Cosmological Probes of Dark Energy

and the encore presentation of

Testing the Isotropy of the Universe

Dragan Huterer

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University of Michigan

Dark Energy

The universe today presents us with a grand puzzle:

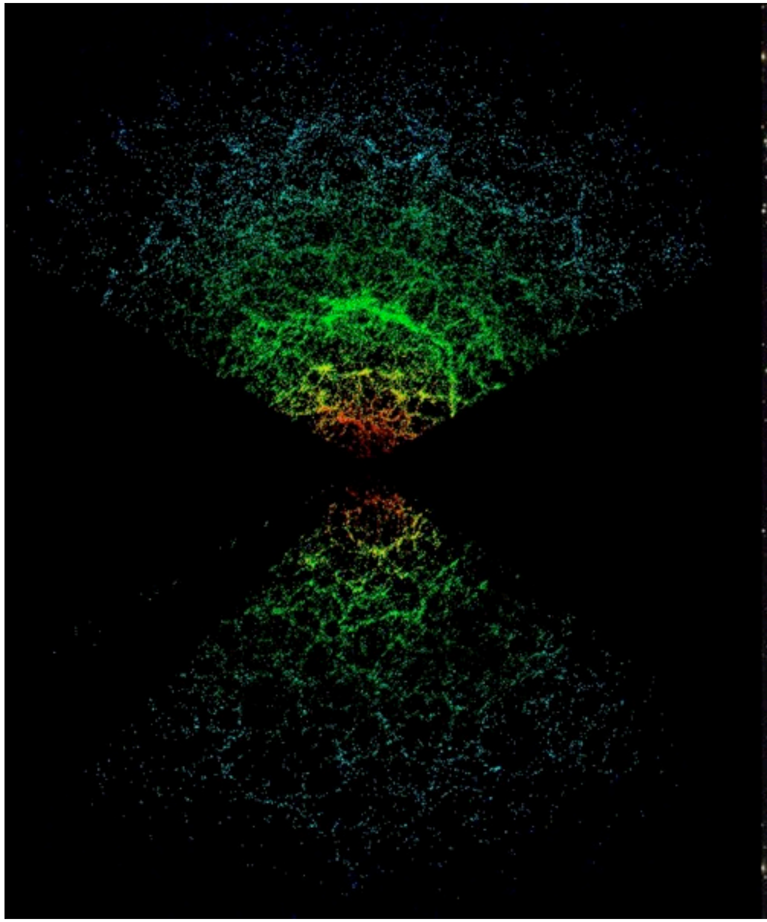
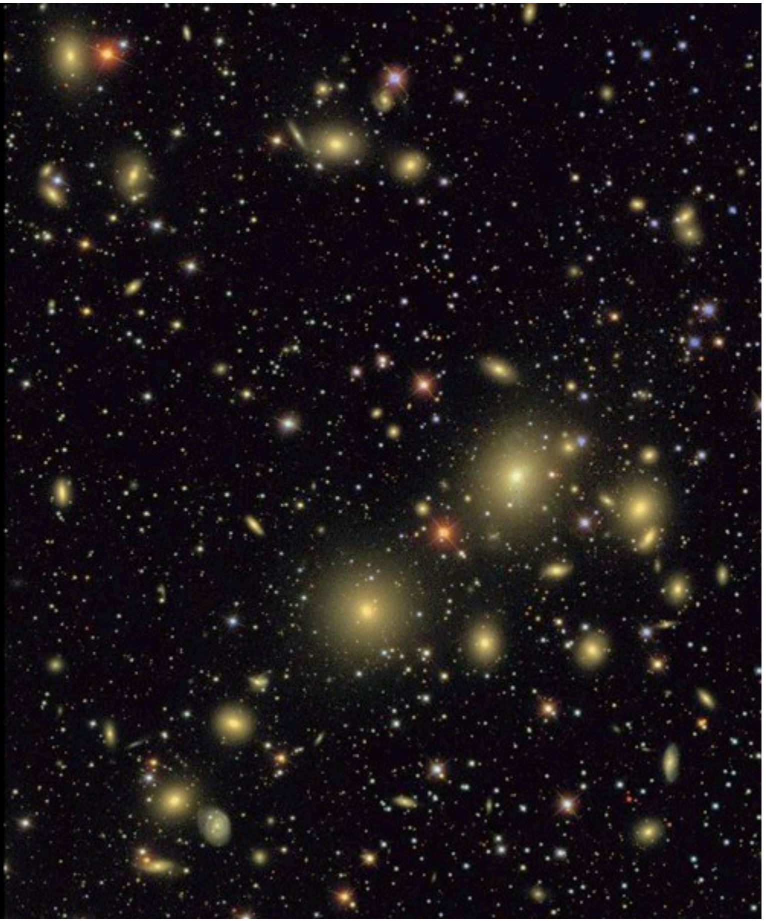
What makes up 95% of it?

Scandalously, we still don't know.

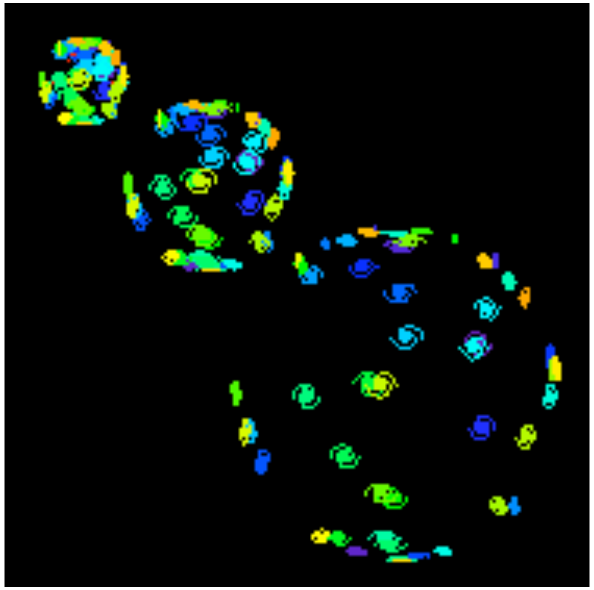
But we are working to get closer to the answer.

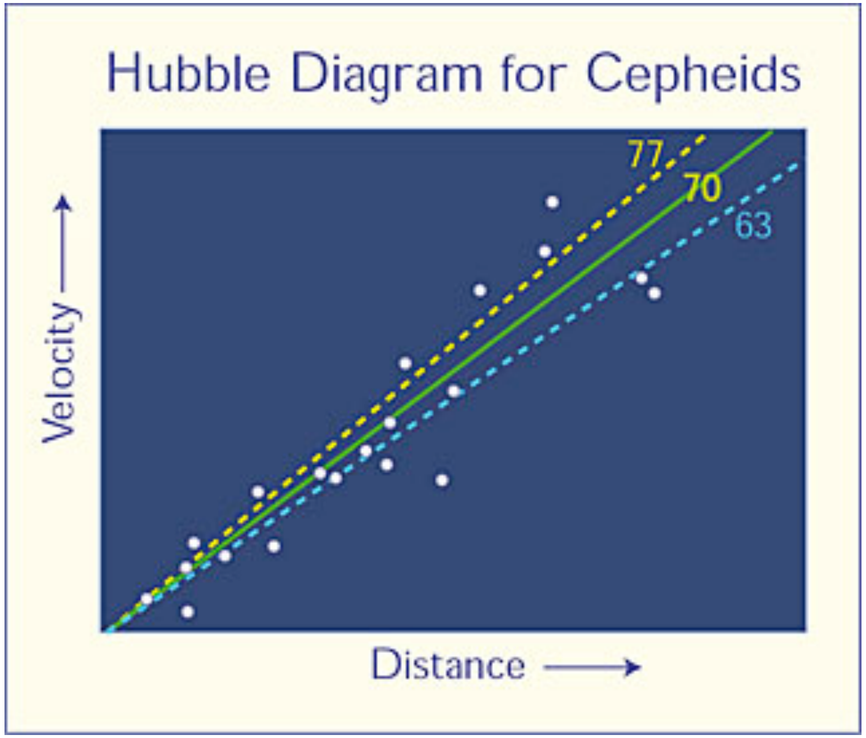
The universe is homogeneous and isotropic

- Homogeneous: appears the same everywhere in space
- Isotropic: appears the same in every direction

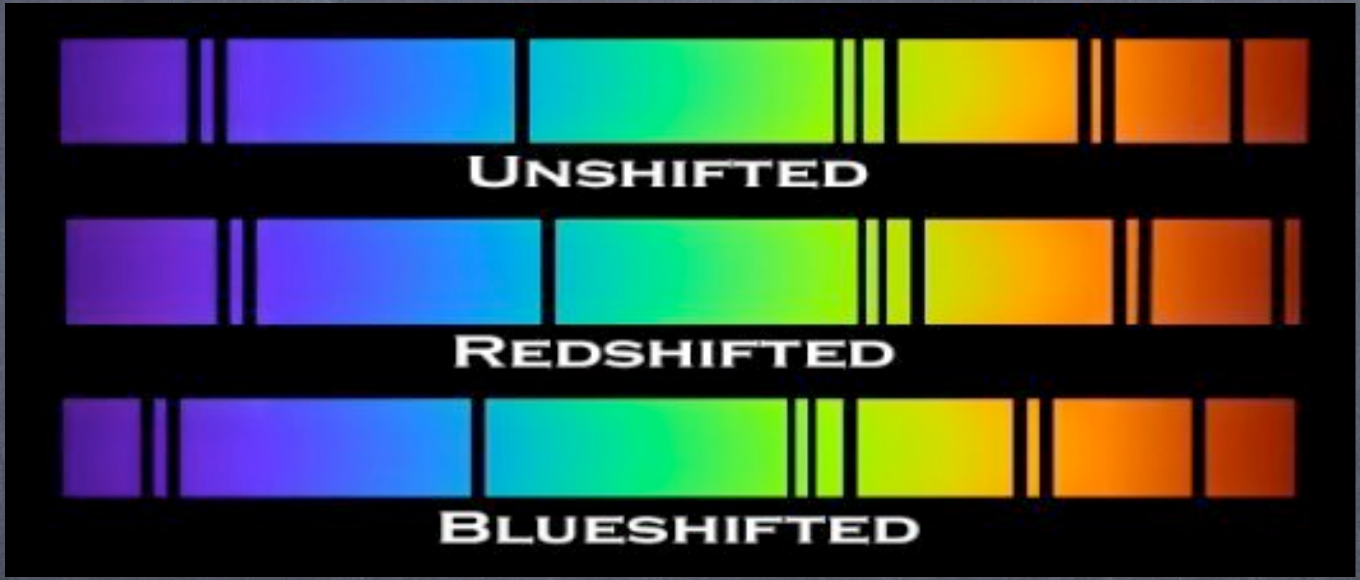
The universe is expanding





Edwin Hubble

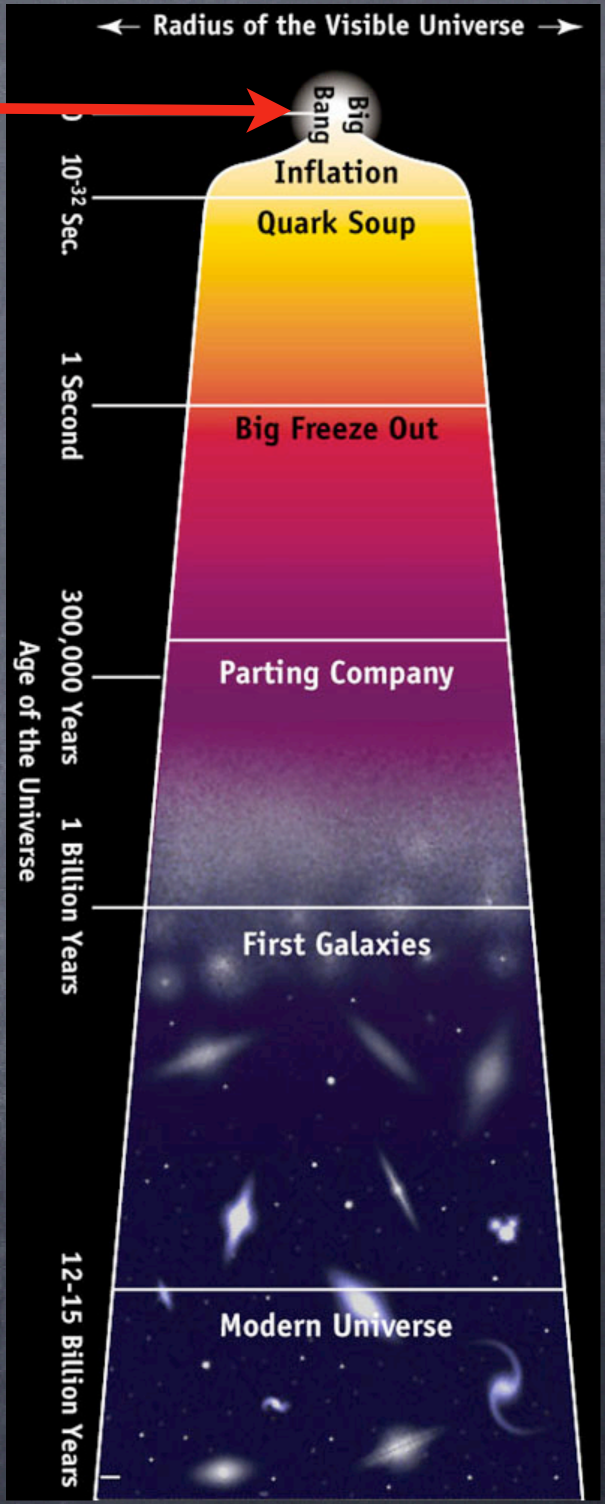
Redshift



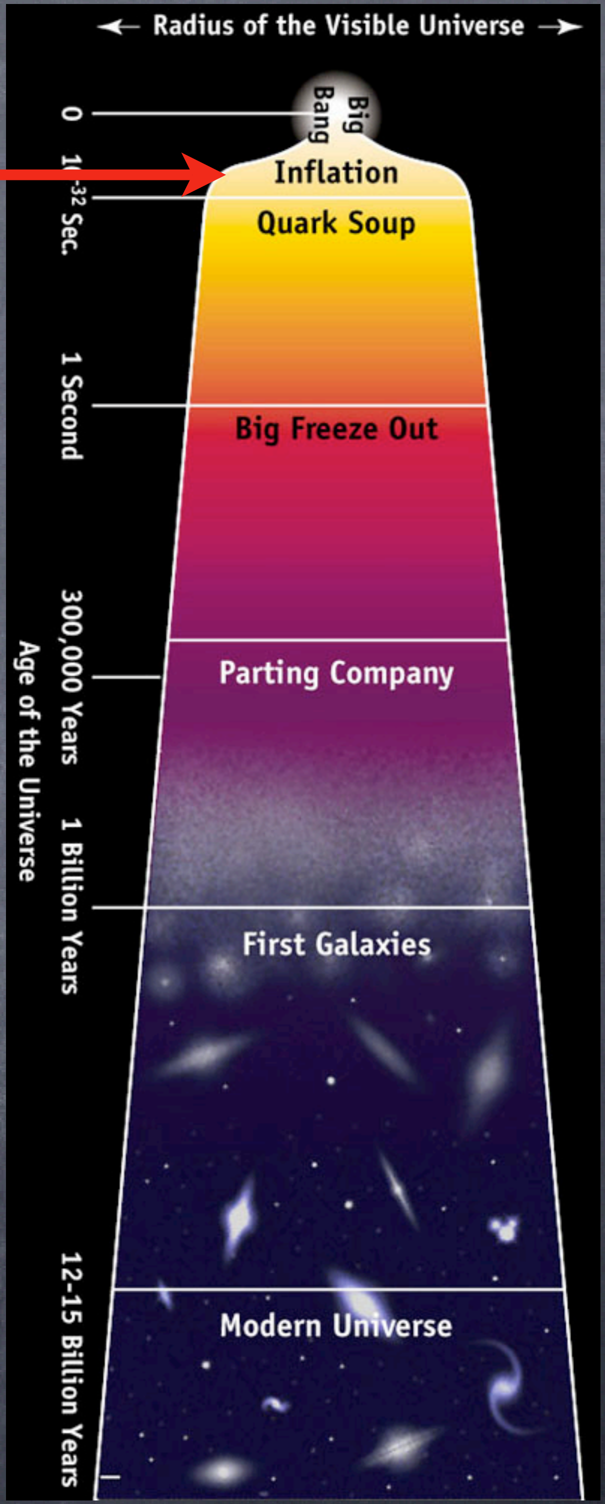
1+redshift = (size of universe now) / (size of universe when light was emitted)

Big Bang (t=0)

- Expansion starts
- Happened "everywhere"
- Details not well known
- Currently beyond reach of any cosmological probe



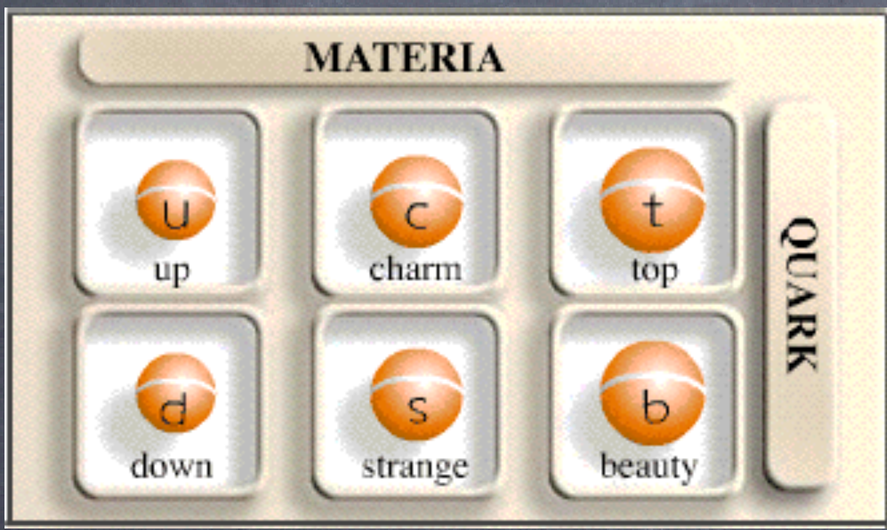
Very early Universe (t=tiny moments after BB)



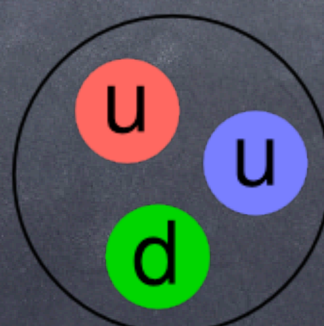
- High energies
- Exotic physics
- Grand Unified Theory? (all forces united)
- Inflation - a period of rapid expansion
- Density fluctuations laid out!

