What do we Know About the Universe?

Andreas Albrecht
UC Davis dept. of Physics
Adapted from a public lecture Lowell Observatory
October 1, 2016

Work supported by UC Davis and the US Department of Energy

Center for Quantum Mathematics and Physics (QMAP)

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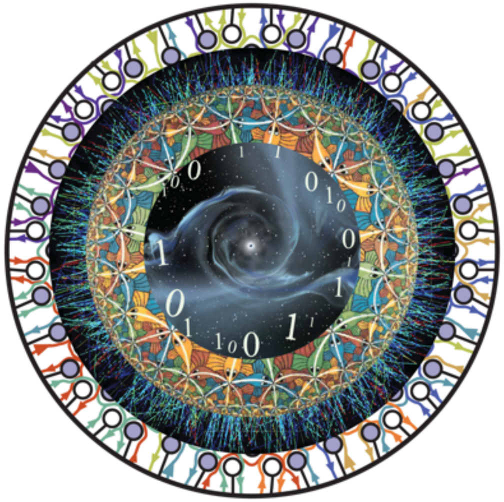
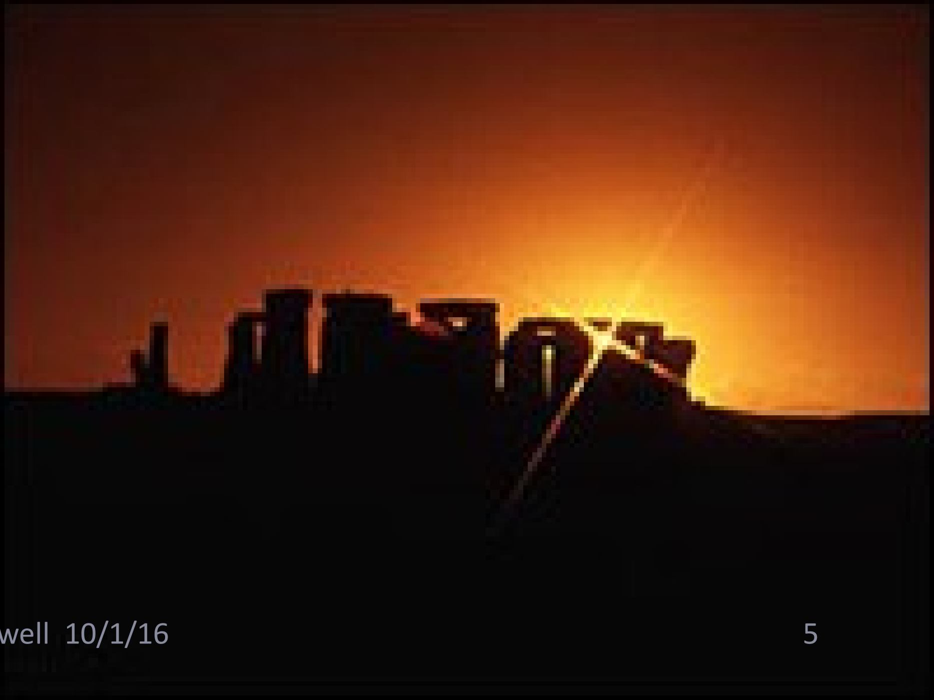


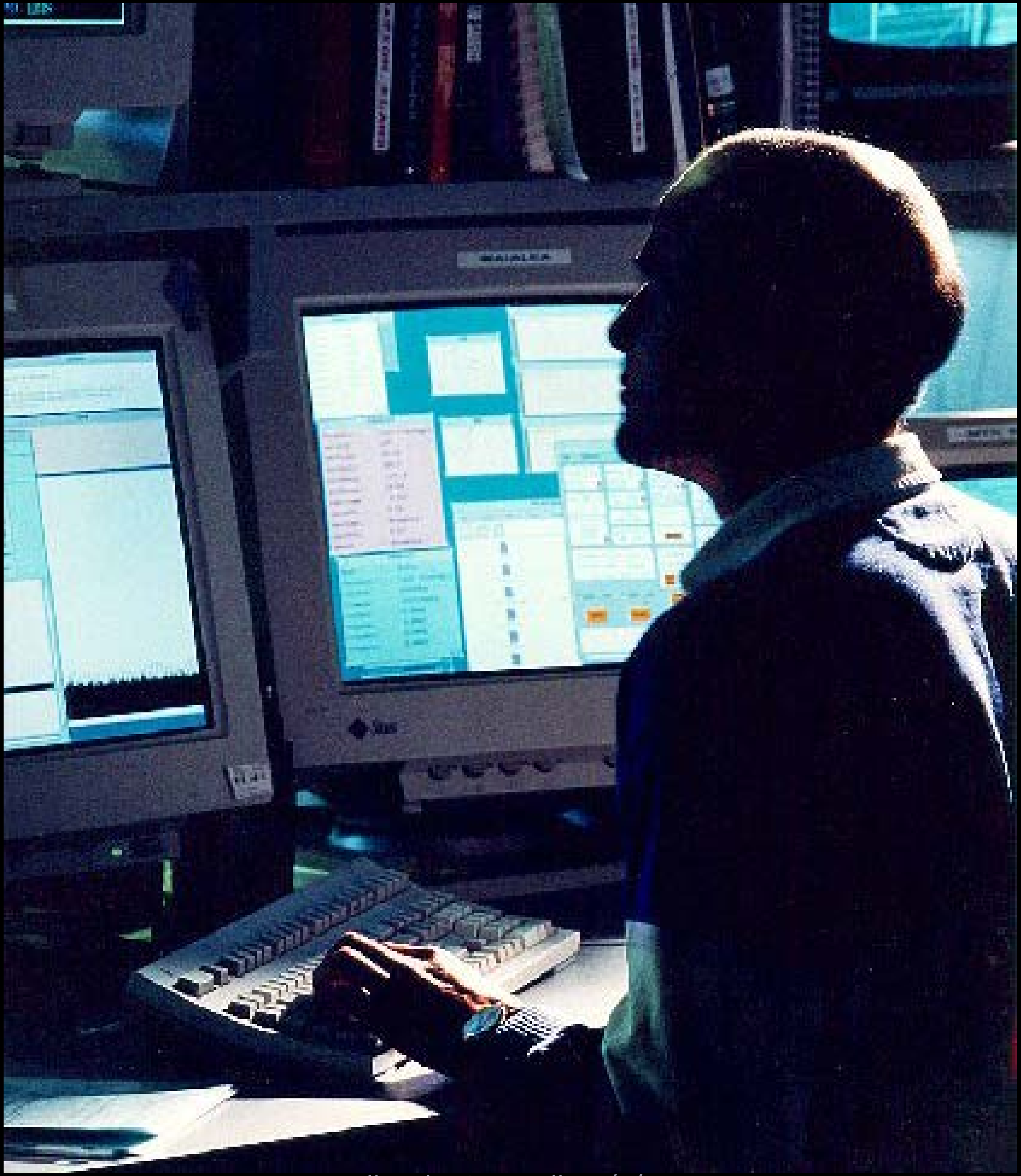
Welcome to the Center for Quantum Mathematics and Physics. QMAP is a new initiative at UC Davis, aimed at fostering a vibrant research environment for addressing foundational questions in modern theoretical and mathematical physics.

Who we are

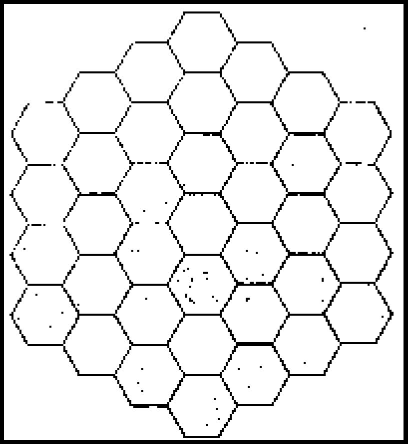
We are theoretical physicists and mathematicians who are interested in tackling questions about how the universe works. At a broad brush, some of the questions we seek to answer are
- What is the origin of space and time? In particular, how does spacetime emerge from a more fundamental description?
- How did our universe start and what is its fate?
- What manifestations of the quantum nature of our world are apparent and important at macroscopic scales?
- What are the mathematical structures describing our world, and what novel surprises do they reveal?

Please refer to the various pages in the Navigation bar above to learn about center's activities and research.





The Keck 10m Telescopes on Mauna Kea, Hawaii



Segments of the Keck 10m Telescope Mirror

Outline

1. Introduction (The "Golden age of cosmology")
2. The Big Picture
3. Some Big ideas
    - Cosmic Inflation
    - The String theory landscape

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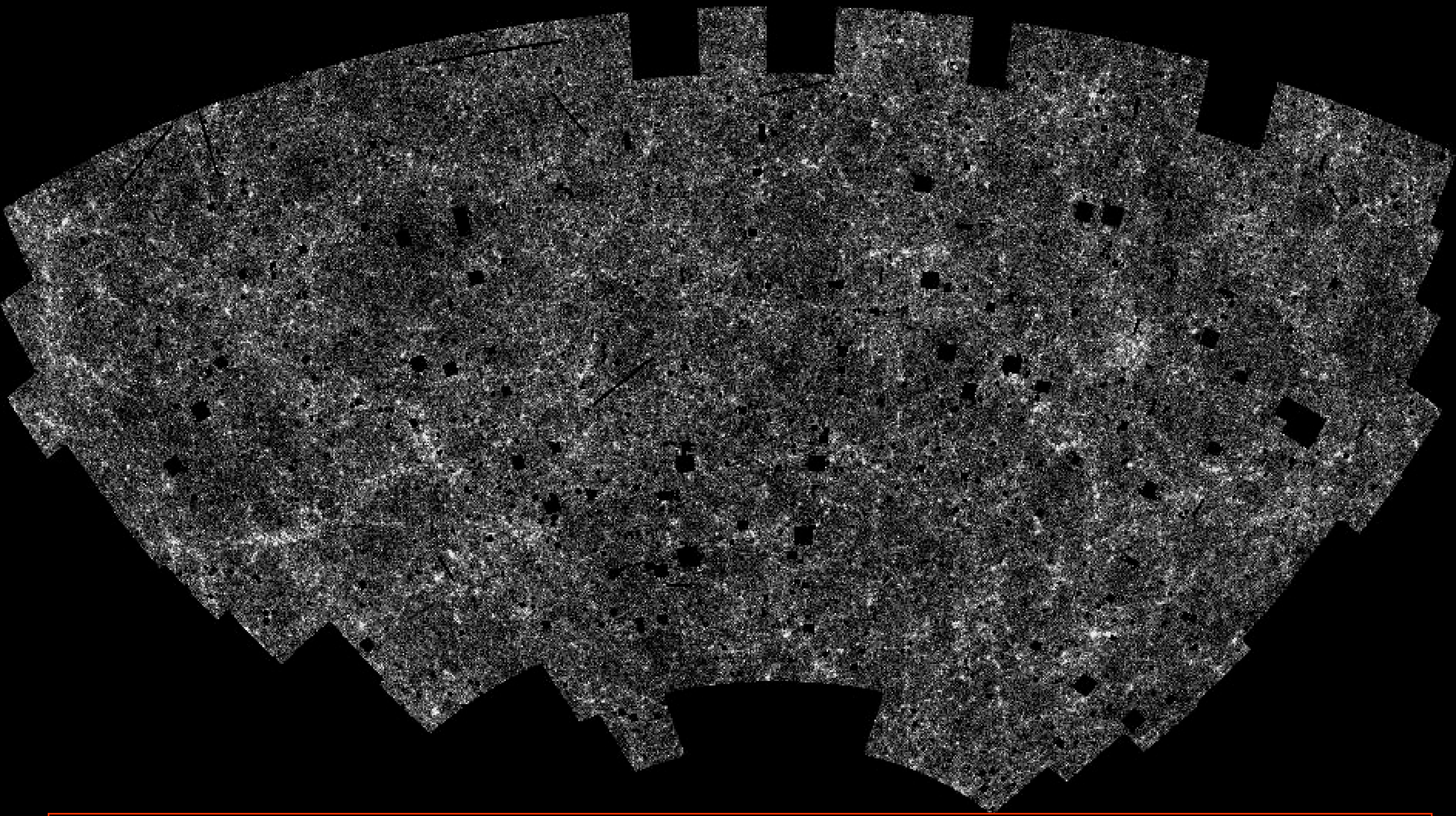
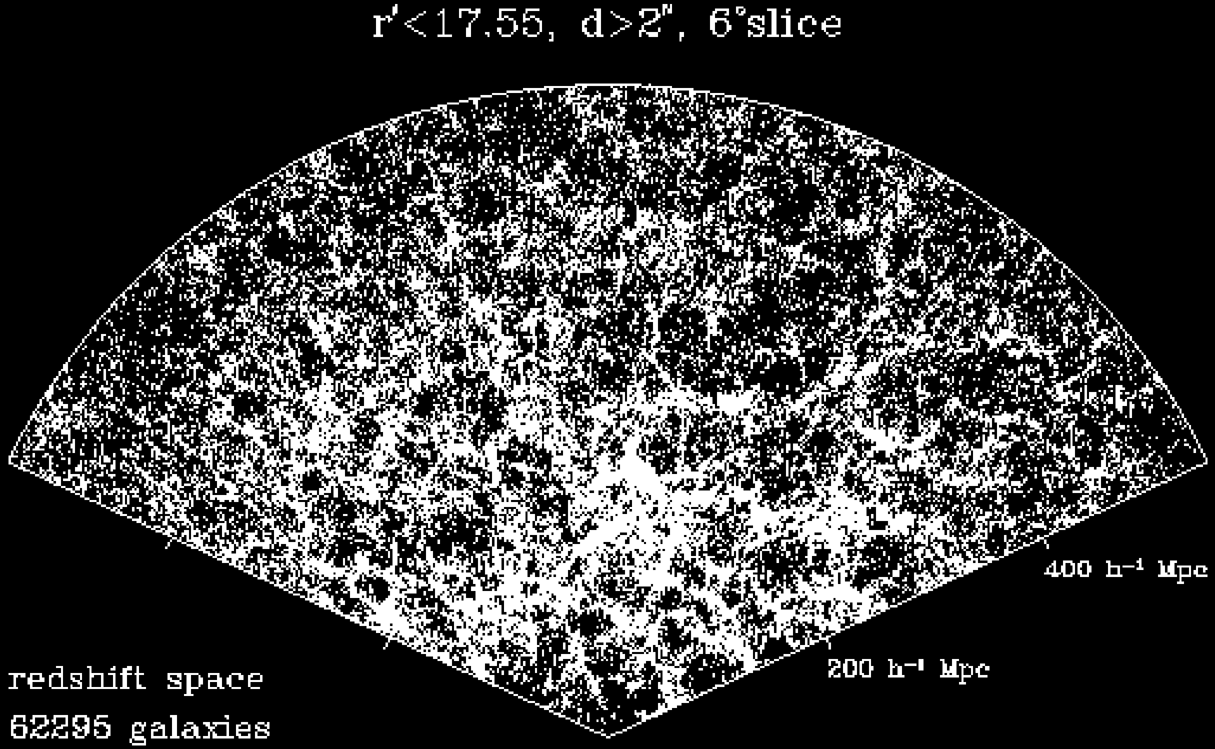


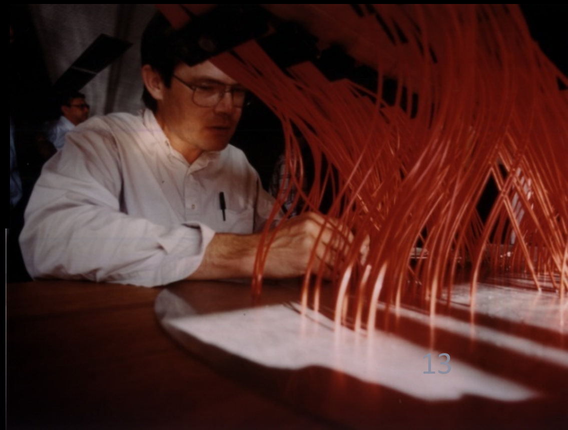
The APM (Automatic Plate Machine) Survey (1992)

Sky positions of 2,000,000 Galaxies

The Sloan Digital Sky Survey

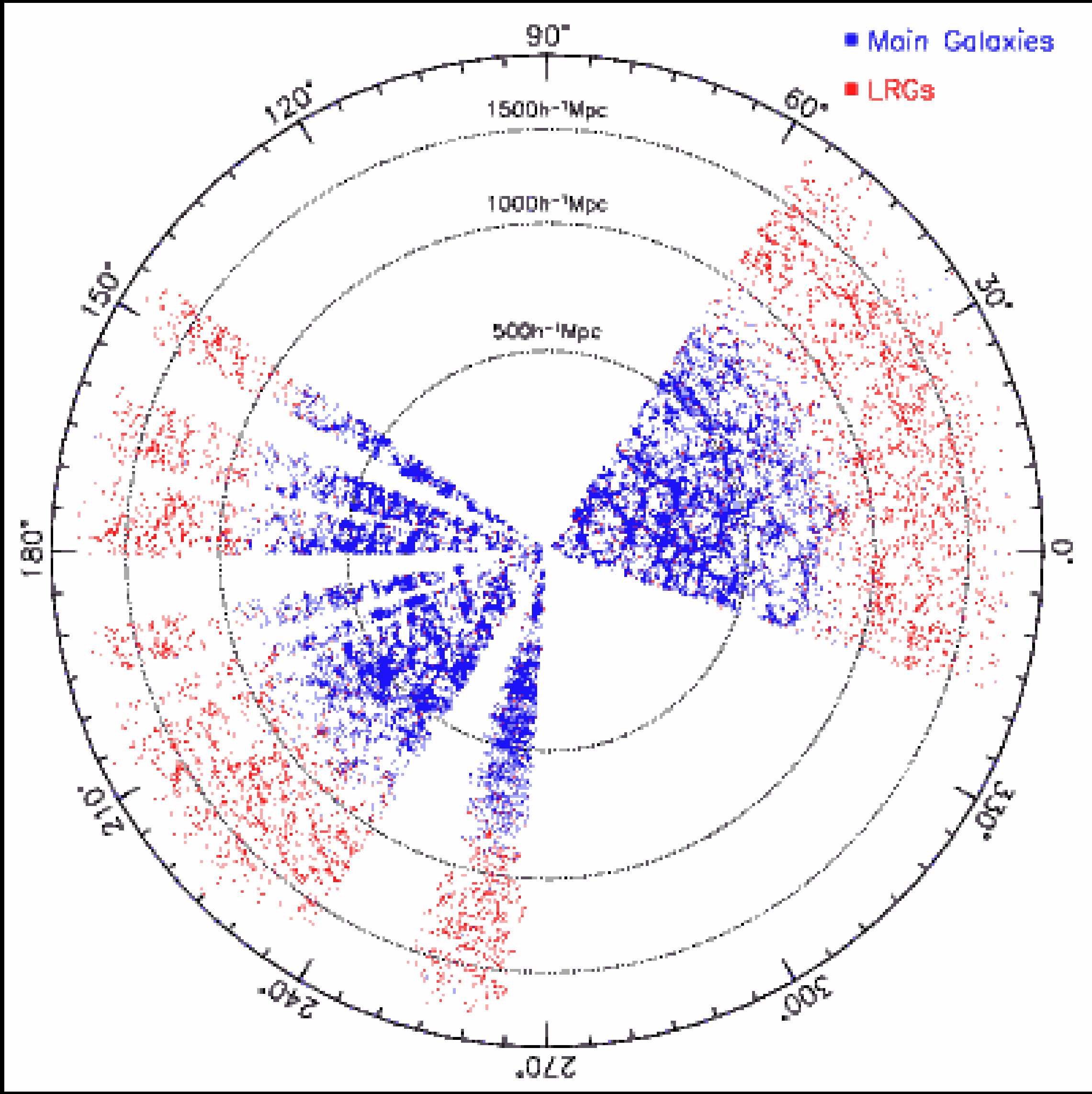
(to locate over 100,000,000 galaxies, 3D positions for 1,000,000)





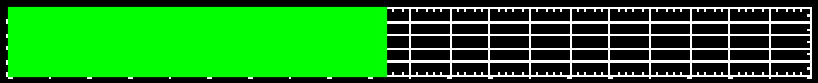
A simulation of just 65,000 Sloan galaxies

June 5 2001: First release of Sloan data (50,000 galaxies)



Sloan Survey Status

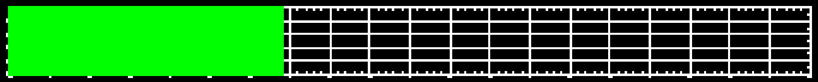
Imaging (Galaxy positions on the sky)



47% Complete Jun 21 2002

➔ 47,000,000 galaxy positions

Spectroscopy (3D galaxy positions)

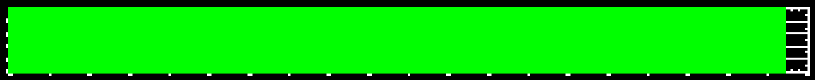


34% Complete Jul 15 2002

➔ 340,000 galaxy positions

Sloan Survey Status

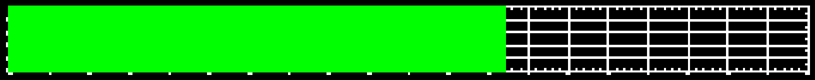
Imaging (Galaxy positions on the sky)



97% Complete Jun 27 2004

→ 97,000,000 galaxy positions

Spectroscopy (3D galaxy positions)

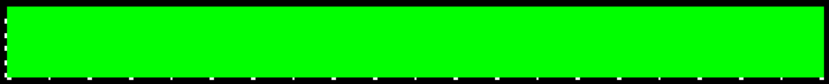


67% Complete Jun 27 2004

→ 670,000 galaxy positions

Sloan Survey Status

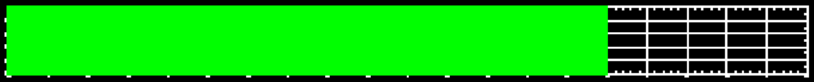
Imaging (Galaxy positions on the sky)



107% Complete Mar 13 2005

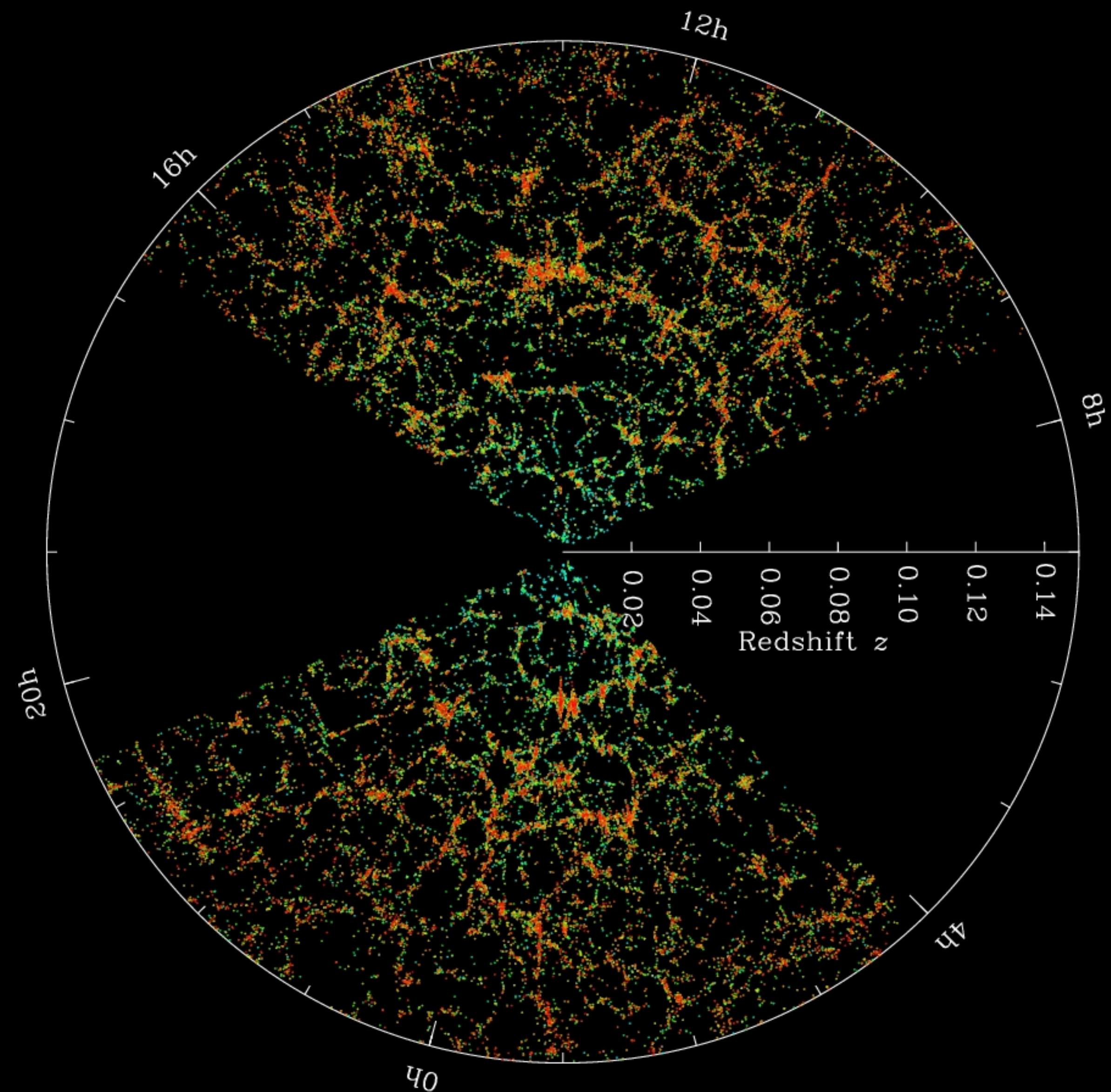
➔ 107,000,000 galaxy positions

Spectroscopy (3D galaxy positions)



