Cosmological Probes of Dark Energy

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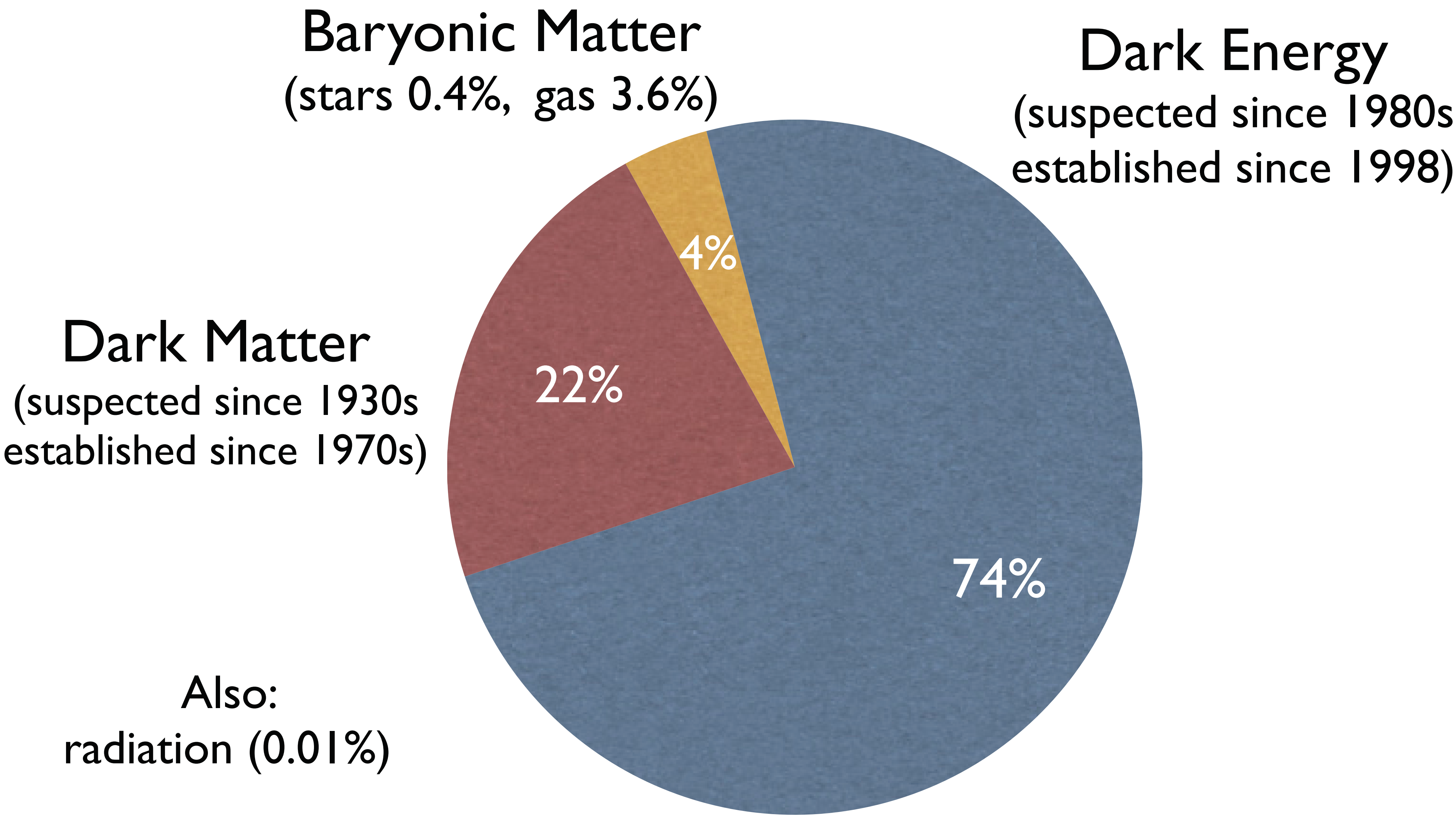
The universe today presents us with a grand puzzle:

What makes up 95% of it?

Scandalously, we still don't know.

But we are working to get closer to the answer.

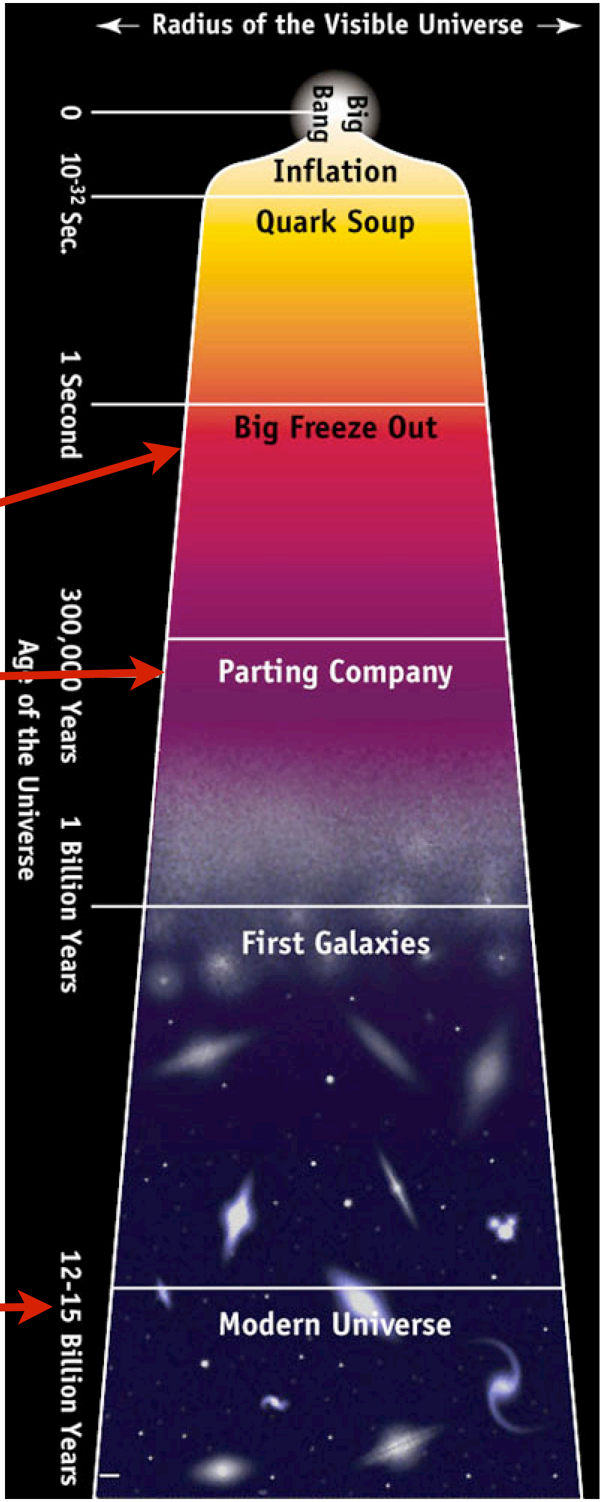
Makeup of universe today



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

Physics quite well understood

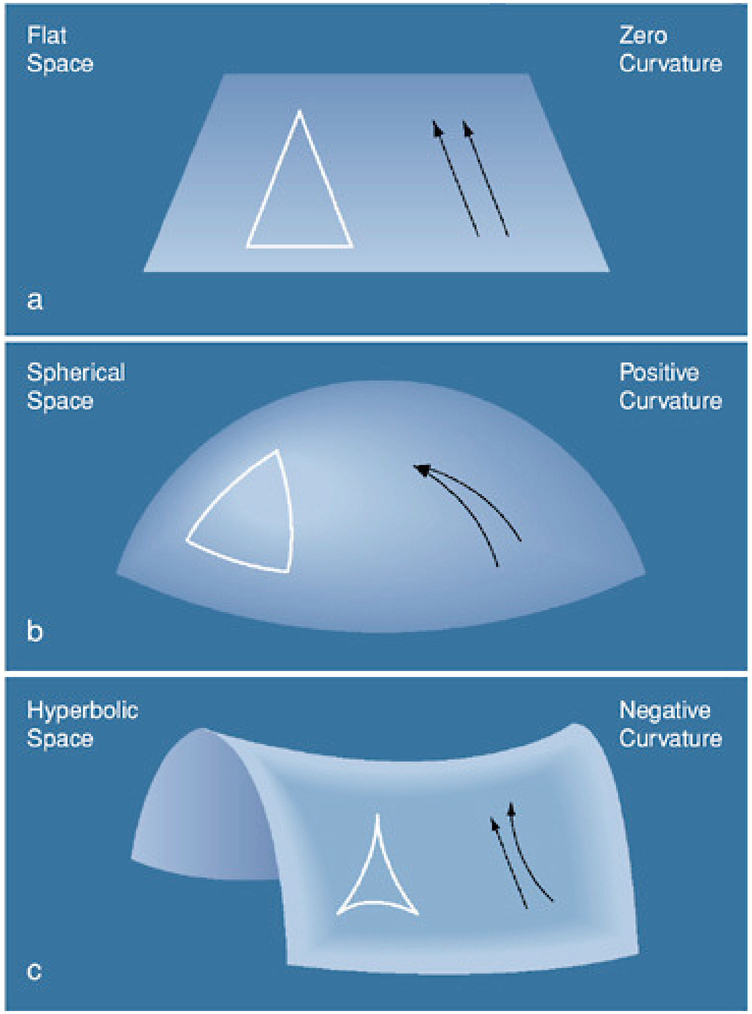
95% of contents only phenomenologically described



Friedmann Equation

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

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



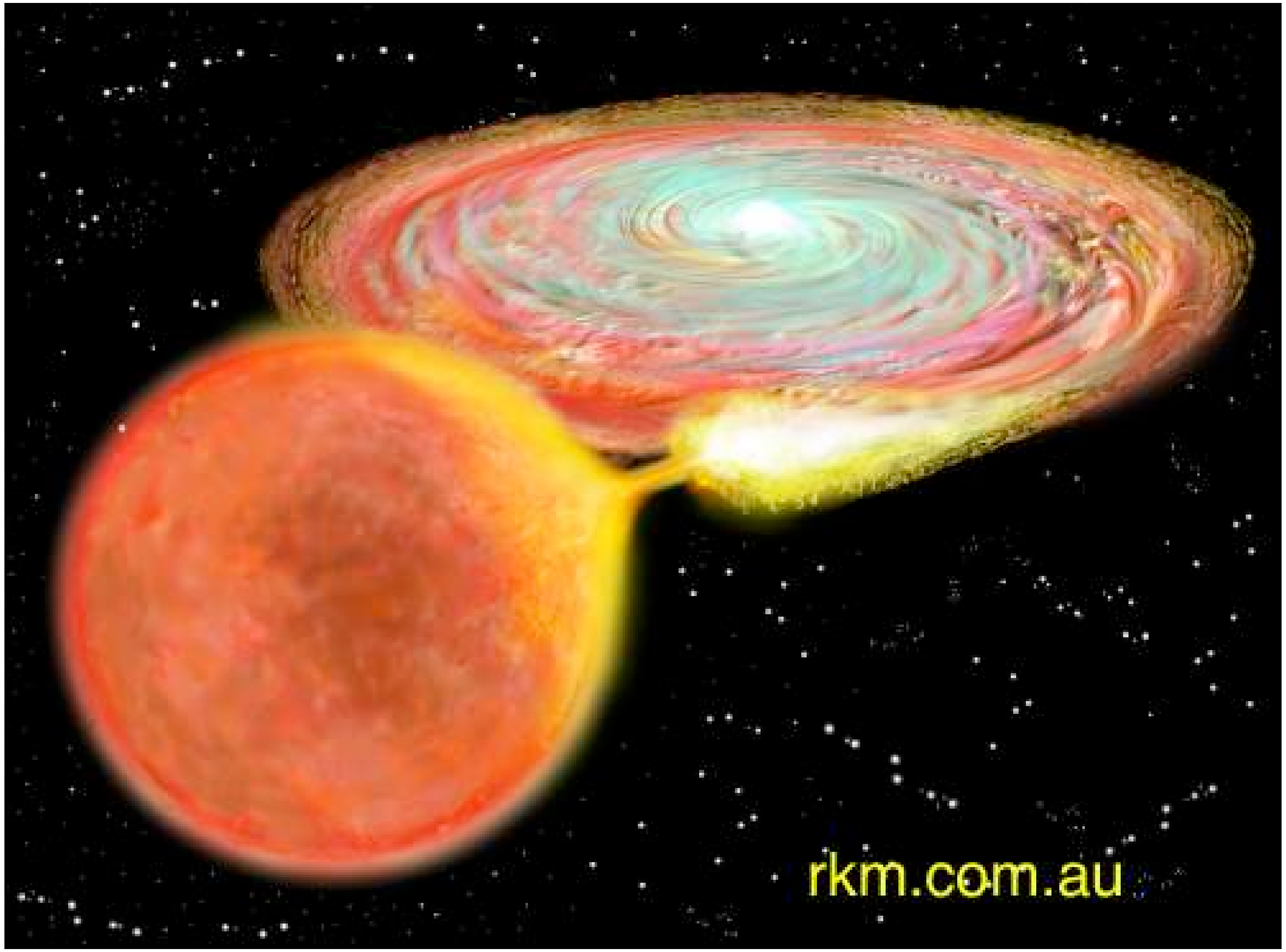
Inflation predicts, and
CMB anisotropy indicates
universe is flat (curvature is zero), so $\Omega_{\rm TOT} = 1$ (or $\kappa = 0$)

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

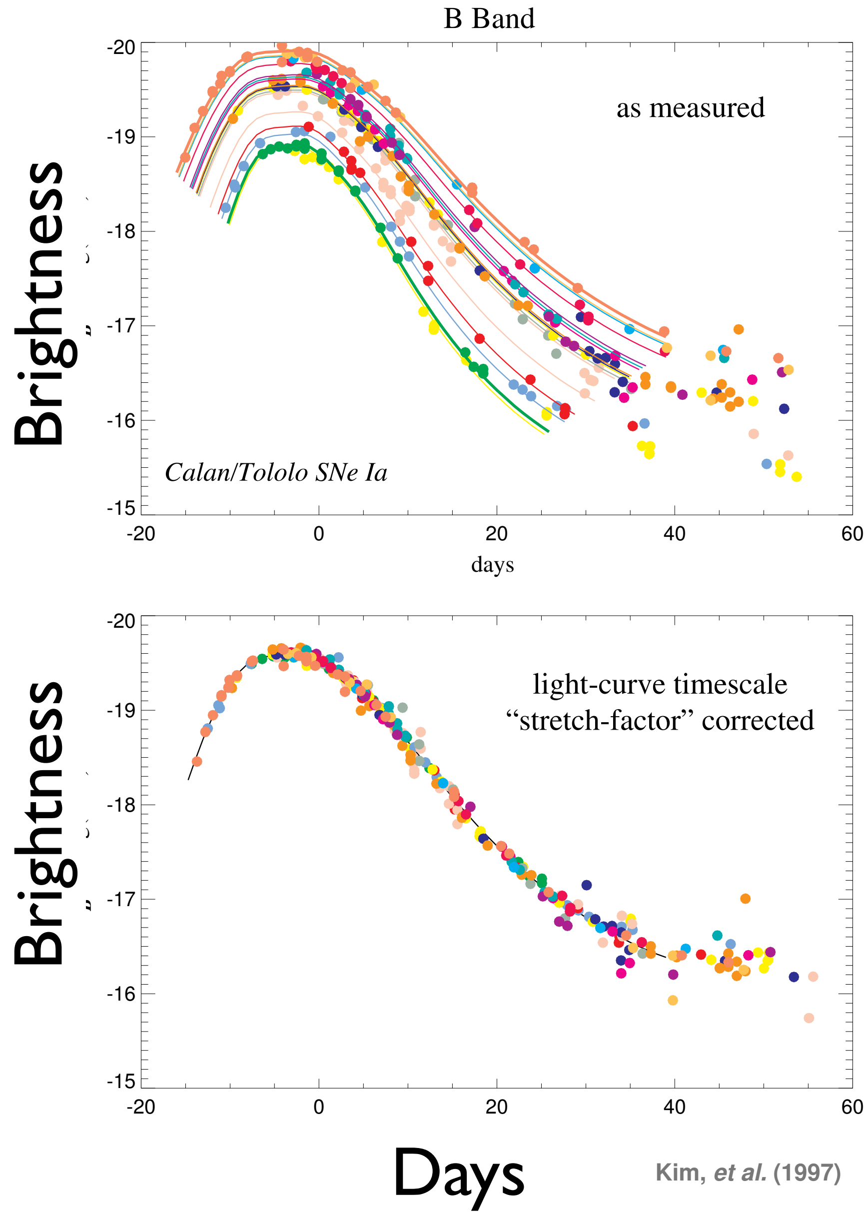
Brightness

Brightness

Days

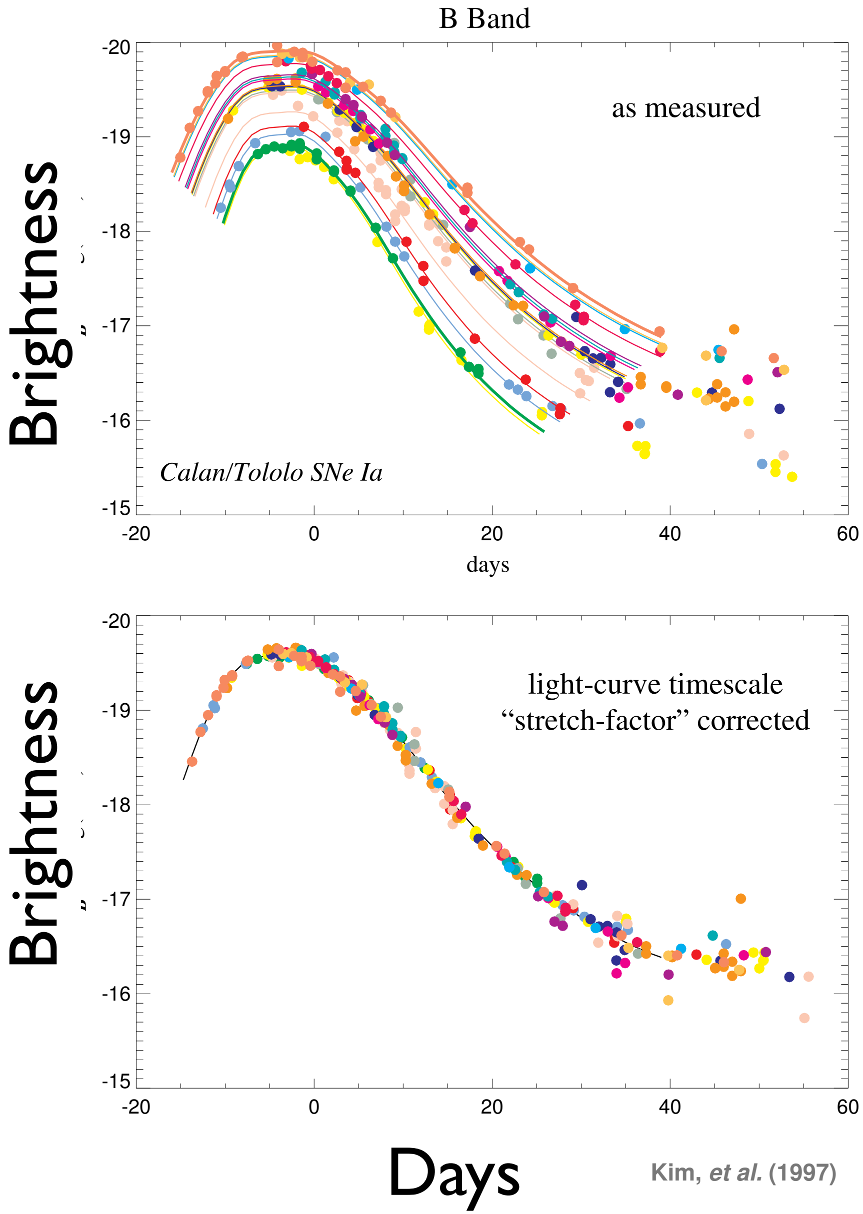
Riess et al 1998; Perlmutter et al 1999

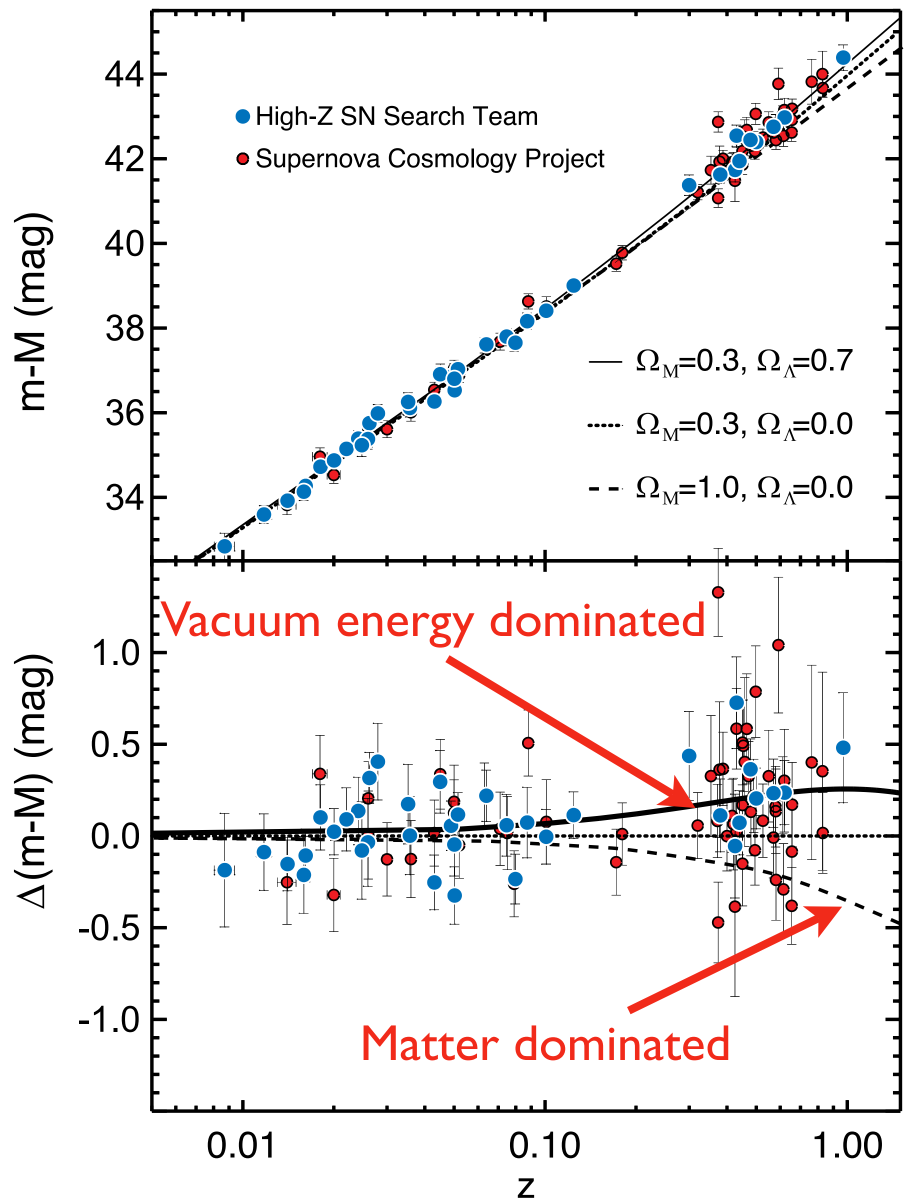
Dark Energy discovery from SNe Ia



Riess et al 1998; Perlmutter et al 1999

Dark Energy discovery from SNe Ia





Riess et al 1998; Perlmutter et al 1999

Dark Energy Parametrization

Distant Sne are dimmer than expected ⇨ the expansion of the universe is accelerating

