A Journey Through the "Clumpy" Universe

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Center for Cosmology, UC Irvine

In collaboration with:
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Kiyotomo Ichiki (Tokyo), Daniel Holz (Los Alamos), Asantha Cooray (UCI).

Kansas State University   High Energy Physics Seminar   October 15, 2008 (Wed)

"For if each Star is little more a mathematical Point,
located upon the Hemisphere of Heaven by Right Ascension and Declination,
then all the Stars, taken together, tho' innumerable,
must like any other set of points,
in turn represent some single gigantic Equation,
to the mind of God as straightforward as, say, the Equation of a Sphere,---
to us unreadable, incalculable.
A lonely, uncompensated, perhaps even impossible Task,---
yet some of us must ever be seeking, I suppose."

-- Thomas Pynchon, Mason & Dixon

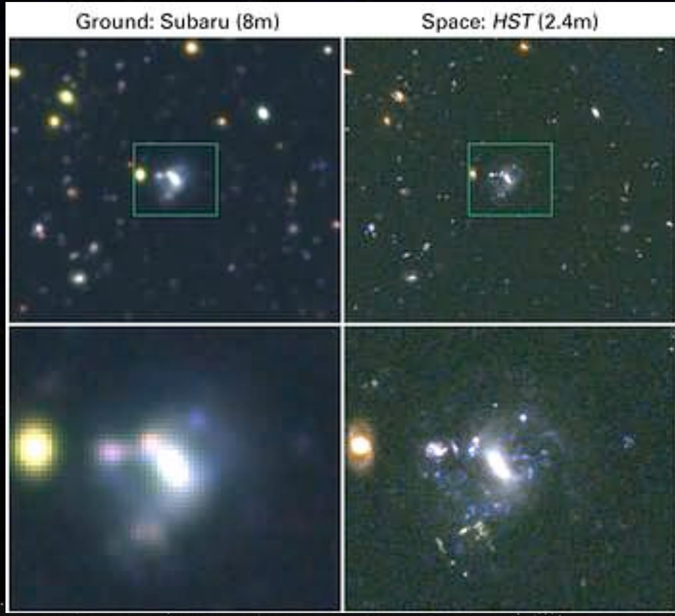
Why Care?

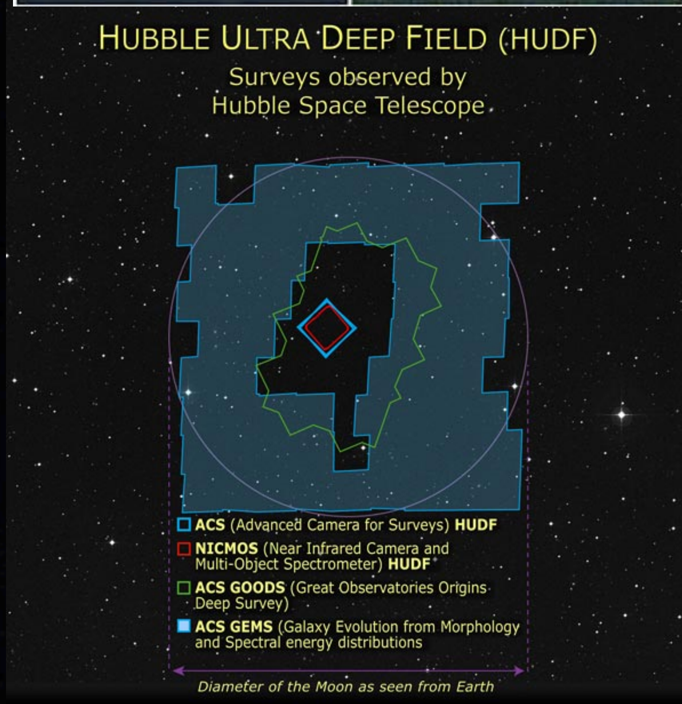
Paul Gauguin (1897)

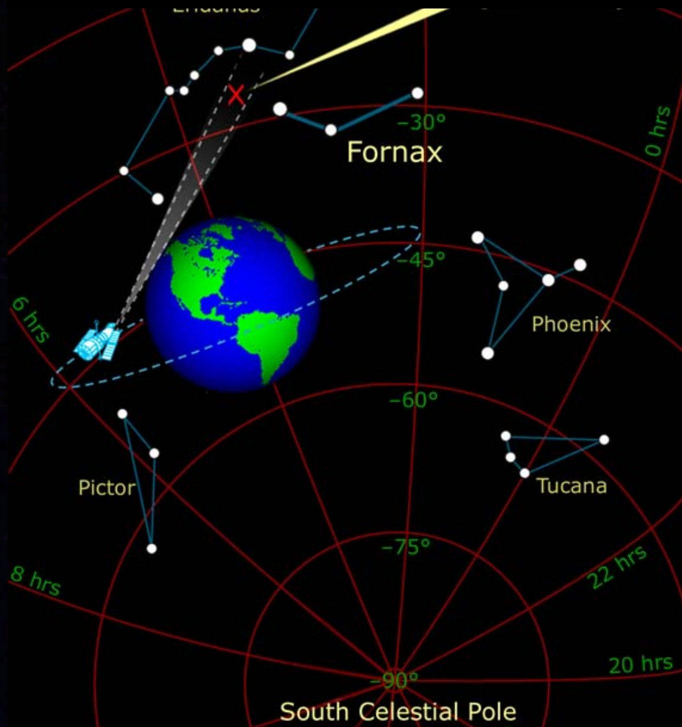
Where do we come from? What are we? Where are we going?

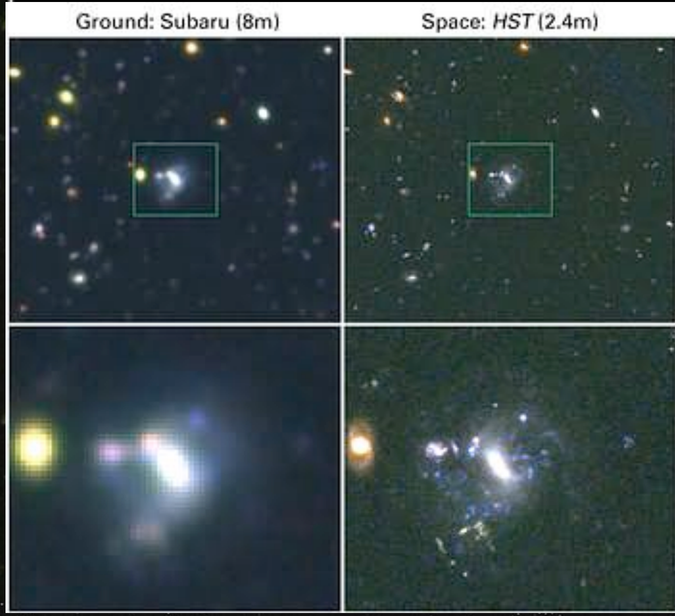
What Do We Know?

What Can We See?


Ground: Subaru (8m)
Space: HST (2.4m)


HUBBLE ULTRA DEEP FIELD (HUDF)
Surveys observed by
Hubble Space Telescope
ACS (Advanced Camera for Surveys) HUDF
NICMOS (Near Infrared Camera and Multi-Object Spectrometer) HUDF
ACS GOODS (Great Observatories Origins Deep Survey)
ACS GEMS (Galaxy Evolution from Morphology and Spectral energy distributions
Diameter of the Moon as seen from Earth


-30°
Fornax
0 hrs
-45°
6 hrs
Phoenix
-60°
Pictor
Tucana
-75°
8 hrs
22 hrs
20 hrs
-90°
South Celestial Pole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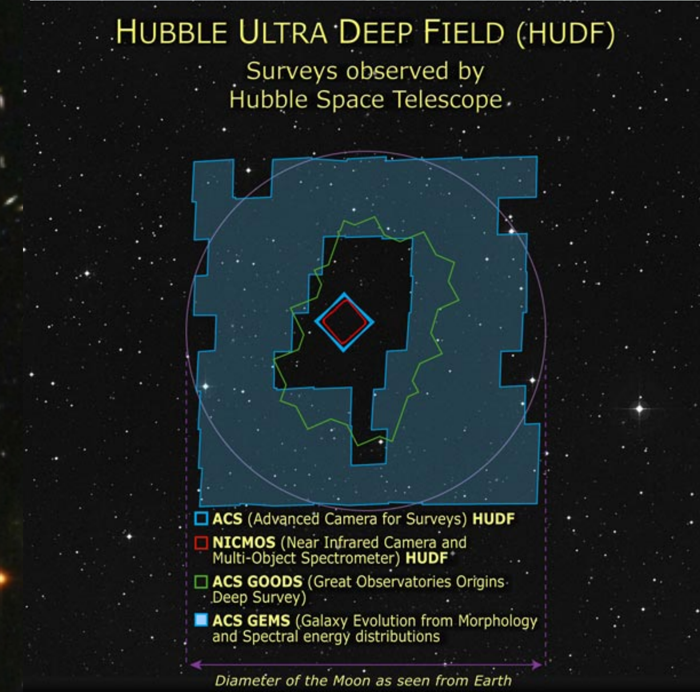
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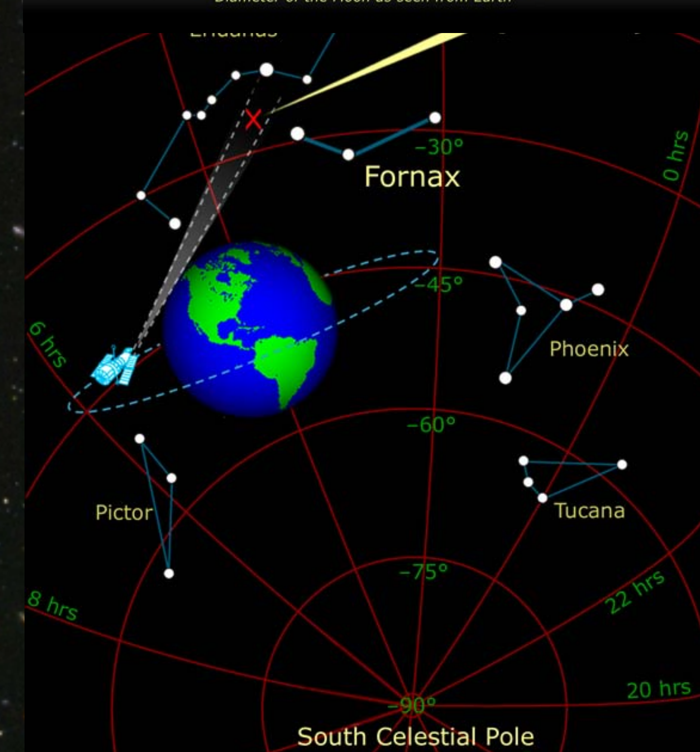
Fornax
Phoenix
Pictor
Tucana
-30°
-45°
-60°
-75°
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0 hrs
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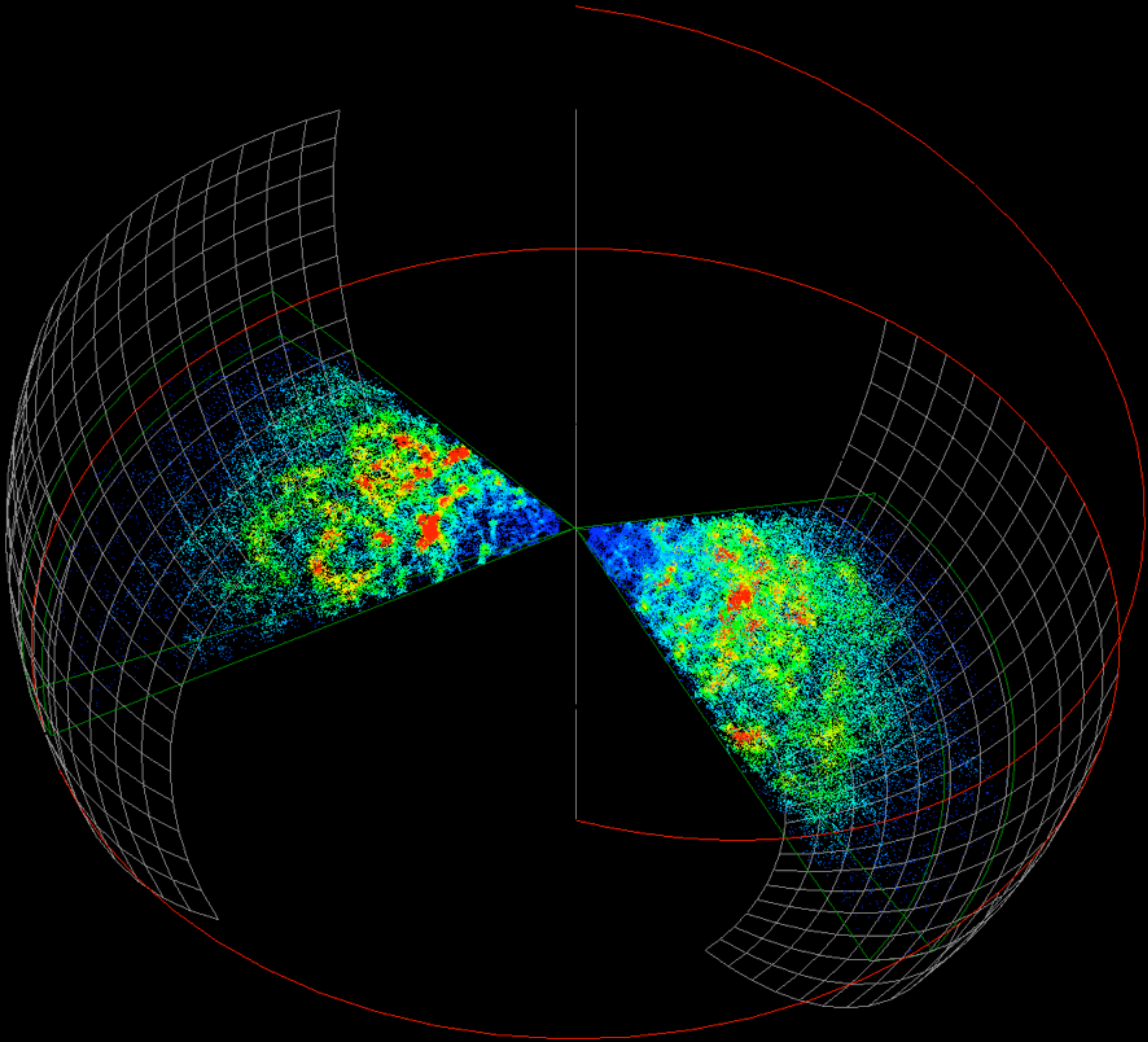
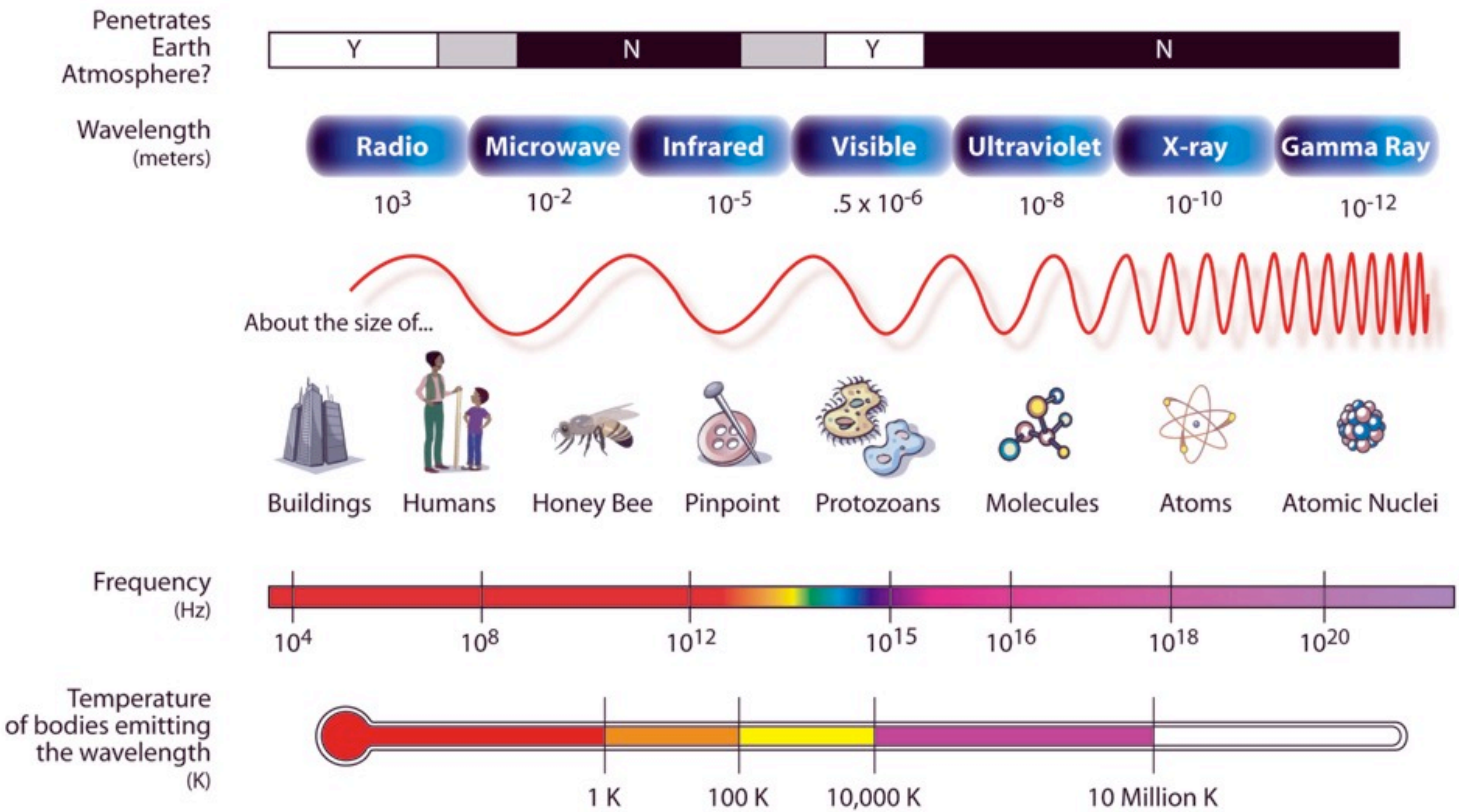
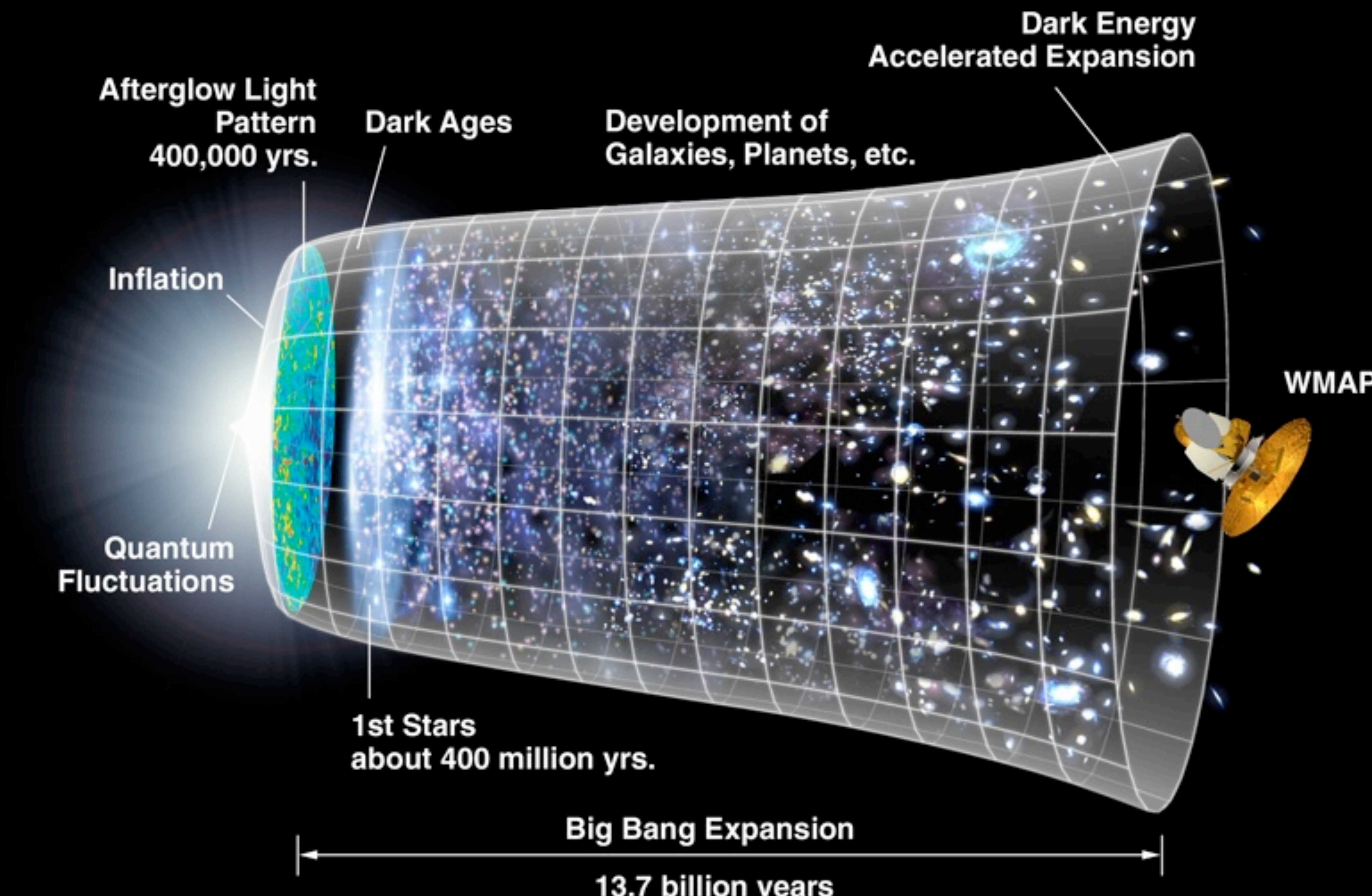
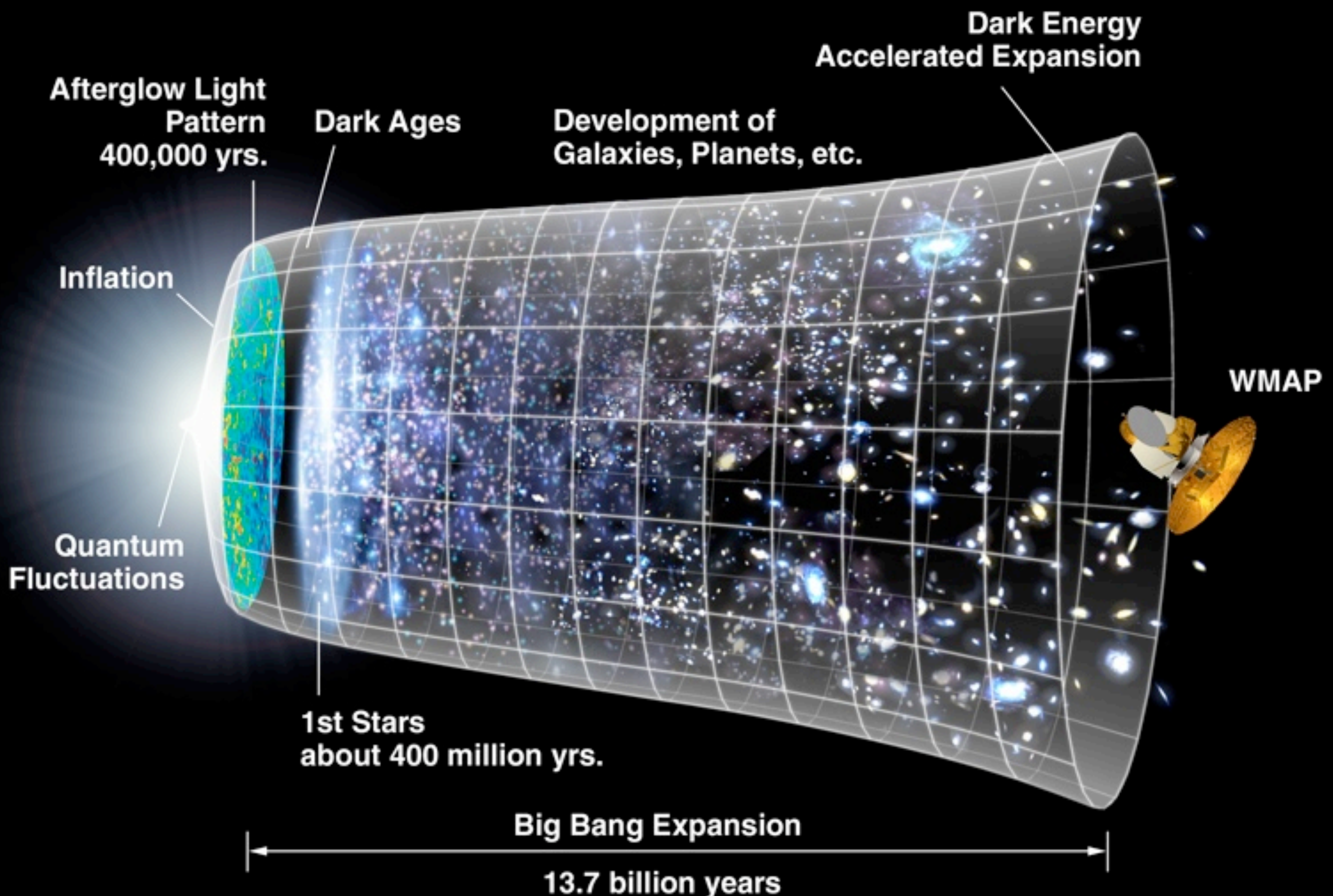
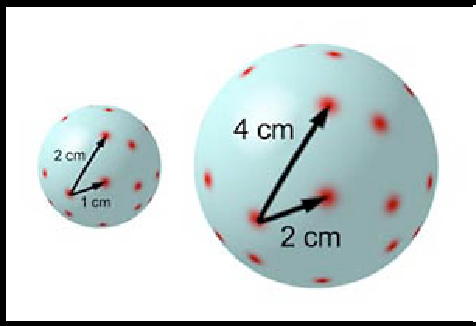


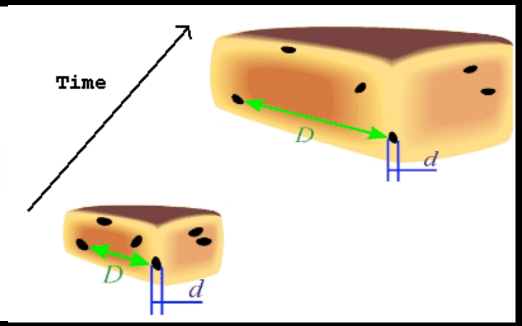
THE ELECTROMAGNETIC SPECTRUM



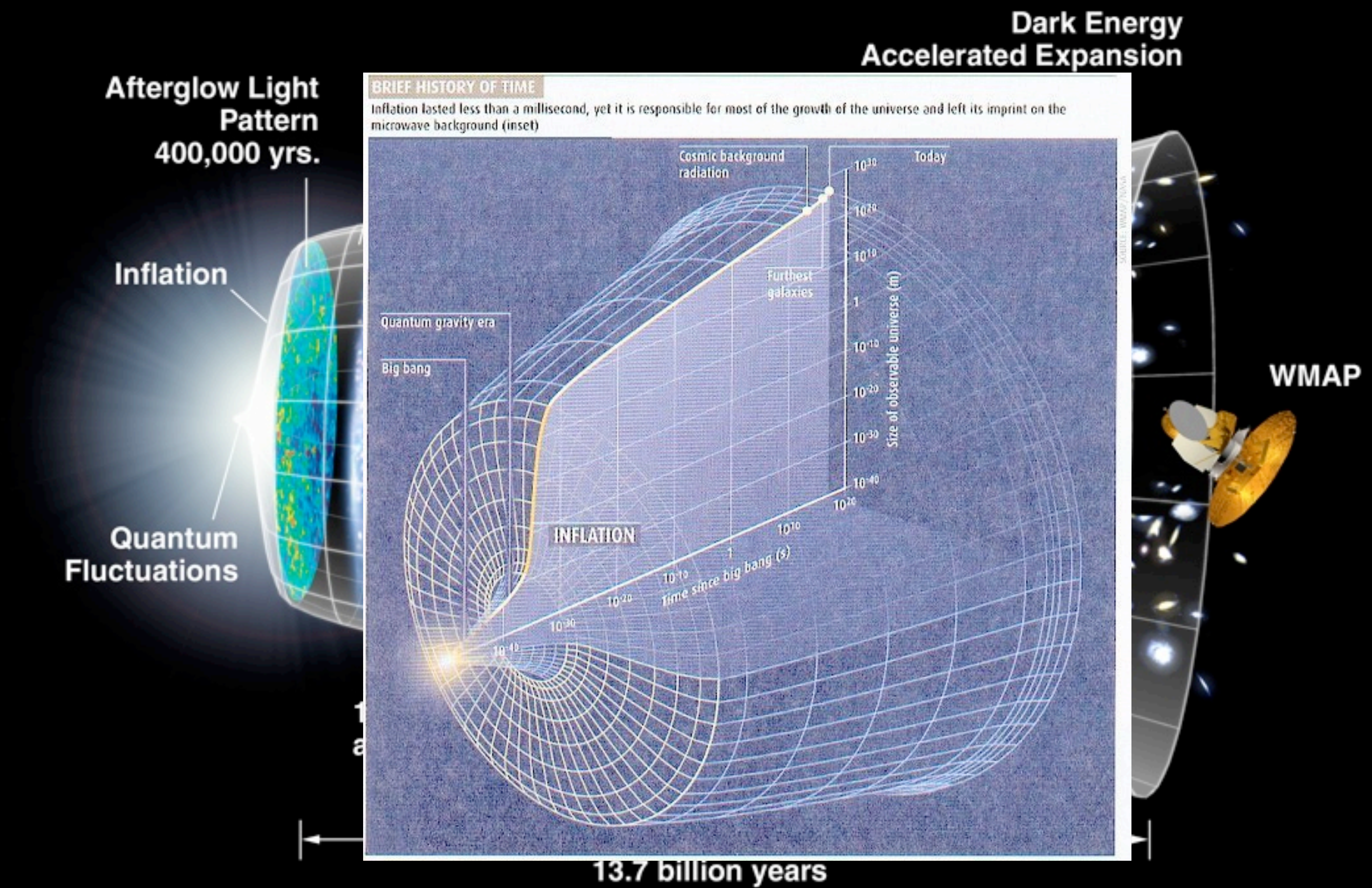

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

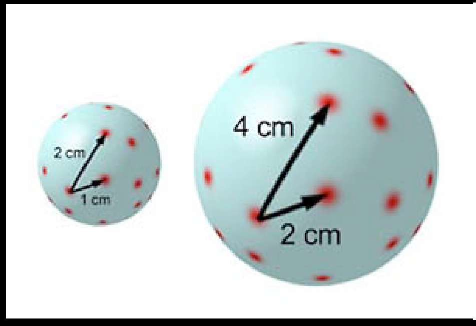


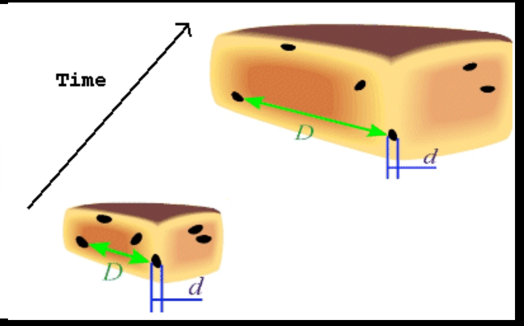




NASA/WMAP Science Team







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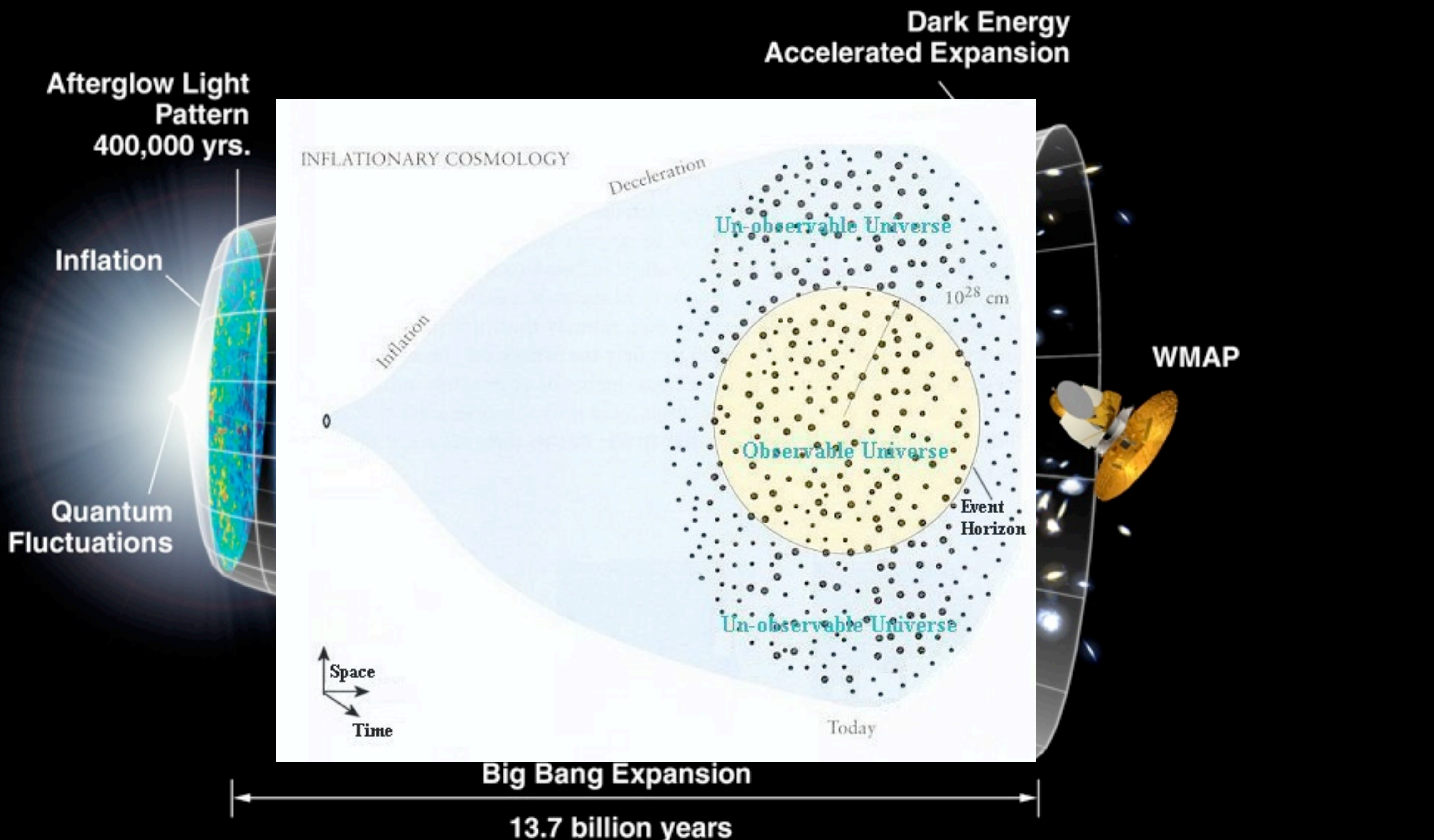
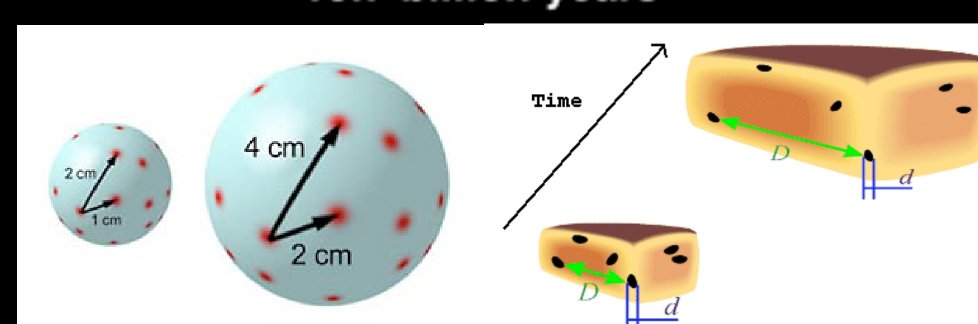
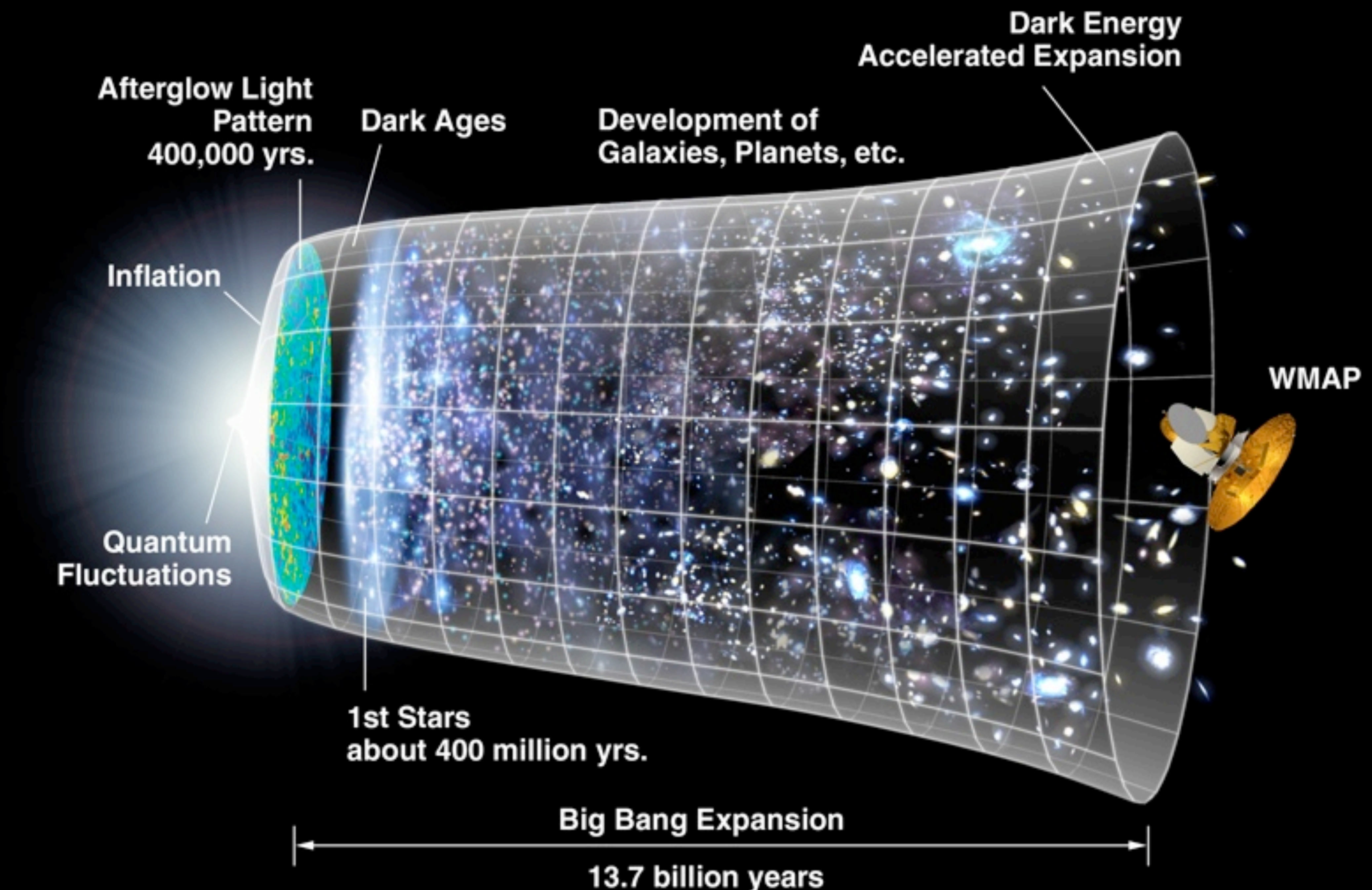
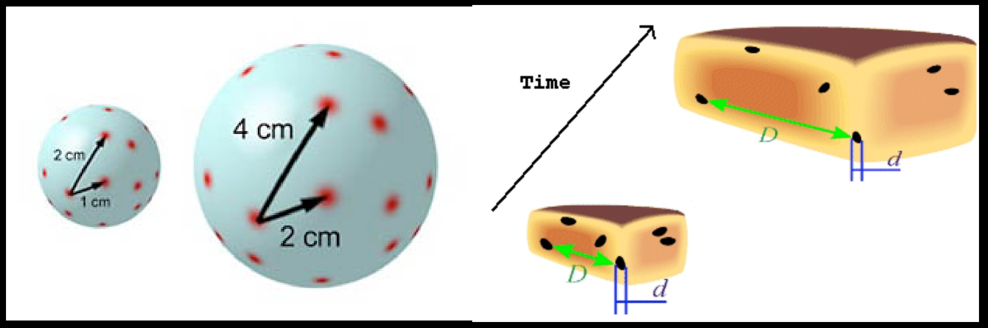

Afterglow Light Pattern 400,000 yrs.
Dark Energy Accelerated Expansion
Inflation
Quantum Fluctuations
WMAP
INFLATIONARY COSMOLOGY
Deceleration
Inflation
Un-observable Universe
10^{28} cm
Observable Universe
Event Horizon
Un-observable Universe
Space
Time
Today
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

