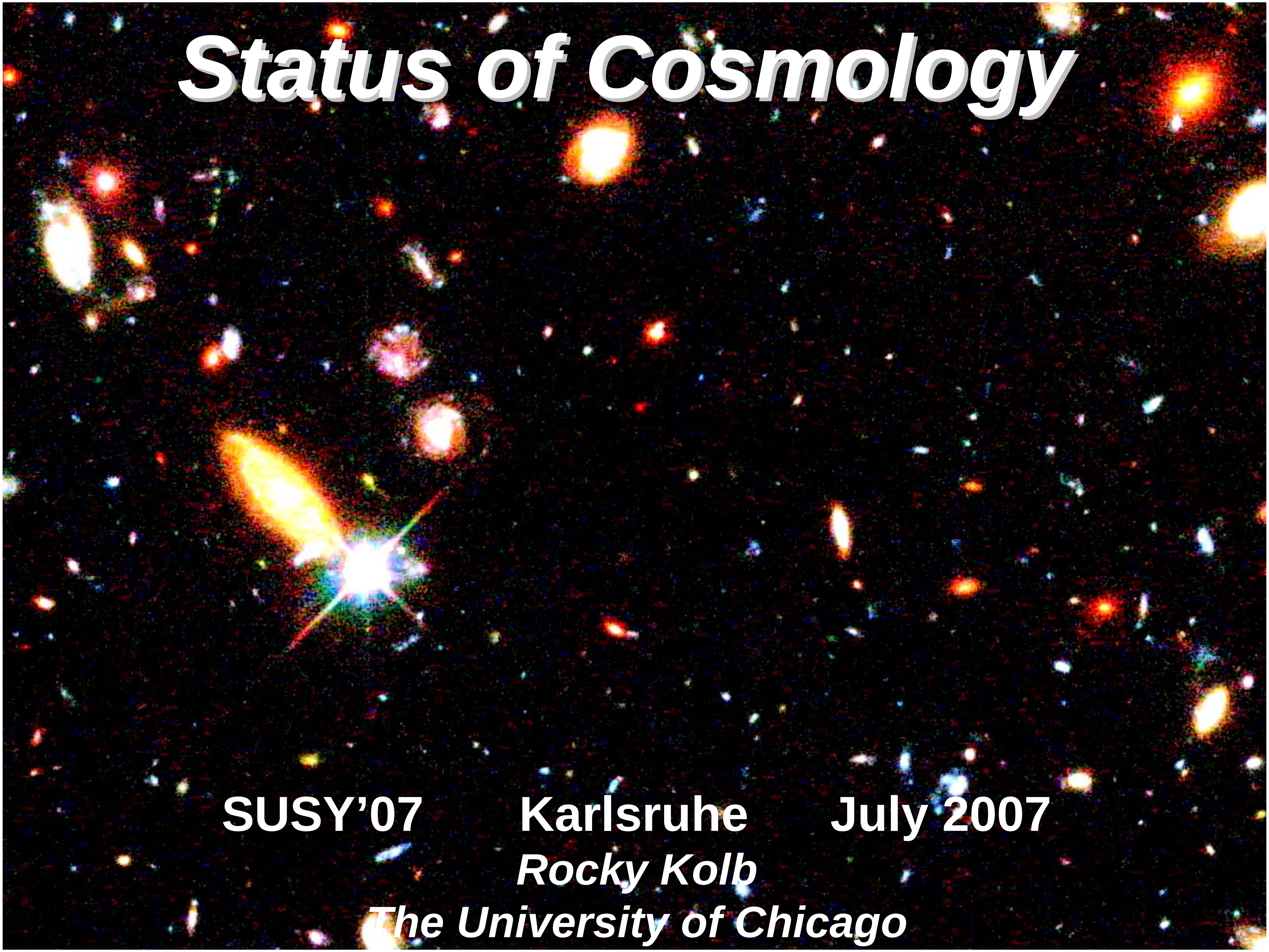
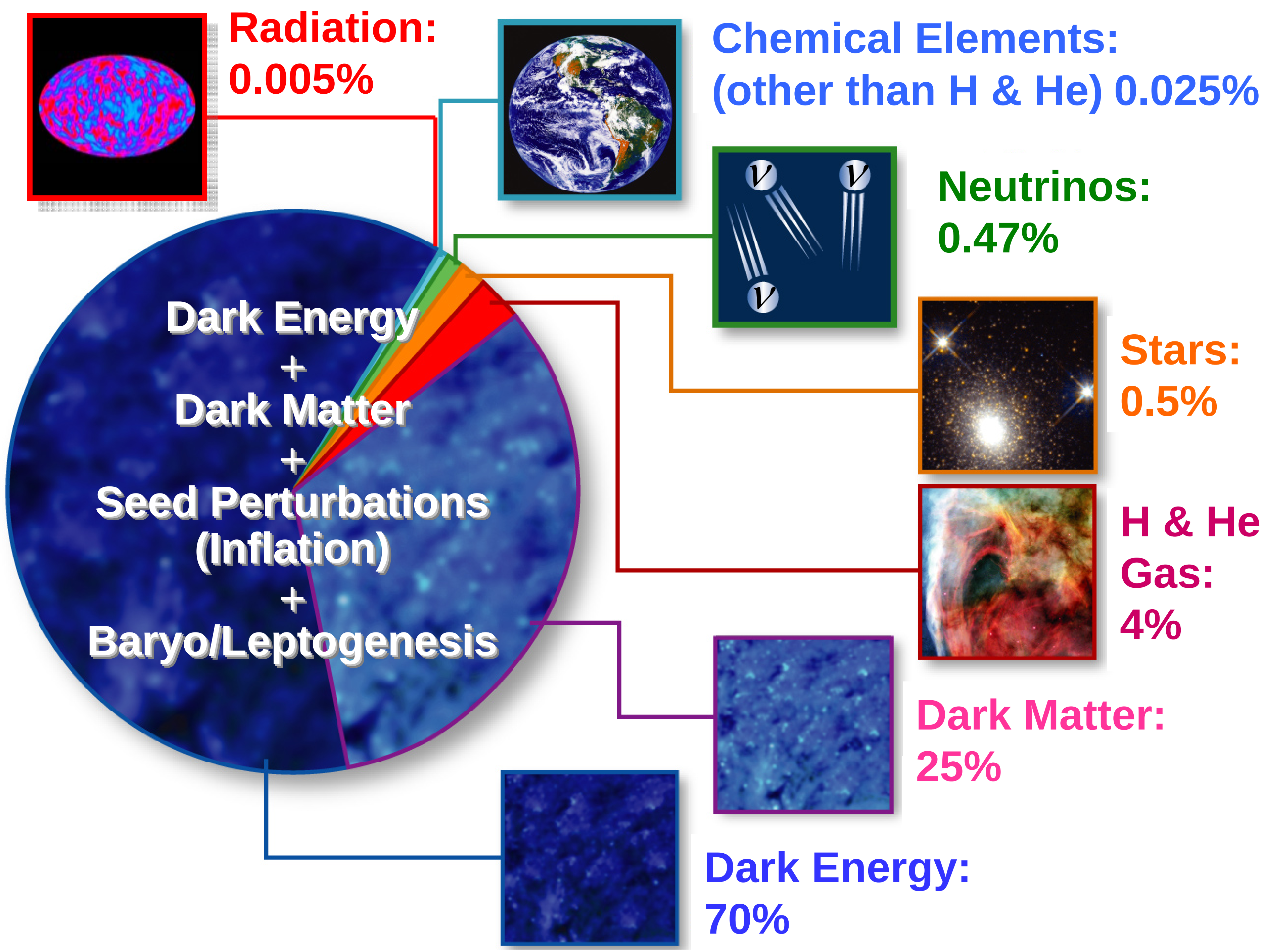


Status of Cosmology

SUSY'07 Karlsruhe July 2007

Rocky Kolb

The University of Chicago


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
H & He
Gas:
4%
Dark Matter:
25%
Dark Energy:
70%
Dark Energy
+
Dark Matter
+
Seed Perturbations
(Inflation)
+
Baryo/Leptogenesis

Precision Cosmology

Dark Energy
+
Dark Matter
+
Seed Perturbations (Inflation)
+
Baryo/Leptogenesis

} The standard model of *cosmology* seems to require physics beyond the standard model of *particle physics*.

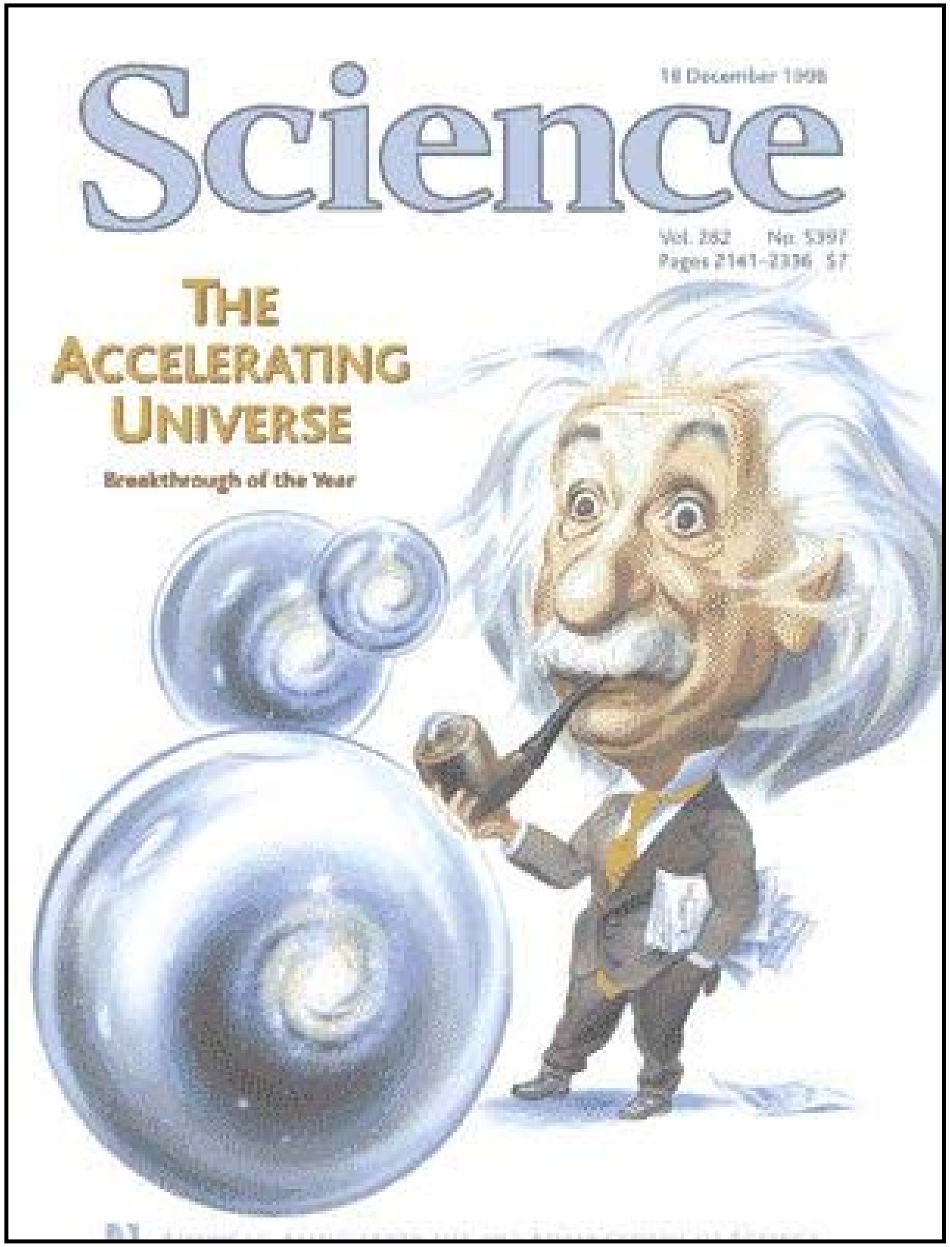
Astronomy can be helpful to physicists!