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

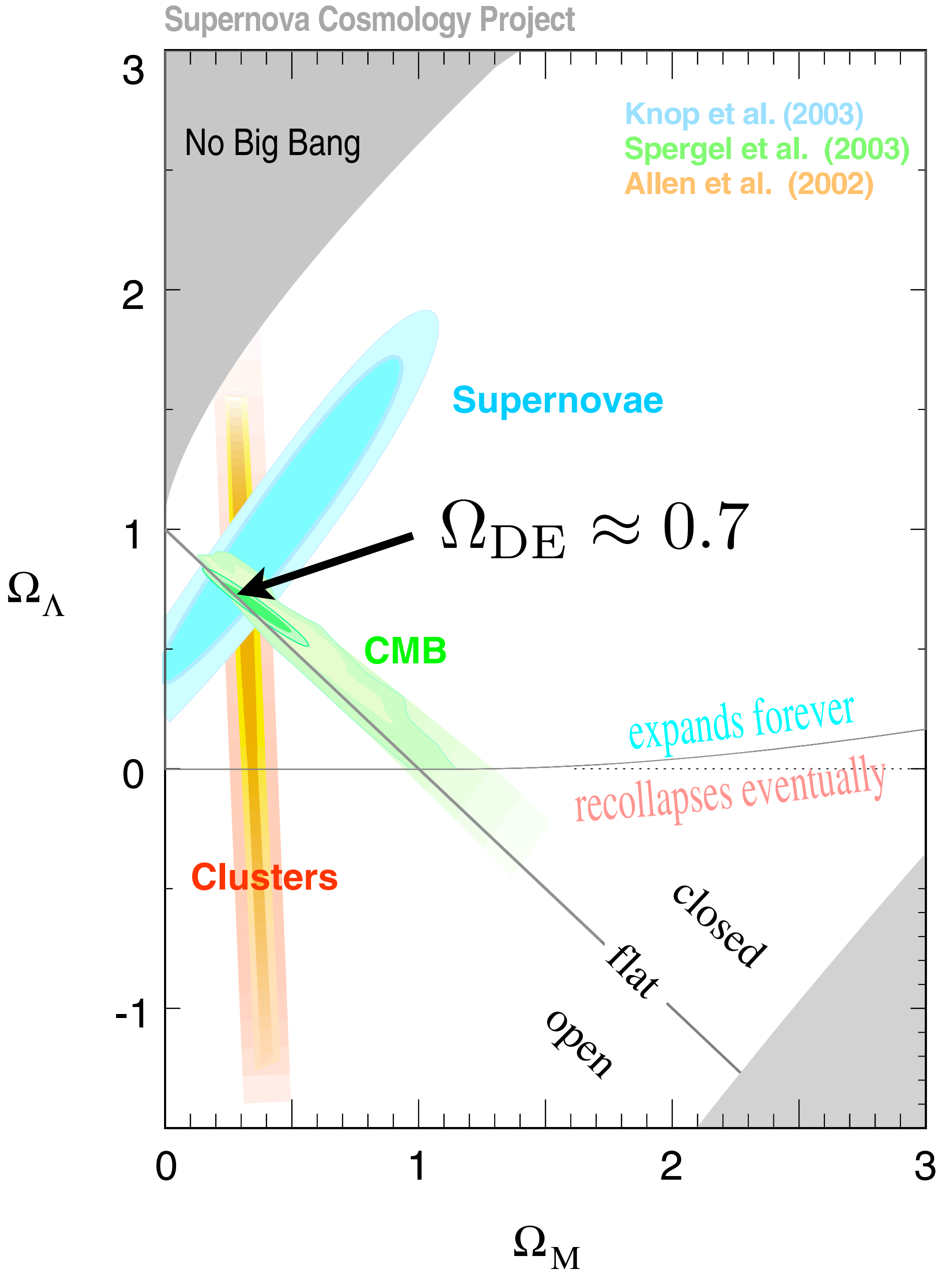
so, pressure of dark energy is strongly negative

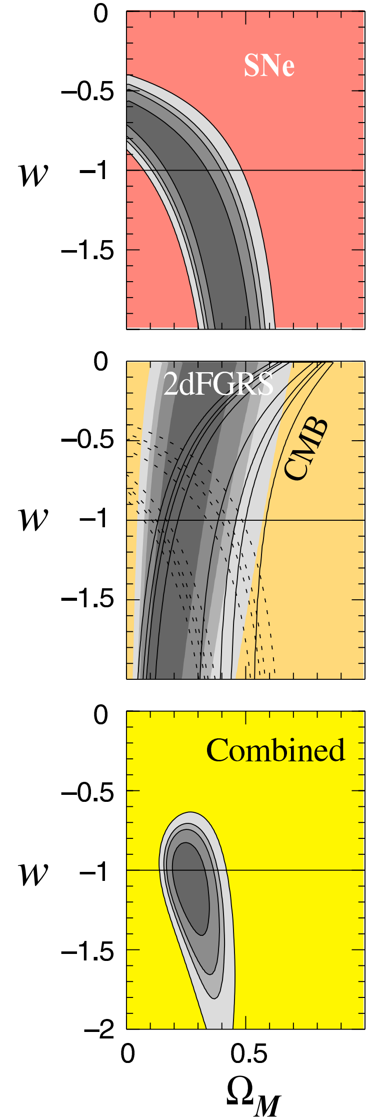
Equation of state ratio: $$w = \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}}$$

Energy density today (relative to critical): $$\Omega_{\mathrm{DE}} = \frac{\rho_{\mathrm{DE}}}{\rho_{\mathrm{crit}}}$$

For vacuum energy $w = -1 \ \ (G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu})$

Current constraints





Supernova Cosmology Project
Knop *et al.* (2003)

Assuming constant w

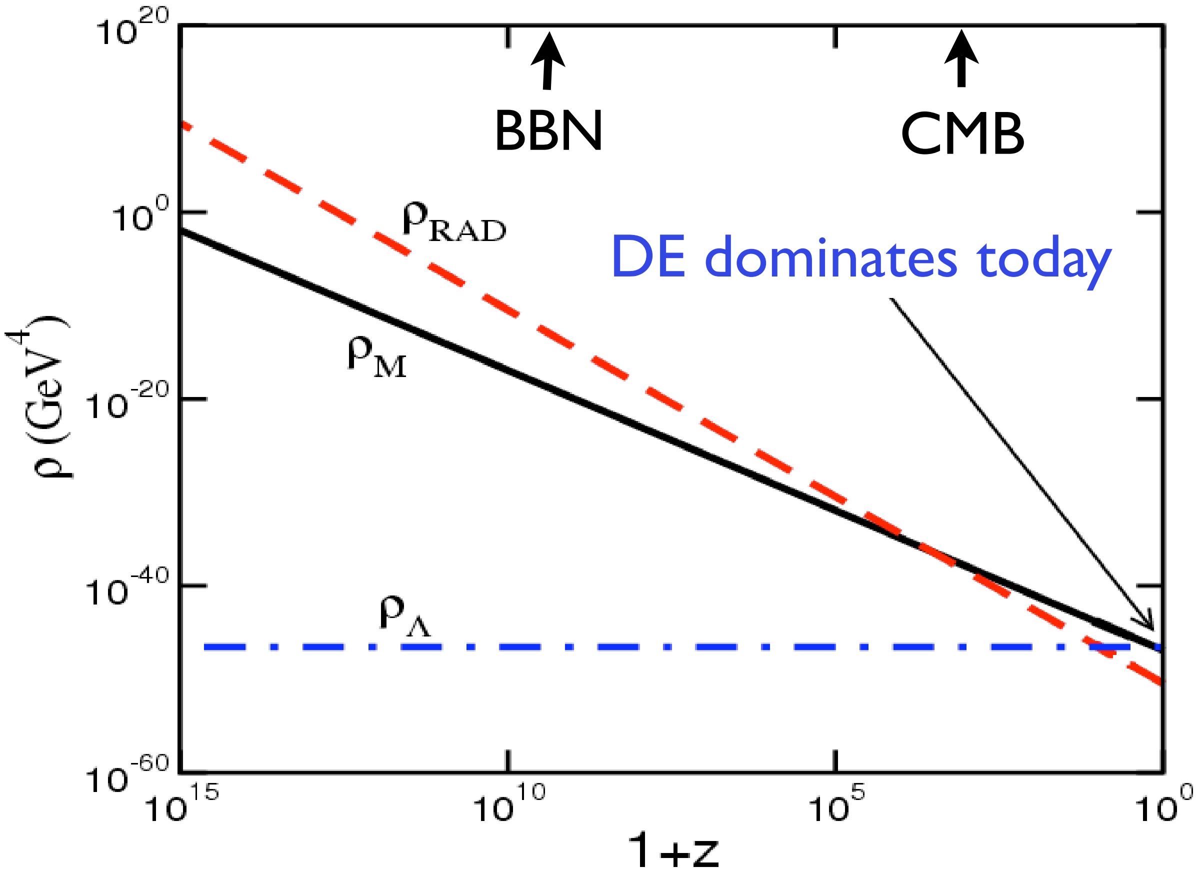
With limits from;
2dFGRS (Hawkins et al. 2002)
and CMB (Bennet et al. 2003, Spergel et al. 2003)

$w = -1.05 \ ^{+0.15}_{-0.20}$ (statistical)
± 0.09 (systematic)

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 $\simeq M_{\mathrm{cutoff}}^4$

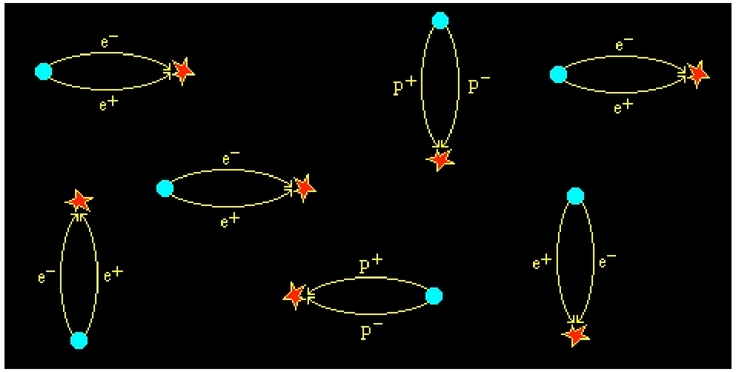
Measured:	$(10^{-3}\mathrm{eV})^4$	
SUSY scale:	$(1\,\mathrm{TeV})^4$	60-120 orders of magnitude smaller than expected!
Planck scale:	$(10^{19}\,\mathrm{GeV})^4$	

In other words:

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

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)

Alternatives to "pure" Cosmological Constant (CC)

Examples:

Modifications to Einstein's General Relativity
(e.g. f(R) theories)

Extra Dimensions (gravity leaks to the 4th dimension)

Unified Dark Energy (Dark Matter, DE are a single fluid)

....

So far, without much success:

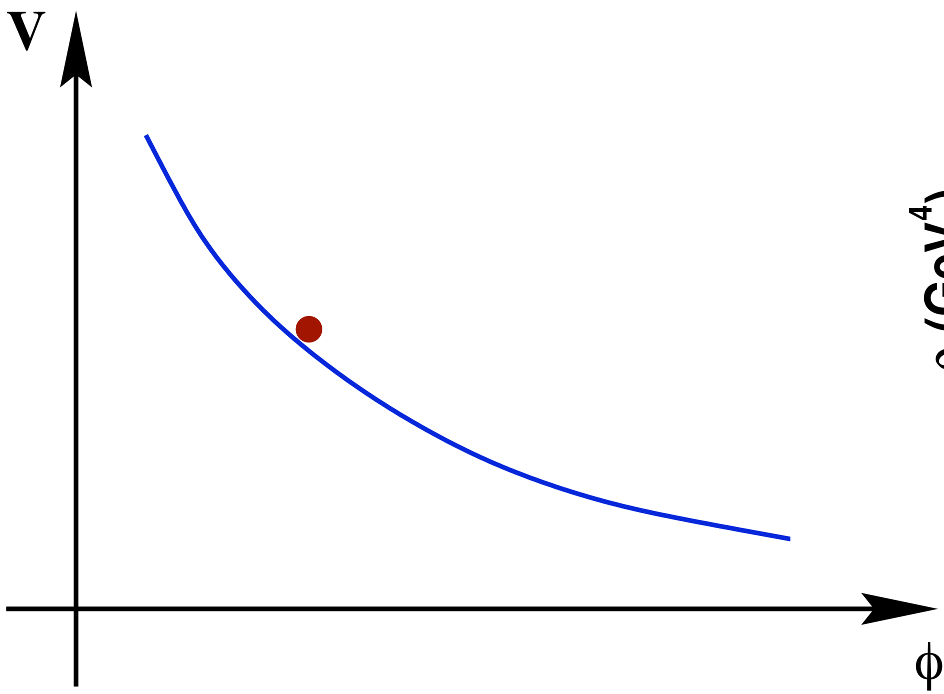
- the smallness (or CC) problem is typically not solved
- reliable predictions are difficult to compute
- Solar System constraints are stringent

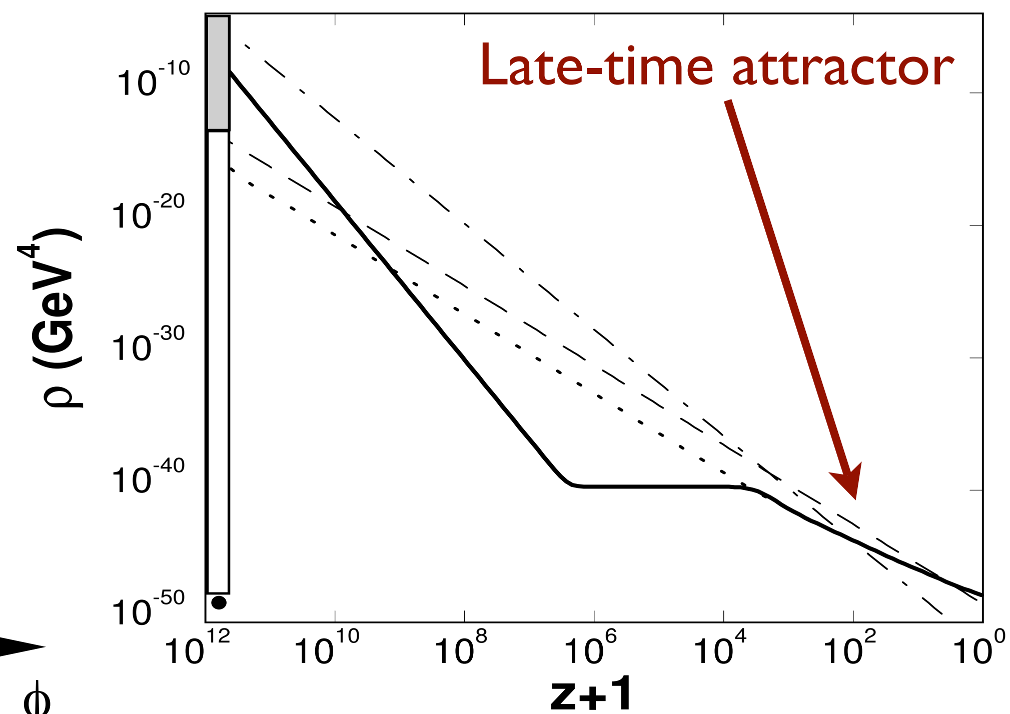
A dynamical DE alternative: quintessence

$$\mathcal{L} = 1/2\, g_{\mu\nu}\, \partial^\mu \phi\, \partial^\nu \phi - V(\phi)$$

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

$$m_\phi \approx 10^{-33}\text{eV}$$





Peebles & Ratra 1987; Freese, Frieman & Olinto 1990; Caldwell, Dave & Steinhardt 1998

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

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

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

What do we do now?

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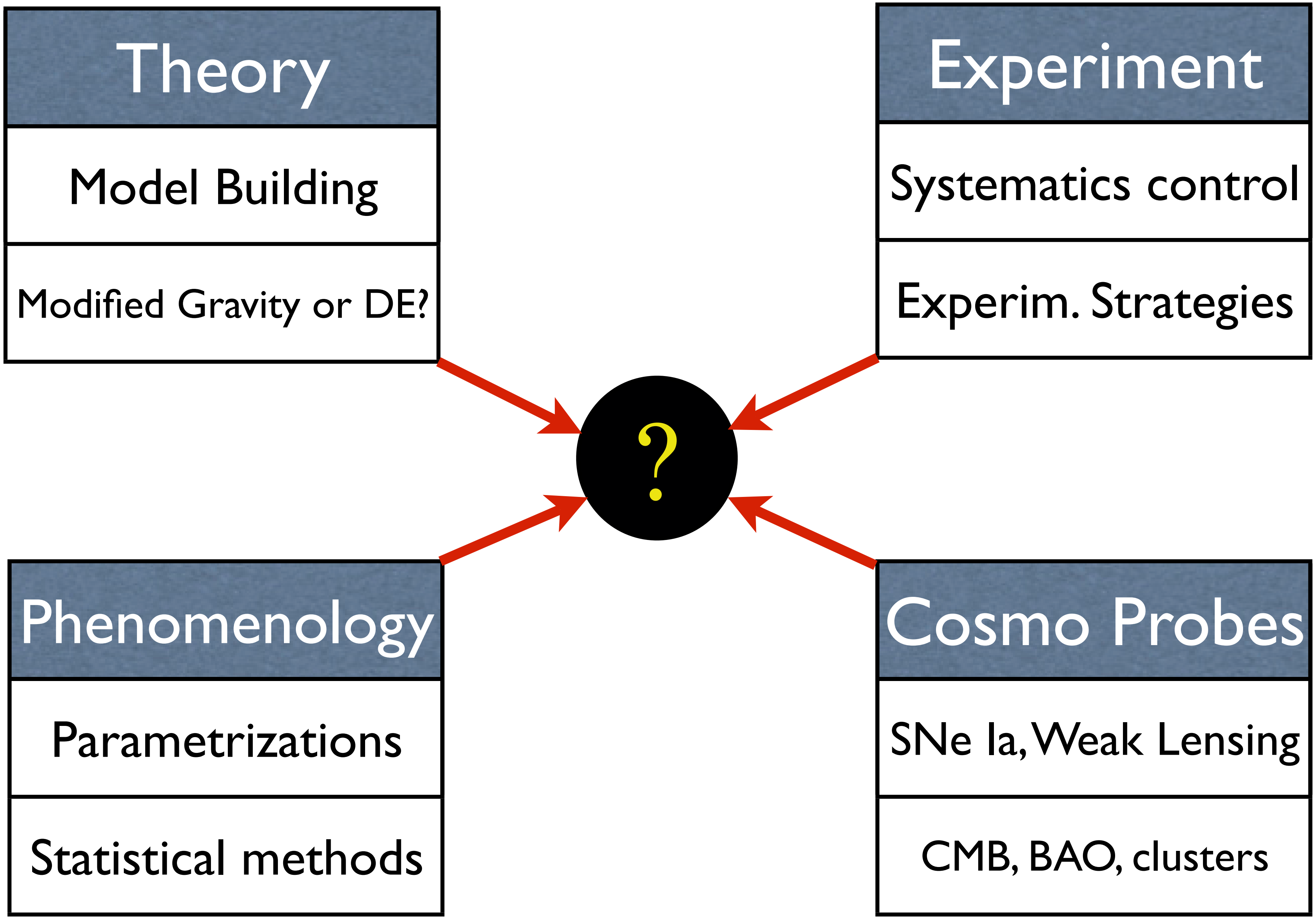
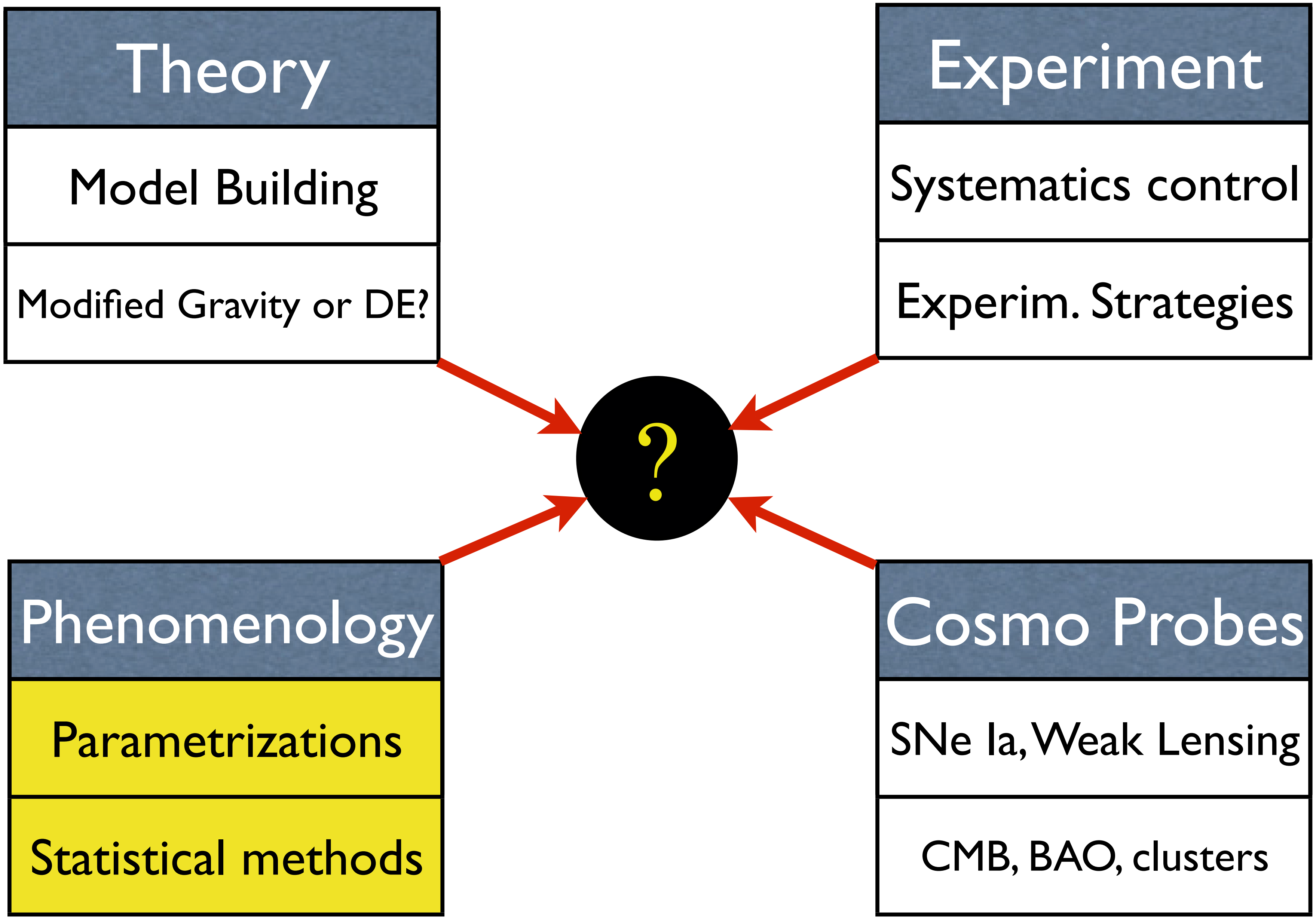
What do we do now?

