Dark Energy
---What it is---
-----What it means---

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Warning

"*For if we are uncritical we shall always find what we want: we shall look for, and find, confirmations, and we shall look away from, and not see, whatever might be dangerous to our pet theories. In this way it is only too easy to obtain what appears to be overwhelming evidence in favor of a theory which, if approached critically, would have been refuted*" (Popper 1957, p. 124).

- General Relativity works beautifully in our Solar System, binary pulsars, black holes...
- Has some beautiful math behind it: pure geometry!
- But GR has yet to be tested in a cosmological context.
- Indeed there are some glaring difficulties!
  - Galaxy rotation curves level out: fix this by assuming Dark Matter.
  - Distant supernovae are less redshifted than expected: assume Dark Energy.
- With these additions, GR works out amazingly well
- But are we maybe just patching up a fundamentally wrong theory??

R.Kirschner: ***"Astrophysicists are often wrong but never in doubt."***

Astronomy Teaches Us Cosmology

- Observed Fact: It's dark out there!
  - Kepler 1610; Olbers 1823; Kelvin 1901...
  - if the universe were static and infinite in space and time, Tsky ~ Tsun!
  - so the universe is **dynamic** or **finite** in space or time or both.
- Observed Fact: the sky is not utterly cold:
  - Penzias & Wilson 1965: 2.7 degK
  - an expanding universe dilutes & redshifts initial heat
  - 2.7 degK is what you'd get if you allowed a hot dense plasma to expand 1000 times beyond its transparency point
- Observed Fact: the oldest stars 75% H, 25% He, 0.01% D
  - what you'd get by cooking matter at a billion degK for 3 minutes
- Conclusion: observable universe started with a hot big bang

Let's not be too complacent....

- By 1900, all of physics was pretty well understood
  - Kepler (1619): three laws of planetary motion
  - Newton (1687): explained as inverse square law, sun being attractor;
  - Even more exciting: moon's motion with Earth being the attractor has the same inverse square coefficient as an apple falling in Newton's courtyard!
  - Local physics may well be universal physics!
  - Carnot (1824), Gibbs (1876): thermodynamics and energy
  - Rayleigh (1894): sound
  - Electricity and magnetism unified by Maxwell (1873); predicted waves
  - Electromagnetic waves demonstrated; speed of light! Hertz (1887)
- All done! but for a few nagging problems...
  - Atoms are unstable in classical electromagnetism
  - Black body spectrum is infinitely intense in classical electromagnetism
  - Stars: how do they work?
- Max Planck (1900) and the quantum hypothesis
- atoms; chemistry; semiconductors; QO; Bell's Theorem.....
- nuclei; CPT; QFT; fundamental particles fields & symmetries....

It's happening again

- The FRW picture works pretty darn well
  - Einstein (1916): general relativity: geometry of space, time, gravity
  - ***Friedmann*** (1922); Lemaitre (1927) : a theory of cosmic dynamics
  - The expanding universe: Slipher; Humason; Hubble (1929)
  - ***Robertson & Walker*** (1934): unique solution for homogeneous universe

$$\Omega_{matter} + \Omega_{radiation} + \Omega_{curvature} = 1$$

  - The expanding universe is predicted to **decelerate**, owing to gravity.
- General Relativity has proven to be highly satisfactory
  - Mathematically elegant! Equivalence Principle etc...
  - Explains anomalous precession of Mercury's orbit
  - Explains bending of starlight and its gravitational redshift
  - Hulse-Taylor binary pulsar and gravitational radiation, as predicted!
  - Black holes predicted! and found (1977 and onward)
- Done!   All that remains is to measure that deceleration.

1998: Acceleration, not Deceleration

- High-Z Supernova Team (B.Schmidt, A. Reiss, ...)
- Supernova Cosmology Project (S.Perlmutter ....)
- Goal: to measure the ***deceleration*** of the Universe
- By 1996, seven distant SNe had been found; by 1998, 42 known
- Finding: distant universe recedes more **slowly** than the nearby Hubble-law prediction based on brightness.
- So the expansion of the universe is accelerating.

4 October 2011: Saul Perlmutter gets a phone call from Stockholm.

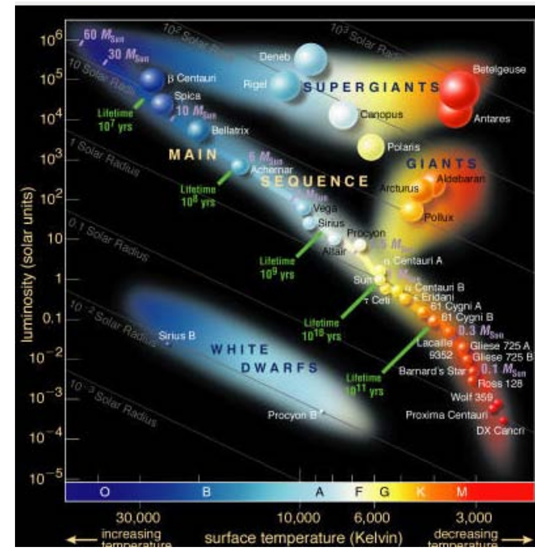
Standard Candle Method and SNe Ia

- Idea is an expanding sphere of light: Flux = Luminosity/($4\pi c^2 T^2$)
- Or in terms of faintness, ApparentMag – AbsoluteMag = μ
- So, μ measures lookback time = "age of universe" when SN exploded
- Also: redshift z = amount of expansion of universe since SN explosion
- Then: speed of expansion of the universe back then ~ $\Delta z/\Delta\mu$
- All we have to do is measure {z,μ} pairs for a bunch of SNe over a range of z.
- Issues with the standard candle method
  - Calibration: standardize using SNe in nearby galaxies; correct for stretch
  - Transparency: must detect and correct accurately host & local reddening
  - Intergalactic gray dust? Must seek out very early SNe: epoch of deceleration
  - Inverse square law: true in a flat universe but must be validated separately
  - How standard is standard, over cosmological time scales?
- Supernovae type Ia are standard to about ±0.7 mag
- Can be further standardized using stretch to about ±0.15mag

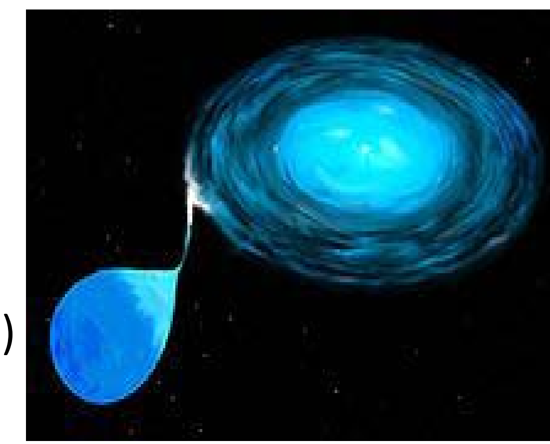
What is a Type Ia Supernova?

- A **white dwarf** is the stellar evolutionary endpoint
  - a MS star => RG branch and loses its envelope
  - the WD is the carbon or oxygen **core**; typically 0.6 Msun
  - too cool to fuse C or O: hence *no energy source*
  - supported against its gravity by electron degeneracy
  - volume shrinks if mass increases. Chandrasekhar:

$$M = N_e^2 \left(\hbar c / G\right)^{3/2} \approx 1.4 Msun$$



- If a WD has a **binary companion** that is shedding mass...
  - the WD can receive some fraction of that material
  - the WD mass can reach the Chandrasekhar limit
  - the WD implodes! core reaches 1 billion degK.
  - the WDS detonates: C + O => Si +Fe + Ni + 10^{46} joules
  - this explosion is sufficient to completely destroy the star