Precision Cosmology

"How helpful to us is astronomy's pedantic accuracy, which I used to secretly ridicule!"

Einstein's statement to Arnold Sommerfeld on December 9, 1915 (regarding measurements of the advance of the perihelion of Mercury)

Dark Energy


18 December 1998
Science
Vol. 282 No. 5397
Pages 2141–2336 $7
THE ACCELERATING UNIVERSE
Breakthrough of the Year

Evolution of $H(z)$ is a key quantity

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

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, $H(z)$

$w = p/\rho = -1$ for Λ

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

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 $H(z)$ through coordinate distance $r(z)$

$$r(z) = \left.\begin{matrix}\sin\\ 1\\ \sinh\end{matrix}\right\}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

- Luminosity distance

  Flux = (Luminosity / $4\pi d_L^2$)

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

- Angular diameter distance

  $\alpha =$ Physical size / d_A

$$d_A(z) \propto \frac{r(z)}{(1+z)}$$

- Volume (number counts)

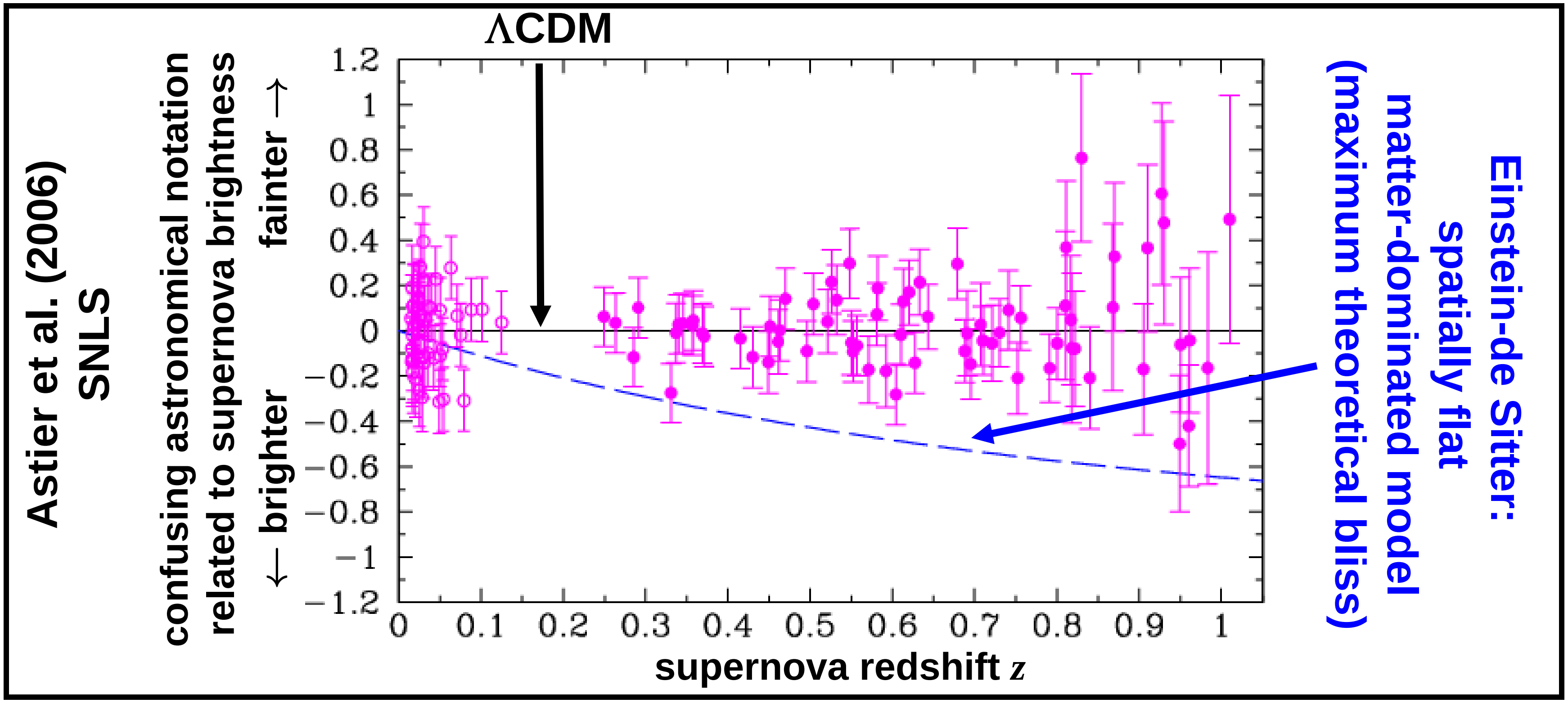
  $N \propto V^{-1}(z)$

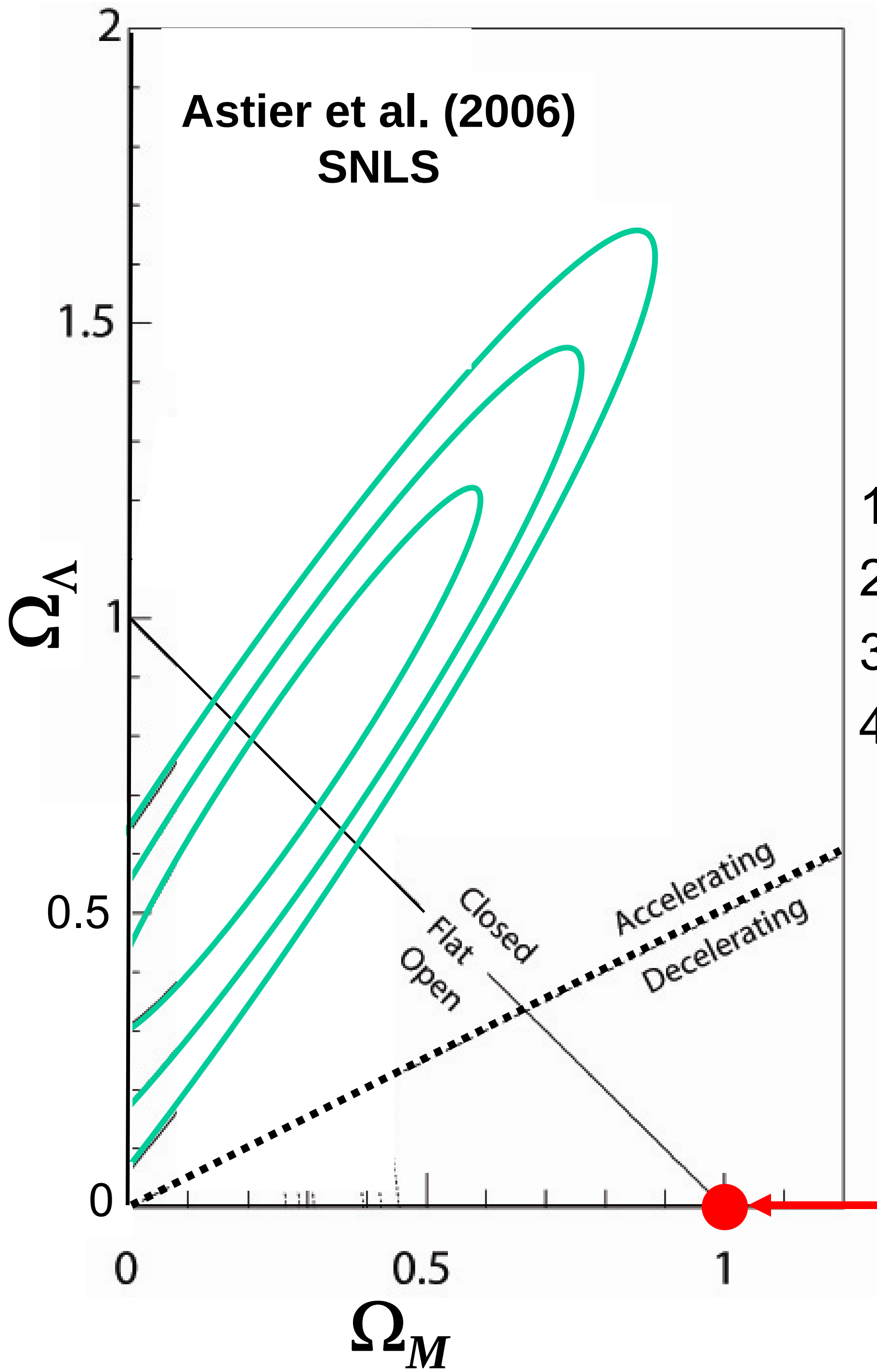
$$dV = \frac{r^2(z)}{\sqrt{1-kr^2(z)}}\, dr\, d\Omega$$

- Age of the universe

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

Supervovae Evidence for Dark Energy





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

1. Observe magnitude & redshift $\longrightarrow d_L(z)$
2. Assume a cosmological model $\longrightarrow d_L(z)$
3. Compare observations & model
4. If cosmoillogical constant

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

   length scale 10^{-3} cm $(10^{+28}$ cm$)$

   mass scale 10^{-4} eV $(10^{-33}$ eV$)$

Einstein-de Sitter
flat, matter-dominated model
(maximum theoretical bliss)

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_M, *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 ($k = 0$ from CMB) ; matter dominated ($\rho = \rho_M$)]

Take Sides!

- Can't hide from the data – ΛCDM too good to ignore
  - SNe
  - Subtraction: $1.0 - 0.3 = 0.7$
  - Weak lensing
  - Large-scale structure
  - Baryon acoustic oscillations
  - …

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

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

- Modify <u>right-hand side</u> of Einstein equations (ΔT_{00})
  1. Constant ("just" Λ)
  2. Not constant (dynamics driven by scalar field: $M \sim 10^{-33}$ eV)
- Modify <u>left-hand side</u> of Einstein equations (ΔG_{00})
  3. Beyond Einstein (non-GR: $f(R)$, branes, *etc*.)
  4. (Just) Einstein (back reaction of inhomogeneities)

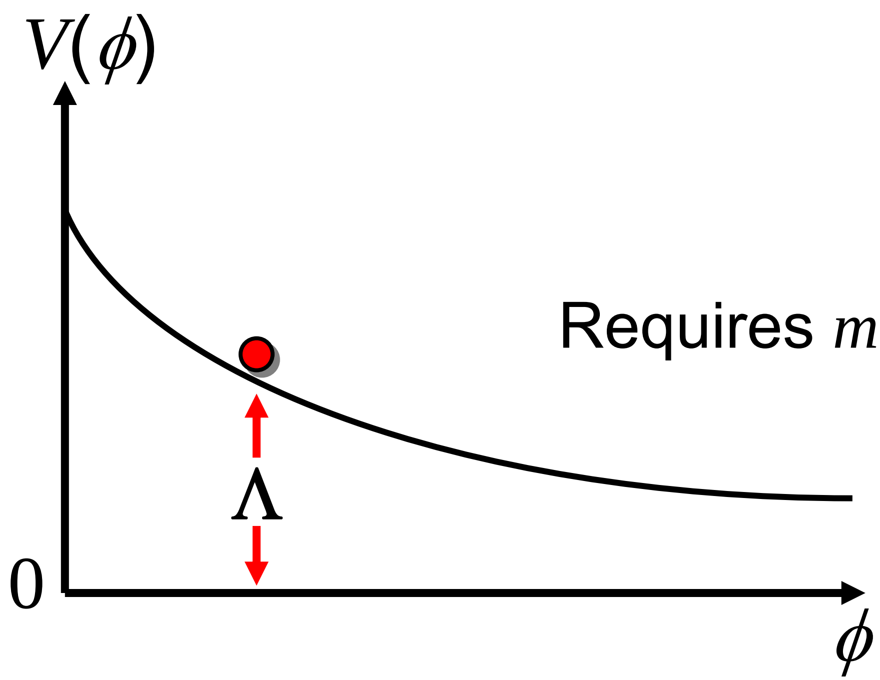
Anthropic/Landscape/DUCTape

- 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

(please see Andrei Linde)