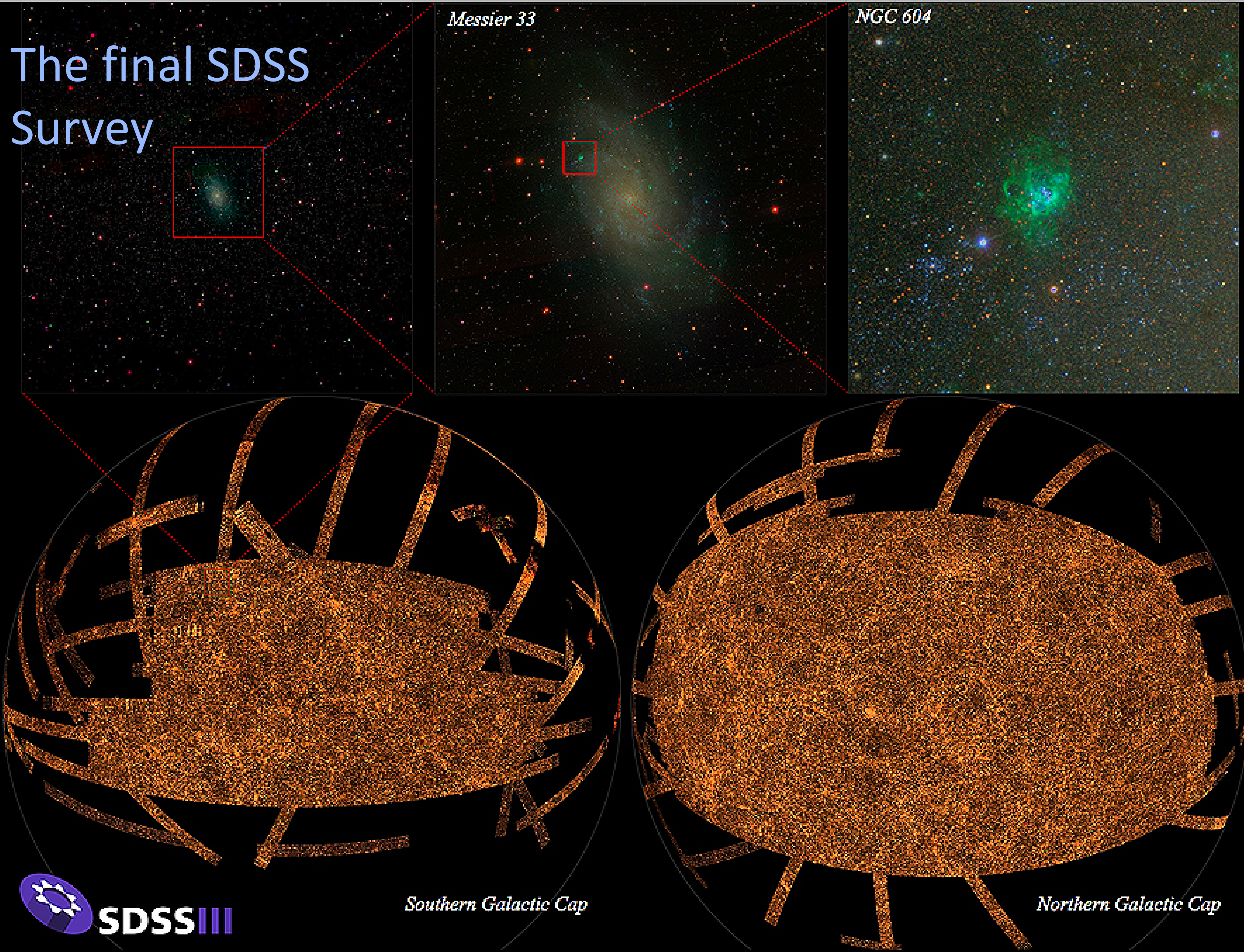
68% Complete Mar 15 2005

➔ 680,000 galaxy positions



Plot of a slice of SDSS galaxies

The final SDSS Survey

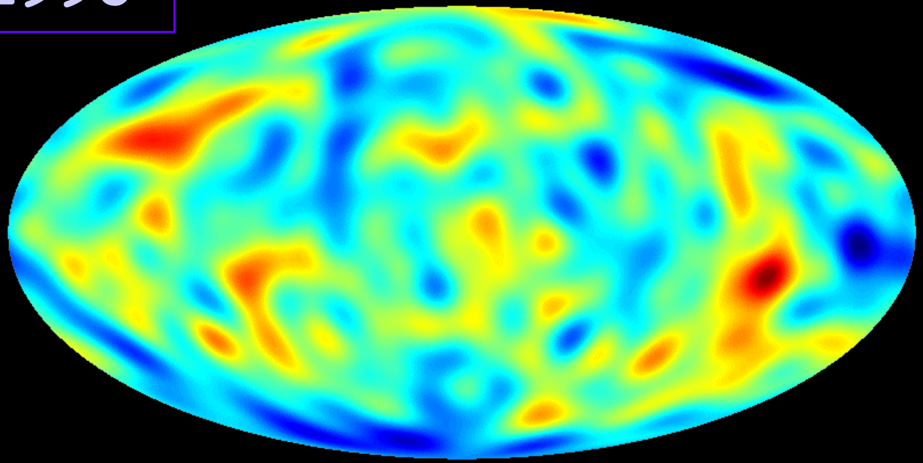


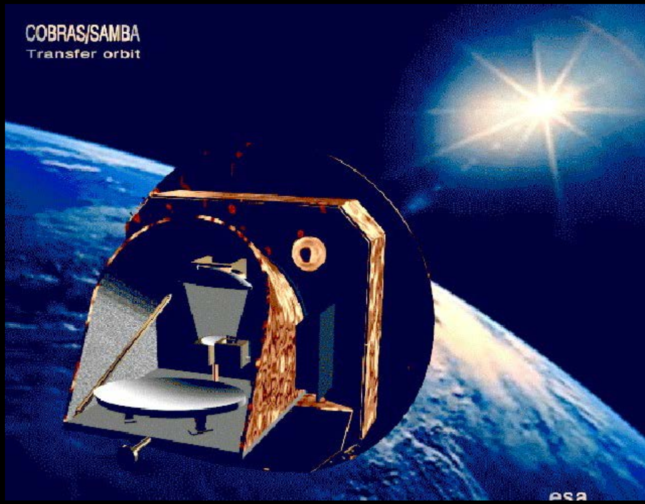
http://sdss.org

Maps of the microwave sky (the "edge of the observable universe")

1993

Real

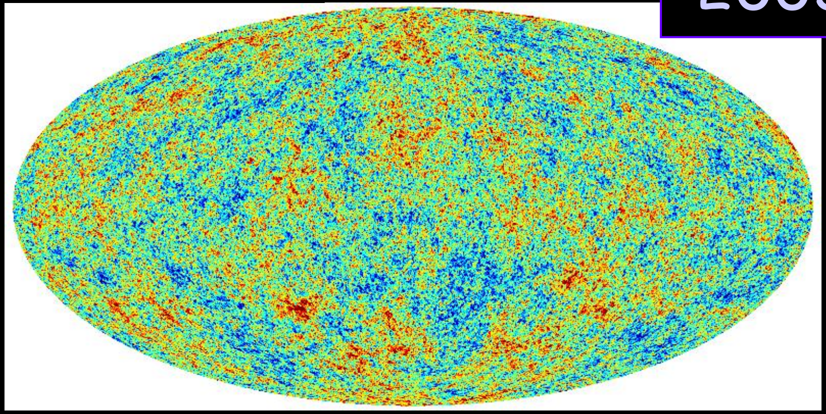


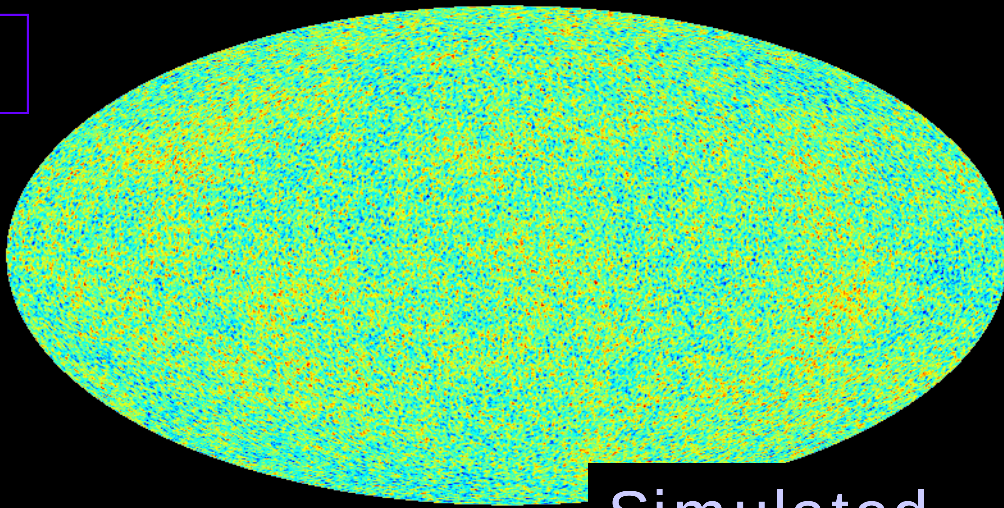


2009

Simulated

2003





Simulated

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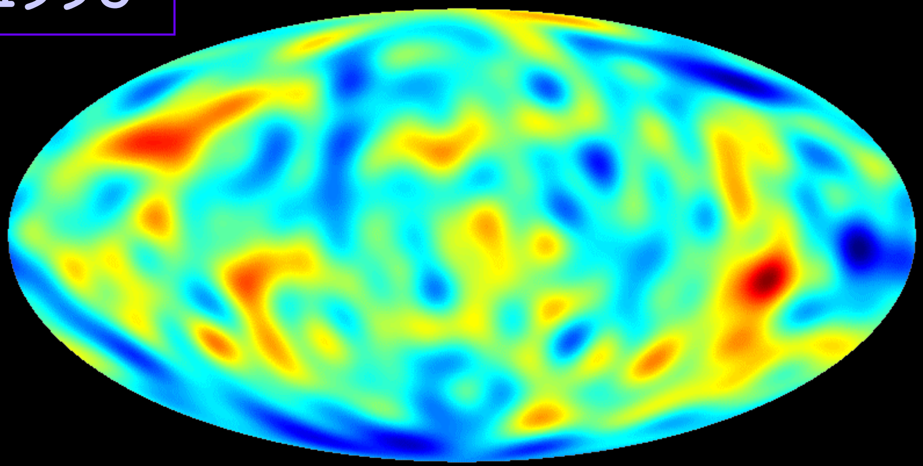
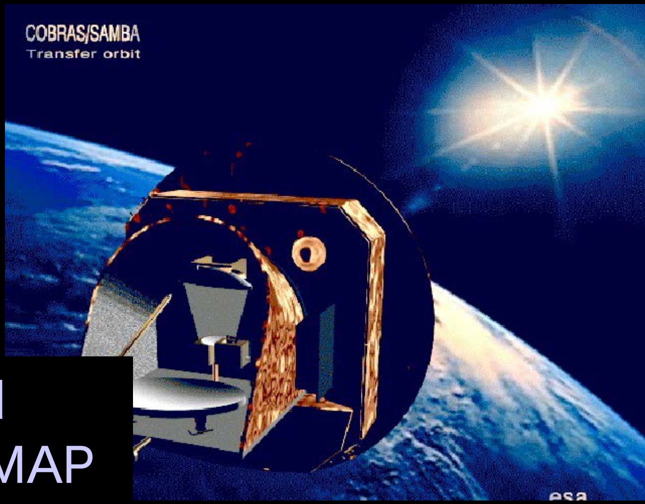


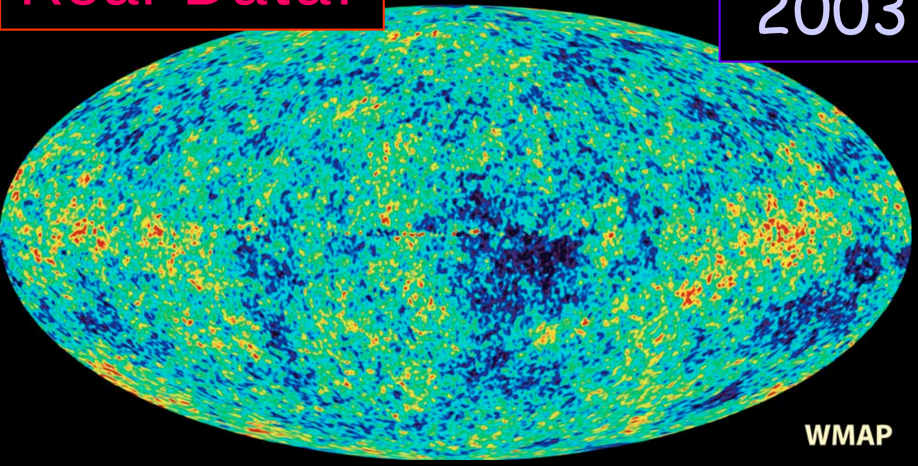


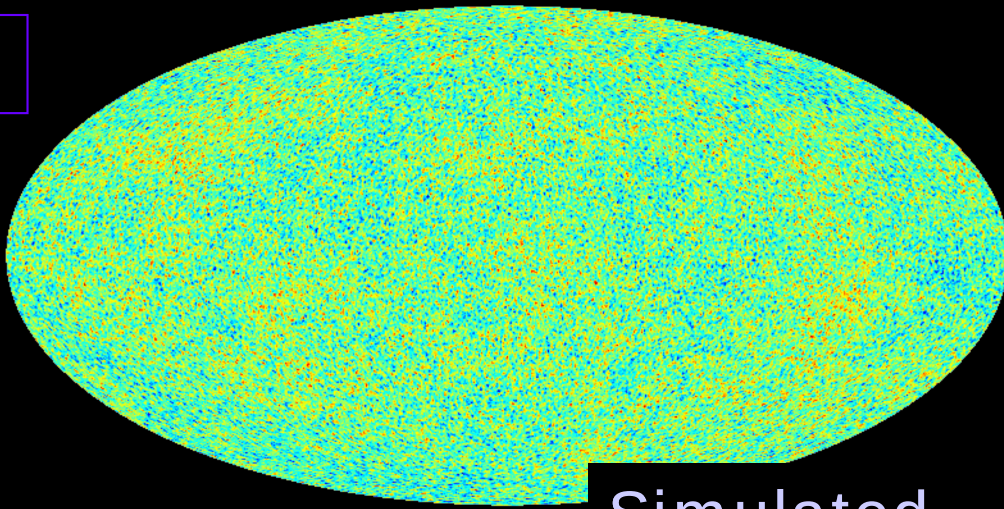
Updated after WMAP announcement, Feb 2003

2009

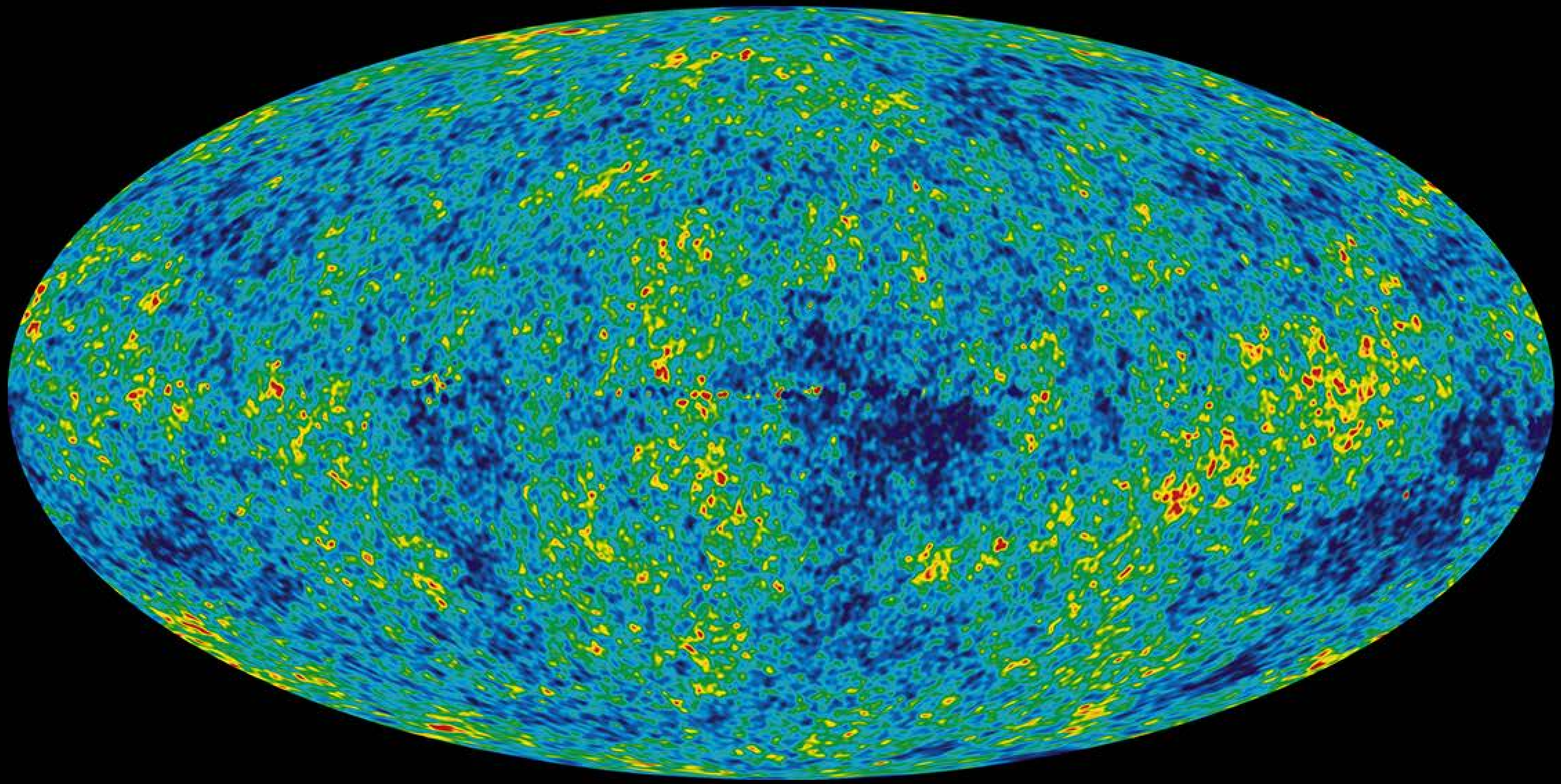
Real Data!

2003

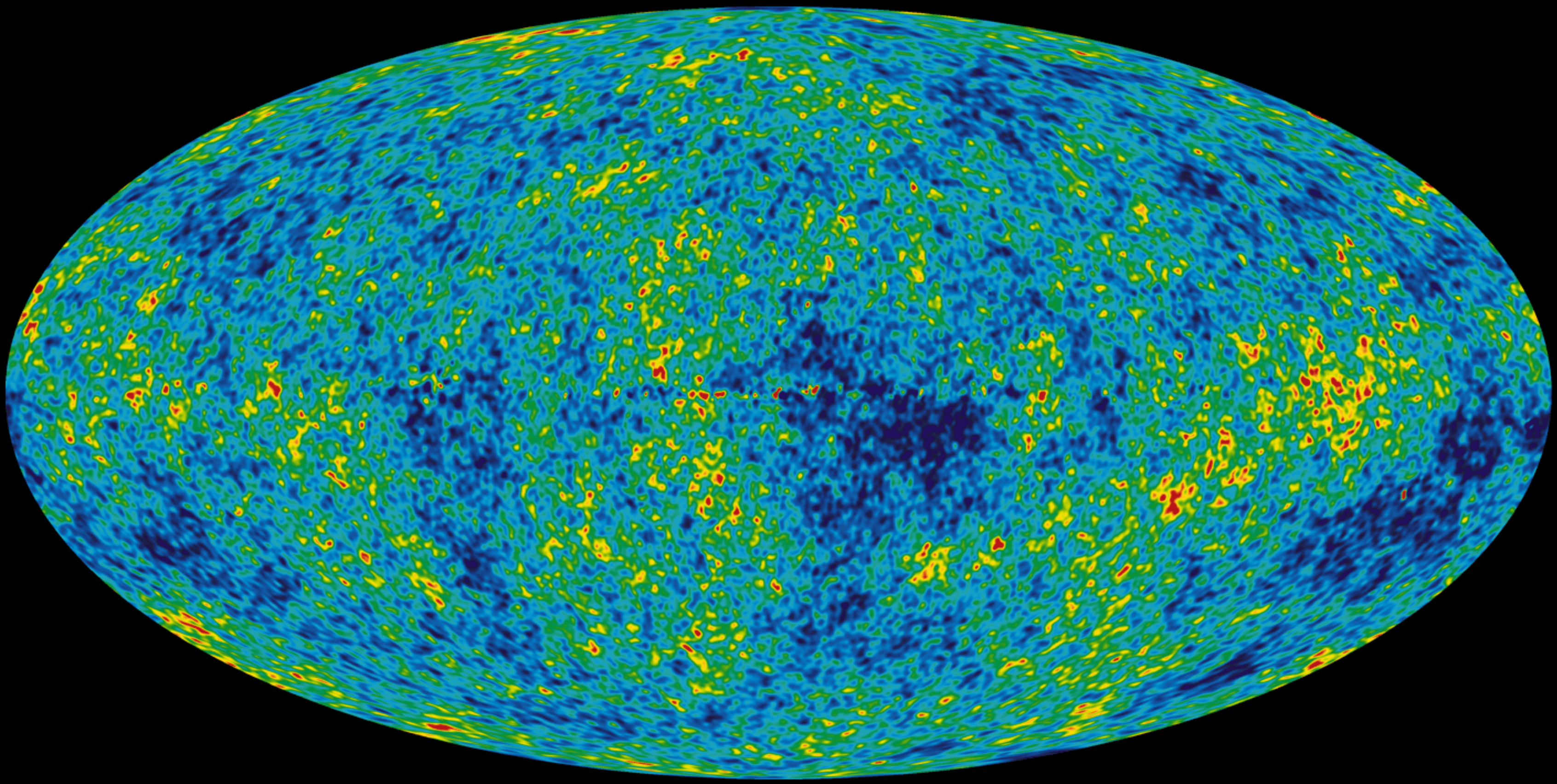




Simulated



WMAP 3-yr map



WMAP 5-yr map

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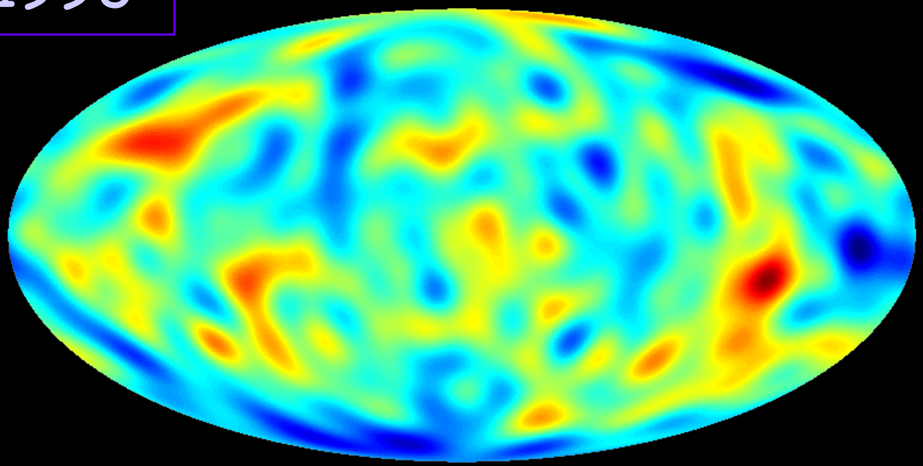
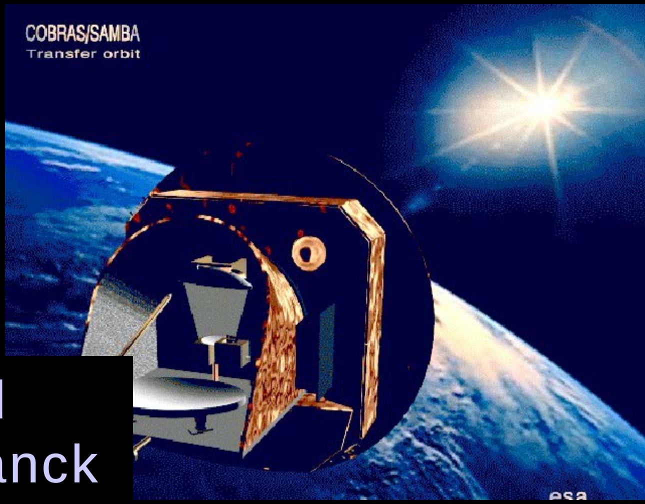


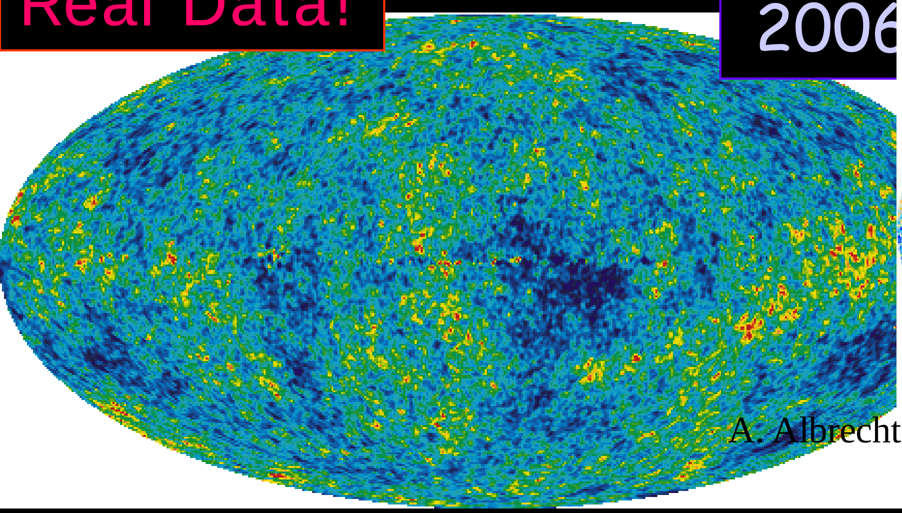


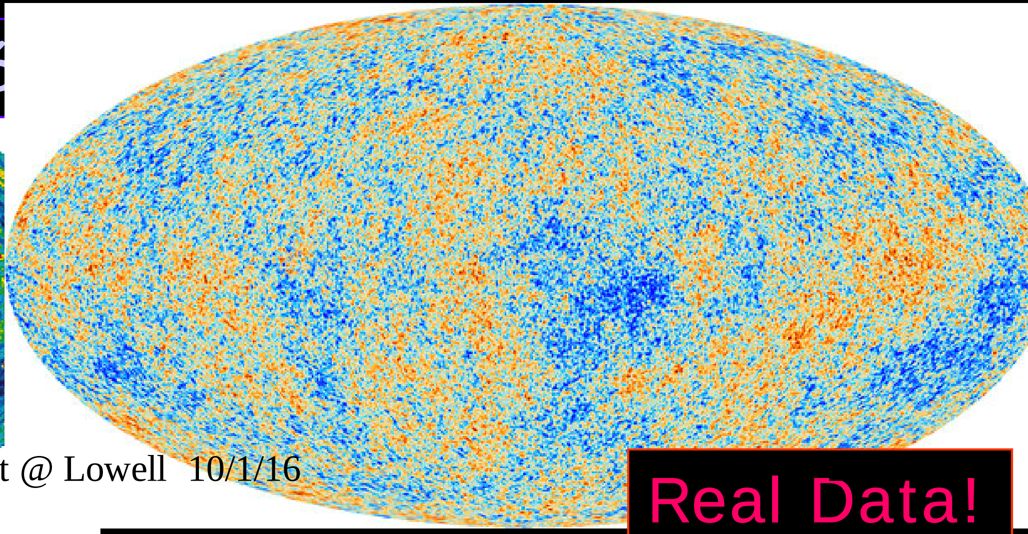
Updated after Planck announcement, 2013

2013

Real Data!

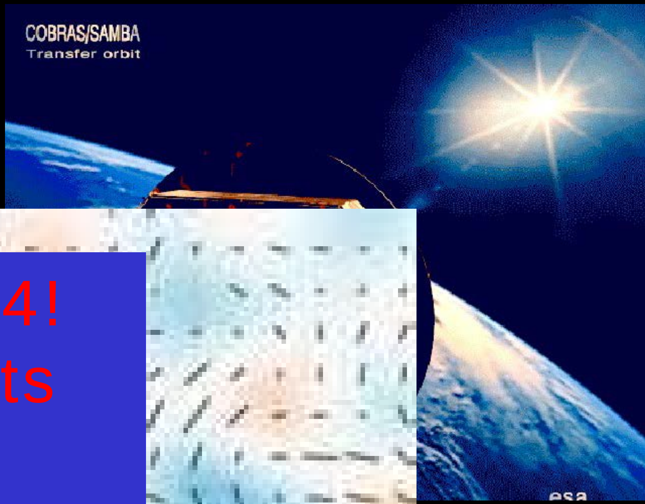
2006





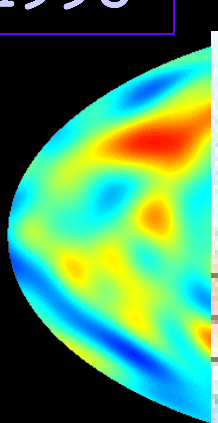
Real Data!