We map out the expansion history as accurately as possible


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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Wish List

Goals:

$$w = \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

$$\Omega_{\rm DE} = \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

Measure $\Omega_{\rm DE}, w$

Measure $\rho_{\rm DE}(z)$ or $w(z)$

Measure any clustering of DE

Wish List

Goals:

$$w = \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}}$$

$$\Omega_{\mathrm{DE}} = \frac{\rho_{\mathrm{DE}}}{\rho_{\mathrm{crit}}}$$

Measure Ω_{DE}, w

Measure $\rho_{\mathrm{DE}}(z)$ or $w(z)$

Measure any clustering of DE

Difficulties:

$w(z)$ enters the observables via integral relations

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$$H^2(z) = H_0^2 \left[\Omega_M (1+z)^3 + \Omega_{DE} \exp\left(3 \int_0^z (1 + w(z')) d\ln(1+z')\right)\right]$$

DE clustering affects cosmology negligibly on scales $\ll H_0^{-1}$

Is dark energy the vacuum energy $(\, w(z) = -1 \,)$?
Is $w(z) = \mathrm{const}\,$?

Simplest ways to approach these questions:

$$w(z) = w_0 + w'\, z$$

$$w(z) = w_0 + w_a\, \frac{z}{1+z}$$

Cooray & Huterer 1999; Linder 2003

Two crucial questions:

Is dark energy the vacuum energy $(\, w(z) = -1 \,)$?
Is $w(z) = \text{const}$?

Simplest ways to approach these questions:

$$w(z) = w_0 + w' \, z$$

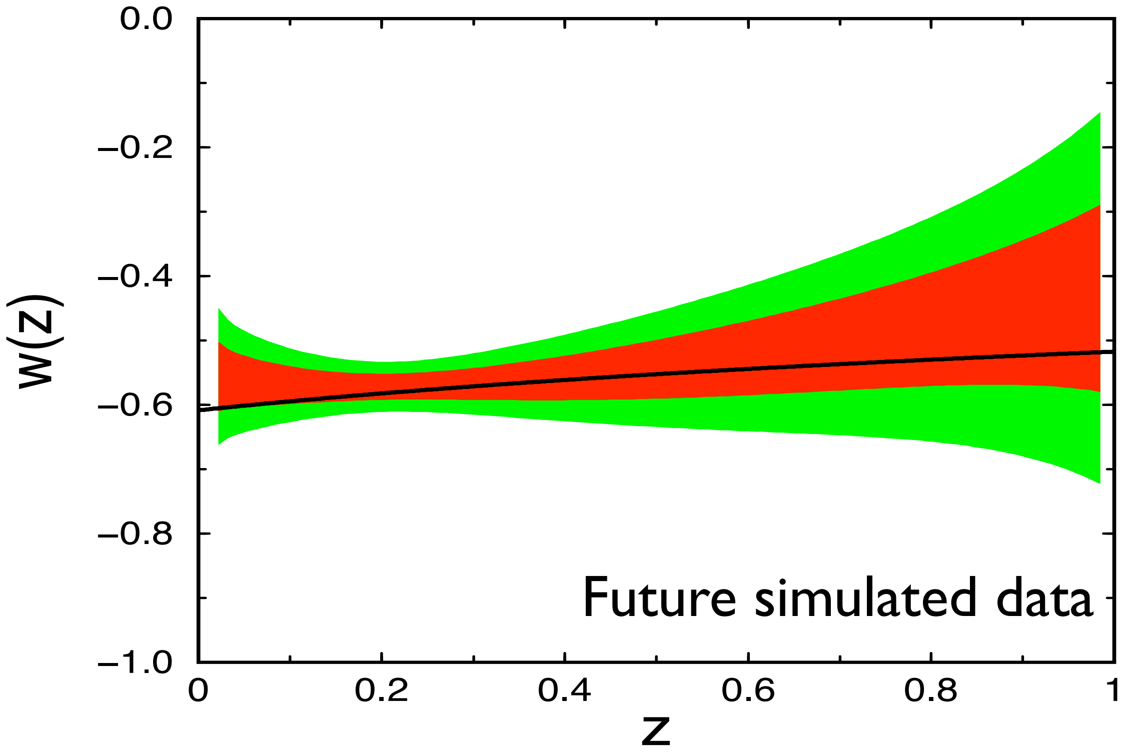
$$w(z) = w_0 + w_a \, \frac{z}{1+z}$$

Cooray & Huterer 1999; Linder 2003

Direct Reconstruction of $w(z)$

$$1 + w(z) = f\left(\frac{dr}{dz}, \frac{d^2r}{dz^2}\right)$$

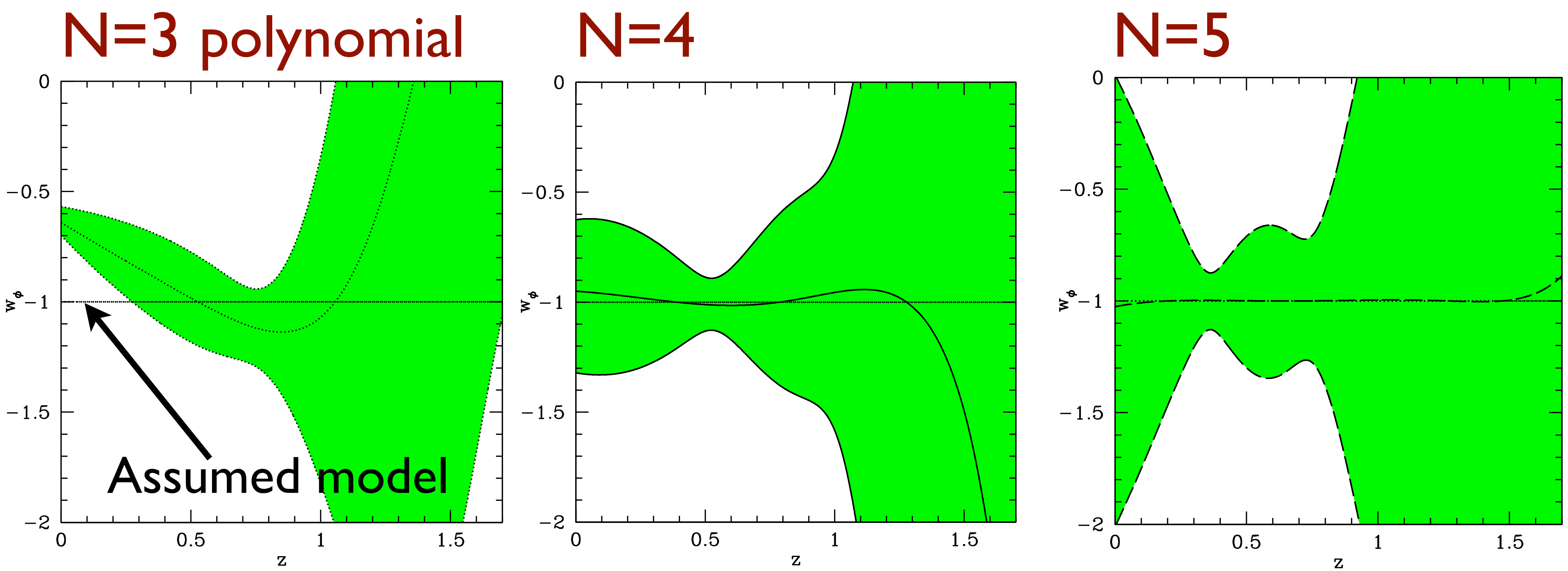
$$V[\phi(z)] = g\left(\frac{dr}{dz}, \frac{d^2r}{dz^2}\right)$$



- The most general possible approach to constrain dark energy, but
- Very hard in practice: needs second derivative of (noisy) data
- Nevertheless, studied, refined and used by many authors

Huterer & Turner 1999

Direct Reconstruction: (parametric) example



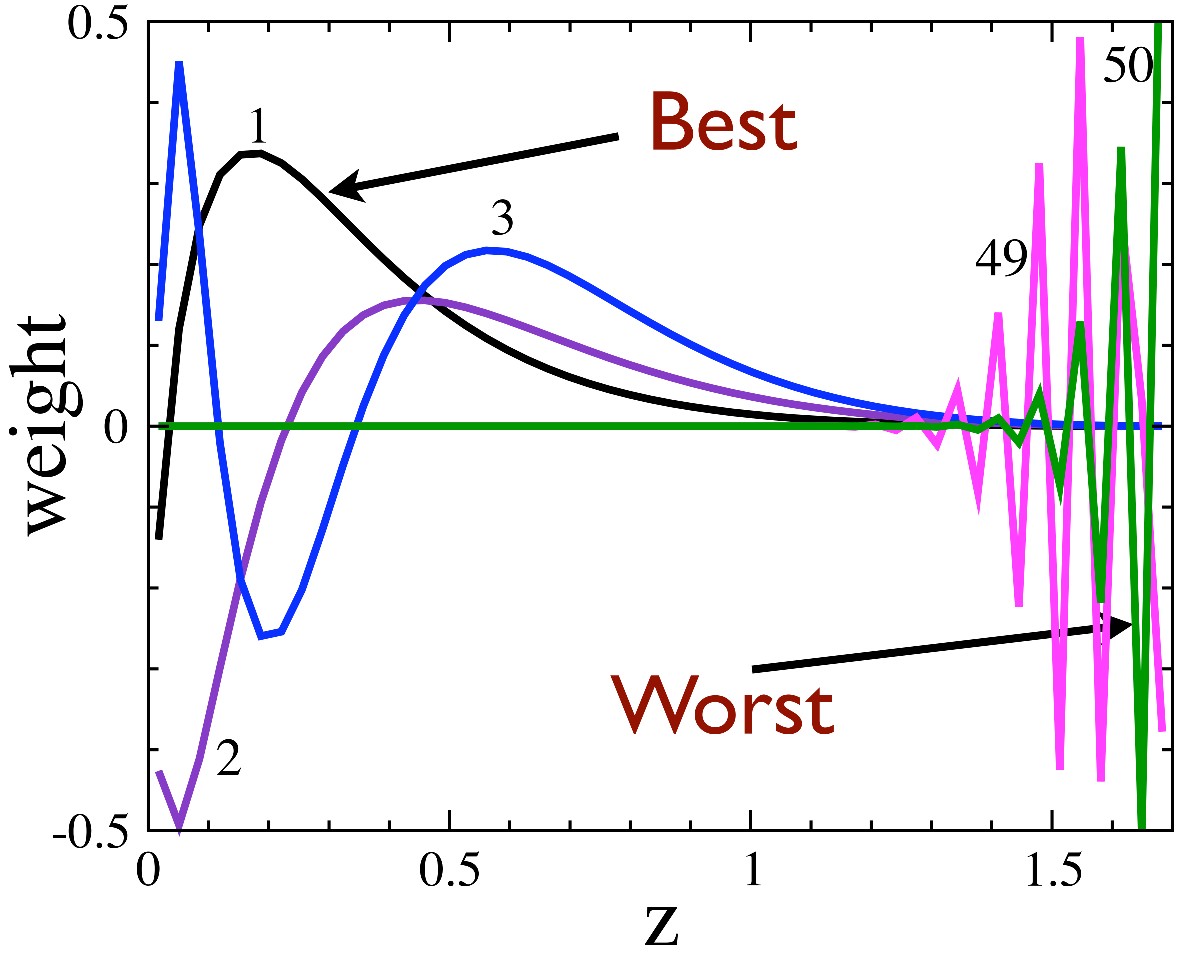
Direct reconstruction of the equation of state leads to biases, or large errors, or both

Weller & Albrecht 2002

Principal Components of $w(z)$

These are best-to-worst measured linear combinations of w(z)

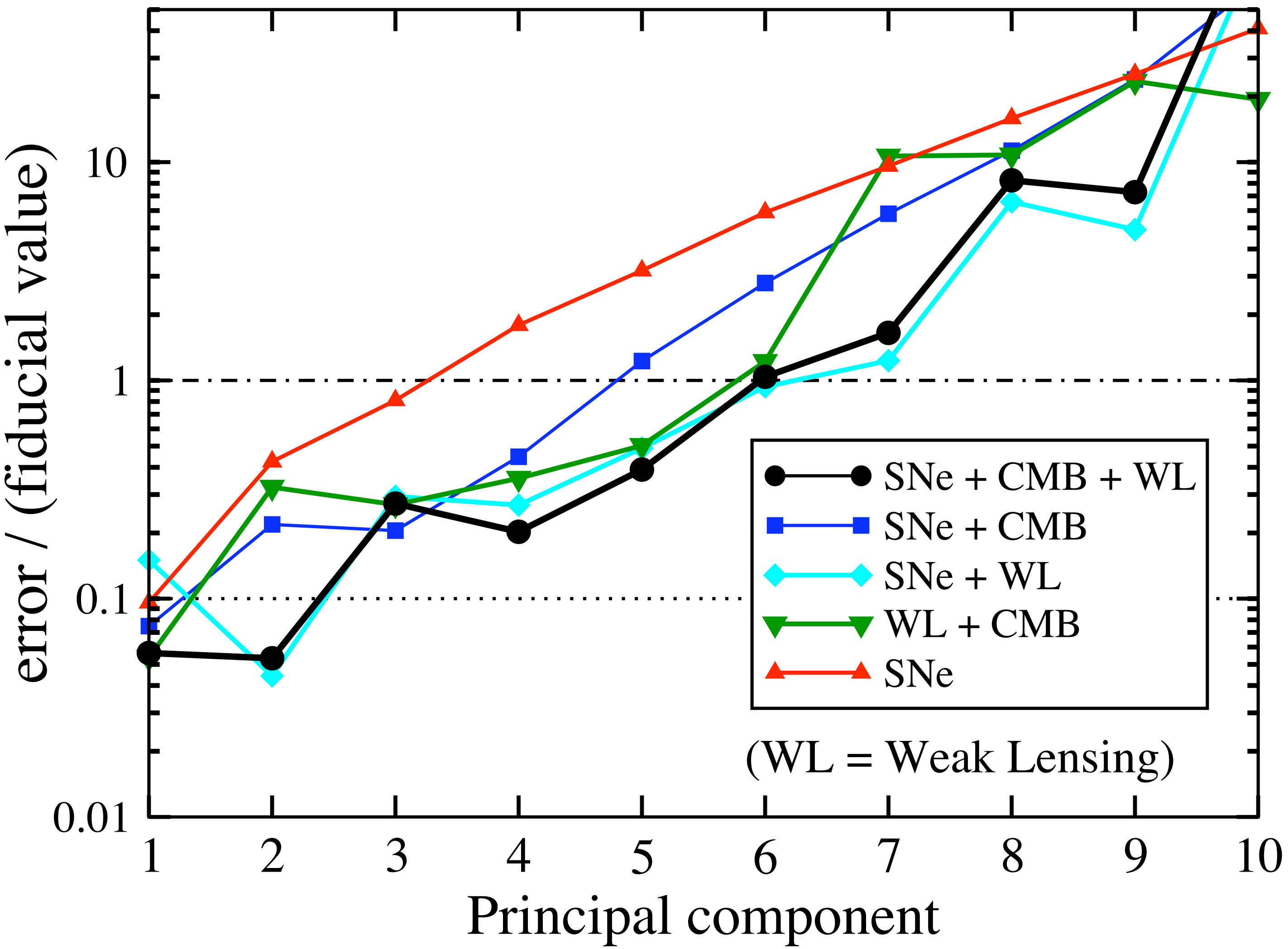
Uncorrelated by construction



- Shows where sensitivity of any given survey is greatest
- Used by various authors to study optimization of surveys
- Used to make model-(in)dependent statements about DE