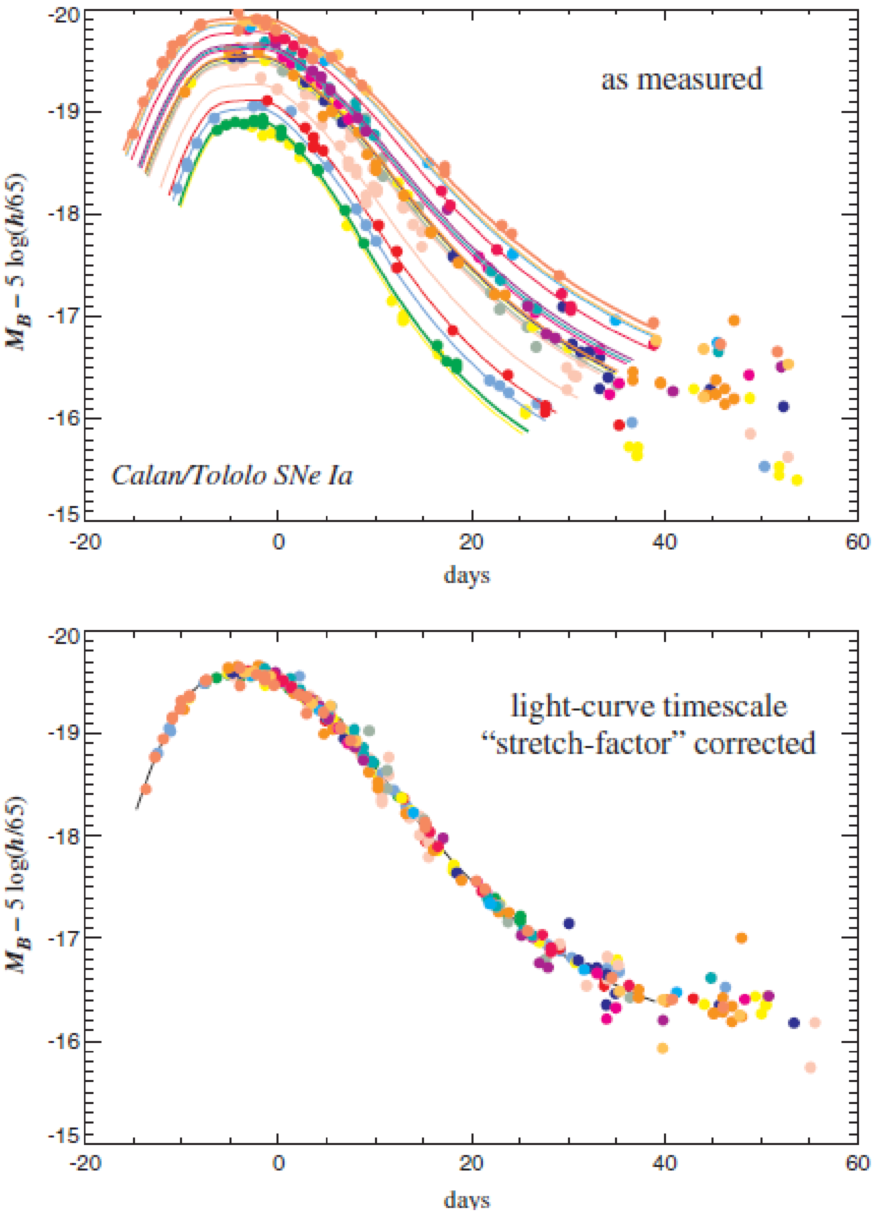


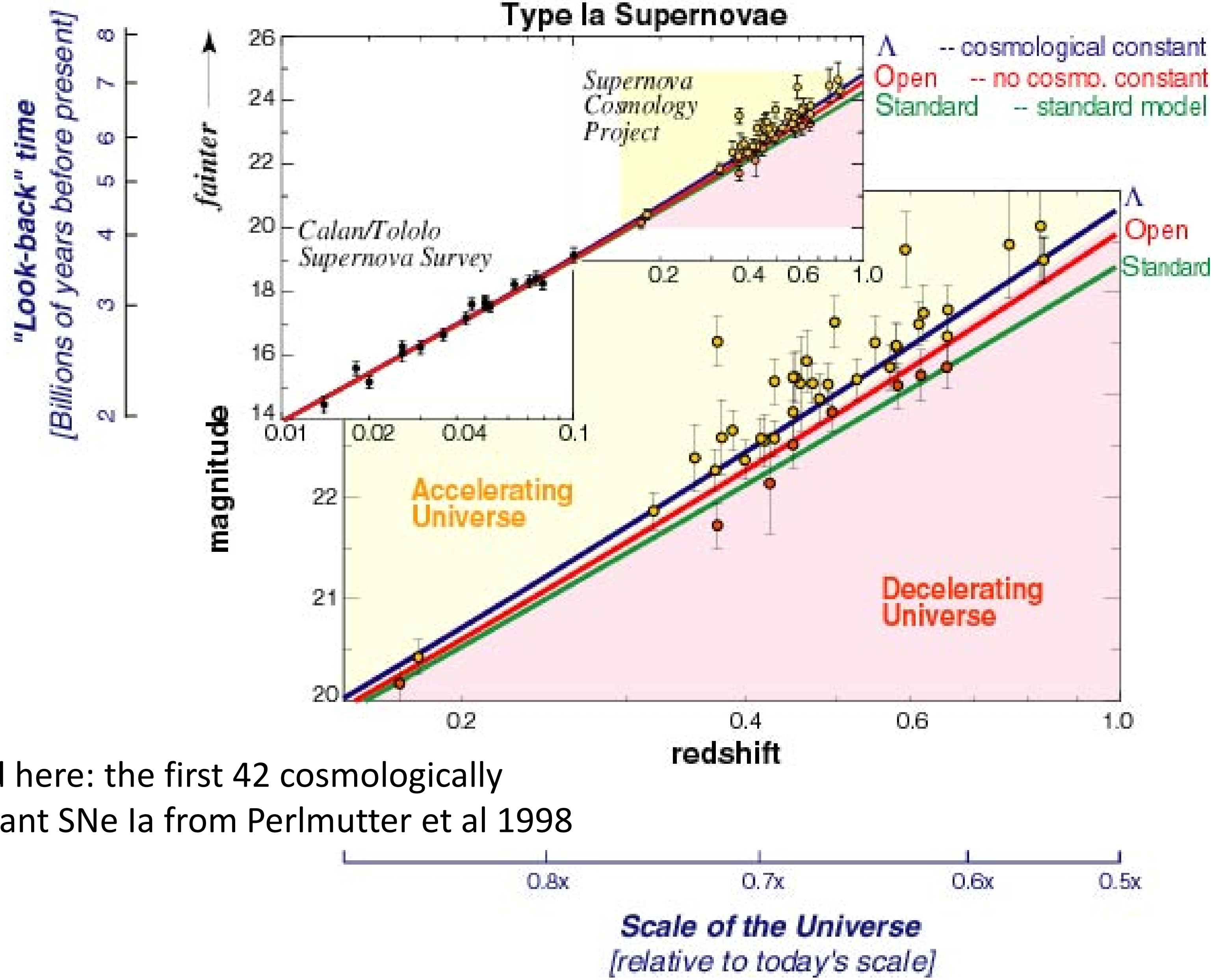
- Result: an expanding envelope of Si, Fe, Ni (little H or He)
- Result: a nicely calibrated amount of mass and energy
- Indeed most SNe Ia peak at m_V=-19.3 ±0.5

How good a standard candle?

- The trigger point is M=1.4 Msun
  - set by fundamental physics!
- However the energy yield comes entirely from the C-O core
- The amount of fuel there varies
  - roughly 0.3 to 0.6 Msun
- Also the fuel is never 100% burned
  - detonation shells, complicated hydro
- Require calibration!
- Philips (1993) discovered the key... brighter SNe last longer
  - this material has high opacity: blocks radiation
  - more material, then more blockage
- So! Calibrate this out.

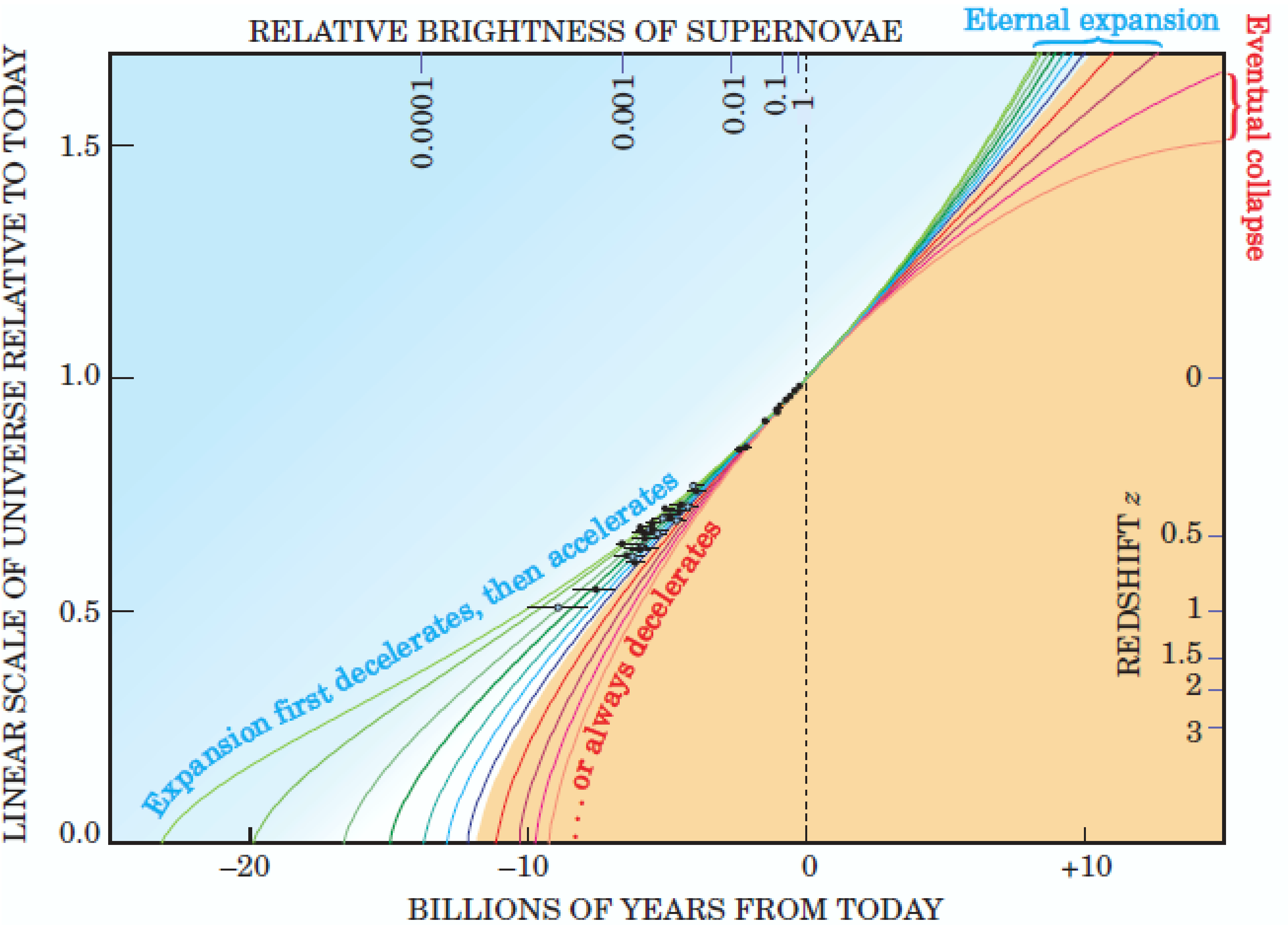
Kim, A.G. 1997; Perlmutter 1999





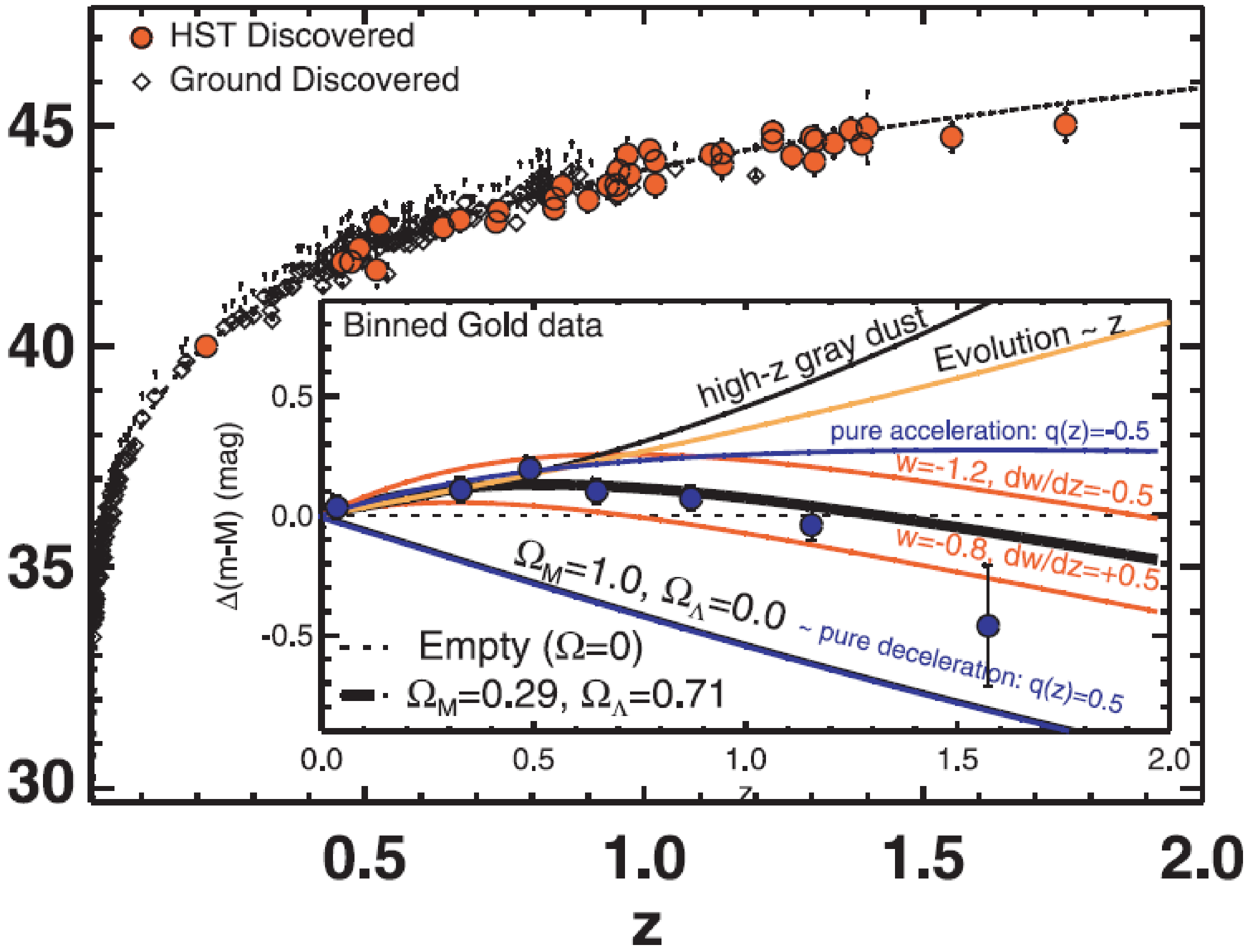
Plotted here: the first 42 cosmologically important SNe Ia from Perlmutter et al 1998

S.Perlmutter *Physics Today* April 2003: “chart recorder plot”