Maps of the microwave sky (the “edge of the observable universe”)



1993

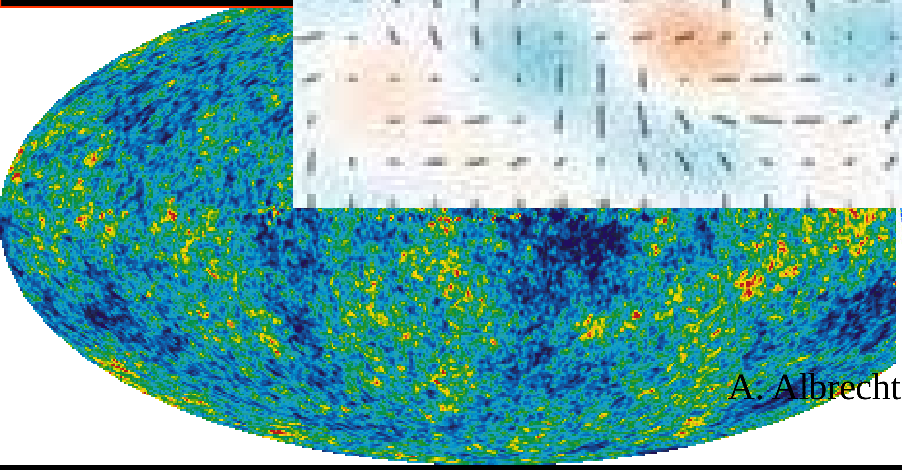
Real

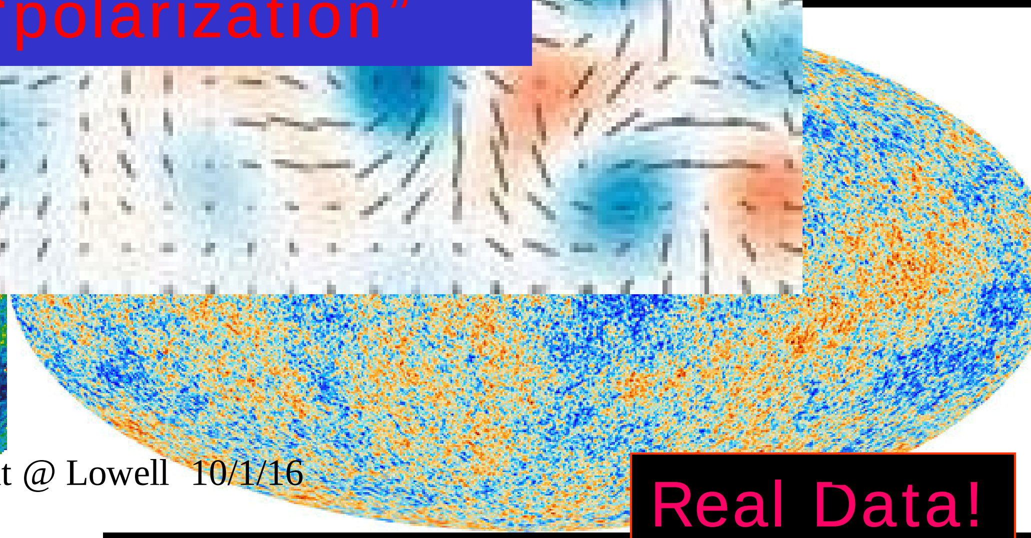


March 17 2014! BICEP2 reports signal from primordial gravitation waves in microwave “polarization”

013

Real Dat





Real Data!

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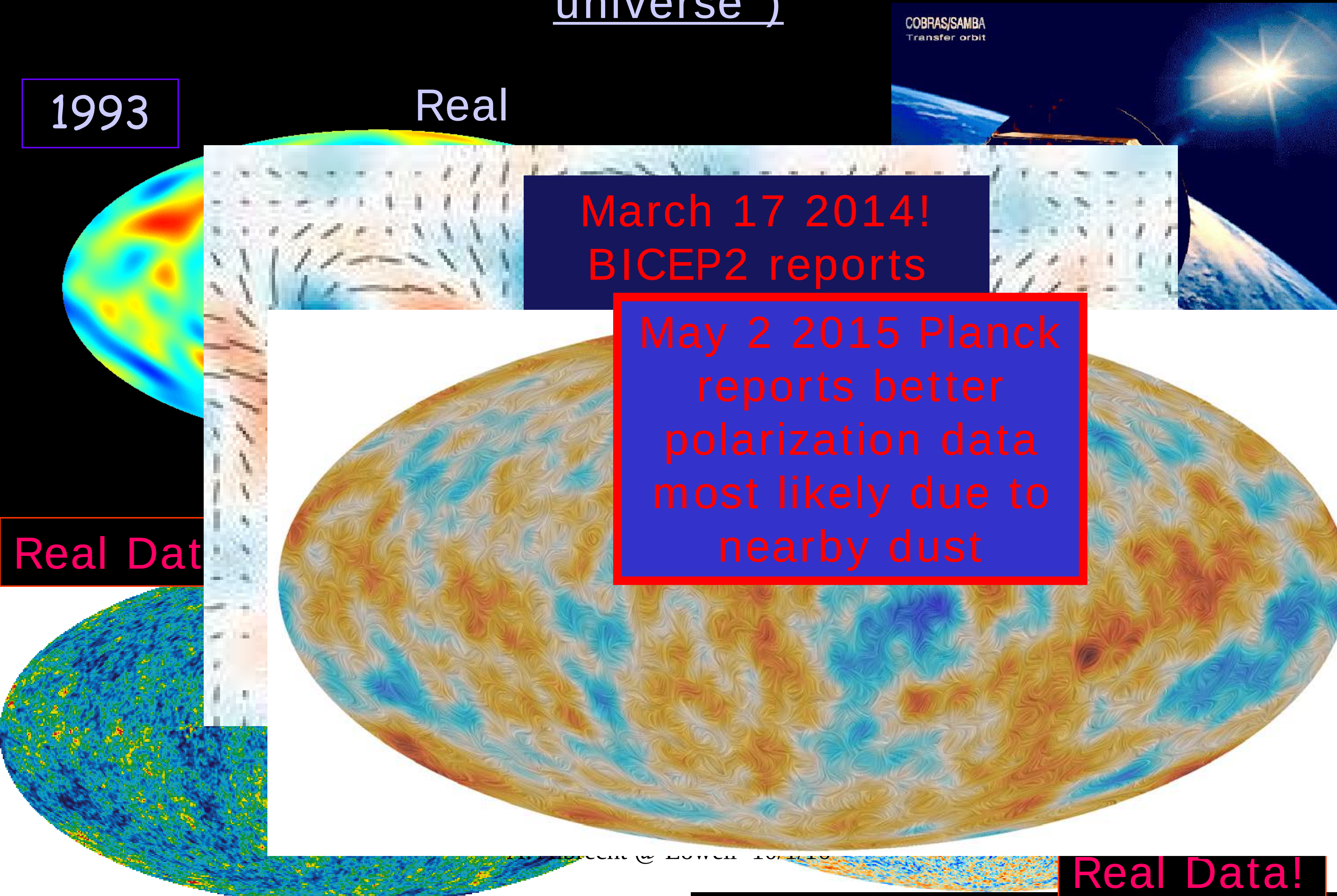


March 17 2014! BICEP2 reports

May 2 2015 Planck reports better polarization data most likely due to nearby dust

Real Dat

Real Data!

Maps of the microwave sky (the “edge of the observable universe”)

1993

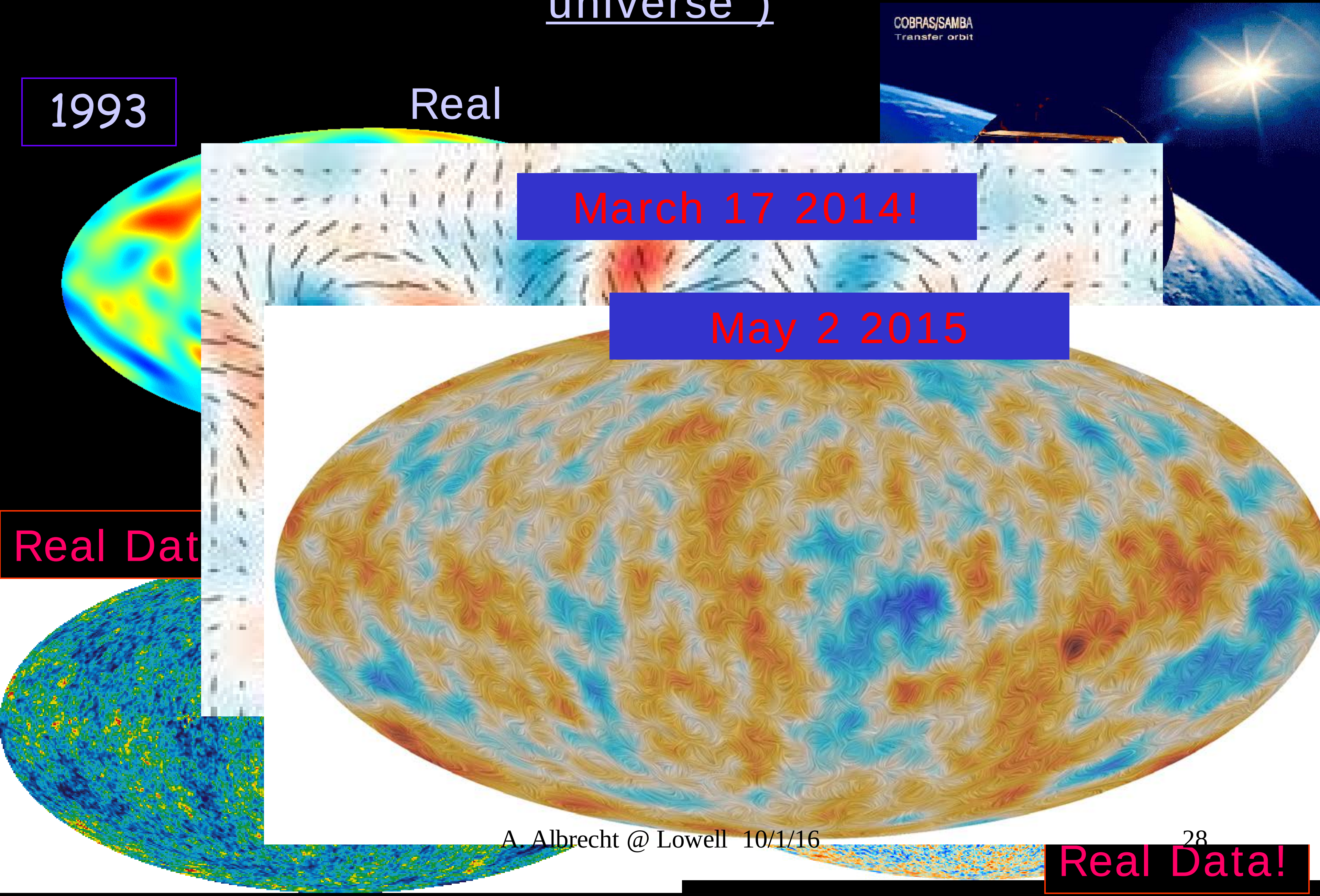
Real

Real Dat

March 17 2014!

May 2 2015

Real Data!



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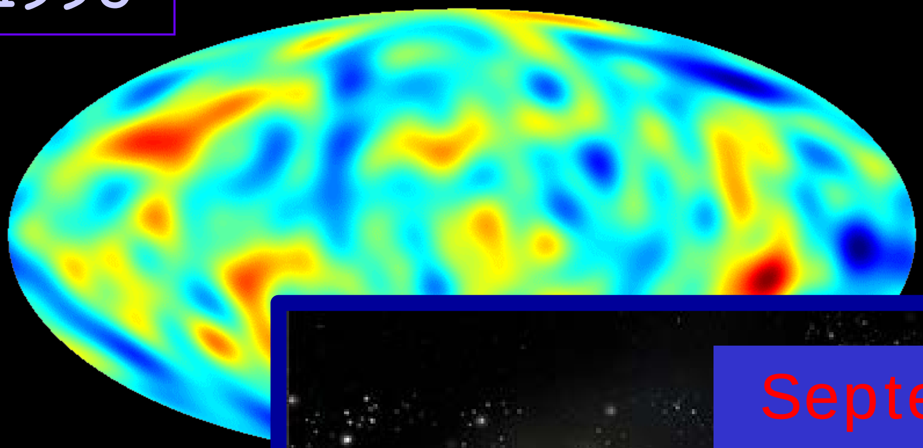
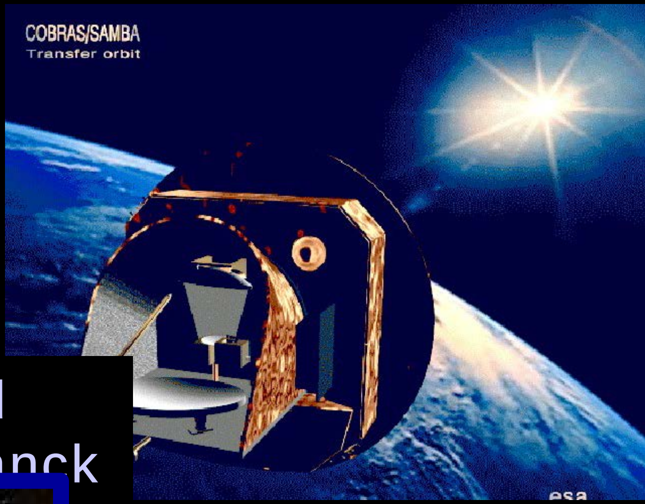
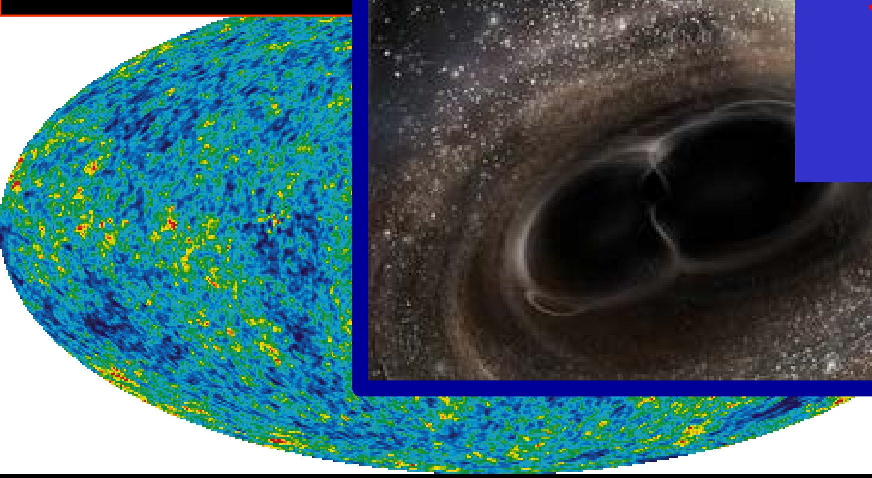




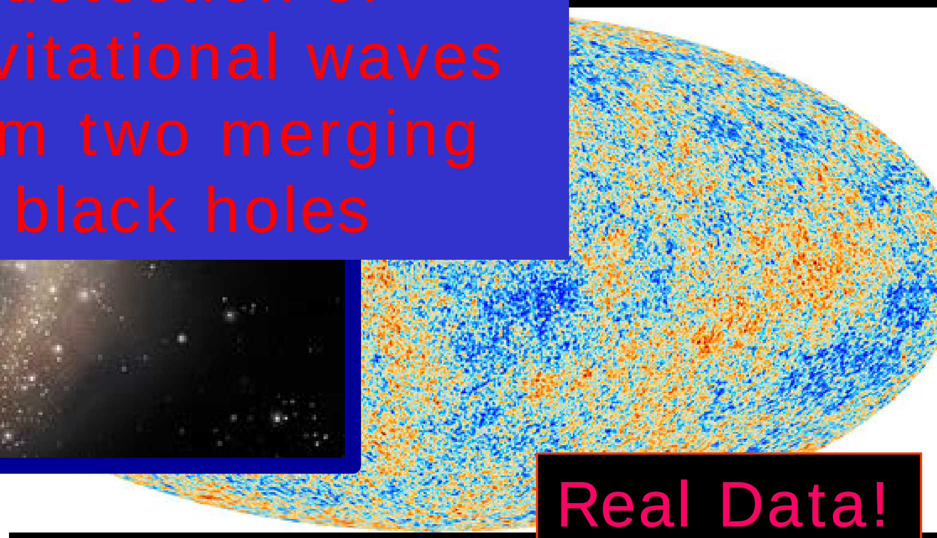
Updated
after Planck

2013

Real Data!



September 14 2015!
LIGO reports direct detection of gravitational waves from two merging black holes



Real Data!

Links related to previous slides

http://www.esa.int/esaSC/120398_index_0_m.html

http://www.rssd.esa.int/index.php?project=planck

http://bicepkeck.org/

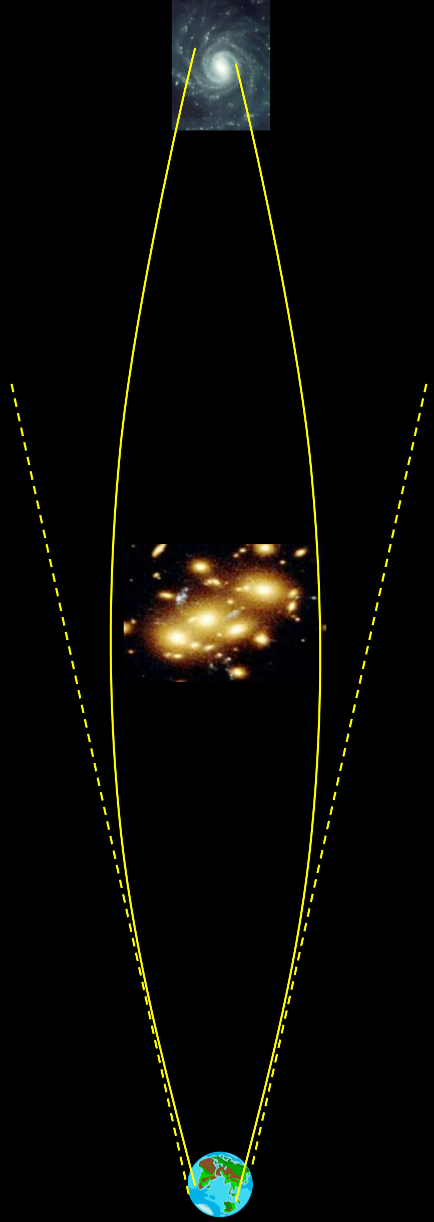
http://www.esa.int/spaceinimages/Images/2015/02/Polarisation_of_the_Cosmic_Microwave_Background

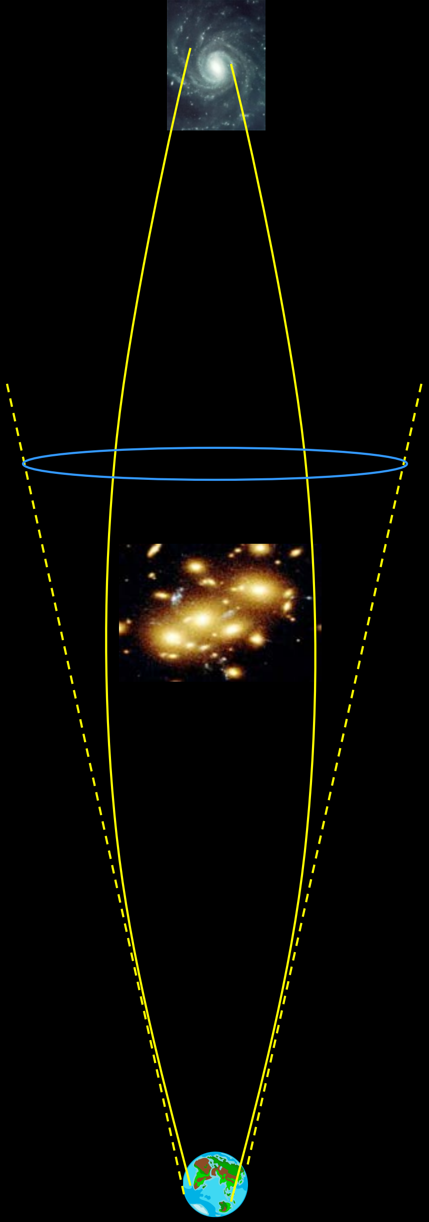
http://www.esa.int/esaSC/120398_index_0_m.html

http://www.rssd.esa.int/index.php?project=planck

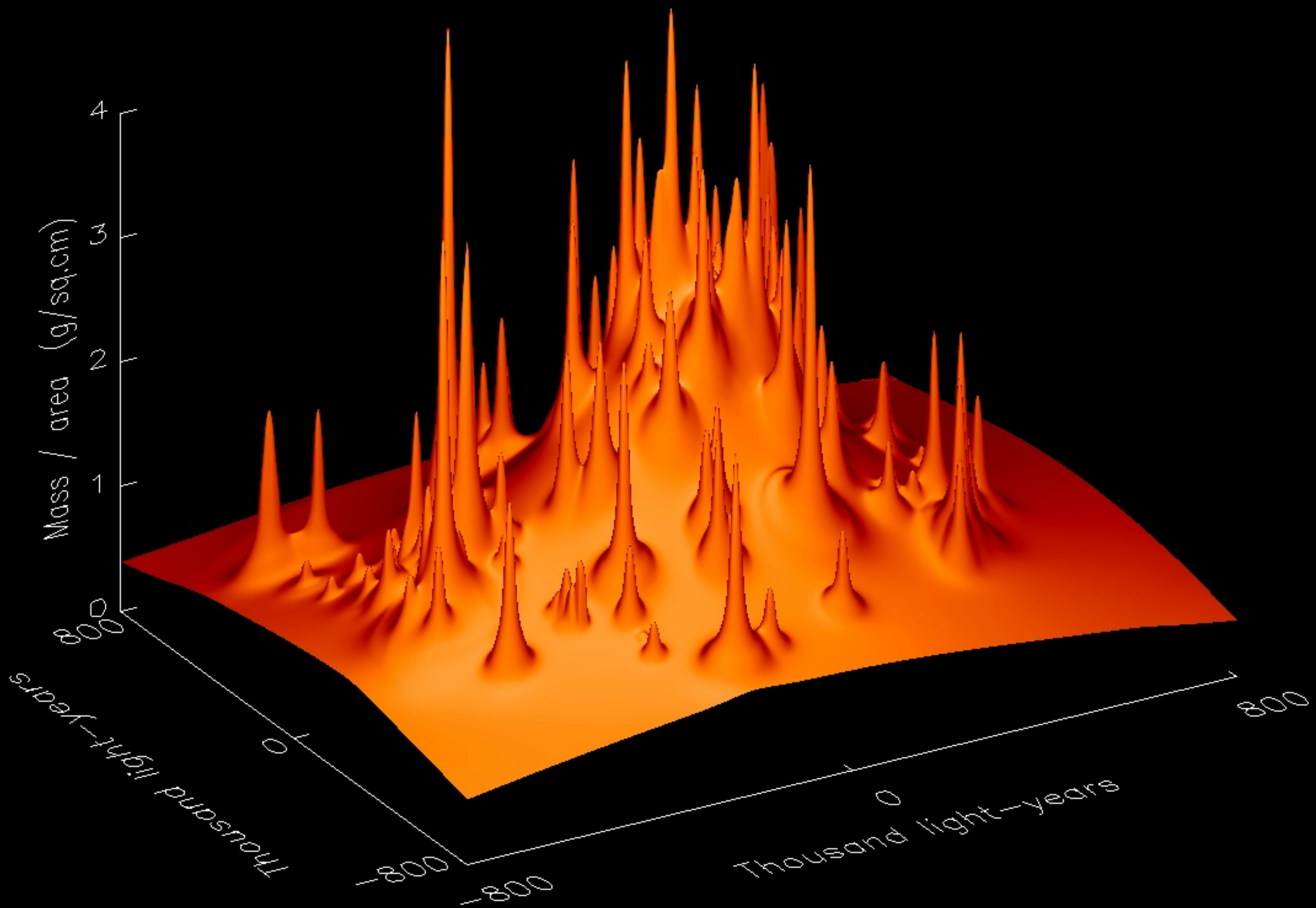
http://albrecht.ucdavis.edu/special-topics/bicep2-story

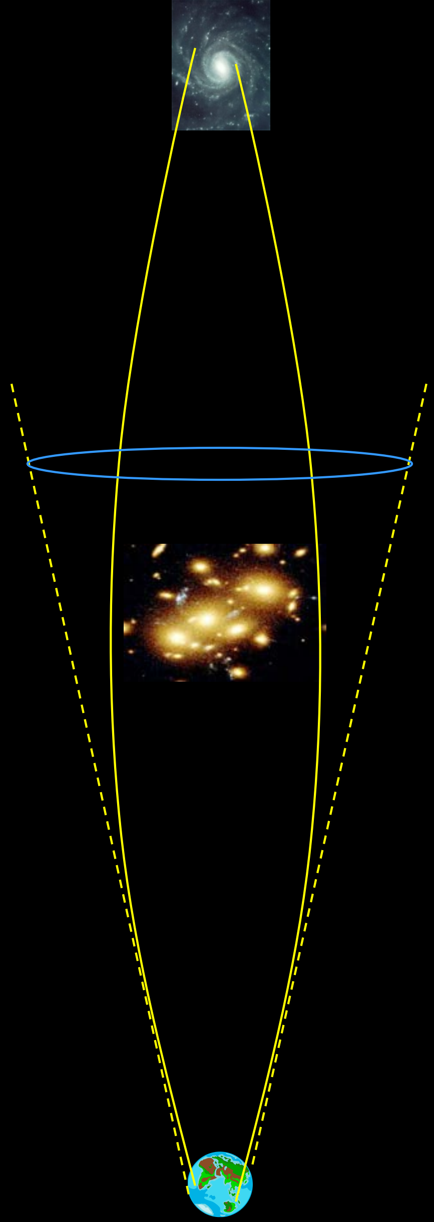
https://www.ligo.caltech.edu/news



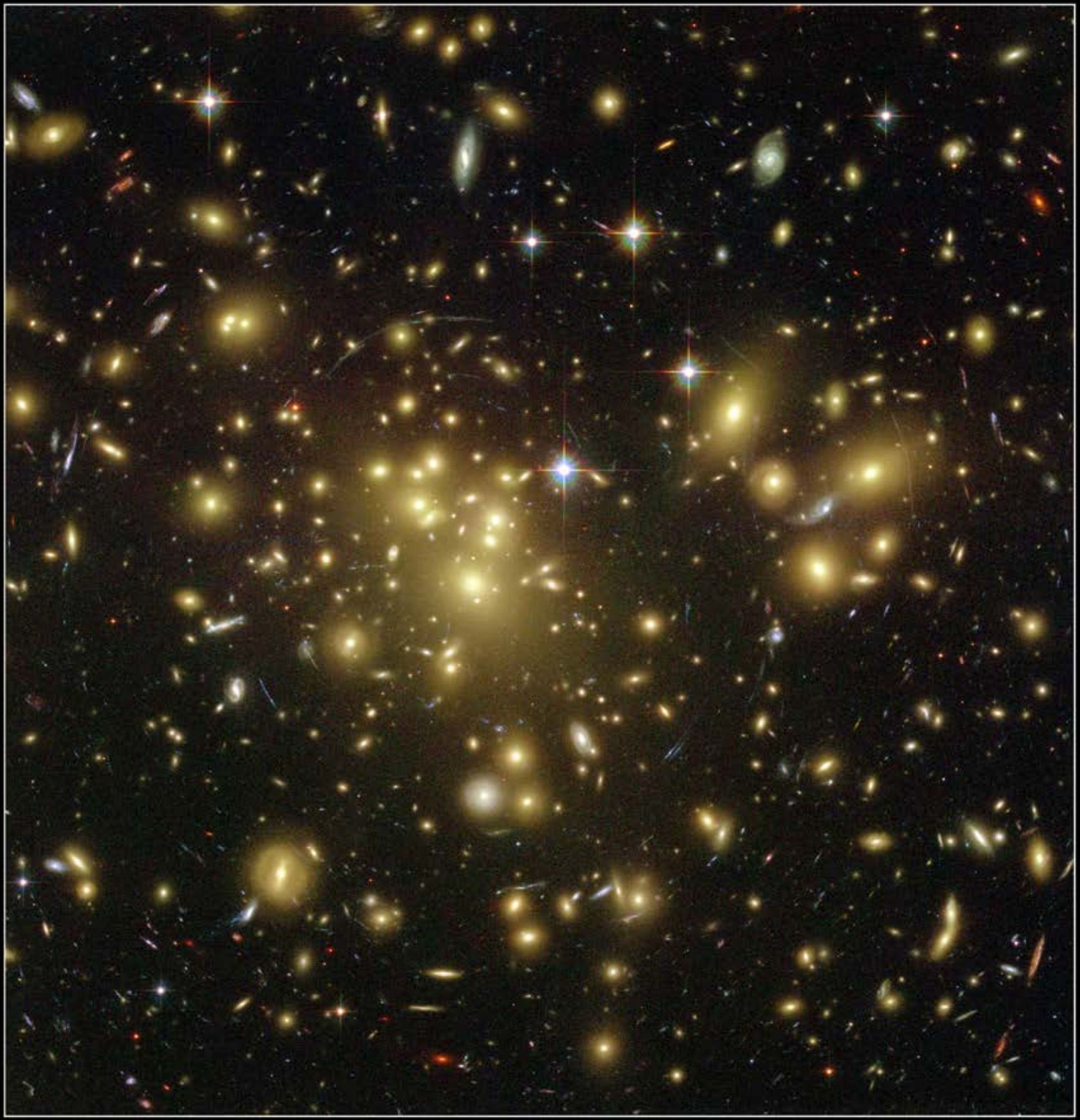


Mass inferred from lensing:
Must have dark matter





1996



Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

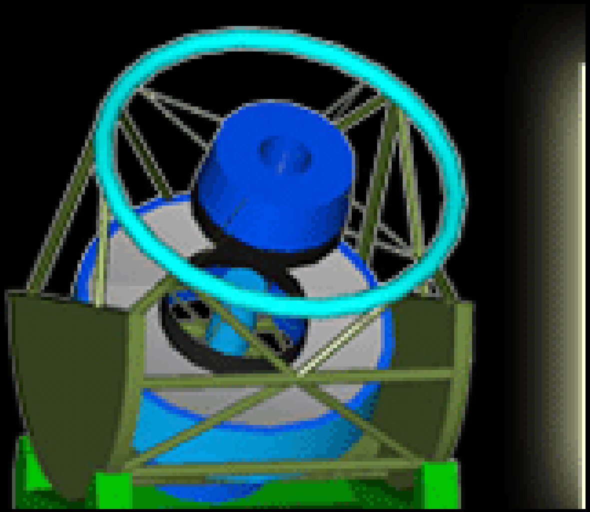
NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