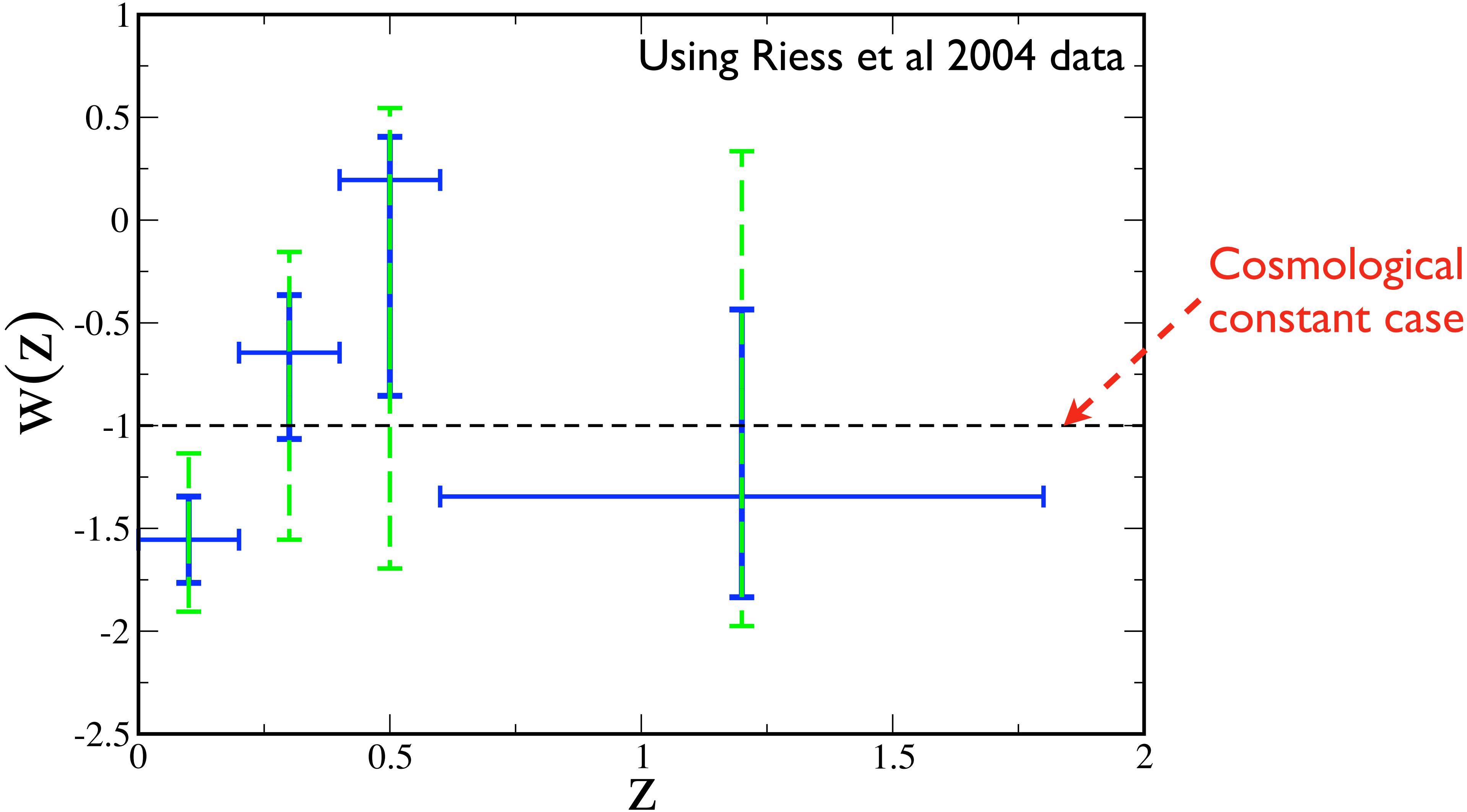
Huterer & Starkman 2003

Principal Components of $w(z)$



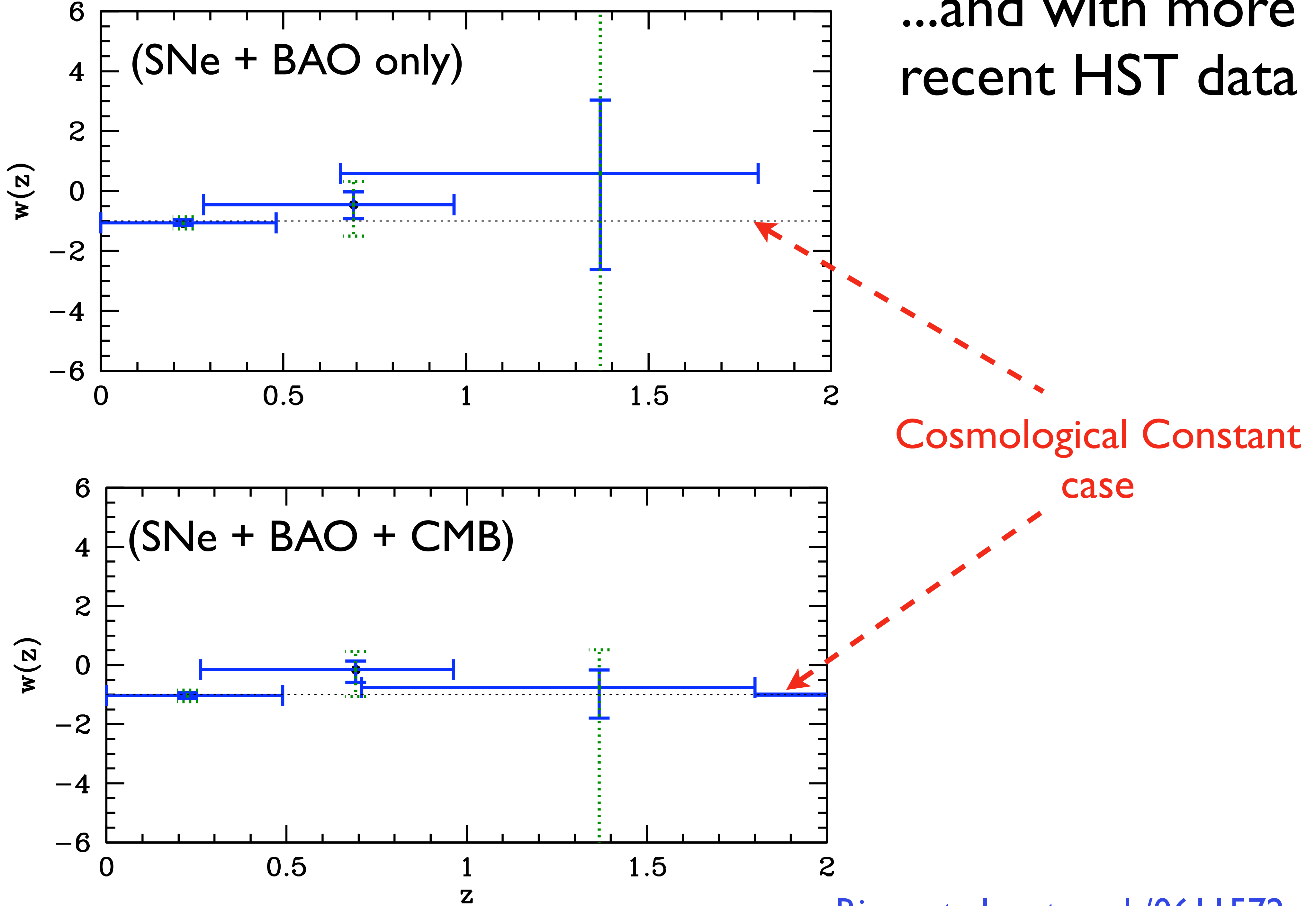
Linder & Huterer 2005

Uncorrelated measurements of Dark Energy evolution

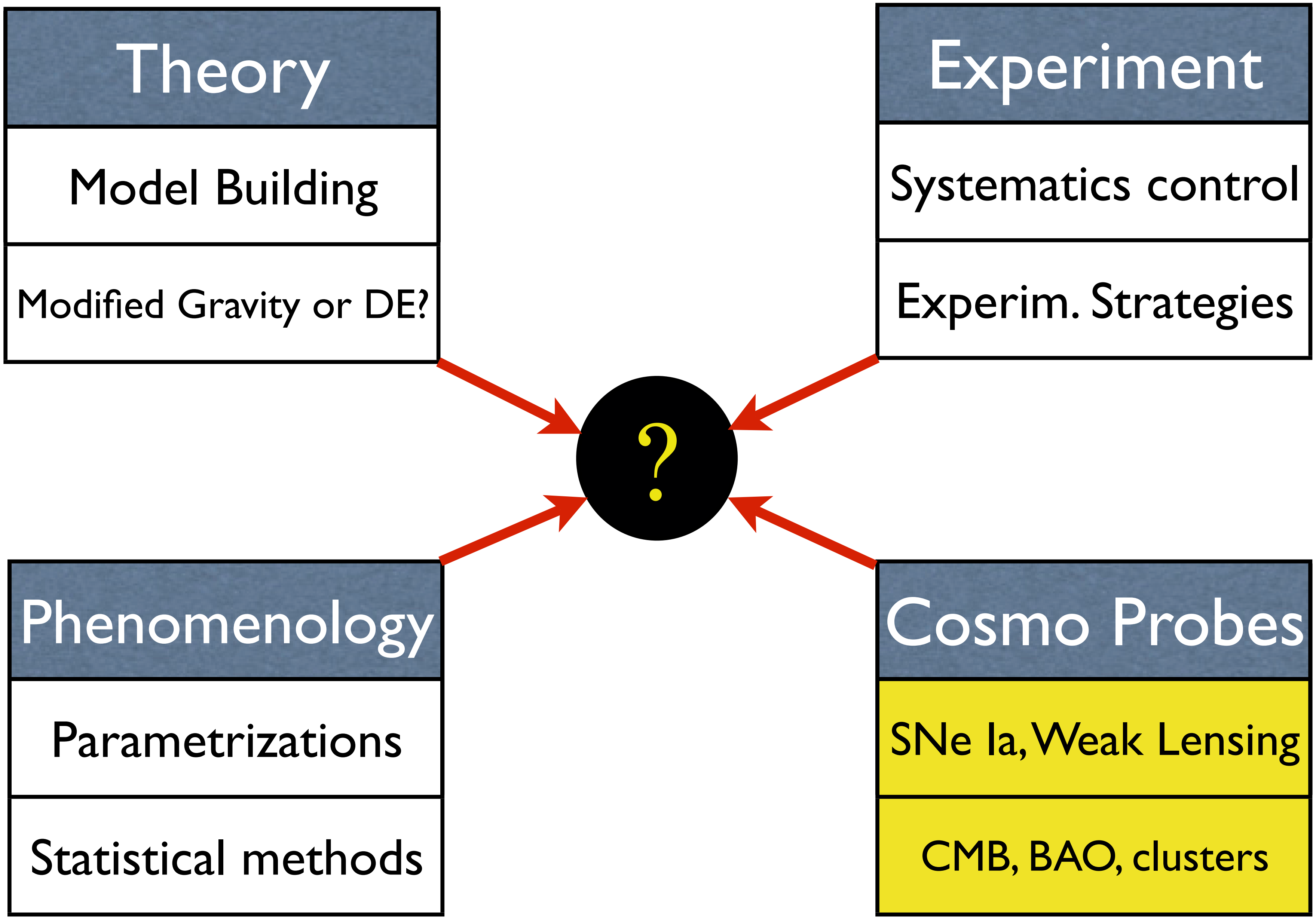


Huterer & Cooray 2005

...and with more recent HST data



Riess et al, astro-ph/0611572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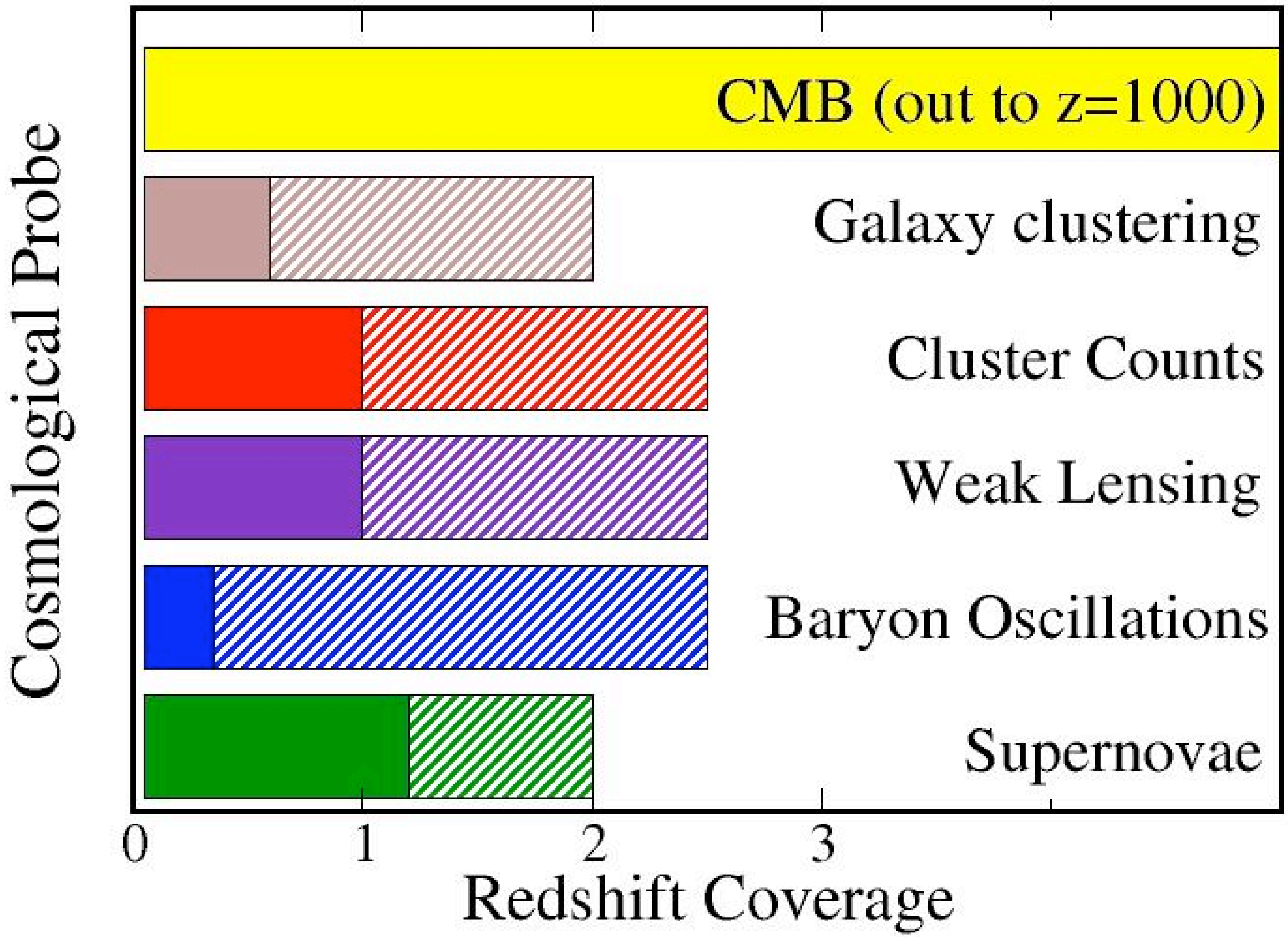
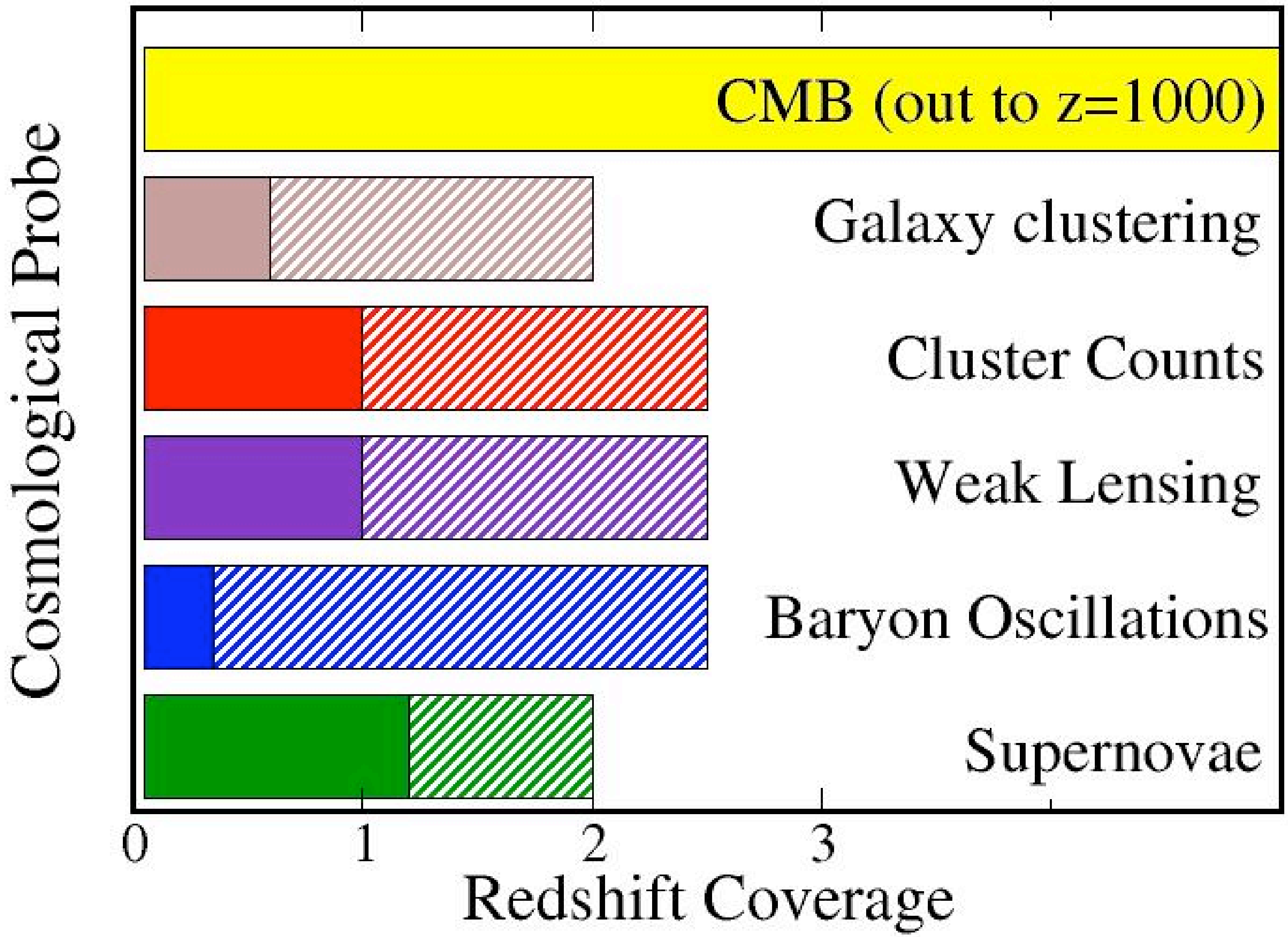
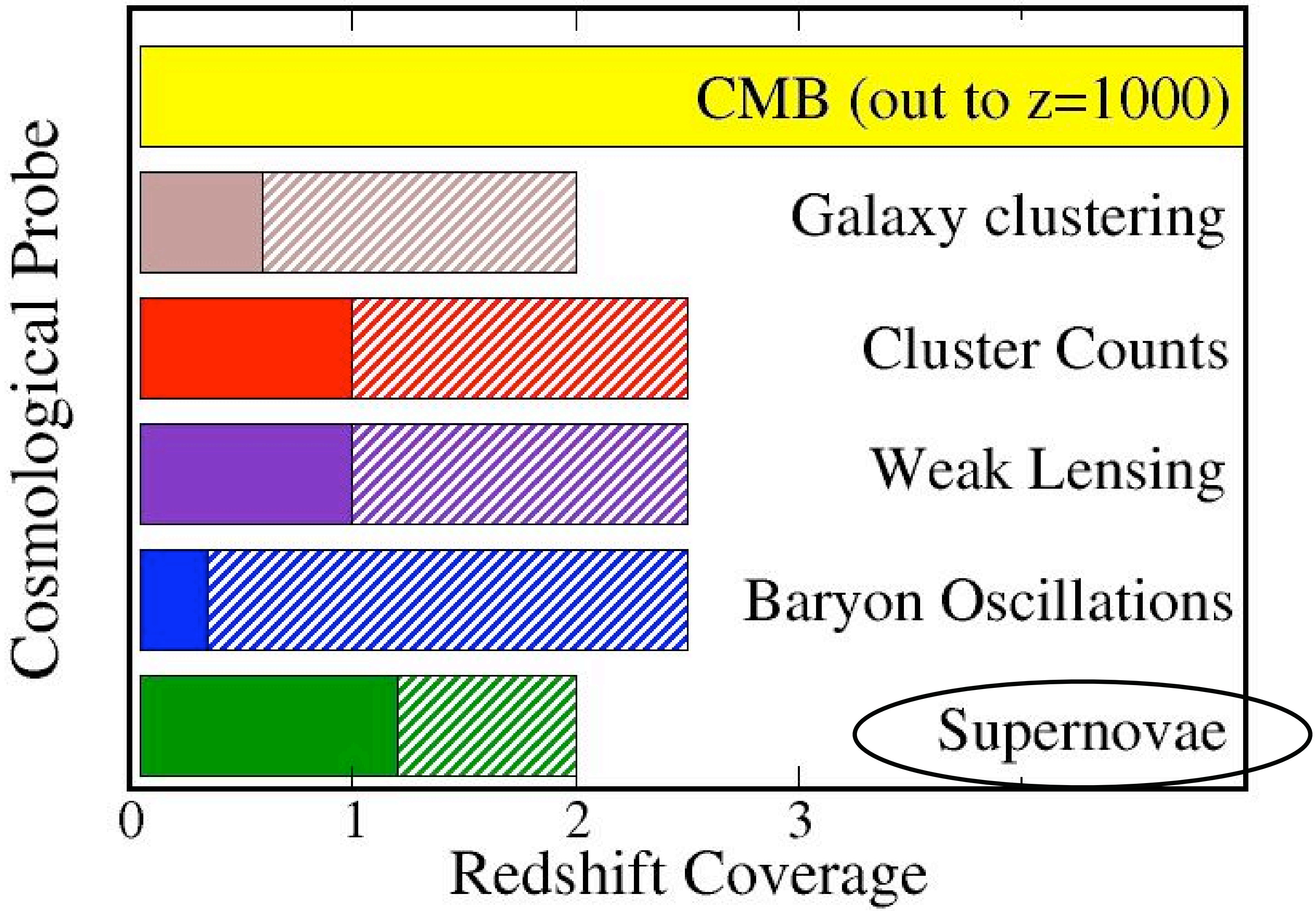

CMB (out to z=1000)
Galaxy clustering
Cluster Counts
Weak Lensing
Baryon Oscillations
Supernovae
Cosmological Probe
0
1
2
3
Redshift Coverage

Cosmological Probes of Dark Energy



Cosmological Probes of Dark Energy



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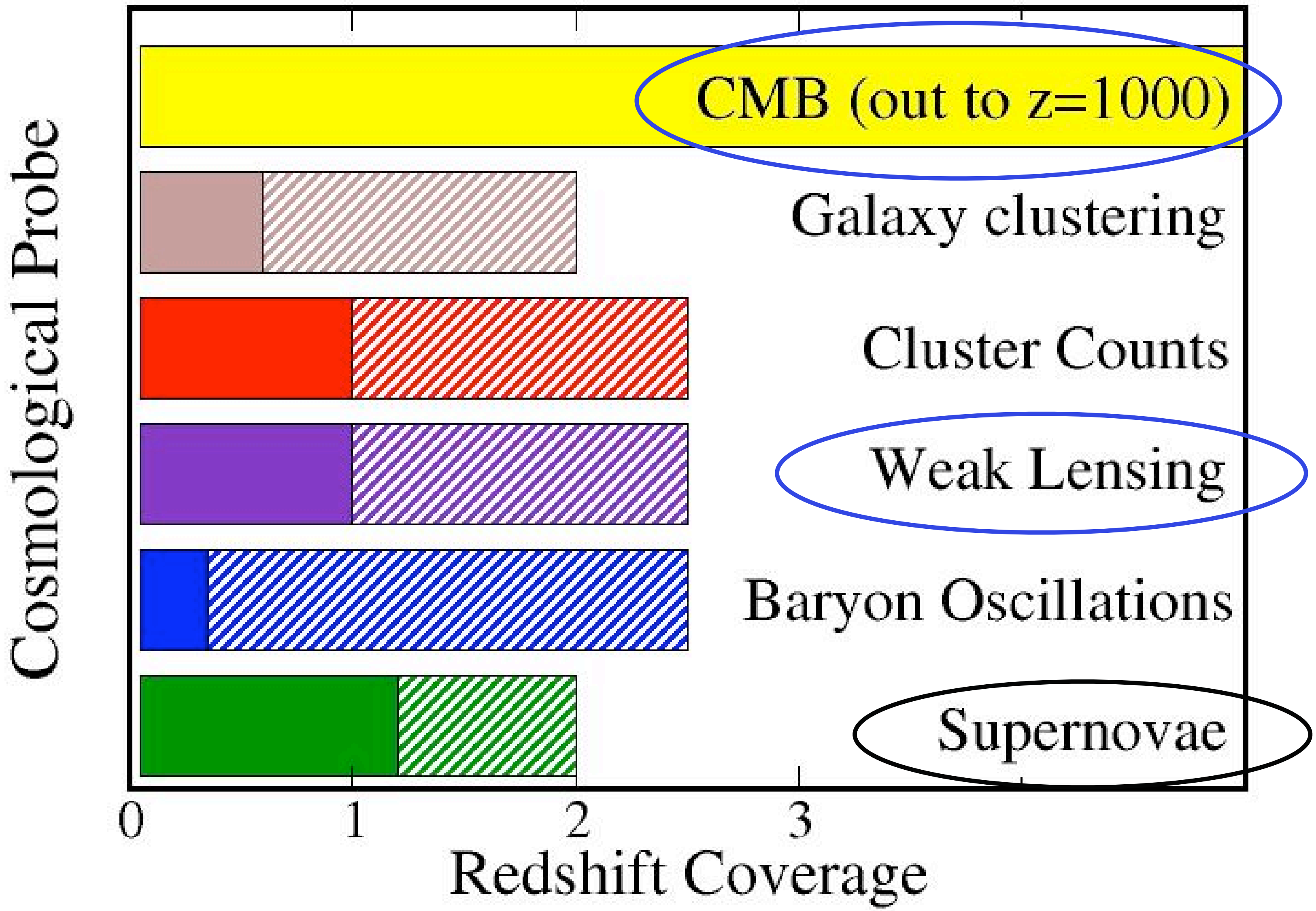
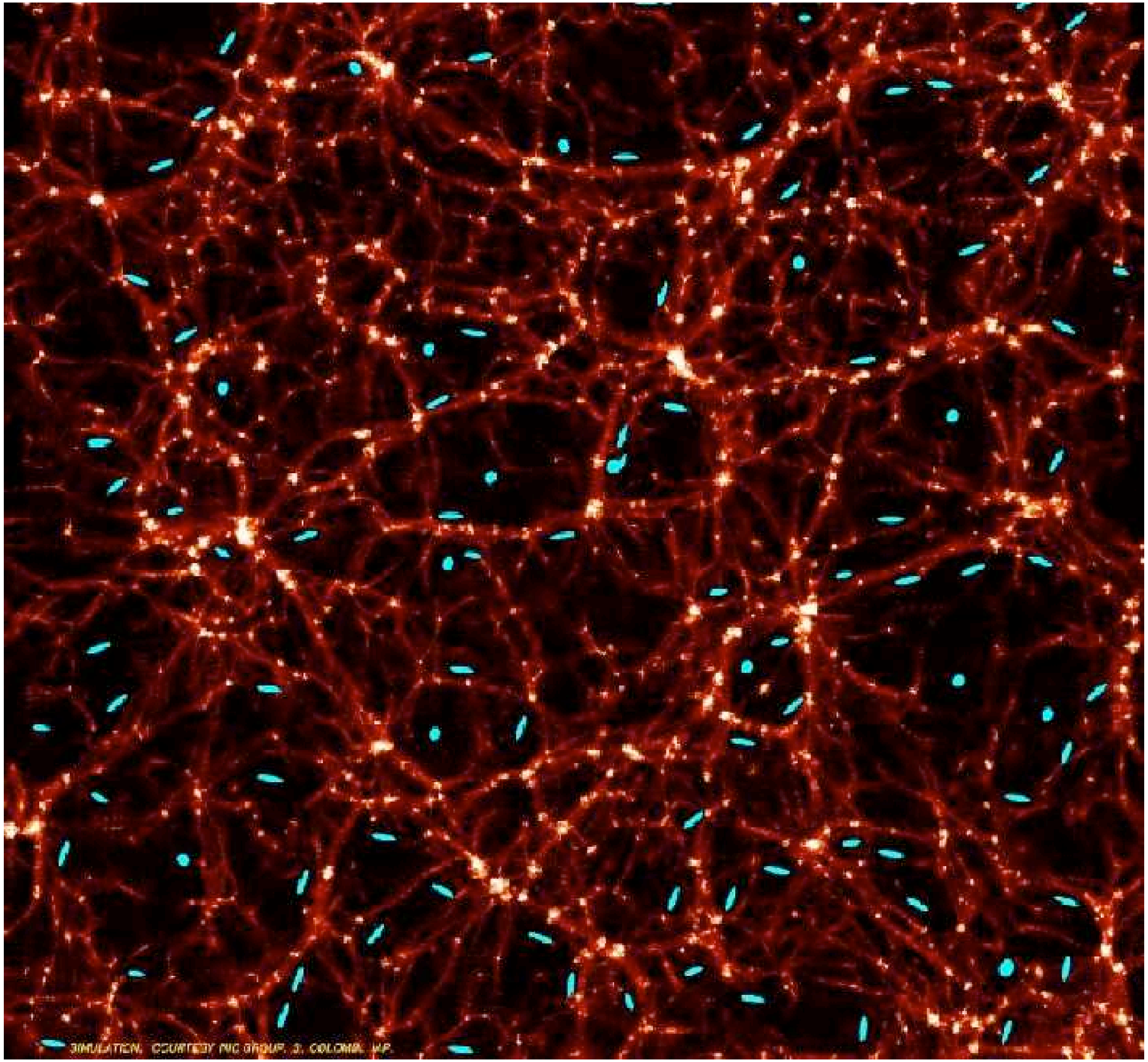