Quark Soup
(t<1 sec)

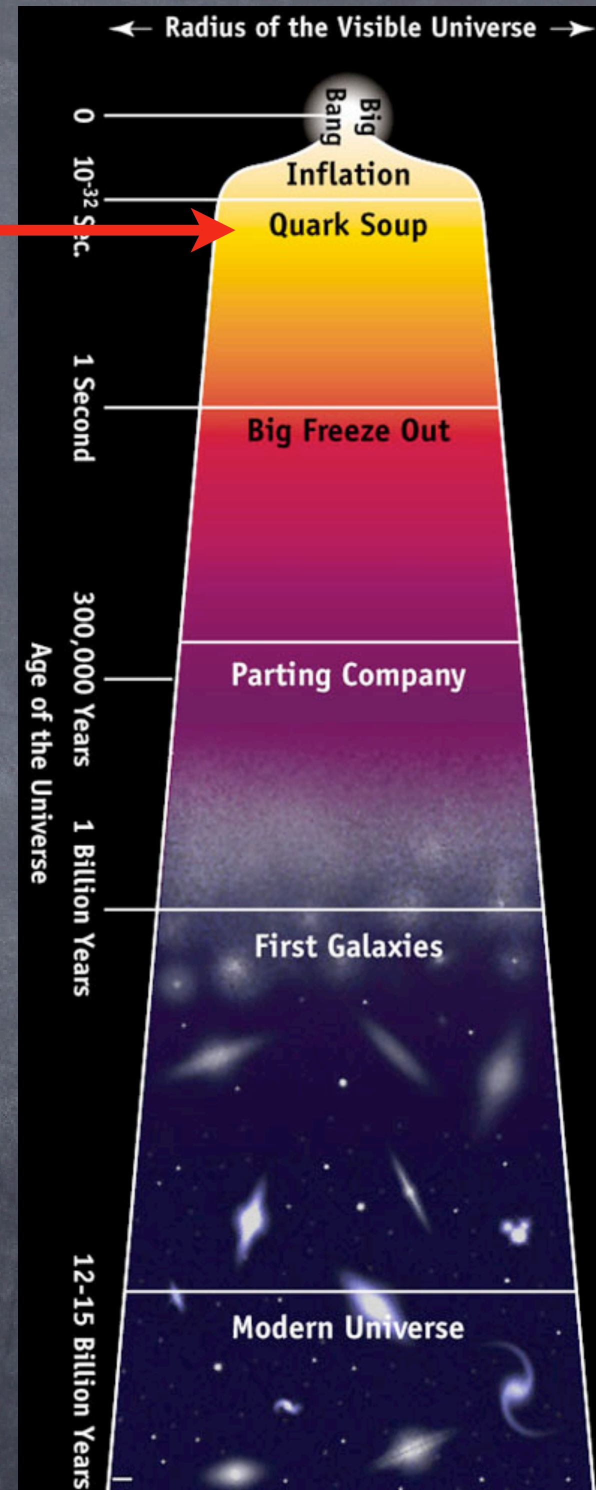
Quarks are free, floating around



Later, they are bound

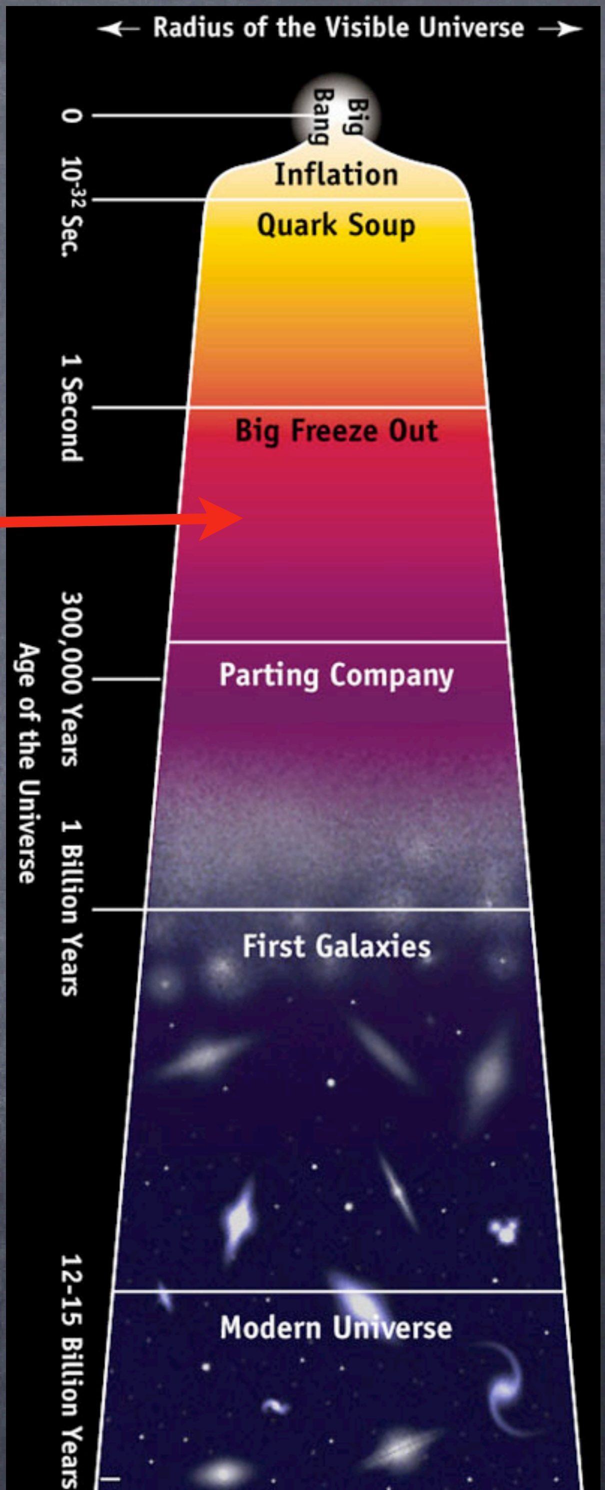


PROTON

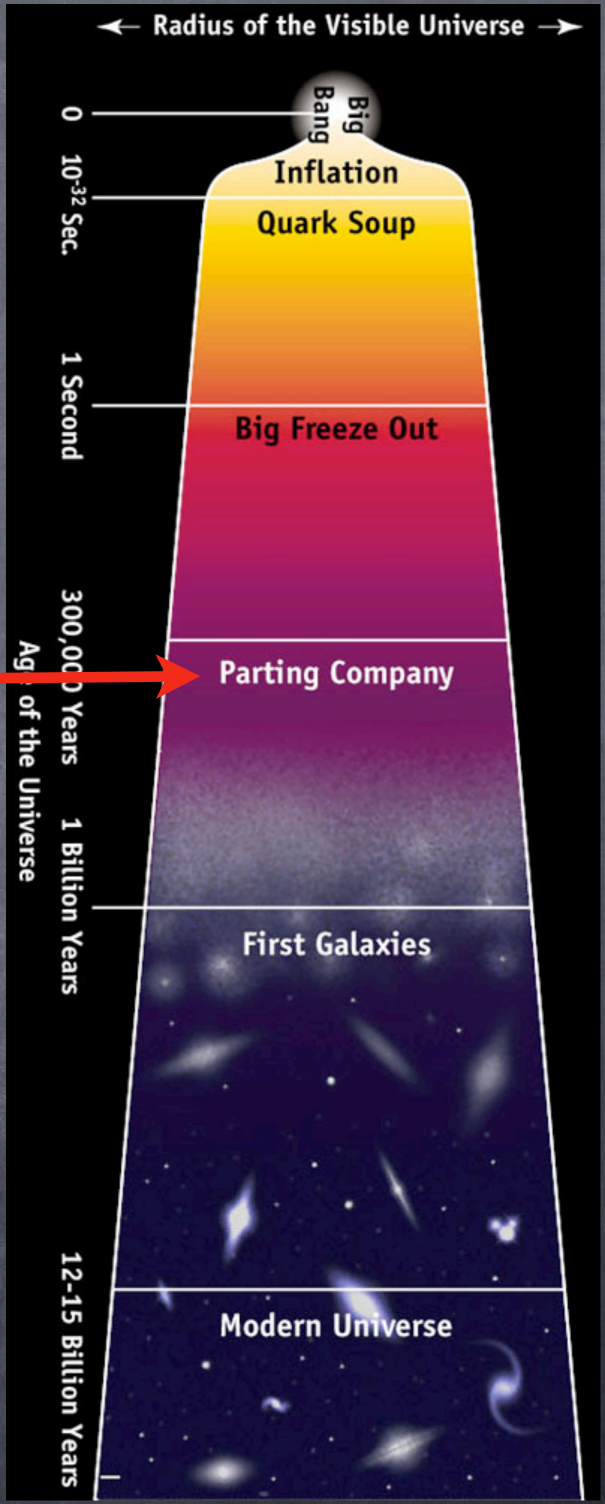


Nucleosynthesis (t=3 minutes)

- Atoms form!
- out of neutrons, protons, electrons...
- Hydrogen, Helium, small quantities of other elements
- Universe is still dominated by radiation (photons)
- Universe is still opaque - photons do not propagate far



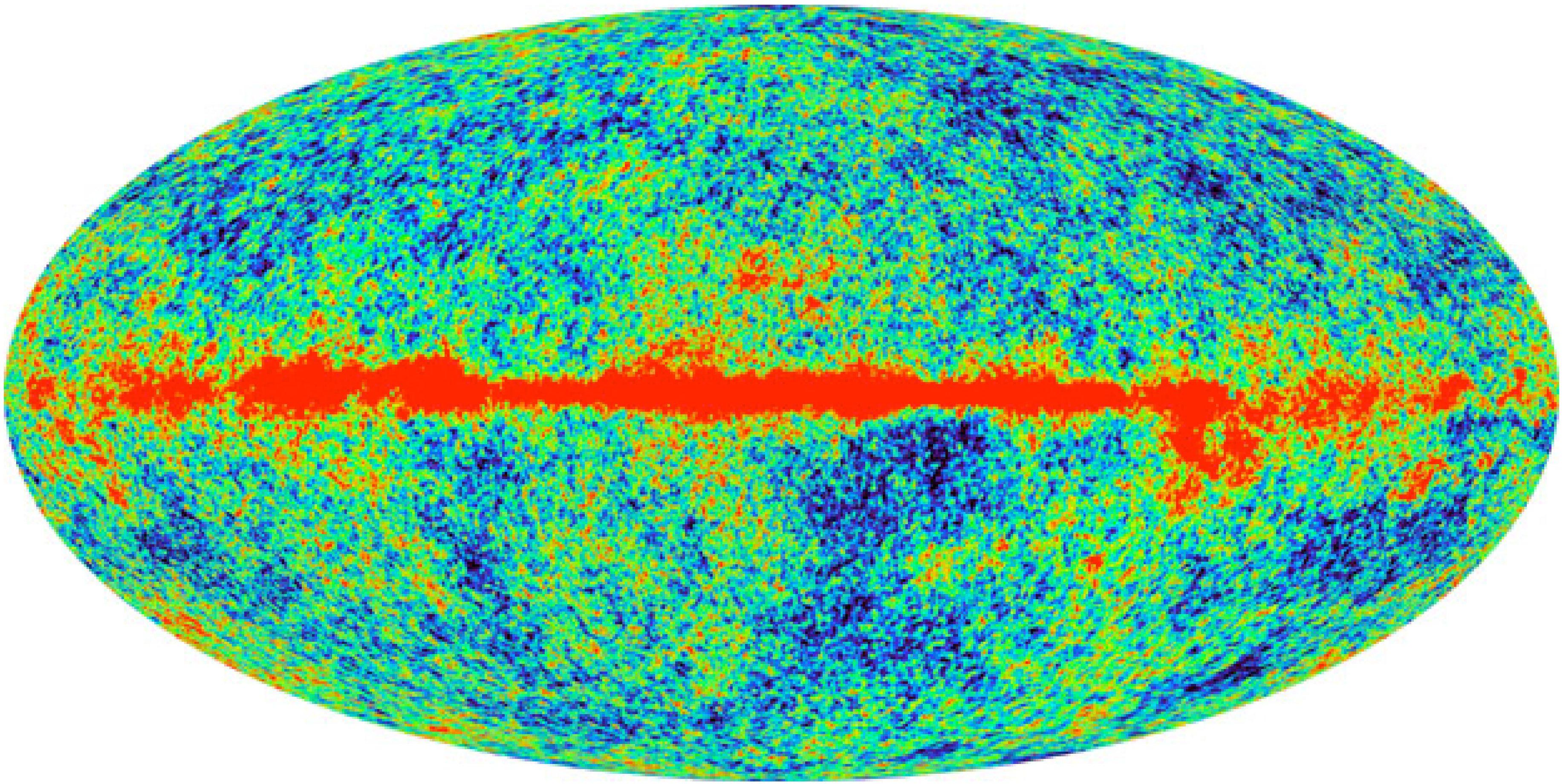
Universe becomes transparent (t=300,000 yrs)



- Radiation finally free to propagate - universe has rarified enough
- The Cosmic Microwave Background radiation we observe has been released at this time
- Temp=2.725 Kelvin
- Uniform to one part in 100,000

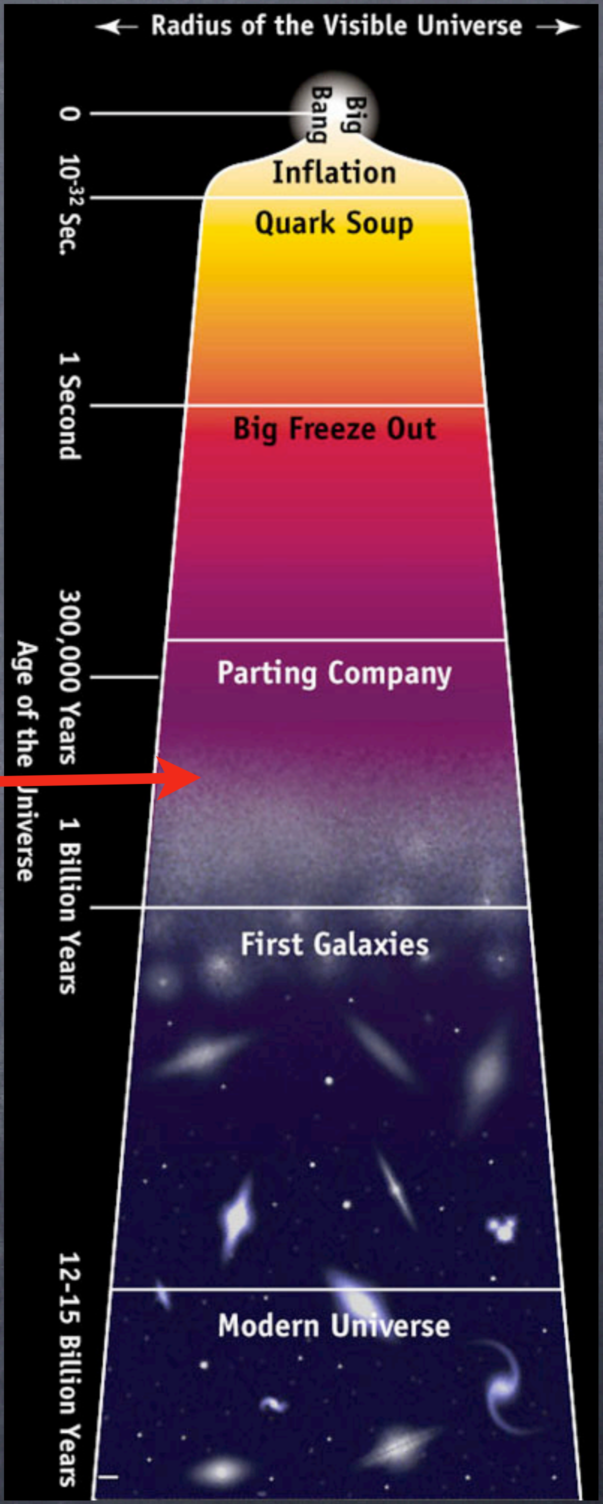
T=2.726 Kelvin

Fluctuations 1 part in 100,000 (of 2.726 Kelvin)



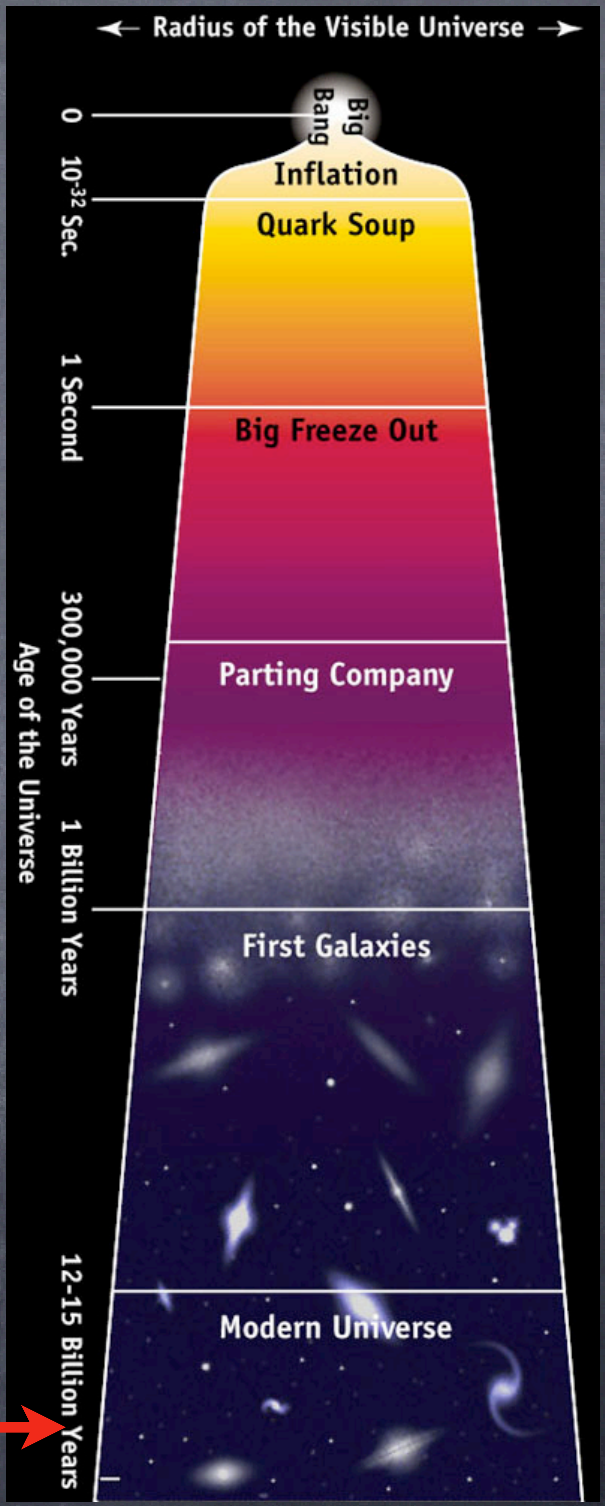
The dark ages
(t< 1 billion yrs)

