Cosmic Acceleration and Dark Energy
For Phy 262

Andreas Albrecht
(based on various seminars and colloquia)

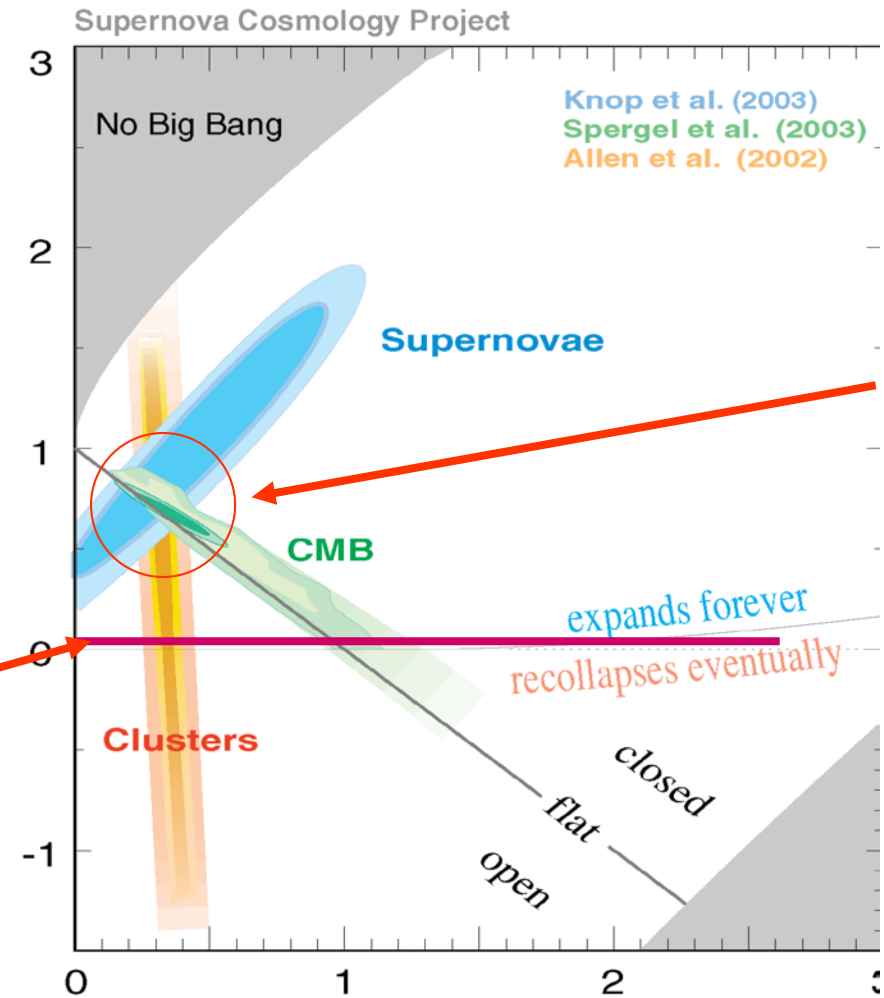
- Slides with a large blue box like this are outlines slides that still need to be updated (due to this slides set being combined from different talks)

OUTLINE needs updating

- The Basics: Data, Directions and Issues
- Anthropics, Landscape & Critique
- Alternative Viewpoints
- Conclusions

Cosmic acceleration

Accelerating matter is required to fit current data



Preferred by data c. 2003

"Ordinary" non accelerating matter

Ω_Λ ↓ Amount of w=-1 matter ("Dark energy") ↑

← Amount of "ordinary" gravitating matter →

Ω_M (Includes Dark Matter)

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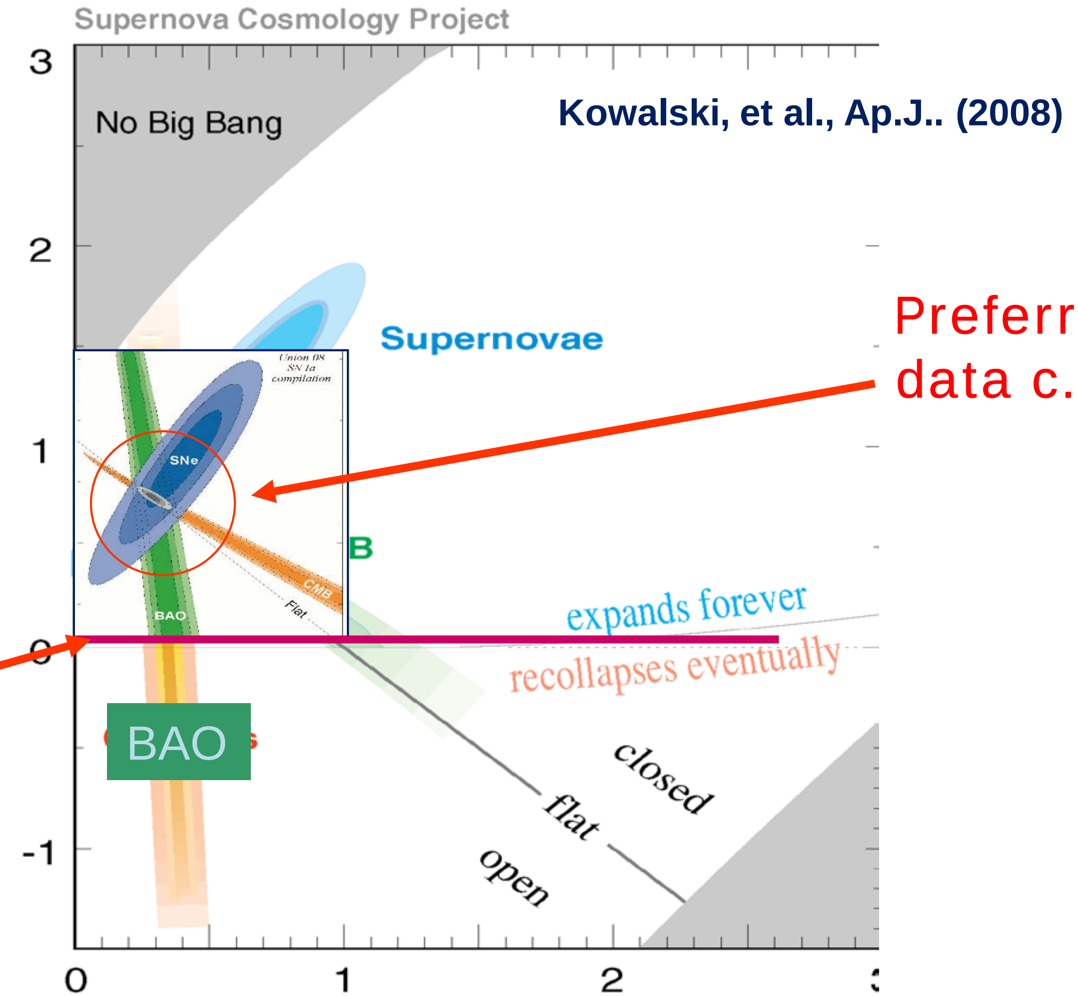

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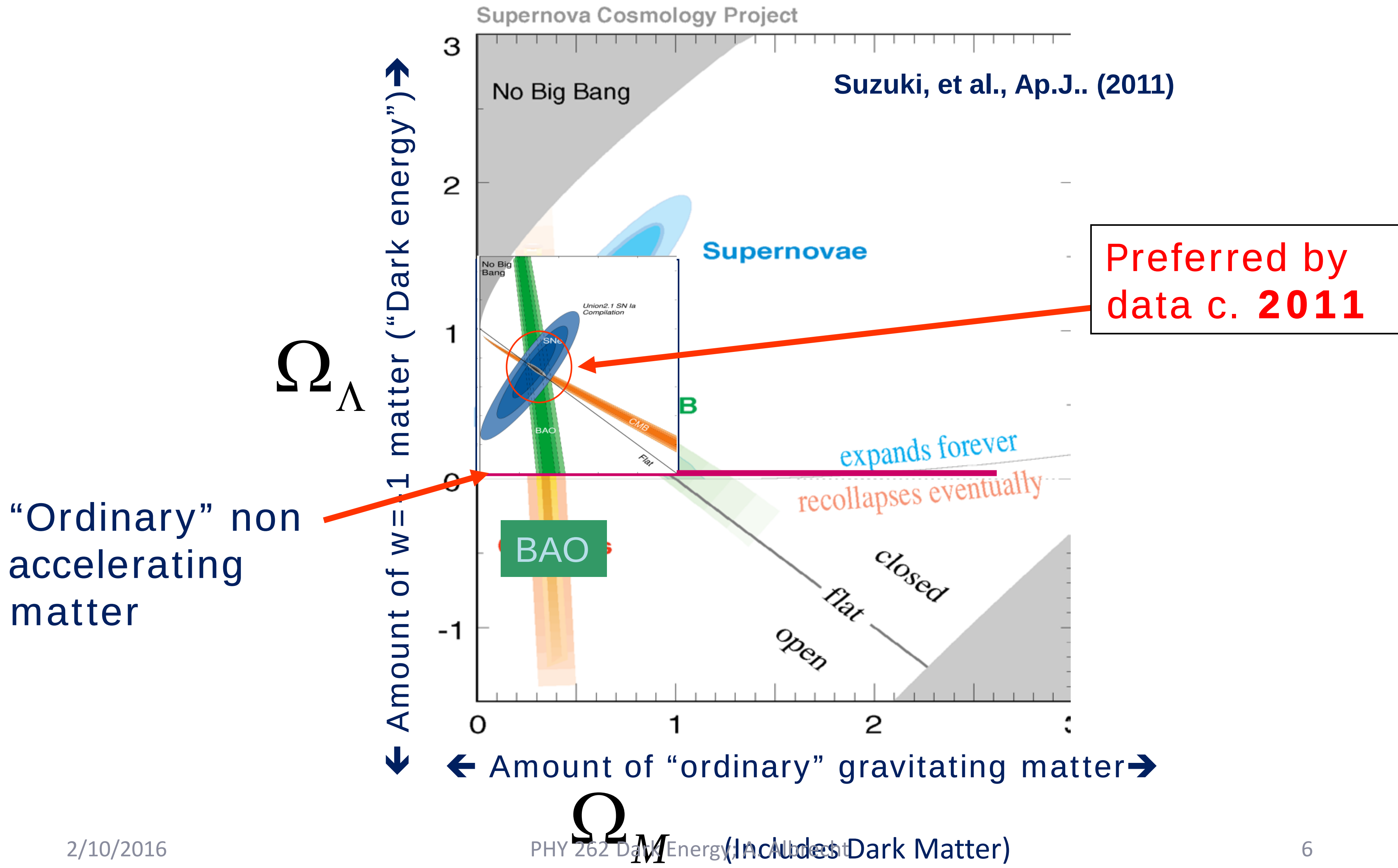

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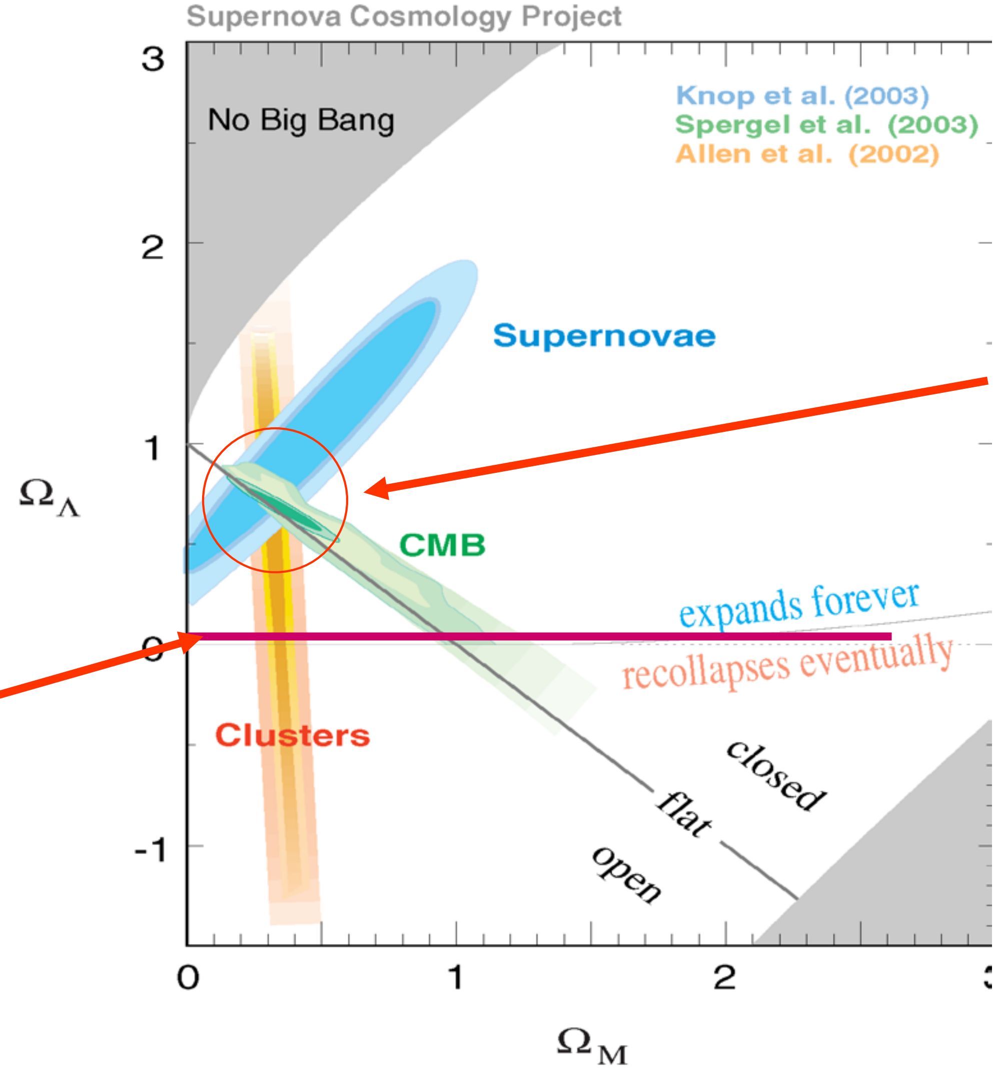

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Friedmann Eqn.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\left(\rho_k + \rho_r + \rho_m + \rho_\Lambda\right)$$

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Scale factor

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Curvature

Relativistic Matter

Non-relativistic Matter

Dark Energy

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Positive acceleration requires

- $w \equiv p/\rho < -1/3$ (unlike any known constituent of the Universe) *or*
- a non-zero cosmological constant *or*
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Some general issues:

Numbers:

- Today, $$\rho_{DE} \approx 10^{-120} M_P^4 \approx \left(10^{-3} eV\right)^4$$

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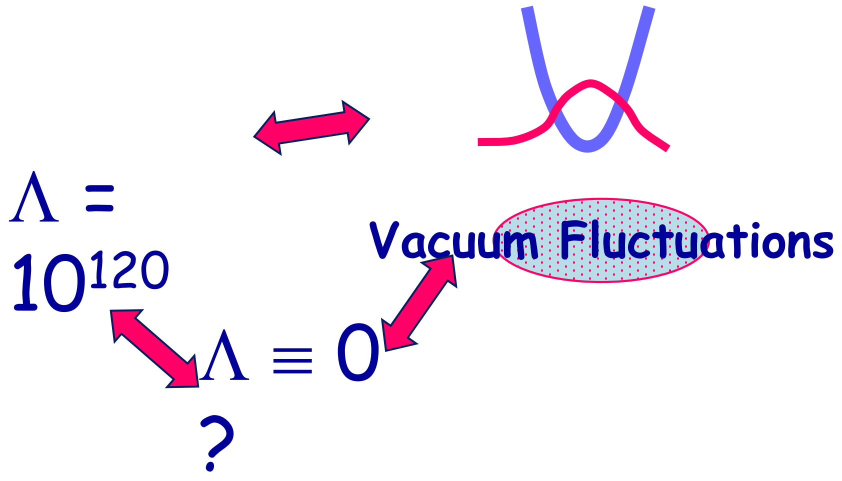
A cosmological constant Λ

- Nice “textbook” solutions BUT
- Deep problems/impacts re fundamental physics
  - Vacuum energy problem



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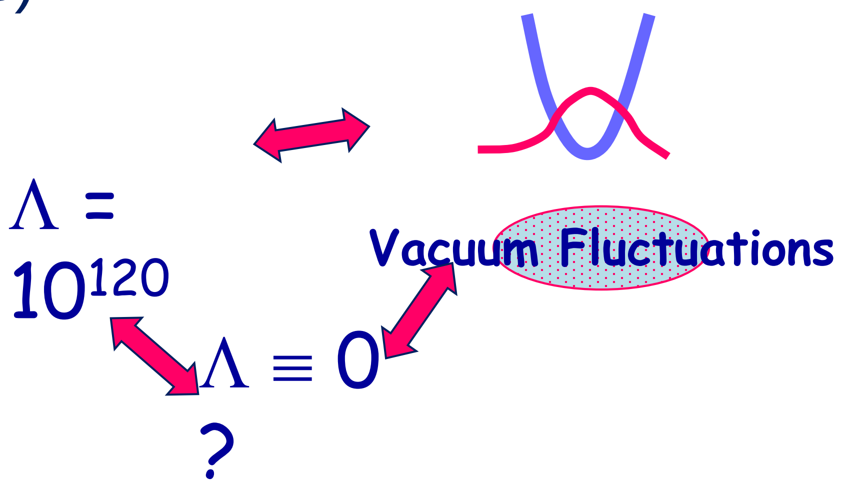

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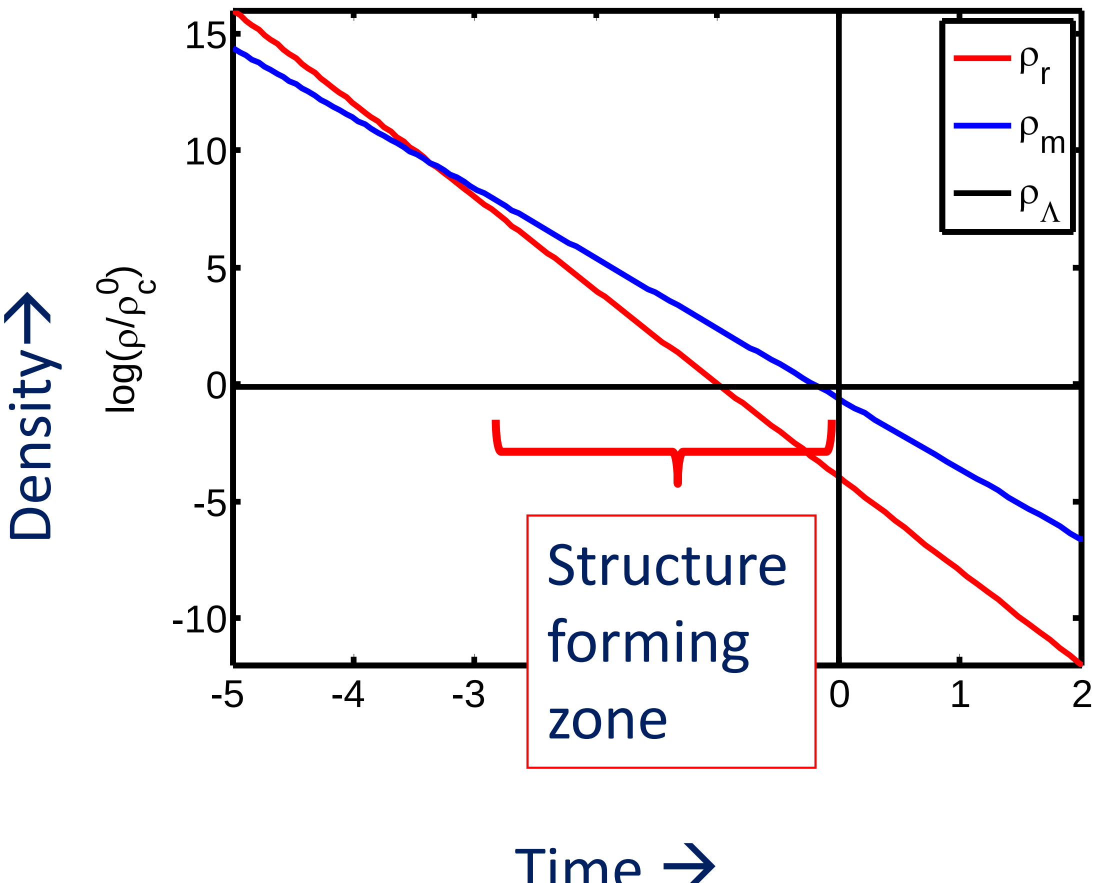

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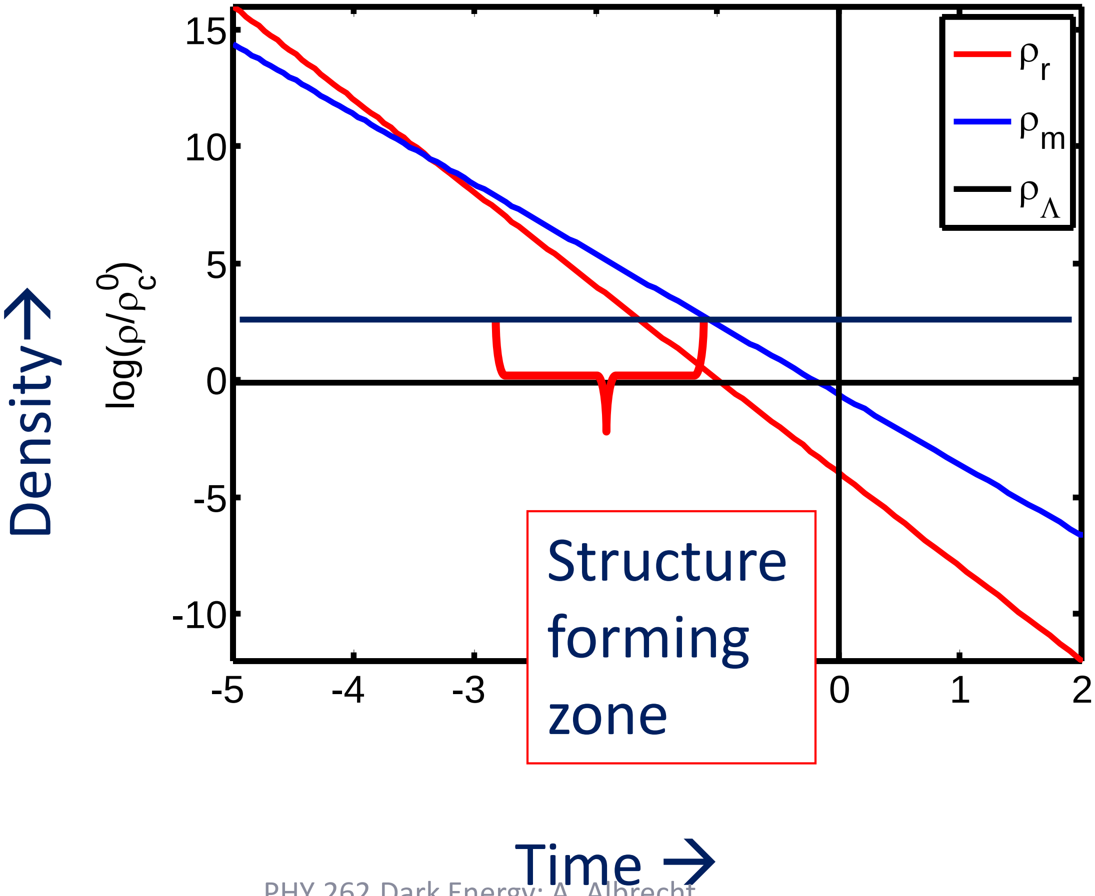

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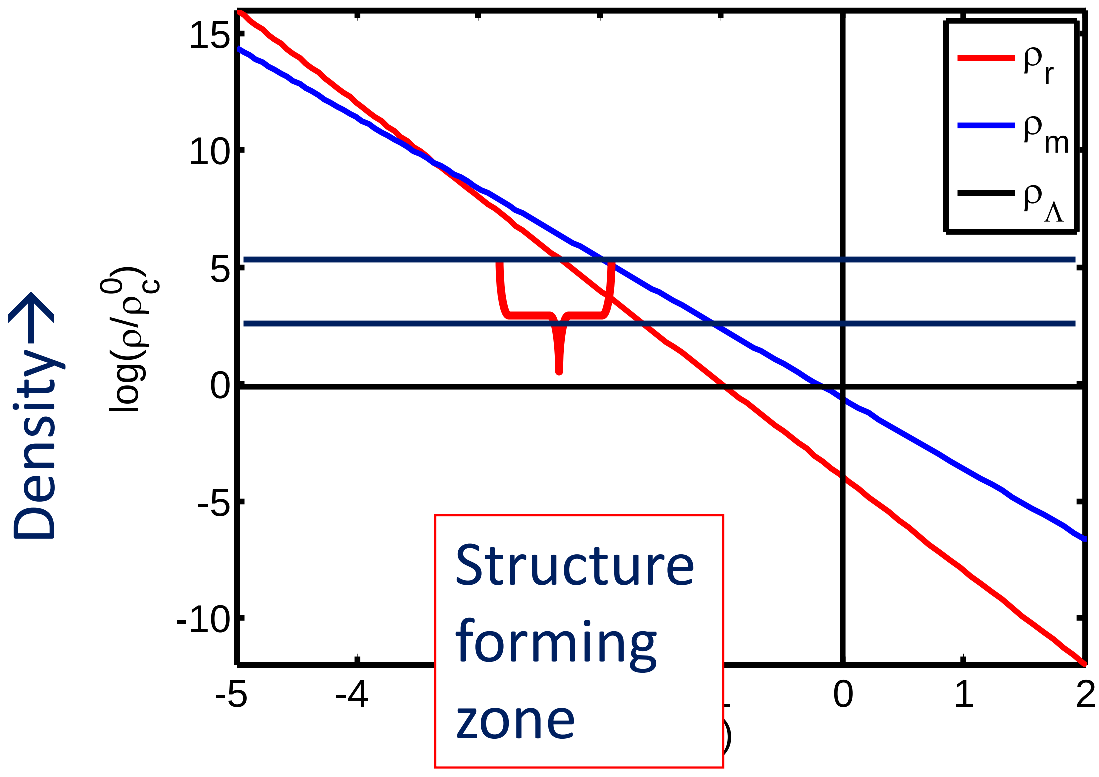

Time →

Anthropics and the value of Λ

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- Can we input that data that we have cosmic structure and predict the (very small) value of Λ? (Life?!)
- To do this one requires:
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- To do this one requires:
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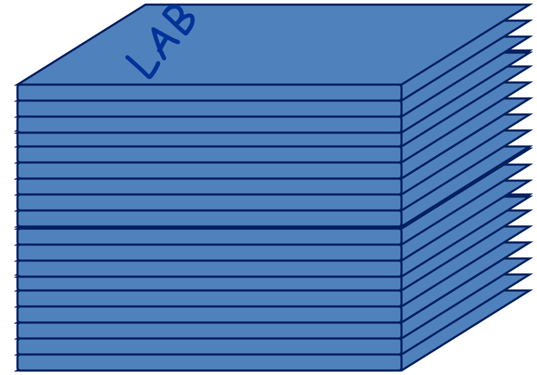
- Weinberg used some simple choices for 1) and 2) and "predicted" a value of Λ in 1987 similar to the value discovered ~10 years later.
- Since then string theorists have argued that the string theory landscape delivers a suitable ensemble of Λ's (Bousso & Polchinski)

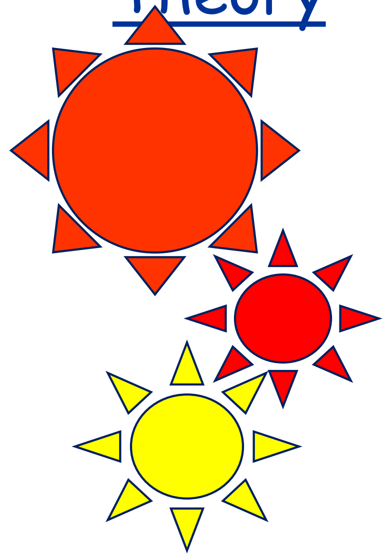
Comment on how we use knowledge ("A" word!)