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!*



Requires $m_\phi \simeq 10^{-33}$ eV

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 $R \approx \mathrm{Gpc}$ — Csaki, Erlich, Hollowood & Terning

- $n = 1$ KK graviton mode very light, $m \approx (\mathrm{Gpc})^{-1}$ — Kogan, Mouslopoulos, Papazoglou, Ross & Santiago

- Einstein & Hilbert got it wrong $f(R)$ — Carroll, Duvvuri, Turner, Trodden

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

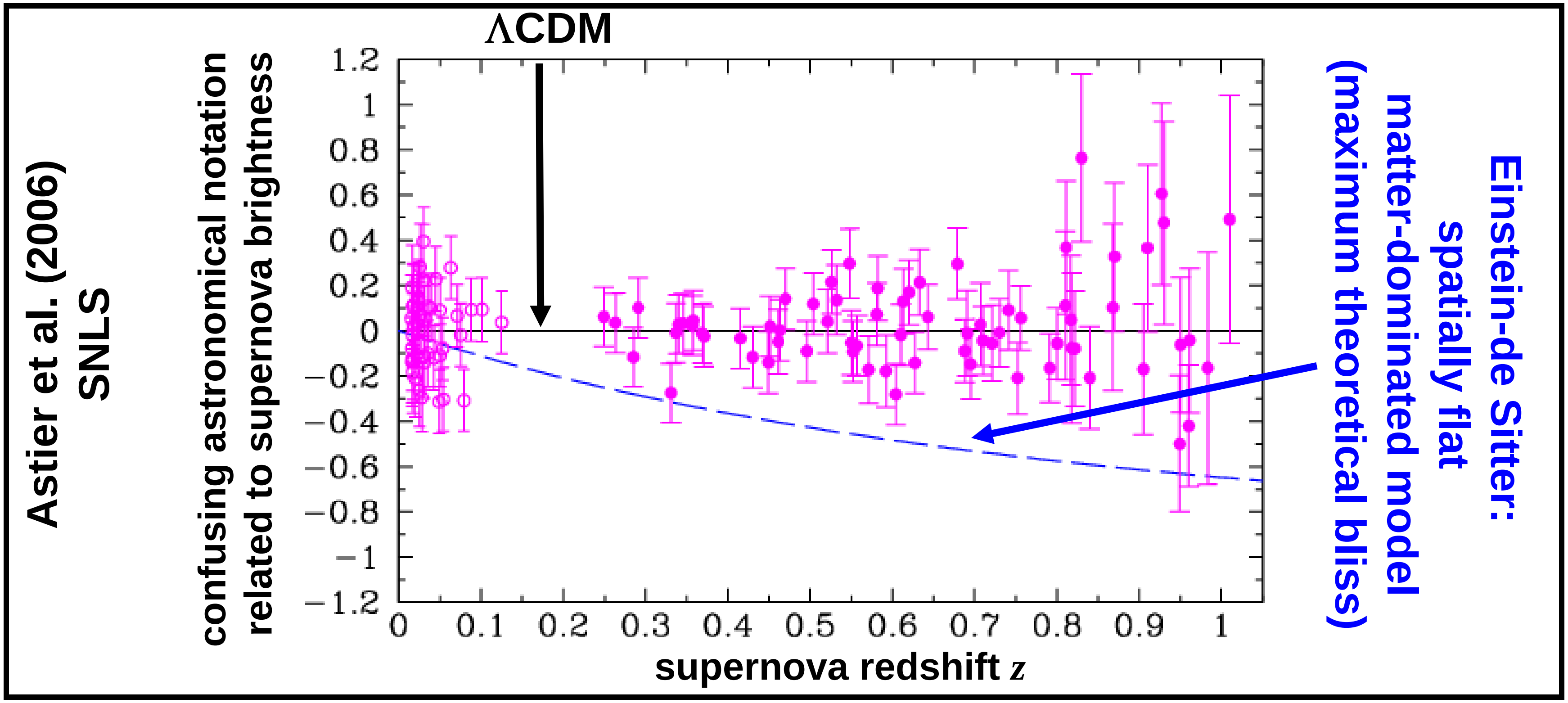
- Backreaction of inhomogeneities — Räsänen; Kolb, Matarrese, Notari & Riotto; Notari; Kolb, Matarrese & Riotto

Dark Energy

"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.

Evidence for Dark Energy



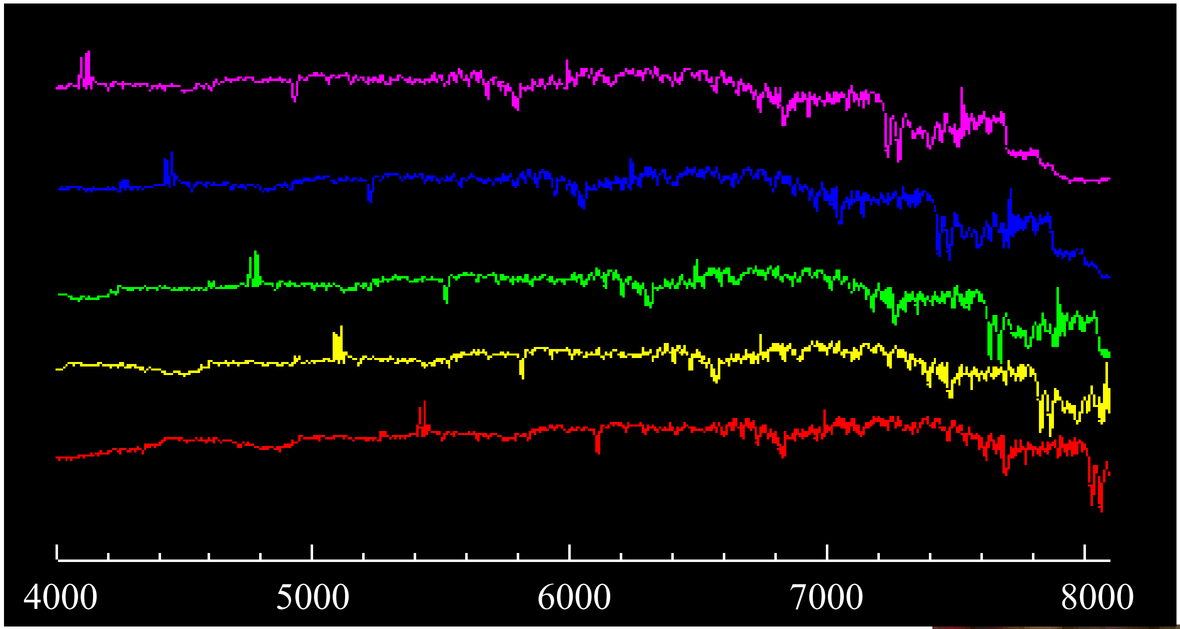
The case for Λ:

1) Hubble diagram (SNe)
2) Subtraction ($1.0 - 0.3 = 0.7$)
3) Baryon acoustic oscillations
4) Weak lensing
5) Galaxy clusters
6) Age of the universe
7) Structure formation

Supernova Type Ia

- Measure redshift and intensity as fn. of time (light curve)
- Systematics (dust, evolution, intrinsic luminosity dispersion, etc.)
- A lot of information per supervova
- 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



