Report of the Dark Energy Task Force

Report to HEPAP
6 July 2006
Rocky Kolb

Dark Energy

Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation.

The acceleration of the Universe is, along with dark matter, the observed phenomenon which most directly demonstrates that our fundamental theories of particles and gravity are either incorrect or incomplete.

Most experts believe that nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration.

For these reasons, the nature of dark energy ranks among the very most compelling of all outstanding problems in physical science.

These circumstances demand an ambitious observational program to determine the dark energy properties as well as possible.

Dark Energy Task Force (DETF)

http://www.nsf.gov/mps/ast/detf.jsp

• Three agencies:	DOE; NASA; NSF
• Two subcommittees:	AAAC (Illingworth); HEPAP (Shochet)
• Two charge letters:	Kinney (NASA); Staffin (DOE); Turner (NSF)
• Thirteen members:	Overlap with AAAC, HEPAP, SDT

DETF Membership

- Members
  - Andy Albrecht, Davis
  - Gary Bernstein, Penn
  - Bob Cahn, LBNL
  - Wendy Freedman, OCIW
  - Jackie Hewitt, MIT
  - Wayne Hu, Chicago
  - John Huth, Harvard
  - Mark Kamionkowski, Caltech
  - Rocky Kolb, Fermilab/Chicago
  - Lloyd Knox, Davis
  - John Mather, GSFC
  - Suzanne Staggs, Princeton
  - Nick Suntzeff, NOAO
- Agency Representatives
  - DOE: Kathy Turner
  - NASA: Michael Salamon
    Ron Hellings
  - NSF: Dana Lehr

Dark Energy Task Force Charge*

"The DETF is asked to advise the agencies on the optimum† near and intermediate-term programs to investigate dark energy and, in cooperation with agency efforts, to advance the justification, specification and optimization of LST# and JDEM‡."

1. Summarize existing program of funded projects
2. Summarize proposed and emergent approaches
3. Identify important steps, precursors, R&D, …
4. Identify areas of dark energy parameter space existing or proposed projects fail to address
5. Prioritize approaches (not projects)

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* Fair range of interpretations of charge.

† Optimum ≡ minimum (agencies); Optimum ≡ maximal (community)

LST ≡ Large Survey Telescope

‡ JDEM ≡ Joint Dark Energy Mission

Dark Energy Task Force (DETF)

http://www.nsf.gov/mps/ast/detf.jsp

- Weekly phonecons plus five face-to-face meetings

- 50 Whitepapers from community

- Updates
  AAAC (Feb 13 2006)
  HEPAP (March 4)
  P5 (April 21)

- Preliminary Report reviewed by six readers suggested by AAAC & HEPAP who made very helpful comments. The DETF responded to each comment and improved the report in the process

- Draft Report submitted to AAAC and HEPAP on 7 May 2006 (5 months late!)

- June 2006, report approved by AAAC

Dark Energy Task Force Report

Context

The issue: acceleration of the Universe
Possibilities: dark energy (Λ or not), non-GR
Motivation for future investigations

Goals and Methodology

Goal of dark energy investigations
Methodology to analyze techniques/implementations

Findings

Techniques & implementations (largely from White Papers)
Systematic uncertainties
What we learned from analysis

Recommendations

A Dark Energy Primer
DETF Fiducial Model and Figure of Merit
Staging Stage IV from the Ground and/or Space
DETF Technique Performance Projections
Dark Energy Projects (Present and Future)
Technical Appendix

Context

1. Conclusive evidence for acceleration of the Universe.
   Standard cosmological framework $\rightarrow$ dark energy (70% of mass-energy).
2. Possibility: Dark Energy constant in space & time (Einstein's Λ).
3. Possibility: Dark Energy varies with time (or redshift z or $a = (1+z)^{-1}$).
4. Impact of dark energy can be expressed in terms of "equation of state"
   $w(a) = p(a) / \rho(a)$ with $w(a) = -1$ for Λ.
5. Possibility: GR or standard cosmological model incorrect.
6. Not presently possible to determine the nature of dark energy.

Context

7. Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation. The acceleration of the Universe is, along with dark matter, the observed phenomenon which most directly demonstrates that our fundamental theories of particles and gravity are either incorrect or incomplete. Most experts believe that nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration. For these reasons, the nature of dark energy ranks among the very most compelling of all outstanding problems in physical science. These circumstances demand an ambitious observational program to determine the dark energy properties as well as possible.

Goals and Methodology

1. The goal of dark-energy science is to determine the very nature of the dark energy that causes the Universe to accelerate and seems to comprise most of the mass-energy of the Universe.
2. Toward this goal, our observational program must:
   a. Determine whether the accelerated expansion is due to a cosmological constant.
   b. If it is not due to a constant, probe the underlying dynamics by measuring as well as possible the time evolution of dark energy, for example by measuring $w(a)$.
   c. Search for a possible failure of GR through comparison of cosmic expansion with growth of structure.
3. $w(a)$ is a continuous function; must parameterize; no parameterization can represent all possibilities; we choose $w(a) = w_0 + (1-a)w_a$; assumes dark energy insignificant at early times.

Because the field is so new, it has suffered from a lack of standardization which has made it very difficult to compare directly different approaches.

To address this problem we have done our own modeling of the different techniques so that they could be compared in a consistent manner.

These quantitative calculations form the basis of our extensive factual findings, on which our recommendations are based

Goals and Methodology

4. Goals of dark-energy observational program through measurement of expansion history of Universe [$d_L(z)$, $d_A(z)$, $V(z)$], and through measurement of growth rate of structure. All described by $w(a)$. If failure of GR, possible difference in $w(a)$ inferred from different types of data.

5. To quantify progress in measuring properties of dark energy we define dark energy figure-of-merit from combination of uncertainties in w_0 and w_a.

   The DETF figure-of-merit is the reciprocal of the area of the error ellipse enclosing the 95% confidence limit in the w_0–w_a plane. Larger figure-of-merit indicates greater accuracy.

6. Figure of merit serves as a quantitative guide to constrain a large, but not exhaustive, set of dark-energy models. The nature of dark energy is poorly understood; no single figure of merit is appropriate for every eventuality. Potential shortcomings of the choice of any figure of merit must be evaluated in the larger context, which includes the critical need to make side-by-side comparisons. In our judgment there is no better choice of a figure of merit available at this time.

Goals and Methodology

7. We made extensive use of statistical (Fisher-matrix) techniques incorporating CMB and H_0 information to predict future performance (75 models).
8. Our considerations follow developments in Stages:
   I. What is known now (12/31/05).
   II. Anticipated state upon completion of ongoing projects.
   III. Near-term, medium-cost, currently proposed projects.
   IV. Large-Survey Telescope (LST) and/or Square Kilometer Array (SKA), and/or Joint Dark Energy (Space) Mission (JDEM).
9. Dark-energy science has far-reaching implications for other fields of physics $\rightarrow$ discoveries in other fields may point the way to understanding nature of dark energy (*e.g.,* evidence for modification of GR).

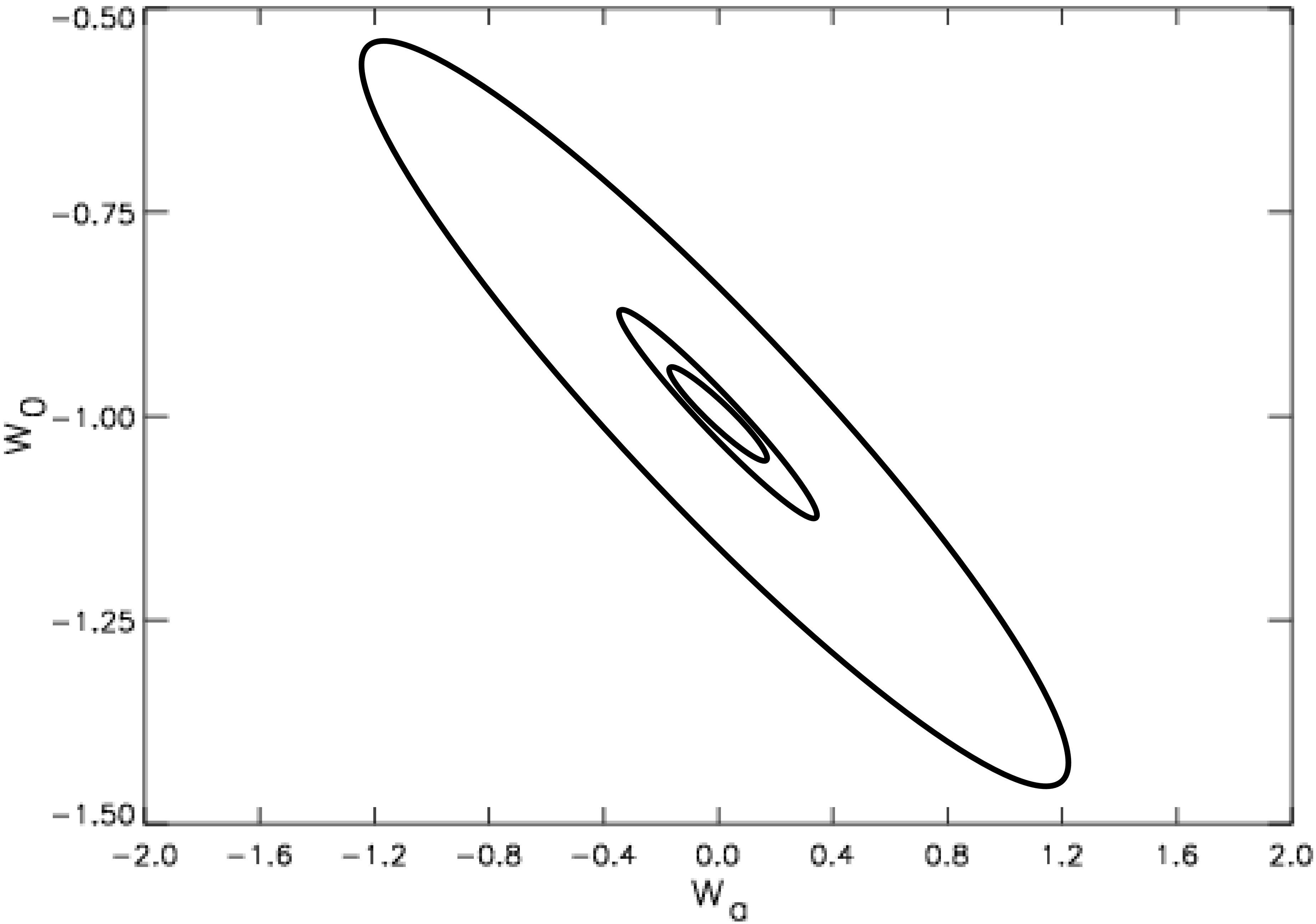
Eighteen Findings

1. Four observational techniques dominate White Papers:
   a. Baryon Acoustic Oscillations (**BAO**) large-scale surveys measure features in distribution of galaxies. BAO: $d_A(z)$ and $H(z)$.
   b. Cluster (**CL**) surveys measure spatial distribution of galaxy clusters. CL: $d_A(z)$, $H(z)$, growth of structure.
   c. Supernovae (**SN**) surveys measure flux and redshift of Type Ia SNe. SN: $d_L(z)$.
   d. Weak Lensing (**WL**) surveys measure distortion of background images due to gravitational lensing. WL: $d_A(z)$, growth of structure.
2. Different techniques have different strengths and weaknesses and sensitive in different ways to dark energy and other cosmo. parameters.
3. Each of the four techniques can be pursued by multiple observational approaches (radio, visible, NIR, x-ray observations), and a single experiment can study dark energy with multiple techniques. Not all missions necessarily cover all techniques; in principle different combinations of projects can accomplish the same overall goals.

Eighteen Findings

4. Four techniques at different levels of maturity:
   - **a.** **BAO** only recently established. Less affected by astrophysical uncertainties than other techniques.
   - **b.** **CL** least developed. Eventual accuracy very difficult to predict. Application to the study of dark energy would have to be built upon a strong case that systematics due to non-linear astrophysical processes are under control.
   - **c.** **SN** *presently* most powerful and best proven technique. If photo-z's are used, the power of the supernova technique depends critically on accuracy achieved for photo-z's. If spectroscopically measured redshifts are used, the power as reflected in the figure-of-merit is much better known, with the outcome depending on the ultimate systematic uncertainties.
   - **d.** **WL** also emerging technique. Eventual accuracy will be limited by systematic errors that are difficult to predict. *If* the systematic errors are at or below the level proposed by the proponents, it is likely to be the most powerful individual technique and also the most powerful component in a multi-technique program.

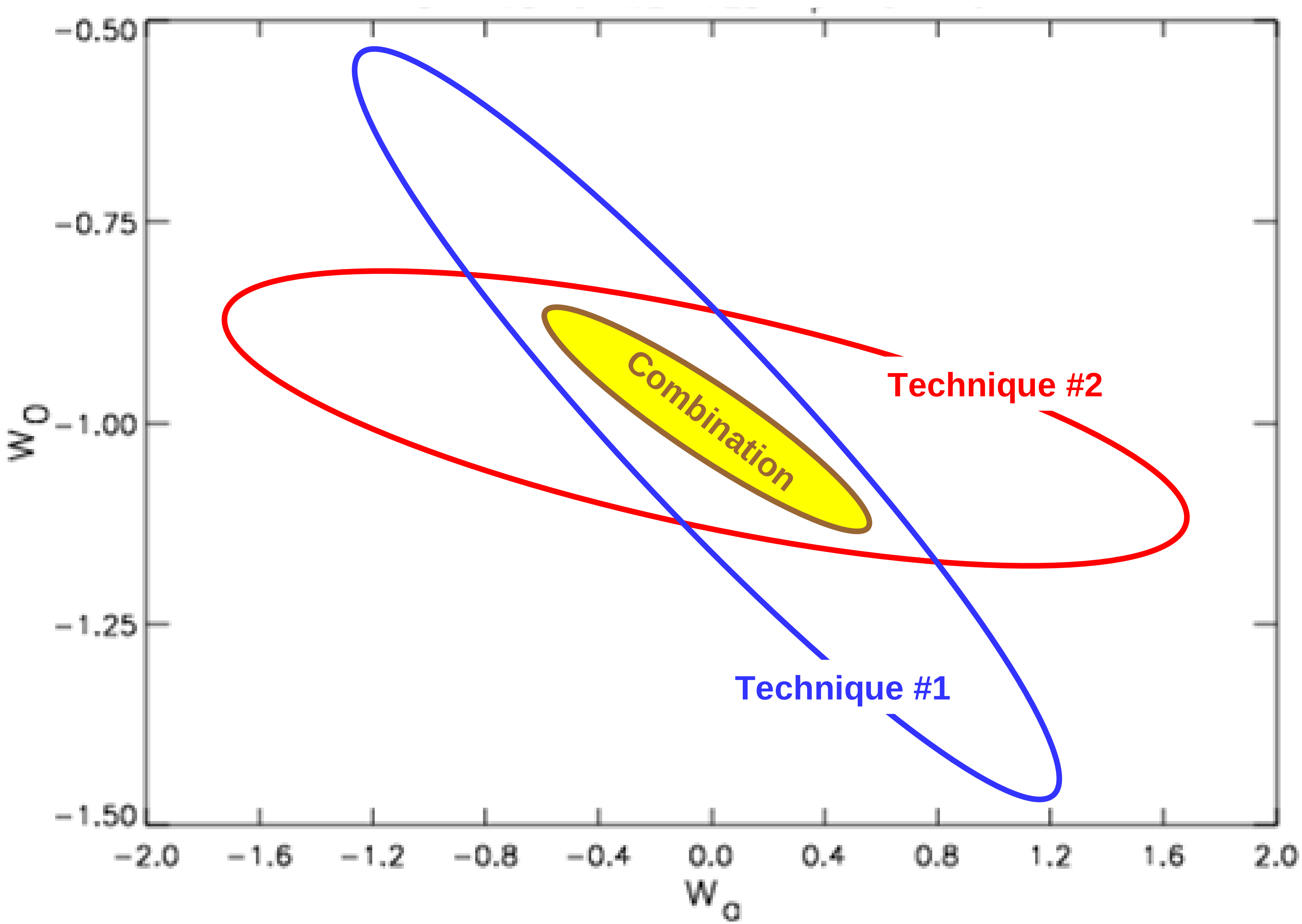
Systematics: none, optimistic, pessimistic



Eighteen Findings

5. A program that includes multiple techniques at Stage IV can provide more than an order-of-magnitude increase in our figure-of-merit. This would be a major advance in our understanding of dark energy.

