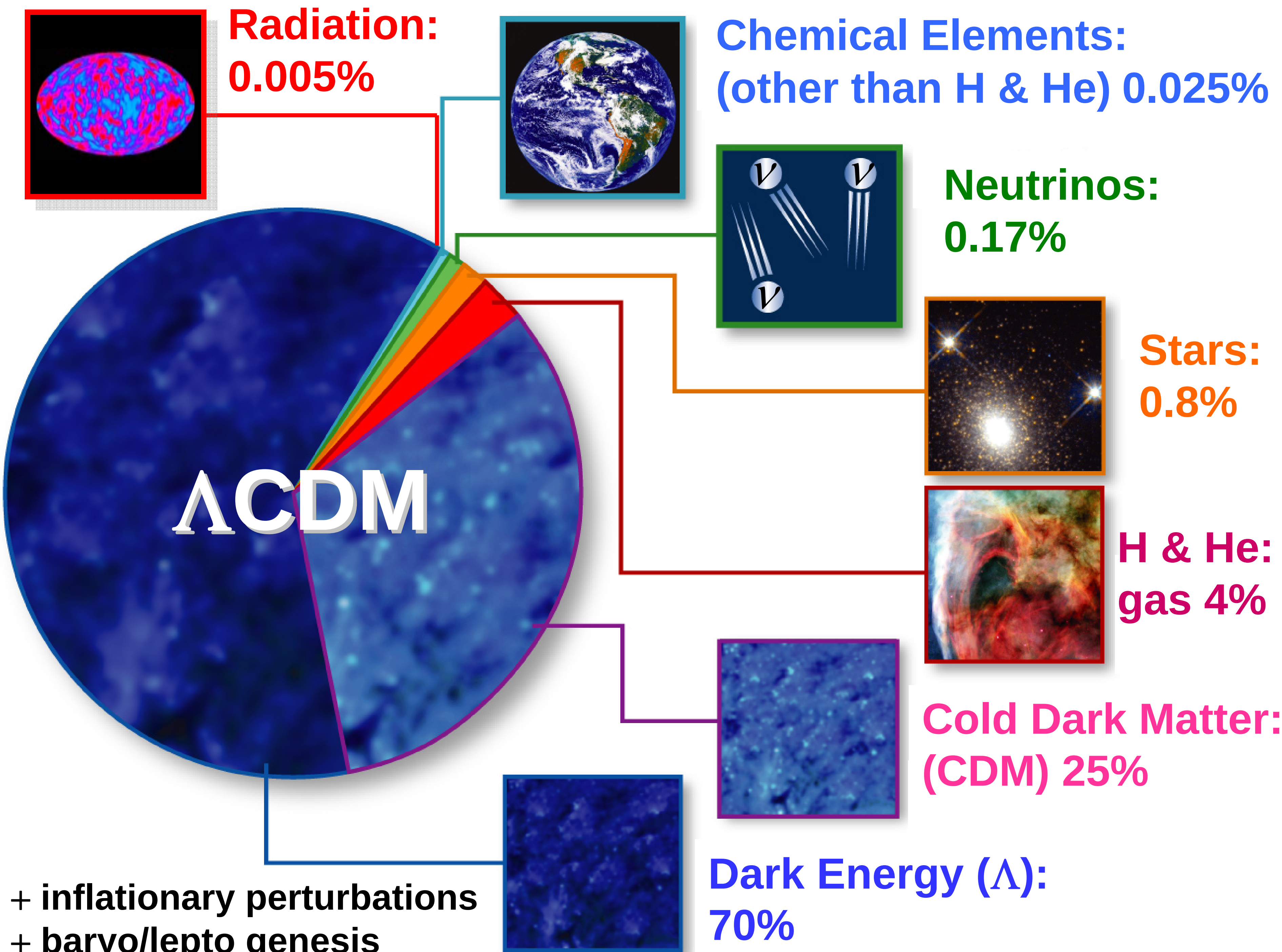
The Dark Universe: Dark Matter and Dark Energy

Rocky I:	The Universe Observed	Monday
Rocky II:	Inflation	Tuesday
Rocky III:	Dark Matter	Wednesday
Rocky IV:	Dark Energy	Thursday

CERN Academic Training Lectures **January 2008**

Rocky Kolb *The University of Chicago*



Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
Stars:
0.8%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM
+ inflationary perturbations
+ baryo/lepto genesis

Evidence for Dark Energy

Measuring the expansion history of the Universe

Expansion Rate Is a Key Quantity

Friedmann equation ($G_{00} = 8\pi G T_{00}$) : Expansion rate $H(z)$

Hubble's constant — curvature — matter — radiation — dark energy

$$H^2(z) = H_0^2\left[\left(1-\Omega_{\mathrm{TOTAL}}\right)(1+z)^2 + \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_w (1+z)^{3(1+w)}\right]$$

CMB — LSS — CMB — $H(z)$

Equation of state parameter: $w = p/\rho$ ($w = -1$ for Λ)

if $w = w(a)$: $(1+z)^{3(1+w)} \rightarrow \exp\left(-3\int_a^1 \frac{da'}{a'}\left[1+w(a')\right]\right)$

Expansion Rate Is a Key Quantity

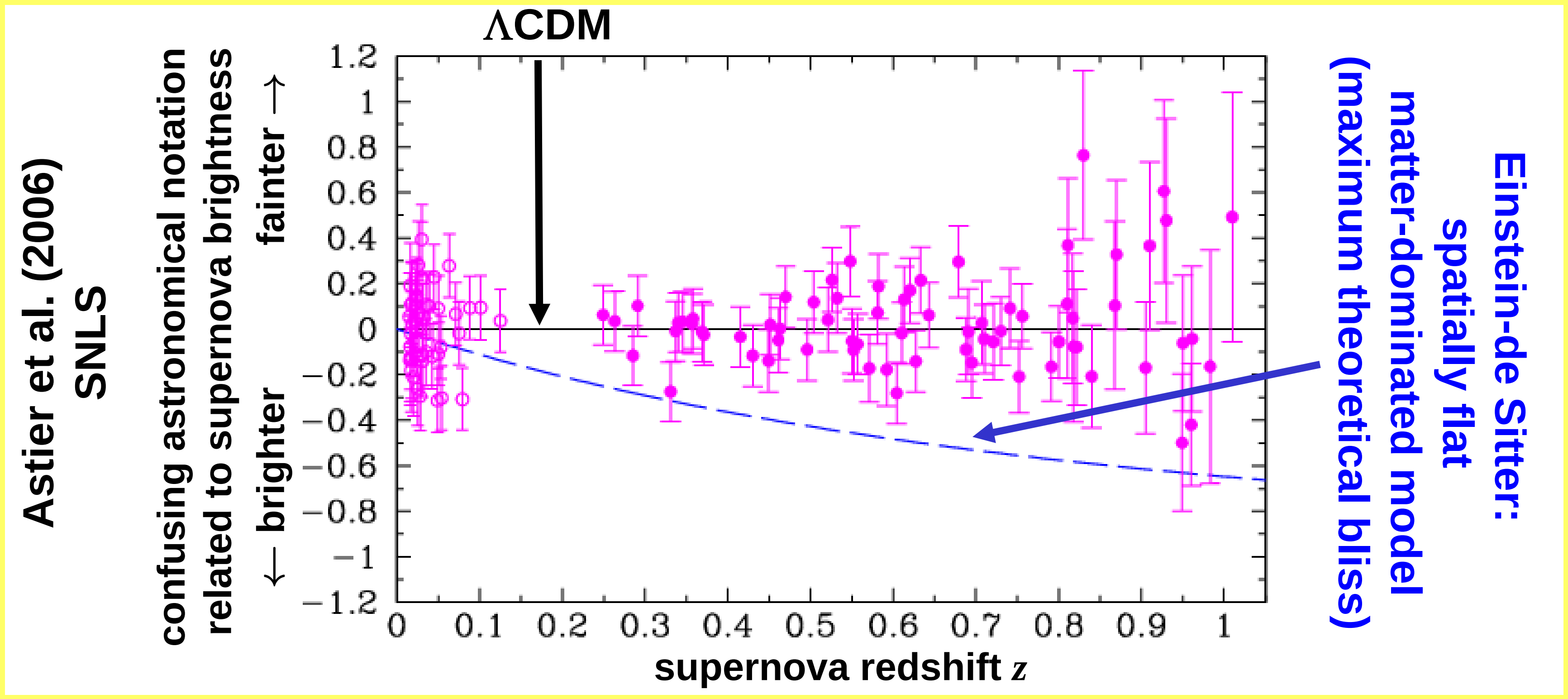
Many (all?) observables based on $H(z)$, e.g., through $\int \frac{dz}{H(z)}$

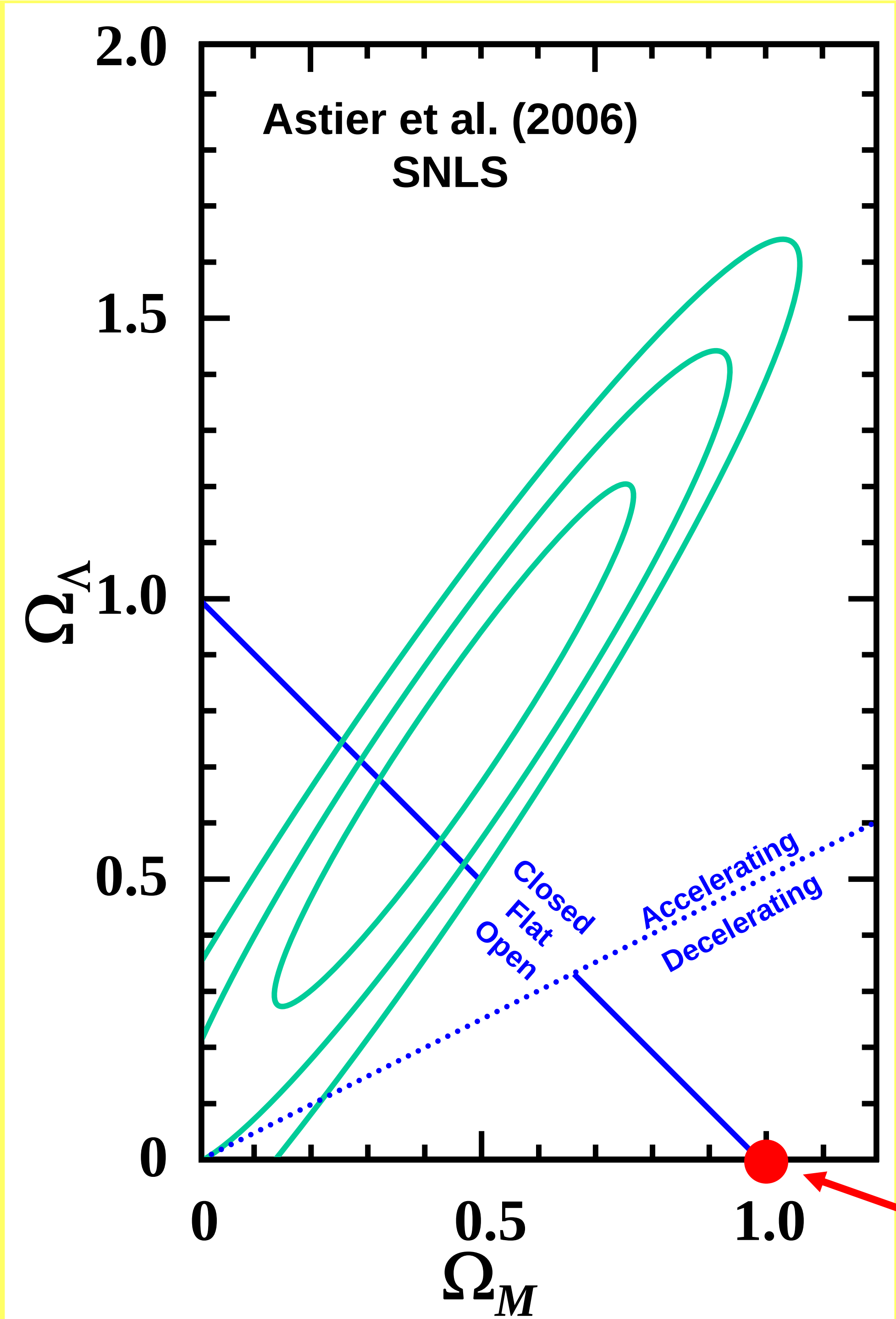
- Luminosity distance Flux = (Luminosity / $4\pi\, d_L{}^2$)
- Angular diameter distance $\alpha =$ Physical size / d_A
- Volume (number counts) $N \propto V^{-1}(z)$
- Age of the universe
- Distances

Evidence for Dark Energy

Luminosity—distance / redshift (Hubble) diagram

Evidence for Dark Energy





Evidence for Dark Energy

1. Find standard candle (SNe IA)
2. Observe magnitude & redshift
3. Assume a cosmological model
4. Compare observations & model

← { Assumes $w = -1$ (i.e., Λ)
Assumes priors on H_0, etc.

5. Fit needs cosmoillogical constant

$$\rho_V \sim 10^{-30}\ \mathrm{g\ cm}^{-3}$$

	ρ_V	$\Lambda = 8\pi G\rho_V$
mass scale	$(10^{-4}\ \mathrm{eV})^4$	$(10^{-33}\ \mathrm{eV})^2$
length scale	$(10^{-3}\ \mathrm{cm})^{-4}$	$(10^{+29}\ \mathrm{cm})^{-2}$

Einstein–de Sitter model

Why Illogical?