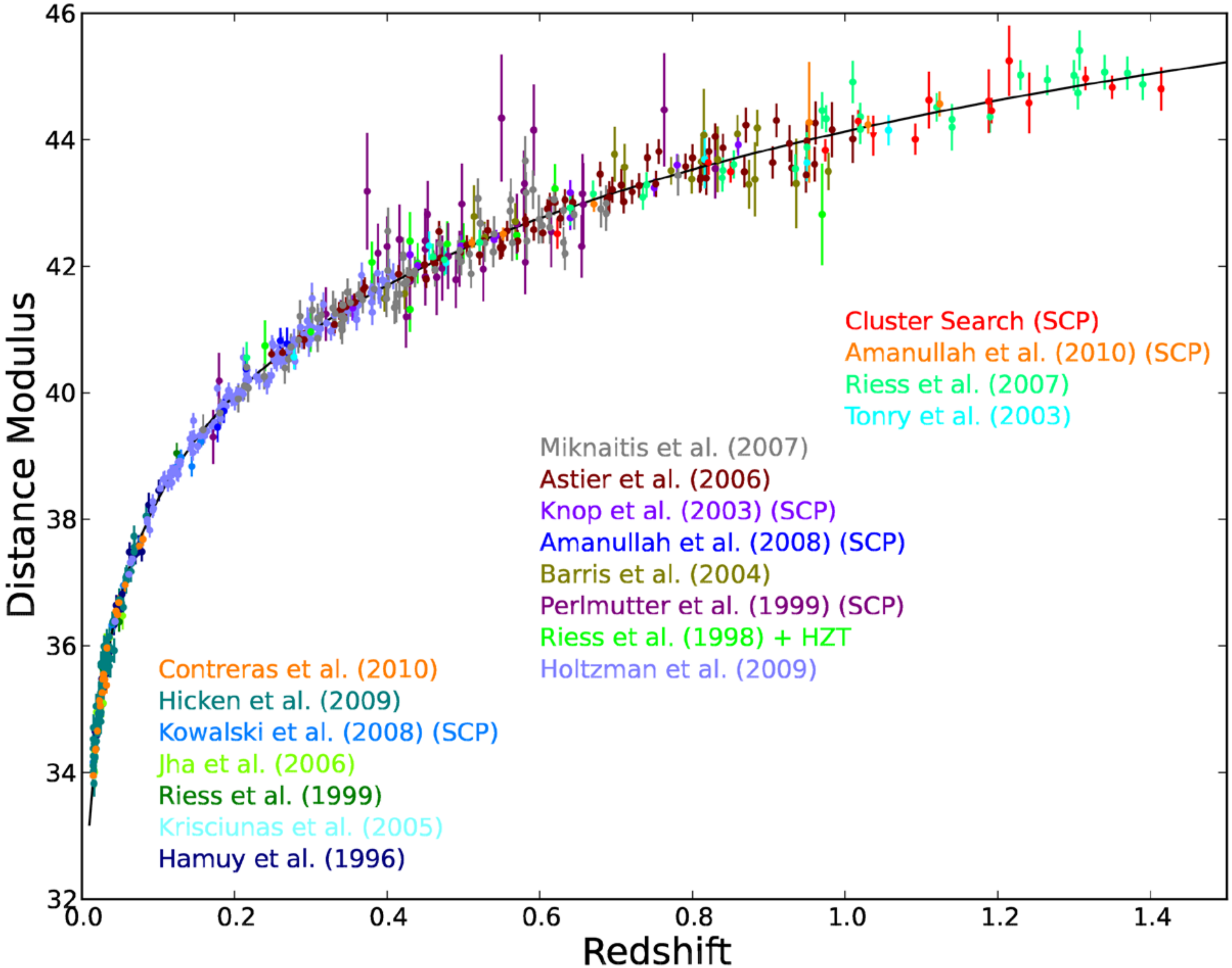


That additional faintness is not absorption or photon decay: it goes away beyond z=1 in the epoch of deceleration

Discovered by Reiss A., et al. ApJ v.659 p.98 (2007)
and since verified by many contemporary studies



Magnitude-redshift diagram, SCP 2011; 565 supernovae type Ia



Can acceleration be modelled in FRW picture?

Yes it can! but it needs "Λ" a.k.a. **dark energy** into the mix. It is really strange....

Unlike gravity it is repulsive.
Unlike matter it has negative pressure.
Unlike particles (but like *virtual* particles) it is built into vacuum.
As the universe expands, you get more and more dark energy.

$$\Omega_{matter} + \Omega_{radiation} + \Omega_{curvature} + \Omega_{\Lambda} = 1$$

26% (22% dark; 4% baryons)	**0.03% CMB Tsky**	**≈0% CMB Flatness**	**74%**	**= 100%**

Einstein's Greatest Blunder:

● Initially, Einstein (and everyone else) thought our universe was static.
● Without Λ, he found there are *no static universes*. They all collapse.
● So he introduced a *cosmological constant Λ* as a kind of antigravity. Works!
● Then 12 years later, Hubble discovered expansion! Λ was no longer needed!
● Einstein regarded his Λ as his greatest blunder, since without it he could have *predicted* the expanding universe.

Present Corroborations of "Dark Energy"

- Baryon acoustic oscillation wavelength 150Mpc ⇔ CMB scale 1^o
  - as expected for a flat universe and Zcmb = 1100 from Tcmb
  - requires Ωmass ~ 0.25 at present day
- Galaxy Power Spectrum Amplitude
  - growth from seed fluctuations ~ 10ppm in CMB driven by matter
  - less growth more recently, as dark energy reduces long range attraction
- Age of the universe ≈ 13.75 GYr for ΛCDM
  - good agreement with WMAP satellite determination age 13.70 GYr
- Weak lensing observations: just getting started
  - reveals the unbiased growth in mass fluctuations
  - agree with computational models based on ΛCDM
- Xray cluster observations: just getting started

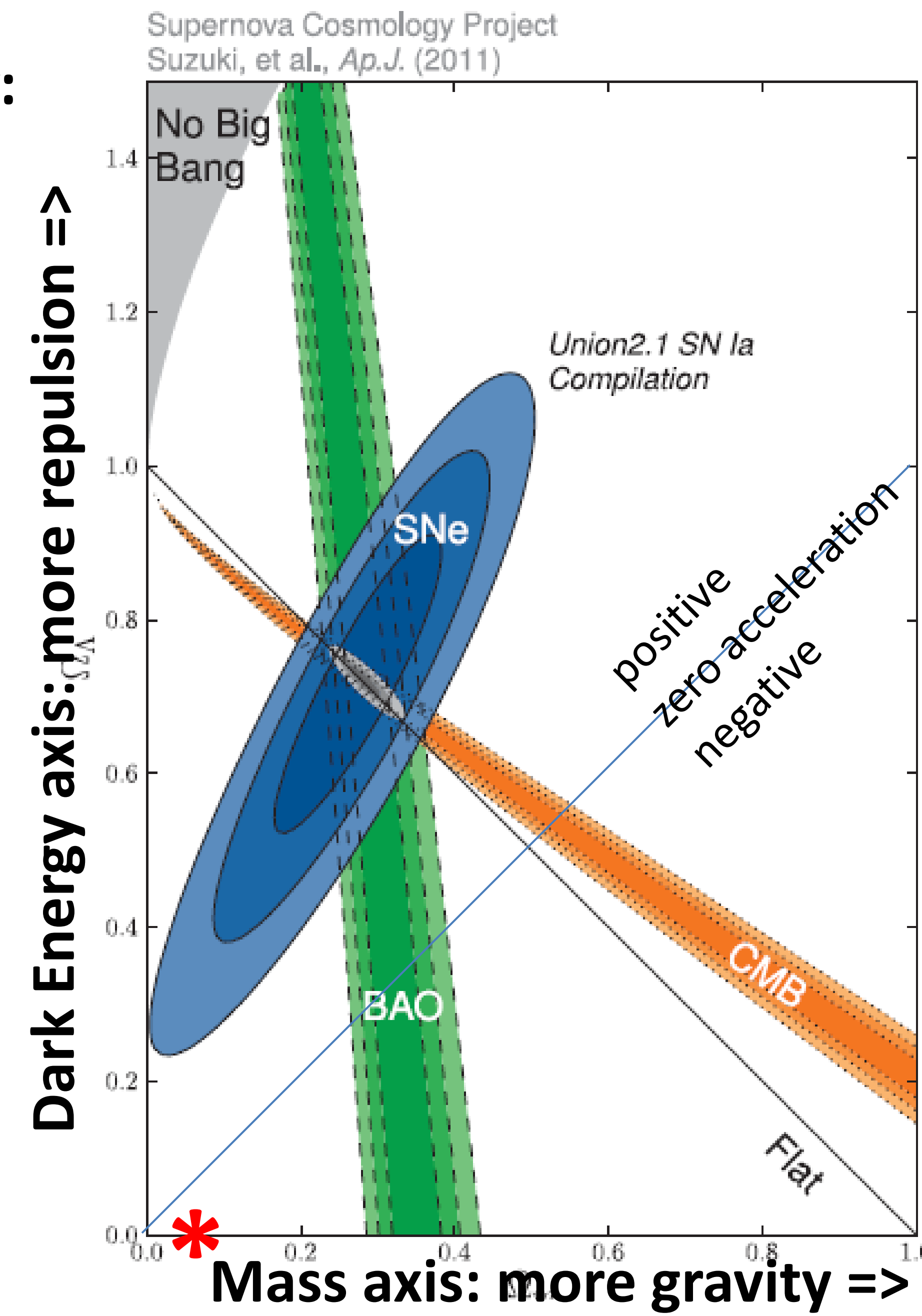
Cosmological Parameters *Now*: a consistent ΛCDM picture

Supernova data: $\Omega_\Lambda > \Omega_{mass}$
Here Ω_Λ is the repulsion;
Ω_{mass} is the attraction;
Repulsion exceeds attraction.

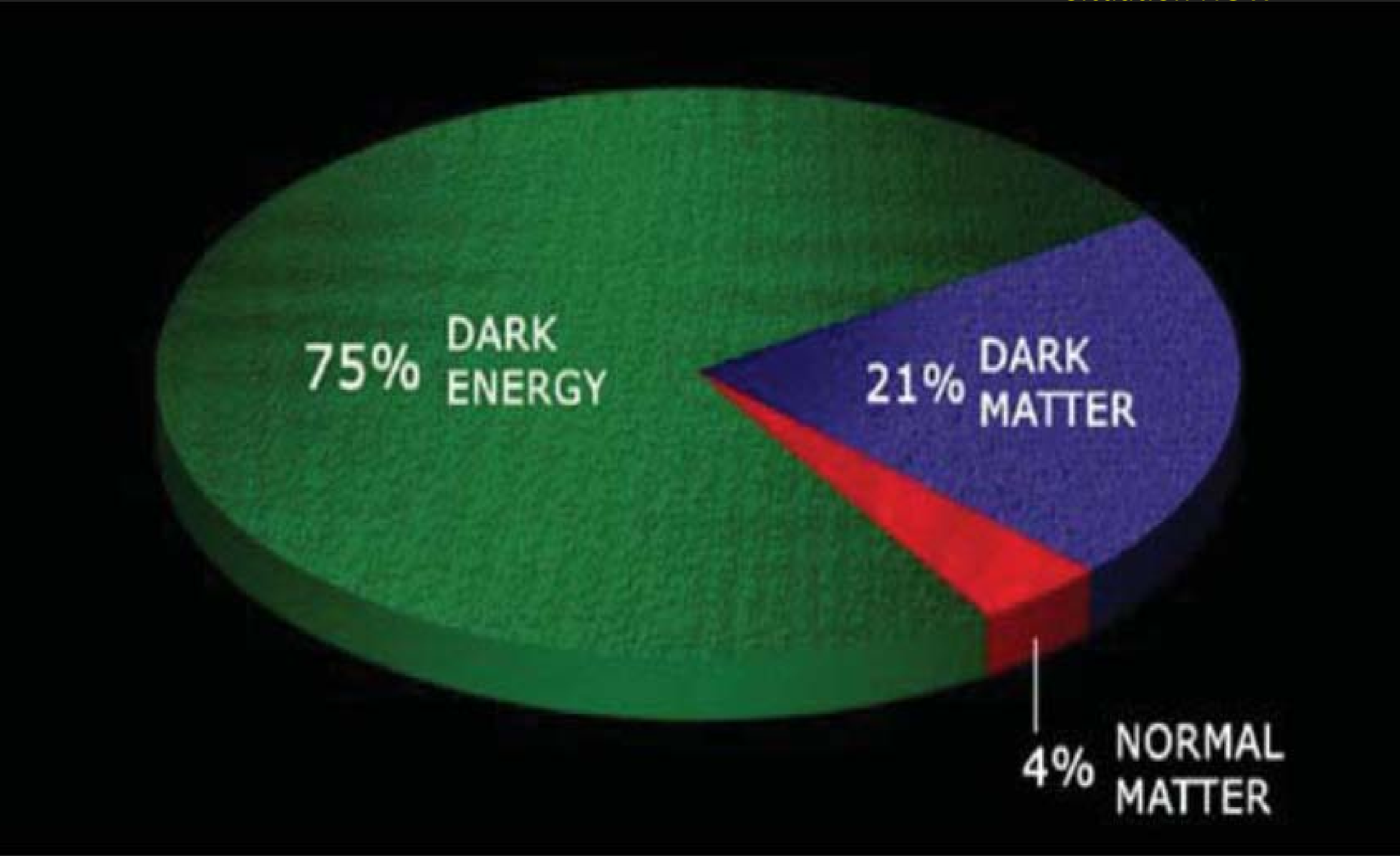
CMB data: Curvature ≈0;
we live in a flat universe;
inverse square law holds;
then if GR holds, $\Omega_\Lambda+\Omega_{mass}=1$.

BAO data : Ωmass≈0.25;

Together $\Omega_\Lambda=0.75$, $\Omega_{mass}=0.25$



Situation NOW



Explanations of "Dark Energy"

there are hundreds more: try Google!