6. No single technique is sufficiently powerful and well established that it is guaranteed to address the order-of-magnitude increase in our figure-of-merit alone. Combinations of the principal techniques have substantially more statistical power, much more ability to discriminate among dark energy models, and more robustness to systematic errors than any single technique. Also, the case for multiple techniques is supported by the critical need for confirmation of results from any single method.



−0.50
−0.75
−1.00
−1.25
−1.50
w_a
−2.0
−1.6
−1.2
−0.8
−0.4
0.0
0.4
0.8
1.2
1.6
2.0
w_0
Combination
Technique #2
Technique #1

Eighteen Findings

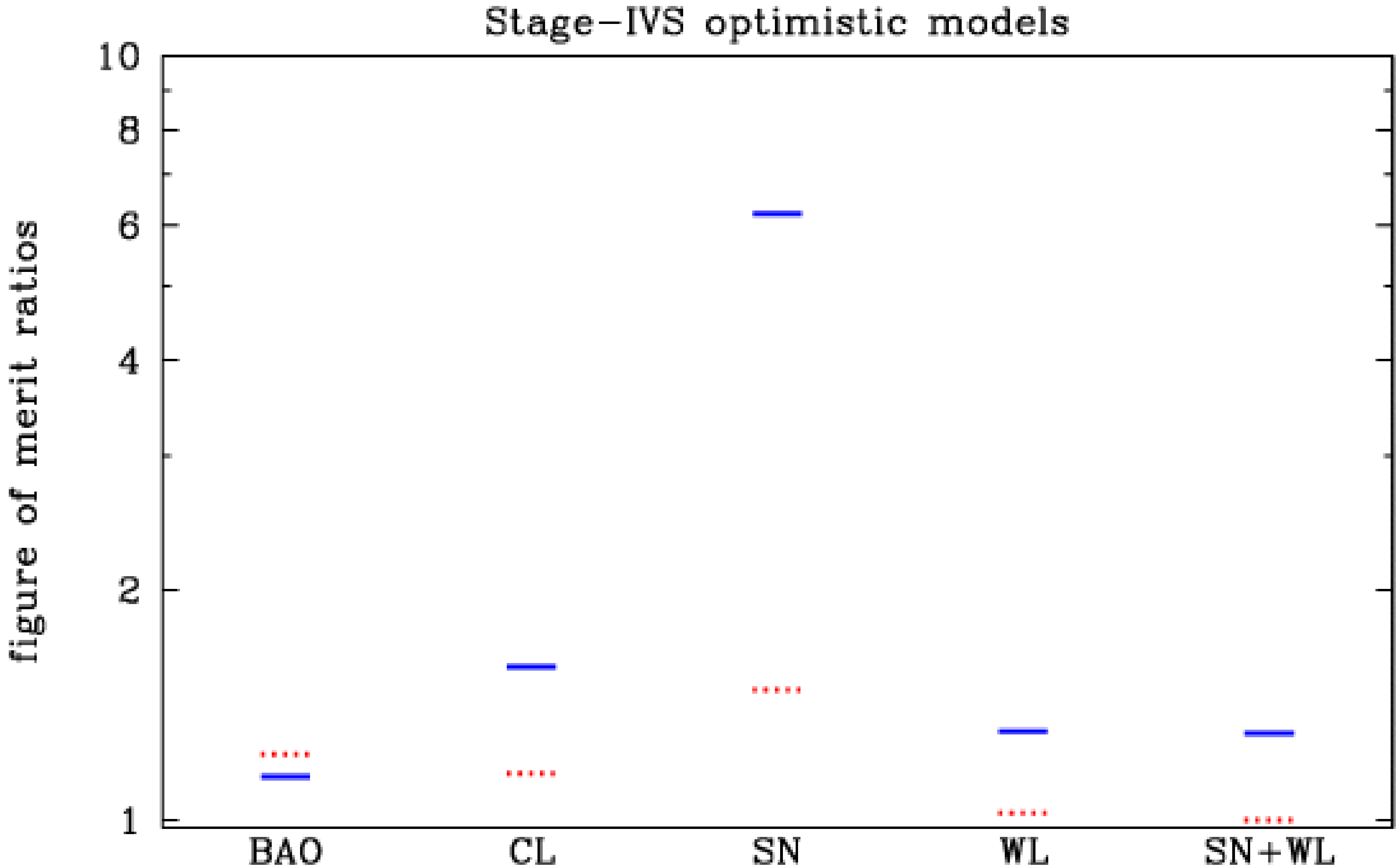
7. Results on structure growth, obtainable from weak lensing or cluster observations, are essential program components in order to check for a possible failure of general relativity.

8. In our modeling we assume constraints on H_0 from current data and constraints on other cosmological parameters expected to come from measurement of CMB temperature and polarization anisotropies.
   a. These data, though insensitive to $w(a)$ on their own, contribute to our knowledge of $w(a)$ when combined with any of the dark energy techniques we have considered.
   b. Increased precision in a particular cosmological parameter may improve dark energy constraints from a single technique, valuable for comparing independent methods.

9. Improvements in cosmological parameters tend not to improve knowledge of dark energy from a multi-technique program

10. Setting spatial curvature to zero greatly helps SN, but modest impact on other techniques. Little difference when in combination.

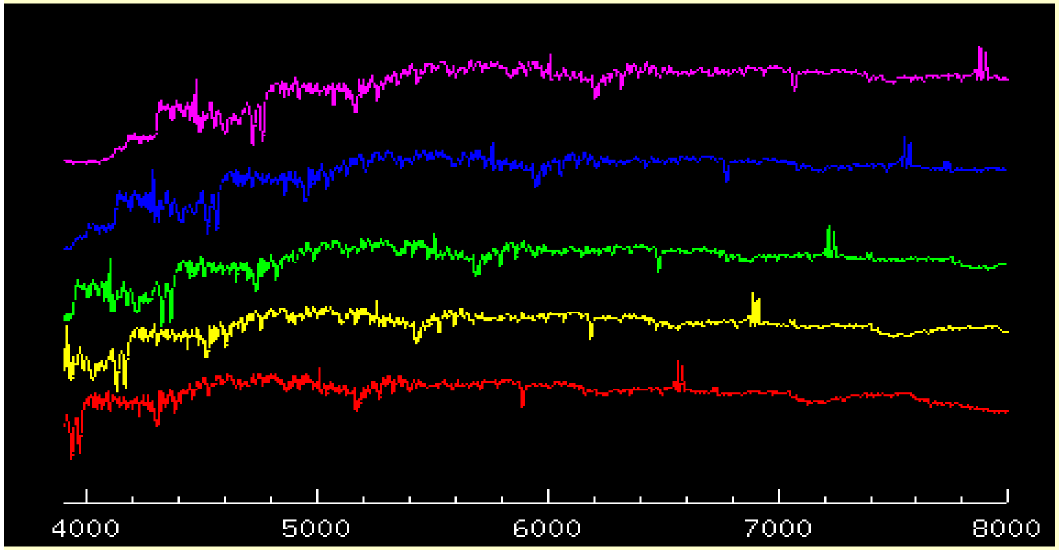
Eighteen Findings



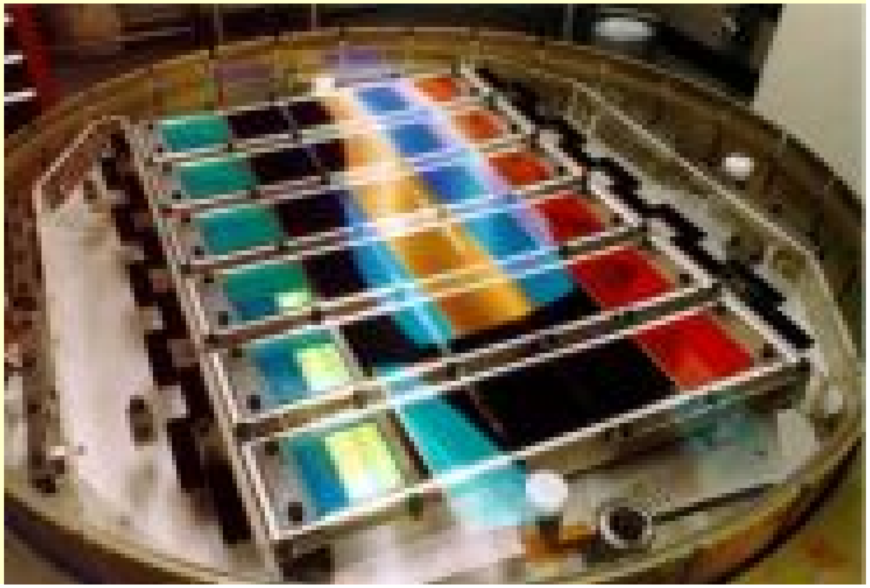
······ $\sigma(H_0)$: 8 km s^{-1} Mpc^{-1} → 4 km s^{-1} Mpc^{-1} —— $k = 0$ prior

Eighteen Findings

11. Optical, IR, and X-ray experiments with very large numbers of astronomical targets will rely on photometrically determined redshifts. The ultimate accuracy that can be attained for photo-z's is likely to determine the power of such measurements.



Traditional redshift from spectroscopy



Photometric redshift from multicolor photometry

Eighteen Findings

12. Our inability to forecast reliably systematic error levels is the biggest impediment to judging the future capabilities of the techniques. We need
    a. **BAO–** Theoretical investigations of how far into the non-linear regime the data can be modeled with sufficient reliability and further understanding of galaxy bias on the galaxy power spectrum.
    b. **CL–** Combined lensing and Sunyaev-Zeldovich and/or X-ray observations of large numbers of galaxy clusters to constrain the relationship between galaxy cluster mass and observables.
    c. **SN–** Detailed spectroscopic and photometric observations of about 500 nearby supernovae to study the variety of peak explosion magnitudes and any associated observational signatures of effects of evolution, metallicity, or reddening, as well as improvements in the system of photometric calibrations.
    d. **WL–** Spectroscopic observations and multi-band imaging of tens to hundreds of thousands of galaxies out to high redshifts and faint magnitudes in order to calibrate the photometric redshift technique and understand its limitations. It is also necessary to establish how well corrections can be made for the intrinsic shapes and alignments of galaxies, removal of the effects of optics (and from the ground) the atmosphere and to characterize the anisotropies in the point-spread function.

Eighteen Findings

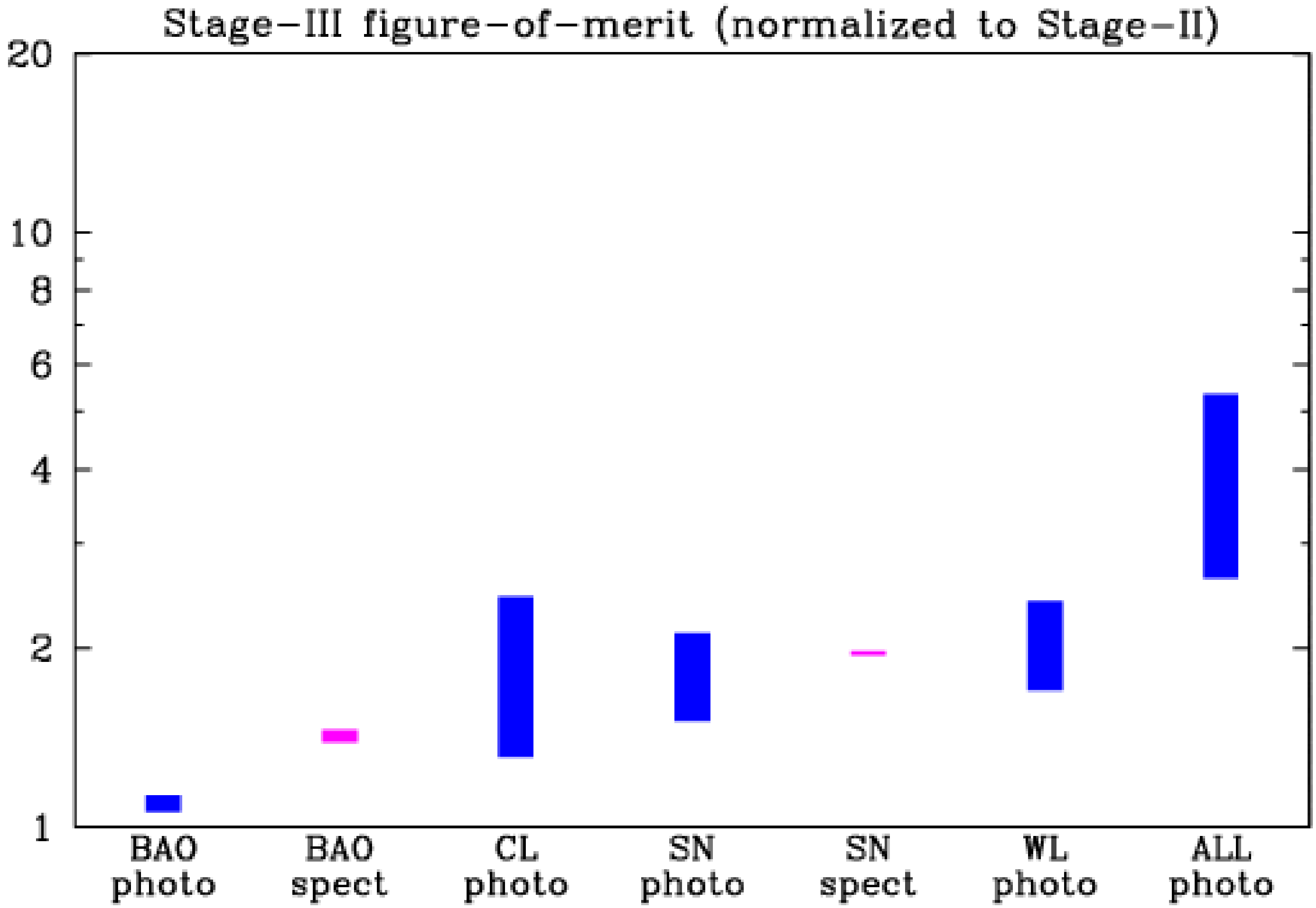
13. Six types of Stage III projects have been considered:
    a. a BAO survey on an 8-m class telescope using spectroscopy
    b. a BAO survey on an 4-m class telescope using photo-z's
    c. a CL survey on an 4-m class telescope using photo-z's for clusters detected in ground-based SZ surveys
    d. a SN survey on a 4-m class telescope using spectroscopy from a 8-m class telescope
    e. a SN survey on a 4-m class telescope using photo-z's
    f. A WL survey on a 4-m class telescope using photo-z's

a. These projects are typically projected by proponents to cost in the range of 10s of $M.