Using Hubble's "advanced camera for surveys" installed June 2002

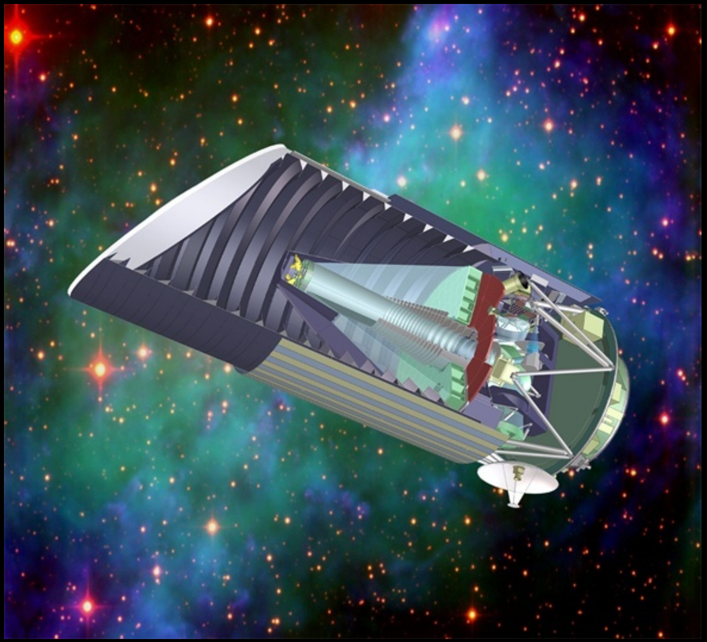
http://hubblesite.org/

http://www.nasa.gov/mission_pages/hubble/main/index.html

Some Future Plans



LSST (Large-aperture Synoptic Survey Telescope)

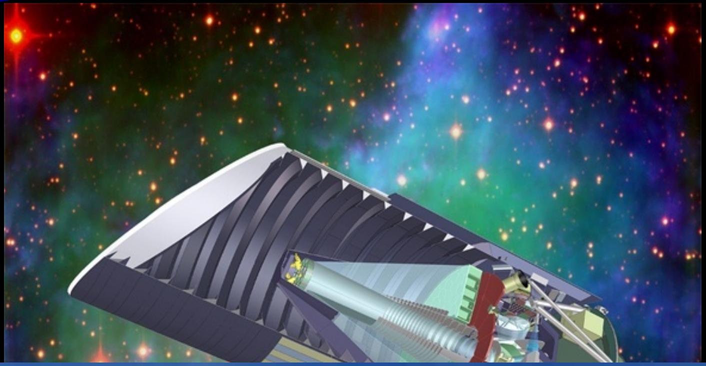


WFIRST

James Webb Space Telescope

Some Fut

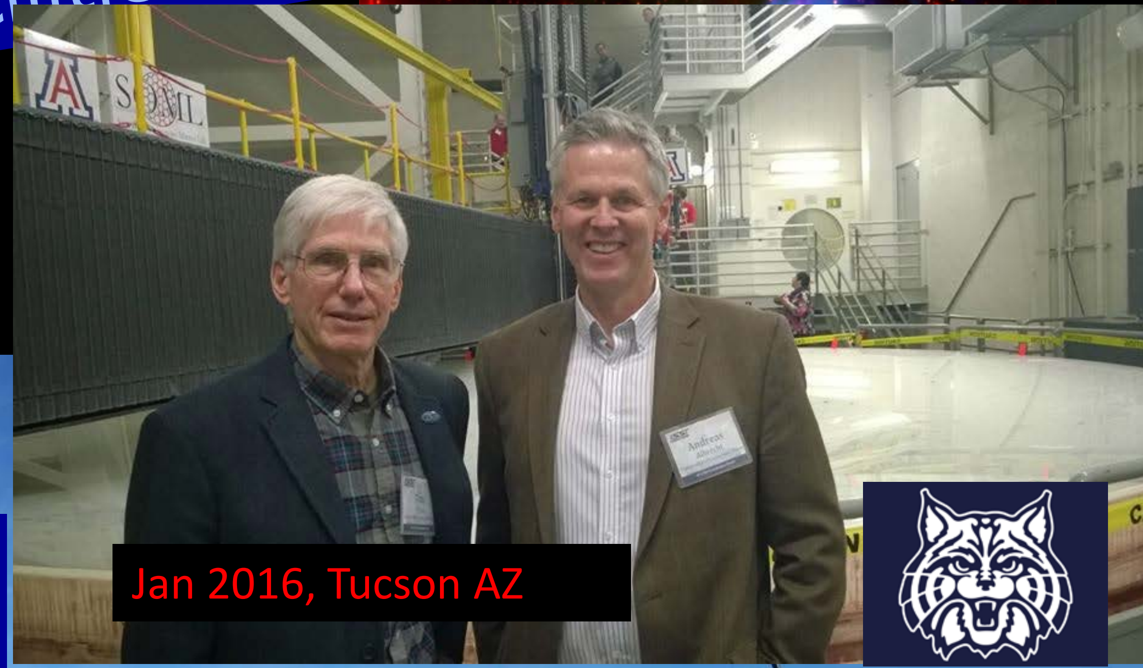
New facilities being built



LSST (Large-aperture Synoptic Survey Telescope)

Some Fut

New facilities being built

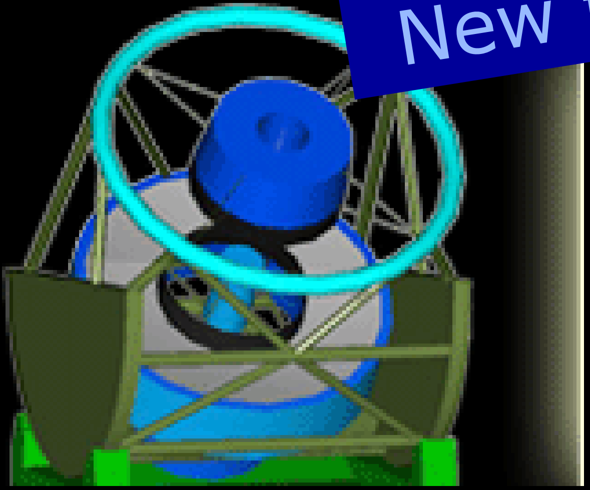


Jan 2016, Tucson AZ

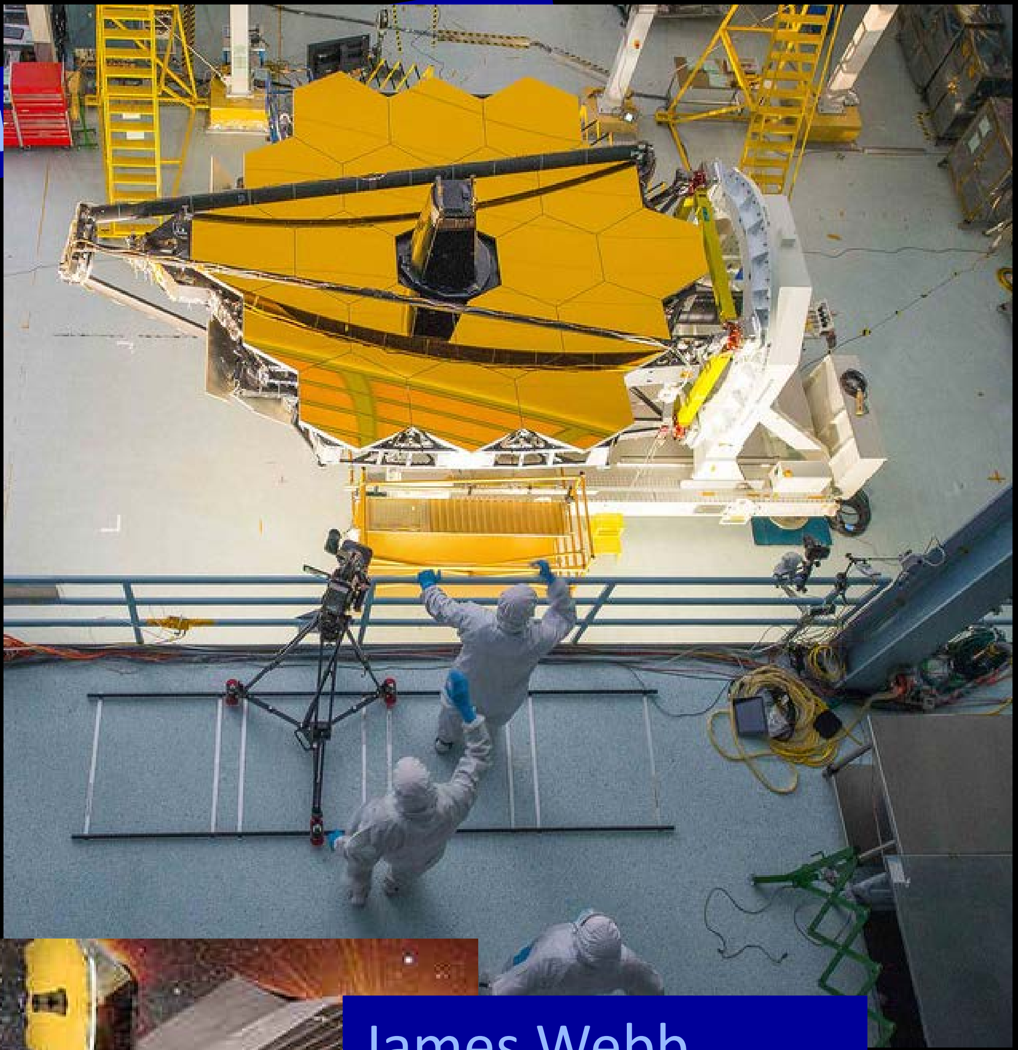
LSST (Large-aperture Synoptic Survey Telescope)

Some F

New faciliti



LSST (Large-aperture Synoptic Survey Telescope)



James Webb Space Telescope (2018 Launch)

Some Fut

New facilities being built

LS
Sy
Te

NASA

WFIRST
WIDE FIELD INFRARED SURVEY TELESCOPE

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Frequently Asked Questions

1. Will the WFIRST mission be a breakthrough in the search for dark matter?

WFIRST will survey large areas of the sky measuring the effects of dark matter on the distribution of galaxies in the universe. It will also observe distant Type Ia supernovae to use them as tracers of dark matter and dark energy. It will provide a huge step forward in our understanding of dark matter and dark energy.

2. In what phase of development is currently the WFIRST spacecraft?

WFIRST is currently in Phase A.The purpose of Phase A is to develop the mission requirements and architecture necessary to meet the programmatic requirements and constraints on the Project and to develop the plans for the Preliminary Design phase.

3. Are the preparations on track for the mid-2020 launch?

Yes, the preparations are on track for a mid-2020 launch.

WFIRST

https://www.lsst.org/

http://jwst.nasa.gov/index.html

http://wfirst.gsfc.nasa.gov/

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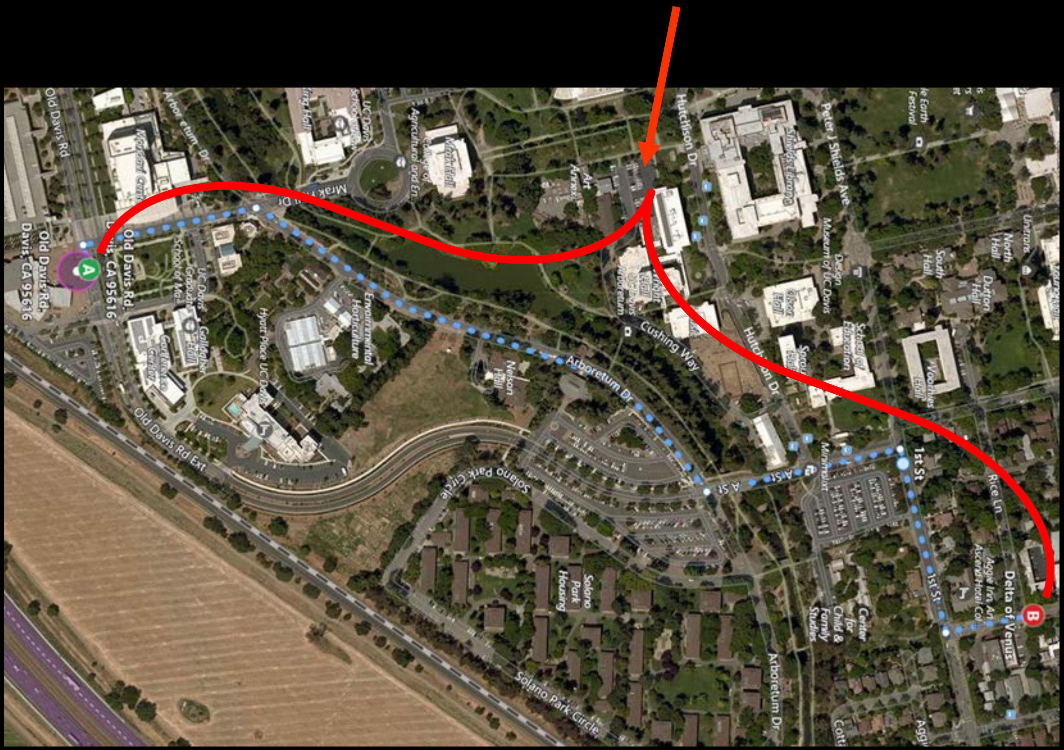
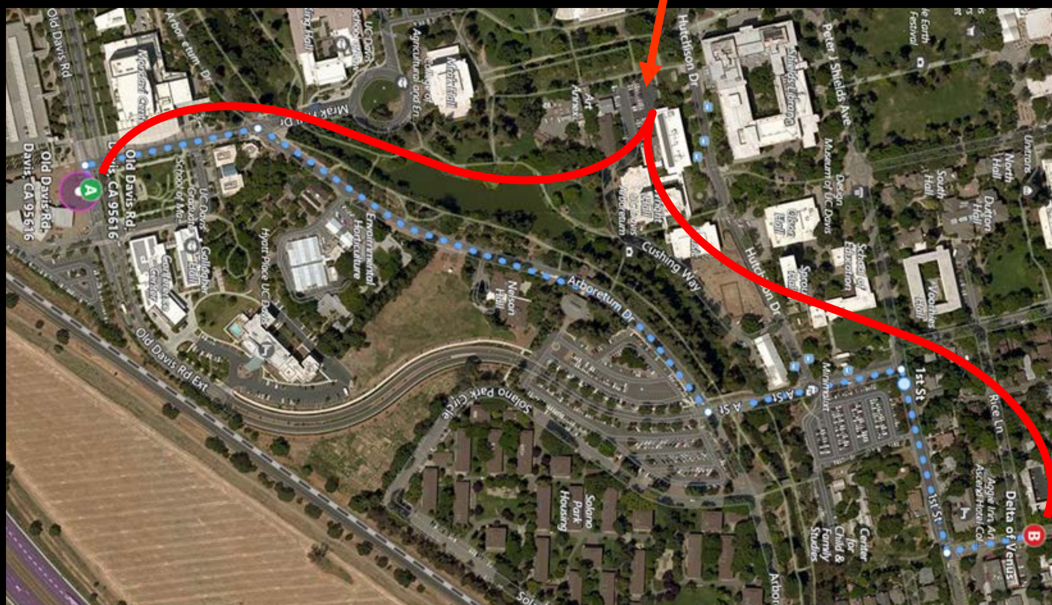
Distances in the Universe

Measure of distance: One Kilometer ≈ Walk from the <u>*Manetti Shrem*</u> to <u>*Delta of Venus*</u>



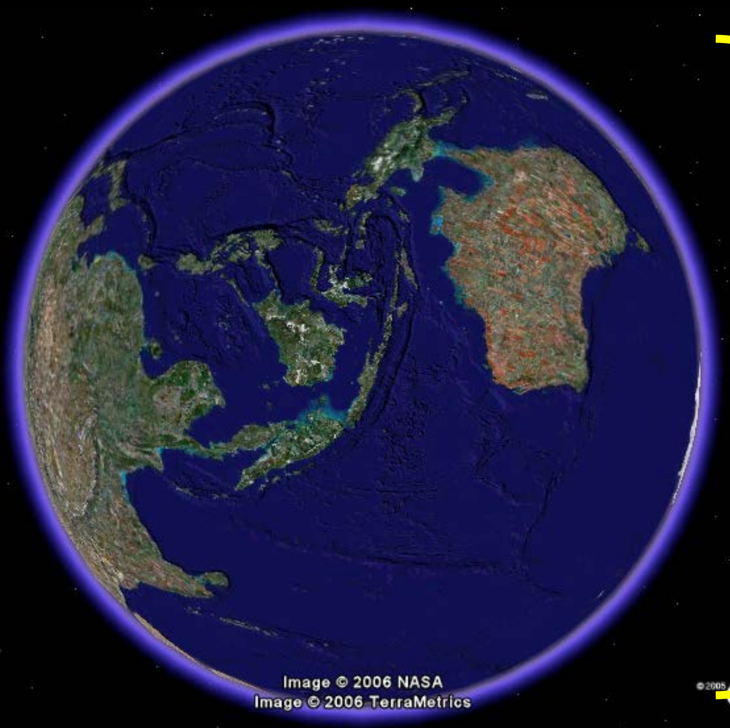
Measure of distance: One Kilometer ≈ Walk from the *Manetti Shrem* to *Delta of Venus*



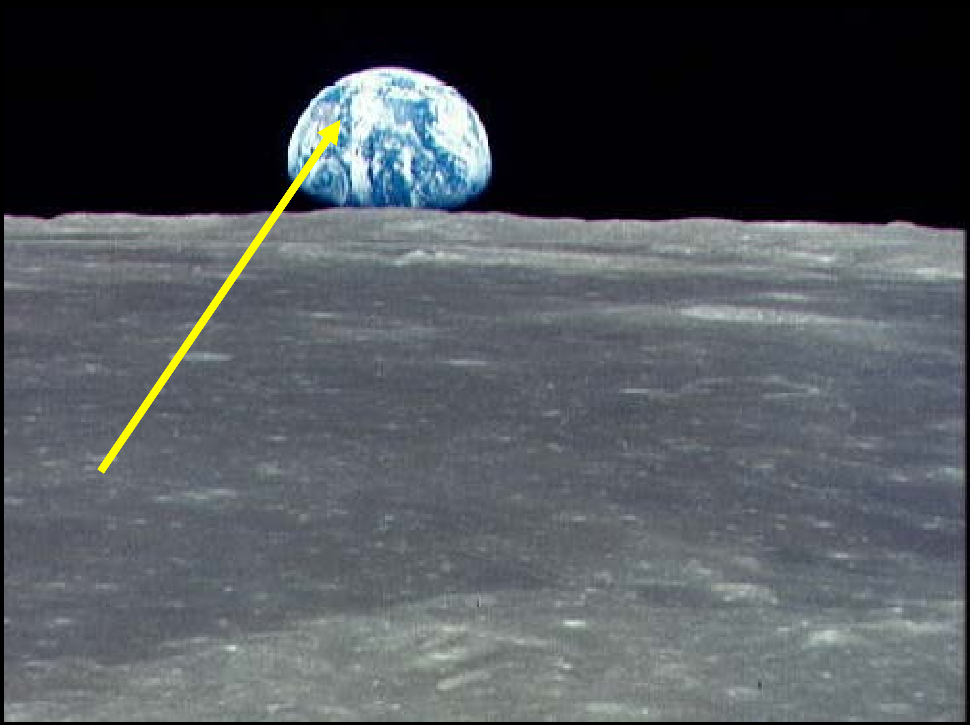
Count cosmic distances as grains of sand:
One grain of sand per kilometer.

Grain of sand (enlarged)

Diameter of earth = 12,760 kilometers ←→
1 Teaspoon of sand

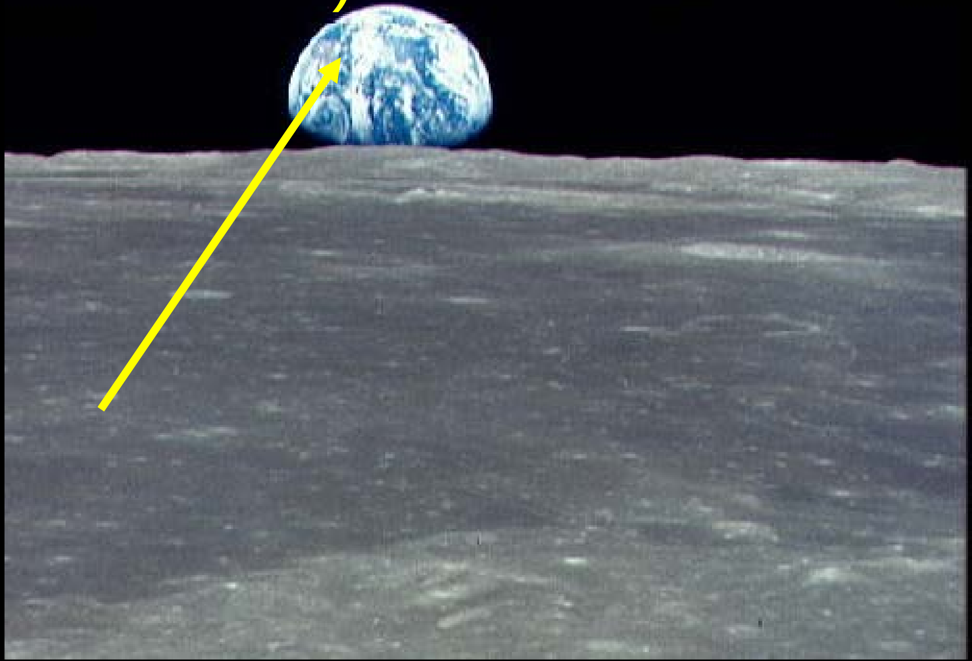


Distance to Moon = 356,410 kilometers ←→
1 Handful of sand

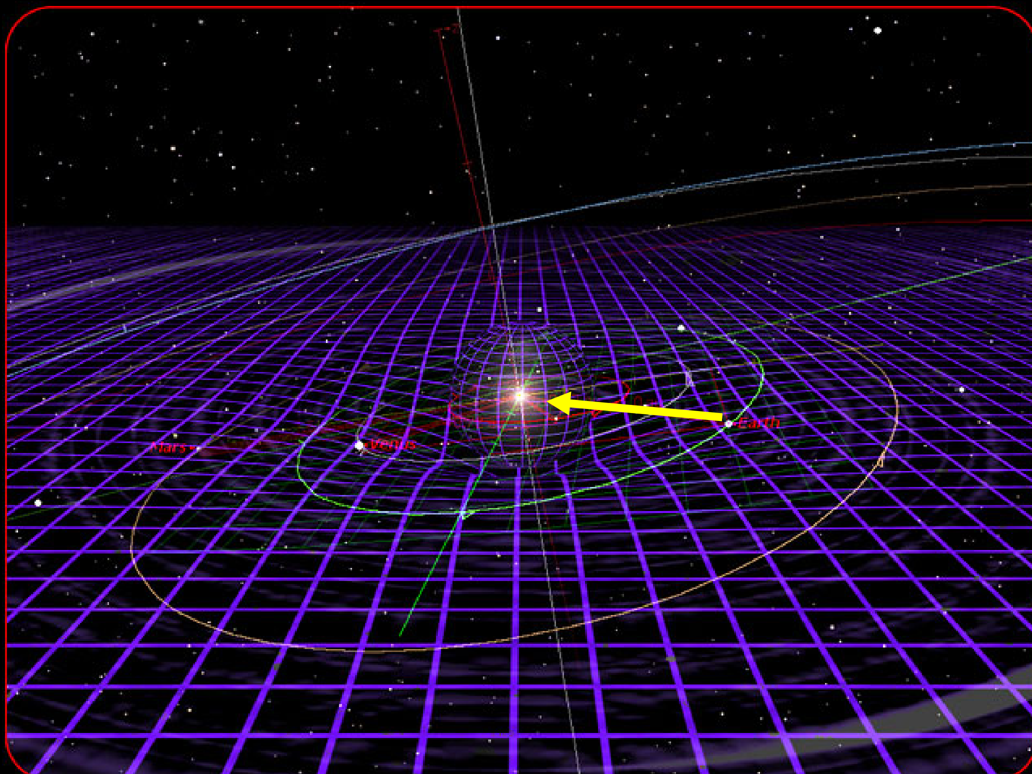


Distance to Moon = 356,410 kilometers ←→
1 Handful of sand

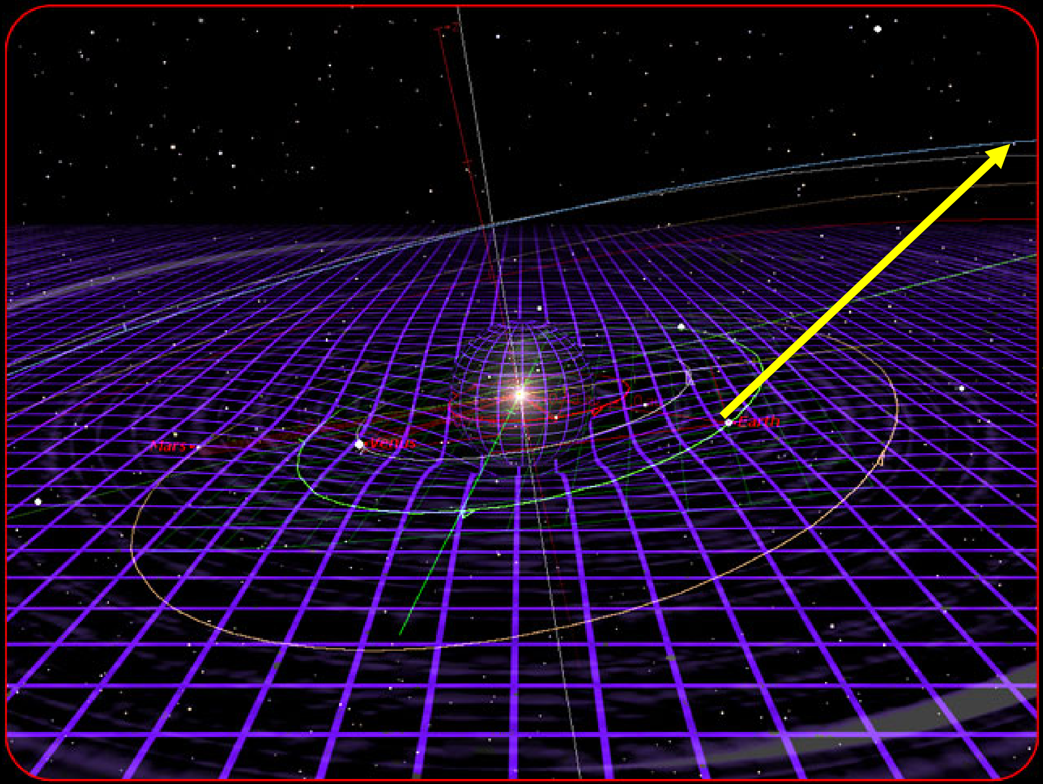
(Also roughly the distance light travels in one second)