- GR+Cosmological constant, built into vacuum
  - could be! but then why so tiny? QFT virtual particles ~ 10^{120} too big!
- GR+possibly time varying Λ, built into vacuum
  - continuum field or fields yet to be discovered
  - quintessence
  - holographic equipartition
- GR at short distances, something else at cosmological distances
  - MOND; TeVeS; "fifth force"; f(R) gravity; Massive gravity; ..
  - all need precision cosmology data to distinguish these
  - but golly GR's gravity works *amazingly* well at short & middle distances
- GR is merely a 3+1 dimensional approximation to something else
  - High dimensional braneworld scenarios from string theory?
  - Ekpyrotic and cyclic models?
  - Multiverse with vast numbers of neighboring universes?
  - Eternal inflation?

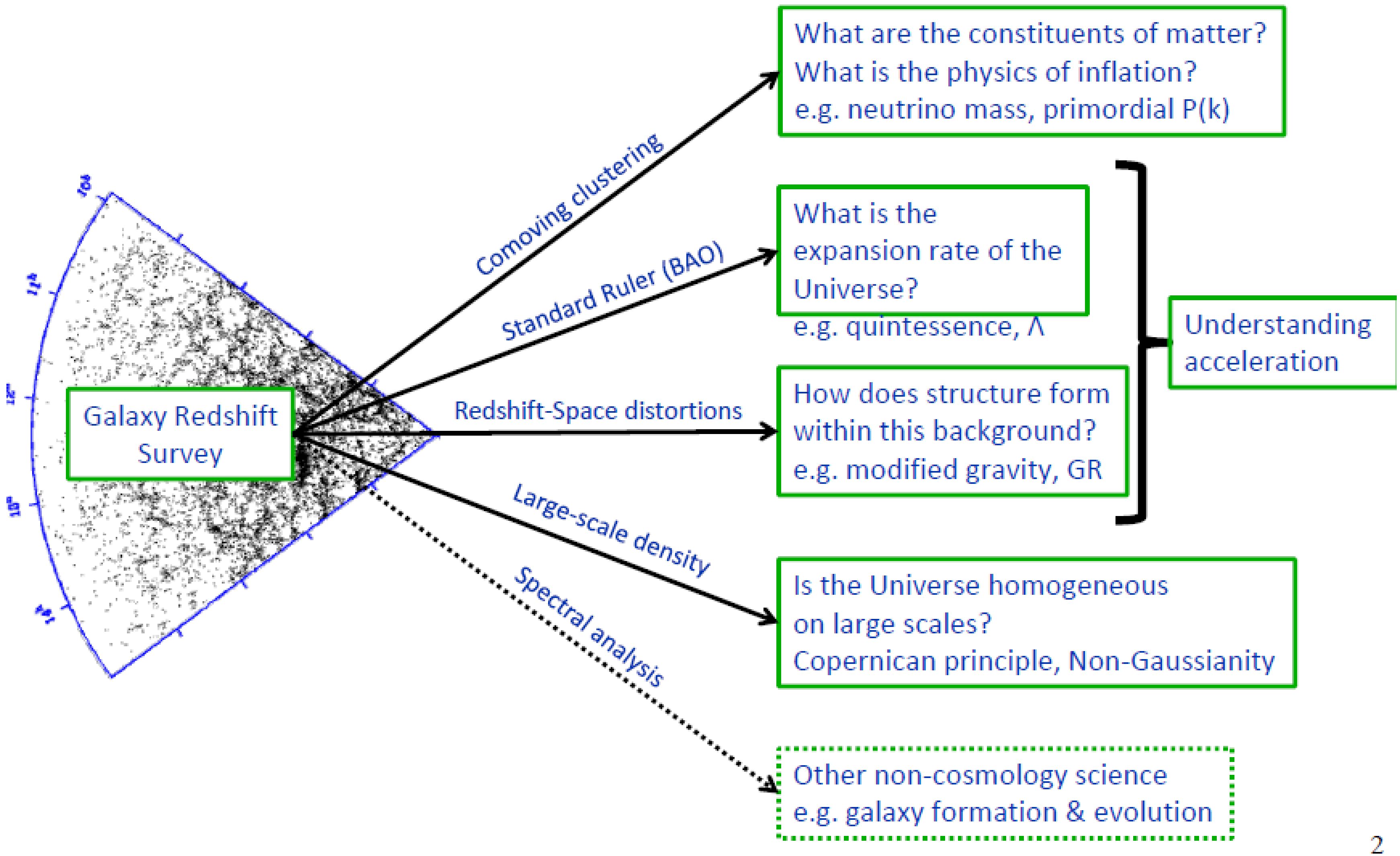
How to *test* these explanations?

- Precision cosmology on local universe won't help much
  - uncertainties in nearby universe are already darn small
- Exploring the distant past *will* help!
  - theories and models differ significantly in distant past
- Distant past here means $0.5<z<2$
  - This is where deceleration changed over into acceleration
- Large numbers of supernovae? yes
  - would give us an improved expansion rate curve
- Huge galaxy redshift surveys? even better
  - a galaxy redshift survey can test lots of features of models

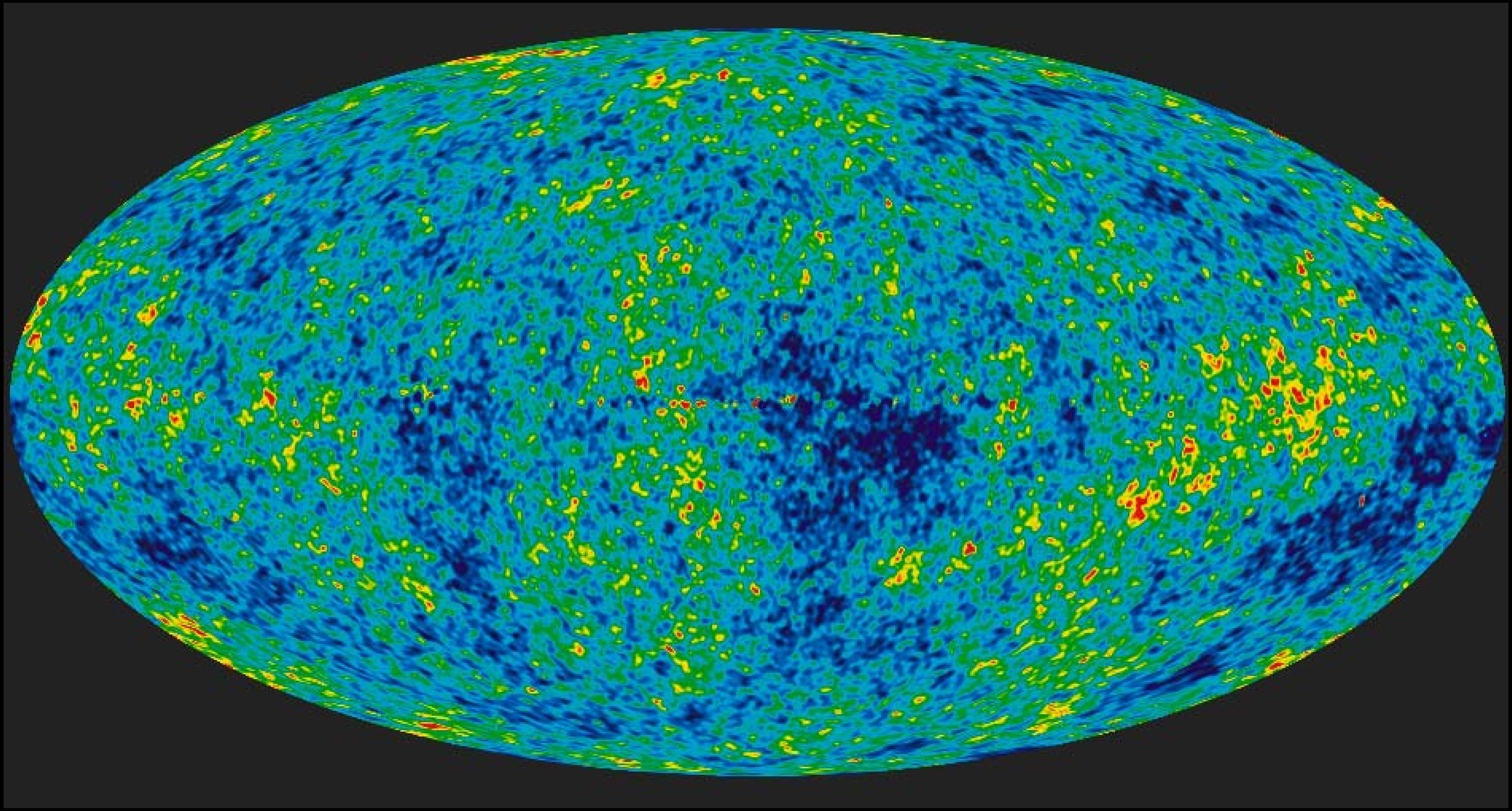
Galaxy Redshift Surveys

- Early Universe: very faint patterns of density & temperature
- Today's Universe: huge contrast! Galaxies, clusters, filaments, voids
- Structure grew over a broad range of redshifts
- Early expansion of the universe: gravity enhances the structure
- Later expansion of the universe: DE suppresses their growth
- **Theory** is key: modelling ΛCDM, and others; compare to detailed data
- Percival (2001); Eisenstein (2005); many other observing programs
- BOSS (SDSS III) (2011) will get 1.5M galaxies to z=0.6; 2.2 Gpc^3
- AAT "WiggleZ" survey (2011) has 200,000 galaxies to z=0.5
- Dark Energy Camera (installed this month) at Blanco, CTIO.
- Subaru Prime Focus Spectrograph: 2400 fibers; 1400 sqdeg to z=2.2
- BigBOSS: 20 million galaxy redshifts, 5000 fibers; 14000 sqdeg to z=1.6

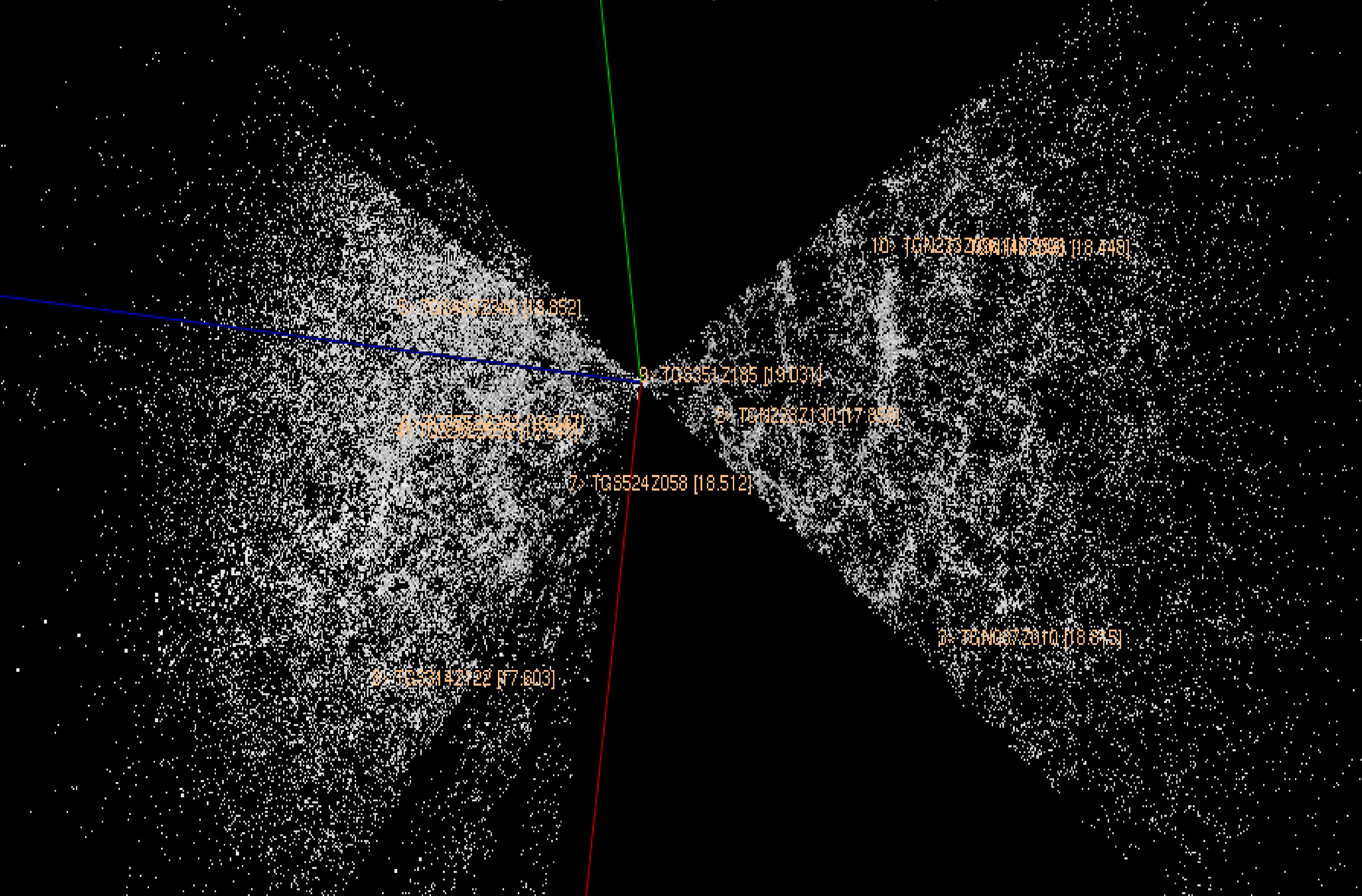
Galaxy Redshift Surveys Answer Many Questions