Total knowledge about the universe→



Input

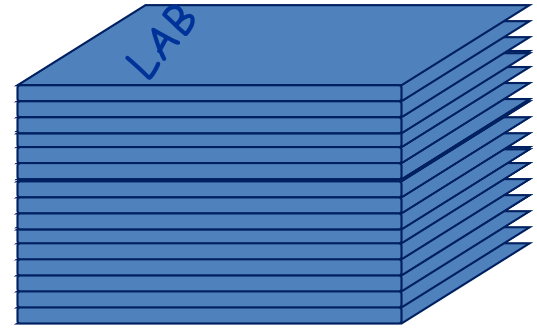
Theory



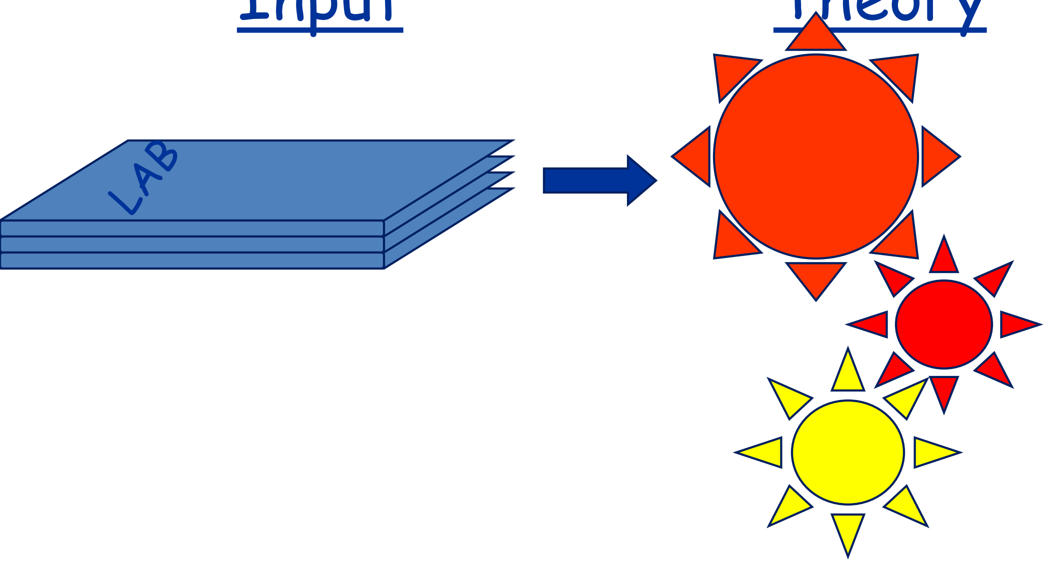
Output

Comment on the “A” word:

Total knowledge about the universe→



Input Theory Output



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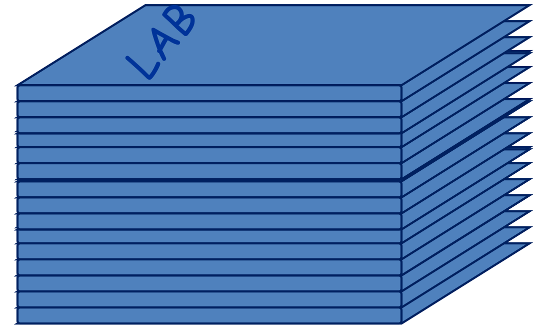
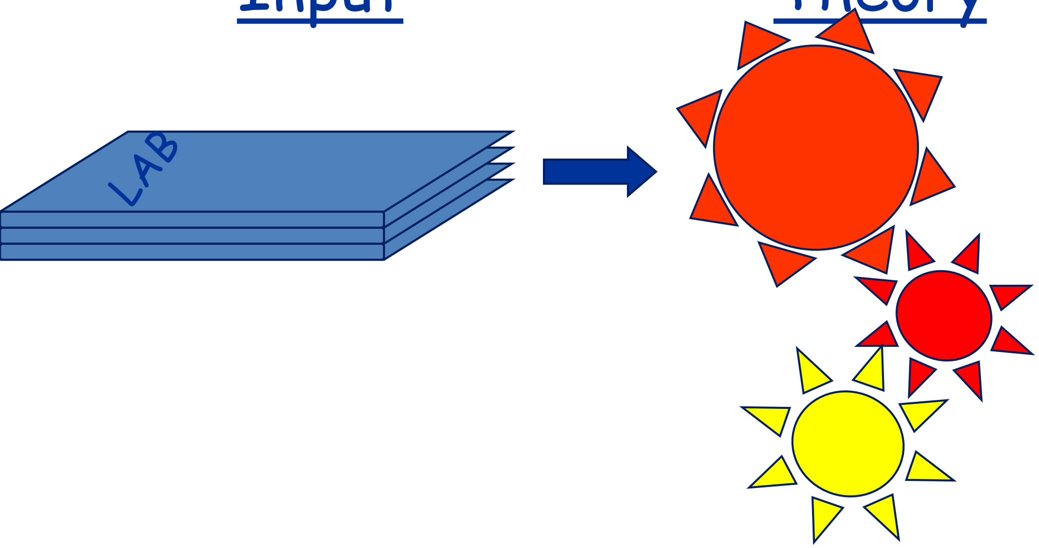


Input　　Theory　　Output



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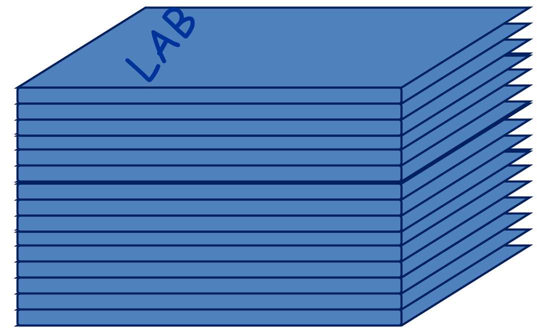

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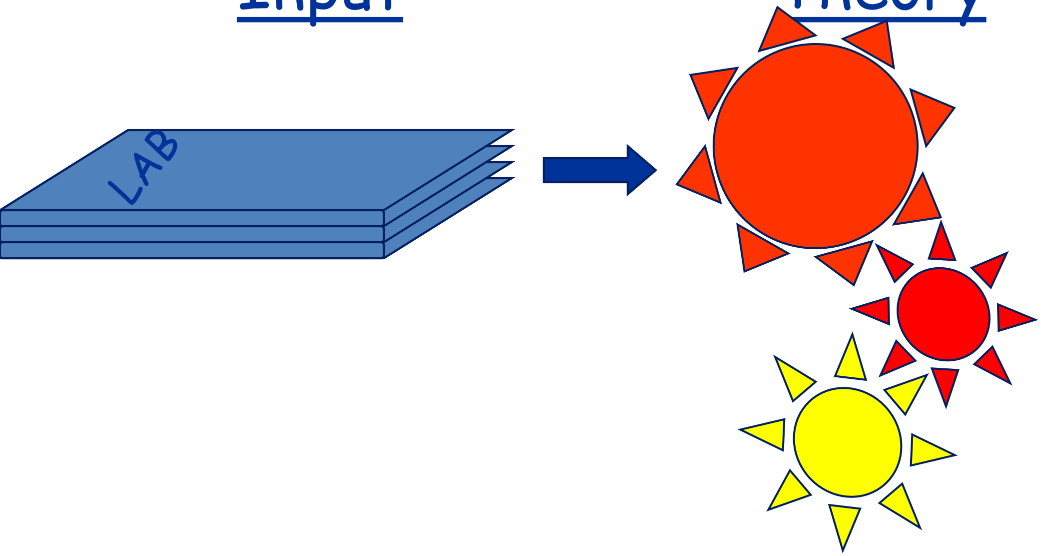

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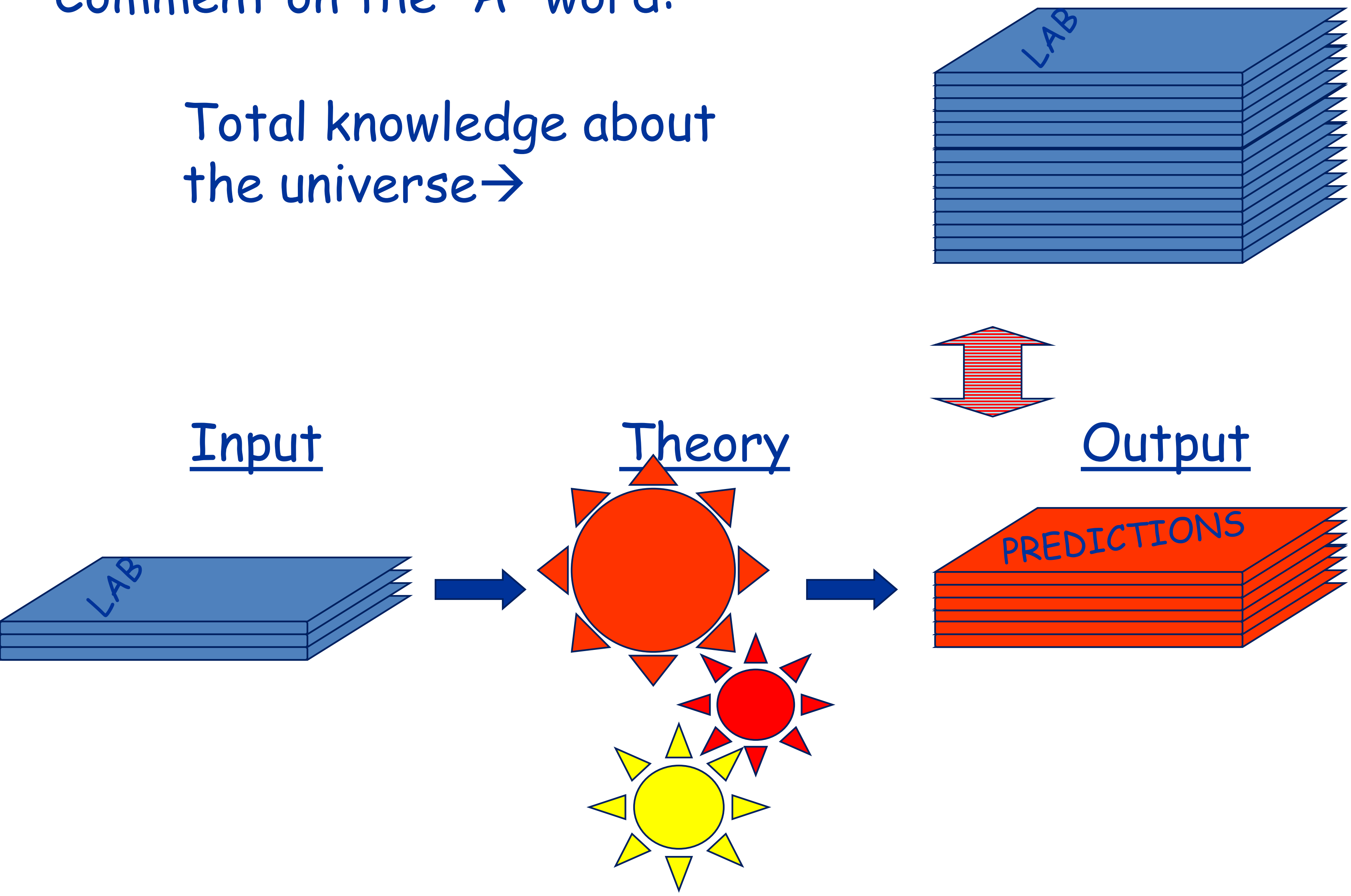
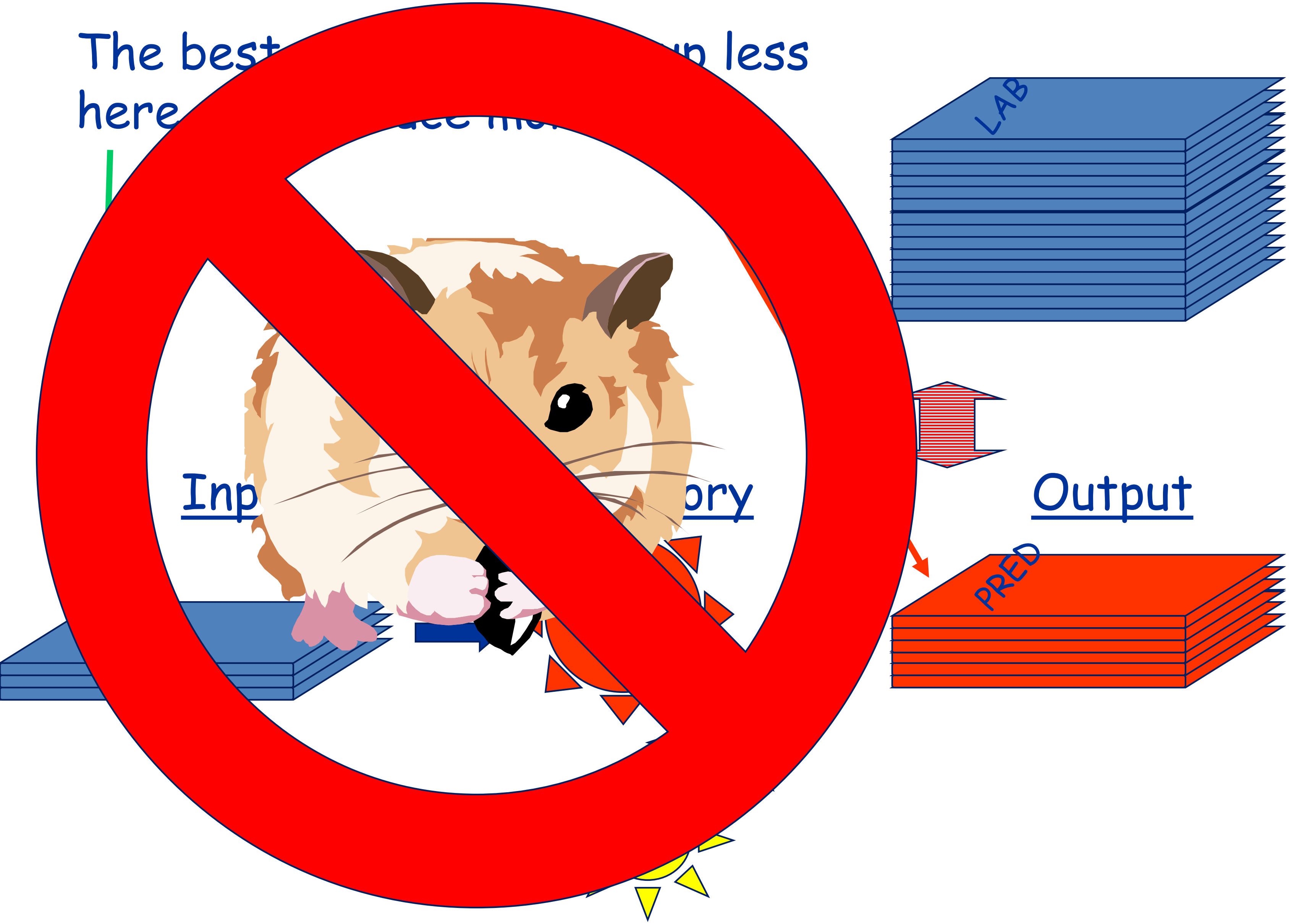


The best … n less
here …



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Can get very different answers depending on how these ingredients are realized

Banks, Dine & Motl

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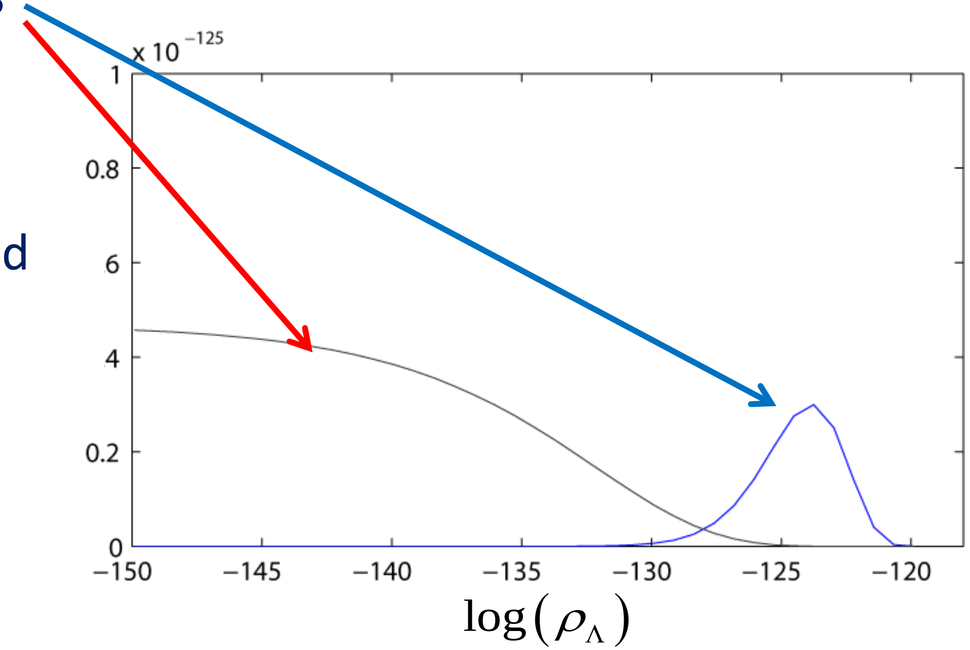
- Use "entropy production weighting” (Causal Entropic Principle, Bousso et al)
- Include variability of world lines due to cosmic structure
- Two different behaviors for late time entropy production in halos

Un-normalized probability density



Phillips & Albrecht 2011

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Eternal inflation

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...ation

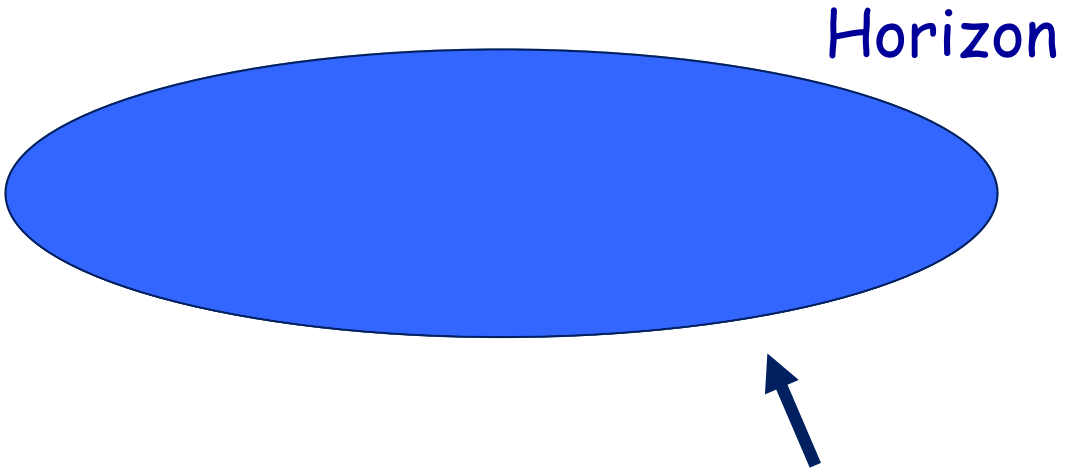
Et...

But see upcoming lectures on inflation

Bounded alternatives to the landscape and eternality

- de Sitter equilibrium cosmology
- Does holography imply non “self reproduction” (→ no eternal inflation)?
- Causal patch cosmology
- Banks-Fischler Holographic cosmology

“De Sitter Space: The ultimate equilibrium for the universe?



$$S \propto A = H^{-2} = \Lambda^{-1}$$

$$T_{GH} = H_{\Lambda} = \sqrt{\frac{8\pi G}{3}\rho_{\Lambda}}$$

Implications of the de Sitter horizon

- Maximum entropy $$S_\Lambda \propto A = H_\Lambda^{-2} = \left(\frac{\Lambda}{3}\right)^{-1}$$

- Gibbons-Hawking Temperature $$T_{GH} = H_\Lambda = \sqrt{\frac{8\pi G}{3}\rho_\Lambda}$$

- Only a finite volume ever observed

- If Λ is truly constant: Cosmology as fluctuating Eqm.

- Maximum entropy $\longrightarrow$ finite Hilbert space of dimension $N = e^{S_\Lambda}$

Banks & Fischler & Dyson et al.

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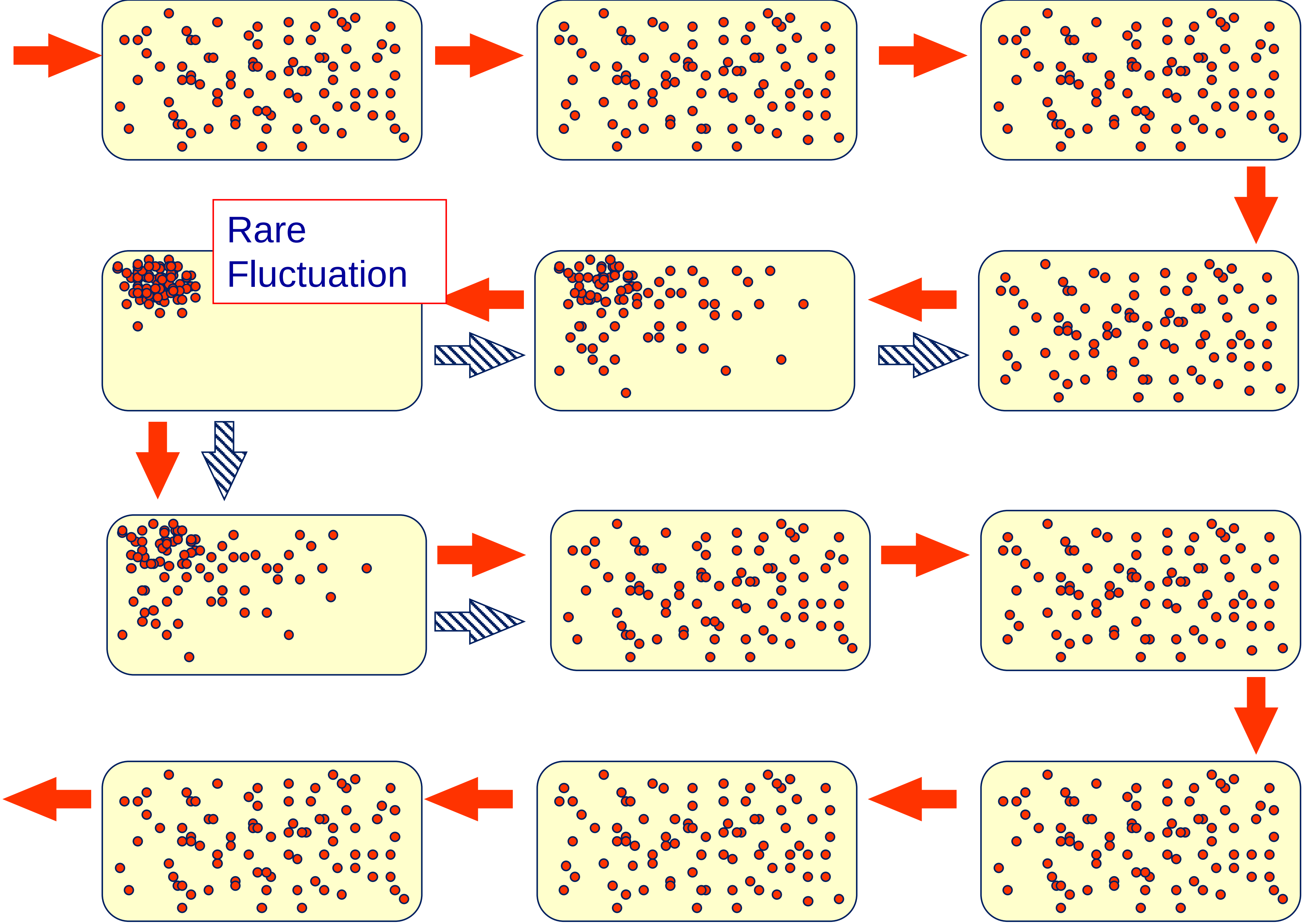
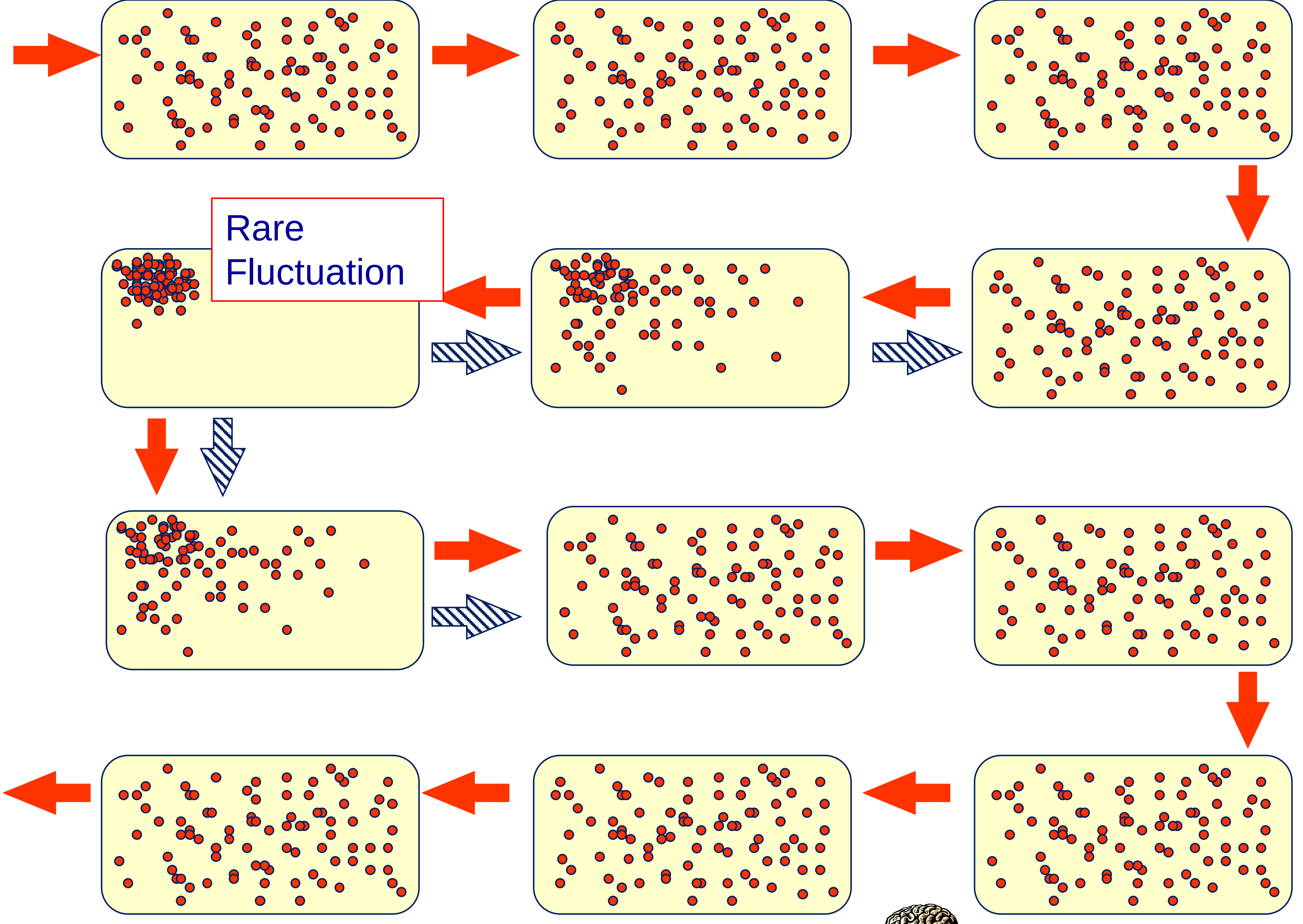
Banks & Fischler & Dyson et al.

dSE cosmology

Equilibrium Cosmology


Rare
Fluctuation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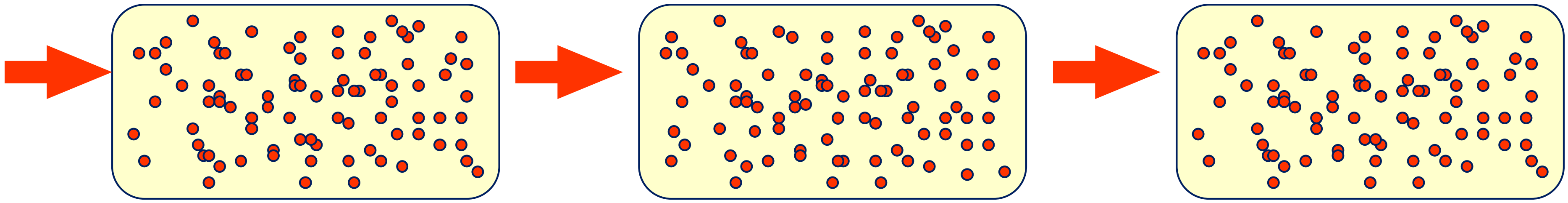
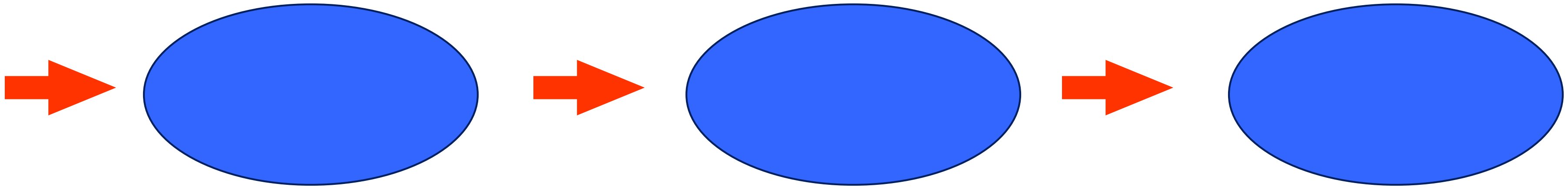
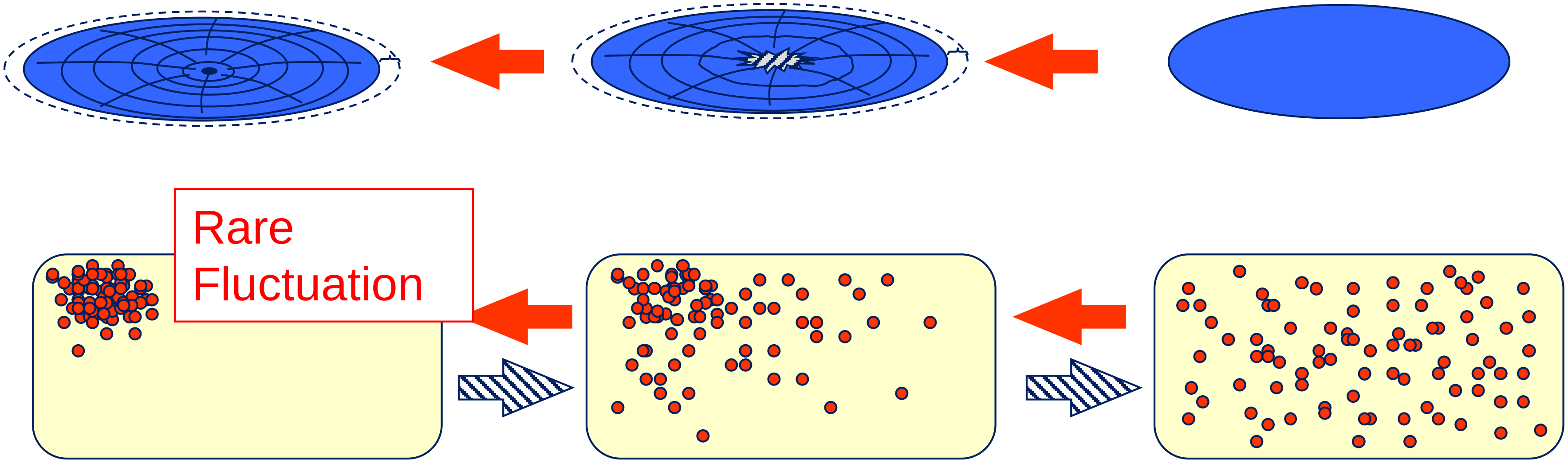
Concept:



Realization:



"de Sitter Space"


Rare
Fluctuation

Fluctuating from dSE to inflation:

- The process of an inflaton fluctuating from late time de Sittter to an inflating state is dominated by the "Guth-Farhi process"
- A "seed" is formed from the Gibbons-Hawking radiation that can then tunnel via the Guth-Farhi instanton.
- Rate is well approximated by the rate of seed formation:

$$\propto e^{-\frac{m_s}{T_{GH}}} = e^{-\frac{m_s}{H_\Lambda}}$$

- Seed mass:

$$m_s = \rho_I \left(cH_I^{-1}\right)^3 = 0.0013kg \left(\frac{\left(10^{16} GeV\right)^4}{\rho_I} \right)^{1/2}$$

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Small seed can produce an entire universe ➔ Evade "Boltzmann Brain" problem

Dark Energy:

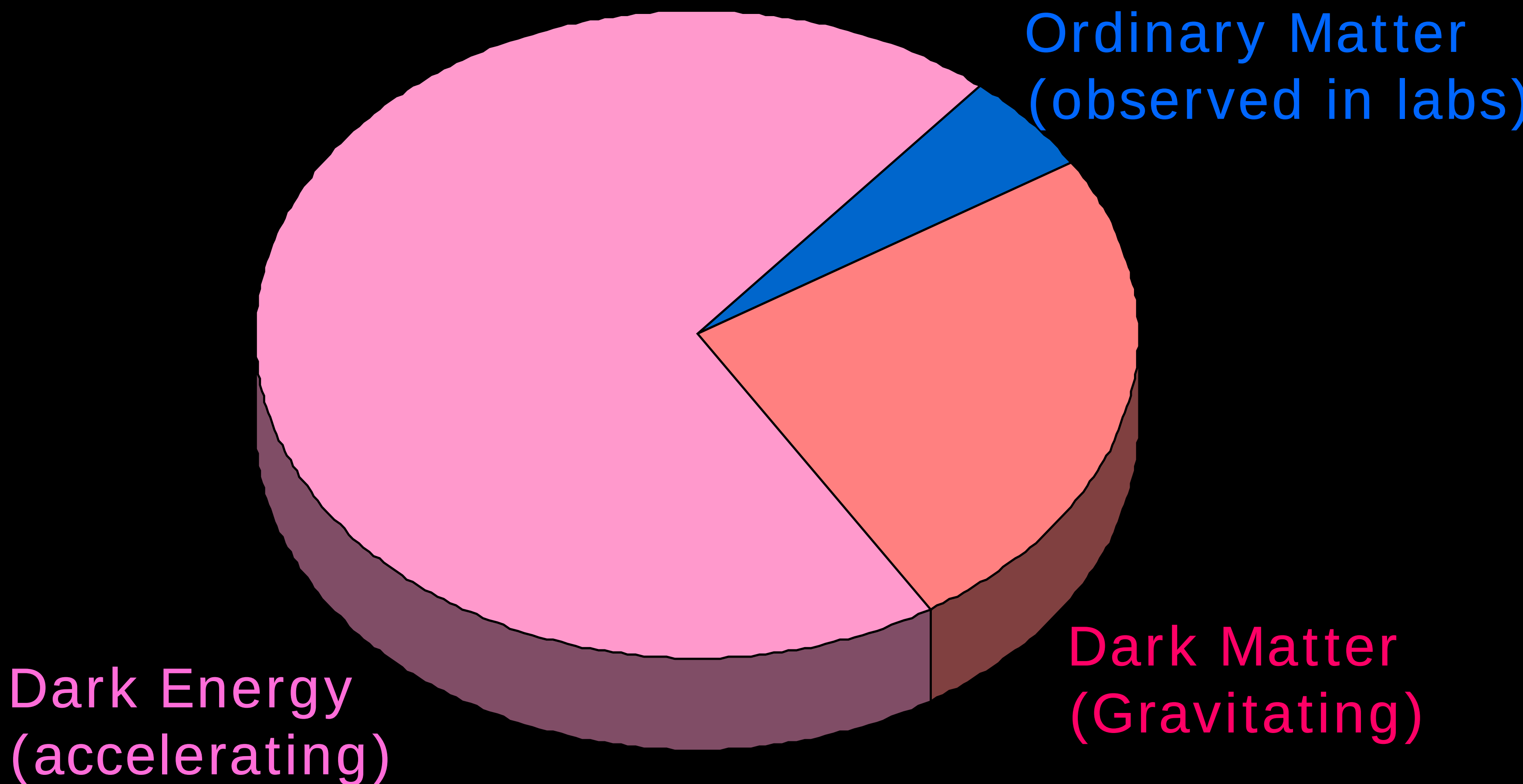
current theoretical issues and progress toward future experiments

A. Albrecht

UC Davis

PHY 262

95% of the cosmic matter/energy is a mystery.
It has never been observed even in our best laboratories



Science
AAAS

American Association for the Advancement of Science

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THE QUESTIONS

The Top 25

Essays by our news staff on 25 big questions facing science over the next quarter-century.

- What Is the Universe Made Of?
- What is the Biological Basis of Consciousness?
- Why Do Humans Have So Few Genes?
- To What Extent Are Genetic Variation and Personal Health Linked?
- Can the Laws of Physics Be Unified?
- How Much Can Human Life Span Be Extended?
- What Controls Organ Regeneration?
- How Can a Skin Cell Become a Nerve Cell?
- How Does a Single Somatic Cell Become a Whole Plant?

...at the moment, the nature of dark energy is arguably the murkiest question in physics--and the one that, when answered, may shed the most light.

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

"Basically, people don't have a clue as to how to solve this problem." - Jeff Harvey

"… would be No. 1 on my list of things to figure out."
- Edward Witten

'This is the biggest embarrassment in theoretical physics"
- Michael Turner

"… Maybe the most fundamentally mysterious thing in basic science."
- Frank Wilczek

QUANTUM UNIVERSE

THE REVOLUTION IN 21ST CENTURY PARTICLE PHYSICS

Questions that describe the current excitement and promise of particle physics.

2

HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

QUANTUM UNIVERSE

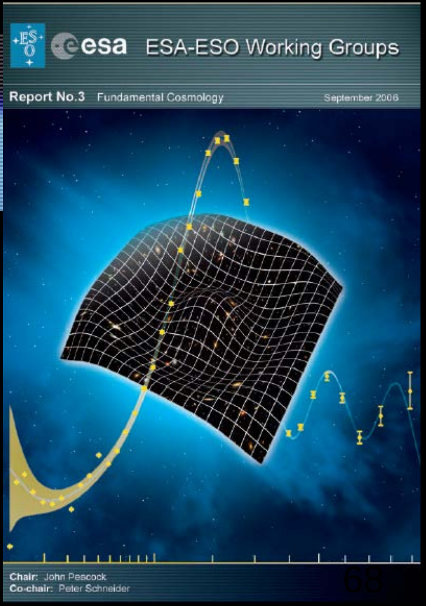
THE REVOLUTION IN 21ST CENTURY PARTICLE PHYSICS

"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."

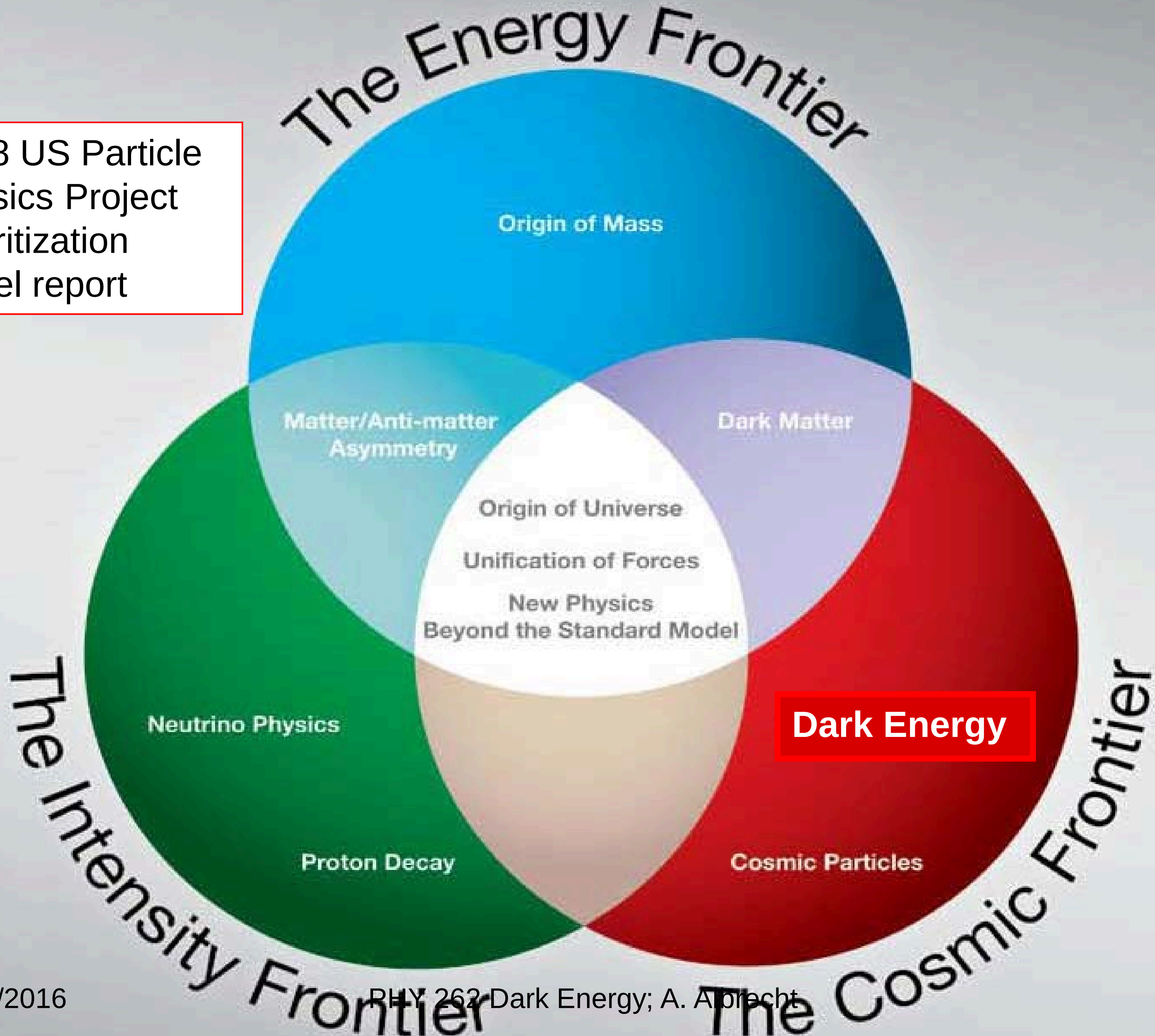
Dark Energy Task Force (DETF) astro-ph/0609591

"Of all the challenges in cosmology, the discovery of dark energy poses the greatest challenge for physics because there is no plausible or natural explanation…"

ESA Peacock report



2008 US Particle Physics Project Prioritization Panel report



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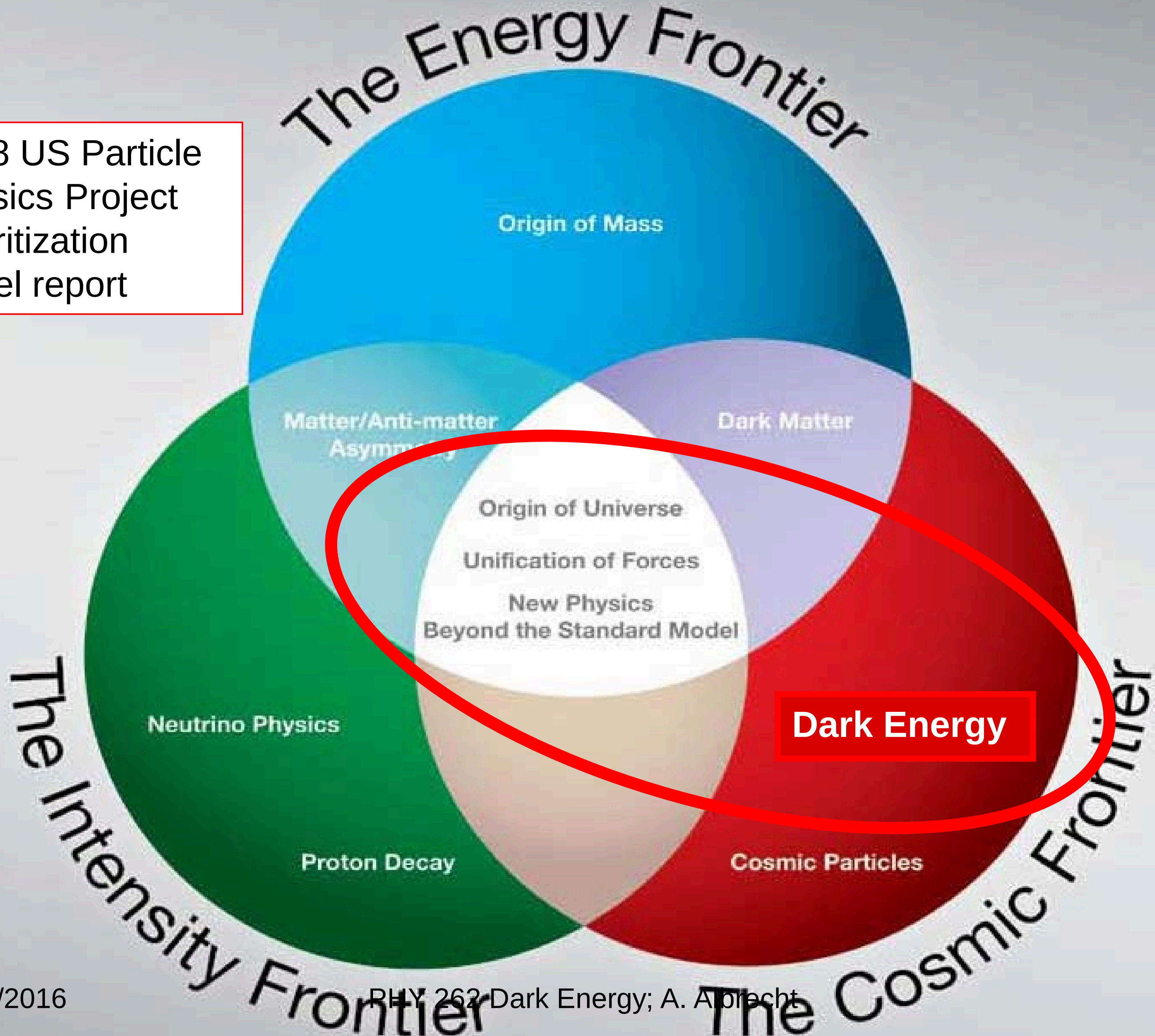

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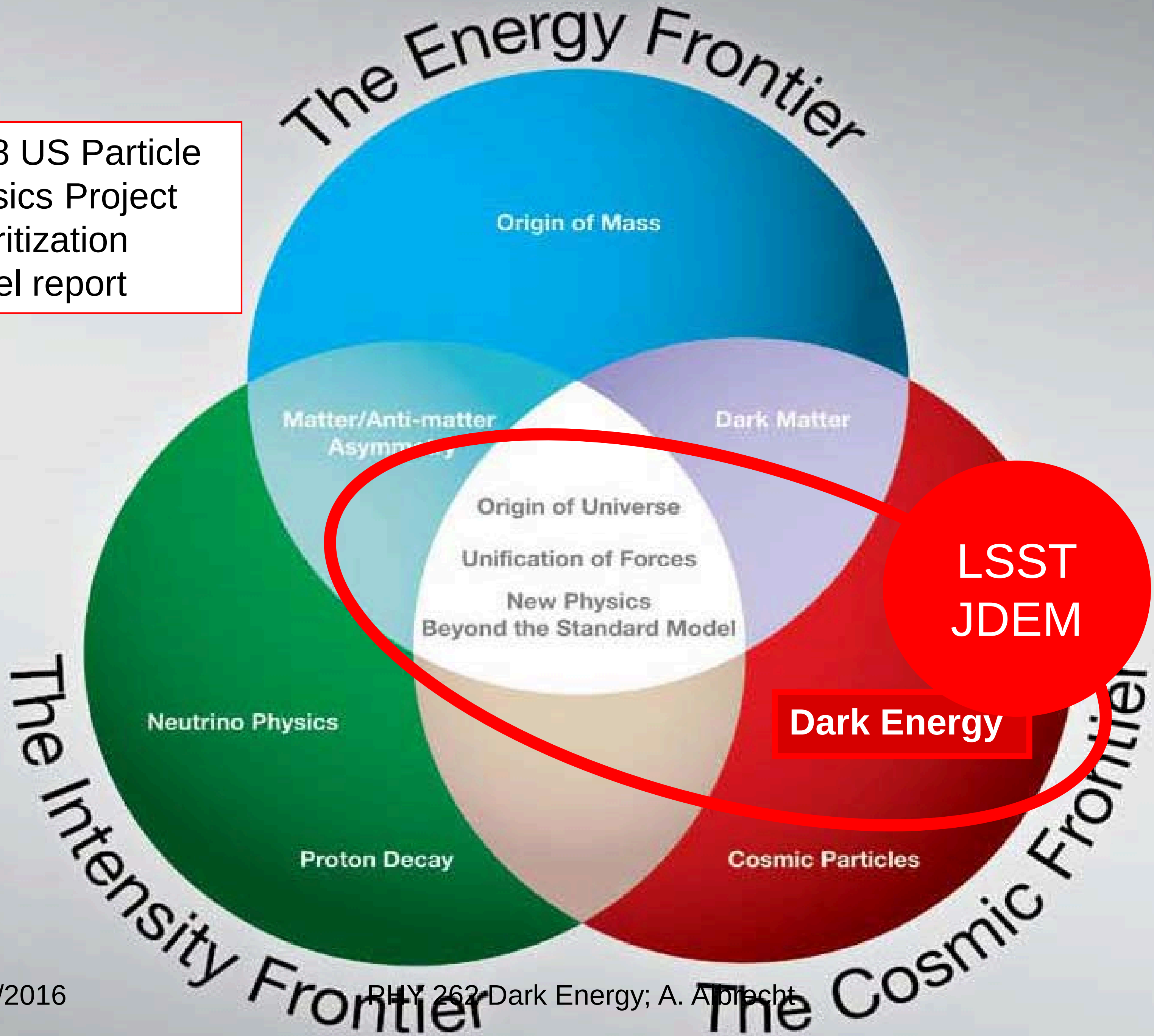


REVEALING THE HIDDEN NATURE OF

SPACE AND TIME

Charting the Course for Elementary Particle Physics

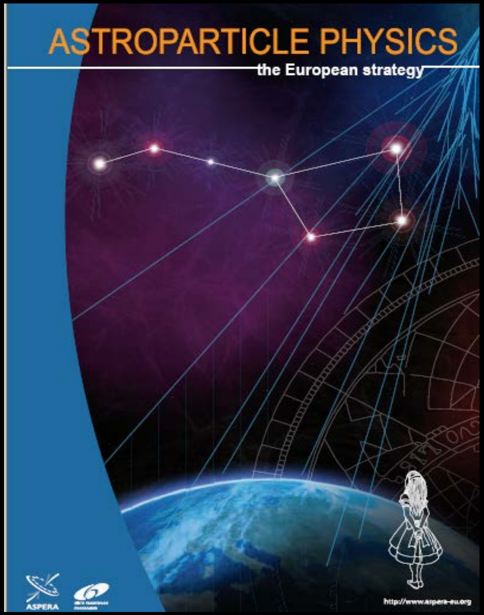
Committee on Elementary Particle Physics in the 21st Century

Board on Physics and Astronomy

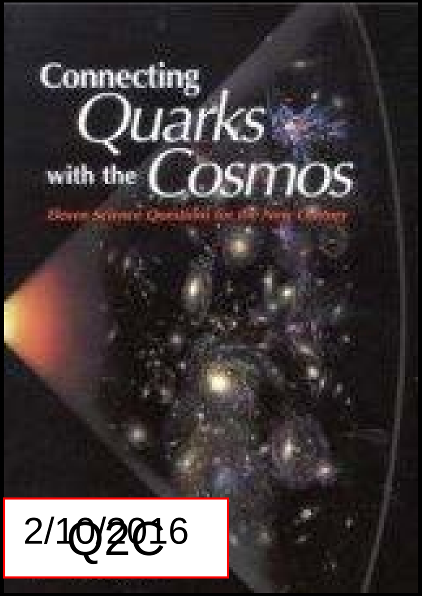
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

(EPP 2010)



ASPERA roadmap



Q2C

NASA's Beyond Einstein Program: An Architecture for Implementation

Committee on NASA's Beyond Einstein Program: An Architecture for Implementation
Space Studies Board
and
Board on Physics and Astronomy
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
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BPAC

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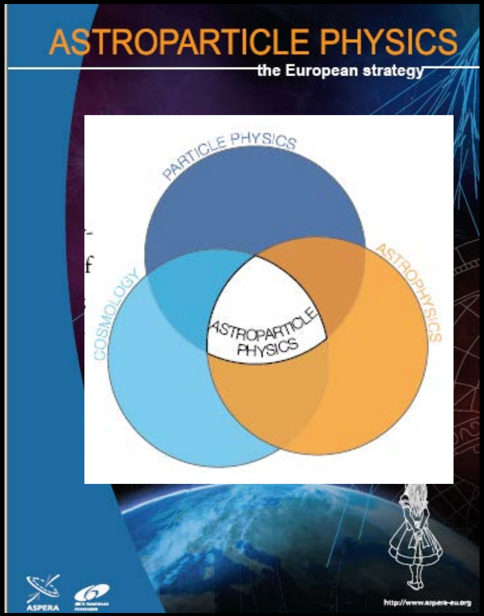

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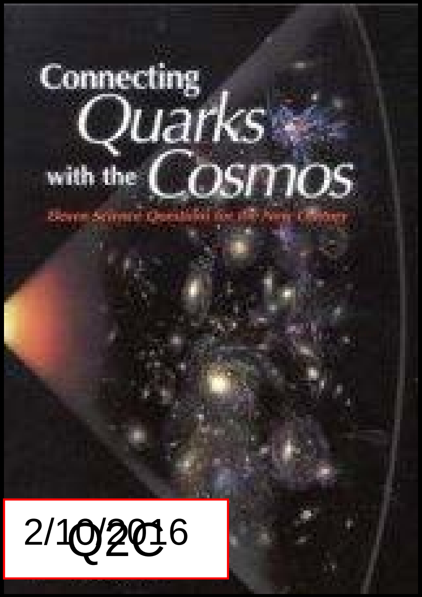

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2/10/2016

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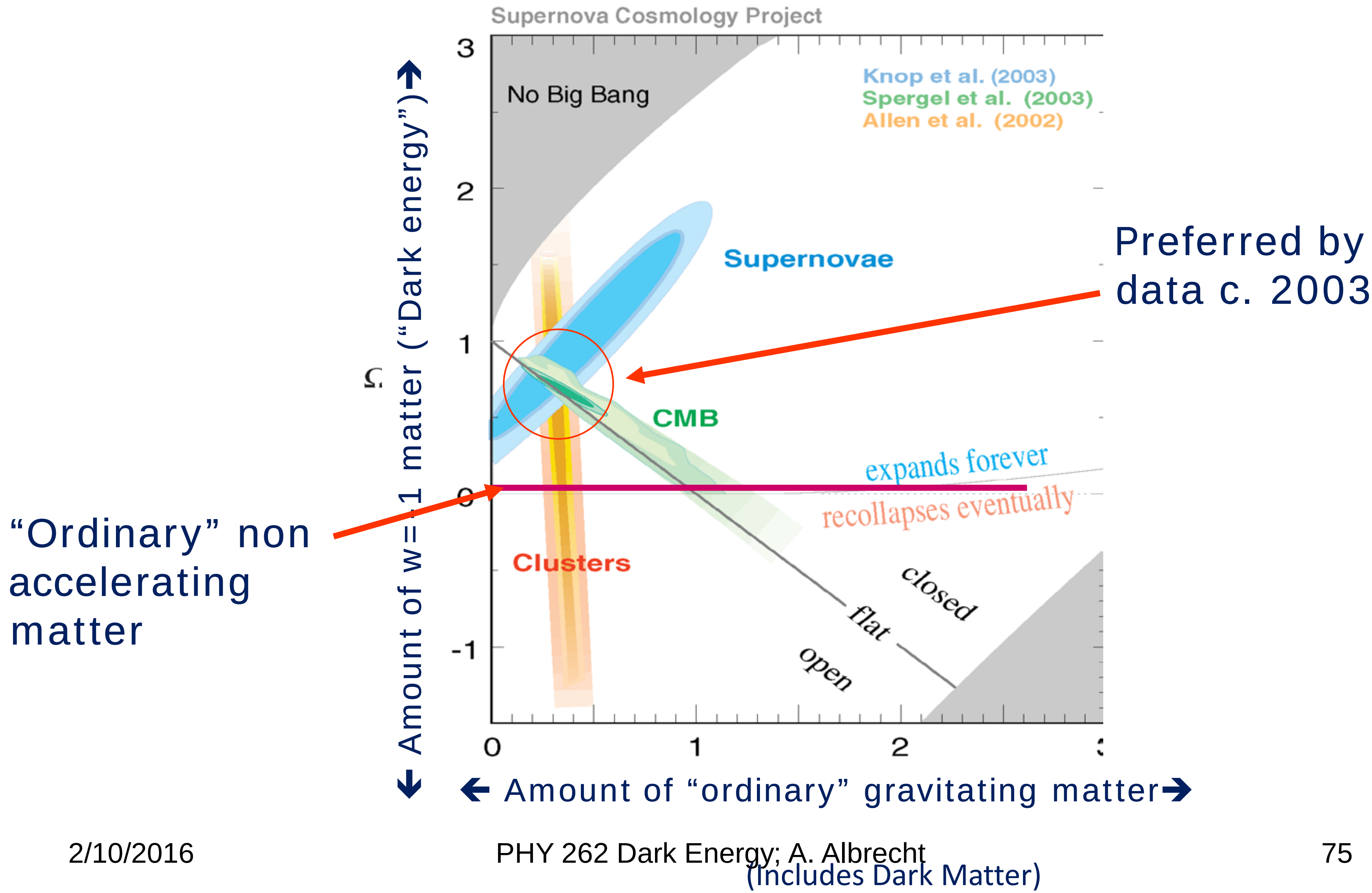
BPAC

?