Weak Gravitational Lensing

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

Key advantage: measures distribution of matter, not light

Weak Gravitational Lensing



Credit: Colombi & Mellier

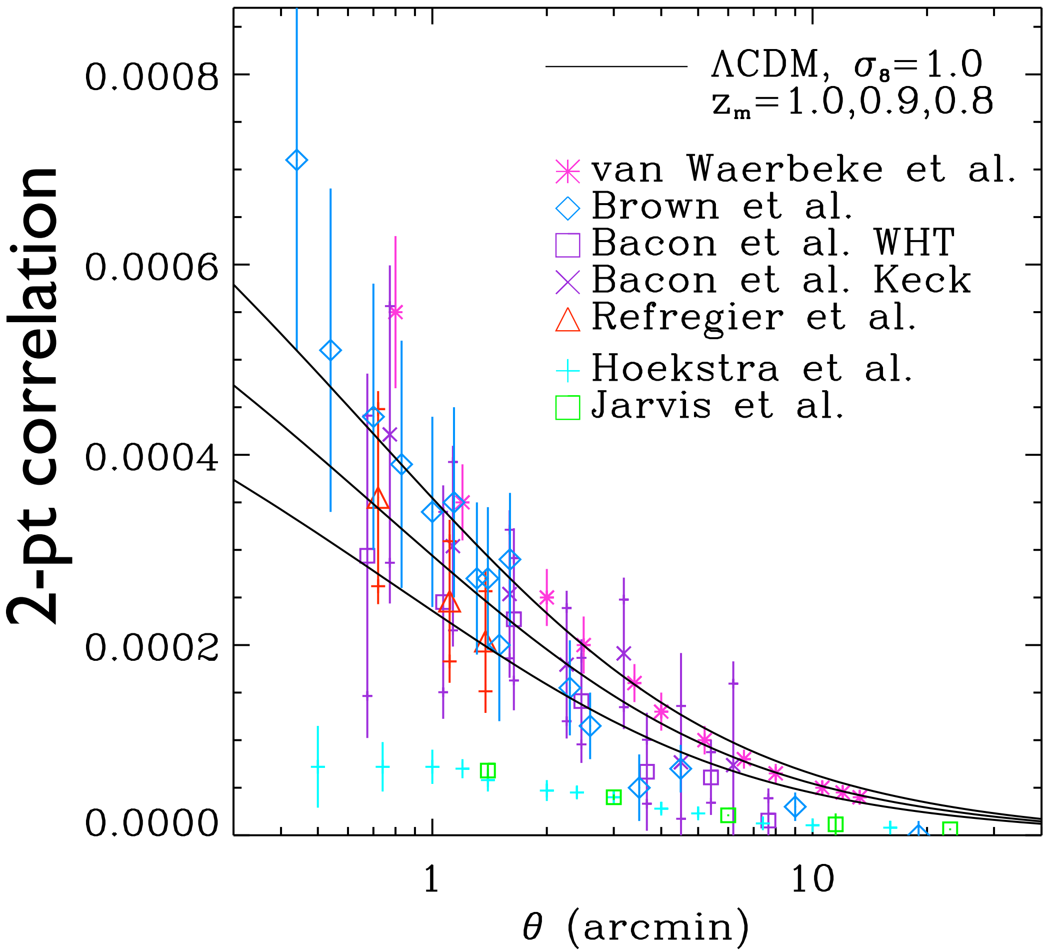
Weak Lensing and Dark Energy

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

distance, volume factors

(dark) matter clustering

- Probes integrated matter density
- Also sensitive to Dark Energy through distance, volume factors



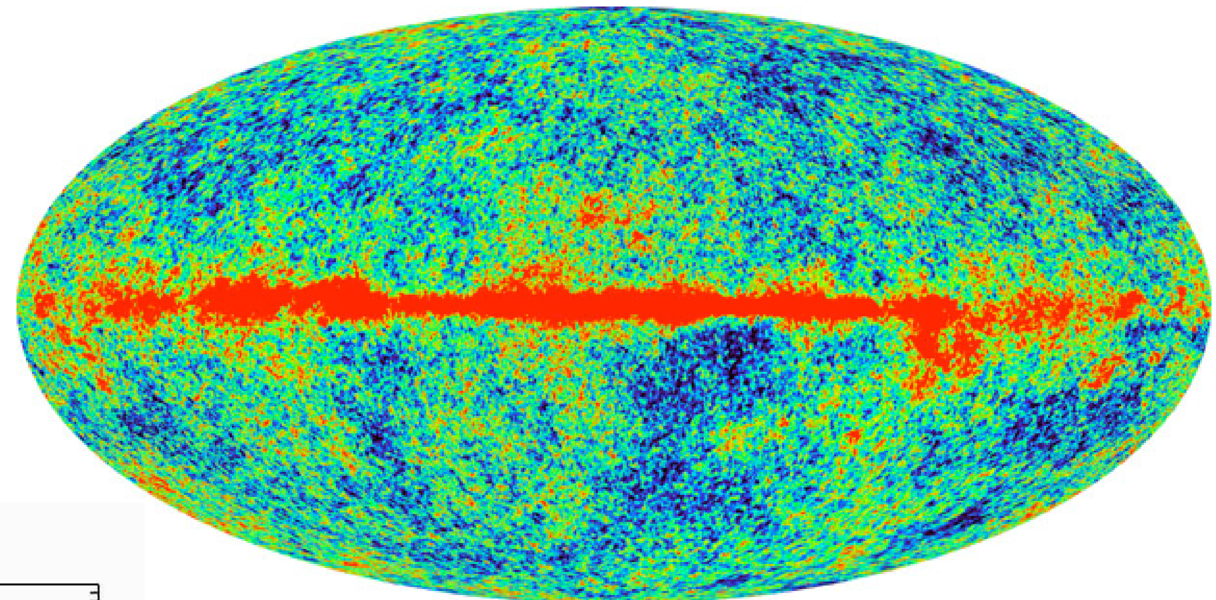
Refregier 2003

Hu & Tegmark 1999, Huterer 2002

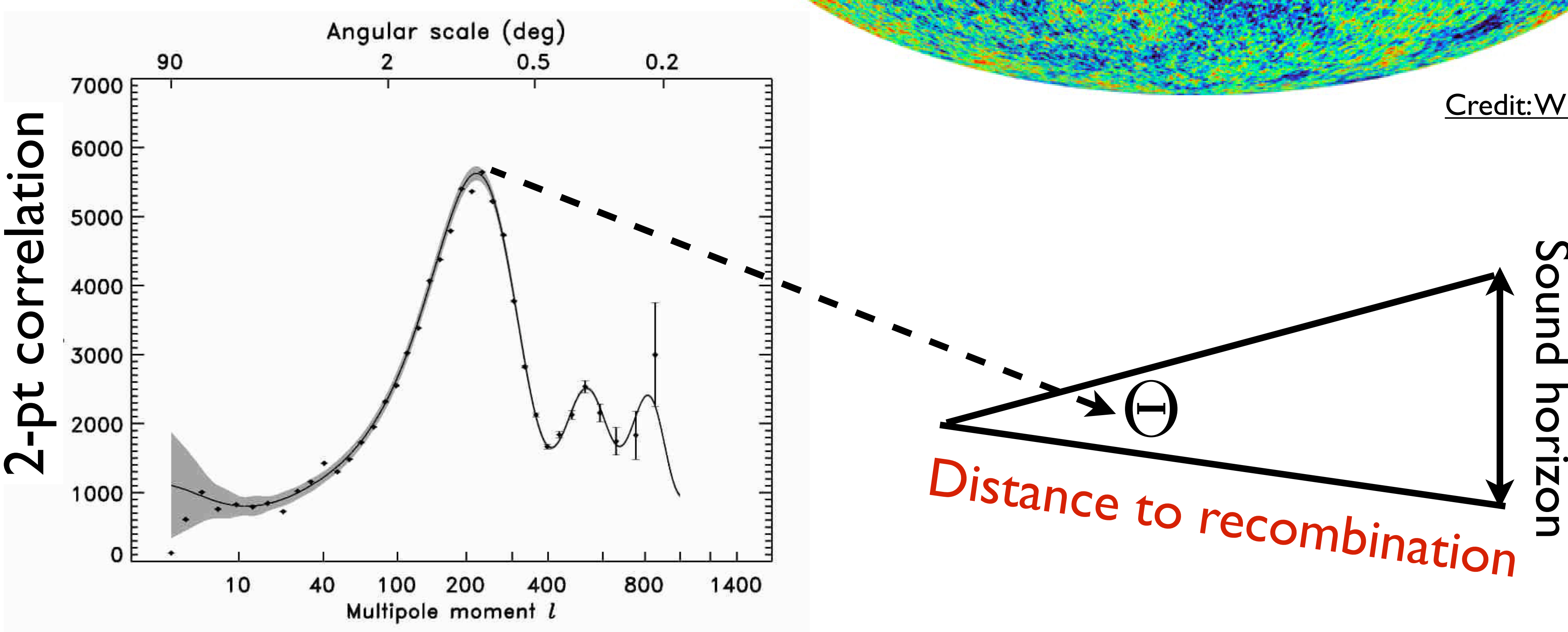
CMB and Dark Energy

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

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



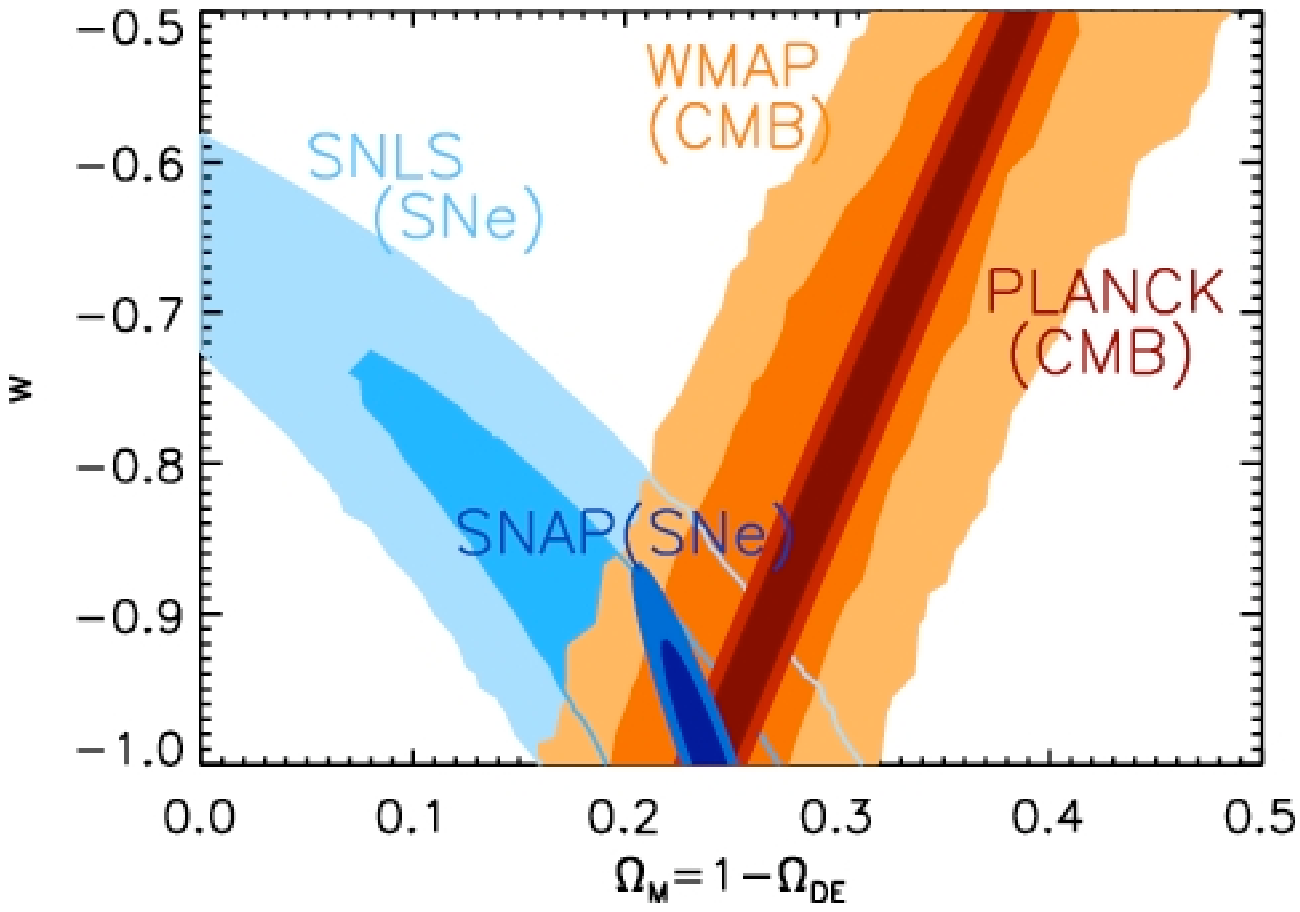
Credit: WMAP team



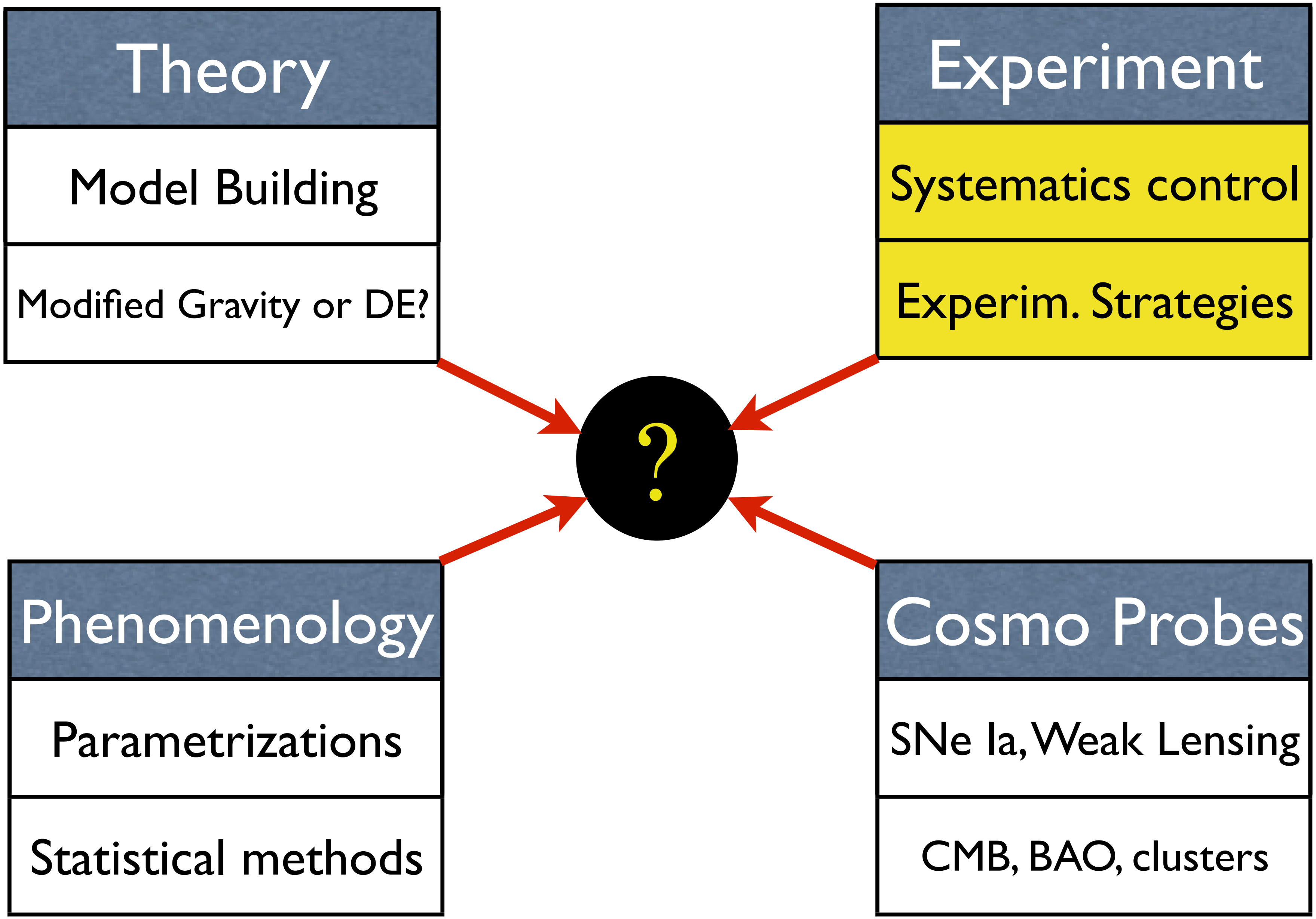
Bennett et al 2003 (WMAP collaboration)

CMB and Dark Energy

One linear combination of DE parameters is measured by the CMB



Hu 2001; Frieman, Huterer, Linder & Turner 2003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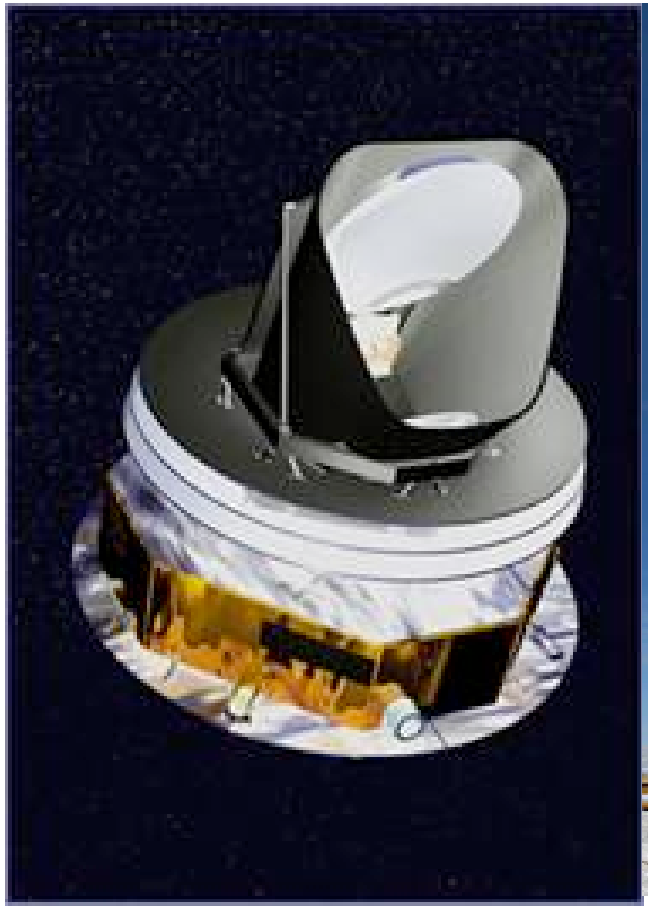
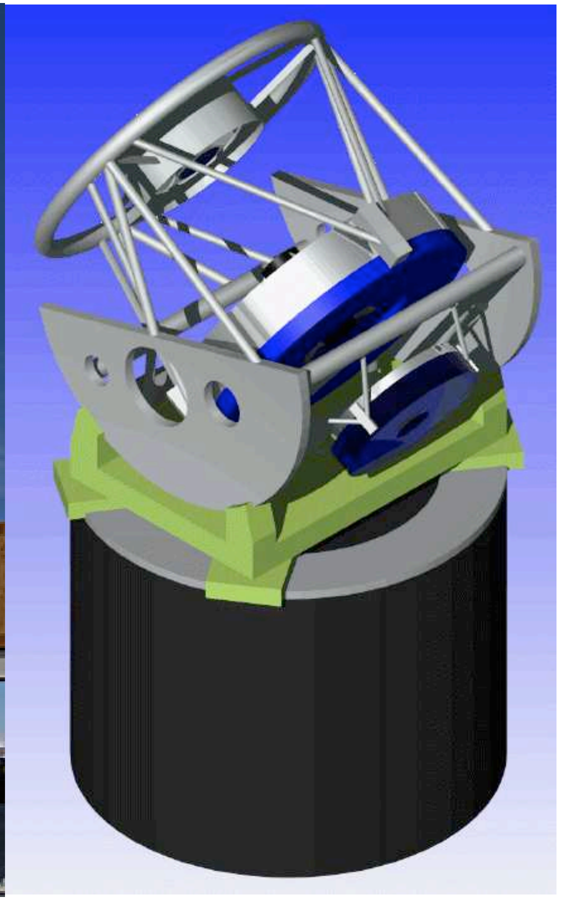
Upcoming Experiments