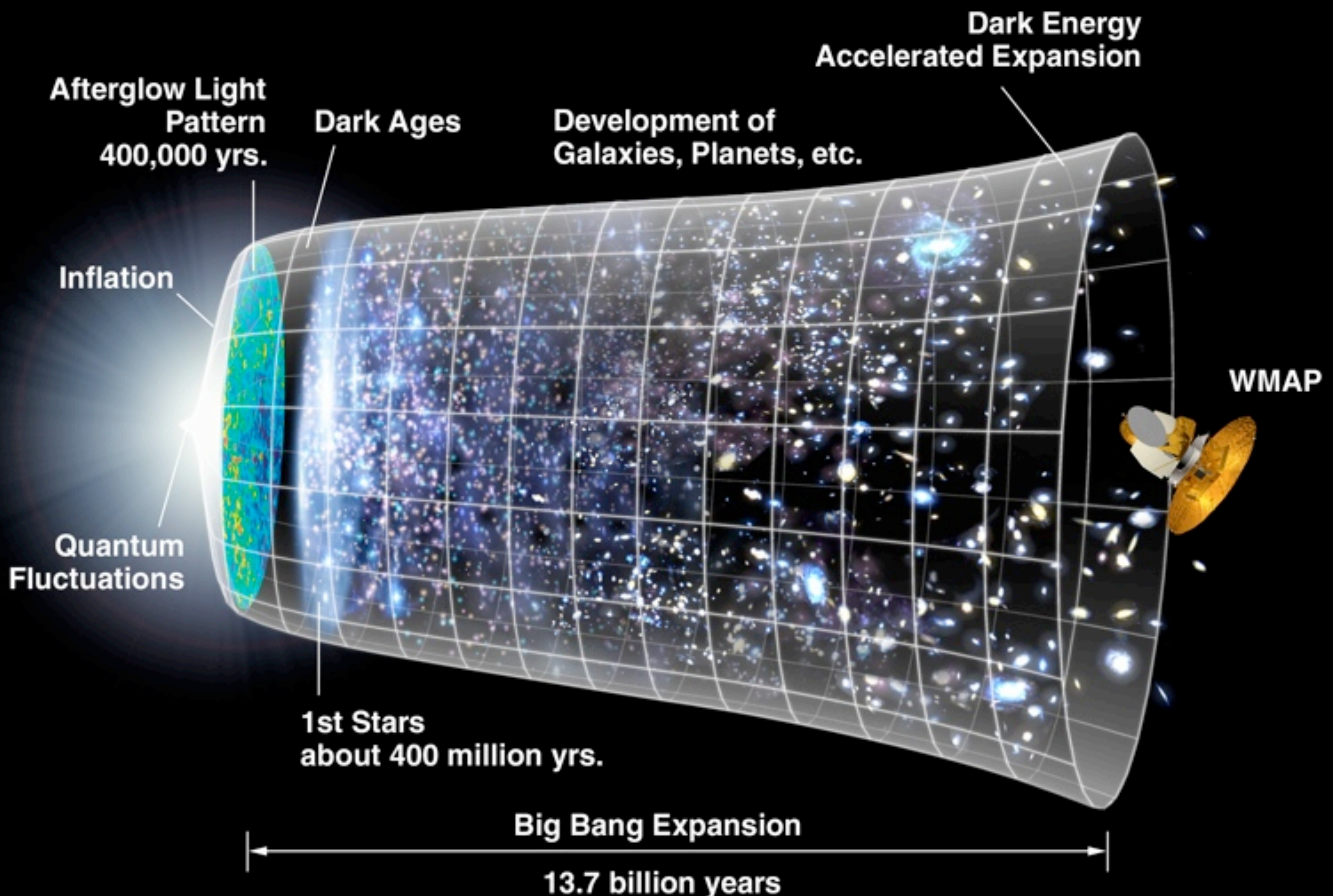

2 cm
1 cm
4 cm
2 cm
Time
D
d
D
d

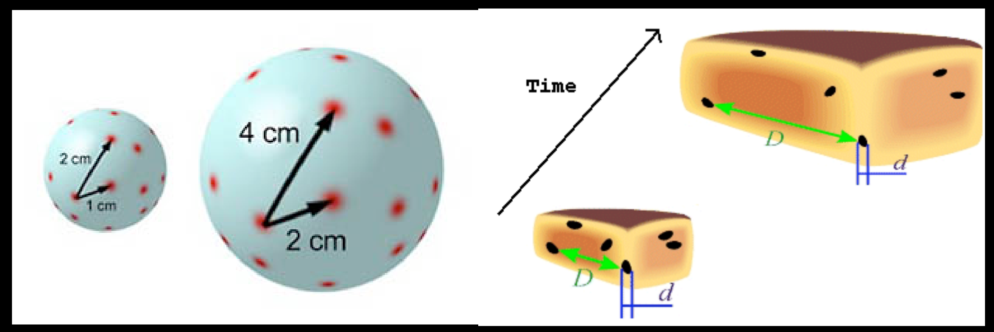




NASA/WMAP Science Team

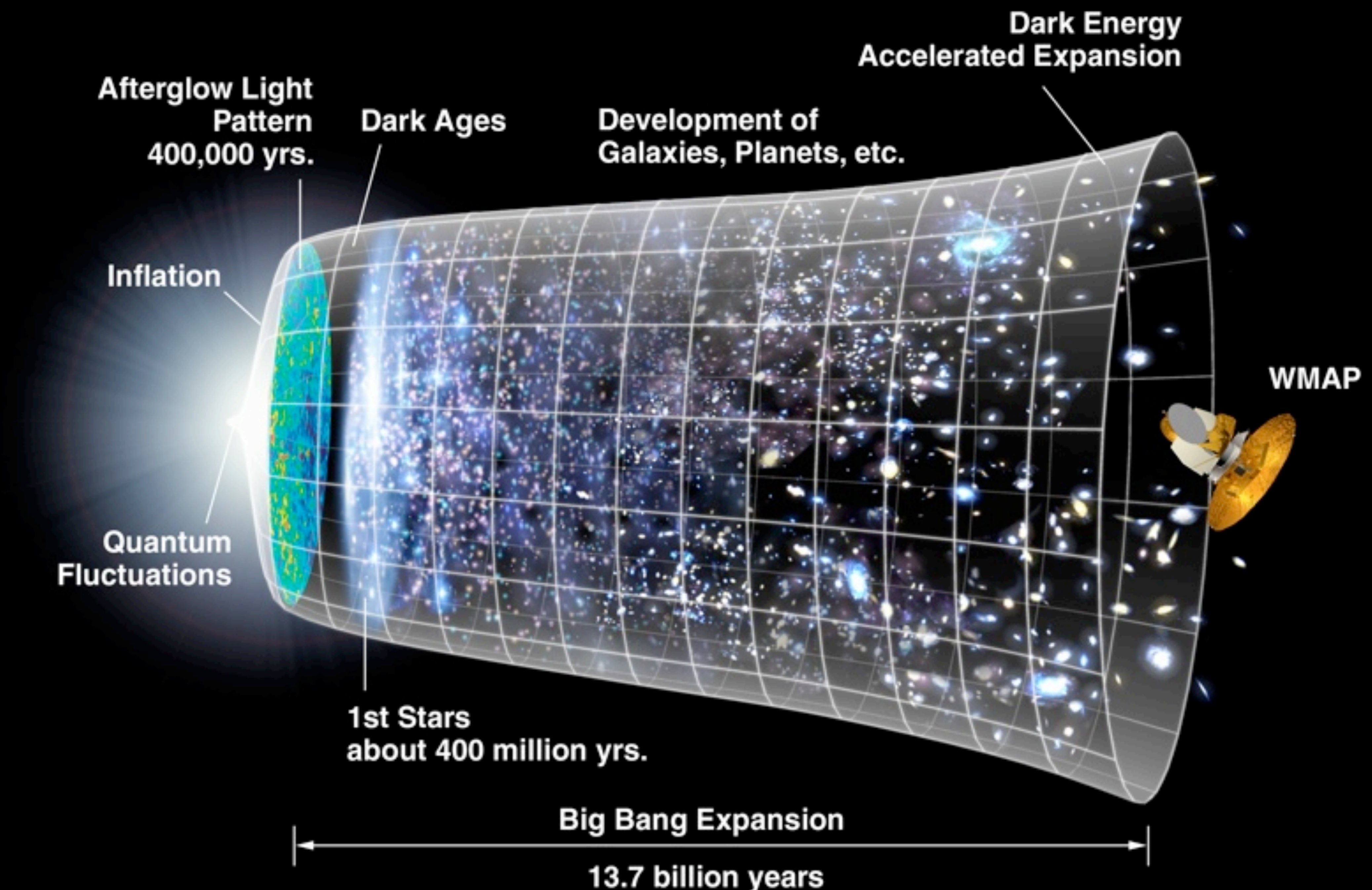
$$H(t) \equiv \frac{\dot{a}}{a}$$

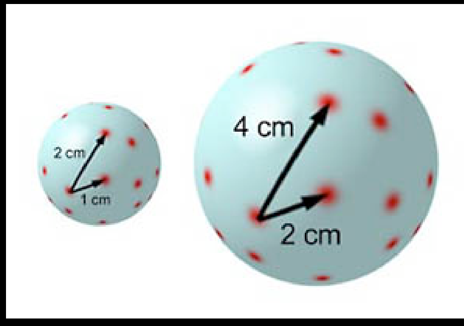


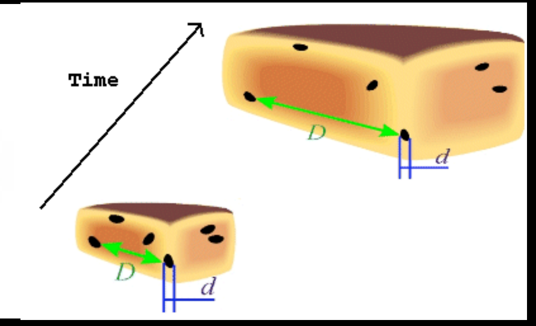


NASA/WMAP Science Team

$$H(t) \equiv \frac{\dot{a}}{a} \qquad 1 + z \equiv \frac{\lambda_{obs}}{\lambda_{emit}} = \frac{1}{a}$$

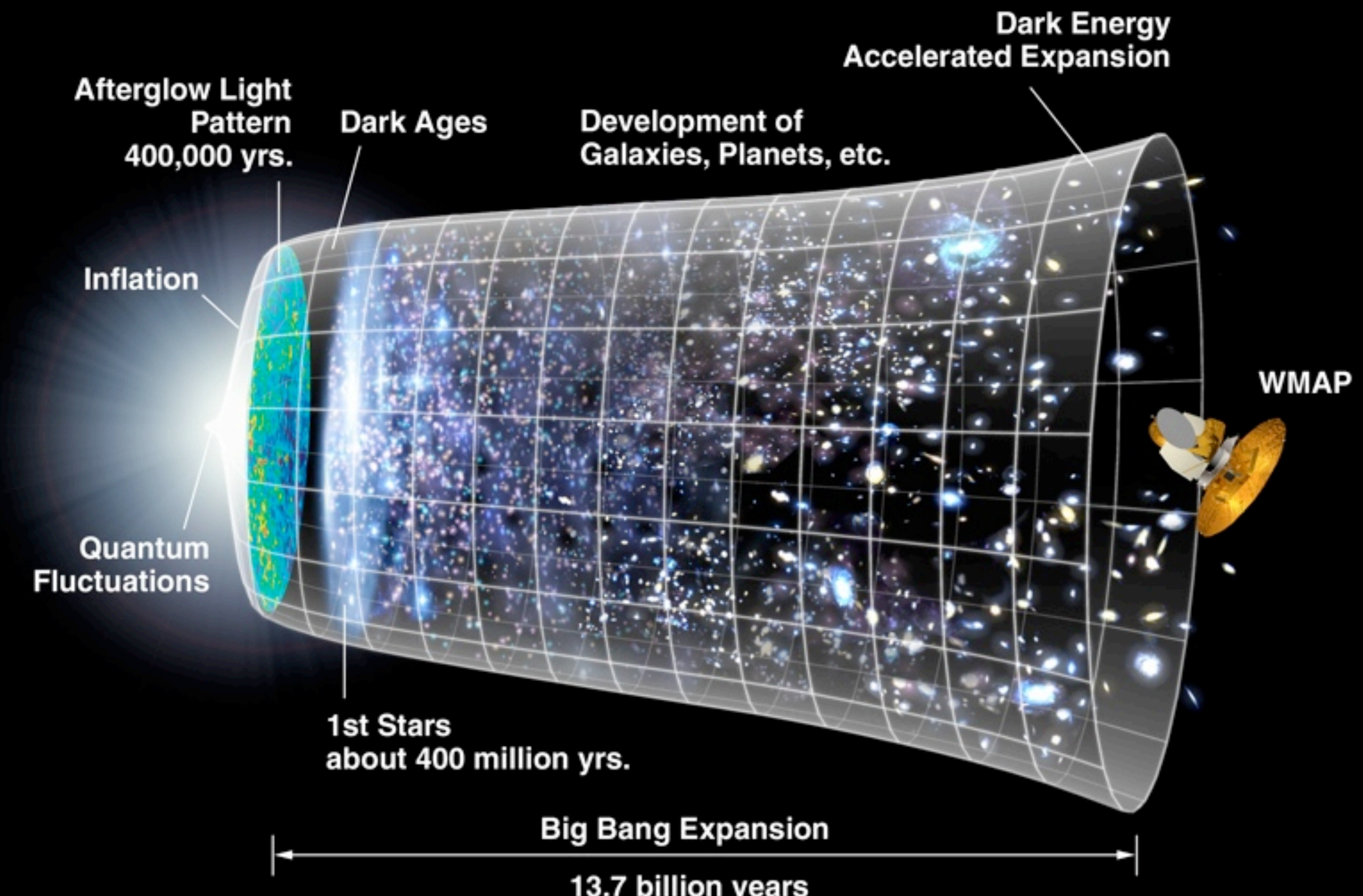


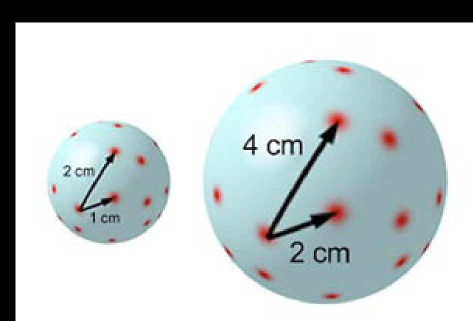


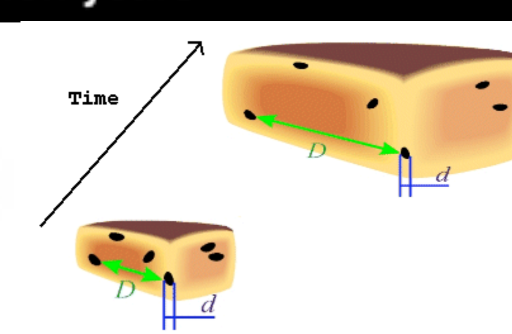


NASA/WMAP Science Team

$$H(t) \equiv \frac{\dot{a}}{a} \qquad 1 + z \equiv \frac{\lambda_{obs}}{\lambda_{emit}} = \frac{1}{a} \qquad T \propto \frac{1}{a} \propto (1+z)$$







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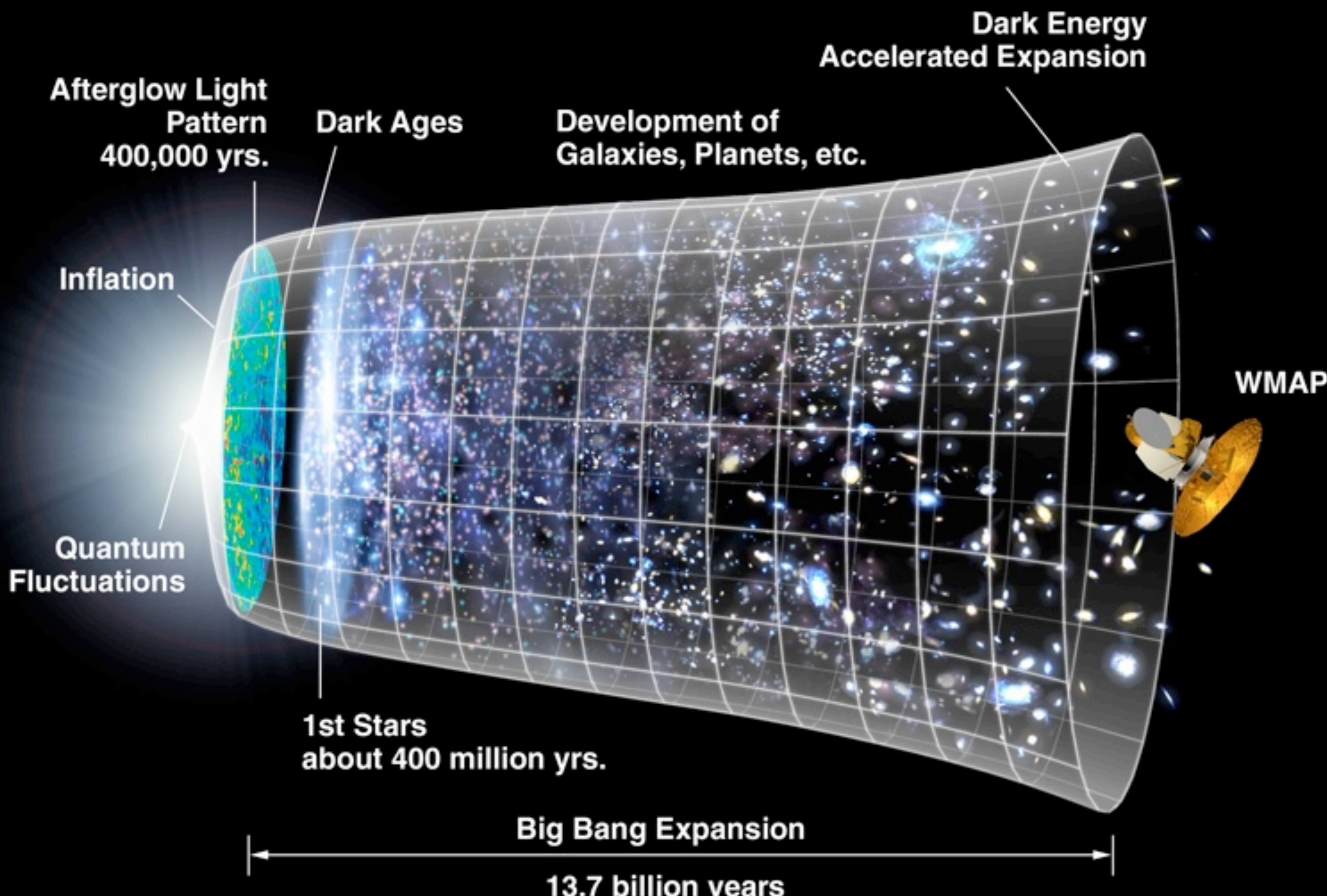
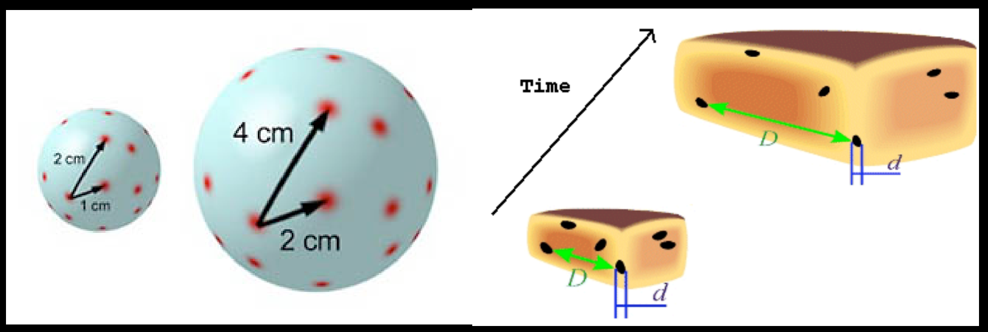


$$z \simeq \frac{v}{c}$$



$$v \simeq cz$$

NASA/WMAP Science Team

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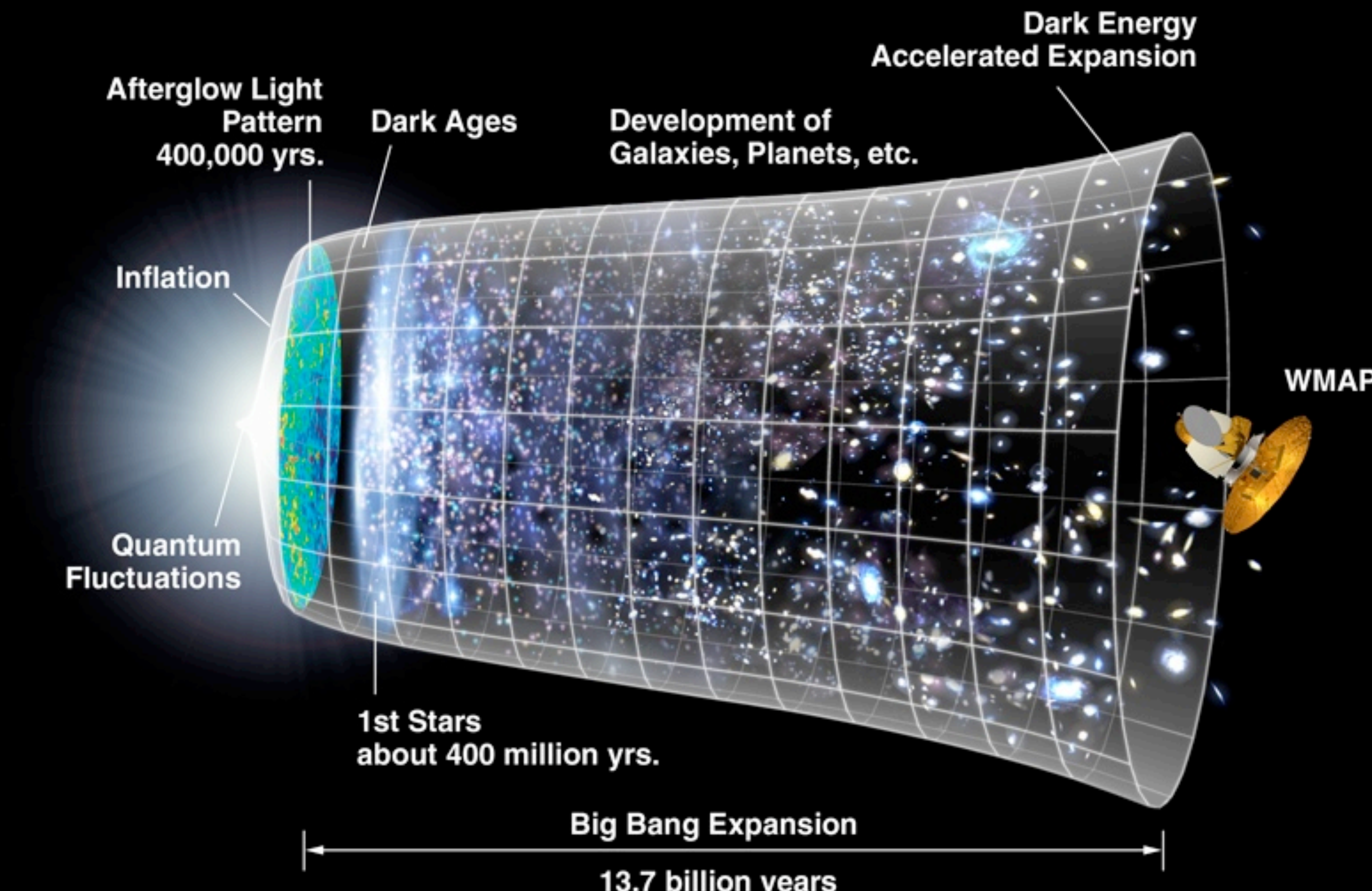
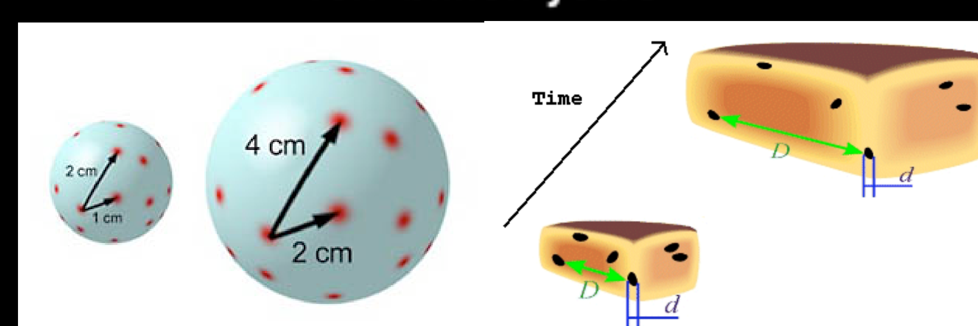
$a = 0$ and $z \to \infty$

at the Beginning!



$a(t_0) = a_0 = 1$ and $z = 0$ Today!

$$z \simeq \frac{v}{c}$$



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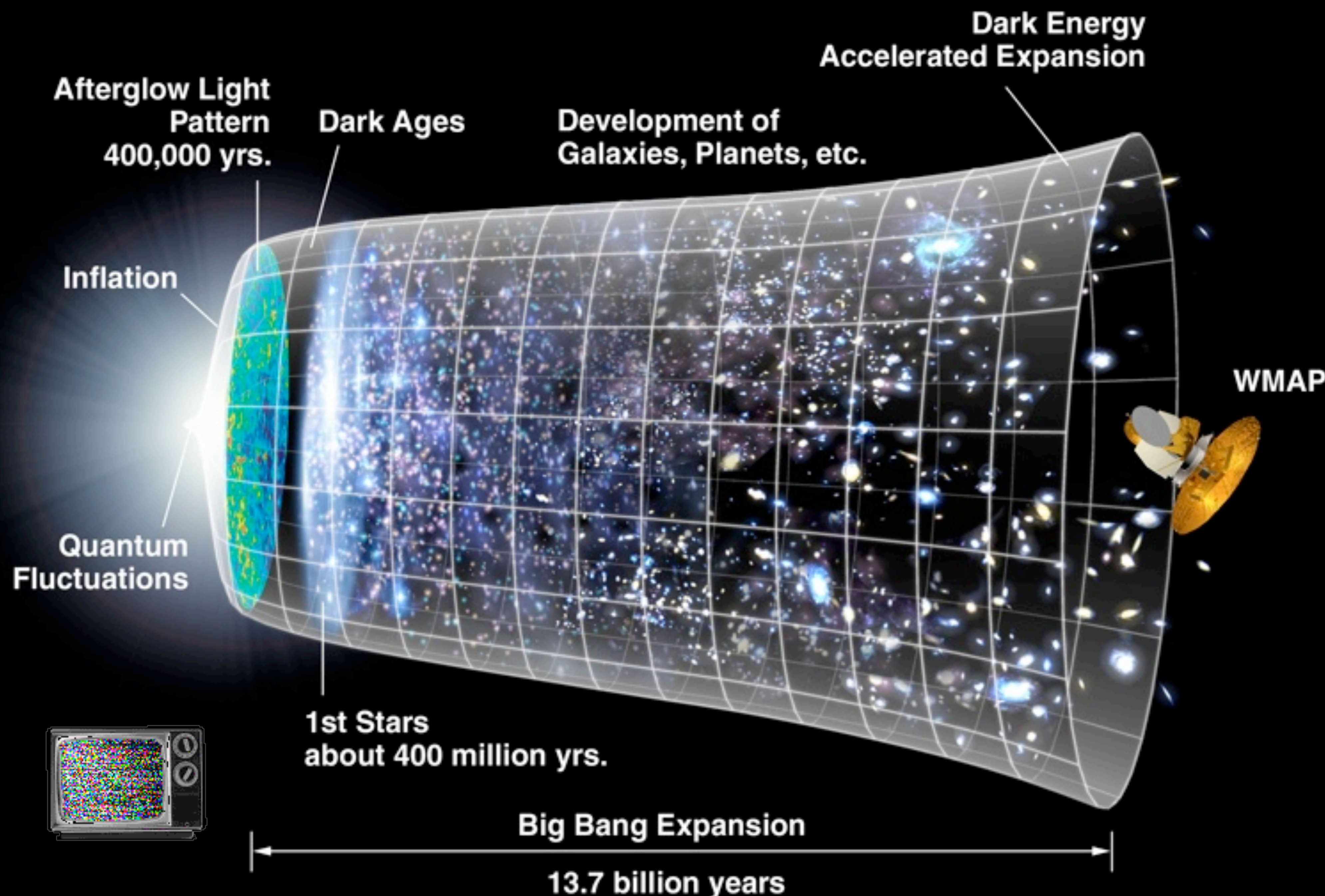

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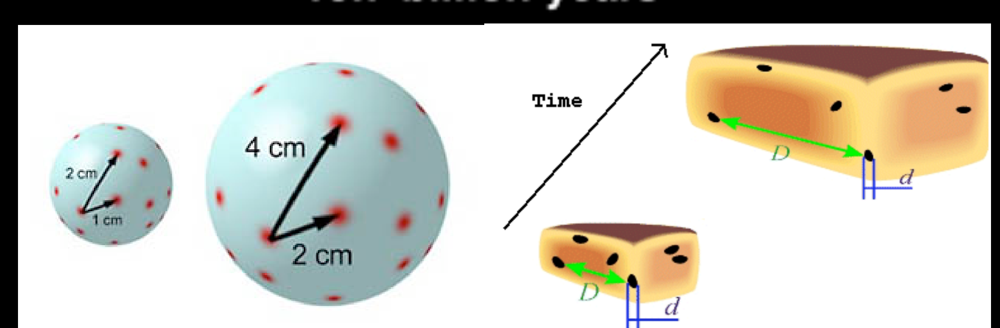

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NASA/WMAP Science Team

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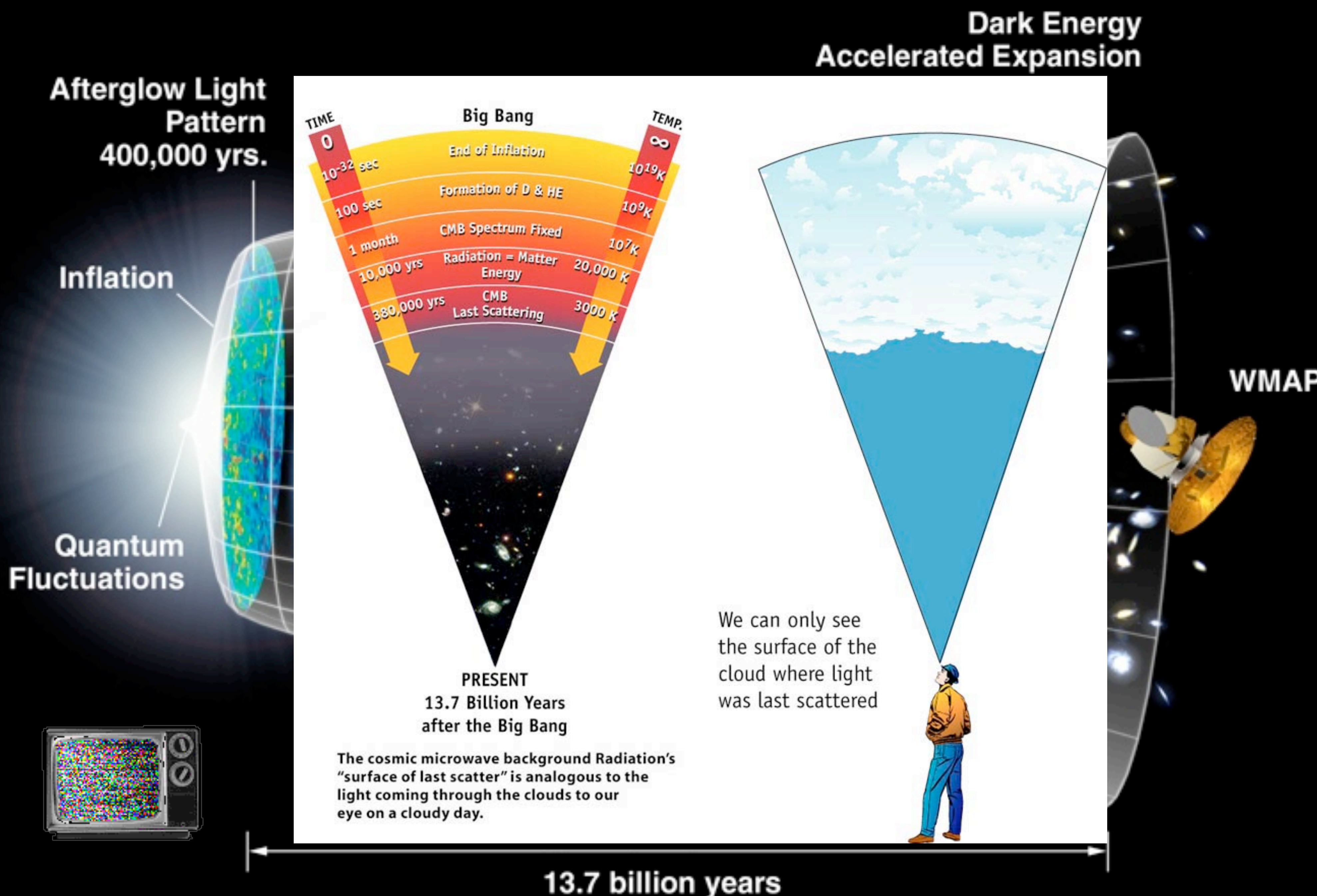
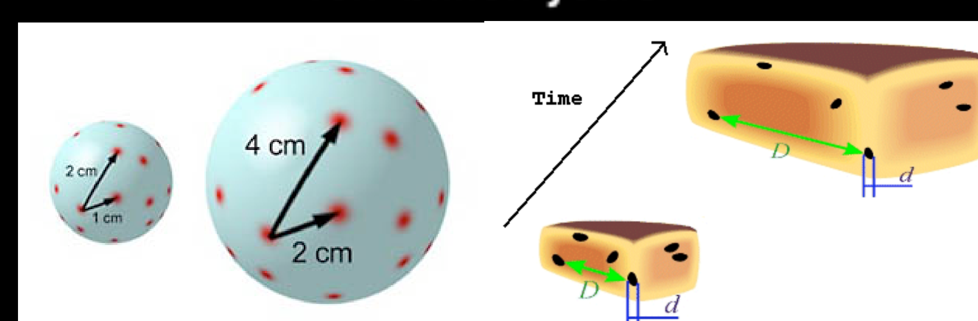
$a = 0$ and $z \to \infty$ at the Beginning!



$a(t_0) = a_0 = 1$ and $z = 0$ Today!

$$z \simeq \frac{v}{c}$$



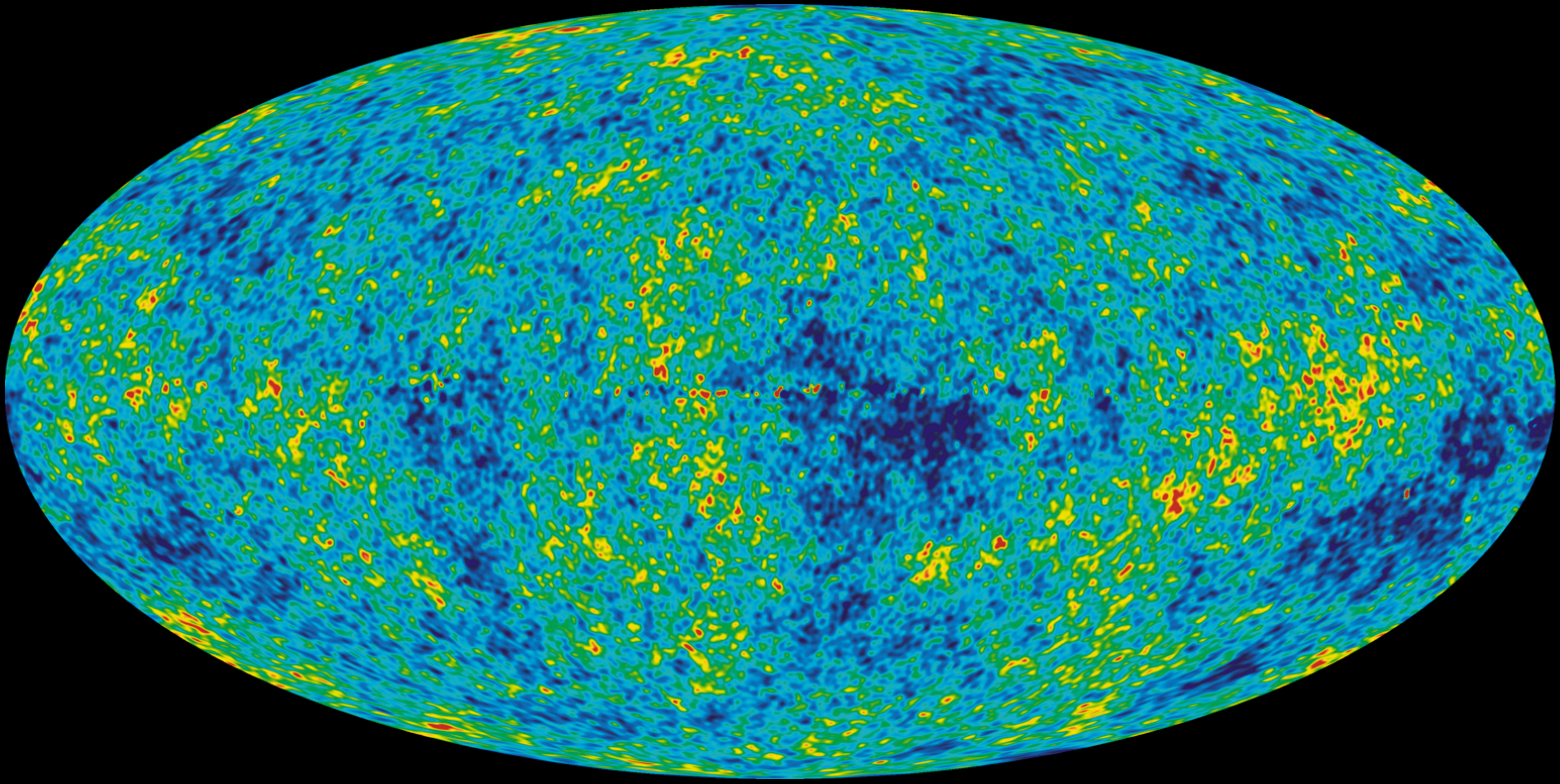
$$v \simeq cz$$

NASA/WMAP Science Team

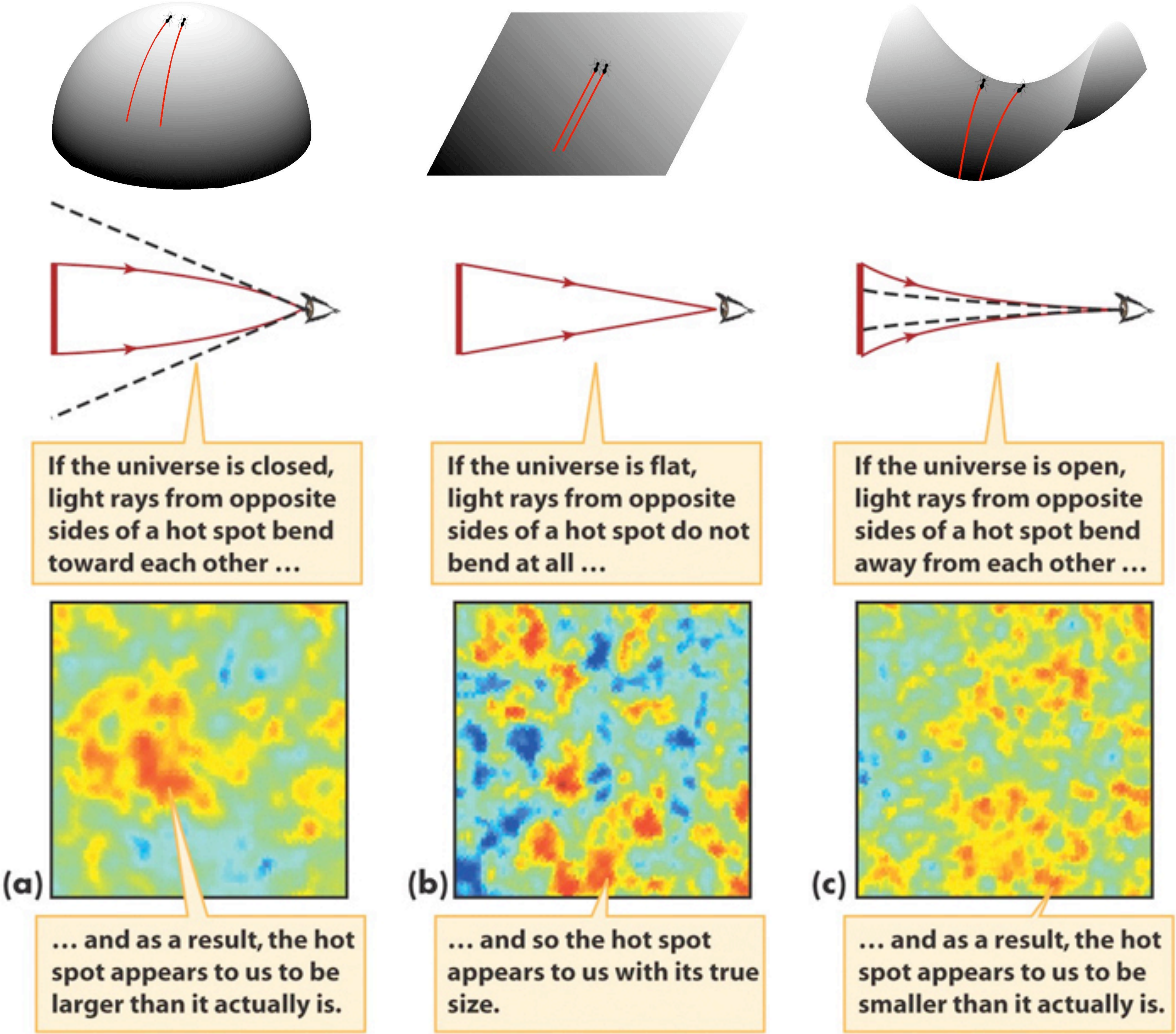
Different Scales

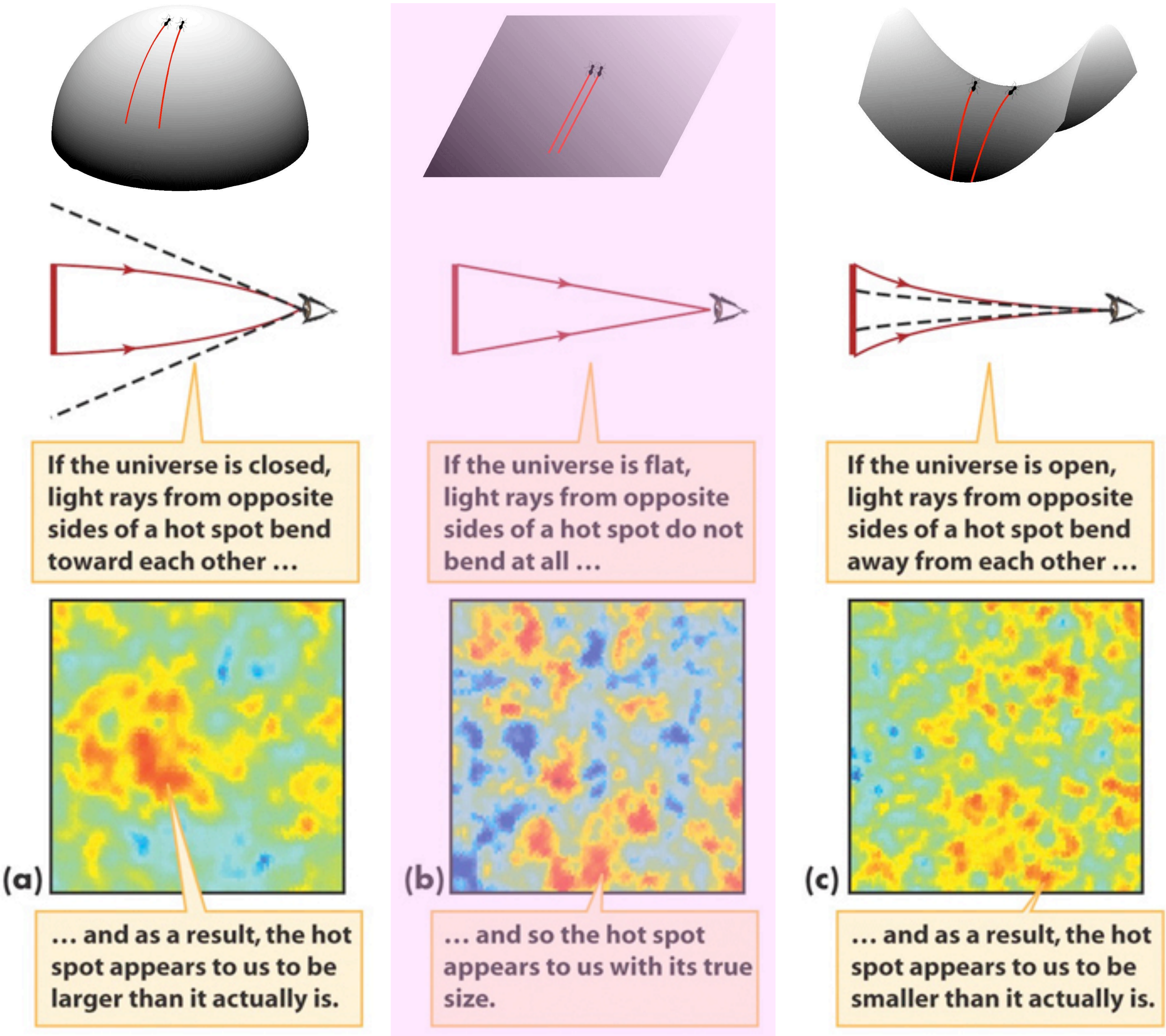
Redshift, z	Time, t (Years)	cz (km/s)	Distance (Mpc/h)	Temperature (K)
0	13.7 billion	0	0	2.725
0.01	13.5 billion	3000	30	2.752
0.033	13.1 billion	10,000	100	2.815
0.1	11.9 billion	30,000	300	2.998
1.0	04.8 billion	300,000	3000	5.450
4.0	~1 billion	1.2 million	12,000	13.625
1100	400,000	0.3 billion	3.3 million	3000

$$1 \text{ Mpc} = 10^6 \text{ pc} = 3.26 \times 10^6 \text{ ly} = 3.08 \times 10^{22} \text{ m}$$



Credit: NASA/WMAP Science Team


If the universe is closed, light rays from opposite sides of a hot spot bend toward each other …
If the universe is flat, light rays from opposite sides of a hot spot do not bend at all …
If the universe is open, light rays from opposite sides of a hot spot bend away from each other …
(a)
(b)
(c)
… and as a result, the hot spot appears to us to be larger than it actually is.
… and so the hot spot appears to us with its true size.
… and as a result, the hot spot appears to us to be smaller than it actually is.