Cosmic acceleration

Accelerating matter is required to fit current data



Cosmic acceleration

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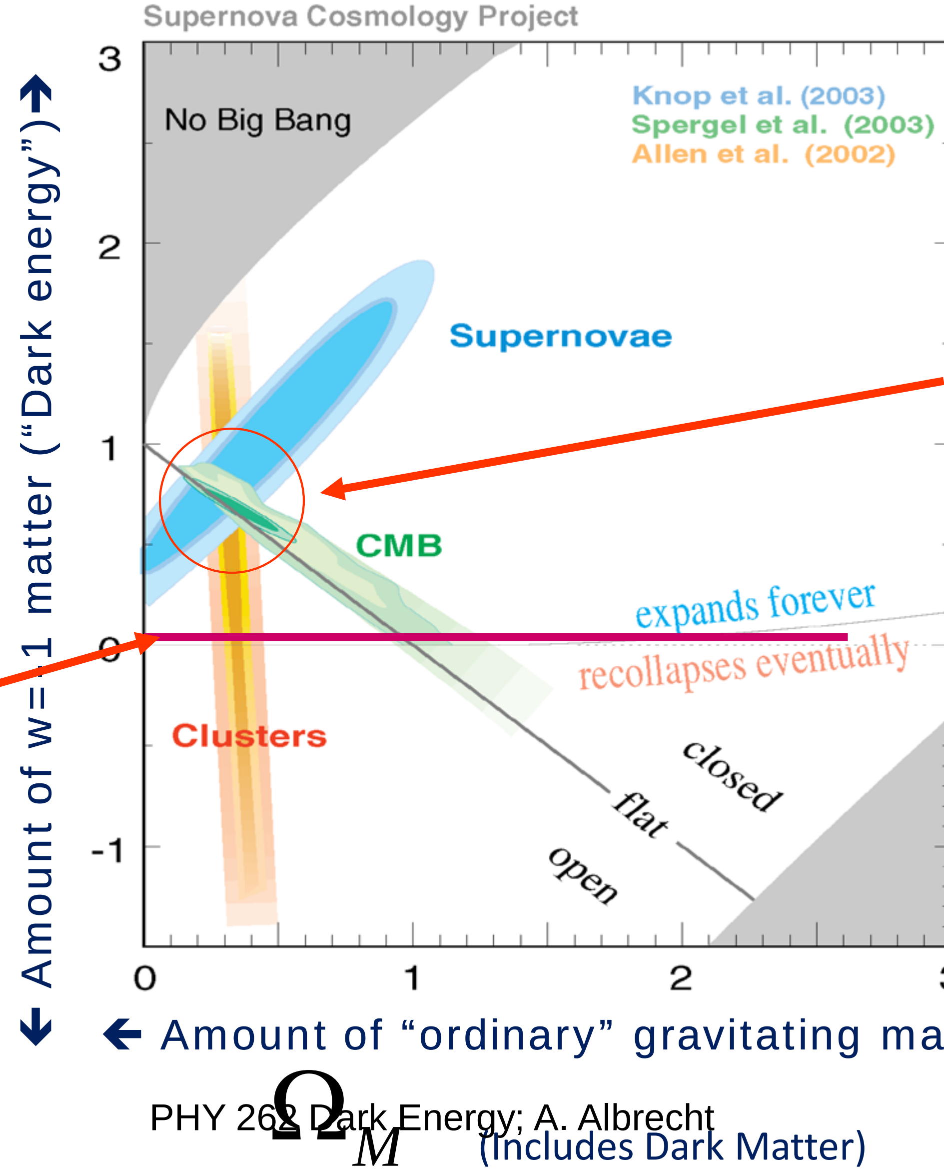
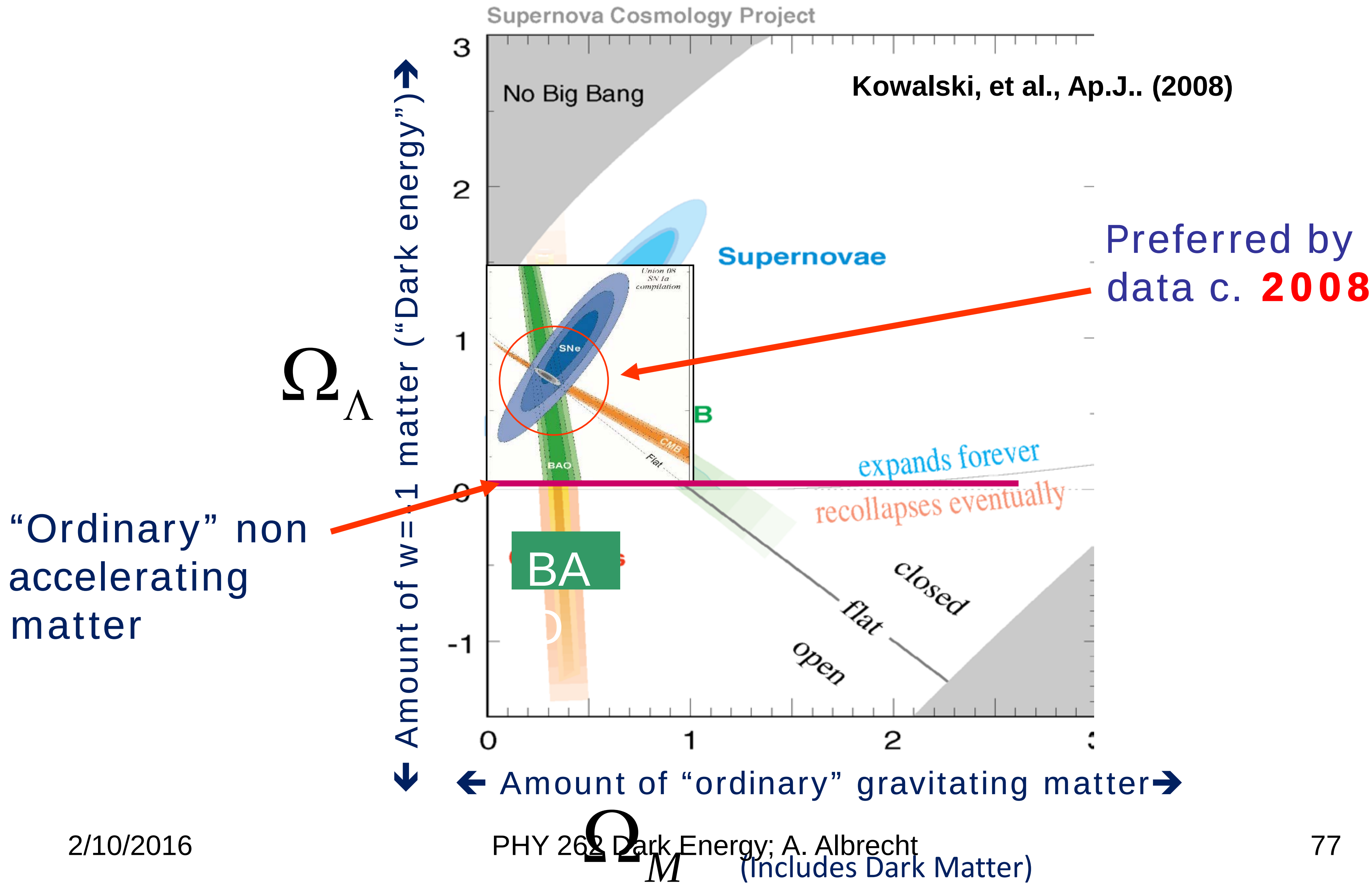


Preferred by data c. 2003

"Ordinary" non accelerating matter

Cosmic acceleration

Accelerating matter is required to fit current data



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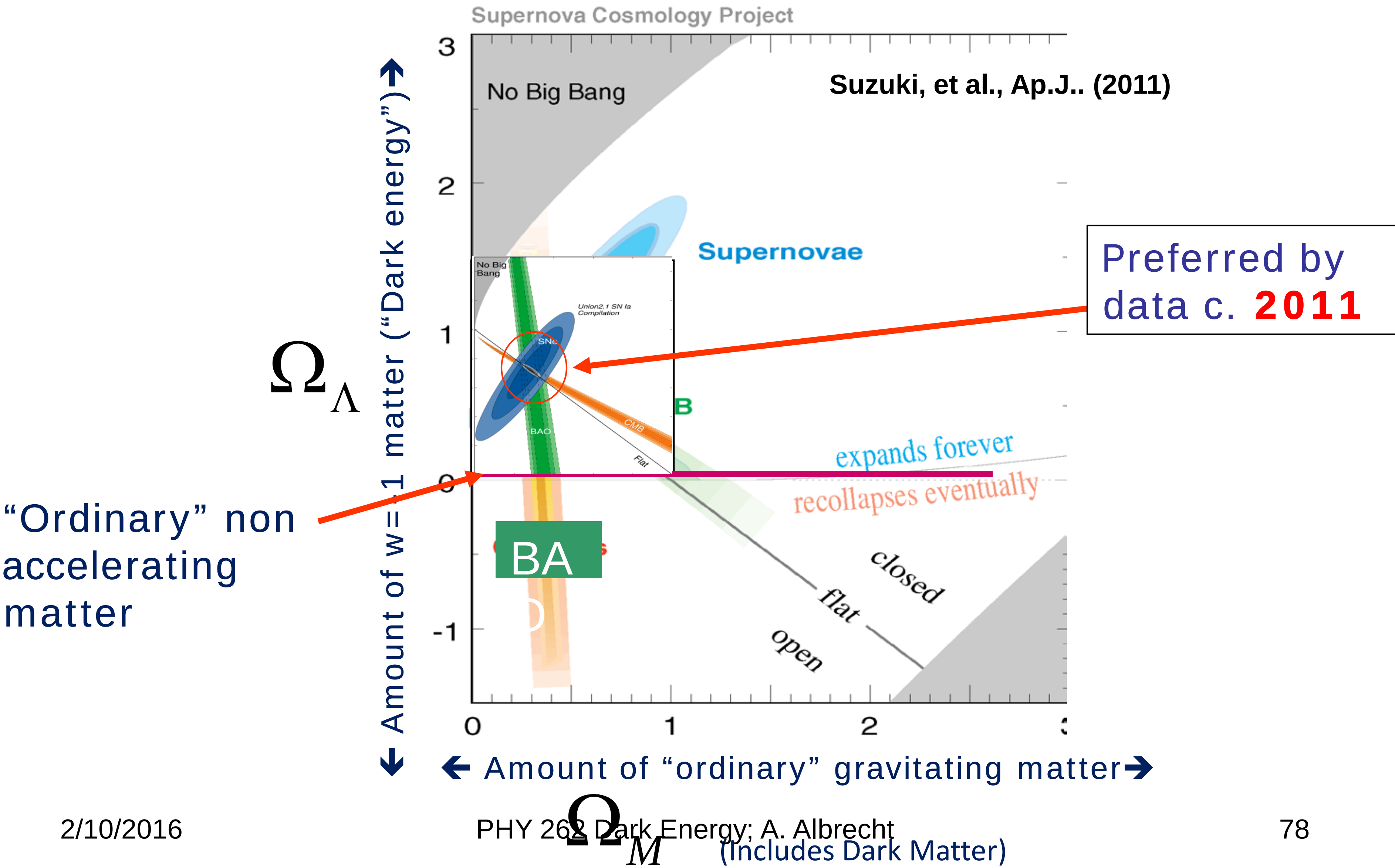

Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation. The acceleration of the Universe is, along with dark matter, the observed phenomenon which most directly demonstrates that our fundamental theories of particles and gravity are 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.

From the Dark Energy Task Force report (2006)

www.nsf.gov/mps/ast/detf.jsp, *astro-ph/0690591*

*My emphasis

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DETF = a HEPAP/AAAC subpanel to guide planning of future dark energy experiments

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More info here

*My emphasis

This talk

Part 1:

A few attempts to explain dark energy

→ Motivations, problems and other comments

→ Theme: We may not know where this revolution is taking us, but it is already underway:

Part 2

Planning new experiments

- DETF
- Next questions

Some general issues:

Properties:

Solve GR for the scale factor *a* of the Universe (*a*=1 today):

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

Positive acceleration clearly requires

- $w \equiv p/\rho < -1/3$ (unlike any known constituent of the Universe) or
- a non-zero cosmological constant or
- an alteration to General Relativity.

Some general issues:

Numbers:

- Today, $$\rho_{DE} \approx 10^{-120} M_P^4 \approx \left(10^{-3} eV\right)^4$$

- Many field models require a particle mass of

$$m_Q \leq 10^{-31} eV \approx H_0$$ from $$m_Q^2 M_P^2 \approx \rho_{DE}$$

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$m_Q \leq 10^{-31} eV \approx H_0$ from $m_Q^2 M_P^2 \approx \rho_{DE}$

Where do these come from and how are they protected from quantum corrections?

Some general issue

Two "familiar" ways to achieve acceleration:

1) Einstein's cosmological constant and relatives $(w = -1)$

2) Whatever drove inflation: Dynamical, Scalar field?

Properties:

Solve GR for the sca

$$\frac{\ddot{a}}{a} = -\frac{4}{}$$

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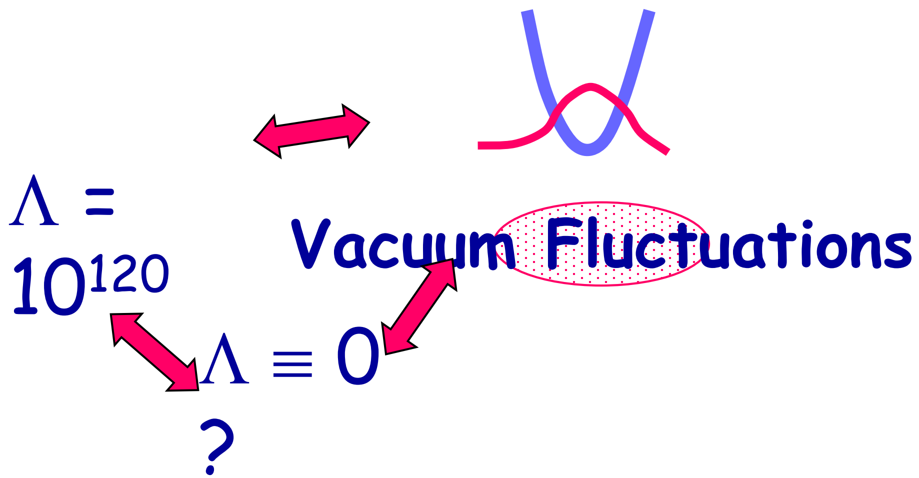
Specific ideas: i) A cosmological constant Λ

- Nice “textbook” solutions BUT
- Deep problems/impacts re fundamental physics
  - Vacuum energy problem (we’ve gotten “nowhere” with this)



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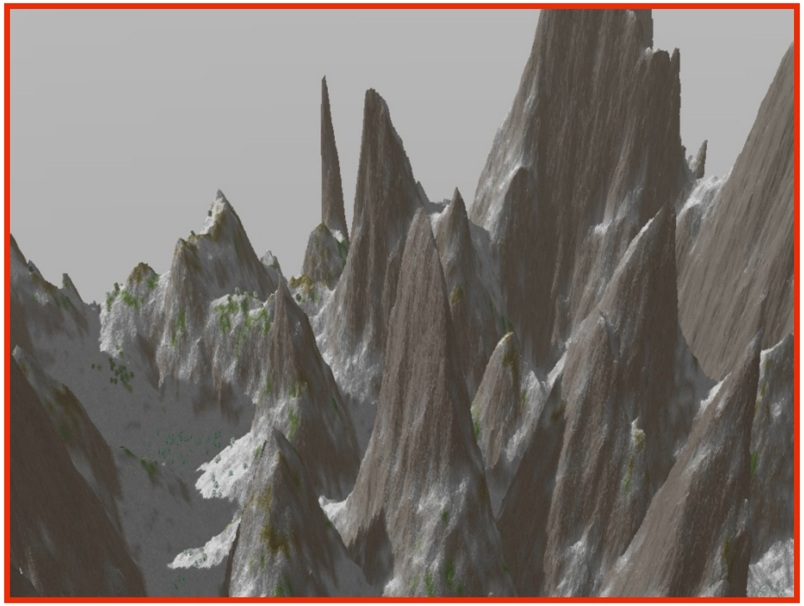
    - ➢ The string theory landscape (a radically different idea of what we mean by a fundamental theory)



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"Theory of Everything"

?

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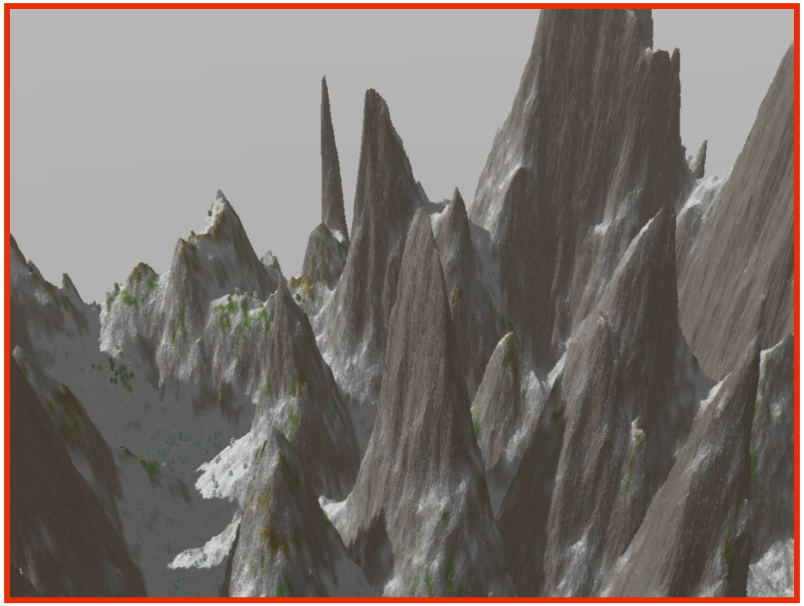

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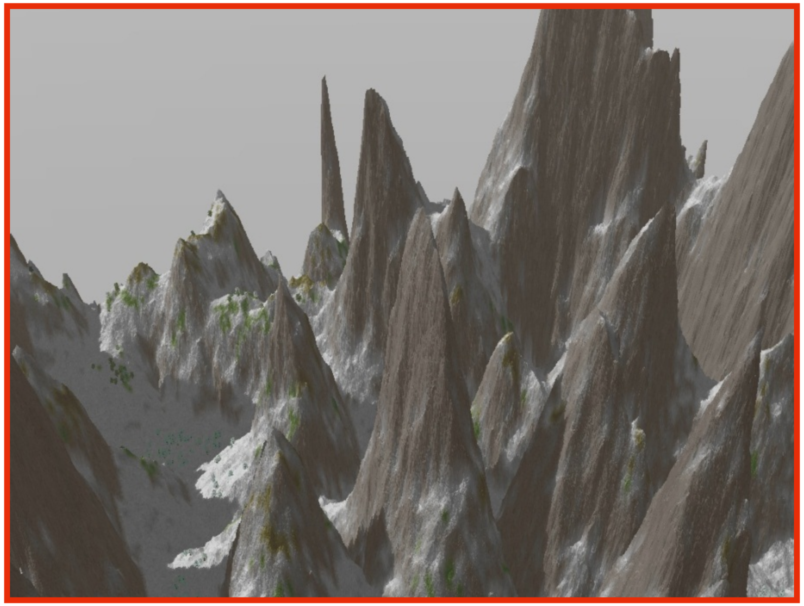
Not exactly a cosmological constant



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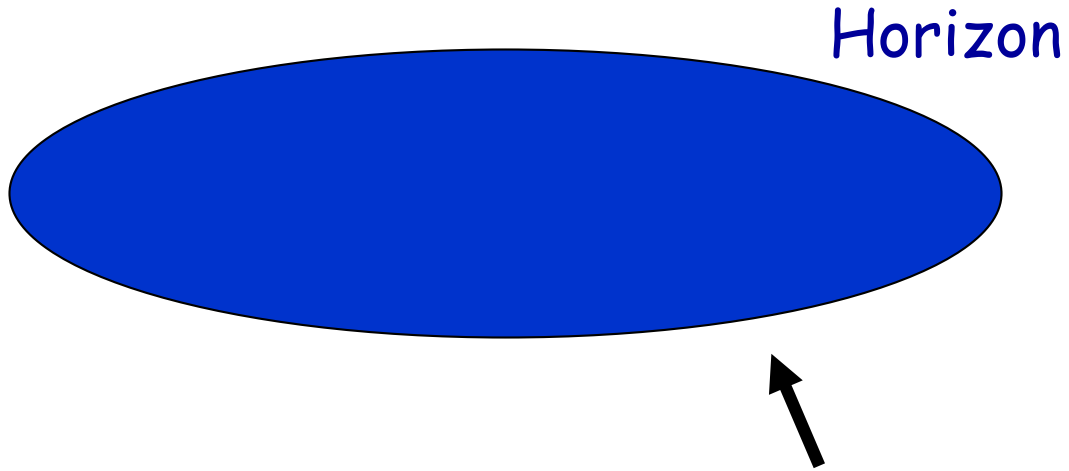
  - De Sitter limit: Horizon ➔ Finite Entropy

Banks, Fischler, Susskind, AA & Sorbo etc.

“De Sitter Space: The ultimate equilibrium for the universe?

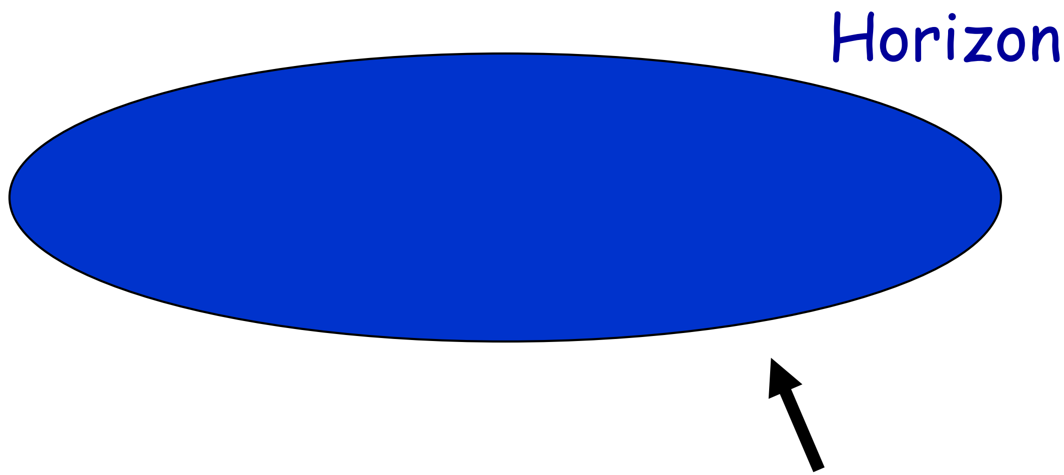


$$S \propto A = H^{-2} = \Lambda^{-1}$$

Quantum effects: Hawking Temperature

$$T = H = \sqrt{\frac{8\pi G}{3}\rho_{DE}}$$

"De Sitter Space: The ultimate equilibrium for the universe?



$$S \propto A = H^{-2} = \Lambda^{-1}$$

Quantum effects: Hawking Temperature

$$T = H = \sqrt{\frac{8\pi G}{3}\varepsilon_{DE}}$$

Does this imply (via " $S = \ln N$ ")

a finite Hilbert space for physics?

Banks, Fischler

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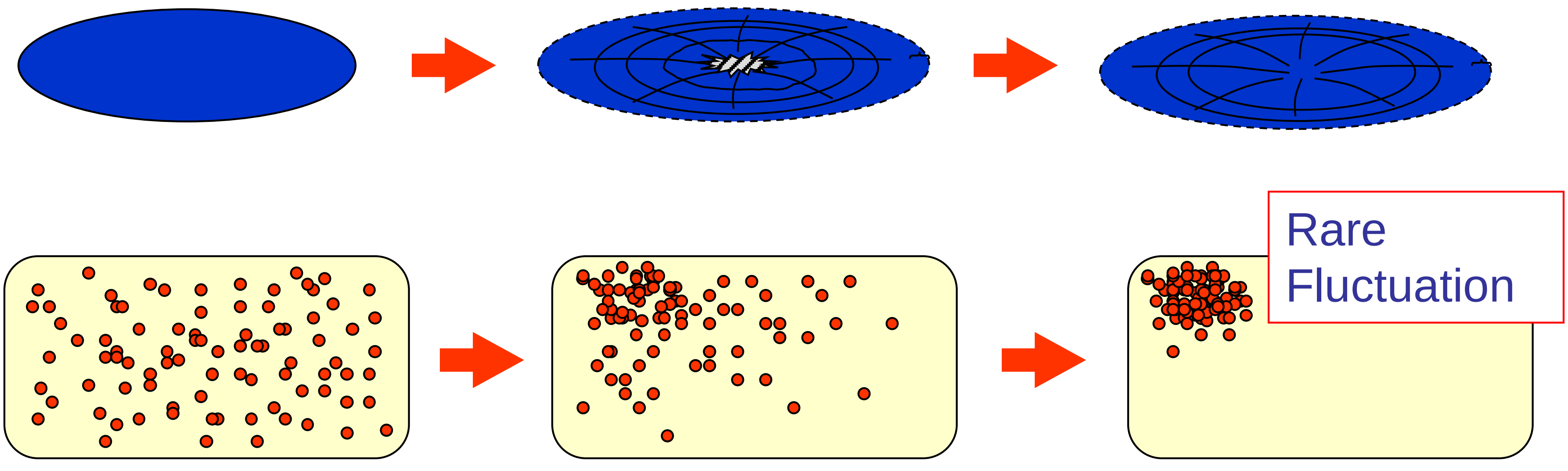

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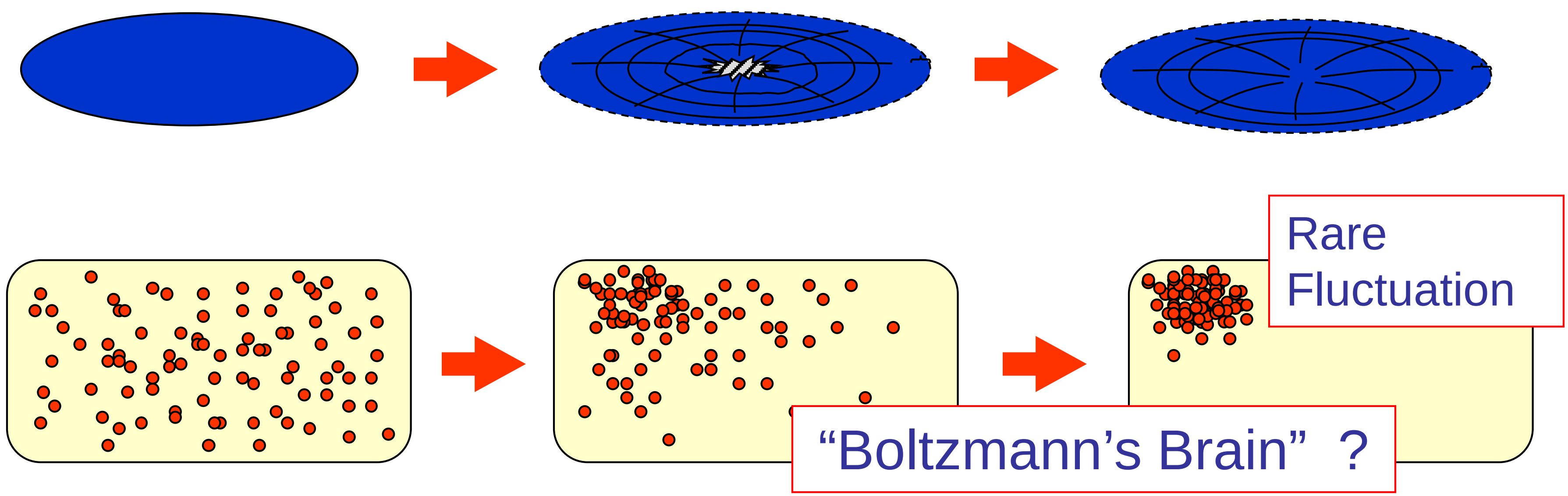

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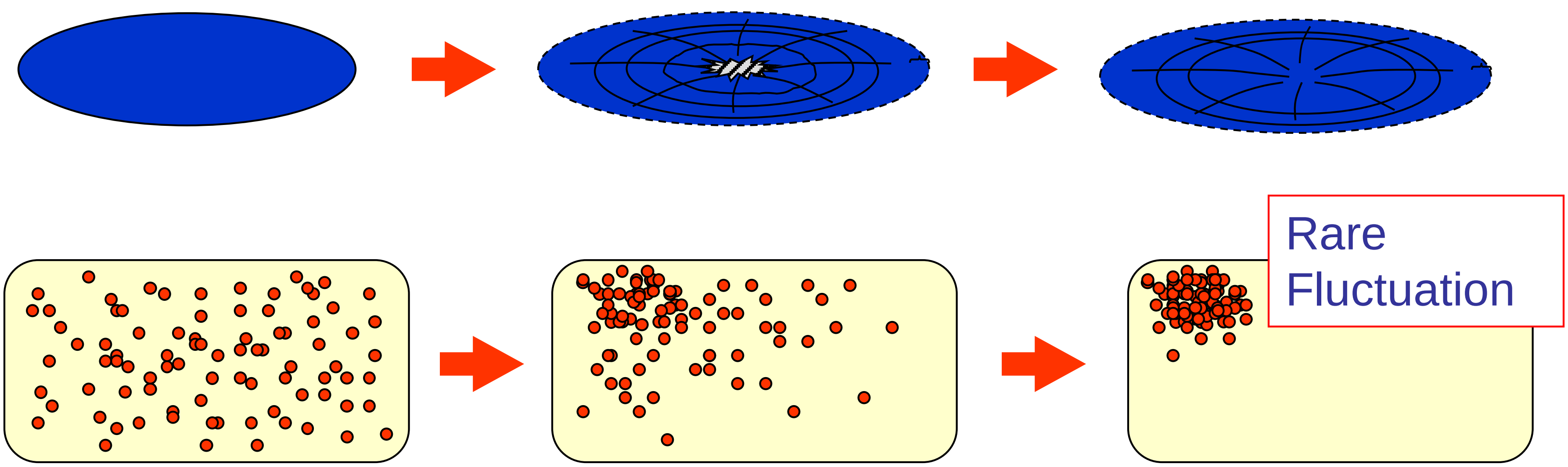

Dyson, Kleban & Susskind.

This picture is in deep conflict with observation

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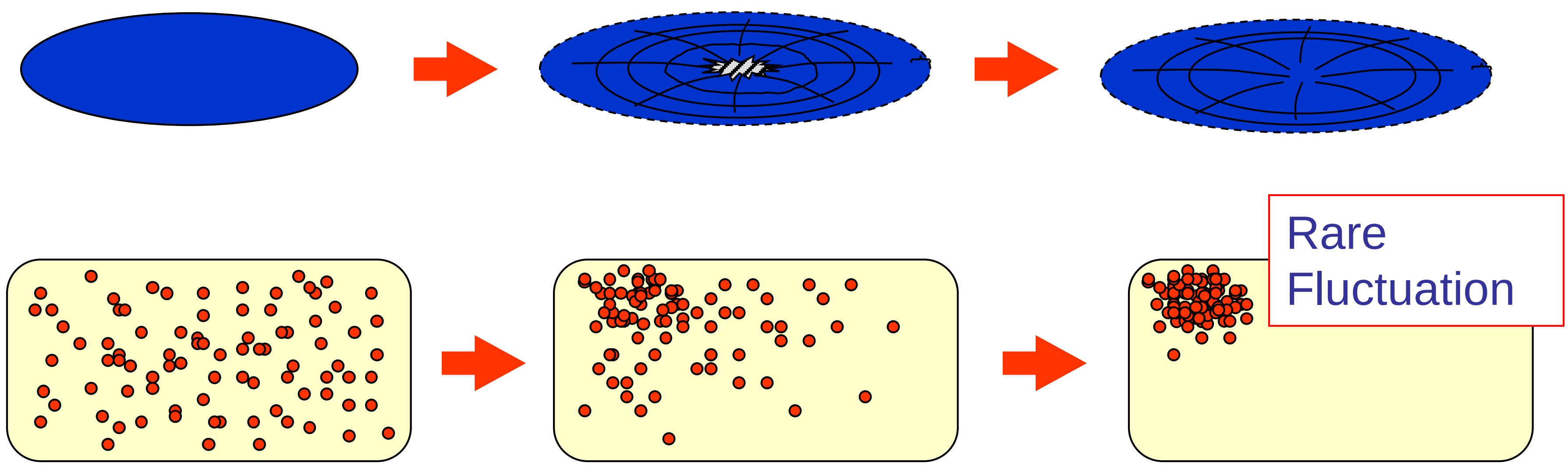

Dyson, Kleban & Susskind.