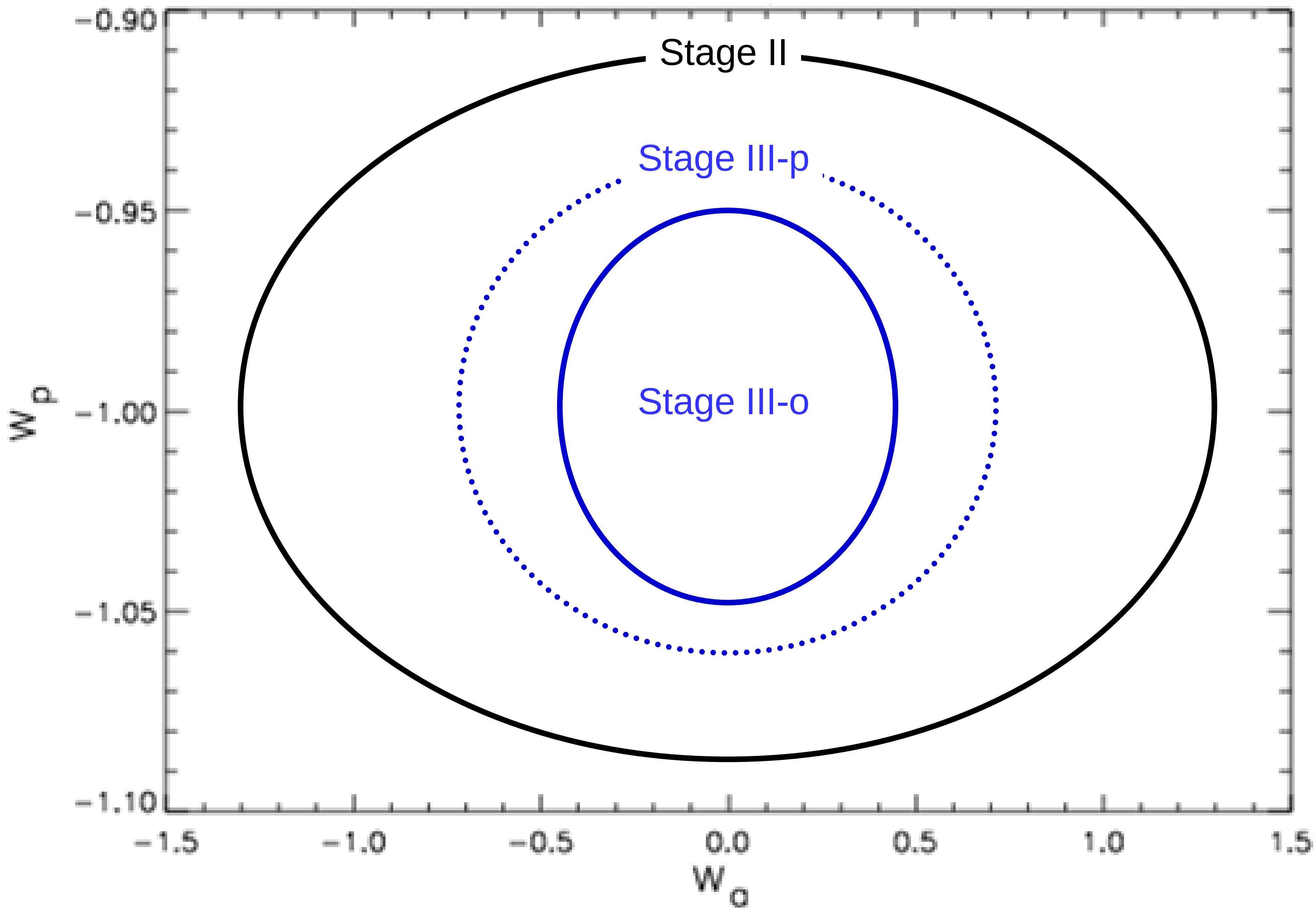
Eighteen Findings

14. Our findings regarding Stage-III projects are
    1. Only an incremental increase in knowledge of dark-energy parameters is likely to result from a Stage-III BAO project using photo-z's. The primary benefit would be in exploring photo-z uncertainties.
    2. A modest increase in knowledge of dark-energy parameters is likely to result from Stage-III SN project using photo-z's. Such a survey would be valuable if it were to establish the viability of photometric determination of supernova redshifts, types, and evolutionary effects.
    3. A modest increase in knowledge of dark-energy parameters is likely to result from any single Stage-III CL, WL, spectroscopic BAO, or spectroscopic SN survey.
    4. The SN, CL, or WL techniques could, individually, produce factor-of-two improvements in the DETF figure-of-merit, if the systematic errors are close to what the proponents claim.
    5. If executed in combination, Stage-III projects would increase the DETF figure-of-merit by a factor in the range of approximately three to five, with the large degree of uncertainty due to uncertain forecasts of systematic errors.

DETF Projections



Combination of all techniques from a Stage-III photometric survey



Eighteen Findings

15. Four types of next-generation (Stage IV) projects have been considered:
    a. an optical Large Survey Telescope (LST), using one or more of the four techniques
    b. an optical/NIR JDEM satellite, using one or more of four techniques
    c. an x-ray JDEM satellite, which would study dark energy by the cluster technique
    d. a Square Kilometer Array, which could probe dark energy by weak lensing and/or the BAO technique through a hemisphere-scale survey of 21-cm emission

    Each of these projects is in the $0.3-1B range, but dark energy is not the only (in some cases not even the primary) science that would be done by these projects. According to the White Papers received by the Task Force, the technical capabilities needed to execute LST and JDEM are largely in hand. The Task Force is not constituted to undertake a study of the technical issues.
16. Each of the Stage IV projects considered (LST, JDEM, and SKA) offers compelling potential for advancing our knowledge of dark energy as part of a multi-technique program.

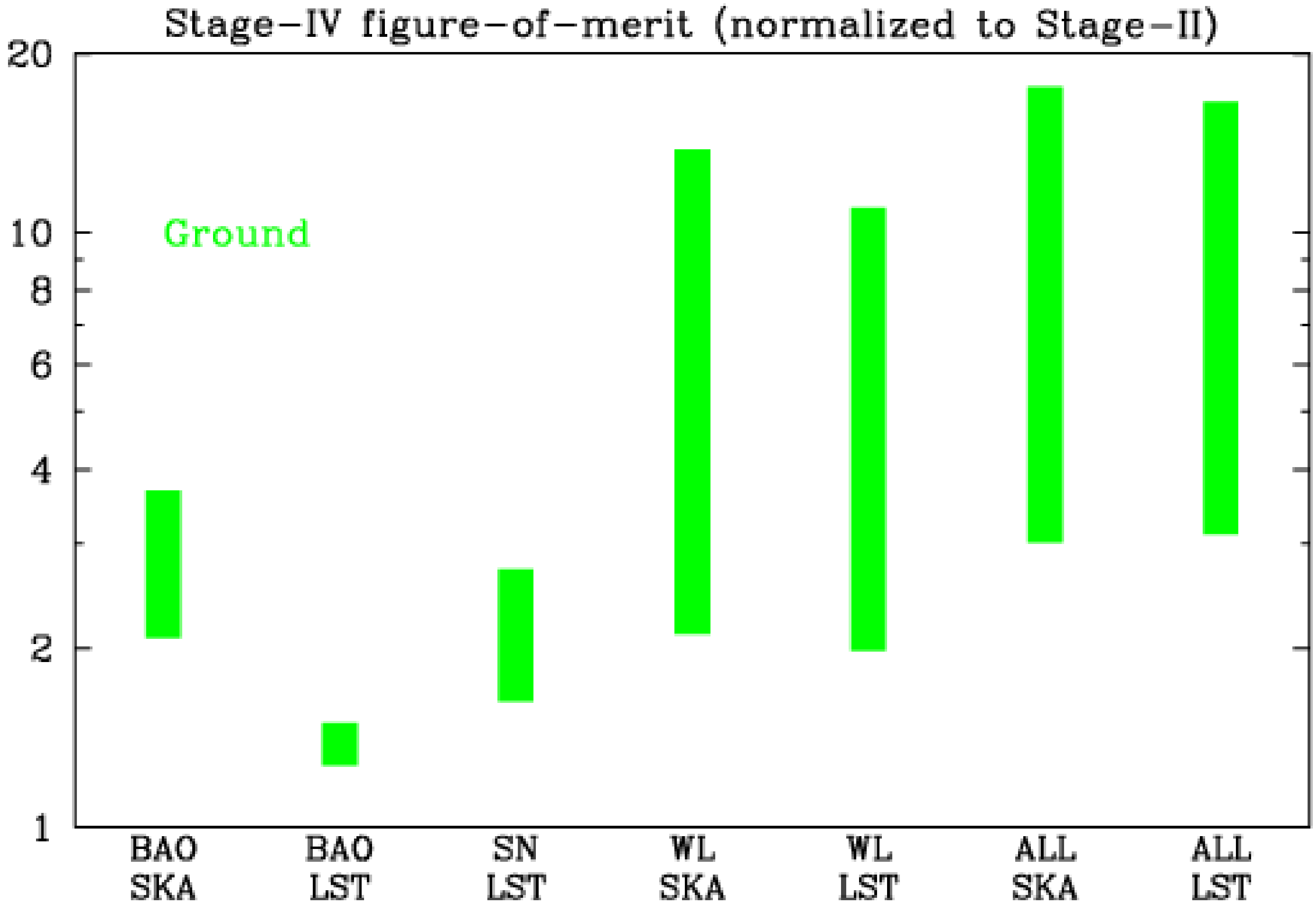
Eighteen Findings

17. The Stage IV experiments have different risk profiles:
    a. SKA would likely have very low systematic errors, but needs technical advances to reduce its cost. The performance of SKA would depend on the number of galaxies it could detect, which is uncertain.
    b. Optical/NIR JDEM can mitigate systematics because it will likely obtain a wider spectrum of diagnostic data for SN, CL, and WL than possible from ground, incurring the usual risks of a space mission.
    c. LST would have higher systematic-error risk, but can in many respects match the statistical power of JDEM if systematic errors, especially those due to photo-z measurements, are small. An LST Stage IV program can be effective only if photo-z uncertainties on very large samples of galaxies can be made smaller than what has been achieved to date.

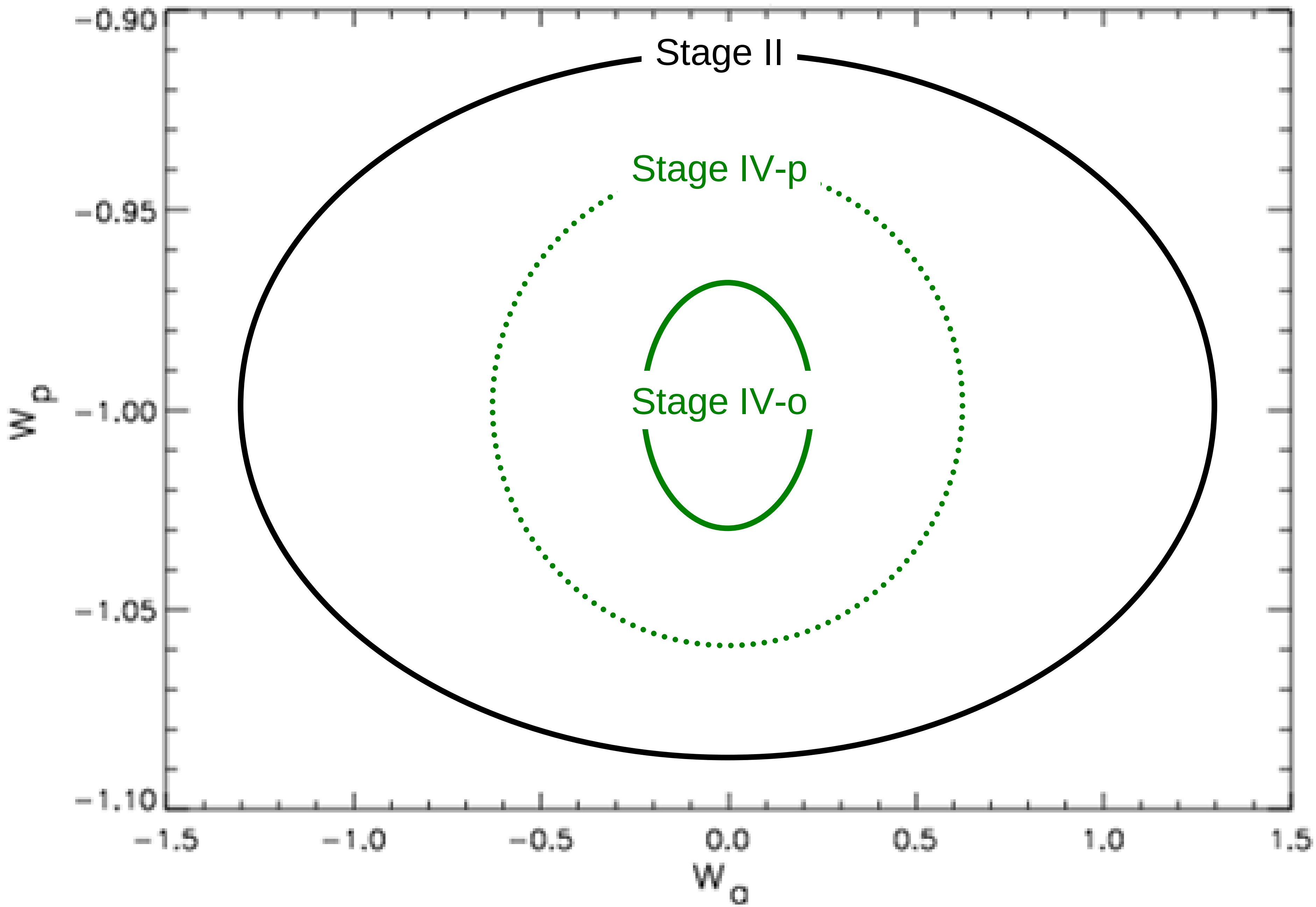
Eighteen Findings

18. A mix of techniques is essential for a fully effective Stage IV program. The technique mix may be comprised of elements of a ground-based program, or elements of a space-based program, or a combination of elements from ground- and space-based programs. No unique mix of techniques is optimal (aside from doing them all), but the absence of weak lensing would be the most damaging provided this technique proves as effective as projections suggest.