Planck



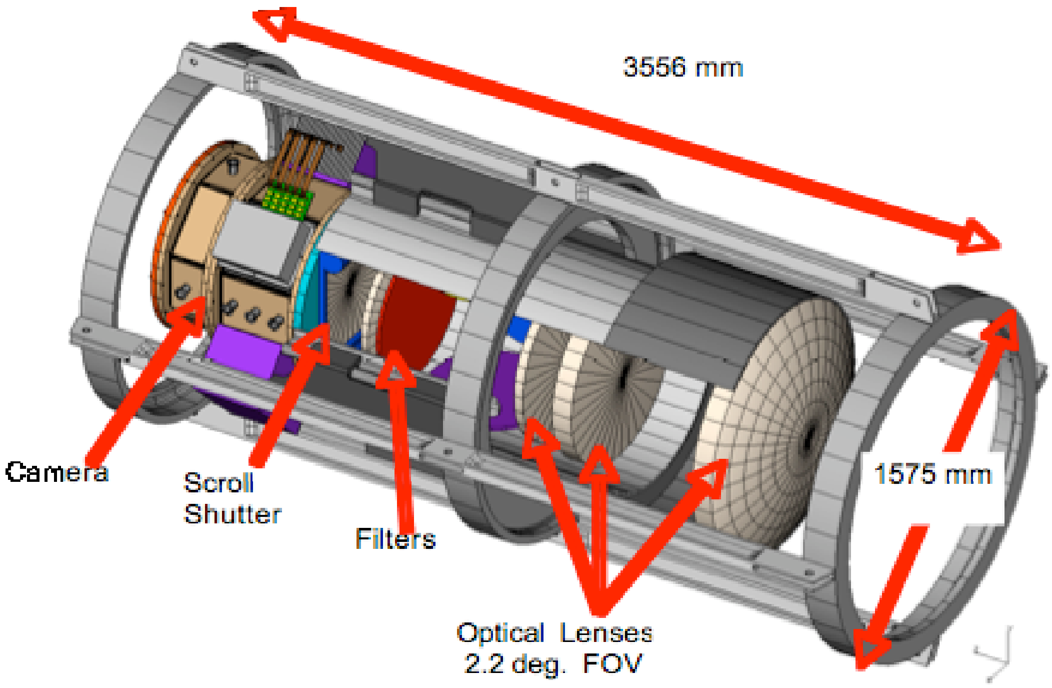
South Pole Telescope

LSST



Lots and lots of data coming our way

Dark Energy Survey



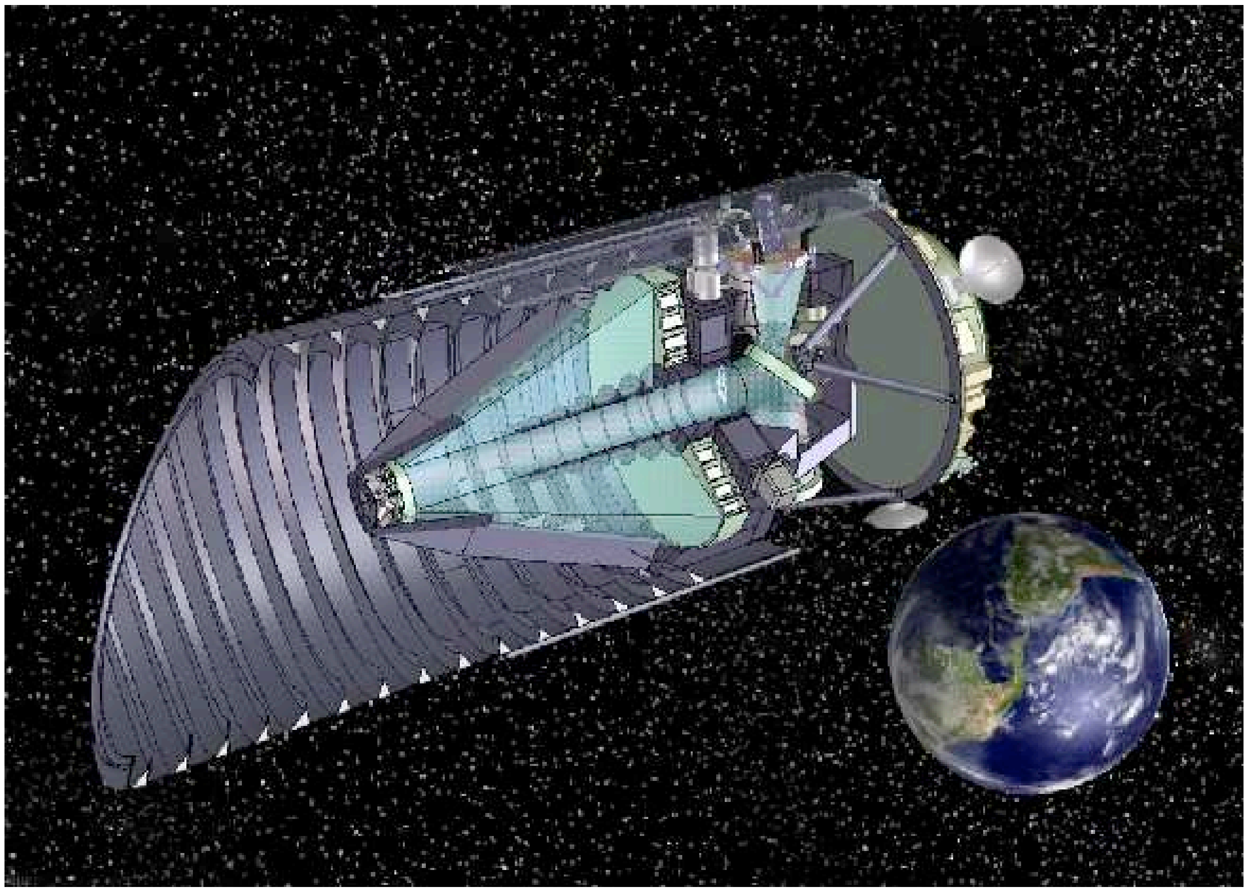
Blanco 4m telescope in Chile

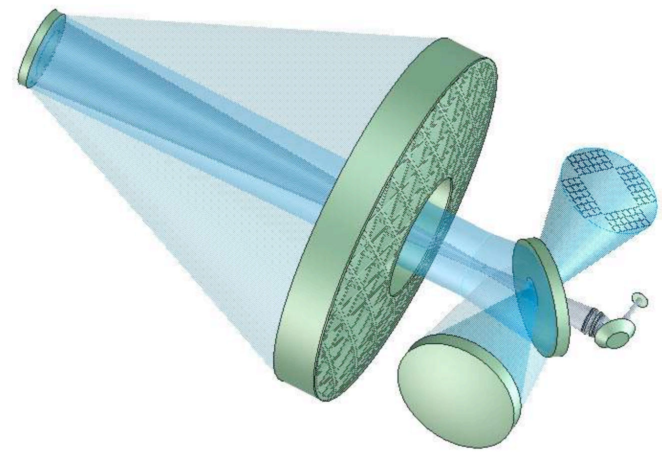
Four techniques to probe Dark Energy:

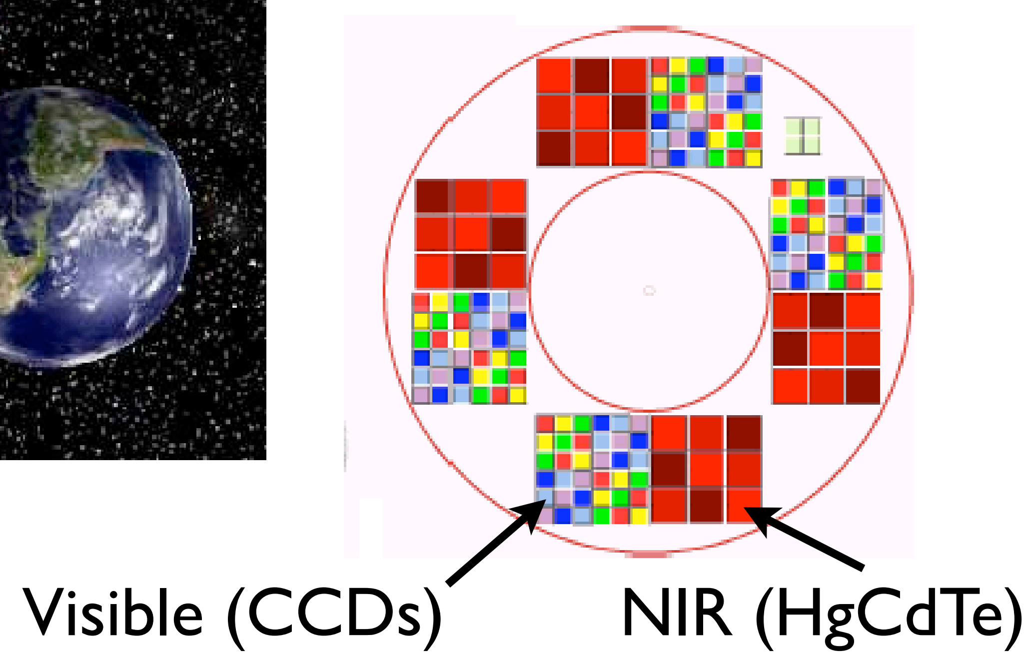
1. Number Counts of clusters
2. Weak Lensing
3. SNe Ia
4. Angular clustering of galaxies

SuperNova/Acceleration Probe

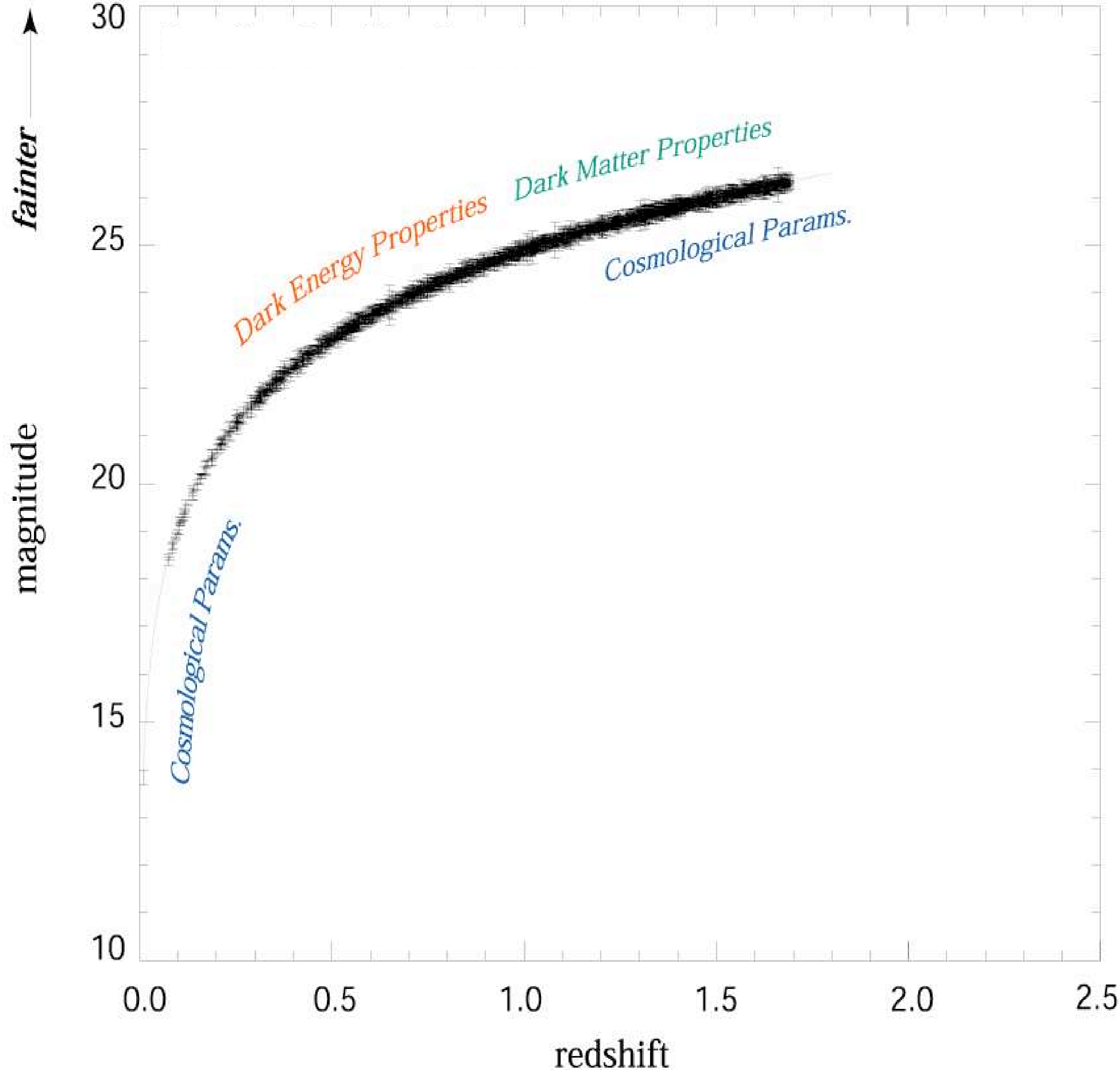
~2500 SNe at $0.1<z<1.7$





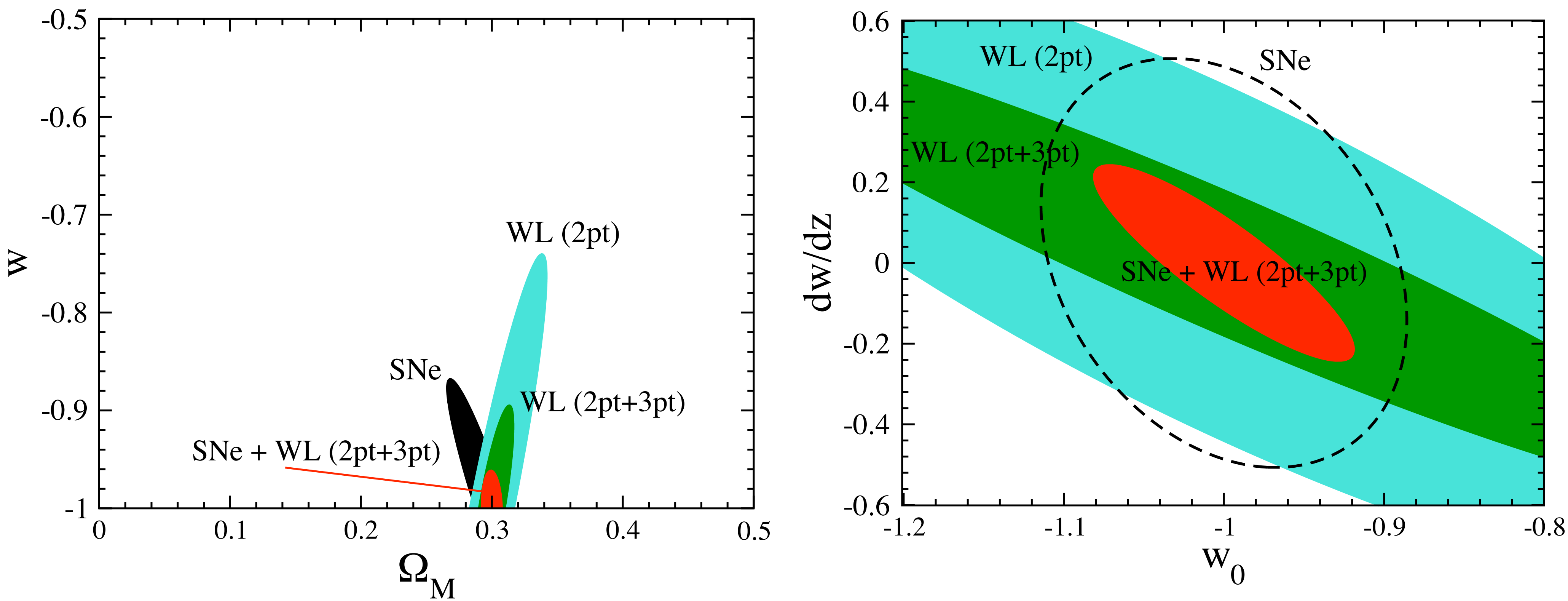


~2500 SNe Ia



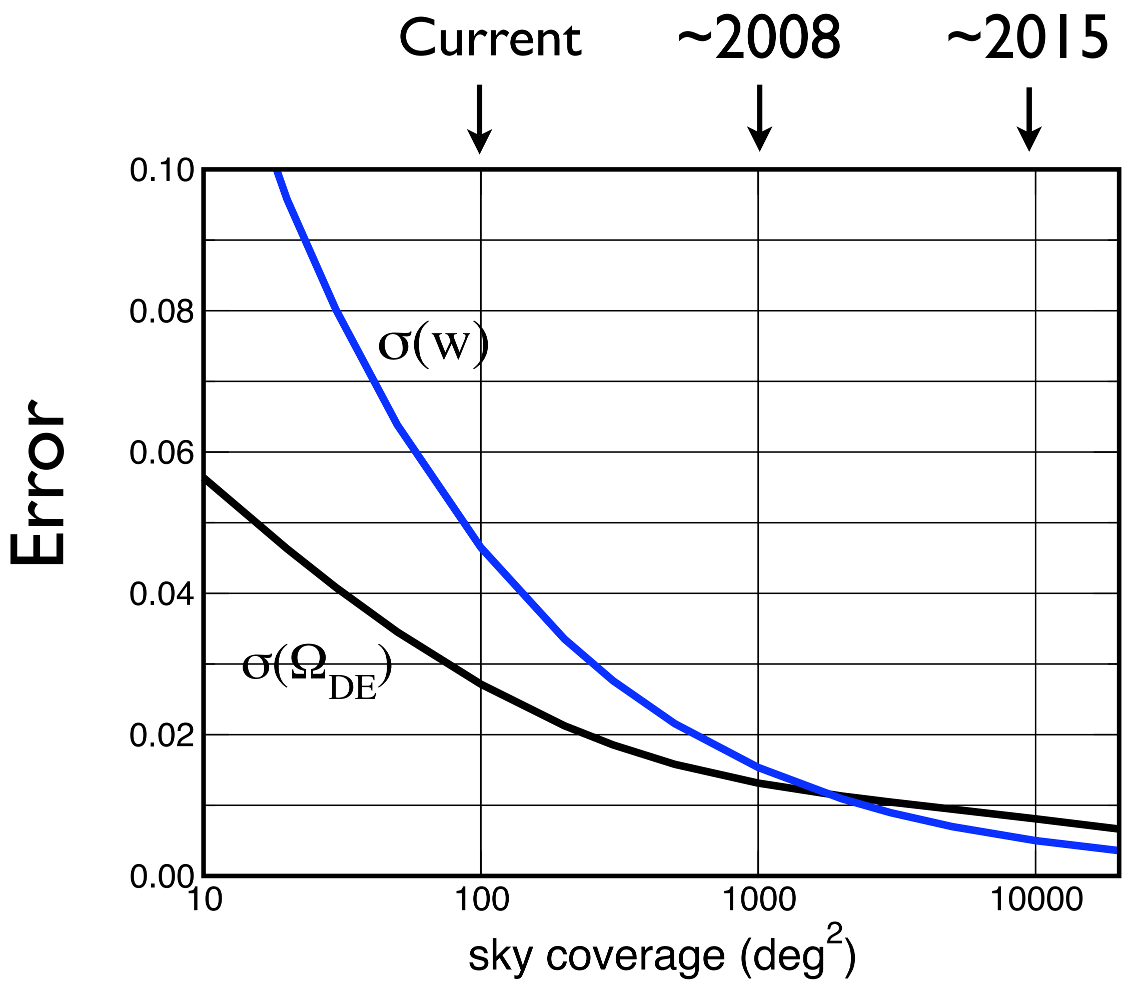
fainter
magnitude
30
25
20
15
10
0.0
0.5
1.0
1.5
2.0
2.5
redshift
Dark Energy Properties
Dark Matter Properties
Cosmological Params.
Cosmological Params.

SNAP expected constraints



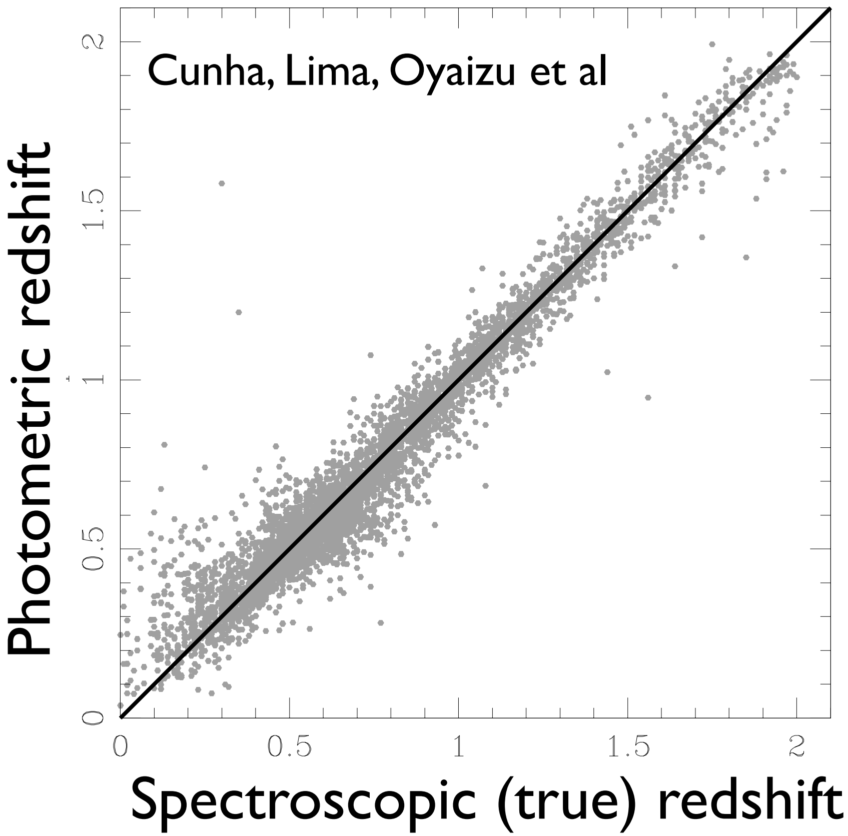
1. Unprecedented SNa Ia dataset
2. Weak Lensing (2pt, 3pt function; cosmography)
3. Huge amount of other science
   (cluster counts, galaxy clustering, galaxy evolution,
   strong lensing, type II supernovae, GRBs, ...)