This picture is in deep conflict with observation (resolved by landscape?)

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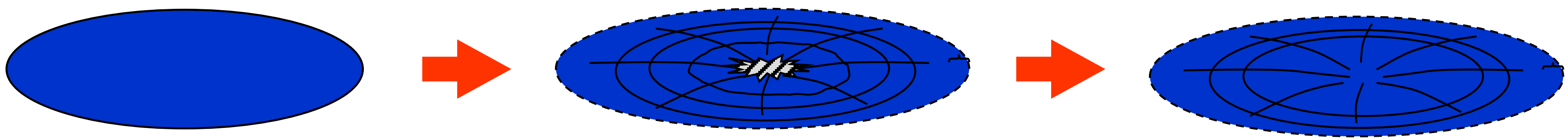

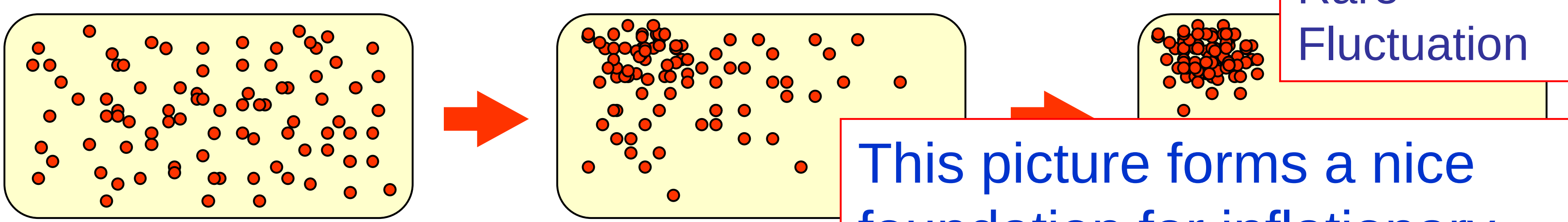

This picture forms a nice foundation for inflationary cosmology

Dyson, Kleban & Susskind, AA & Sorbo et

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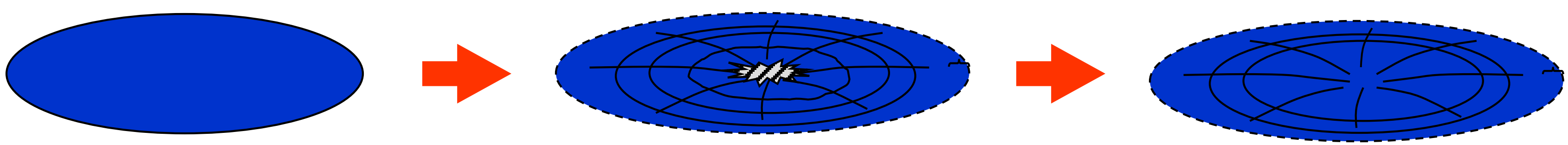

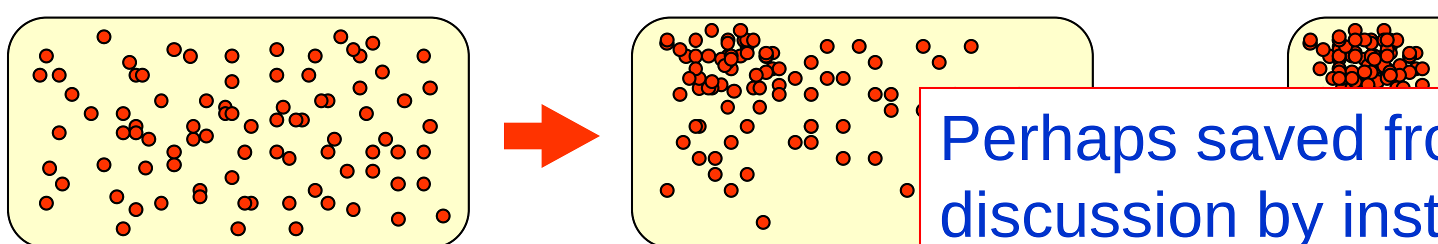

Rare Fluctuation

Perhaps saved from this discussion by instability of De Sitter space (Woodard *et al*)

~~*Dyson, Kleban & Susskind, AA & Sorbo*~~

Specific ideas: i) A cosmological constant Λ

- Nice "textbook" solutions BUT
- Deep problems/impacts re fundamental physics

Λ is not the "simple option"

Some general issues:

<u>Alternative Explanations?:</u>

Is there a less dramatic explanation of the data?

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<u>Alternative Explanations?:</u>

Is there a less dramatic explanation of the data?

For example is supernova dimming due to

- dust? (Aguirre)
- γ-axion interactions? (Csaki et al)
- Evolution of SN properties? (Drell et al)

Many of these are under increasing pressure from data, but such skepticism is critically important.

Some general issues:

Alternative Explanations?:

Is there a less dramatic explanation of the data?

Or perhaps

- Nonlocal gravity from loop corrections (Woodard & Deser)

- Misinterpretation of a genuinely inhomogeneous universe (ie. Kolb and collaborators)

Specific ideas: ii) A scalar field ("Quintessence")

- Recycle inflation ideas (resurrect $\Lambda = 0$ dream?)
- Serious unresolved problems
  - Explaining/ protecting $m_Q \leq 10^{-31} eV \approx H_0$
  - 5th force problem
  - Vacuum energy problem
  - What is the Q field? (inherited from inflation)
  - Why now? (Often not a separate problem)

Specific ideas: ii) A scalar field ("Quintessence")

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Result?

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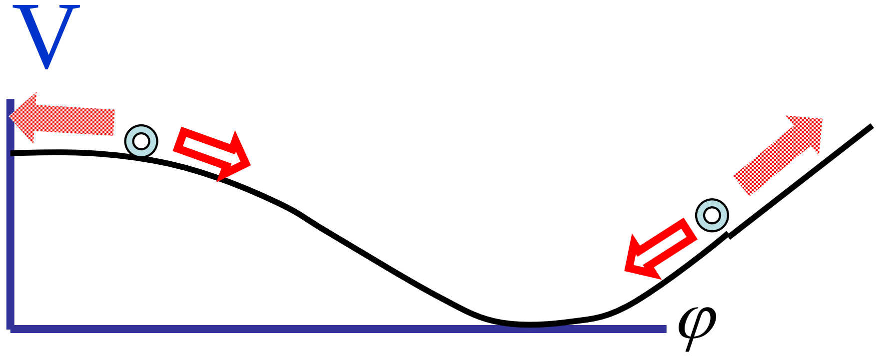
Learned from inflation: A slowly rolling (nearly) homogeneous scalar field can accelerate the universe

$$\ddot{\phi} + 3H\dot{\phi} = -V'$$

$$w \equiv \frac{p}{\rho} \approx -1 + \frac{\dot{\phi}^2}{V}$$



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Dynamical

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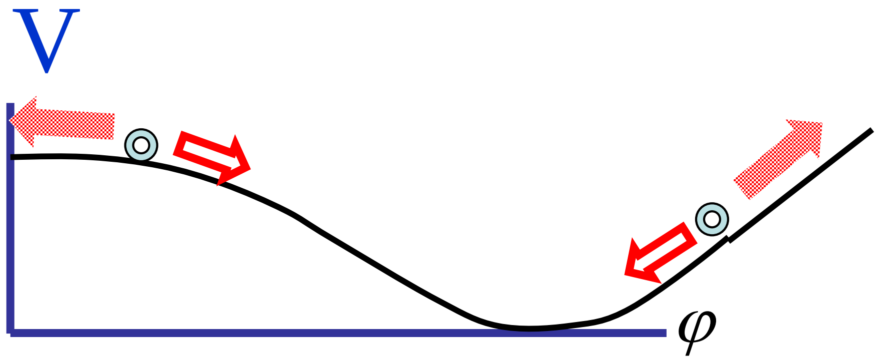
$$\neq 0$$



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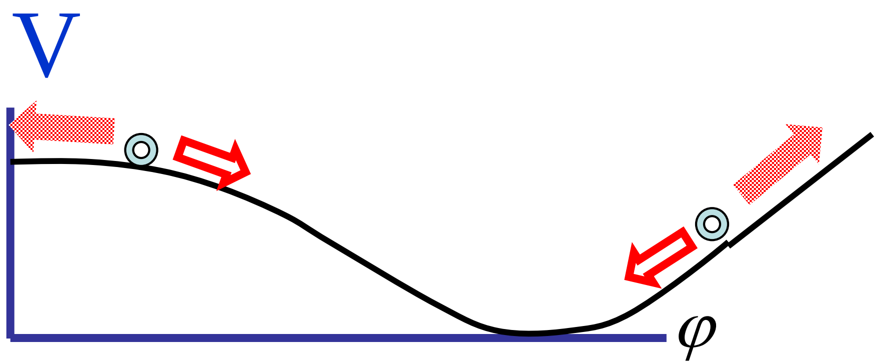

Rolling scalar field dark energy is called “quintessence”

Some quintessence potentials

Exponential (Wetterich, Peebles & Ratra)

PNGB aka Axion (Frieman et al)

Exponential with prefactor (AA & Skordis)

Inverse Power Law (Ratra & Peebles, Steinhardt et al)

Some quintessence potentials

Exponential (Wetterich, Peebles & Ratra)

$$V(\varphi) = V_0 e^{-\lambda\varphi}$$

PNGB aka Axion (Frieman et al)

$$V(\varphi) = V_0(\cos(\varphi/\lambda) + 1)$$

Exponential with prefactor (AA & Skordis)

$$V(\varphi) = V_0\left(\chi(\varphi - \beta)^2 + \delta\right)e^{-\lambda\varphi}$$

Inverse Power Law (Ratra & Peebles, Steinhardt et al)

$$V(\varphi) = V_0\left(\frac{m}{\varphi}\right)^{\alpha}$$

The potentials

Stronger than average motivations & interest

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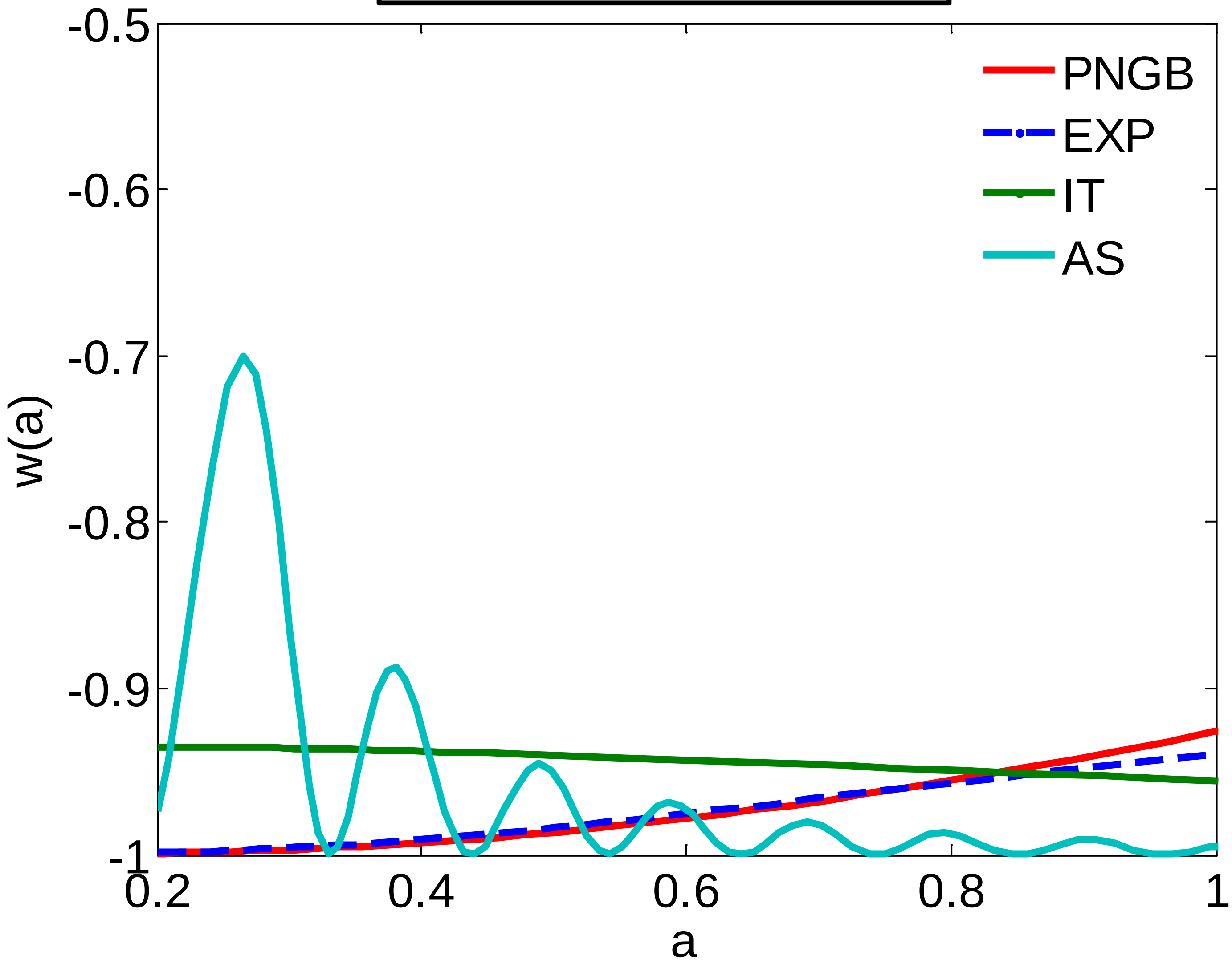
$$V(\varphi) = V_0\left(\frac{m}{\varphi}\right)^\alpha$$

…they cover a variety of behavior.



a = "cosmic scale factor" ≈ time

Dark energy and the ego test

Specific ideas: ii) A scalar field ("Quintessence")

- Illustration: Exponential with prefactor (EwP) models:

$$V(\varphi) = V_0\left(\left(\varphi - B\right)^2 + A\right)\exp\left(-\varphi\lambda\right)$$

AA & Skordis 1999
http://arxiv.org/abs/astro-ph/9908085

- All parameters O(1) in Planck units,
- motivations/protections from extra dimensions & quantum gravity

Burgess & collaborators

(e.g. $B = 34$ $A = .005$ $\lambda = 8$ $V_0 = 1$)

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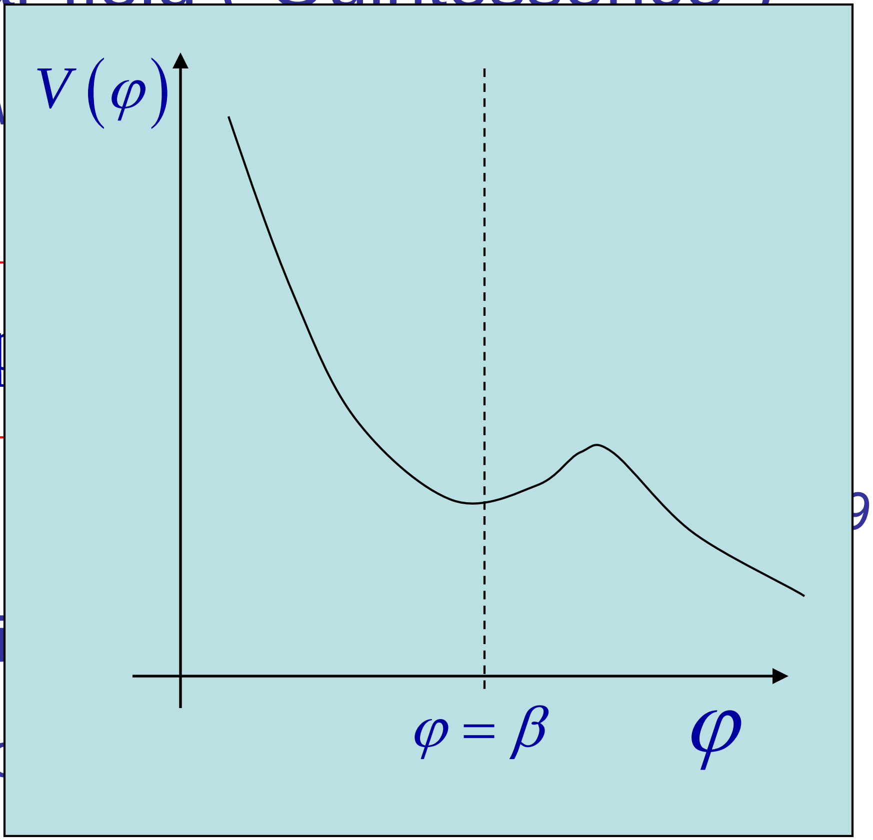

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➢ All parameters O(1) i

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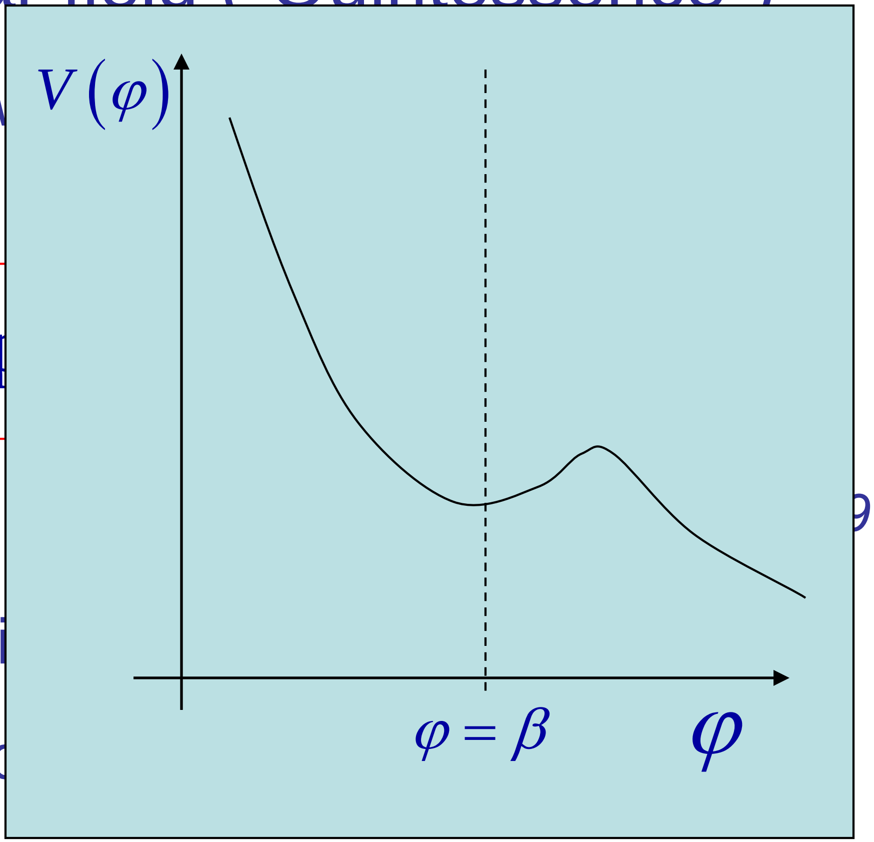

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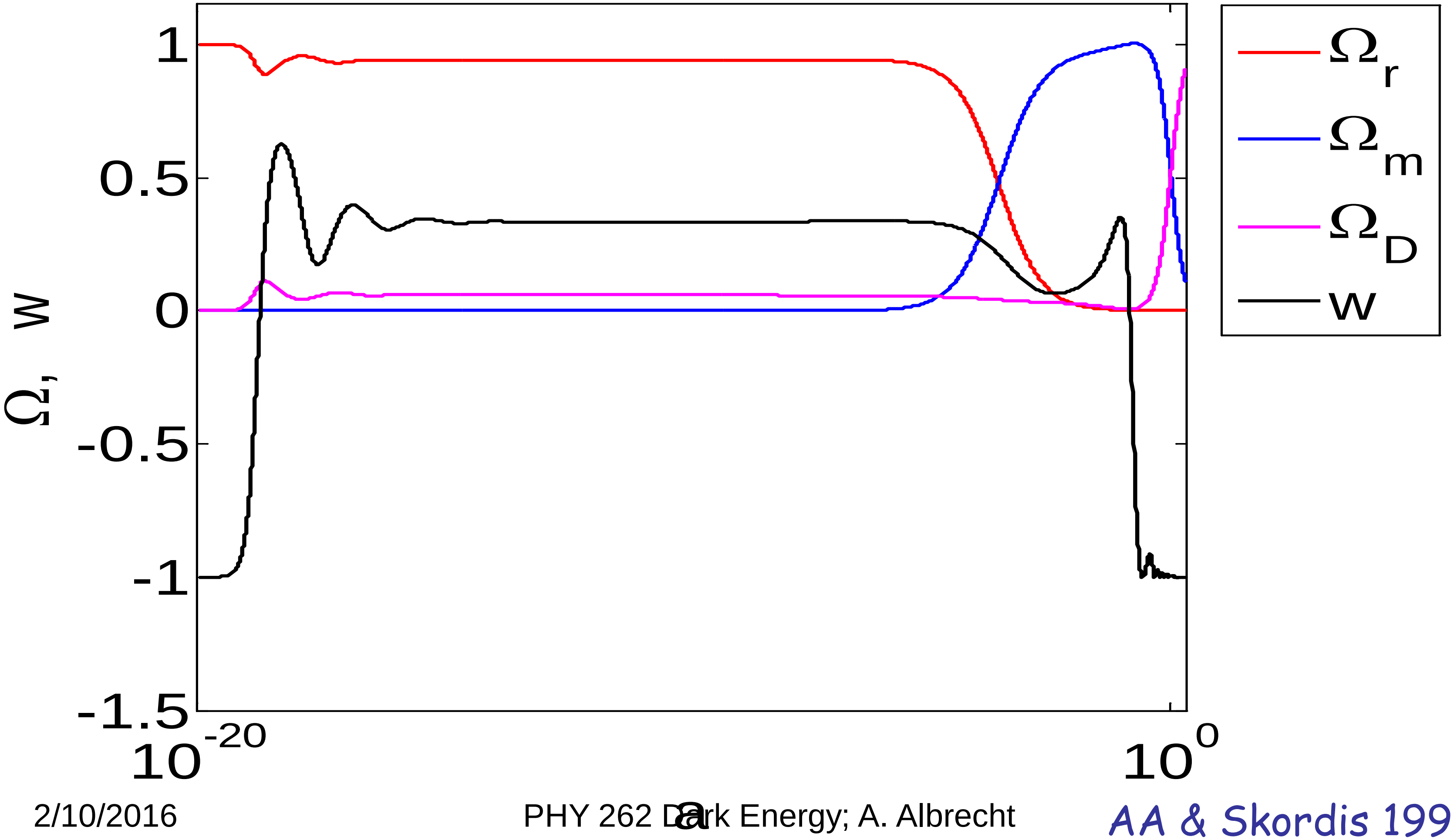

AA & Skordis 1999

Specific ideas: iii) A mass varying neutrinos ("MaVaNs")

Faradon, Nelson & Weiner

- Exploit

$$\Delta m_\nu \approx \rho_{DE}^{1/4} \approx 10^{-3} eV$$

- Issues
  - ➢ Origin of "acceleron" (varies neutrino mass, accelerates the universe)
  - ➢ gravitational collapse

Afshordi et al 2005

Spitzer 2006

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Spitzer 2006

Specific ideas: iv) Modify Gravity

- Not something to be done lightly, but given our confusion about cosmic acceleration, well worth considering.
- Many deep technical issues

e.g. DGP (Dvali, Gabadadze and Porrati)

Ghosts

Charmousis et al

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Ghosts Charmousis et al

See "Origins of Dark Energy" meeting May 07 for numerous talks

This talk

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A few attempts to explain dark energy

- Motivations, Problems and other comments

→ Theme: We may not know where this revolution is taking us, but it is already underway:

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Planning new experiments

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A few attempts to explain dark energy

- Motivations, Problems and other comments

→ Theme: We may not know where this revolution is taking us, but it is already underway:

Part 2

Planning new experiments

- DETF

- Next questions

Astronomy Primer for Dark Energy

From DETF

Solve GR for the scale factor *a* of the Universe (*a*=1 today):

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

Positive acceleration clearly requires $w \equiv p/\rho < -1/3$ unlike any known constituent of the Universe, or a non-zero cosmological constant - or an alteration to General Relativity.

The second basic equation is

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}$$

Today we have $H_0^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho_0}{3} + \frac{\Lambda}{3} - k$

Hubble Parameter

We can rewrite this as

$$1 = \frac{8\pi G_N \rho_0}{3H_0^2} + \frac{\Lambda}{3H_0^2} - \frac{k}{H_0^2} \equiv \Omega_\rho + \Omega_\Lambda + \Omega_k$$

To get the generalization that applies not just now (a=1), we need to distinguish between non-relativistic matter and relativistic matter. We also generalize Λ to dark energy with a constant *w*, not necessarily equal to -1:

non-rel. matter **curvature**

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right]$$

rel. matter **Dark Energy**

What are the observable quantities?

Expansion factor *a* is directly observed by redshifting of emitted photons: *a=1/(1+z)*, *z* is "redshift."

Time is *not* a direct observable (for present discussion). A measure of elapsed time is the *distance* traversed by an emitted photon:

$$0 = ds^2 = c^2 dt^2 - a^2(t)[dr^2 + r_0^2 S_k^2(r/r_0) d^2\Omega] \quad \Rightarrow$$

$$D(z) = \int_{t(z)}^{t_0} \frac{c\,dt'}{a(t')} = \int_0^z \frac{c\,dz'}{H(z')}$$

This ***distance-redshift relation*** is one of the diagnostics of dark energy. Given a value for curvature, there is 1-1 map between *D(z)* and *w(a).*

Distance is manifested by changes in flux, subtended angle, and sky densities of objects at fixed luminosity, proper size, and space density. These are one class of observable quantities for dark-energy study

Another observable quantity:

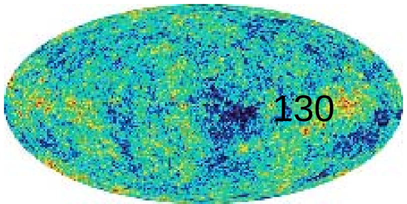
The progress of gravitational collapse is damped by expansion of the Universe. Density fluctuations arising from inflation-era quantum fluctuations increase their amplitude with time. Quantify this by the ***growth factor g*** of density fluctuations in linear perturbation theory. GR gives:

$$\ddot{g} - 2H\dot{g} = 4\pi G \rho_m g = \frac{3\Omega_m H_0^2}{2a^3} g$$

This ***growth-redshift relation*** is the second diagnostic of dark energy. If GR is correct, there is 1-1 map between *D(z)* and *g(z).*

If GR is incorrect, observed quantities may fail to obey this relation.

Growth factor is determined by measuring the density fluctuations in nearby dark matter (!), comparing to those seen at z=1088 by WMAP.