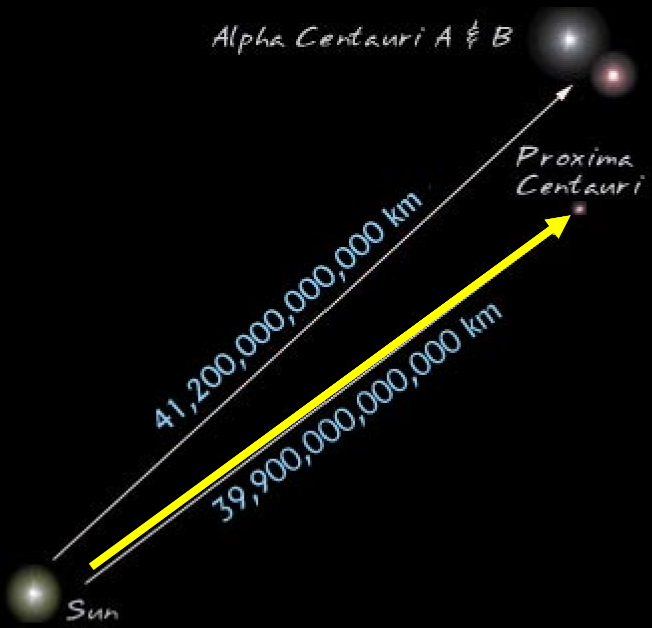
Distance from Earth to Sun = 149,600,000 kilometers (8 light minutes) ←→ 1 Milkshake cup of sand



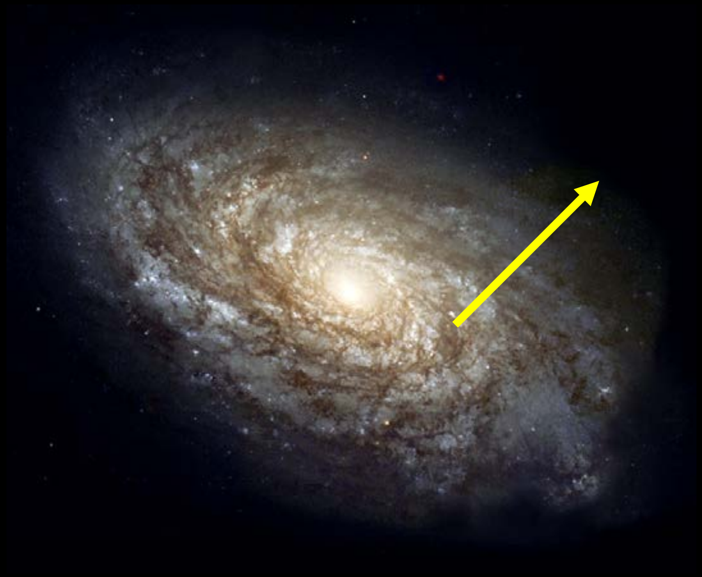
Distance from Earth to Pluto = 6,000,000,000 kilometers ⇔ 1 wheelbarrow of sand



Distance from Earth to Nearest Star = 40,000,000,000,000 kilometers ⟺ 1 dumpster of sand



Distance from Earth to Edge of our galaxy = 1,000,000,000,000,000,000 kilometers ←→ 1 Physics/Geology Bulidng full of sand



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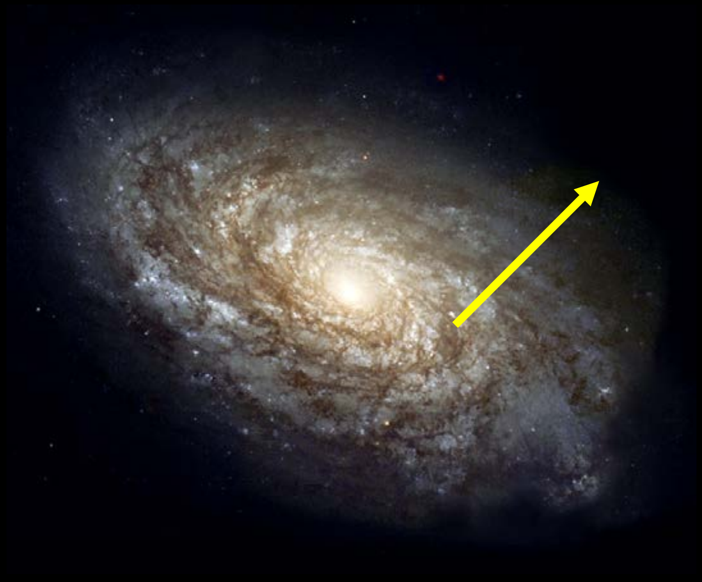
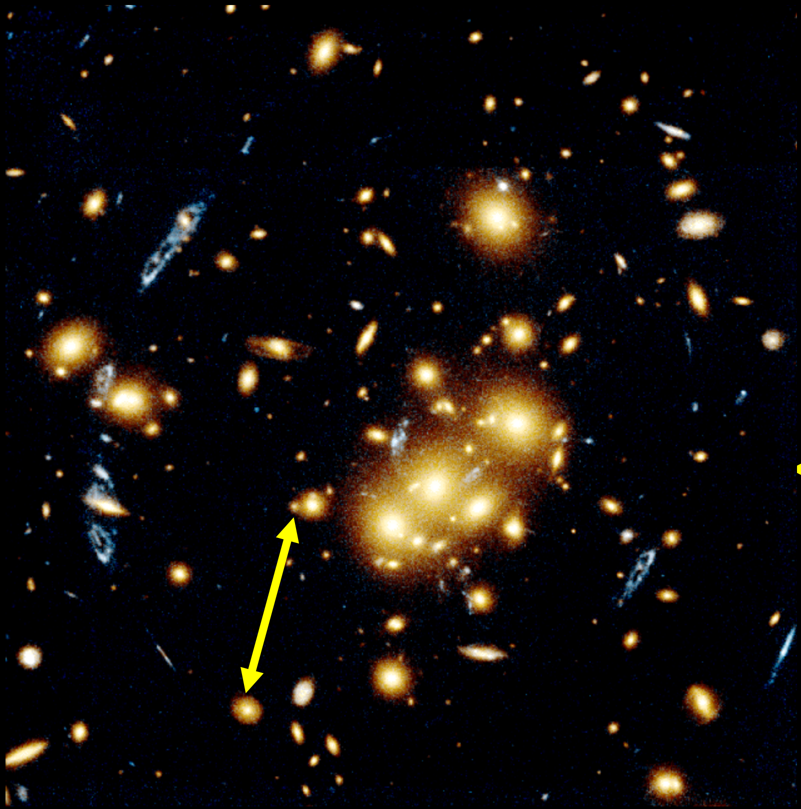
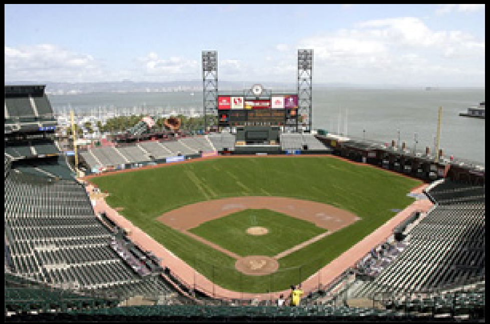
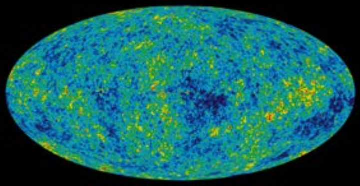


Average distance between galaxies = 3×10^{19} kilometers ⇔ 1 baseball stadium full of sand

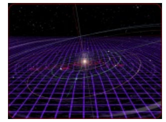
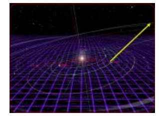
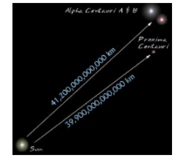


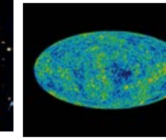


Farthest visible “object” in the universe: 1×10^{23} kilometers ←→ mountain range of sand





$1 km$

0

Earth diameter

$1.3\times10^{4}\,km$

4.1

Distance to Moon

$3.6\times10^{5}\,km$

5.6

Earth-Sun distance

$1.4\times10^{8}\,km$

8.1

Earth-Pluto distance

$6\times10^{9}\,km$

9.8

Distance to nearest star

$4\times10^{13}\,km$

13.6

Distance to edge of galaxy

$10^{18}\,km$

18

Average galaxy sep.

$3\times10^{19}\,km$

19.5

Most distant "object"

$10^{23}\,km$

23

$\log\left(d\,/\,km\right)$

What we know about the big picture

1) On large scales the matter in the Universe is spread out very smoothly ("Homogeneous")

Mean density: $10^{-29}\, gram / cm^3$

2) The Universe is <u>expanding</u>

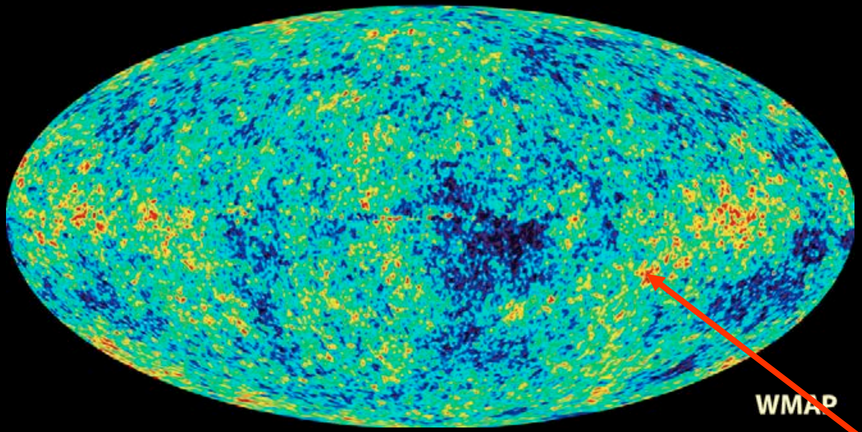
Distance

Hubble law: $v = Hr$

Expansion Speed

$$H = \left(\frac{3m/\sec}{100 lightyears} \right)$$

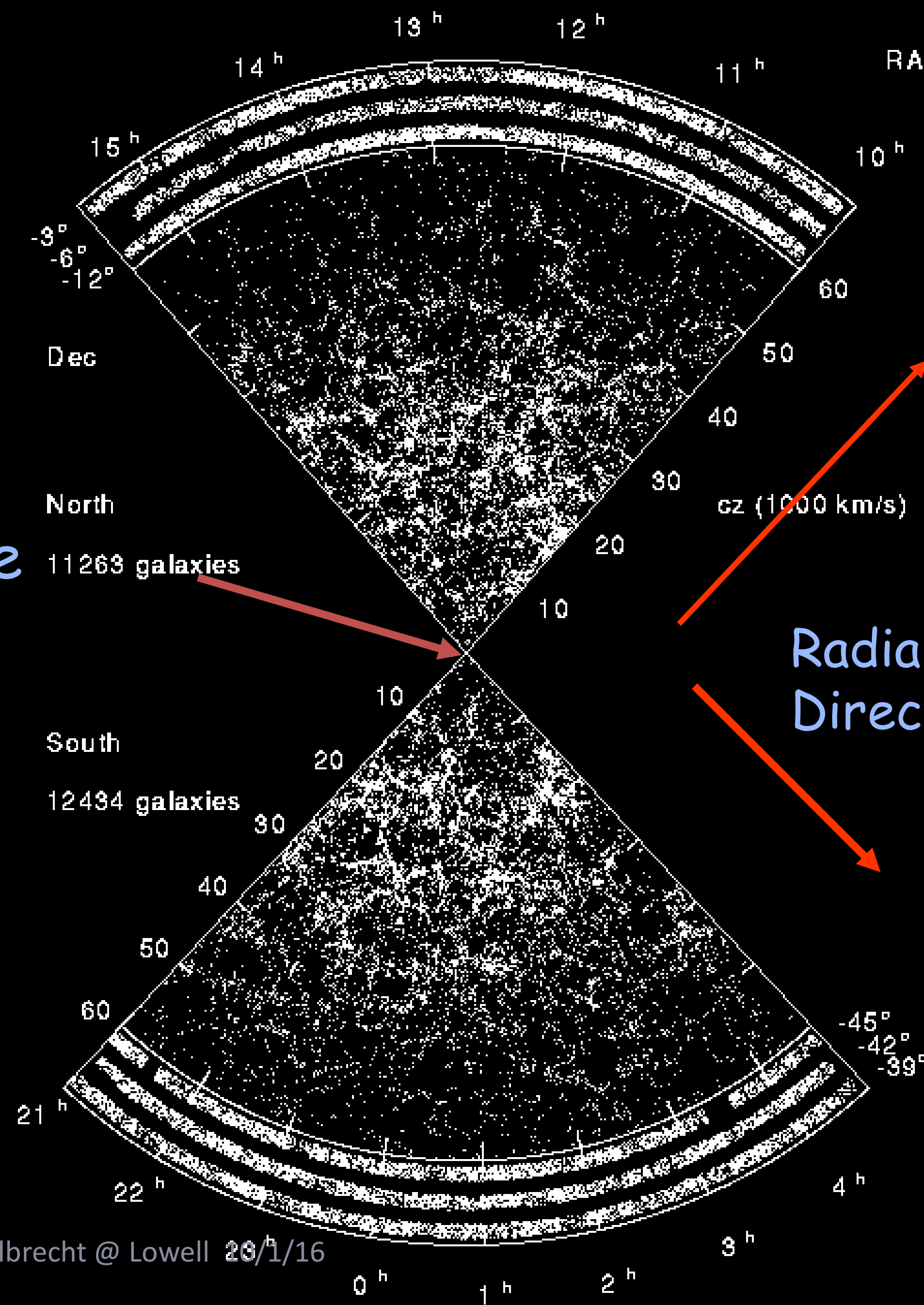
The homogeneity of the Universe



Isotropy of the microwave background (from the "edge of the observable universe") to one part in 100,000

The homogeneity of the universe

We are here

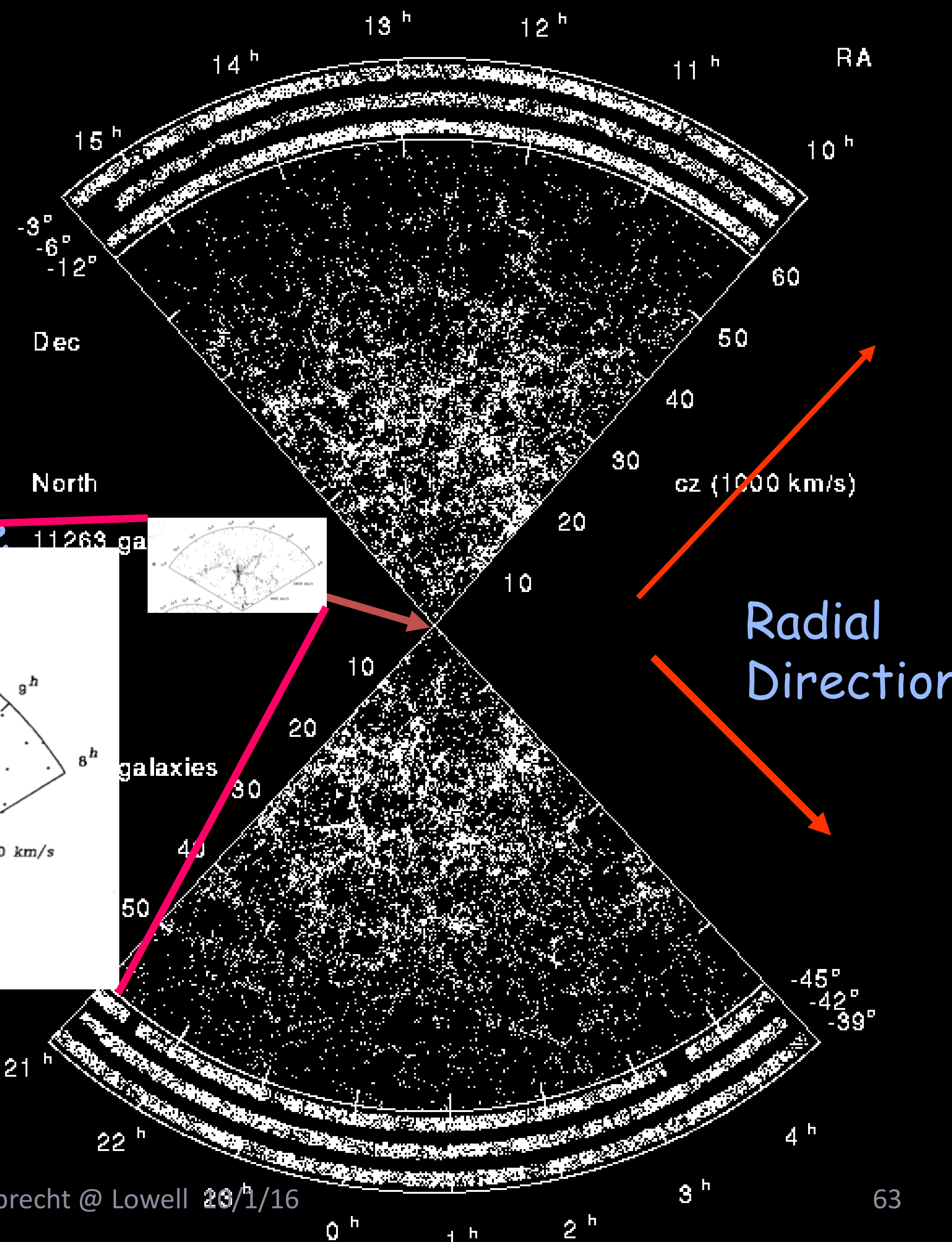


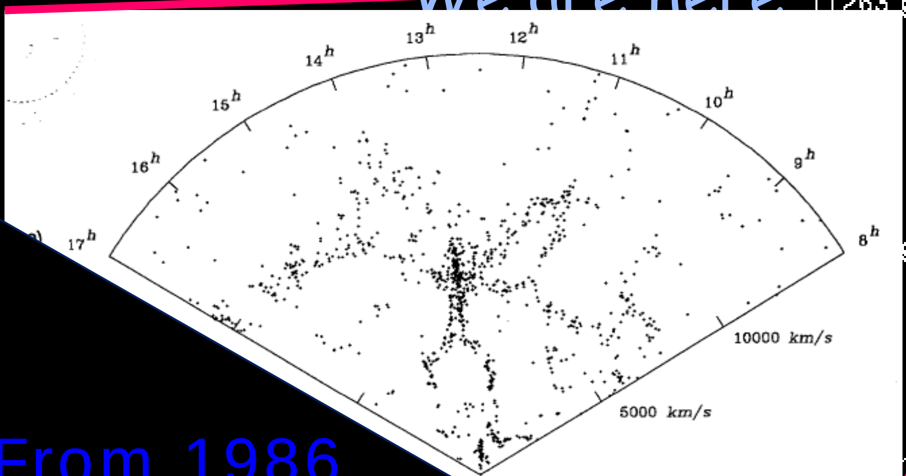
Radial Direction

Galaxy surveys

The homogeneity of the universe

We are here



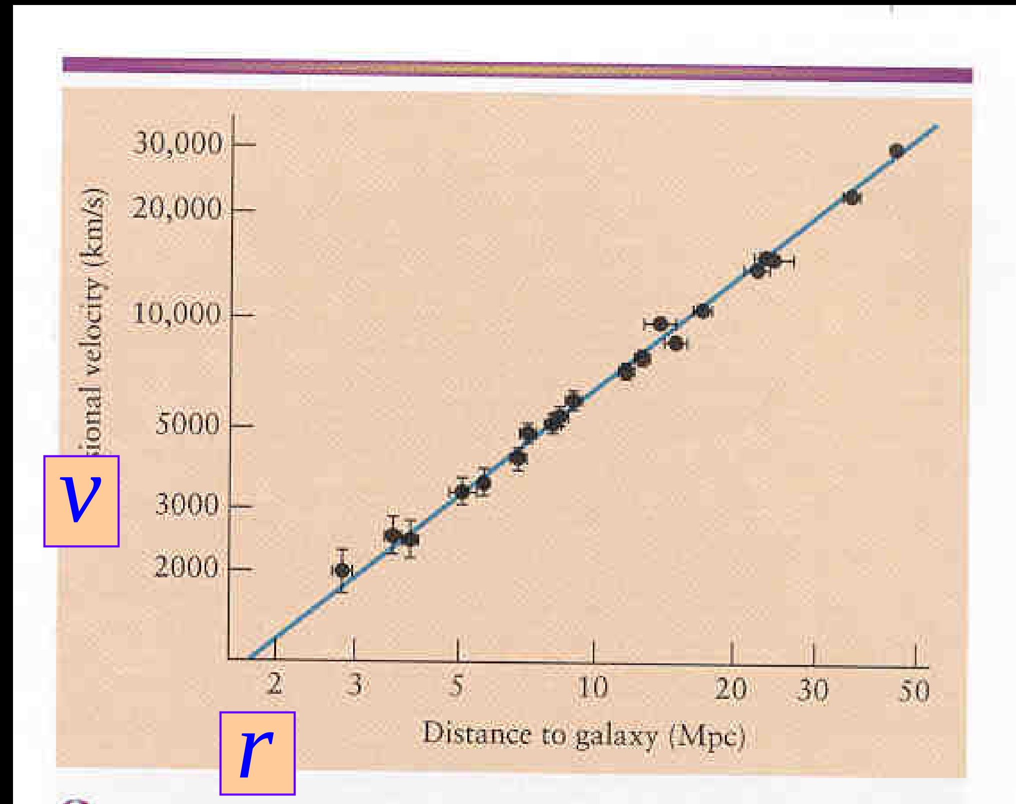


From 1986

Radial Direction

Galaxy surveys

The Hubble law

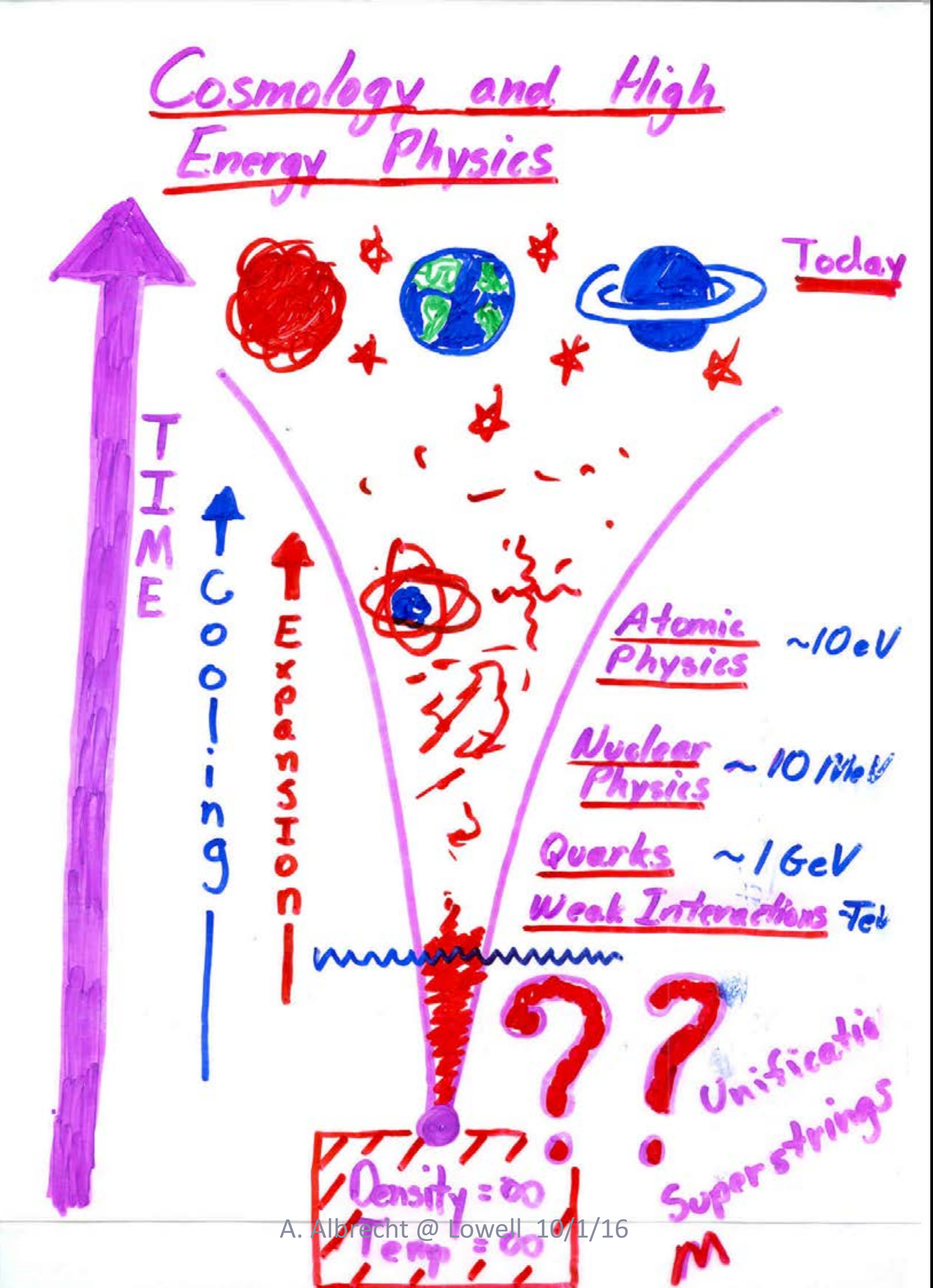


$$v = Hr$$

$$H = \left(\frac{3m/\sec}{100 lightyears} \right)$$

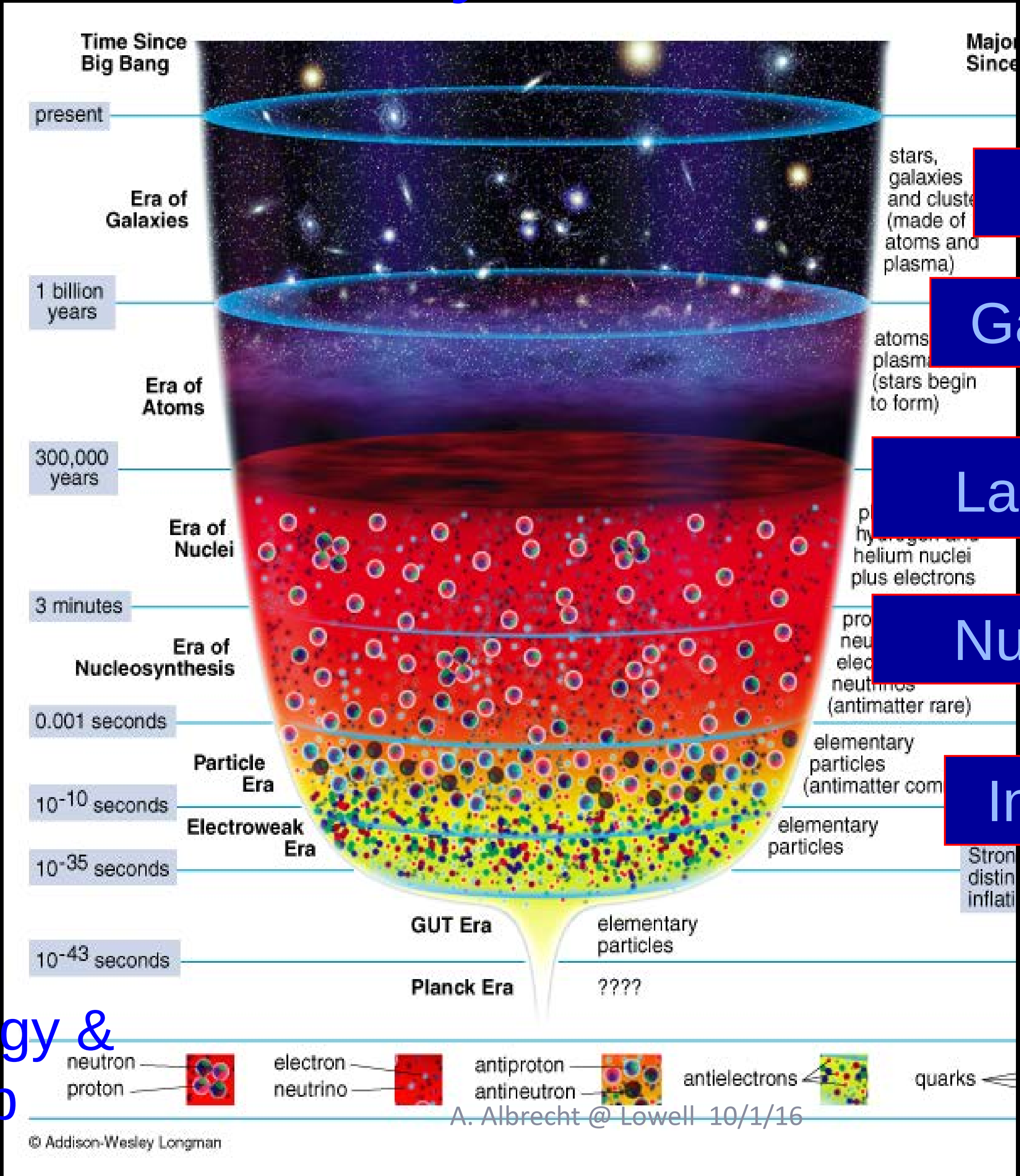
Hubble Expansion

Hot, Dense past


Cosmology and High Energy Physics
Today
TIME
Cooling
Expansion
Atomic Physics ~10eV
Nuclear Physics ~10 MeV
Quarks ~1GeV
Weak Interactions TeV
Unification
Superstrings
M
Density = ∞
Temp = ∞

Time

The History of the Universe



Today

Dark Energy

Galaxy Formation

Last Scattering

Nuclear & HEP

Inflation?