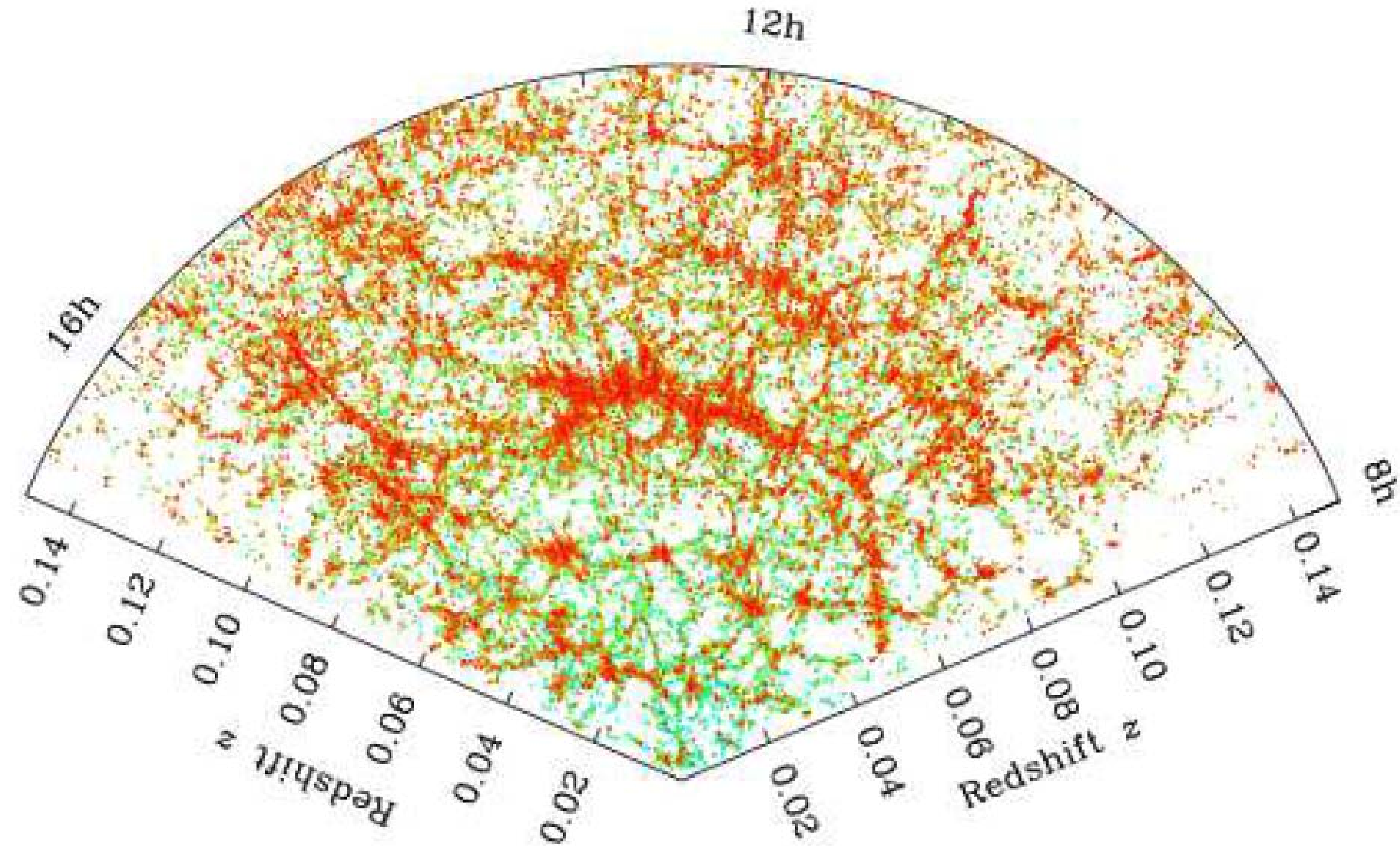
All-sky cosmic microwave background WMAP satellite year 7 results



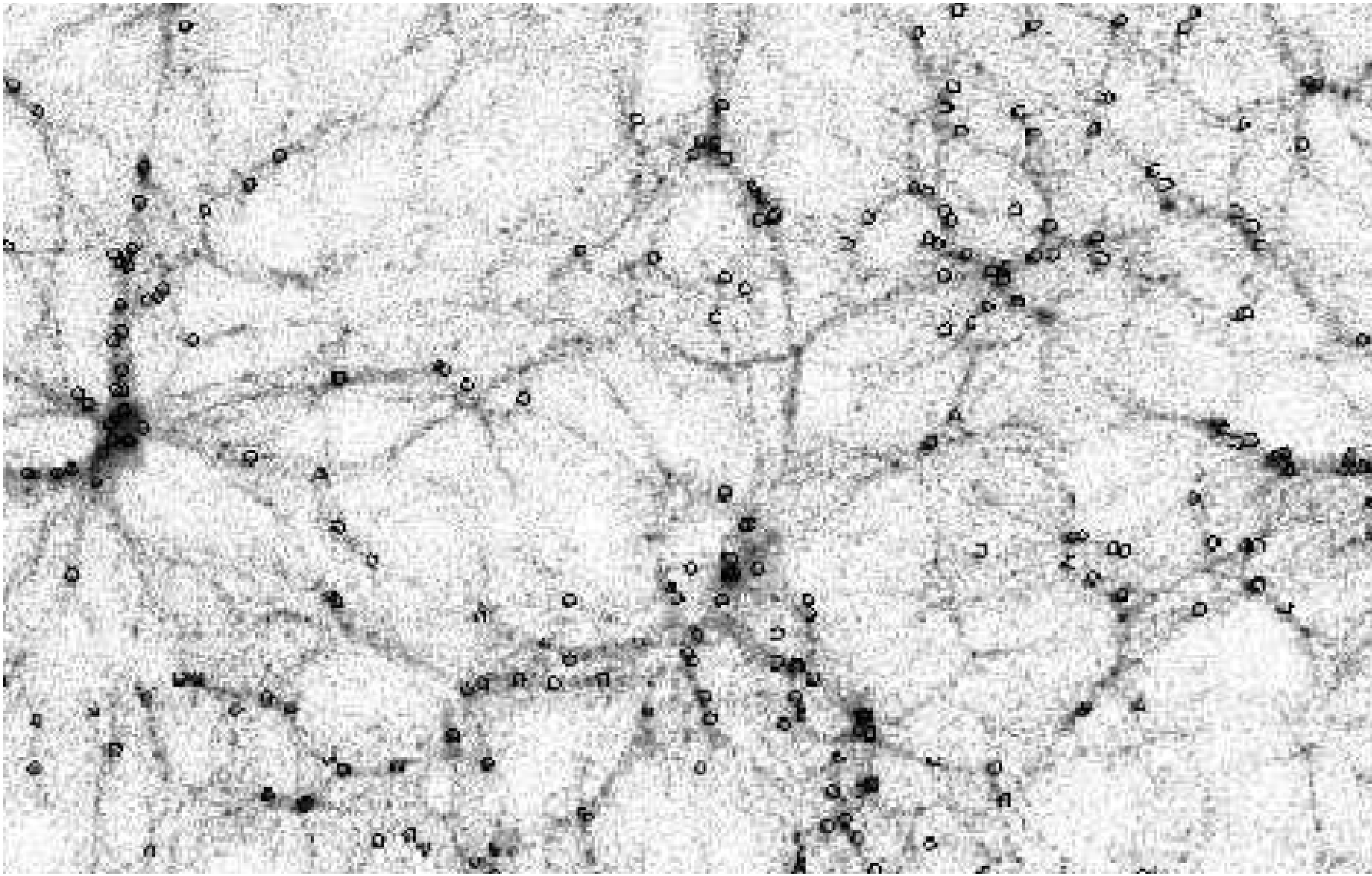
2 degree field Galaxy Redshift Survey



Galaxies today are strongly clustered! SDSS Main Galaxy Sample, Zehavi et al 2011.



Computer simulations model growth of structure: Dark Matter and Galaxies (Coil 2012)



BigBOSS

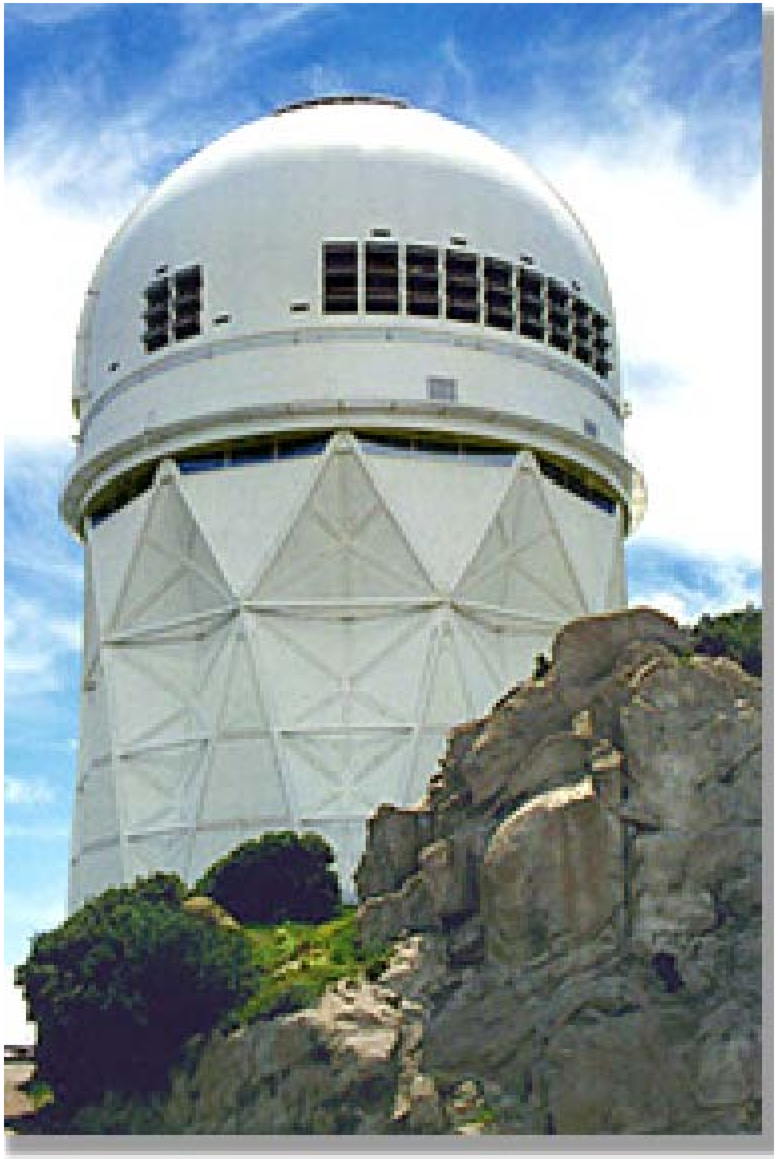
The Mayall 4m Telescope at
Kitt Peak National Observatory
Commissioned 1973

2009: NOAO requested proposals to modernize and update this facility

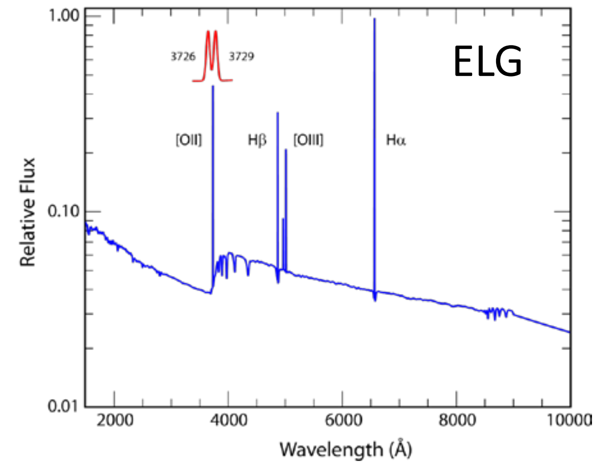
Our group at UC Berkeley – along with quite a few collaborators! -- proposed BigBOSS, the big baryon oscillation spectroscopic survey. Approved 500 nights!