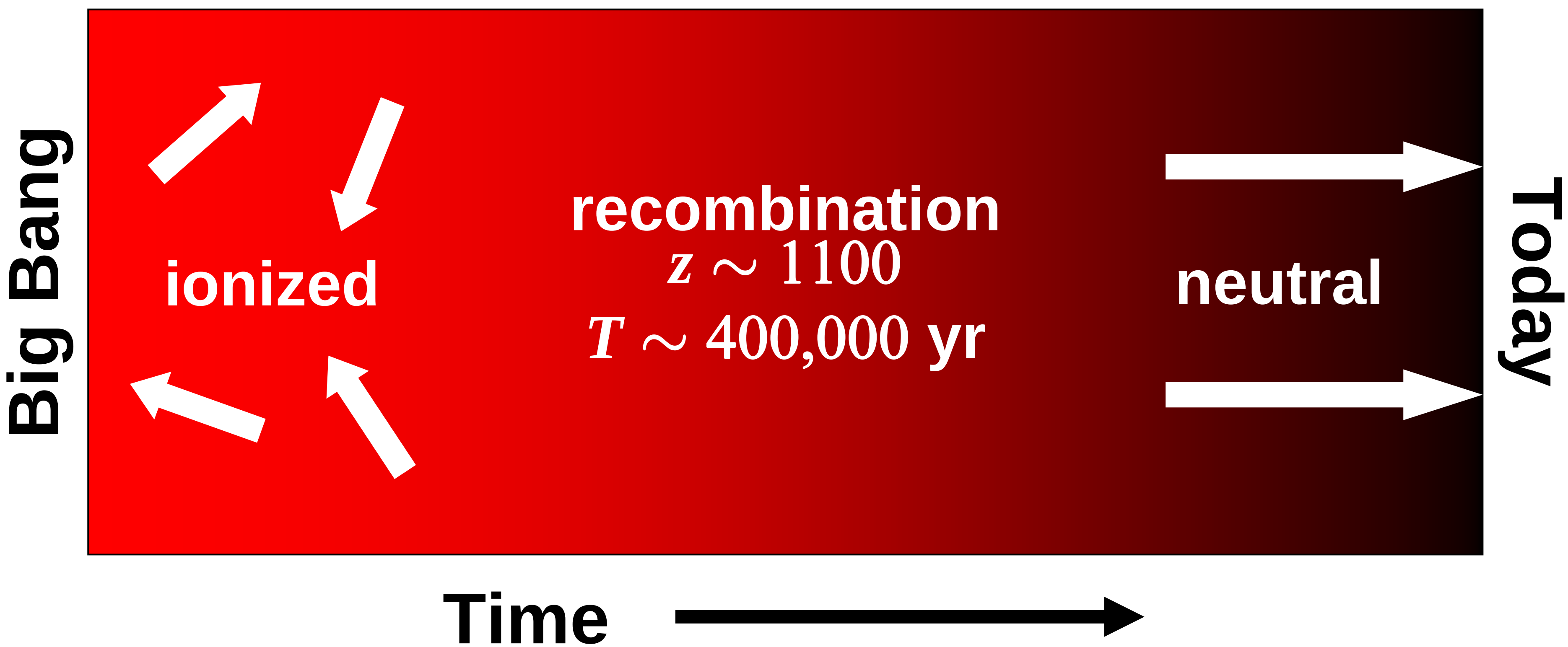
Traditional redshift from spectroscopy

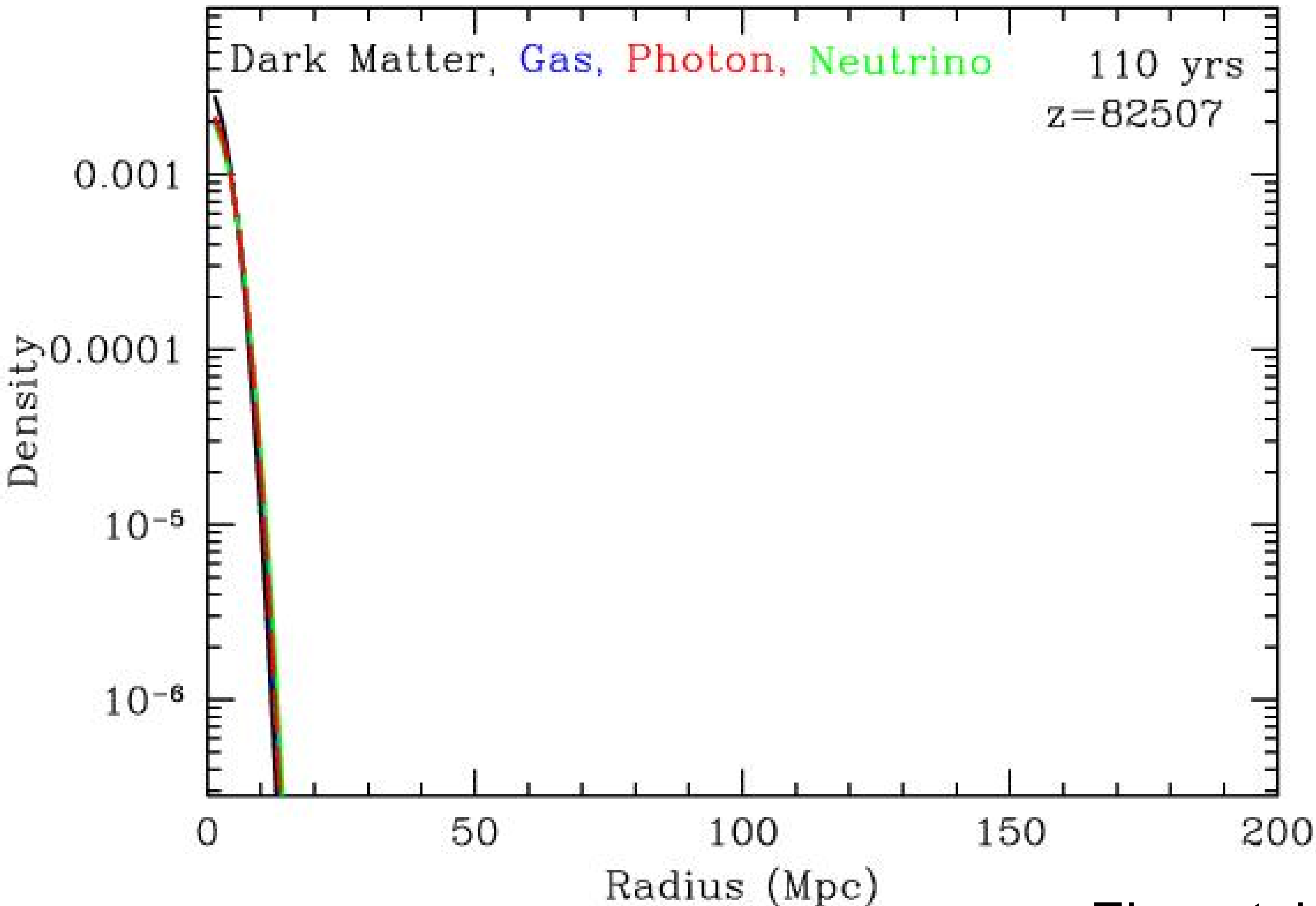
Photometric redshift from multicolor photometry

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)

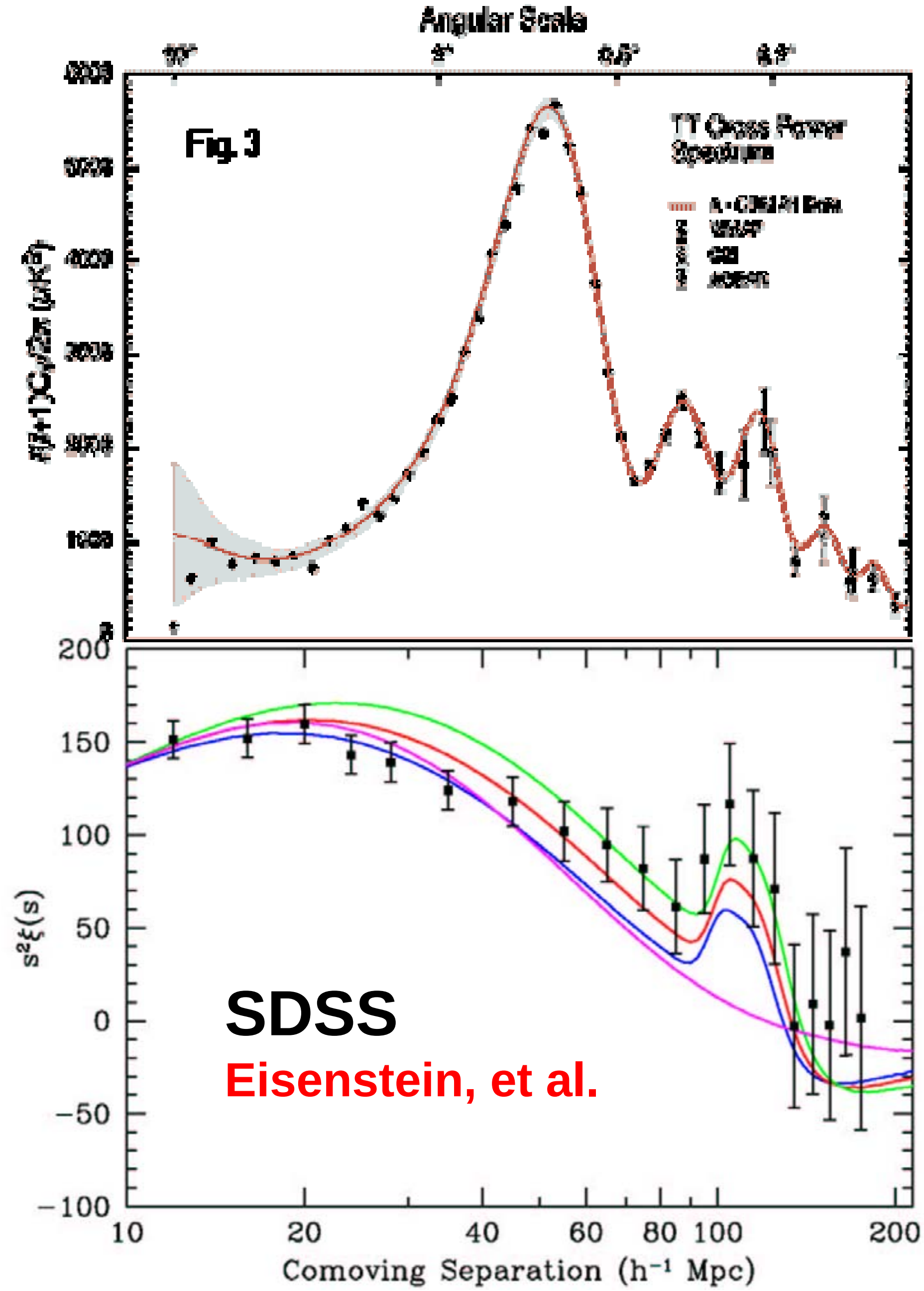




Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
Density
0.001
0.0001
10⁻⁵
10⁻⁶
0
50
100
150
200
Radius (Mpc)