- Universe is dark, slowly becomes matter dominated
- First stars ionize the hydrogen atoms
- First stars and first galaxies eventually form

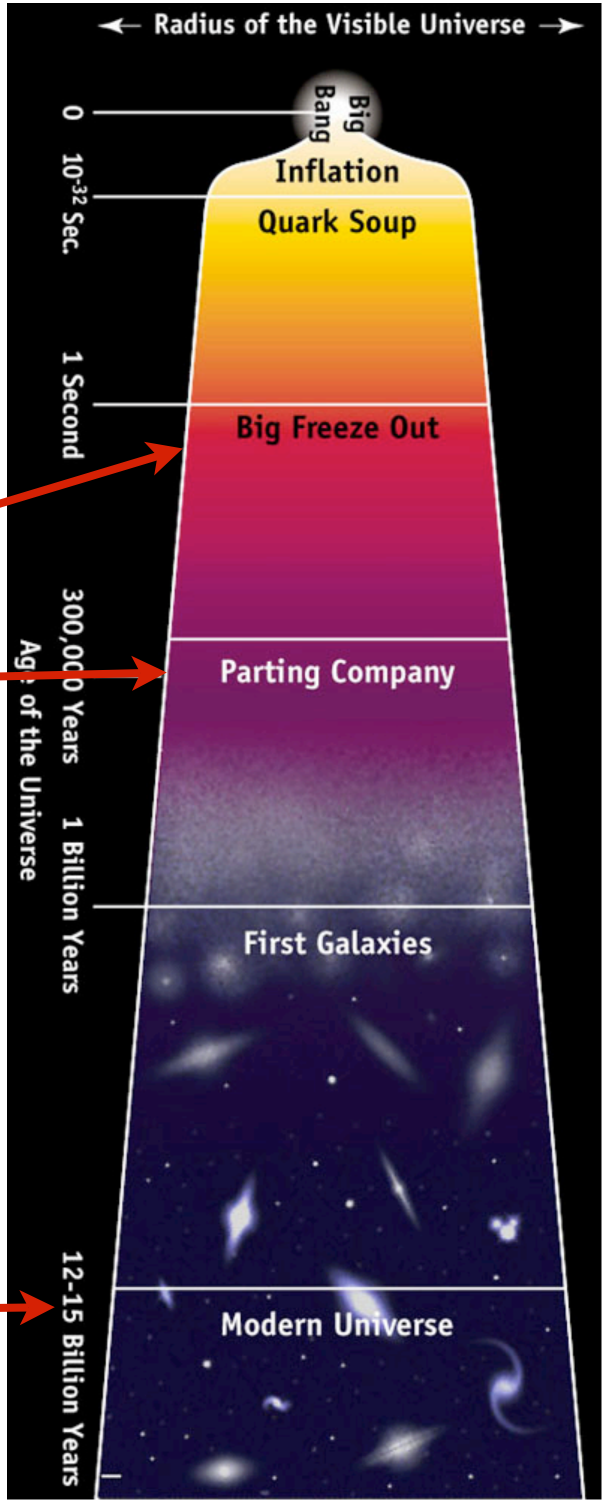


Modern Universe (t< 13.7 billion yrs)

- Stars, Galaxies, Clusters of galaxies everywhere
- Even more Dark Matter than we cannot directly see
- Universe is matter dominated - or so we thought!
- A big surprise is in store!



Some of the early history of the Universe is actually understood better!



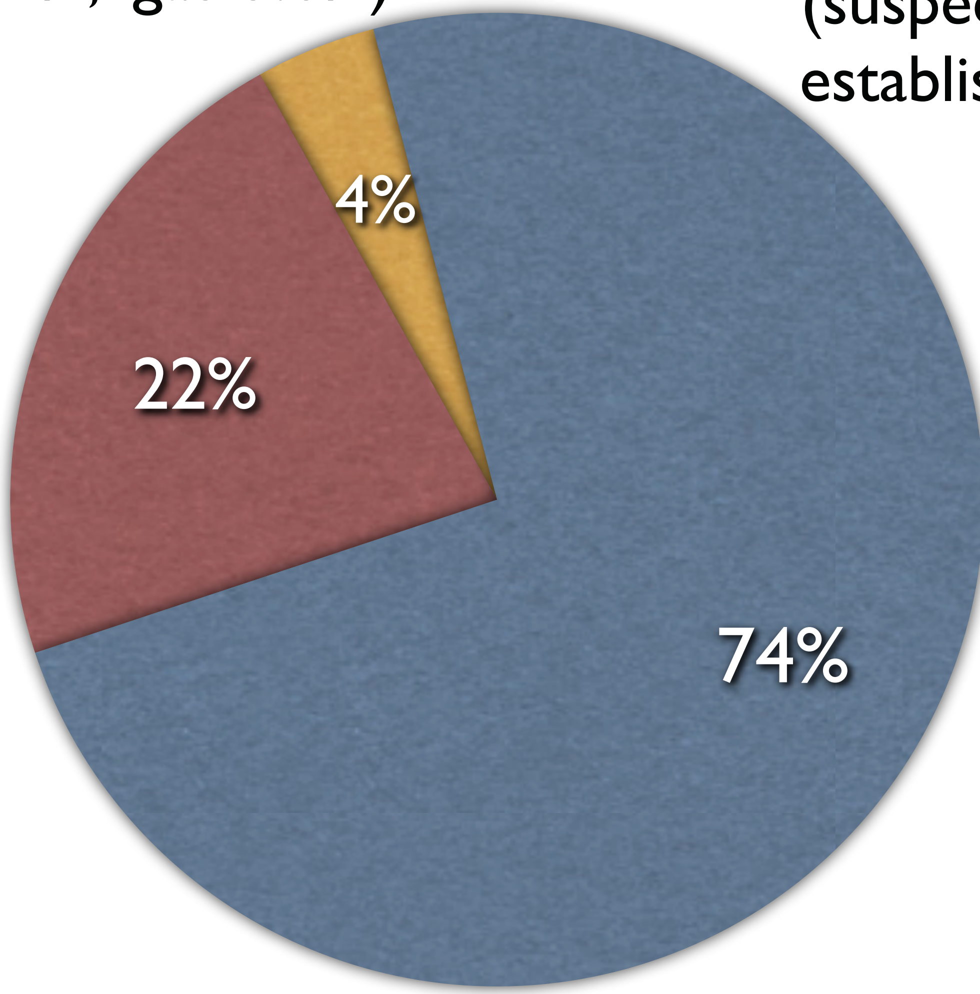
Physics quite well understood

95% of contents only phenomenologically described

Makeup of universe today

Visible Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)



Dark Matter
(suspected since 1930s
established since 1970s)

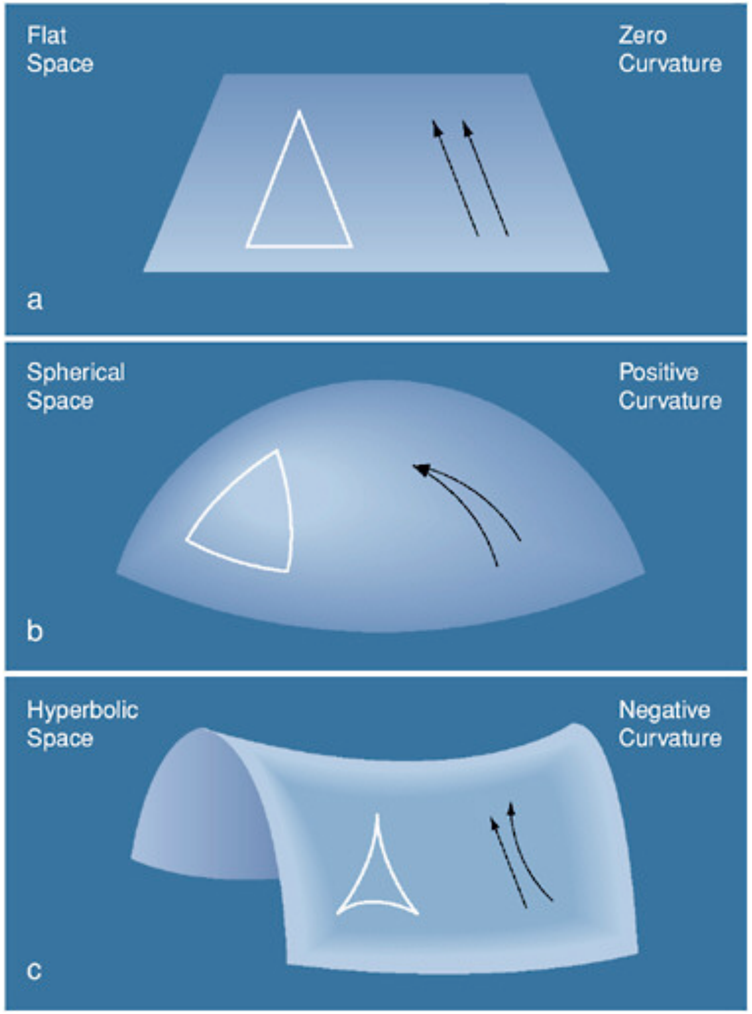
Also:
radiation (0.01%)

Cosmology 101

Friedmann Equation

$$H^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2}$$

define $\Omega \equiv \rho\frac{8\pi G}{3H^2} \equiv \frac{\rho}{\rho_{\rm crit}}$



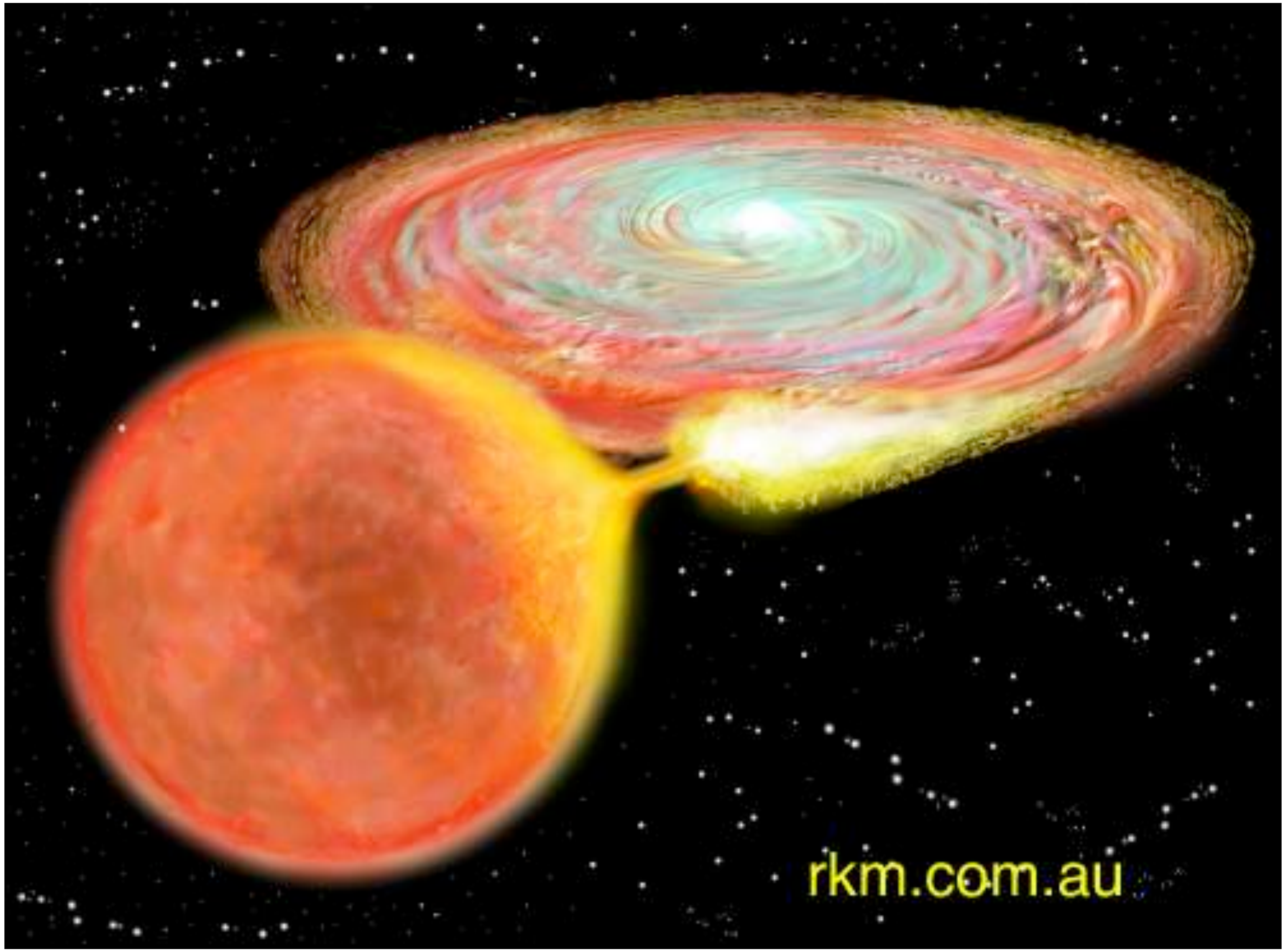
Inflation predicts, and
CMB anisotropy indicates
universe is flat (curvature is zero), so $\Omega_{\rm TOT} = 1$ (or $\kappa = 0$)

Galaxy distribution indicates matter makes up 25% of critical density, so $\Omega_{\rm M} \approx 0.25$

So where is 75% of the energy density?

Type Ia Supernovae

A white dwarf accretes matter from a companion.

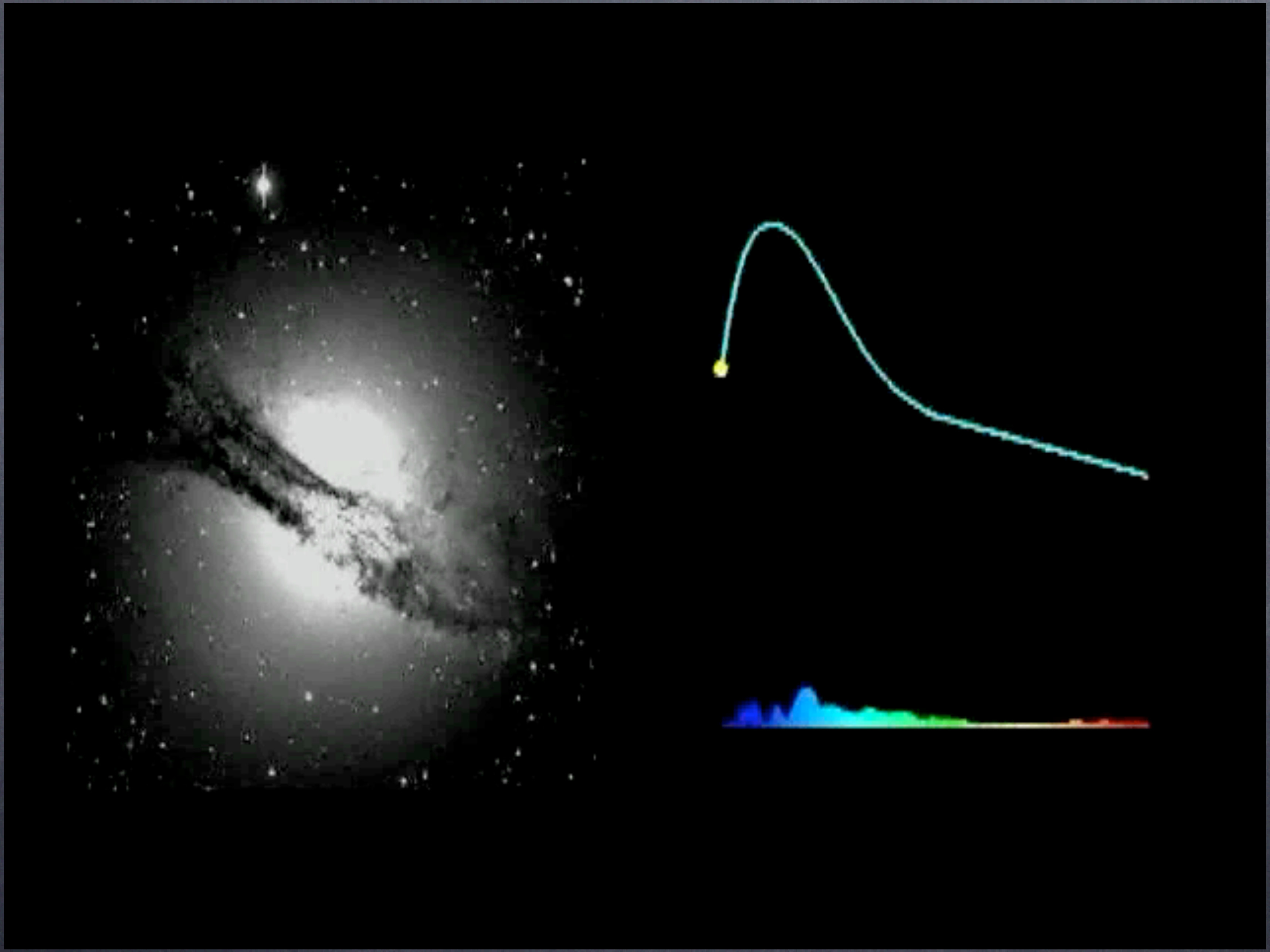


SNe Ia are "Standard Candles"