To be funded through two routes:
1. Observatory upgrades: NSF/NOAO
2. New hardware & software: US DoE and many international partners.

BigBOSS is presently in a two-year pilot feasibility study.



BigBOSS Science: Redshift Surveys



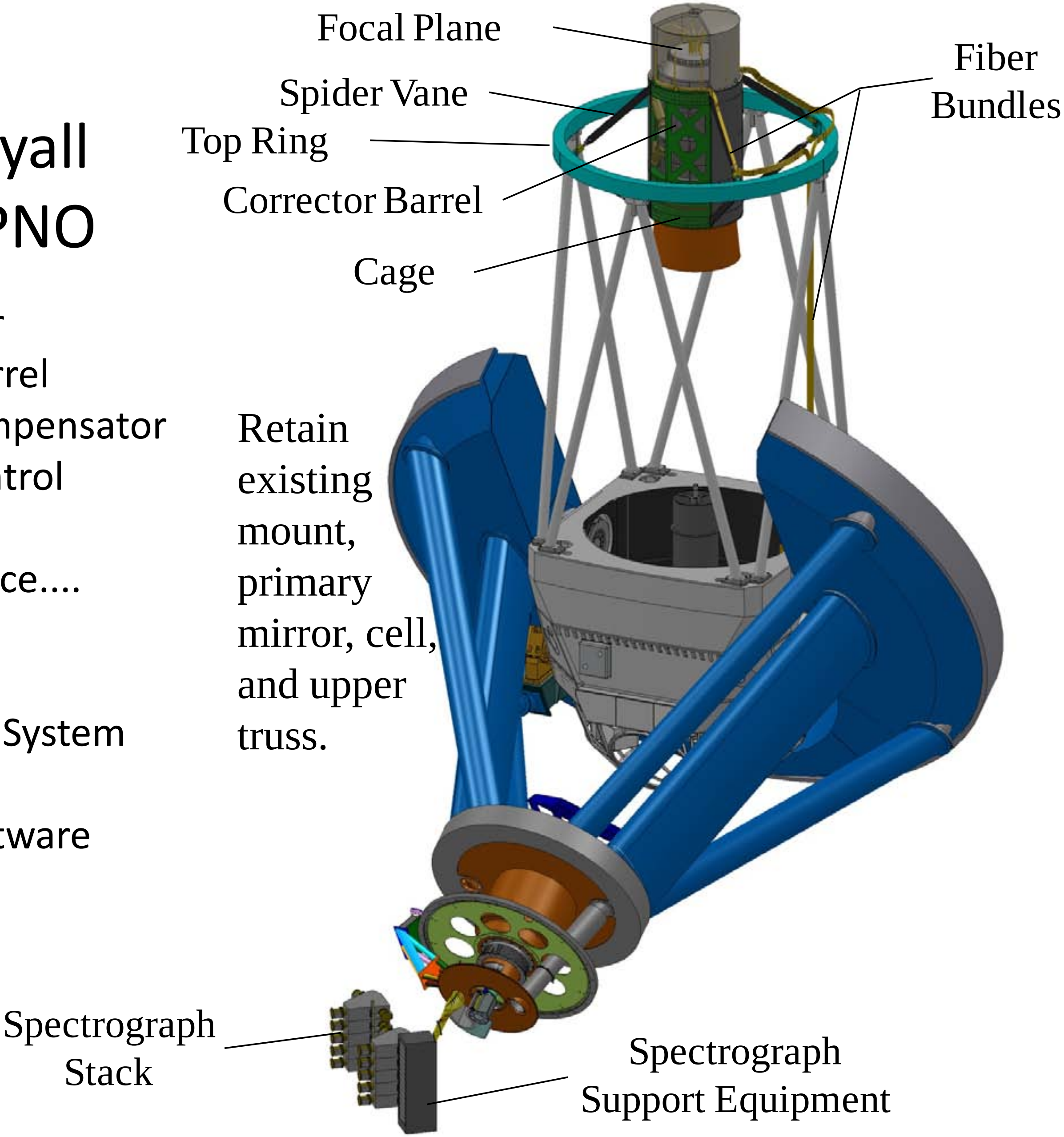
- Luminous Red Galaxies: $0.5<z<1.0$
  - about 4 million of these
- Emission Line Galaxies: $0.5<z<1.6$
  - about 20 million of these
- QSO Ly-α forest, $2.2<z_{qso}<3.5$
  - about a half million of these.

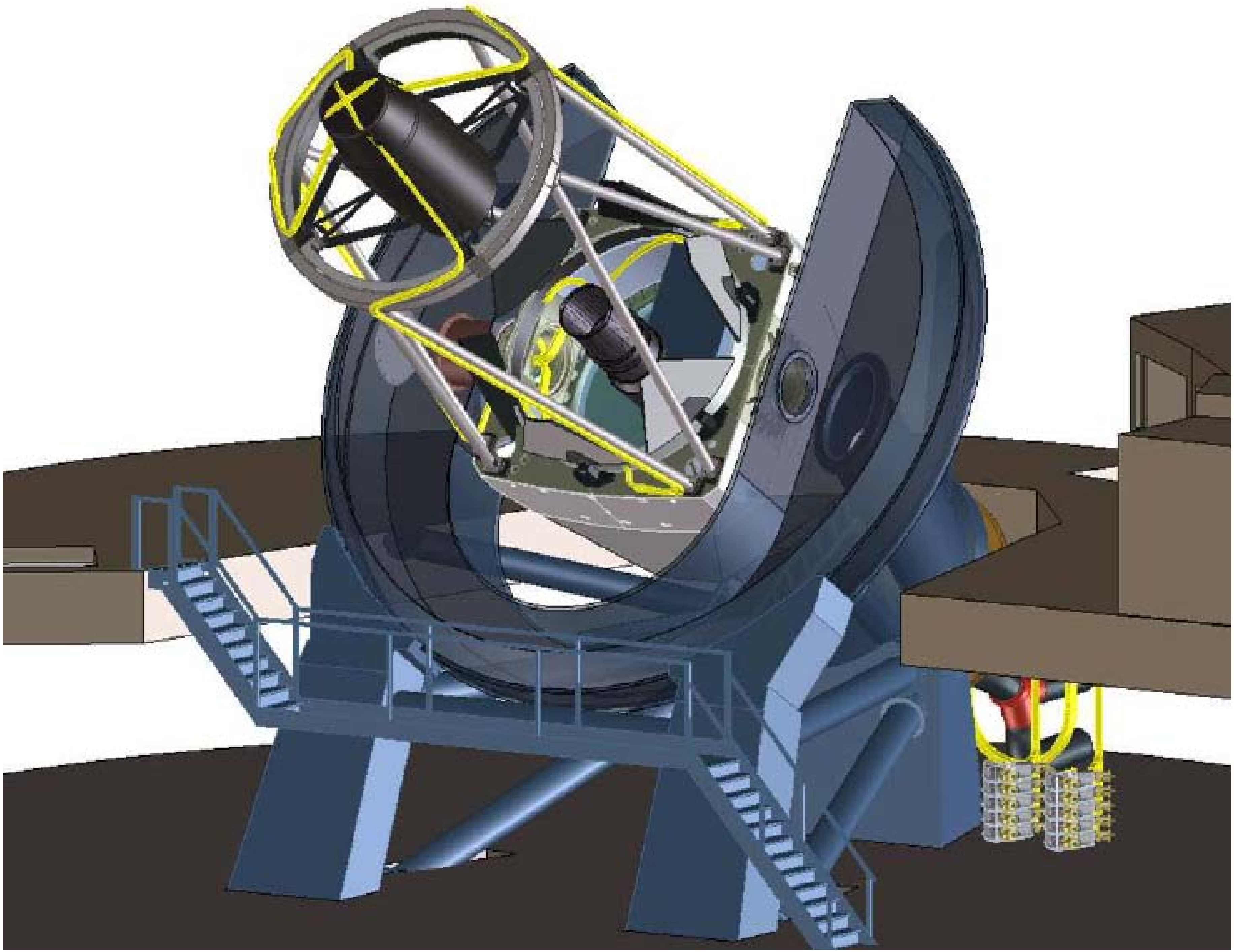
- On the Mayall 4m, this harvest will require...
  - 500 dark nights spread over ~ 5 years
  - 5000 fibers available every good night: equals 2.5 million fiber nights
  - 3 degree diameter field of view
  - spectroscopic resolving power of several thousand
  - wavelength coverage 0.36 to 0.98 µm
  - pretty much the whole sky available at KPNO: 14000 sq degrees
- Guest observer program: 1% of BigBOSS = 25000 fiber nights
- Bright time: BigBOSS becomes a facility instrument for MW science
- Hope to commission & start observing in 2017

Proposed BigBOSS upgrade to the Mayall 4m telescope at KPNO

Prime Focus 6D Manipulator
Prime Focus Corrector & Barrel
Atmospheric Dispersion Compensator
Focal Plate with thermal control
5000 robotic actuators
5000 fibers! size; performance....
Ten 3-arm spectrographs
30 CCDs with cryostats
Sensor electronics and Data System
Control software team
Fiber Viewing Camera & software
Target idenfitication Team
Spectroscopic Analysis Team
Simulation Team
Calibration Team
Managers! (5 nations!)

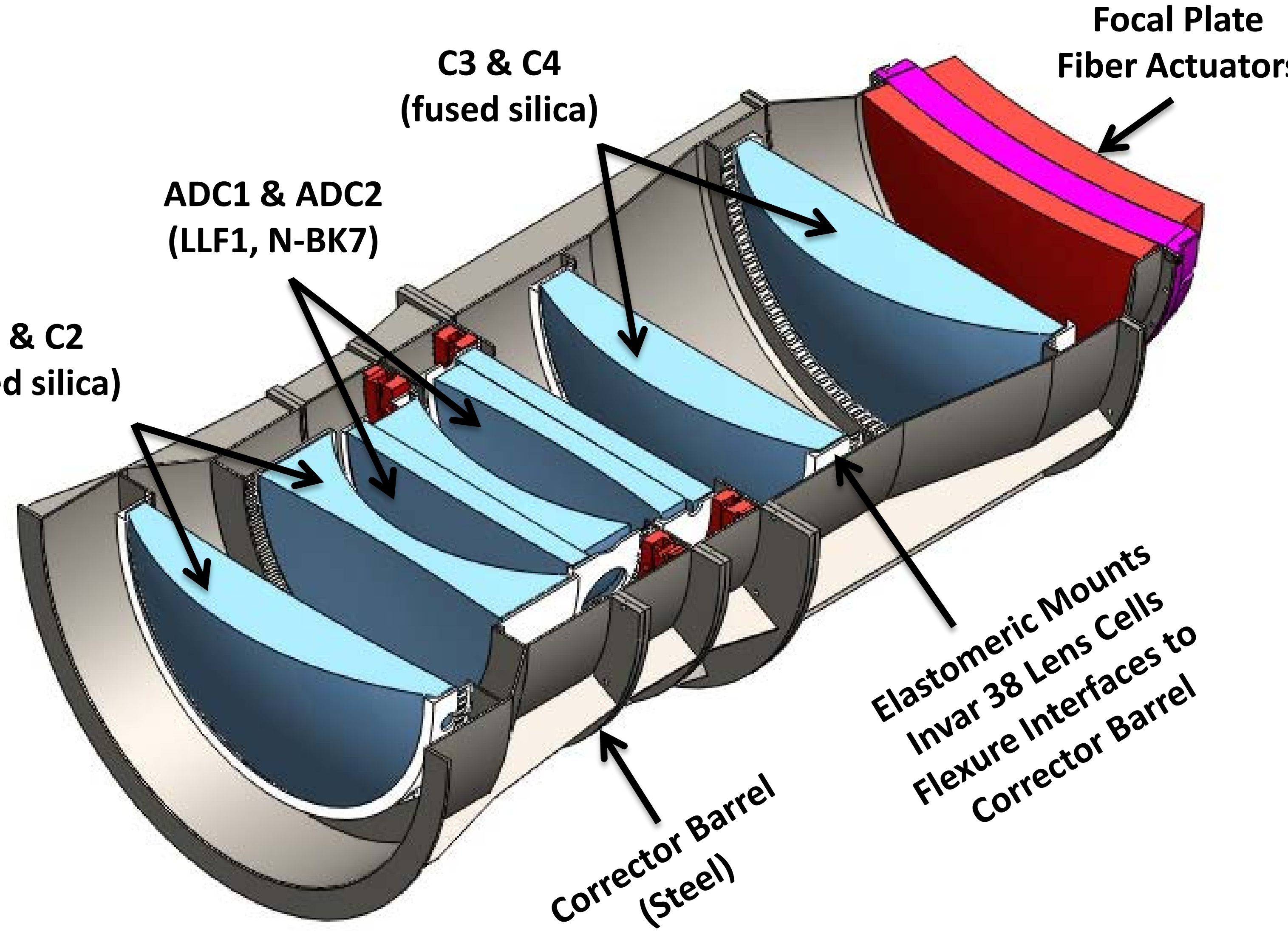
Retain existing mount, primary mirror, cell, and upper truss.