Eisenstein

Baryon Acoustic Oscillations

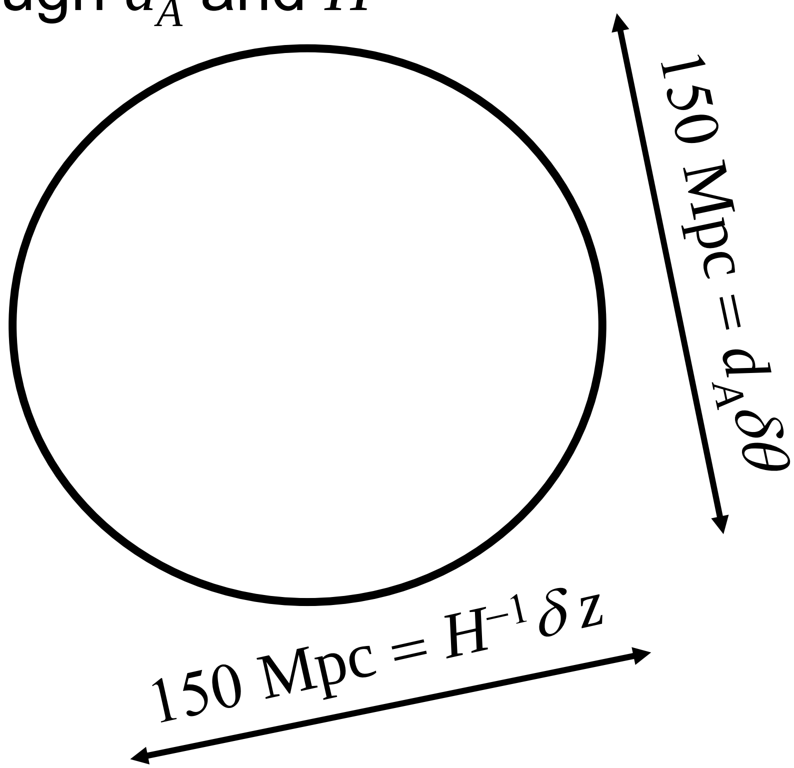


Baryon Acoustic Oscillations

- 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

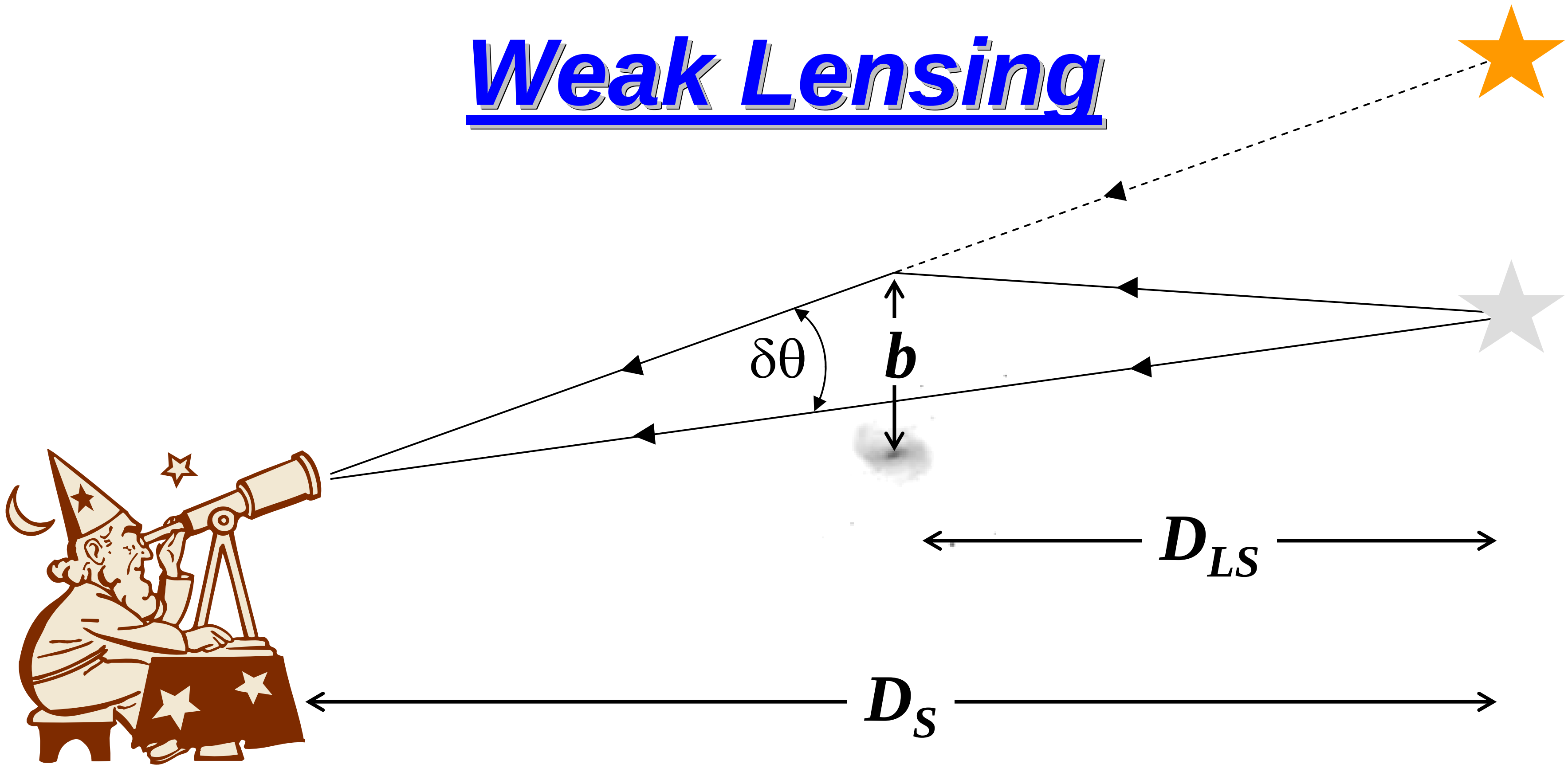
Sensitivity to dark energy

- 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

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

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

What's ahead

2010 2015 2020 2025

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

Large Resources

Not all on same cost basis
My estimate of costs

DES	$18M
Darkcam	$18M
PanSTARRS	$70M
HETDEX	$25M
HyperSuprime	$20M
WFMOS	$60M
Total	$211M
and later……..	
LSST	$500M
SKA	$700m
JDEM	$1B
Total	$2.2B
Grand Total	$2.4B

Dark Energy Task Force* Strategy:

- Determine as well as possible whether the accelerating expansion is consistent with being due to a cosmological constant.

- 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 by determining $w(a)$.

- 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.

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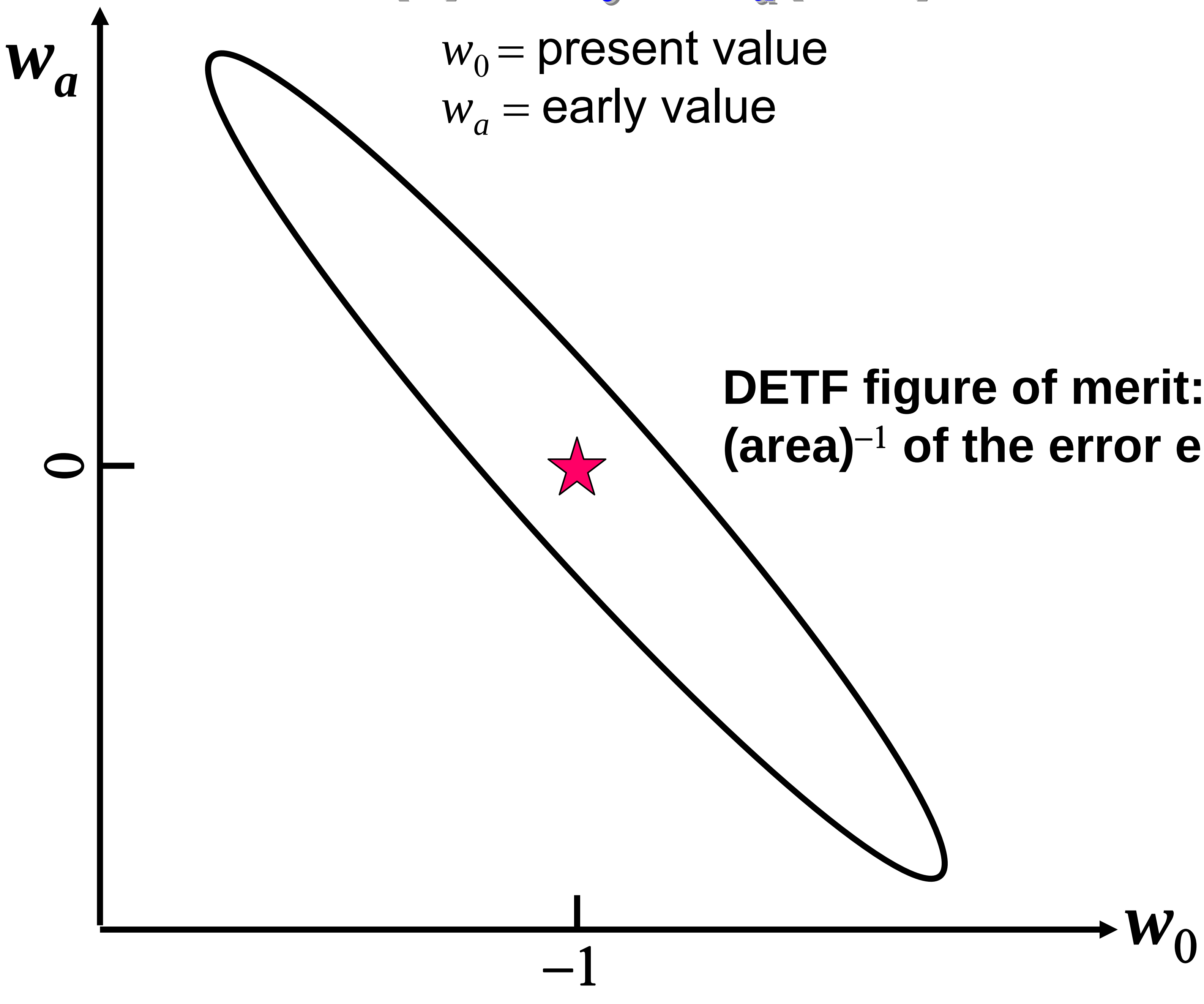
* DETF