If the universe is closed, light rays from opposite sides of a hot spot bend toward each other …
… and as a result, the hot spot appears to us to be larger than it actually is.
(a)
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If the universe is open, light rays from opposite sides of a hot spot bend away from each other …
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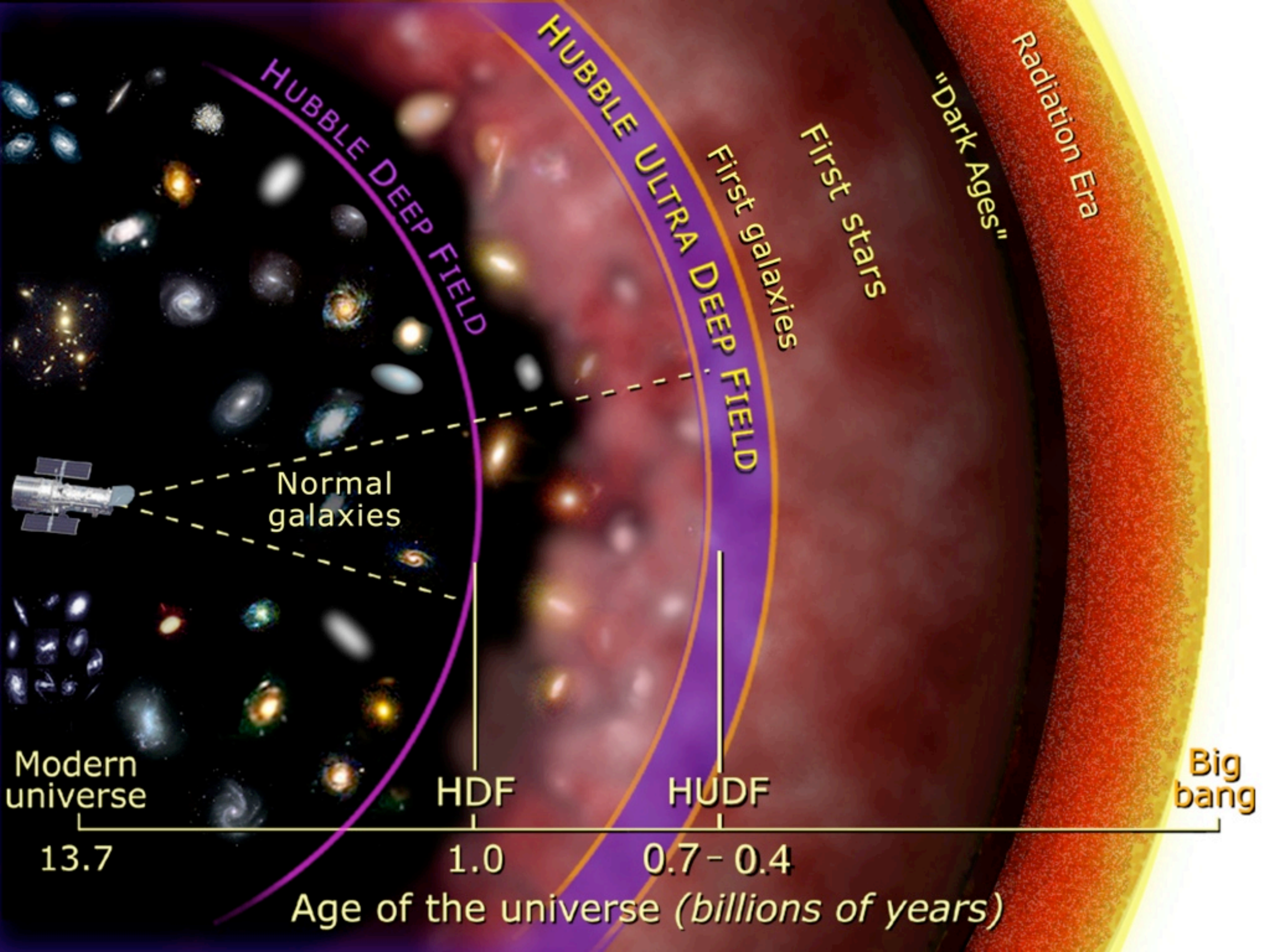
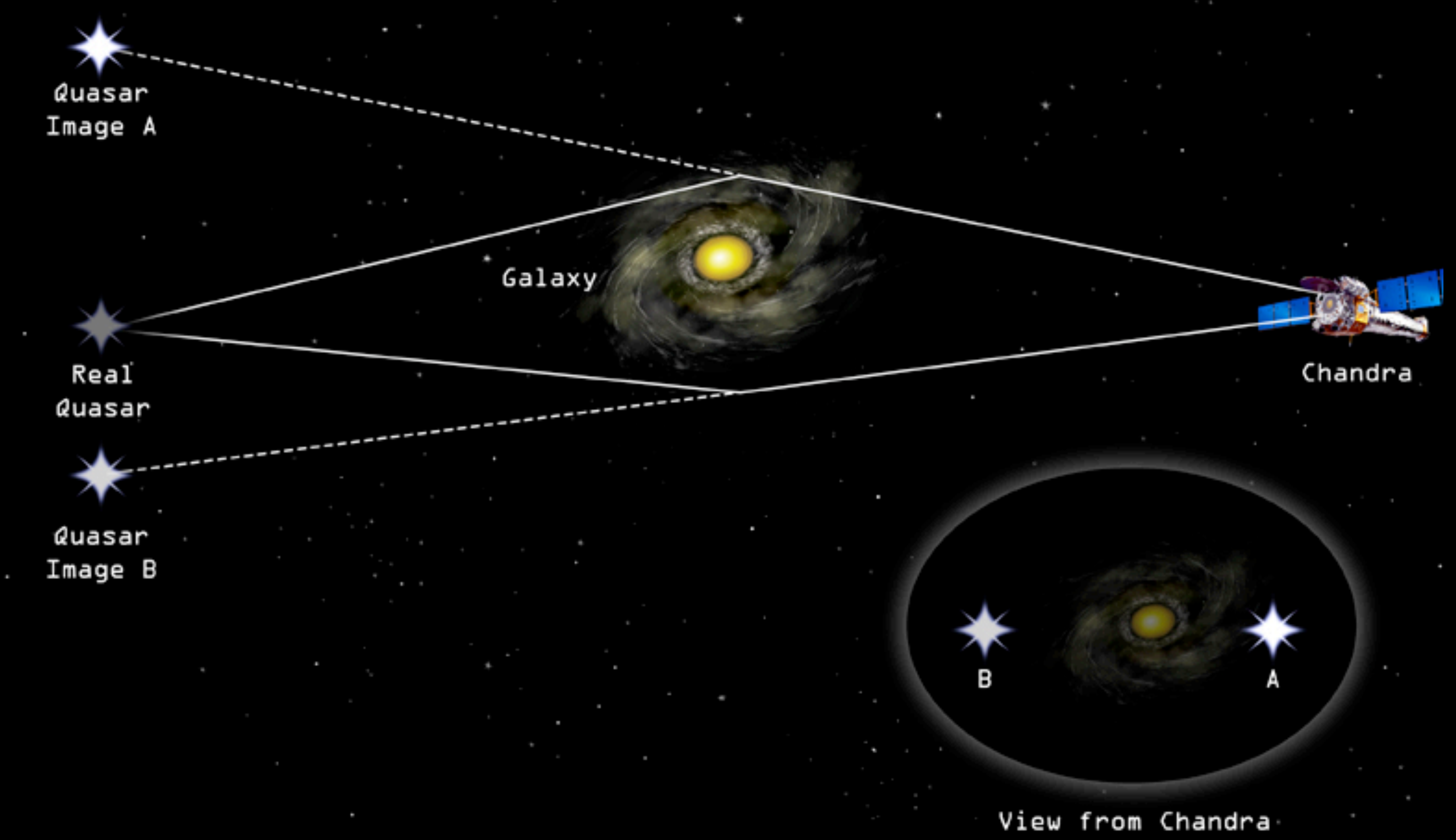
(c)



Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)


Are we sure we are counting everything?

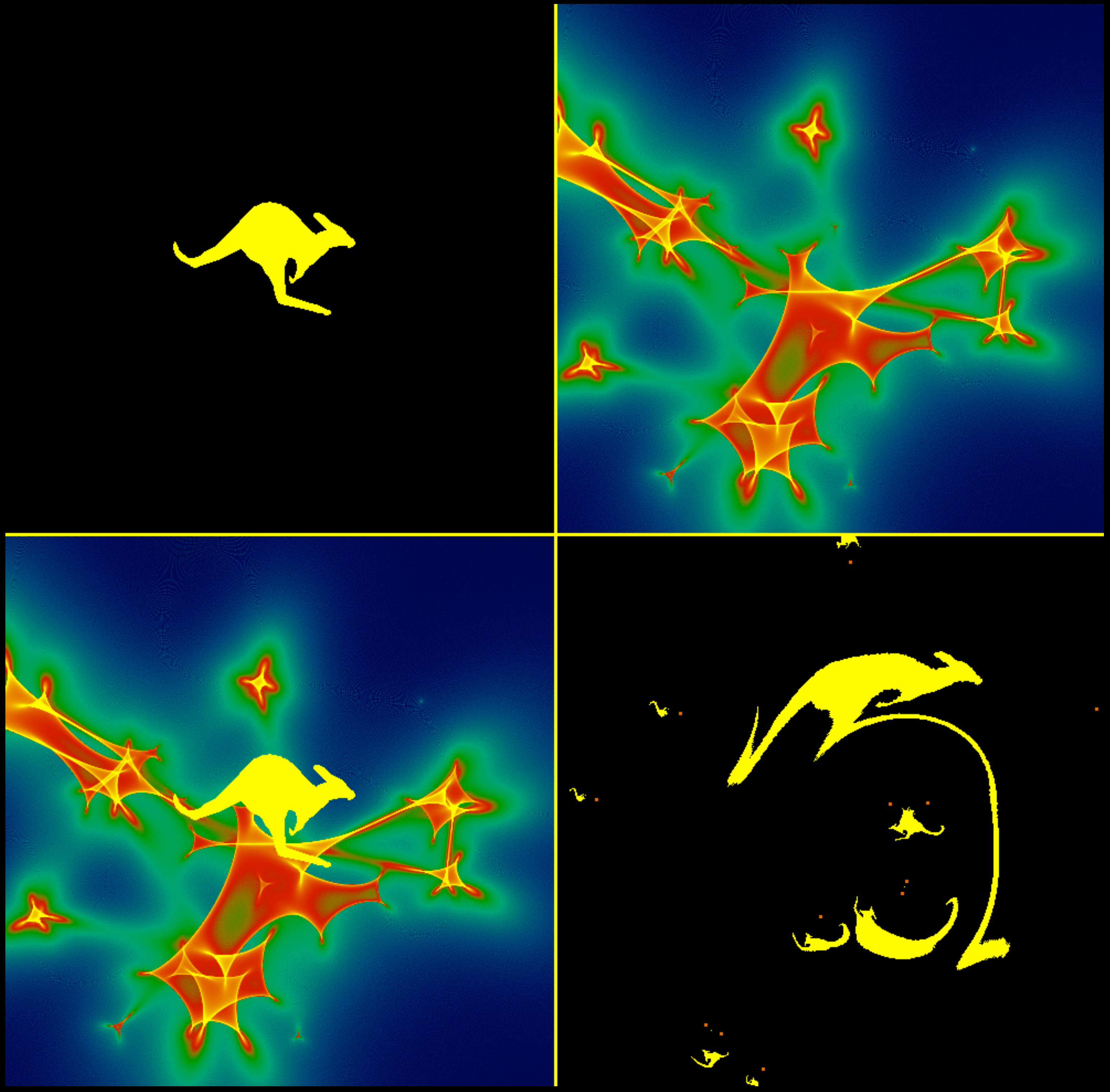
Seeing the Unseen... Gravitational Lensing

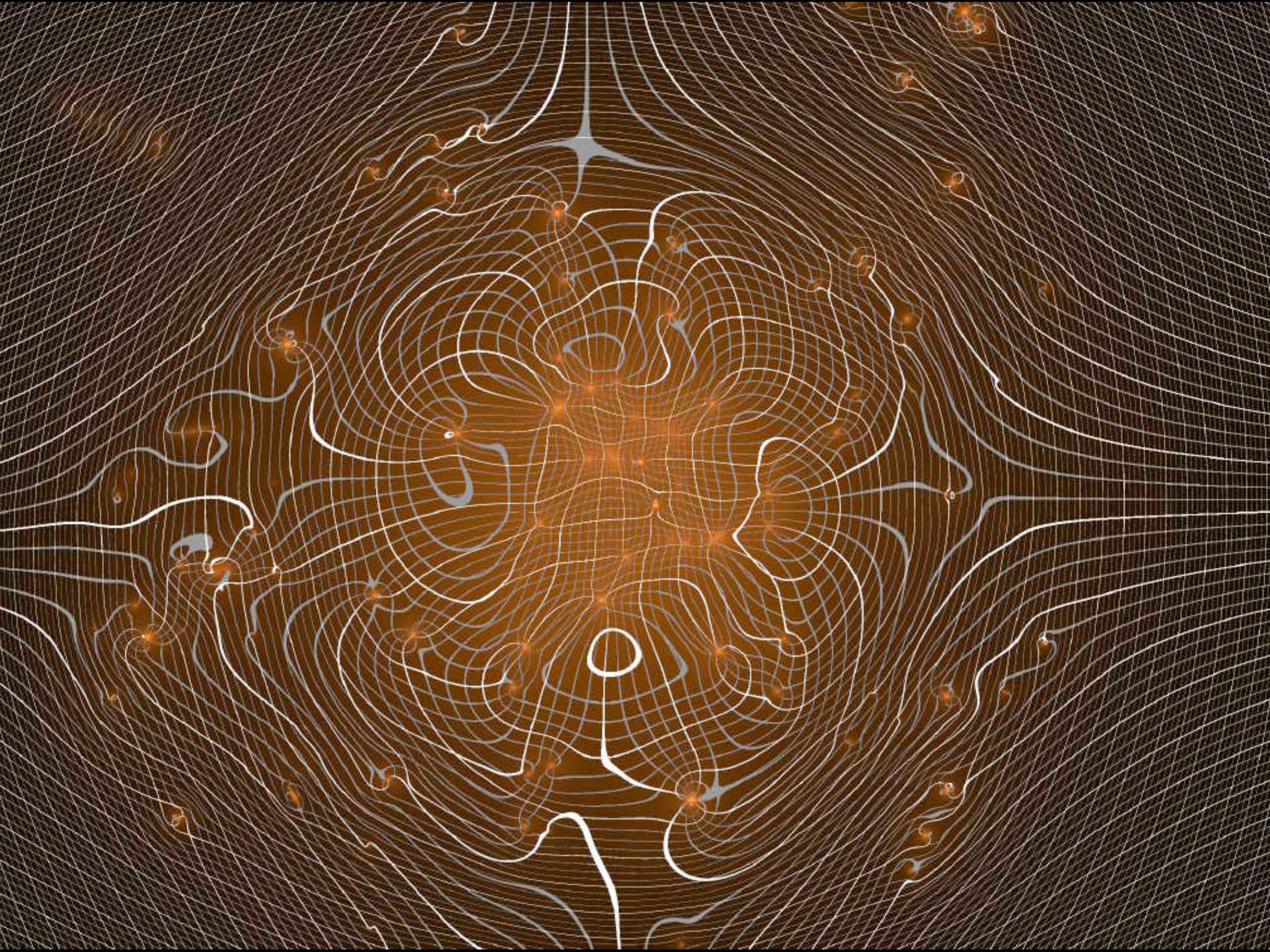


Seeing the Unseen... Gravitational Lensing

Lensing Galaxy

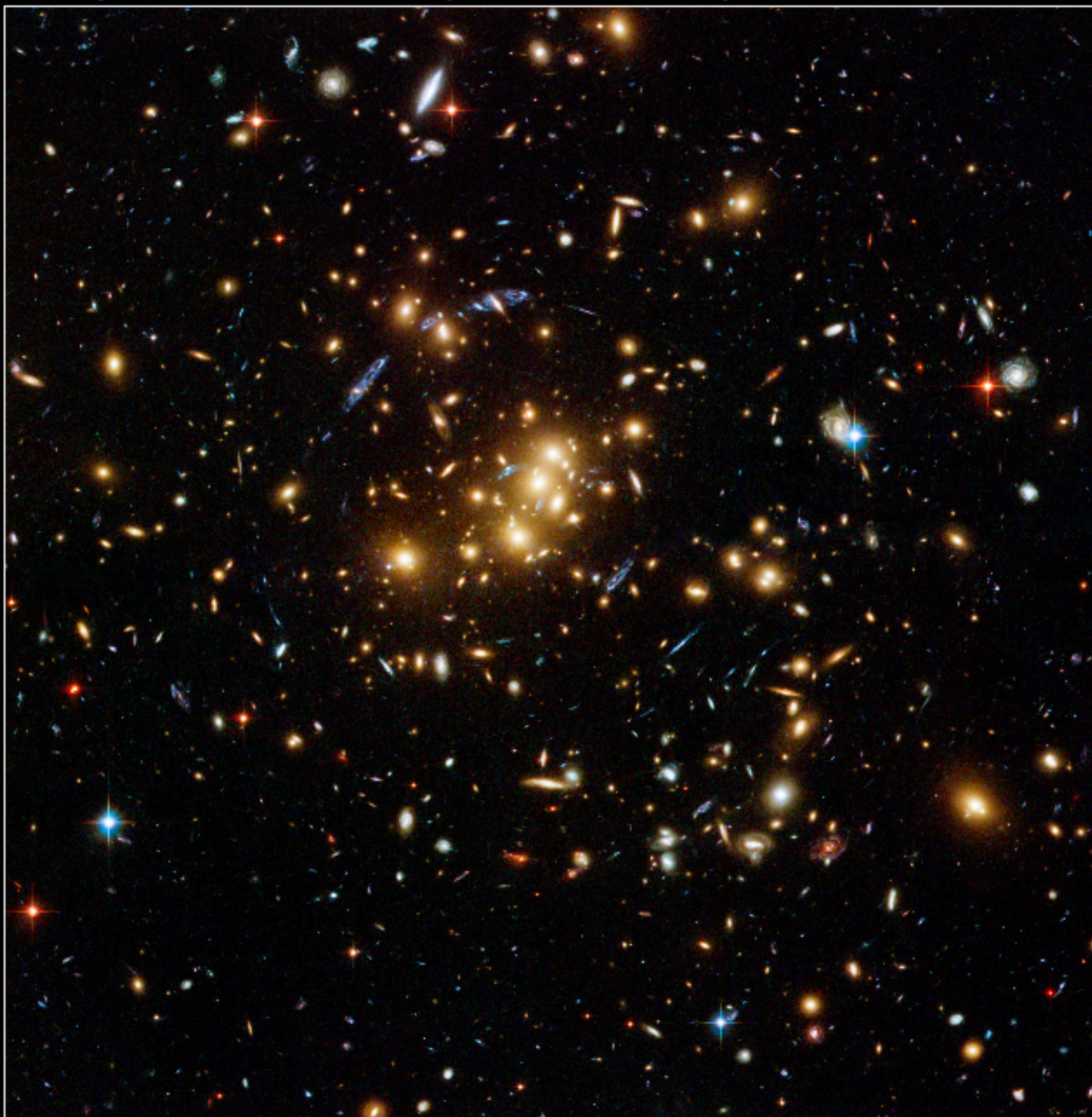
Seeing the Unseen... Gravitational Lensing



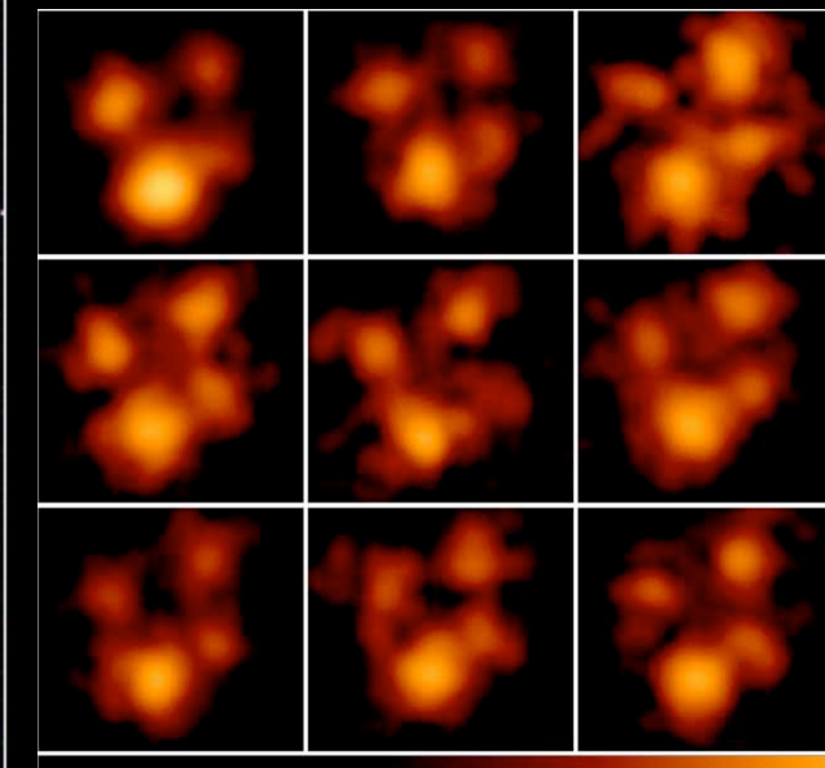


Reconstruction of Dark Matter Distribution from Observation

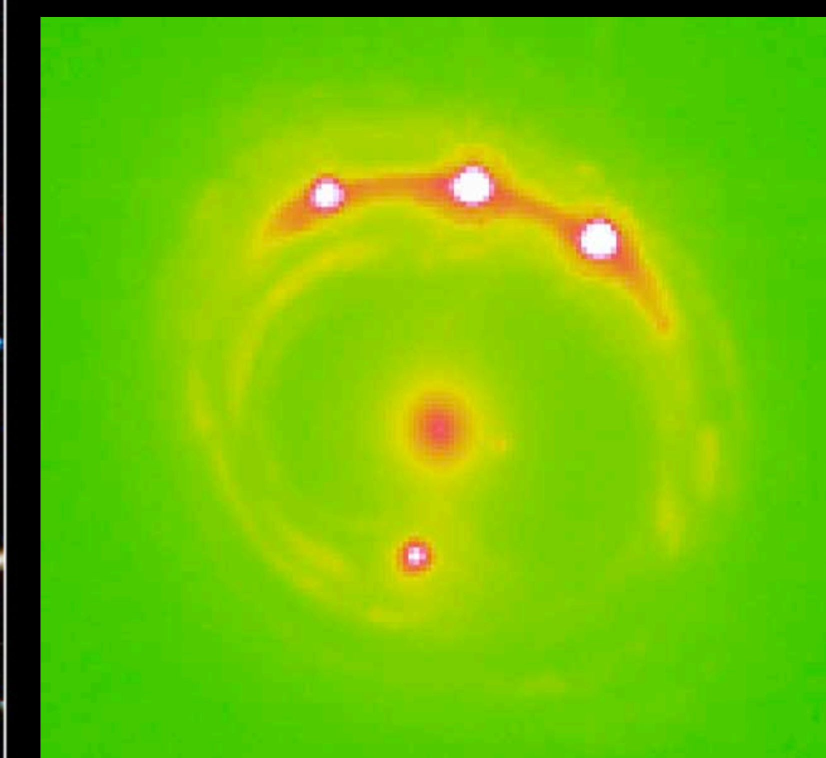
Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652) *HST* • ACS/WFC



NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17b



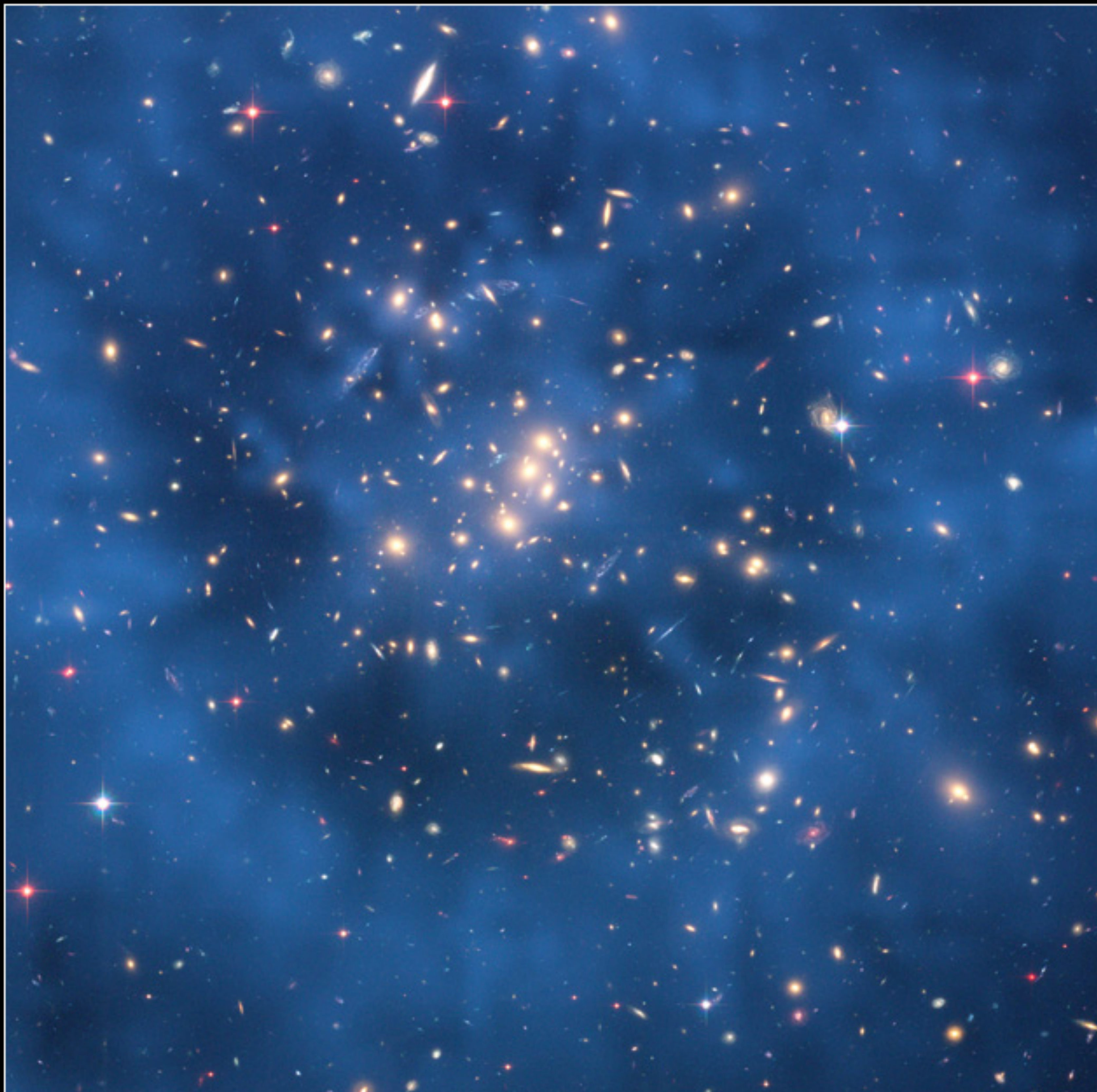
X-Ray images of Quasar Q2237+0305
(Mosaic courtesy: Ohio State University)



Optical images of Quasar RXJ1131-1231
(courtesy: Ohio State University)

Reconstruction of Dark Matter Distribution from Observation

Dark Matter Ring in Cl 0024+17 (ZwCl 0024+1652) *HST* • ACS/WFC



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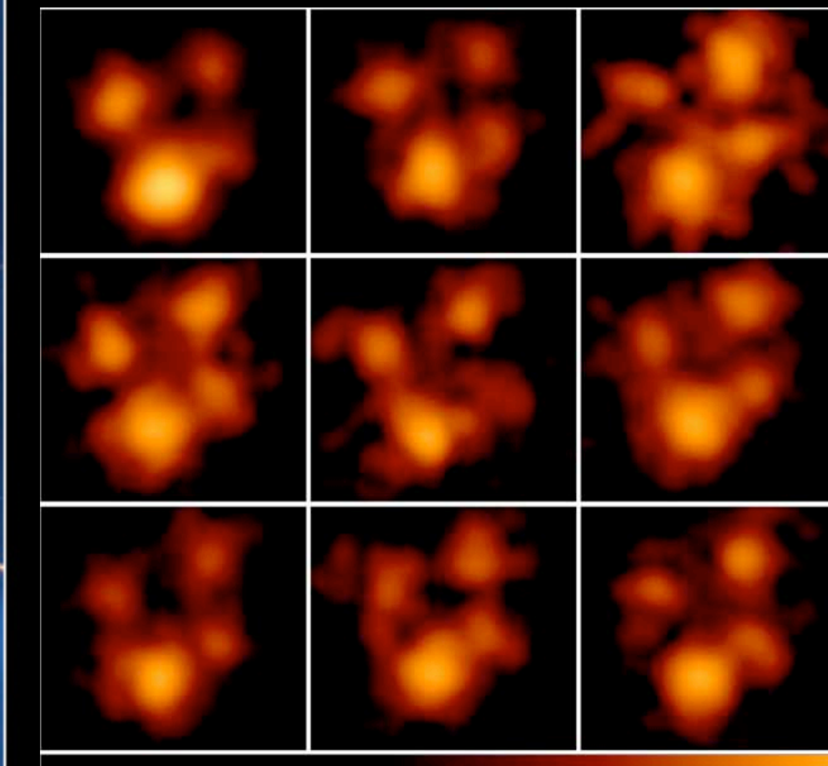

X-Ray images of Quasar Q2237+0305
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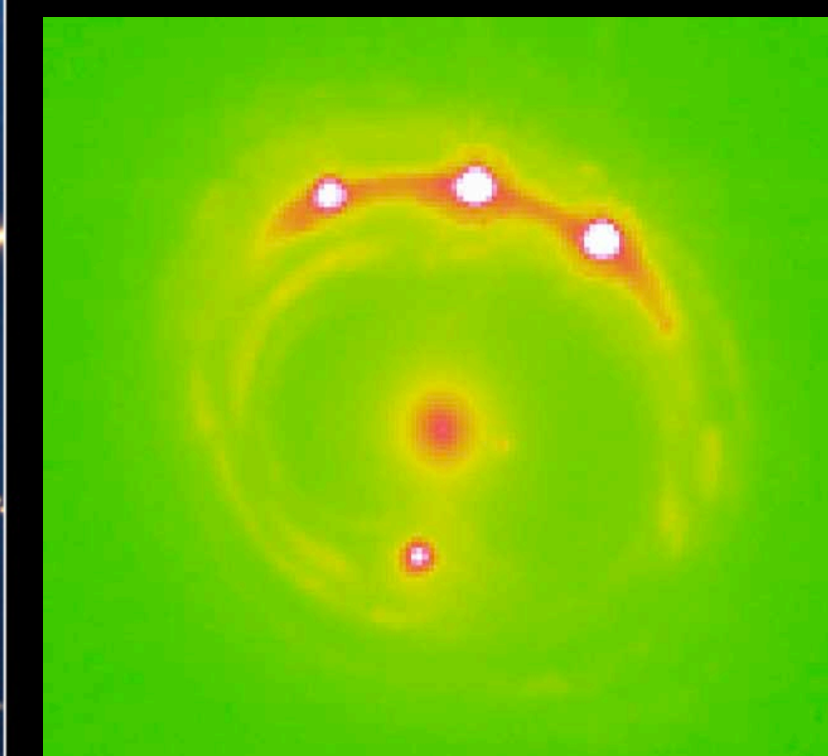
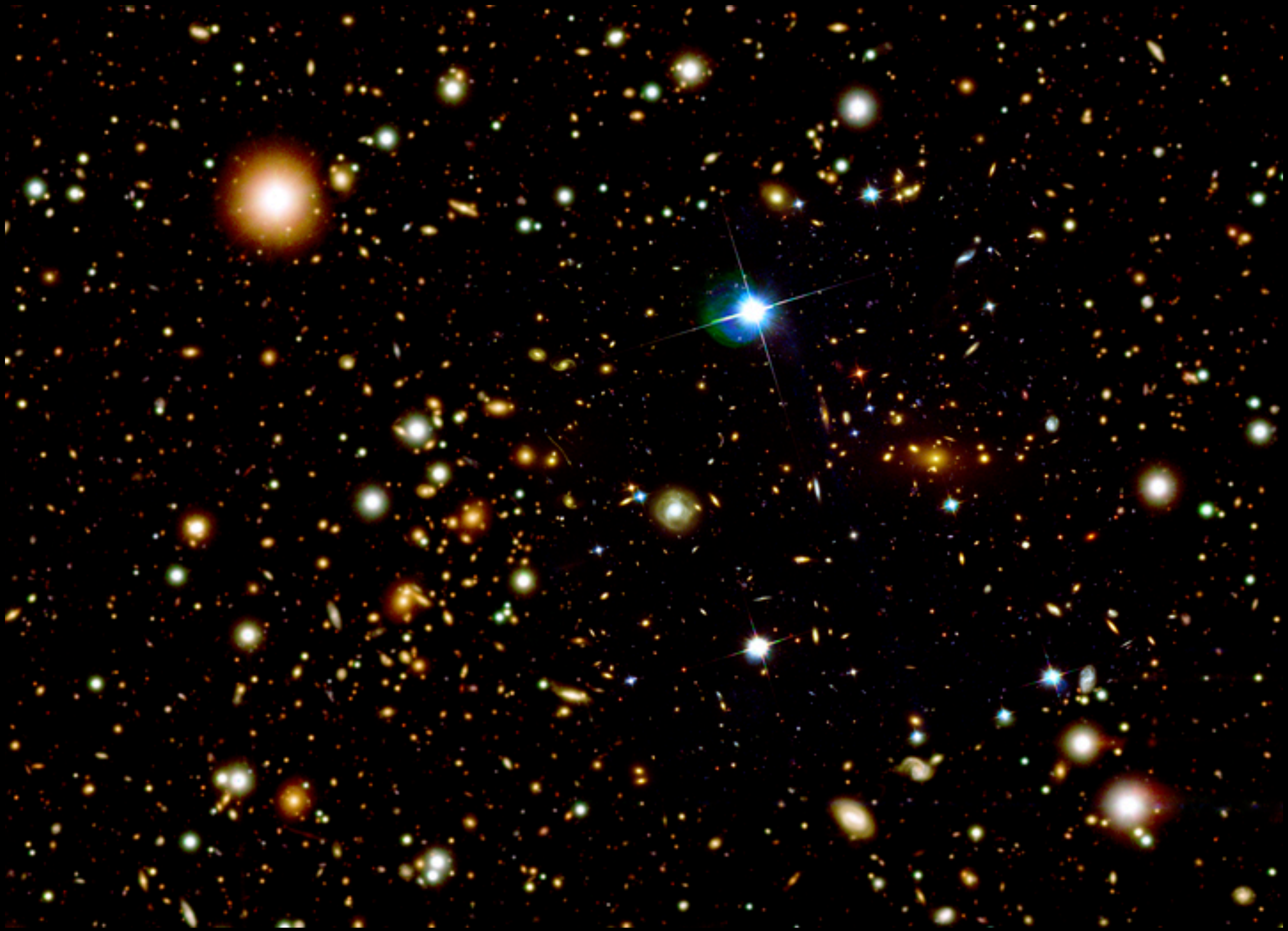


Optical images of Quasar RXJ1131-1231
(courtesy: Ohio State University)

Dark Matter Expose: Bullet Cluster

OPTICAL



X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/
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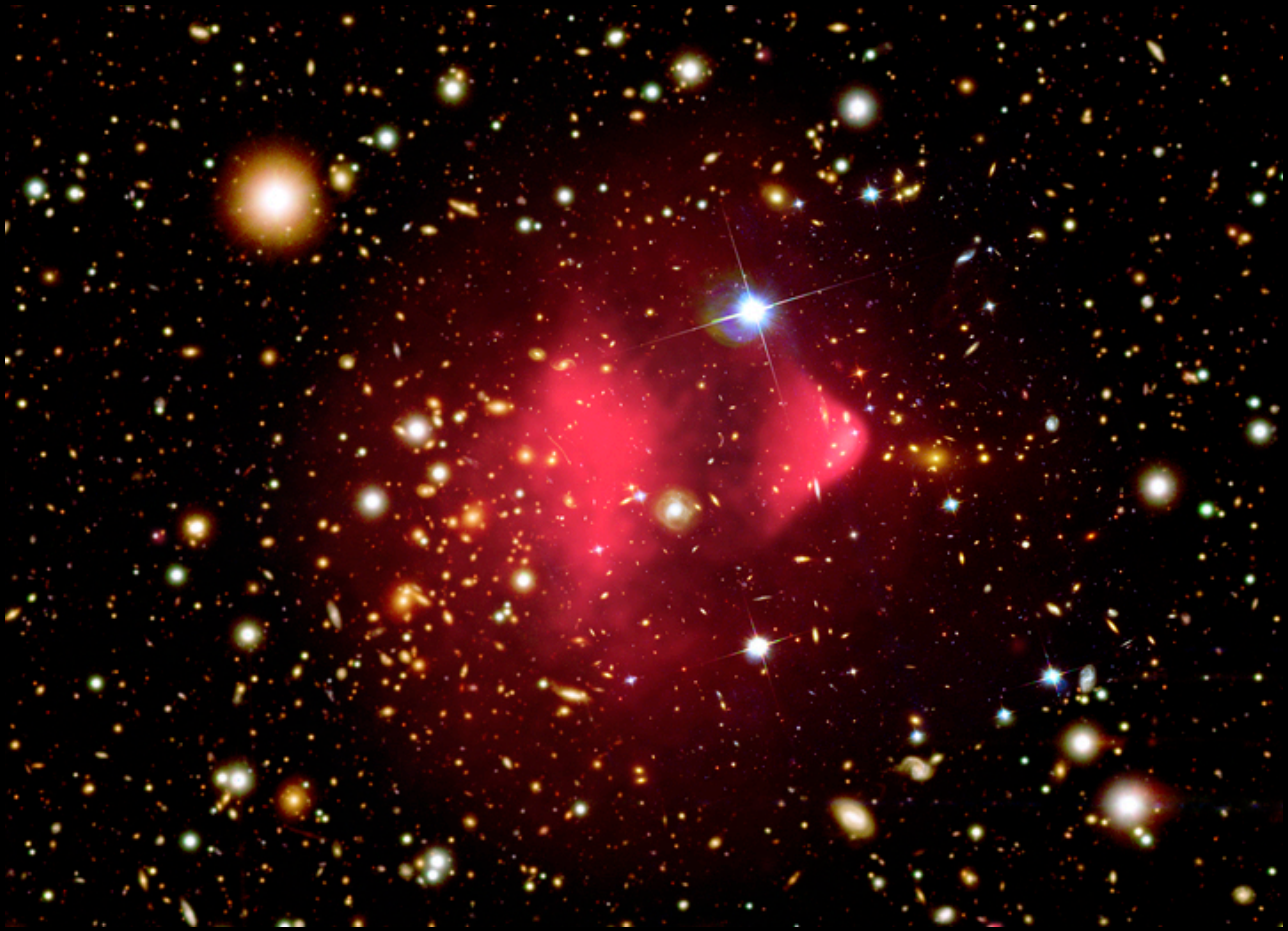
Dark Matter Expose: Bullet Cluster



OPTICAL

X-Ray

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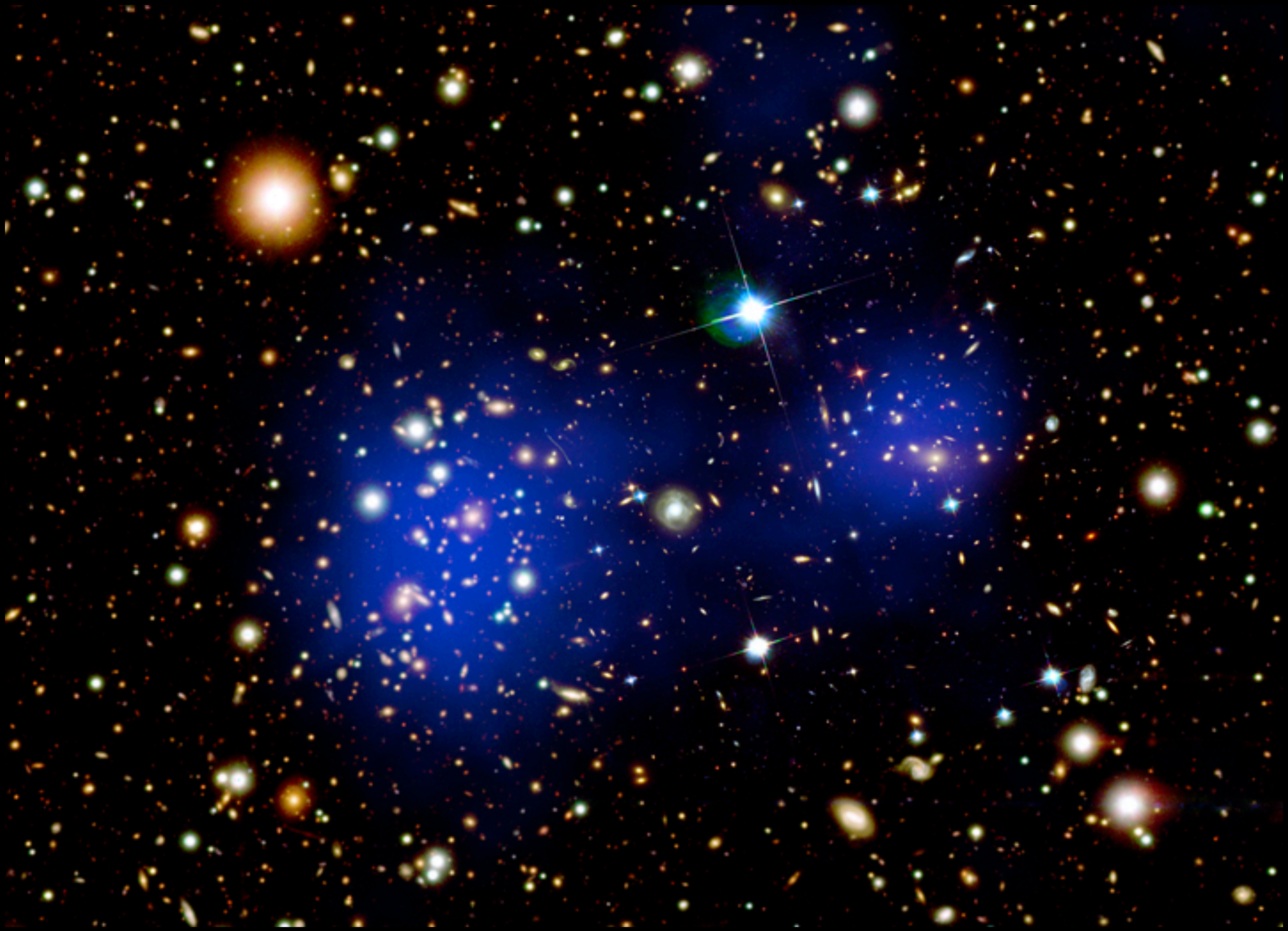