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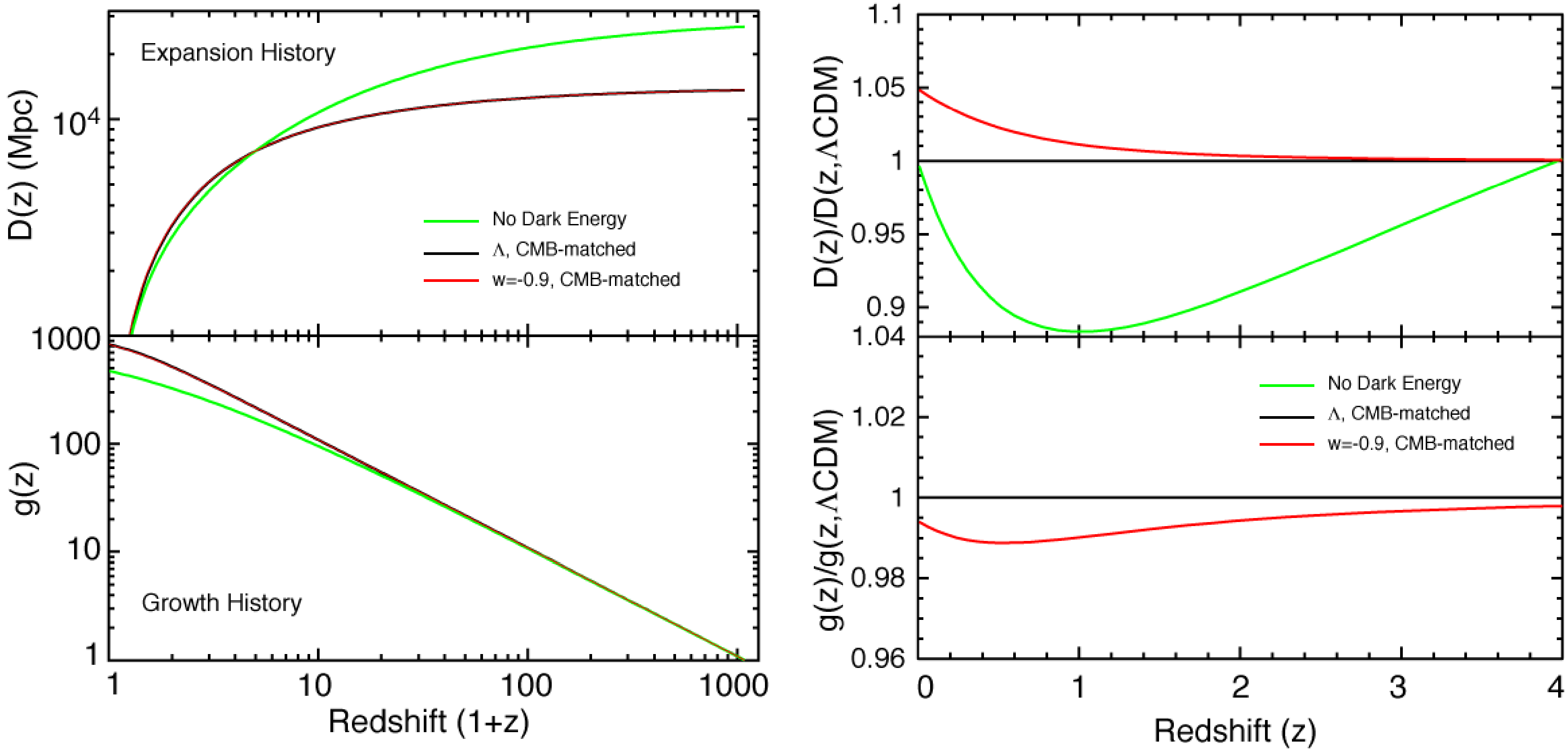
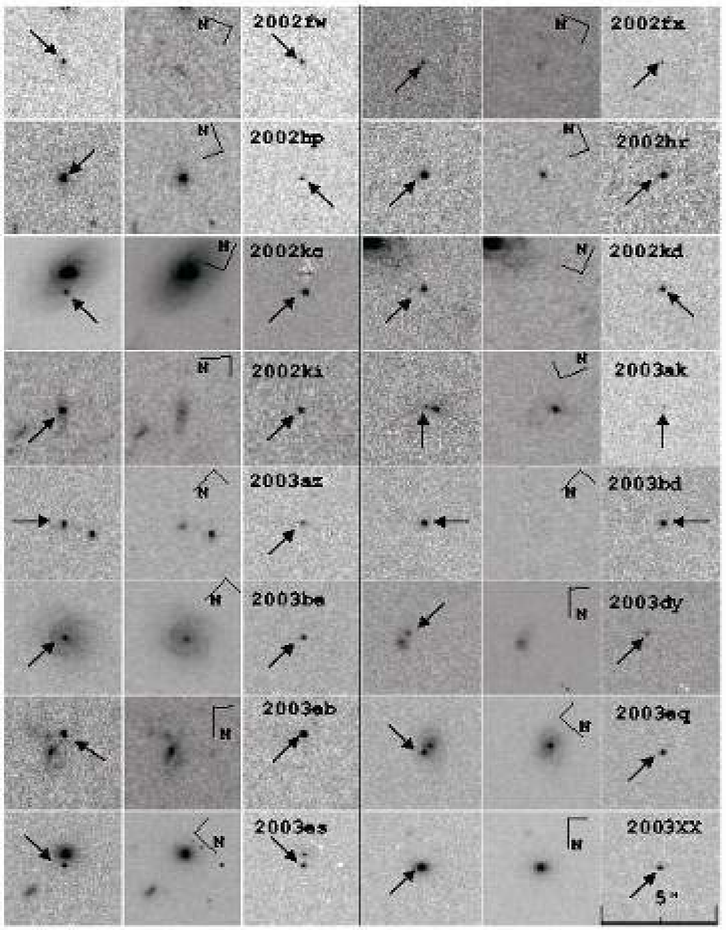


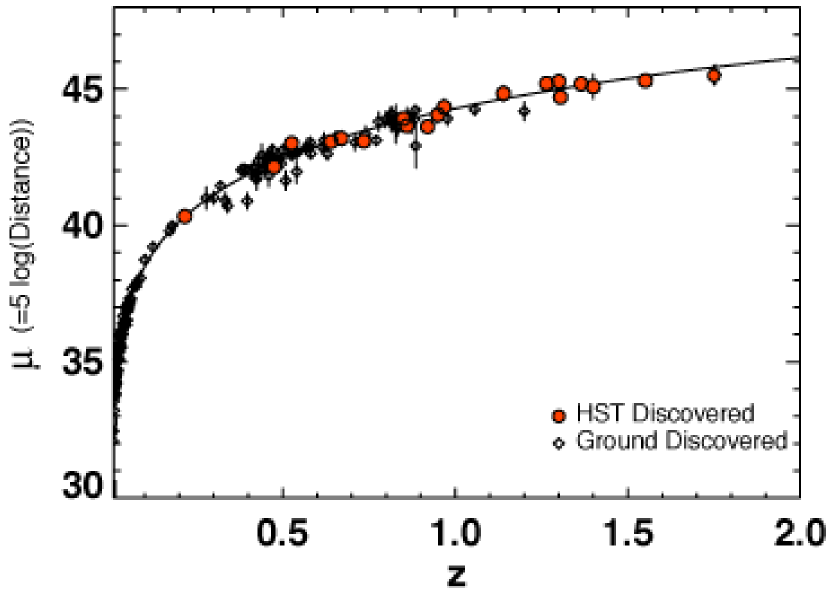
Dark Energy with Type Ia Supernovae

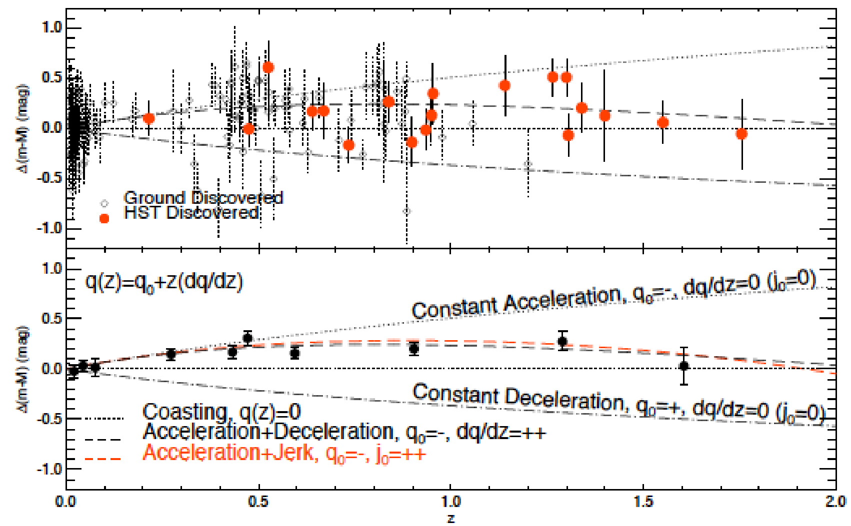
- Exploding white dwarf stars: mass exceeds Chandrasekhar limit.
- If luminosity is fixed, received flux gives relative distance via $Qf = L/4\pi D^2$.
- SNIa are *not* homogeneous events. Are all luminosity-affecting variables manifested in observed properties of the explosion (light curves, spectra)?

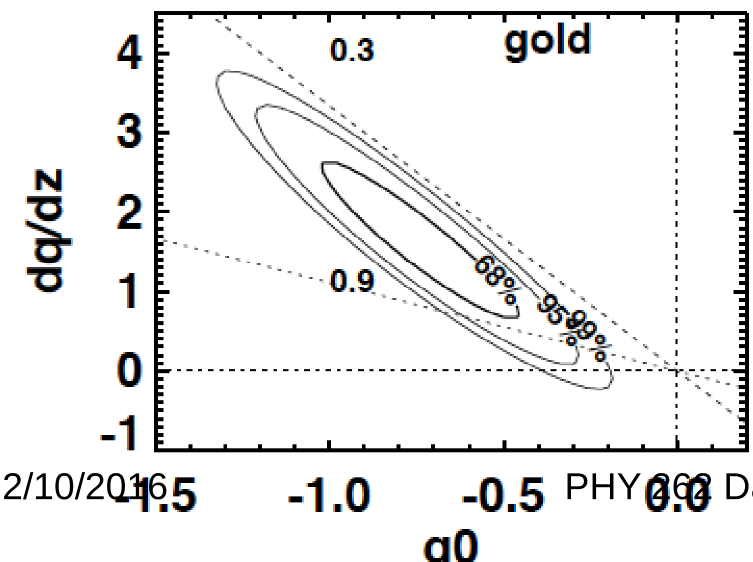


Supernovae Detected in HST GOODS Survey (Riess et al)

Dark Energy with Type Ia Supernovae





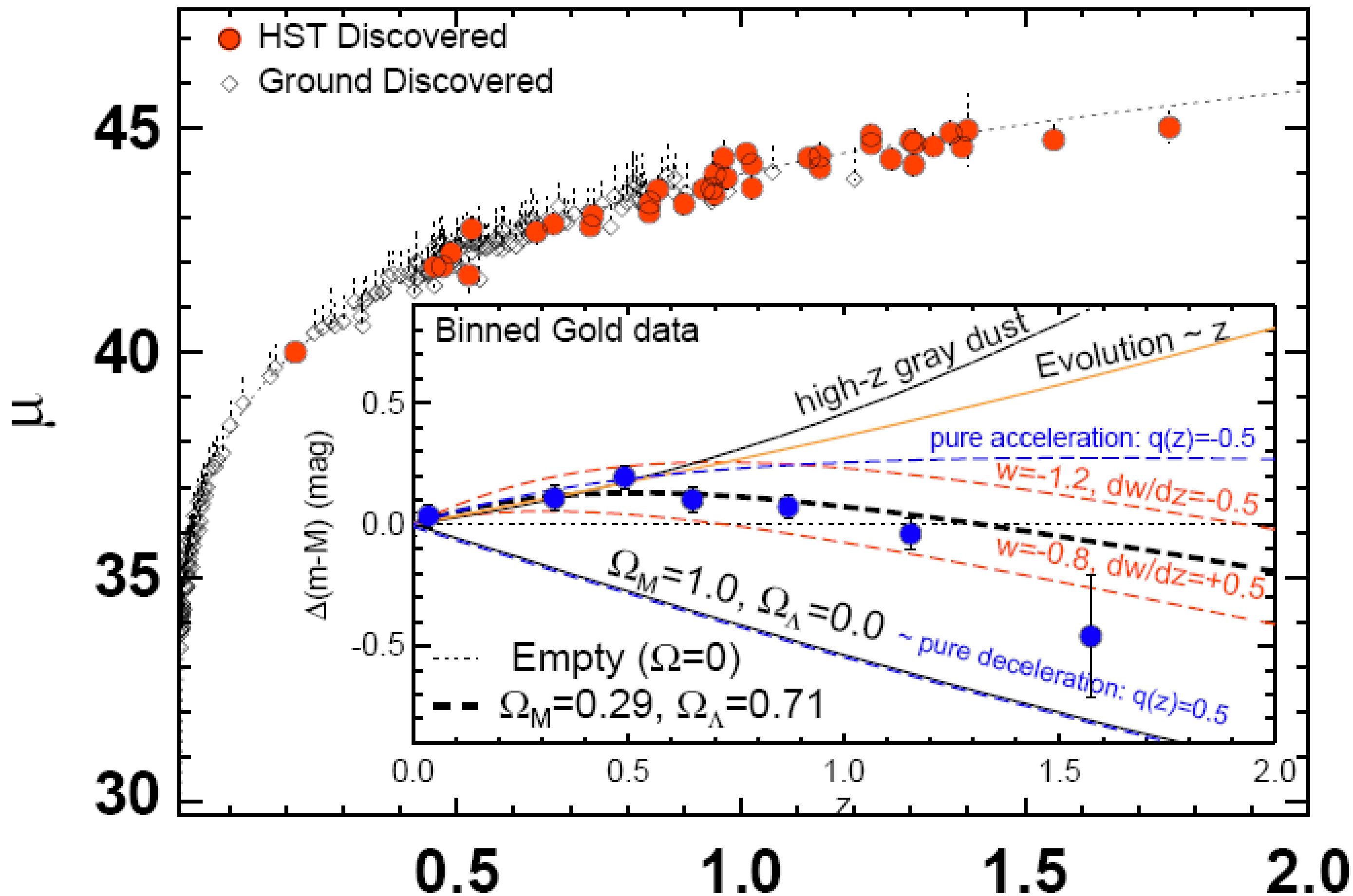


Example of SN data:
HST GOODS Survey (Riess et al)

Clear evidence of acceleration!

$$q_0 \equiv -\frac{\ddot{a}_0 a_0}{\dot{a}_0^2} = \frac{1}{2}\left[\Omega_m + \Omega_X(1+3w)\right]$$

Riess et al astro-ph/0611572



Dark Energy with Baryon Acoustic Oscillations

•Acoustic waves propagate in the baryon-photon plasma starting at end of inflation.

•When plasma combines to neutral hydrogen, sound propagation ends.

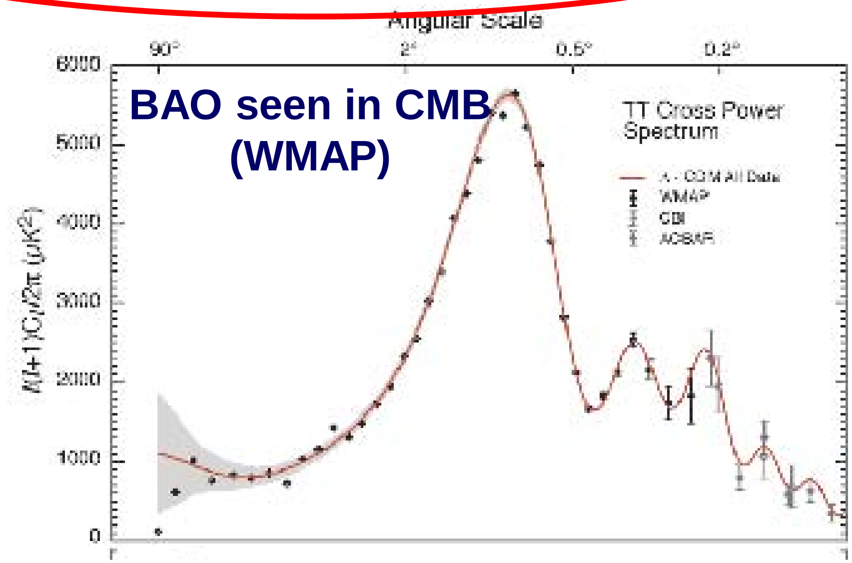
•Cosmic expansion sets up a predictable standing wave pattern on scales of the Hubble length. The Hubble length (~*sound horizon* $r_{s)}$ ~140 Mpc is imprinted on the matter density pattern.

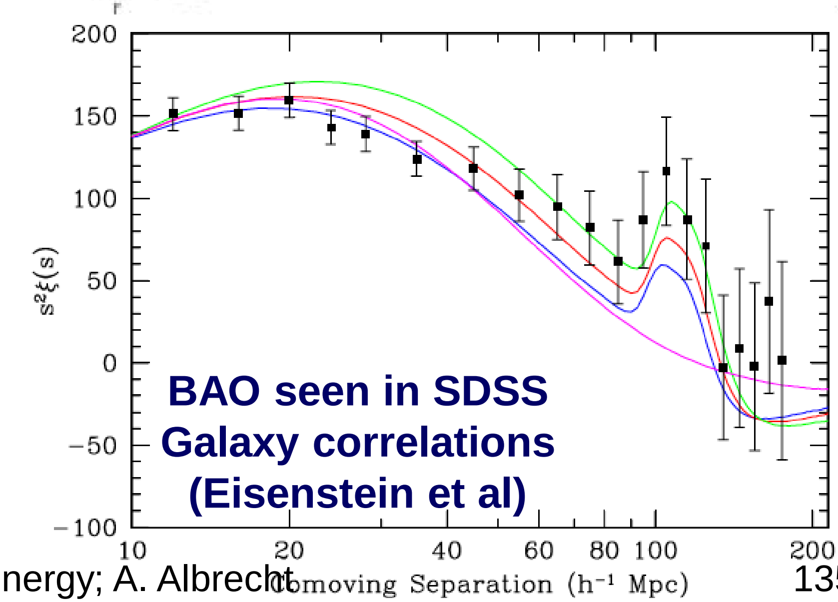
•Identify the angular scale subtending r_s then use $\theta_s = r_s/D(z)$

•WMAP/Planck determine r_s and the distance to z=1088.

•Survey of galaxies (as signposts for dark matter) recover **D(z), H(z)** at 0<z<5.

•Galaxy survey can be visible/NIR or 21-cm emission





Dark Energy with Galaxy Clusters

- Galaxy clusters are the largest structures in Universe to undergo gravitational collapse.

- Markers for locations with density contrast above a critical value.

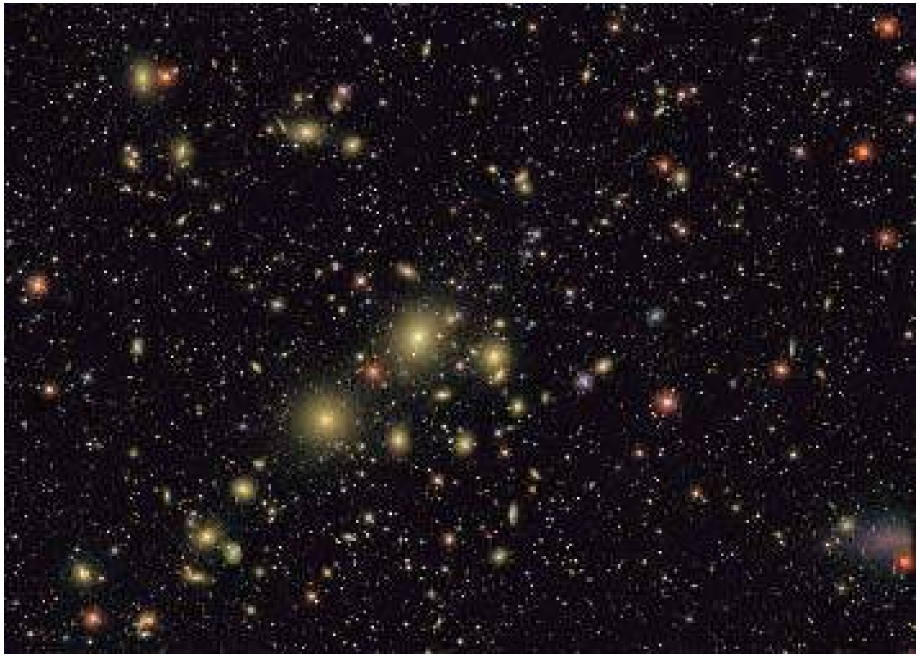
- Theory predicts the *mass function* *dN/dMdV.* We observe *dN/dzdΩ.*

- Dark energy sensitivity:

$$dV/d\Omega\, dz \propto D^2(z)H(z)$$

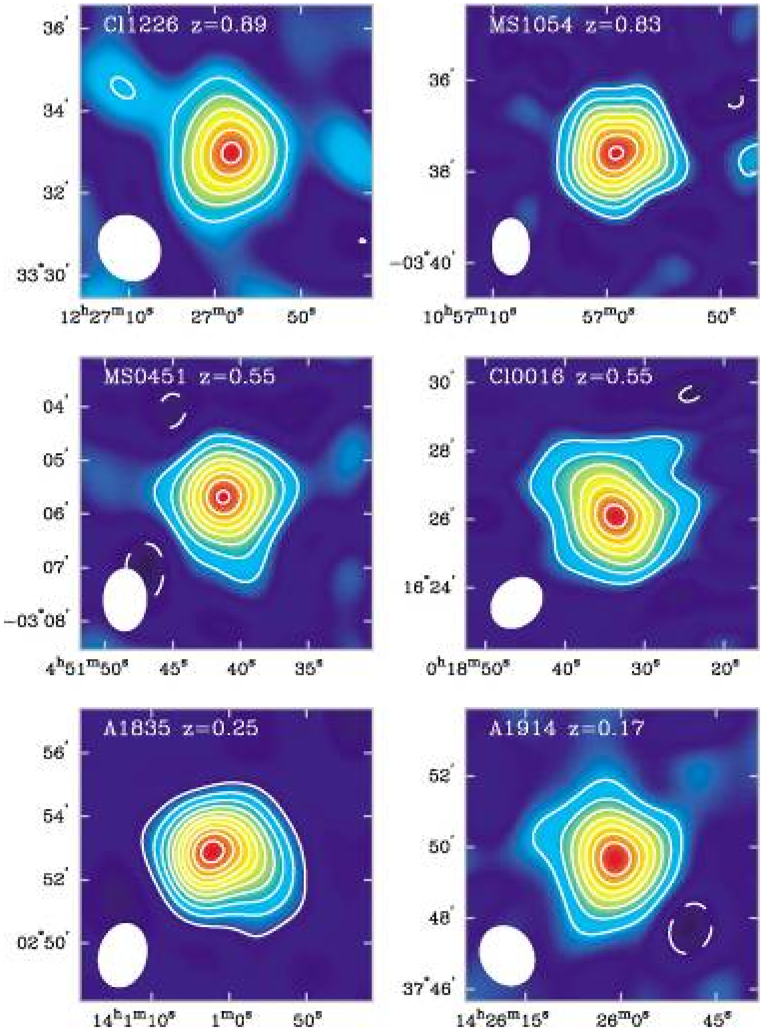
- Mass function is very sensitive to M; very sensitive to ***g(z).***

- Also very sensitive to ***mis-estimation*** of mass, which is not directly observed.

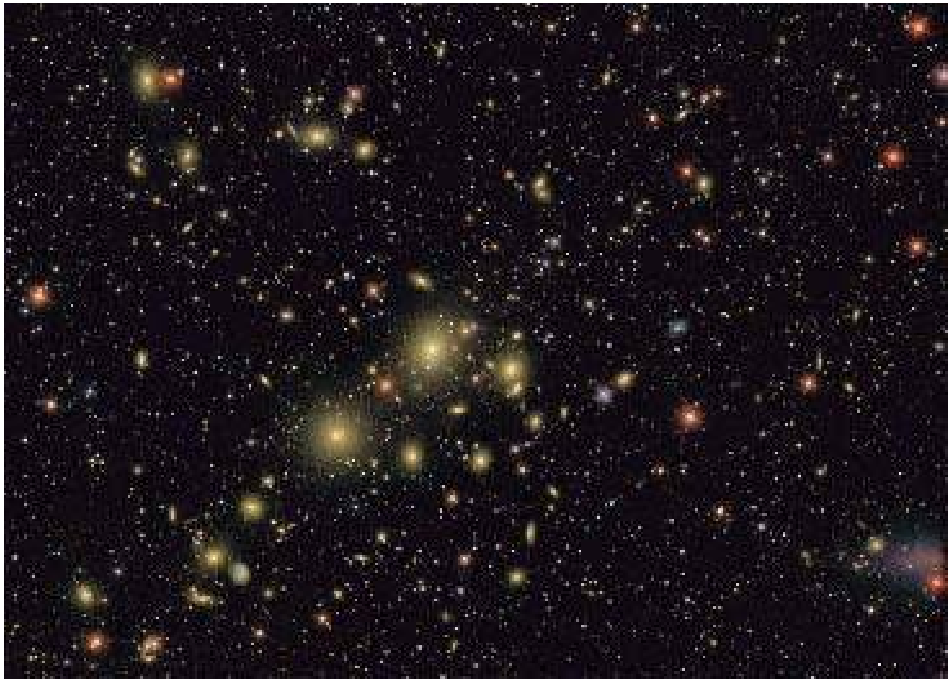


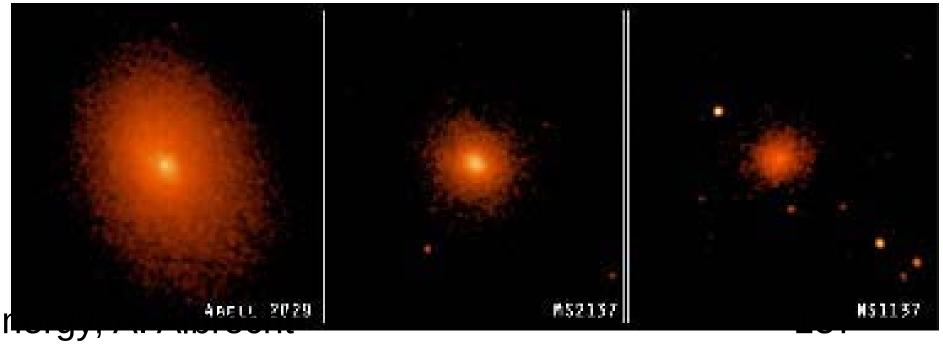
Cluster method probes both D(z) and g(z)

Dark Energy with Galaxy Clusters



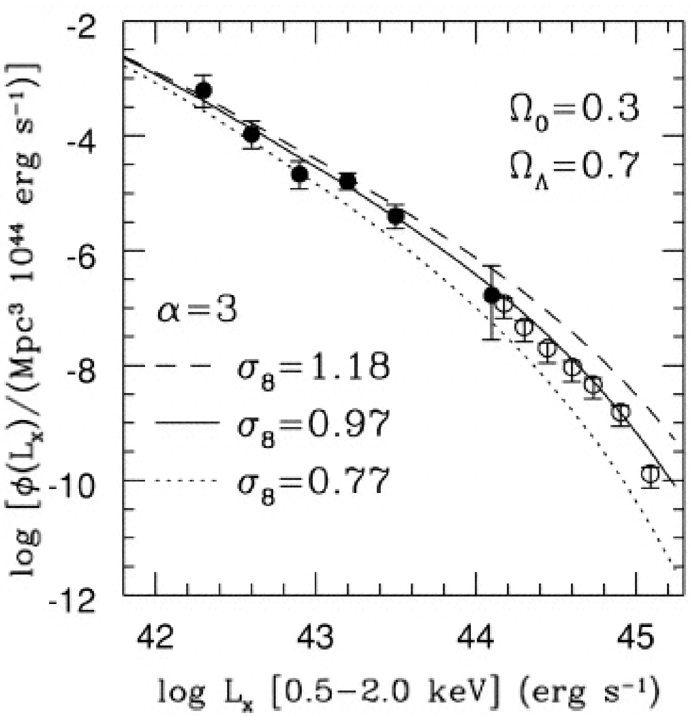
30 GHz View
(Carlstrom et al)
Sunyaev-Zeldovich effect

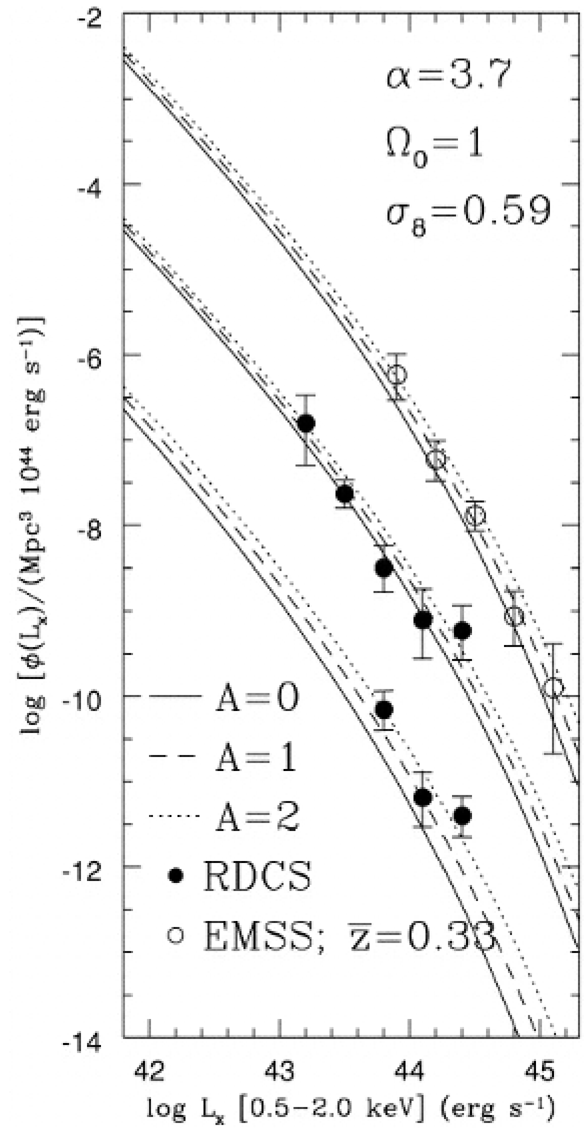




Galaxy Clusters from ROSAT X-ray surveys

From Rosati et al, 1999:





ROSAT cluster surveys yielded ~few 100 clusters in controlled samples.

Future X-ray, SZ, lensing surveys project few x 10,000 detections.

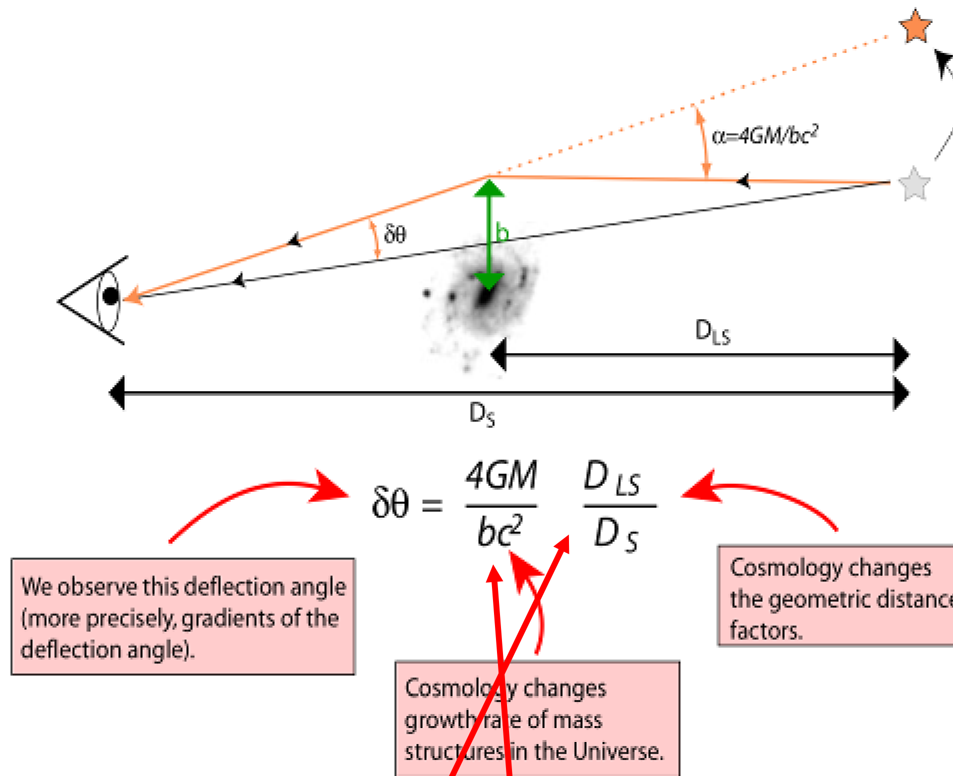
Dark Energy with Weak Gravitational Lensing

•Mass concentrations in the Universe deflect photons from distant sources.

