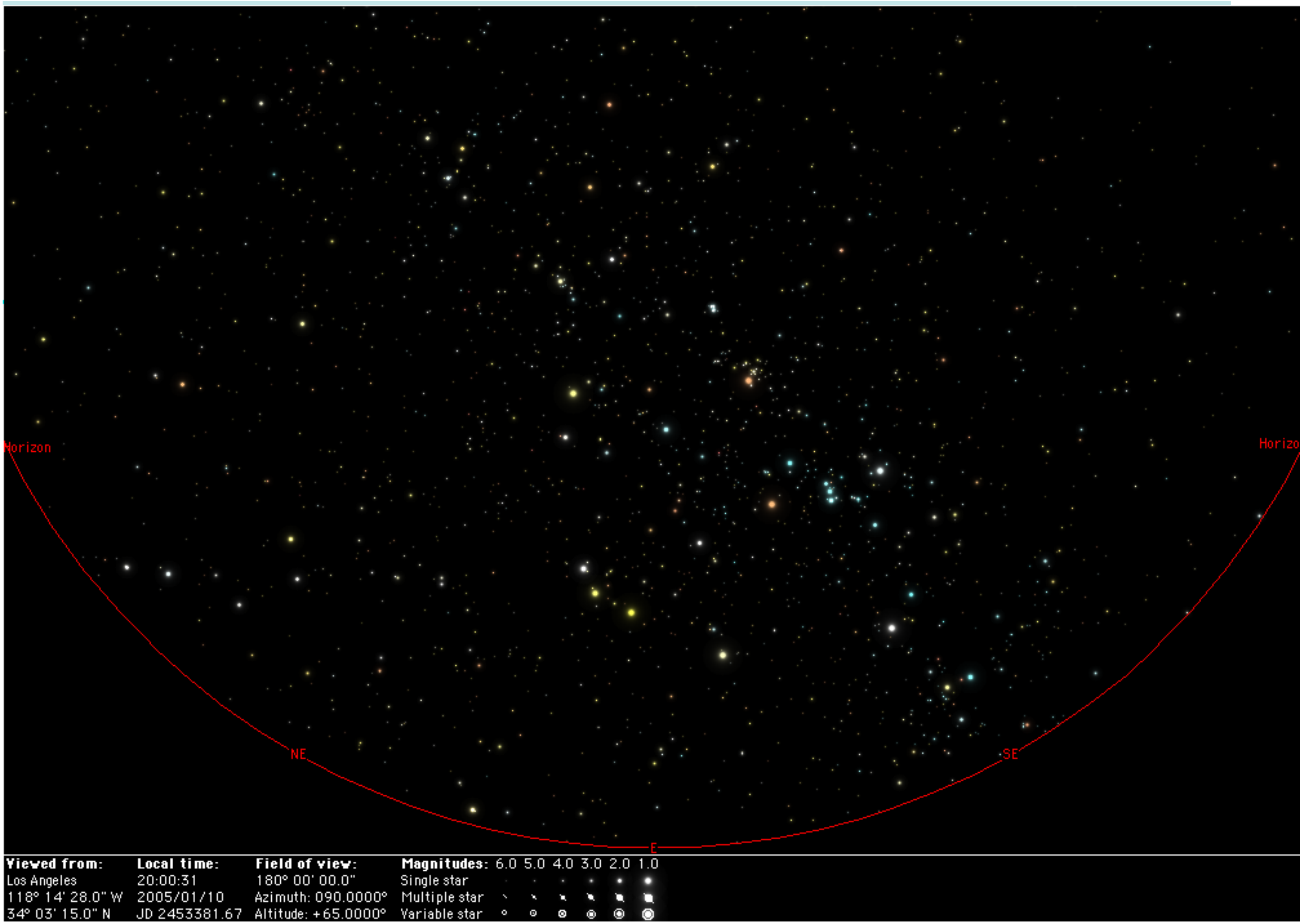
Dark Matter and Dark Energy

Kim Griest UCSD

June 2012



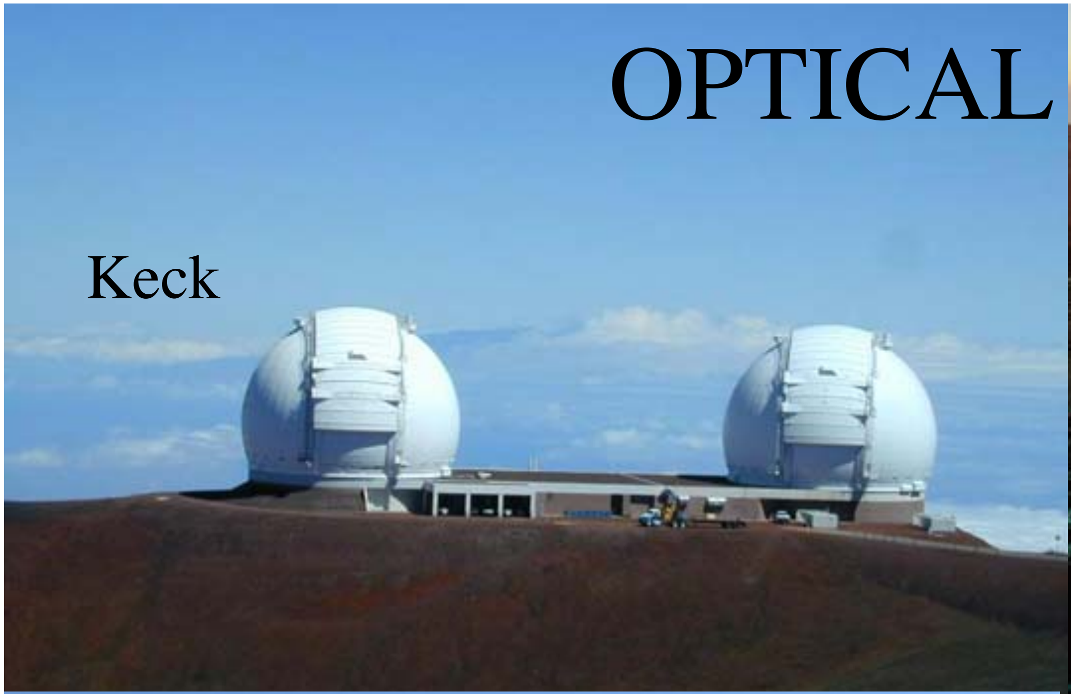
Viewed from:
Los Angeles
118° 14' 28.0" W
34° 03' 15.0" N