(car headlights example)

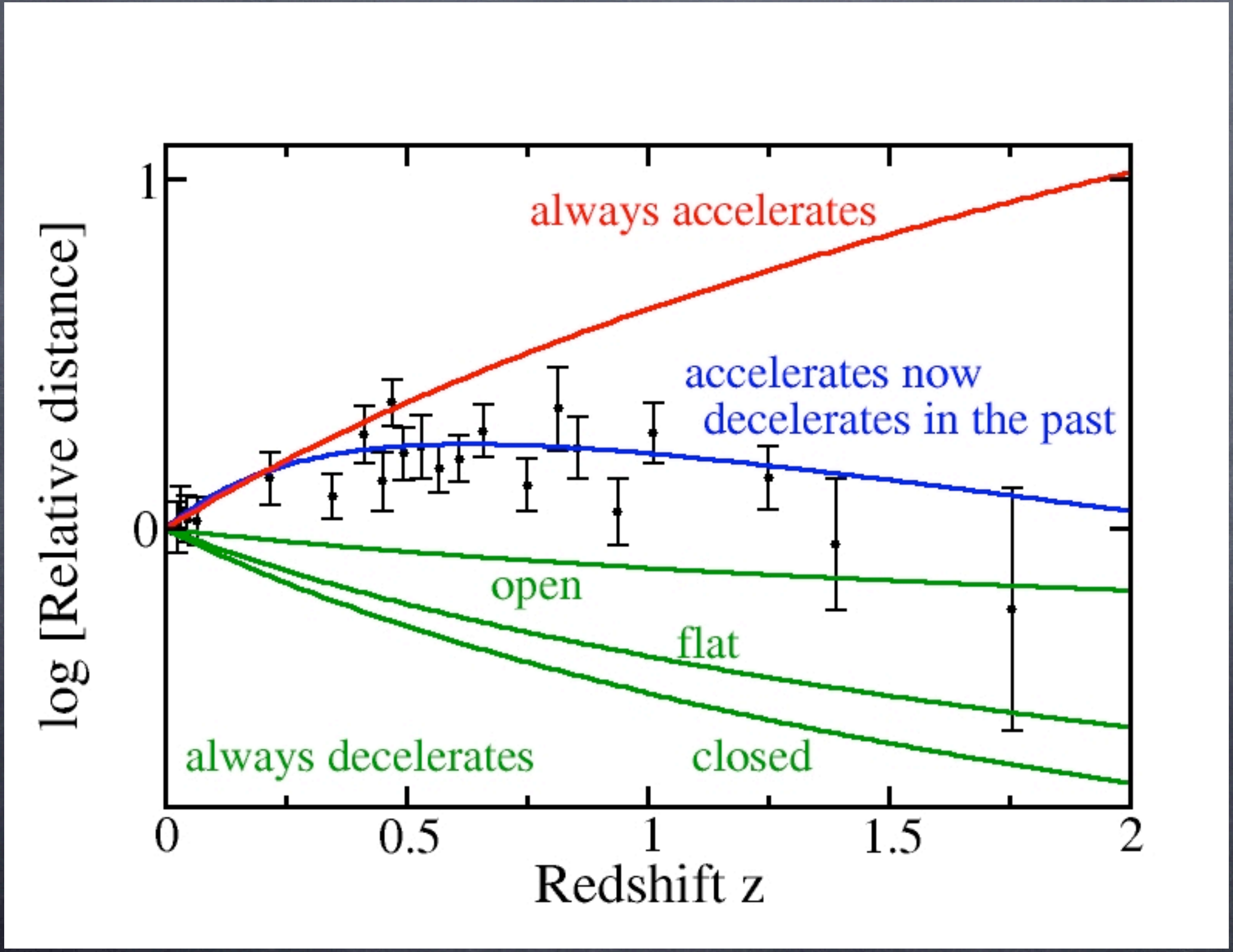
If you know the intrinsic brightness of the headlights, you can estimate how far away the car is

A way to measure (relative) distances to objects far away



credit: Supernova Cosmology Project

So, starting in the mid-1990s...

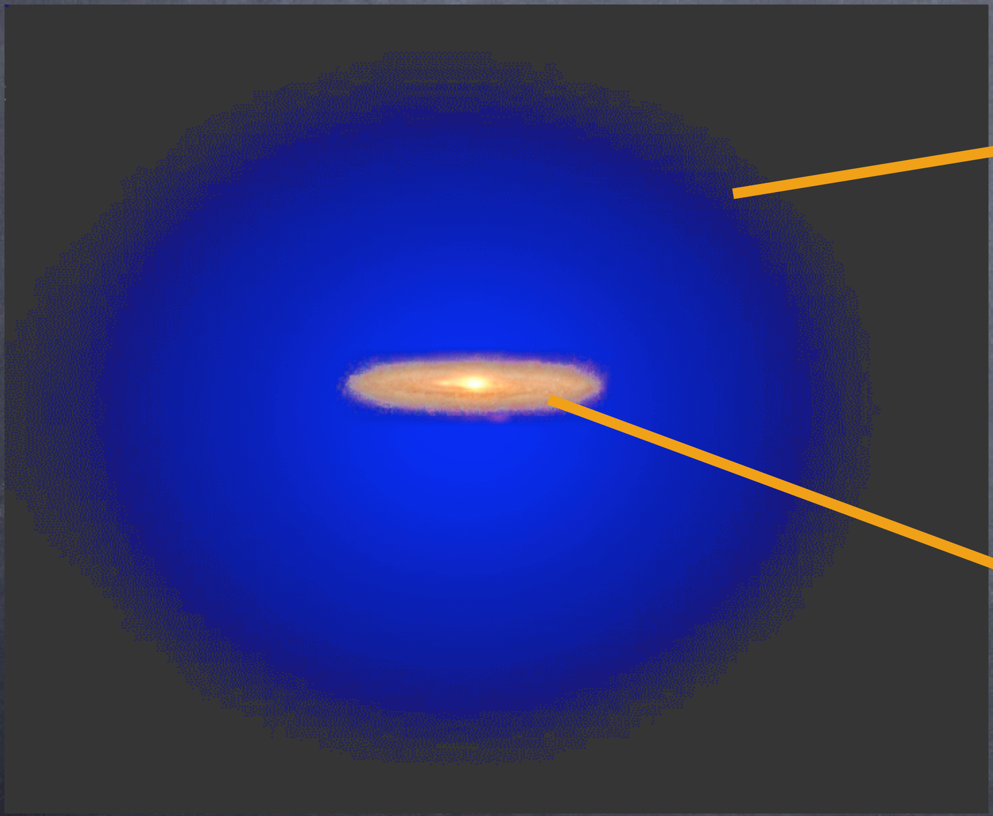


Dr. Michael Turner
University of Chicago

Dark Energy

- Universe is dominated by something other than dark matter
- This new component - "dark energy" - makes the universe expand faster and faster (i.e. slower as we look in the past)
- This new component is smooth
- Other than that, we don't know much!

Recall: Dark Matter is in "halos" around galaxies



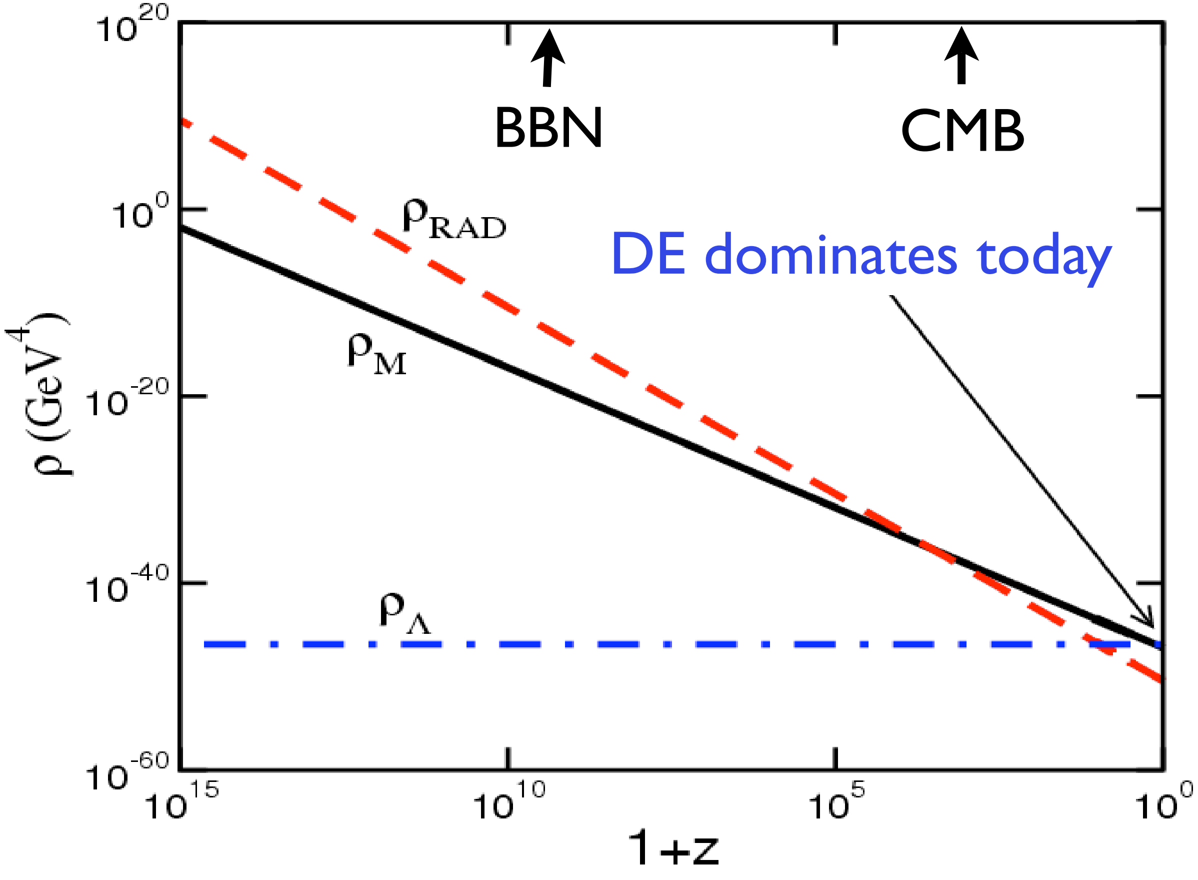
(invisible)
Dark Matter halo

(visible) light
from galaxy

Fine Tuning Problems I: "Why Now?"

Dark Energy was much less important at earlier epochs.

So why is it comparable to matter today?



$$\frac{\rho_{\rm DE}(z)}{\rho_{\rm M}(z)} = \frac{\Omega_{\rm DE}}{\Omega_M}(1+z)^{3w}$$

Fine Tuning Problems II: "Why so small"?

Vacuum Energy: QFT predicts it to be $\simeq M_{\rm cutoff}^4$

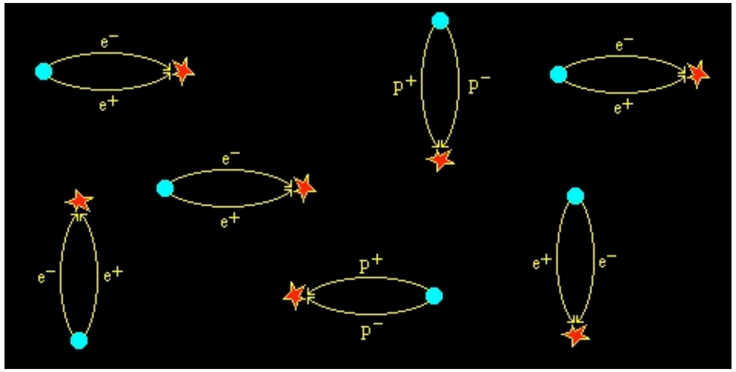
Measured:	$(10^{-3}\text{eV})^4$	60-120 orders of magnitude smaller than expected!
SUSY scale:	$(1\,\text{TeV})^4$	
Planck scale:	$(10^{19}\,\text{GeV})^4$	

In other words:

$$\Lambda\left(\frac{\hbar G}{c^5}\right) \equiv \Lambda t_{\rm pl}^2 \approx \left(H_0^{-1}/t_{\rm pl}\right)^{-2} \sim 10^{-120}$$

The smallness problem

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$



Is there a cancellation mechanism that sets vacuum energy to nearly but not precisely zero?

Is there a huge number of universes with different values of the CC, and we just happen to live in one that supports life? (Anthropic)

Steven Weinberg:

``Right now, not only for cosmology but for elementary particle theory, this is the bone in our throat"

Frank Wilczek:

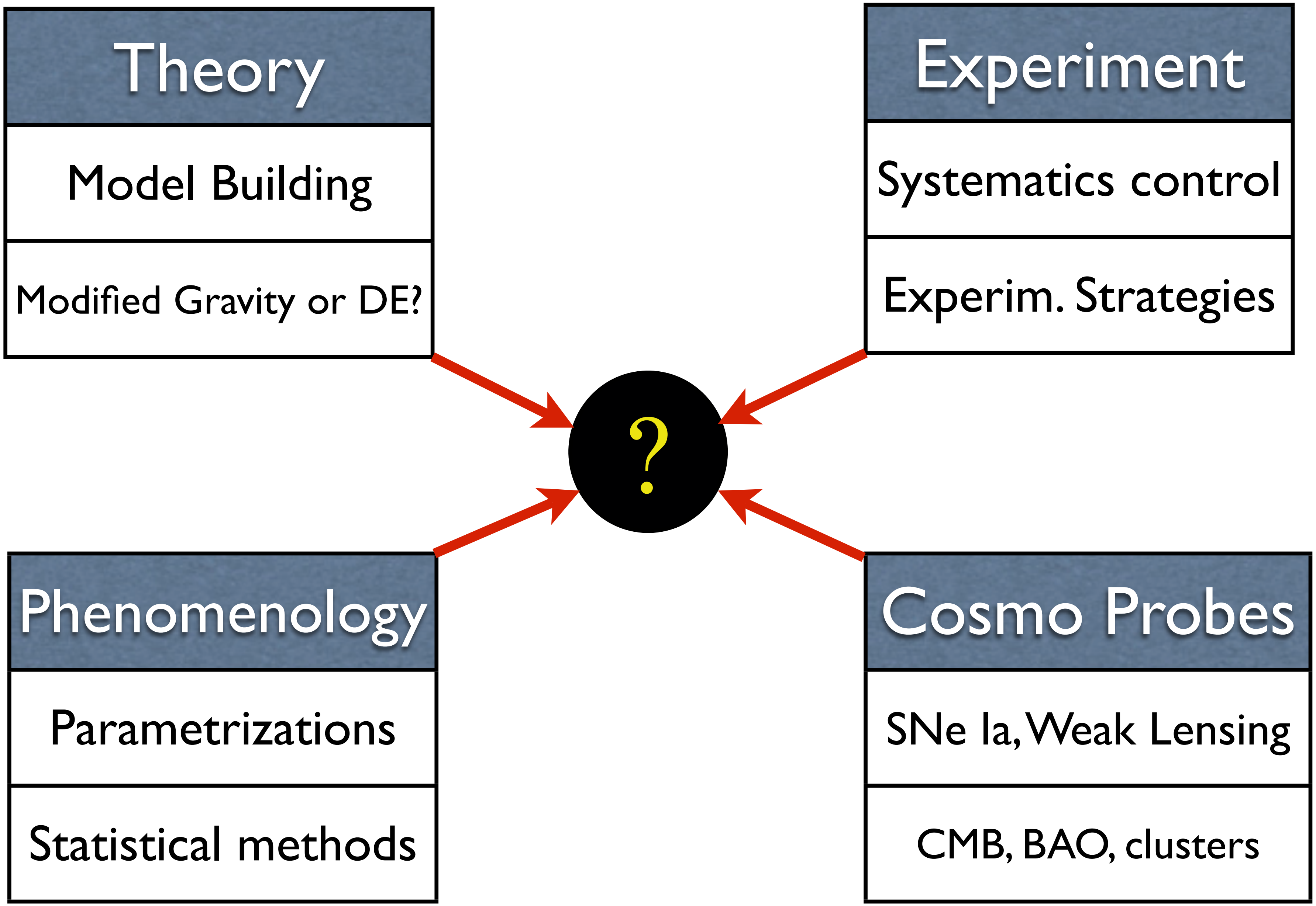
``... maybe the most fundamentally mysterious thing in all of basic science"