Upcoming dark energy probes: systematics control is key weak lensing example

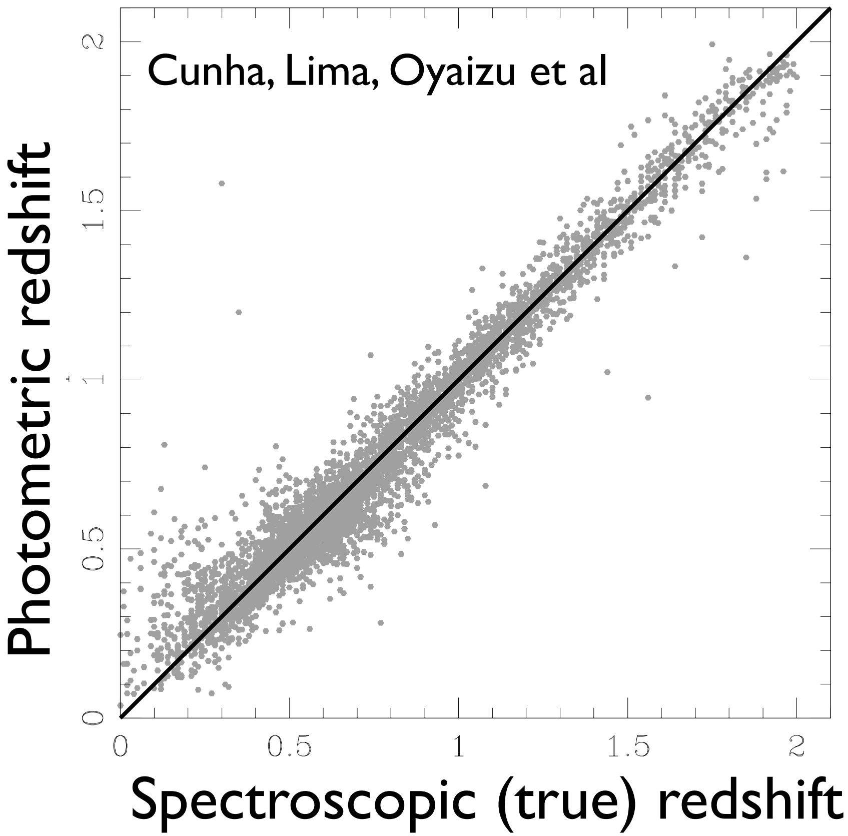


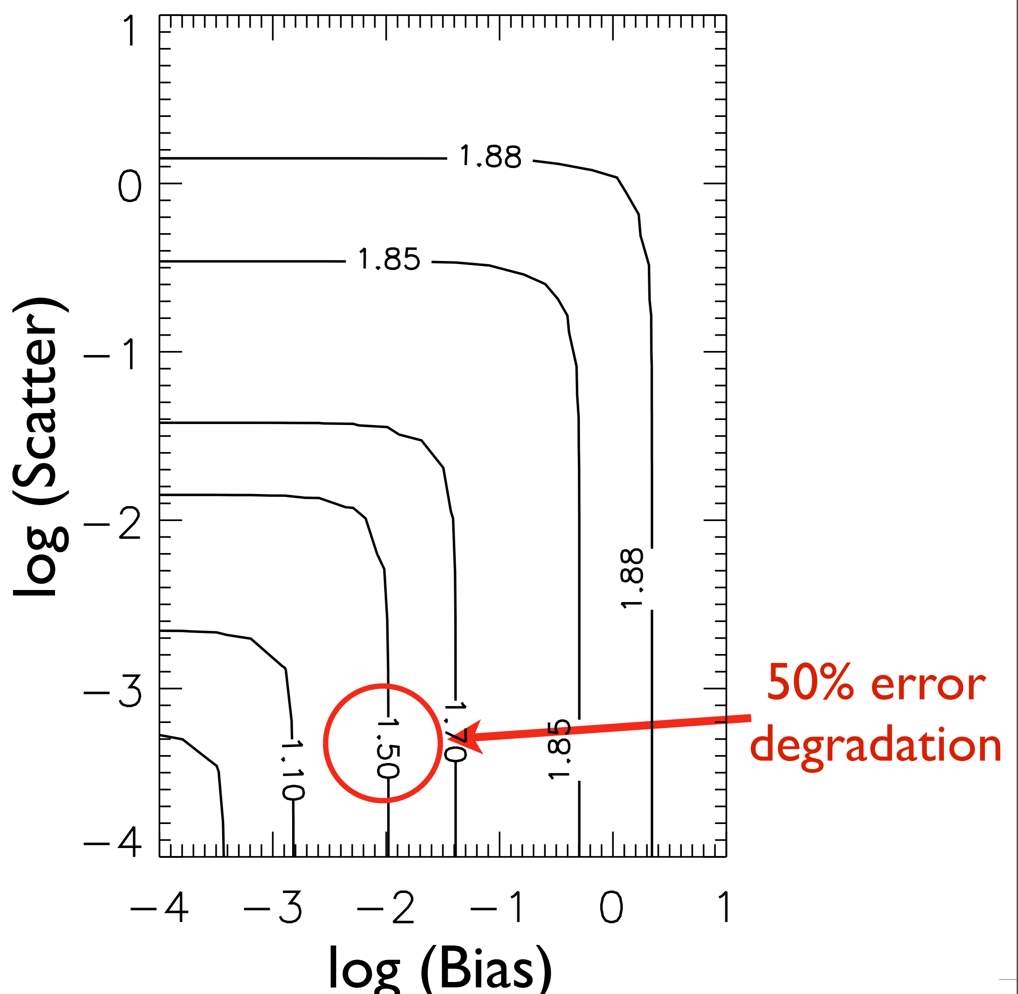
- More powerful experiments need more stringent control of systematics
- Systematics requirements directly affect the experiment design and strategy

Weak Lensing Experimental Systematics: redshift errors



Weak Lensing Experimental Systematics: redshift errors

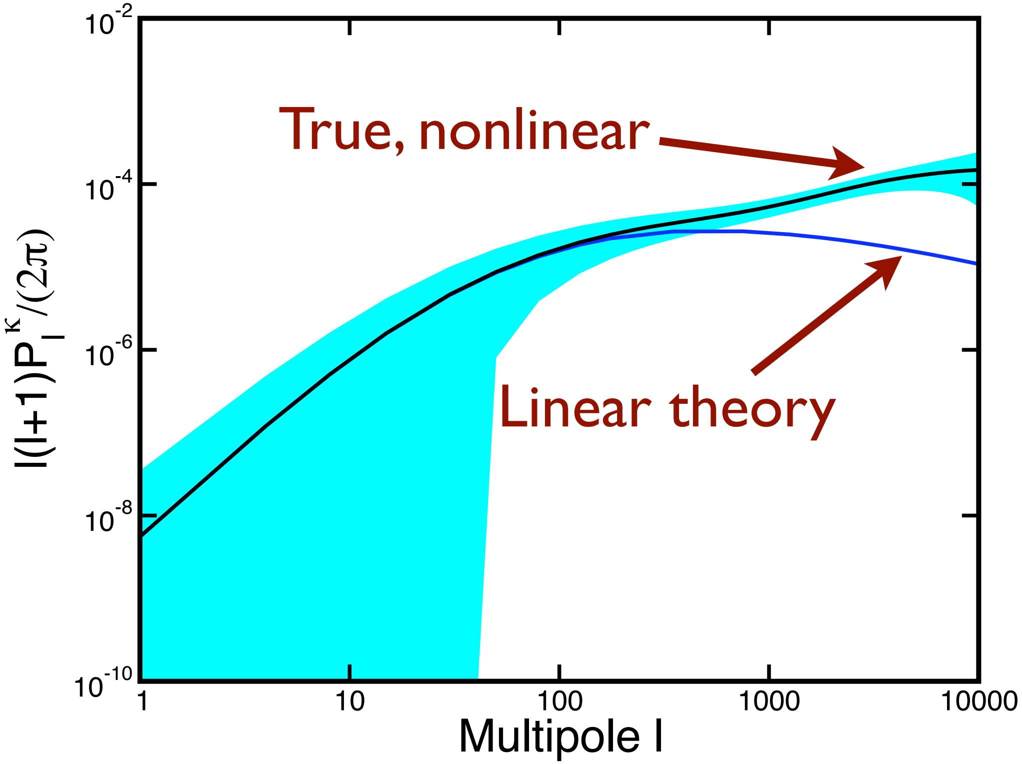




Results directly affect telescope design (e.g. # of filters)

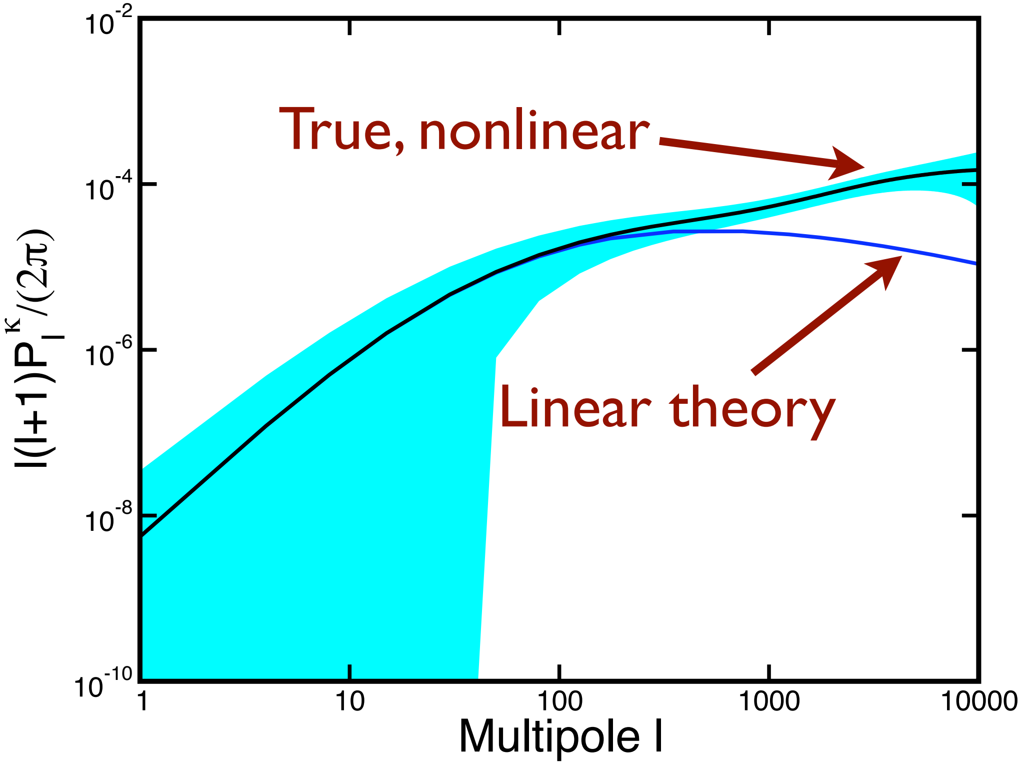
Ma, Hu & Huterer 2006; Huterer, Takada, Bernstein & Jain 2005

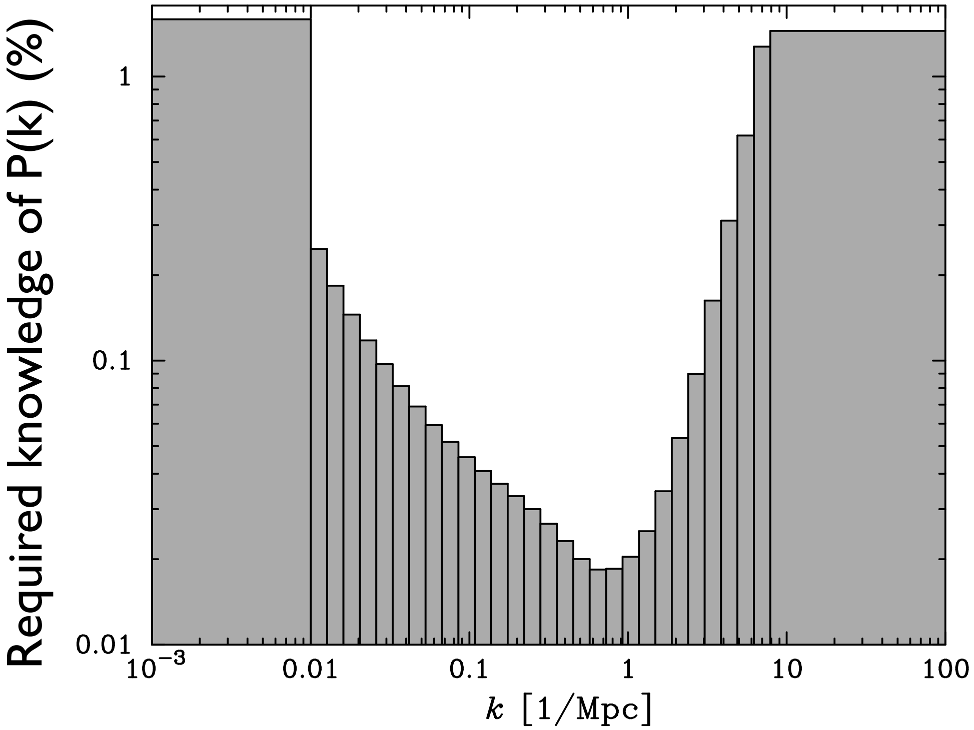
Weak Lensing
Theory Systematics

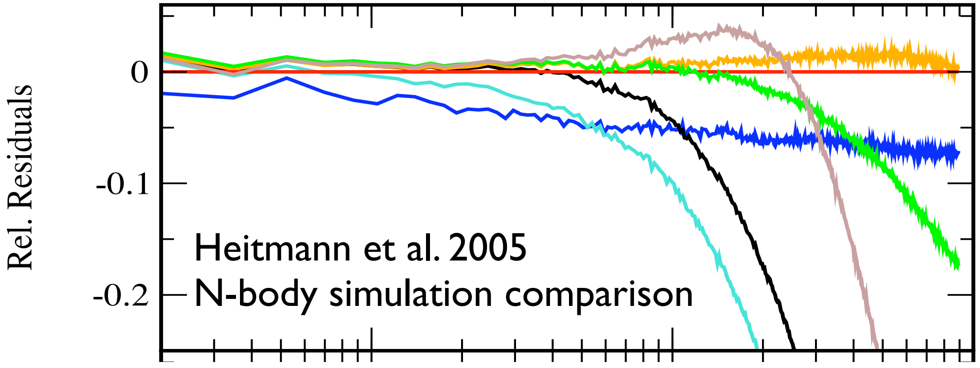


Huterer & Takada 2005,
Huterer & White 2005

Weak Lensing
Theory Systematics







Sets quantitative goals for
accuracy of simulations

Huterer & Takada 2005,
Huterer & White 2005

The glorious future

Say the systematics are taken care of,
the future is now,
and we have access to data from surveys

What else do we need to have at hand?

- Reliable predictions for classes of models and how to distinguish them
- Understanding how to separate DE from modified gravity
- Alternative, complementary probes of DE
- Sophisticated statistical methods for data mining

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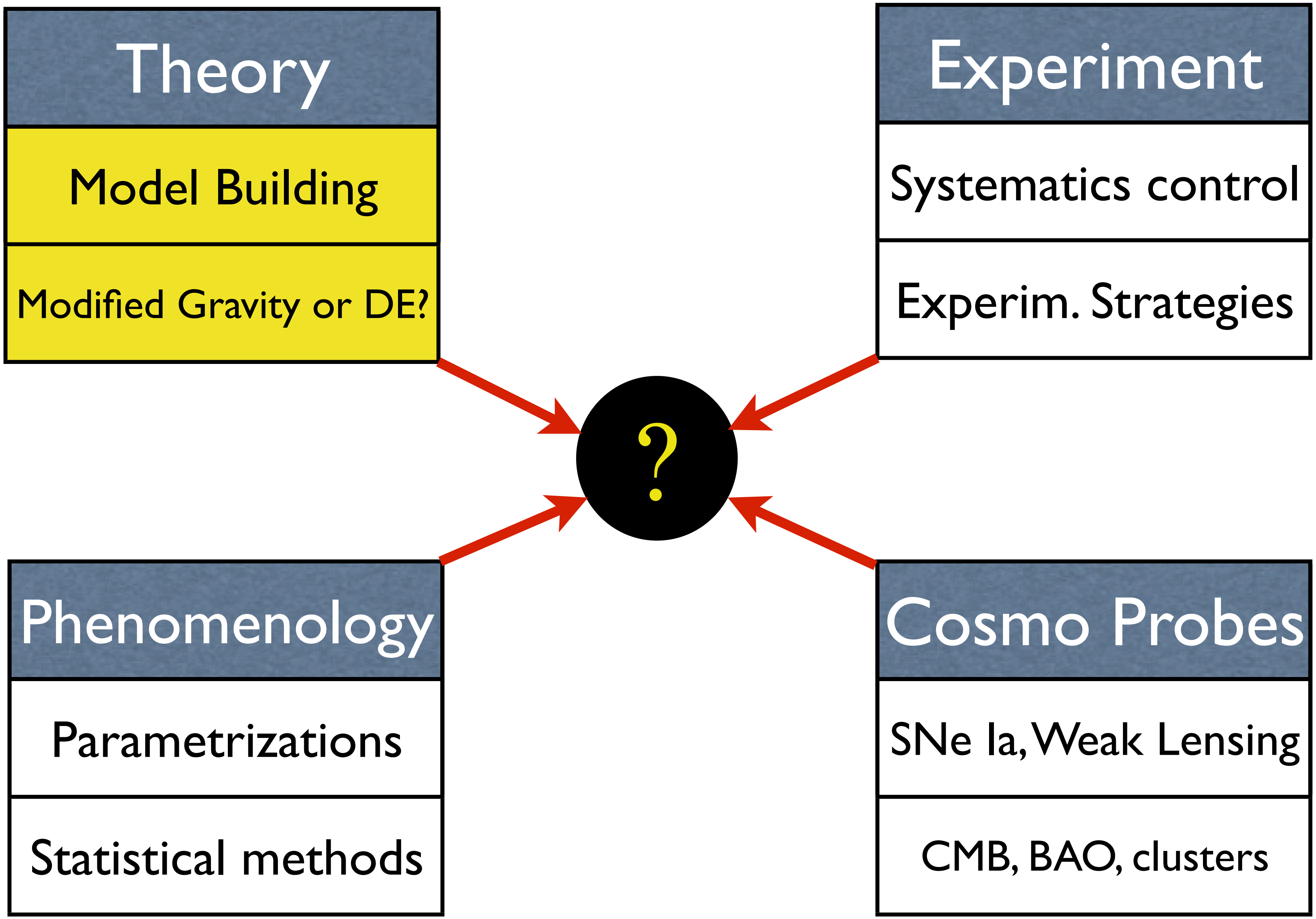
Theory
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Modified Gravity or DE?
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Experim. Strategies
?
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Cosmological implications of a dark energy model scan

Idea: test cosmological implications by considering all DE models within a given (large) class

- What constraints are obtained on w(z), rho(z) within this class? On w_0 and w_a?
- Does the class of models itself significantly limit the range of DE histories?
- Is it worth spending $$$ for future experiments, or have "all reasonable non-Lambda models already been ruled out"?

D. Huterer & H. Peiris, astro-ph/0610427

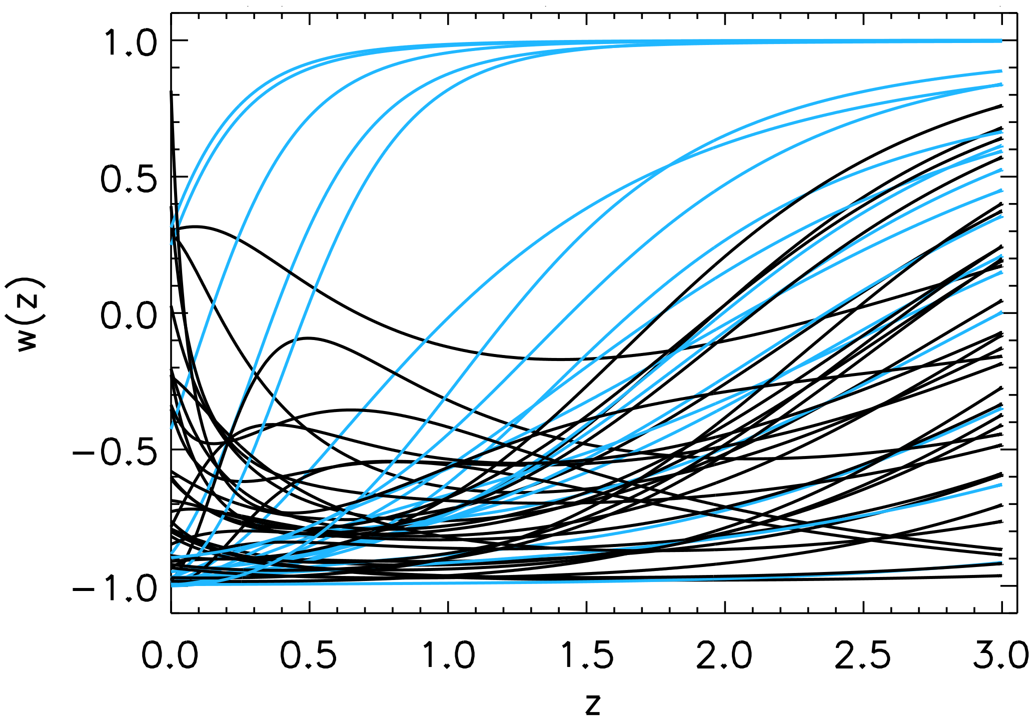
Scan through quintessence models

Adopting to DE the flow-equation formalism from inflation:

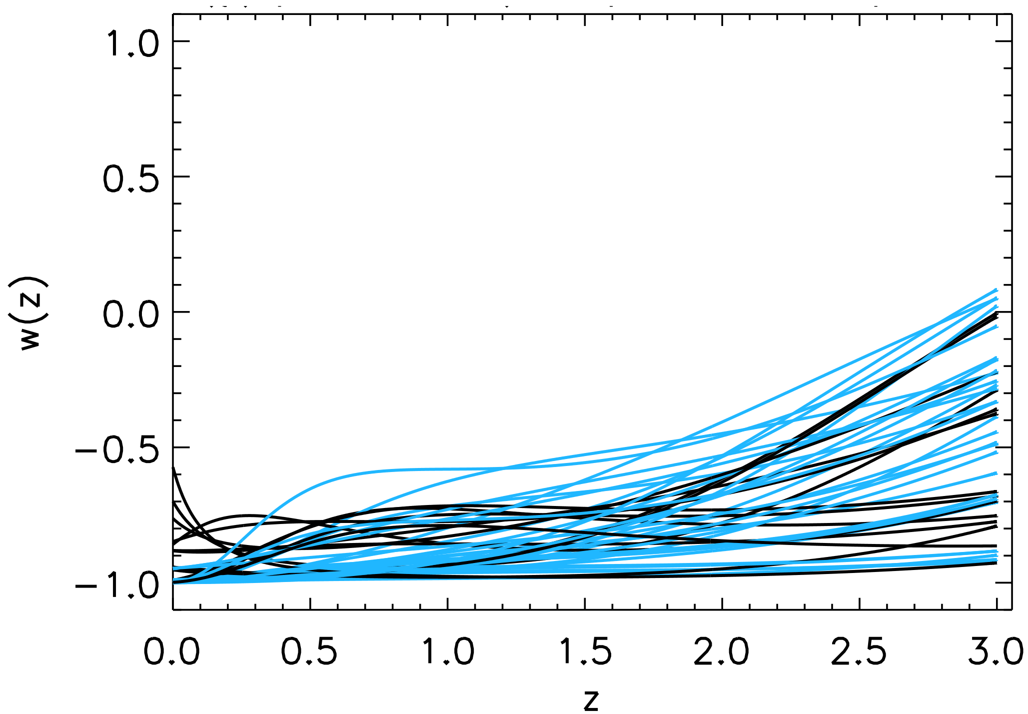
Scan all (sample millions) of models, and ICs, within a general paradigm - e.g. quintessence with polynomial potentials

$$w(z) = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

sample DE models in prior



sample DE models in posterior



Huterer & Peiris, astro-ph/0610427

DE Monte Carlo algorithm

- Set the class of models you are considering
- Generate models using a wide range of ICs
- For each model, compute the dark energy history w(z) and any other observables
- Compute the likelihood of the model from data
- Repeat