Extra Dimensions?

High Energy & Temp

The History of the Universe

Time

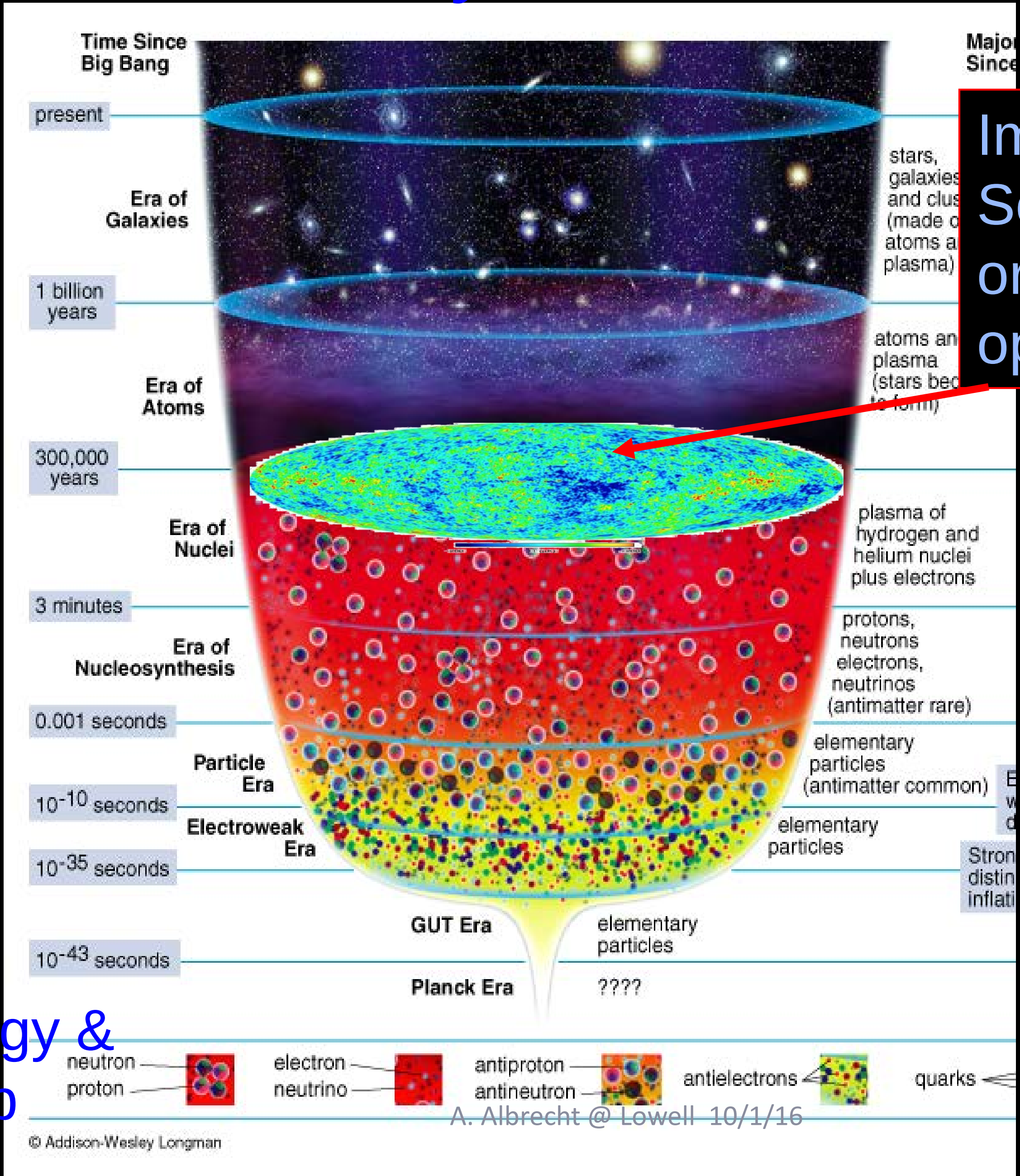


Image of the "Last Scattering Surface" or "edge of opaqueness"

High Energy & Temp

Time

The History of the Universe

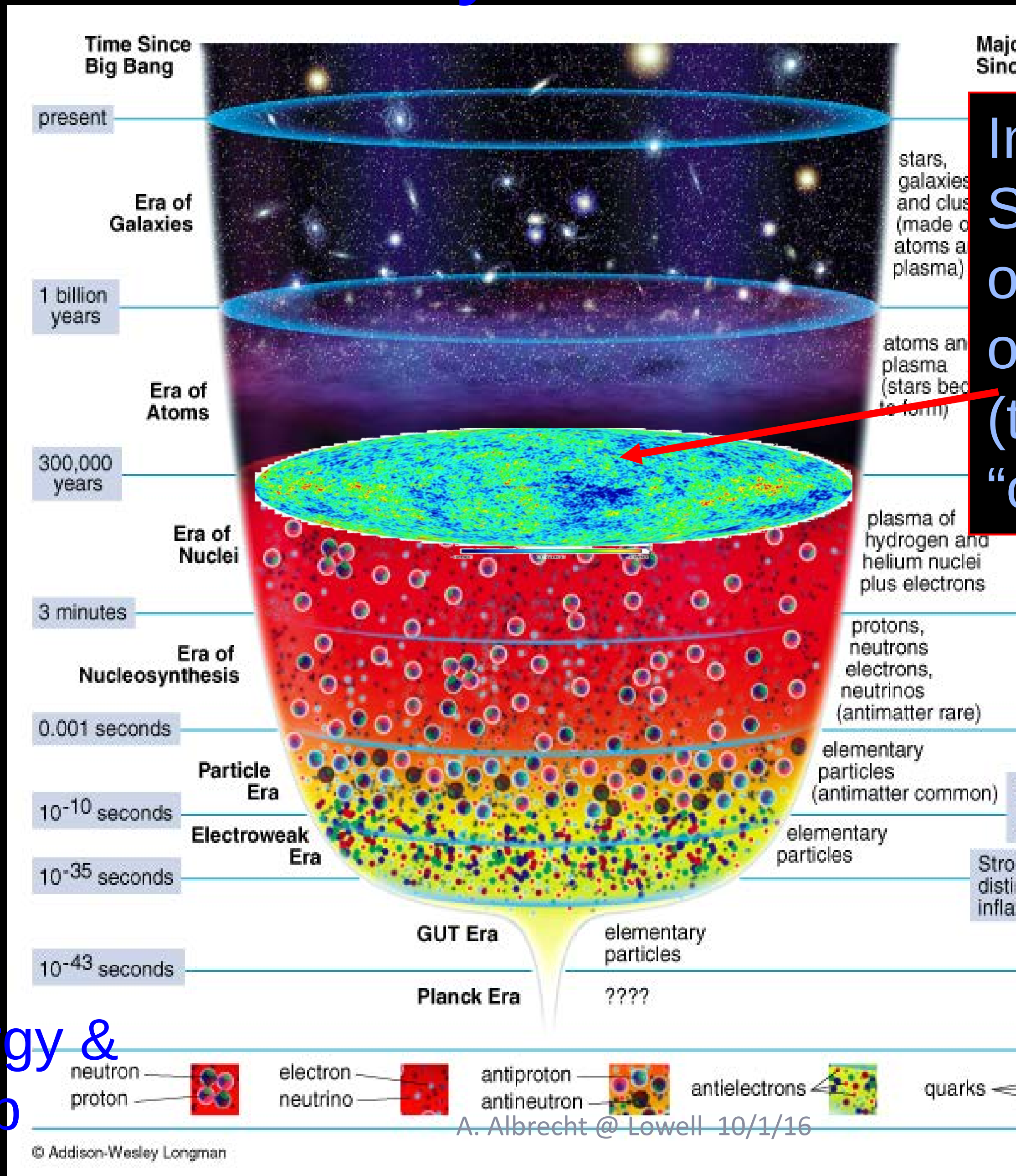
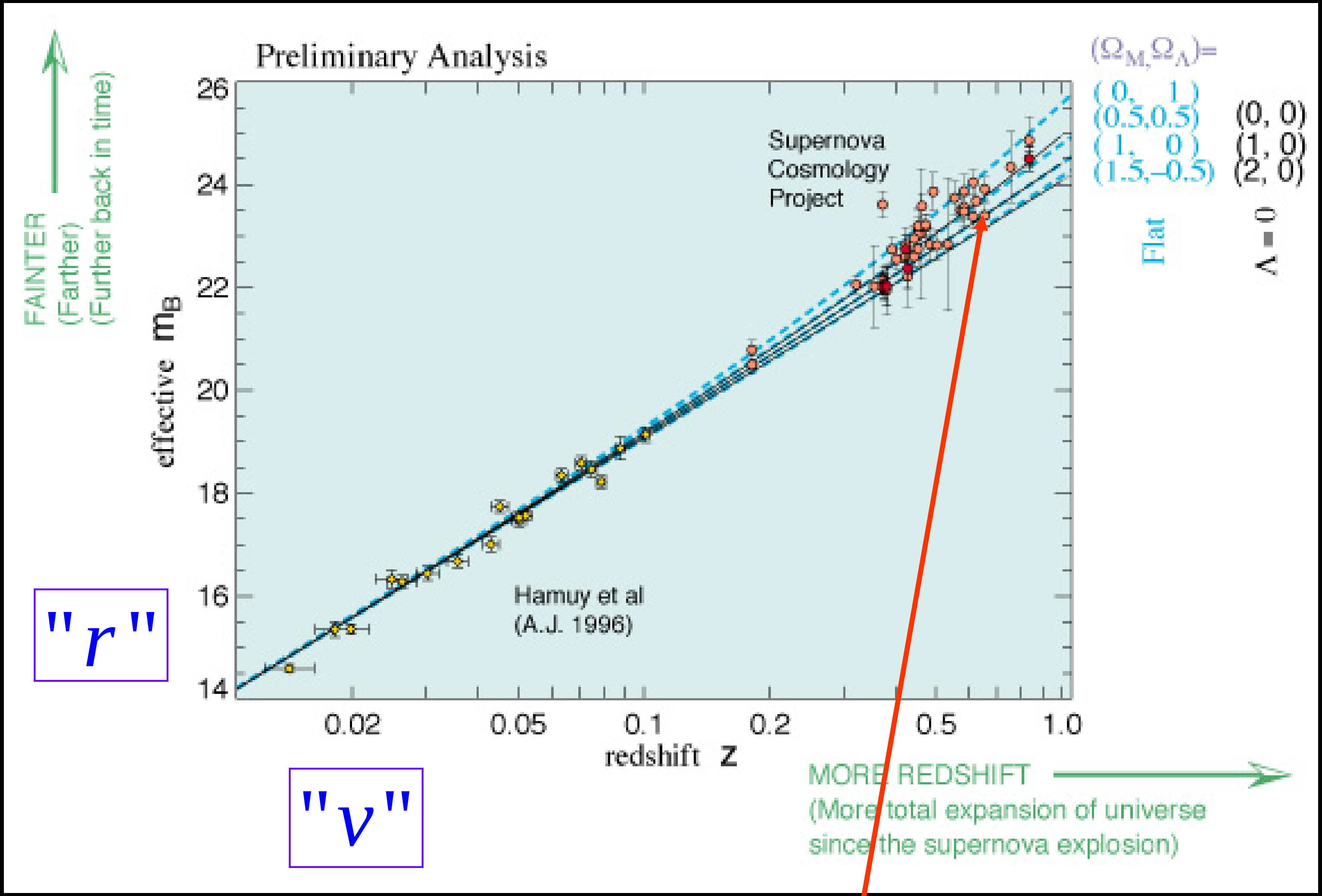


Image of the “Last Scattering Surface” or “edge of opaqueness” (the most distant “object”)

High Energy & Temp

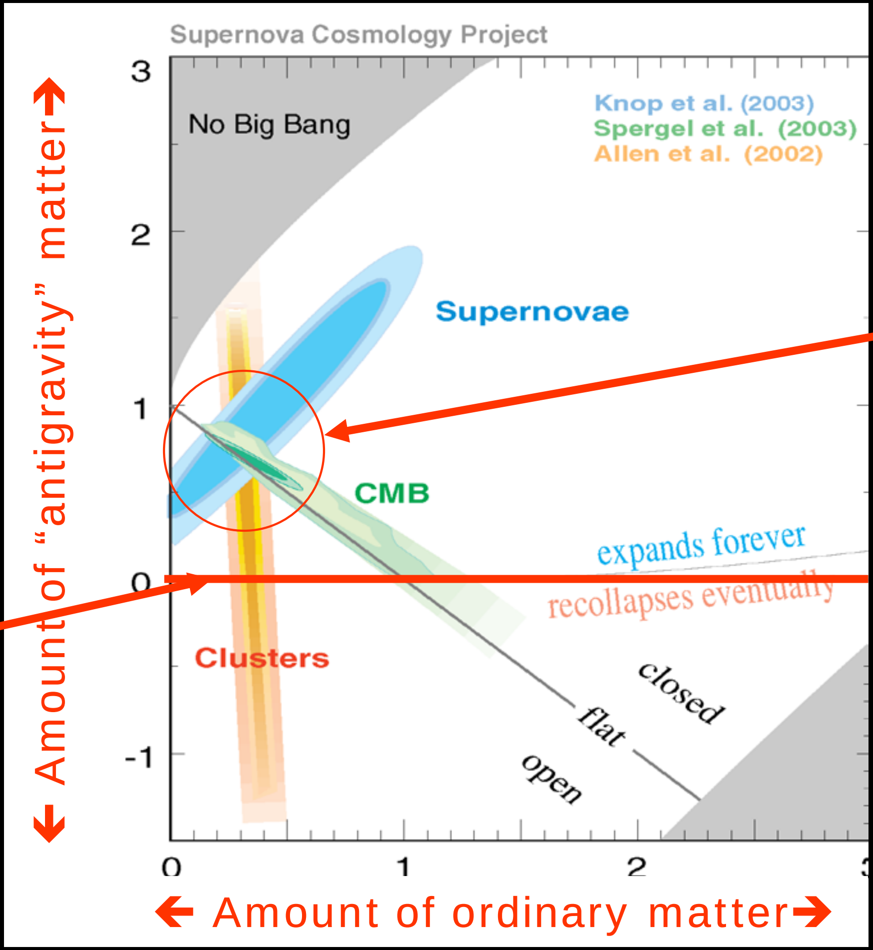
Acceleration of the universe



The Hubble law at great distances depends on the variations of the Hubble "constant" H with time.

Cosmic acceleration

Using supernovae (exploding stars) as cosmic "mileposts", *acceleration* of the Universe has been detected.

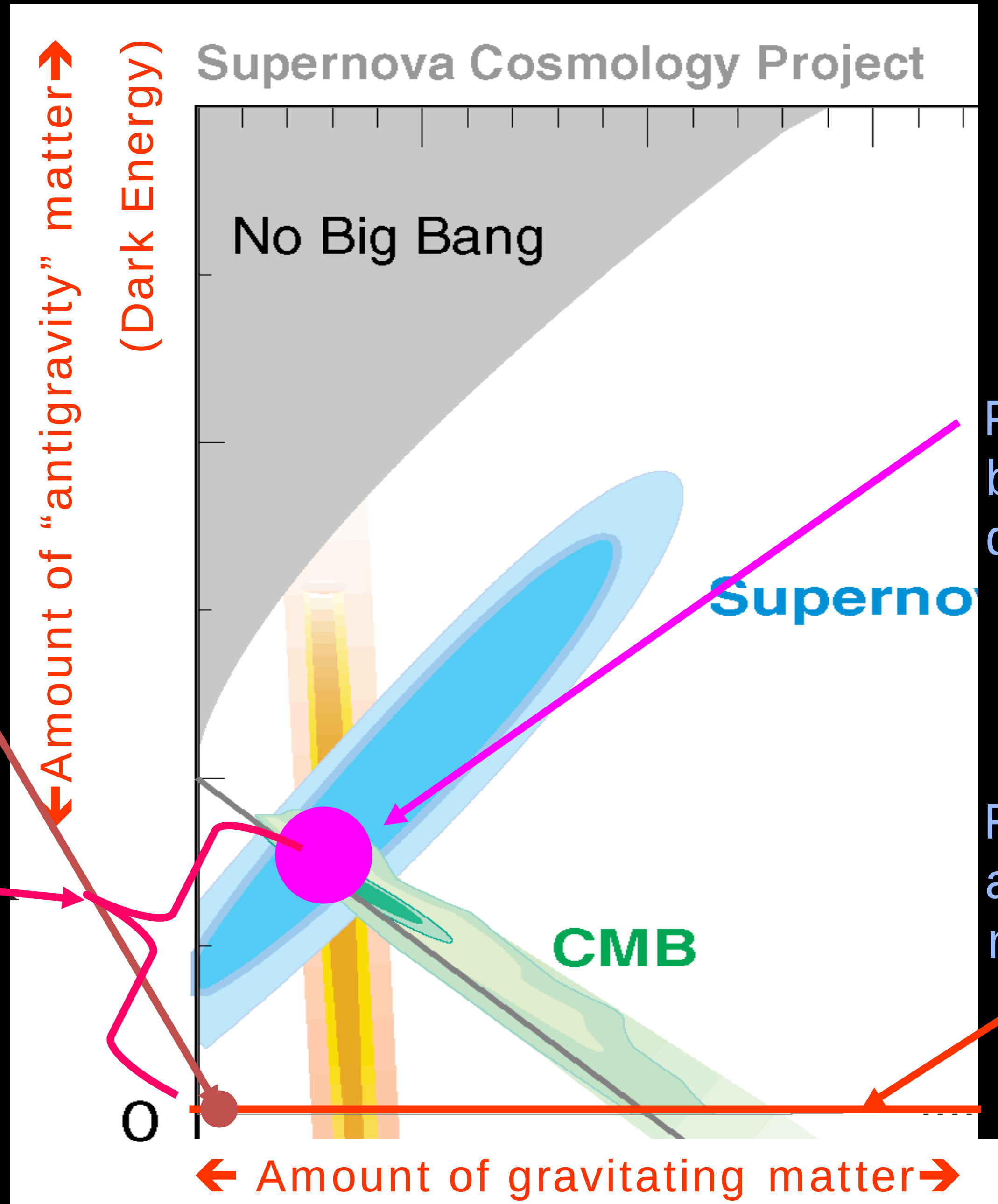


Preferred by modern data

"Ordinary" non accelerating matter

Mass-Energy of the a Universe made *only* out of standard model matter

Surprise factor



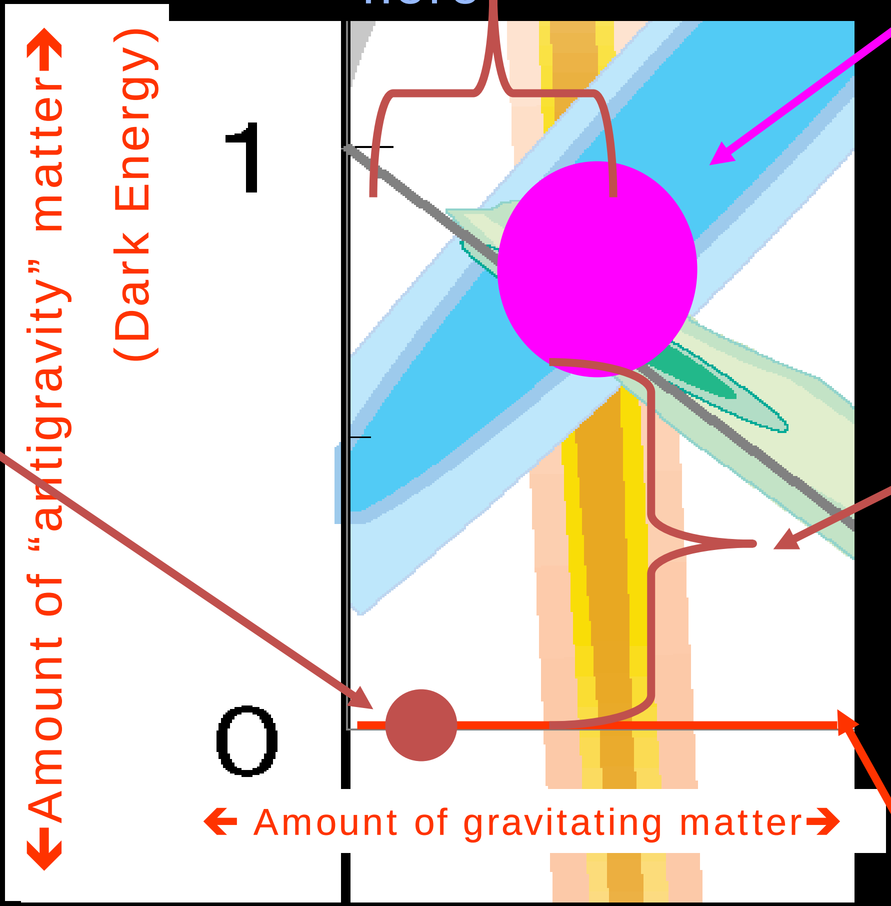
Preferred by modern data

Red line: No anti-gravity matter

Need to add dark matter here

Preferred by modern data

Mass-Energy of the a Universe made *only* out of standard model matter



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Cosmic acceleration (newest data)

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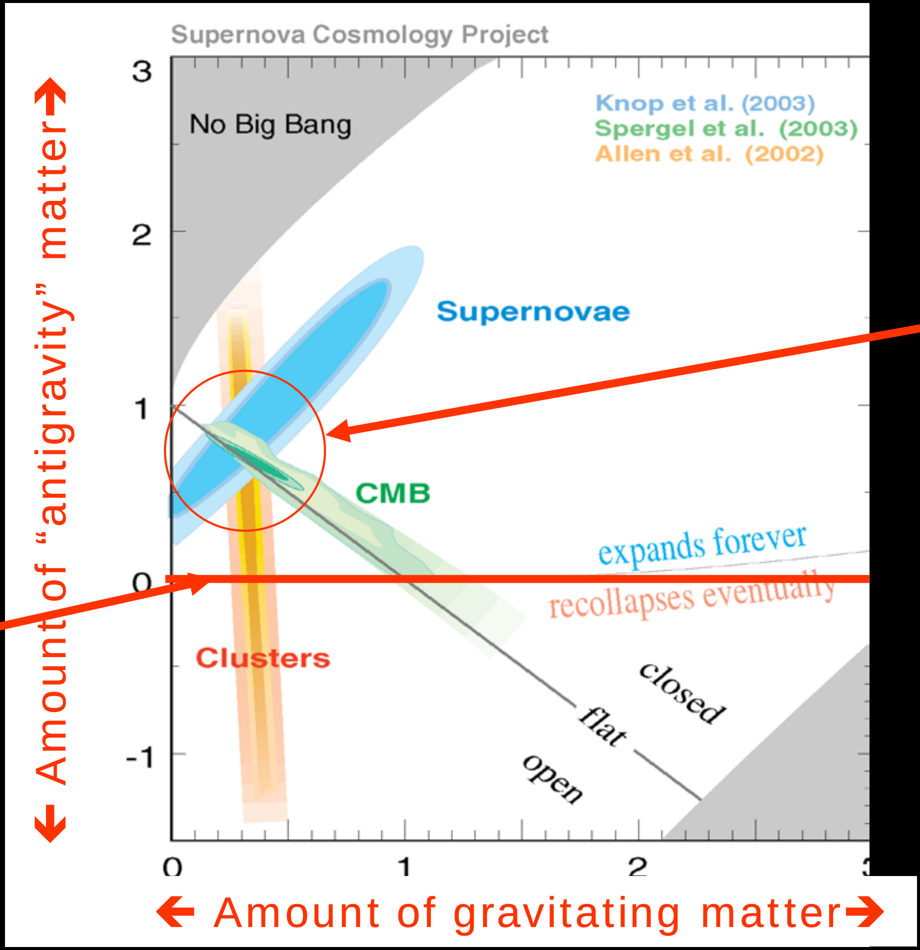
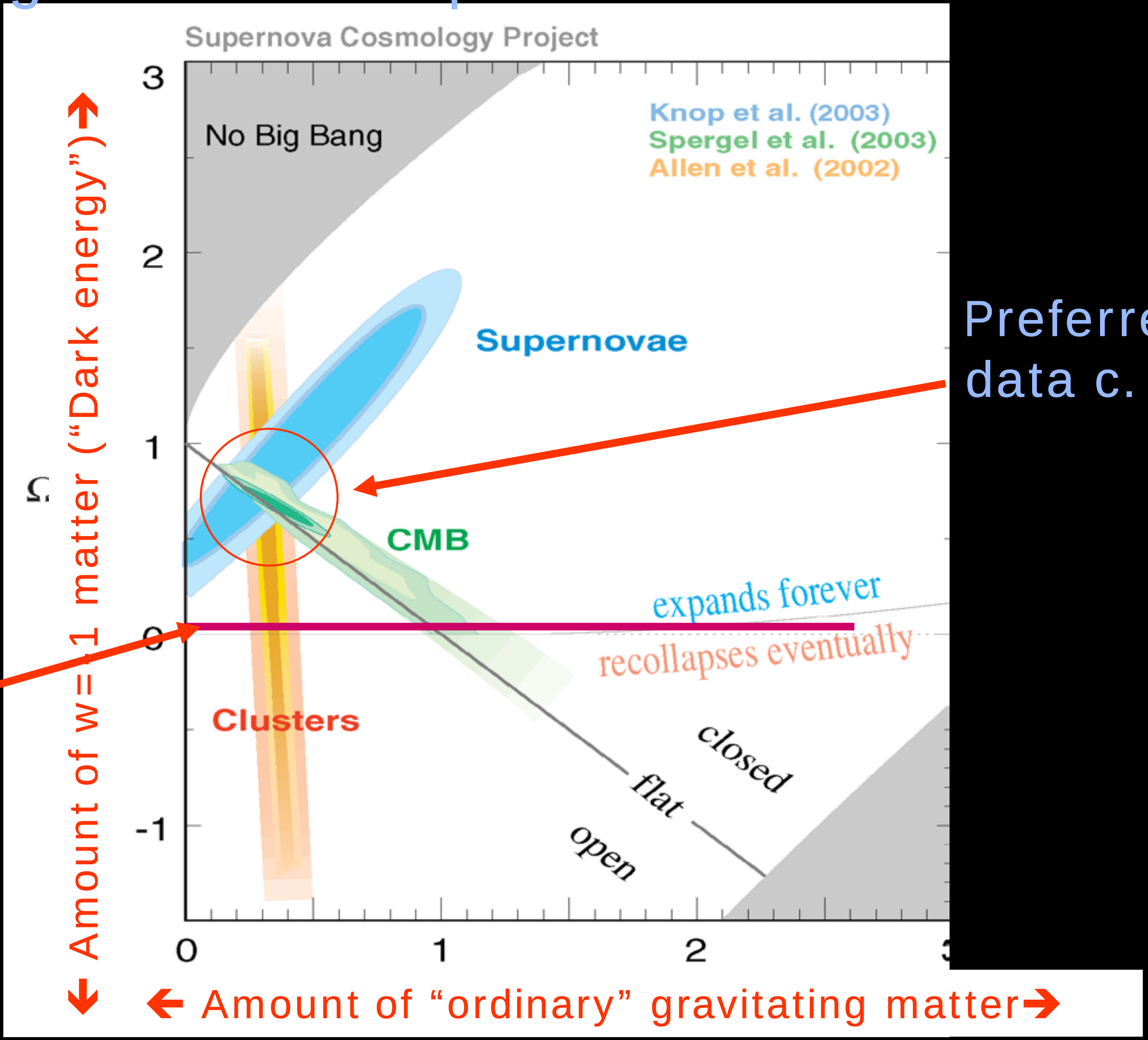