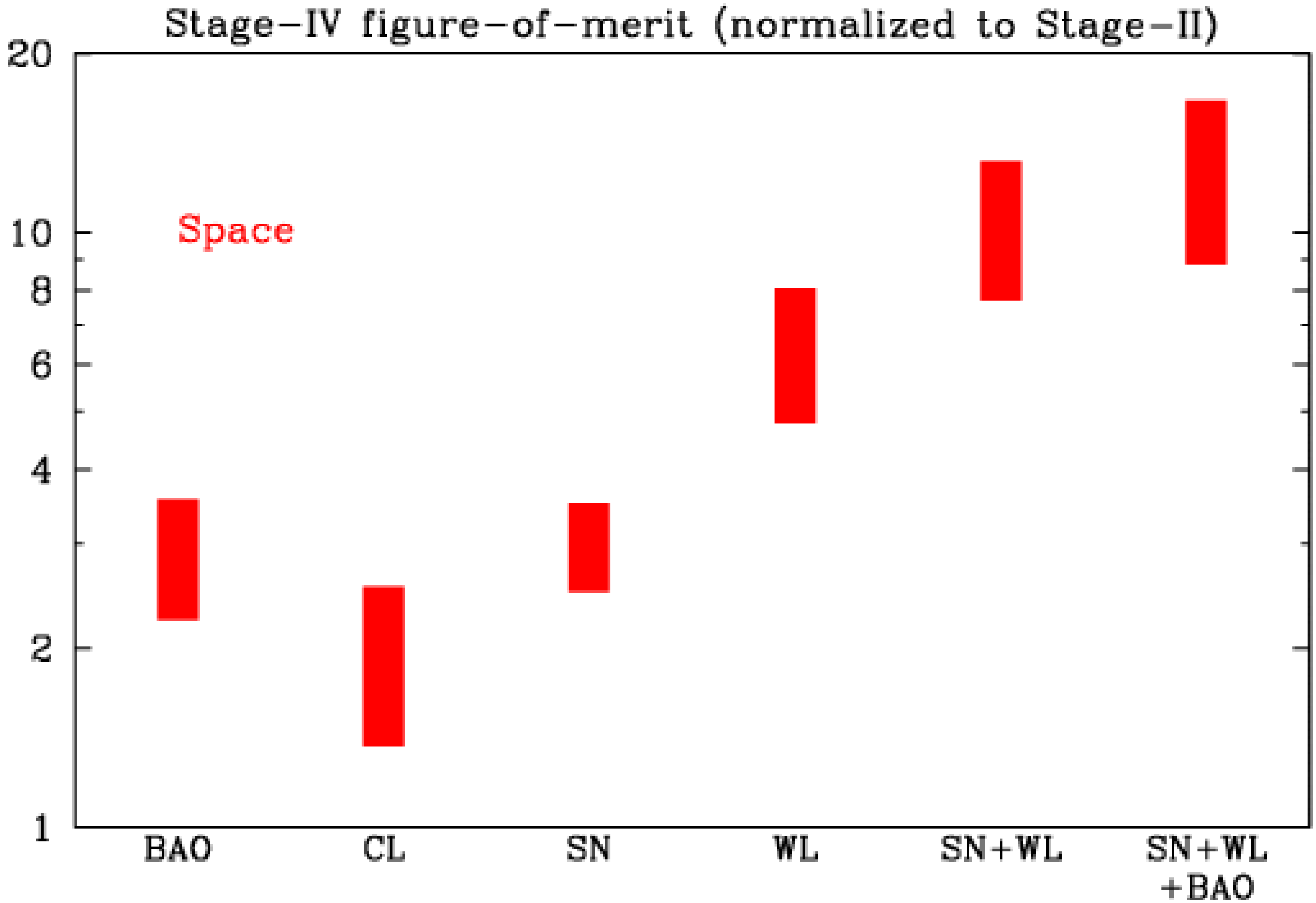
DETF Projections



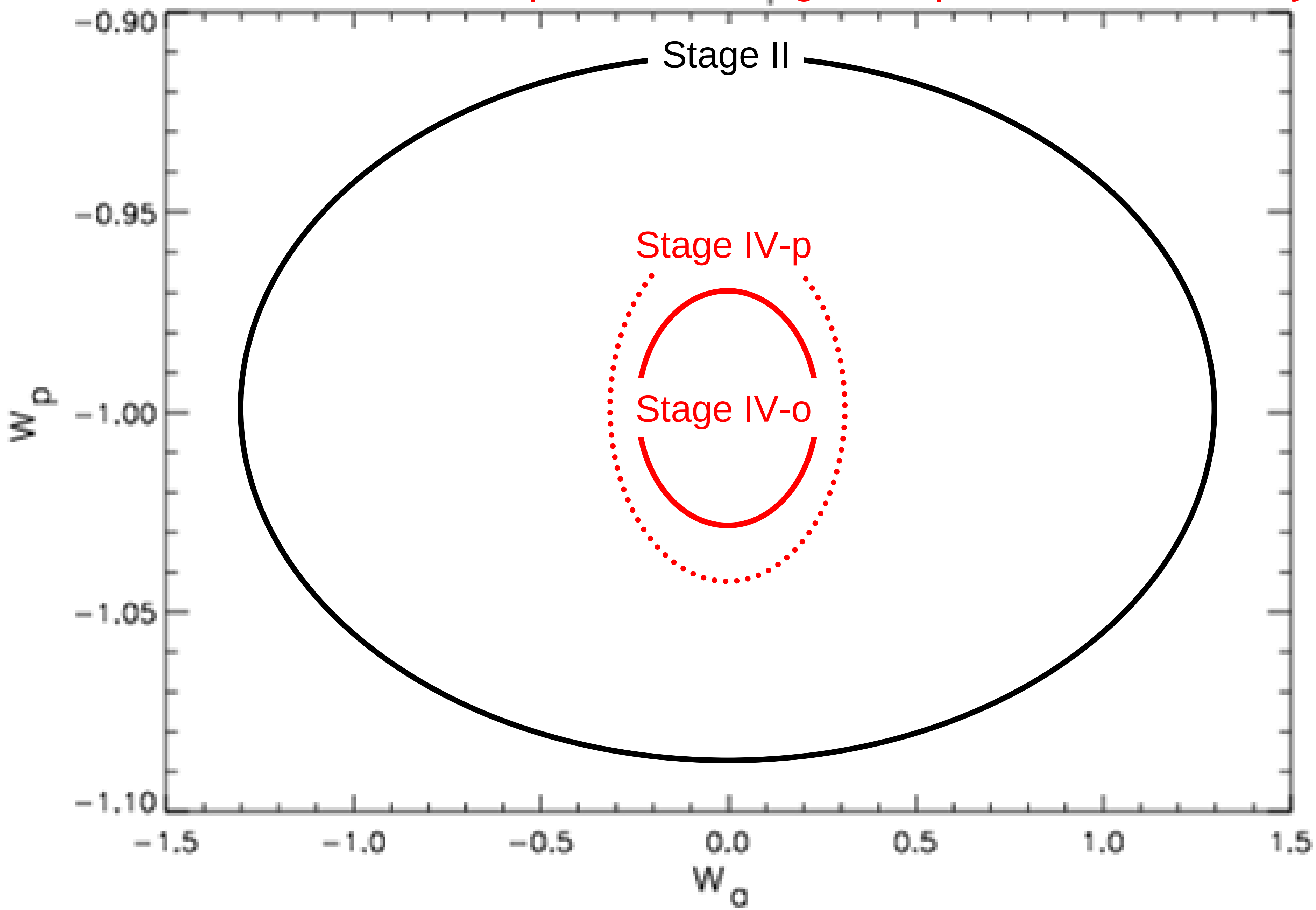
Combination of all techniques from Stage-IV ground-based survey



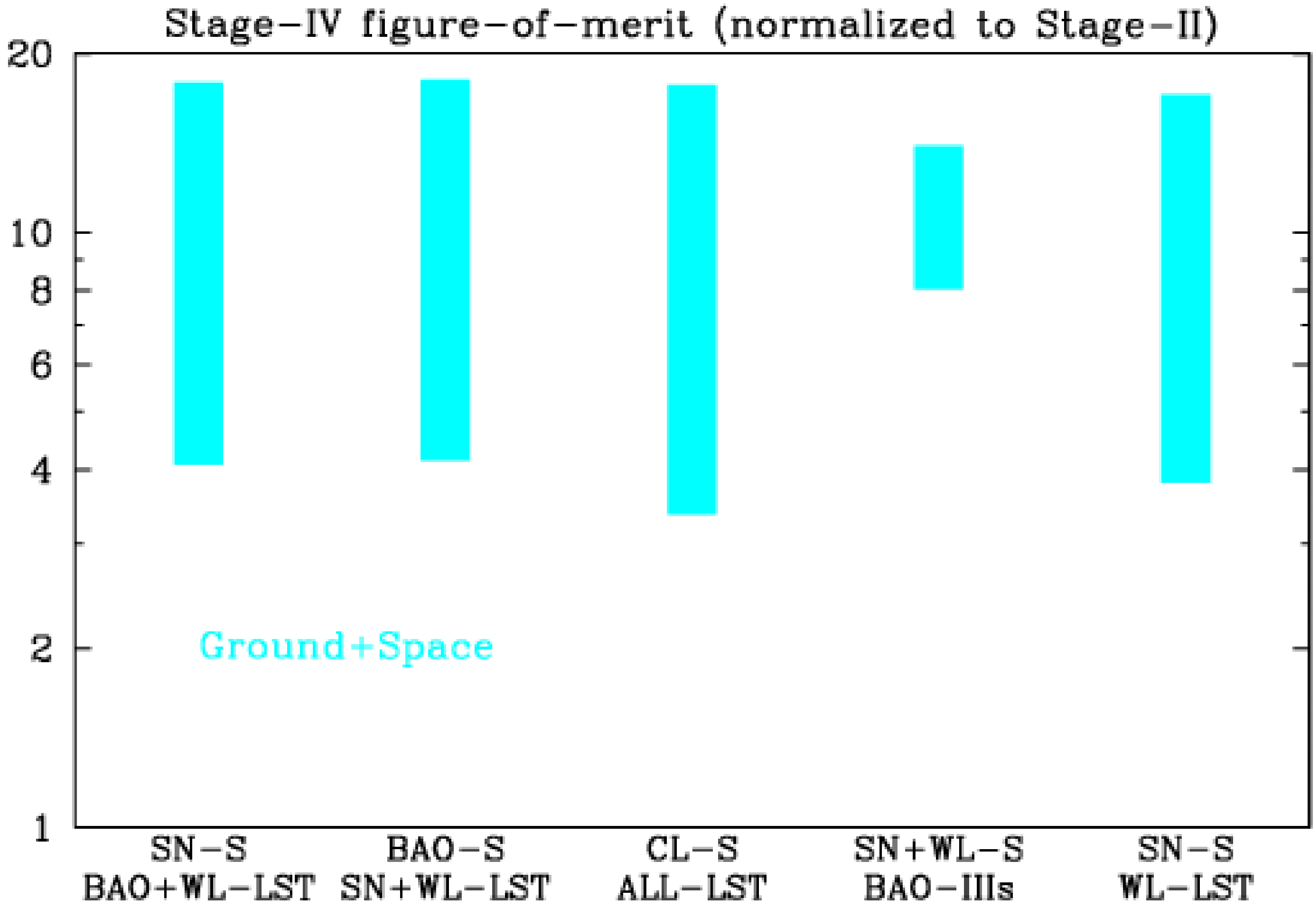
DETF Projections



Combination of all techniques from Stage-IV space-based survey



DETF Projections



Recommendations

O. **An immediate and dramatic increase in funding for all theoretical cosmology efforts in the Chicago area.**

**(This course of action is so obvious
it is not actually stated in the report)**

Six Recommendations

I. We strongly recommend that there be an aggressive program to explore dark energy as fully as possible, since it challenges our understanding of fundamental physical laws and the nature of the cosmos.

II. We recommend that the dark energy program have multiple techniques at every stage, at least one of which is a probe sensitive to the growth of cosmological structure in the form of galaxies and clusters of galaxies.

III. We recommend that the dark energy program include a combination of techniques from one or more Stage III projects designed to achieve, in combination, at least a factor of three gain over Stage II in the DETF figure-of-merit, based on critical appraisals of likely statistical and systematic uncertainties.

Six Recommendations

IV. **We recommend that the dark energy program include a combination of techniques from one or more Stage IV projects designed to achieve, in combination, at least a factor of ten gain over Stage II in the DETF figure-of-merit, based on critical appraisals of likely statistical and systematic uncertainties. Because JDEM, LST, and SKA all offer promising avenues to greatly improved understanding of dark energy, we recommend continued research and development investments to optimize the programs and to address remaining technical questions and systematic-error risks.**

V. **We recommend that high priority for near-term funding should be given as well to projects that will improve our understanding of the dominant systematic effects in dark energy measurements and, wherever possible, reduce them, even if they do not immediately increase the DETF figure-of-merit.**

Six Recommendations

VI. We recommend that the community and the funding agencies develop a coherent program of experiments designed to meet the goals and criteria set out in these recommendations.

DETF Legacy

I. Standardization
  1. Parameterize dark energy as $w_0 - w_a$
  2. Eight-parameter cosmological model
  3. Priors
  4. Figure of merit

II. Importance of combinations
  1. Soon will have a website with library of Fisher matrices & combiner programs (All power to the people!)

III. DETF Technique Performance Projections
  1. Thirty-two (count 'em, 32!) data models
  2. Optimistic & pessimistic projections
  3. Four techniques, two stages, five platforms

IV. Use DETF Technique Performance Projections as a guideline!!!
  1. We may be off-base (proposers must justify systematic-error budget!)
  2. People get smarter

From the transmittal letter

The report is a comprehensive study of the dark energy issue, perhaps the most compelling of all outstanding problems in physical science. In the Report, we outline the crucial need for a vigorous program to explore dark energy as fully as possible, since it challenges our understanding of fundamental physical laws and the nature of the cosmos. We recommend that program elements include

1. Prompt critical evaluation of the benefits, costs, and risks of proposed long-term projects.
2. Commitment to a program combining observational techniques from one or more of these projects that will lead to a dramatic improvement in our understanding of dark energy. (A quantitative measure for that improvement is presented in the report.)
3. Immediately expanded support for long-term projects judged to be the most promising components of the long-term program.
4. Expanded support for ancillary measurements required for the long-term program and for projects that will improve our understanding and reduction of the dominant systematic measurement errors.
5. An immediate start for nearer term projects designed to advance our knowledge of dark energy and to develop the observational and analytical techniques that will be needed for the long-term program.

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  Gary Bernstein, Penn
  Bob Cahn, LBNL
  Wendy Freedman, OCIW
  Jackie Hewitt, MIT
  Wayne Hu, Chicago
  John Huth, Harvard
  Mark Kamionkowski, Caltech
  Rocky Kolb, Fermilab/Chicago
  Lloyd Knox, Davis
  John Mather, GSFC
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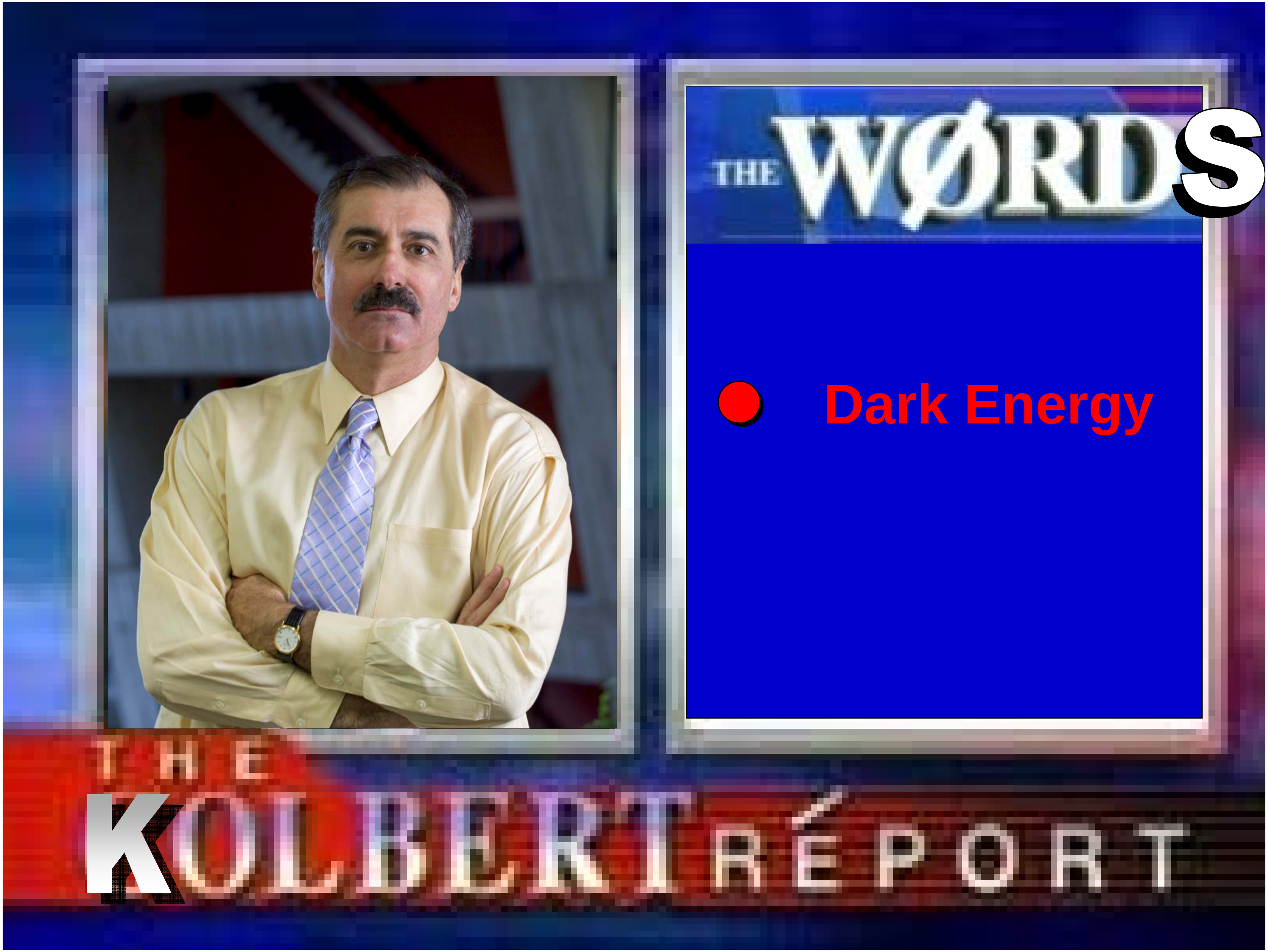
THE WØRDS
Dark Energy
THE KOLBERT RÉPORT

Back-up Background Slides
(NOT DETF)

How We "Know" There Is Dark Energy

- Assume model cosmology:
  - Friedmann equation ($G_{00} = 8\pi G\, T_{00}$): $H^2 + k/a^2 = 8\pi G\rho / 3$
  - Energy (and pressure) content: $\rho = \rho_M + \rho_R + \rho_\Lambda + \ldots$
  - Input or integrate over cosmological parameters: H_0, *etc*.

- Calculate observables $d_L(z), d_A(z), \ldots$

- Compare to observations

- Model cosmology fits with ρ_Λ, but not without ρ_Λ

- All evidence for dark energy is *indirect*: observed $H(z)$ is *not* described by $H(z)$ calculated from the Einstein-de Sitter model (Friedmann-Lemaître-Robertson-Walker model with $k = 0$; $\rho = \rho_M$)

Evolution of $H(z)$ Is a Key Quantity

Robertson–Walker metric

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Many observables based on
the comoving distance *r*(*z*)

$$\int_0^{r(z)} \frac{dr'}{\sqrt{1-kr'^2}} = \int_0^t \frac{dt'}{a(t')} = \int_0^z \frac{dz'}{H(z')}$$

- Physical distance

$$D(z) \propto r(z)$$

- Luminosity distance
  Flux = Luminosity / $4\pi\, d_L{}^2$

$$d_L(z) \propto r(z)(1+z)$$

- Angular diameter distance
  Angular diameter = Physical size / d_A

$$d_A(z) \propto r(z)/(1+z)$$

- Number counts in a volume $dV(z)$

$$dV(z) \propto \left[r^2(z)/H(z)\right] dz\, d\Omega$$

- Age of the universe

$$t(z) \propto \int_0^z \frac{dz'}{(1+z')H(z')}$$

Growth of structure

Growth of structure in FLRW:

$$\ddot{\delta}_i + 2H\dot{\delta}_i = 4\pi G\rho_0 \sum_j \frac{\rho_j}{\rho_0}\delta_j + ?$$

- $H = H$(dark energy)
- Modified gravity: additional term on r.h.s.