Lensing

X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/
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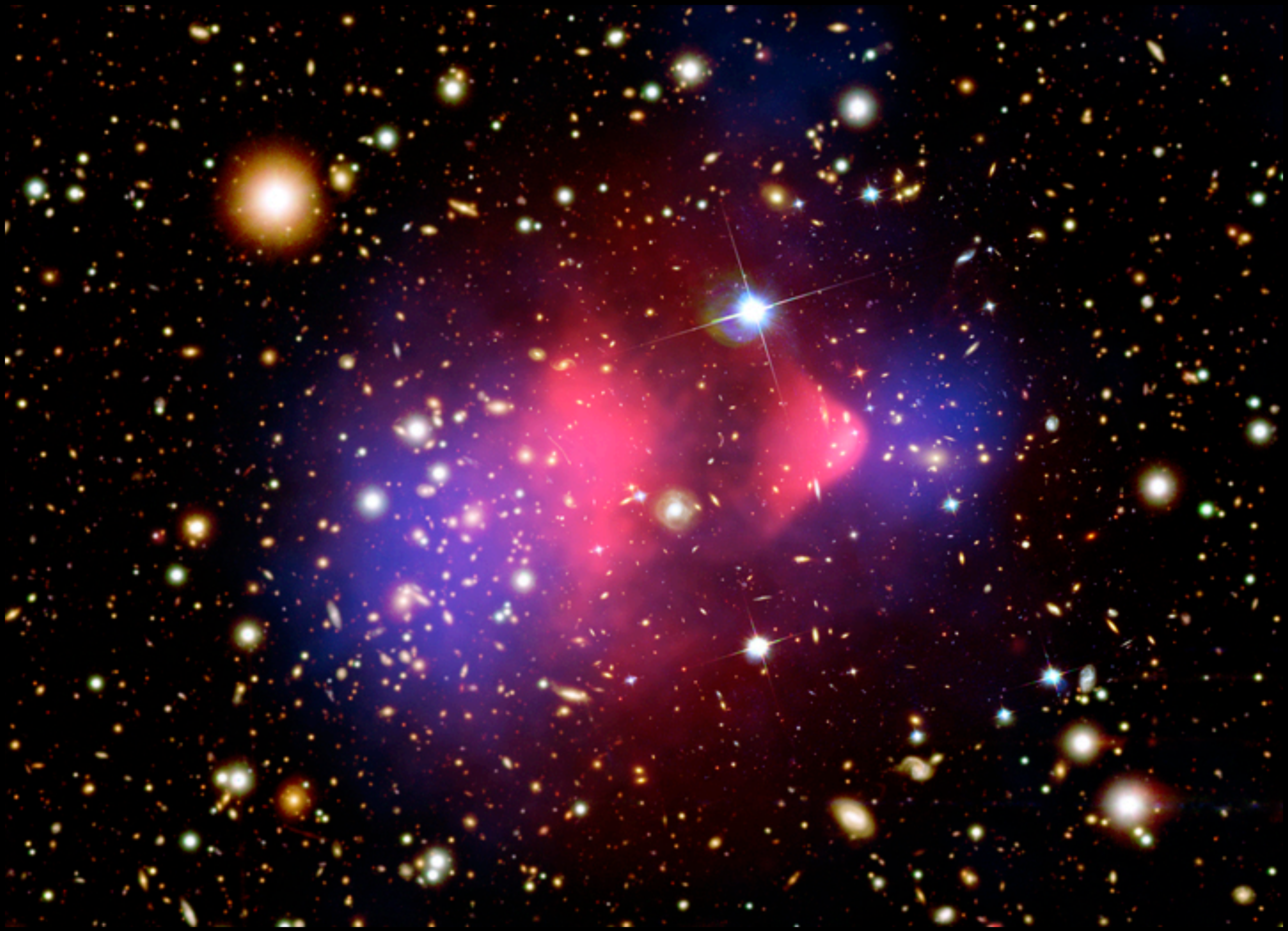
Dark Matter Expose: Bullet Cluster

OPTICAL



X-Ray

Lensing

X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/ D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

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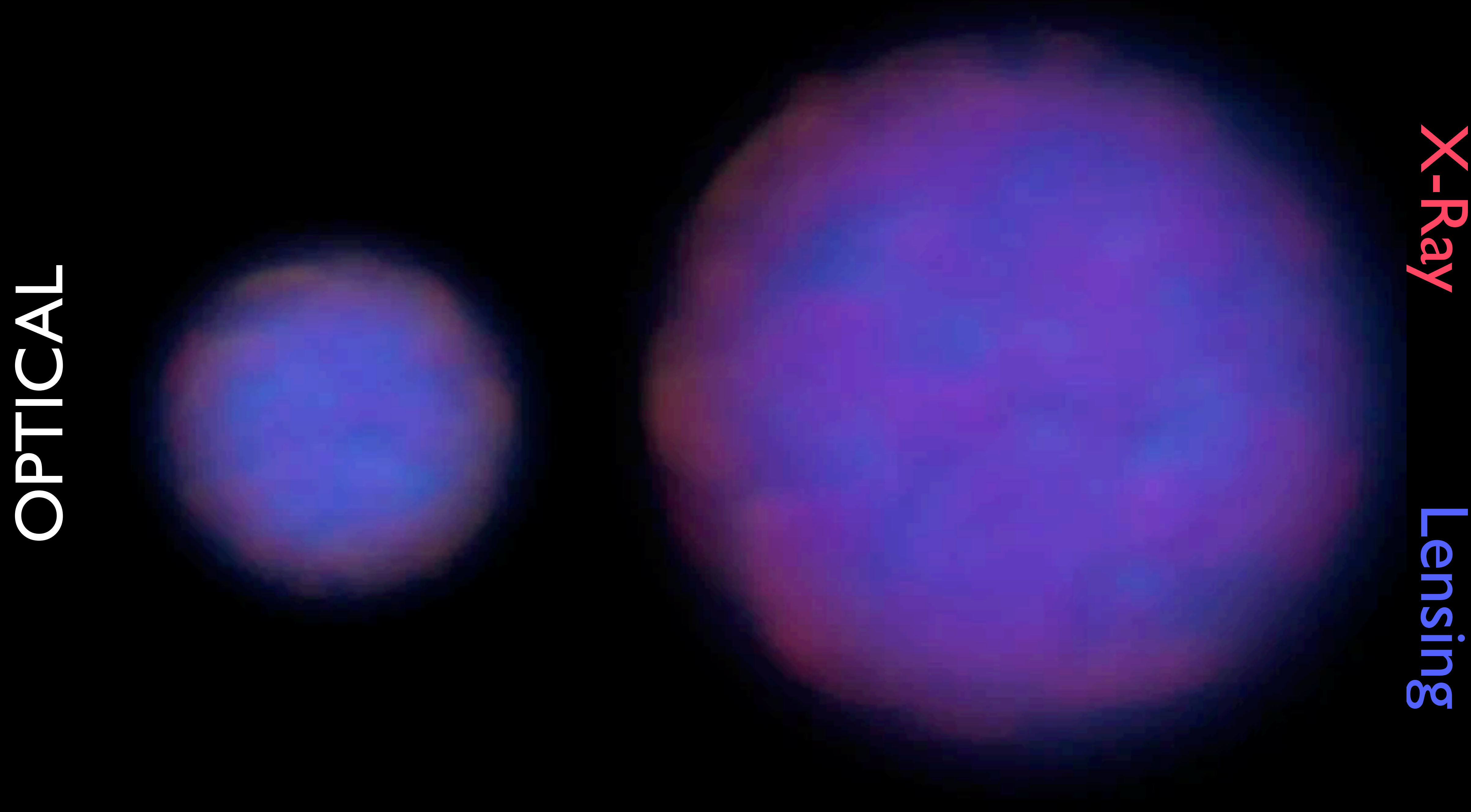

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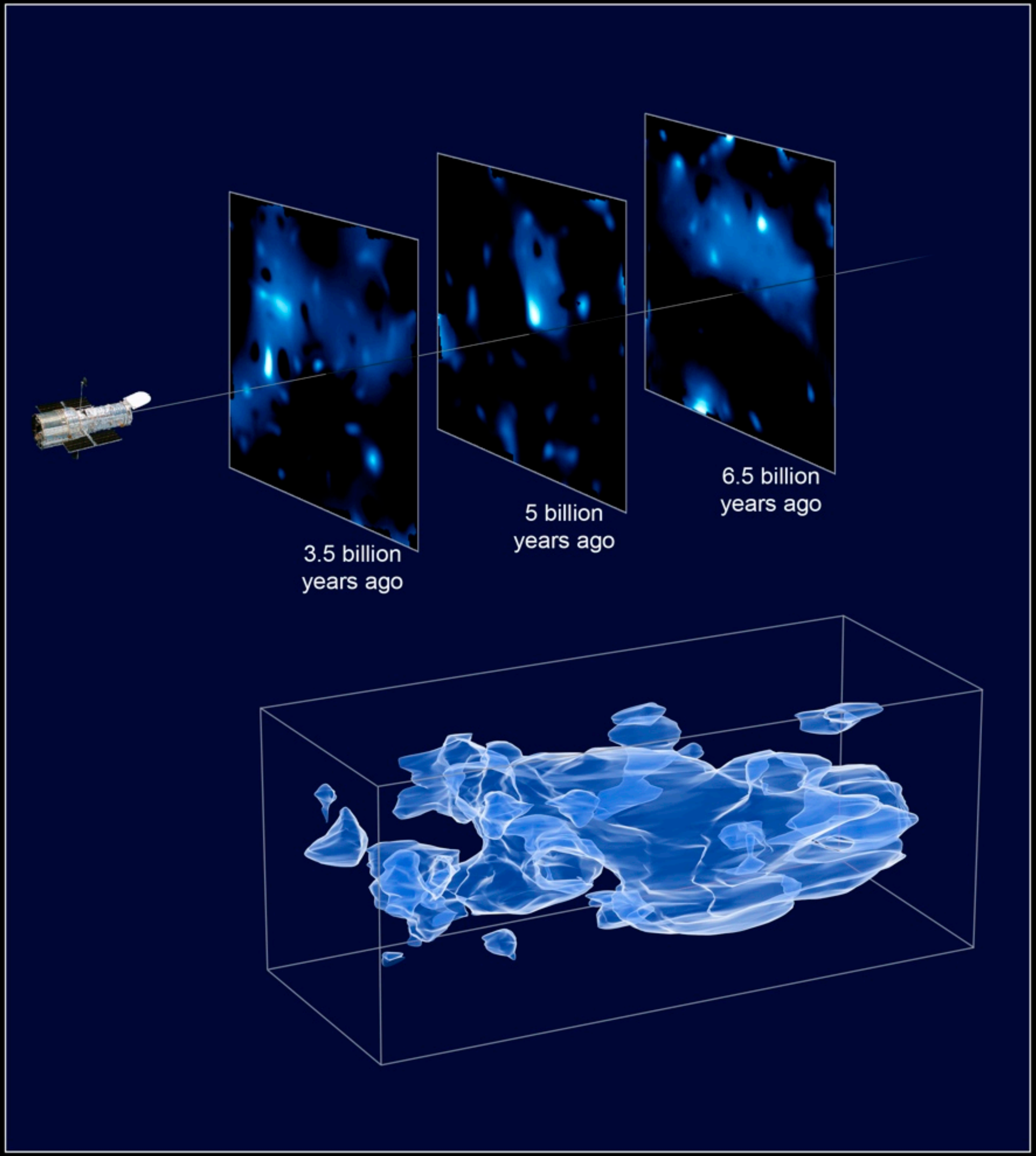
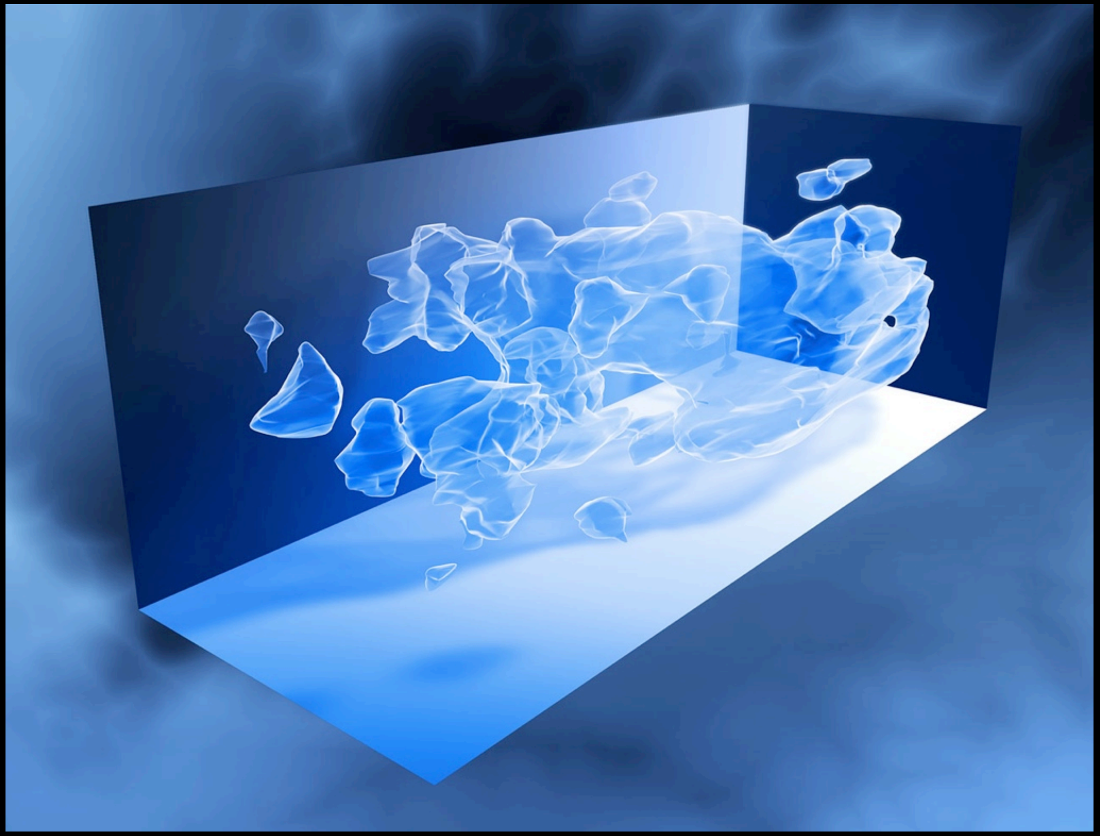
Distribution of Dark Matter

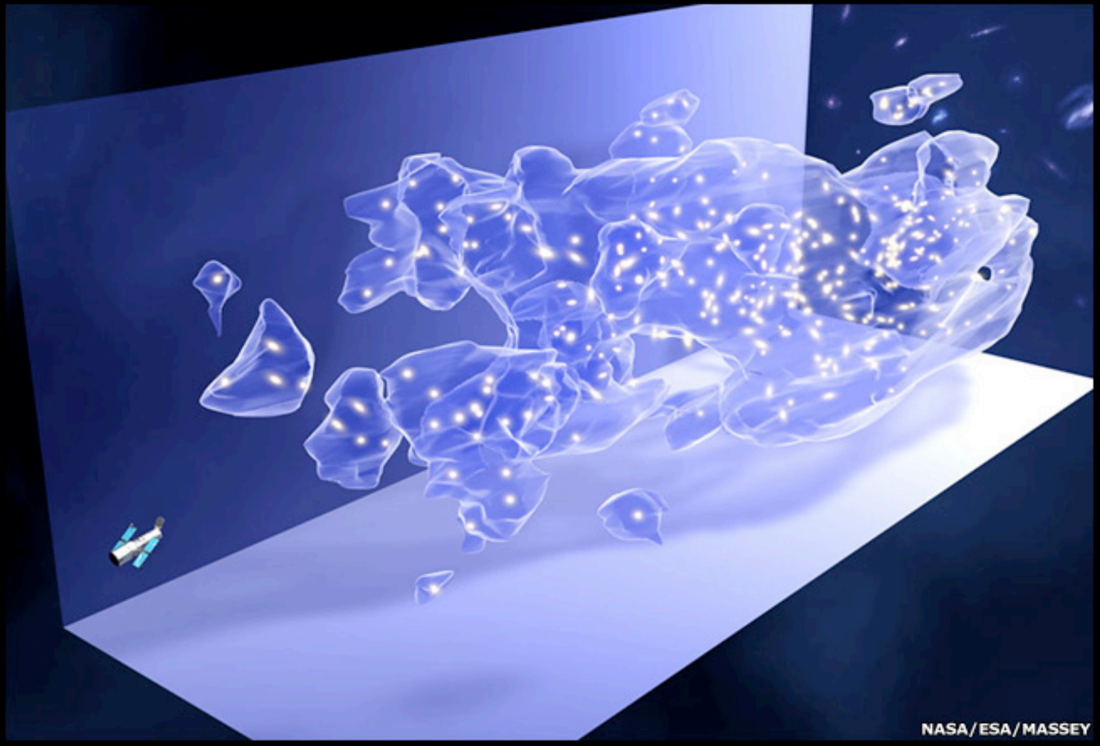
HST ▪ ACS/WFC



NASA, ESA, and R. Massey (California Institute of Technology)

STScI-PRC07-01a





Are we sure we are counting everything?

THE ASTROPHYSICAL JOURNAL, **284**:439–444, 1984 September 15

TESTS OF COSMOLOGICAL MODELS CONSTRAINED BY INFLATION

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University
Received 1984 February 6; accepted 1984 March 23

ABSTRACT

The inflationary scenario requires that the universe have negligible curvature along constant-density surfaces. In the Friedmann-Lemaître cosmology that leaves us with two free parameters, Hubble's constant H_0 and the density parameter Ω_0 (or, equivalently, the cosmological constant Λ). I discuss here tests of this set of models from local and high-redshift observations. The data agree reasonably well with $\Omega_0 \sim 0.2$.

Are we sure we are counting everything?

THE ASTROPHYSICAL JOURNAL, **325**:L17–L20, 1988 February 15

COSMOLOGY WITH A TIME-VARIABLE COSMOLOGICAL "CONSTANT"

P. J. E. PEEBLES AND BHARAT RATRA
Joseph Henry Laboratories, Princeton University
Received 1987 October 20; accepted 1987 November 23

ABSTRACT

If the potential $V(\phi)$ of the scalar field that drove inflation had a power-law tail at large ϕ, $V \approx \phi^{-\alpha}$, the mass density, ρ_ϕ, associated with ϕ would act like a cosmological constant that decreases with time less rapidly than the mass densities of matter and radiation. If ρ_ϕ were appreciable at the present epoch it could help reconcile the low dynamical estimates of the mean mass density with the negligibly small space curvature preferred by inflation.

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THE ASTROPHYSICAL JOURNAL, **325**:L17–L20, 1988 February 15

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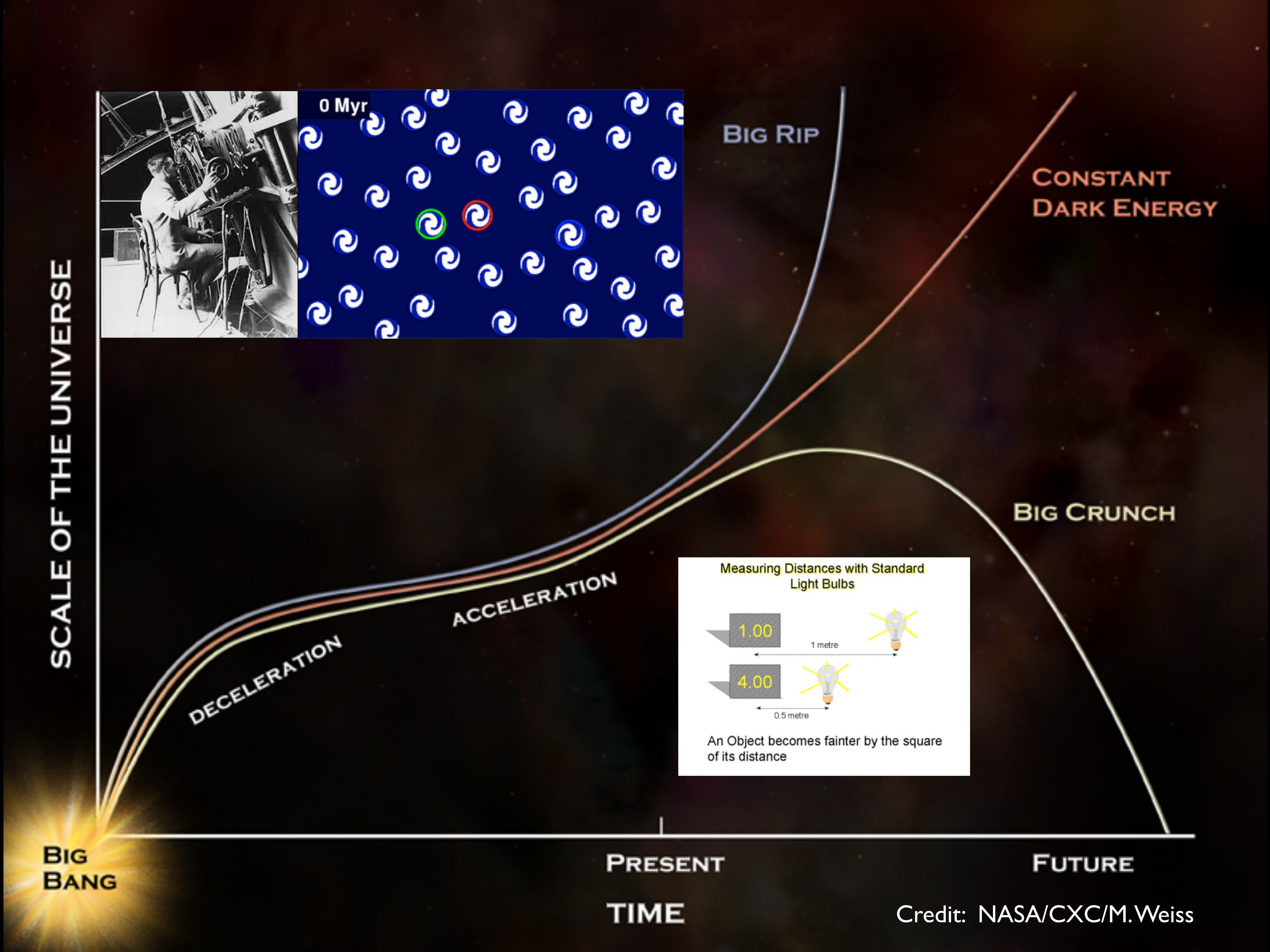
Are we sure we are counting everything?

PHYSICAL REVIEW D **VOLUME 37, NUMBER 12** **15 JUNE 1988**

Cosmological consequences of a rolling homogeneous scalar field

Bharat Ratra and P. J. E. Peebles
Joseph Henry Laboratories, Department of Physics, Princeton University, Princeton, New Jersey 08544
(Received 16 February 1988)

The cosmological consequences of a pervasive, rolling, self-interacting, homogeneous scalar field are investigated. A number of models in which the energy density of the scalar field red-shifts in a specific manner are studied. In these models the current epoch is chosen to be scalar-field dominated to agree with dynamical estimates of the density parameter, $\Omega_{\mathrm{dyn}} \sim 0.2$, and zero spatial curvature. The required scalar-field potential is "nonlinear" and decreases in magnitude as the value of the scalar field increases. A special solution of the field equations which is an attractive, time-dependent, fixed point is presented. These models are consistent with the classical tests of gravitation theory. The Eötvös-Dicke measurements strongly constrain the coupling of the scalar field to light (nongravitational) fields. Nucleosynthesis proceeds as in the standard hot big-bang model. In linear perturbation theory the behavior of baryonic perturbations, in the baryon-dominated epoch, do not differ significantly from the canonical scenario, while the presence of a substantial amount of homogeneous scalar-field energy density at low red-shifts inhibits the growth of perturbations in the baryonic fluid. The energy density in the scalar field is not appreciably perturbed by nonrelativistic gravitational fields, either in the radiation-dominated, matter-dominated, or scalar-field-dominated epochs. On the basis of this effect, we argue that these models could reconcile the low dynamical estimates of the mean mass density with the negligibly small spatial curvature preferred by inflation.


0 Myr
Big Rip
Constant
Dark Energy
Big Crunch
Scale of the Universe
Deceleration
Acceleration
Measuring Distances with Standard
Light Bulbs
1.00
1 metre
4.00
0.5 metre
An Object becomes fainter by the square
of its distance
Big
Bang
Present
Future
Time
Credit: NASA/CXC/M.Weiss

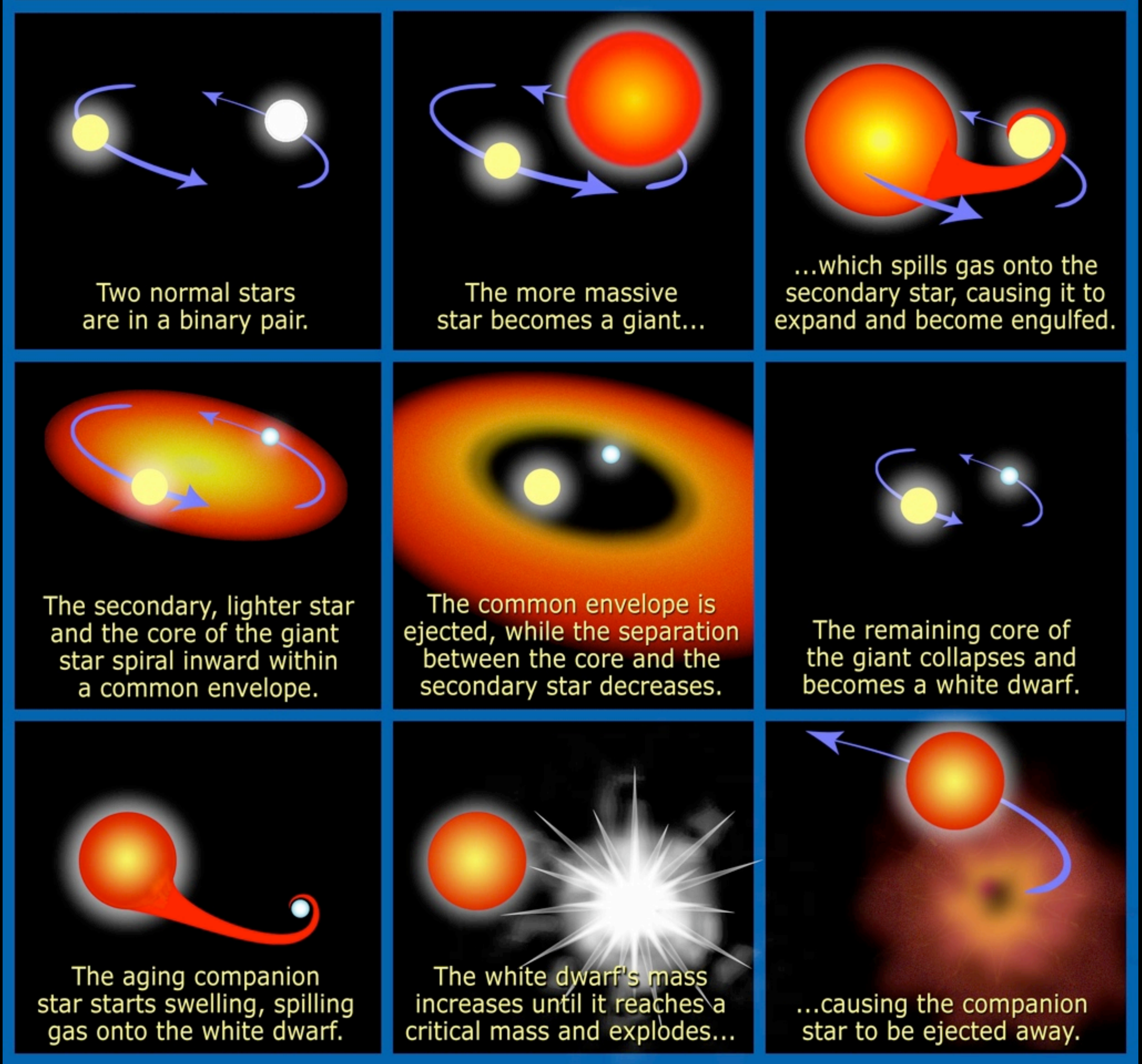


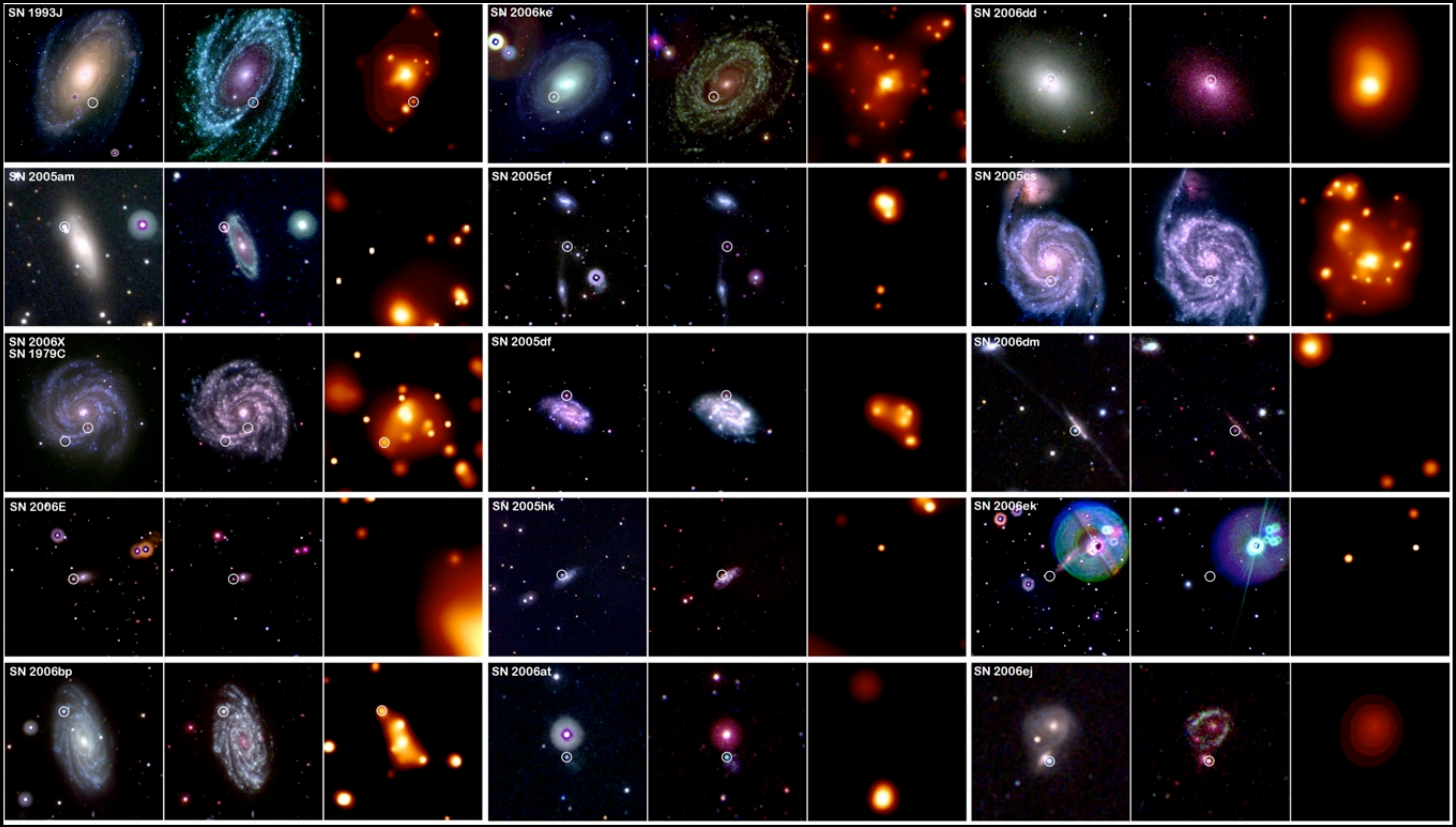
Illustration credit: NASA, ESA, and A. Field (STScI)

SN 1994D in Galaxy NGC 4526

Credit: NASA, ESA, The Hubble Key Project Team
and the Hugh-Z Supernova Search Team

15 Supernovae

Each shown in three wavelengths: Optical, Ultraviolet and X-ray...



Credit: NASA, Swift, S. Immler

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4]
PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2]
B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7]
R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4]
NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]
Received 1998 March 13; revised 1998 May 6

Illustration: John Kascht

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER,[1] G. ALDERING, G. GOLDHABER,[1] R. A. KNOP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3]
A. GOOBAR,[4] D. E. GROOM, I. M. HOOK,[5] A. G. KIM,[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3]
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B. J. BOYLE
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A. V FILIPPENKO AND T. MATHESON
Department of Astronomy, University of California, Berkeley, CA

A. S. FRUCHTER AND N. PANAGIA[9]
Space Telescope Science Institute, Baltimore, MD

H. J. M. NEWBERG
Fermi National Laboratory, Batavia, IL

AND

W. J. COUCH
University of New South Wales, Sydney, Australia

(THE SUPERNOVA COSMOLOGY PROJECT)
Received 1998 September 8; accepted 1998 December 17

The Astrophysical Journal, 607:665–687, 2004 June 1
Ⓔ

TYPE Ia SUPERNOVA DISCOVERIES AT $z > 1$ FROM THE *HUBBLE SPACE TELESCOPE*: EVIDENCE FOR PAST DECELERATION AND CONSTRAINTS ON DARK ENERGY EVOLUTION[1]

Adam G. Riess,[2] Louis-Gregory Strolger,[2] John Tonry,[3] Stefano Casertano,[2] Henry C. Ferguson,[2] Bahram Mobasher,[2]
Peter Challis,[4] Alexei V. Filippenko,[5] Saurabh Jha,[5] Weidong Li,[5] Ryan Chornock,[5] Robert P. Kirshner,[4]
Bruno Leibundgut,[6] Mark Dickinson,[2] Mario Livio,[2] Mauro Giavalisco,[2]
Charles C. Steidel,[7] Txitxo Benítez,[8] and Zlatan Tsvetanov[8]
Received 2004 January 20; accepted 2004 February 16

The Astrophysical Journal, 607:665–687, 2004 June 1

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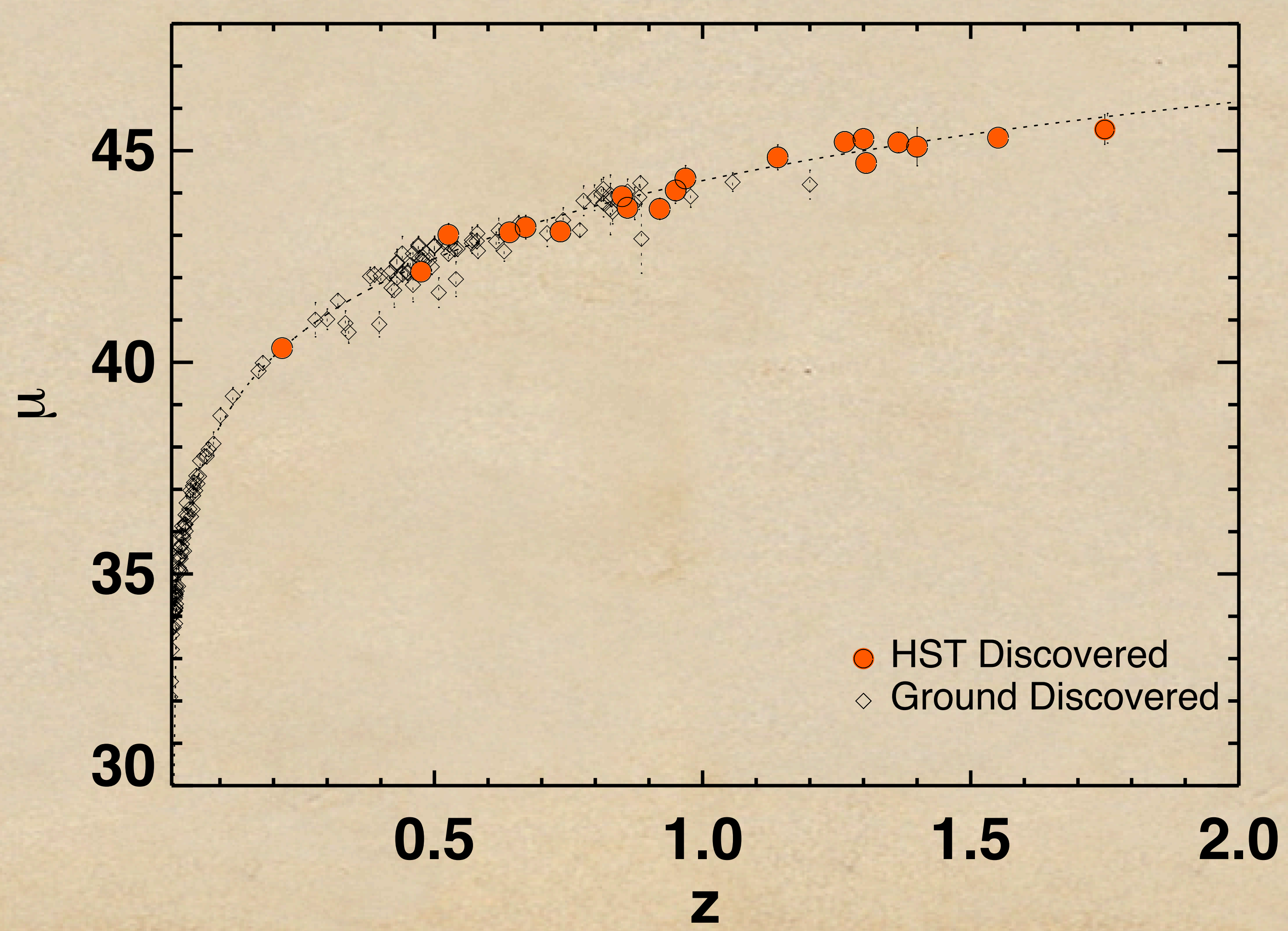

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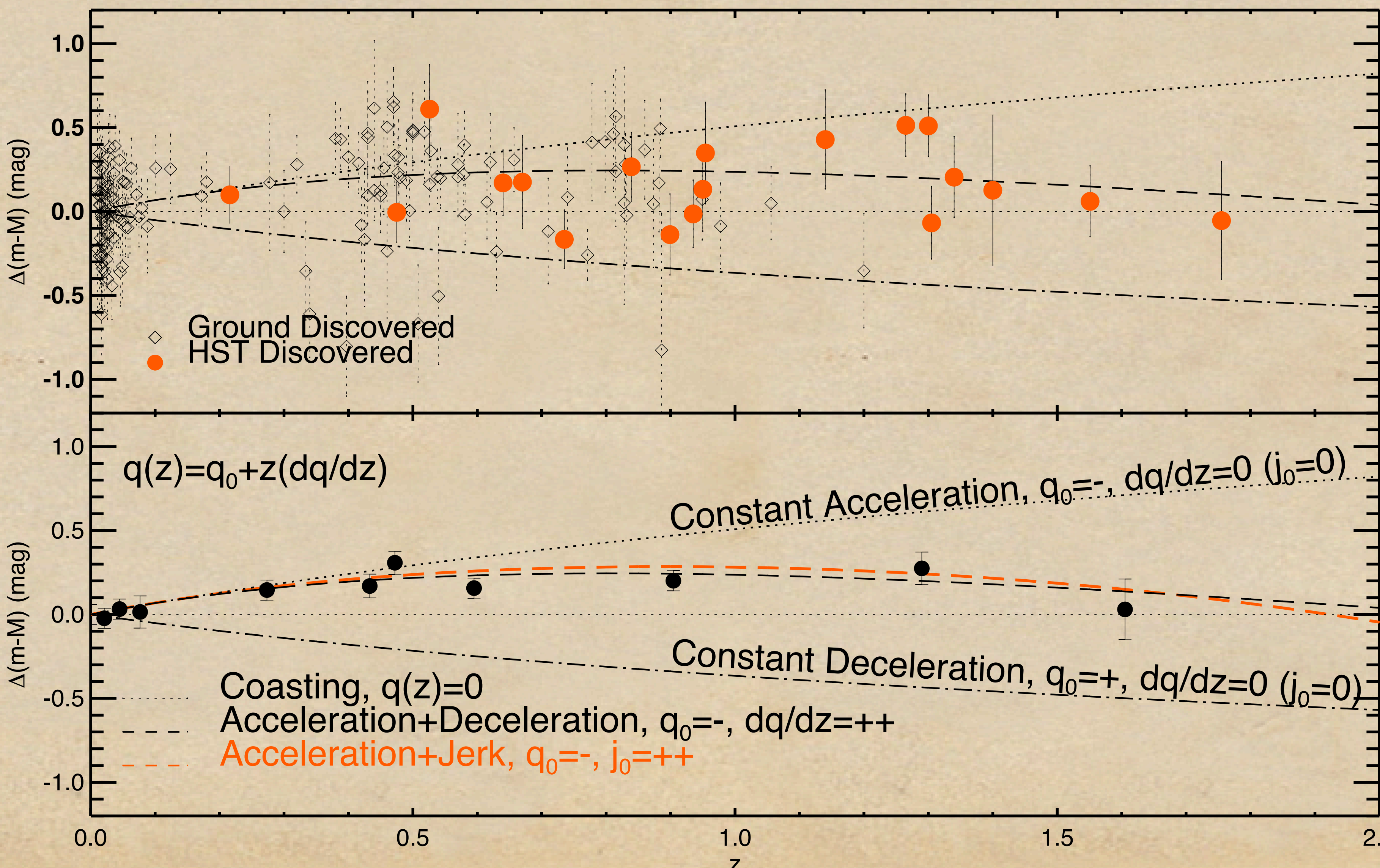
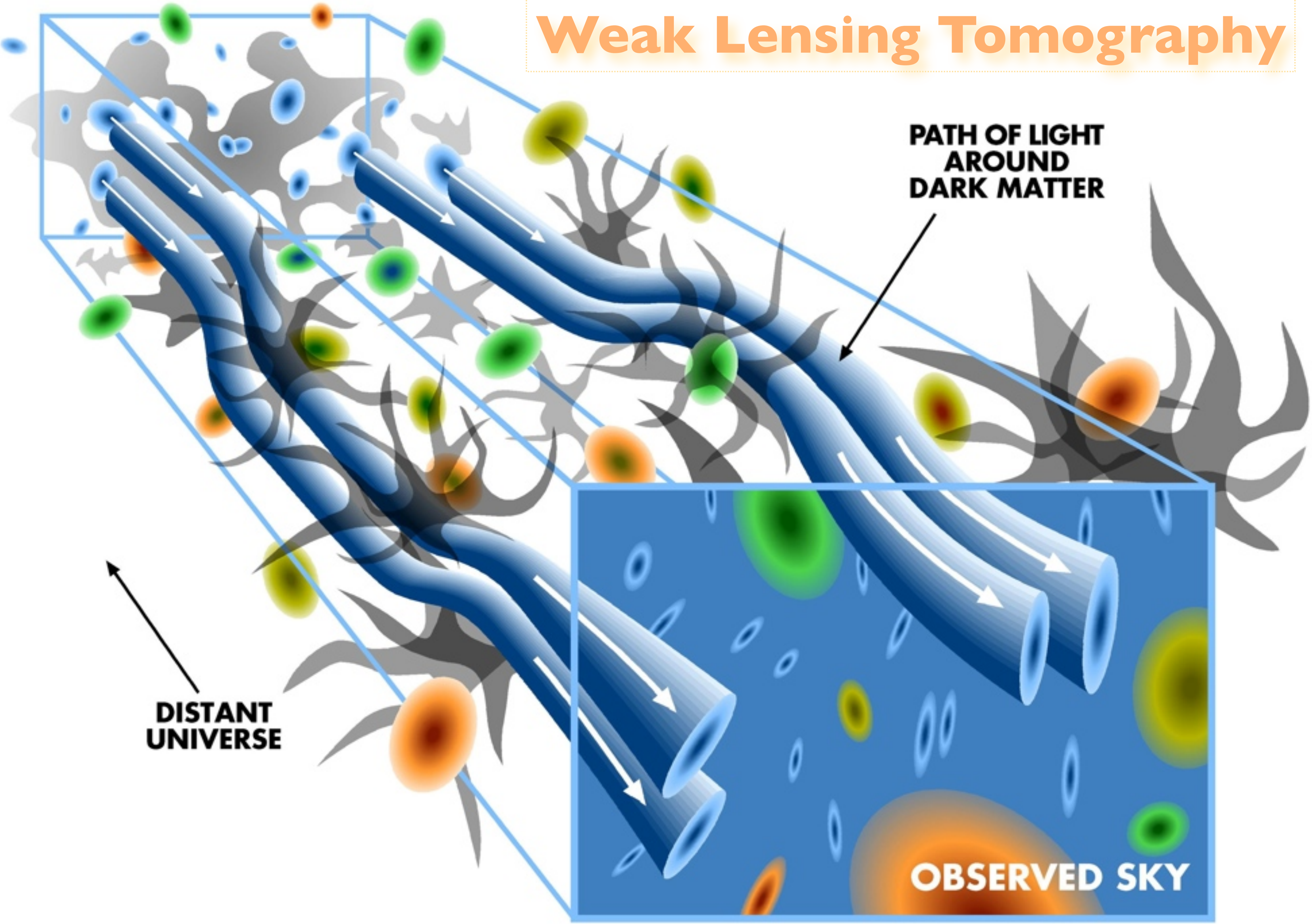
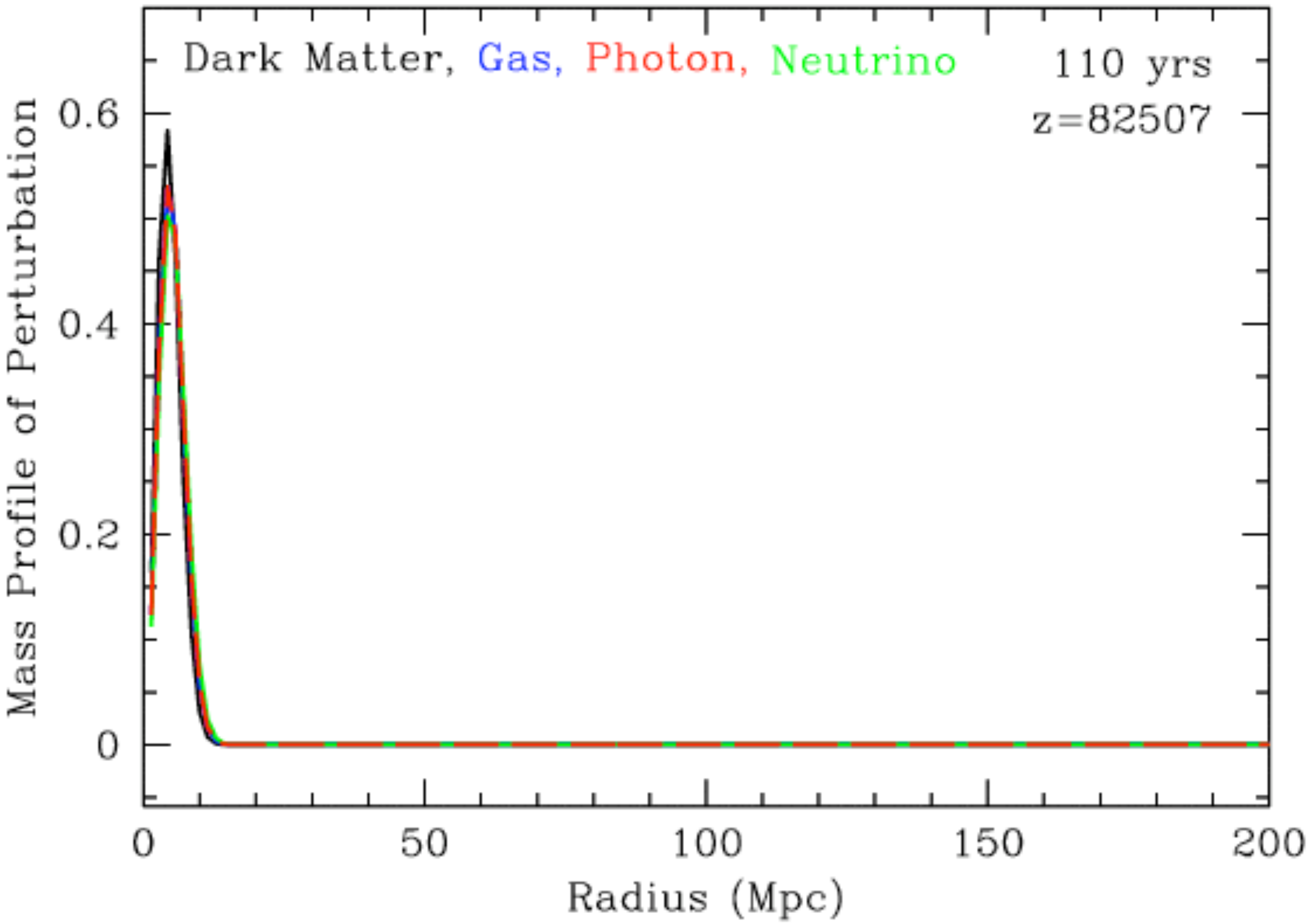