Local time:
20:00:31
2005/01/10
JD 2453381.67

Field of view:
180° 00' 00.0"
Azimuth: 090.0000°
Altitude: +65.0000°

Cassini-H:
Saturn
And Dione

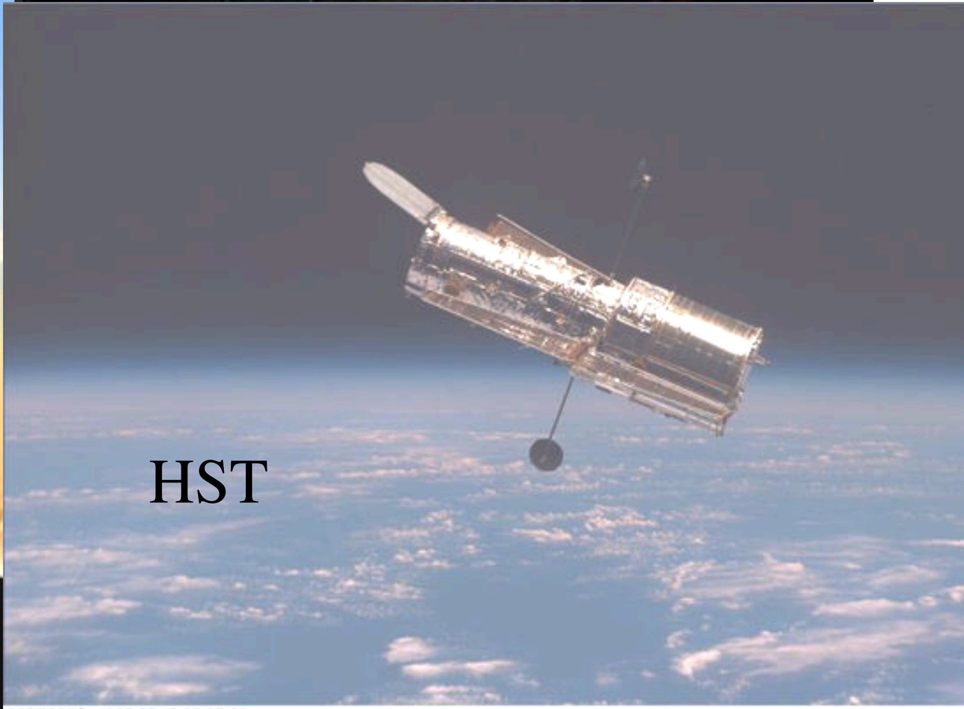
OPTICAL



Keck

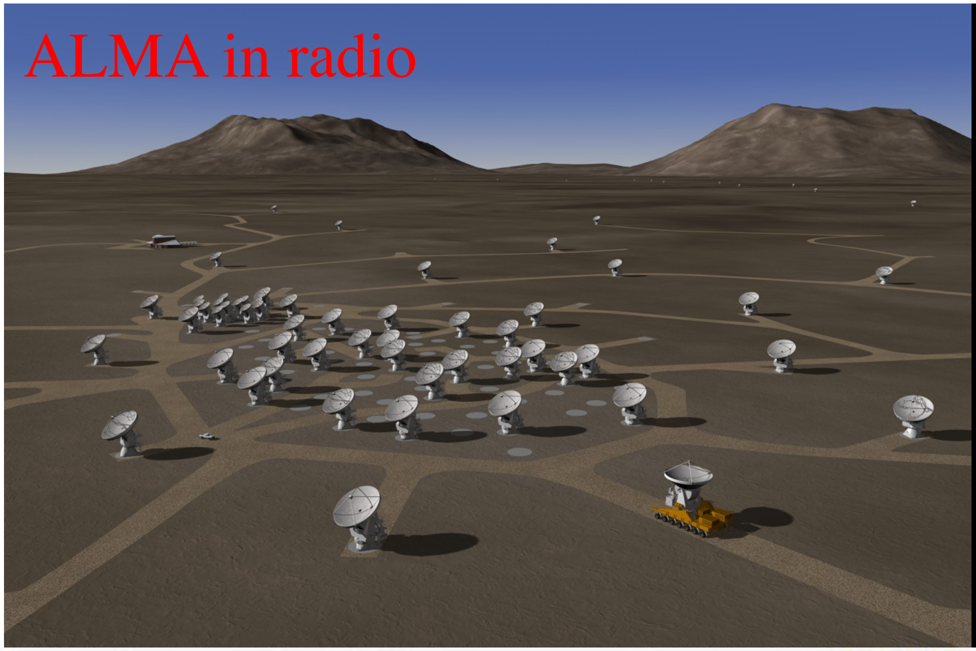
VLT

TMT



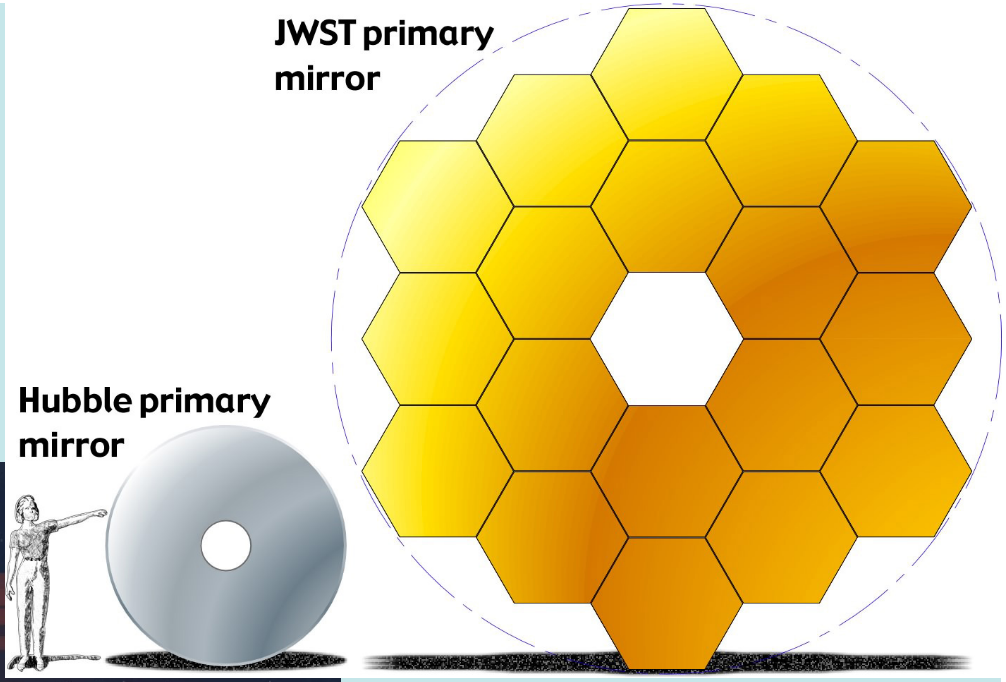
HST

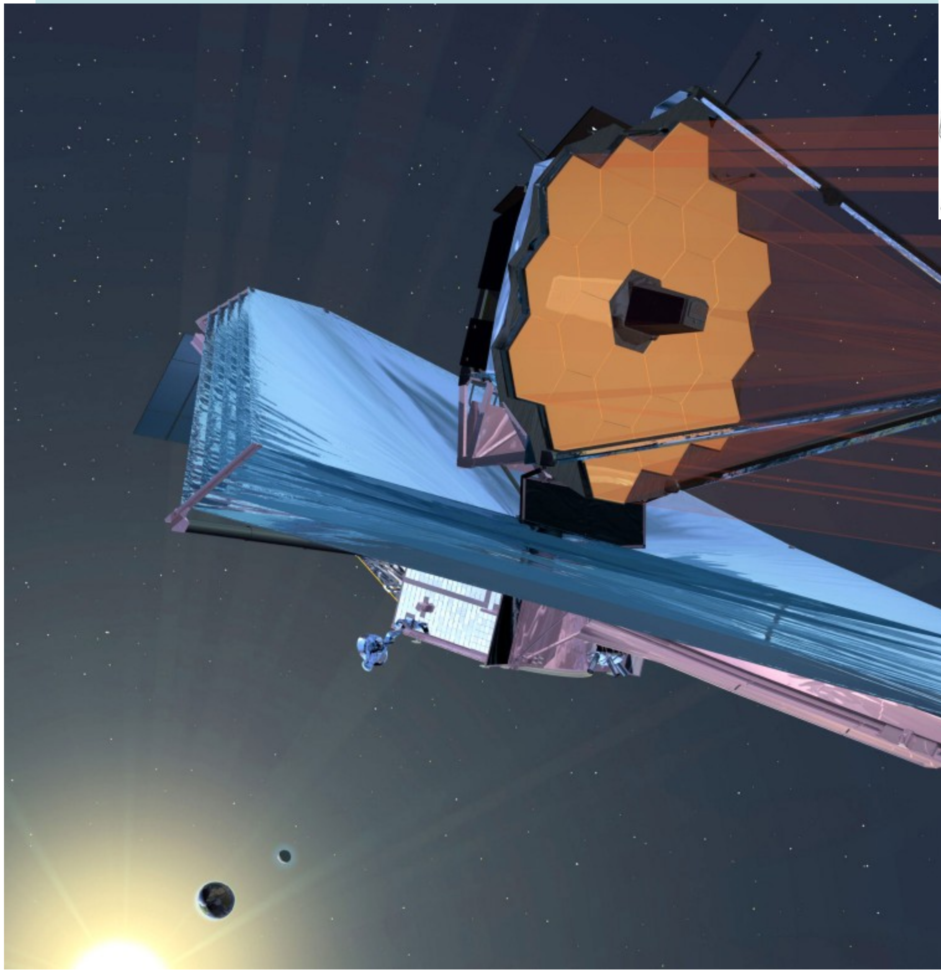
S82E5938 1997:02:19 07:07:00


ALMA in radio

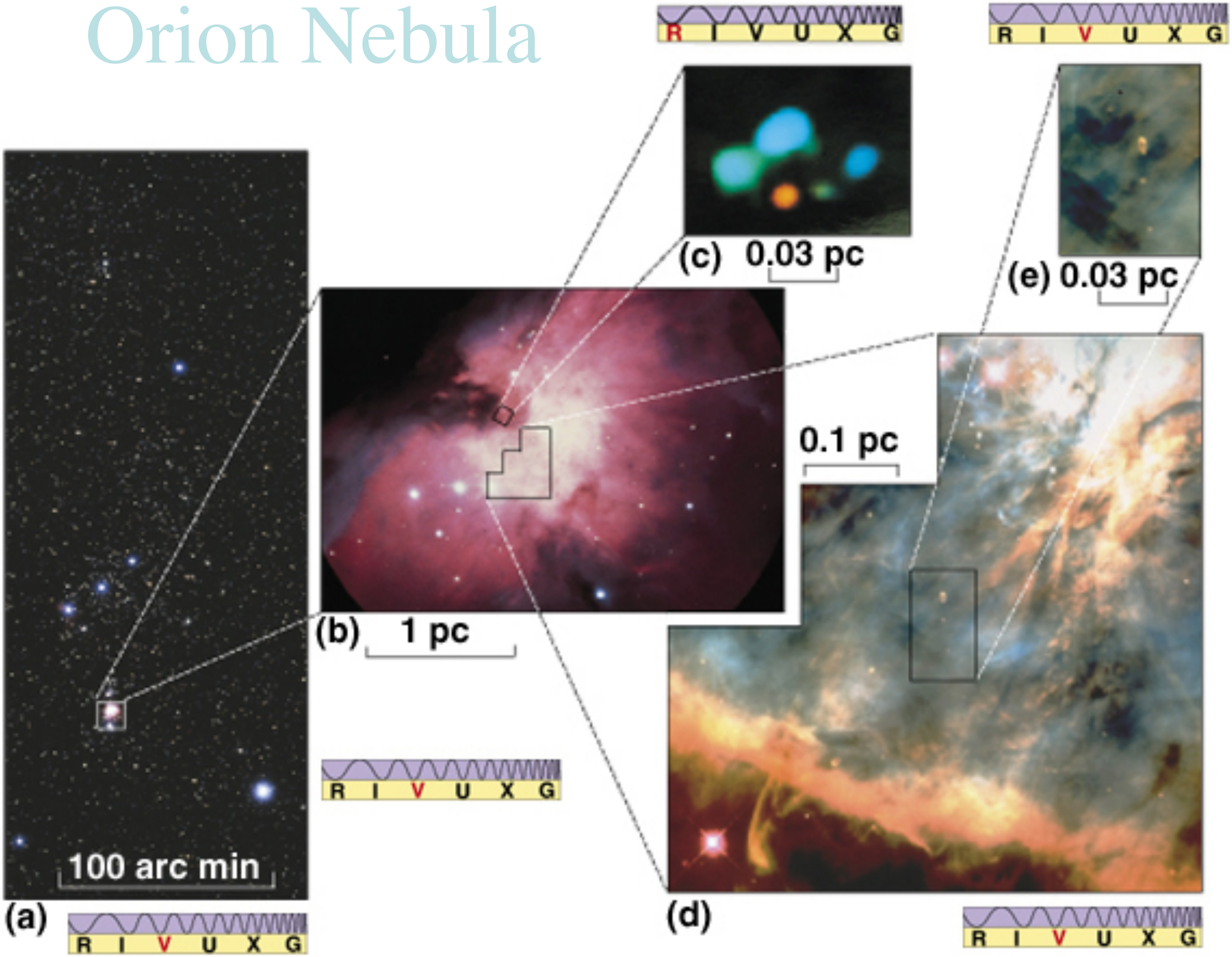

CHANDRA in X-ray

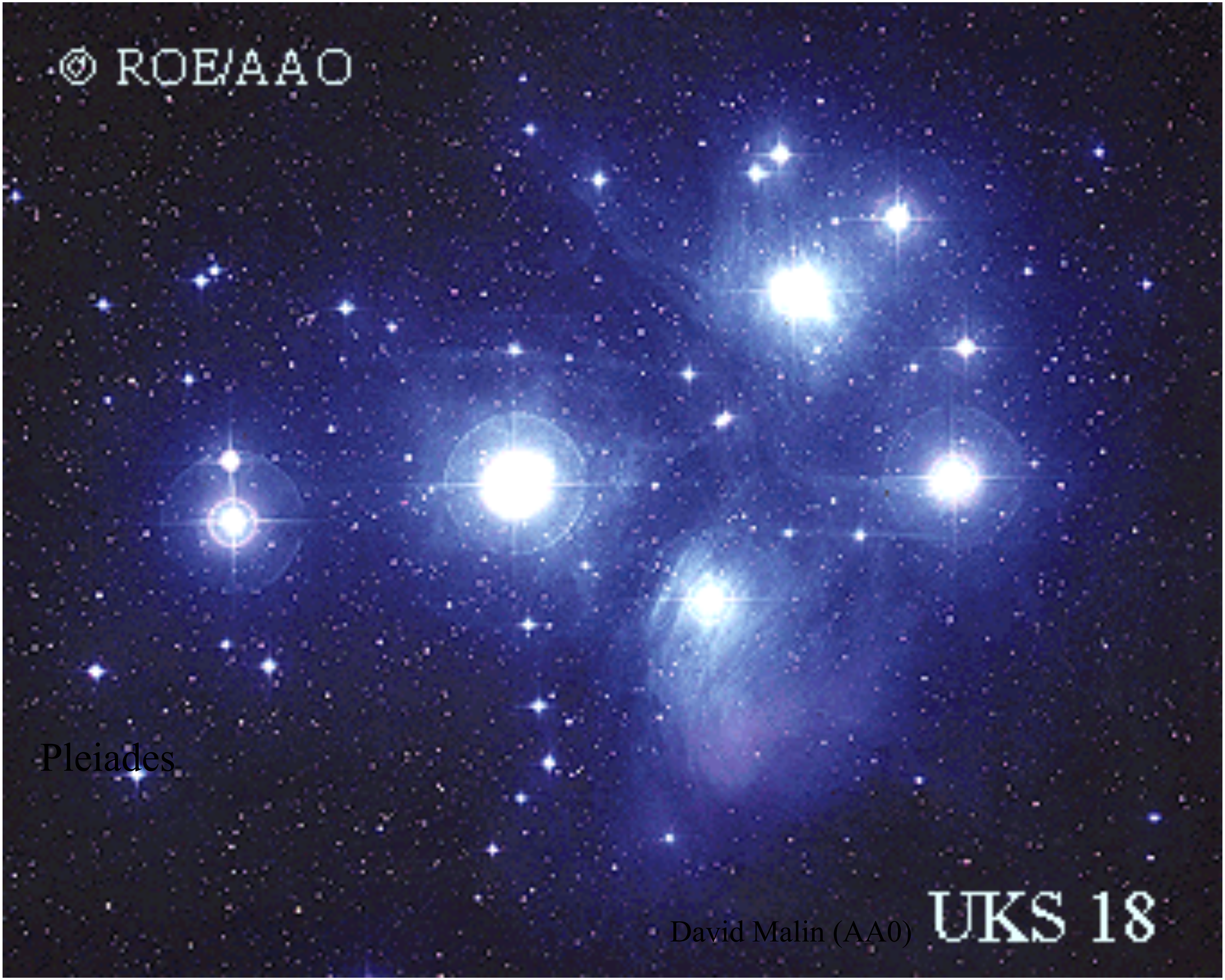
JWST in the infrared





Orion Nebula

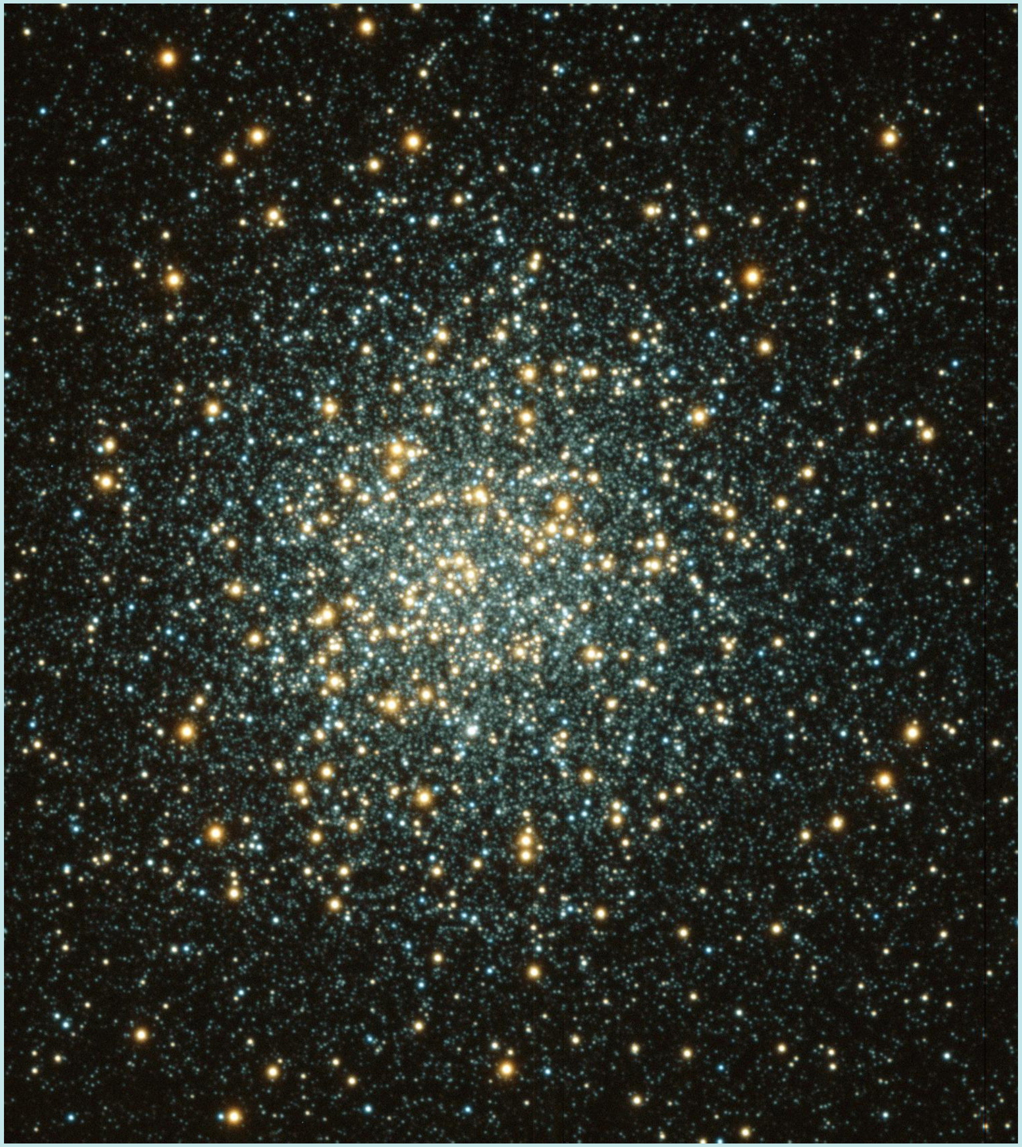


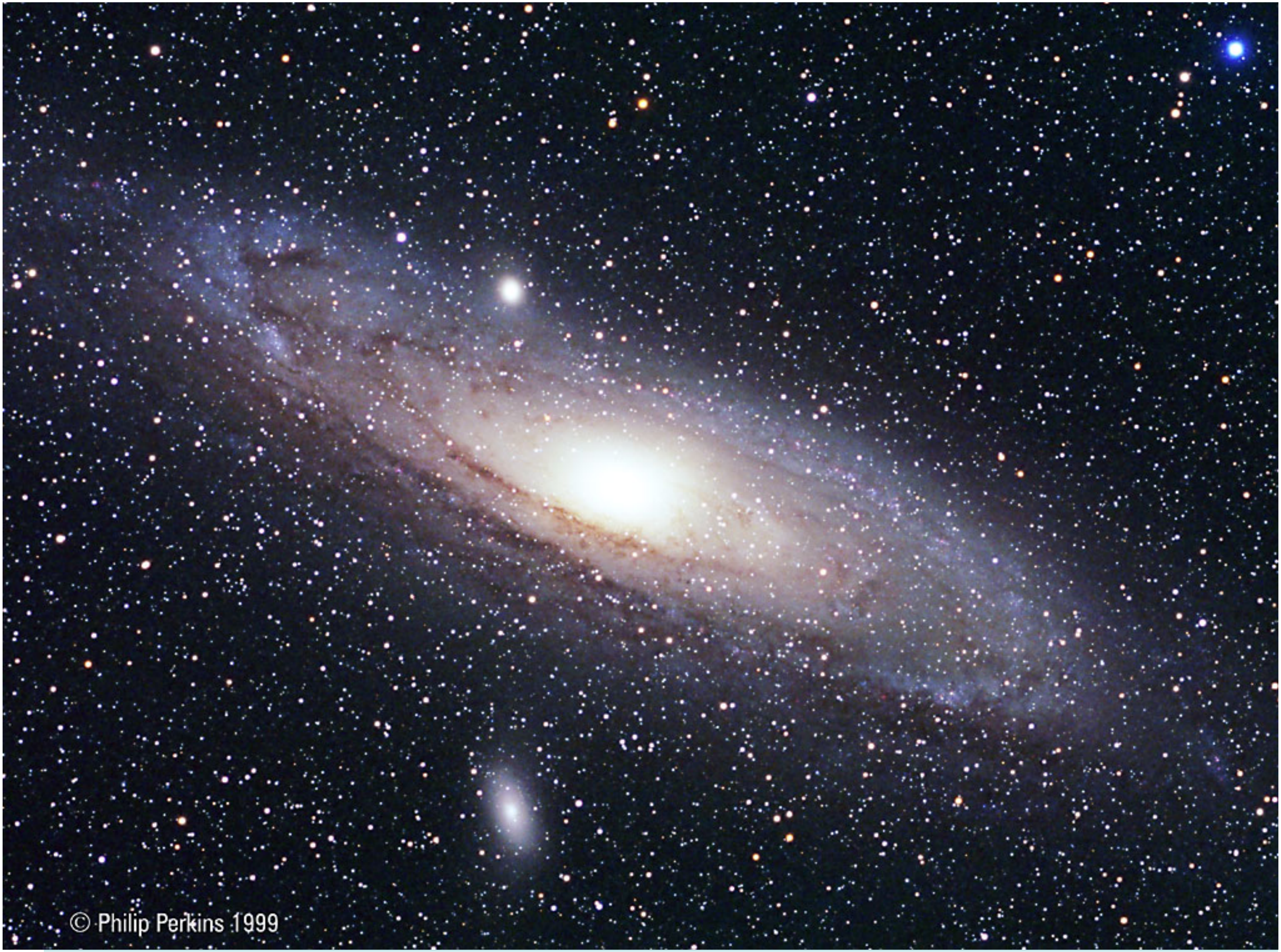


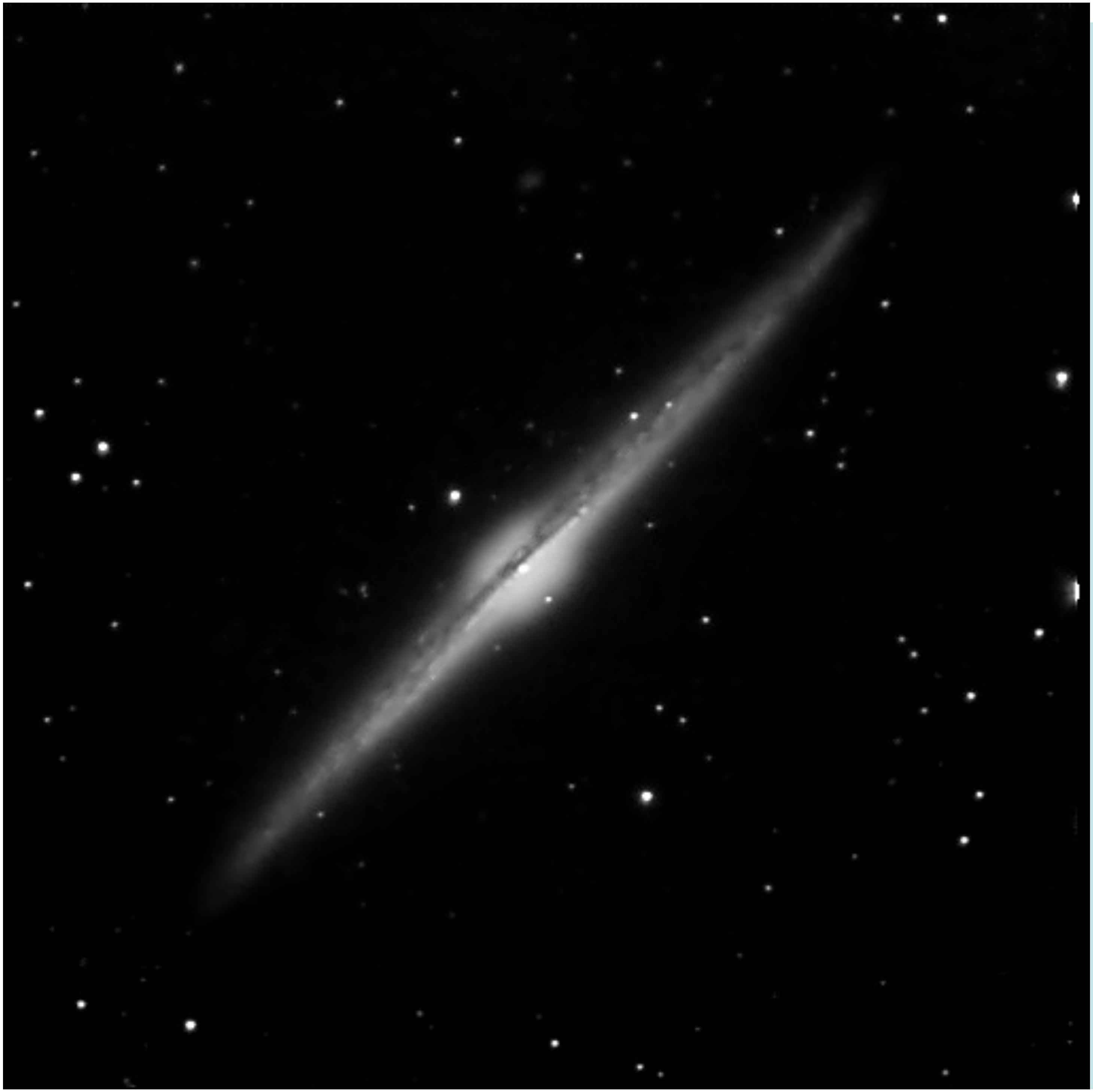
Pleiades

David Malin (AA0)

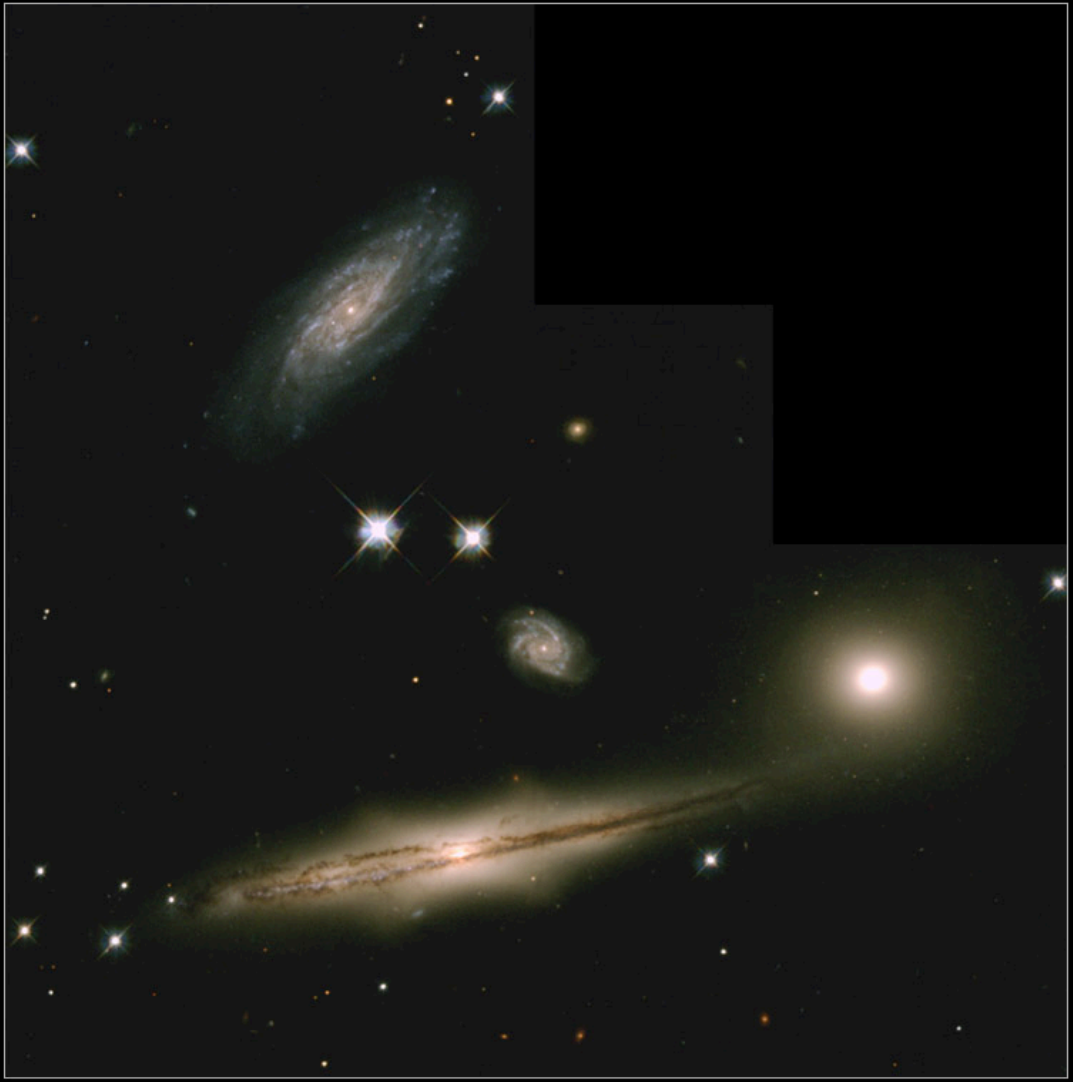
M3





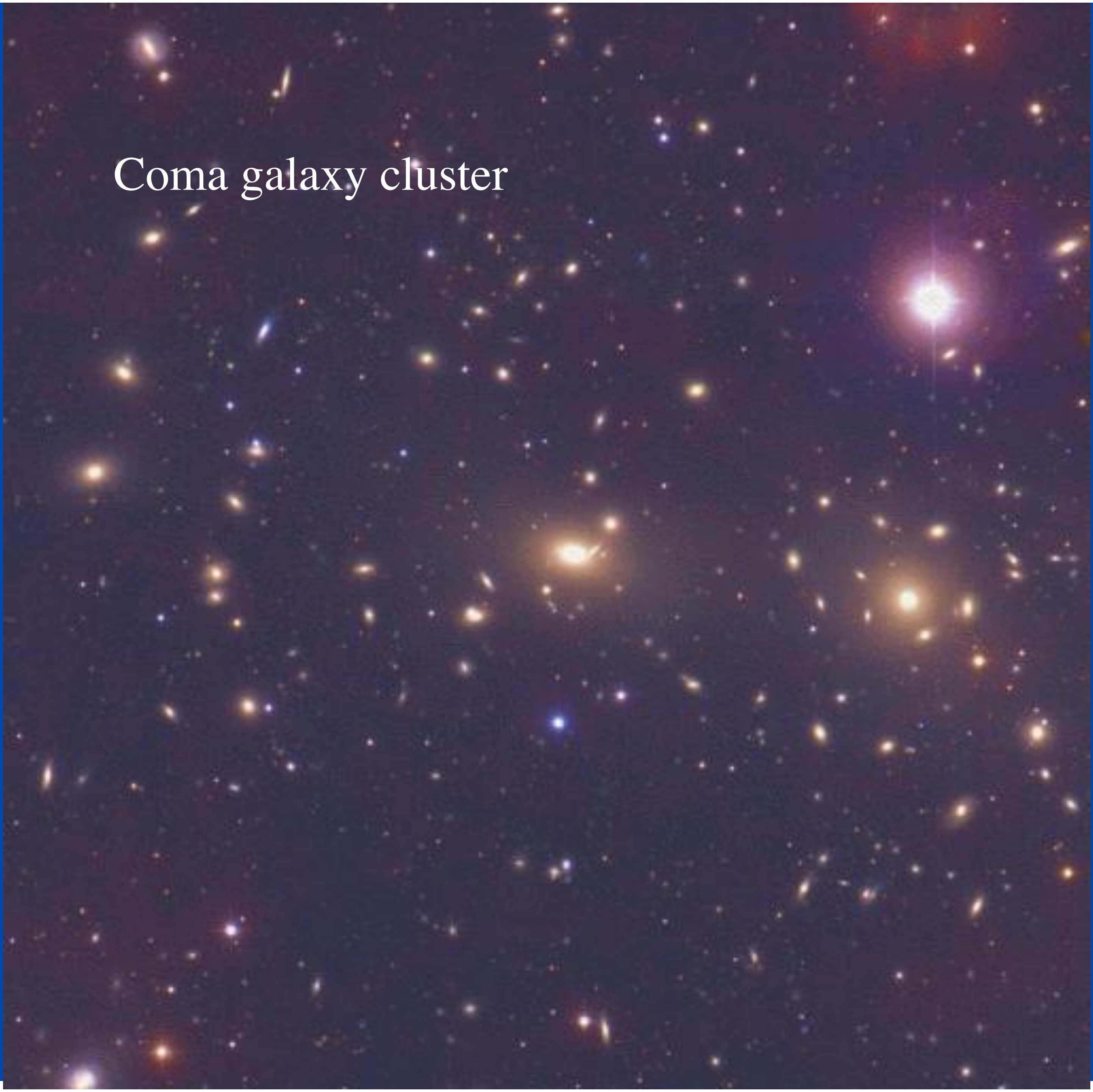


Hickson Compact Group 87



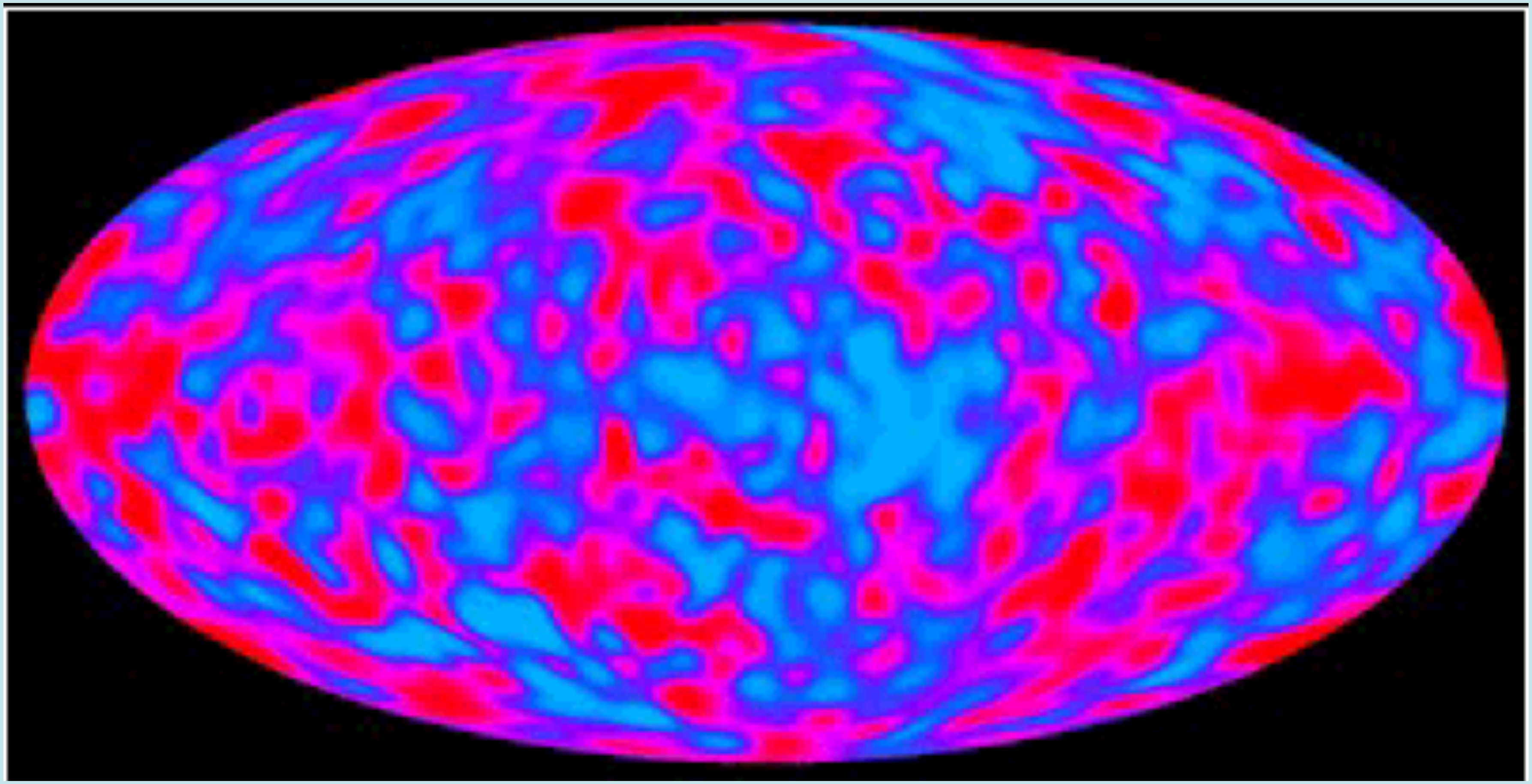
Hubble Heritage

PRC99-31 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)