Phenomenology

- Model expansion rate of the Universe with $(\Sigma\, \Omega_i = 1)$
  - Matter: ρ_M / a^{-3} Ω_M
  - Radiation: ρ_R / a^{-4} Ω_R
  - Dark Energy: ρ_{DE} / $a^{-3[1+w(z)]}$ Ω_{DE} $(?{-1} \leq w \leq -1/3)$
  - Curvature: ρ_k / a^{-2} $\Omega_k = 1 - \Omega_{DE} - \Omega_M - \Omega_R$
- In typical model cosmology there are something like 8 cosmological parameters.

  Dark energy: $w(z) = w_0 + w_a(1-a) = w_0 + w_a\, z/(1+z)$ and Ω_{DE}
- All parameterizations of $w(z)$ are quirky
- Cosmological constant: $w_0 = -1$ and $w_a = 0$
- Theory predictions dense in w_0 and w_a
- No magic goal (say w_0 to 1% or w_a to 3%).

DETF Science Goals

The goal of dark-energy science is to determine the very nature of the dark energy that causes the Universe to accelerate and seems to comprise most of the mass-energy of the Universe.

1. Exclude ΛCDM ($w_0 = -1$ and $w_a = 0$), *i.e.,* a null hypothesis test
2. If it is not due to a constant, probe the underlying dynamics by measuring as well as possible the time evolution of dark energy, for example by measuring $w(a)$.
3. Search for a possible failure of GR through comparison of cosmic expansion with growth of structure.
4. Precise determination of Ω_Λ is not that crucial.*

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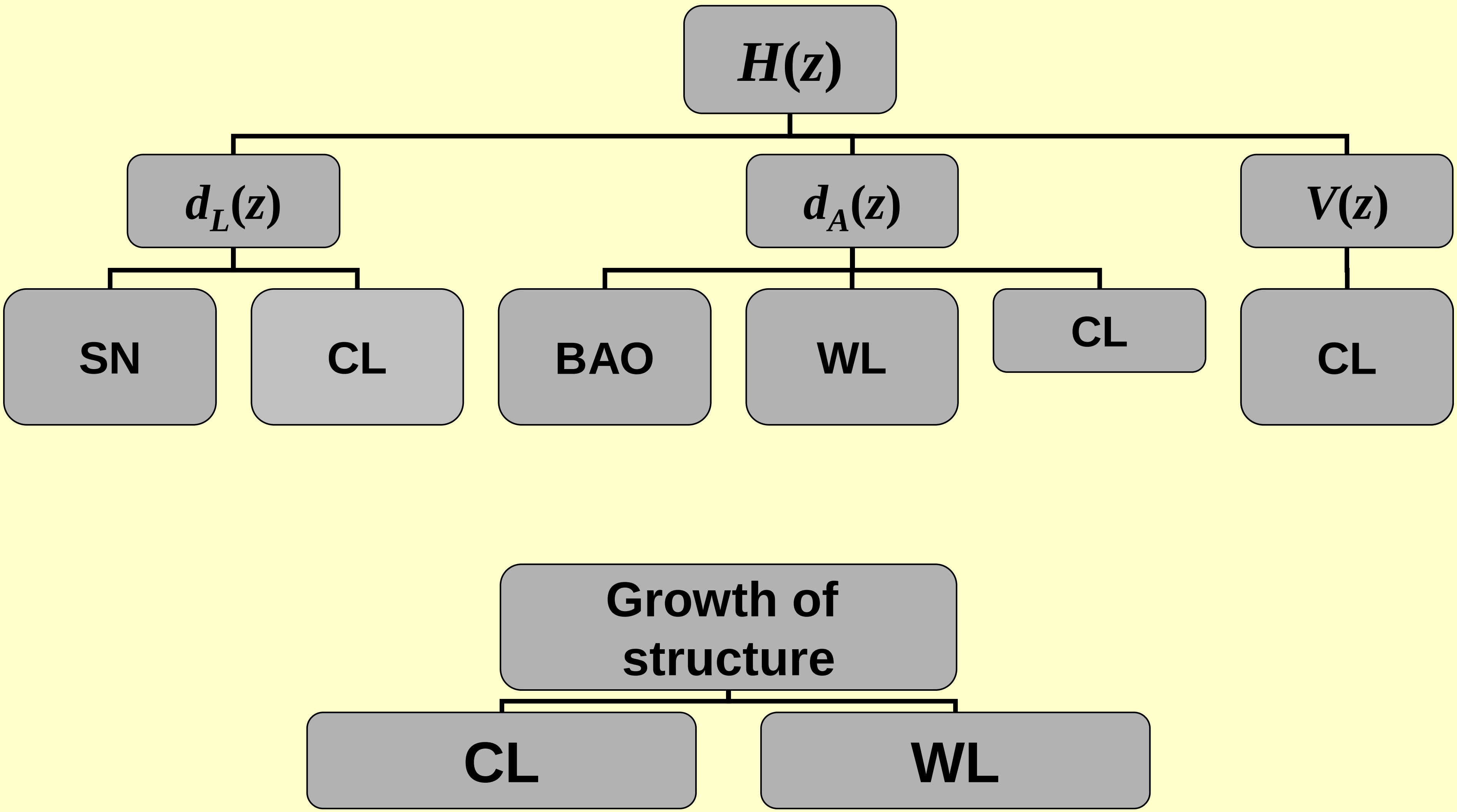
* Present theoretical predictions for Ω_Λ are off by 120 orders-of-magnitude, so don't require much precision.

Observational program



Supernova Type IA

Inverse-square law: Flux = Luminosity / $4\pi\, d_L^2$ $\quad d_L(z) \propto r(z)(1+z)$

$r(z)$ determined from $\displaystyle\int_0^{r(z)} \frac{dr'}{\sqrt{1-kr'^2}} = \int_0^z \frac{dz'}{H(z')}$

$$H^2(z) = H_0^2(z)\left[\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{DE}(1+z)^{3[1+w(z)]}\right]$$

$$\Omega_M + \Omega_k + \Omega_{DE} = 1$$

- Have to measure redshift and intensity as fn. of time (light curve)
- Systematics (dust, evolution, intrinsic luminosity dispersion, etc.)
- Present procedure:
  - Discover SNe by wide-area survey (the “easy” part)
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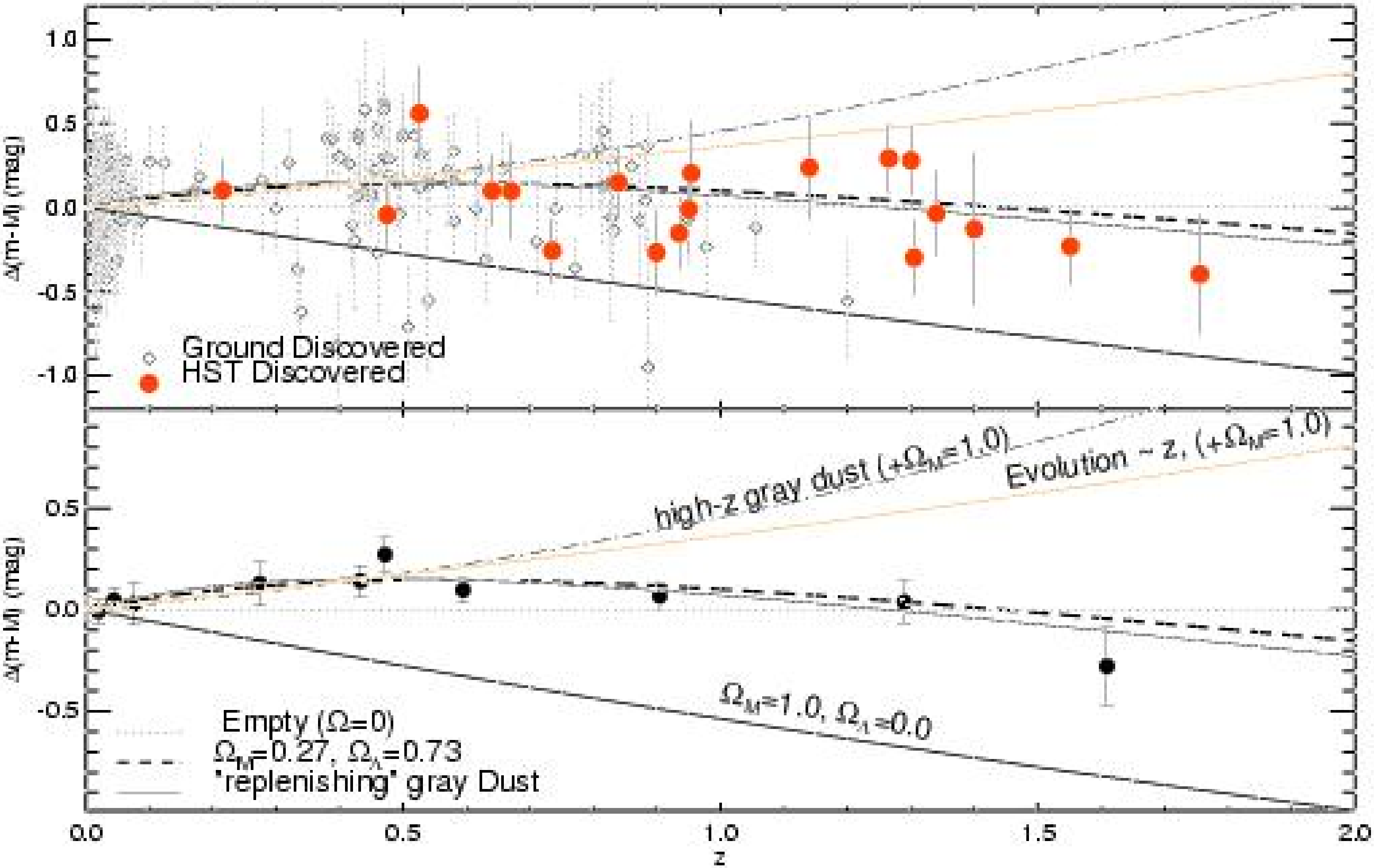
Supernova Type IA



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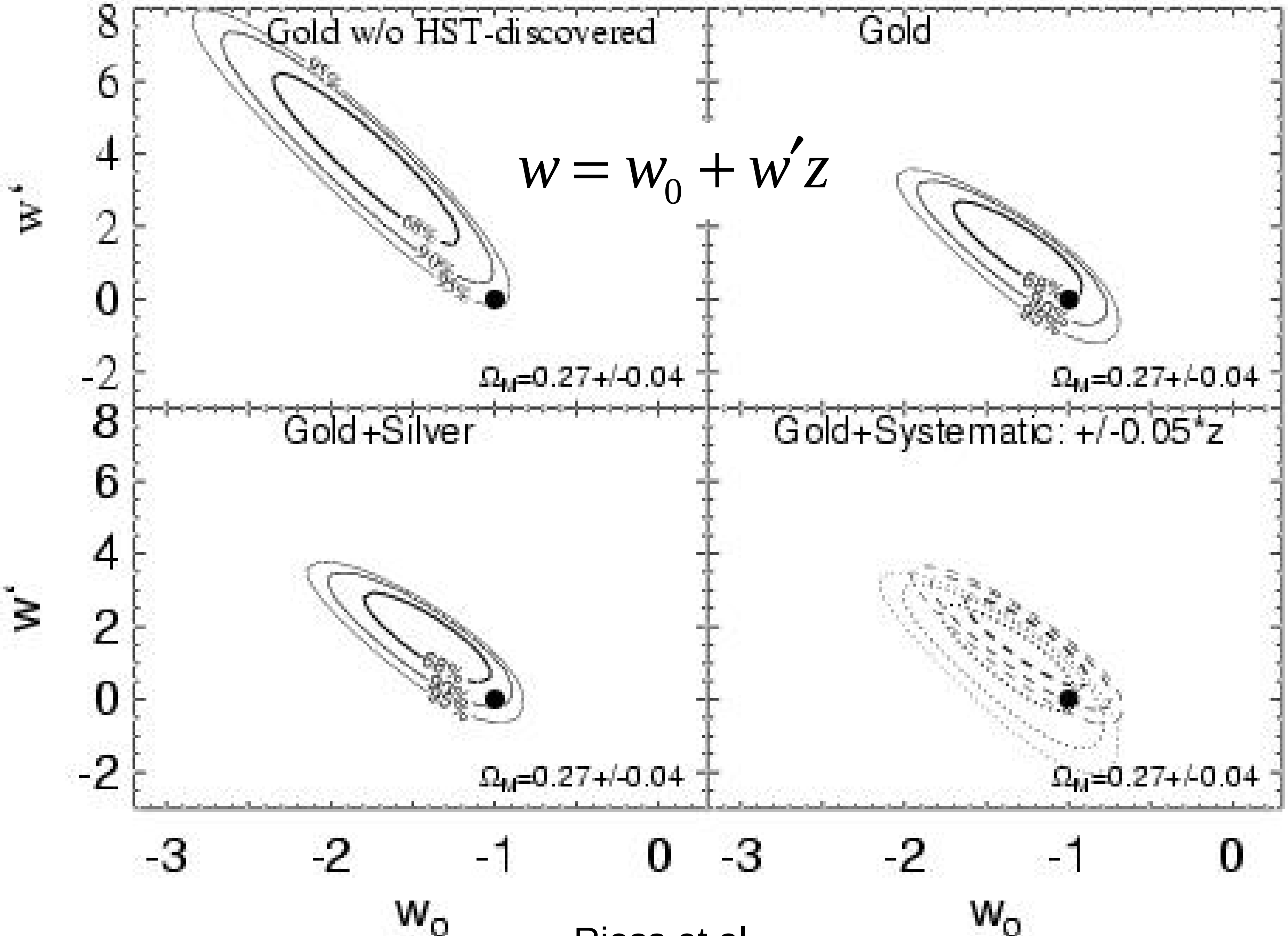
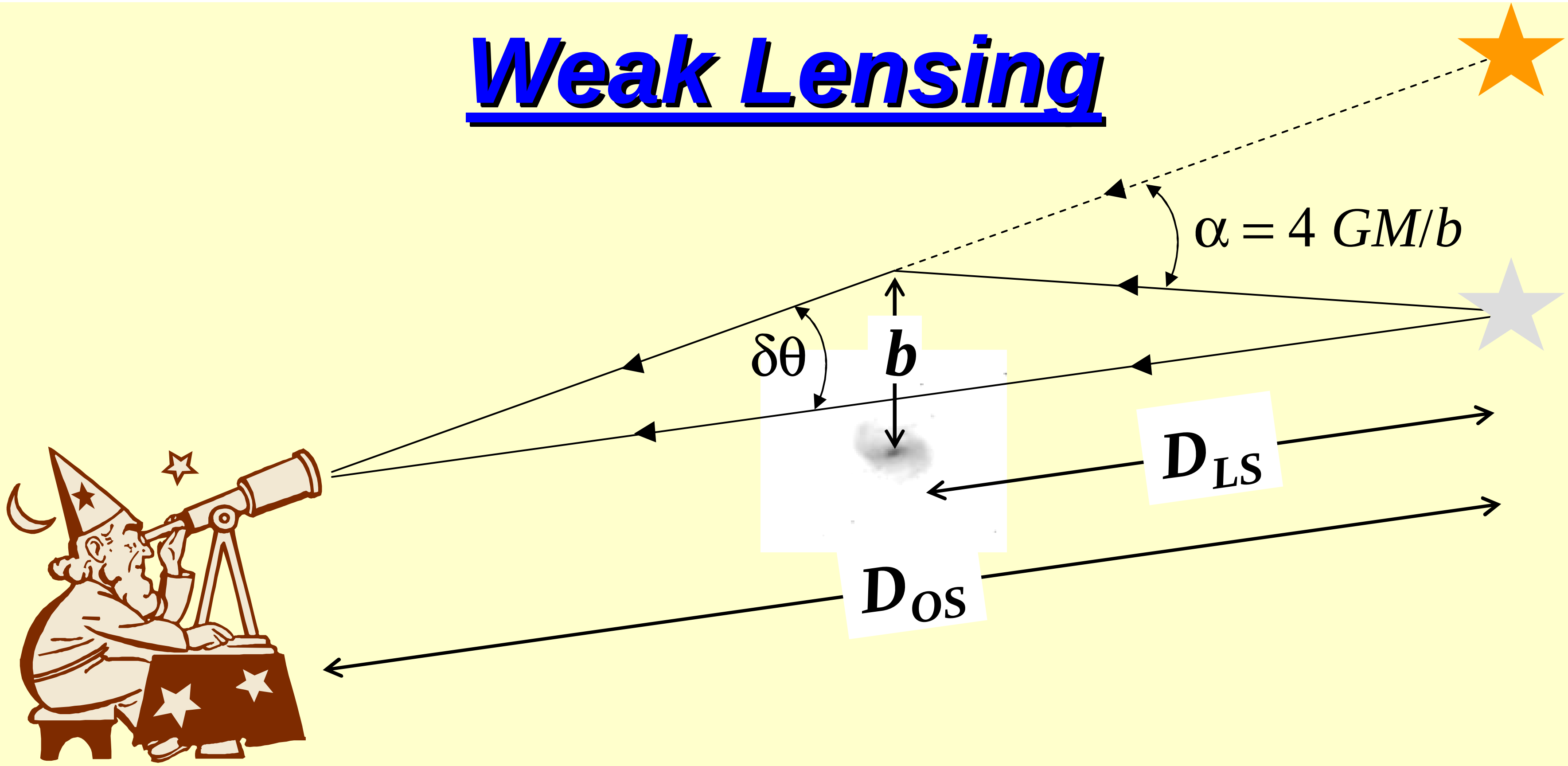


$$w = w_0 + w'z$$

Riess et al.