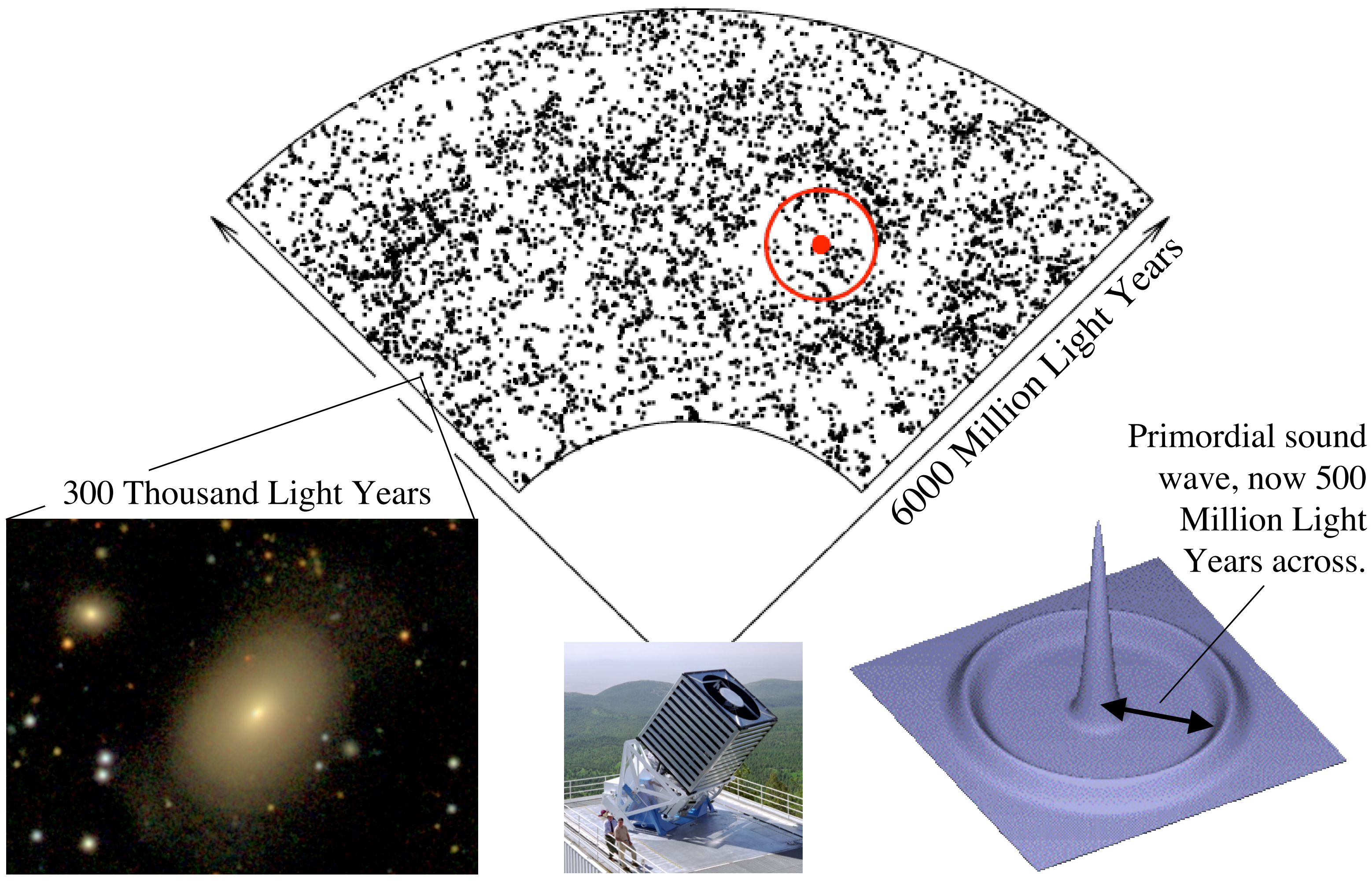
Weak Lensing Tomography



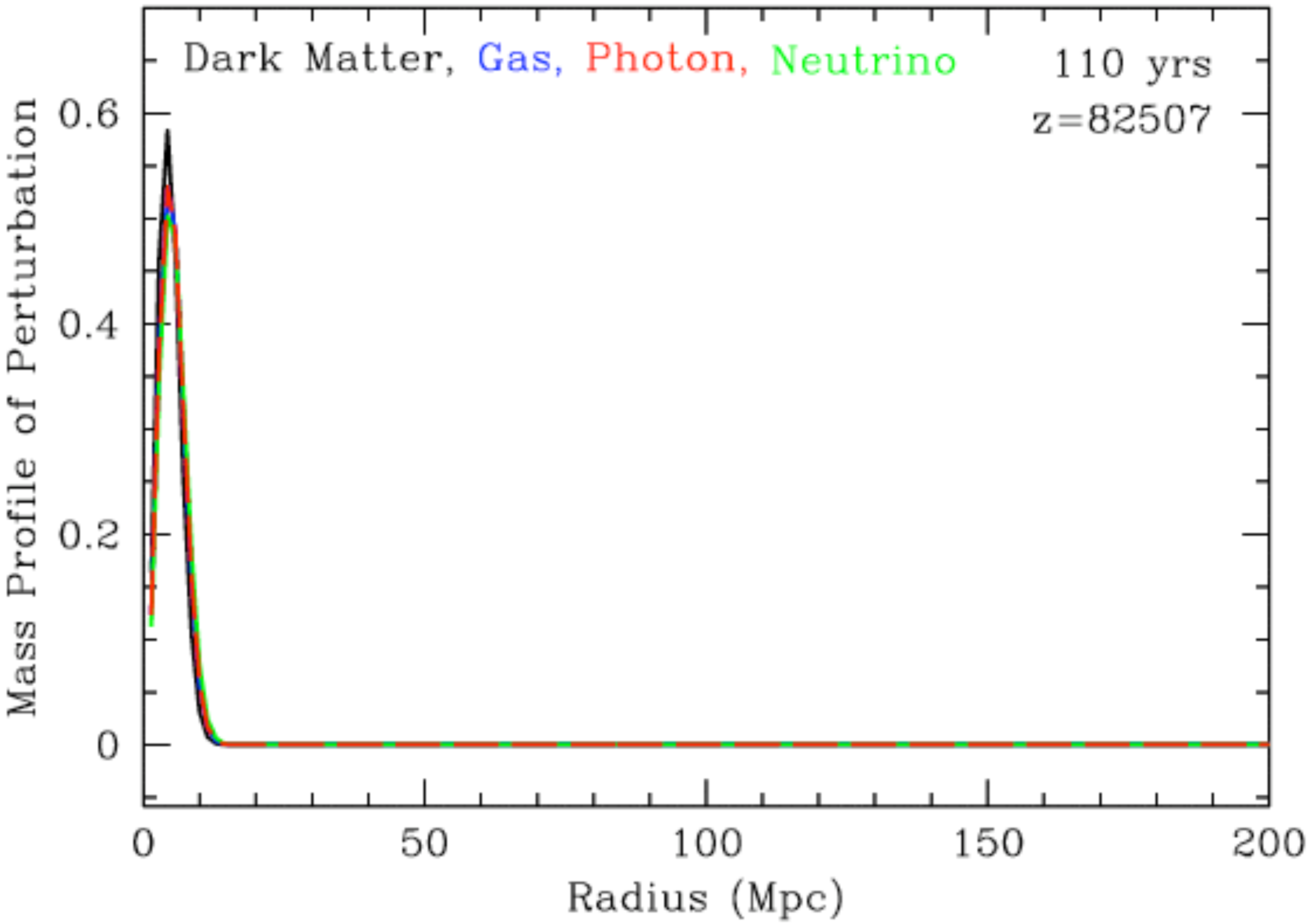
http://www.lsst.org/Science/darkenergy2.shtml



Baryon Acoustic Oscillation (BAO)



Credit: Daniel Eisenstein, Martin White, Sloan Digital Sky Survey



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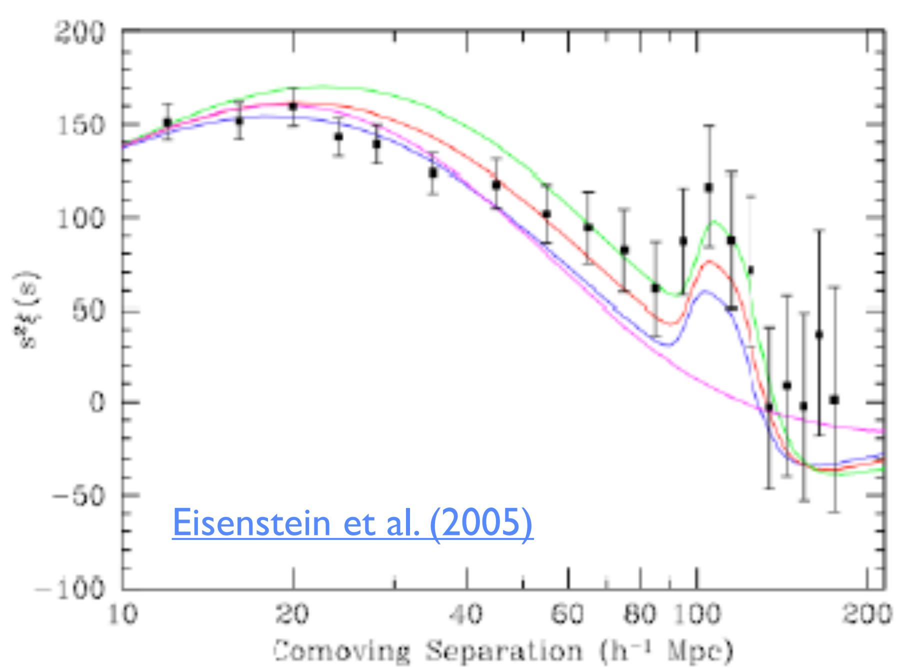

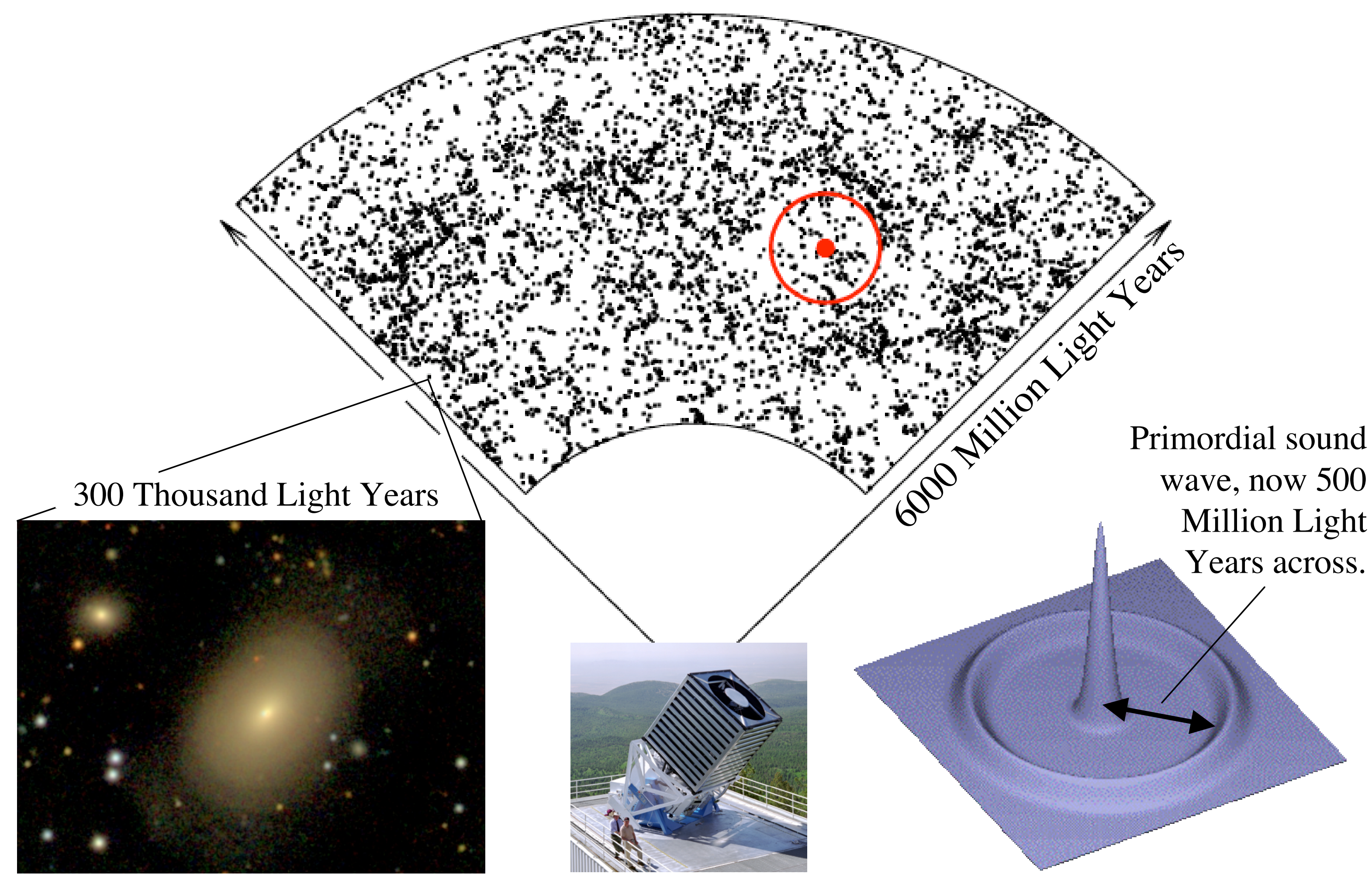

Credit: Daniel Eisenstein, Martin White, Sloan Digital Sky Survey

The Astrophysical Journal, 650: L5–L8, 2006 October 10

COSMOLOGICAL CONSTRAINTS FROM HUBBLE PARAMETER VERSUS REDSHIFT DATA

Lado Samushia and Bharat Ratra
Department of Physics, Kansas State University, 116 Cardwell Hall, Manhattan, KS 66506
Received 2006 July 12; accepted 2006 August 25; published 2006 September 22

ABSTRACT

We use the Simon et al. determination of the redshift dependence of the Hubble parameter to constrain cosmological parameters in three dark energy cosmological models. We consider the standard ΛCDM model, the XCDM parameterization of the dark energy equation of state, and a slowly rolling dark energy scalar field with an inverse power-law potential. The constraints are restrictive, consistent with those derived from Type Ia supernova redshift-magnitude data, and complement those from galaxy cluster gas mass fraction versus redshift data.

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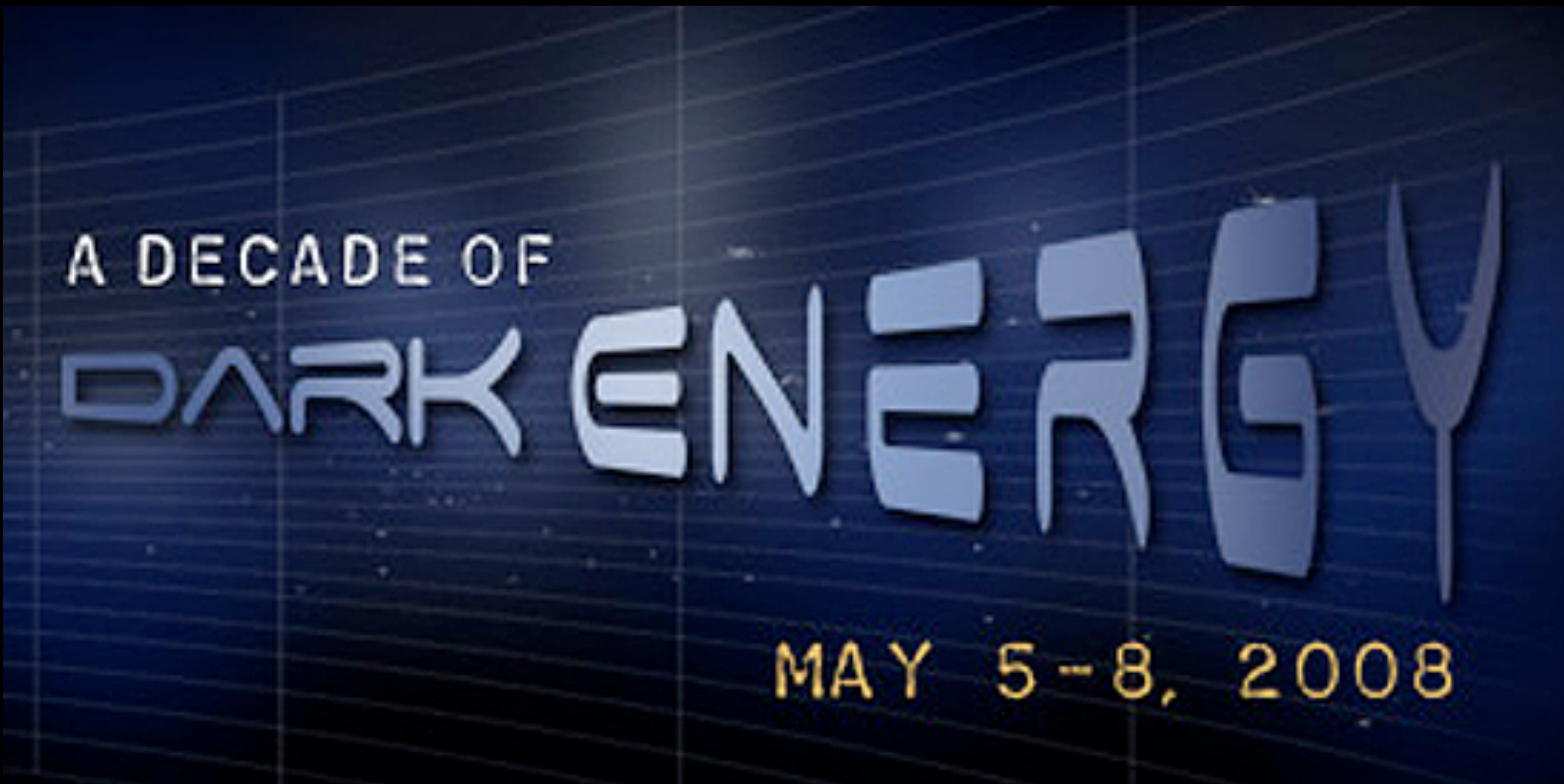
Constraints on dark energy from baryon acoustic peak and galaxy cluster gas mass measurements

Lado Samushia[1,2] and Bharat Ratra[1]

ABSTRACT

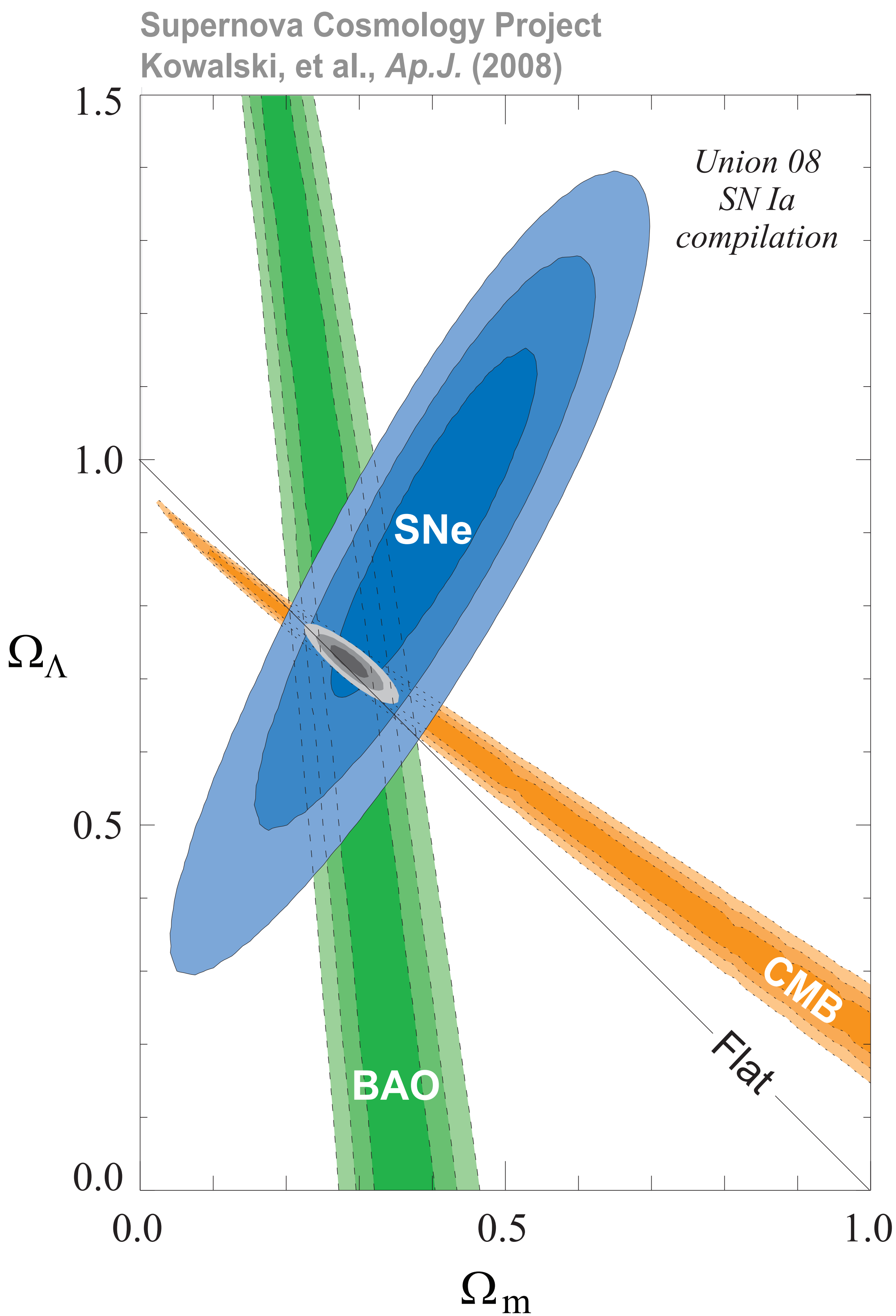
We use baryon acoustic peak measurements by Eisenstein et al. (2005) and Percival et al. (2007a) and galaxy cluster gas mass fraction measurements of Allen et al. (2008) to constrain parameters of three different dark energy mod-

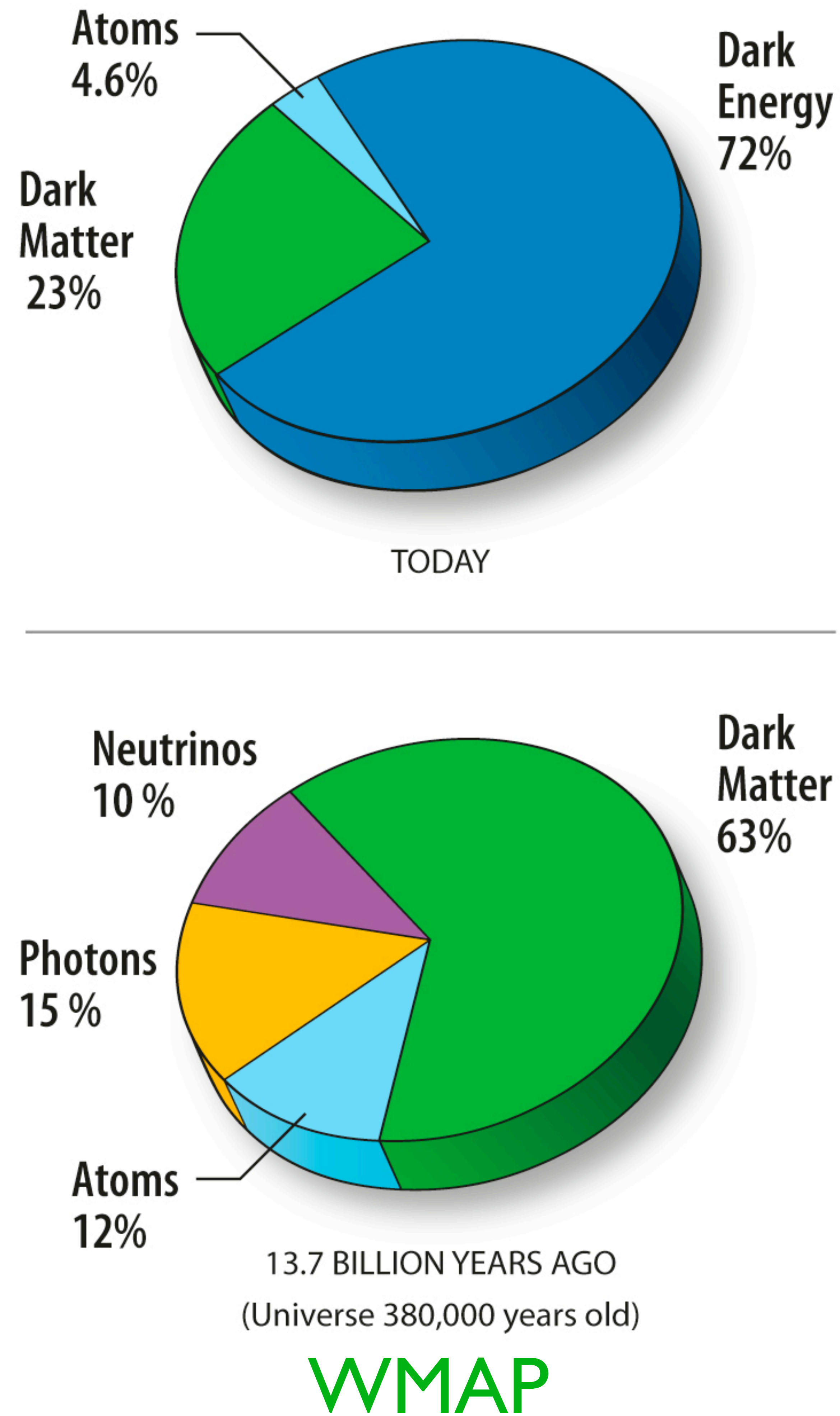
Where Do We Stand?
After...



Space Telescope Science Institute, Baltimore, MD

$$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\text{stat})^{+0.036}_{-0.039}(\text{sys})$$





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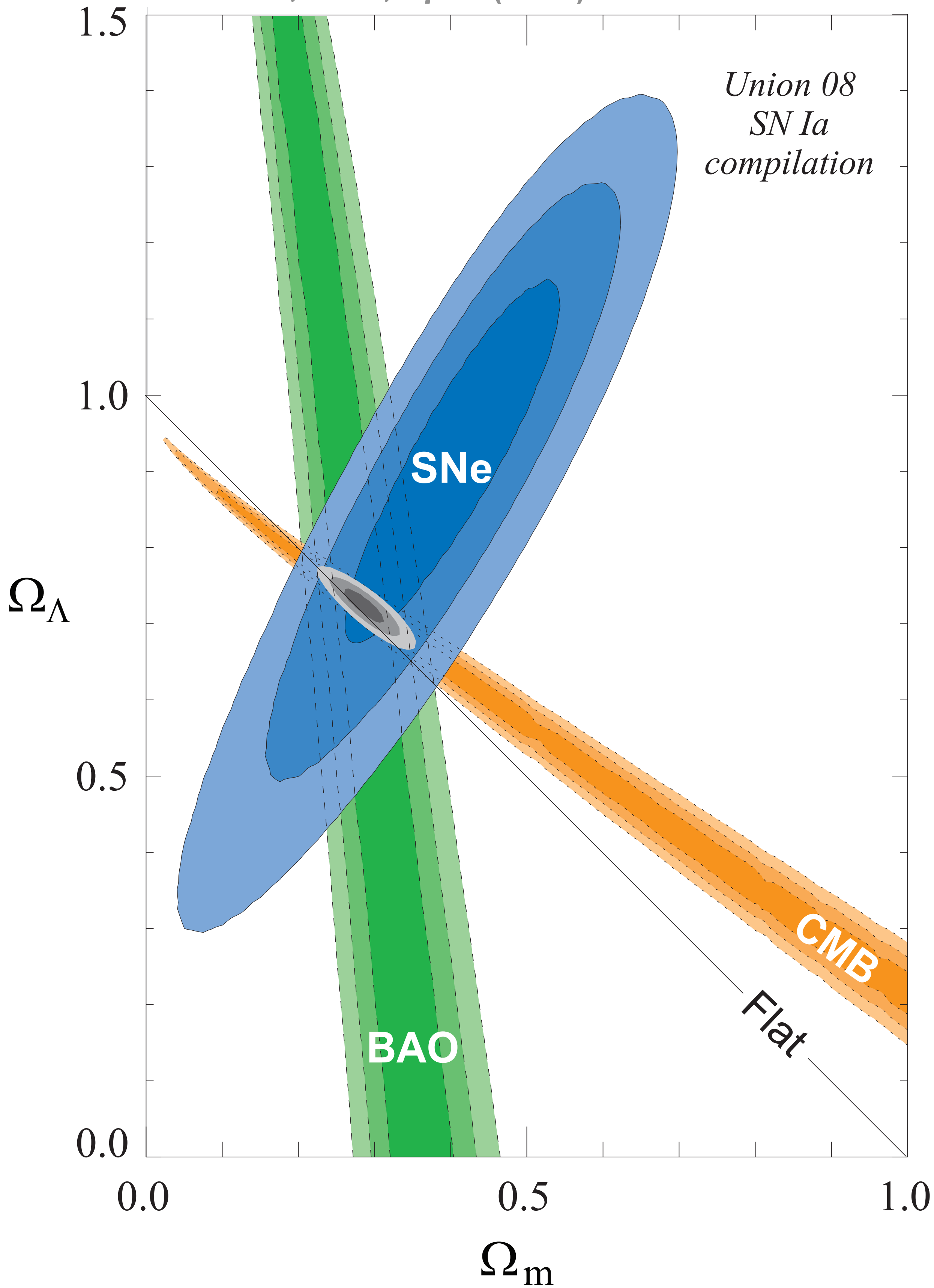
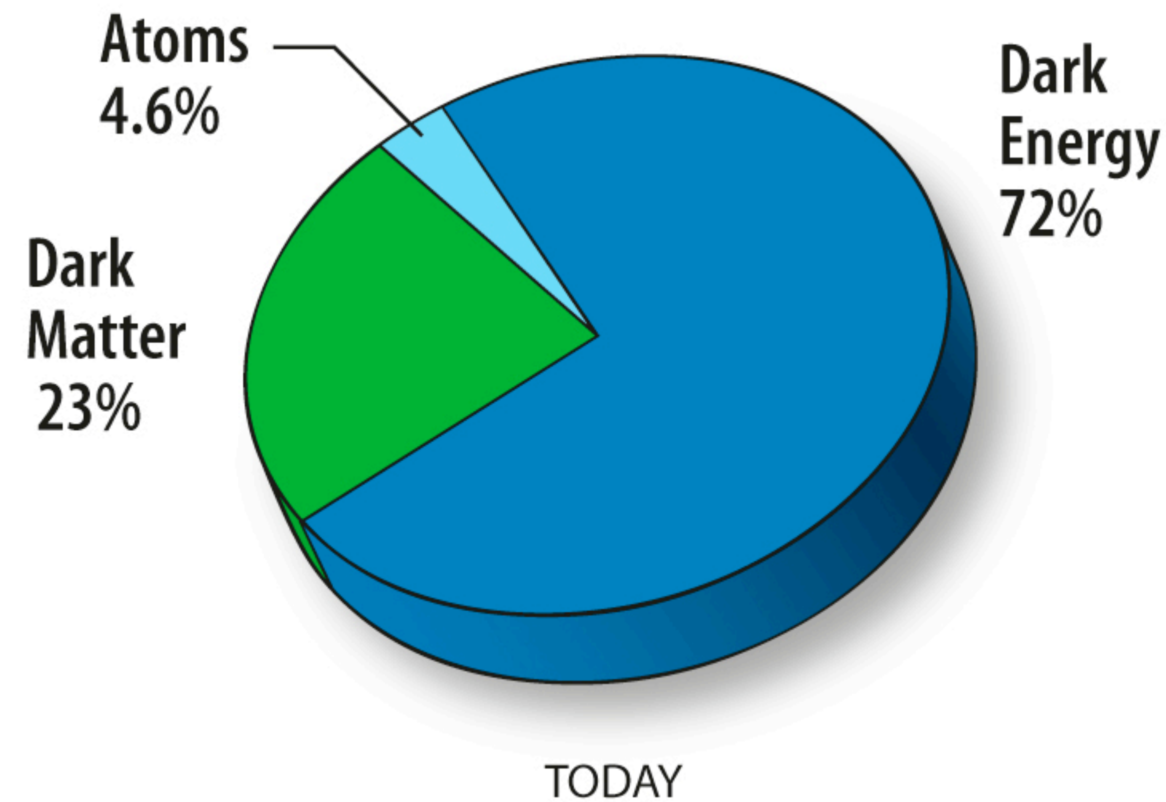
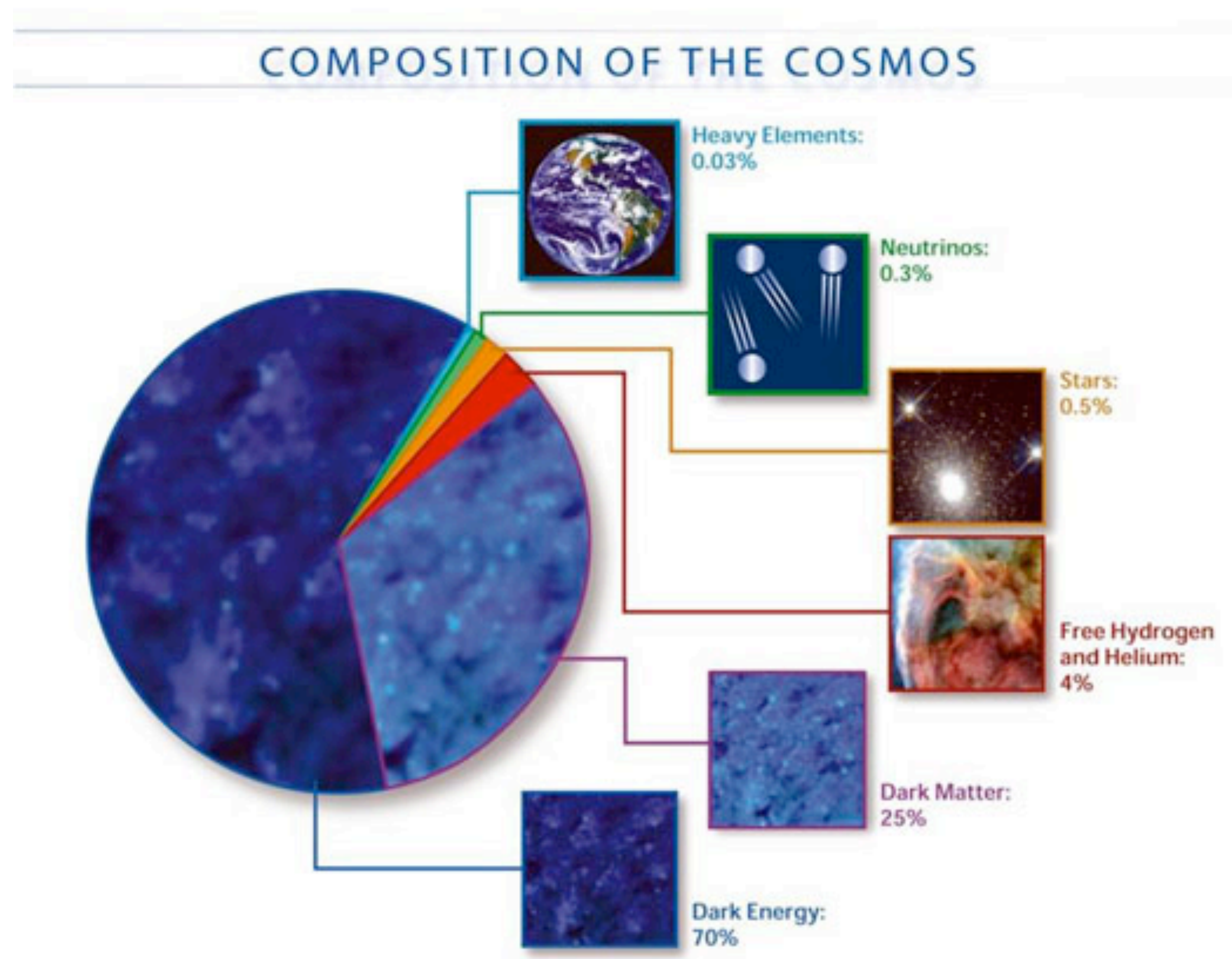
Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)







WMAP

What is Dark Energy?

What is Dark Energy?

"Dark Energy is made from an exclusive blend of vital L-amino acids, beneficial vitamins and bionutrients that allows faster and greater ion penetration of the cell walls, visibly enhancing the rate of growth"

GrowLightSource.com

Cosmic Acceleration

Modified Gravity

Dark Energy

$$H^2 - \boxed{\frac{H}{r_c}} = \frac{8\pi G}{3}(\rho + \rho_V)$$

Modification of Friedmann equation (5D Gravity)

Phenomenological modification to the GR Lagrangian

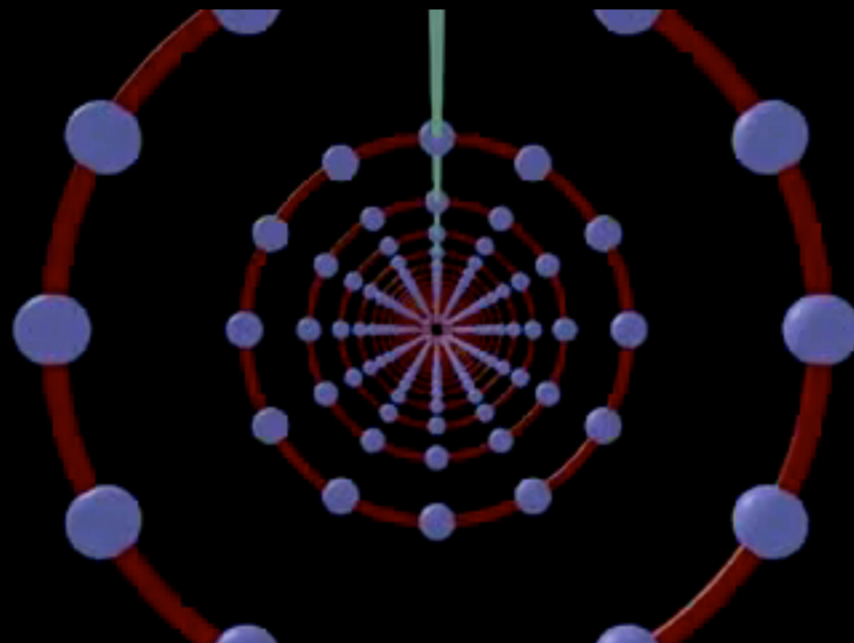
Vacuum Energy (Cosmological Constant)

Scalar Fields
Evolving Equation of State

New Physics/Surprises?