Illogical magnitude (what's it related to?):

	ρ_V	$\Lambda = 8\pi G\rho_V$
mass scale	$(10^{-4}\ \mathrm{eV})^4$	$(10^{-33}\ \mathrm{eV})^2$
length scale	$(10^{-3}\ \mathrm{cm})^{-4}$	$(10^{+29}\ \mathrm{cm})^{-2}$

Cosmoillogical Constant

All fields: harmonic oscillators with zero-point energy

$$\rho = \sum_{all\ particles} \pm \int d^3k \sqrt{k^2+m^2} \simeq \sum_{all\ particles} \pm \int^{\Lambda_C} dk\ k^3$$

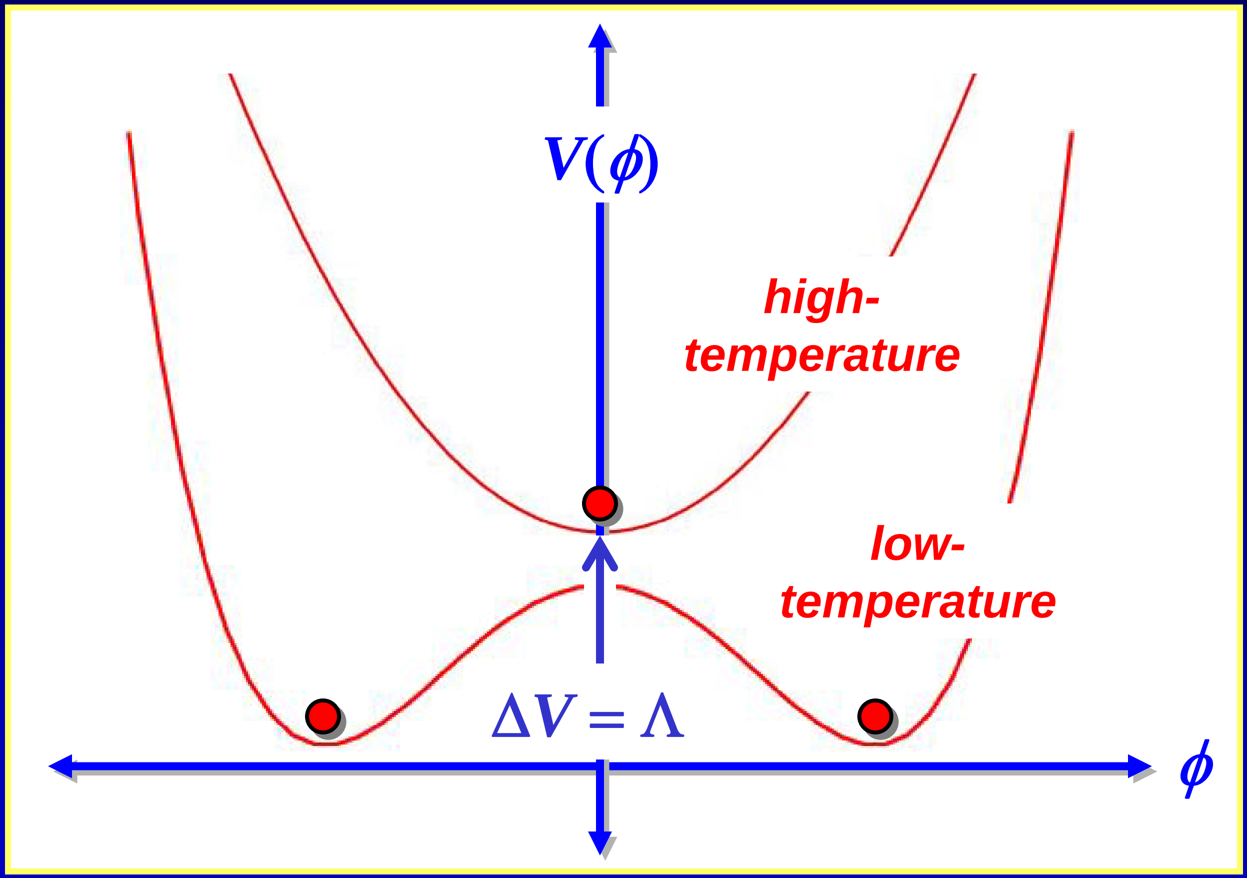
$$\Lambda_C = \infty: \quad \rho_\Lambda = \infty^4 \quad = \text{ relax, it's field theory}$$

$$\Lambda_C = M_{Pl}: \quad \rho_\Lambda = M_{Pl}^4 \quad = \left(10^{28}\ \text{eV}\right)^4 = 10^{112}\ \text{eV}^4$$

$$\Lambda_C = M_{SUSY}: \quad \rho_\Lambda = M_{SUSY}^4 \quad = \left(10^{12}\ \text{eV}\right)^4 = 10^{48}\ \text{eV}^4$$

$$\Lambda_C = 10^{-4}\text{eV}: \quad \rho_\Lambda = \rho_{\text{Observed}} \quad = \left(10^{-4}\ \text{eV}\right)^4 = 10^{-16}\ \text{eV}^4$$

Cosmoillogical Constant



GUT: 10^{100} eV^4 SUSY: 10^{48} eV^4

EWK: 10^{45} eV^4 CHIRAL: 10^{32} eV^4

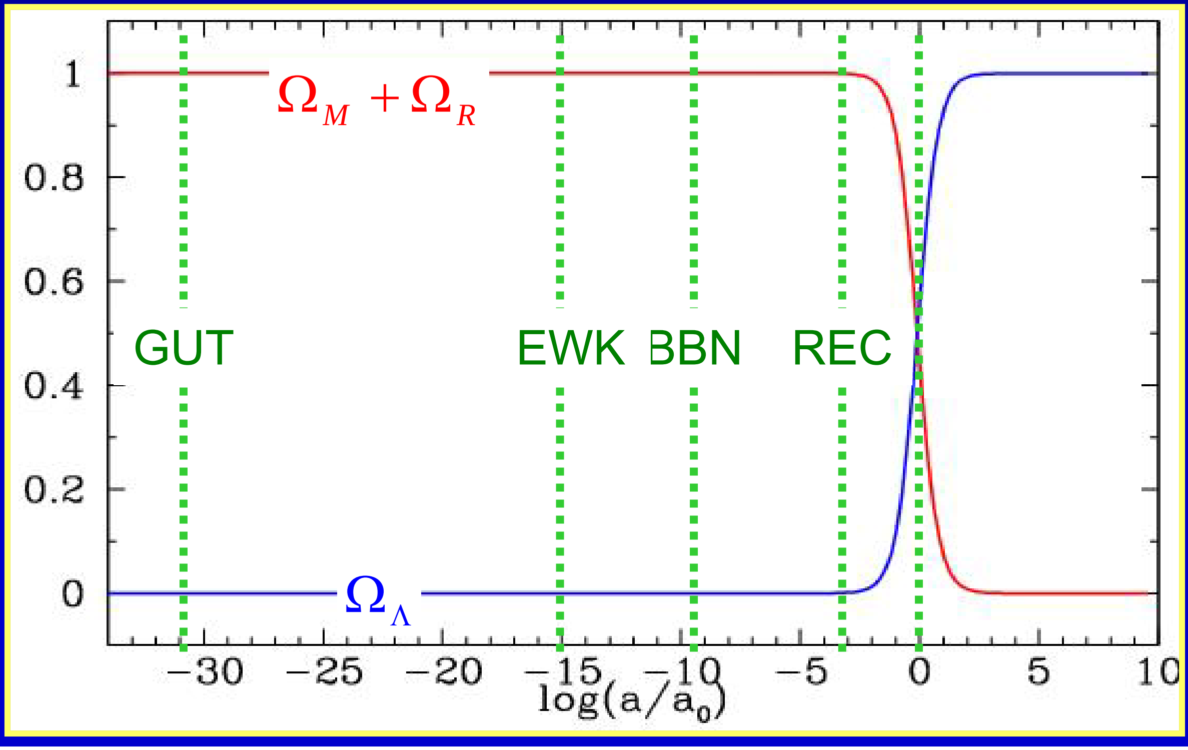
OBSERVED: 10^{-16} eV^4

Why Illogical?

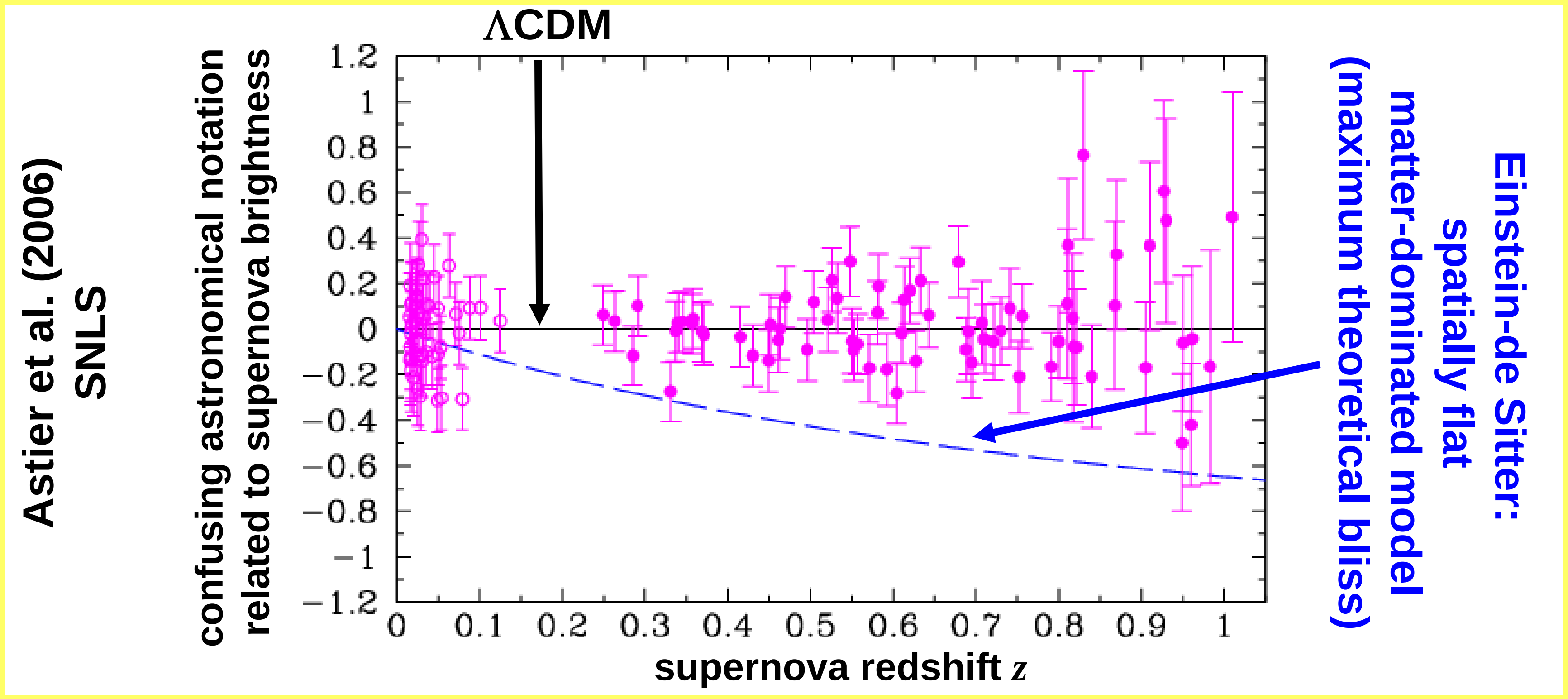
Illogical magnitude (what's it related to?):

	ρ_V	$\Lambda = 8\pi G\rho_V$
mass scale	$(10^{-4}\ \text{eV})^4$	$(10^{-33}\ \text{eV})^2$
length scale	$(10^{-3}\ \text{cm})^{-4}$	$(10^{+29}\ \text{cm})^{-2}$

Illogical timing (cosmic coincidence?):



Evidence for Dark Energy



The case for Λ:

1) Hubble diagram (SNe)
2) Cosmic Subtraction
3) Baryon acoustic oscillations
4) Weak lensing
5) Galaxy clusters
6) Age of the universe
7) Structure formation

How Do We "Know" Dark Energy Exists?

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

- Calculate observables $d_L(z)$, $d_A(z)$, $H(z)$, …

- 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 [spatially flat (from CMB) ; matter dominated ($\rho = \rho_M$)]

Taking Sides!