Weak Lensing



observe deflection angle

$$\delta\theta = \frac{4GM}{b}\frac{D_{LS}}{D_{OS}}$$

dark energy affects geometric distance factors

dark energy affects growth rate of *M*

Weak Lensing

The signal from any single galaxy is *very* small,
but there are a *lot* of galaxies! Require photo-z's?

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  - use stars to correct
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- DES (2009)
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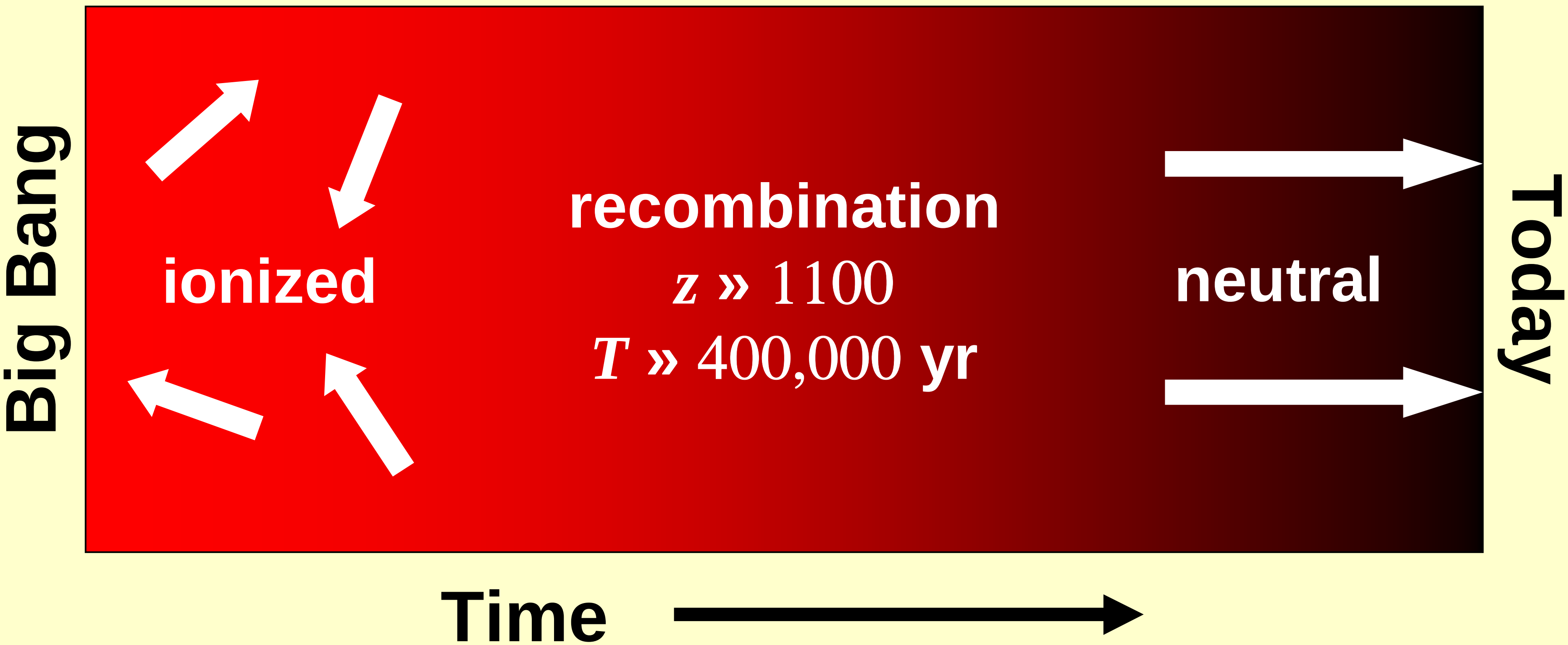
Baryon Acoustic Oscillations

Pre-recombination

- universe ionized
- photons provide enormous pressure and restoring force
- perturbations oscillate (acoustic waves)

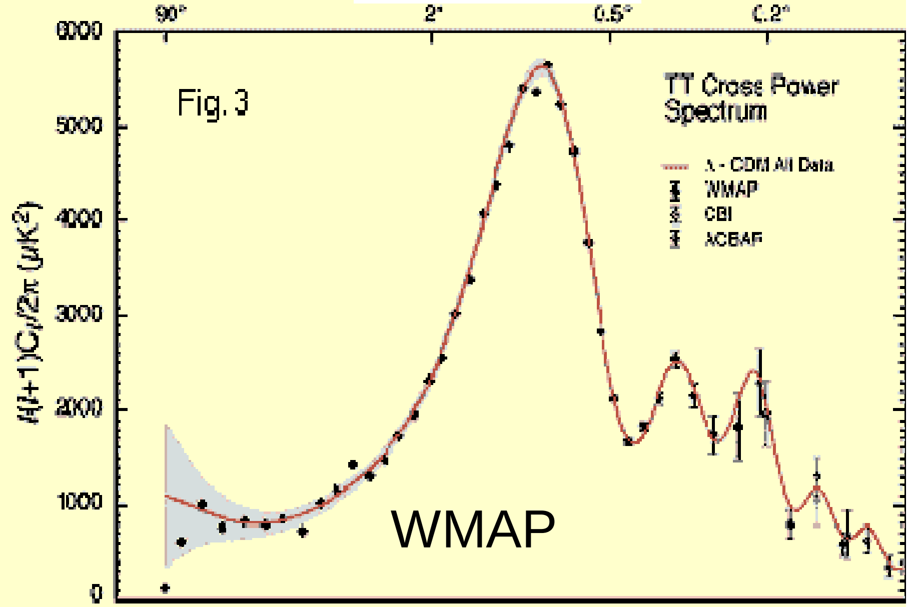
Post-recombination

- universe neutral
- photons travel freely (decouple from baryons)
- perturbations grow (structure formation)



Baryon Acoustic Oscillations

- Each overdense region is an overpressure that launches a spherical sound wave
- Wave travels outward at $0.57c$
- Photons decouple, travel to us and observable as CMB acoustic peaks



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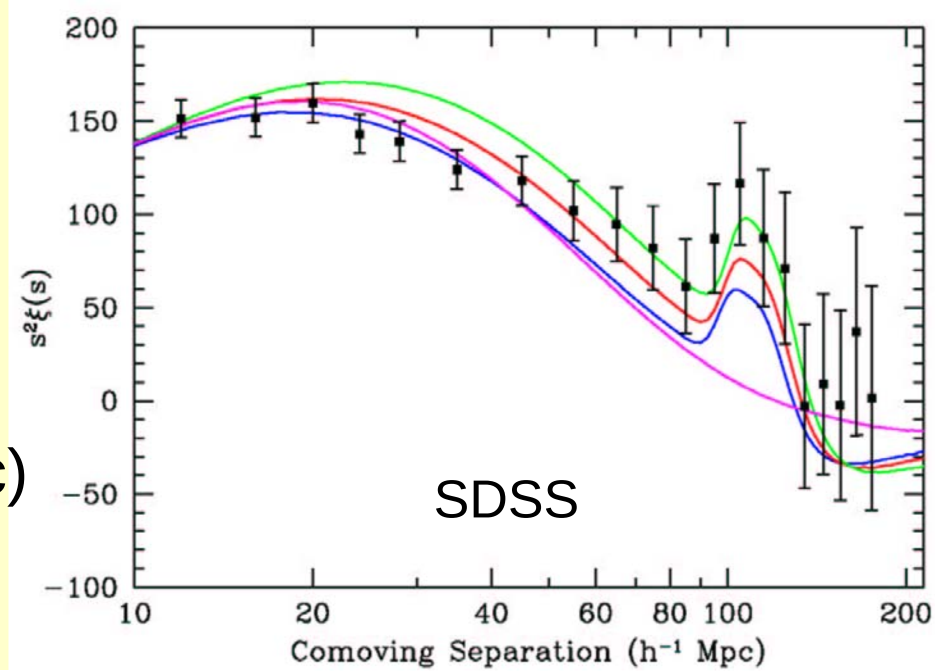

Baryon Acoustic Oscillations

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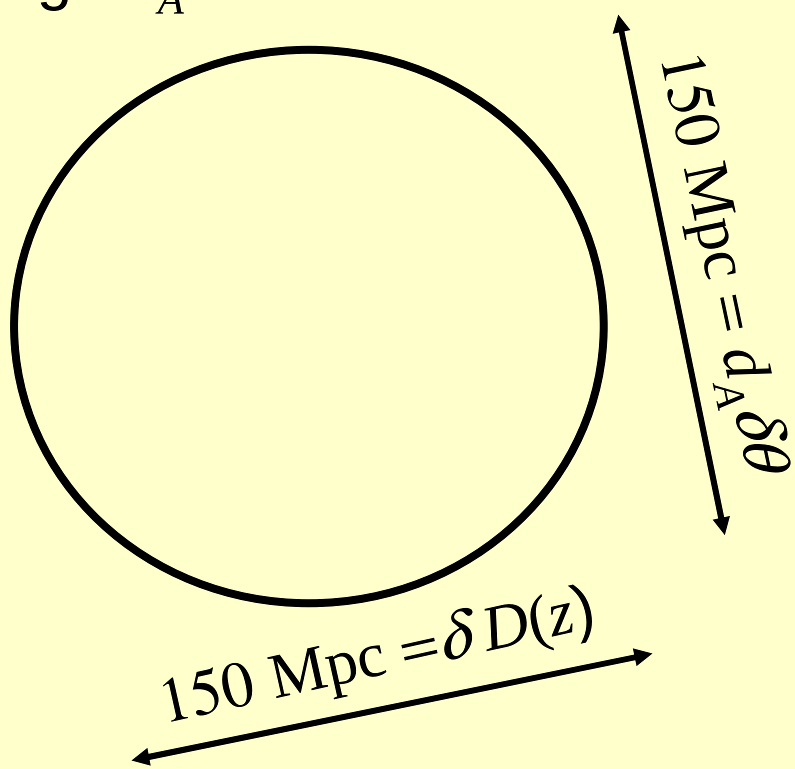

Baryon Acoustic Oscillations

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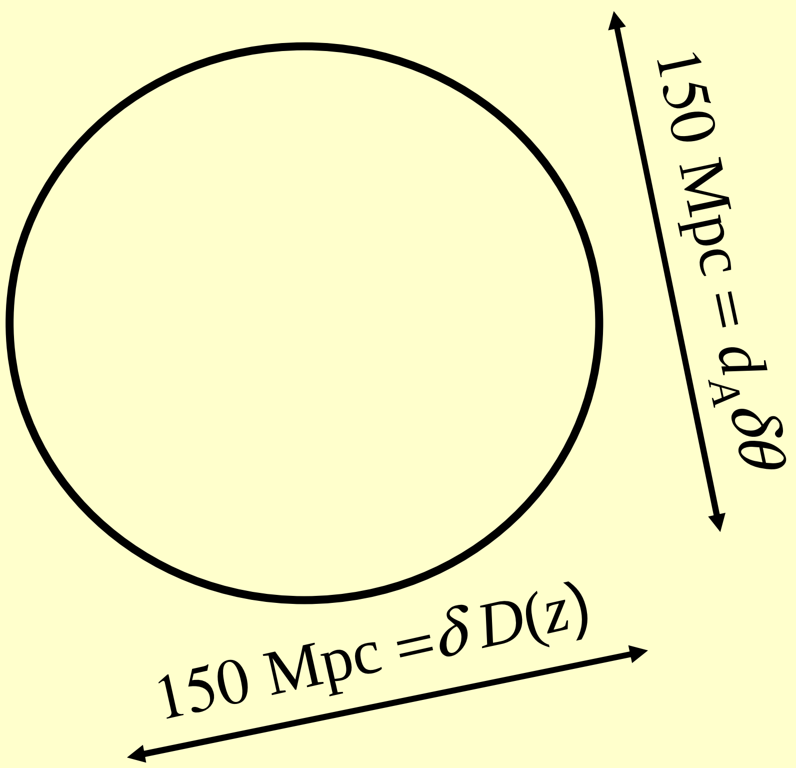

Clusters

Cluster redshift surveys measure

- cluster redshift distribution
- cluster mass distribution as function of z
- spatial clustering of clusters

Sensitivity to dark energy

- volume-redshift relation
- angular-diameter distance–redshift relation
- growth rate of structure
- power spectrum shape (transfer fn.)

Cluster selection must be well understood

- “by eye” in optical samples
- ICM properties (x-ray, SZE effect)
- weak lensing shear
- best probably x-ray or SZE with optical confirmation
- need photo-z’s

Clusters

Things to learn

- photo-z's
- proxy for cluster mass
- spatial clustering of clusters
- "self-calibration"
- numerical simulations of structure formation

Things to work on

- theory of structure formation/halo mass fn. and evolution
- cluster selection
- cluster mass proxy

What's Ahead

2006 — 2010 — 2015

Lensing
CFHTLS SUBARU DES, VISTA DUNE LSST SKA
DLS SDSS ATLAS KIDS Hyper suprime Pan-STARRS JDEM

BAO
FMOS LAMOST DES, VISTA,VIRUS WFMOS LSST SKA
SDSS ATLAS Hyper suprime Pan-STARRS JDEM

SNe
CFHT CSP ESSENCE DES LSST
SDSS CFHTLS Pan-STARRS JDEM

Clusters
AMI APEX SPT DES
XCS SZA AMIBA ACT

CMB
WMAP 2/3 WMAP 6 yr
Planck Planck 4yr

2005 — 2010 — 2015

Large Resources

Not all on same cost basis
My estimate of costs

DES	$18M
Darkcam	$18M
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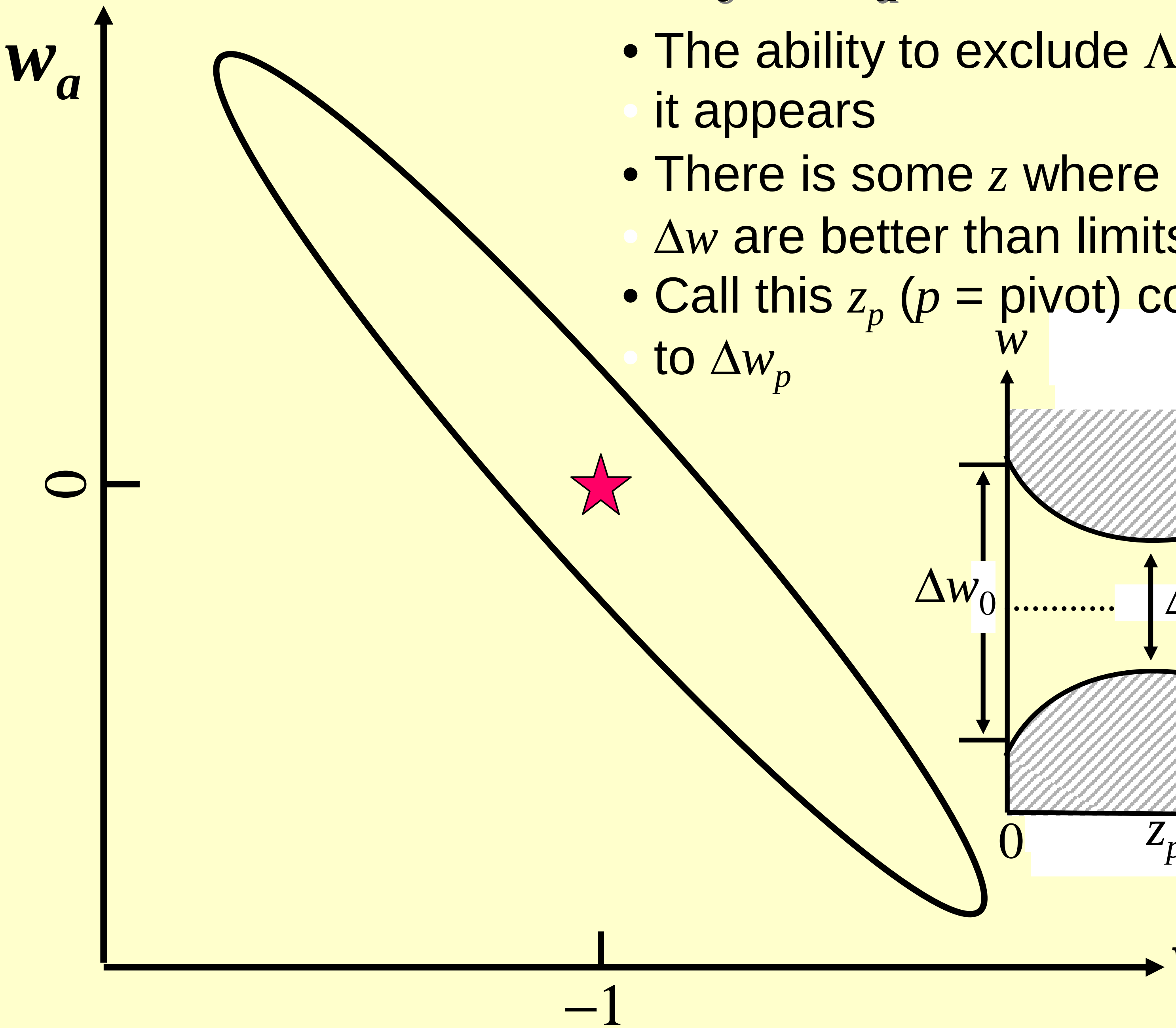
HETDEX	$25M
HyperSuprime	$20M
WFMOS	$60M
Total	$211M
and later……..	
LSST	$500M
SKA	$700m
JDEM	$600M–$1B
Total	$1.8B–$2.2B
Grand total	$2B–$2.4B