Coma galaxy cluster

Hubble Deep Field

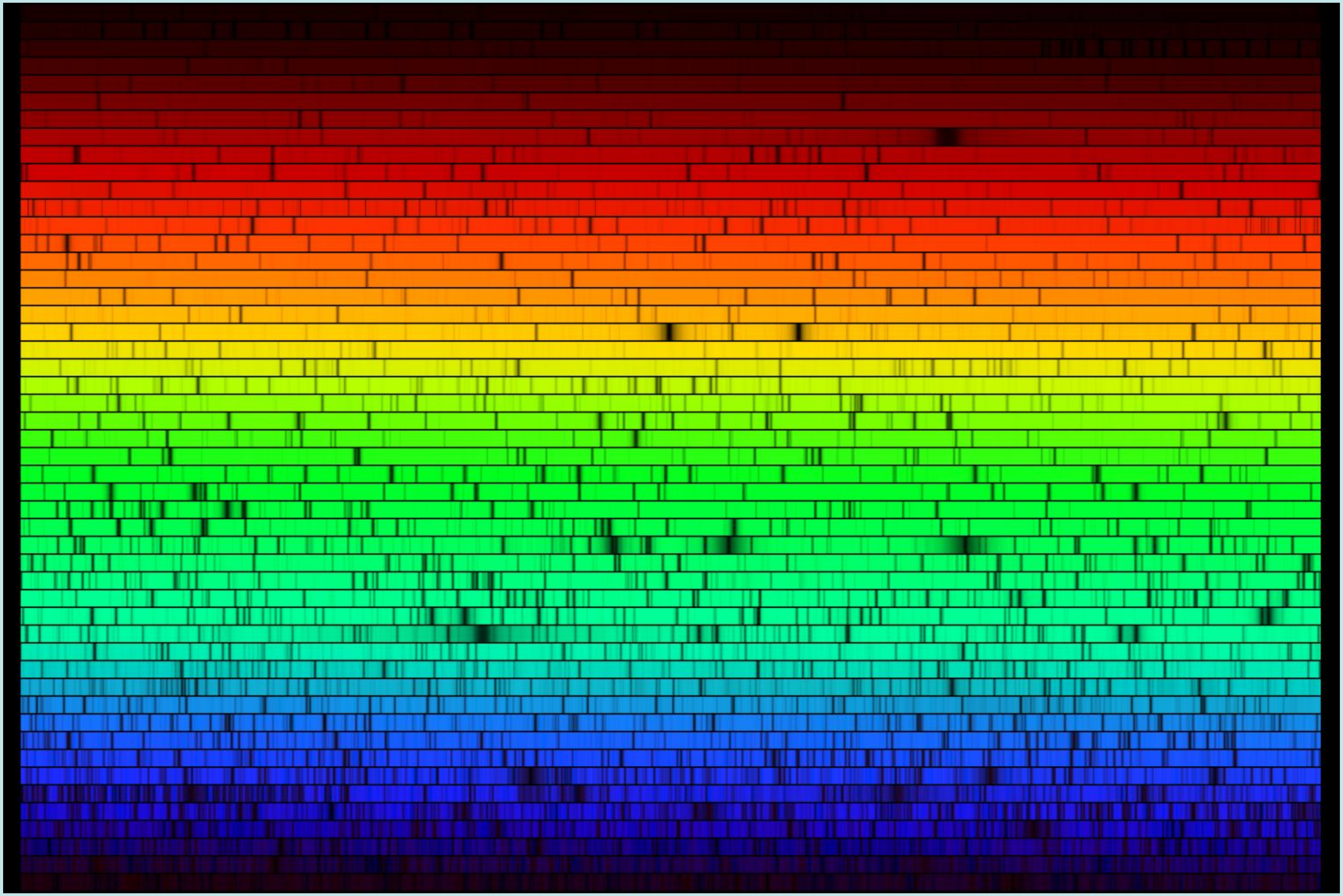
Cosmic Microwave Background: Relic Radiation from Big Bang

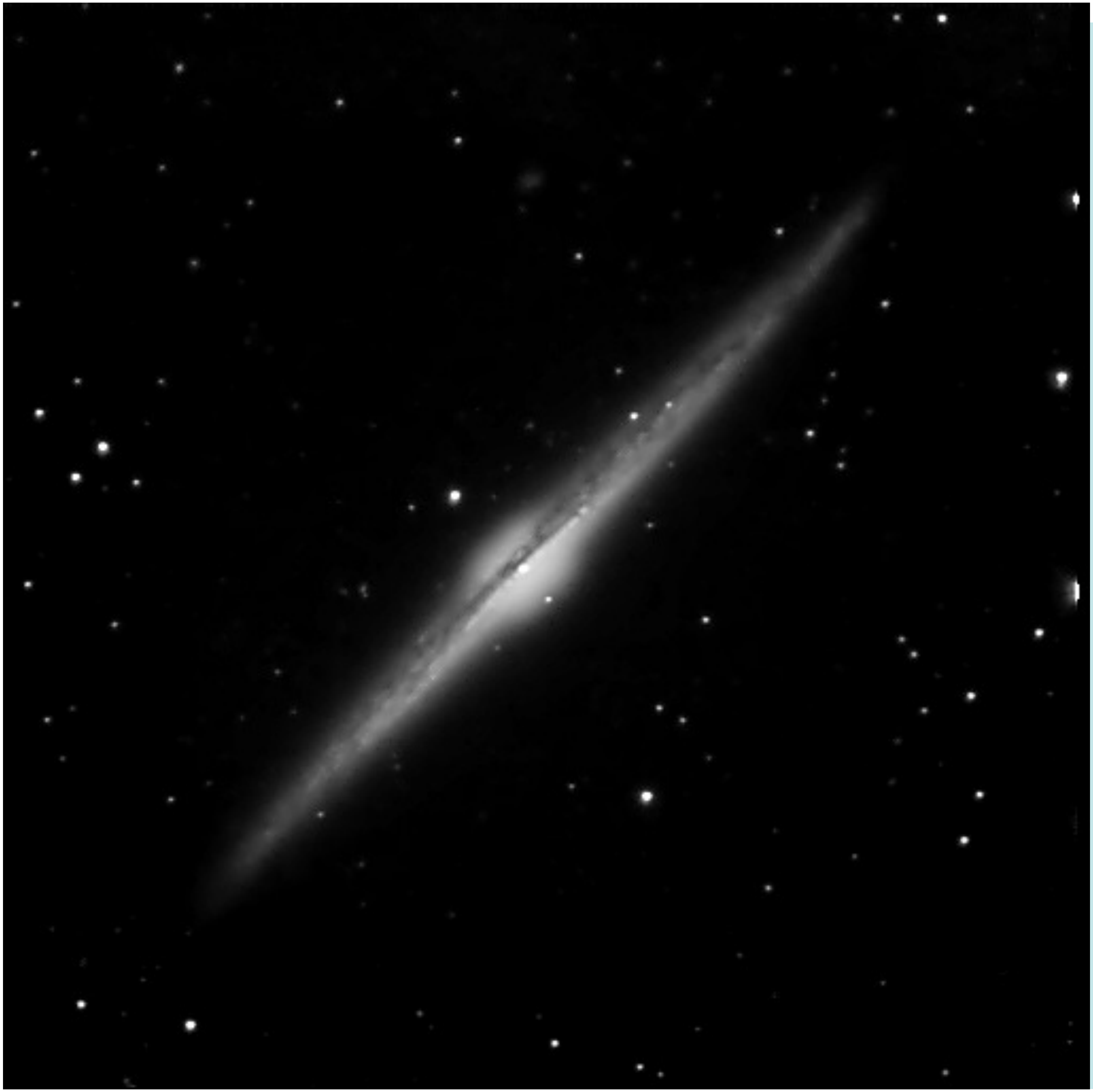


NASA COBE

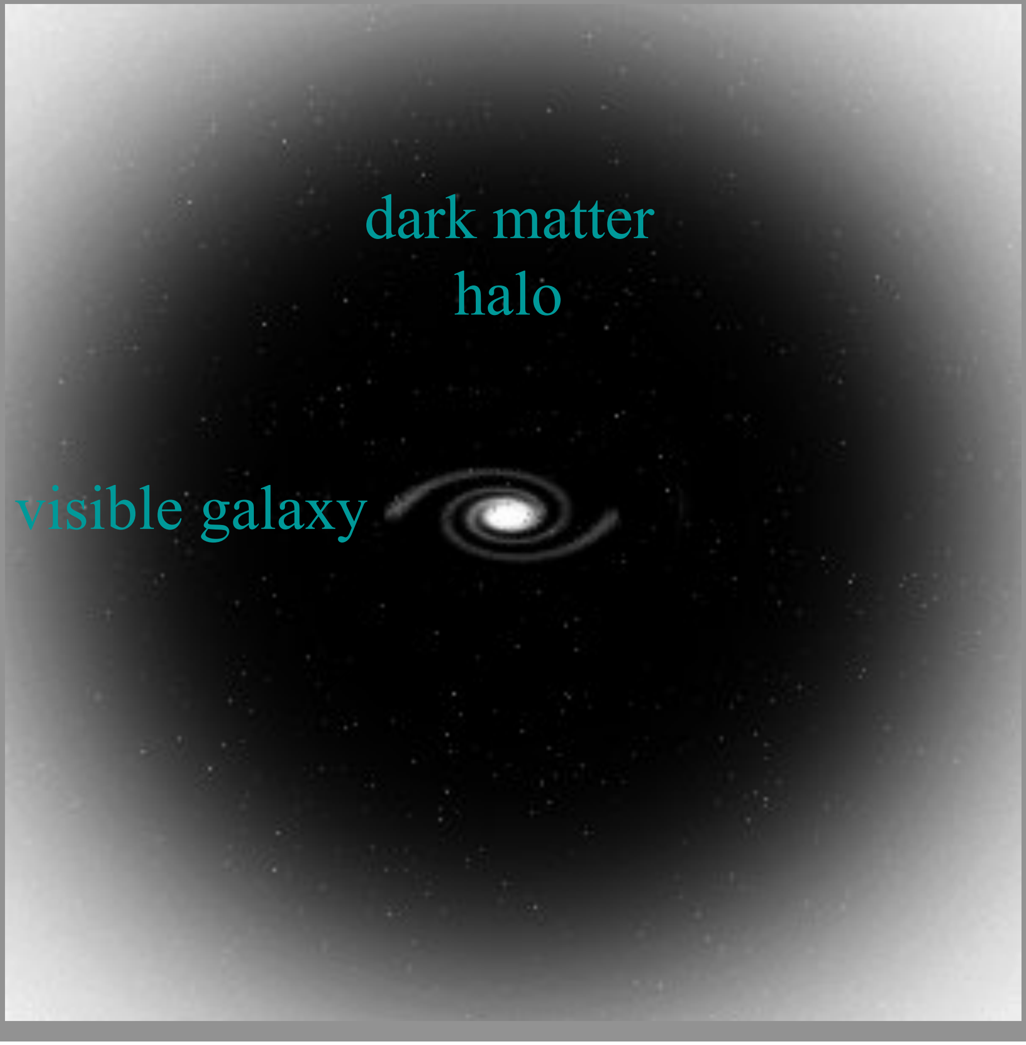
- Where is the Dark Matter?

Keck HIRES Echelle spectrum: 415nm-662nm

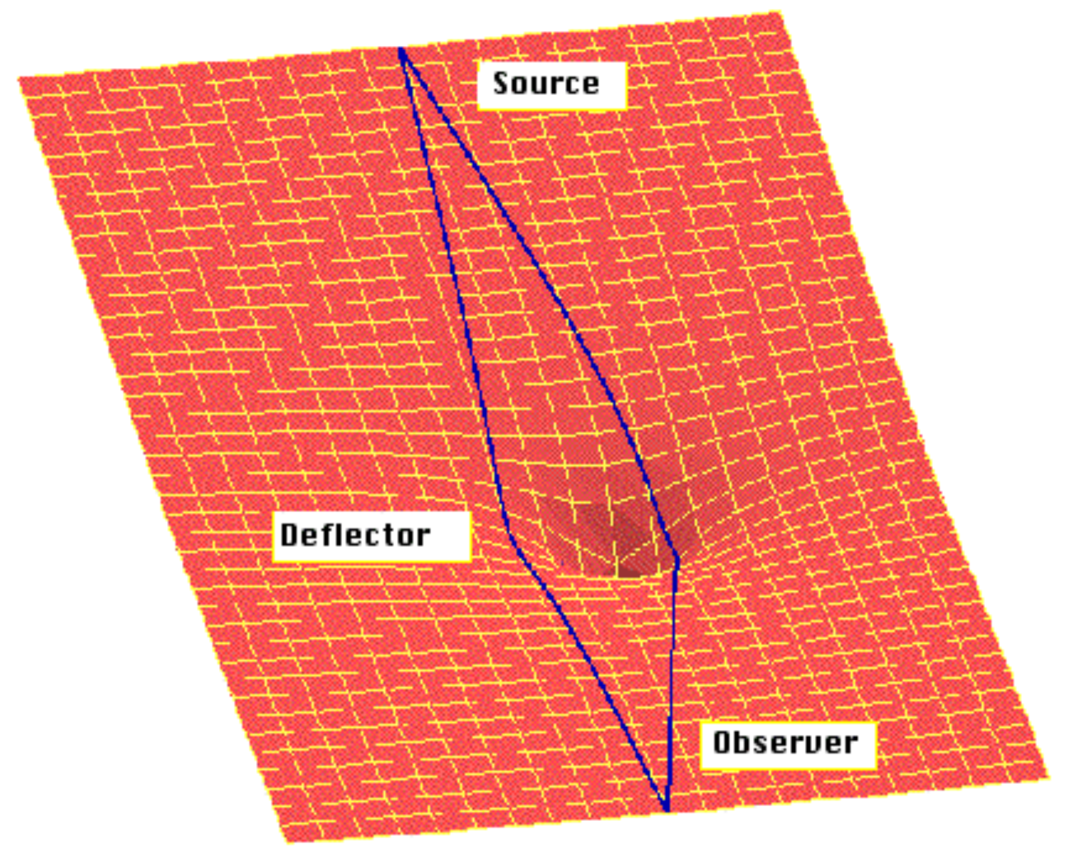




More Than Meets the Eye: Galaxy with Dark Matter Halo

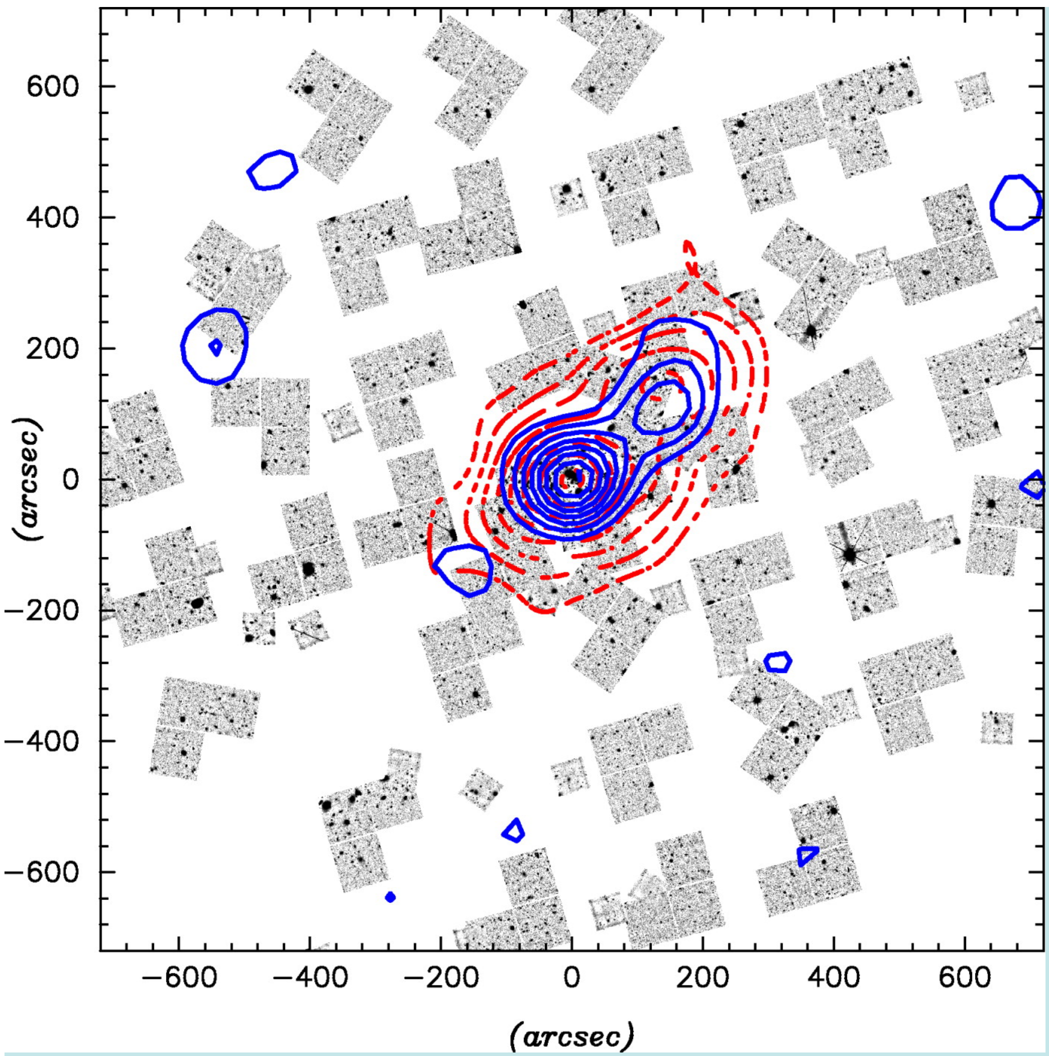


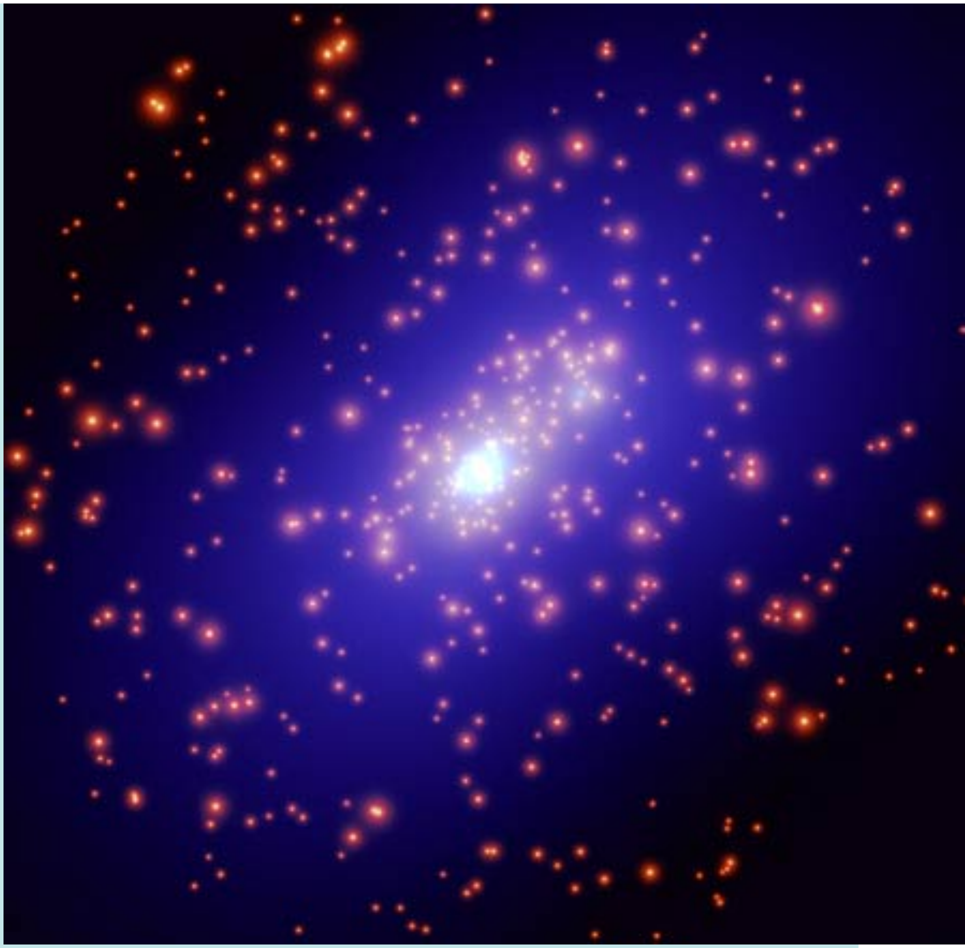
Gravitational Lensing



$$\Delta\theta = \frac{4GM}{bc^2}$$

Light bending => split and magnify image, move images around, and shear image shape





Oliver Czoske, Lars Bähren

- A mosaic of HST/WFPC2 exposures of the cluster of galaxies Cl0024+1654 has been used to derive the distribution of dark matter out to a large distance from the cluster centre. The distribution of the dark matter is shown in blue, while the cluster galaxies are shown in red.

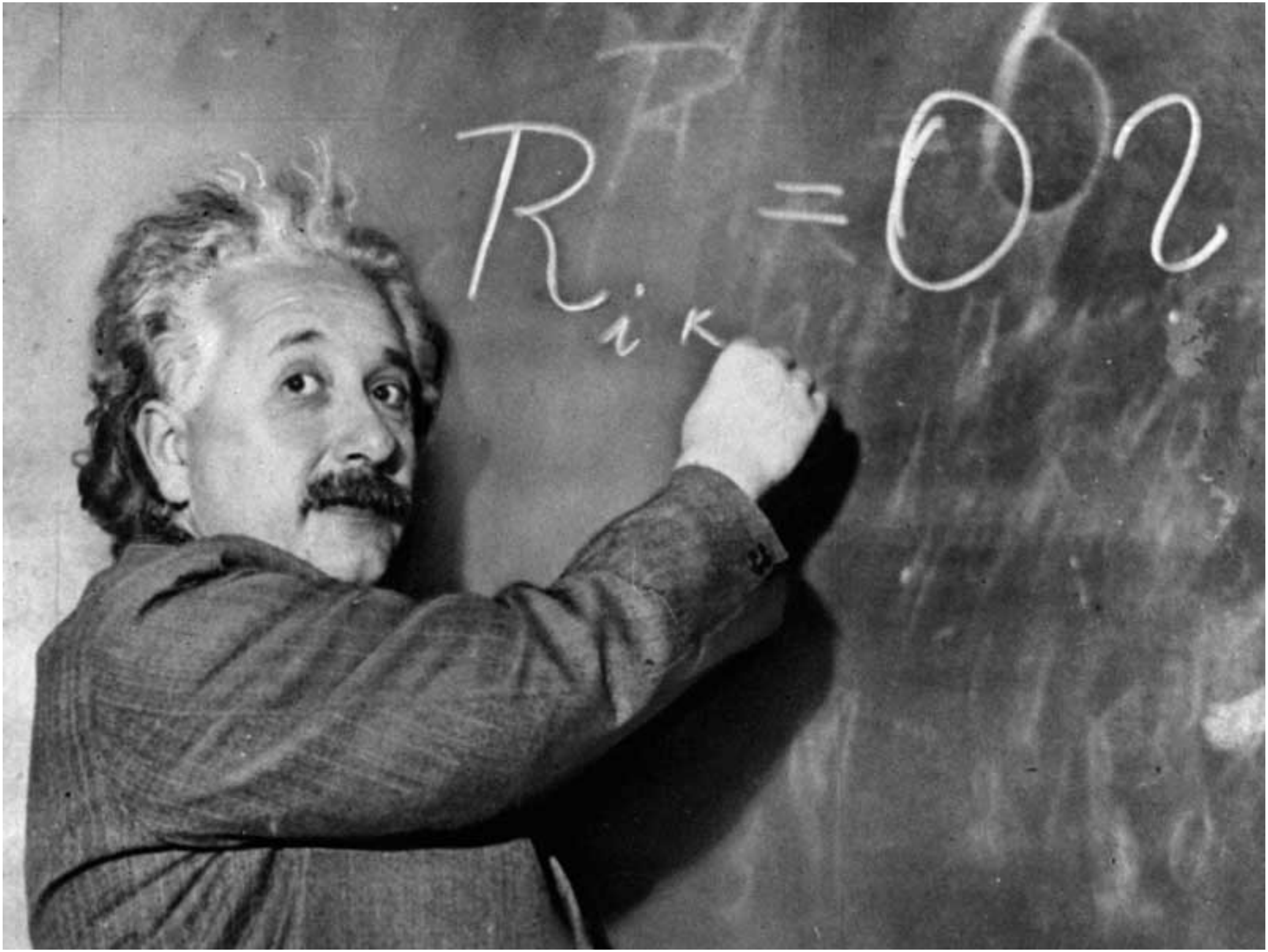
Chandra X-rays in pink; HST/Magellan stars in white; mass
Via gravitational lensing in blue (Clowe, et al)

So Dark Matter exists and there is 5 times more of it than atoms.
But what could Dark Matter be?