Credit: NASA/STScI/G. Bacon

Gravitational Waves



Credit: Michael
Penn State Schuylkill

Gravitational Waves

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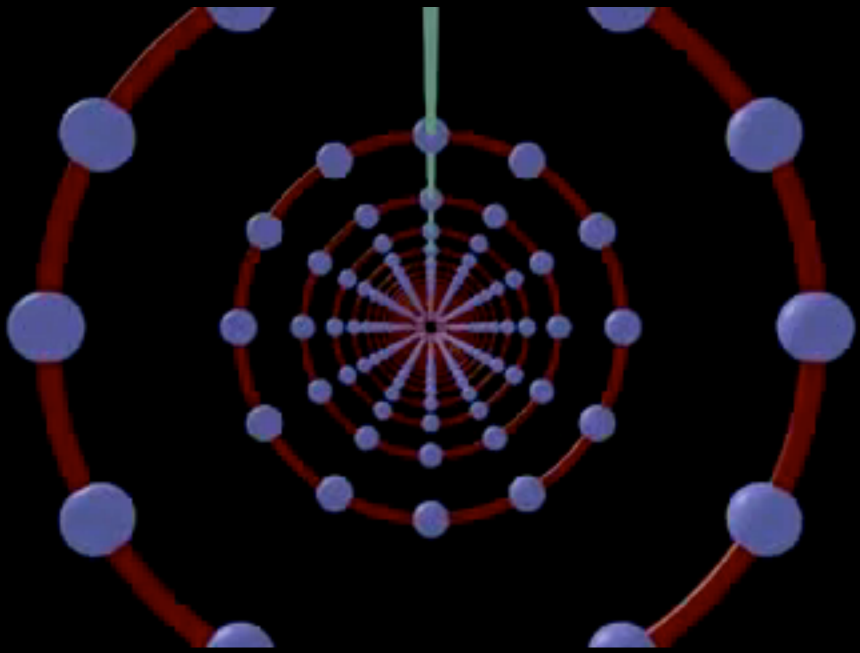
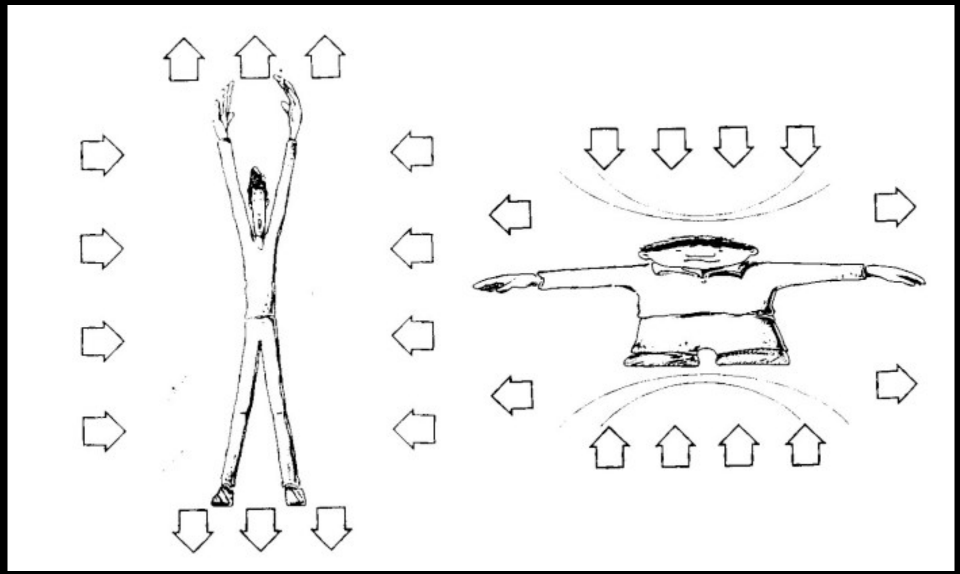
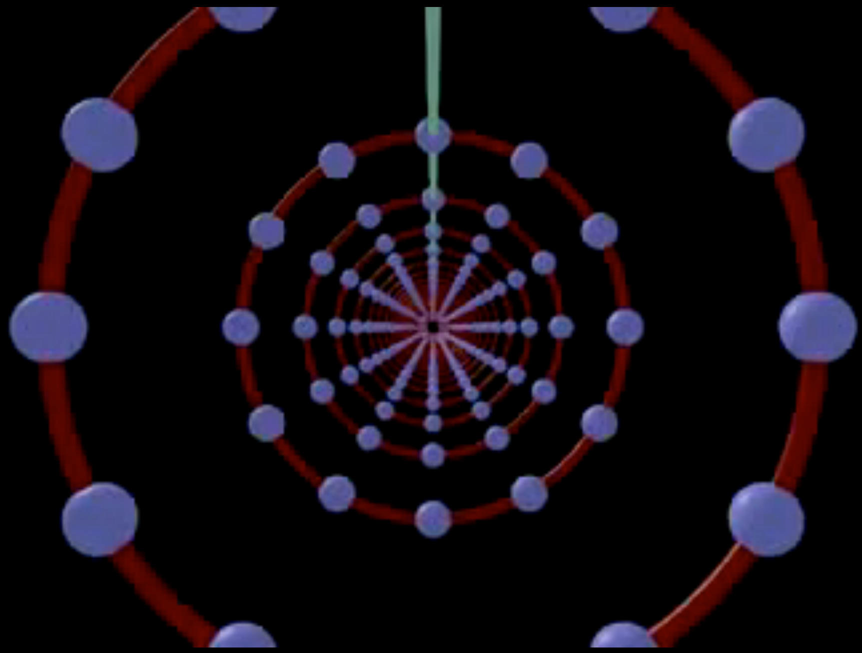




credit: http://www.lnl.infn.it/~auriga/

Gravitational Waves

Credit: Michael
Penn State Schuylkill



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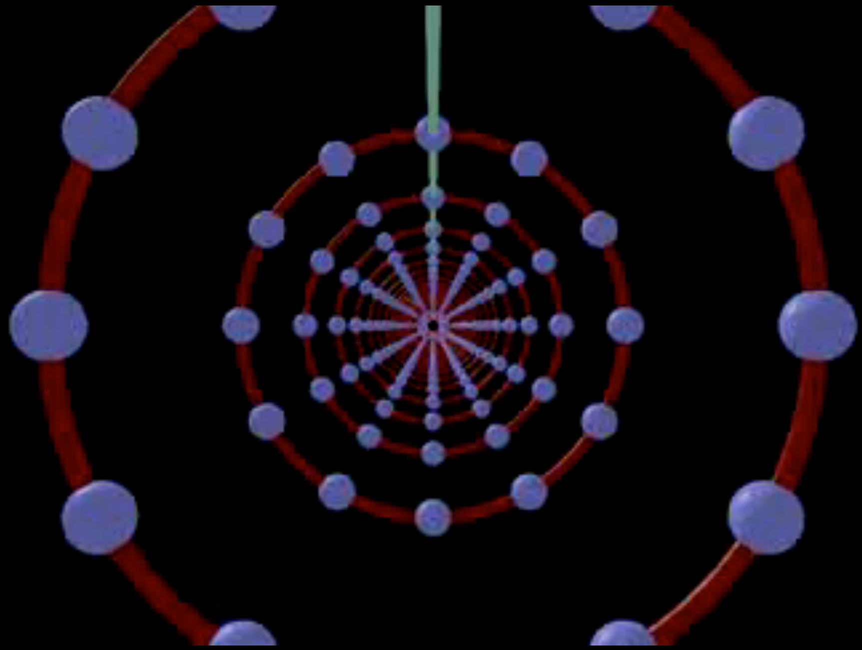

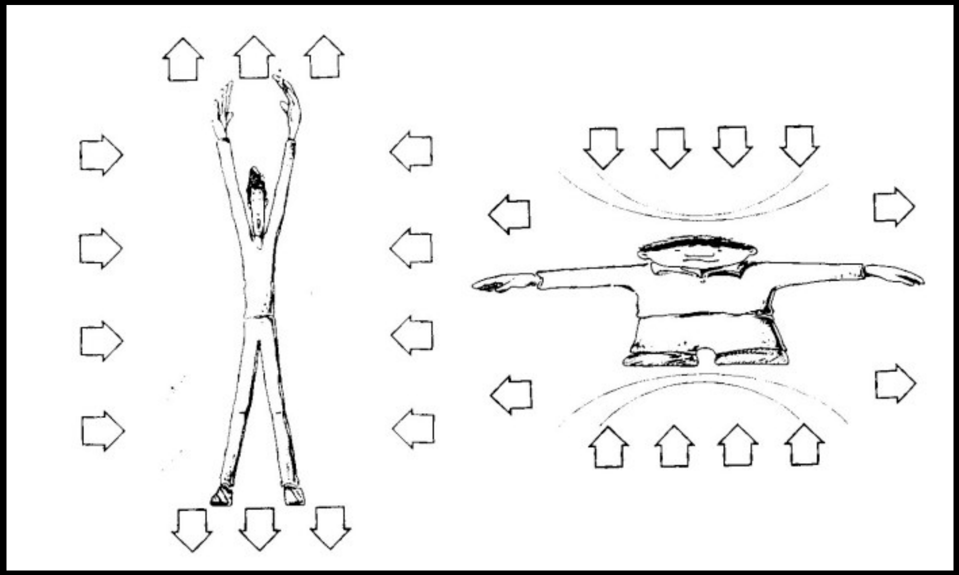

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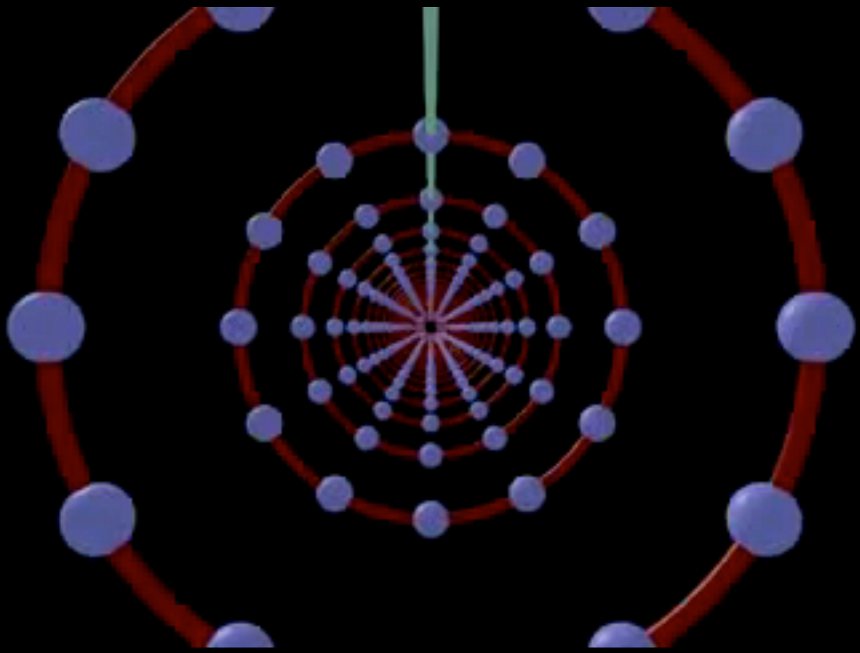

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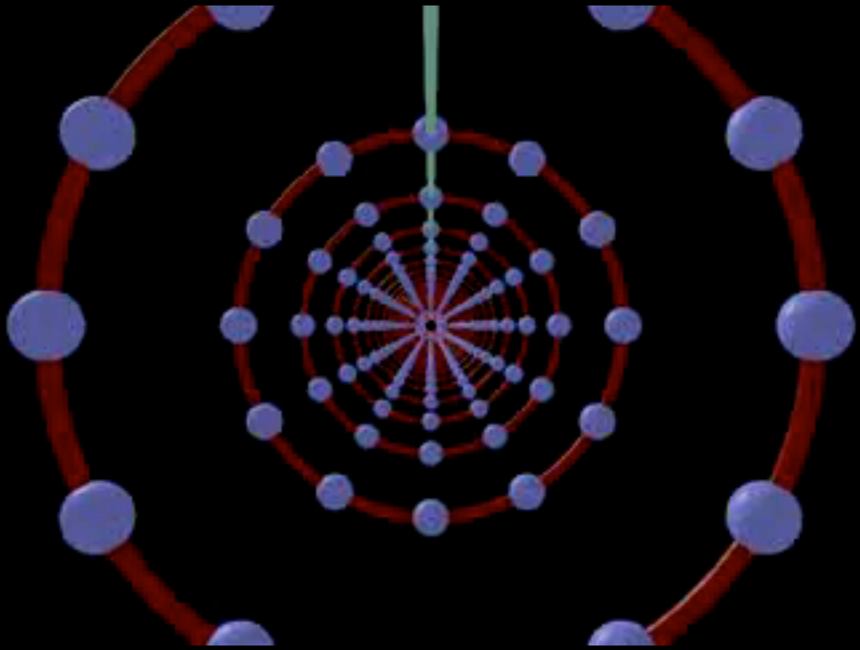

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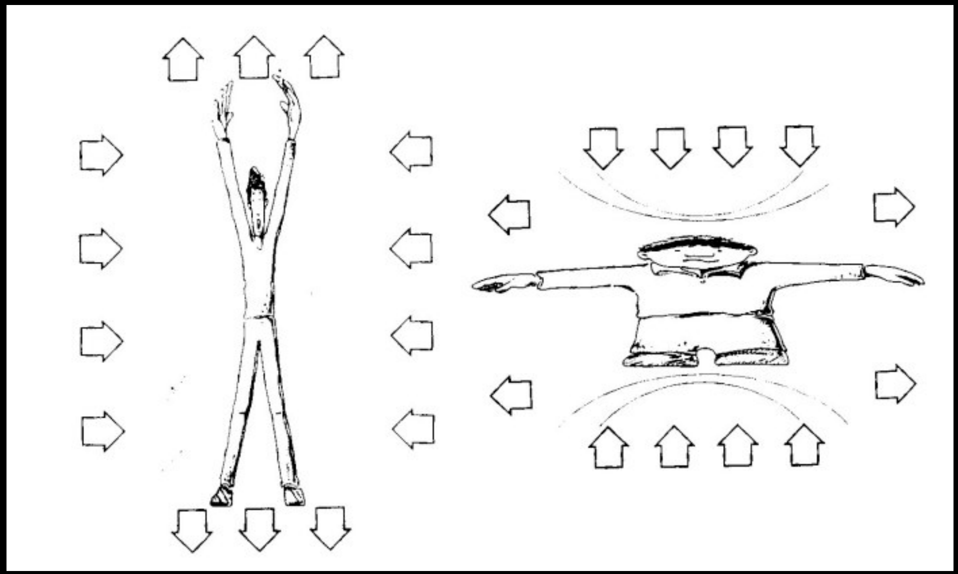
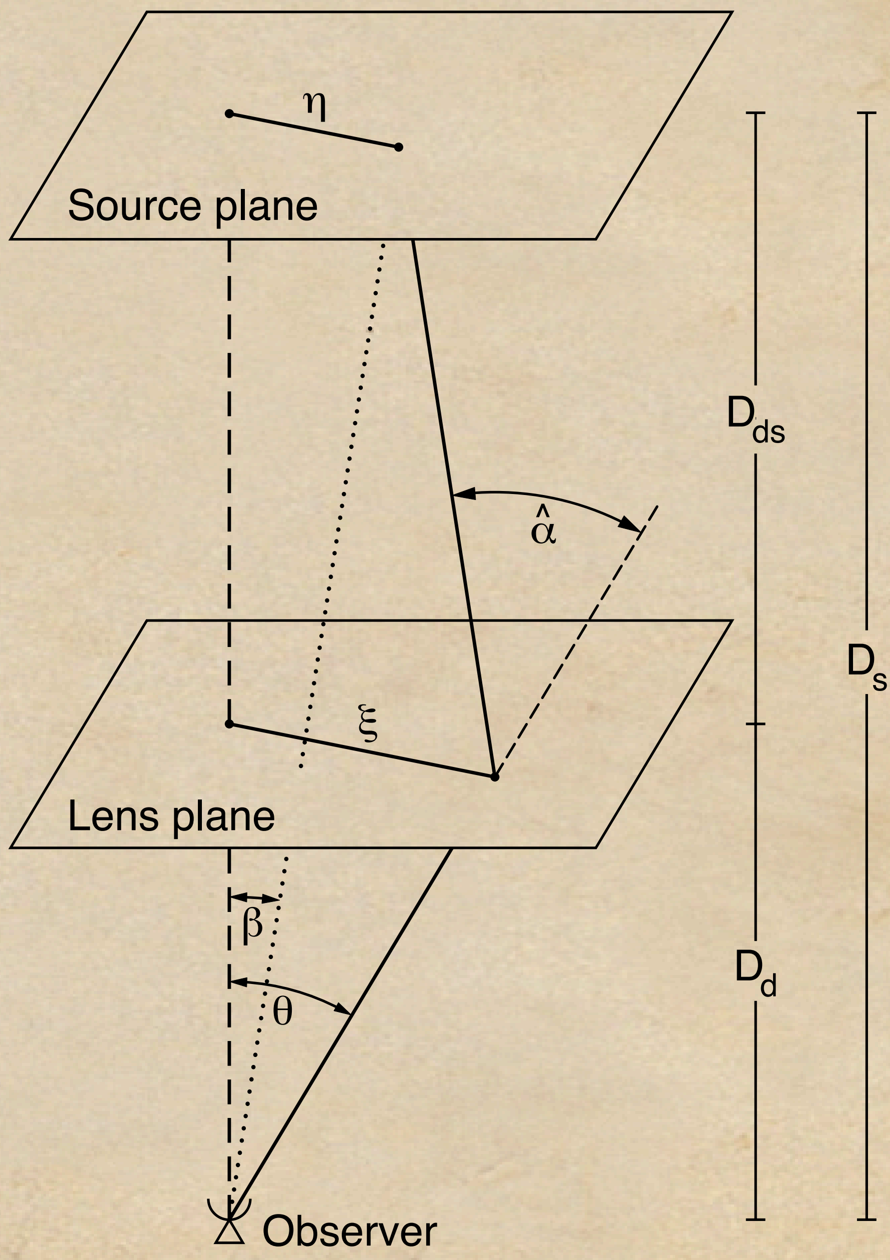


credit: http://www.lnl.infn.it/~auriga/

Gravitational Lensing 201

The Deflection:

$$\boxed{\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})}$$



Credit: Bartelmann and Schneider 2001

Gravitational Lensing 201

The Deflection:

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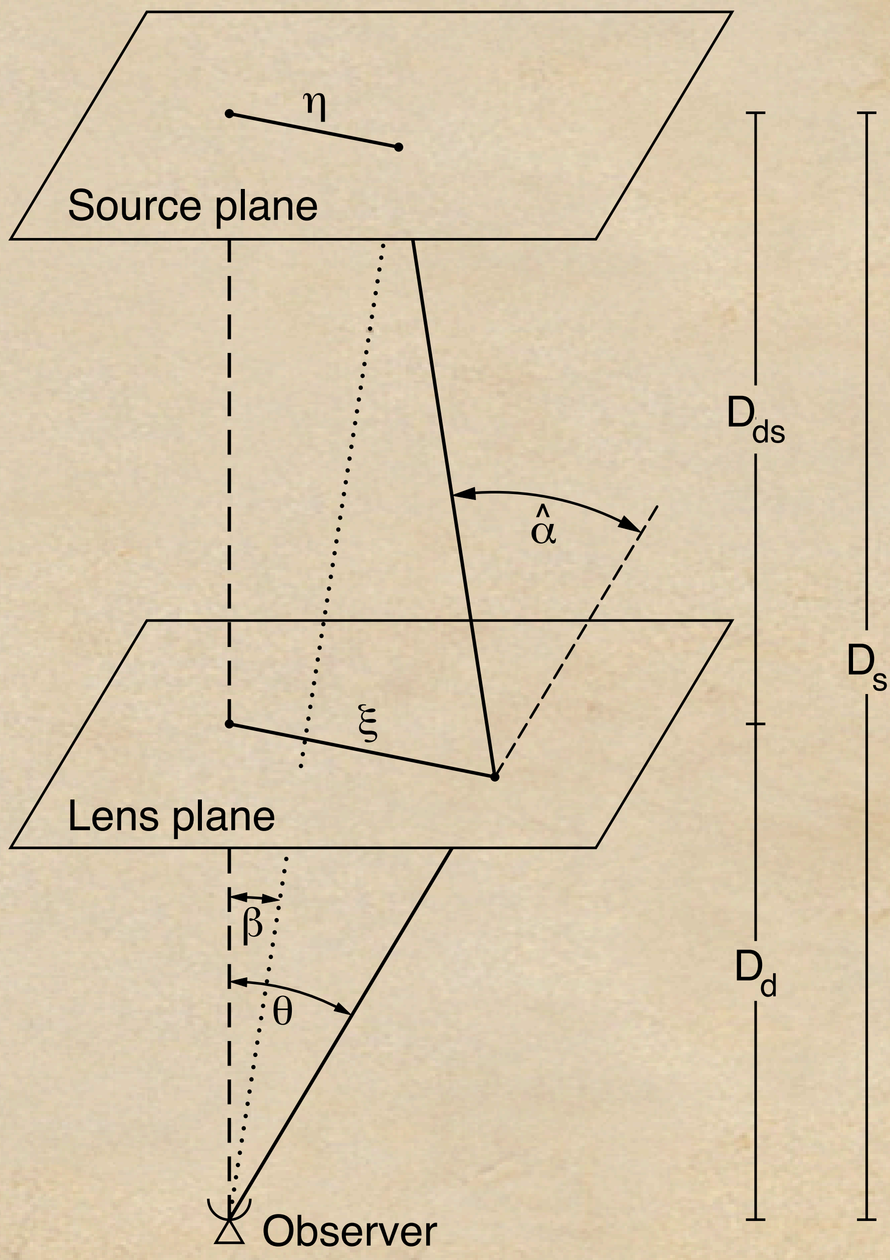

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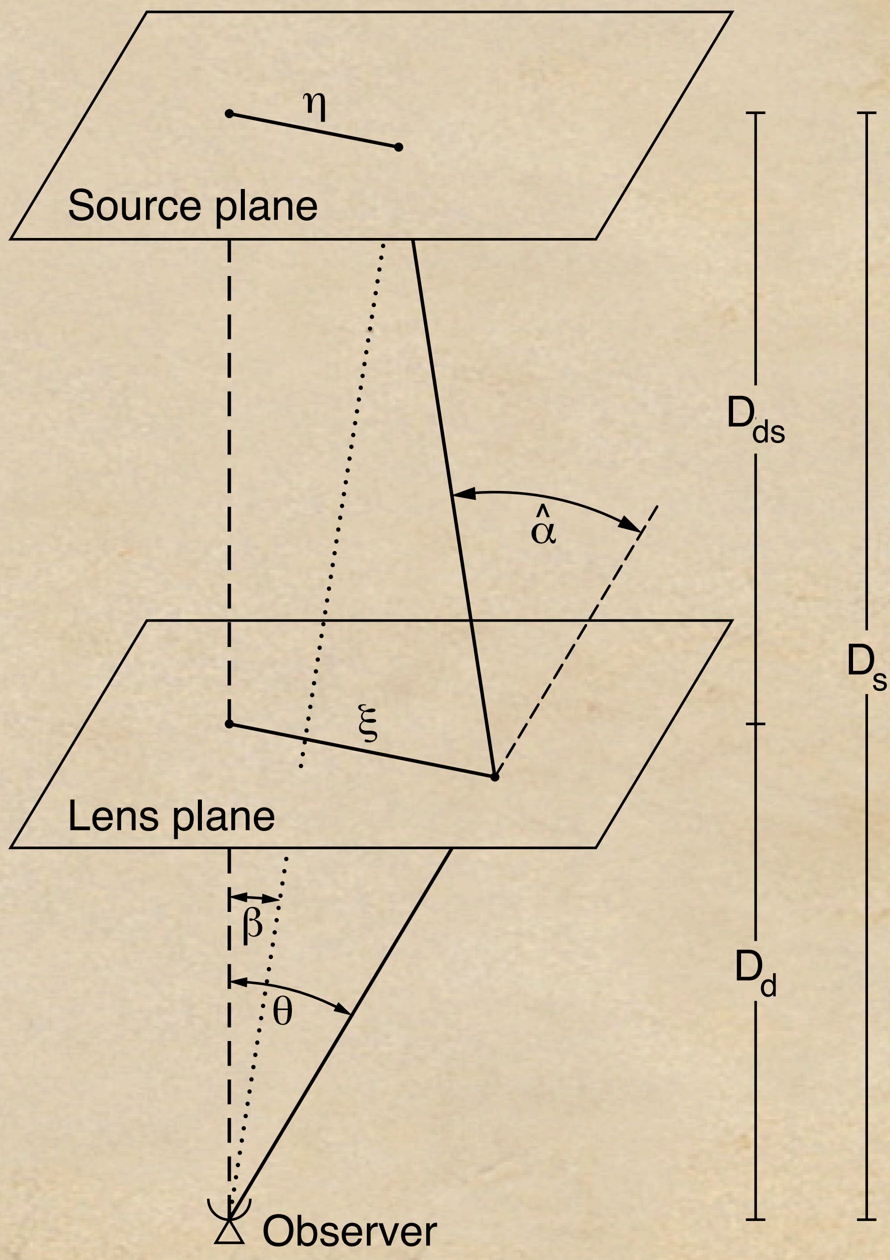

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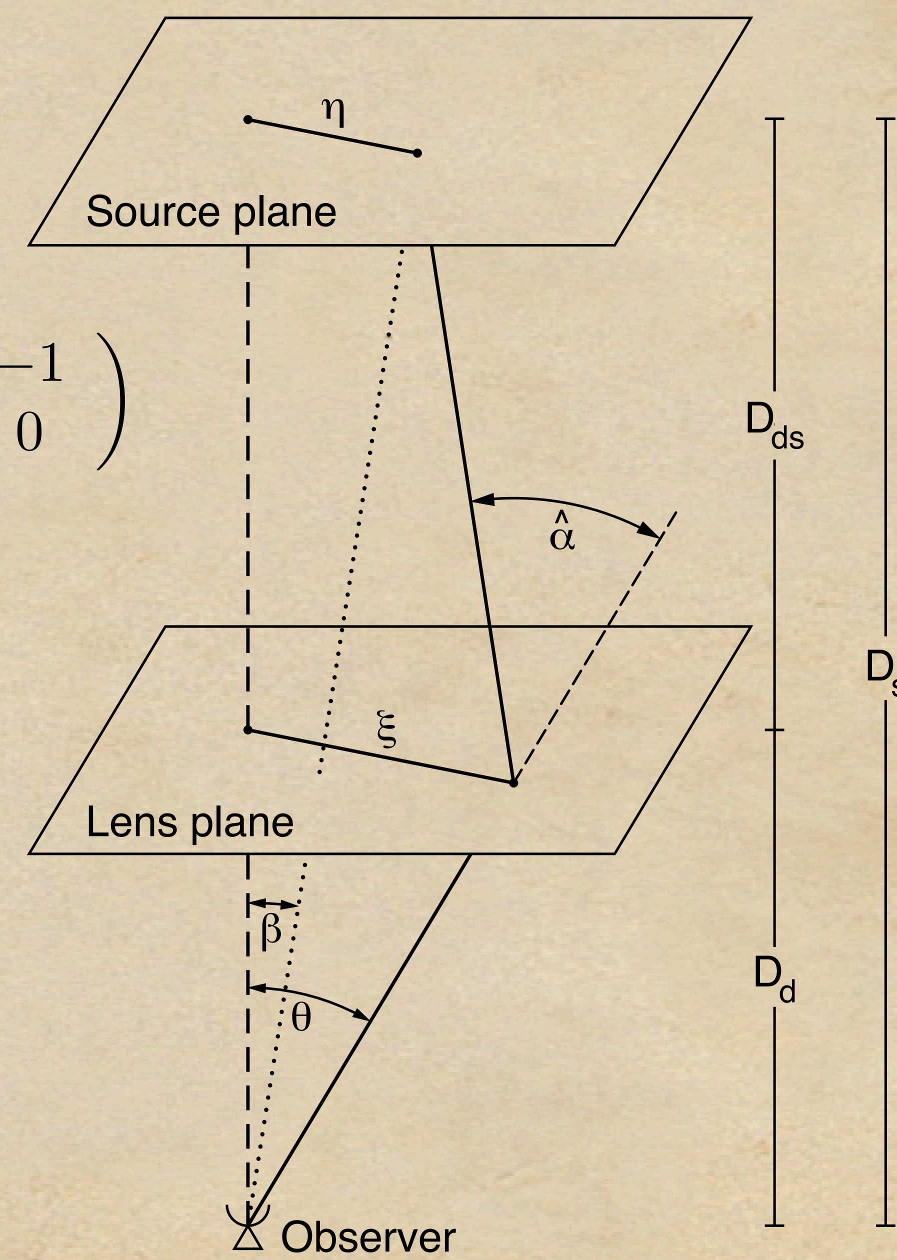
$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$= (1-\kappa)\delta_{ij} - \gamma_{ij} + \omega\epsilon_{ij}$$

trace

symmetric traceless

antisymmetric rotation



Credit: Bartelmann and Schneider 2001

Gravitational Lensing 201

The Deflection:

D.S., P. Serra, A. Cooray, K. Ichiki, D. Baumann,
PRD, 77, 103515 (2008)

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$$\alpha(\vec{\theta}) = \nabla\phi$$

$$\mathcal{A}_{ij} = \frac{\partial x_i^S}{\partial x_j^I}$$

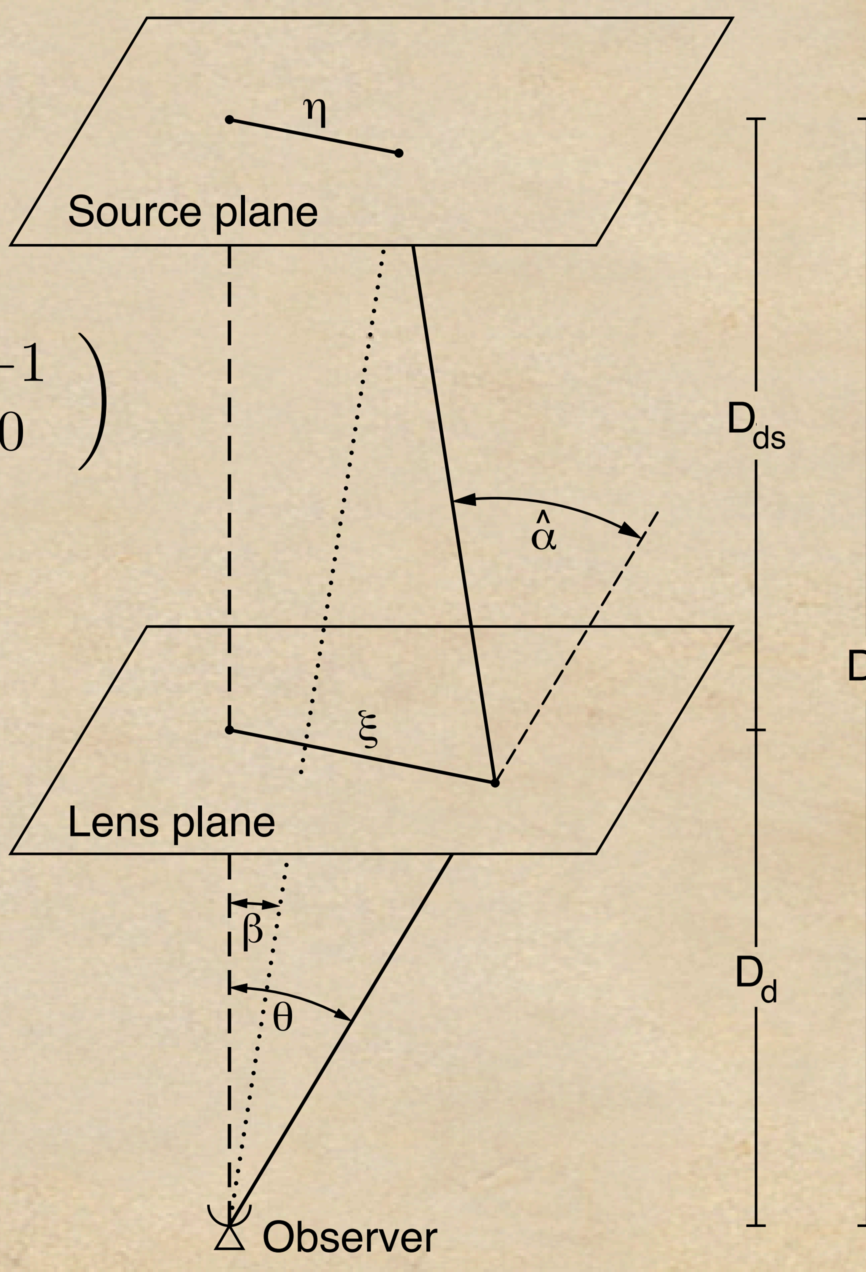
$$= (1-\kappa)\delta_{ij} - \gamma_{ij} + \omega\epsilon_{ij}$$

$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

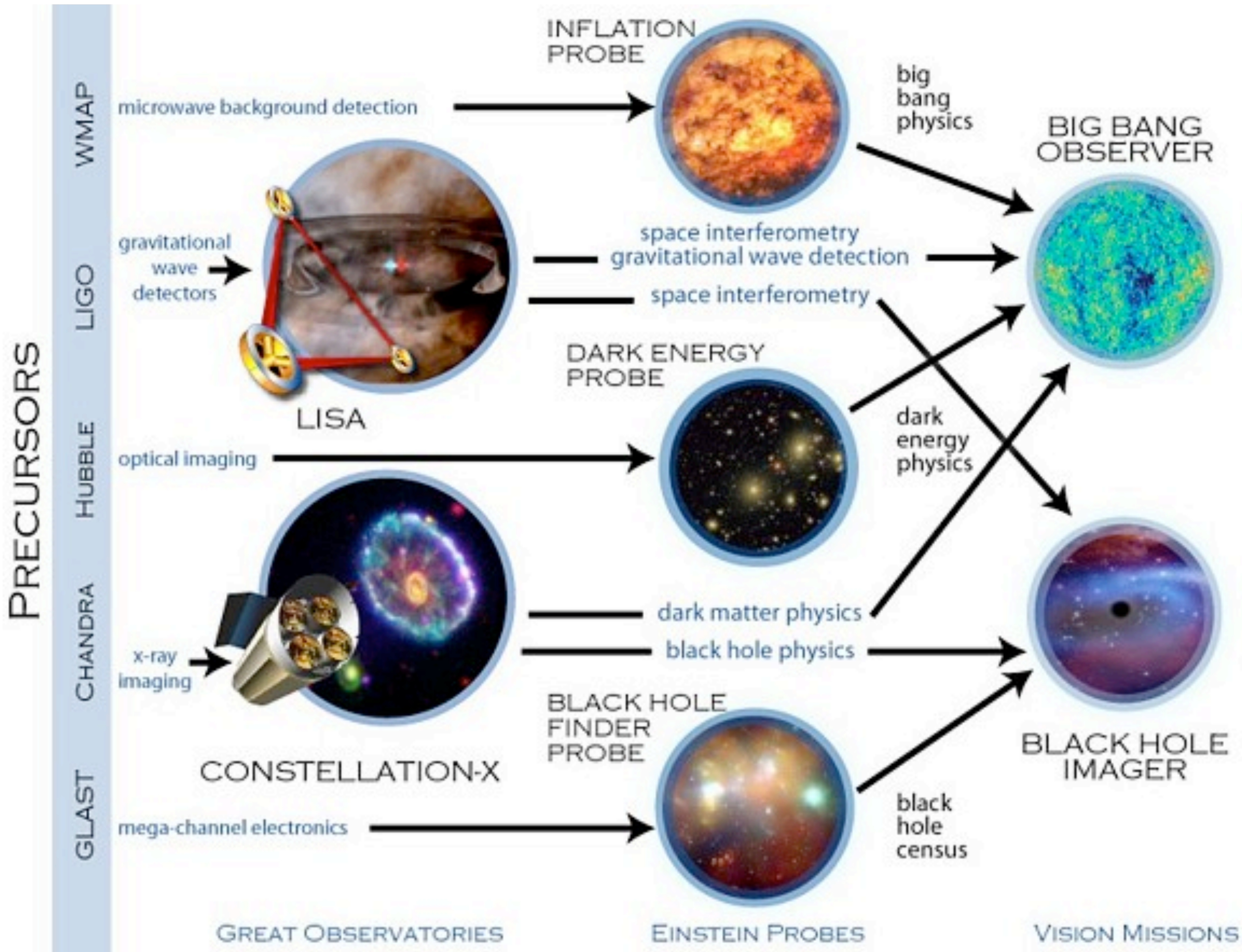
trace

symmetric traceless

antisymmetric rotation



Credit: Bartelmann and Schneider 2001


PRECURSORS
WMAP
LIGO
HUBBLE
CHANDRA
GLAST
microwave background detection
gravitational wave detectors
optical imaging
x-ray imaging
mega-channel electronics
LISA
CONSTELLATION-X
INFLATION PROBE
DARK ENERGY PROBE
BLACK HOLE FINDER PROBE
space interferometry gravitational wave detection
space interferometry
dark matter physics
black hole physics
big bang physics
dark energy physics
black hole census
BIG BANG OBSERVER
BLACK HOLE IMAGER
GREAT OBSERVATORIES
EINSTEIN PROBES
VISION MISSIONS

A Journey Through the "*Clumpy*" Universe

Devdeep Sarkar
Center for Cosmology, UC Irvine

in collaboration with:

Alexandre Amblard (UCI), Paolo Serra (UCI), Daniel Baumann (Princeton),
Kiyotomo Ichiki (Tokyo), Daniel Holz (Chicago/LANL),
Asantha Cooray (UCI)

Kansas State University   High Energy Physics Seminar   October 15, 2008 (Wed)

Two Stories

Start With...

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- SN plays a key role
- Systematics: Worry! Worry!
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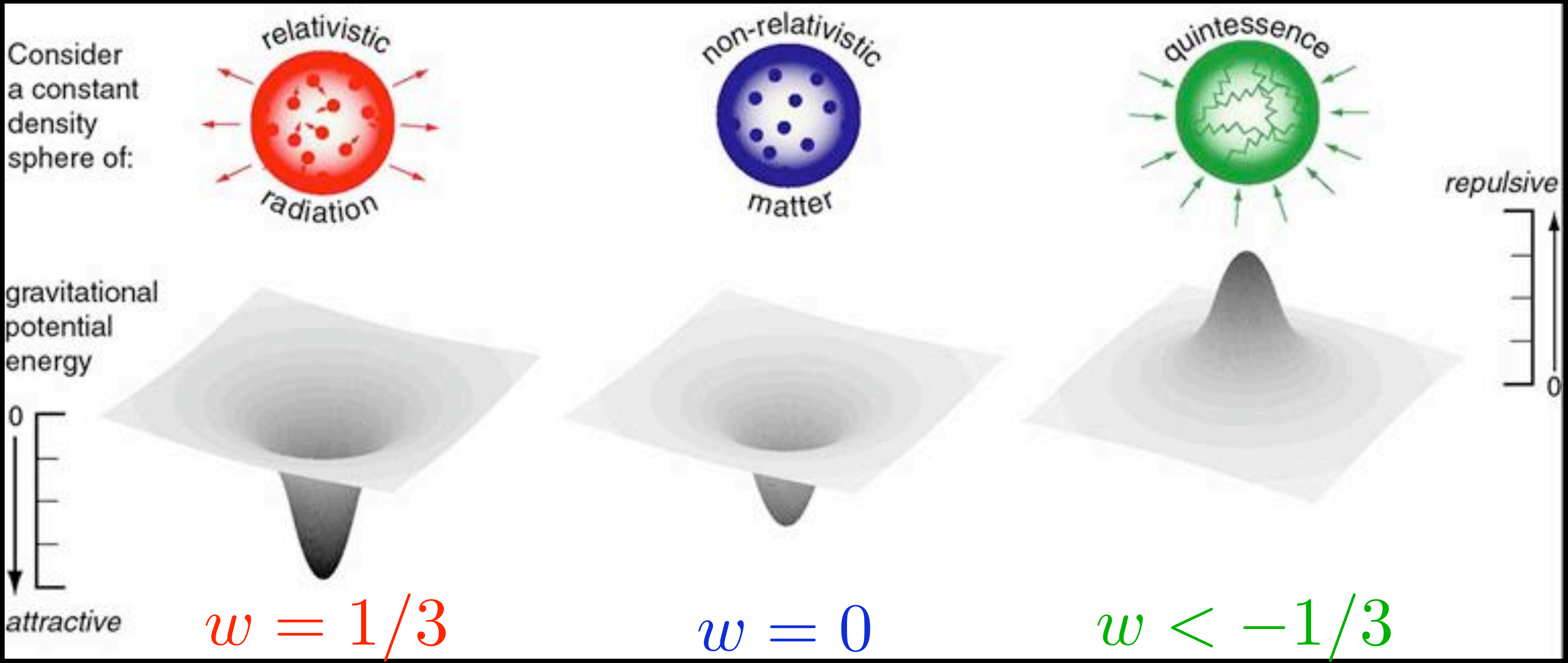
Dark Energy Equation Of State

$$T^{\nu}_{\mu} = diag(\rho, -p, -p, -p) \qquad p = w\rho$$



For Cosmological Constant... $w = -1$

Dark Energy Equation Of State

$$T_\mu^\nu = diag(\rho, -p, -p, -p) \qquad p = w\rho$$

Constraints on dark energy models from radial baryon acoustic scale measurements

Lado Samushia[1,2] and Bharat Ratra[1]

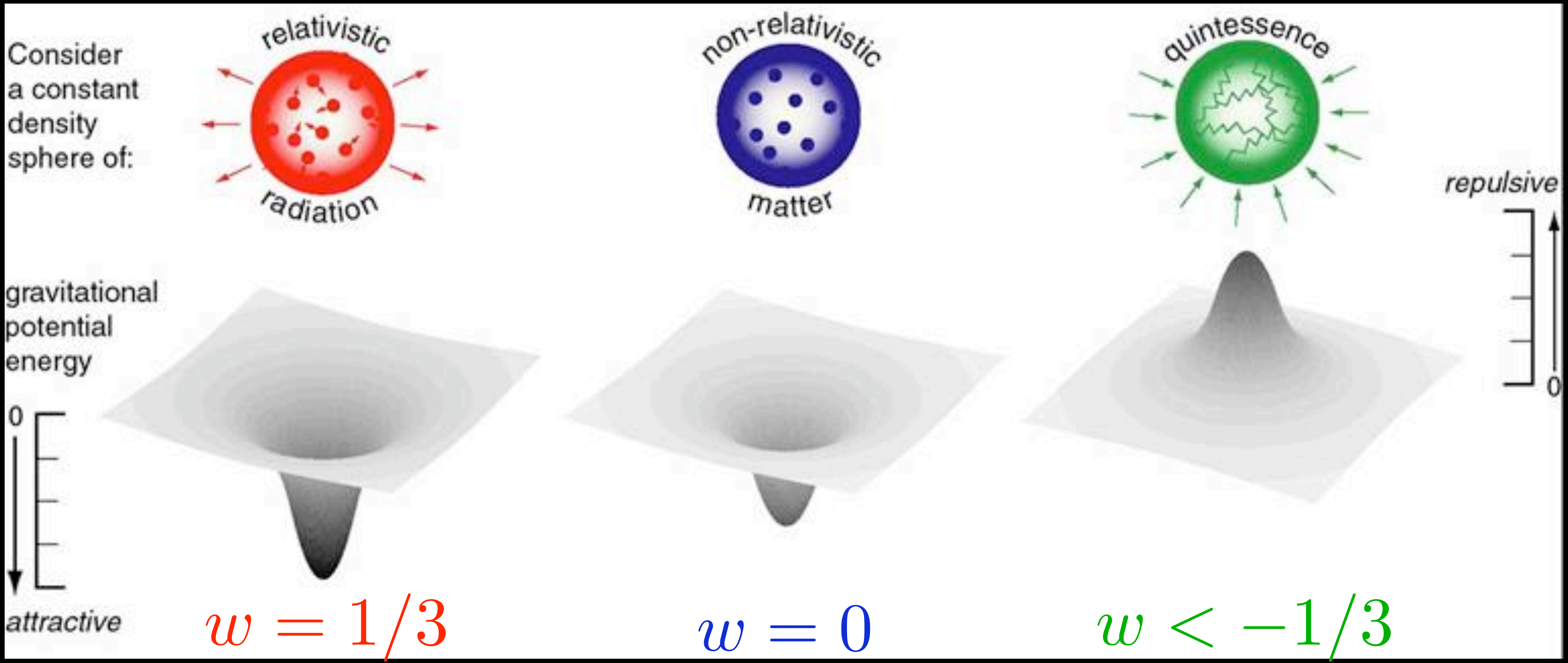
ABSTRACT

We use the radial baryon acoustic oscillation (BAO) measurements of Gaztañaga et al. (2008a) to constrain parameters of dark energy models. These constraints are comparable with constraints from other "non-radial" BAO data. The radial BAO data are consistent with the time-independent cosmological constant model but do not rule out time-varying dark energy.

For Cosmological Constant... $w = -1$

Dark Energy Equation Of State

$$T^{\nu}_{\mu} = diag(\rho, -p, -p, -p) \qquad p = w\rho$$



For Cosmological Constant... $w = -1$

DE EOS Revisited: Different Approaches...

(A) Parameterize w(z) [Adopted by the DETF]

$$\boxed{w(a) = w_0 + (1-a)w_a}$$

Chevallier & Polarski (2001)
(Linder 2003)

DE EOS Revisited: Different Approaches...

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$$\boxed{w(z) = w_0 + w_a z/(1+z)}$$

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DE EOS Revisited: Different Approaches...

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$$\boxed{w(z) = w_0 + w_a z/(1+z)}$$

Chevallier & Polarski (2001)
(Linder 2003)

(B) Non-Parametric w(z)

- ✓ Unbiased Estimate of DE Density (Wang & Lovelace 2001)
- ✓ Principal Component Approach (Huterer & Starkman 2003)
- ✓ Uncorrelated Estimates (Huterer & Cooray 2005)
- ✓ ...