- Can't hide from the data – ΛCDM too good to ignore
  - SNe
  - Subtraction
  - Baryon acoustic oscillations
  - Galaxy clusters
  - Weak lensing
  - …

} $H(z)$ not given by Einstein–de Sitter

$$G_{00}\,(\text{FLRW}) \neq 8\pi G\, T_{00}(\text{matter})$$

- Modify right-hand side of Einstein equations (ΔT_{00})
  1. Constant ("just" a cosmoillogical constant)
  2. Not constant (dynamics driven by scalar field)

- Modify left-hand side of Einstein equations (ΔG_{00})
  3. Beyond Einstein (non-GR: branes, $f\,(R)$, *etc*.)
  4. (Just) Einstein (back reaction of inhomogeneities)

Theoretical Tools for the Right-Hand Side

1964 Austin-Healey Sprite

1974 Fiat 128

Theoretical Tools for the Right-Hand Side

scalar fields
(quintessence)

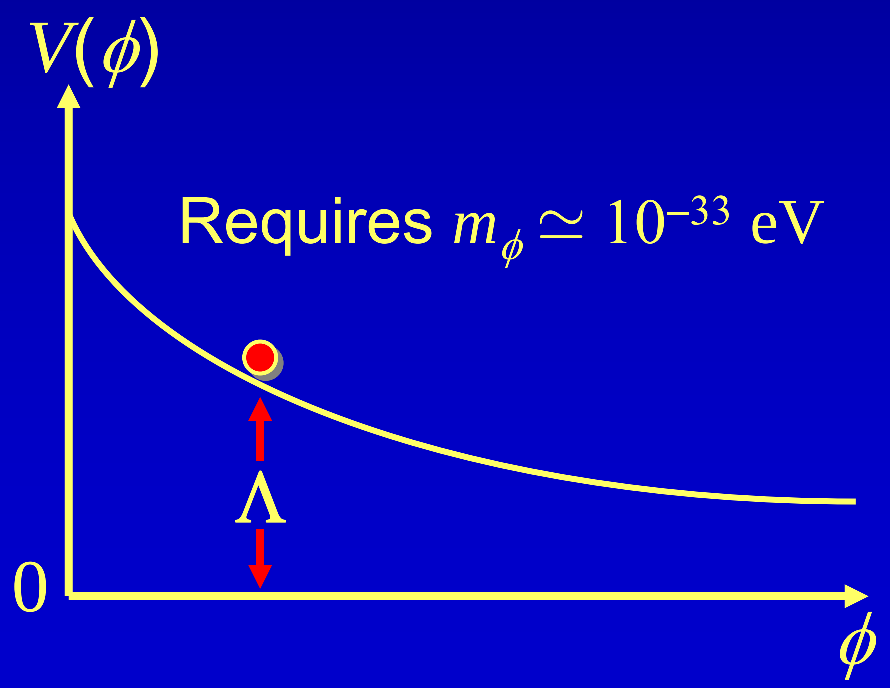
anthropic principle
(the landscape)

Anthropic/Landscape/DUCTape/Faith-Based

- Many sources of vacuum energy
- String theory has many ($>10^{500}$?) vacua
- Some of them correspond to cancellations that yield a small Λ
- Although exponentially uncommon, they are preferred because …
- More common values of Λ results in an inhospitable universe

Quintessence/WD–40

- Many possible contributions.
- Why then is total so small?
- Perhaps unknown dynamics sets global vacuum energy equal to zero……*but we're not there yet!*



Modifying the Left-Hand Side

- Braneworld modifies Friedmann equation — Binetruy, Deffayet, Langlois
- Gravitational force law modified at large distance — Deffayet, Dvali & Gabadadze
  Five-dimensional at cosmic distances
- Tired gravitons — Gregory, Rubakov & Sibiryakov; Dvali, Gabadadze & Porrati
  Gravitons metastable - leak into bulk
- Gravity repulsive at distance $R \approx \text{Gpc}$ — Csaki, Erlich, Hollowood & Terning
- $n = 1$ KK graviton mode very light, $m \approx (\text{Gpc})^{-1}$ — Kogan, Mouslopoulos, Papazoglou, Ross & Santiago
- Einstein & Hilbert got it wrong $f(R)$ — Carroll, Duvvuri, Turner, Trodden

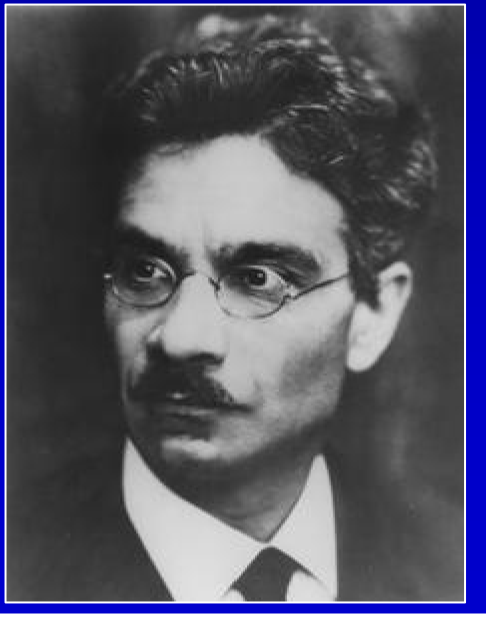
$$S = (16\pi G)^{-1} \int d^4x \sqrt{-g} \left(R - \mu^4 / R \right)$$

- Backreaction of inhomogeneities — Räsänen; Kolb, Matarrese, Notari & Riotto; Notari; Kolb, Matarrese & Riotto

<u>*Dark Energy*</u>

"Nothing more can be done by the theorists. In this matter it is only you, the astronomers, who can perform a simply invaluable service to theoretical physics."

Einstein in August 1913 to Berlin astronomer Erwin Freundlich encouraging him to mount an expedition to measure the deflection of light by the sun.

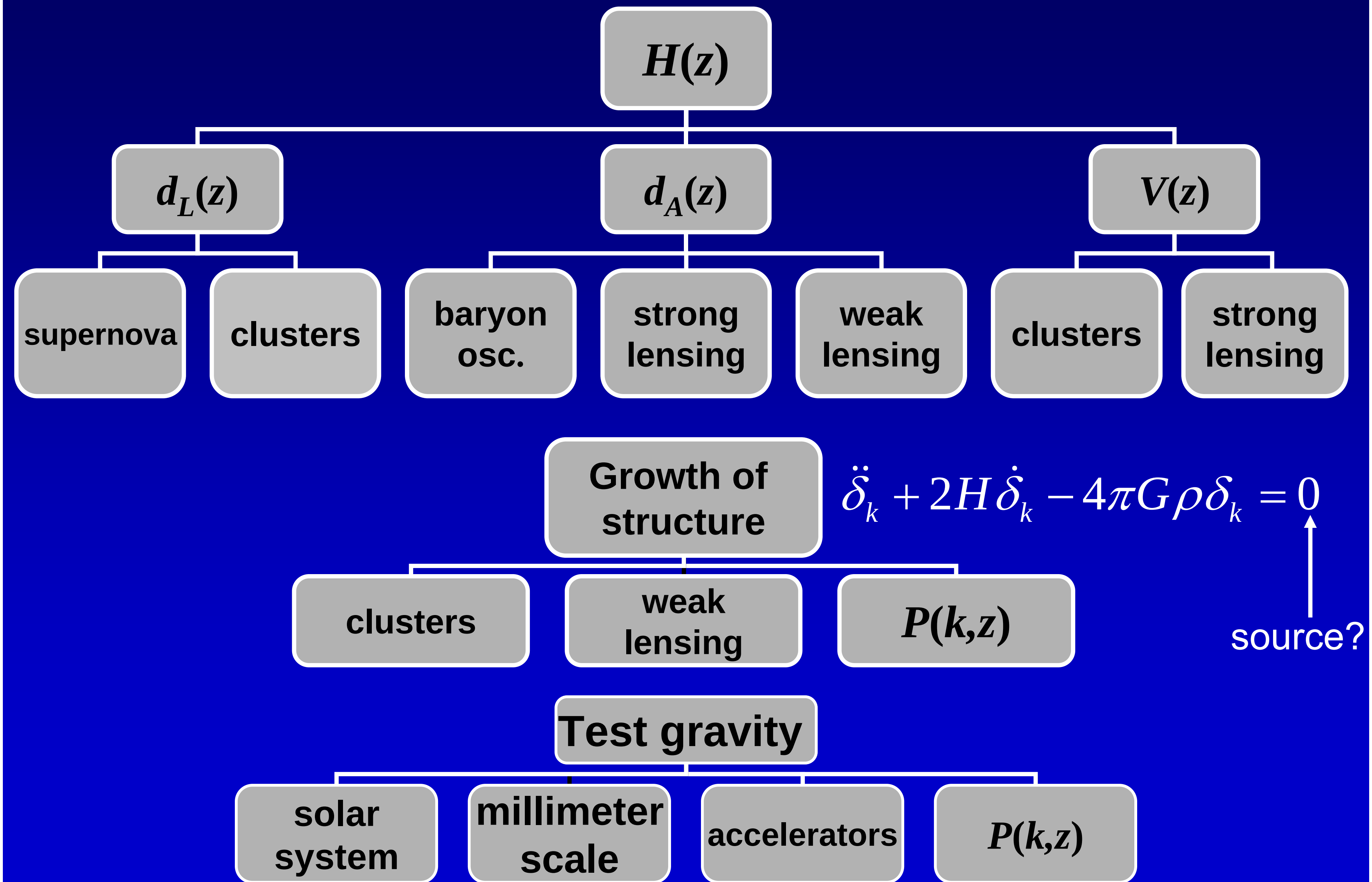


DETF* Experimental Strategy:

- Determine as well as possible whether the accelerating expansion is consistent with being due to a cosmological constant. (Is $w = -1$?)
- If the acceleration is not due to a cosmological constant, probe the underlying dynamics by measuring as well as possible the time evolution of the dark energy. (Determine $w(z)$.)
- Search for a possible failure of general relativity through comparison of the effect of dark energy on cosmic expansion with the effect of dark energy on the growth of cosmological structures like galaxies or galaxy clusters. (Hard to quantify.)

* Dark Energy Task Force

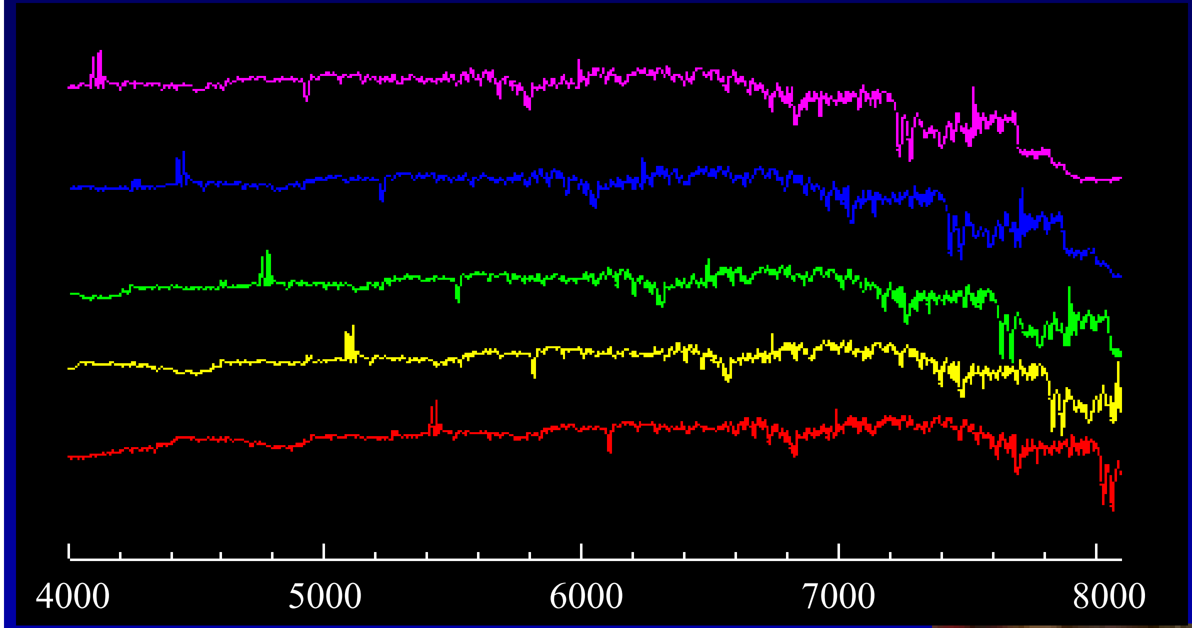
Observational Program



Supernova Type Ia

- Measure redshift and intensity as function of time (light curve)
- Systematics (dust, evolution, intrinsic luminosity dispersion, *etc.*)
- A lot of information per supernova
- Well developed and practiced
- Present procedure:
  - Discover SNe by wide-area survey (the "easy" part)
  - Follow up with spectroscopy (the "hard" part) (requires a lot of time on 8m-class telescopes)
  - Photometric redshifts?