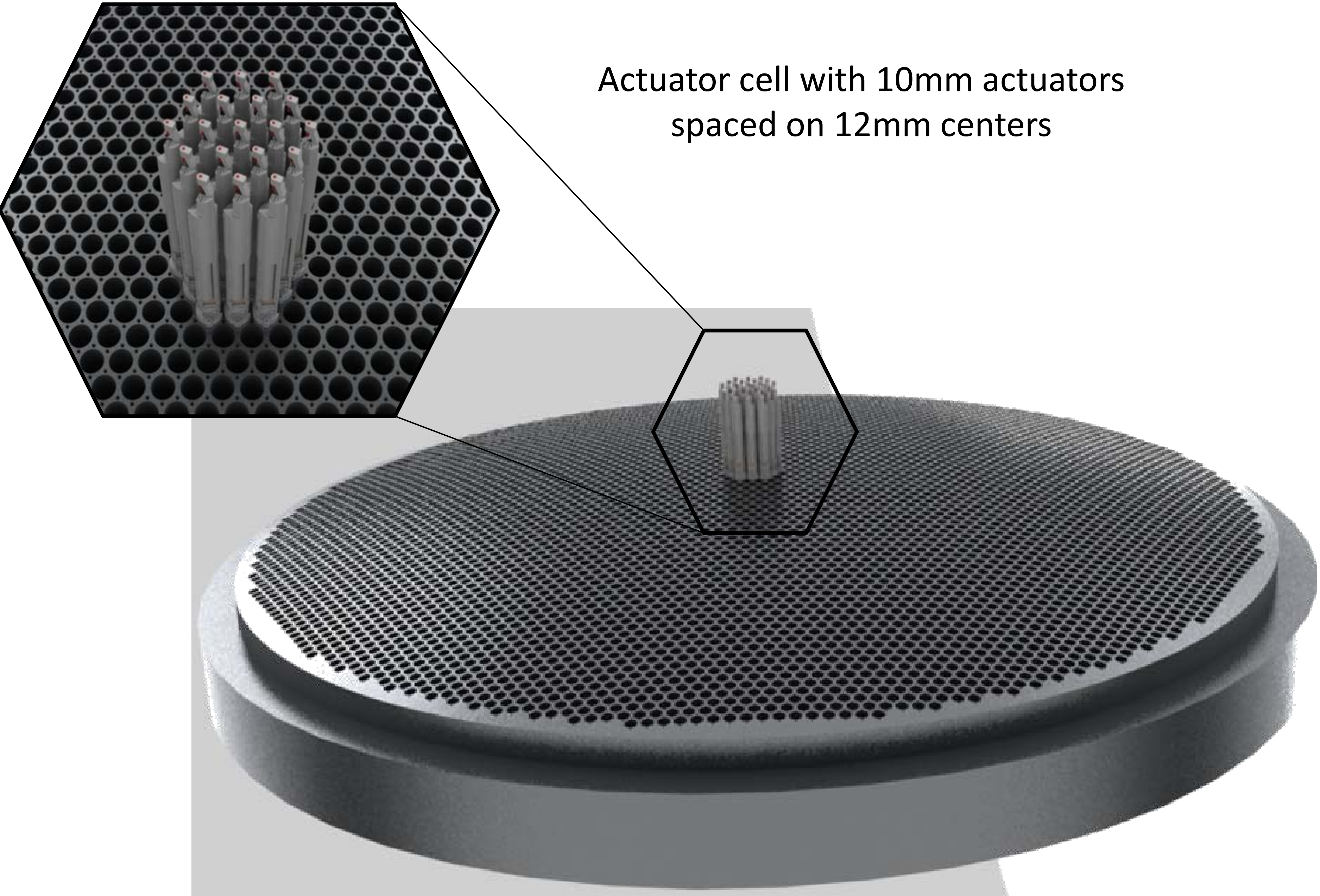




BigBOSS Prime Focus Corrector

with a built-in atmospheric dispersion compensator





0.95m ϕ Focal Plate; 5000 actuator positions (Courtesy of IAA, Spain)

Fiber Positioning Robot Development

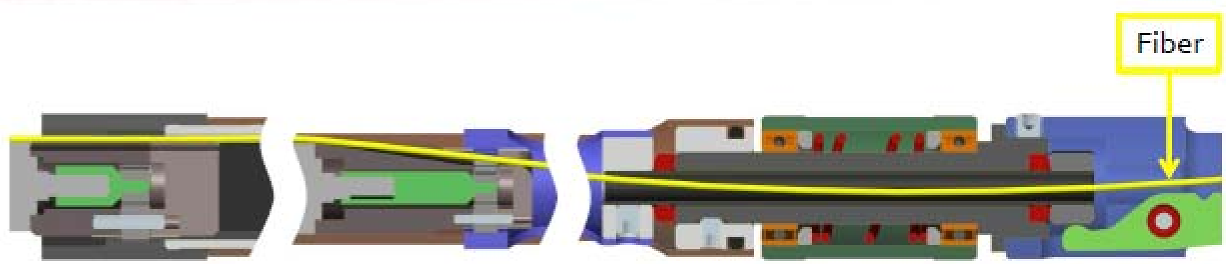
Two-axis positioning along focal surface

15mm working span with 5 micron errors

Must be low electrical power yet quick to reposition

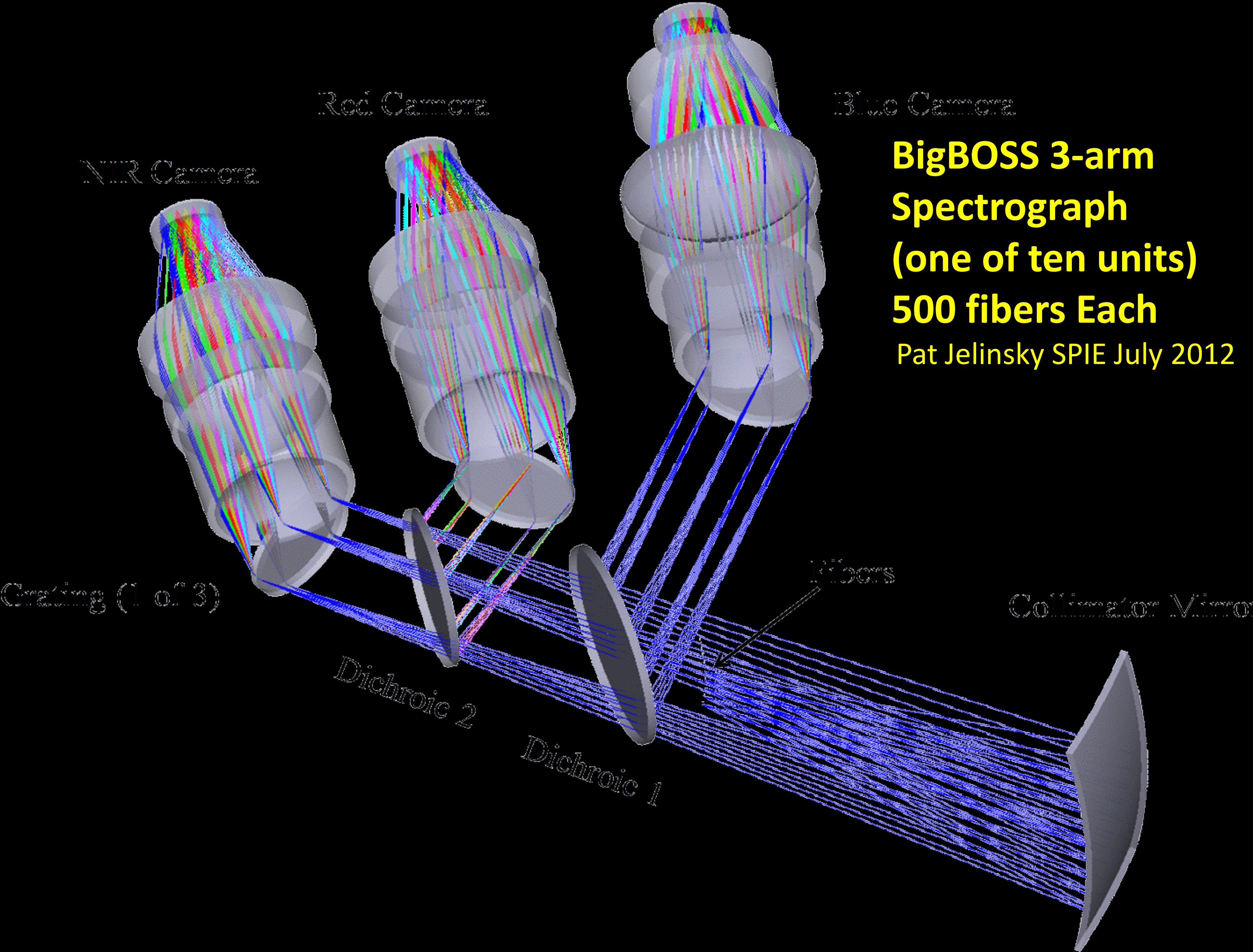
Reliability is also very important

Team: US, China



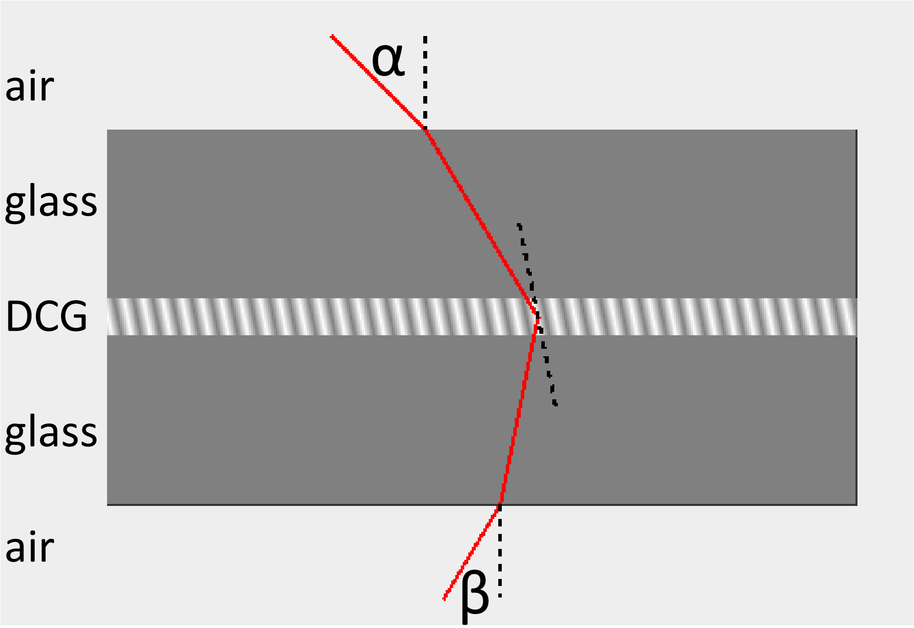
BigBOSS 3-arm Spectrograph (one of ten units) 500 fibers Each