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

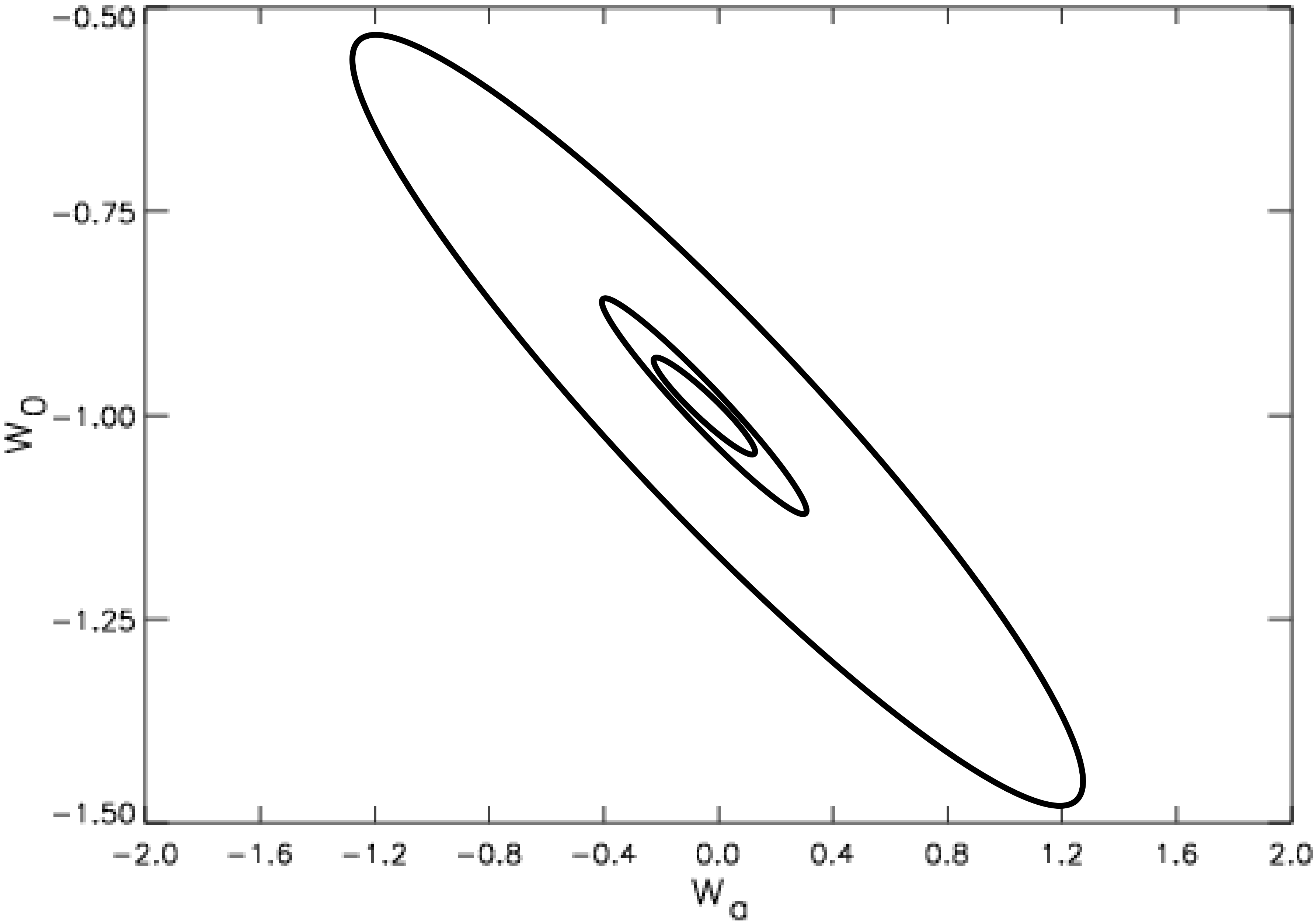
w_0 = present value

w_a = early value

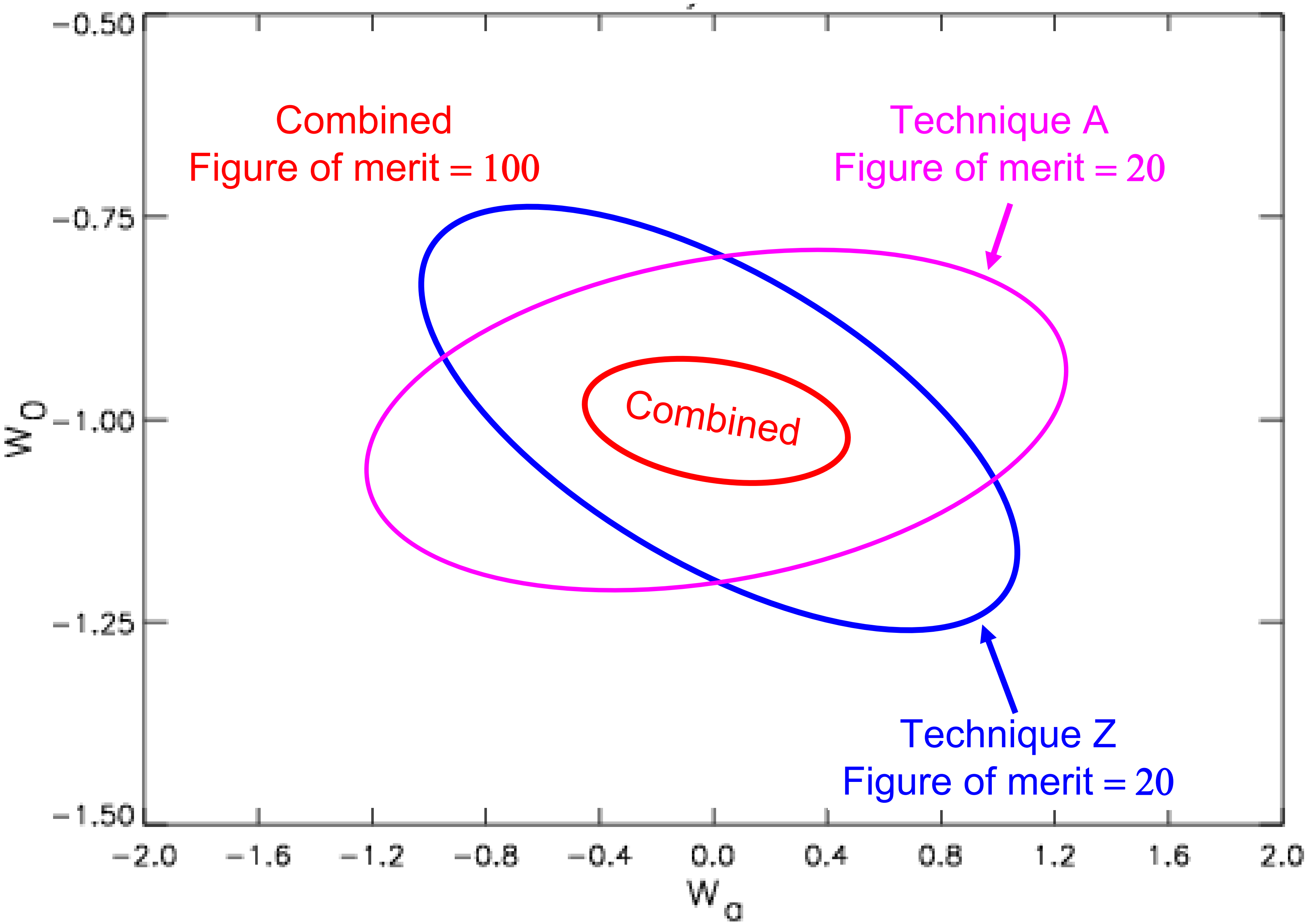


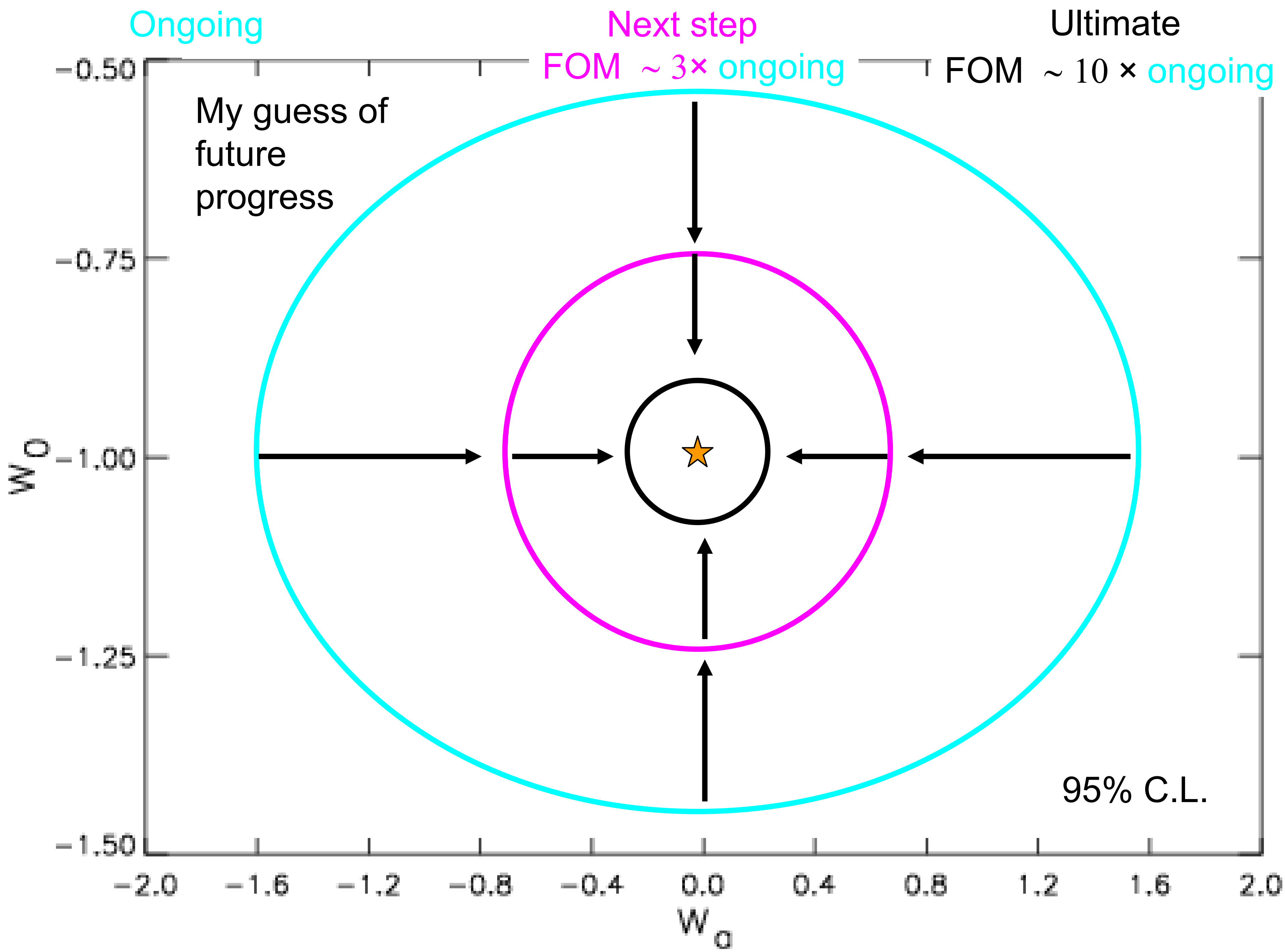
DETF figure of merit:
(area)$^{-1}$ of the error ellipse

Systematics: none, optimistic, pessimistic



The Power of Two (or Three, or Four)




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

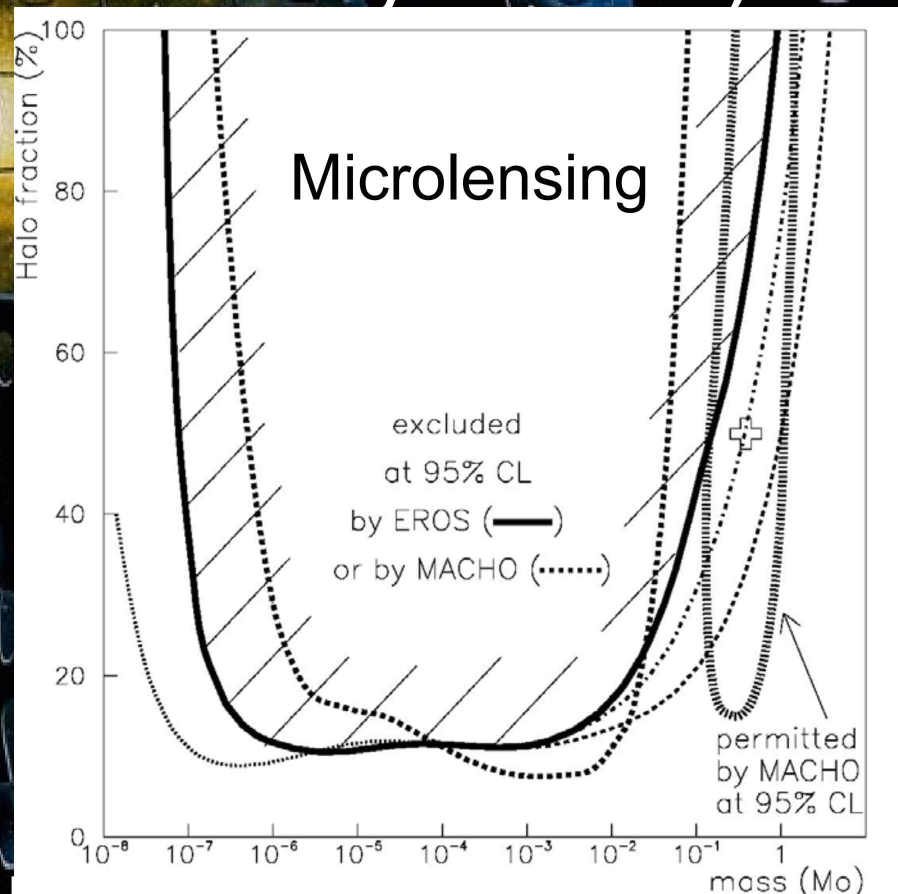
Dark Matter

- MOND (Modified Newtonian Dynamics)

Dark Matter

- MOND (Modified Newtonian Dynamics)
- Planets
- Dwarf stars
- Size challenged stars

  brown red white
- Black holes
- Particle relic from the bang



Particle Relic from the Bang

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, axino, …) (cold dark matter)
- LKP (lightest Kaluza-Klein particle)
- axions, axion clusters
- solitons (Q-balls; B-balls; Odd-balls, ….)
- supermassive wimpzillas

Mass range

$10^{-6}\,\mathrm{eV}\ \ (10^{-40}\,\mathrm{g})$ axions

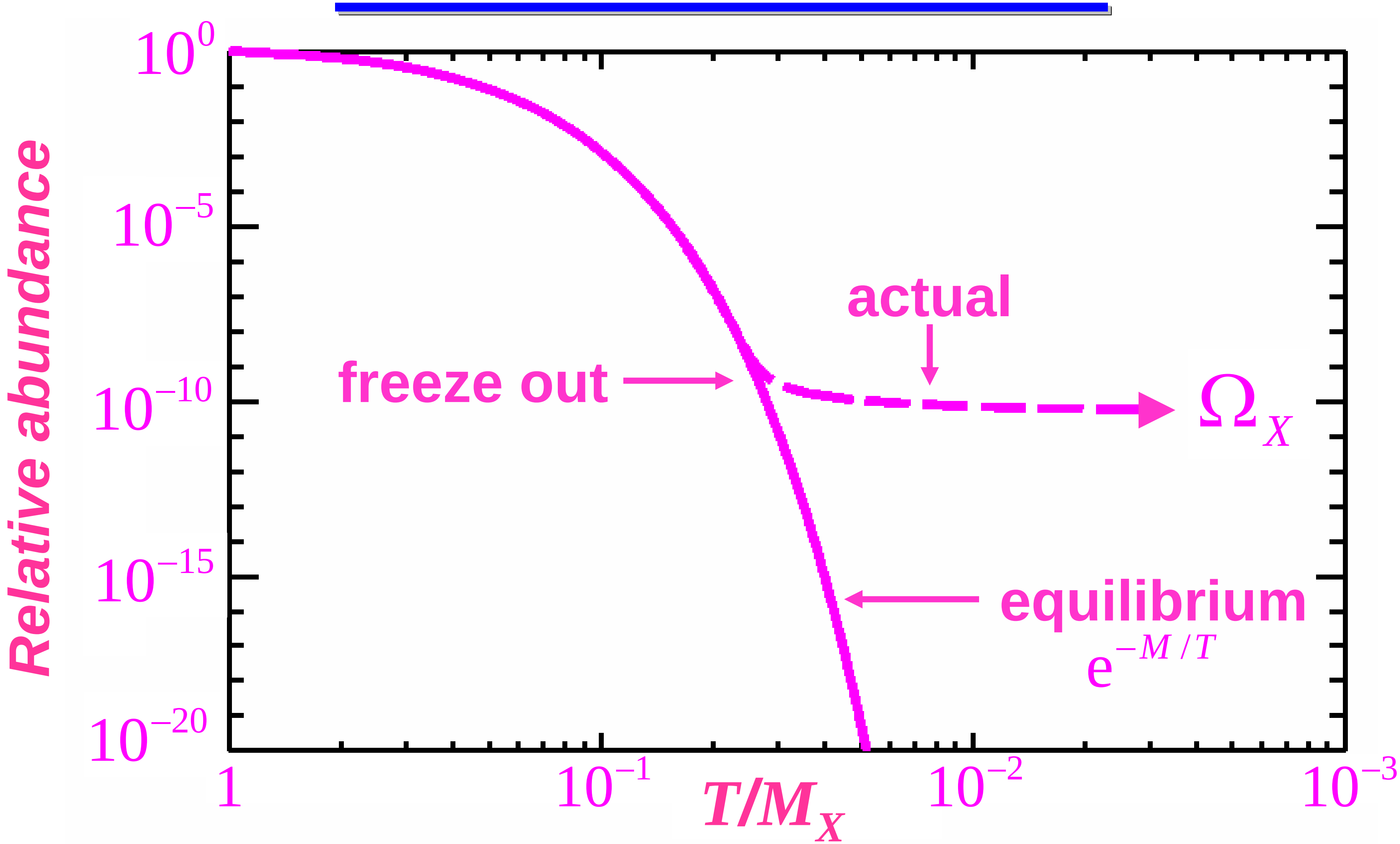
$10^{-8}\,M_{\odot}\ \ (10^{25}\,\mathrm{g})$ axion clusters