Photometric Redshifts



Traditional redshift from spectroscopy

Photometric redshift from multicolor photometry

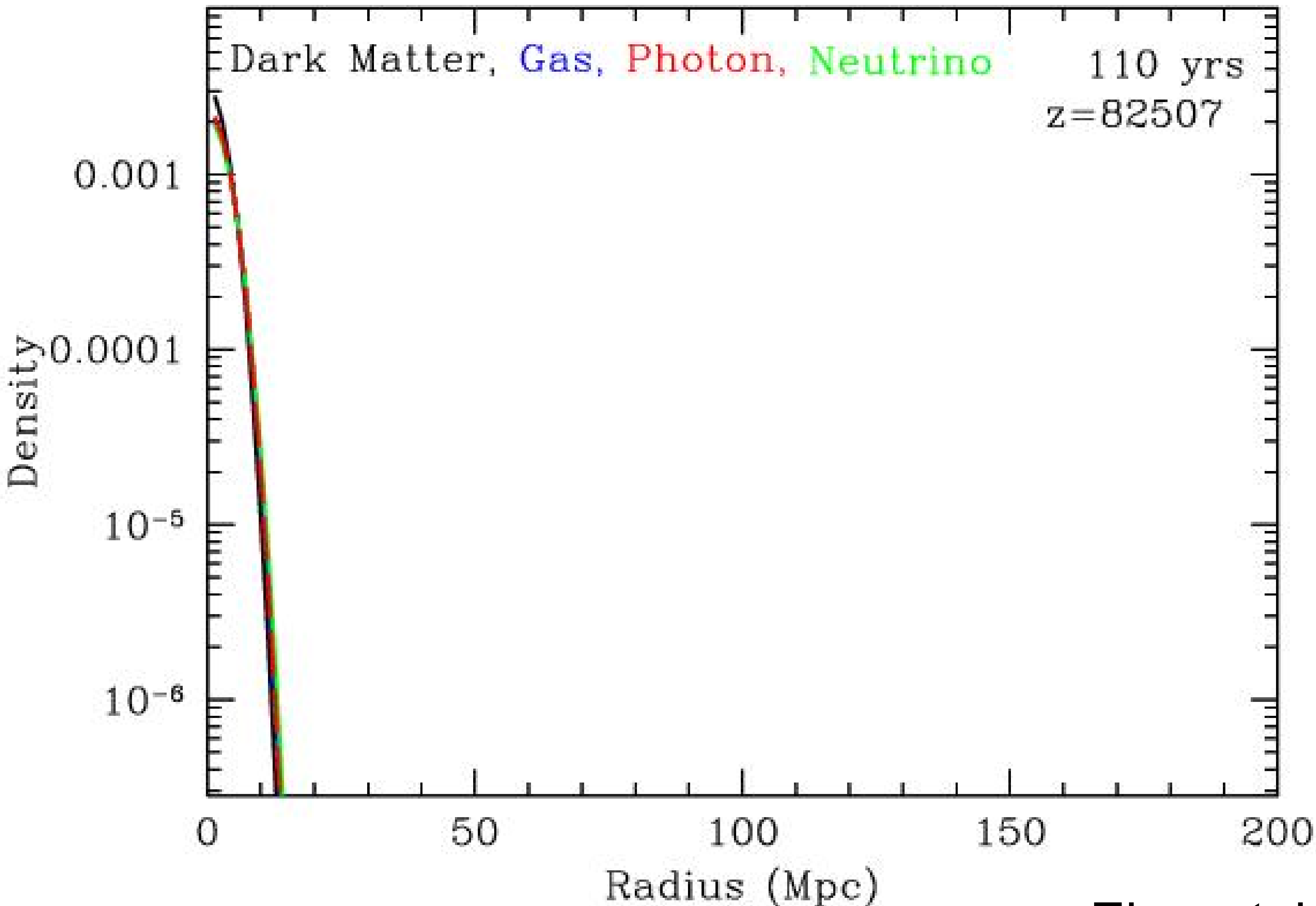
Baryon Acoustic Oscillations

Pre-recombination

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

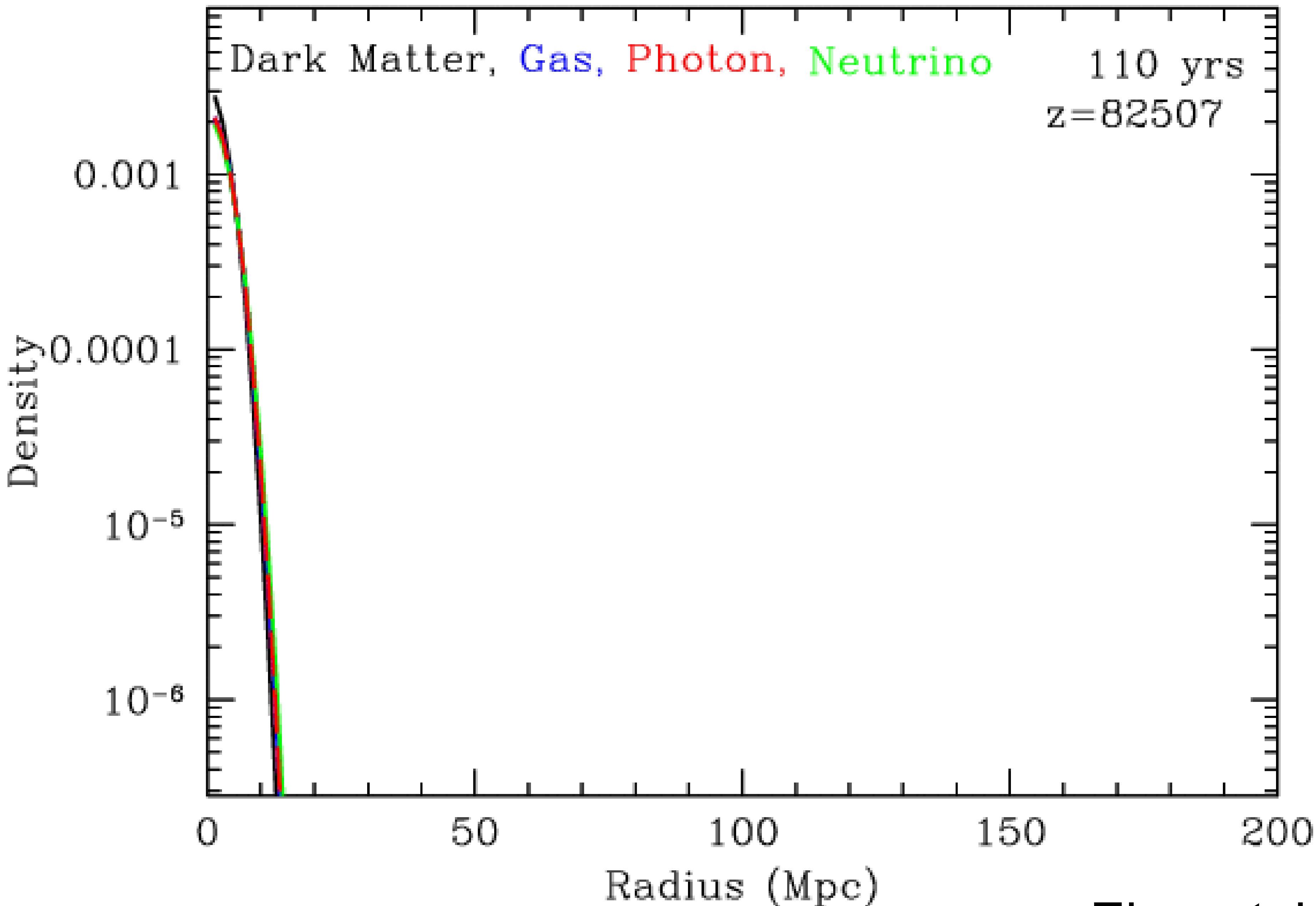
Post-recombination

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



Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
0.001
0.0001
10^{-5}
10^{-6}
Density
0
50
100
150
200
Radius (Mpc)

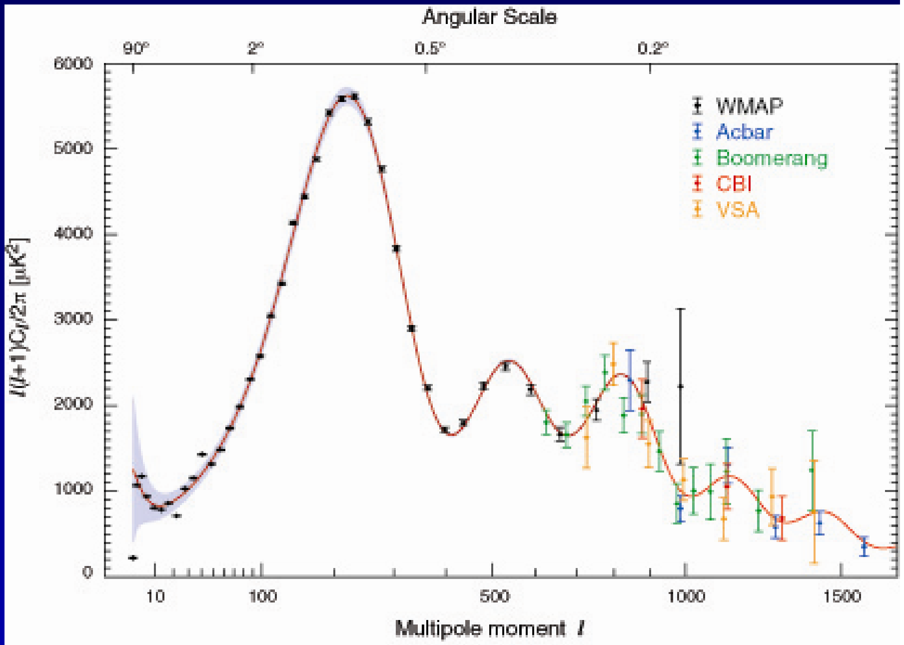
Eisenstein


Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
Density
0.001
0.0001
10^{-5}
10^{-6}
0
50
100
150
200
Radius (Mpc)

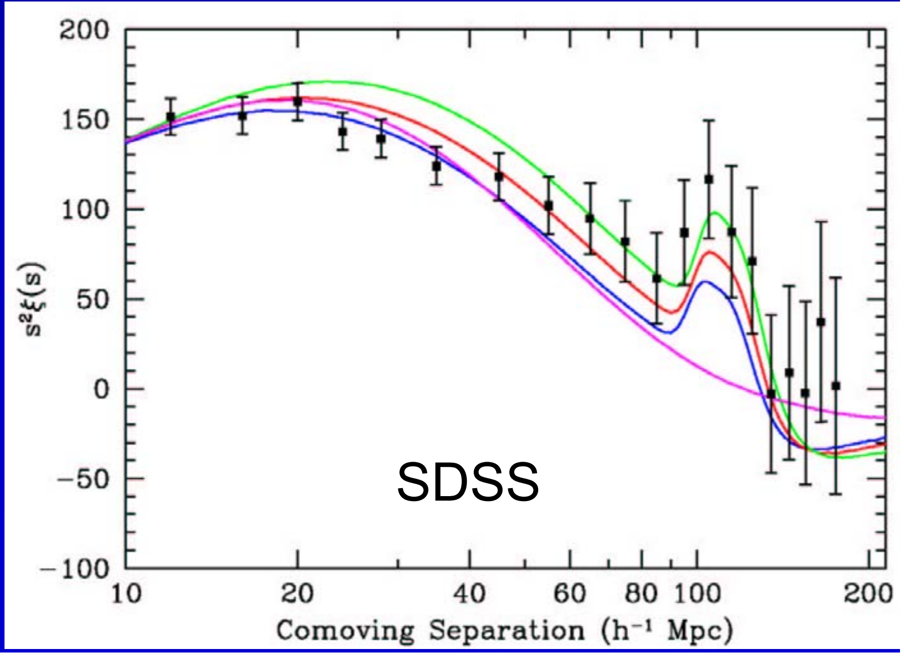
Eisenstein

Baryon Acoustic Oscillations

- Each overdense region is an overpressure that launches a spherical sound wave
- Wave travels outward at $c/\sqrt{3}$
- Photons decouple, travel to us and observable as CMB acoustic peaks

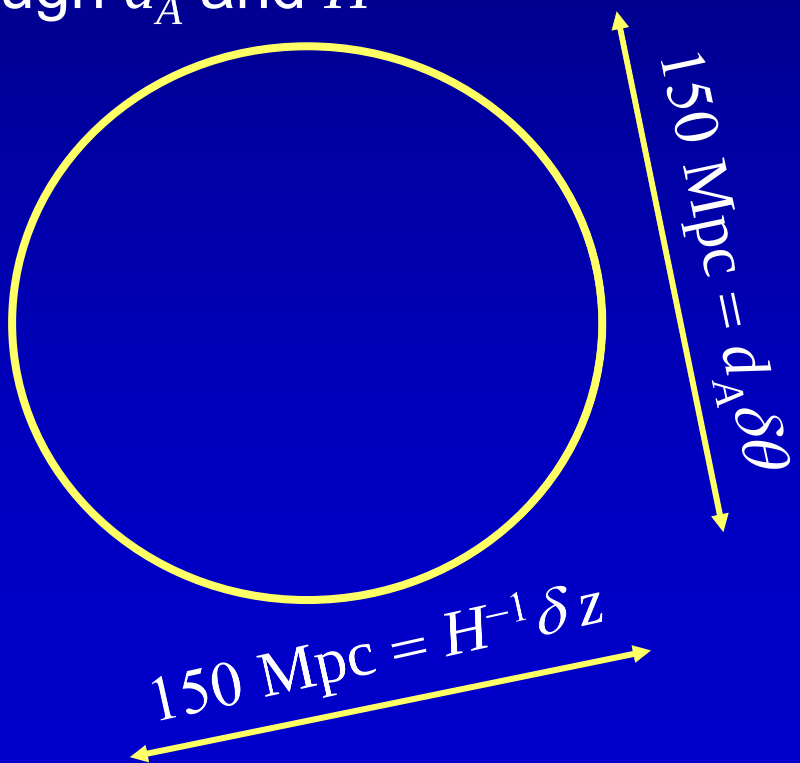


- Sound speed plummets, wave stalls
- Total distance traveled 150 Mpc imprinted on power spectrum