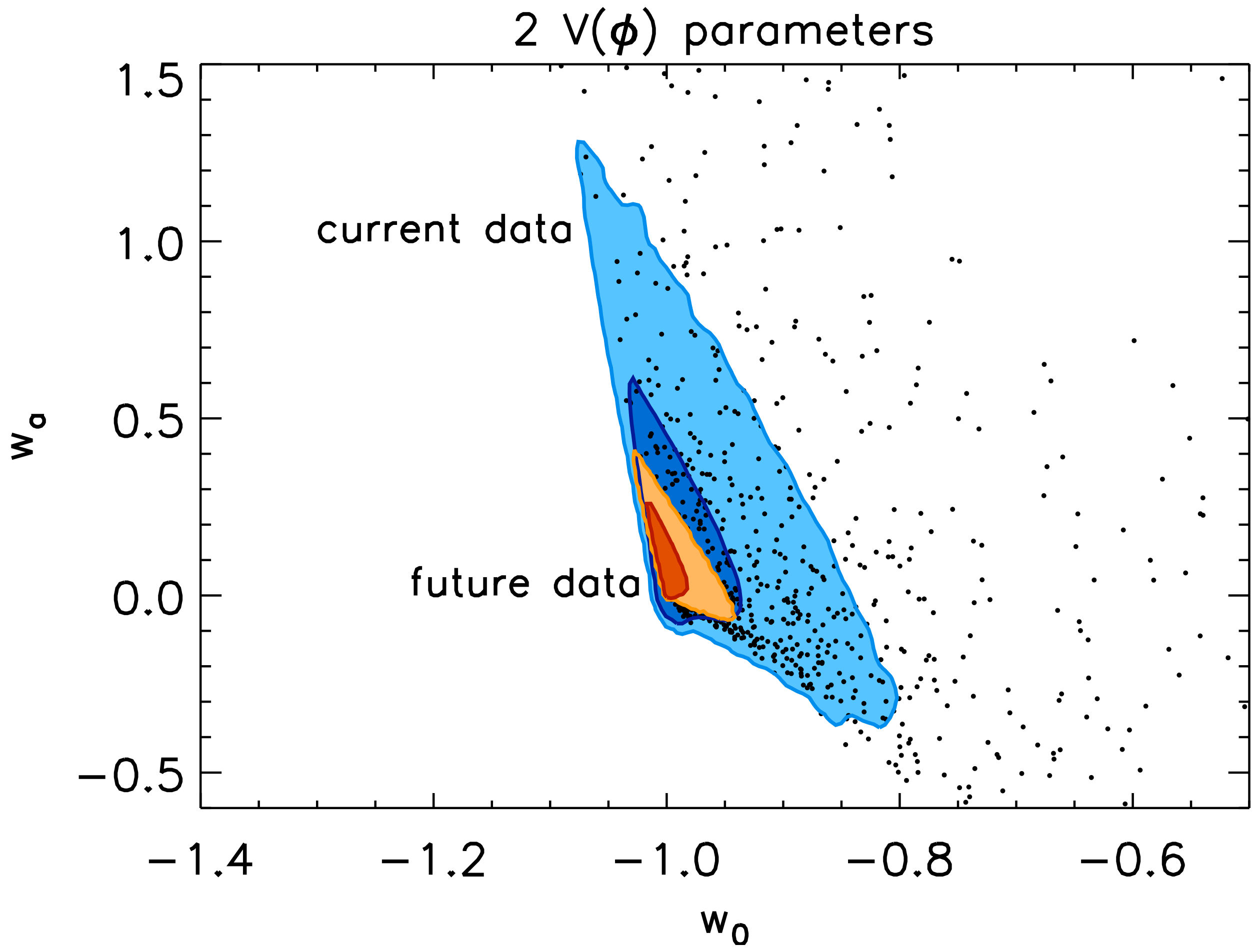
Initial conditions prior:

$$
\begin{aligned}
\Omega_{\rm DE}^{\rm start} &\in [0, 1] \\
w^{\rm start} &\in [-1, 1] \\
\epsilon^{\rm start} &\in [0, \infty] \\
\eta^{\rm start} &\in [-\infty, \infty]
\end{aligned}
$$

+ other cosmo parameters
(+ higher slow roll parameters)

Huterer & Peiris, astro-ph/0610427

Scan through quintessence models

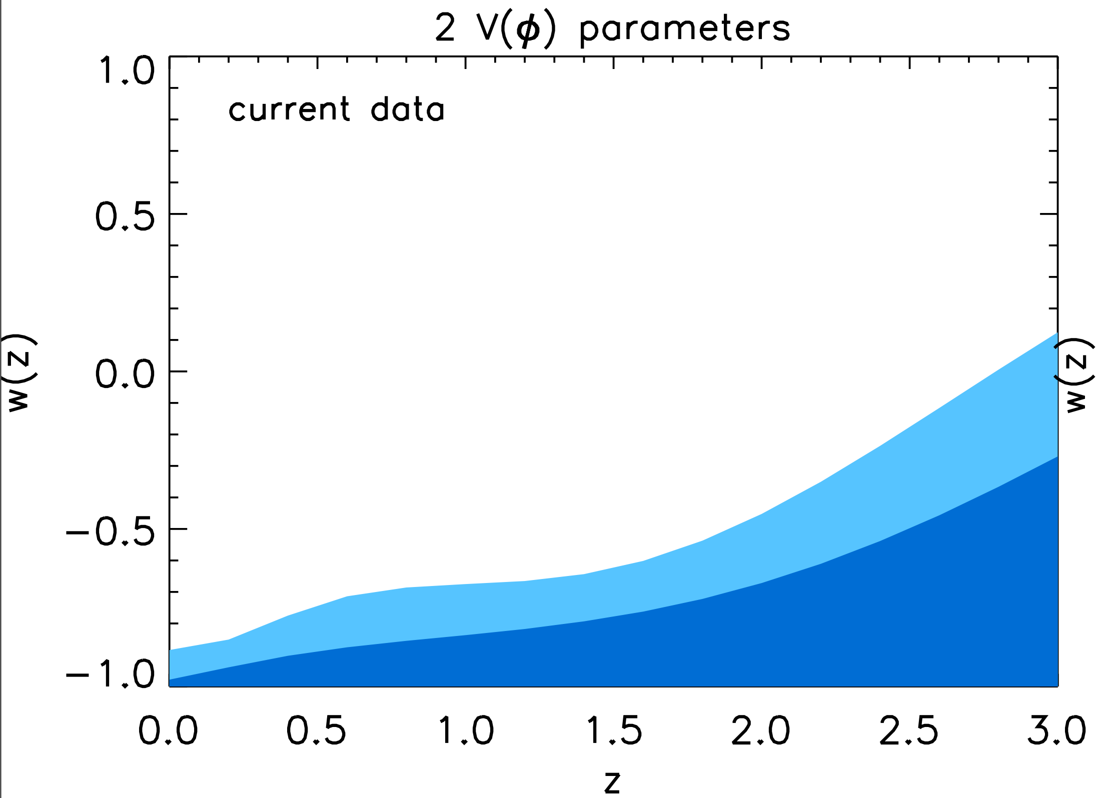


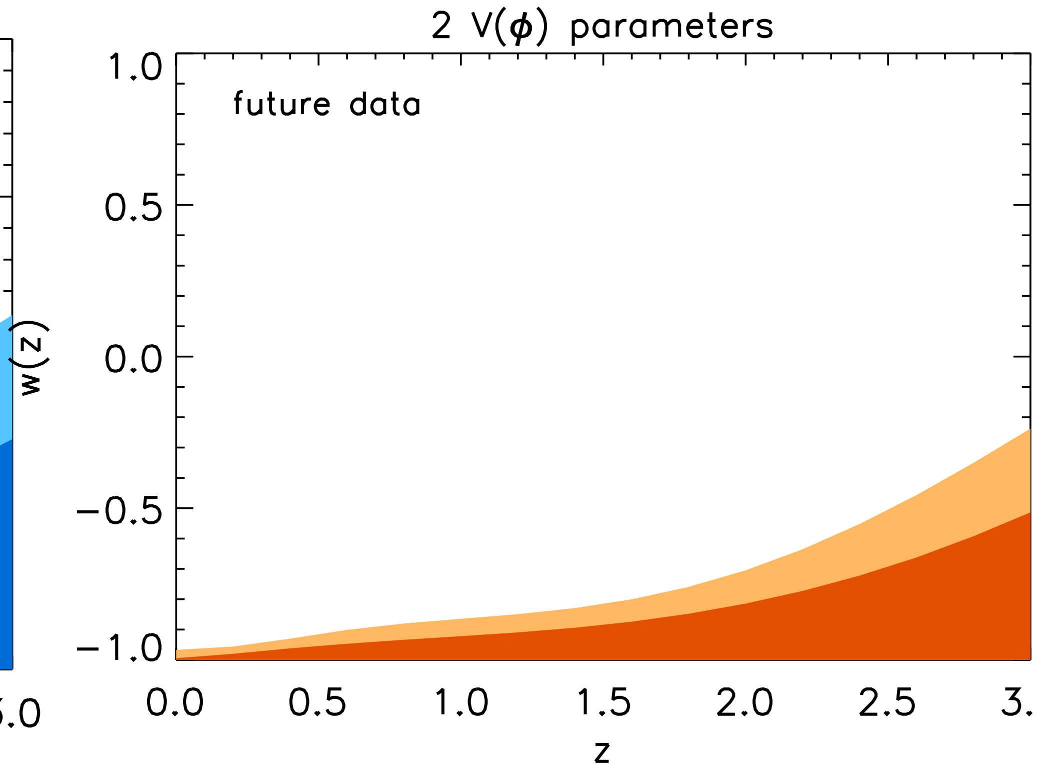
$$w(z) = w_0 + w_a \frac{z}{1+z}$$

Also allows straightforward computation and constraints on the principal components, phase-space flows, figures of merit....

Huterer & Peiris, astro-ph/0610427

Reconstruction of w(z)

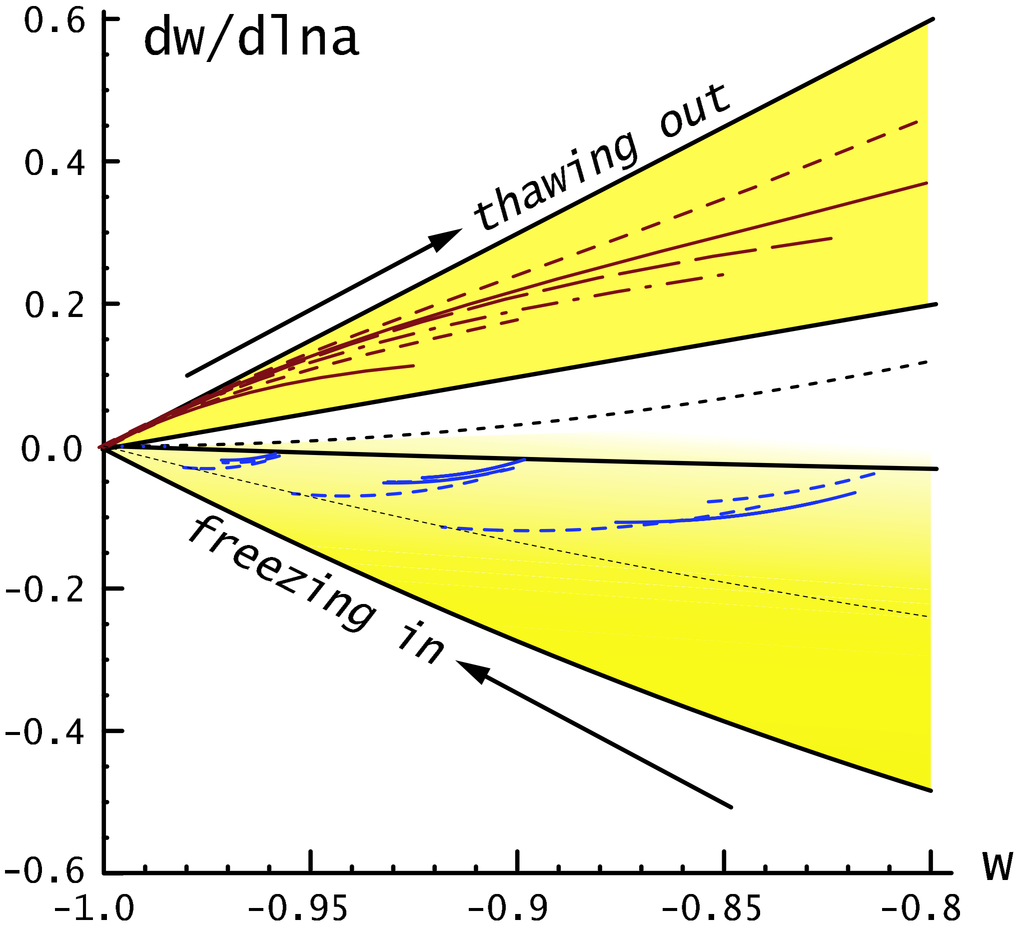




N.B. This scalar-field-model reconstruction is much more stable than the general non-parametric reconstruction

Huterer & Peiris, astro-ph/0610427

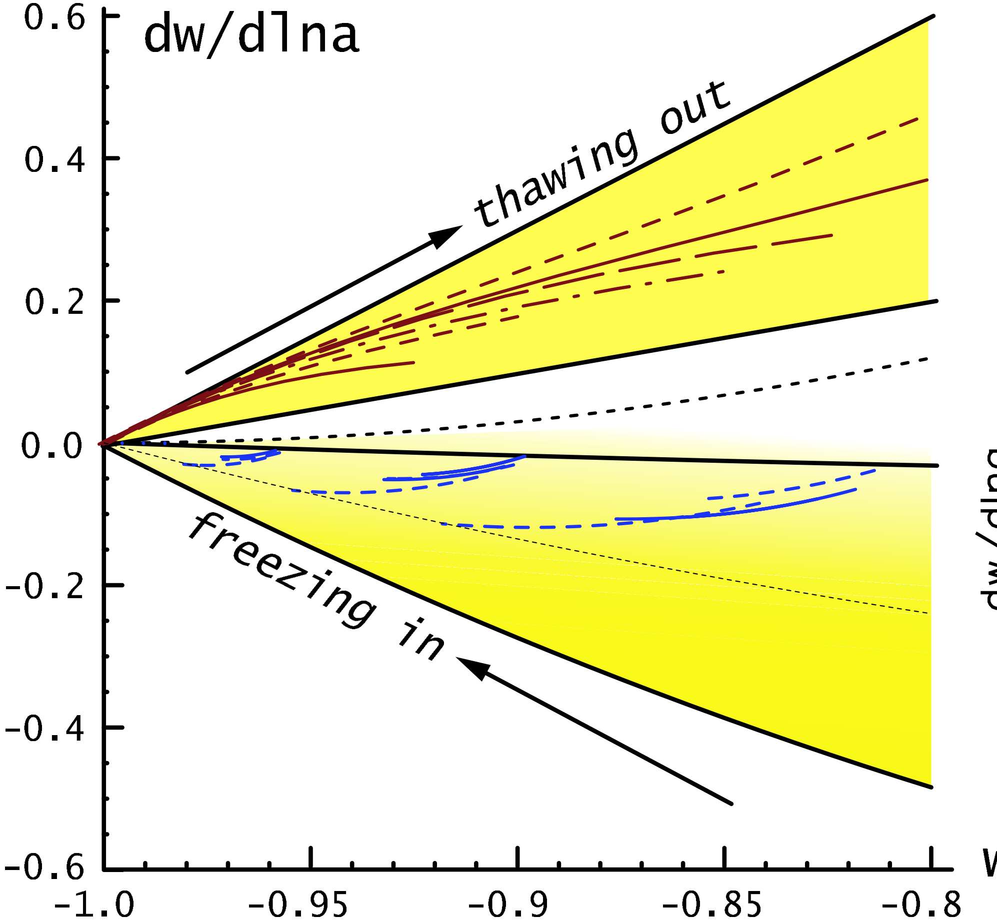
Generic behavior of scalar fields (??)



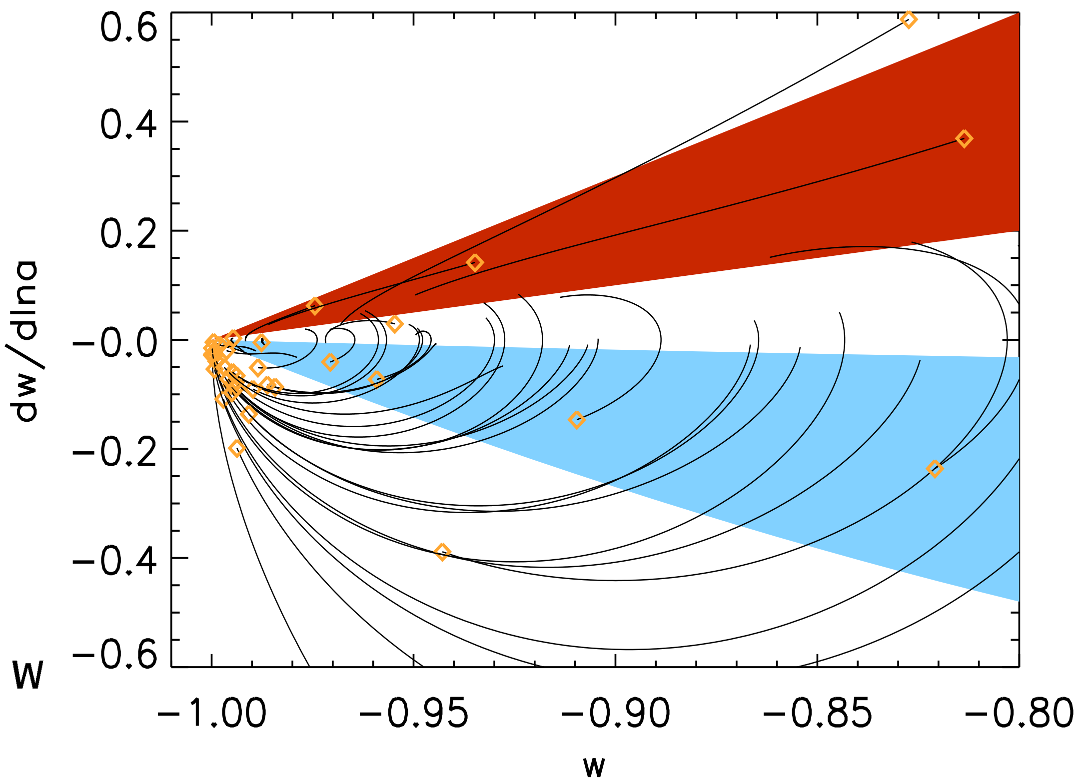
- Do scalar field models follow the freezing/thawing behavior?
- The claim was based on specific scalar field models

Caldwell & Linder 2005

Generic behavior of scalar fields (??)



More general models do NOT cleanly fall into freezing/thawing

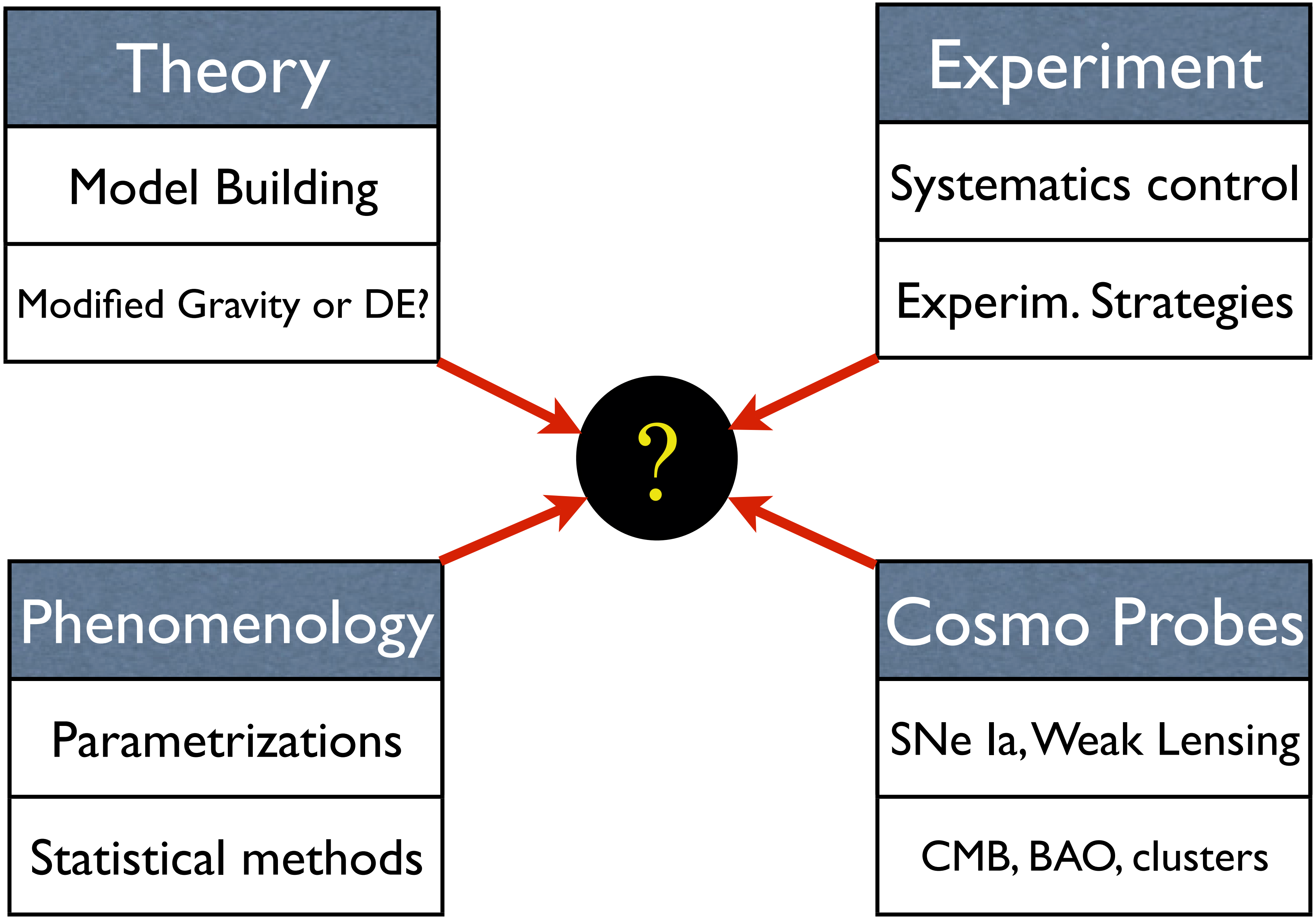


Caldwell & Linder 2005

Huterer & Peiris, astro-ph/0610427

Conclusions

- Recent accelerated expansion of the universe is a great mystery of modern physics and cosmology
- Constraints on the expansion history are becoming tight; however, fundamental understanding is lacking
- Incredible amount of new data is starting to come in, sophisticated analytical, statistical and numerical methods are required
- We need a combination of experiments that are
  - ground and space probes,
  - expansion and growth probes,
  - linear and nonlinear theory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Are beyond-LCDM cases favored by the evidence?

E.g. for two extra parameters, D=2 $(\epsilon^{\mathrm{start}}, \eta^{\mathrm{start}})$

$$\mathrm{BIC} = -2\ln\mathcal{L}_{\mathrm{max}} + D\ln N_{\mathrm{data}}$$

gain ≈ 1 ($\chi^2 = 107$ vs. 108)

penalty

$$2\ln(119) \approx 9.5$$

With current data, no evidence whatsoever for extra parameters

Dark Energy Monte-Carlo scalar field reconstruction

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

+ Friedmann Equation

Potential is specified via "slow-roll" parameters

$$\epsilon = \frac{m_{\rm pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \qquad {}^{\ell}\lambda = \left(\frac{m_{\rm pl}^2}{8\pi}\right)^{\ell} \frac{(V')^{\ell-1}}{V^{\ell}} \frac{d^{\ell+1}V}{d\phi^{\ell+1}};\ \ \ell \geq 1$$

$$V(\phi) = V_0\left[1 + A_1\phi + A_2\phi^2 + \ldots + A_{M+1}\phi^{M+1}\right]$$

Cosmological data

- Current data
  - SNLS SNe (~115), includes low-z
  - WMAP: $\theta_A, \Omega_M h^2, \Omega_B h^2$
  - BAO (SDSS, distance to z=0.35)
  - H_0 to 10% (Hubble Key Project)
- Future data - centered on LCDM
  - SNAP SNe (~2800) with systematics
  - Planck: $\theta_A, \Omega_M h^2, \Omega_B h^2$
  - BAO (10,000 sq. deg, $0.5<z<2.0$)
  - H_0 to 5%