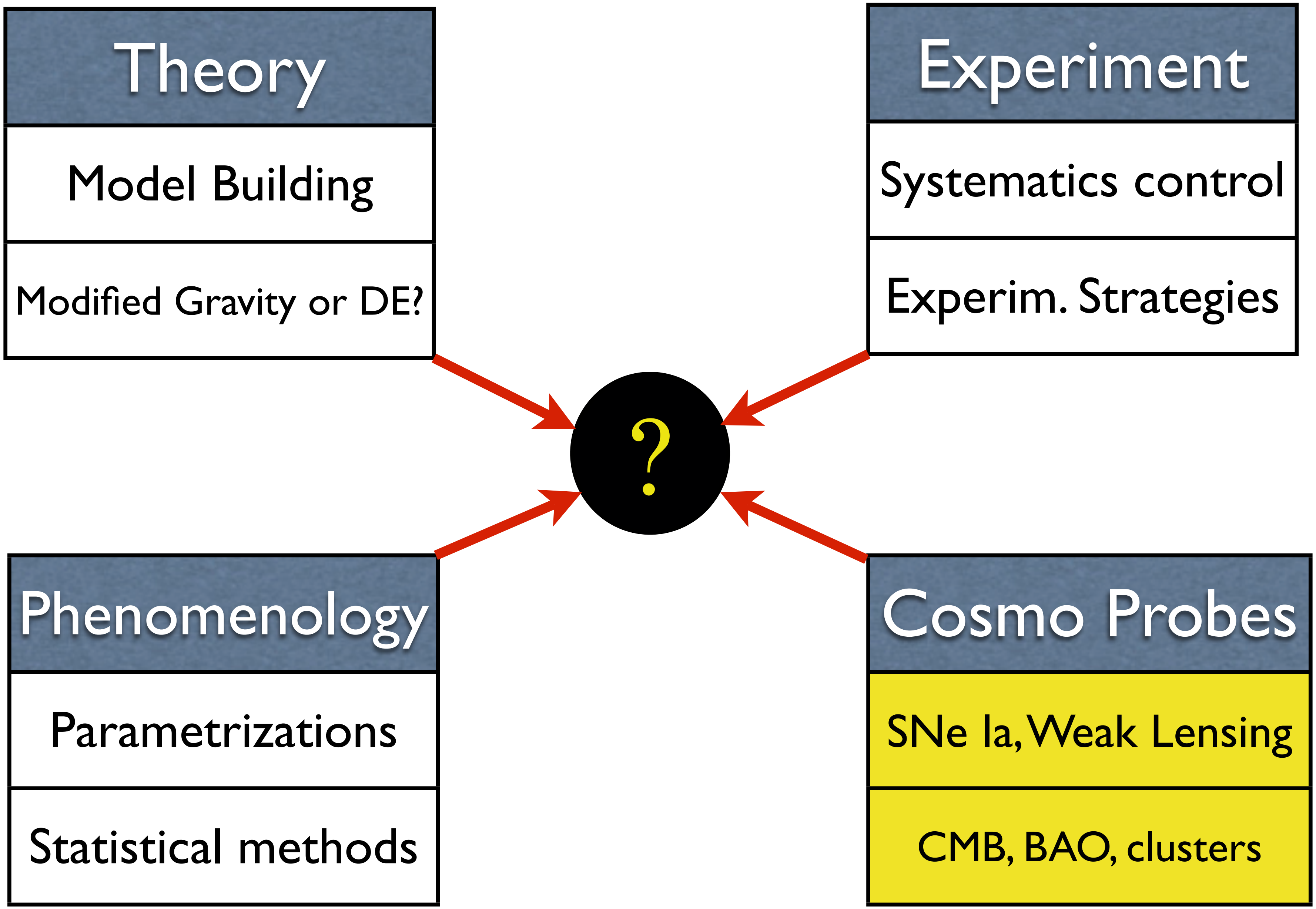
Ed Witten:

``... would be the number 1 on my list of things to figure out"

Michael Turner:

"... the biggest embarrassment in theoretical physics"


Theory
Model Building
Modified Gravity or DE?
Experiment
Systematics control
Experim. Strategies
?
Phenomenology
Parametrizations
Statistical methods
Cosmo Probes
SNe Ia, Weak Lensing
CMB, BAO, clusters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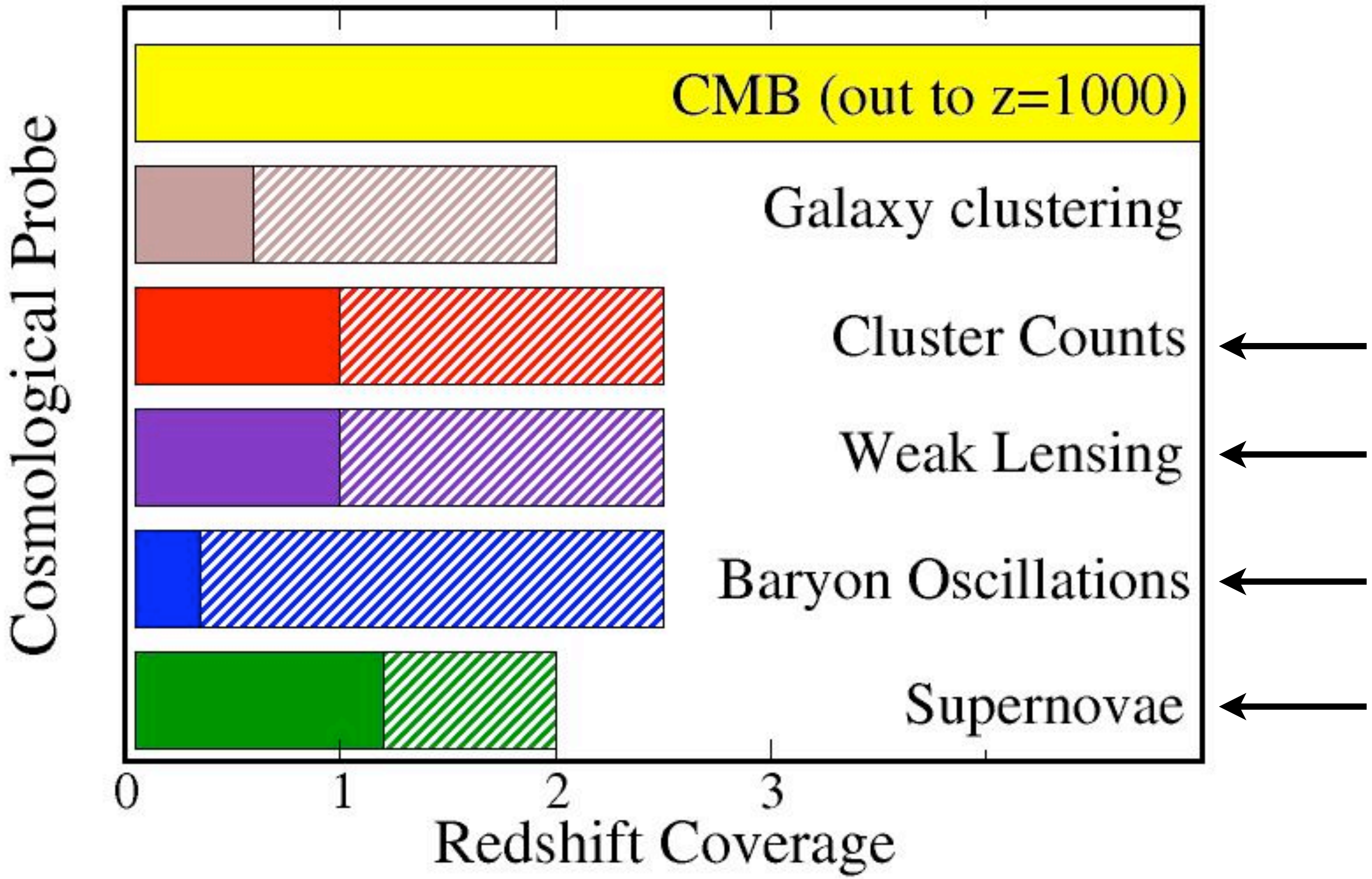
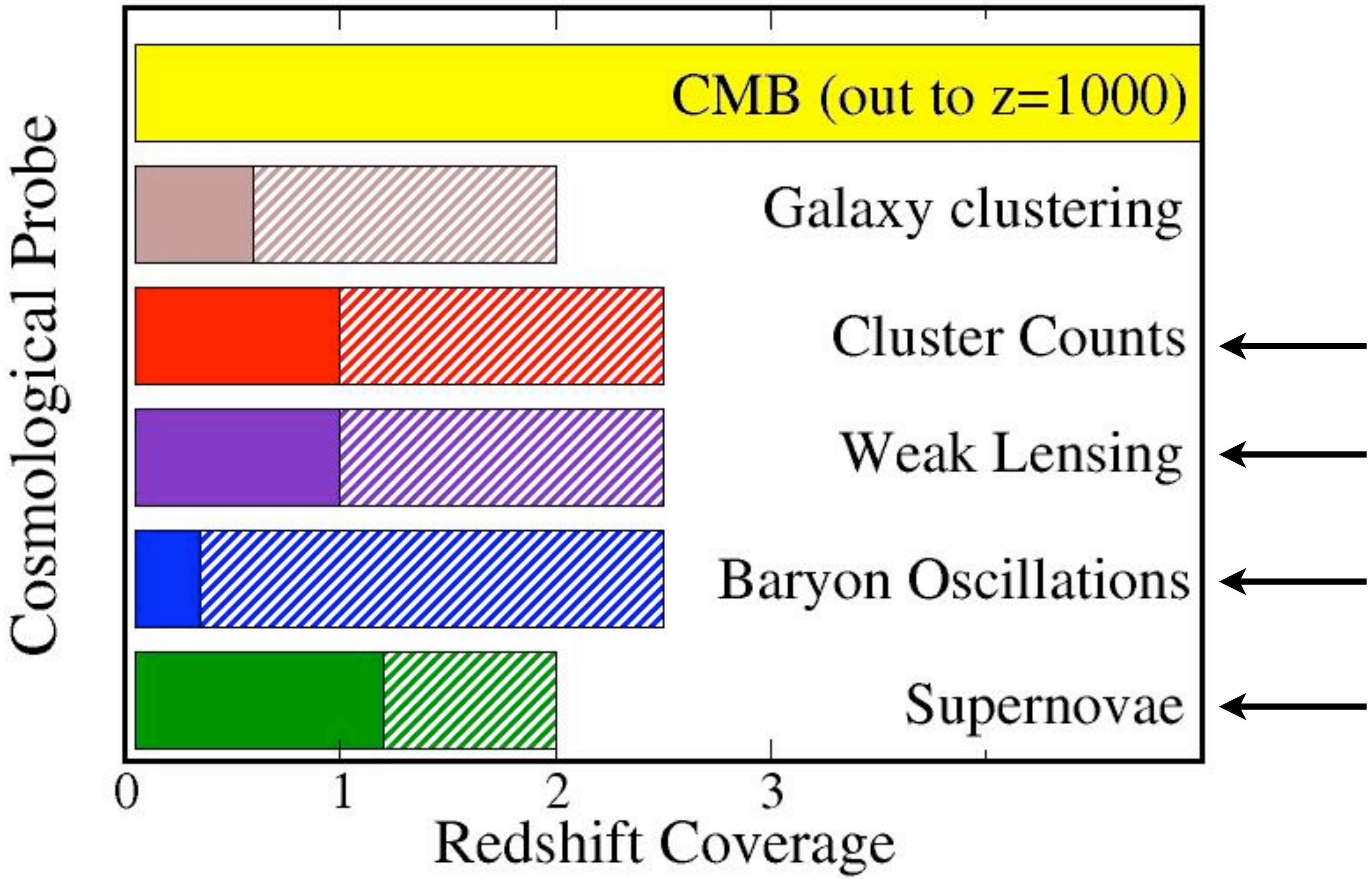
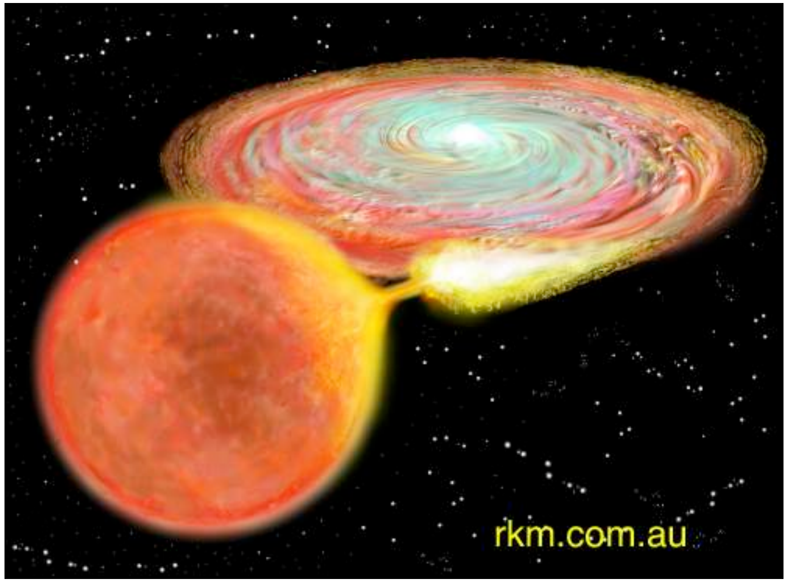
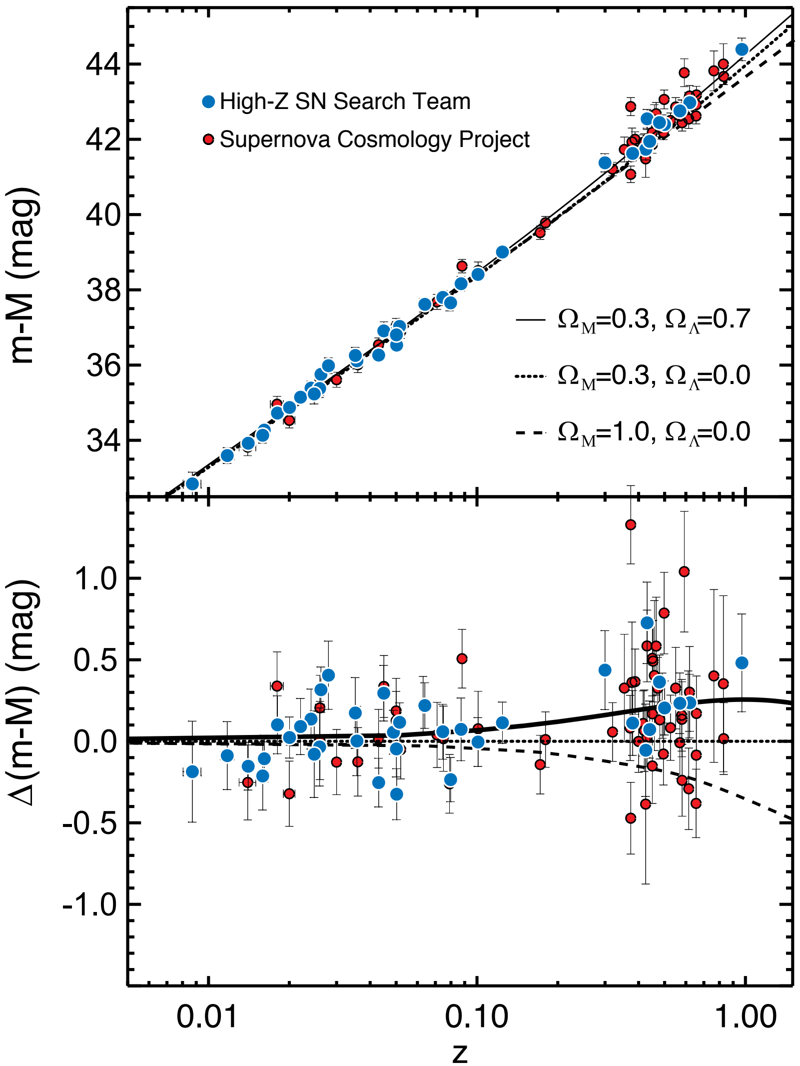

CMB (out to z=1000)
Galaxy clustering
Cluster Counts
Weak Lensing
Baryon Oscillations
Supernovae
Cosmological Probe
0
1
2
3
Redshift Coverage

Four principal probes of Dark Energy



Type Ia Supernovae



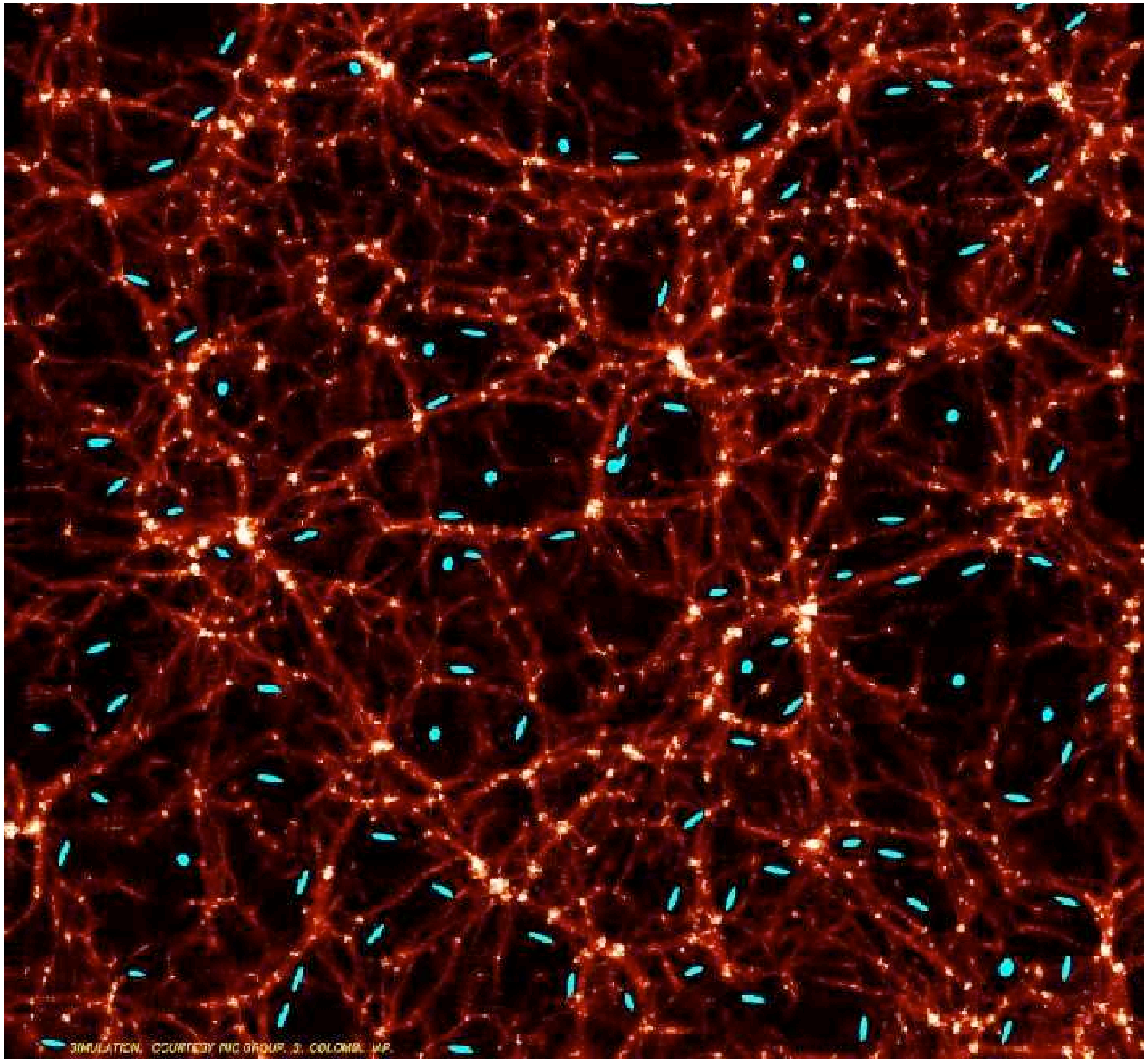


Advantages: each SN provides constraints
Challenges : controlling evolution of SNe