Baryon Acoustic Oscillations

- Acoustic oscillation scale depends on $\Omega_M h^2$ and $\Omega_B h^2$ (set by CMB acoustic oscillations)
- It is a small effect ($\Omega_B h^2 \ll \Omega_M h^2$)
- Dark energy enters through d_A and H



Baryon Acoustic Oscillations

- Virtues
  - Pure geometry.
  - Systematic effects should be small.
- Problems:
  - Amplitude small, require large scales, huge volumes
  - Photometric redshifts?
  - Nonlinear effects at small z, cleaner at large $z \sim 2\text{–}3$
    Dark energy not expected to be important at large z

Galaxy Clusters

Cluster redshift surveys measure

- cluster mass, redshift, and spatial clustering

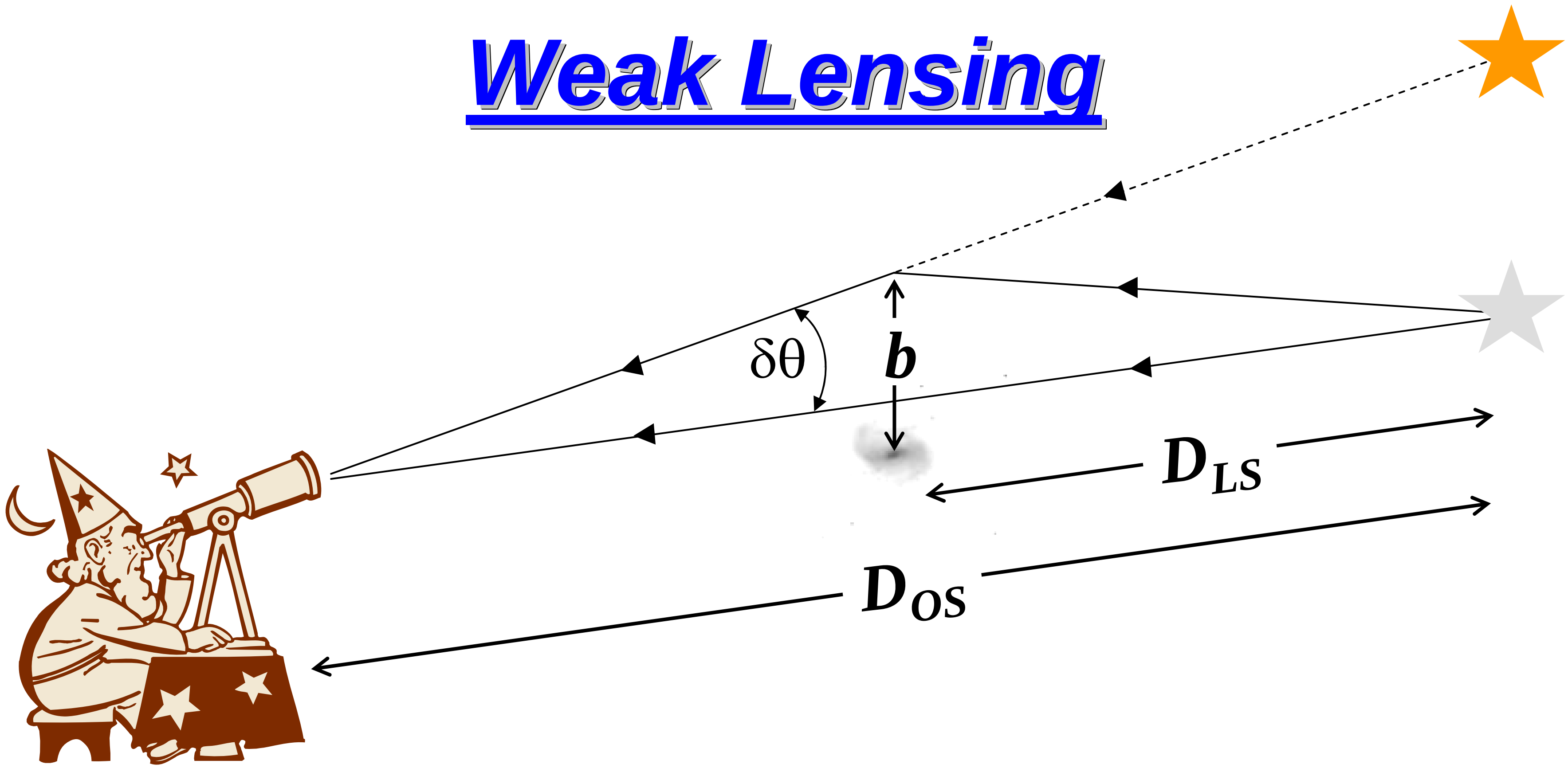
Sensitivity to dark energy

- volume-redshift relation
- angular-diameter distance–redshift relation
- growth rate of structure
- amplitude of clustering

Problems:

- cluster selection must be well understood
- proxy for mass?
- need photo-z's

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?

Systematic errors:

- Dominant source is PSF of atmosphere and telescope
- Errors in photometric redshifts

Space vs. Ground:

- Space: no atmosphere PSF
- Space: Near IR for photo-z's
- Ground: larger aperture
- Ground: less expensive

The Landscape:

- Current projects
  - 100's of sq. degs. deep multicolor data
  - 1000's of sq. degs. shallow 2-color data
- DES (2010)
  - 1000's of sq. degs. deep multicolor data
- LSST (2013)
  - full hemisphere, very deep 6 colors

DETF Cosmological Model

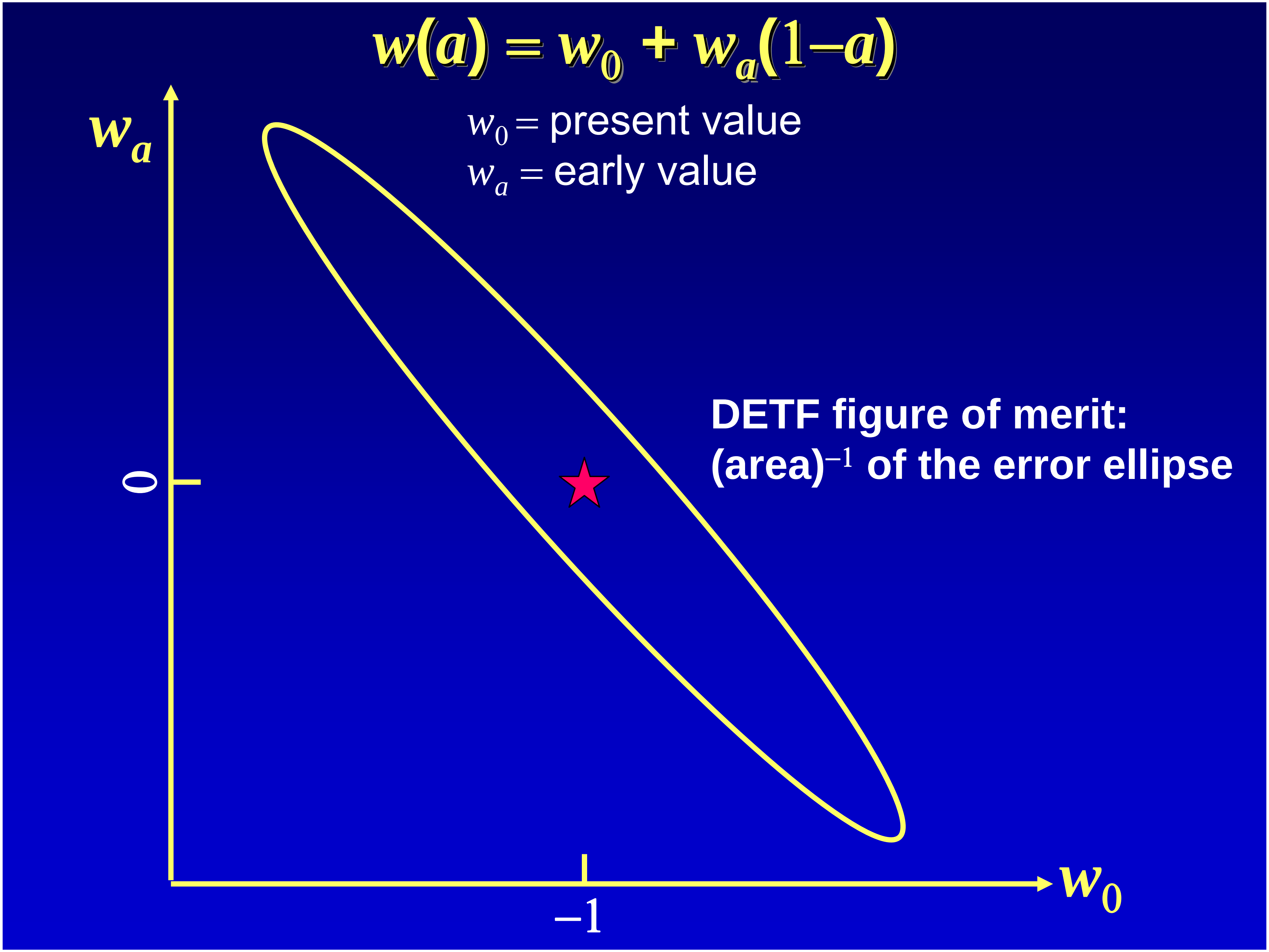
Parameterize dark-energy equation of state parameter w as:

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

- Today ($a = 1$) $w(1) = w_0$
- In the far past ($a \to 0$) $w(0) = w_0 + w_a$

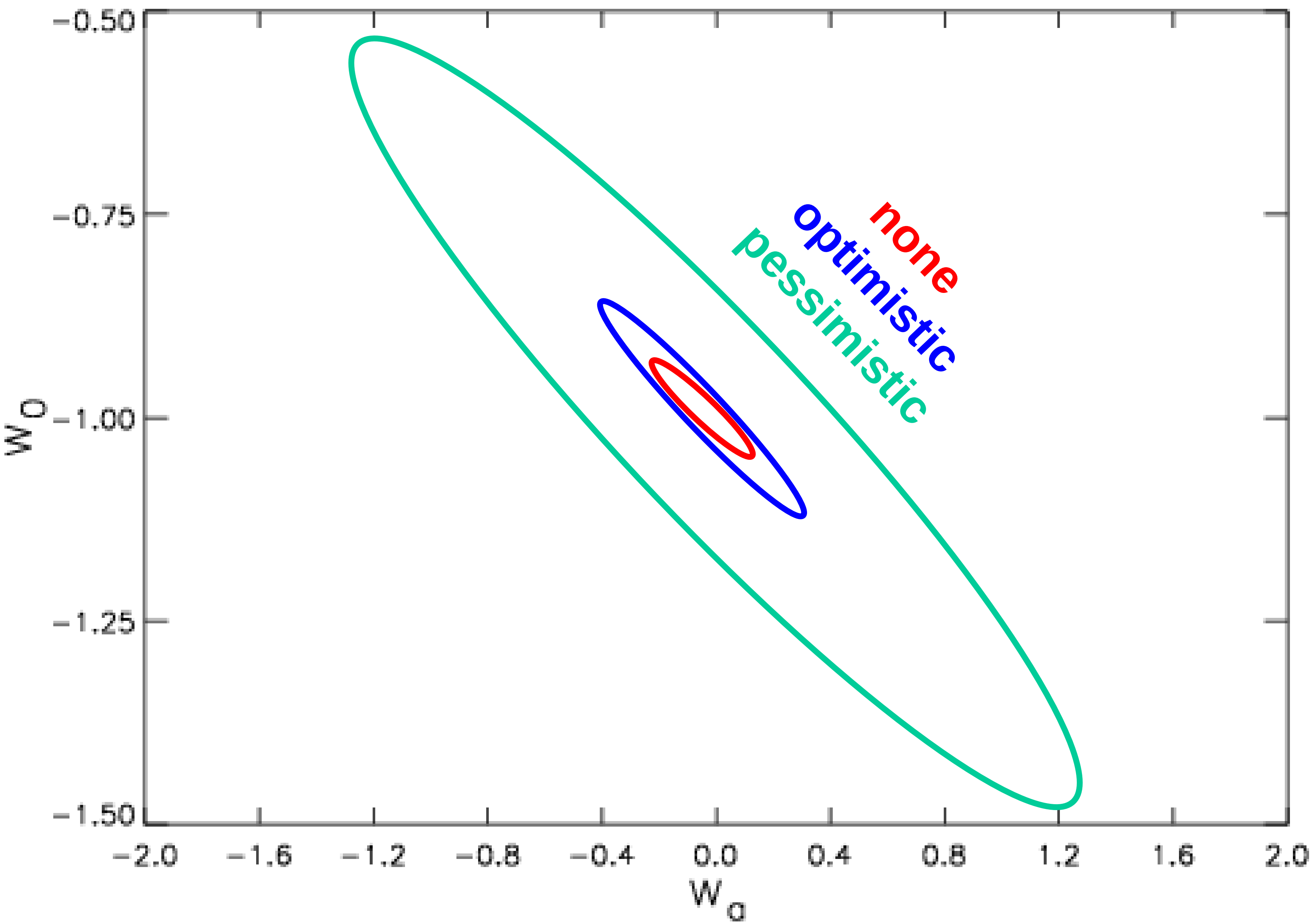
Standard eight-dimensional cosmological model:

w_0 :	the present value of the dark-energy w parameter
w_a :	the rate of change of the dark-energy w parameter
Ω_{DE} :	the present dark-energy density
Ω_M :	the present matter density
Ω_B :	the present baryon density
H_0 :	the Hubble constant
δ_ζ :	amplitude of *rms* primordial curvature fluctuations
n_S :	the spectral index of primordial perturbations.