Interaction strength range

Noninteracting: wimpzillas

Strongly interacting: B balls

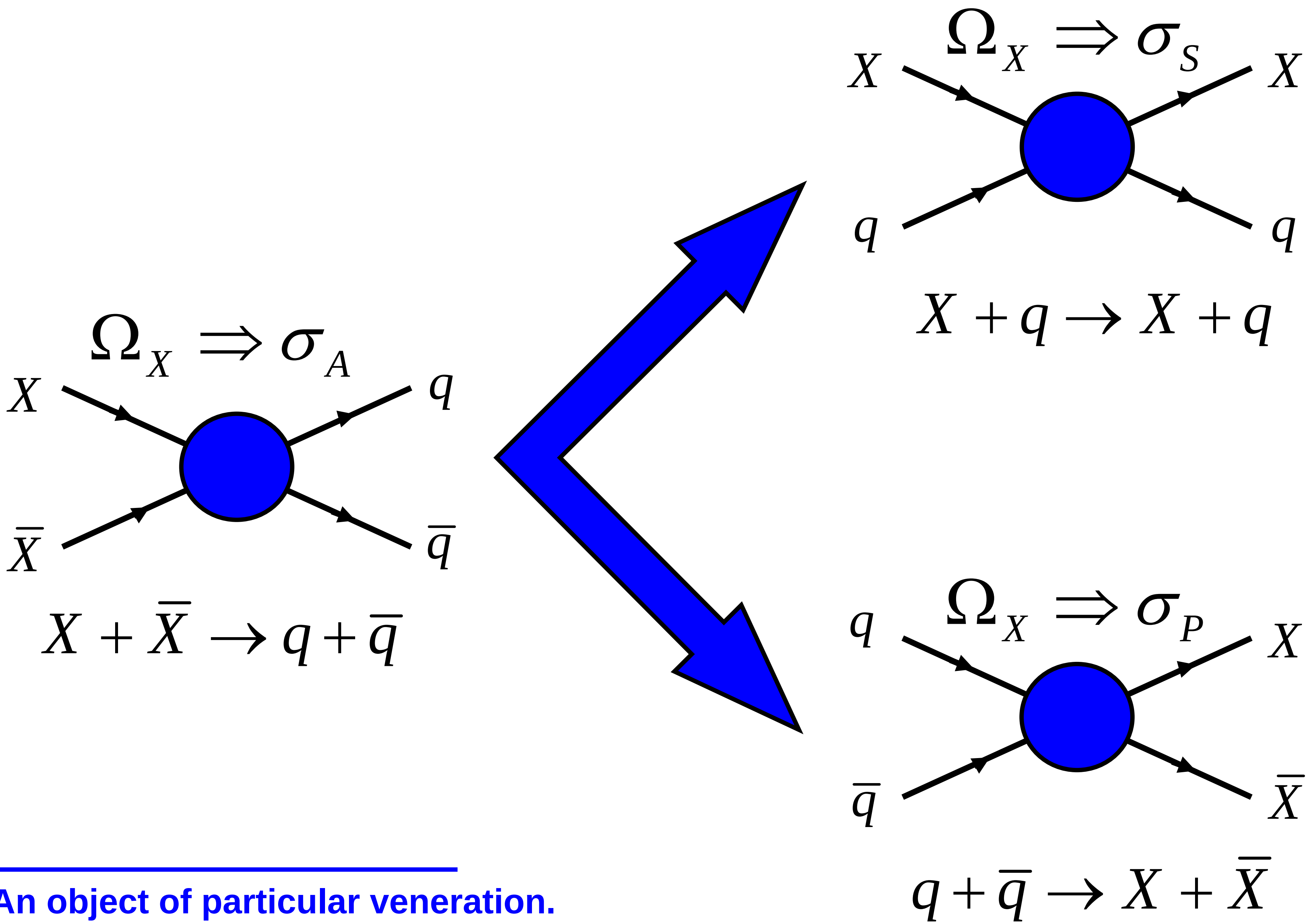
Cold Thermal Relic*



$\Omega_X \propto \sigma_A^{-1}$ ***(independent of mass)***

*** An object of particular veneration.**

Cold Thermal Relic*



* An object of particular veneration.

Cold Thermal Relic*

- **Direct detection (σ_S)**

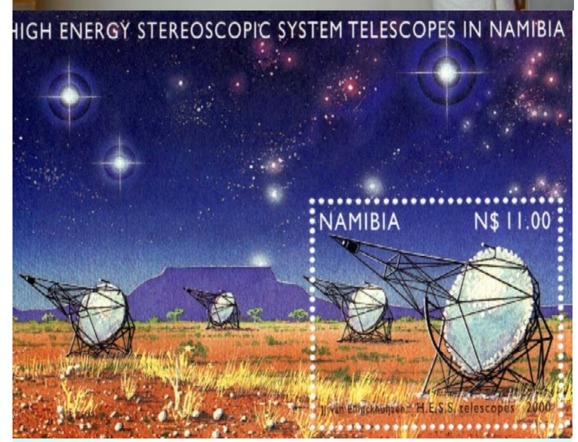
  More than a dozen experiments

- **Indirect detection (σ_A)**

  Annihilation in sun, Earth, galaxy. . .

  neutrinos, positrons,

  antiprotons, γ rays, . . .



- **Accelerator production (σ_P)**

  Tevatron, LHC, ILC

* **An object of particular veneration.**

Cold Thermal Relic*

Favorite cold thermal relic: the neutralino

- Study "constrained" MSSM models
- Typical SUSY models consistent w/ collider data have too small annihilation cross section $\rightarrow$ too large Ω
- Need chicanery to increase annihilation cross section
  - s-channel resonance through light H and Z poles
  - co-annihilation with $\tilde{\tau}$ or $\tilde{t}$
  - large tanβ (s-channel annihilation via broad A resonance)
  - high values of m_0–LSP Higgsino-like & annihilates into W & Z pairs (focus point)
  - …
  - or, unconstrained

* An object of particular veneration.

Cold Thermal Relic*

Favorite cold thermal relic: the neutralino

- Direct detectors, indirect detectors, colliders race for discovery
- Suppose by SUSY 2009 have credible signals from all three???

How will we know we all seeing the same phenomenon?

- Lots of opinions (papers)
  - Will learn enough from LHC (Arnowitt & Dutta)
  - Need ILC (Baltz, Battaglia, Peskin, Wizansky)
  - Depends where in SUSY space (Chung, Everett, Kong, Matchev)
  - …
- *Let's hope for this problem!!!!*

*** An object of particular veneration.**

Cold Thermal Relic*

Favorite cold thermal relic: the neutralino

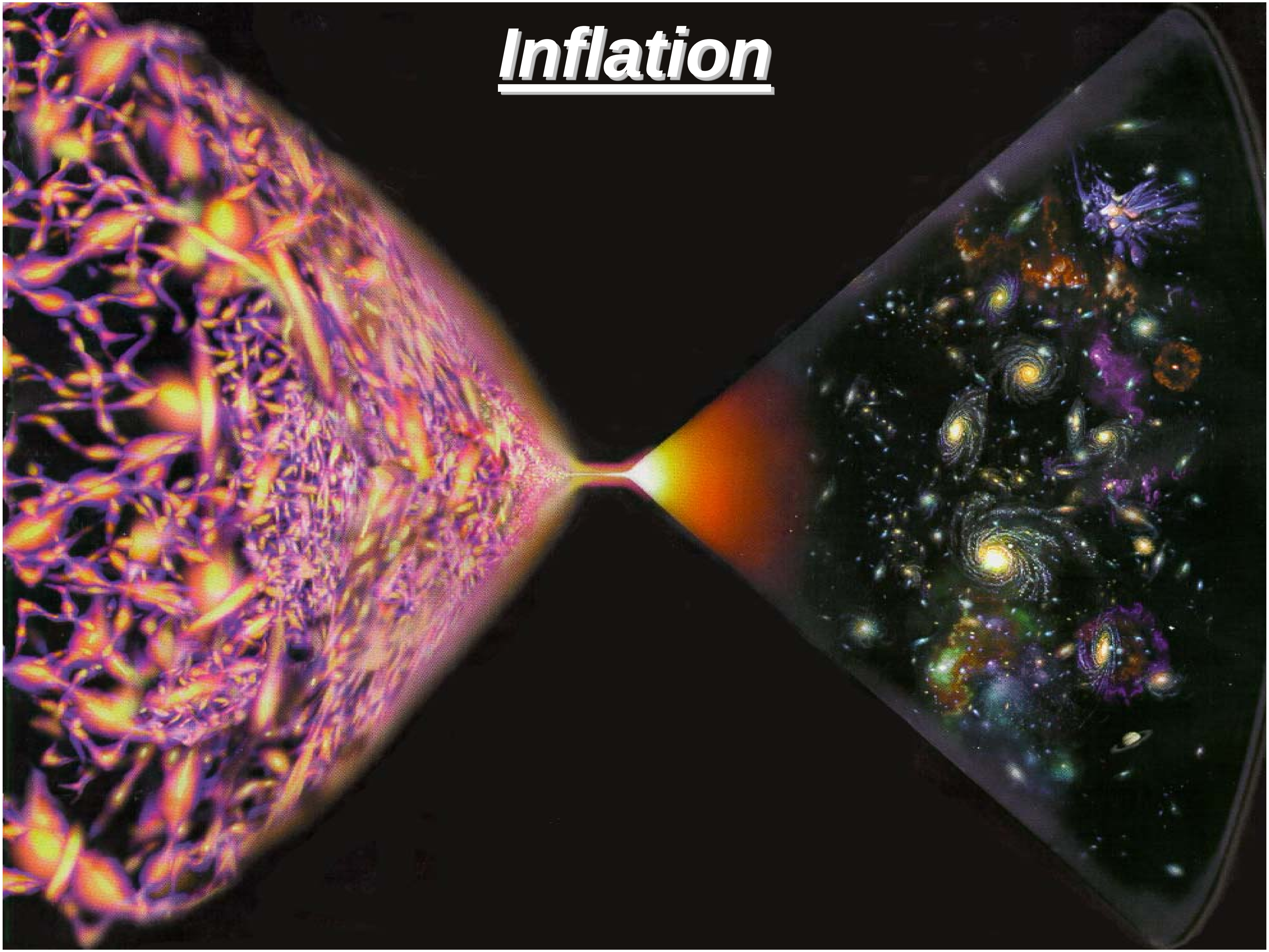
"a simple, elegant, compelling explanation for a complex physical phenomenon"

"For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation."