$w(a) = w_0 + w_a(1-a)$



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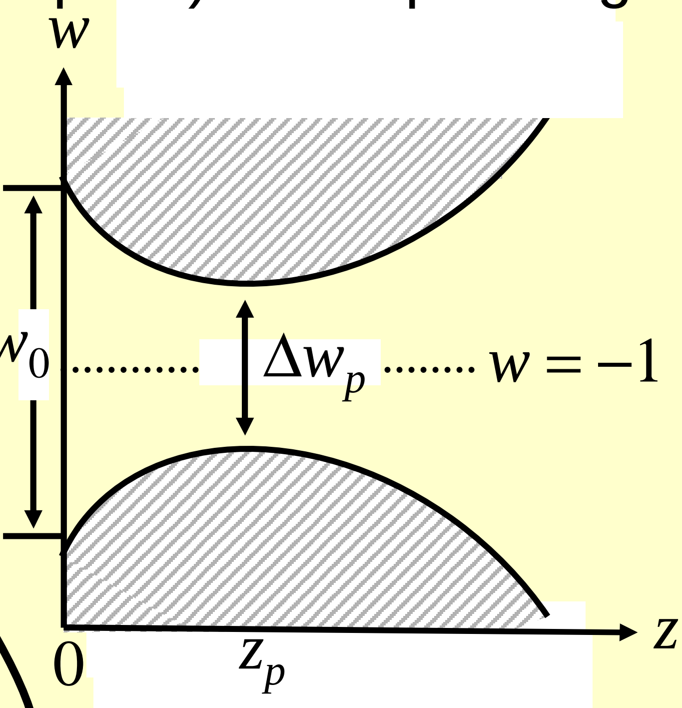
- Call this z_p (p = pivot) corresponding to Δw_p



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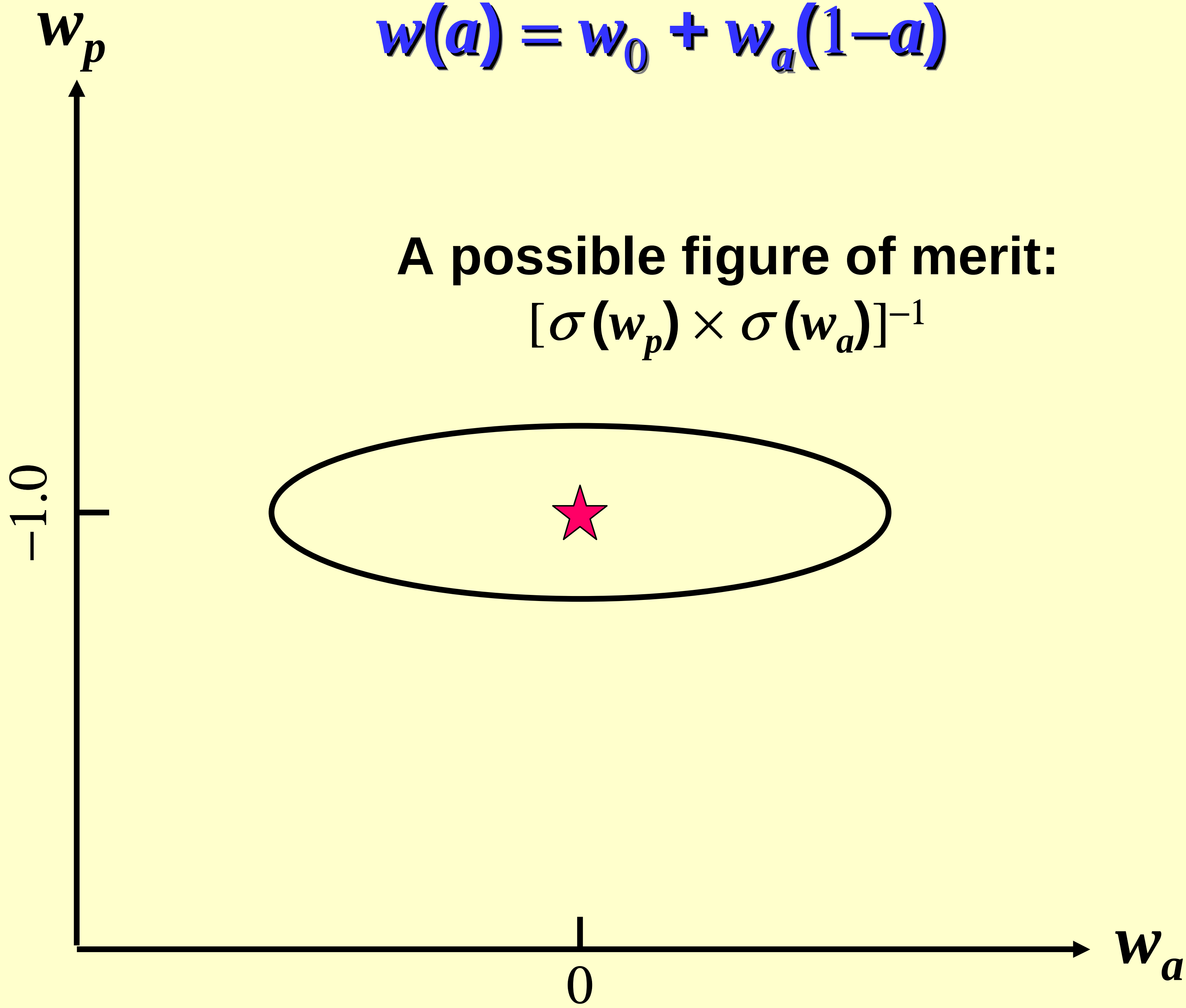
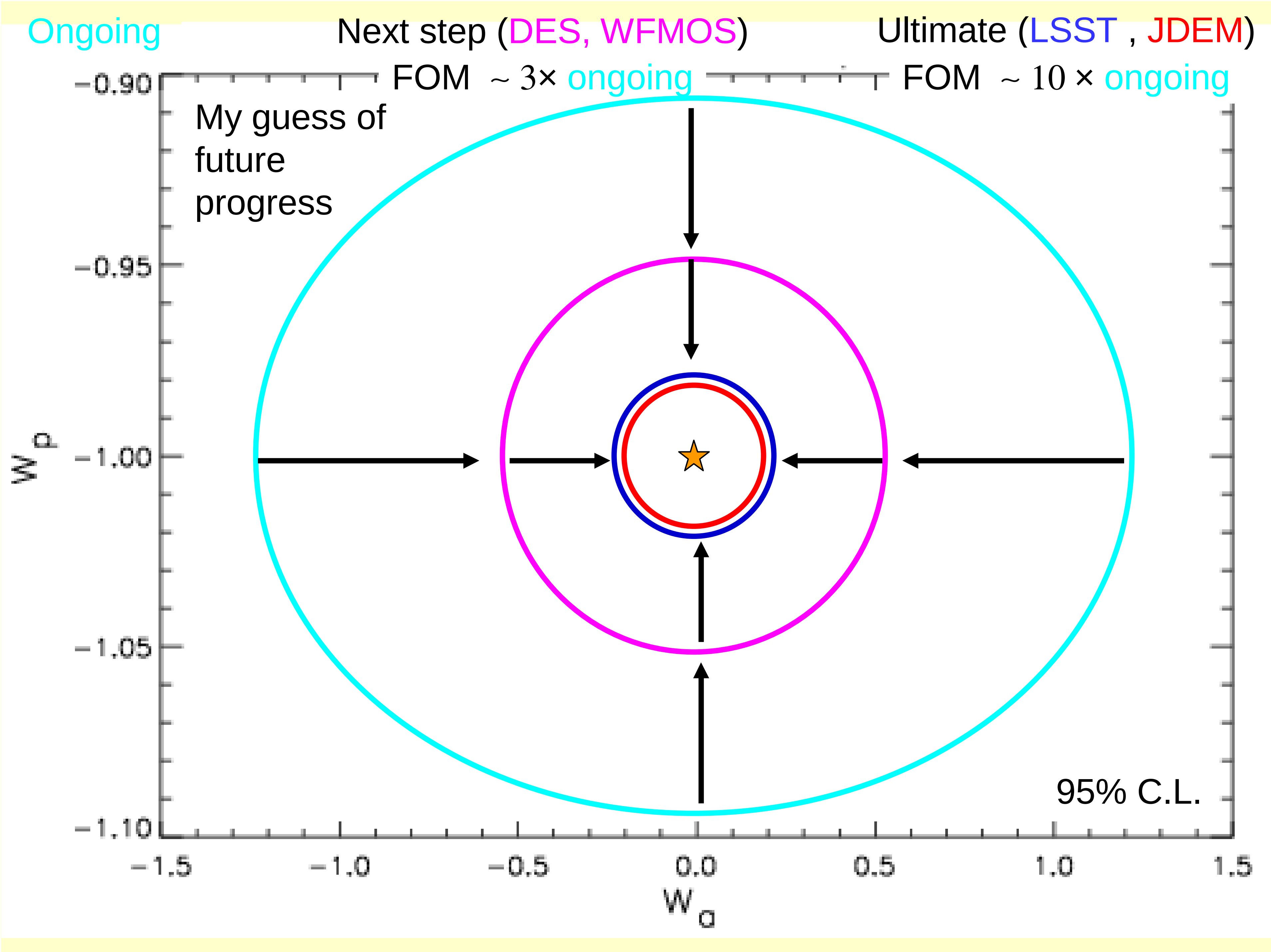


A possible figure of merit:

$$[\sigma(w_p) \times \sigma(w_a)]^{-1}$$


Ongoing
Next step (DES, WFMOS)
Ultimate (LSST , JDEM)
FOM ~ 3× ongoing
FOM ~ 10 × ongoing
My guess of future progress
95% C.L.
−0.90
−0.95
−1.00
−1.05
−1.10
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
w_p
w_a

Conclusions

The expansion history of the universe, $H(z)$, is not described by Einstein-de Sitter. Evidence:

1. Well established: Supernova Ia
2. Circumstantial: subtraction, age, structure formation, …
3. Emergent techniques: baryon acoustic oscillations, clusters, weak lensing

Explanations:

1. Dark energy
   - "constant" vacuum energy "Λ"
   - time varying vacuum energy (low-mass scalar fields)
2. Modification of GR
   - growth rate of structure modified
3. Standard cosmological model (FLRW) not applicable
   - Should make predictions for cosmological observables: effective $H(z)$

Phenomenology:

1. $w(z)$: w_0, w_a
2. Figure of merit: $w_0 \times w_a$
3. Order of magnitude improvement in figure of merit feasible

BAO

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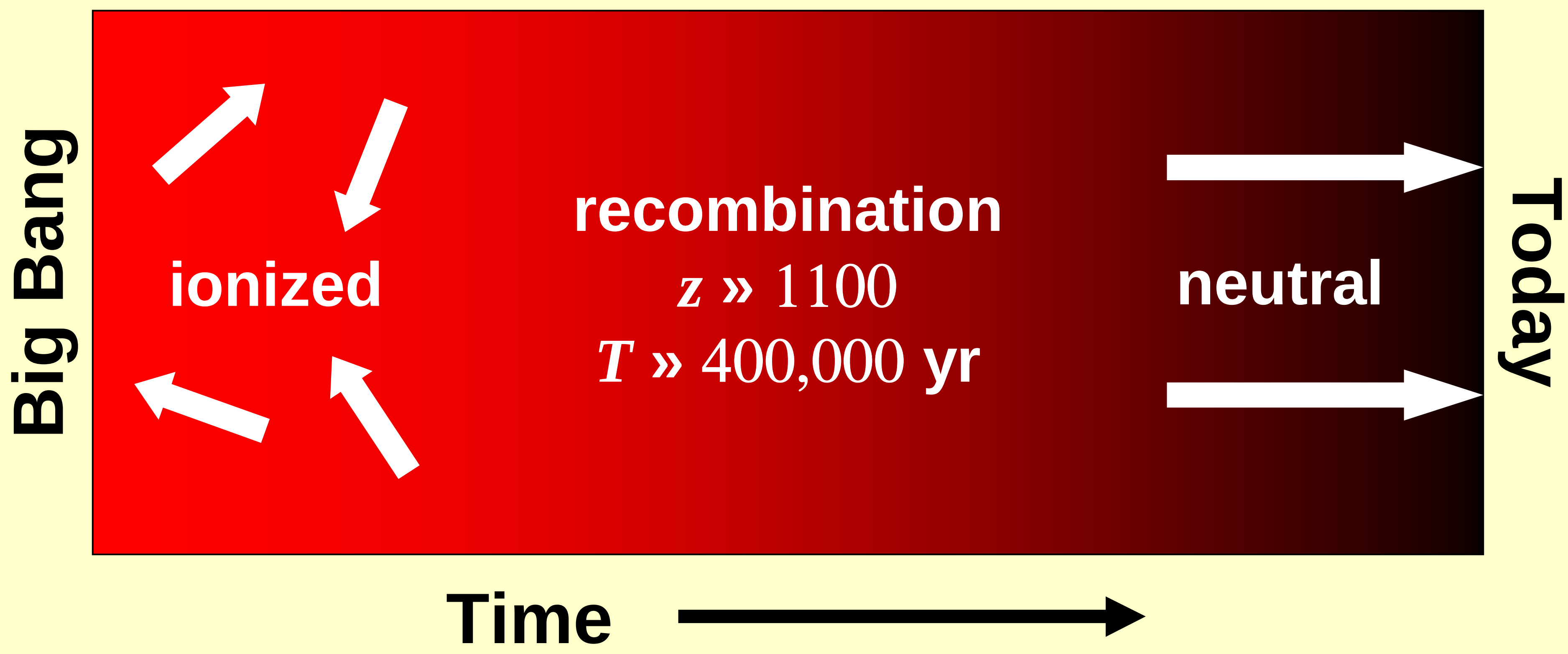