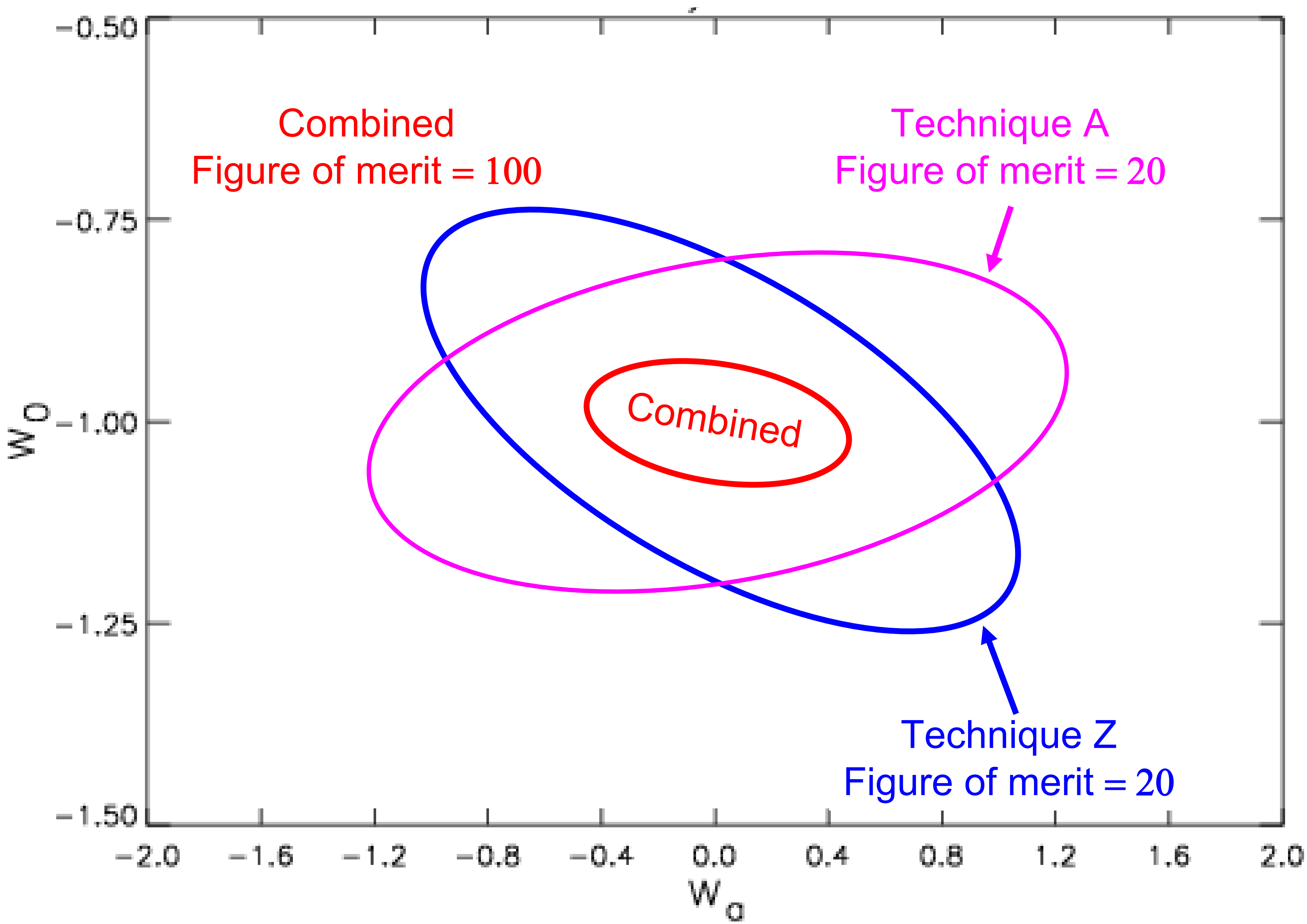


$w(a) = w_0 + w_a(1-a)$
w_0 = present value
w_a = early value
DETF figure of merit:
(area)$^{-1}$ of the error ellipse
w_a
0
w_0
-1

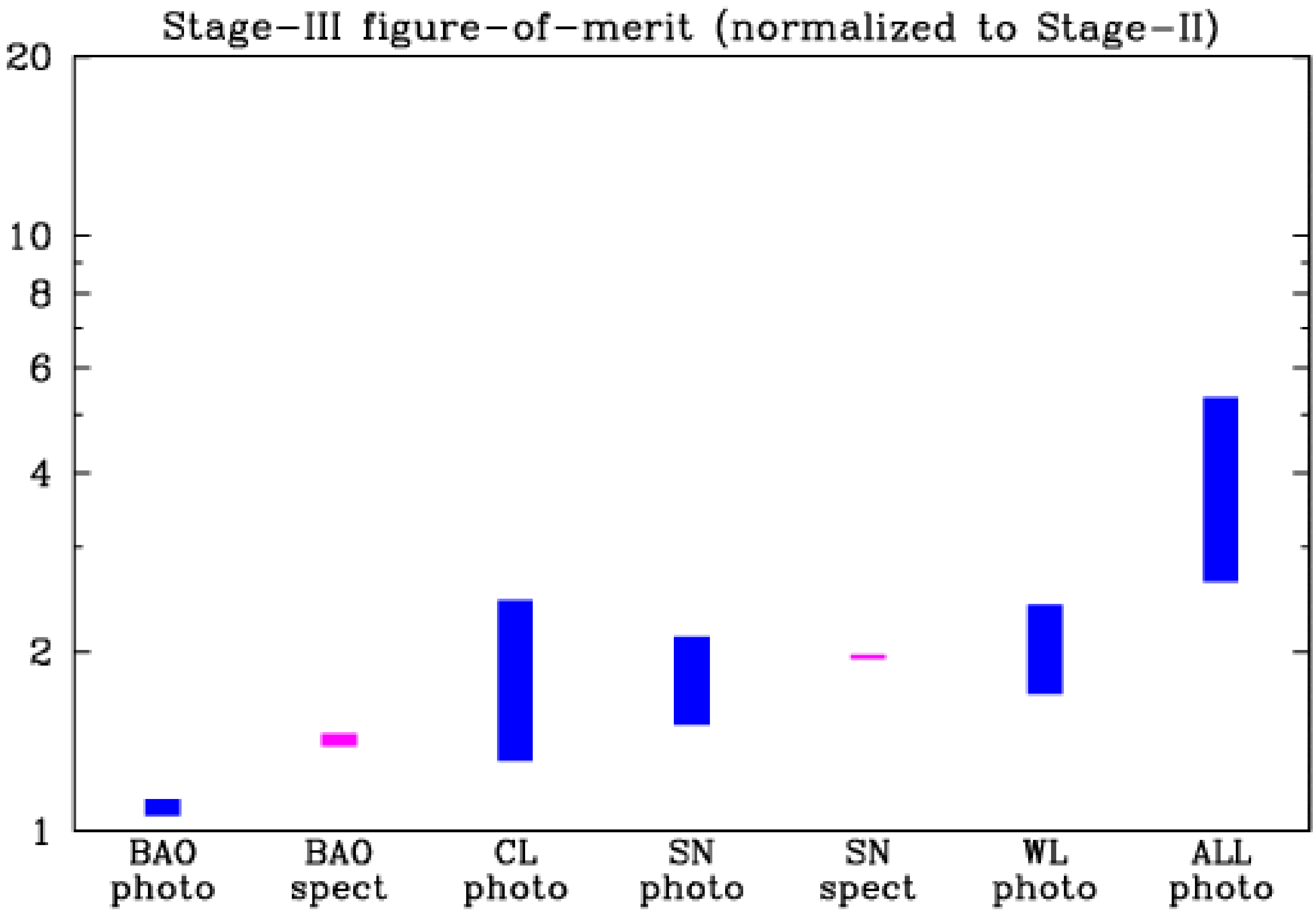
Systematics Are the Key



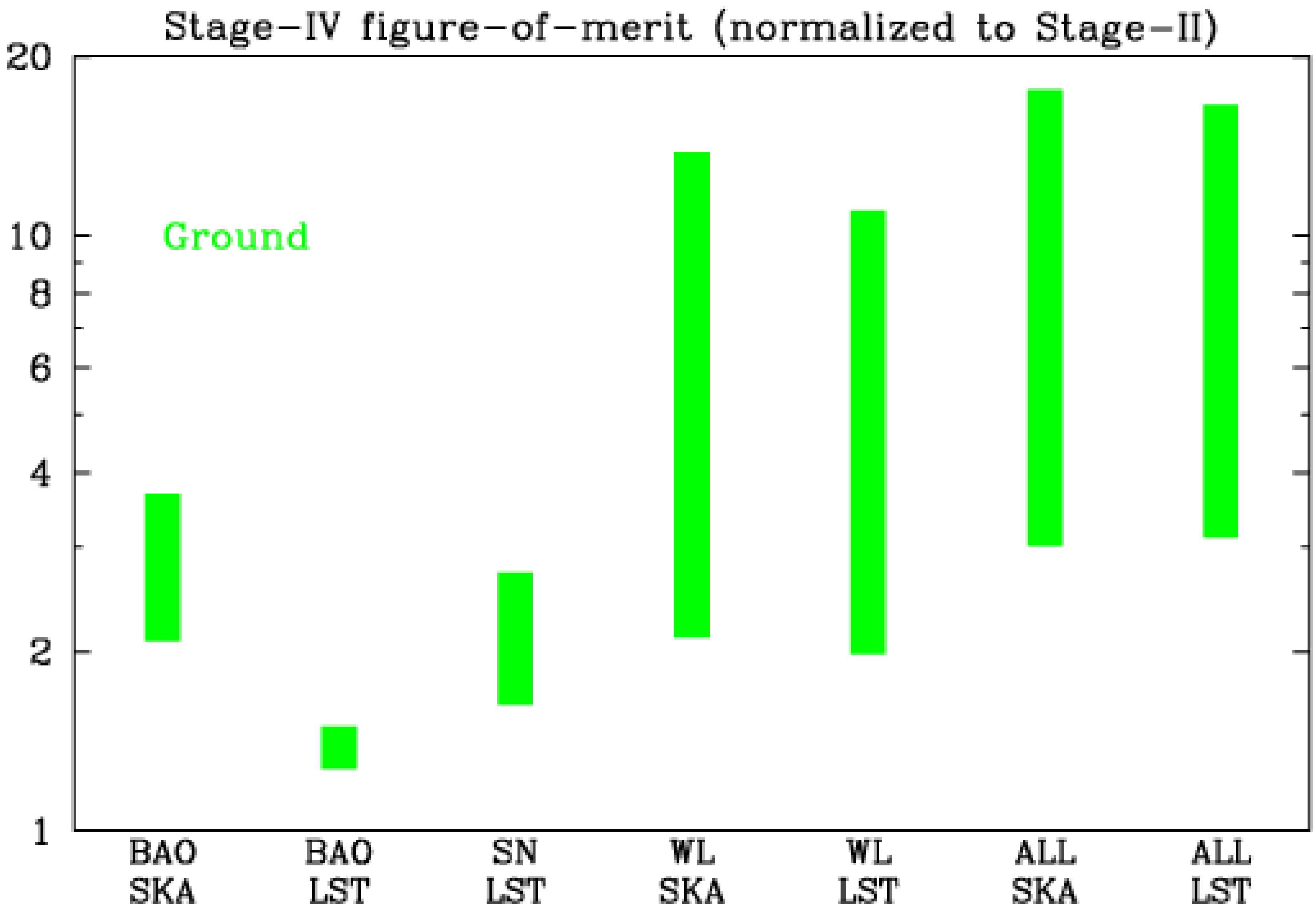
The Power of Two (or 3, or 4)