Weak Gravitational Lensing

Credit: NASA, ESA and R. Massey (Caltech)

Weak Gravitational Lensing



Credit: Colombi & Mellier

Weak Lensing and Dark Energy

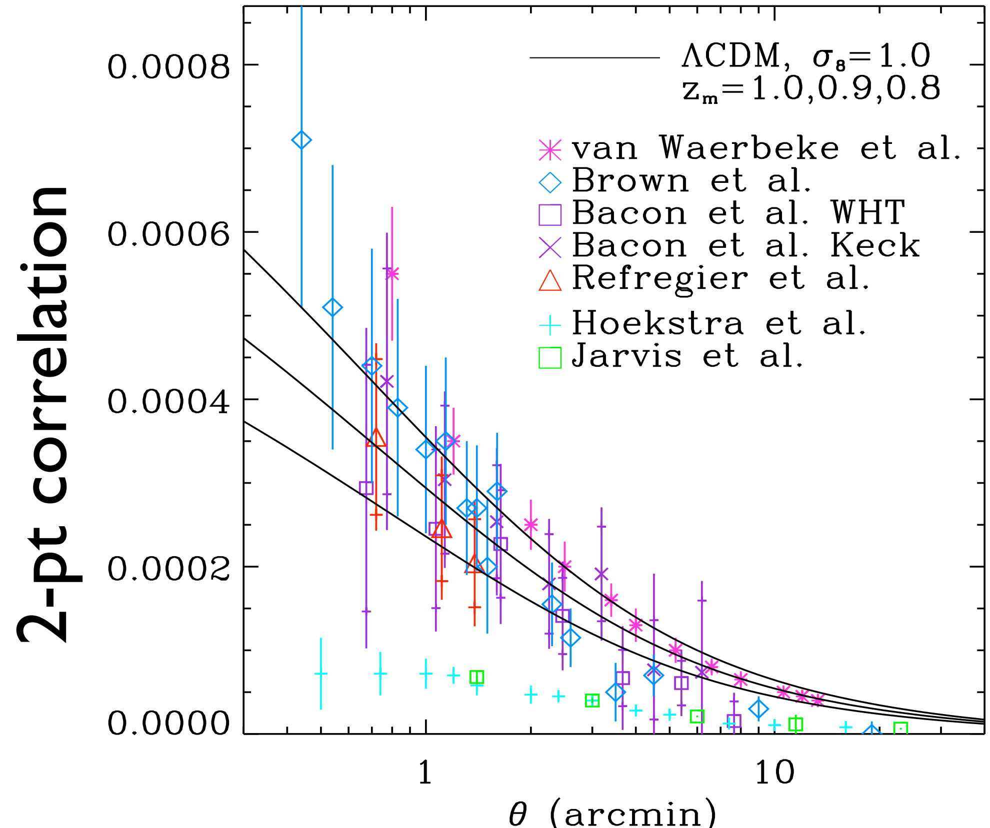
WL measures integral over the line of sight

$$P_{\text{shear}} \simeq \int_0^\infty W(r) P_{\text{matter}}(r) dr$$

distance,
volume factors

(dark) matter
clustering

- Also sensitive to Dark Energy through distance, volume factors



Refregier 2003

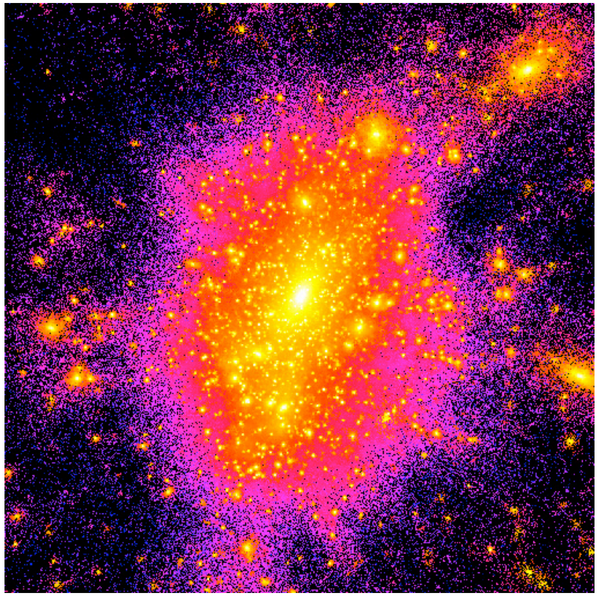
Advantages: sensitive to mass, not light -> "just" gravity

Challenges : measuring galaxy shapes is hard!

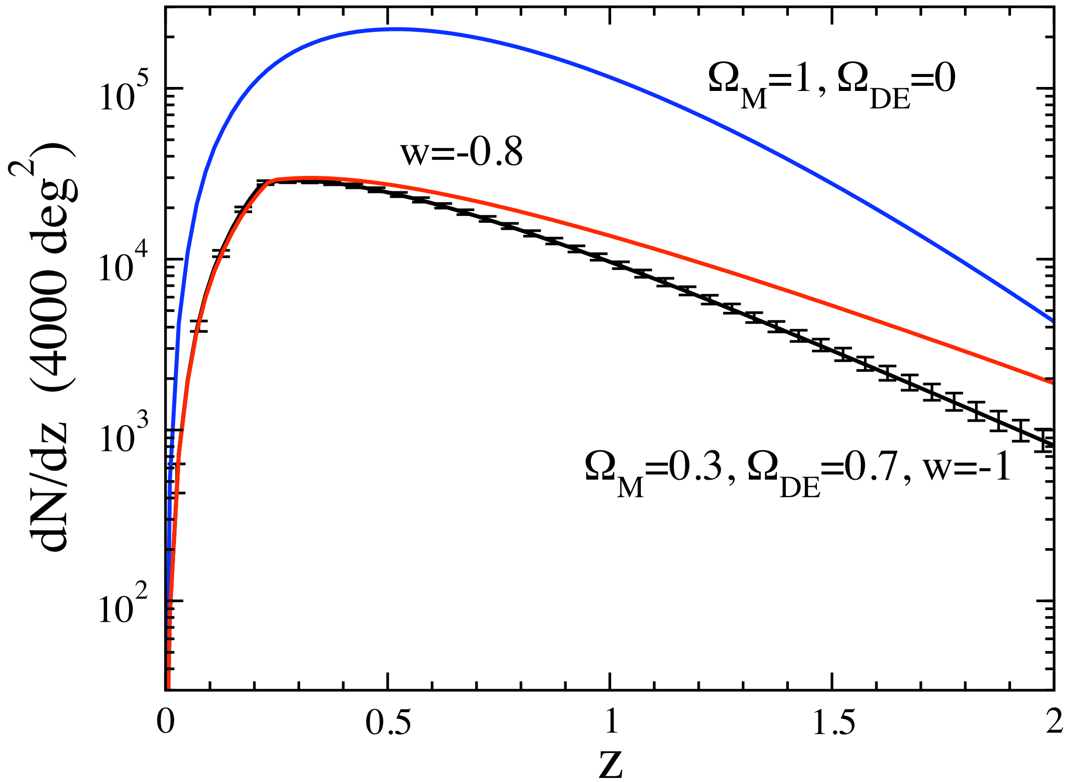
Galaxy cluster counts

(major topic of research at Michigan!)

$$\frac{d^2N}{d\Omega\, dz} = n(z)\, \frac{r(z)^2}{H(z)}$$



Credit: Quinn, Barnes, Babul, Gibson

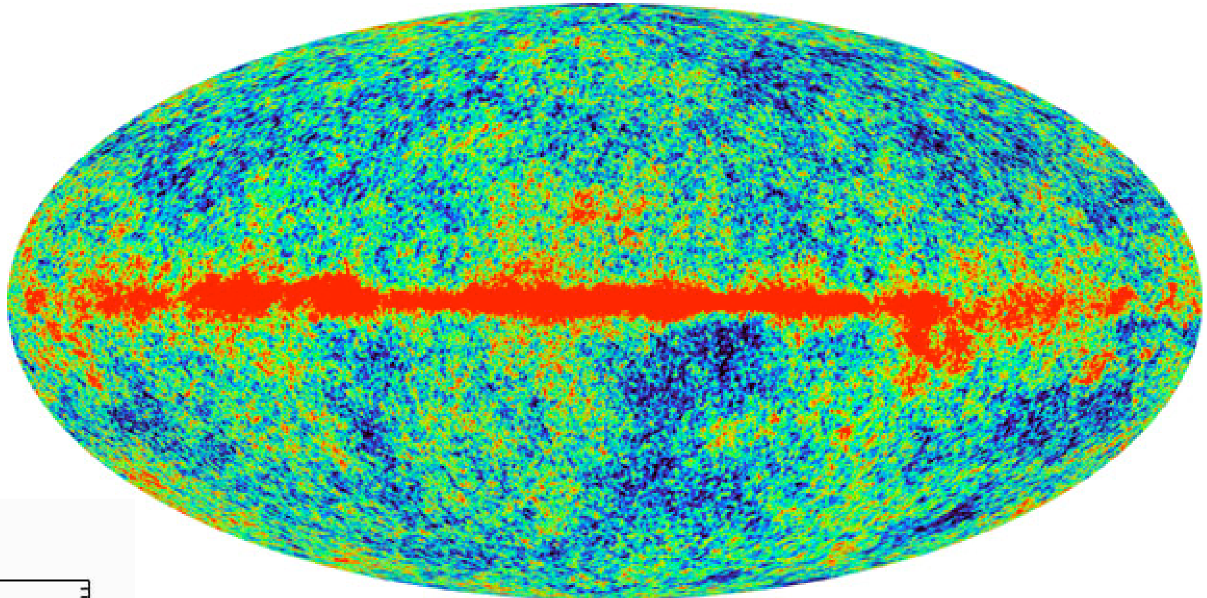


Advantages: abundance is exponentially sensitive to (some) parameters
Challenges : relation between mass and observable (temp, flux)

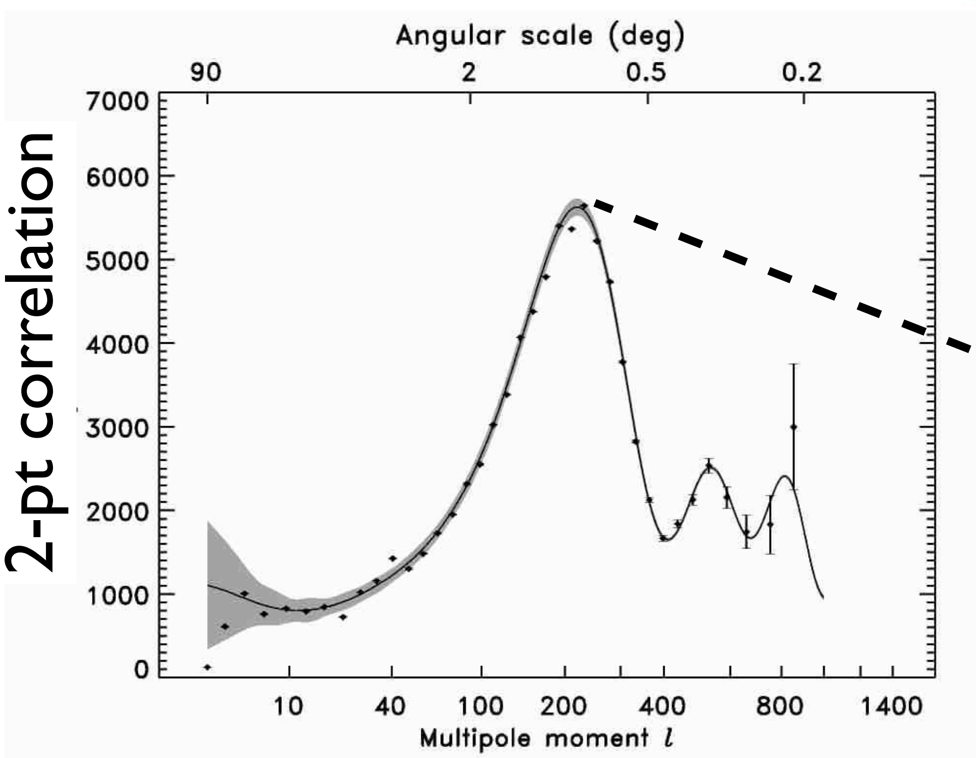
CMB and Dark Energy

$$T = 2.726\,\mathrm{K}$$

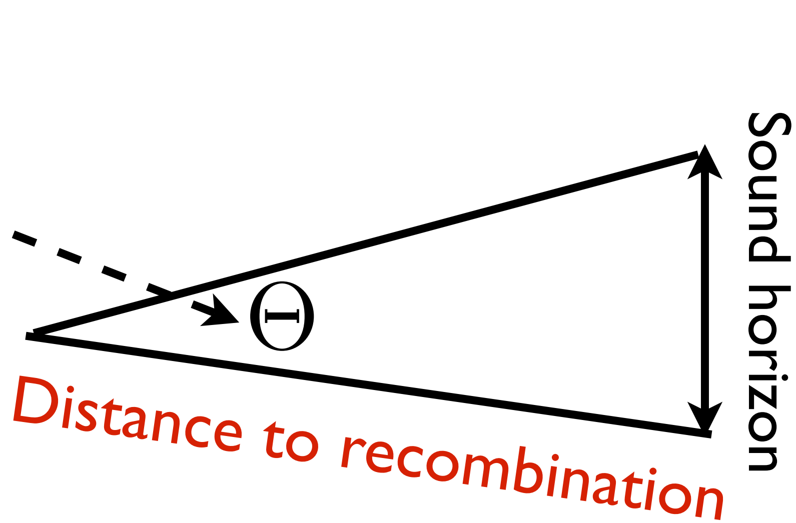
$$\frac{\delta T}{T} \approx 10^{-5}$$



Credit: WMAP team

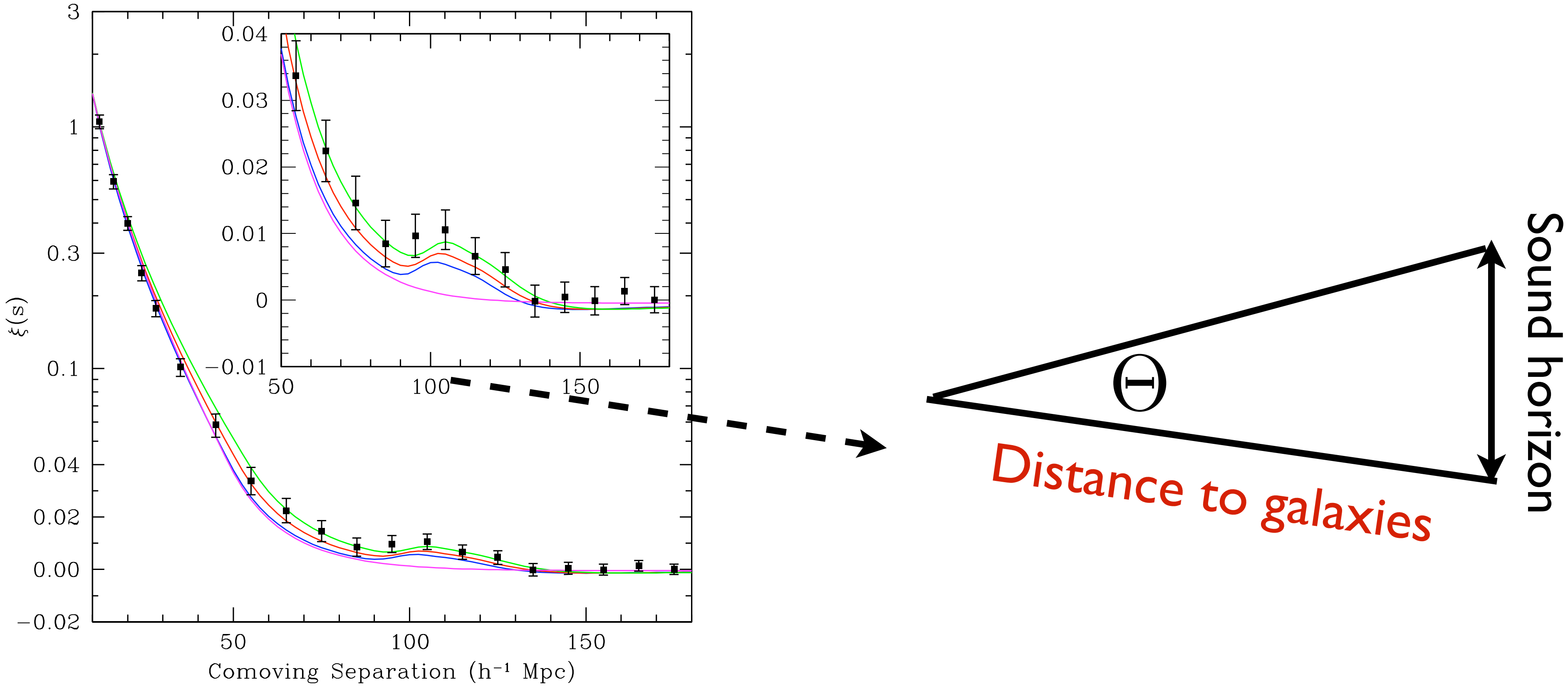


Bennett et al 2003 (WMAP collaboration)