•Displacement of background images is unobservable, but their distortion (shear) is measurable.

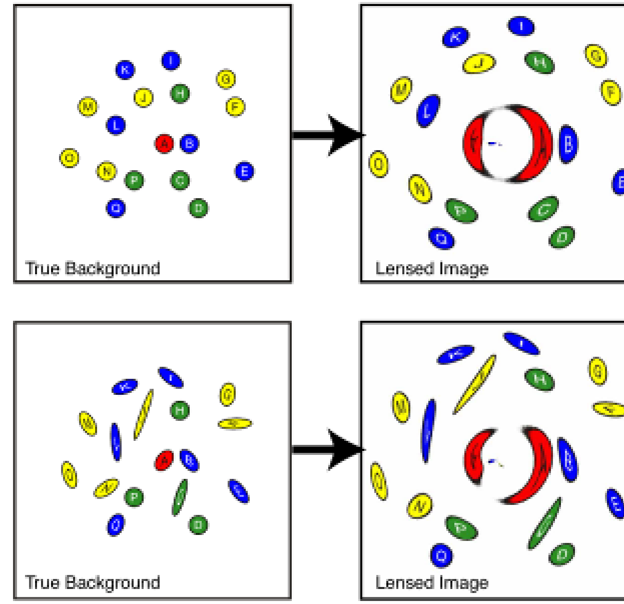
•Extent of distortion depends upon size of mass concentrations and relative distances.

•Depth information from redshifts. Obtaining 10^8 redshifts from optical spectroscopy is infeasible. "photometric" redshifts instead.



Lensing method probes both D(z) and g(z)

Dark Energy with Weak Gravitational Lensing



In **weak lensing**, shapes of galaxies are measured. Dominant noise source is the (random) intrinsic shape of galaxies. Large-N statistics extract lensing influence from intrinsic noise.

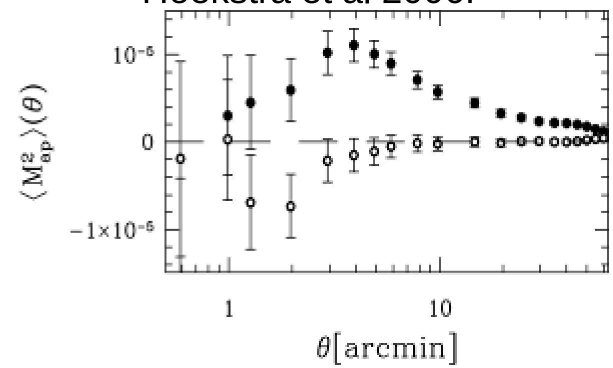
Choose your background photon source:

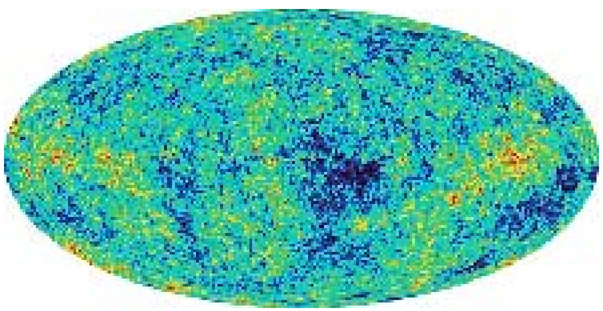
Faint background galaxies:

Use visible/NIR imaging to determine shapes.

Photometric redshifts.

Hoekstra et al 2006:





Photons from the CMB:

Use mm-wave high-resolution imaging of CMB.

All sources at z=1088.

(lensing not yet detected)

21-cm photons:

Use the proposed Square Kilometer Array (SKA).

Sources are neutral H in regular galaxies at z<2, or the neutral Universe at z>6

(lensing not yet detected)

Q: Given that we know so little about the cosmic acceleration, how do we represent source of this acceleration when we forecast the impact of future experiments?

Consensus Answer: (*DETF, Joint Dark Energy Mission Science Definition Team JDEM STD*)

- Model dark energy as homogeneous fluid → all information contained in $w(a) \equiv p(a)/\rho(a)$
- Model possible breakdown of GR by inconsistent determination of *w(a)* by different methods.

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➔ We know very little now

Recall:

Some general issue…

Two “familiar” ways to achieve acceleration:

1) Einstein’s cosmological constant and relatives $(w = -1)$

2) Whatever drove inflation: Dynamical, Scalar field?

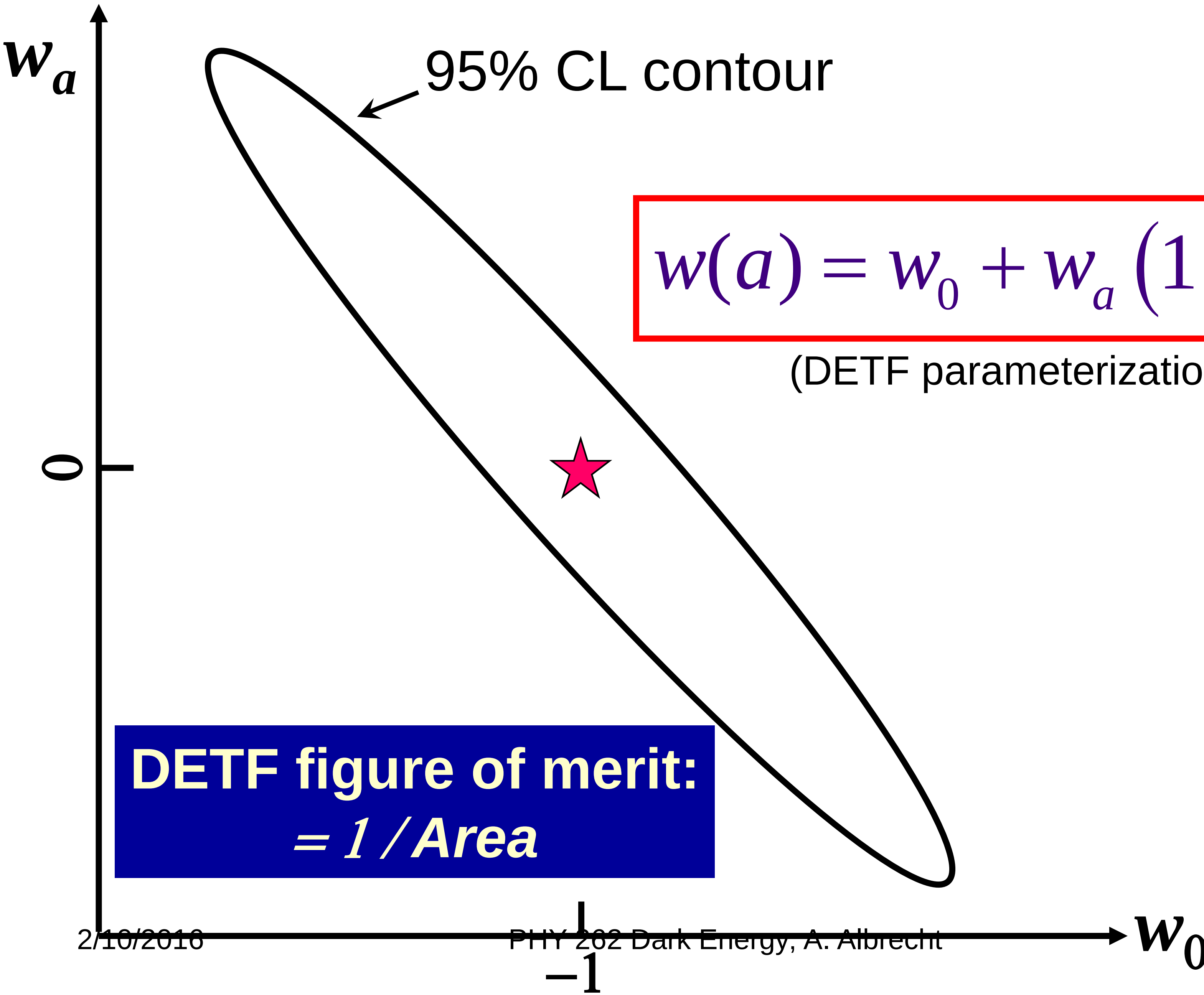
Properties:

Solve GR for the sca… :

$$\frac{\ddot{a}}{a} = -\frac{4}{…}$$

Positive acceleration clearly requires

- $w \equiv p/\rho < -1/3$ (unlike any known constituent of the Universe) or
- a non-zero cosmological constant or
- an alteration to General Relativity.



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

(DETF parameterization… Linder)

DETF figure of merit:
= 1 / Area

The DETF stages (data models constructed for each one)

Stage 2: Underway

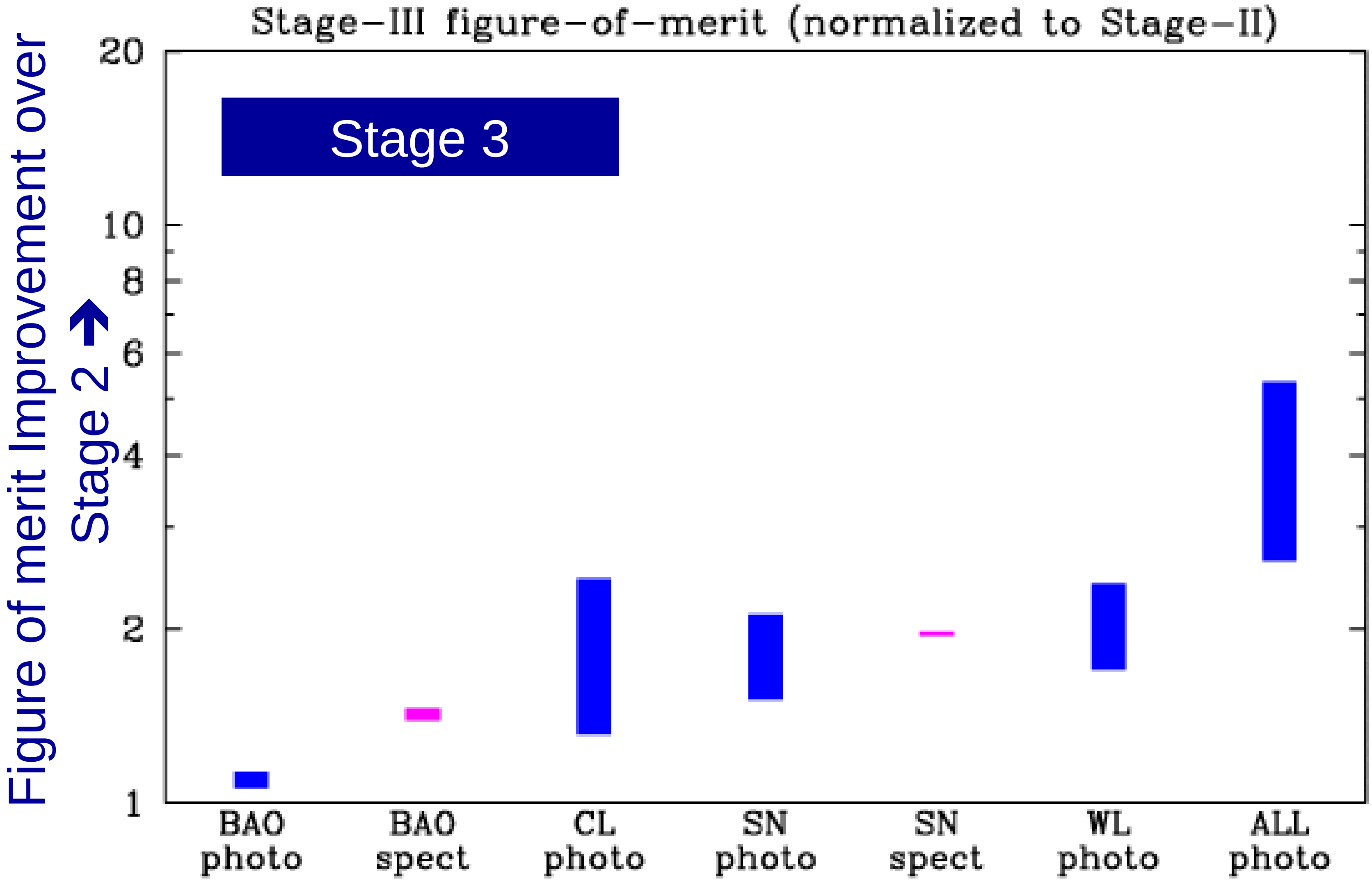
Stage 3: Medium size/term projects

Stage 4: Large longer term projects (ie JDEM, LST)

DETF modeled

- SN
- Weak Lensing
- Baryon Oscillation
- Cluster data

DETF Projections



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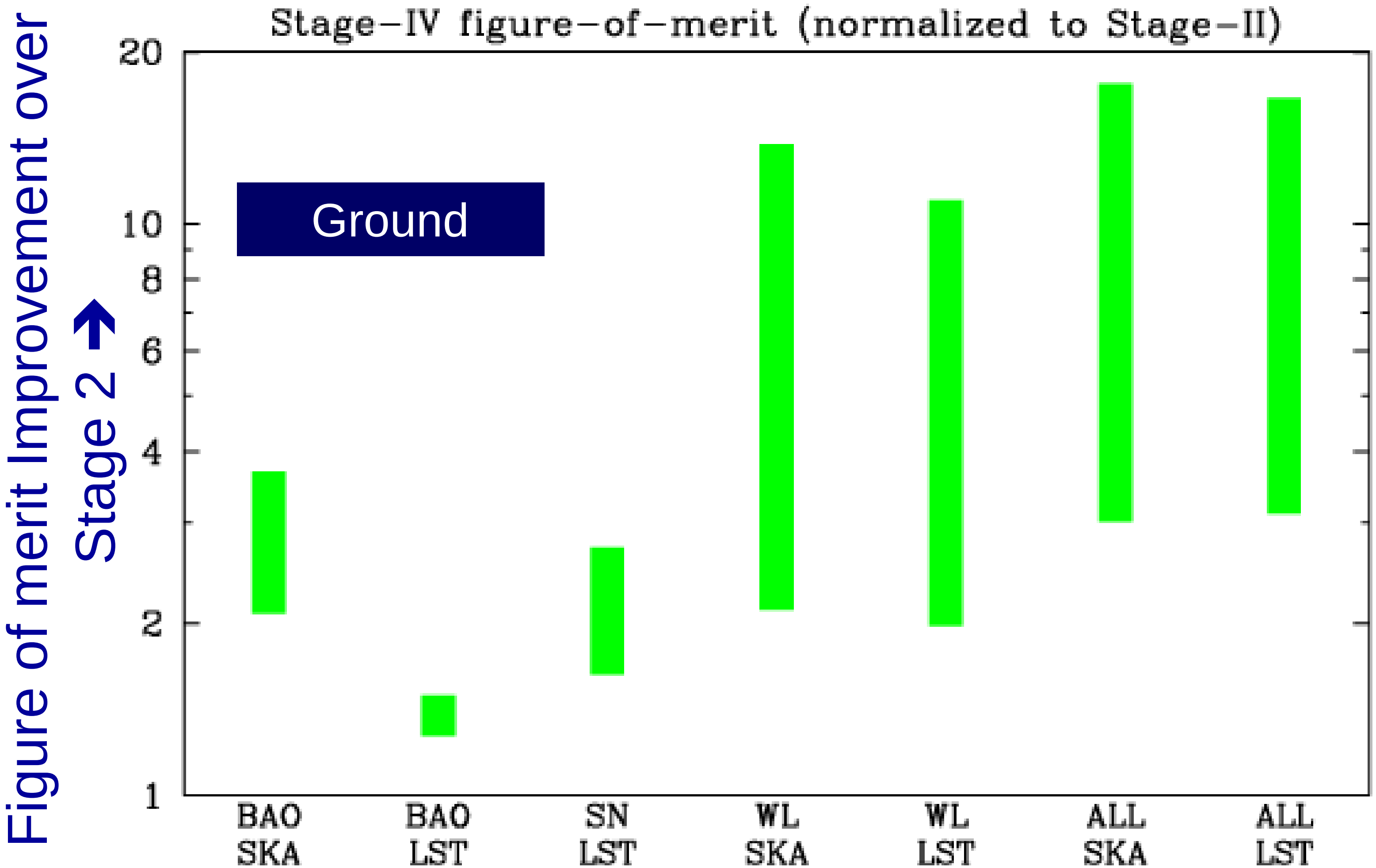

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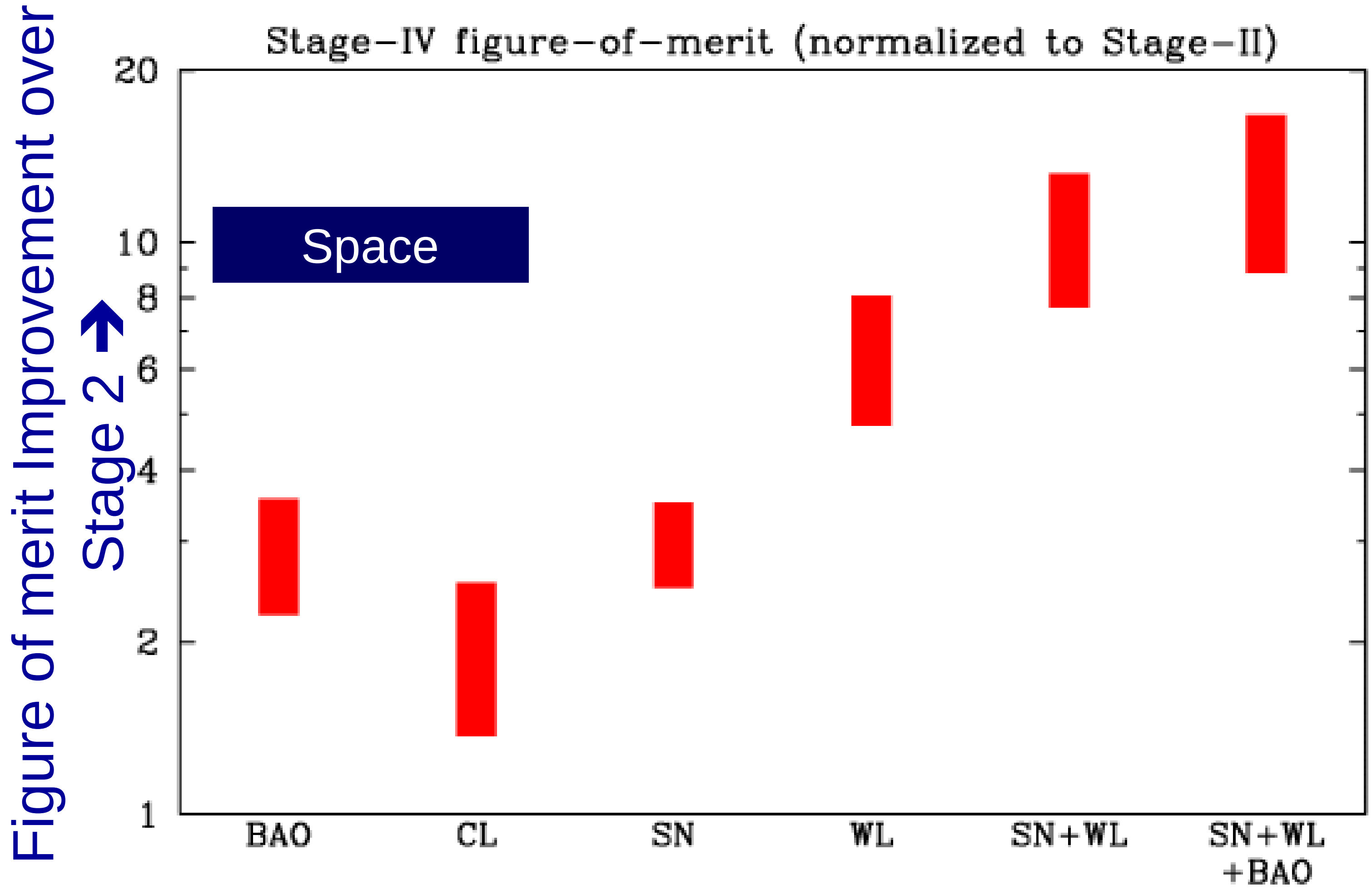

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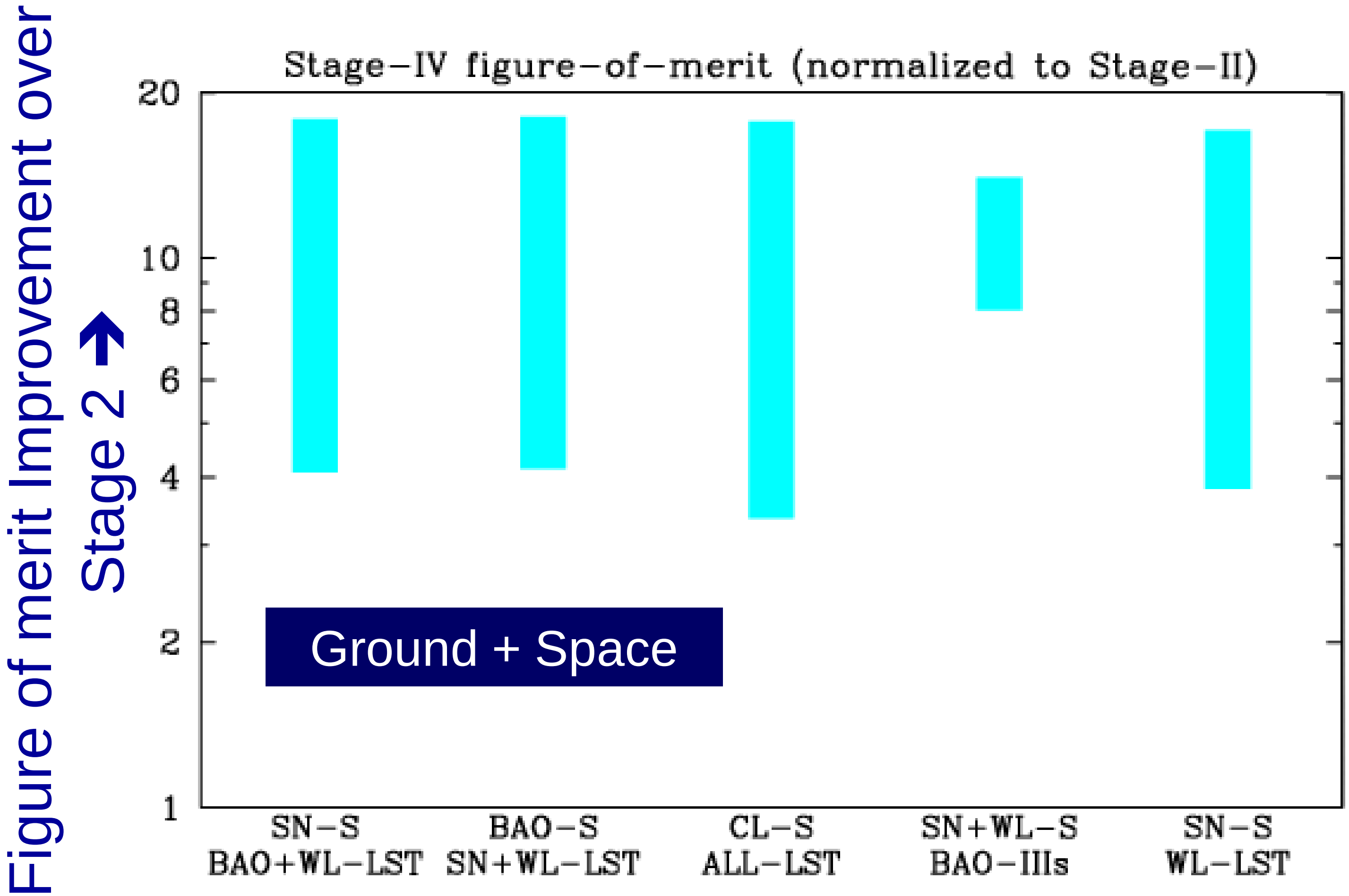
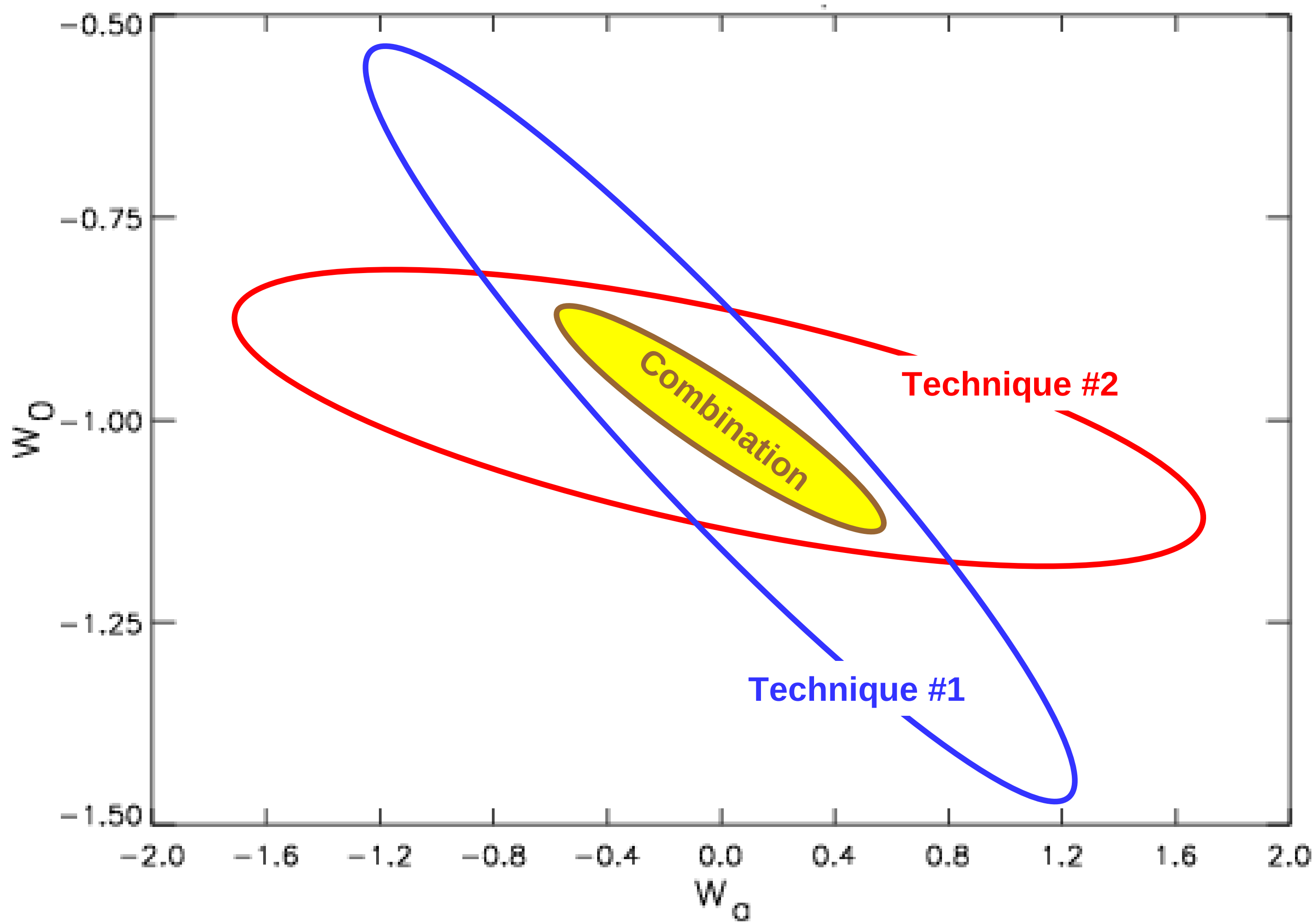


A technical point: The role of correlations



From the DETF Executive Summary

One of our main findings is that no single technique can answer the outstanding questions about dark energy: combinations of at least two of these techniques must be used to fully realize the promise of future observations.

Already there are proposals for major, long-term (Stage IV) projects incorporating these techniques that have the promise of increasing our figure of merit by a factor of ten beyond the level it will reach with the conclusion of current experiments. What is urgently needed is a commitment to fund a program comprised of a selection of these projects. The selection should be made on the basis of critical evaluations of their costs, benefits, and risks.

The Dark Energy Task Force (DETF)

➔ Created specific simulated data sets (Stage 2, Stage 3, Stage 4)

➔ Assessed their impact on our knowledge of dark energy as modeled with the *w0-wa* parameters

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

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Followup questions:

→ In what ways might the choice of DE parameters biased the DETF results?

→ What impact can these data sets have on specific DE models (vs abstract parameters)?

→ To what extent can these data sets deliver discriminating power between specific DE models?

→ How is the DoE/ESA/NASA Science Working Group looking at these questions?

The Dark Energy Task F

Created specific sim
4)

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modeled with the *w0*

NB: To make concrete comparisons this work ignores various possible improvements to the DETF data models.