For a review: Please see Sahni and Starobinsky (2006) [arXiv:astro-ph/0610026]

“Seeing” The Dark Energy

...via its effect on the expansion of the Universe

$$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + (1 - \Omega_k - \Omega_m) F(z)\right]^{1/2}$$

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$$F(z) = \exp\left(3 \int_0^z dz' \frac{1 + w(z')}{1 + z'}\right)$$

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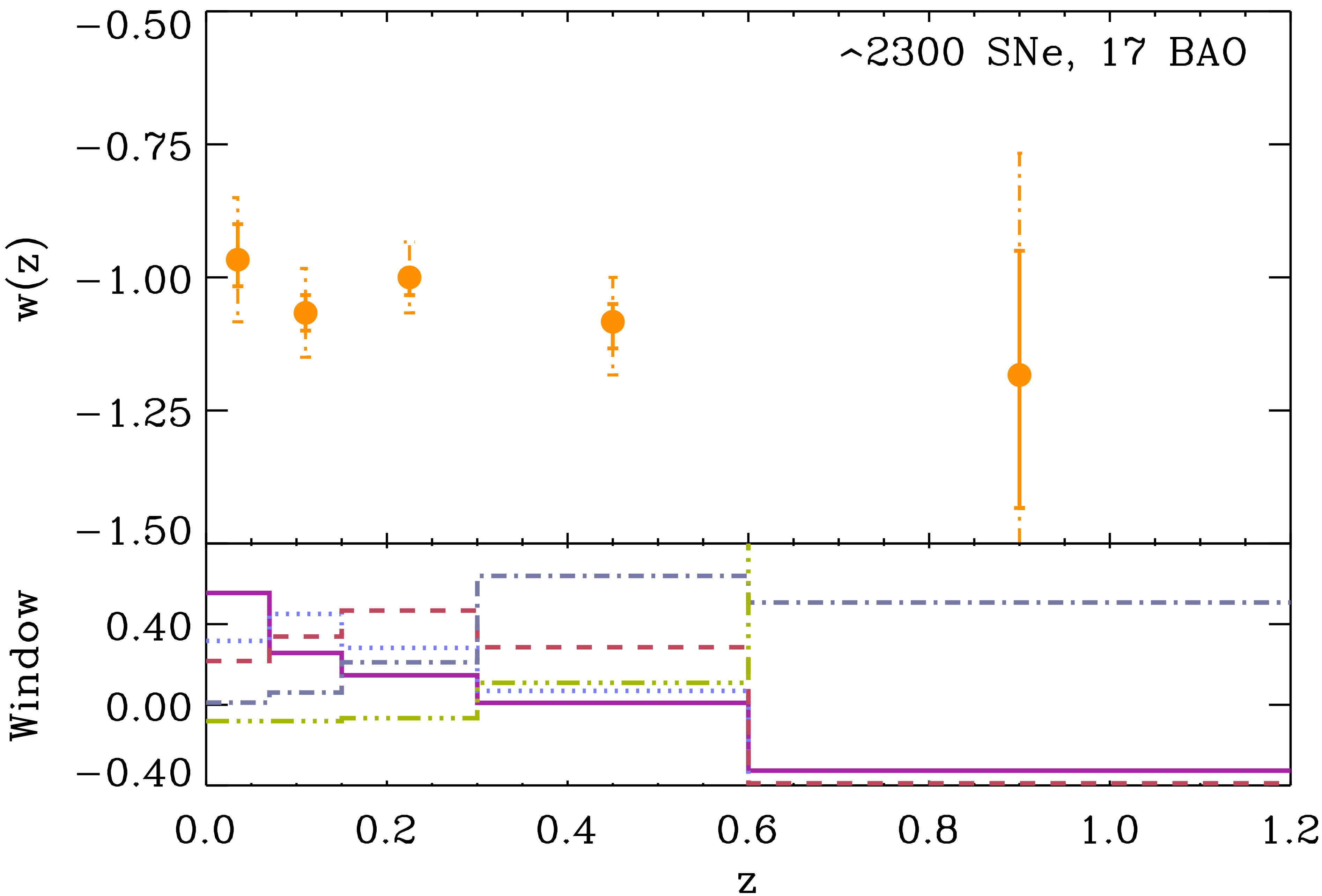
Approaches...

- Standard Candles: Luminosity Distance of SNe
- Standard Rulers:
  - Angular Diameter Distance via BAO
  - Distance to the Last Scattering Surface
- Weak Lensing Tomography

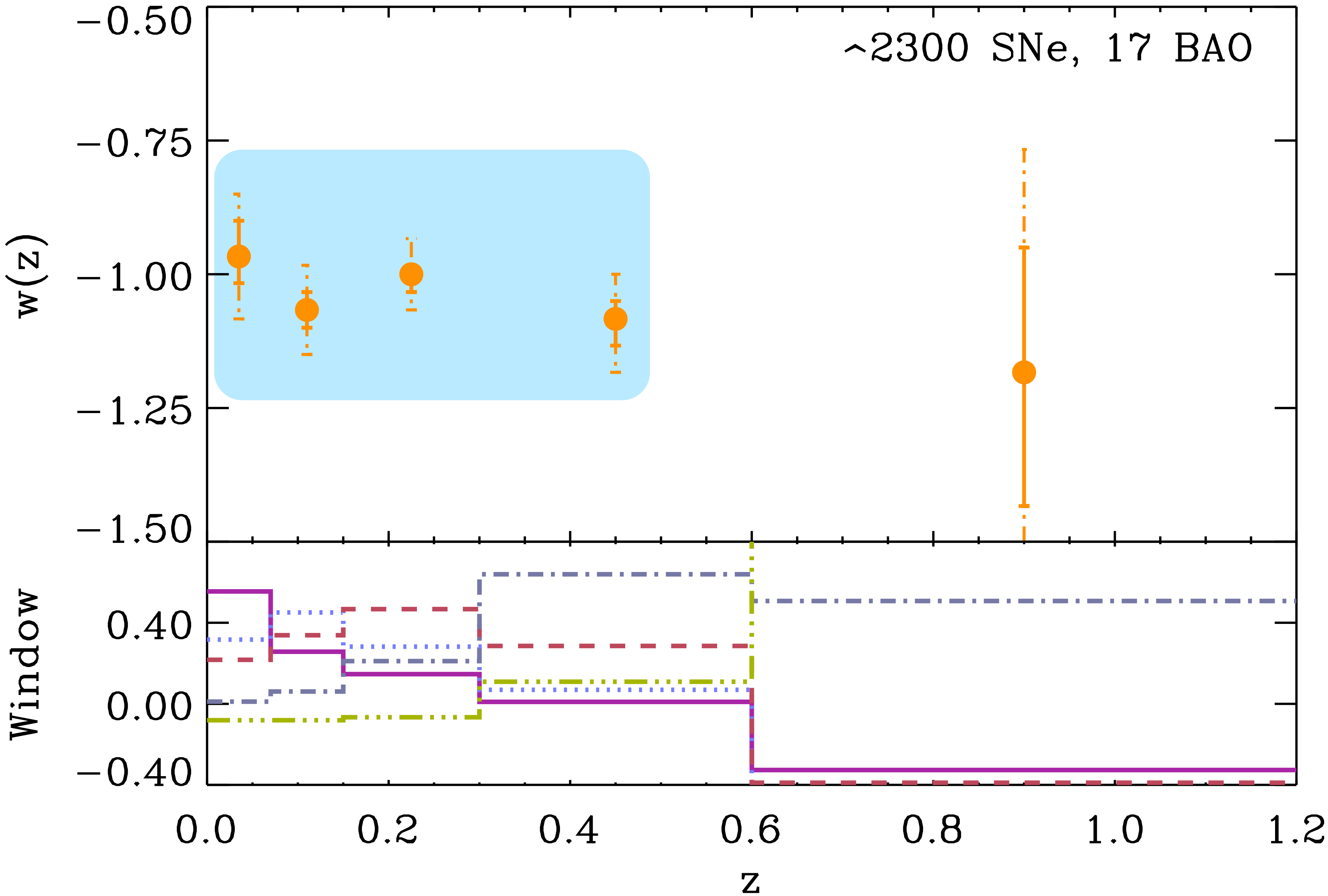
Binned Estimates: Future



w_1	0-.07
w_2	.07-.15
w_3	0.15-.3
w_4	0.3-0.6
w_5	0.6-1.2
w_6	1.2-2.0

D.S., S. Sullivan, S. Joudaki, A. Amblard, D. Holz, A. Cooray; PRL, 100, 241302 (2008)

Binned Estimates: Future



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D.S., S. Sullivan, S. Joudaki, A. Amblard, D. Holz, A. Cooray; PRL, 100, 241302 (2008)

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Codes

http://dsarkar.org/code.html

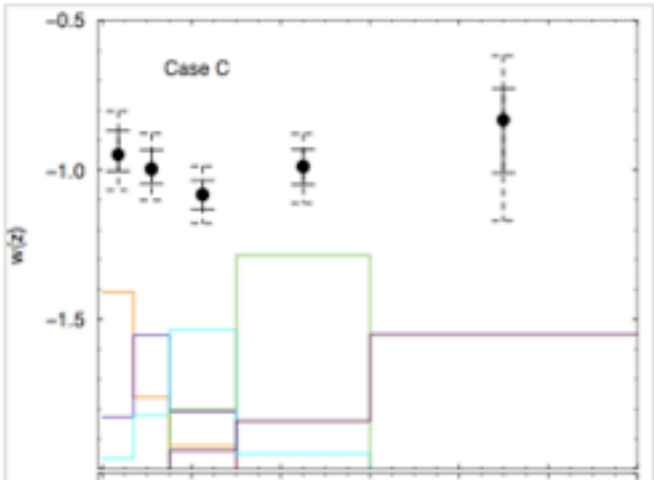
ters_IDL Devdeep Sarkar NYSE Arca ::...Java version Gordon Rese... Processes) NYSE Arca ::...Java version CMBLSS_IUCAA_2008 CADC's Inter...eeting List Nvu – The C...nd Win

DevdeepSarkar

center for cosmology, uc irvine

wzBinned Code

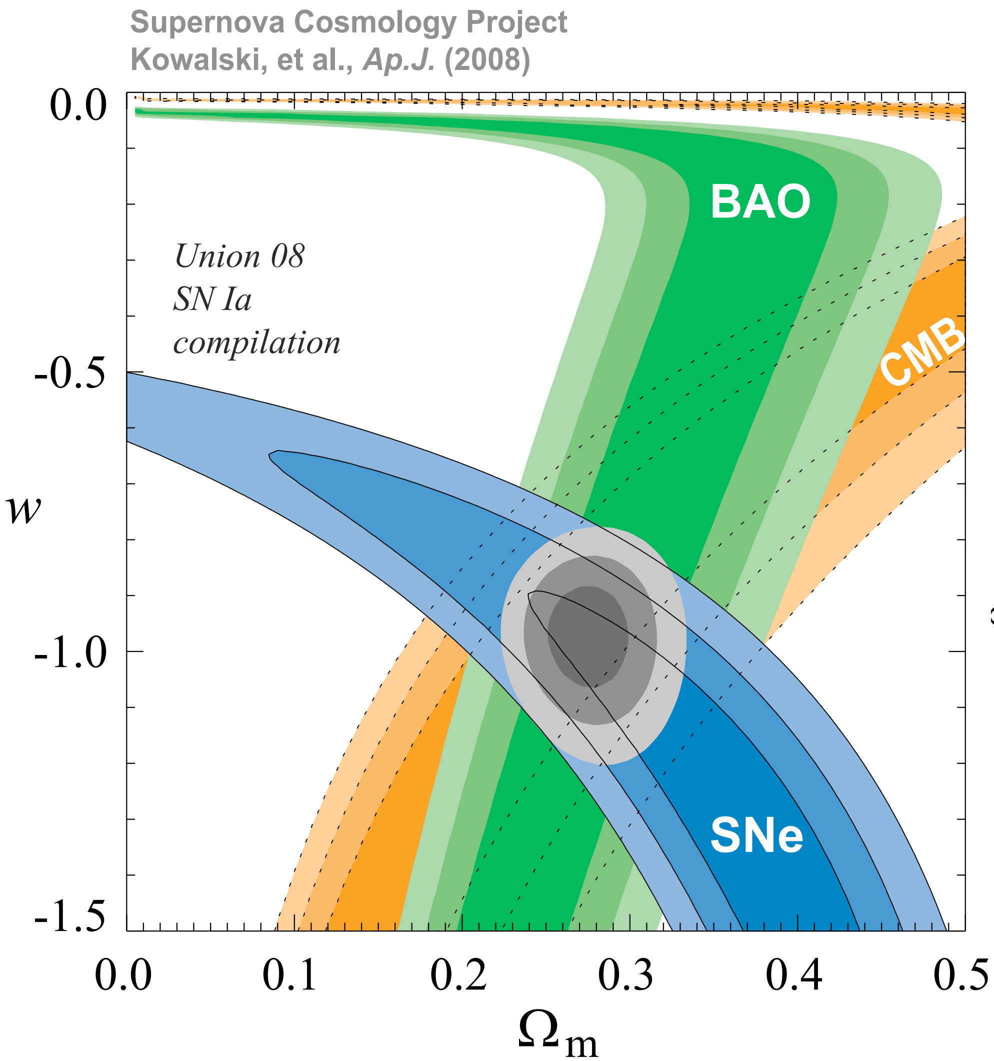
wzBinned is a numerical code to extract uncorrelated binned estimates of the dark energy equation of state, w(z), using Type Ia supernovae distance-redshift data and other cosmological probes and priors. It is written in C programming language and based on Markov chain Monte Carlo method. For further details please refer to Sarkar et al., Phys. Rev. Lett. 100 241302 (2008), and Sullivan et al., JCAP 09 004 (2007).

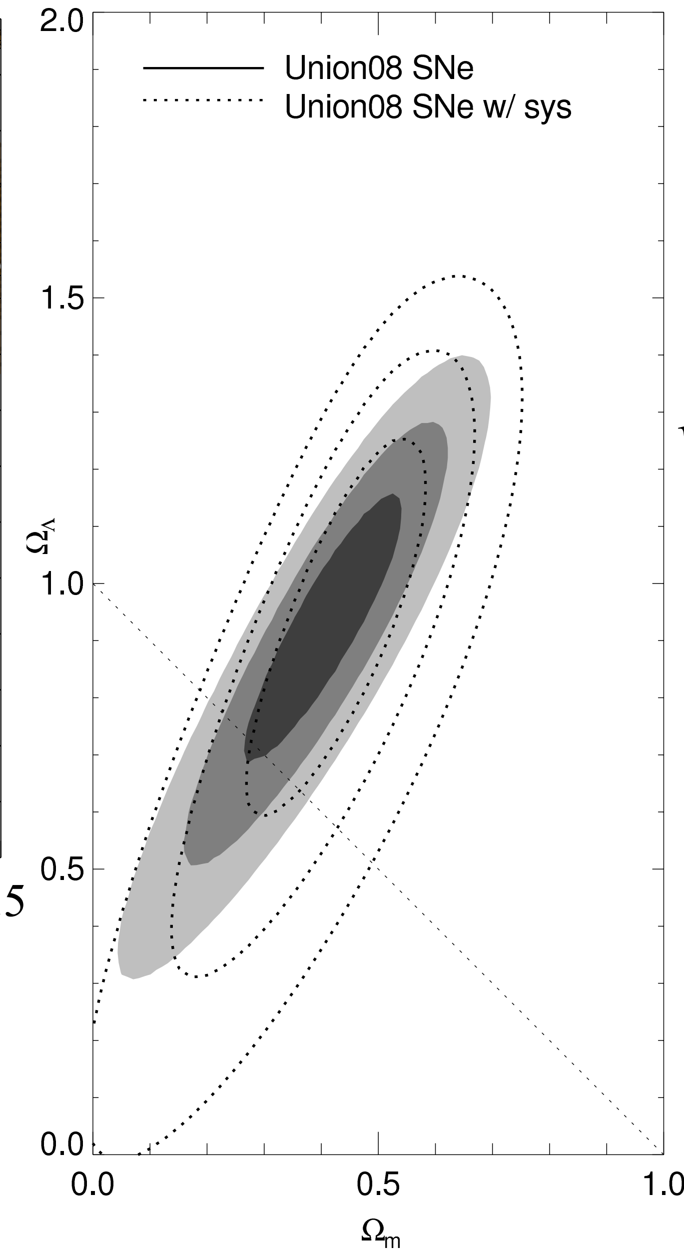


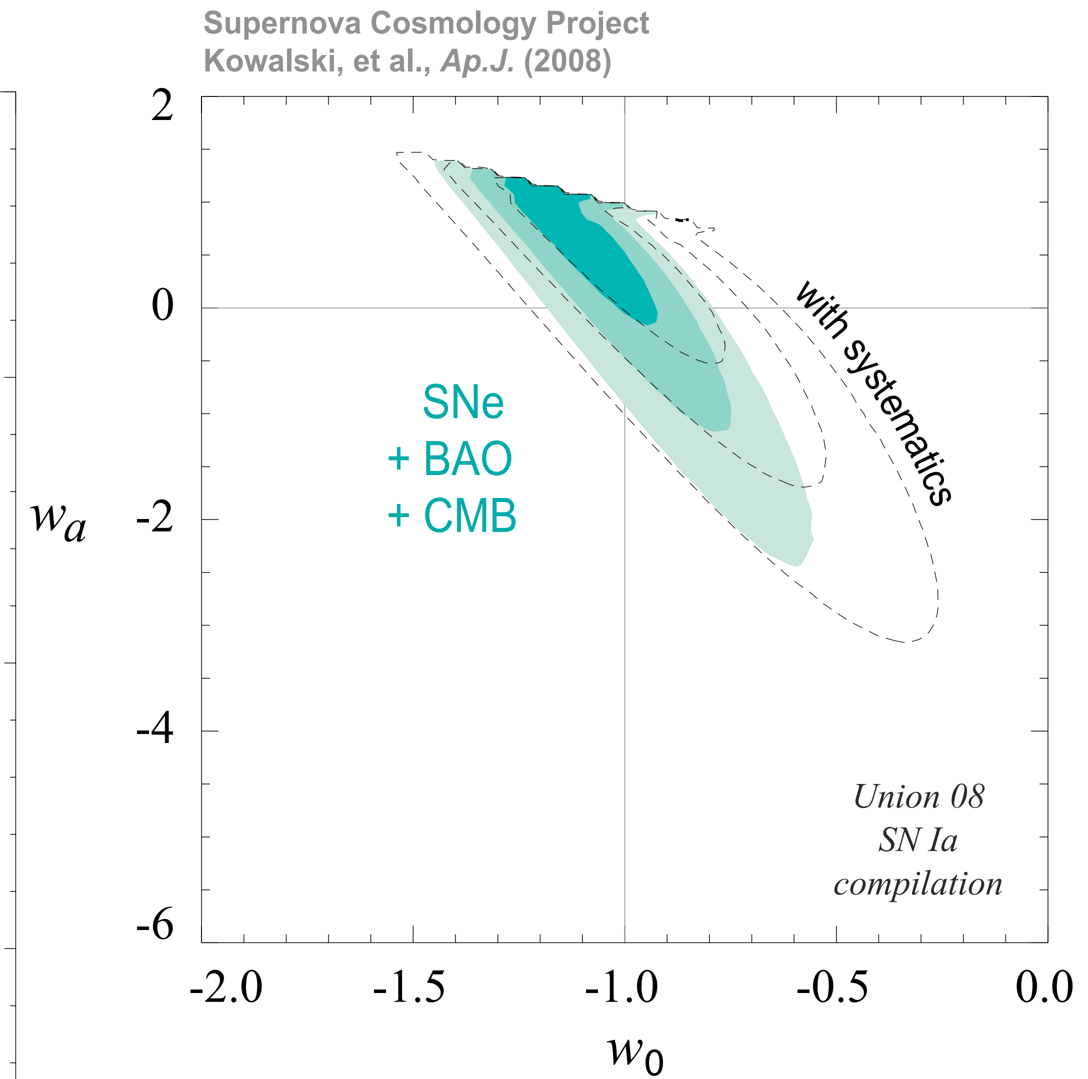
Other Resources

- COSMOMC
- CMBFAST
- IDL Astro

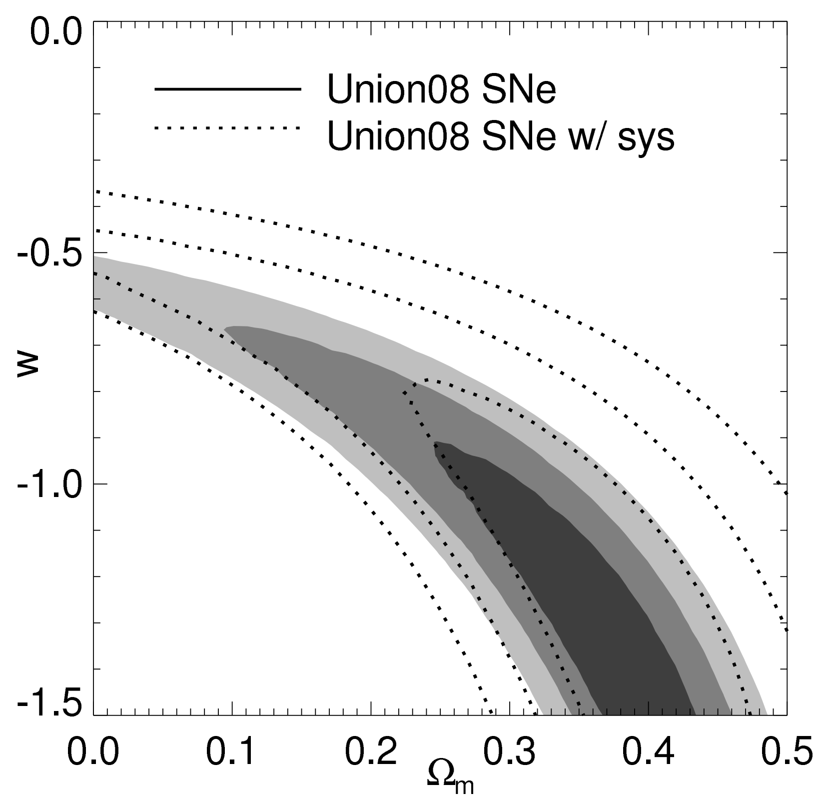
Systematic Matters!







Kowalski et al. (2008)



$$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\mathrm{stat})^{+0.036}_{-0.039}(\mathrm{sys})$$

$$w = -0.969^{+0.059}_{-0.063}(stat)^{+0.063}_{-0.066}(sys)$$

Challenges: Systematic Uncertainties

source of uncertainty	common (mag)	sample-dep.(mag)	treatment
Extinction	0.013	-	Multi-band photometry including near-IR
Calibration	0.021	0.021	Calibration of standard stars (optical thru near-IR) to <1%
Malmquist	-	0.020	High S/N lightcurves & spectra; requirement of pre-rise data
Lightcurve	0.028	-	SN spectra with broad λ, temporal coverage
Evolution	0.015	-	High-resolution spectroscopy

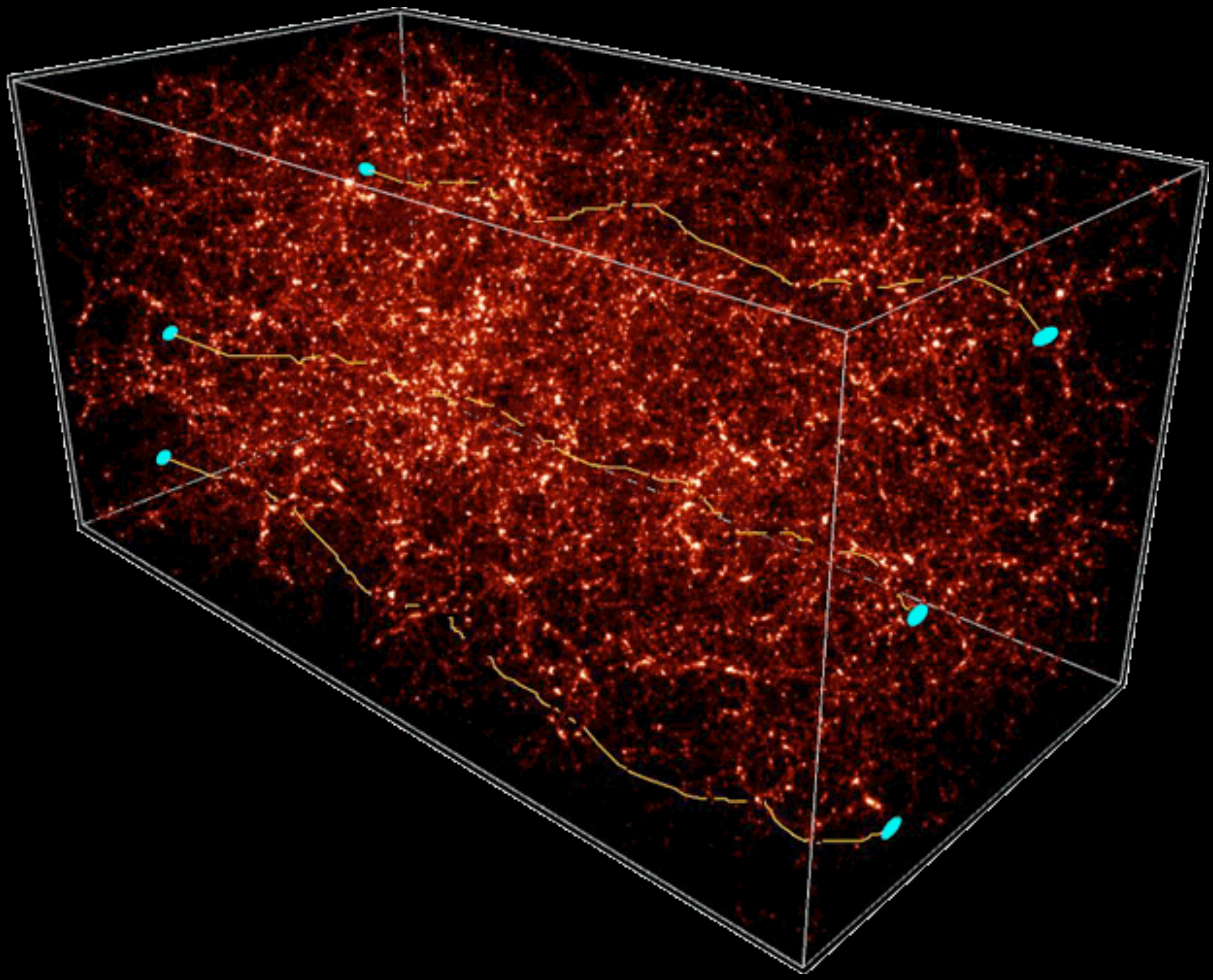
Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

2-Population	D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)
Lensing	

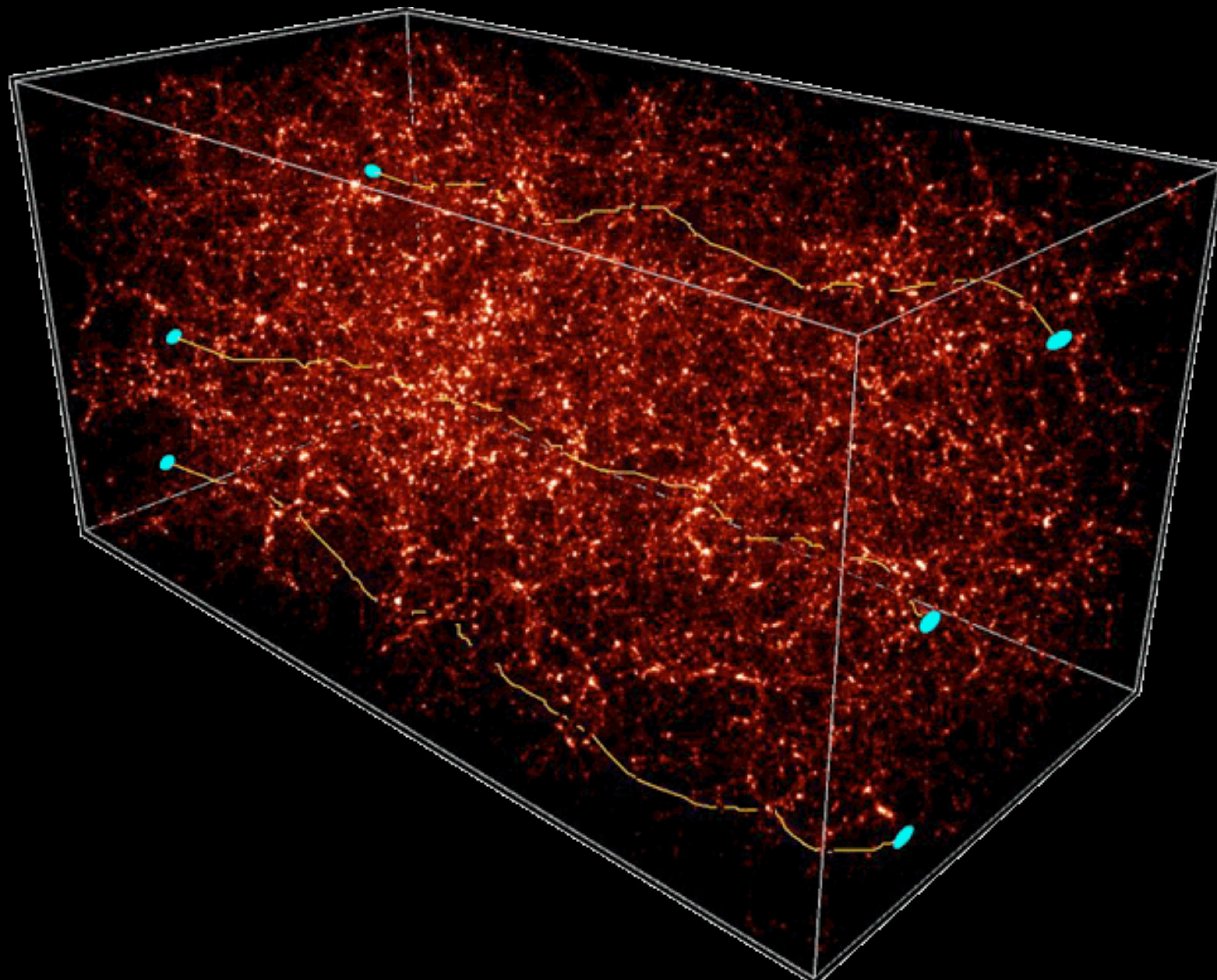
Influence of Gravitational Lensing?

Lensing Galaxy

Influence of Gravitational Lensing?

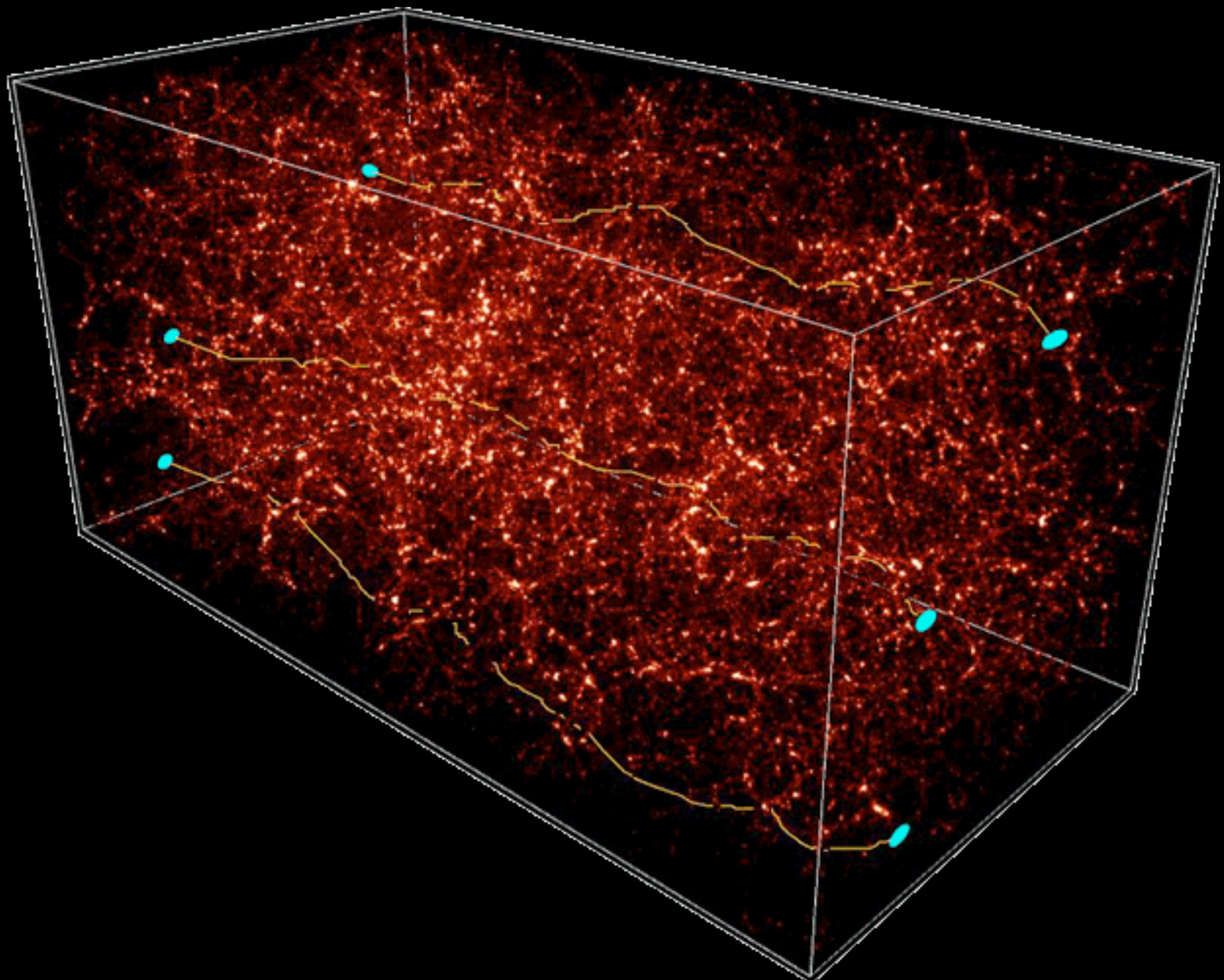


Influence of Gravitational Lensing?



$$\mathcal{F}^{\rm obs,lensed}(z,\hat{\mathbf{n}}) = \mu(z,\hat{\mathbf{n}})\mathcal{F}^{\rm obs,true}(z)$$

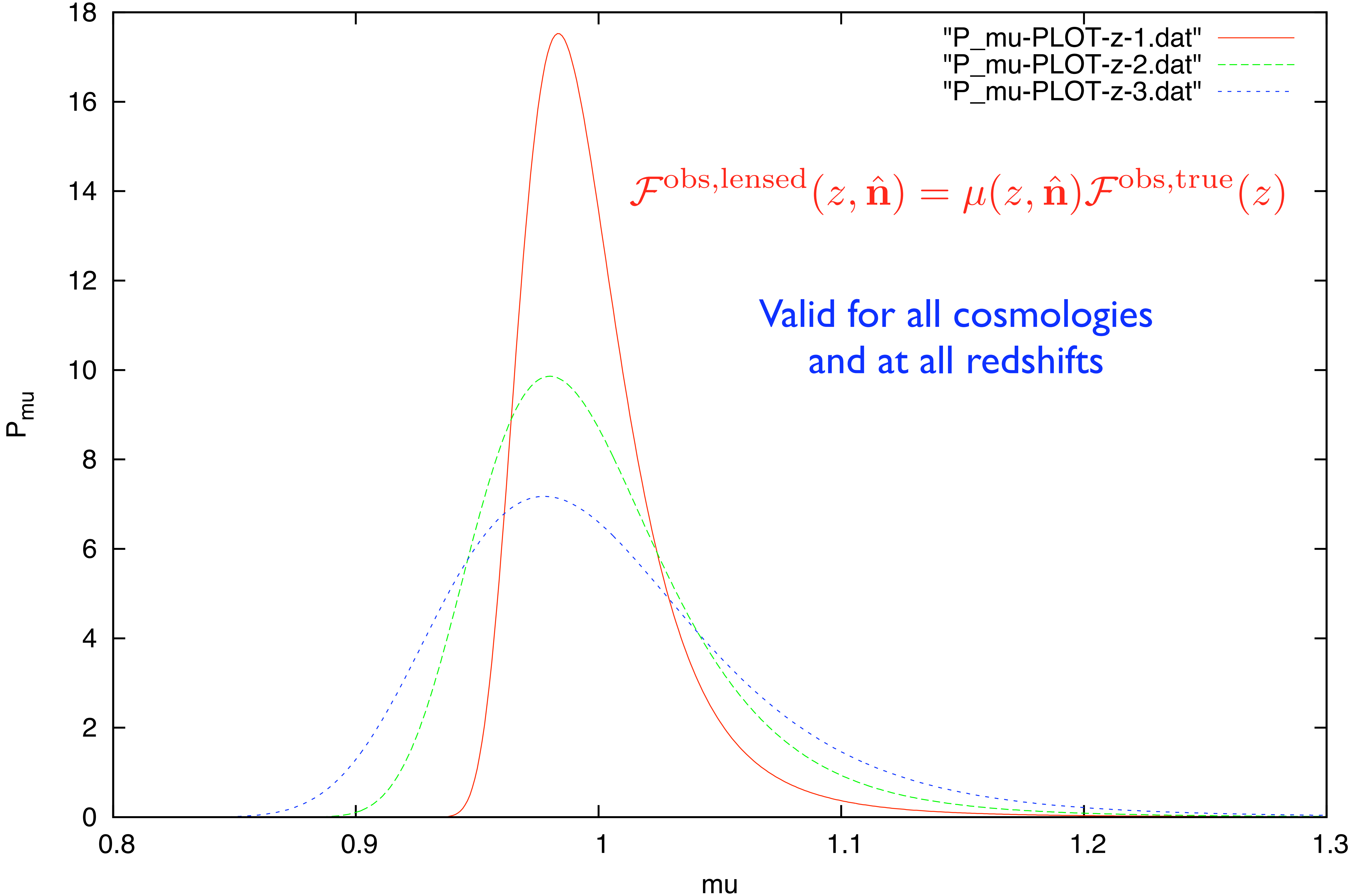
Influence of Gravitational Lensing?



$$\mathcal{F}^{\mathrm{obs,lensed}}(z,\hat{\mathbf{n}}) = \mu(z,\hat{\mathbf{n}})\mathcal{F}^{\mathrm{obs,true}}(z)$$

Weak lensing can modify the SNa flux & bias estimates of w

Our Analysis with Mock Catalogs



Wang, Y., Holz, D. E., & Munshi, D., 2002, ApJ, ***572****, L15*

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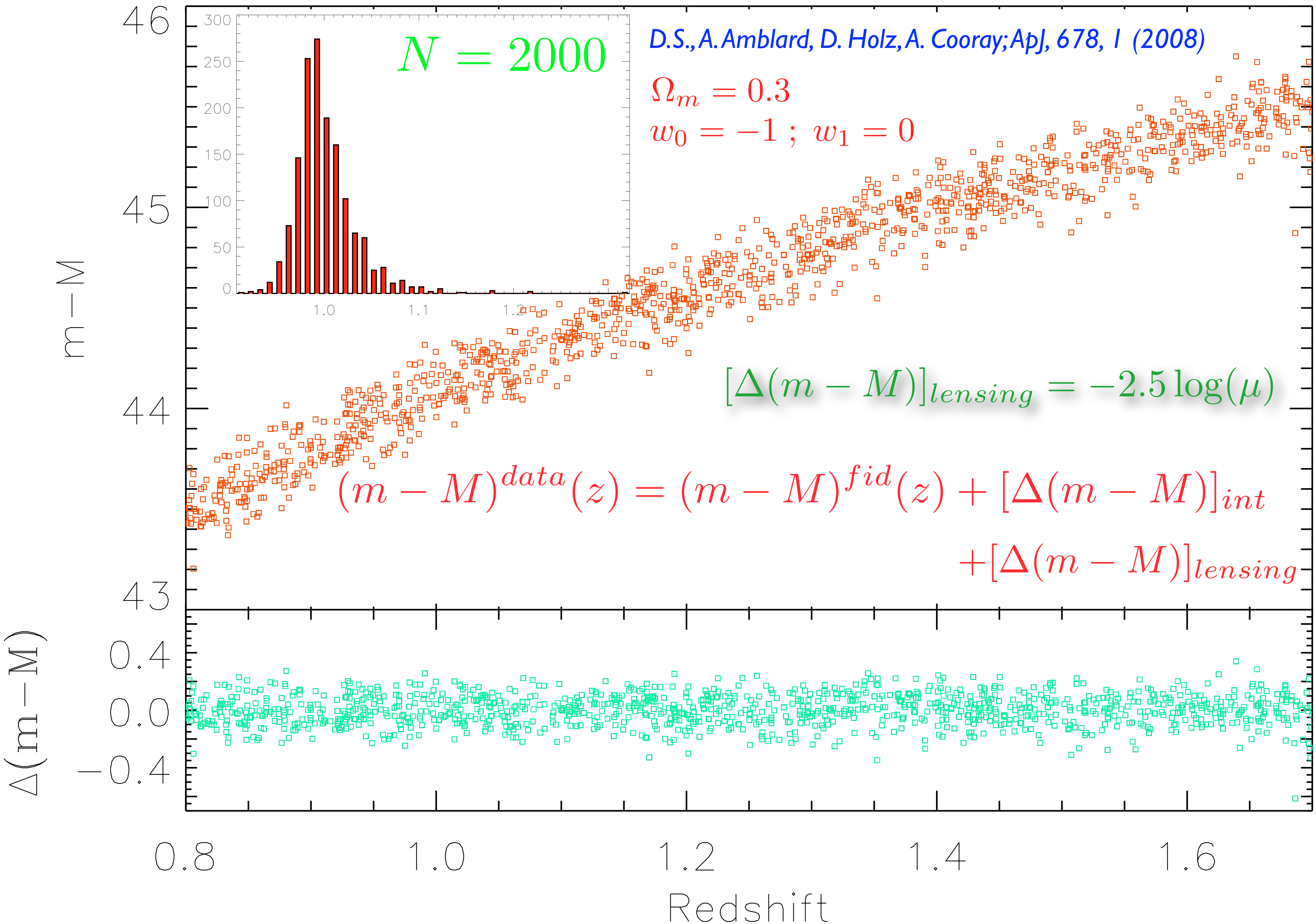
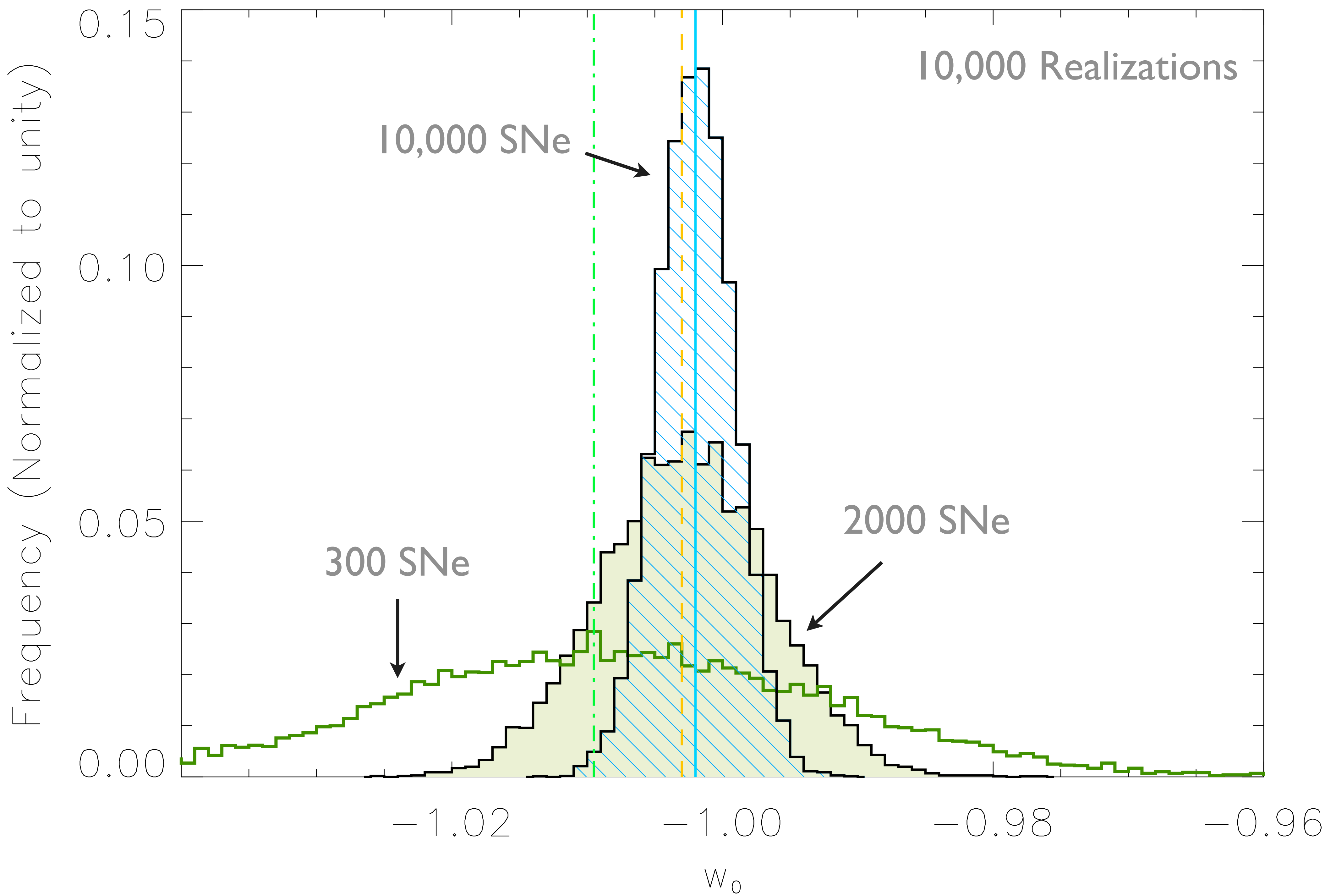
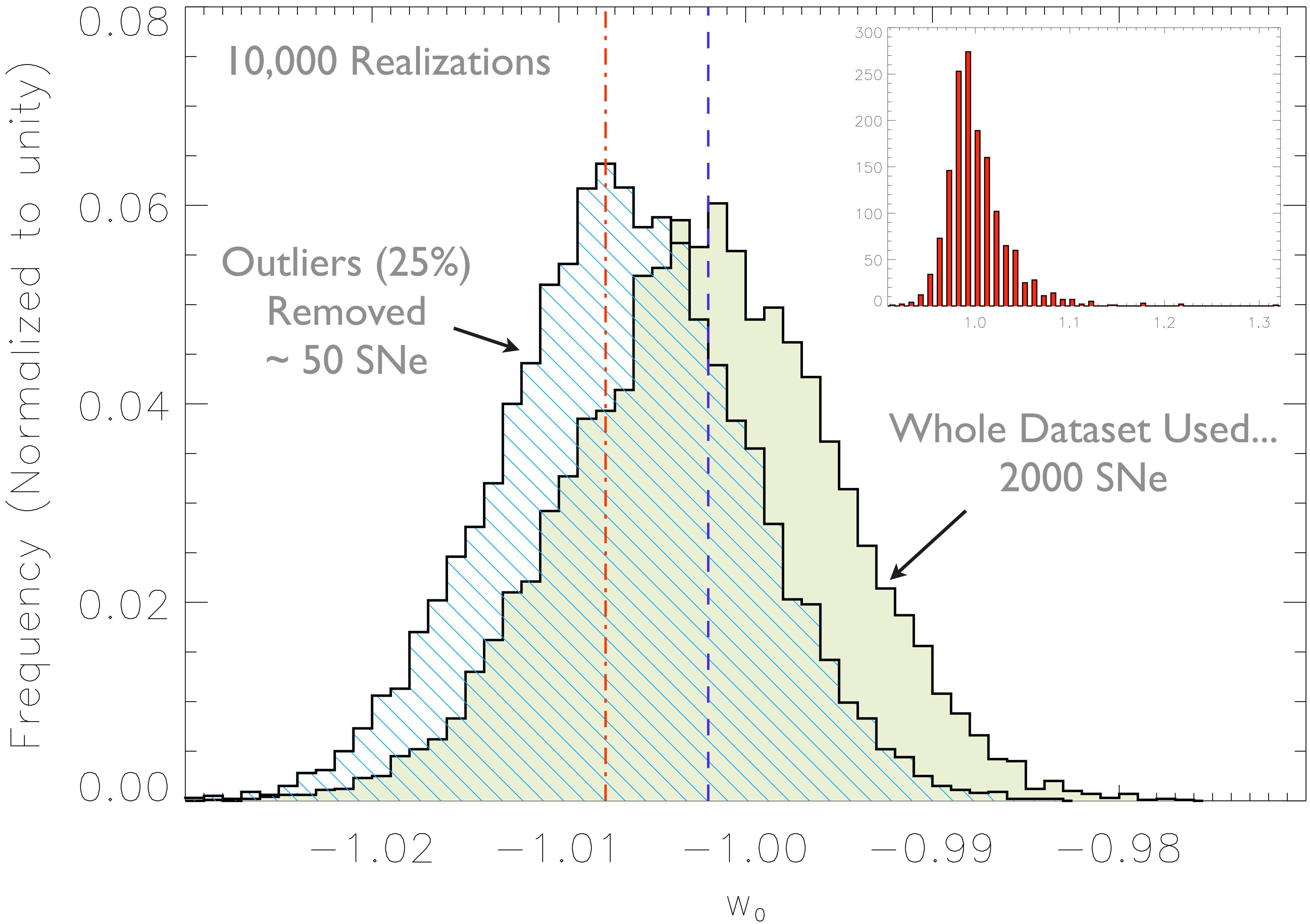