Baryon Acoustic Oscillations

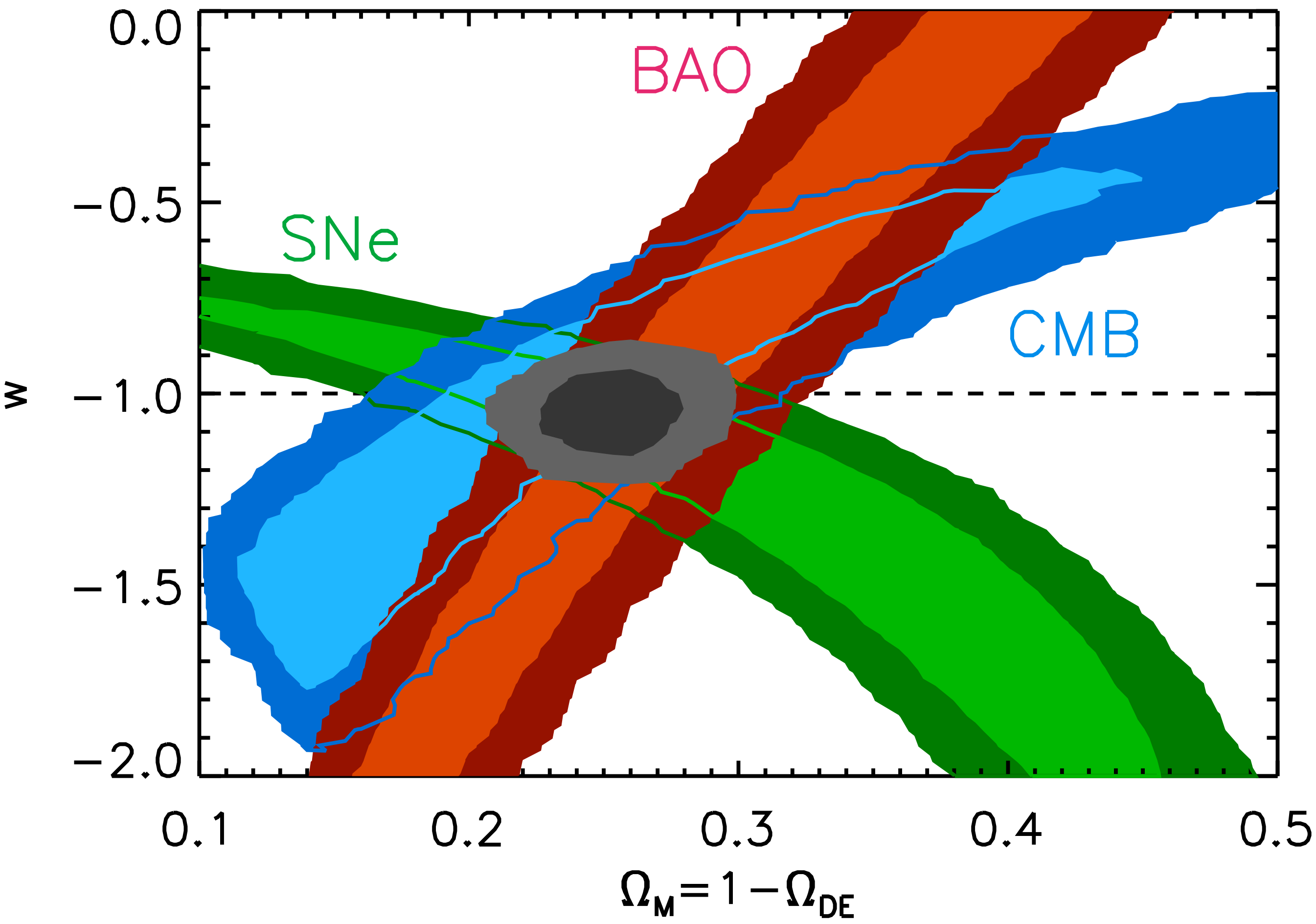
Eisenstein et al 2005 (SDSS collaboration)

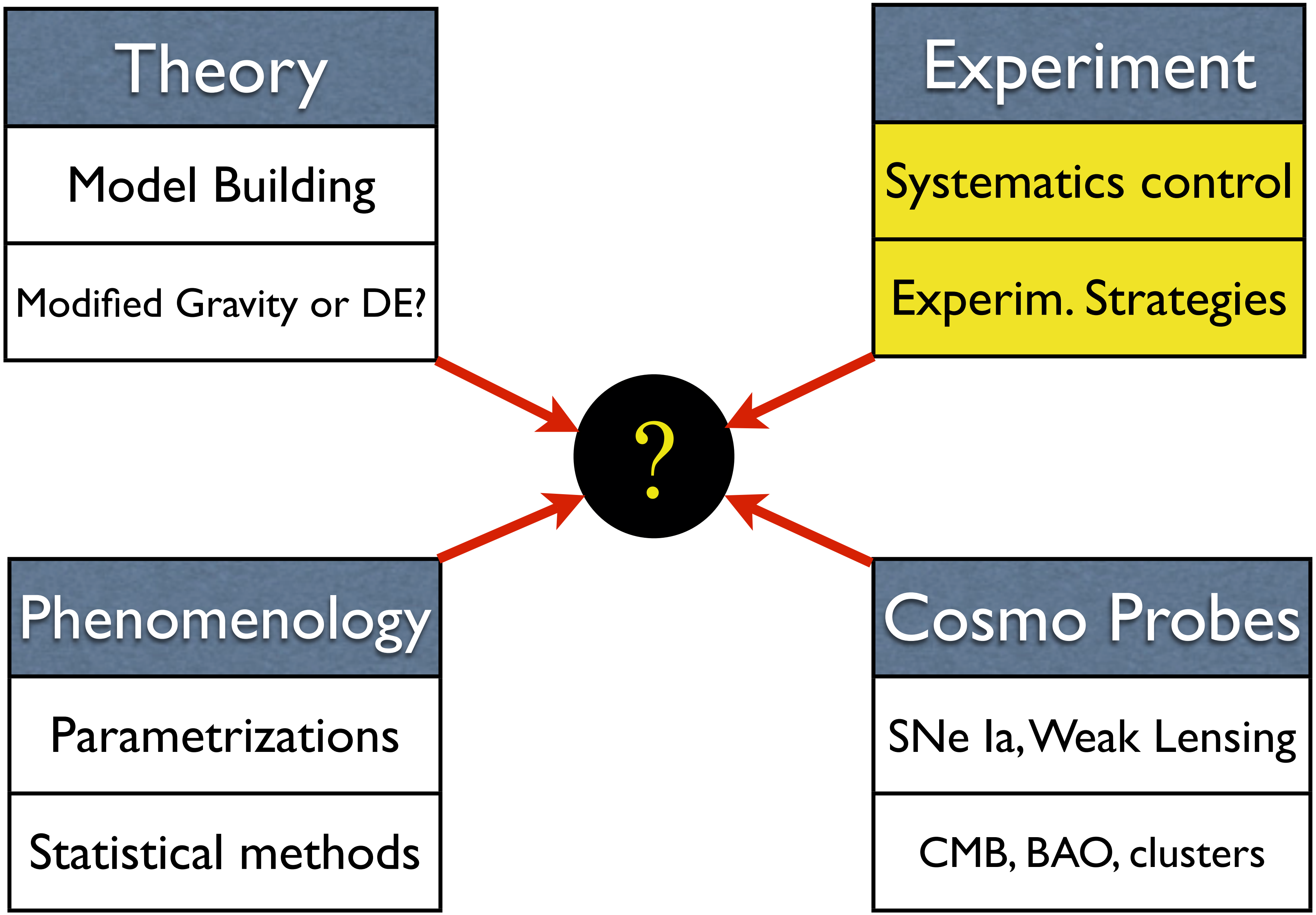


Advantages: relatively clean, geometric measurement

Challenges : millions of spectroscopic redshifts required

Cosmological probes of DE: current summary

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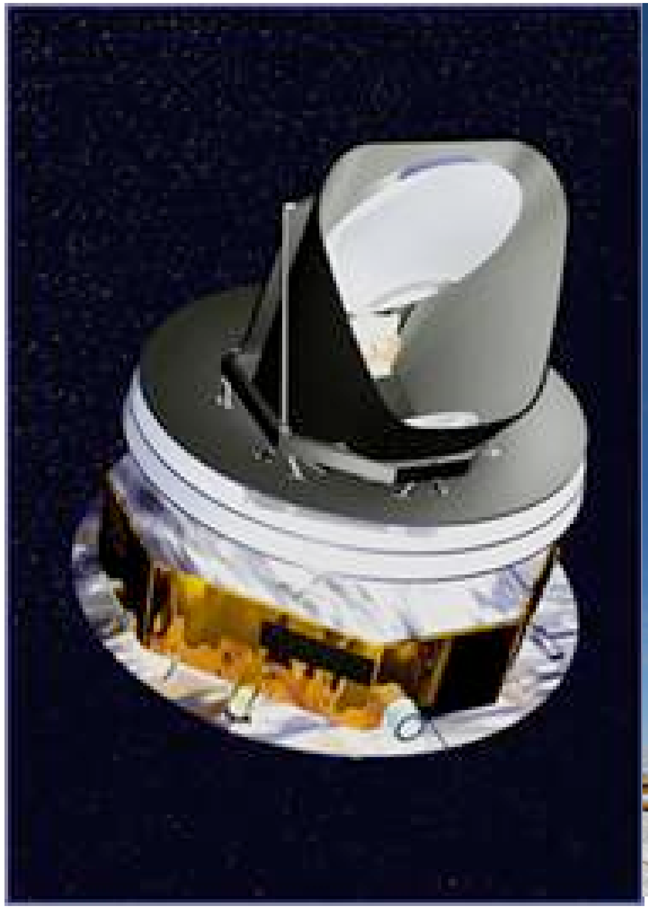
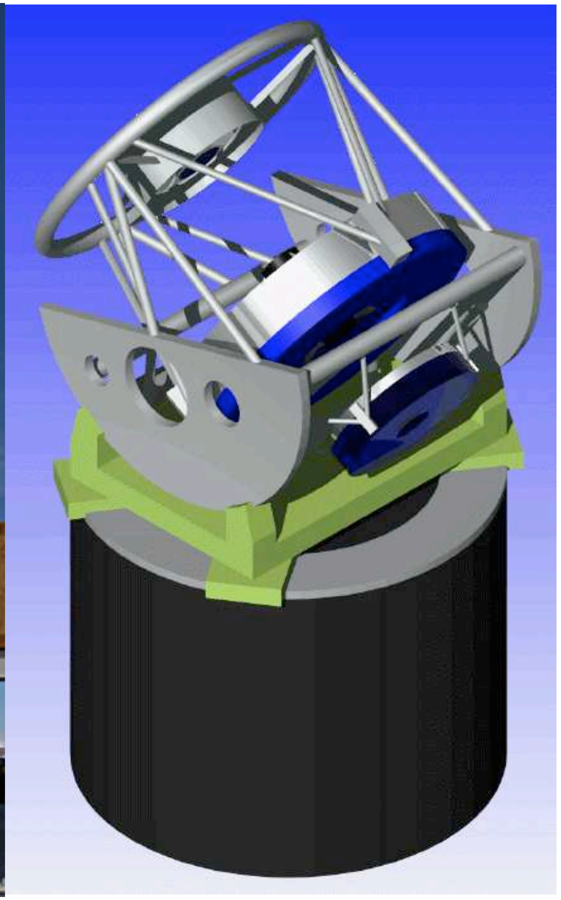
Upcoming Experiments

Planck



South Pole Telescope

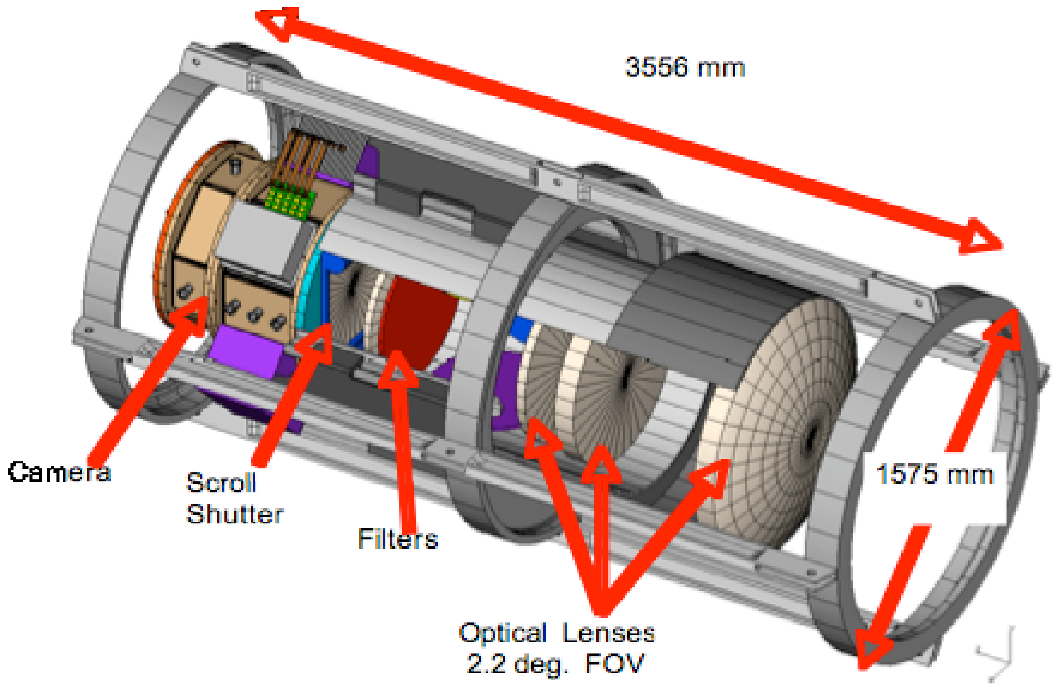
LSST



Lots and lots of data coming our way

Dark Energy Survey

UNIVERSITY OF MICHIGAN



Blanco 4m telescope in Chile

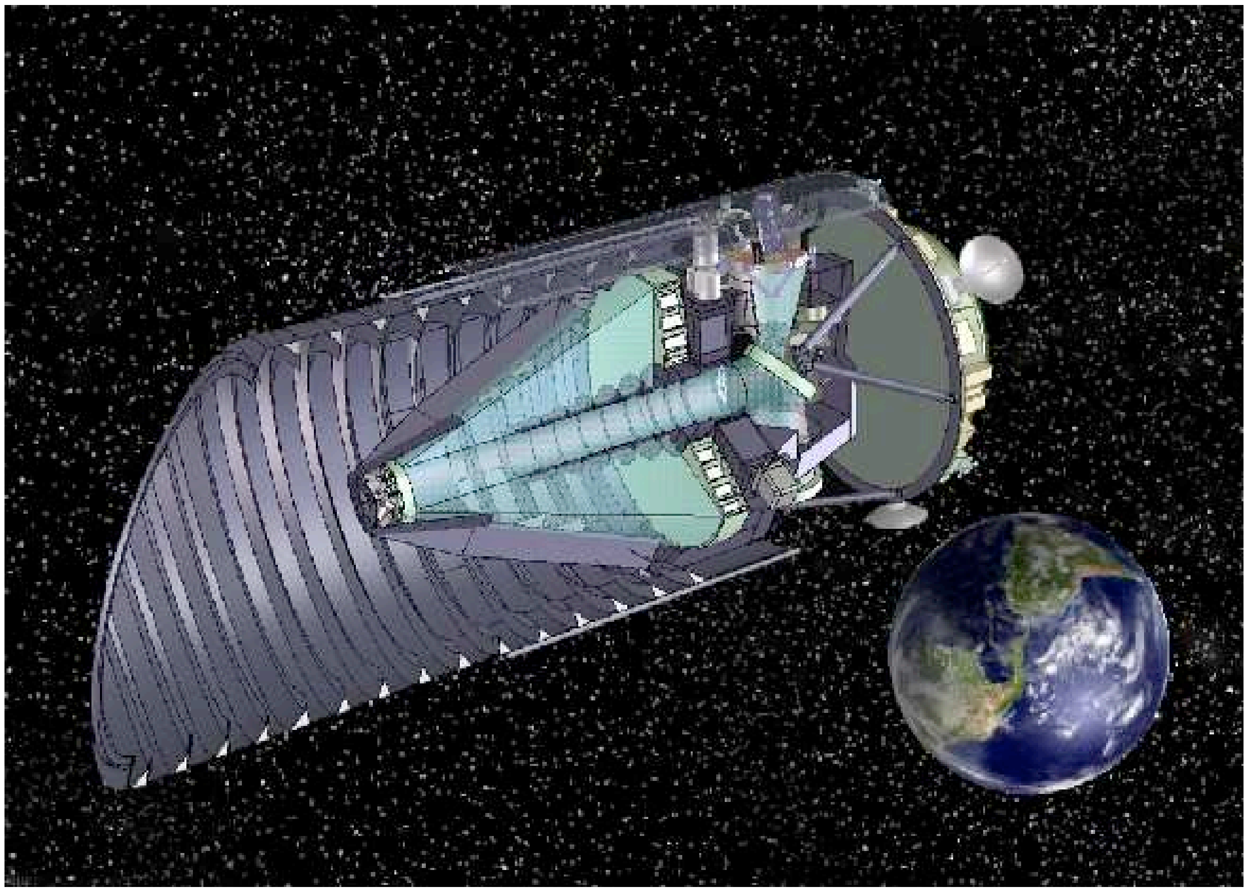
Four techniques to probe Dark Energy:

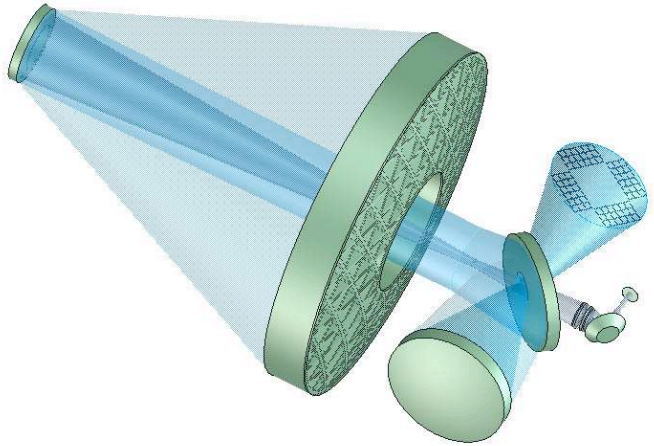
1. Number Counts of clusters
2. Weak Lensing
3. SNe Ia
4. Angular clustering of galaxies