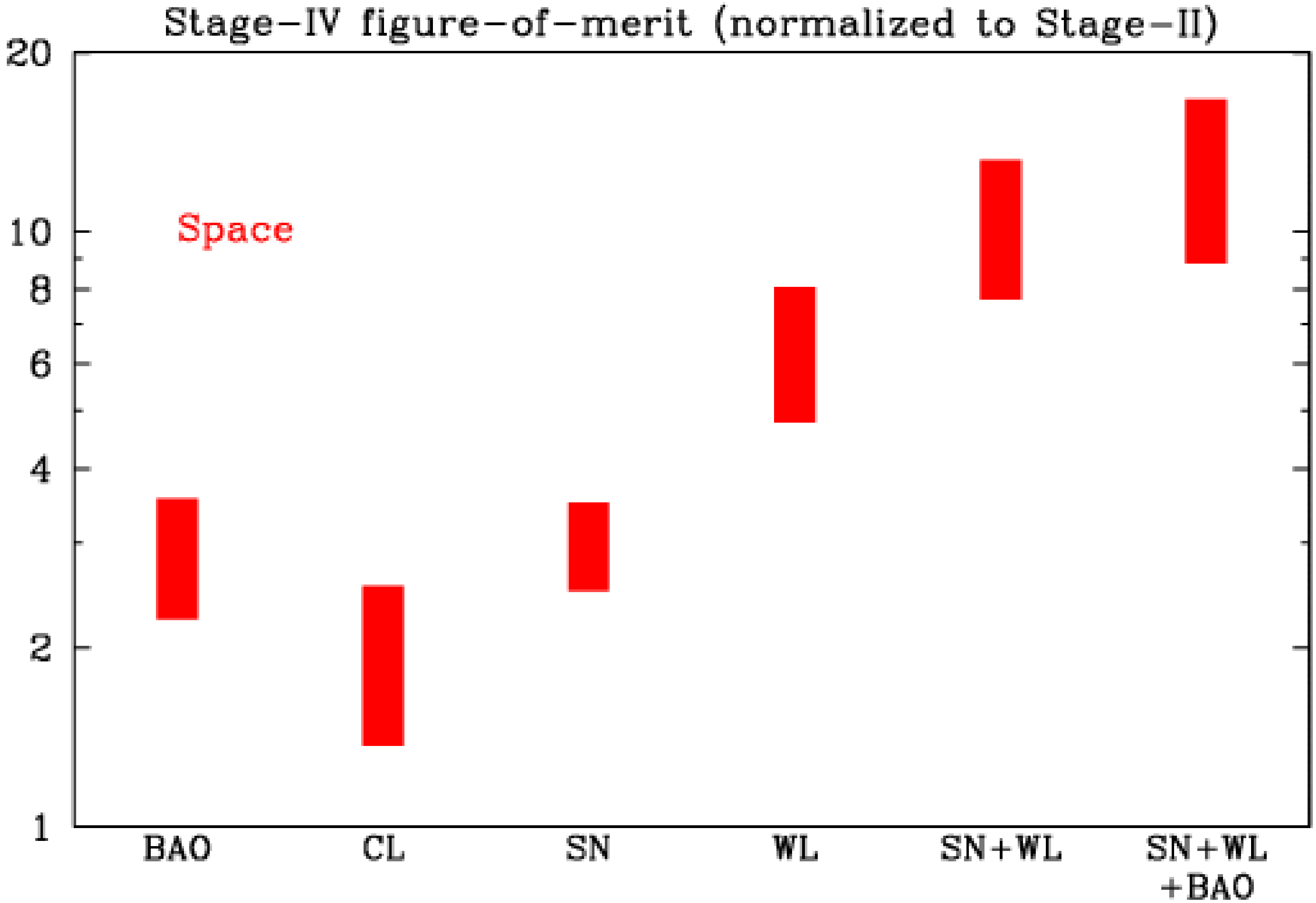
DETF Projections



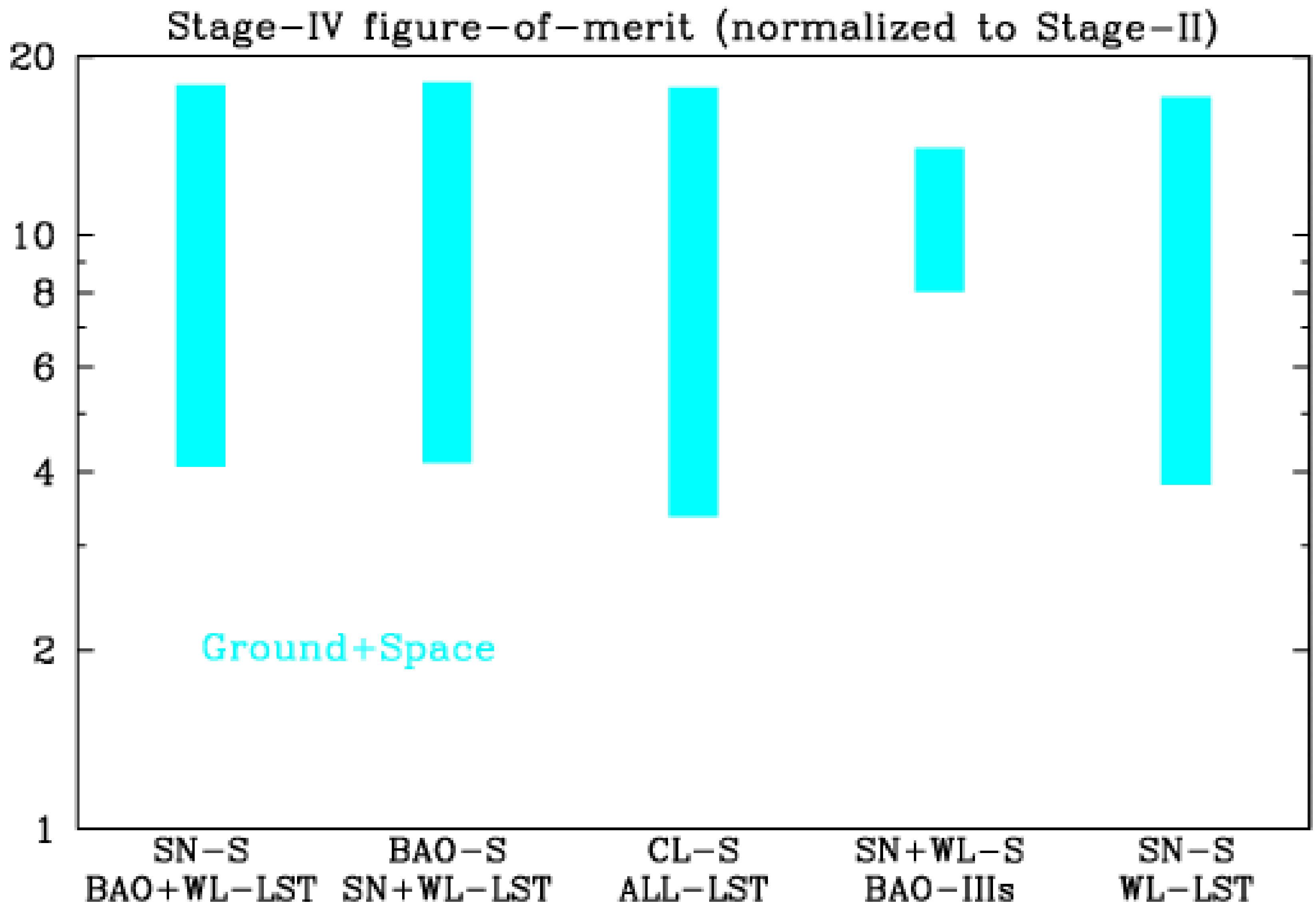
DETF Projections

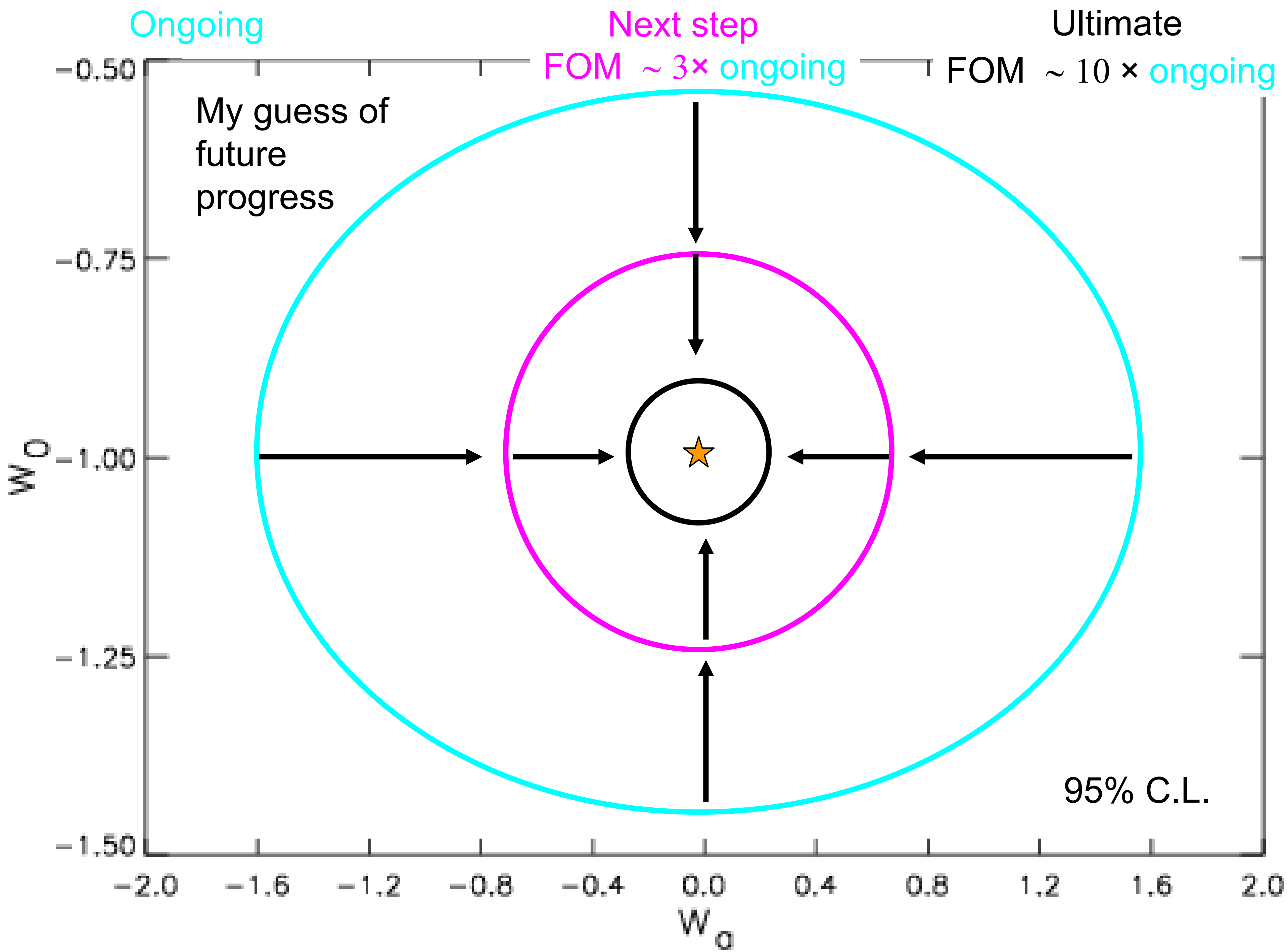


DETF Projections



DETF Projections




Ongoing
Next step
FOM ~ 3× ongoing
Ultimate
FOM ~ 10 × ongoing
My guess of future progress
95% C.L.
−0.50
−0.75
−1.00
−1.25
−1.50
w_0
−2.0
−1.6
−1.2
−0.8
−0.4
0.0
0.4
0.8
1.2
1.6
2.0
w_a

What's Ahead

2008 2010 2015 2020

Lensing CFHTLS SUBARU DES, VISTA DUNE LSST SKA

DLS SDSS ATLAS KIDS Hyper suprime JDEM

Pan-STARRS

BAO FMOS LAMOST DES, VISTA,VIRUS WFMOS LSST SKA

SDSS ATLAS Hyper suprime JDEM

Pan-STARRS

SNe CSP ESSENCE DES LSST

SDSS CFHTLS Pan-STARRS JDEM

Clusters AMI APEX SPT DES

XCS SZA AMIBA ACT

CMB WMAP 2/3 WMAP 5 yr

Planck Planck 4yr

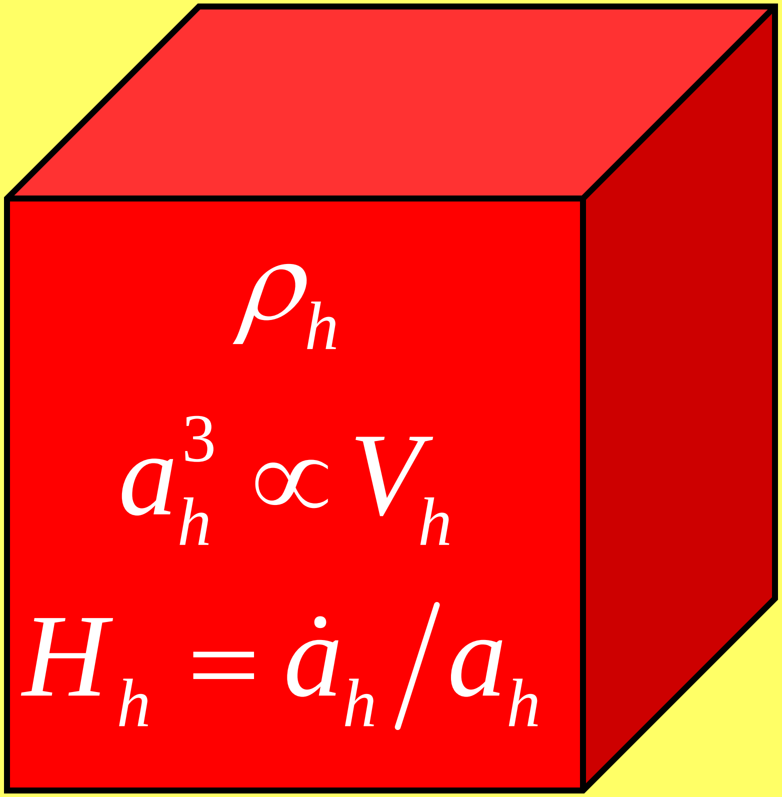
Roger Davies

Acceleration from inhomogeneities

- Most conservative approach — nothing new
  - no new fields (like $10^{-33}\,\mathrm{eV}$ mass scalars)
  - no extra long-range forces
  - no modification of general relativity
  - no modification of gravity at large distances
  - no Lorentz violation
  - no extra dimensions, bulks, branes, etc.
  - no anthropic/landscape/faith-based reasoning
- Magnitude?: calculable from observables related to $\delta\rho/\rho$
- Why now?: acceleration triggered by era of non-linear structure