Effect of Weak Lensing on Estimates of "w"



D.S., A. Amblard, D. Holz, A. Cooray; ApJ, 678, 1 (2008)

Effect of Removing the Outliers



D.S., A. Amblard, D. Holz, A. Cooray; ApJ, 678, 1 (2008)

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Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

2-Population	D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)
Lensing	Need a large # of SNe per redshift bin to keep bias < 1%

Two Stories

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Primordial Non-Gaussianity: Primary CMB Bispectrum

Gaussian Quantum Fluctuation

Falk et al. (1993) $\Big\downarrow$ $$\delta\phi \sim g_{\delta\phi}\left(\eta + m_{pl}^{-1} f_\eta \eta^2\right)$$ $\Big\downarrow$ Starobinsky (1986) Gangui et al. (1994)

Non-Gaussian Inflation Fluctuation

$\Big\downarrow$ $$\Phi \sim m_{pl}^{-1} g_\Phi \left(\delta\phi + m_{pl}^{-1} f_{\delta\phi}\delta\phi^2\right)$$ $\Big\downarrow$ Salopek & Bond (1990)

Non-Gaussian Curvature Perturbation

$\Big\downarrow$ $$\frac{\Delta T}{T} \sim g_T\left(\Phi + f_\Phi \Phi^2\right)$$ $\Big\downarrow$ Pyne & Carroll (1996)

Non-Gaussian CMB Anisotropy

Primordial Non-Gaussianity: Primary CMB Bispectrum

Combining all the contributions:

$$\frac{\Delta T(\mathbf{x})}{T} \sim g_T \Phi(\mathbf{x})$$

where:

$$\Phi(\mathbf{x}) = \Phi_L(\mathbf{x}) + f_{NL}\left[\Phi_L^2(\mathbf{x}) - \langle\Phi_L^2(\mathbf{x})\rangle\right]$$

Non-Linear
Coupling Parameter

Measurement of non-Gaussian CMB anisotropies potentially constrains non-linearity, "slow-rollness", and "adiabaticity" in inflation.
- Komatsu 2002

Primordial Non-Gaussianity: Primary CMB Bispectrum

Non-Gaussianity from the simplest inflation model is very small:

$$f_{NL} \sim 0.01 - 1$$

Much higher level of primordial non-Gaussianity is predicted by

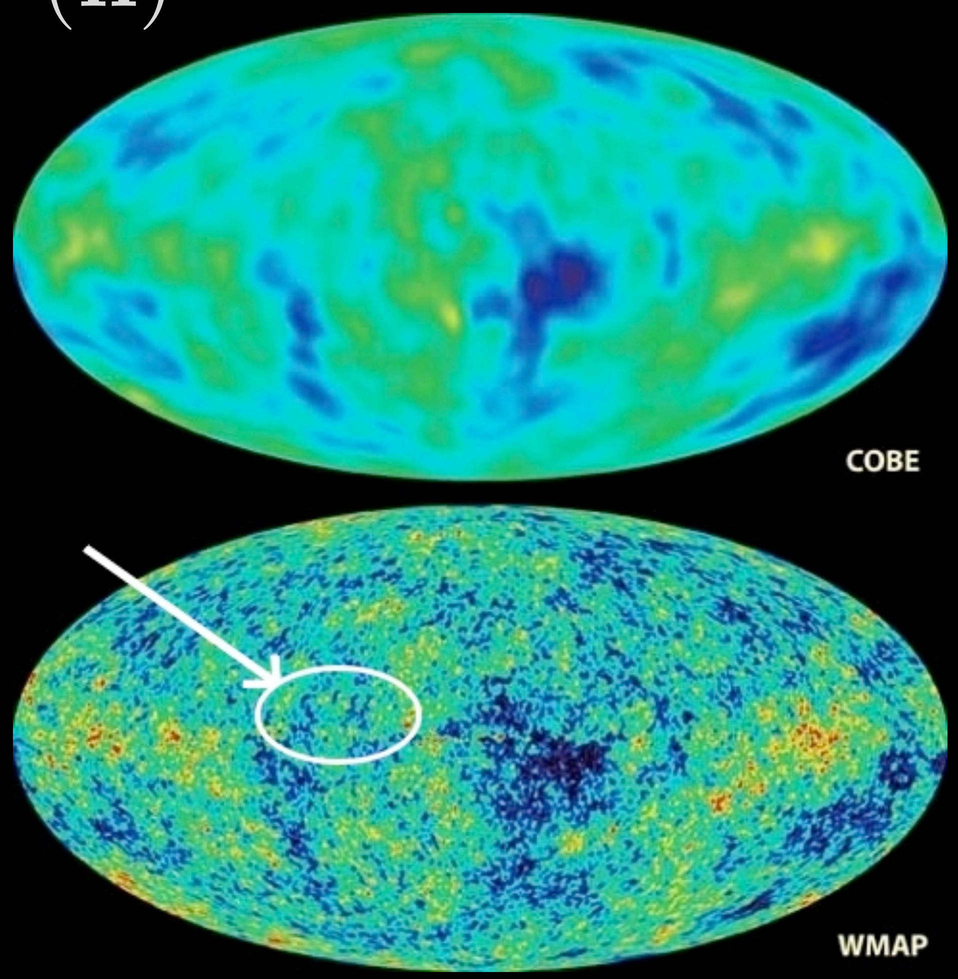
- Models with multiple scalar fields
- Non-Adiabatic Fluctuations
- Features in the inflation potential
- Non-canonical kinetic terms
- ...

Review: N. Bartolo, E. Komatsu, S. Matarrese, and A. Riotto, Phys. Rep. 402, 103 (2004).

Primary CMB Bispectrum

The CMB Temperature Perturbation in the Sky:

$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{T} = \sum_{lm} \Theta_{lm} Y_l^m(\hat{\mathbf{n}})$$



Power Spectrum:

$$\langle \Theta_{lm} \Theta_{l'm'} \rangle = \delta_{l,l'} \delta_{m,m'} C_l^{\Theta\Theta}$$

Angular Bispectrum:

$$\langle \Theta_{l_1 m_1} \Theta_{l_2 m_2} \Theta_{l_3 m_3} \rangle = \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B^{\Theta}_{l_1 l_2 l_3}$$

Measurement of primordial non-Gaussianity

PRL **100,** 181301 (2008) PHYSICAL REVIEW LETTERS week ending 9 MAY 2008

Evidence of Primordial Non-Gaussianity (f_{NL}) in the Wilkinson Microwave Anisotropy Probe 3-Year Data at 2.8σ

Amit P. S. Yadav[1] and Benjamin D. Wandelt[1,2]

[1]*Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, Illinois 61801, USA*
[2]*Department of Physics, University of Illinois at Urbana-Champaign, 1110 W. Green Street, Urbana, Illinois 61801, USA*
(Received 7 December 2007; revised manuscript received 6 March 2008; published 7 May 2008)

We present evidence for primordial non-Gaussianity of the local type (f_{NL}) in the temperature anisotropy of the cosmic microwave background. Analyzing the bispectrum of the Wilkinson Microwave Anisotropy Probe 3-year data up to $\ell_{\max} = 750$ we find $27 < f_{\mathrm{NL}} < 147$ (95% C.L.). This amounts to a rejection of $f_{\mathrm{NL}} = 0$ at 2.8σ, disfavoring canonical single-field slow-roll inflation. The signal is robust to variations in $l_{\max}$, frequency and masks. No known foreground, instrument systematic, or secondary anisotropy explains it. We explore the impact of several analysis choices on the quoted significance and find 2.5σ to be conservative.

FIVE-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP[1]) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

E. Komatsu [1], J. Dunkley [2,3,4], M. R. Nolta [5], C. L. Bennett [6], B. Gold [6], G. Hinshaw [7], N. Jarosik [2], D. Larson [6], M. Limon [8] L. Page [2], D. N. Spergel [3,9], M. Halpern [10], R. S. Hill [11], A. Kogut [7], S. S. Meyer [12], G. S. Tucker [13], J. L. Weiland [10], E. Wollack [7], and E. L. Wright [14]

Submitted to the Astrophysical Journal Supplement Series

ABSTRACT

$$-9 < f_{NL}^{local} < 111 \text{ and } -151 < f_{NL}^{equil} < 253 (95\% \, CL)$$

Measurement of primordial non-Gaussianity

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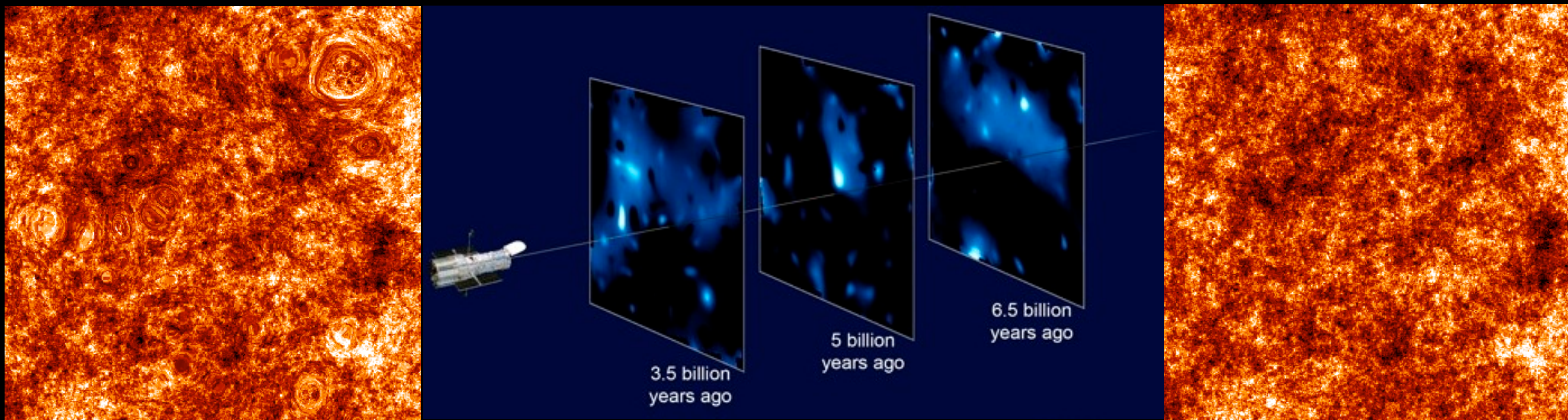
Constraints on local primordial non-Gaussianity from large scale structure

Anže Slosar,[1] Christopher Hirata,[2] Uroš Seljak,[3,4] Shirley Ho,[5] and Nikhil Padmanabhan[6]

$$-29(-65) < f_{NL} < +70(+93)$$

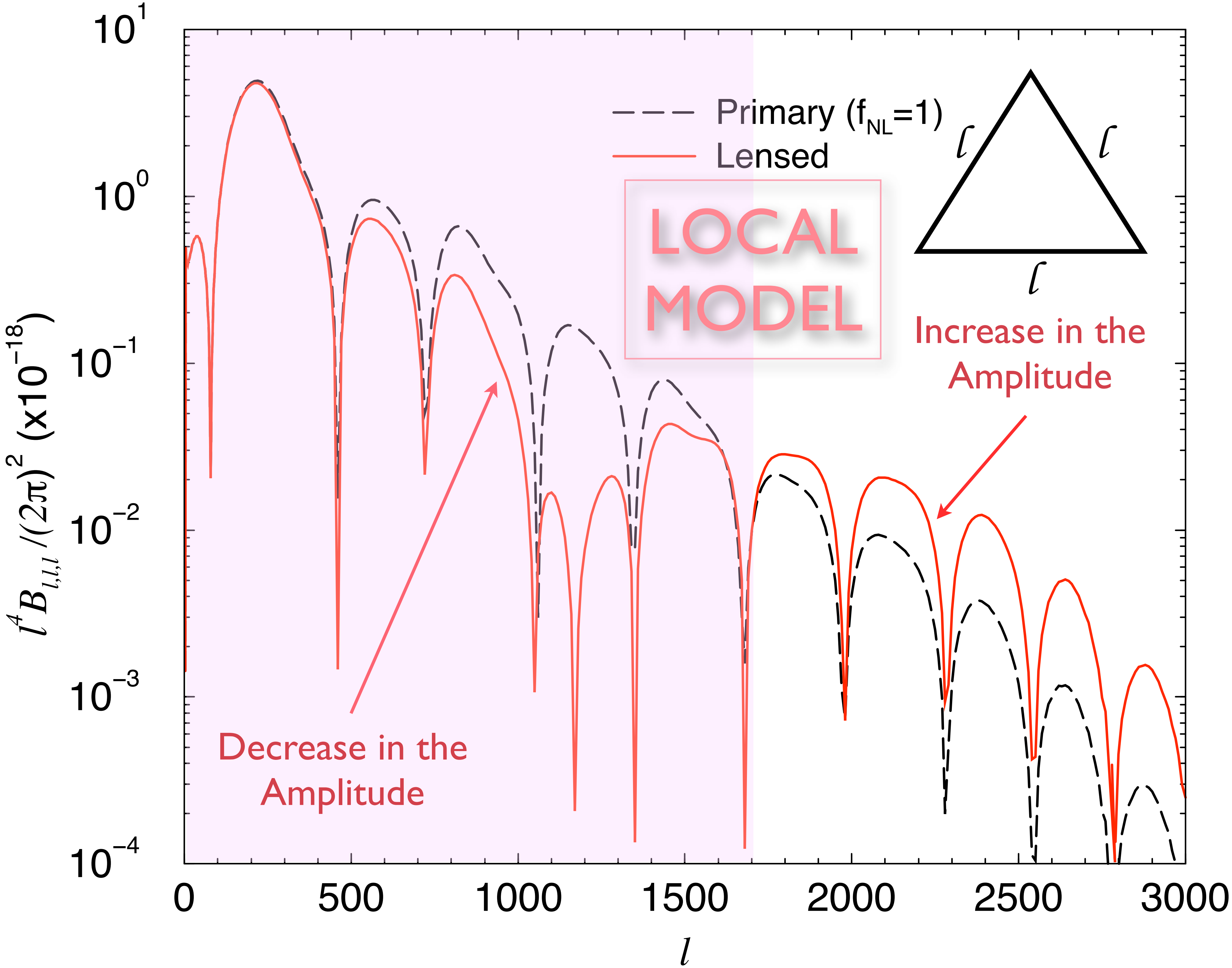
Weak Lensing of the Primary Bispectrum



$$
\begin{aligned}
\tilde{\Theta}(\hat{\mathbf{n}}) &= \Theta[\hat{\mathbf{n}} + \hat{\alpha}] \\
&= \Theta[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})] \\
&\approx \Theta(\hat{\mathbf{n}}) + \nabla_i\phi(\hat{\mathbf{n}})\nabla^i\Theta(\hat{\mathbf{n}}) + \frac{1}{2}\nabla_i\phi(\hat{\mathbf{n}})\nabla_j\phi(\hat{\mathbf{n}})\nabla^i\nabla^j\Theta(\hat{\mathbf{n}})
\end{aligned}
$$

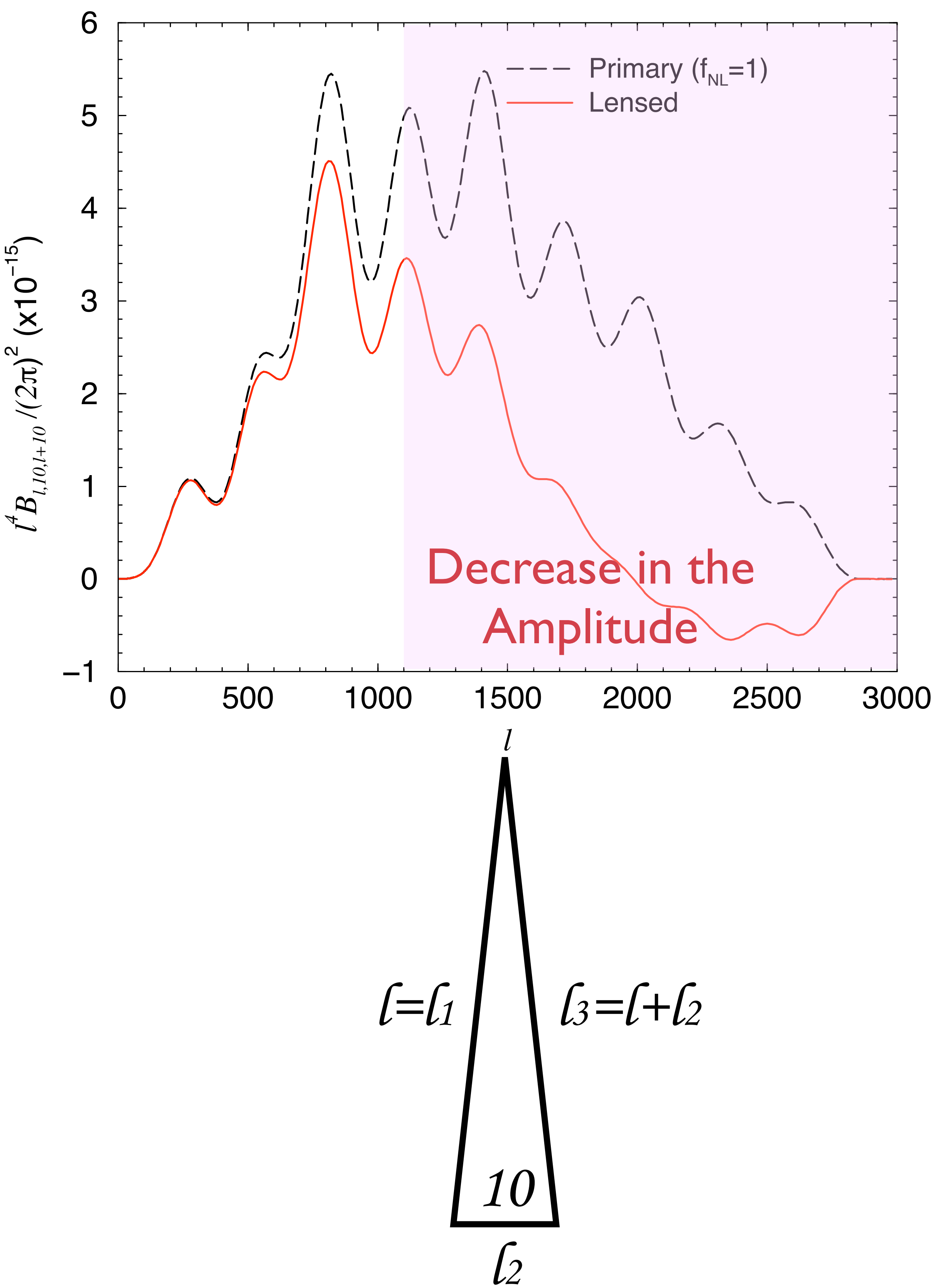
$$
\tilde{B}^{\Theta}_{l_1 l_2 l_3} = \sum_{m_1 m_2 m_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle \tilde{\Theta}_{l_1 m_1} \tilde{\Theta}_{l_2 m_2} \tilde{\Theta}_{l_3 m_3} \rangle
$$

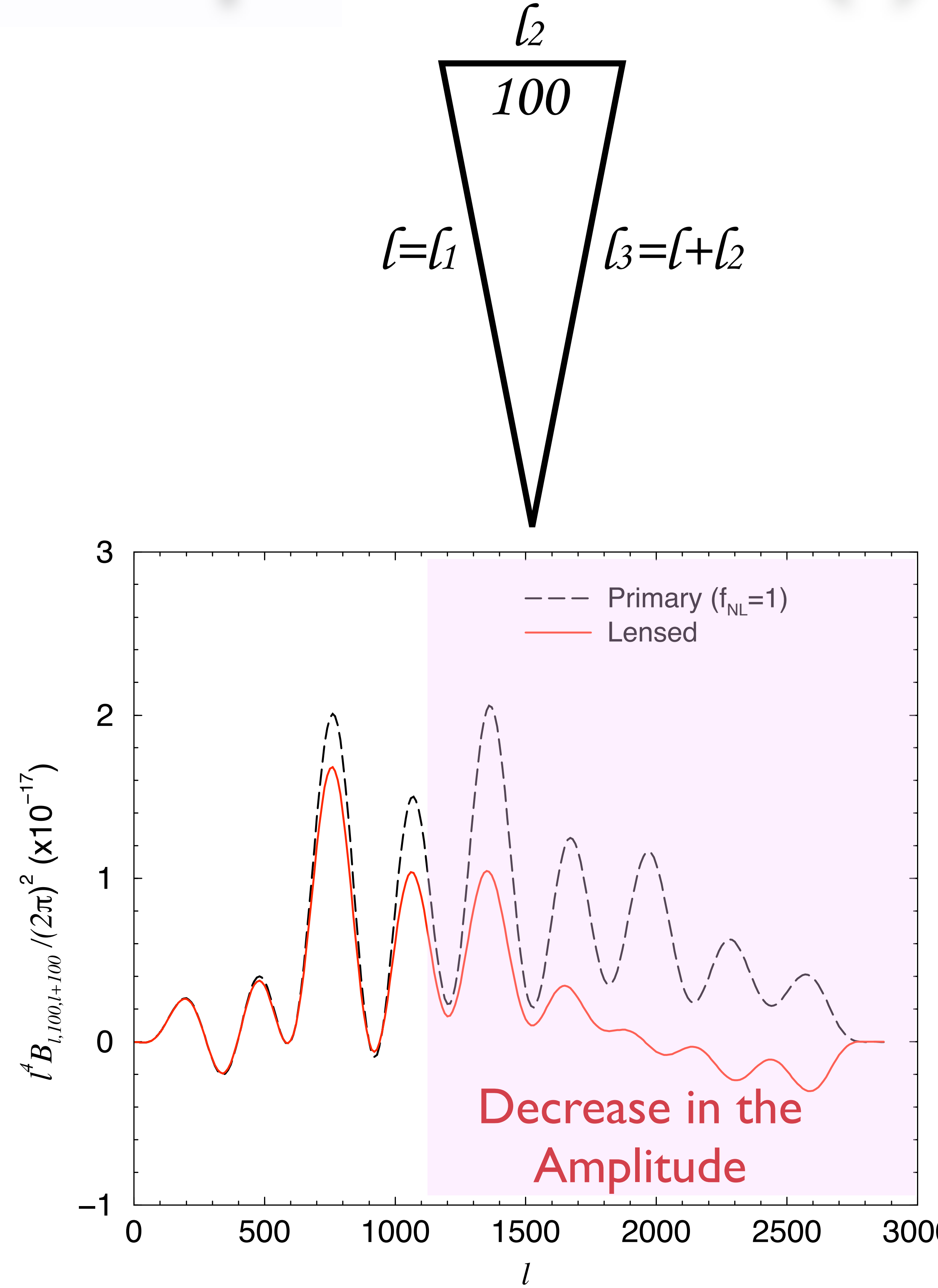
CMB Bispectrum of the Equilateral Case



A. Cooray, D.S., P. Serra; PRD, 77, 123006 (2008)

CMB Bispectrum of the Squeezed Case(s)



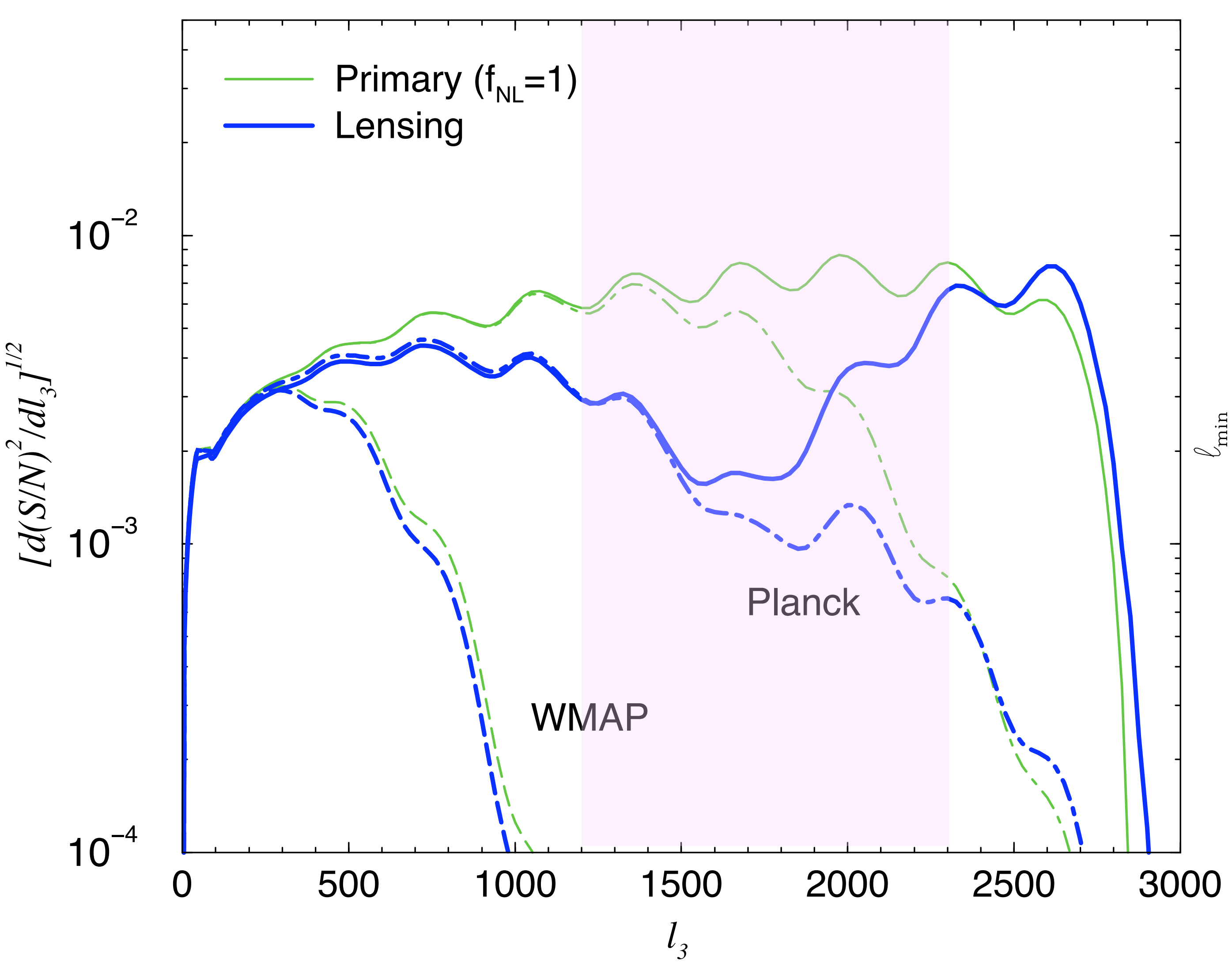


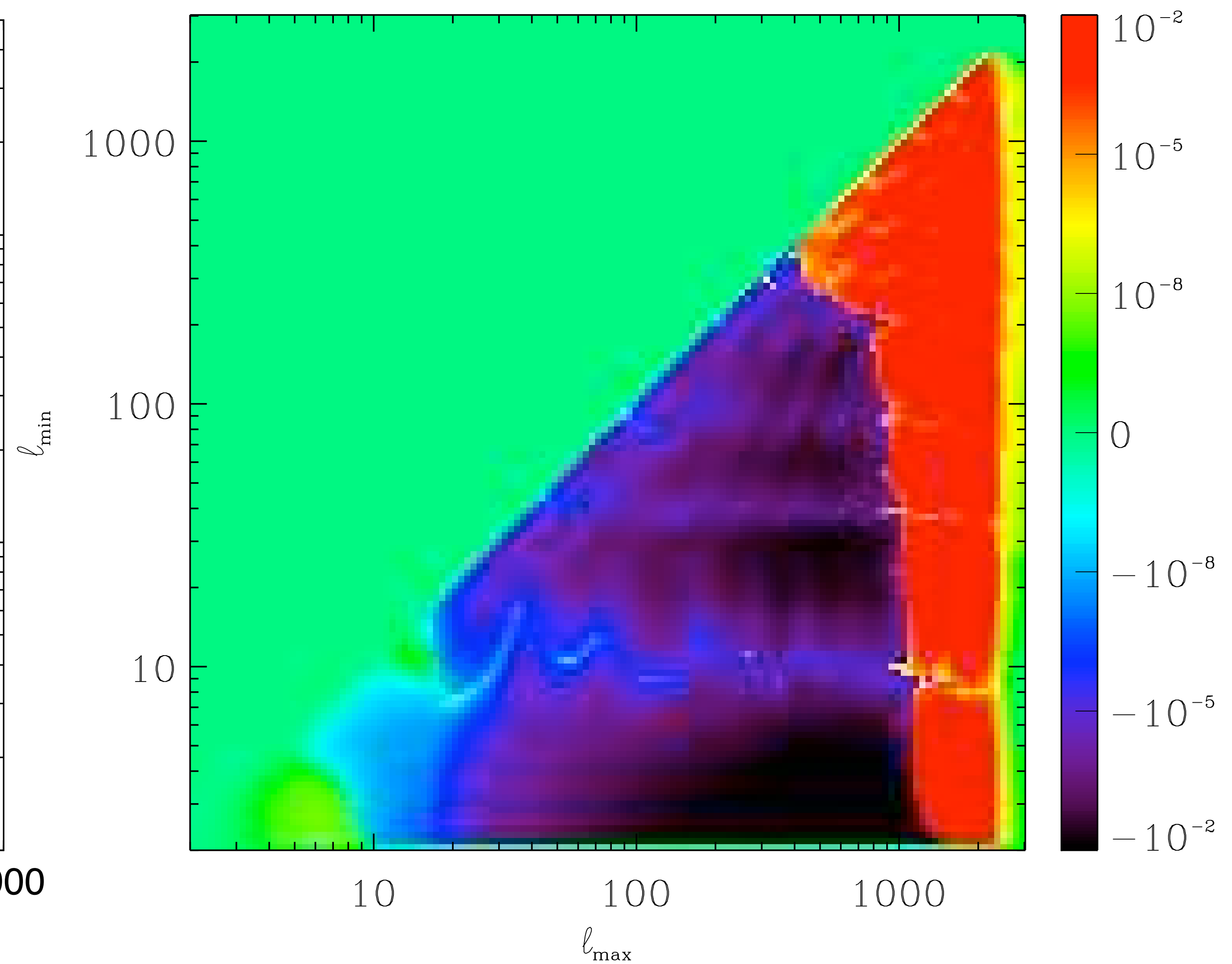
A. Cooray, D.S., P. Serra; PRD, 77, 123006 (2008)

Reduction in the S/N due to Lensing

$$\left(\frac{S}{N}\right)^2 = \sum_{l_1 l_2 l_3} \frac{(B^{\Theta}_{l_1 l_2 l_3})^2}{6 C^{tot}_{l_1} C^{tot}_{l_2} C^{tot}_{l_3}}$$

$$\frac{d\left[\left(\frac{S}{N}\right)^2_{lensed} - \left(\frac{S}{N}\right)^2_{unlensed}\right]}{d\log l_{max}\, d\log l_{min}}$$

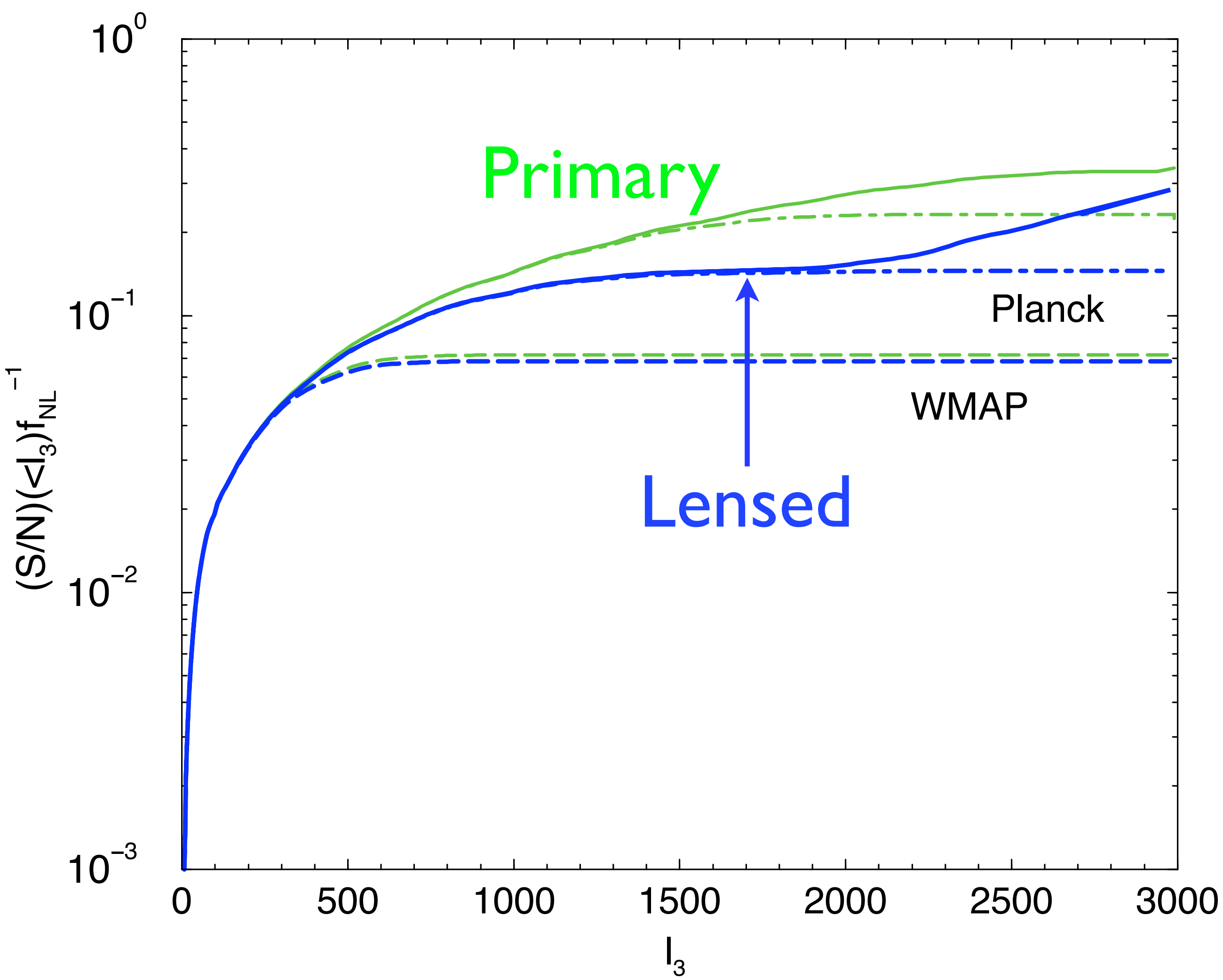


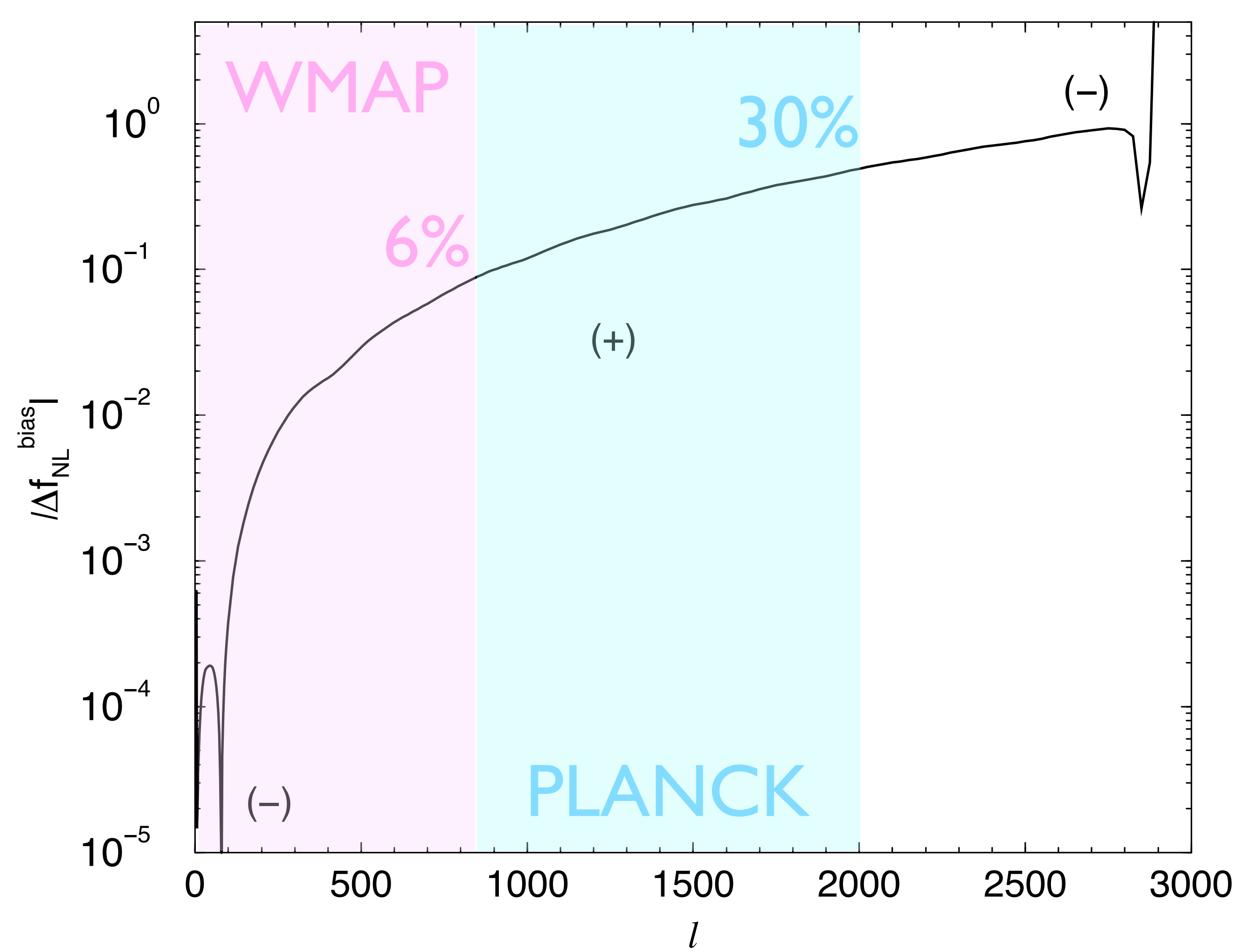


A. Cooray, D.S., P. Serra; PRD, 77, 123006 (2008)

Bias in the Non-Gaussianity Parameter

$$\frac{\Delta f}{\hat{f}_{NL}} \equiv \frac{f_{NL}^{true} - \hat{f}_{NL}}{\hat{f}_{NL}} = 1 - \frac{\sum B^{\Theta}_{l_1 l_2 l_3} \sigma^{-2} \tilde{B}^{\Theta}_{l_1 l_2 l_3}}{\sum B^{\Theta}_{l_1 l_2 l_3} \sigma^{-2} B^{\Theta}_{l_1 l_2 l_3}}$$





Minimum detectable value of f_{NL}
7 (instead of 5) for Planck

A. Cooray, D.S., P. Serra; PRD, 77, 123006 (2008)

Two Stories

Start With...

Lensing of Supernova

- DE Equation of State (EOS)
- SN plays a key role
- Systematics: Worry! Worry!
- SN Lensing
  - Details of Photon Path
  - Effect on the EOS

And Then...

of the CMB Bispectra

- Why Non-Gaussianity?
- Why in CMB Bispectrum?
- The f_{NL}
- WL of CMB Bispectrum
  - Analytic Sketch
  - Numerical Results

Summary

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- We have discussed the concordance model of the Universe. Understanding the nature of the mysterious dark energy component, search for dark matter candidates, and constraining inflationary models are some of the major challenges.

- We have shown that the next-generation surveys will be able to constrain the dark energy equation of state in three or more independent redshift bins to better than 10%.

- For a JDEM-like survey, we have shown that the bias in the equation of state measurement, introduced due to gravitational lensing of SNe, is less than a percent level (so long as all the SNe are used in the Hubble diagram).

- We have discussed the lensing modification to the CMB bispectrum and demonstrated that lensing leads to an overall decrease in the amplitude of the primary bispectrum at multipoles of interest between 100 and 2000 through additional smoothing introduced by lensing. For a high resolution experiment such as Planck, the lensing modification to the bispectrum must be properly included when attempting to estimate the primordial non-Gaussianity. An ignorance will bias the estimate at the level of 30%.

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