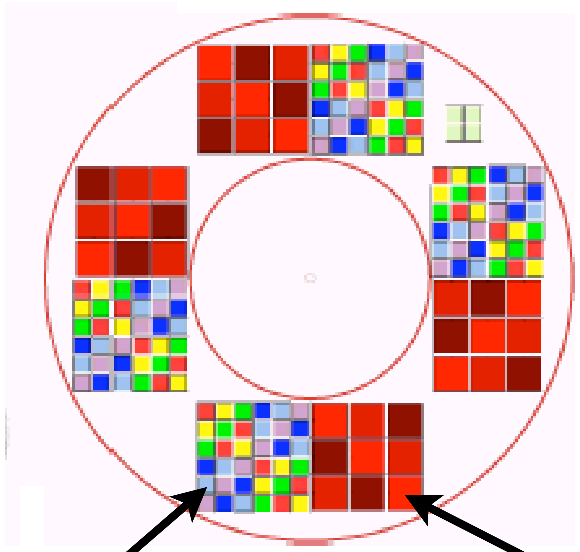
SuperNova/Acceleration Probe

UNIVERSITY OF MICHIGAN

~2500 SNe at 0.1<z<1.7

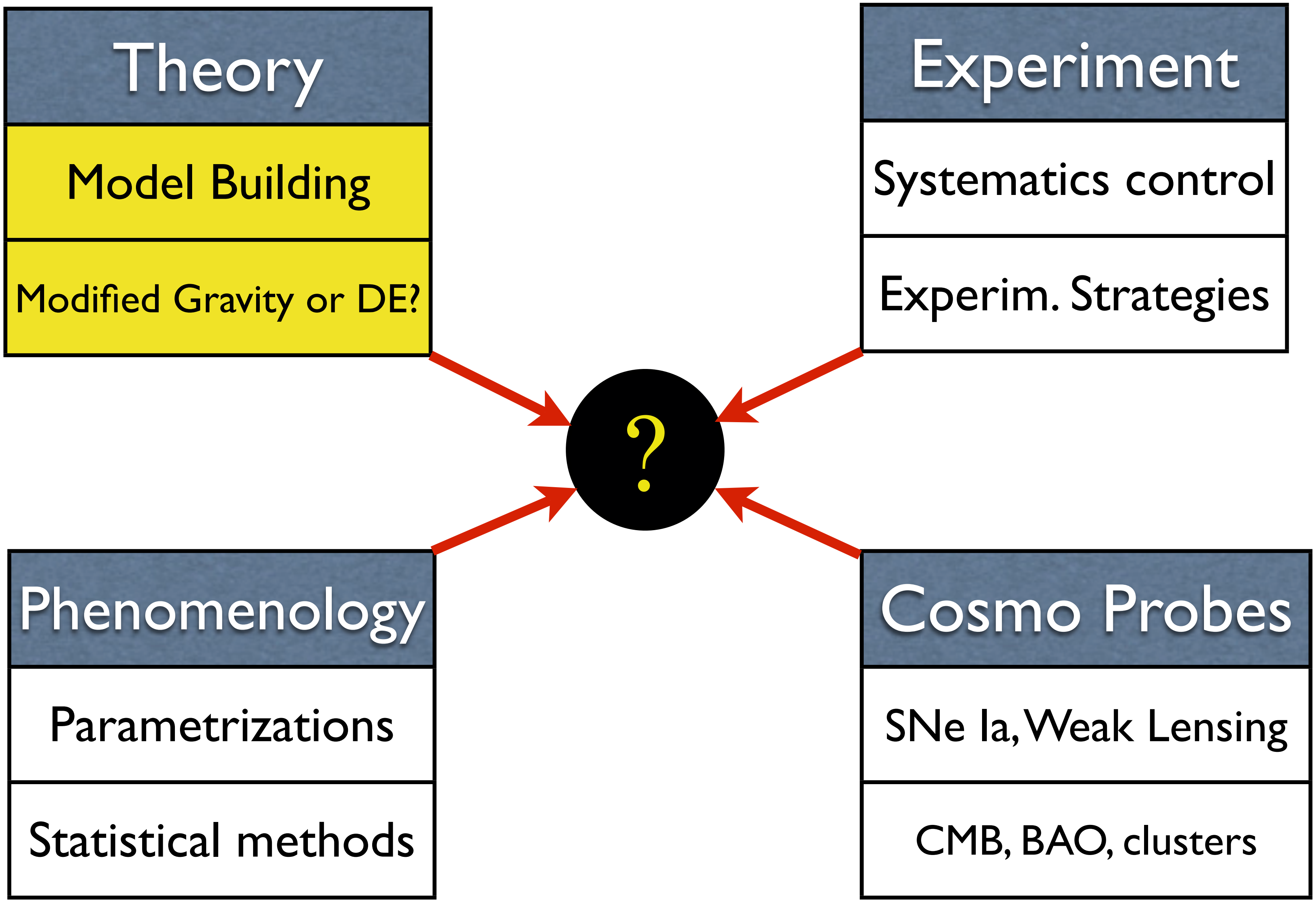






Visible (CCDs)

NIR (HgCdTe)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What if gravity deviates from GR?

For example:

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \qquad \text{or} \qquad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

↓ Modified gravity

↓ Dark energy

Dark Energy or Modified Gravity?

- A given DE and modified gravity models may both fit the expansion history data very well, but they will differ in the predicted growth history

- In standard GR, H(z) determines distances and growth of structure

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi\rho_M\delta = 0$$

- So check if this is true by measuring separately

Distances
(a.k.a. kinematic probes)
(a.k.a. 0^{th} order cosmology)

Growth
(a.k.a. dynamical probes)
(a.k.a. 1^{st} order cosmology)

Dark Energy cosmology at Michigan

Theory	Phenomenology	Simulations	Experiment
Freese Huterer (Adams) (Kane) (Pierce) (Zurek)	Evrard Huterer McKay	Evrard	Gerdes McKay Lorenzon Tarle (Huterer)

DES: Evrard, Gerdes, Lorenzon, McKay, Tarle, (Huterer)

SNAP: Gerdes, Huterer, Lorenzon, McKay, Tarle

+ numerous research scientists, postdocs, collaborators...

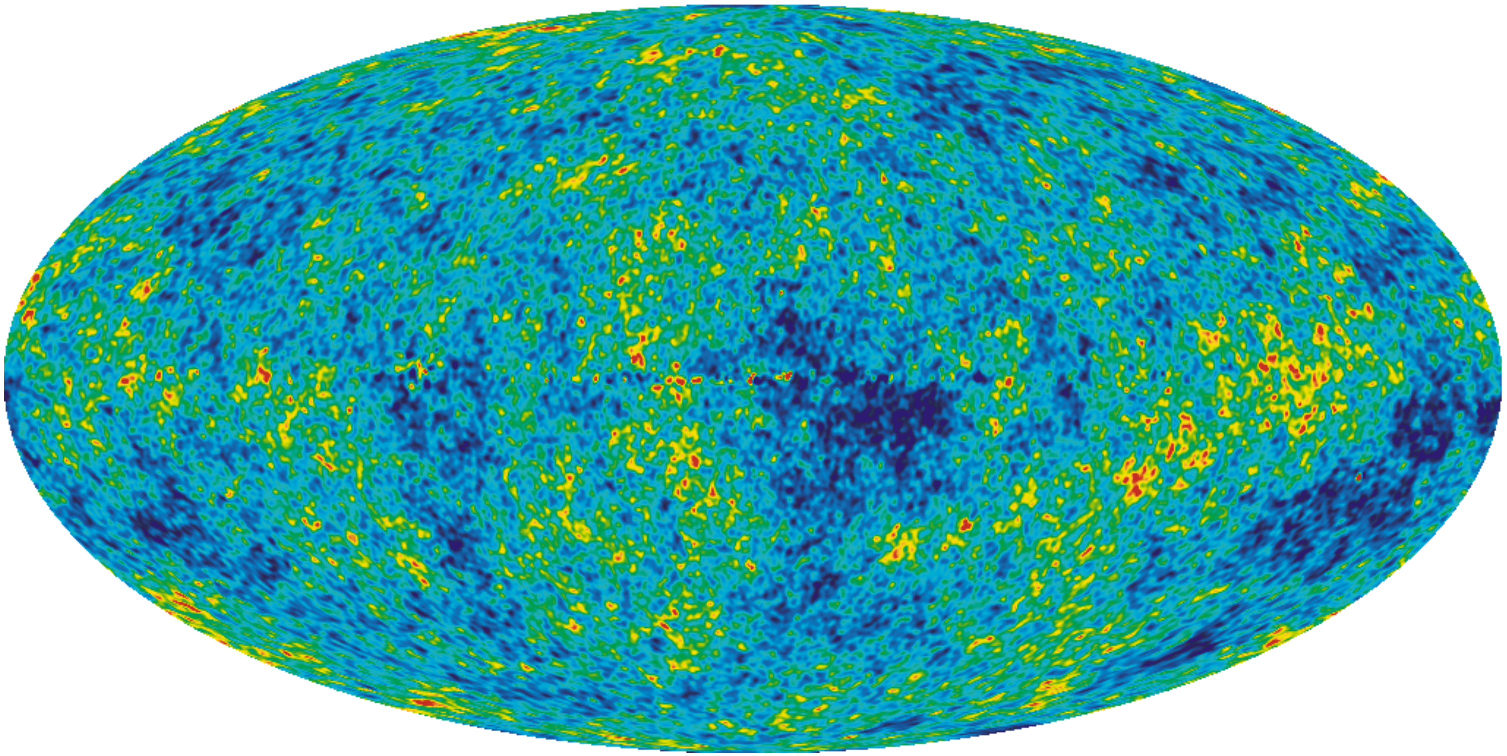
bonus feature:

Testing the Isotropy of the Universe

Dragan Huterer

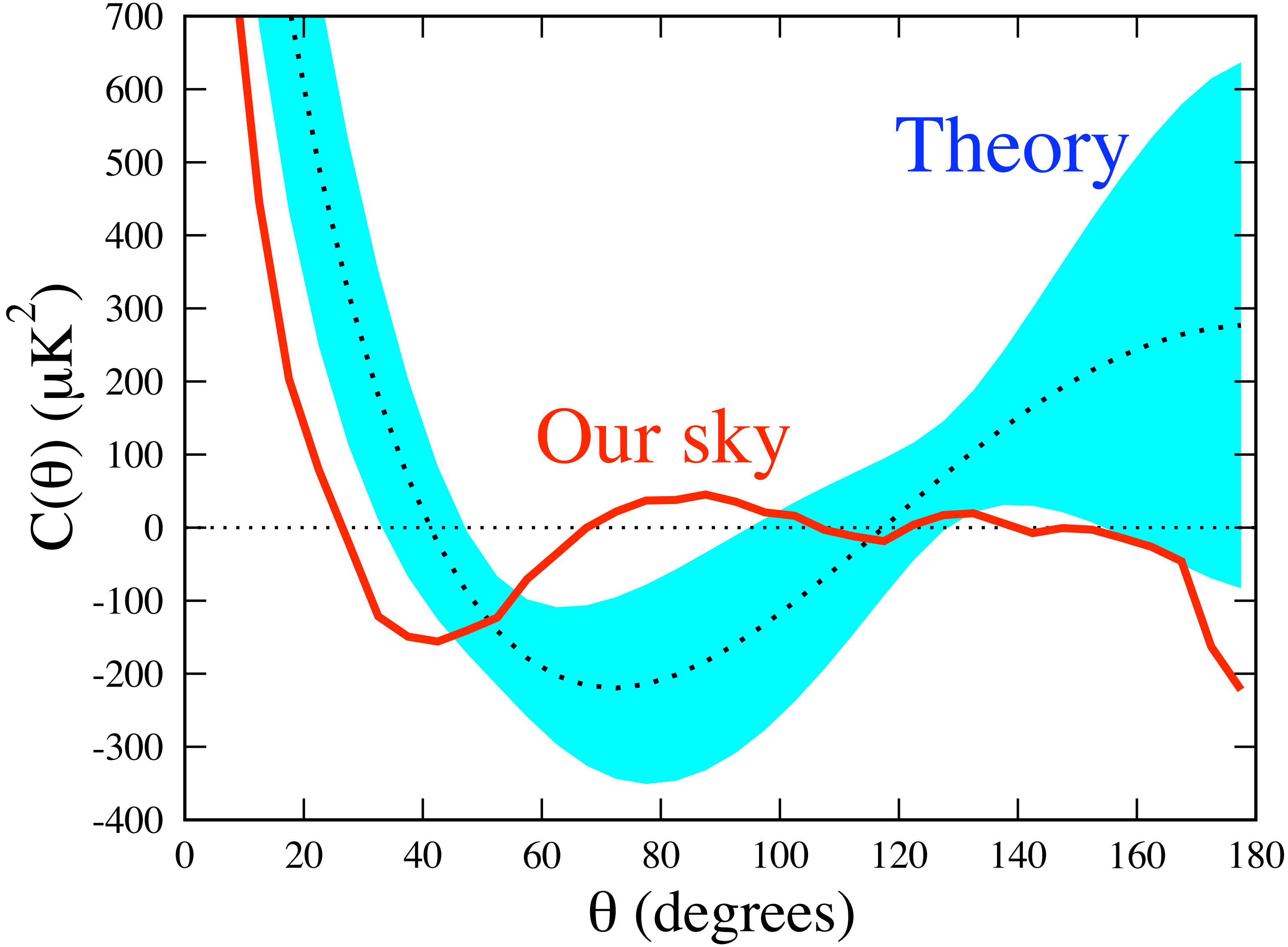
Principal collaborators:
Craig Copi (Case Western Reserve University),
Dominik Schwarz (Bielefeld University, Germany),
Glenn Starkman (Case Western Reserve University)

How does the universe look at largest observable scales?



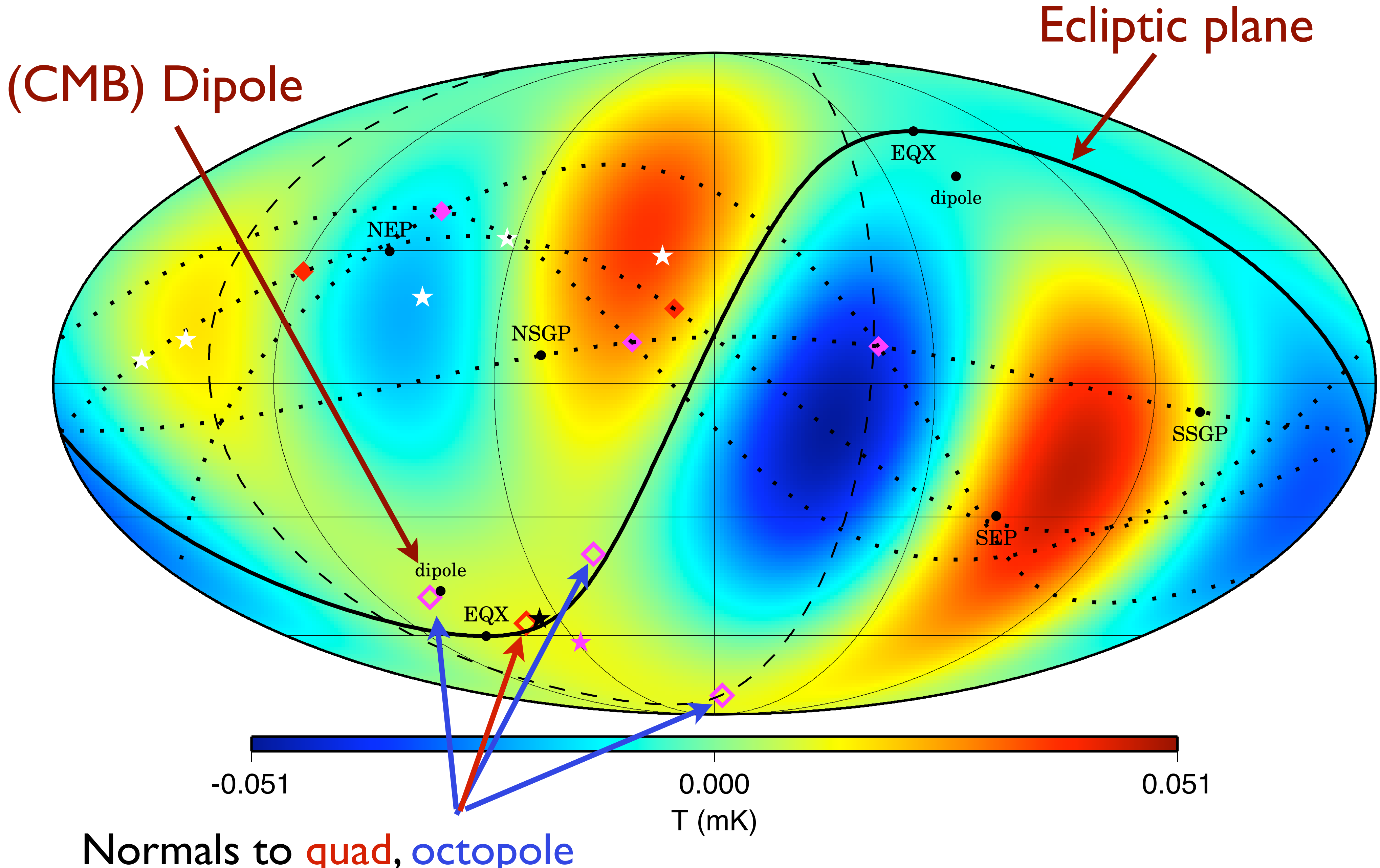
ILC map, WMAP collaboration

2-pt angular correlation function vanishes above 60 deg



Copi, Huterer, Schwarz & Starkman astro-ph/0605135

CMB is aligned with the solar system!



Schwarz, Starkman, Huterer & Copi 2004

4 classes of explanations:

- Astrophysical (e.g. an object or other source of radiation in the Solar System)
  - BUT: we think we know the Solar System. It would need to be a large source *and* undetected in data cross-checks.
- Instrumental (e.g. there is something wrong with WMAP instrument measuring CMB at large scales)
  - BUT: the instruments have been extremely well calibrated and checked. Plus, why would they pick out the Ecliptic plane?
- Cosmological (e.g. some property of the universe – inflation or dark energy for example – that we do not understand)
  - This is the most exciting possibility. BUT: why would the new/unknown physics pick out the Ecliptic plane?
- These alignments are a pure fluke!
  - BUT: they are <0.1% likely!

A variety of projects

- Studying various statistics from CMB maps
- Studying the effects of Solar System objects (Kuiper Belt objects, dust clouds, ...)
- Using large-scale structure to test isotropy of the universe
- Studying instrumental effects that would lead to preferred directions
- Building cosmological models that would lead to preferred directions

Astronomy-Math-Physics

My group at UM

Carlos Cunha (postdoc);
arrived this week

Cameron Gibelyou;
2nd year grad student

Wendy Wong and Ray Zhang (undergrads)

Further reading references

Dark Energy (short - 10 page) review:

Turner & Huterer, www.arxiv.org/abs/arXiv:0706.2186

Dark Energy (long - 54 page) review:

Frieman, Turner & Huterer, www.arxiv.org/abs/arXiv:0803.0982

SNAP experiment:

snap.lbl.gov

CMB alignments review:

Huterer, New Astronomy Reviews 50, 868 (2006), www.arxiv.org/abs/astro-ph/0608318