- Tommy Gold

*** An object of particular veneration.**

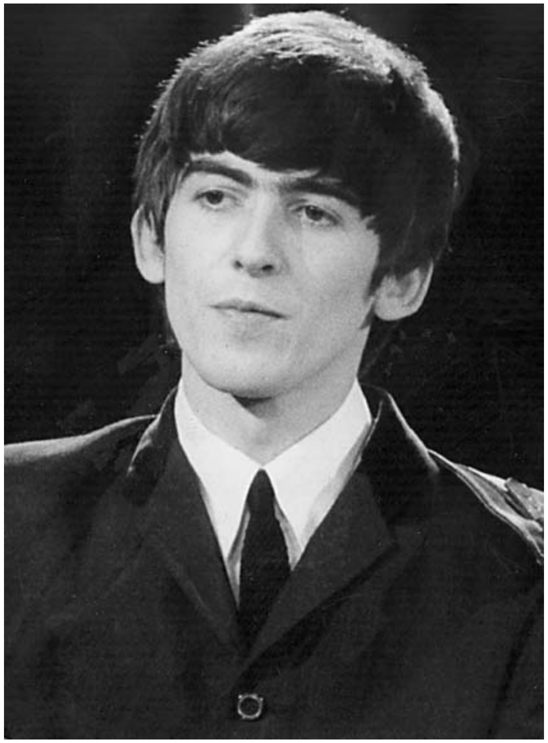
Inflation



Inflation

- The inflaton scalar potential must be flat–stable to radiative corrections
- SUSY to the rescue?
- Not so fast … (see Lyth & Riotto, Phys. Rep. 1999)
- Many models give $V(\phi) \sim \ln\phi$ hybrid models
- But no general prediction for
  - scalar spectral index n
  - running of n (n')
  - amplitude of gravitational wave background (r)
- Again, need observational guidance

Harrison-Zel'dovich Spectrum ?



$$n \equiv 1?$$

$$n' \equiv 0?$$

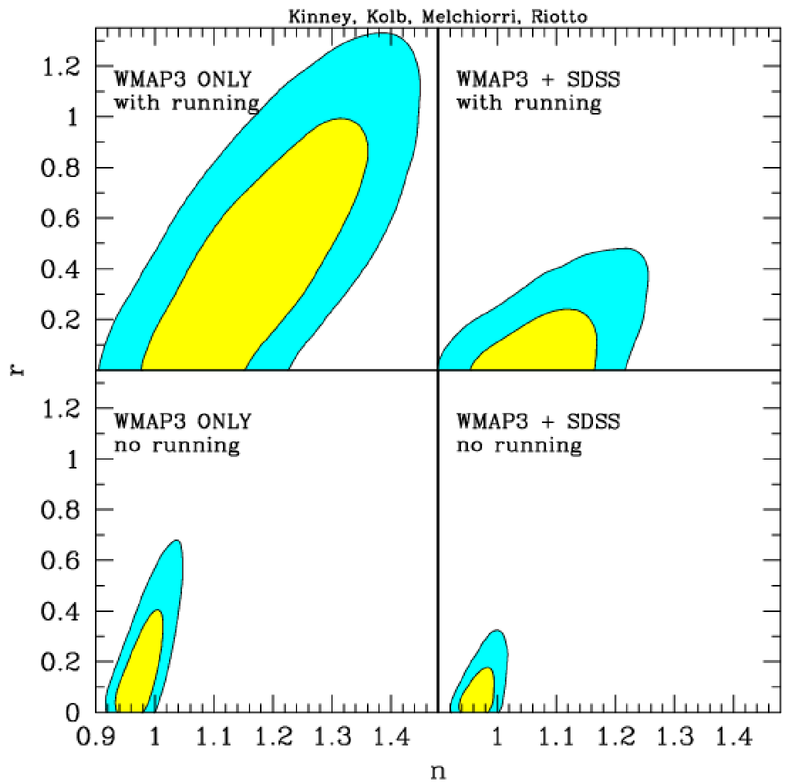
$$r \equiv 0?$$

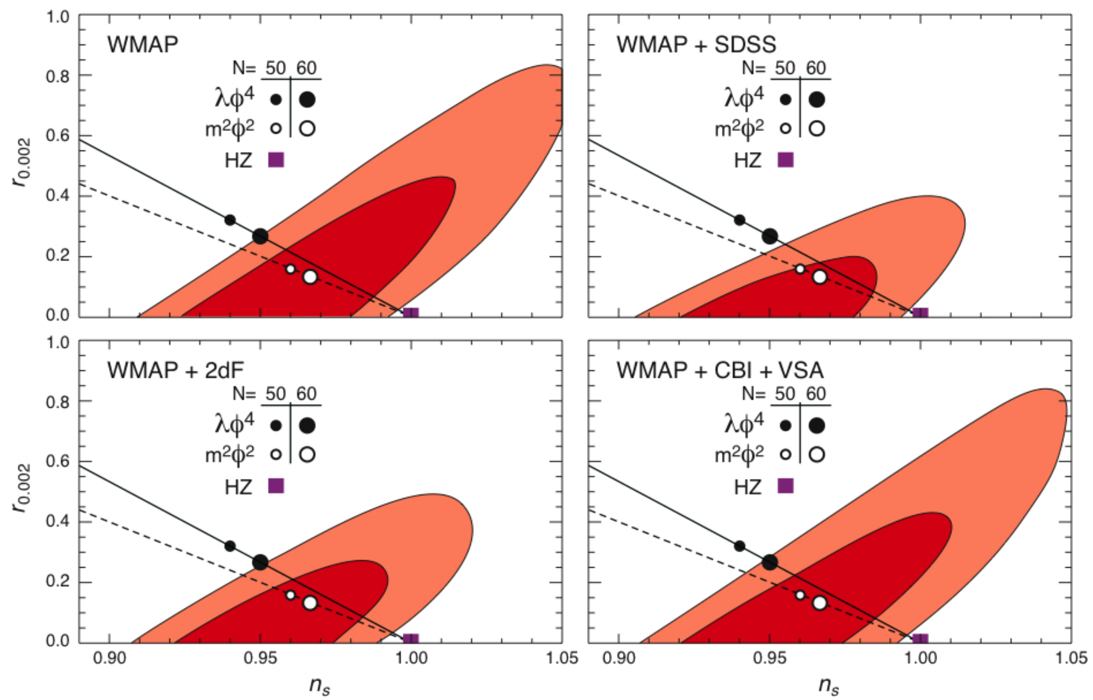
Fixed point of ignorance

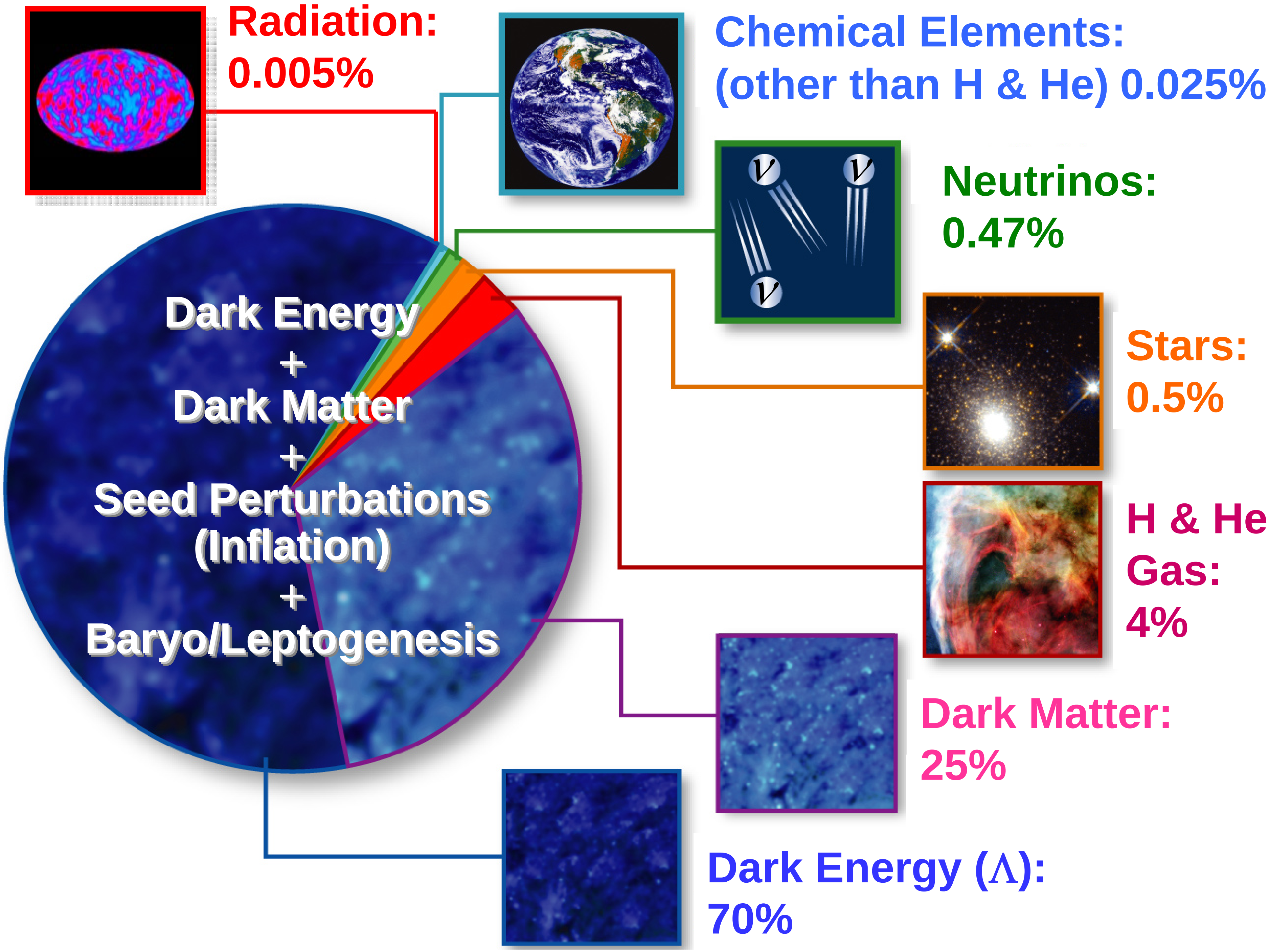
- **Observational question: Combine CMB & LSS?**
- **Theoretical question: What if exact Harrison-Zel'dovich**

Harrison-Zel'dovich Spectrum ?

1. priors?
2. chain?
3. data sets used?
4. …



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Dark Energy (Λ):
70%
Dark Energy
+
Dark Matter
+
Seed Perturbations
(Inflation)
+
Baryo/Leptogenesis

Status of Cosmology

SNOOZY’07 Karlsruhe July 2007

Rocky Kolb

The University of Chicago