Preferred by modern data

"Gravitating" non accelerating matter

Cosmic acceleration

Accelerating matter is required to fit current data

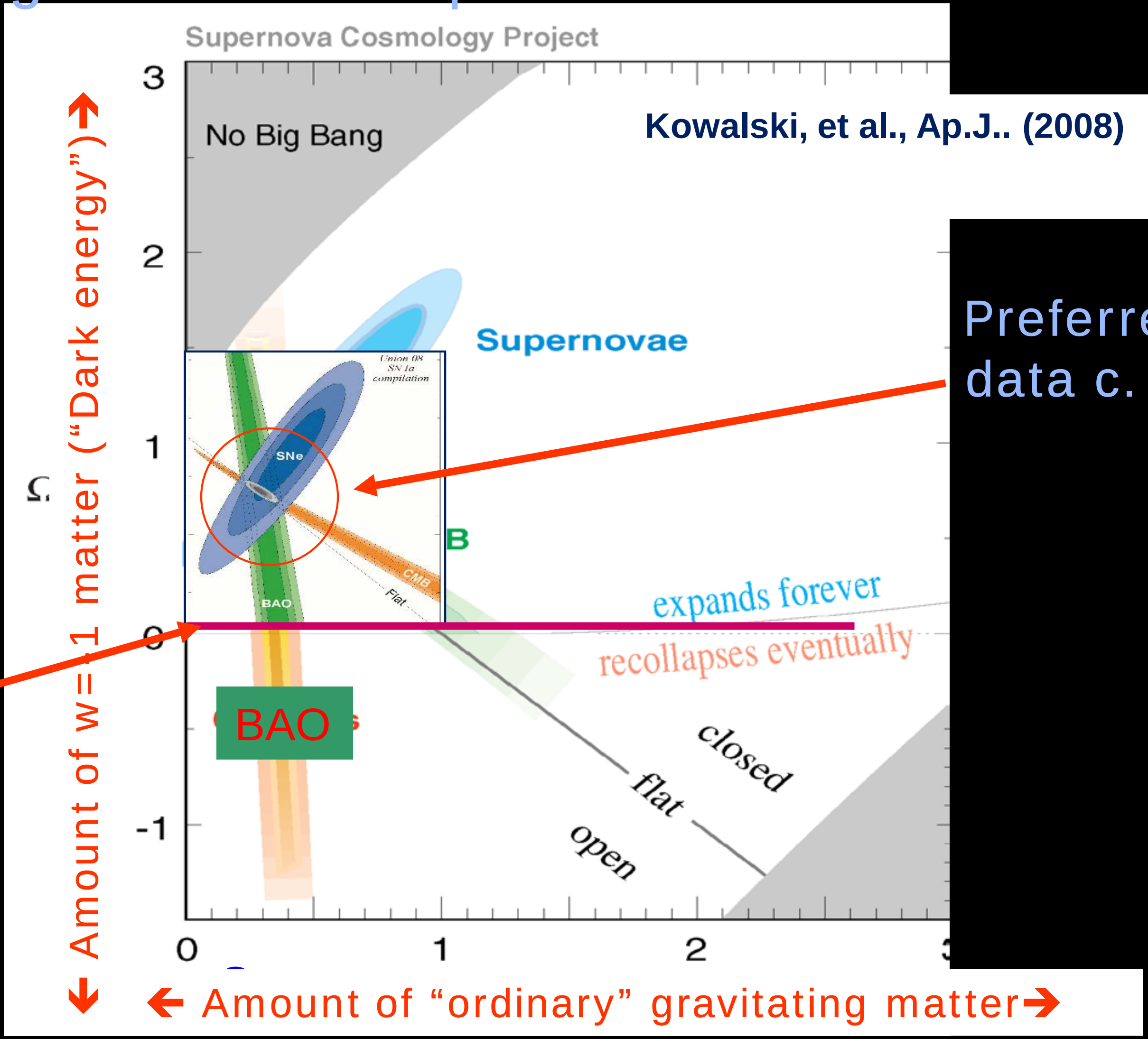


Preferred by data c. 2003

"Ordinary" non accelerating matter

Cosmic acceleration

Accelerating matter is required to fit current data



Preferred by data c. **2008**

"Ordinary" non accelerating matter

Cosmic acceleration

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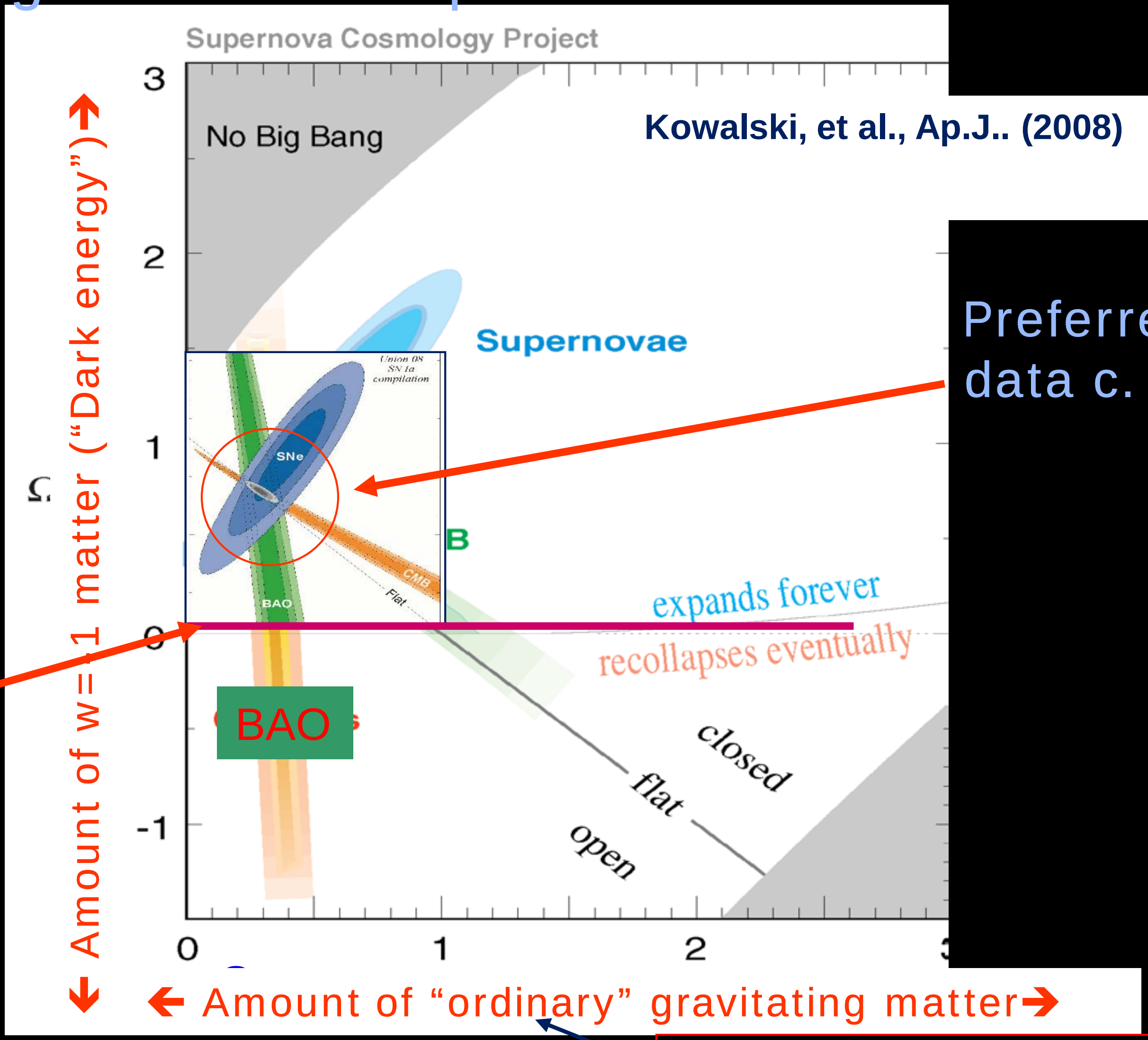
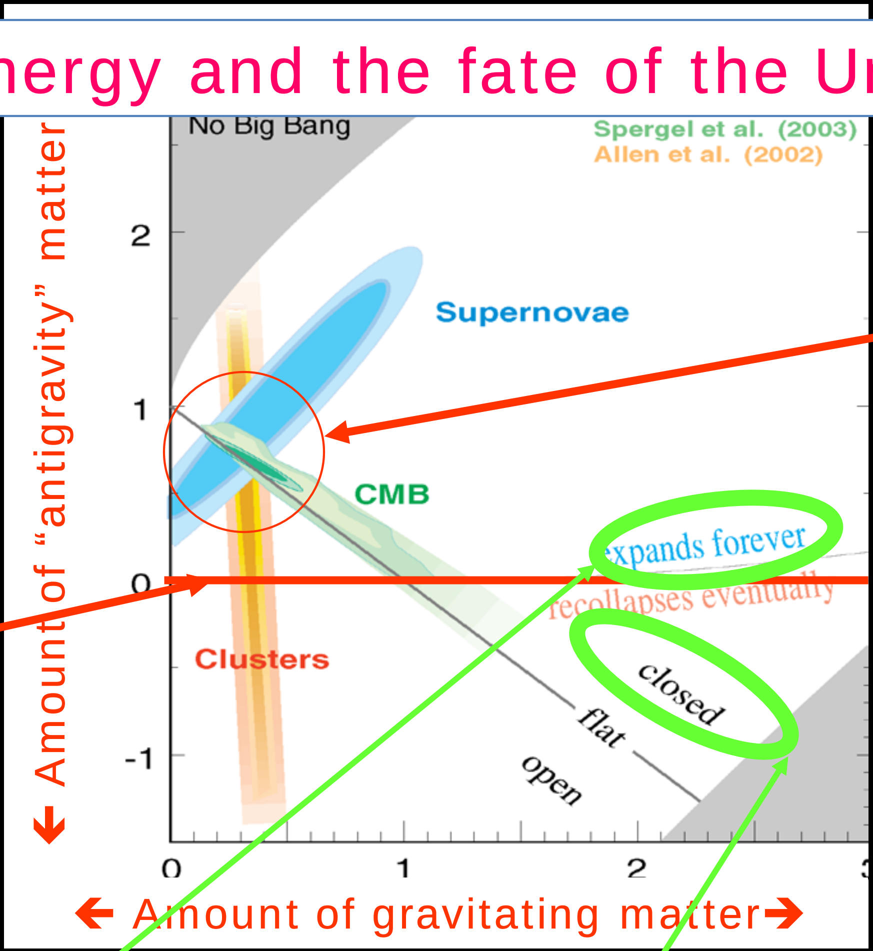


Preferred by data c. **2008**

"Ordinary" non accelerating matter

(Includes dark matter)

Dark Energy and the fate of the Universe

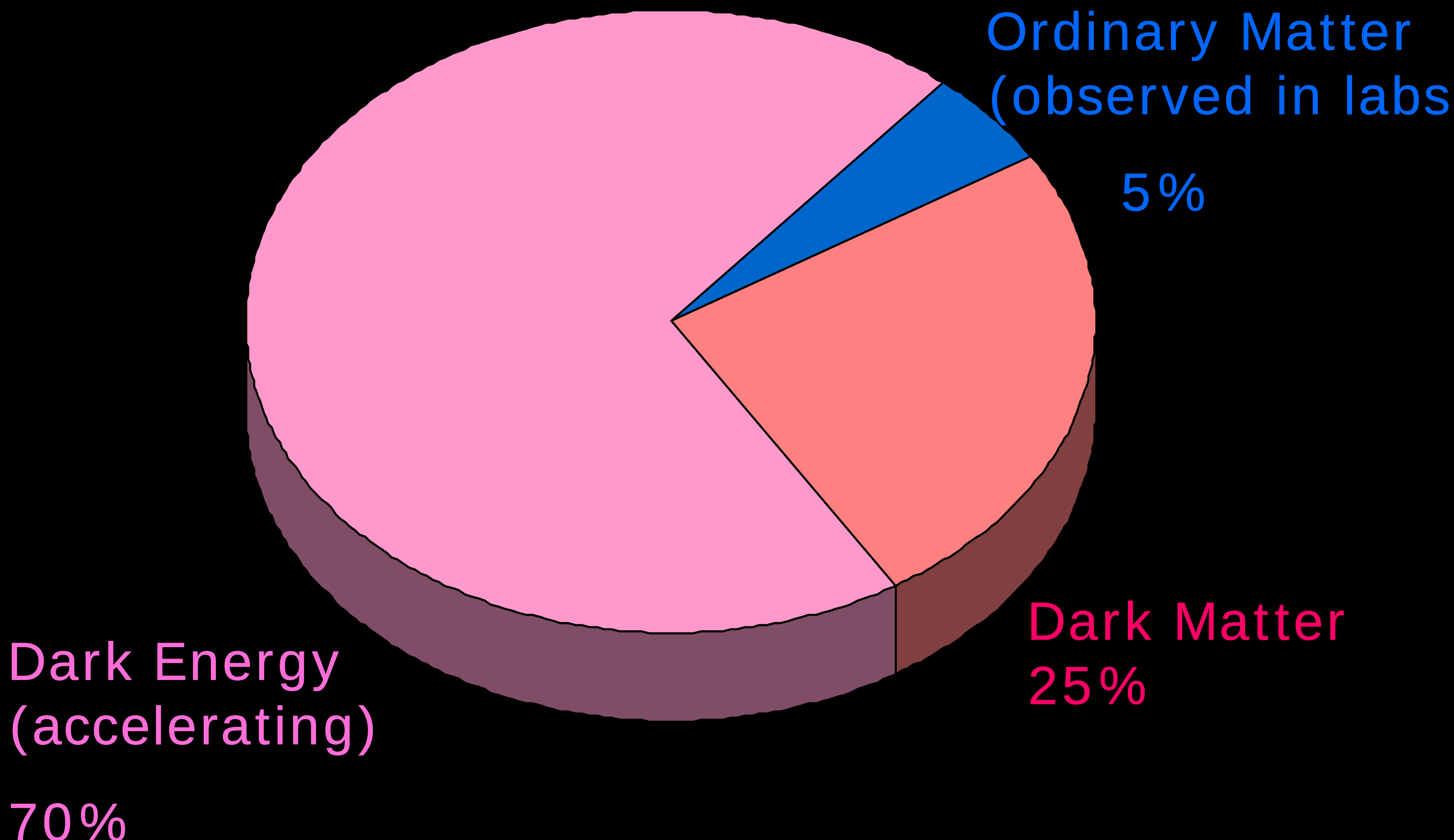


Preferred by modern data

"Gravitating" non accelerating matter

In the presence of dark energy, the simple connection between open/closed/flat and the future of the universe no longer holds

95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories



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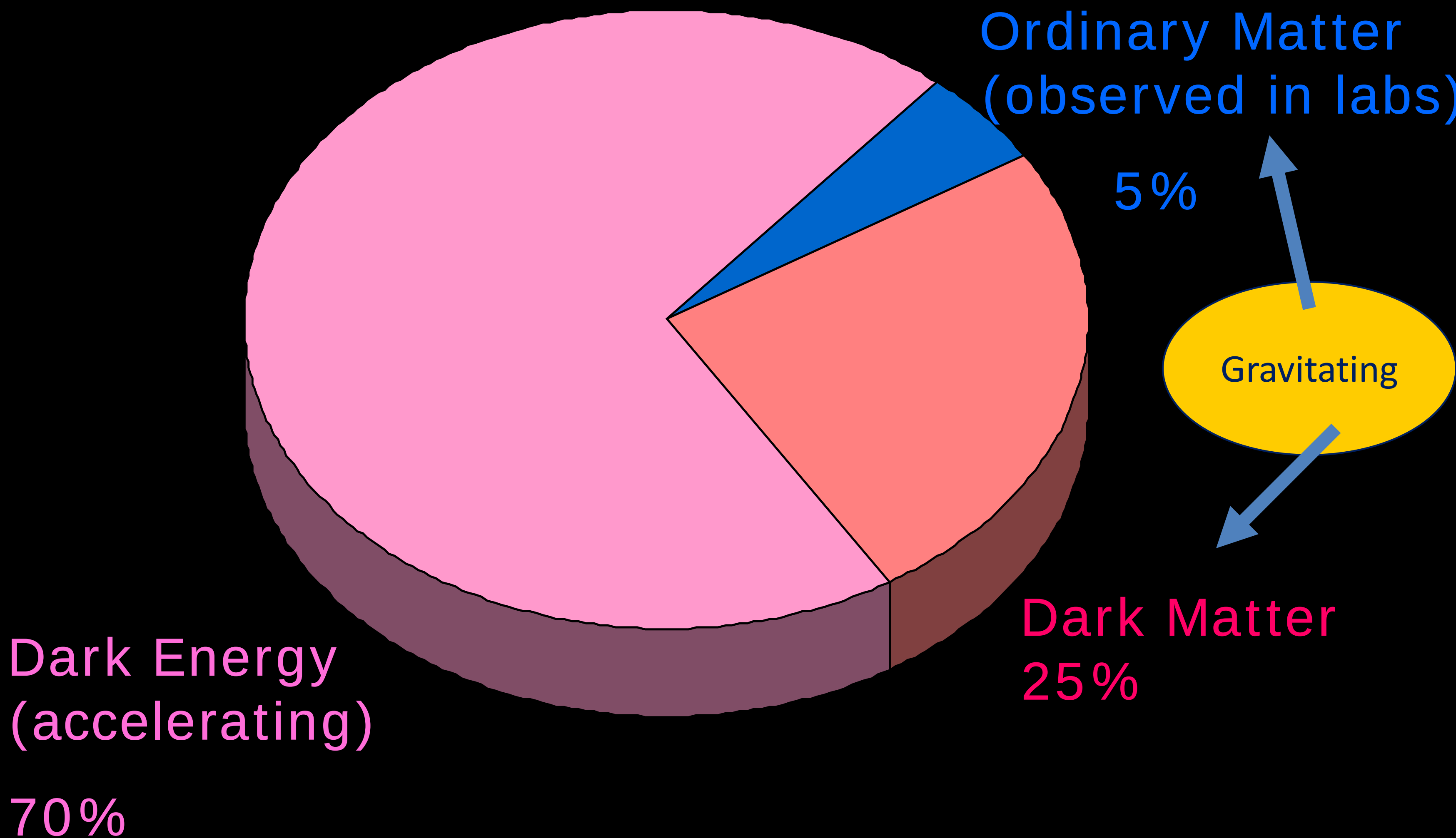

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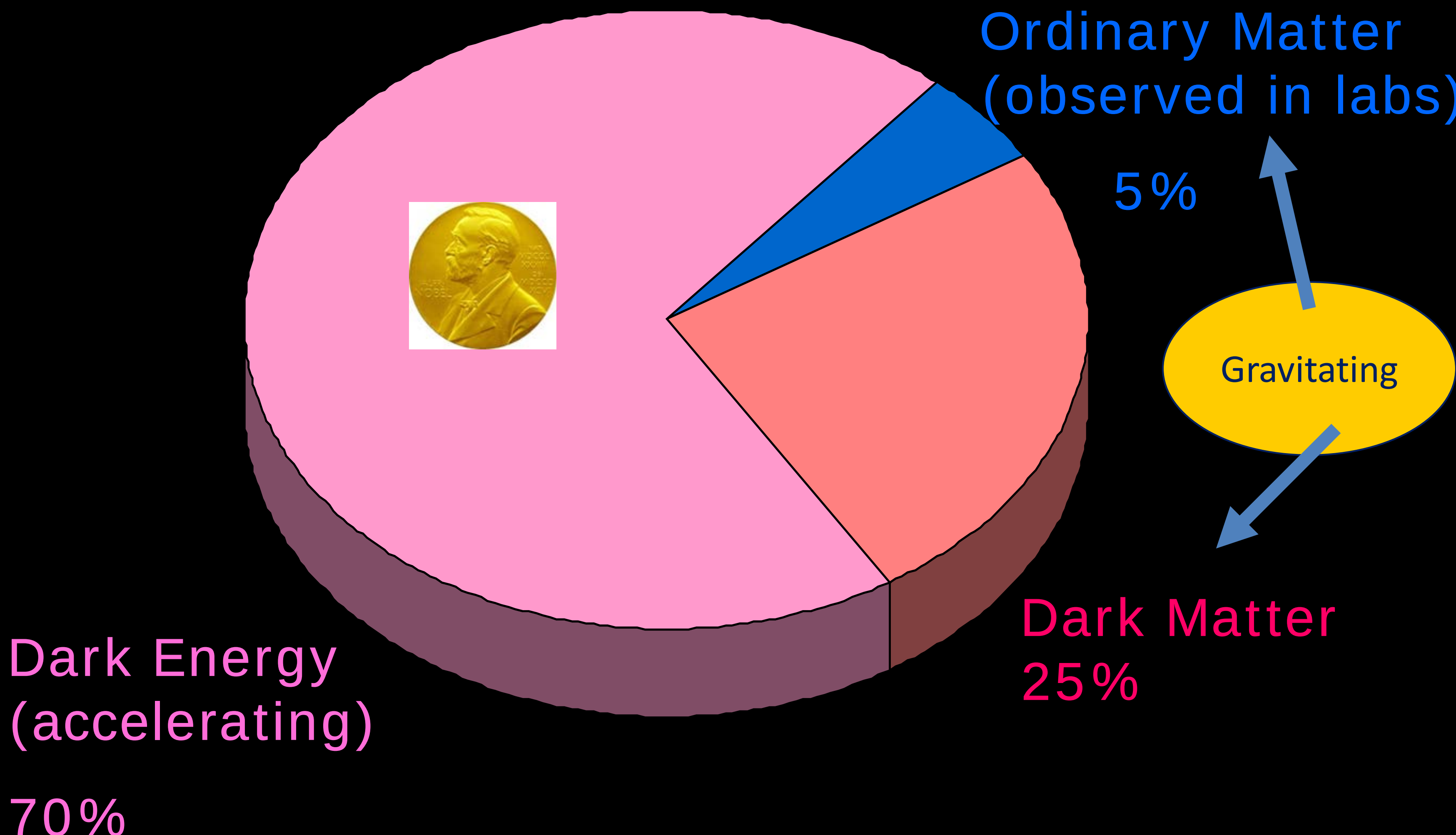

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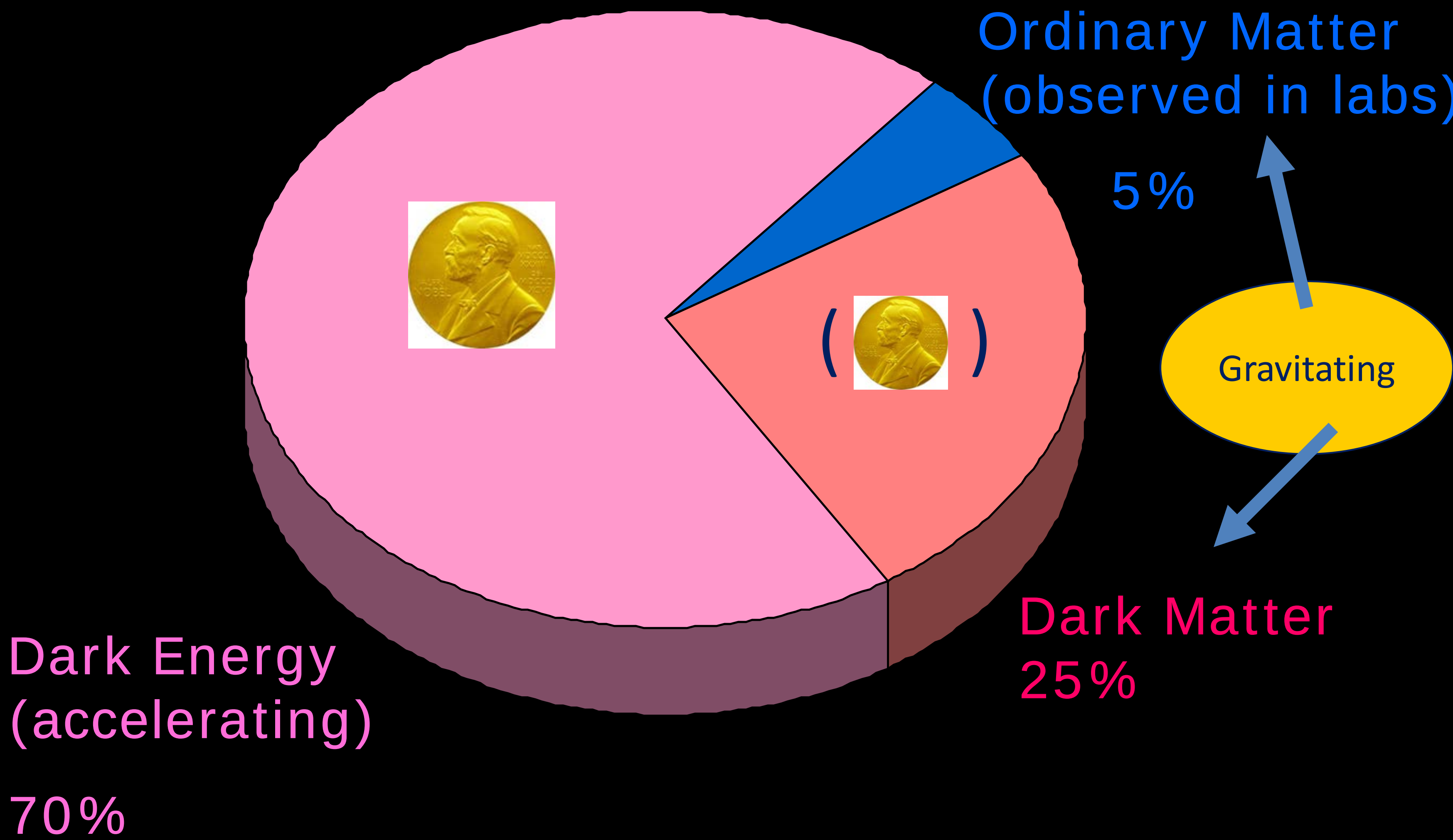

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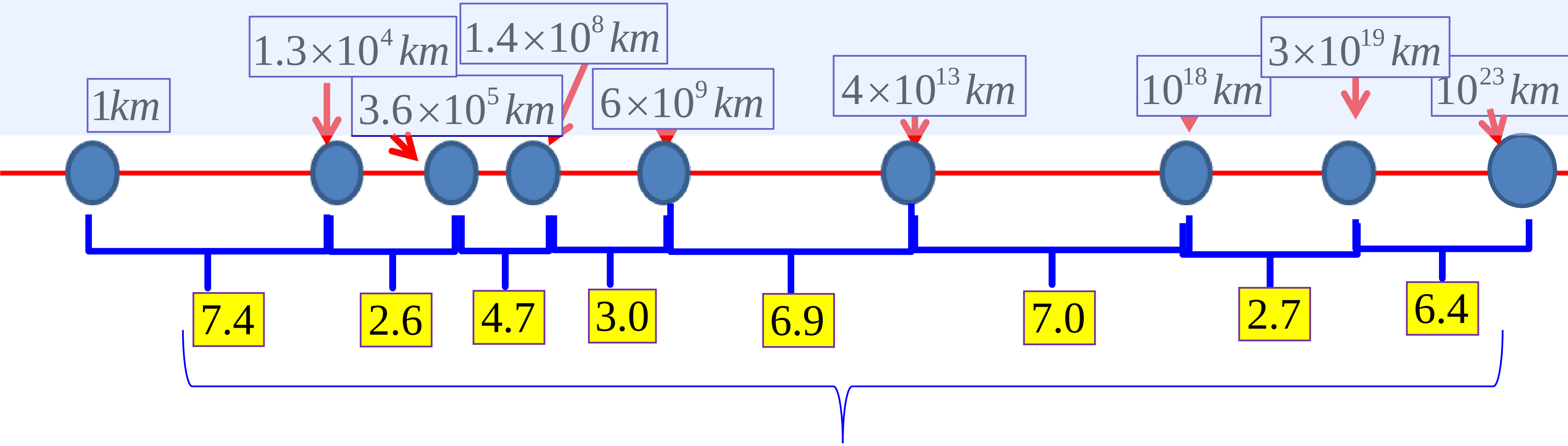
Cosmic Inflation

- A period of accelerated expansion in the very early universe

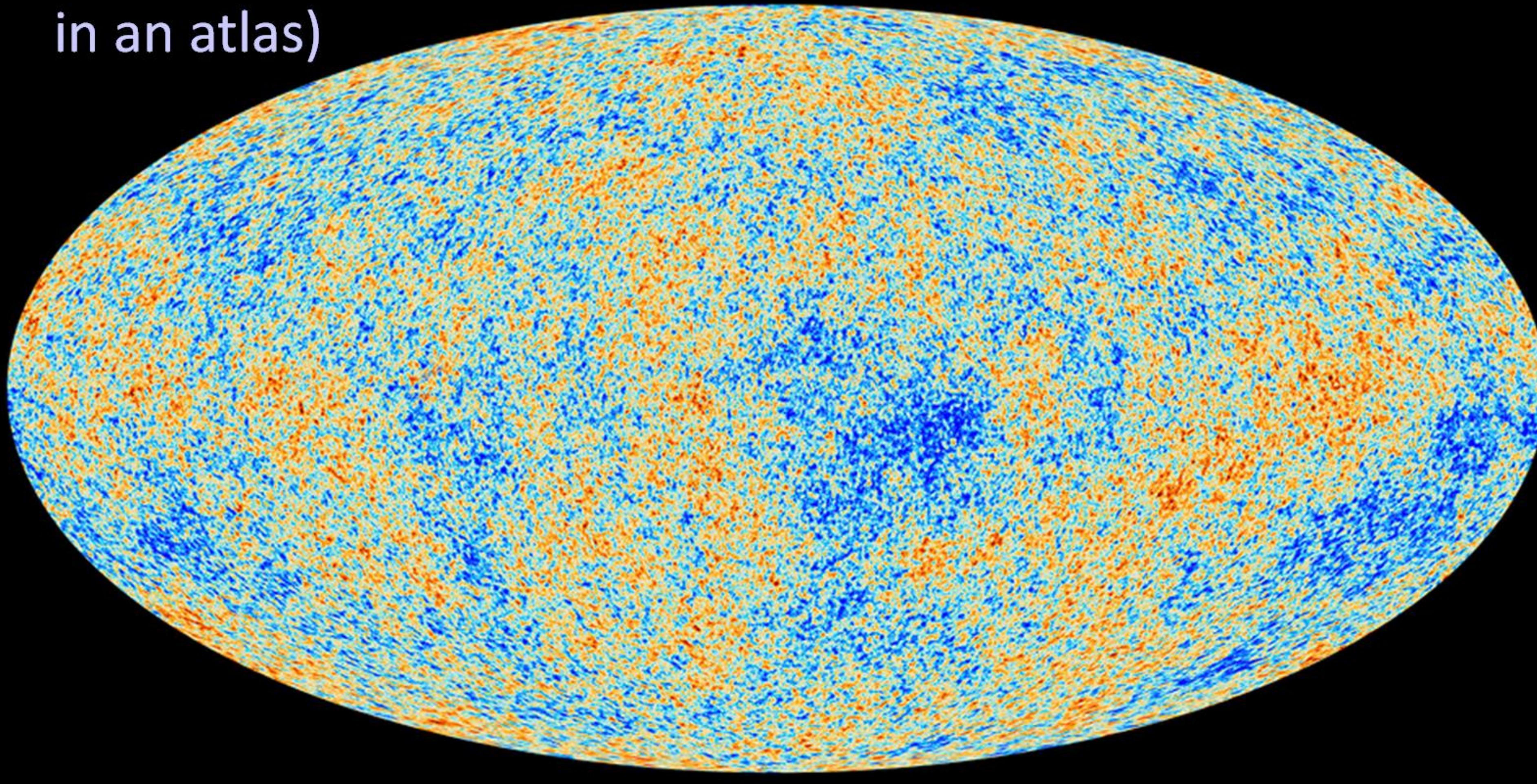
- Motivated by particle physics (related to the recently discovered Higgs particle).
- In most models inflation operates when the temperature was 10^{25} times greater than today!