- Weakly Interacting Massive Particles (WIMPs)
  - Predicted from supersymmetry
  - Come from early universe in right number
  - Probably detectable
- Massive Compact Halo Objects (MACHOs)
  - Black holes, dead or dim stars, planets, quark nuggets
  - Ruled out by our experiment!
- Axions
- Very small primordial black holes
- Other exotic particles
- Stuff from extra dimensions
- Non-Newtonian gravity
- Etc., etc. etc., or none-of-the above
- See talk by Manoj Kaplinghat

- Where is the Dark Energy?

Hubble Deep Field


$R_{ik} = 0$

GR replaces gravity as a force with the curvature of spacetime. Says local matter and energy (&stress) curves spacetime and determines the metric, and the metric determines distances and times, telling matter how to move. In flat space (energy=0) the metric is:

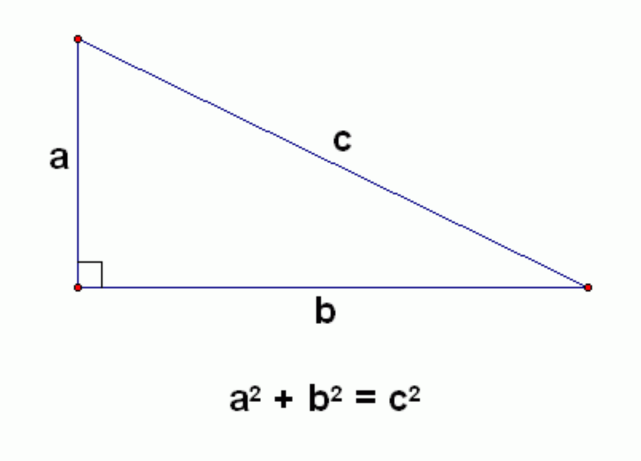
$$ds^2 = dx^2 + dy^2 + dz^2 - c^2 dt^2$$

Einstein plugged in uniform density of stars (galaxies) and found:

$$ds^2 = R(t)^2(dx^2 + dy^2 + dz^2) - c^2 dt^2$$

with scale factor: $R(t) \approx (t/t_0)^{2/3}$

Thus distances between galaxies increase even for galaxies at rest in the local frame! (expansion of Universe)



Can answer common questions:

What is U expanding into? What if t=0? Where did big bang happen? Can galaxies move apart faster than c?

I said R~$t^{2/3}$ for uniform cold matter, but Einstein's field equations give equations for R in terms of energy density, ρ, pressure, p, and curvature, k: (Called FRW equations)

$$\frac{d}{dR}(\rho R^3) = -3pR^2$$ (Bianchi, i.e. energy conservation)

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{R^2} + \Lambda/3$$

$$H^2 = \frac{(dR/dt)^2}{R^2}$$

$$\frac{d^2R/dt^2}{R} = -\frac{4\pi G}{3}(\rho + 3p) + \Lambda/3$$

In 1917 Einstein put p=0 and discovered no static solution!

Added Cosmological constant Λ, then equations were modified.

Adjusted value of Λ to give static solution (but unstable!)

Hubble (1929) found the expansion; Einstein said "out with Λ".

Now Λ is a form of vacuum or dark energy; in fact most popular form. Why is it Dark Energy?

Different substances give different solutions for R(t). All depends on p.

Radiation ($p=\rho/3$):	$R \sim t^{1/2}$	$\rho \sim R^{-4}$	$d^2R/dt^2 < 0$ (deceleration)
Matter ($p=0$):	$R \sim t^{2/3}$	$\rho \sim R^{-3}$	$d^2R/dt^2 < 0$ (deceleration)
Vacuum ($p=-\rho$):	$R \sim e^{\Lambda t/3}$	$\rho \sim R^{0}$	$d^2R/dt^2 > 0$ (acceleration)

Why does vacuum energy give negative pressure and acceleration?

Since density is constant, $dR/dt \sim R\sqrt{\rho}$ => exponential growth, and pressure is negative due to local conservation of energy.

This was all known in the 1920's. Non-zero Λ came in and out of style as needed. This all changed in 1997.

Two groups discovered $d^2R/dt^2 > 0 \quad \text{(acceleration)}$ (Perlmutter, et al; Schmidt, et al.). This meant $(\rho+3p)<0$! Λ which $p=-\rho$ satisfies.

Science

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THE ACCELERATING UNIVERSE

Breakthrough of the Year

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Photo: Lawrence Berkeley National Lab

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

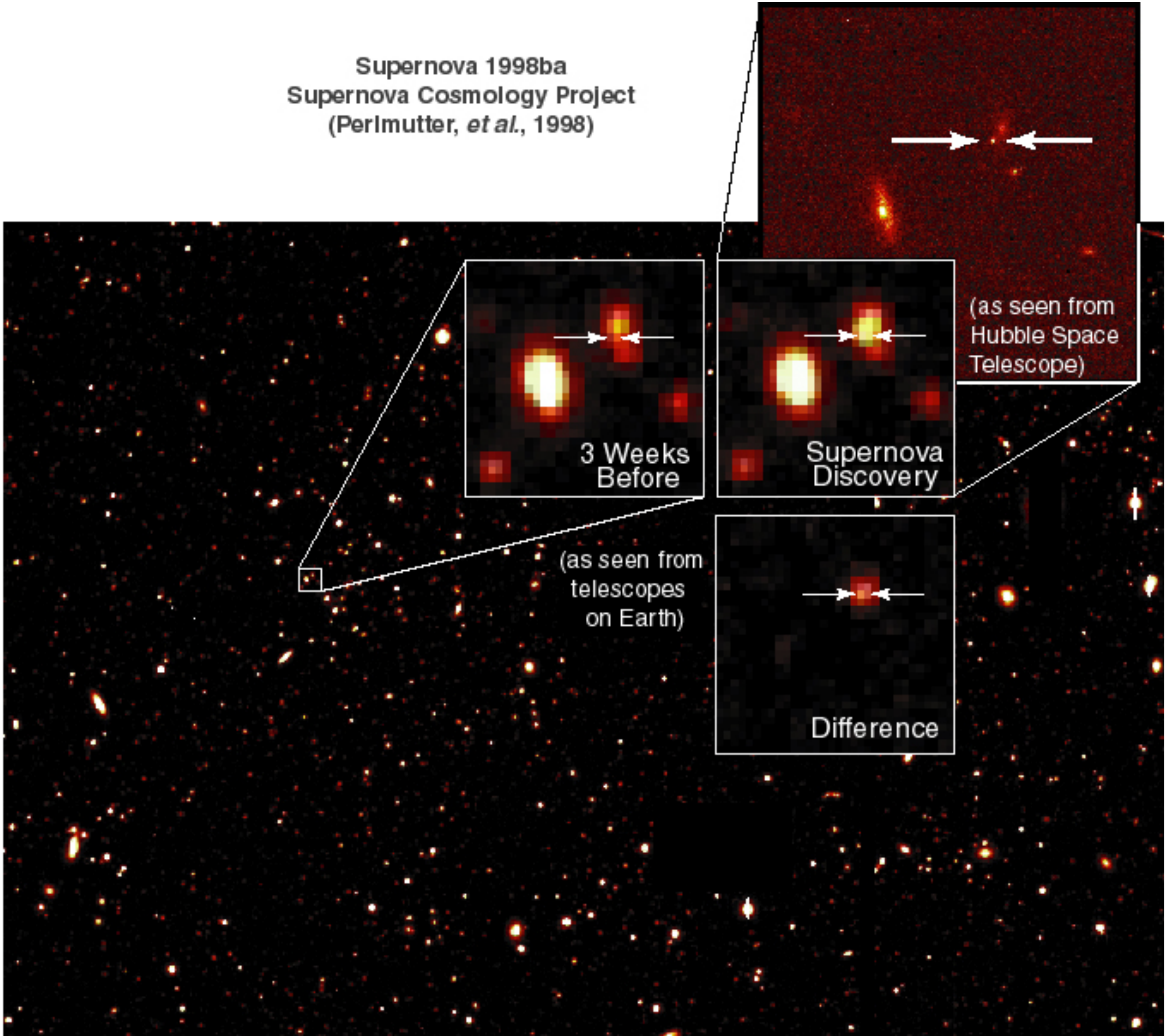
Brian P. Schmidt

Photo: Scanpix/AFP

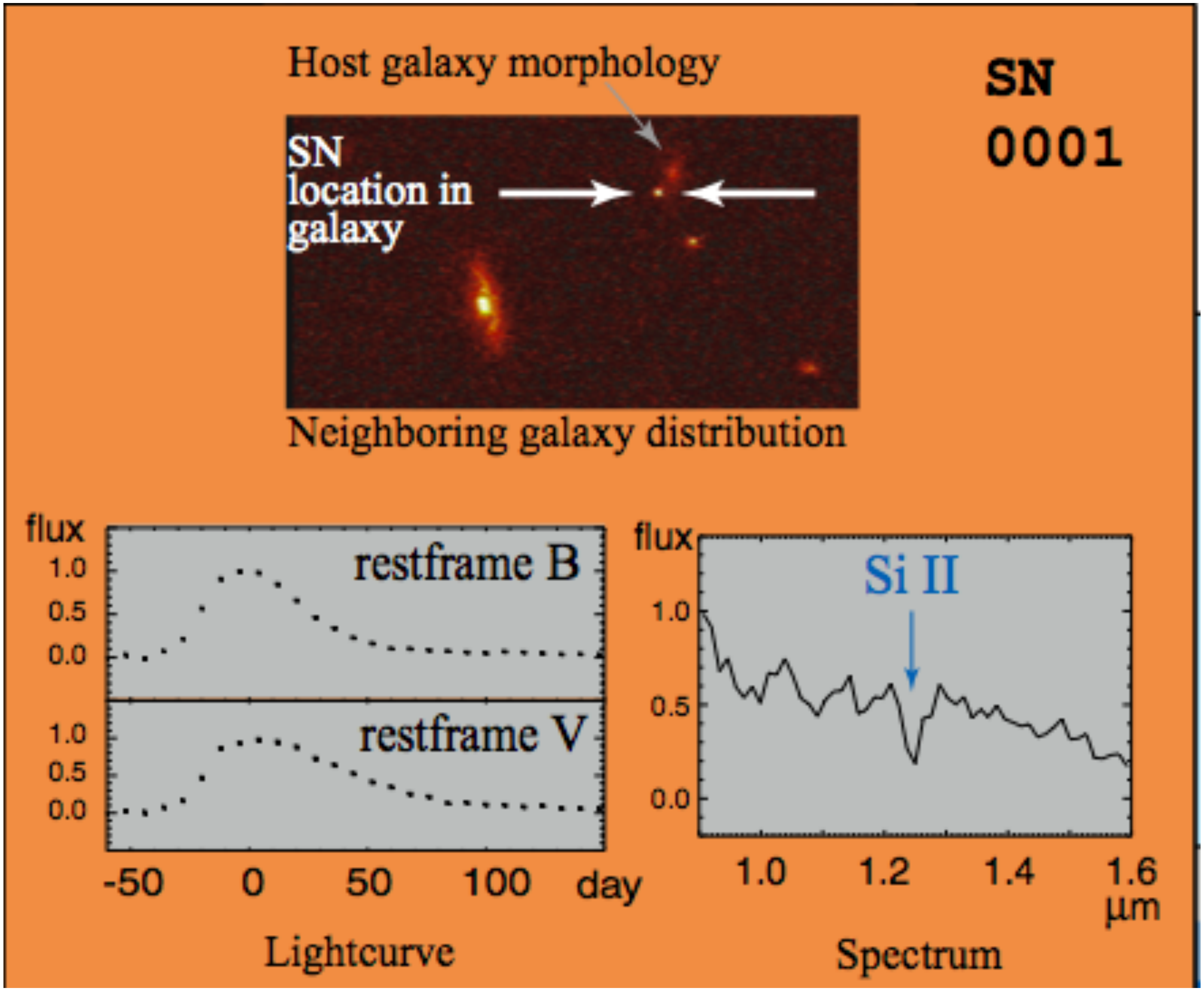
Adam G. Riess

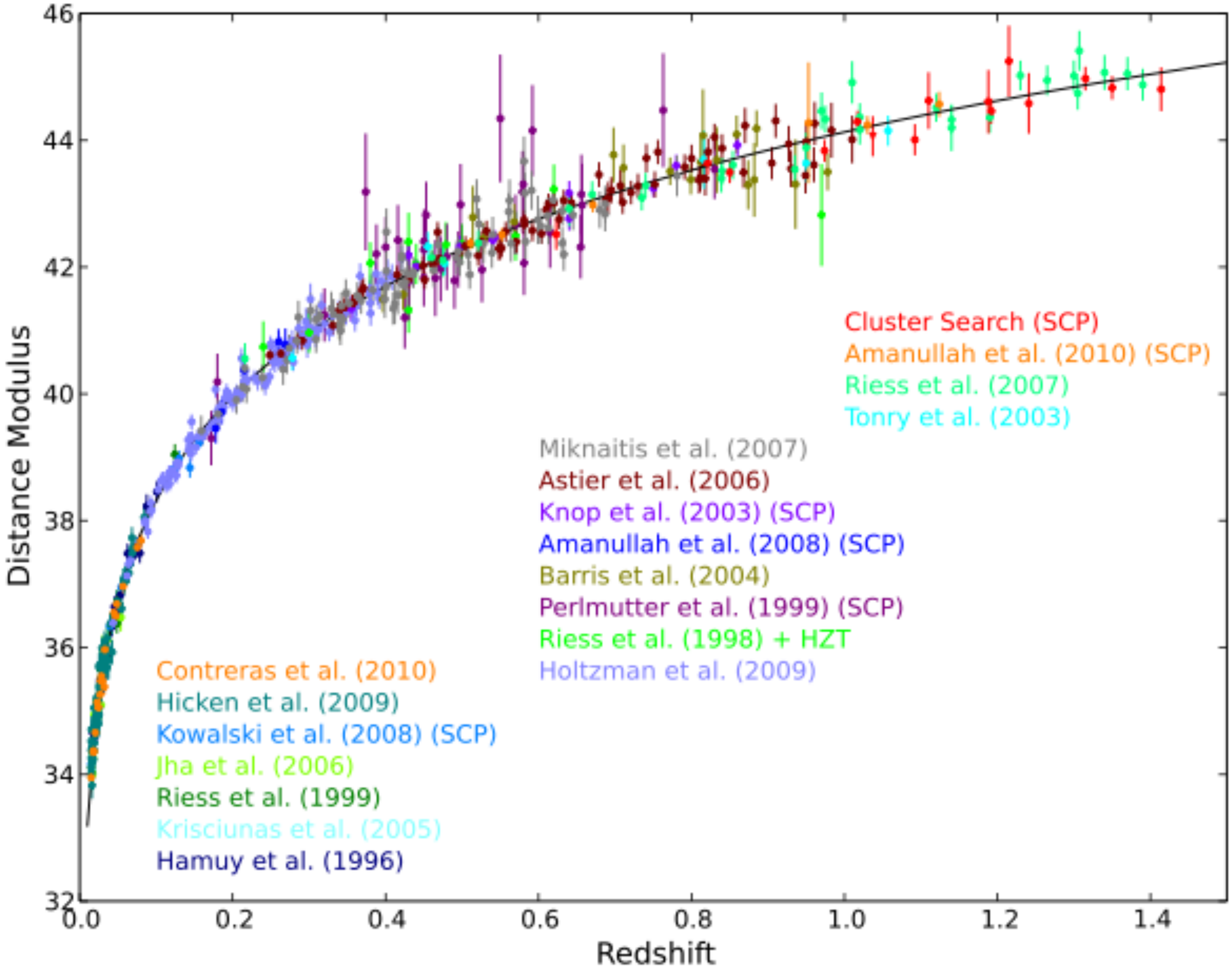
The Nobel Prize in Physics 2011 was awarded *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"* with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.

Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)



Supernova Ia are good standard candles: Measure distance vs. redshift





580 Supernova Ia (Suzuki, et al. 2012 (UNION2.1))
Also need CMB data. Together find Universe is flat (k=0) to within 0.7%.

Define critical density $\rho_{crit} = \frac{3H_0^2}{8\pi G}$, and $\Omega_X = \rho_X/\rho_{crit}$, to find

$$H^2 = \frac{(dR/dt)^2}{R^2} = H_0^2[\Omega_{matter}(R_0/R)^3 + \Omega_{radiation}(R_0/R)^4 + \Omega_{vacuum}$$

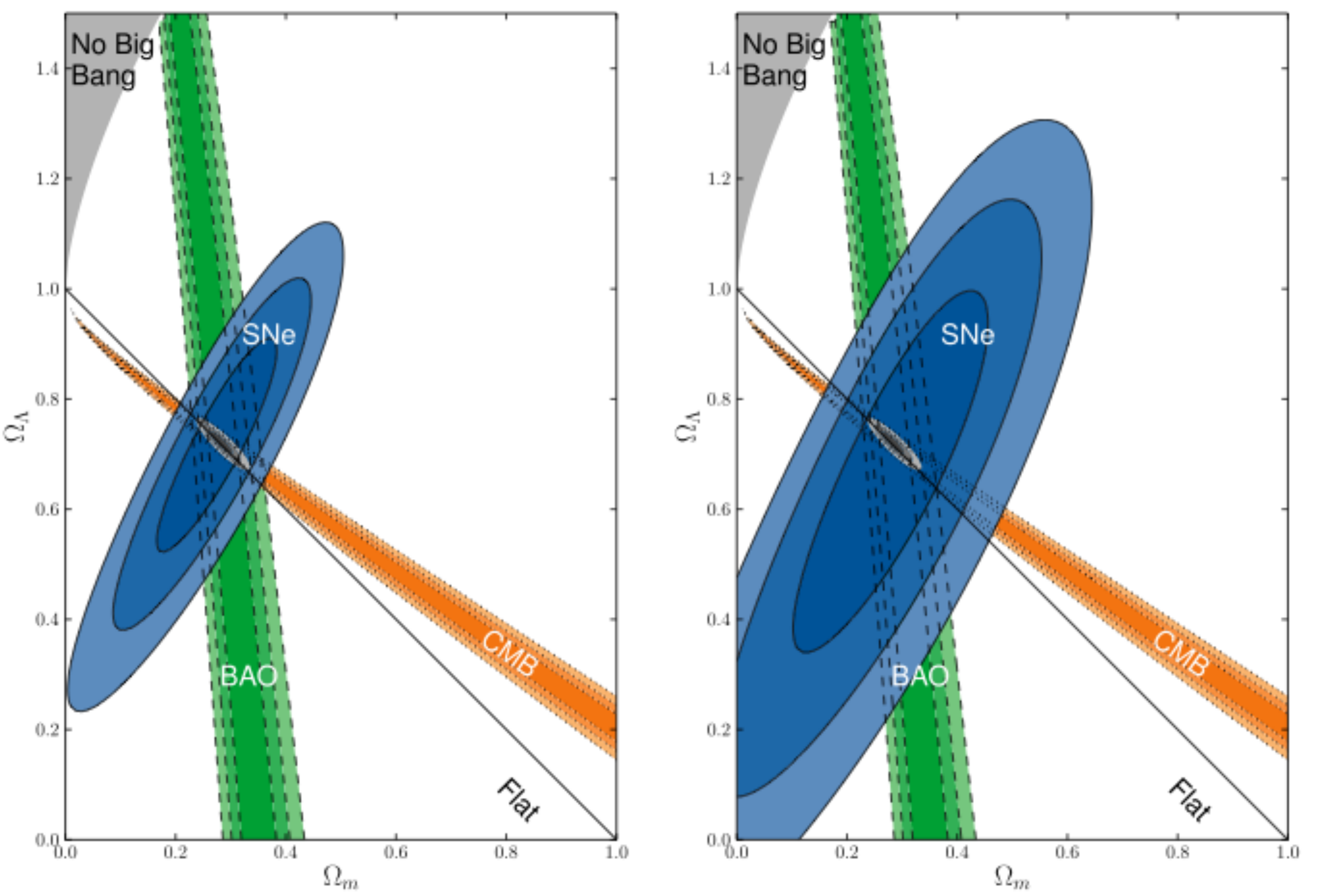
$$-(\Omega_{total} - 1)(R_0/R)^2].$$

Where Dark Energy enters via: $\Omega_V = \Omega_\Lambda = \Lambda/(3H_0^2)$

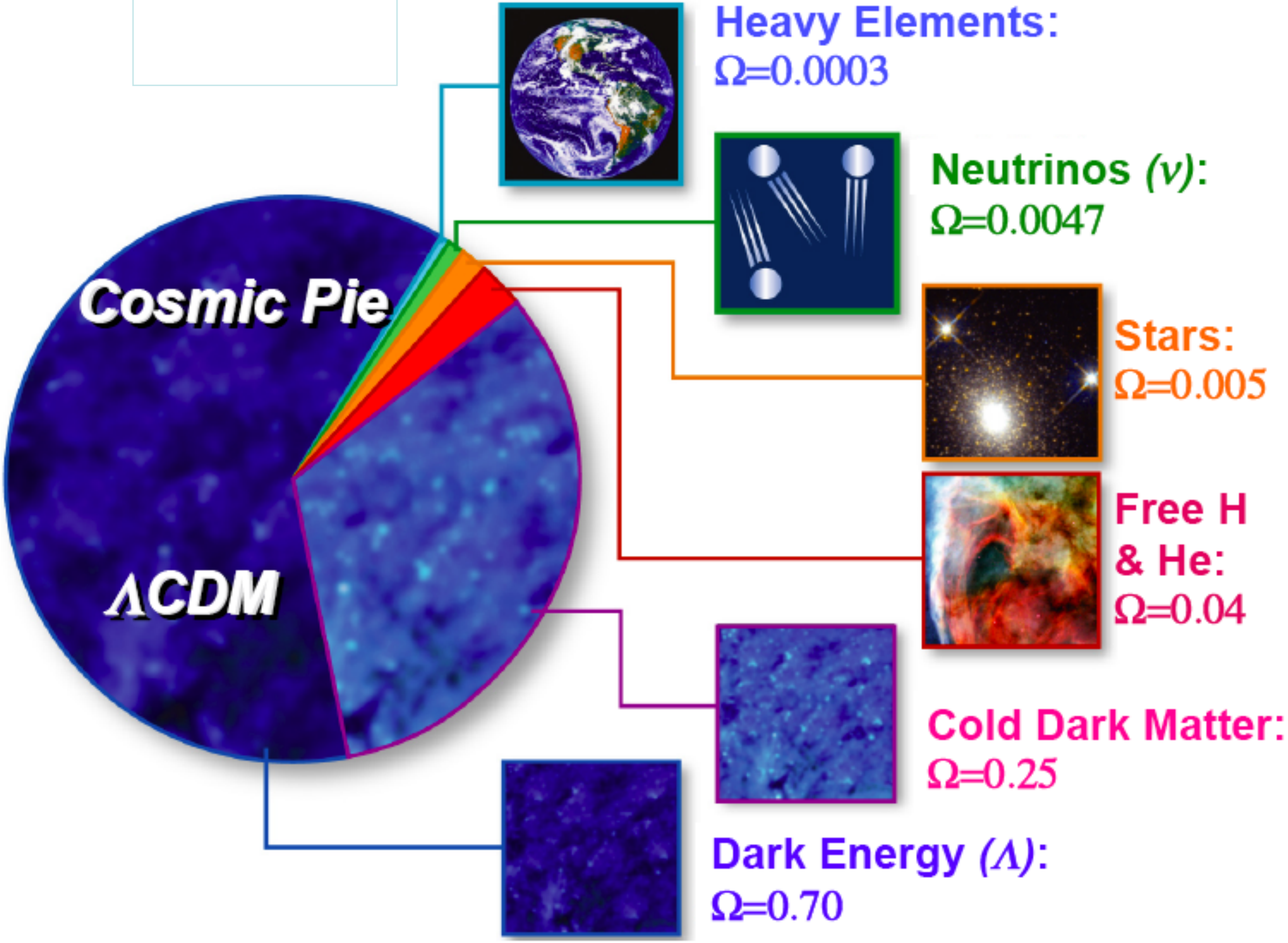
Note scale factor, R, follows from easily measured redshift, z, of atomic lines:

$$R_0/R = 1 + z, \qquad z = \Delta\lambda/\lambda$$

Can find H by measuring densities, or determine densities by measuring H as we go back in time.



