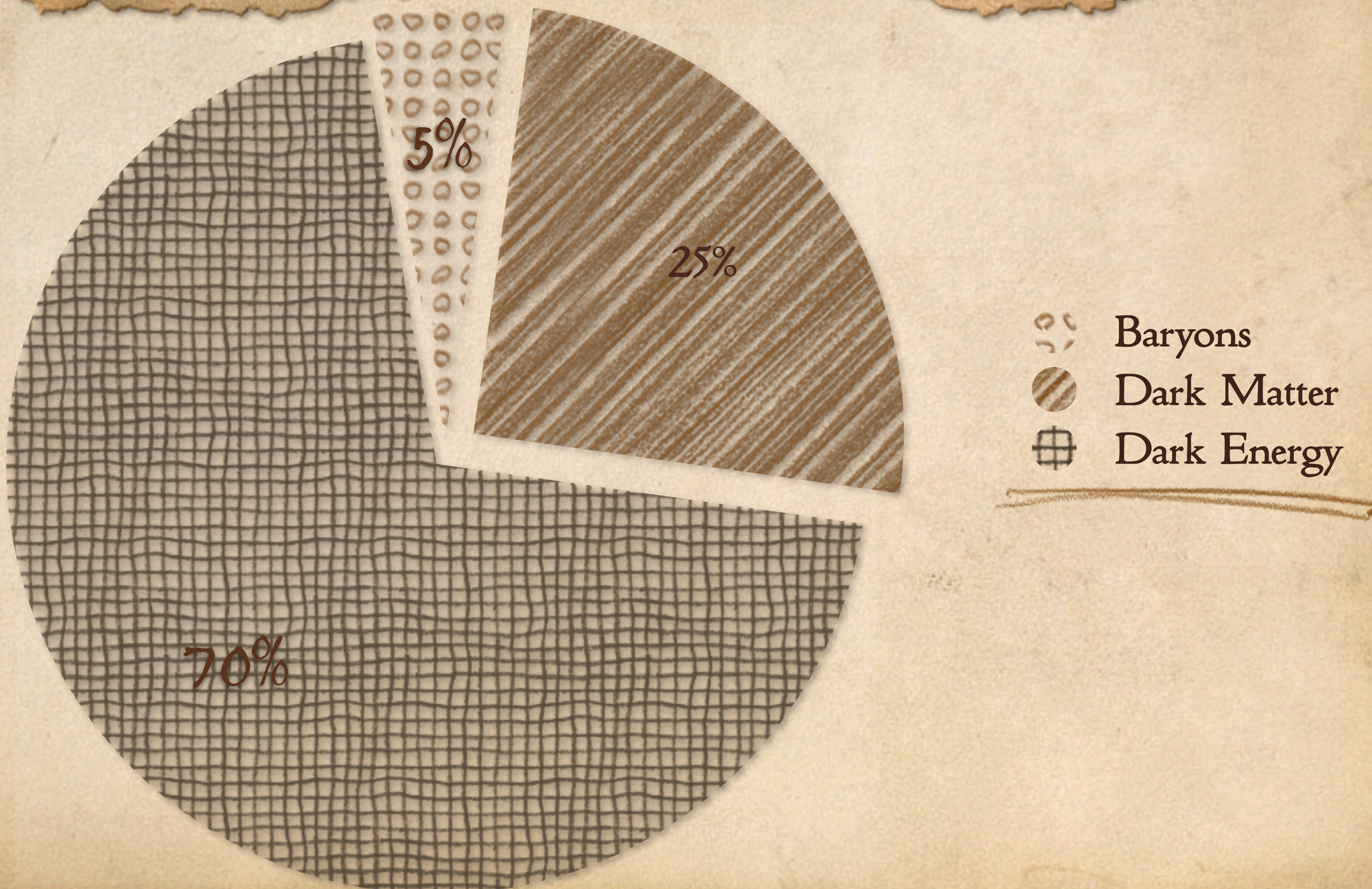
See talks by Laurence Perotto

(Un)masking Dark Energy

- The dominant component determining the evolution of the Universe
- None of the existing theories can adequately account for the Dark Energy
- Great interest in determining whether the amount of Dark Energy is changing or has always been constant

putting it all together

Pie Chart - 100 yrs in the making



Turn of the 21st Century

- Physics is:
  - Classical mechanics & Thermodynamics
  - Electromagnetism &Newtonian gravity

  AND

  - Quantum Mechanics & Statistical Mechanics
  - Electroweak theory & General Relativity, & ...

Turn of the 21st Century

- Physics is alive and kicking !!!
- Concurrent development of astrophysical theory and experimental results
- Many current and future experiments have great promise for answering today's questions

Cosmic Inventory :

Matter,

Dark Matter,

and a whole lot of

Dark Energy