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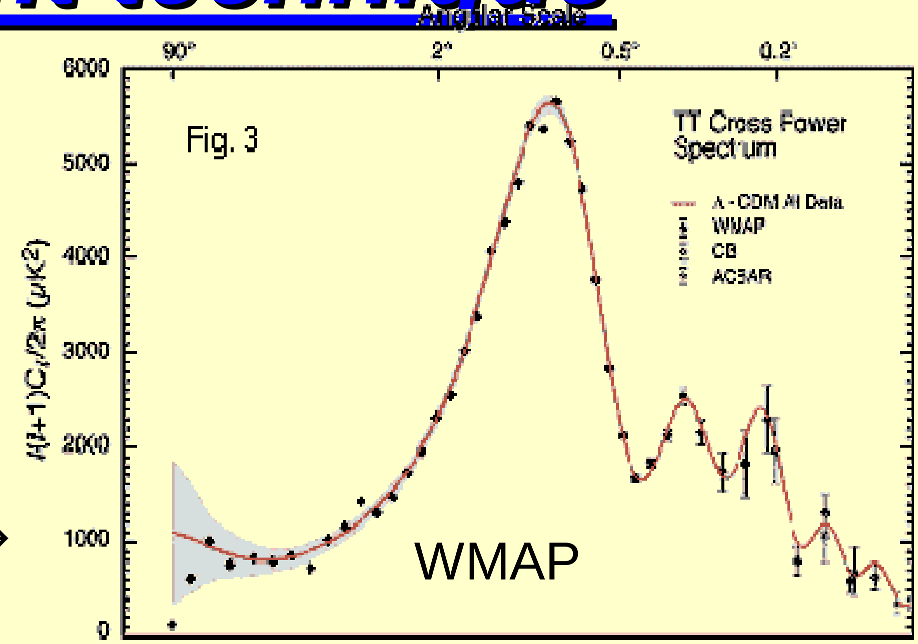

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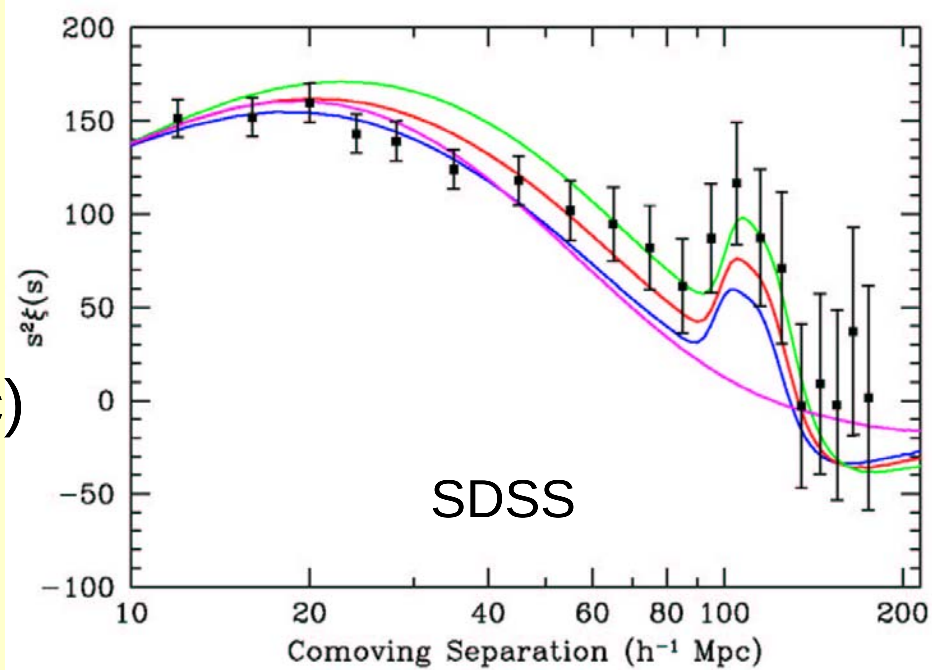

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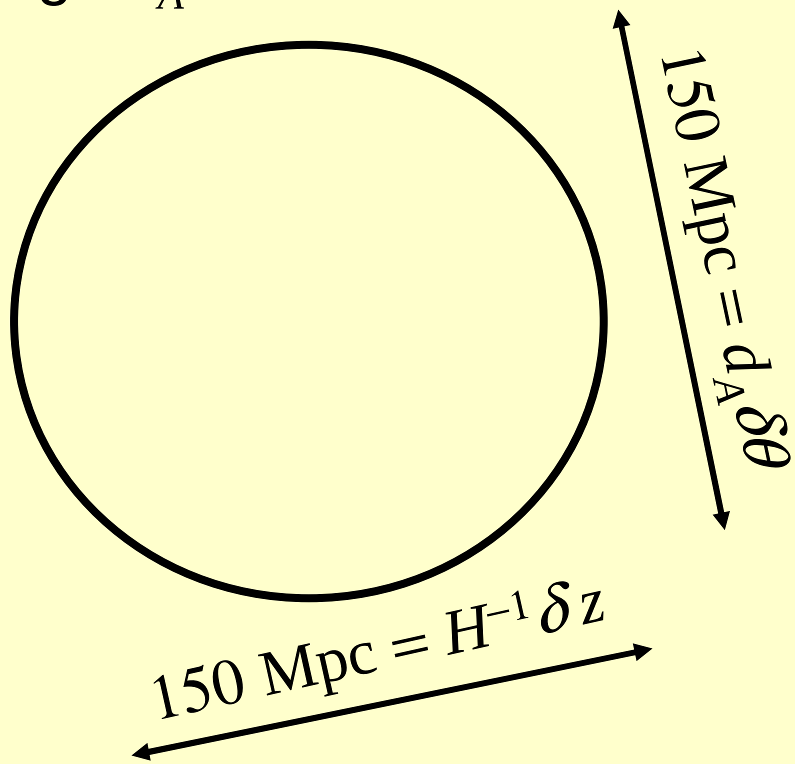

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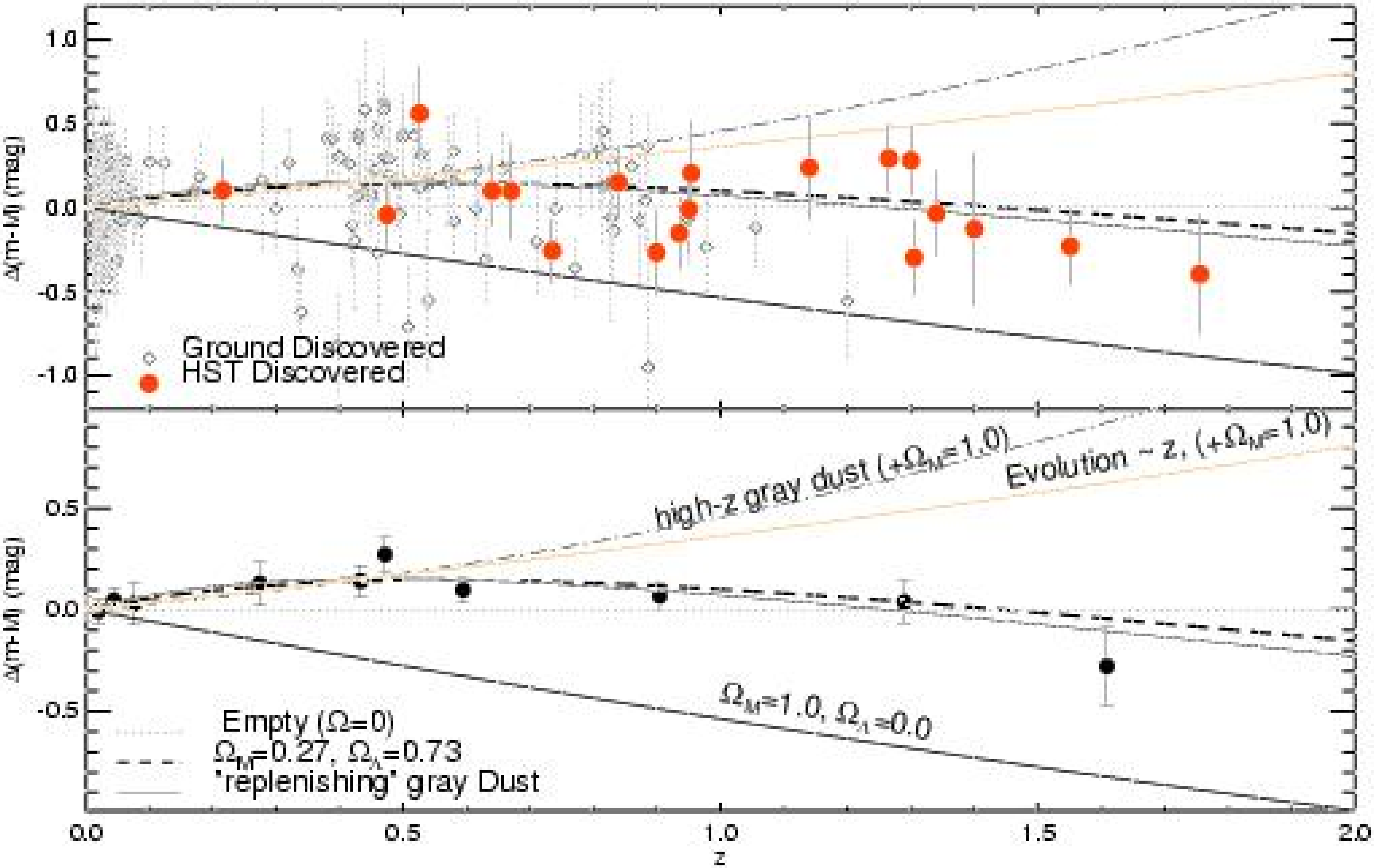

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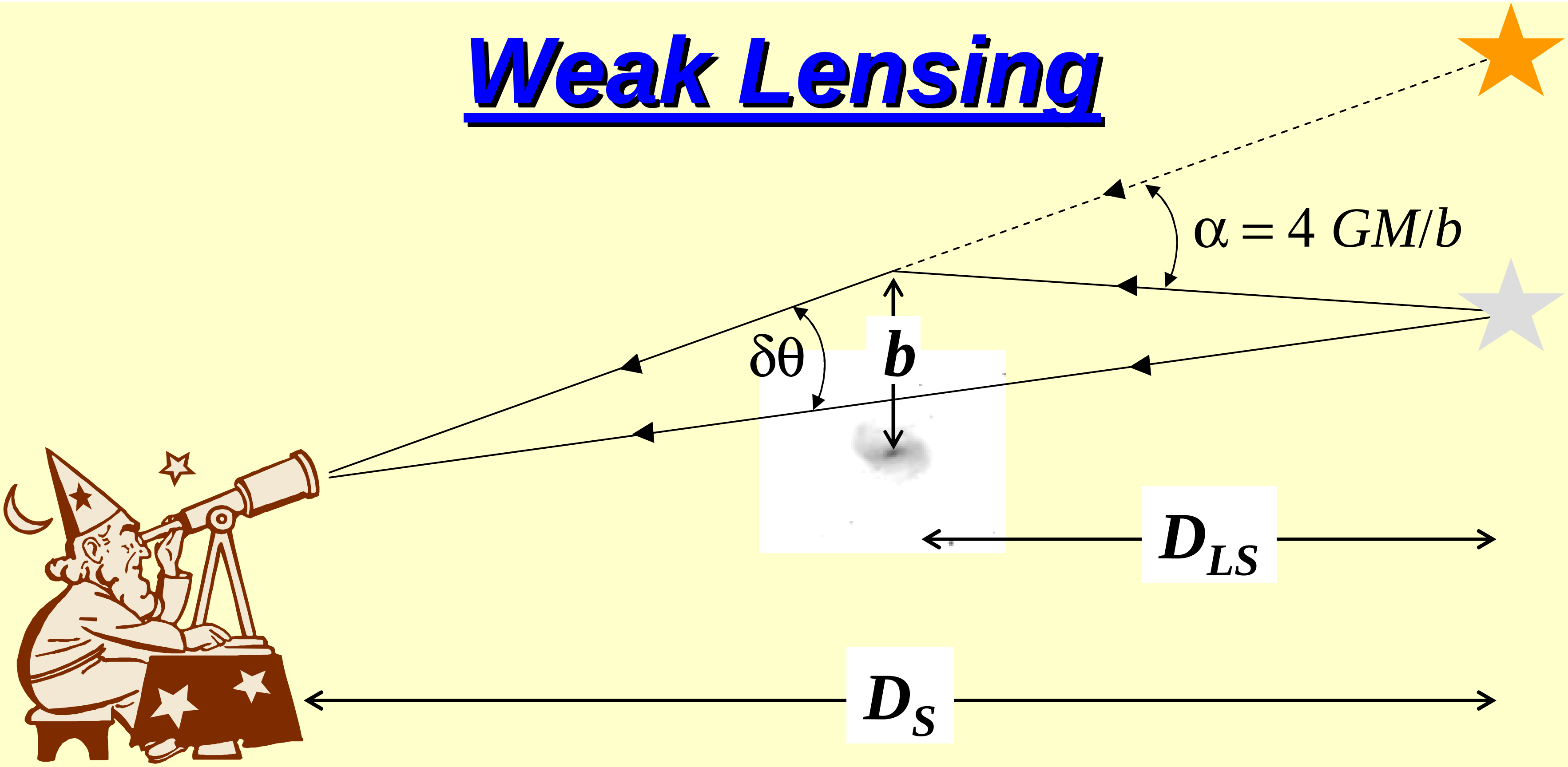

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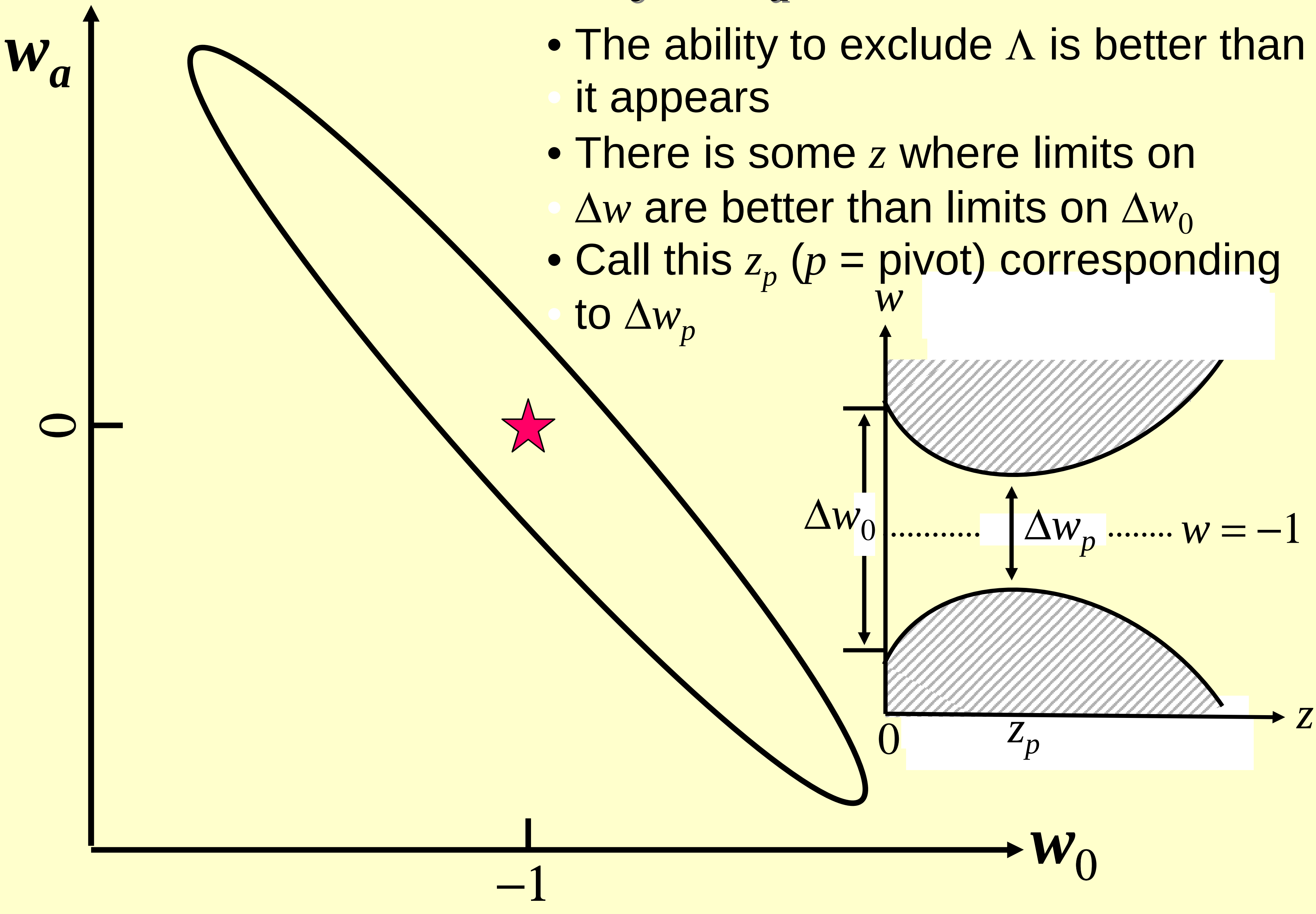

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