580 SNIa plus CMB plus BAO (Suzuki, et al. 2012 (Union2.1)
Left panel: without systematic errors, Right panel: with systematic errors (w assumed constant) Results: Omega_Lambda = 0.729+-0.011, w= -1.013 +- 0.07



Heavy Elements:
$\Omega=0.0003$

Neutrinos ***(ν)*****:**
$\Omega=0.0047$

Stars:
$\Omega=0.005$

Free H & He:
$\Omega=0.04$

Cold Dark Matter:
$\Omega=0.25$

Dark Energy ***(Λ)*****:**
$\Omega=0.70$

Multiple observations and lines of reasoning lead to consensus model

- Cosmic Microwave Background (space and ground)
- Large Scale Structure (galaxy clustering)
- Age of globular clusters
- Cluster mass measurements
- Hubble constant measurements
- Etc.

We are stuck with dark energy (aka vacuum energy), but what is it?

- Key property is acceleration ($d^2R/dt^2 > 0$) This is controlled by w = pressure/density = p/ρ.

$$\frac{\left(d^2R/dt^2\right)}{R} = \frac{4\pi G}{3}\left(-\rho_{matter} - 2\rho_{radiation} - \rho_\Lambda(1+3w)\right)$$

- => needs “negative pressure”, with $w < -1/3$
- Quantum field theory readily predicts vacuum energy which has $w = -1$ exactly (aka “cosmological constant”)
  - – Higgs vacuum (trillions of tons/cm^3), QCD vacuum, etc.
  - – => Cosmological Constant Problem: 120 orders of magnitude off!
- Cosm. Constant or something else?
- Need to measure w now and in the past to understand dark energy

$$d^2R/dt^2 = \Lambda/3 - \frac{4\pi G}{3}(\rho + 3p)$$

Like to distinguish between 3 broad classes of possibilities

1. Einstein cosmological constant => Universe expands ever faster and our fate is isolation.
2. General relativity (GR) is correct, but vacuum energy of some quantum field (e.g. quintessence) dominates => fate of Universe depends on details of some new quantum field theory.
3. GR needs modification (e.g. extra dimensions/brane world) => can’t discuss fate until know the theory.

Therefore need very precise measurement of expansion history to find equation of state: w=pressure/density and dw/dt now and back in time.

- For example, if density of DE changes with time => cosmological constant eliminated, or if w not precisely -1.
- In GR, geometry (R(t)) determines growth of structure; if gravity differs from GR, results from geometry may differ from growth of structure => probably need to measure both geometry and growth to test if DE is due to non-GR physics.

So what methods can we use?

$$H(z)^2 + k(1+z)^2 = \frac{8\pi G}{3}(\rho_{atoms} + \rho_{DM} + \rho_{rad} + \rho_{DE})$$

- Curvature and density of atoms, DM, and radiation are measurable, but density of DE is not. So we must measure indirectly, through H(z), which is also not directly measurable. Can only measure integrals.
- Geometrical methods:

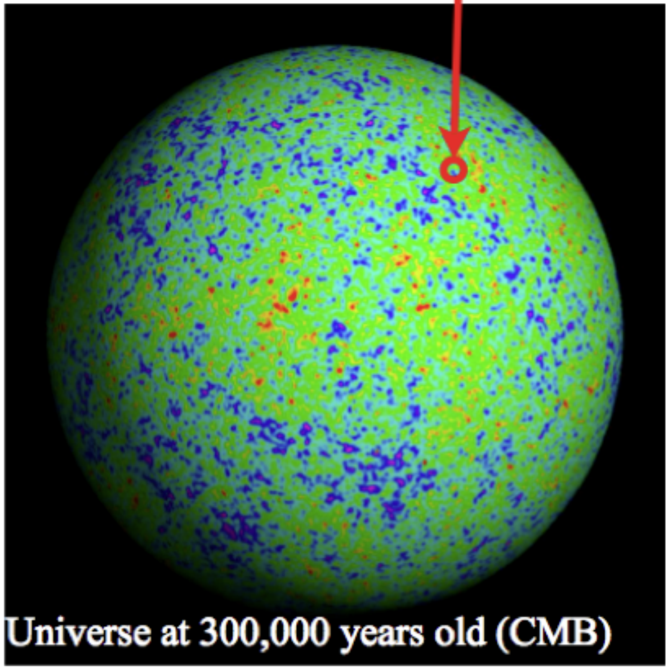
Comoving distance		$r(z) = \int dz/H(z)$
Standard Candles	Supernovae	$d_L(z) = (1+z)\, r(z)$
Standard Rulers	Baryon Oscillations	$d_A(z) = (1+z)^{-1}\, r(z)$
Standard Population	Clusters	$dV/dzd\Omega = r^2(z)/H(z)$ (for flat Universe only)

- Growth of structure methods: include Weak lensing and cluster mass measurements (actually need both geometry and growth)

Lyman Alpha Forest: what can it do?

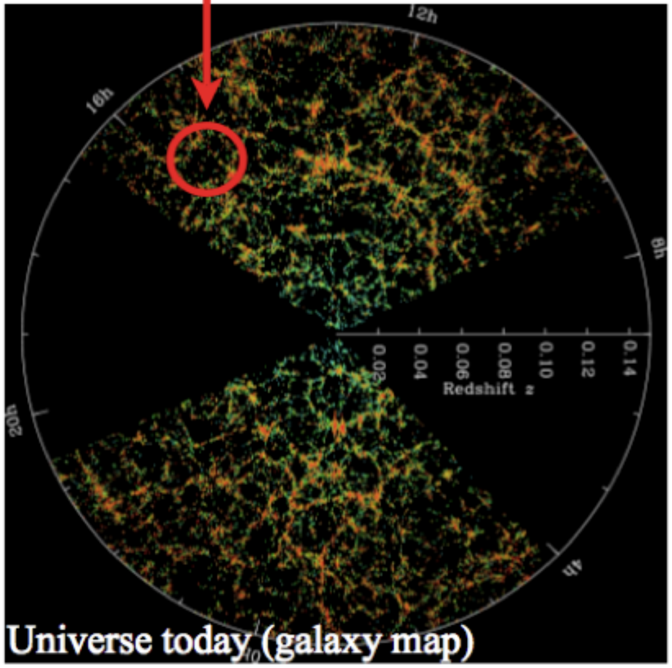
What are baryon acoustic oscillations (BAO)?

These fluctuations of 1 part in 10^5 gravitationally grow into...



Universe at 300,000 years old (CMB)

...these ~unity fluctuations today

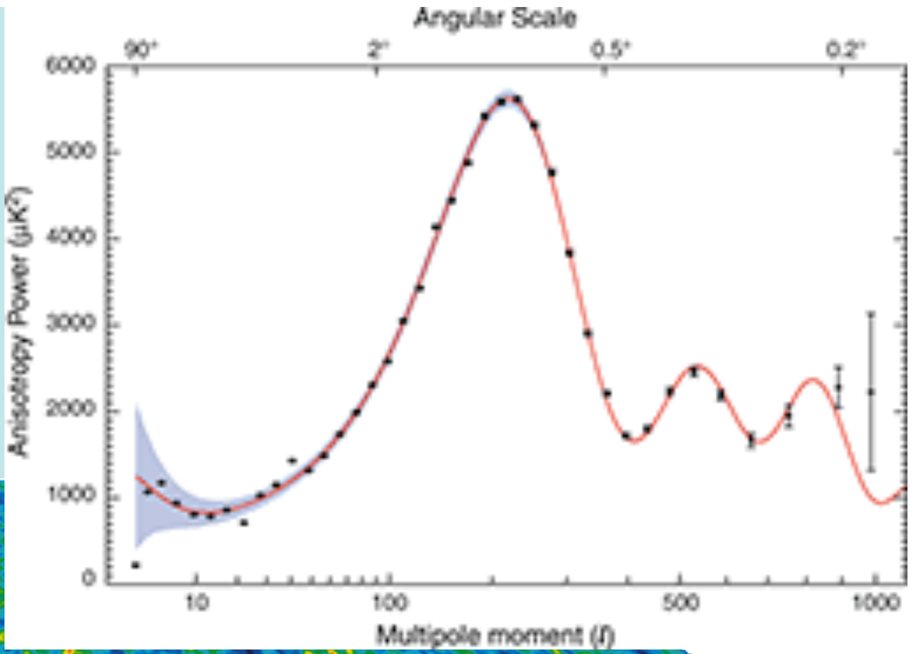


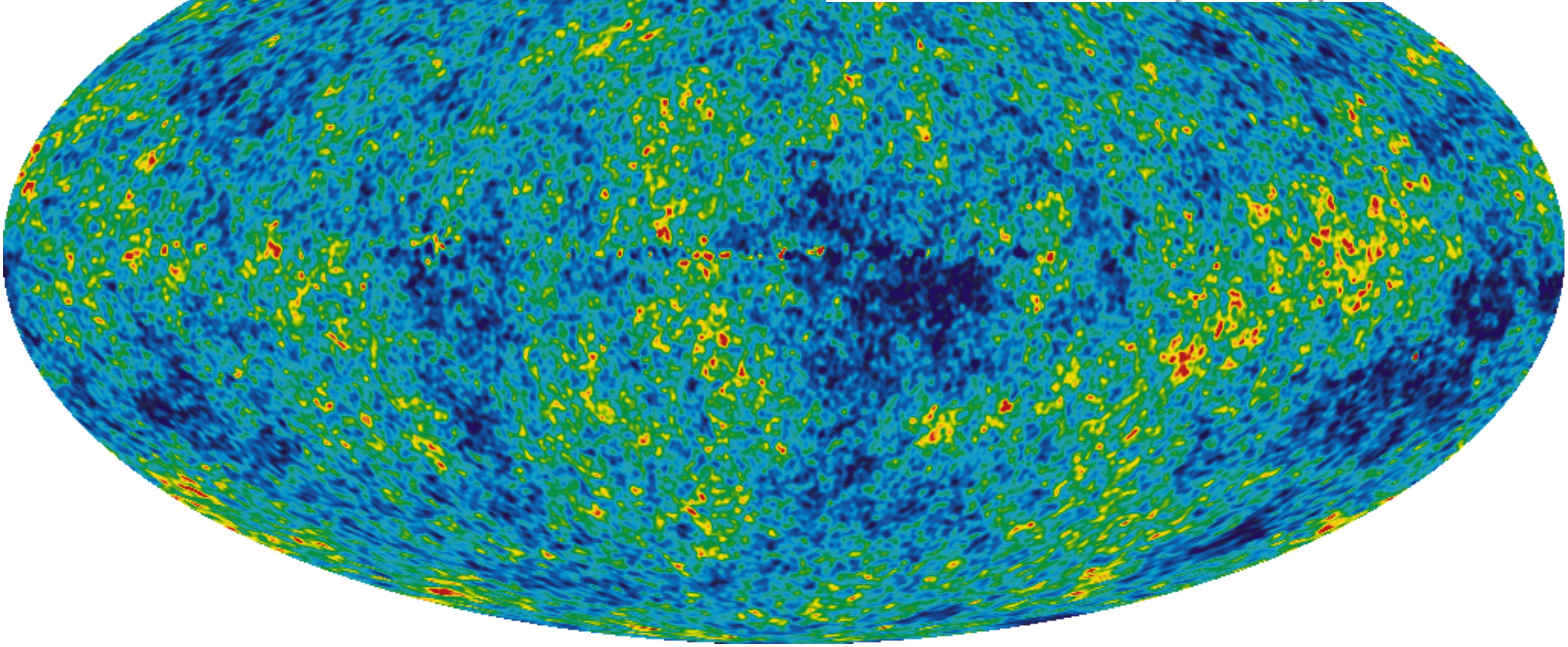
Universe today (galaxy map)

This sound wave can be used as a "standard ruler"
Dark energy changes this apparent ruler size

Courtesy slide from David Schlegel

WMAP 3-year data and power spectrum





Baryon Acoustic Oscillations: Peaks in power spectrum put down during early Universe (e.g. CMB) also show up in galaxy-galaxy correlation function

- Standard ruler => d_A vs. redshift (geometry only)
- Baryons only 4% => signal small => need redshift of lots of galaxies (e.g. 2 million)
- Can go to high redshift easily; relatively clean since using galaxies only as tracers

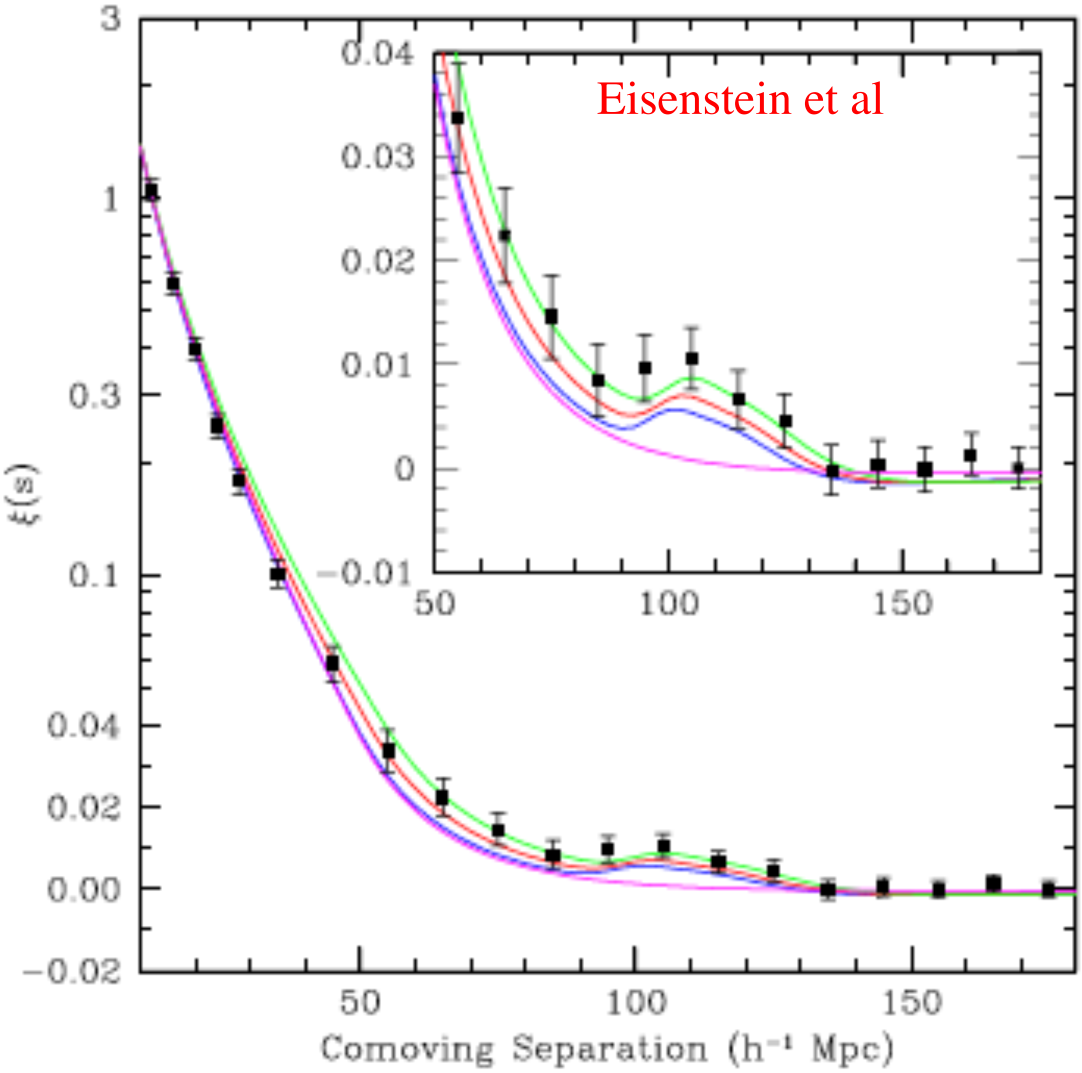
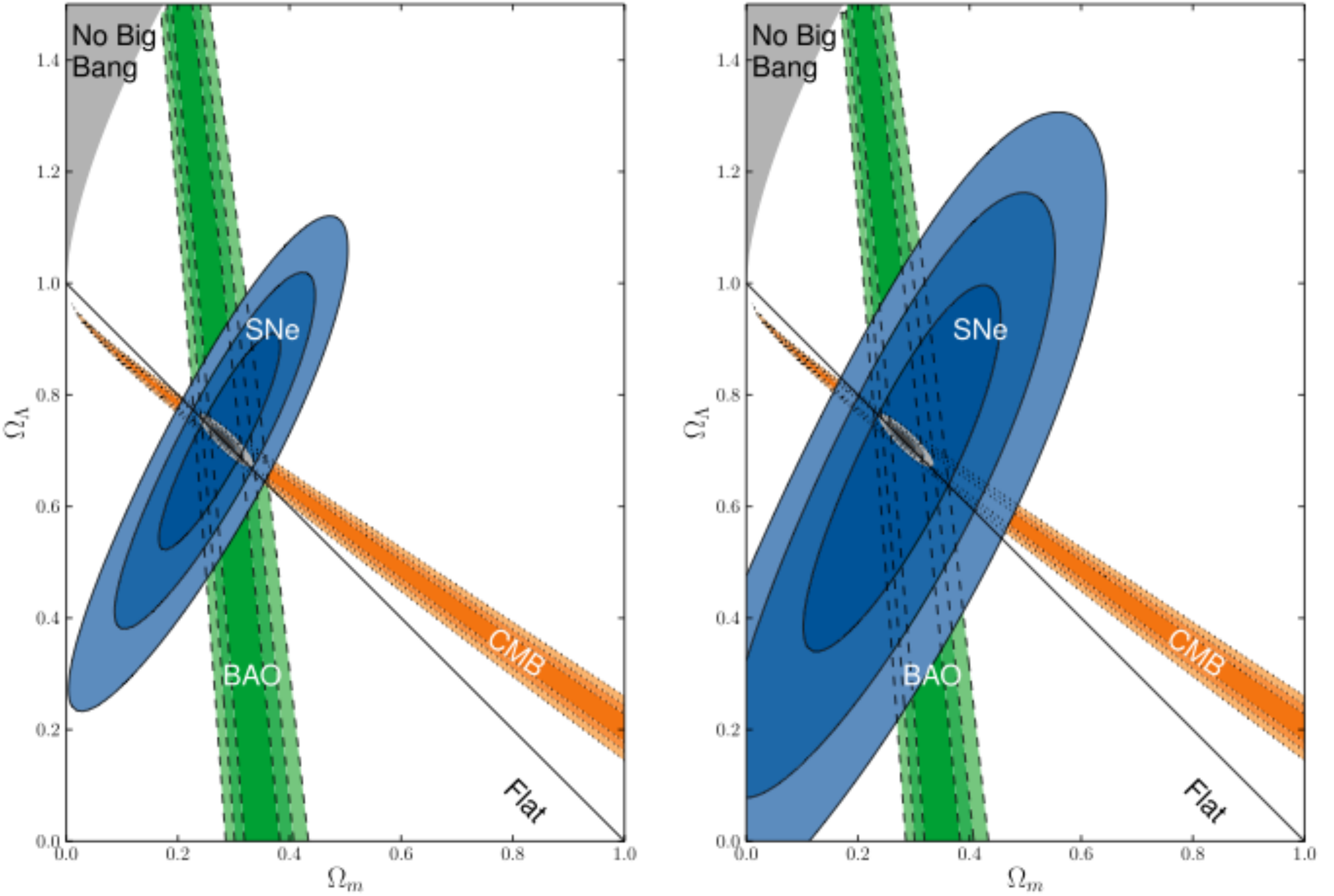


FIG. 2.— The large-scale redshift-space correlation function of the SDSS LRG sample. The error bars are from the diagonal elements of the mock-catalog covariance matrix; however, the points are cor-