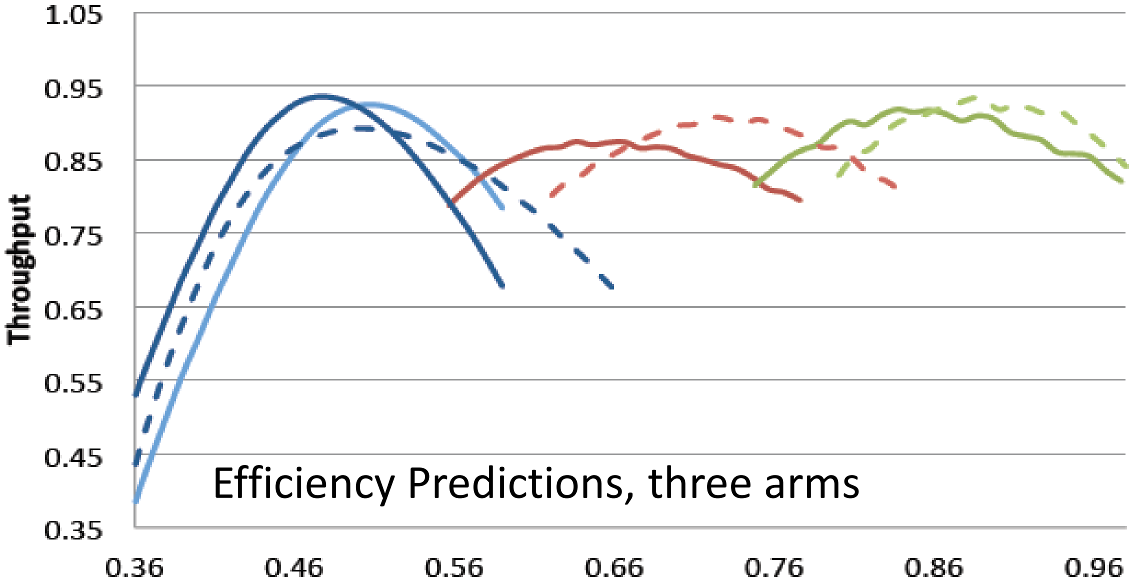
Pat Jelinsky SPIE July 2012



Volume-phase Holographic Diffraction Gratings

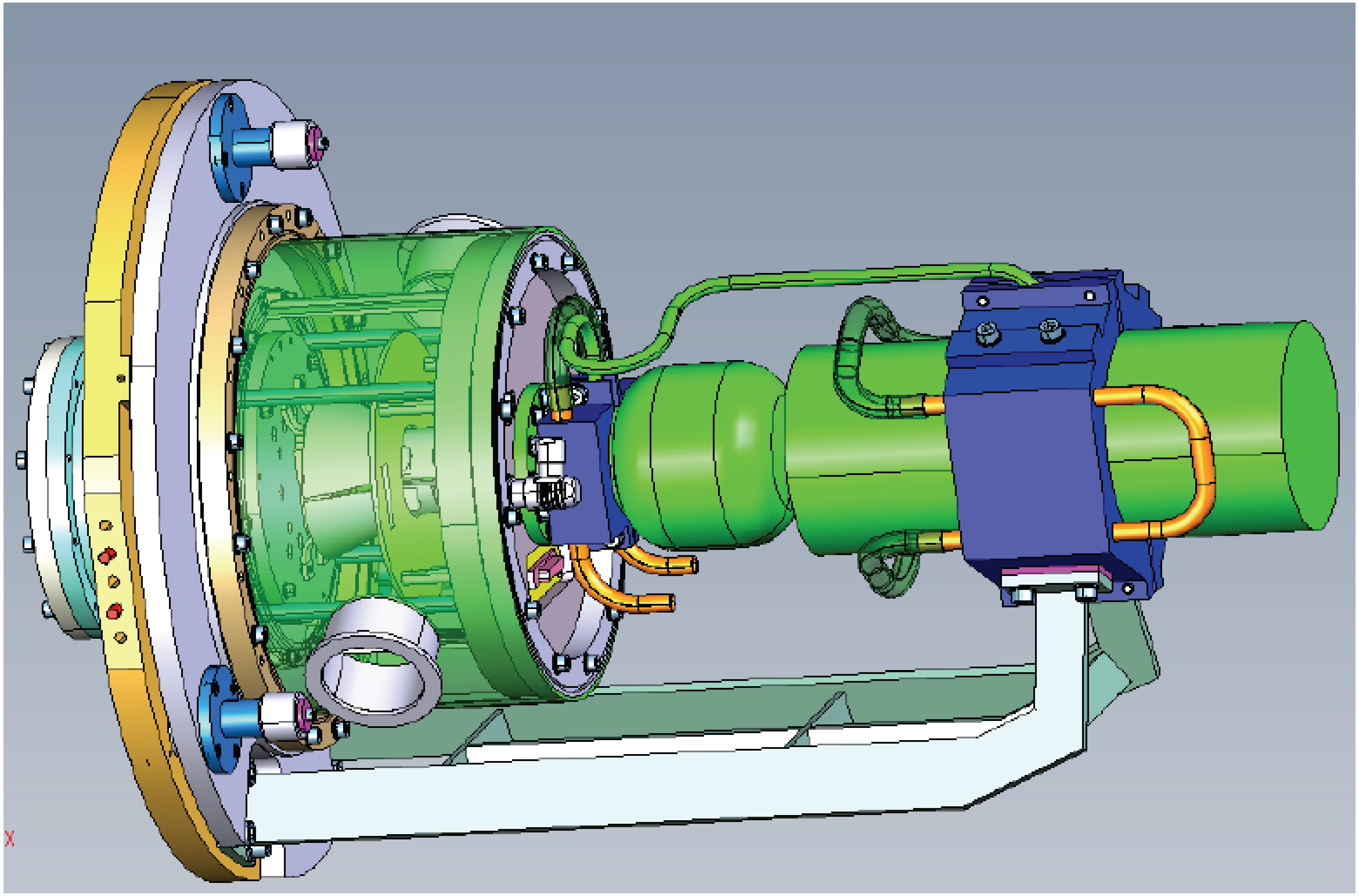
Claire Poppett SPIE July 2012





Cryostat and cold mount for 4K x 4K Si CCD sensor

being developed by collaborators at CEA, France



Guest Observing Program

Rockoski, C., 219th AAS Jan 2012

- Will receive ~ 1% of dark night fibers, 1^{st} 5 years
  - this is 5,000 fiber nights per year of dark time.   Huge!
- Expected to receive ~ 50% of other nights
  - about 250,000 fiber nights per year. Huger!
- Support GAIA and other imaging surveys
- Milky Way streams & satellite galaxies
- Globular Clusters
- Halo population Stars
- Chemical evolution of galaxies vs type
- ...and whatever the community wants to do.

BigBOSS Collaboration

... and still growing!

US Members:

Brookhaven National Laboratory, Carnegie Mellon University, Fermi National Accelerator Laboratory, Johns Hopkins University, Lawrence Berkeley National Laboratory, National Optical Astronomy Observatory, New York University, The Ohio State University, SLAC National Accelerator Laboratory, University of California, Berkeley, University of Kansas, University of Michigan, University of Pittsburgh, University of Utah, Yale University.

International Institutions:

Ewha Womans University, Korea; French Participation Group (APC, IAP- Paris; CPP, CPT, LAP Marseille; CEA, IRFU – Saclay); Spanish Participation Group (IAA, Granada; IAC, Tenerife; ICC, Barcelona; IFT, Madrid; U. Valencia); Shanghai Astronomical Observatory, UK Participation Group (Durham, Edinburgh, UC London, Portsmouth); University of Science and Technology of China.

DARK ENERGY

MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY

Michael Turner, U.Chicago, Feb 2012

Further Reading

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Weinberg D. et al., “Observational Probes of Cosmic Acceleration,” arXiv 1201.2434 (2012): 253 pages!
Wiltshire, D.L., “Gravitational energy as Dark Energy,” arXiv 1102.2045 (2011)

Three fun websites

http://bigboss.lbl.gov/

includes links to all our 219th AAS papers & posters

www.MikeLampton.com

what I've been doing.

www.StellarSoftware.com

home of the Beam Four optical ray tracer.

Einstein's integrated field equations (1917)

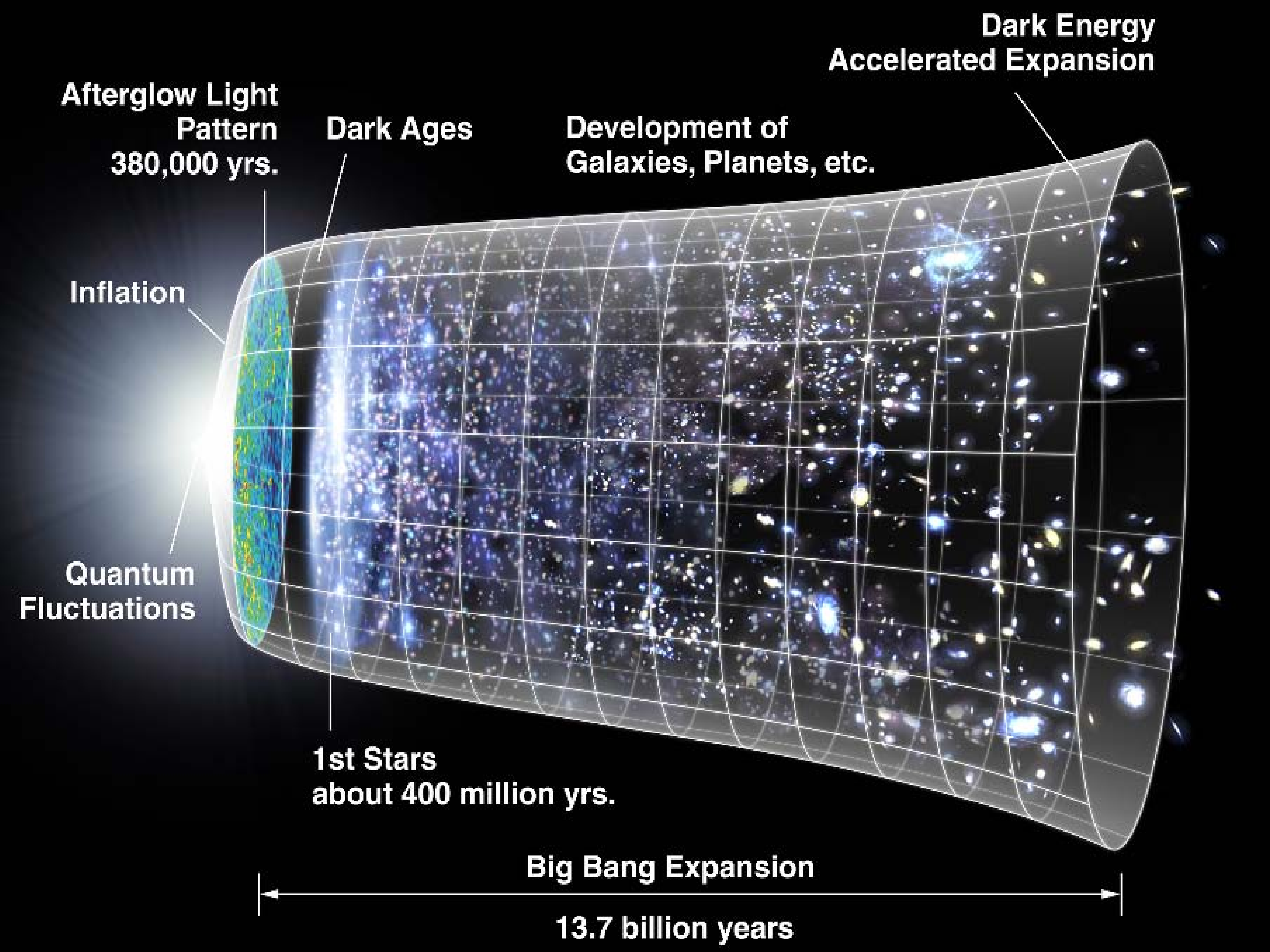
$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G\rho}{3} + \frac{\Lambda c^2}{3} - \frac{kc^2}{R^2}$$

Velocity equation: mass and Λ add

$$\frac{\ddot{R}}{R} = \frac{\Lambda c^2}{3} - \frac{4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right)$$

Acceleration equation: mass and Λ subtract

- Static universe with mass requires a positive lambda
- Expanding decelerating universe allows lambda=0.
- Danger! Runaway solution if lambda is large and positive!



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years