Acceleration from inhomogeneities

Homogeneous model

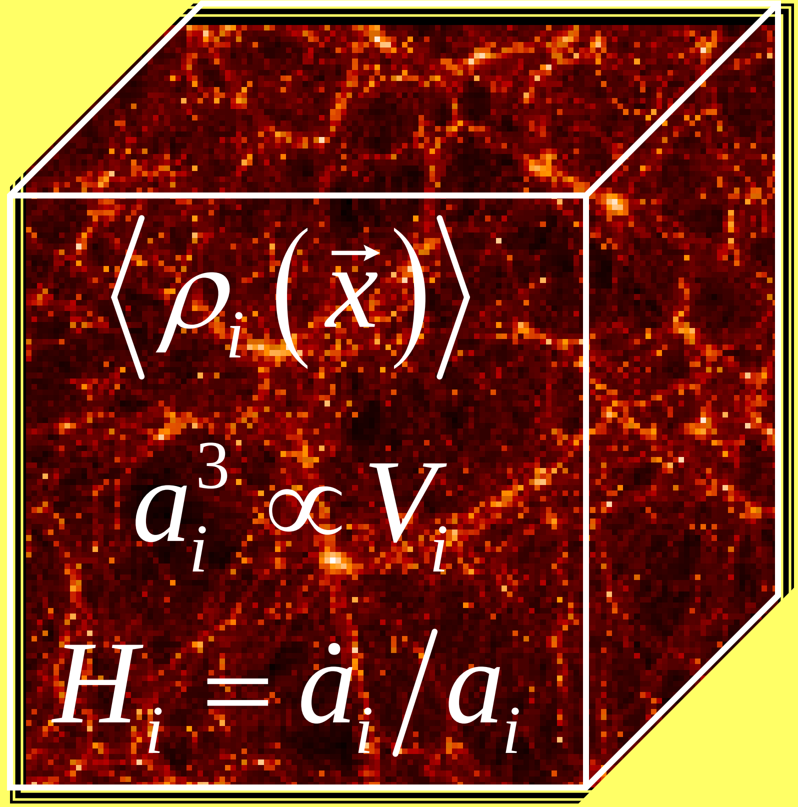


$$\rho_h$$

$$a_h^3 \propto V_h$$

$$H_h = \dot{a}_h / a_h$$

Inhomogeneous model



$$\langle \rho_i(\vec{x}) \rangle$$

$$a_i^3 \propto V_i$$

$$H_i = \dot{a}_i / a_i$$

$$\rho_h = \langle \rho_i(\vec{x}) \rangle \Rightarrow H_h = H_i \ ?$$

We think not!

(Buchert & Ellis)

Acceleration from inhomogeneities

- View scale factor as zero-momentum mode of gravitational field
- In homogeneous/isotropic model it is the only degree of freedom
- Inhomogeneities: non-zero modes of gravitational field
- Non-zero modes interact with and modify zero-momentum mode

Cosmology $\leftrightarrow$ scalar field theory analogue

	cosmology	scalar-field theory
zero-mode	a	$\langle\phi\rangle$ (vev of a scalar field)
non-zero modes	inhomogeneities	thermal/finite-density bkgd.
physical effect	modify $a(t)$ *e.g.*, acceleration	modify $\langle\phi(t)\rangle$ *e.g.*, phase transitions

Acceleration from inhomogeneities

Standard approach	Our approach
• Model an inhomogeneous Universe as a homogeneous Universe model with $\rho = \langle\rho\rangle$	• Expansion rate of inhomogeneous Universe $\neq$ expansion rate of homogeneous Universe with $\rho = \langle\rho\rangle$
• $a(t) \propto V^{1/3}$ is the zeromode of a homogeneous model with $\rho = \langle\rho\rangle$	• Inhomogeneities modify zeromode [effective scale factor is $a_D \equiv V_D{}^{1/3}$]
• Inhomogeneities only have a local effect on observables	• Effective scale factor has a (global) effect on observables
• Cannot account for observed acceleration	• Potentially can account for acceleration without dark energy or modified GR

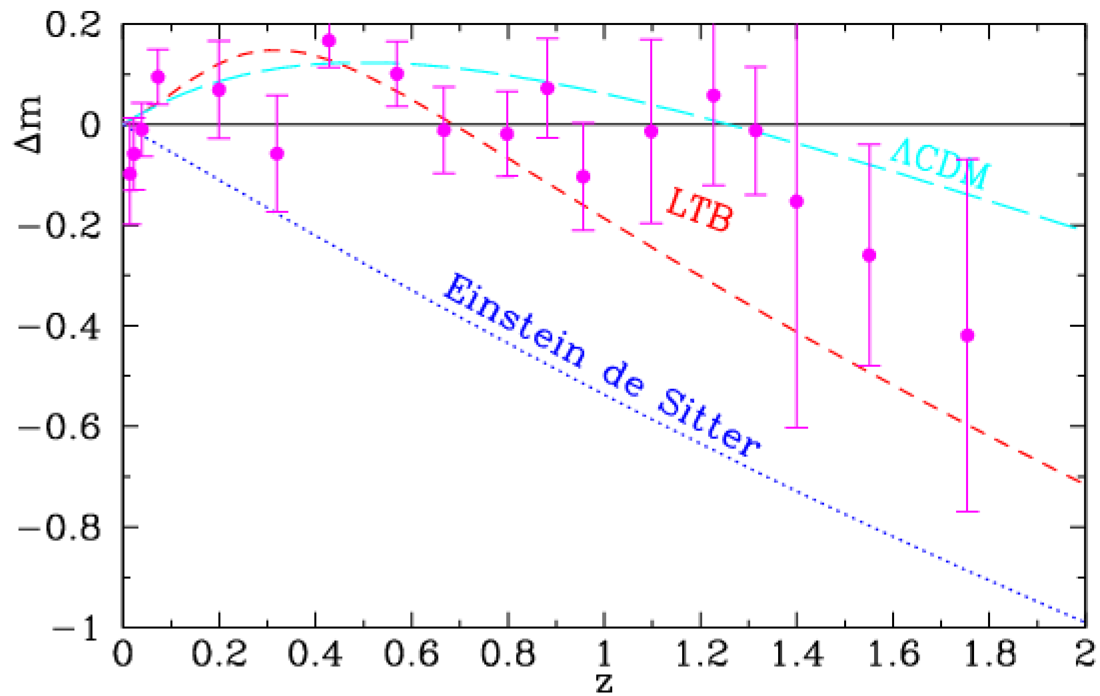
Lemaître–Tolman–Bondi

Celerier 1999 astro-ph/9907206
Iguchi, Nakamura, Nakao 2002 *Prog. of Theo. Phys.* 809
Moffat 2005 astro-ph/0505326
Nambu and Tanimoto 2005 gr-qc/0507057
Mansouri 2005 astro-ph/0512605
Chang, Gu, Hwang 2005 astro-ph/0512651
Alnes, Amarzguioui, Grøn 2006 *Phys. Rev.* D73 083519
Mansouri 2006 astro-ph/0601699
Apostolopoulos, Brouzakis, Tetradis, Tzavara 2006 astro-ph/0603234
Garfinkle 2006 gr-qc/0605088
Kai, Kozaki, Nakao, Nambu, Yoo 2006 gr-qc/0605120

Lemaître–Tolman–Bondi

- Spherical model
- Overall Einstein–de Sitter
- Inner underdense Gpc region
- Calculate $d_L(z)$
- Compare to SNIa data
- Fit with $\Lambda = 0$!

Alnes, Amarzguioui, Grøn



(counterexample to all no-go theorems)

Acceleration from inhomogeneities

- No dark energy
- No acceleration in the normal sense
  (no individual fluid element accelerates)
- No one seems to like this idea

Conclusions: Two Sides To Every Story

The expansion history of the universe is not described by the Einstein-de Sitter model.

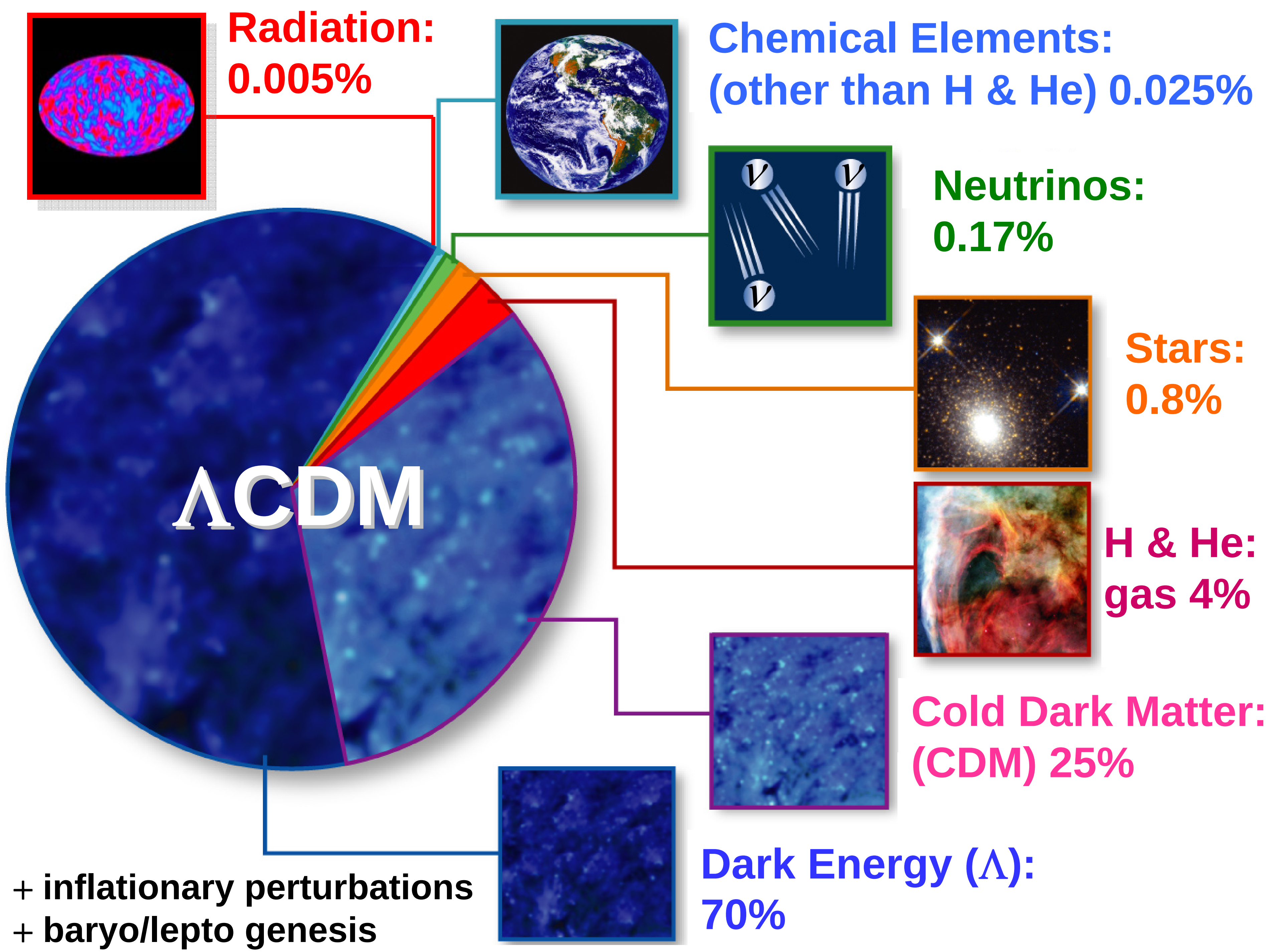
1. Well established: Supernova Ia
2. Circumstantial: subtraction, age, structure formation, …
3. Emergent techniques: baryon acoustic oscillations, clusters, weak lensing

Explanations:

1. Right-Hand Side: Dark energy
   - "constant" vacuum energy, *i.e.,* Λ
   - time varying vacuum energy, *i.e.,* quintessence
2. Left-Hand Side
   - Modification of GR
   - Standard cosmological model (FLRW) not applicable

Phenomenology:

1. Measure evolution of expansion rate: is $w = -1$?
2. Order of magnitude improvement feasible


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
Stars:
0.8%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM
+ inflationary perturbations
+ baryo/lepto genesis

The Dark Universe: Dark Matter and Dark Energy

Rocky I:	**The Universe Observed**	**Monday**
Rocky II:	**Inflation**	**Tuesday**
Rocky III:	**Dark Matter**	**Wednesday**
Rocky IV:	**Dark Energy**	**Thursday**

CERN Academic Training Lectures **January 2008**

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