2 million gals, .15<z<.3,



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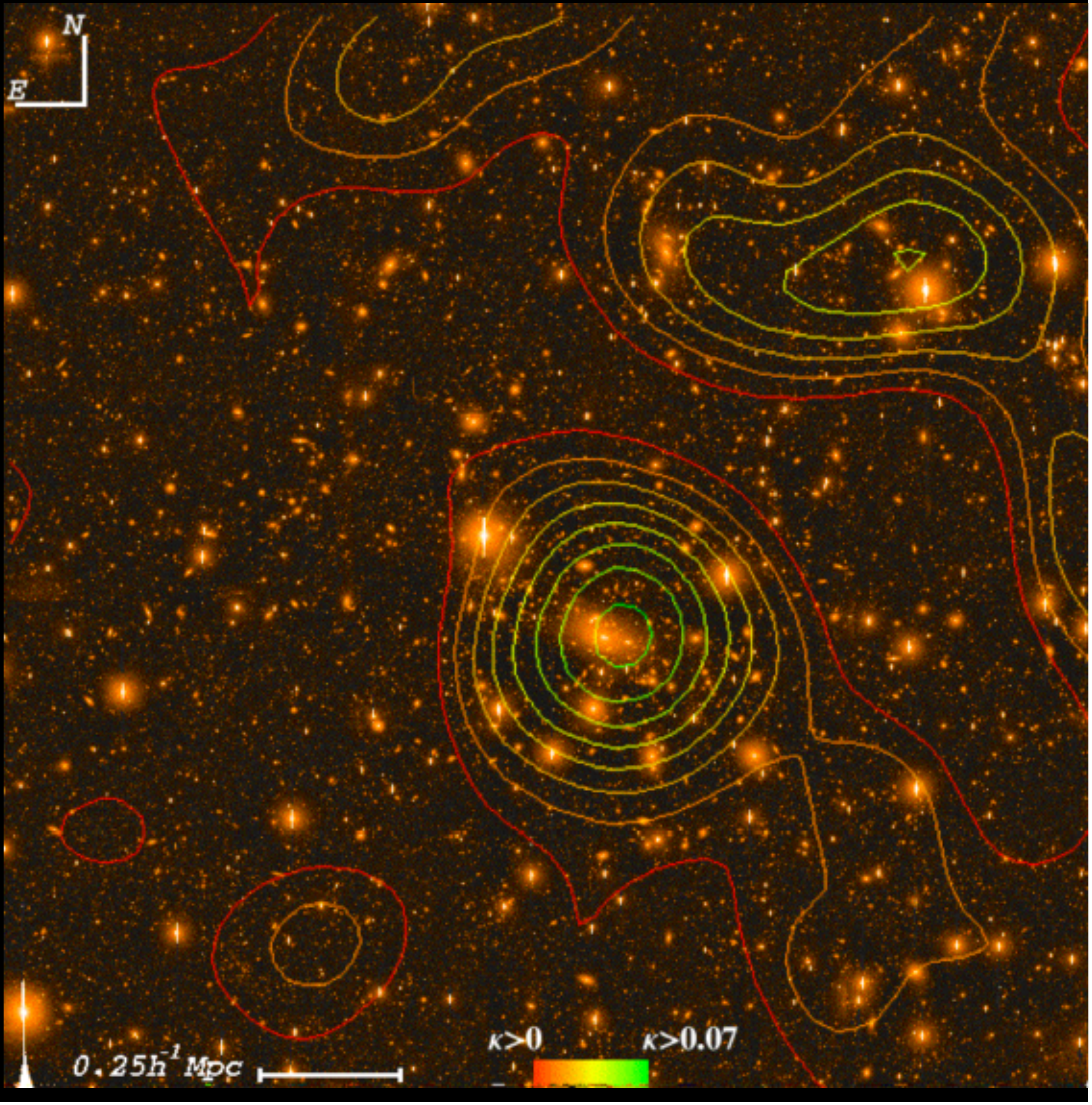
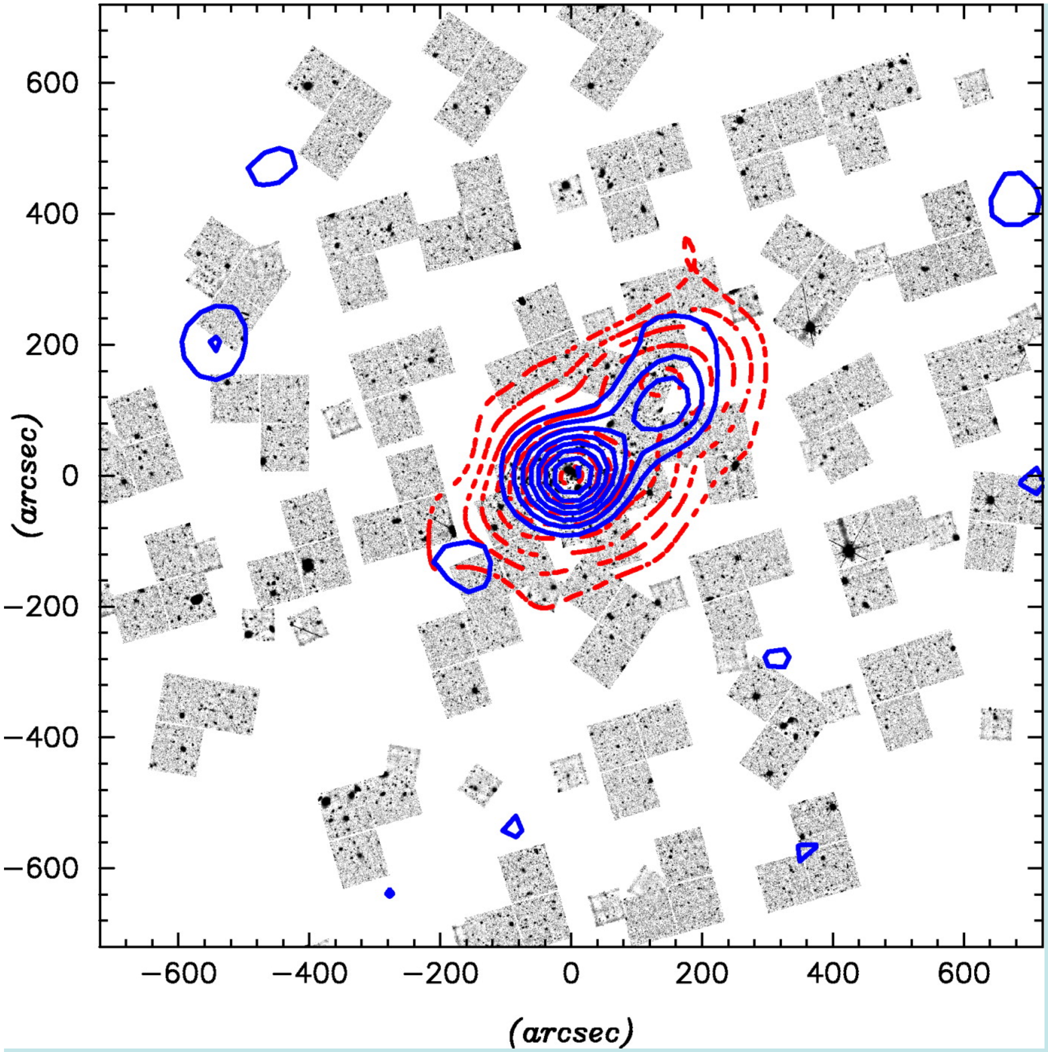
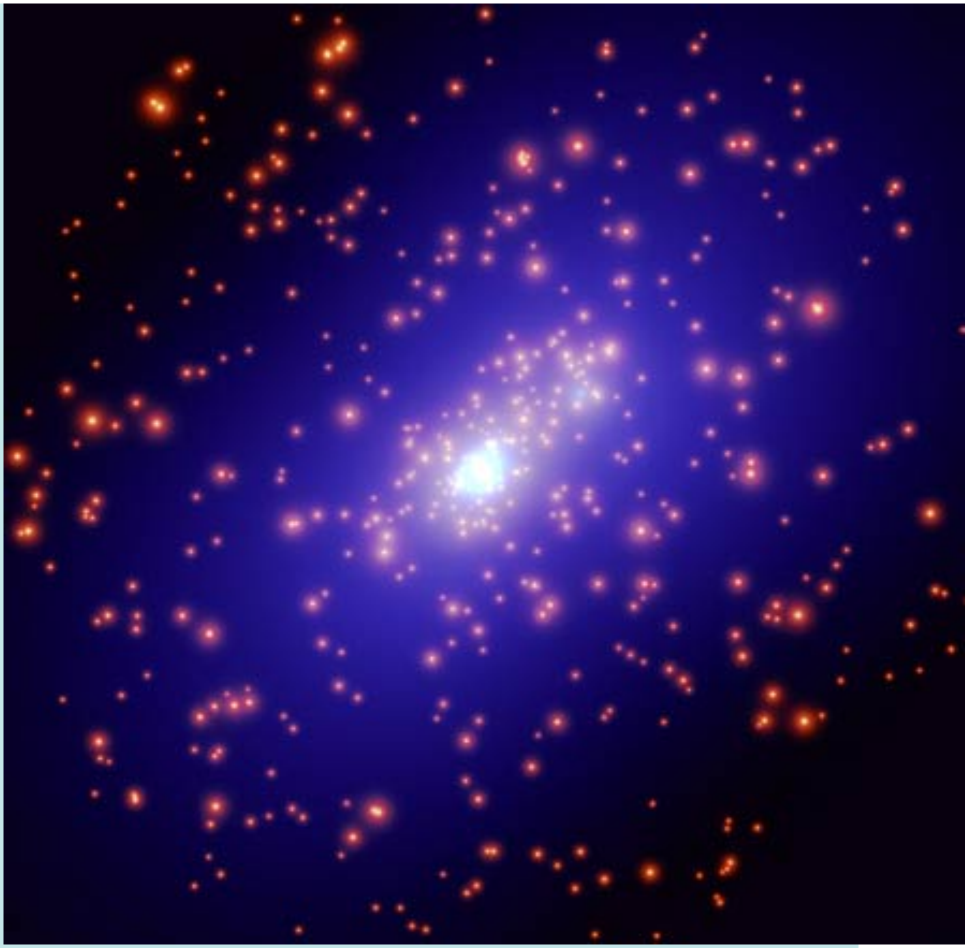
Left panel: without systematic errors, Right panel: with systematic errors (w assumed constant) Results: Omega_Lambda = 0.729+-0.011, w= -1.013 +- 0.07

Weak Lensing: uses small distortions in shape of galaxies

- Distortion depends on both distance and mass(growth function)
- Distortion is 0.1% to 2% compared to 30% intrinsic shape variation
- => need $>10^8$ galaxies and good control of systematics (e.g. stable PSF, atmosphere, telescope)





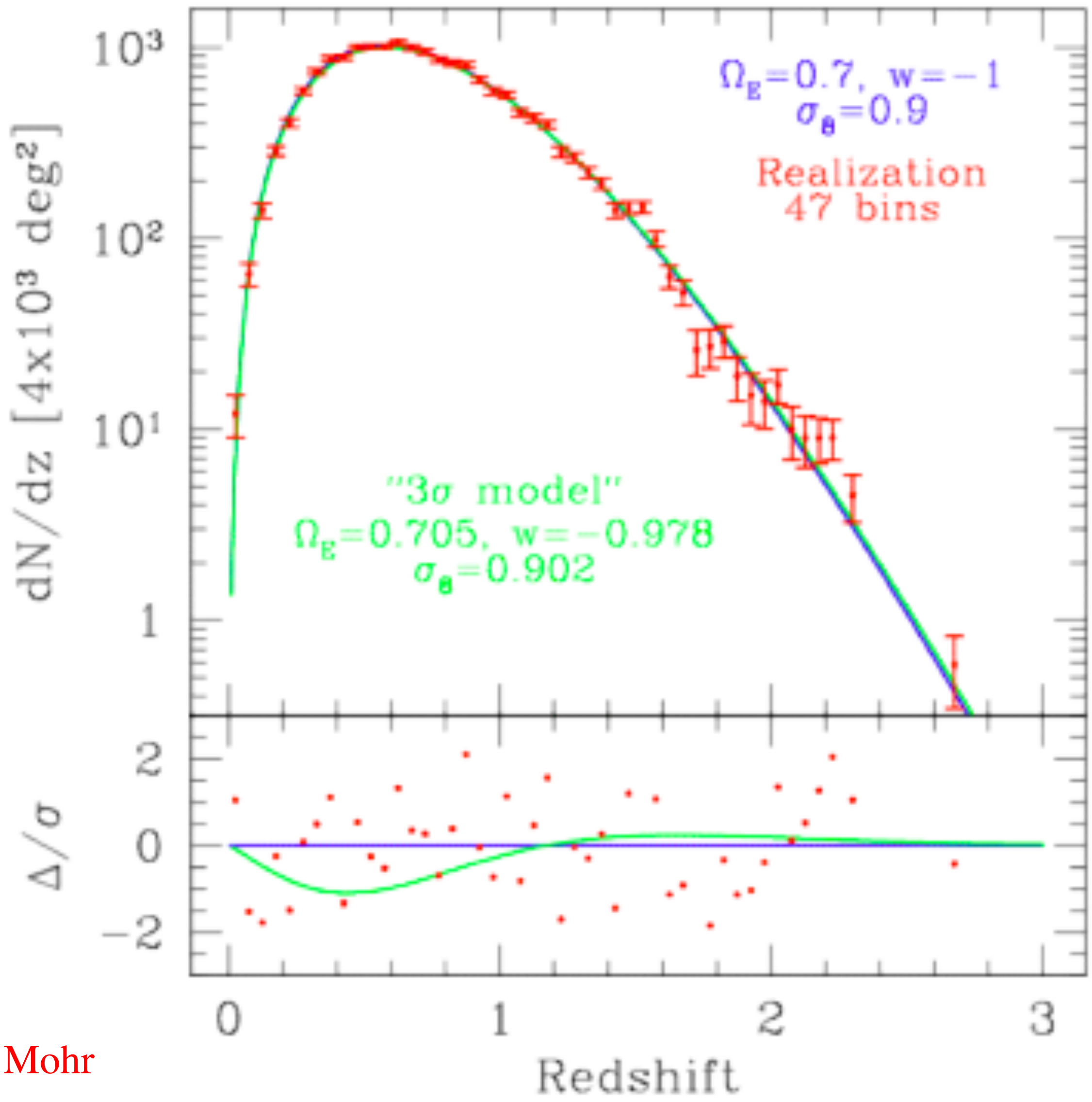


Oliver Czoske, Lars Bähren

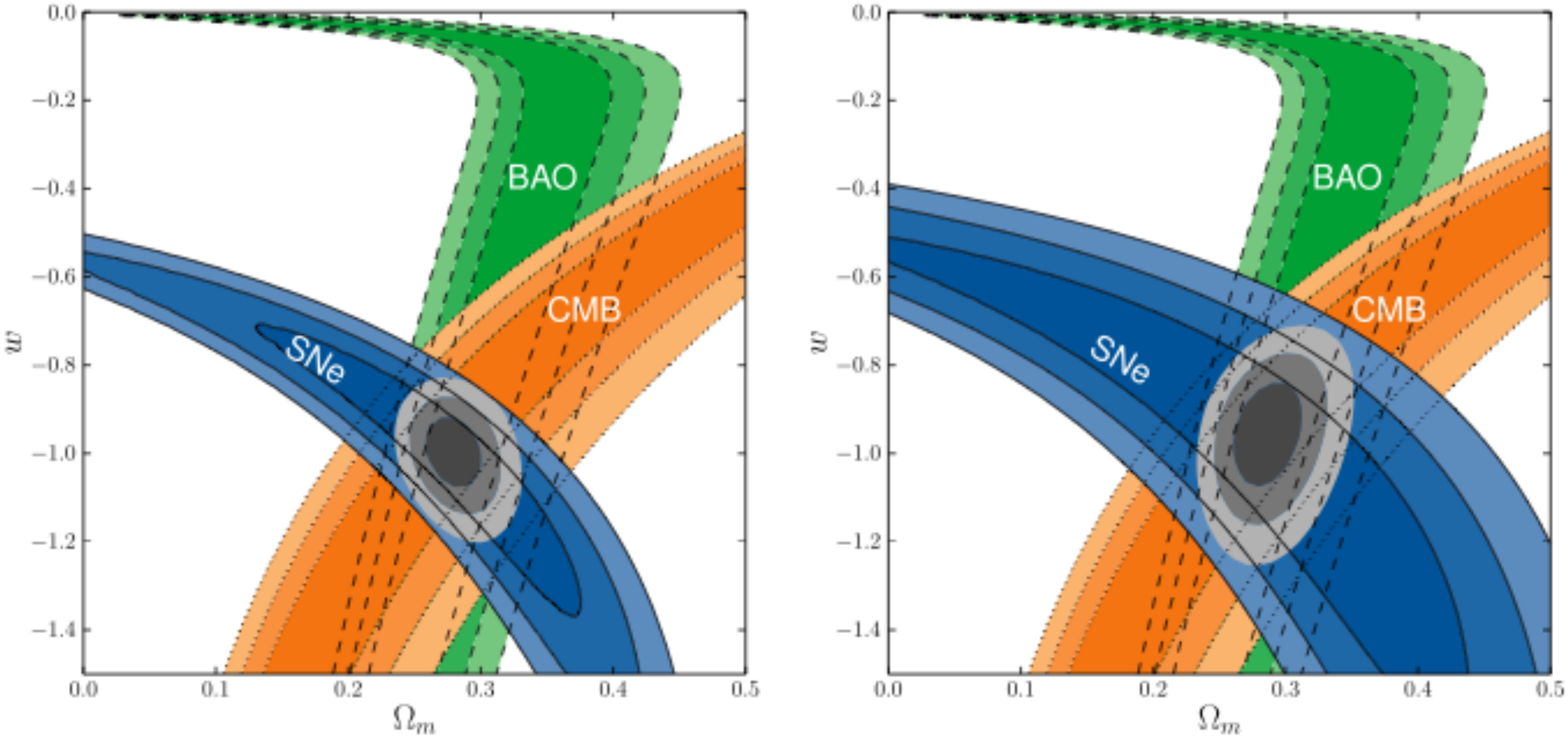
- A mosaic of HST/WFPC2 exposures of the cluster of galaxies Cl0024+1654 has been used to derive the distribution of dark matter out to a large distance from the cluster centre. The distribution of the dark matter is shown in blue, while the cluster galaxies are shown in red.

Clusters: Several ways: e.g. count clusters vs redshift

- Depends on both number above certain mass (growth), and volume vs. z (geometry)
- Most undeveloped method: systematics not well understood, e.g. very sensitive to mass estimate which is hard
- But steep drop in number of clusters at high mass gives very sensitive probe
- May be ways to "self-calibrate"



Mohr



580 SN1a plus CMB plus BAO; Suzuki, et al. 2012 (Union2.1)
Left panel: statistical errors only, Right panel includes systematic error
Gives w = -1.013 +- 0.07

Conclude:
1. w still not that well constrained
2. Cosmological Constant may or may not be the case
3. Need better data

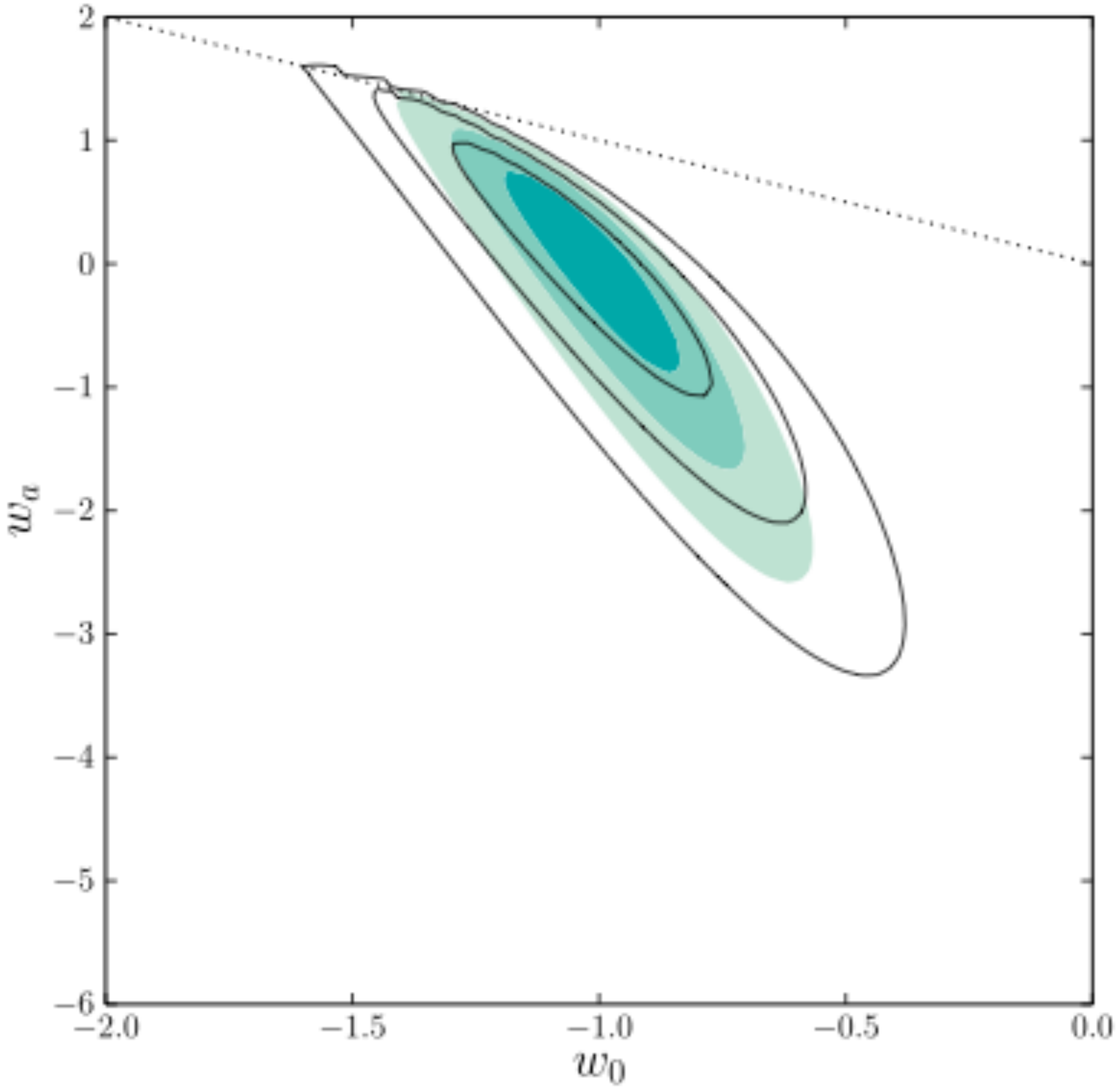


Figure 7. 68.3%, 95.4%, and 99.7% confidence regions of the (w_0, w_a) plane from SNe combined with the constraints from BAO, CMB, and H_0, both with (solid contours) and without (shaded contours) systematic errors. Zero curvature has been assumed. Points above the dotted line $(w_0 + w_a > 0)$ violate early matter domination and are disfavored by the data.

There are many experiments, currently underway or planned, that will measure w and w_a, e.g.

- HST (as usual!)
- Dark Energy Survey (DES with SPT) (Clusters, etc.)
- PanSTARRS (Weak Lensing; SNIa)
- BOSS and BigBOSS (BAO)
- Several Supernova experiments (SNIa)
- PLANCK (CMB)
- HEXDEX, Subaru, etc. (several)
- LSST (Weak Lensing, SNIa, etc.)
- EUCLID (several)
- WFIRST (several)
- Square Kilometer Array (SKA) (several)
- Plus dozens of other existing and planned experiments, plus new ones being thought of all the time

Future

- Four promising methods, not clear which is best; probably important to use several (for complimentarity and different systematic errors)
  - Supernovae Ia (geometry)
  - Weak Lensing (geometry and growth of structure)
  - Baryon Acoustic Oscillations (geometry)
  - Clusters (geometry and growth)
- Can probably eventually get factor of 10 increase in precision, but space mission may be necessary for this

Potential Philosophical Problem

- How accurately do we need to measure w?
  - If Cosmological constant is answer, then w= -1 exactly, now, in the past, and forever
  - If $w \neq -1$, or $w_a \neq 0$, even by a small amount, then exponential expansion may stop and fate of Universe would be different, so important to know.
  - But suppose we measure close to -1, how much should we spend to get another factor of a few closer? Cannot ever prove w = -1 exactly.
  - Some think we don't need to measure w at all! They think it is already known, w= -1, since only the cosmological constant makes sense to them.
  - Connected to the "anthropic principle" and the "landscape" idea from string theory.