- Conceptually similar in some ways to the acceleration observed today (interesting relationship between the two)

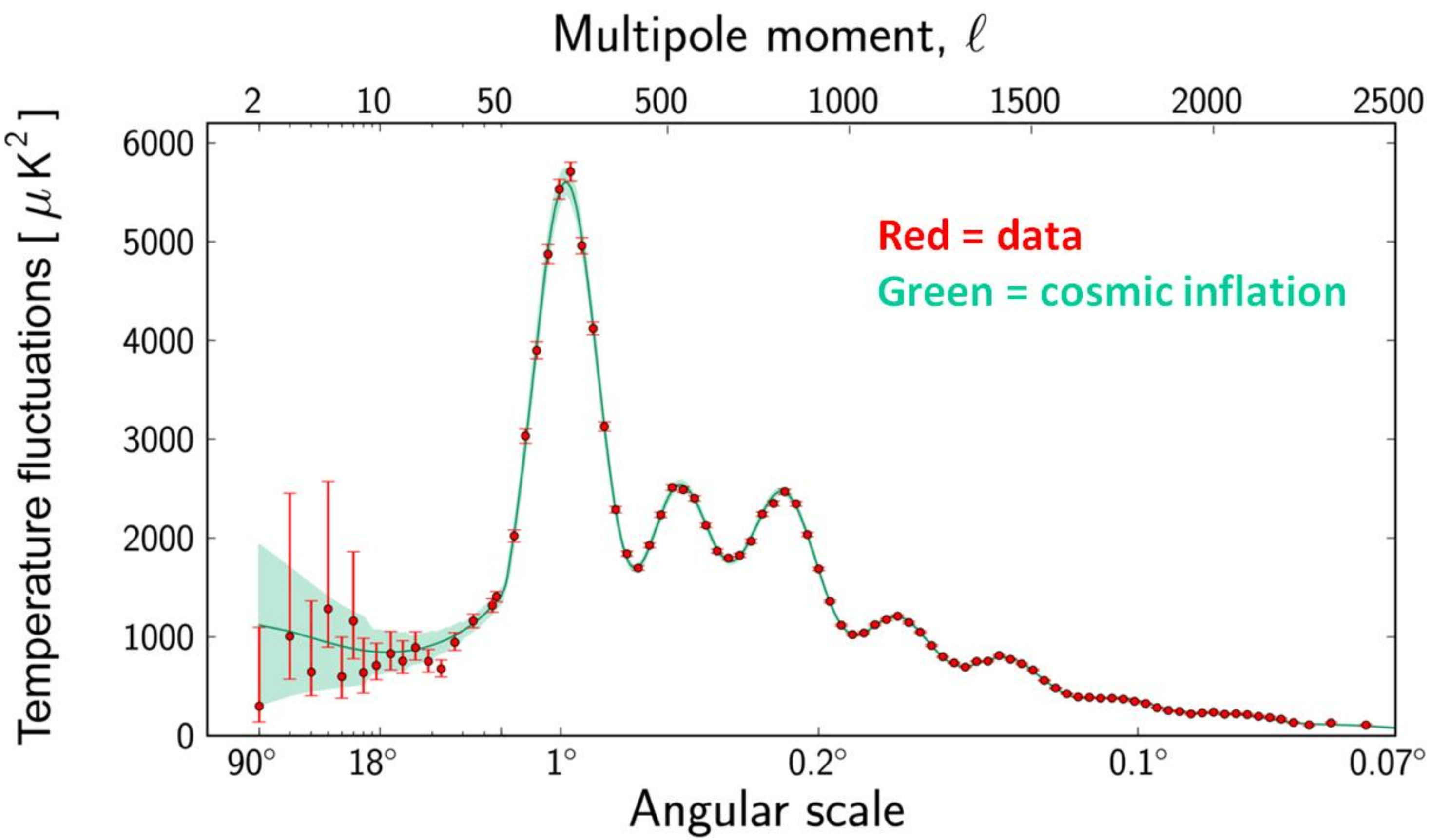


- Cosmic inflation creates features in the universe on all these different lengths.
- The yellow boxes give the time between "feature creation" in units of 10^{-40} seconds!

Cosmic Microwave Background (CMB) map produced by the Planck satellite (sphere shown using a projection, like in an atlas)

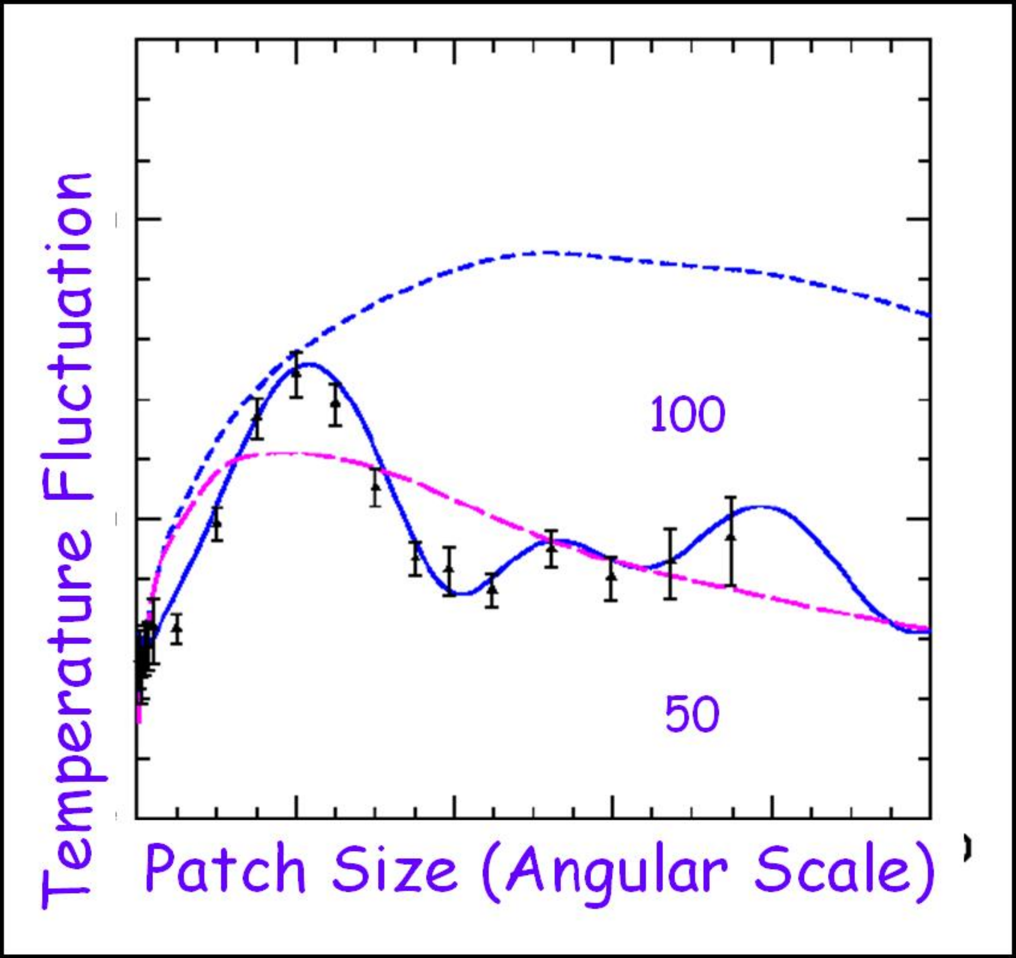


The map shows minute variations in the temperature (just 1 part in 100,000, or in the 5th decimal place).



This plot shows one way to quantify the feature in the CMB map. Roughly, the x-axis labels patch size, and the y-axis show how strongly the temperature typically varies among patches of that size.

Using the CMB to learn about the Universe



solid=inflation model

dashed=defect models

(magenta=desperate)

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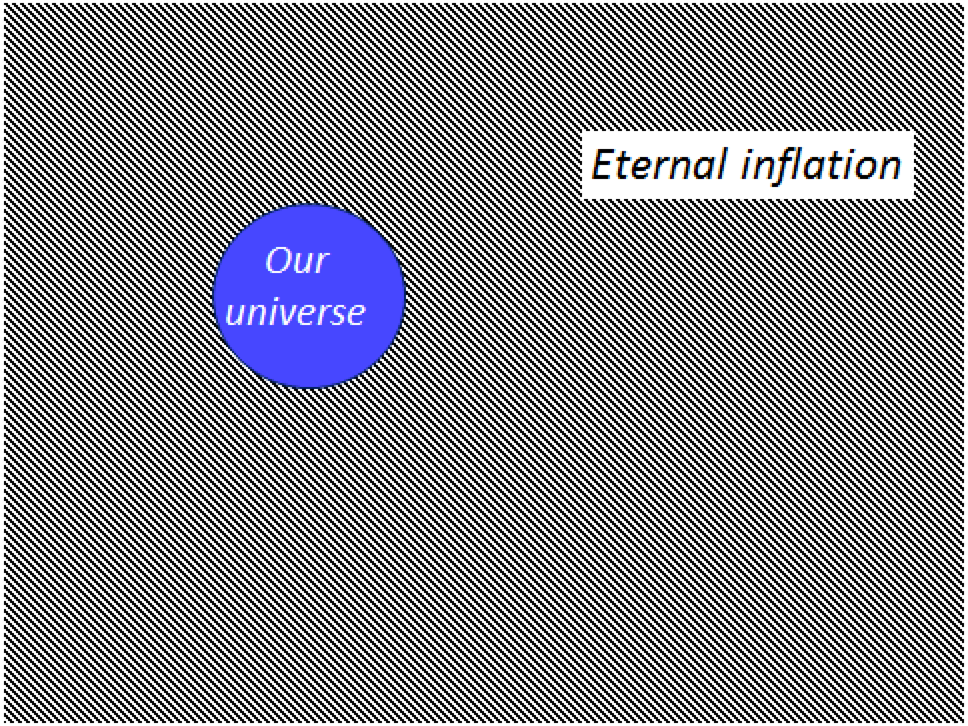
- Very problematic aspects emerge when we attempt to complete the picture. (The cause of intensive research and debate among the experts.)

- May cosmologists believe in "eternal inflation" (our universe exists in a "pocket" with eternal inflation all around us).



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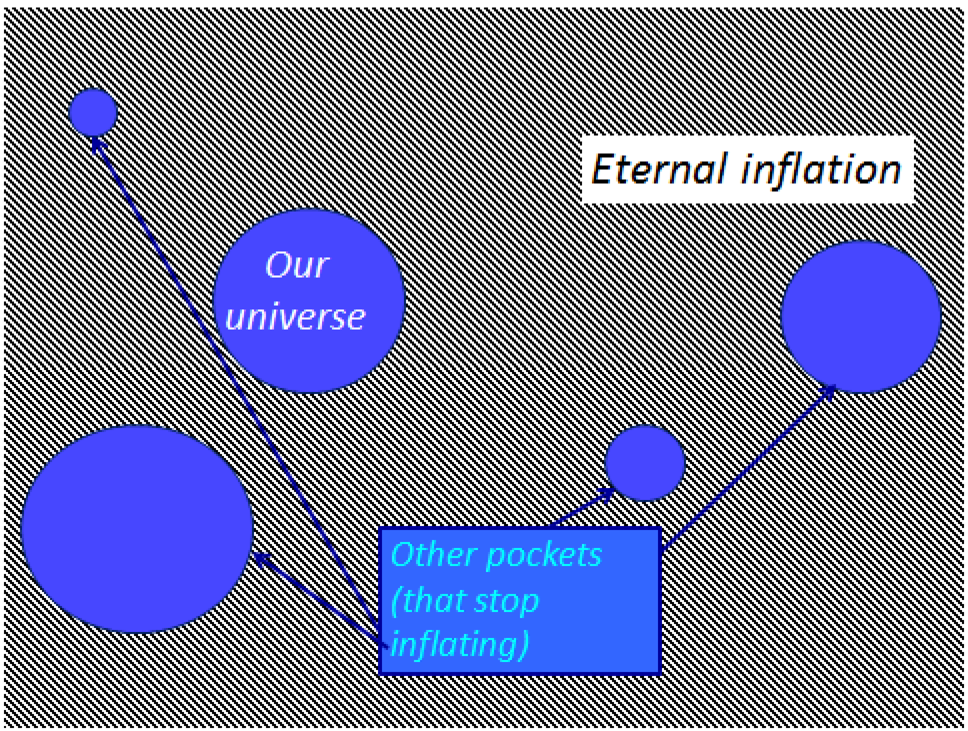

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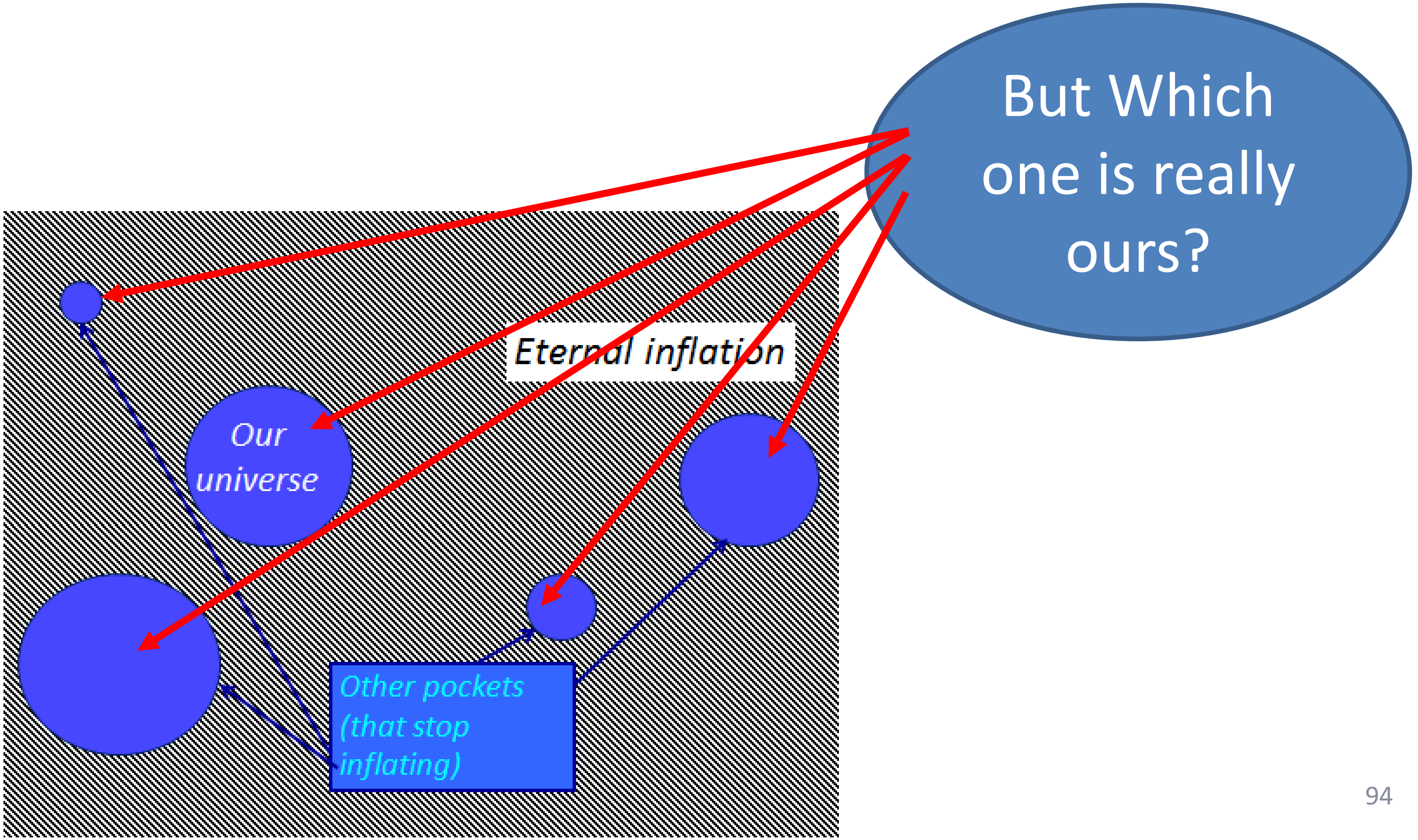

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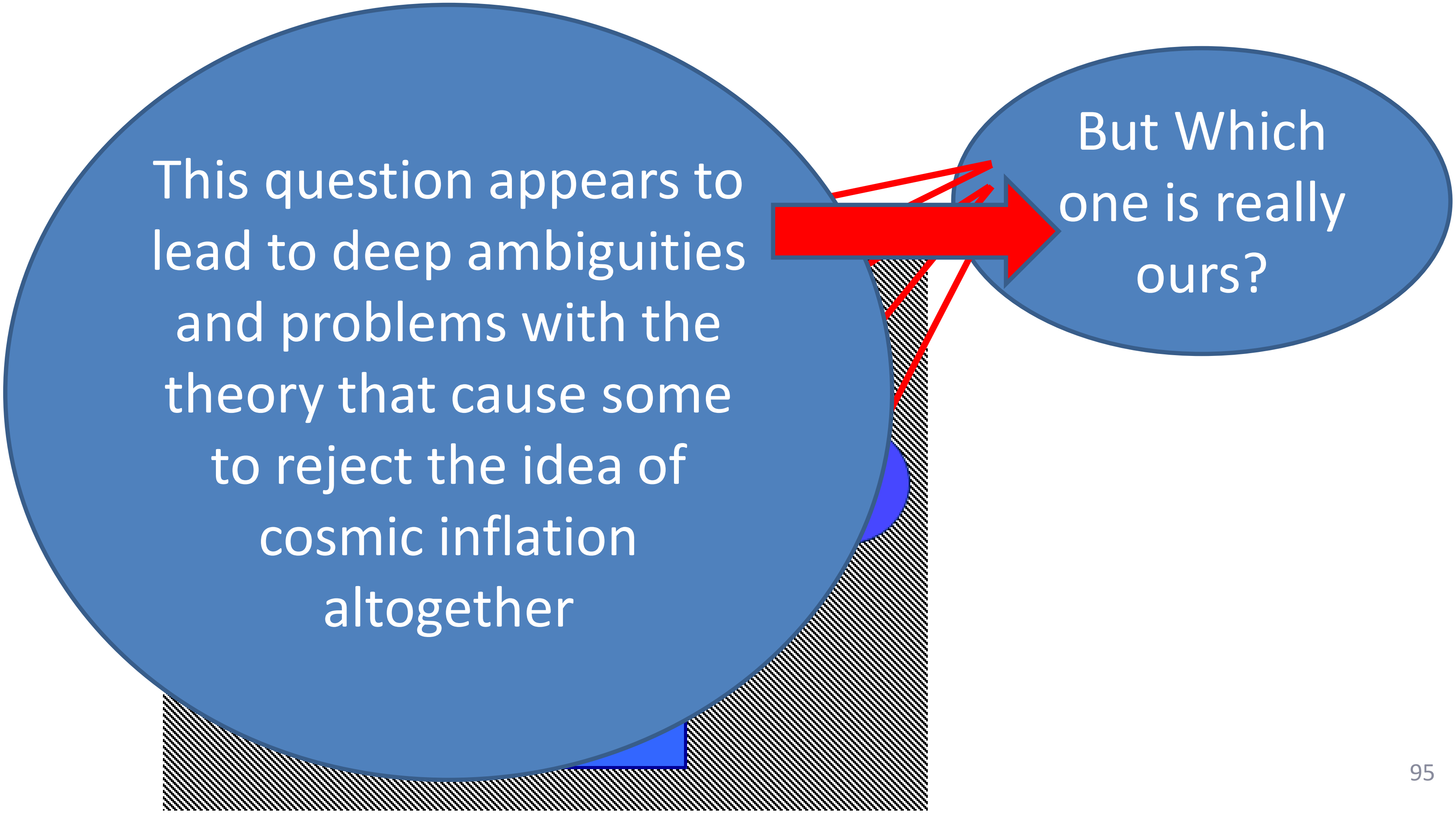

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A very exciting place to be!

Cosmic Inflation

Multiverse debate, World Science Festival 2013

- ...rly
- ...ently
- observed today (interesting relationship...

https://www.youtube.com/watch?v=2Qt-eGKa34M

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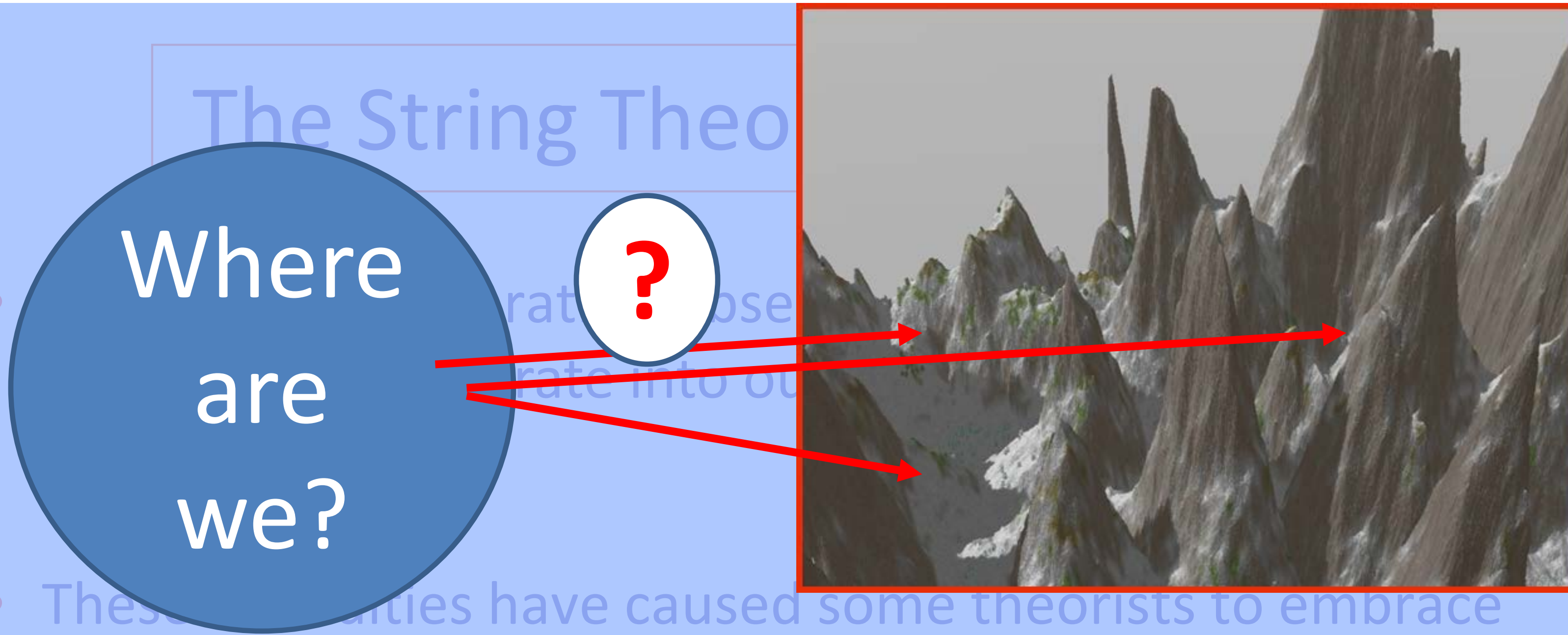
- Instead of the physical world around us exhibiting "the fundamental laws", according to the STL picture the universe is made of a landscape of different "worlds" which with their own laws of physics.



- Instead of the physical world around us exhibiting “the fundamental laws”, according to the STL picture the universe is made of a landscape of different “worlds” which with their own laws of physics.

The String Theo

Where are we?

?

A radical change from how we thought we should be doing physics

- These ... ities h... the “string theory land...

- Instead of the physical world around us exhibiting “the fundamental laws”, according to the STL picture the universe is made of a landscape of different “worlds” which with their own laws of physics.

Conclusions

- The search for a “big picture” of the Universe that explains why the region we observe should take this form has proven challenging, but has generated exciting ideas.
- We know we can do science with the Universe
- It appears that there is something right about cosmic inflation
- dSE cosmology offers a finite alternative to the extravagant (and problematic) infinities of eternal inflation
- Predictions of observable levels of cosmic curvature from dSE cosmology will give an important future test

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Amazing data and facilities

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We have learned a huge amount about the Universe

Conclusions

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Our theories are both remarkably successful and provocative/confusing

Conclusions

e “C

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- The S