Conclusions

- Dark energy is here to stay in one form or another: Perhaps most important unsolved problem in the physical sciences!
  - Watch for new limits on w and w_a, especially indication that $w \neq -1$, or $w_a \neq 0$
  - The fate of the Universe depends upon these numbers
- Prospects are very good on experimental side: several good methods ready to go
- Space mission may be necessary to reach high precision, but an enormous amount is being done from ground

Scalar Field Models (aka quintessence)

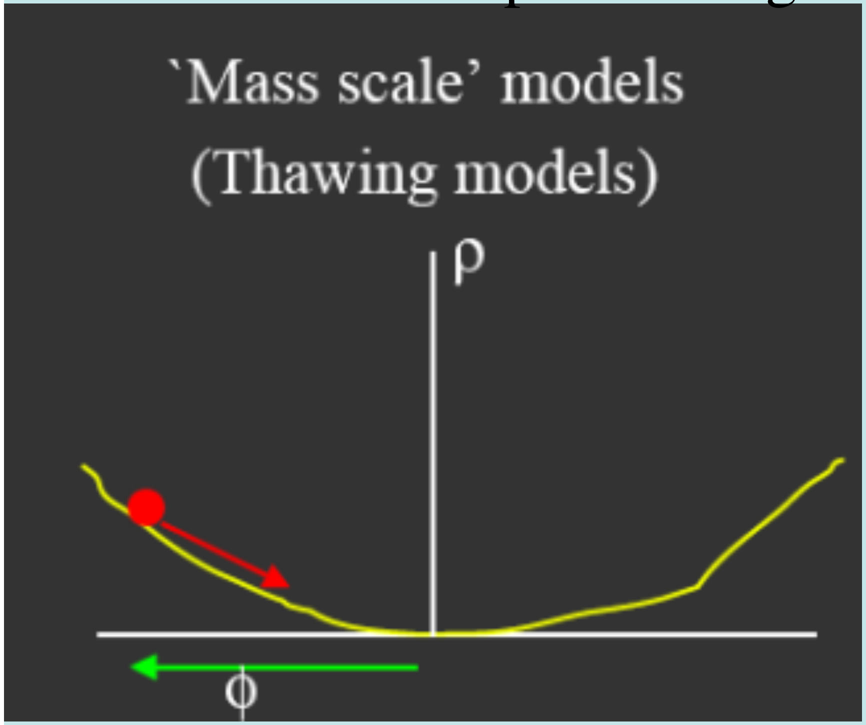
FRW eqs. plus:

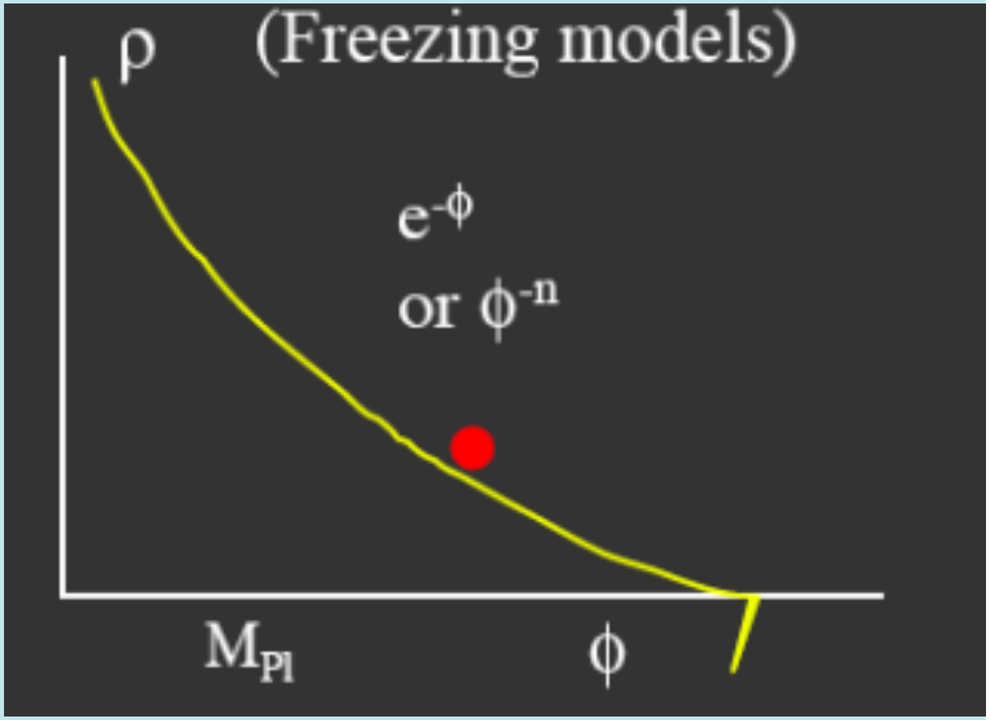
$$\frac{d^2\phi}{dt^2} + 3H\frac{d\phi}{dt} + \frac{dV}{d\phi} = 0$$

$$\rho_\phi = V(\phi) + \tfrac{1}{2}\dot{\phi}^2$$

$$p_\phi = -V(\phi) + \tfrac{1}{2}\dot{\phi}^2$$

Different potentials give two broad classes of models:





(Pictures by Frieman)

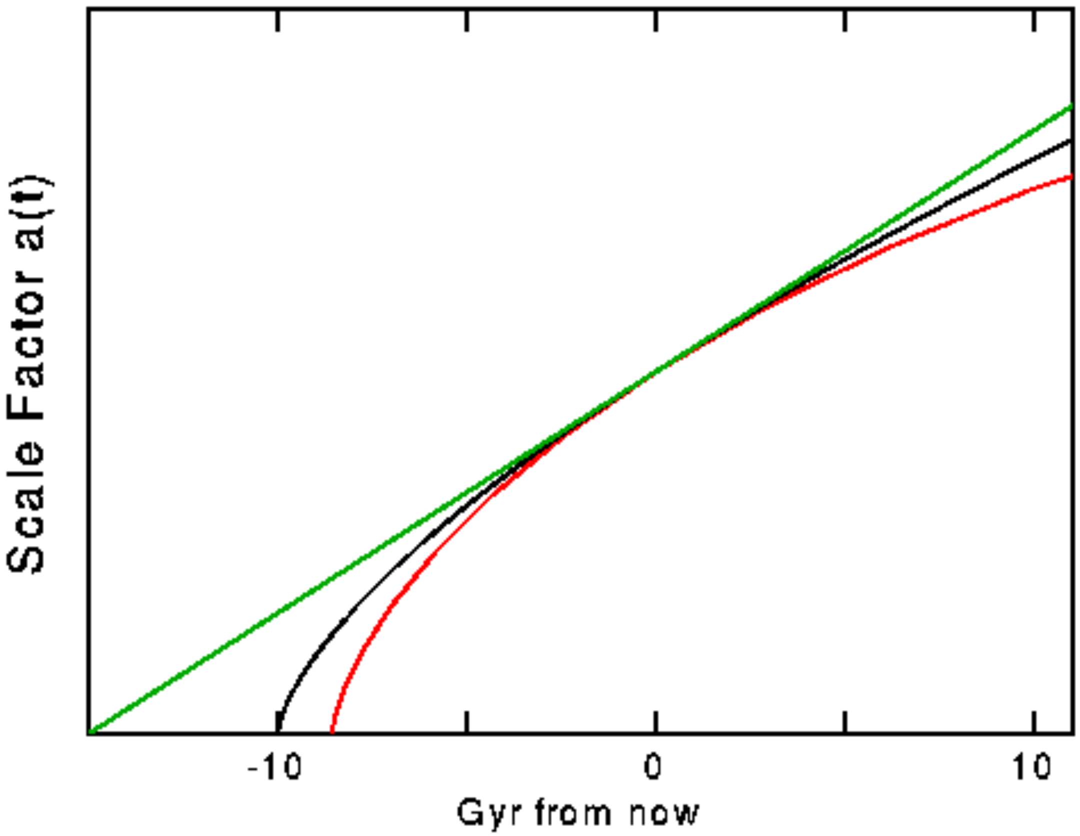
$$V = M^4(1 + \cos\frac{\phi}{f})$$

$$V = \lambda\phi^n$$

$$V = M^{4+n}\phi^{-n}$$

$$V = M^{4+n}\phi^{-n}\exp(\alpha\phi^2/M_{pl}^2)$$

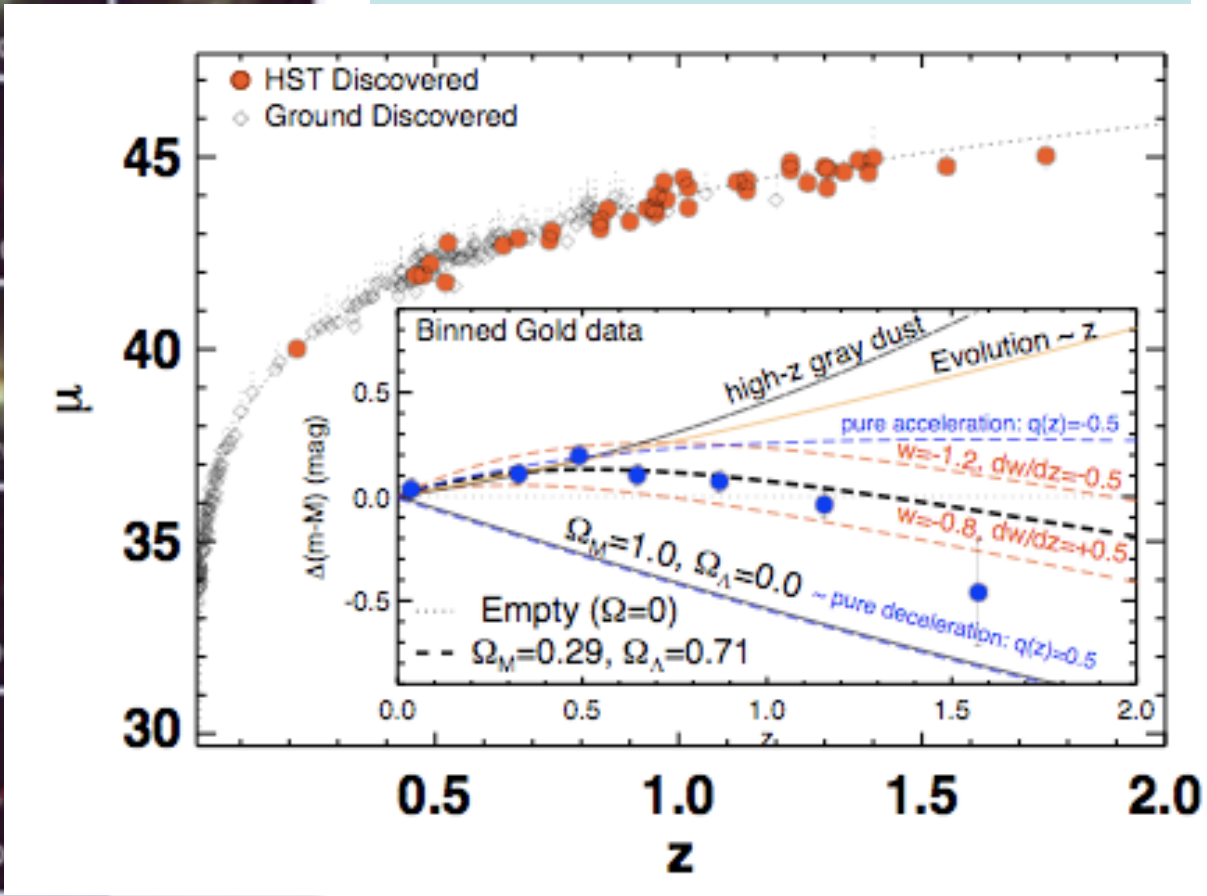
Fate of Universe depends upon total density and cosmological constant



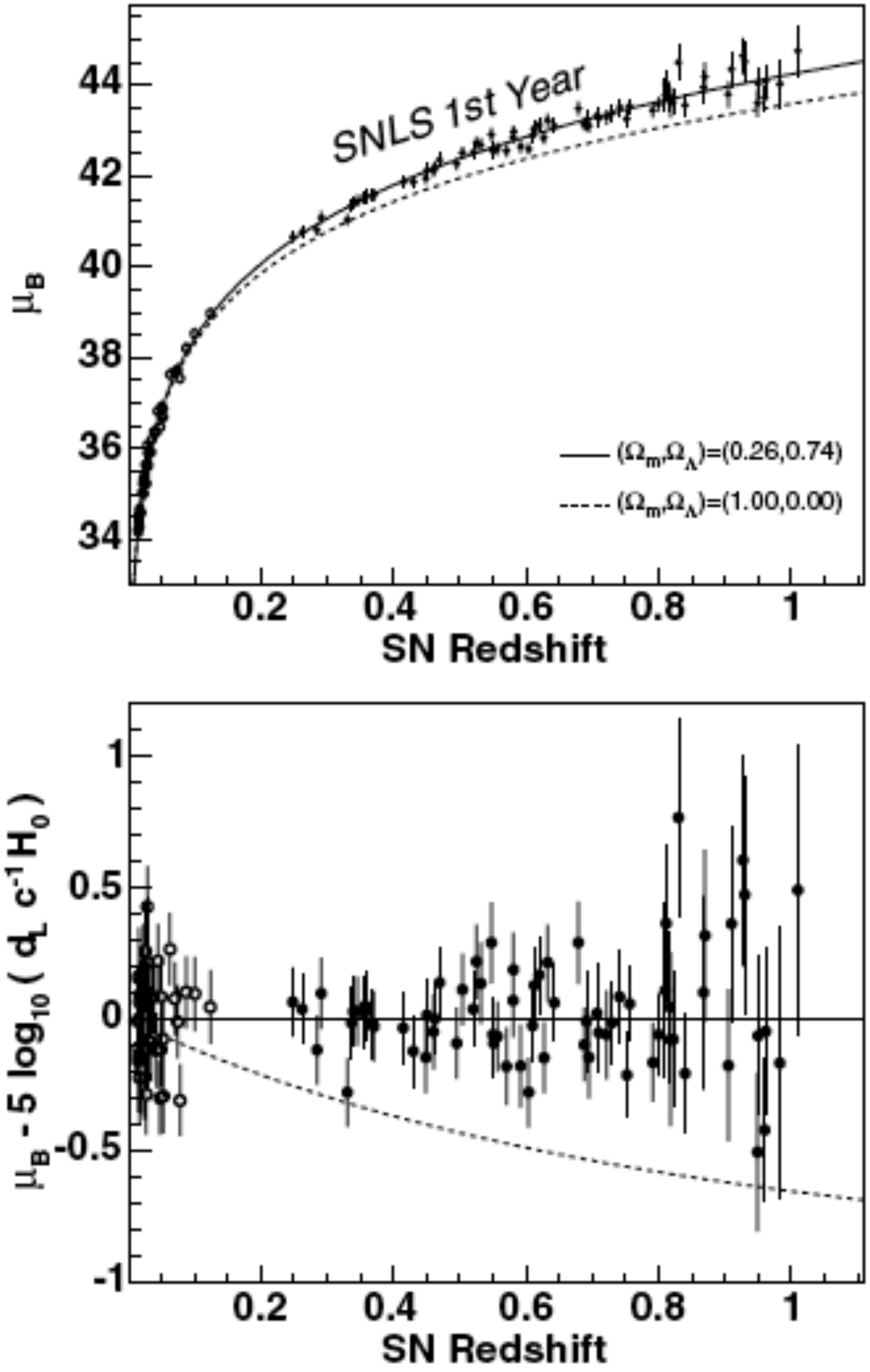
The figure above shows the scale factor vs time measured from the present for H_o = 65 km/sec/Mpc and for Omega$_o$ = 0 (green), Omega$_o$ = 1 (black), and Omega$_o$ = 2(red). The age of the Universe is 15, 10 and 8.6 Gyr in these three models. The recollapse of the Omega$_o$ = 2 model occurs when the Universe is 11 times older than it is now, and all observations indicate Omega$_o$ < 2, so we have at least 80 billion more years before any Big Crunch.

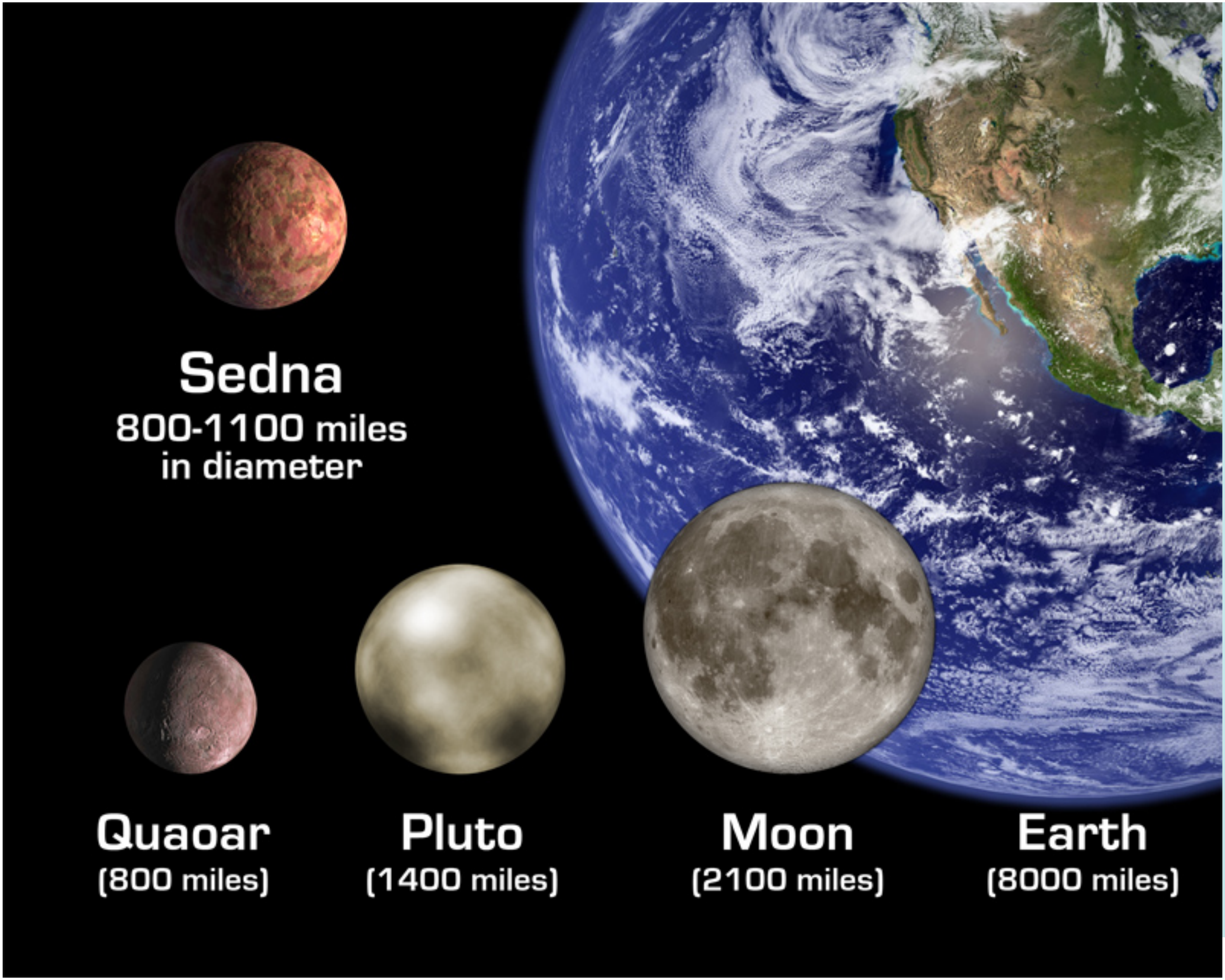
(From Ned Wright’s cosmology tutorial)

Riess, et al. 2006



(Astier, et al 2006)

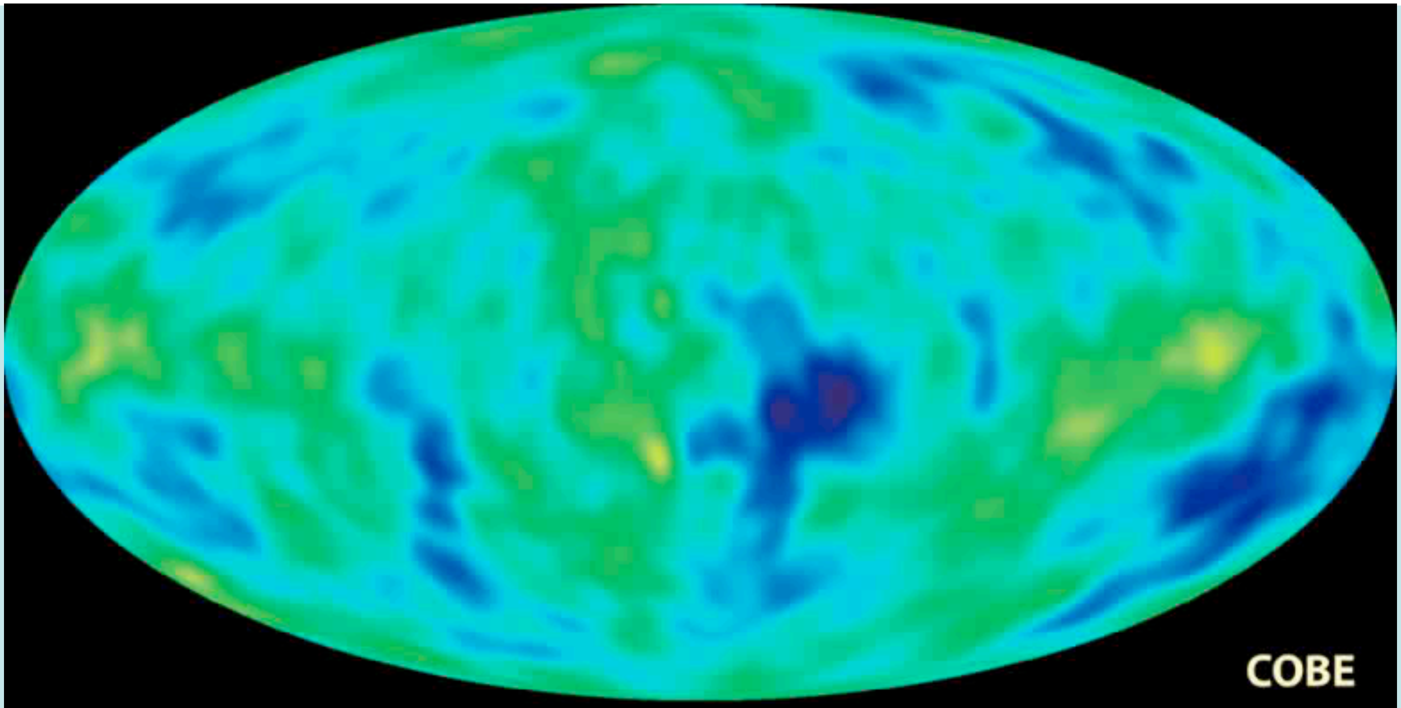



Sedna
800-1100 miles
in diameter
Quaoar
(800 miles)
Pluto
(1400 miles)
Moon
(2100 miles)
Earth
(8000 miles)

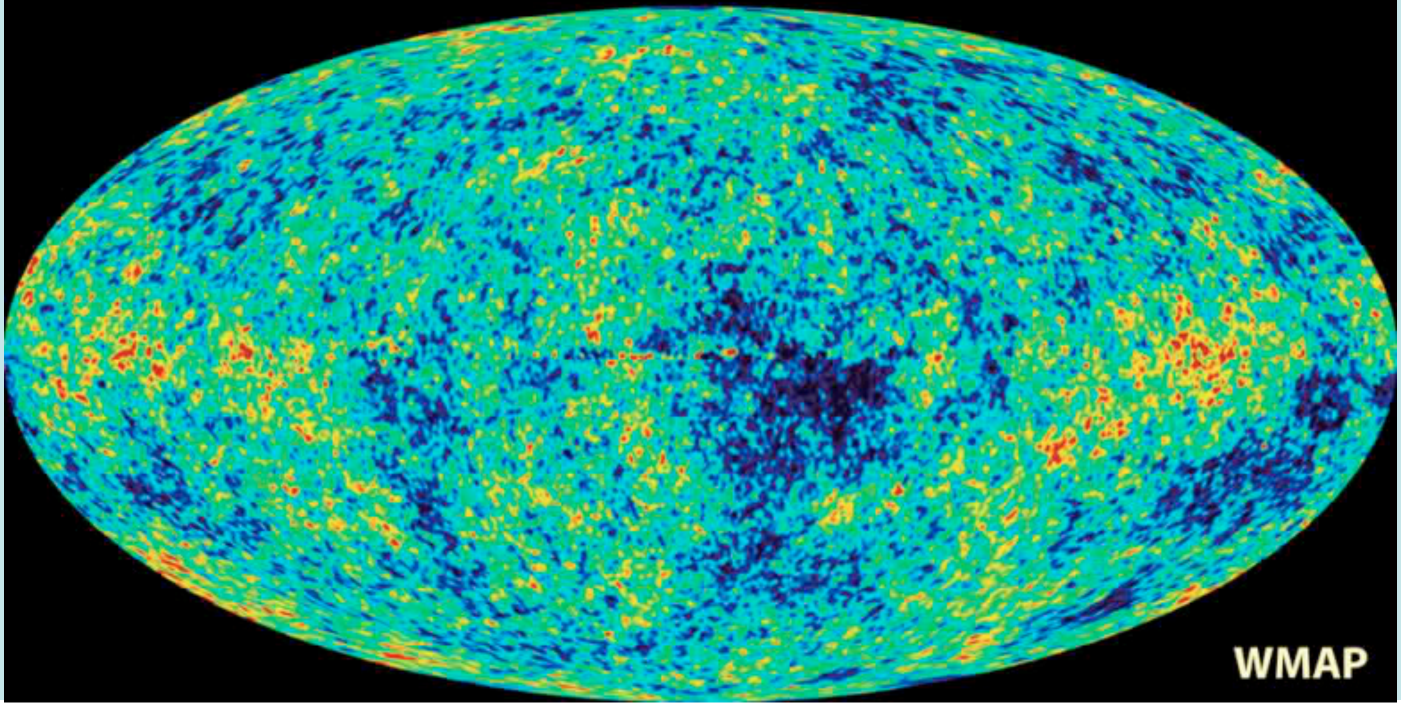
S82E5938 1997:02:19 07:07:00

How far back in time (to what z) does one need to measure?

- Today $\Omega_{DE} = 0.7$, Ω_{matter}=.3
- Since Ω_{matter} scales as R^{-3}, at z=.33 they were equal and at z=2, $\rho_{vacuum}/\rho_{matter} = 0.1$
- By z=4, vacuum energy is only 1% of matter energy
- => CMB (z=1100) is not that helpful for DE. Need measurements from z=0 to z=1 or 2 (unless vacuum energy not constant in time!)

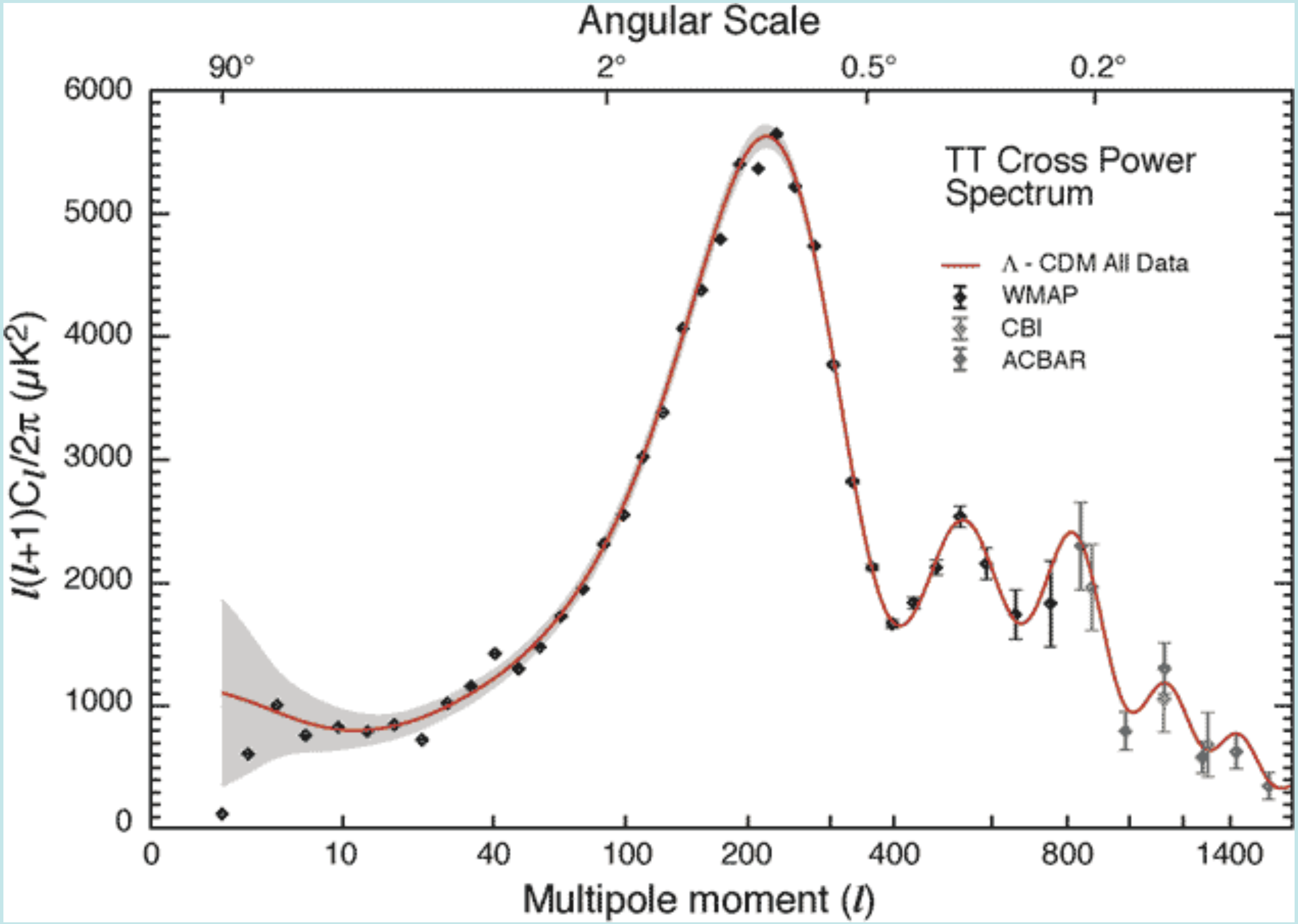


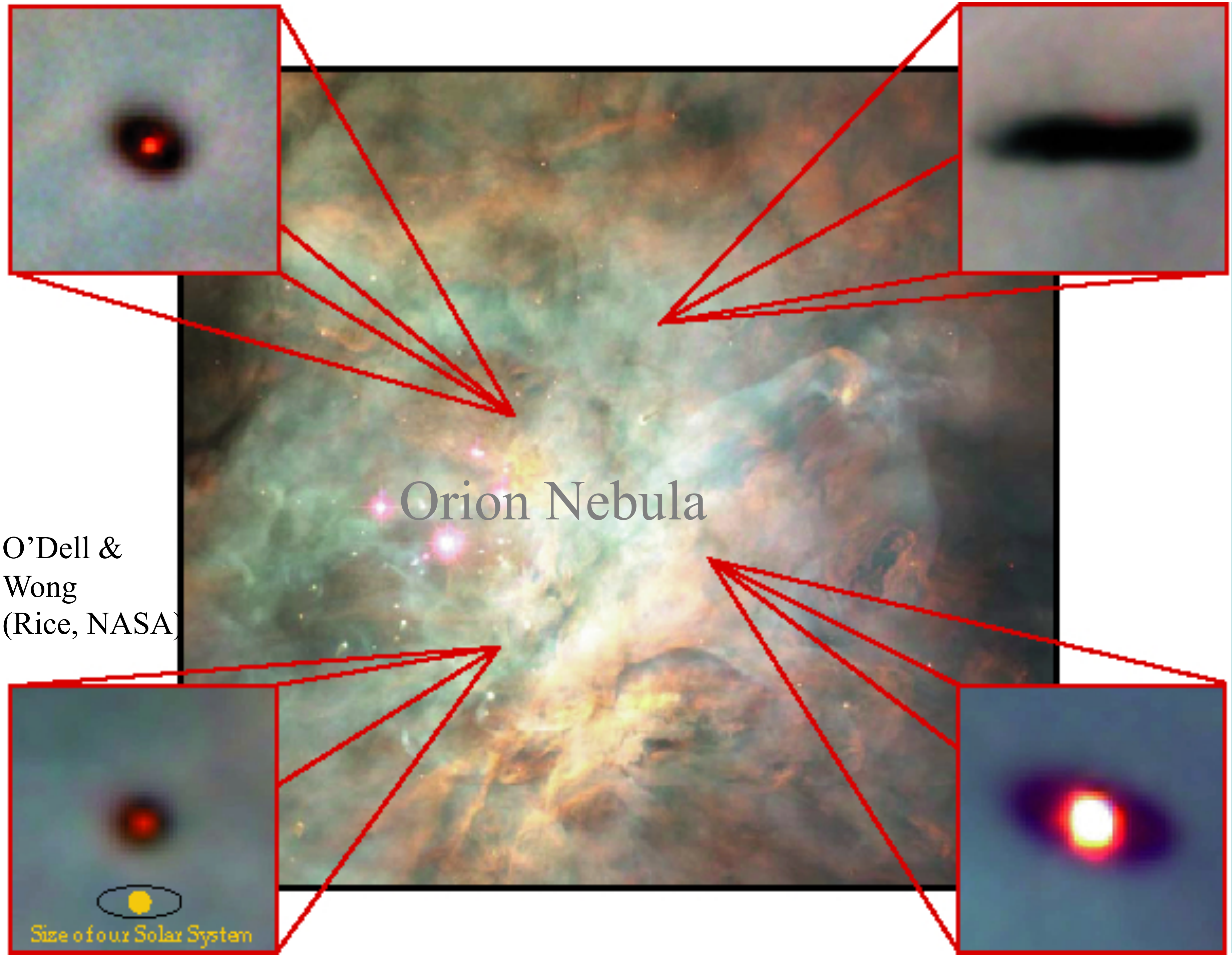
COBE



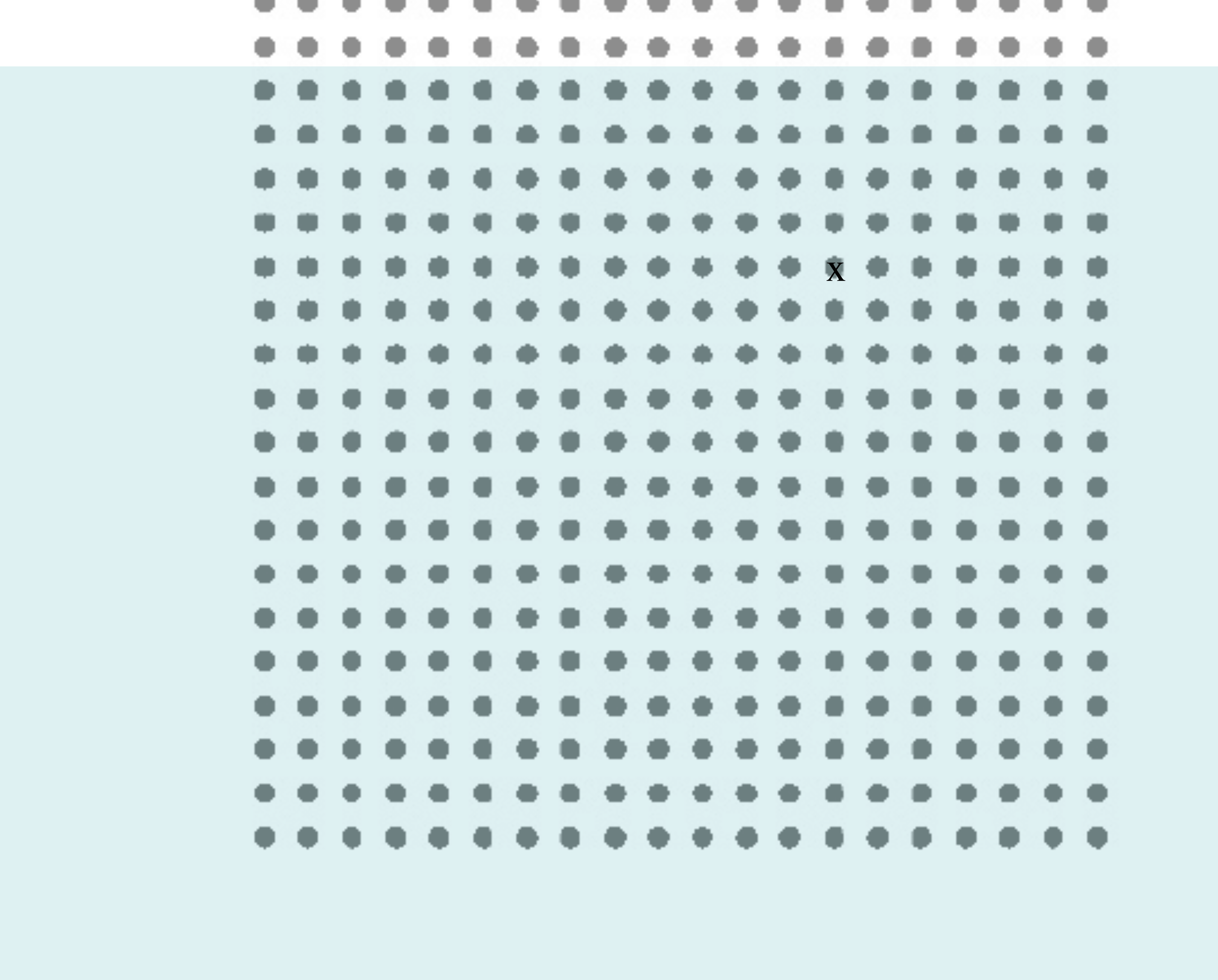
WMAP

WMAP -7 Power spectrum





O’Dell & Wong (Rice, NASA)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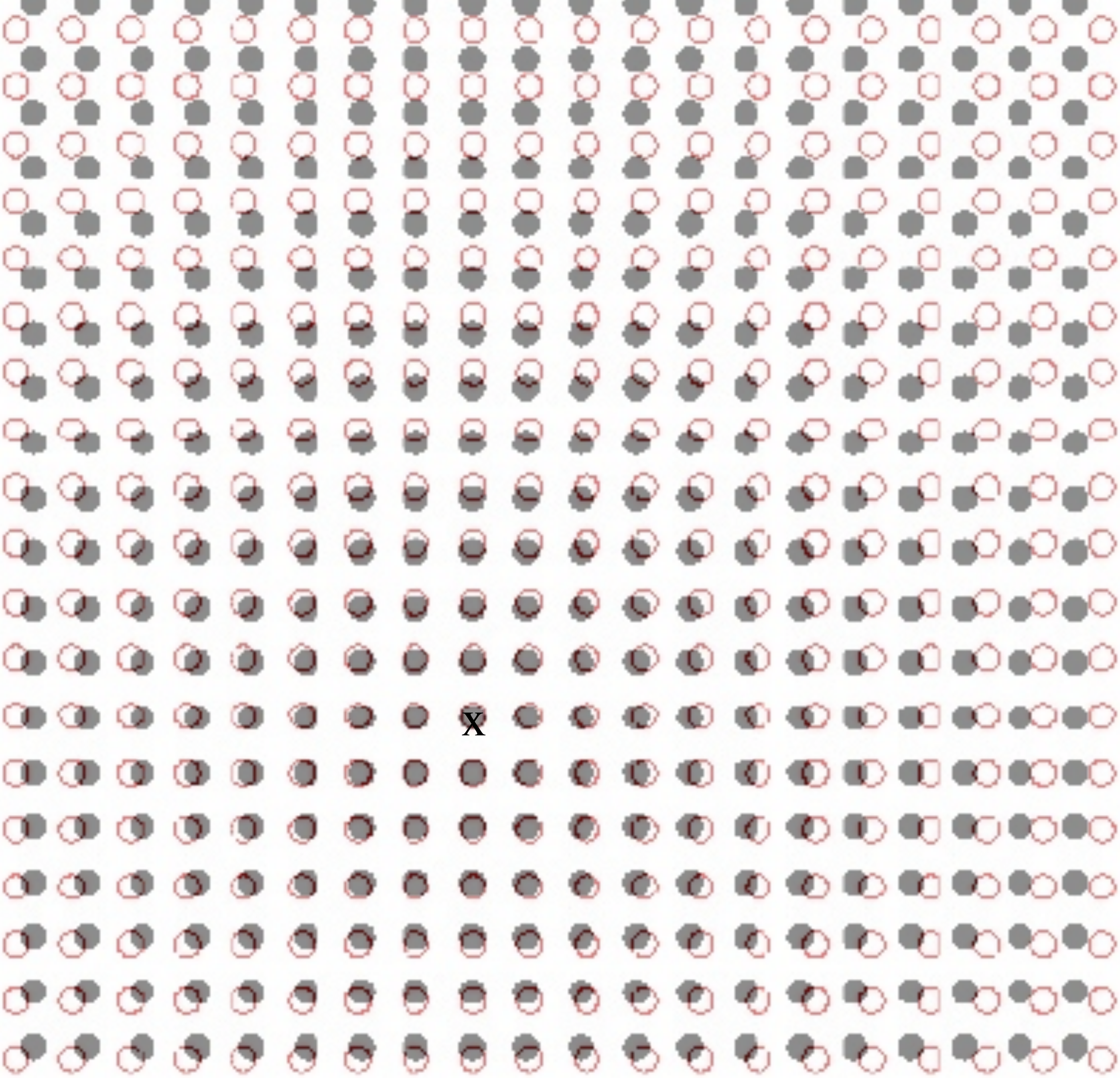
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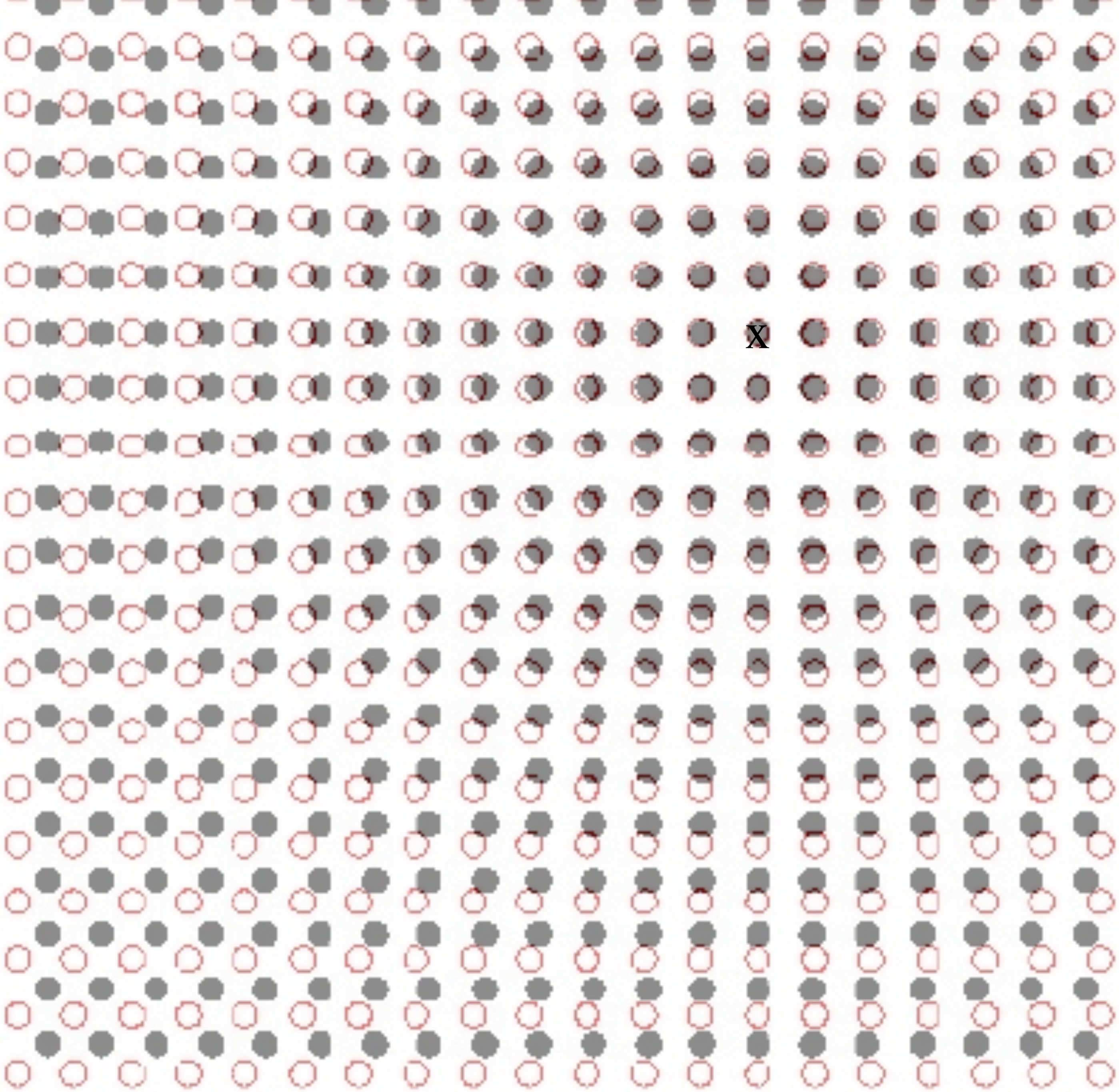
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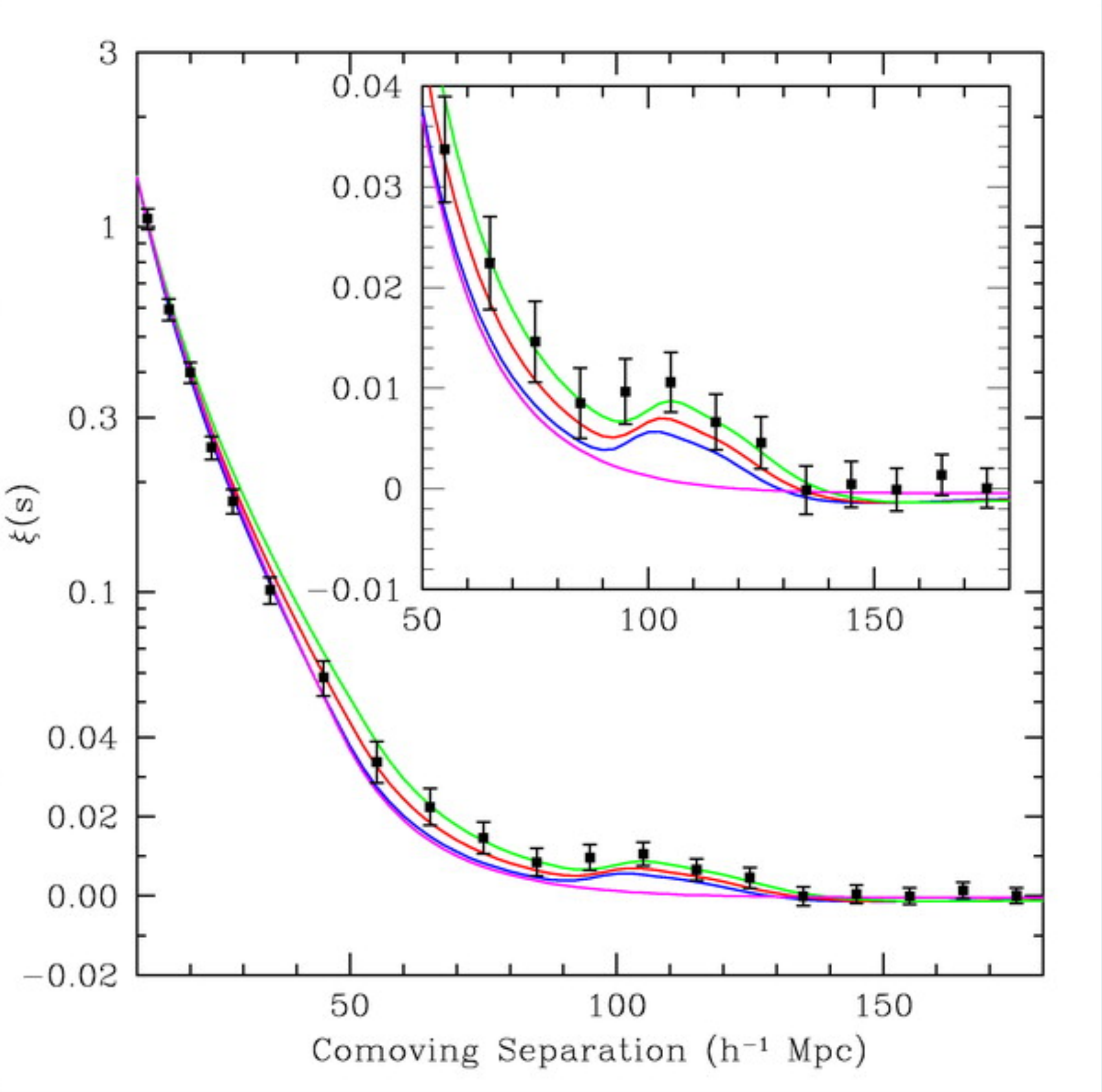

- Eisenstein et al 2005, SDSS BAO detection
- 46,000 Luminous Red Galaxies: $0.16<z<0.47$
- $\mathrm{Omega}_m = 0.273 \pm 0.025 + 0.123(1+w)$ @ $z=0.35$
- $D_V(z=0.35) = 1370 \pm 64$ Mpc

Space probably needed

- DETF says factor 10 increase in figure of merit should be required. Says only ground based methods that can get there (LSST and SKA) are more risky, nearly as expensive as a space mission, and return results on long time scale (LSST in 2024, SKA after).
- Was long claimed SNIa could be done as well from ground, but careful simulations showed space was needed to get to high enough redshifts to measure a change in DE density. HST measurements are bearing this out.
- Systematic errors will probably limit accuracy: space probably needed to reduce and control these.