(see for example J Newman, H Zhan *et al* *&* Schneider *et al*)

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DETF

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ALSO

Ground/Space synergies

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Summary

→ In what ways might the choice of DE parameters have skewed the DETF results?

A: Only by an overall (possibly important) rescaling

→ What impact can these data sets have on specific DE models (vs abstract parameters)?

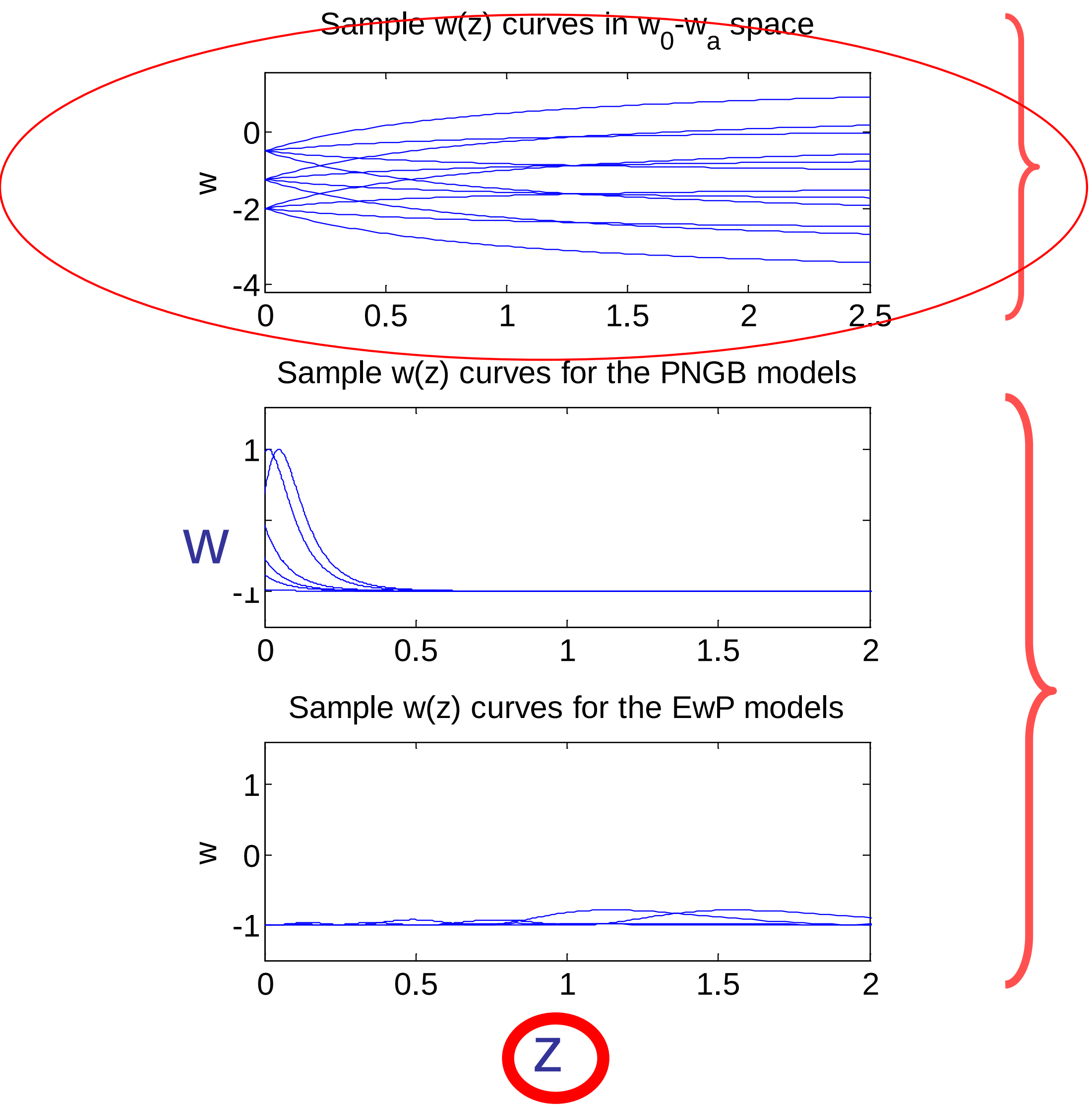
A: Very similar to DETF results in w0-wa space

To what extent can these data sets deliver discriminating power between specific DE models?

A:

- DETF Stage 3: Poor
- DETF Stage 4: Marginal… Excellent within reach (AA)

How good is the w(a) ansatz?



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w0-wa can only do these

DE models can do this
(and much more)

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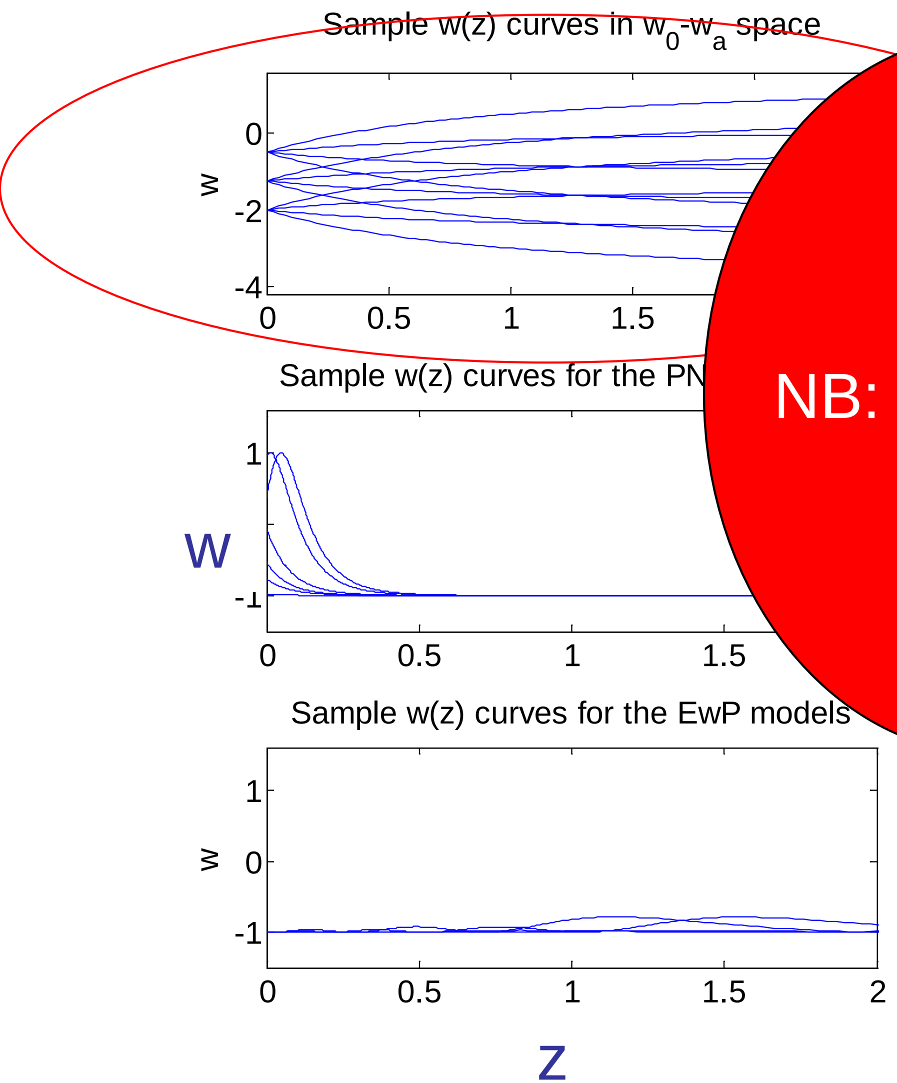

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NB: Better than

$$w(a) = w_0$$

& flat

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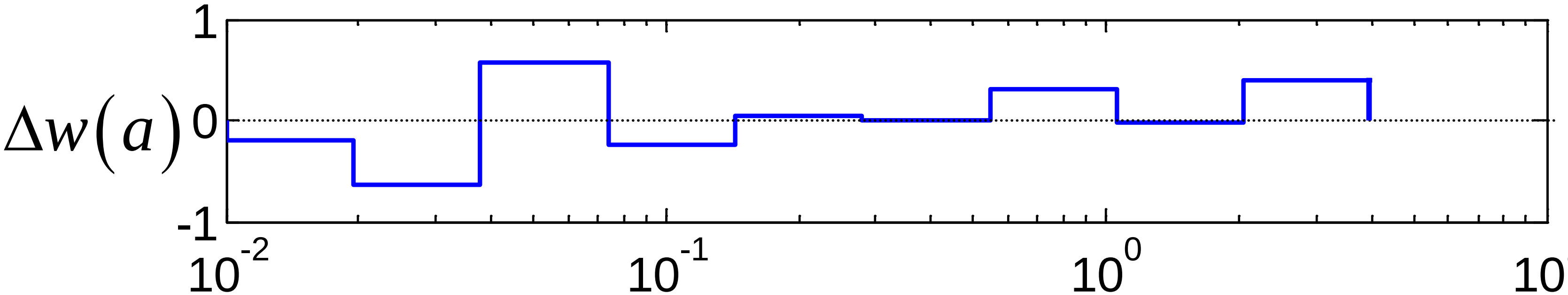
Try *N*-D stepwise constant w(a)



$$w(a) = -1 + \Delta w(a) = -1 + \sum_{i=1}^{N} \Delta w_i T(a_i, a_{i+1})$$

N parameters are coefficients of the "top hat functions" $T(a_i, a_{i+1})$

AA & G Bernstein 2006 (astro-ph/0608269). More detailed info can be found at http://www.physics.ucdavis.edu/Cosmology/albrecht/MoreInfo0608269/

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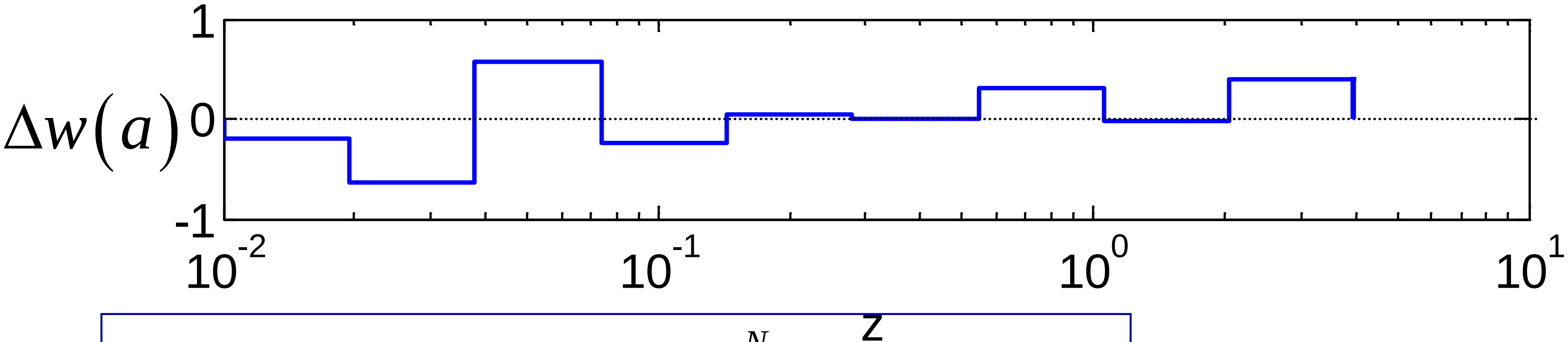

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Used by

Huterer & Turner;
Huterer & Starkman;
Knox et al;
Crittenden & Pogosian
Linder; Reiss et al;
Krauss et al
de Putter & Linder;
Sullivan et al

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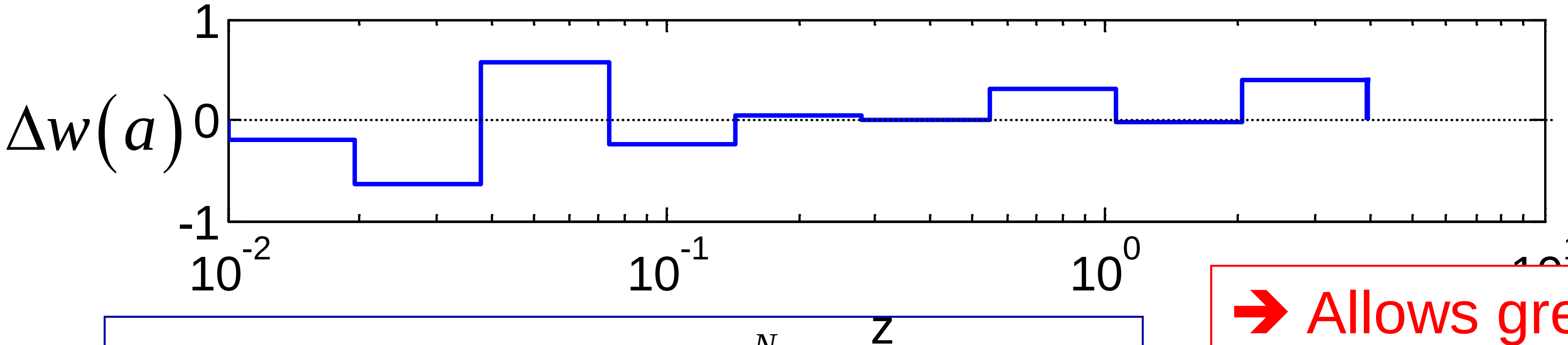

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- ➔ Allows greater variety of w(a) behavior
- ➔ Allows each experiment to "put its best foot forward"
- ➔ Any signal rejects Λ

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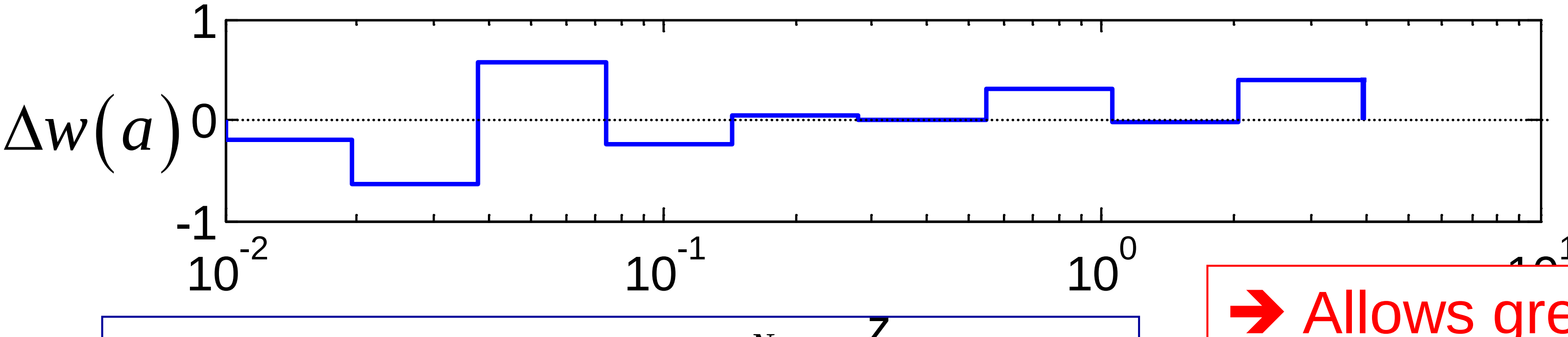

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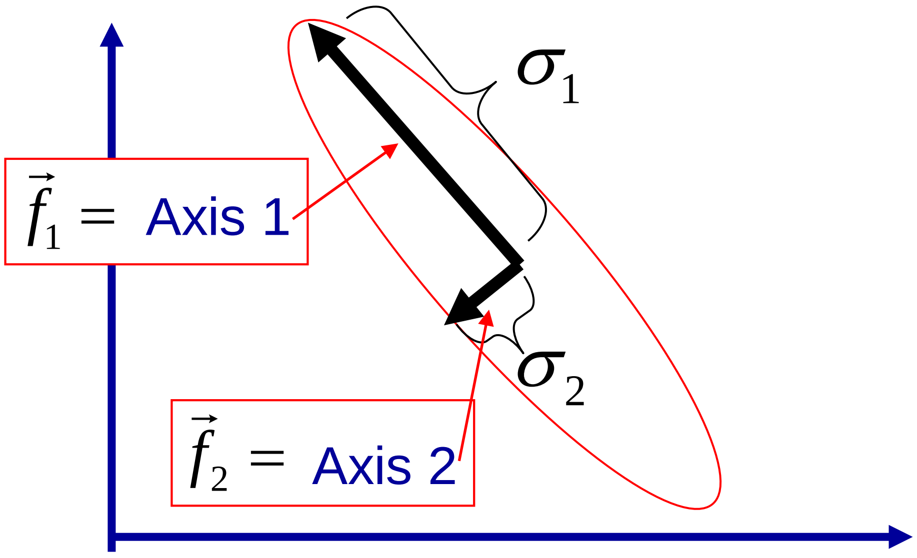
"Convergence"

AA & G Bernstein 2006

Q: How do you describe error ellipsis in *N*D space?

A: In terms of *N* principle axes $\vec{f}_i$ and corresponding *N* errors σ_i:

2D illustration:



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Principle component analysis

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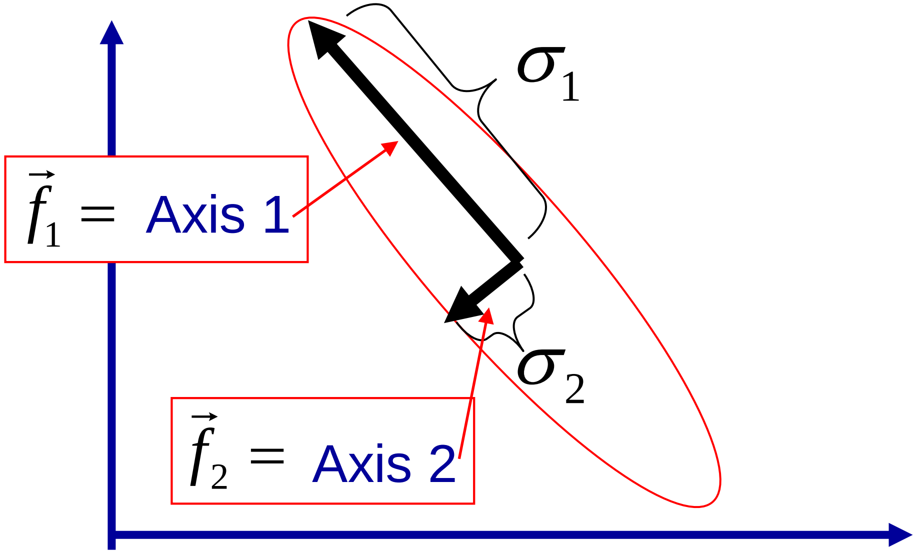

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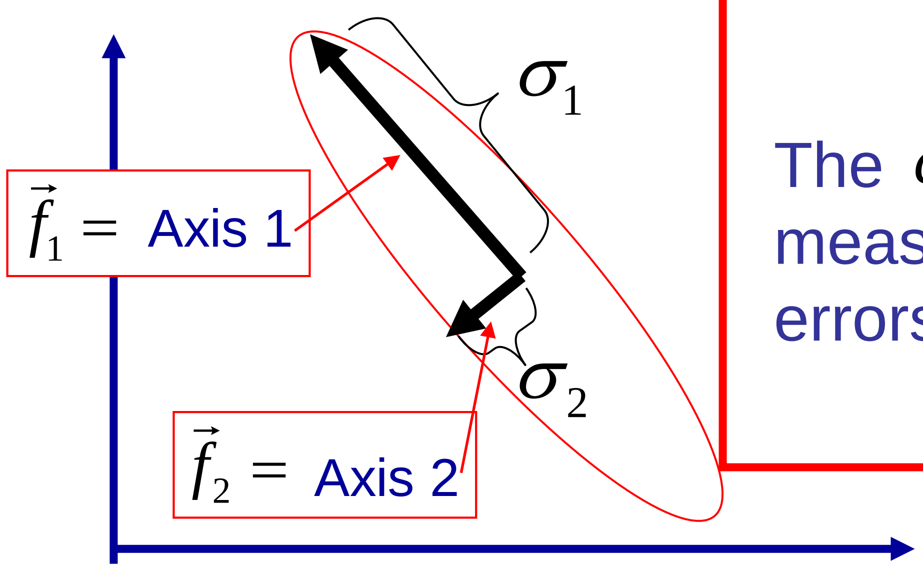

NB: in general the $\vec{f}_i$s form a complete basis:

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

The c_i are independently measured qualities with errors σ_i

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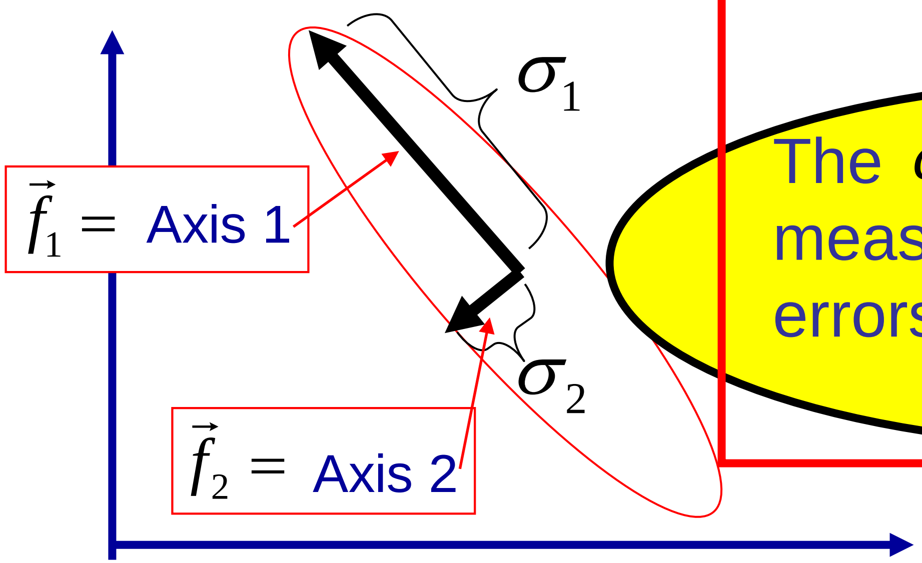

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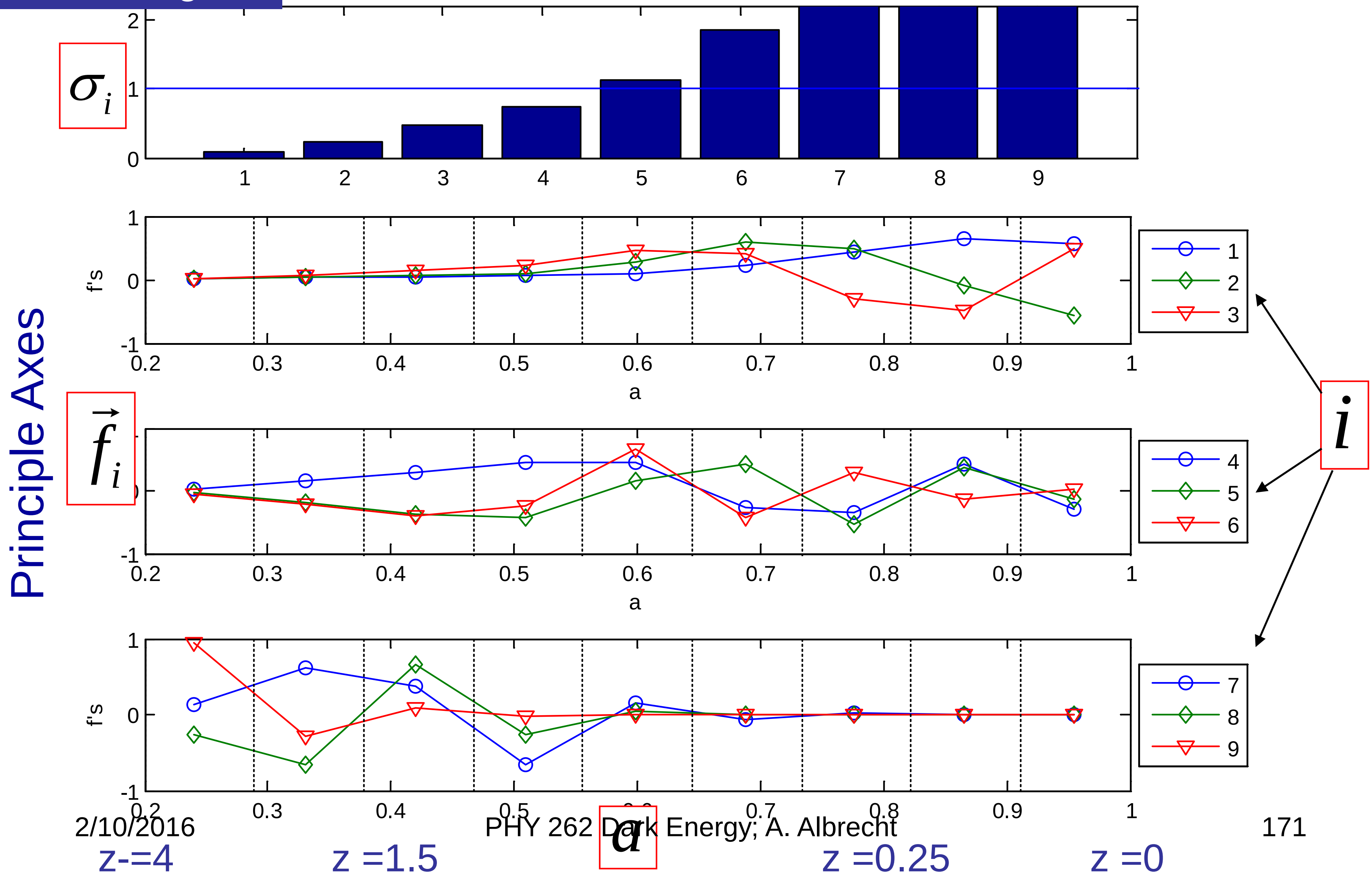
Characterizing 9D ellipses by principle axes and corresponding errors

DETF stage 2



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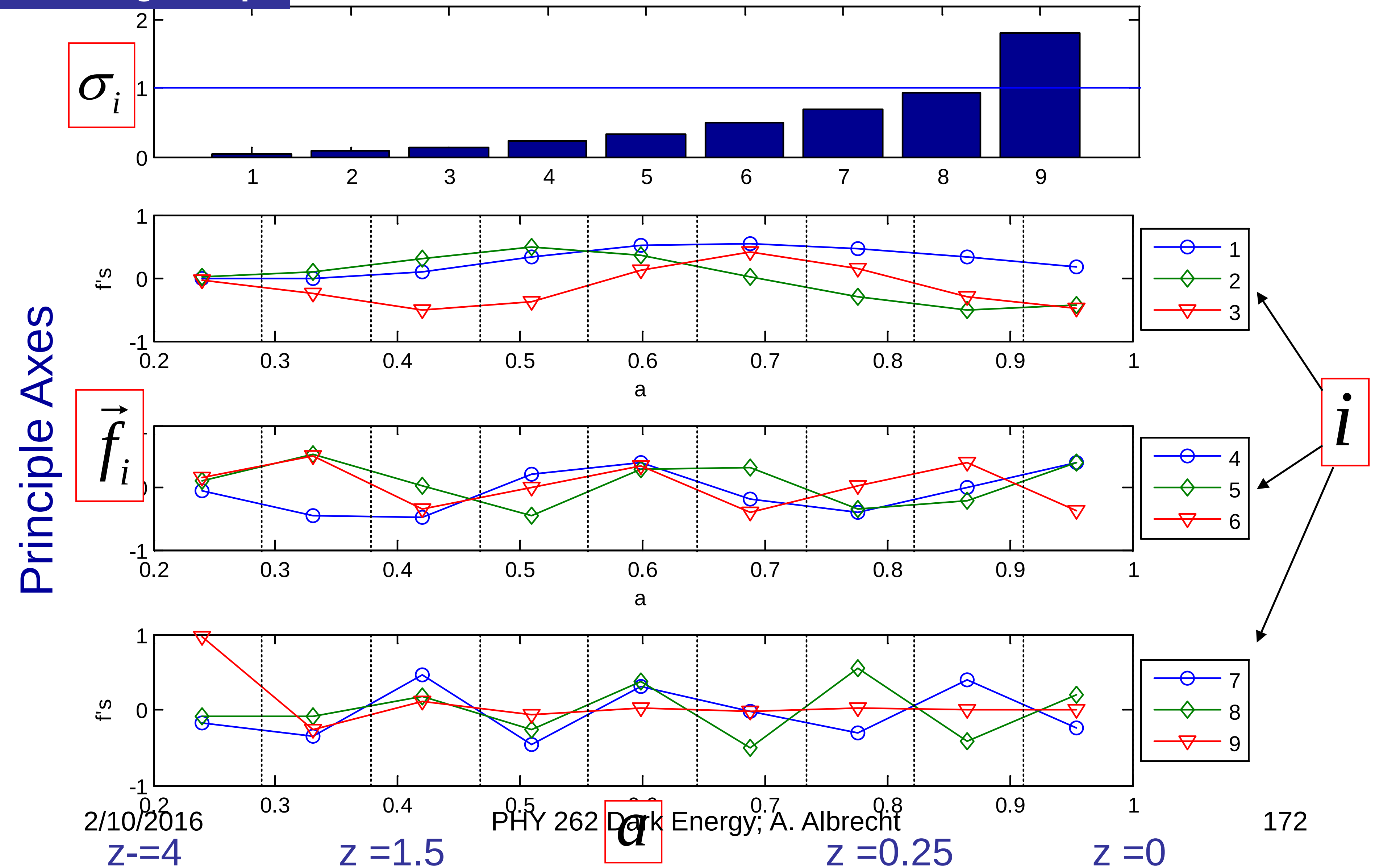
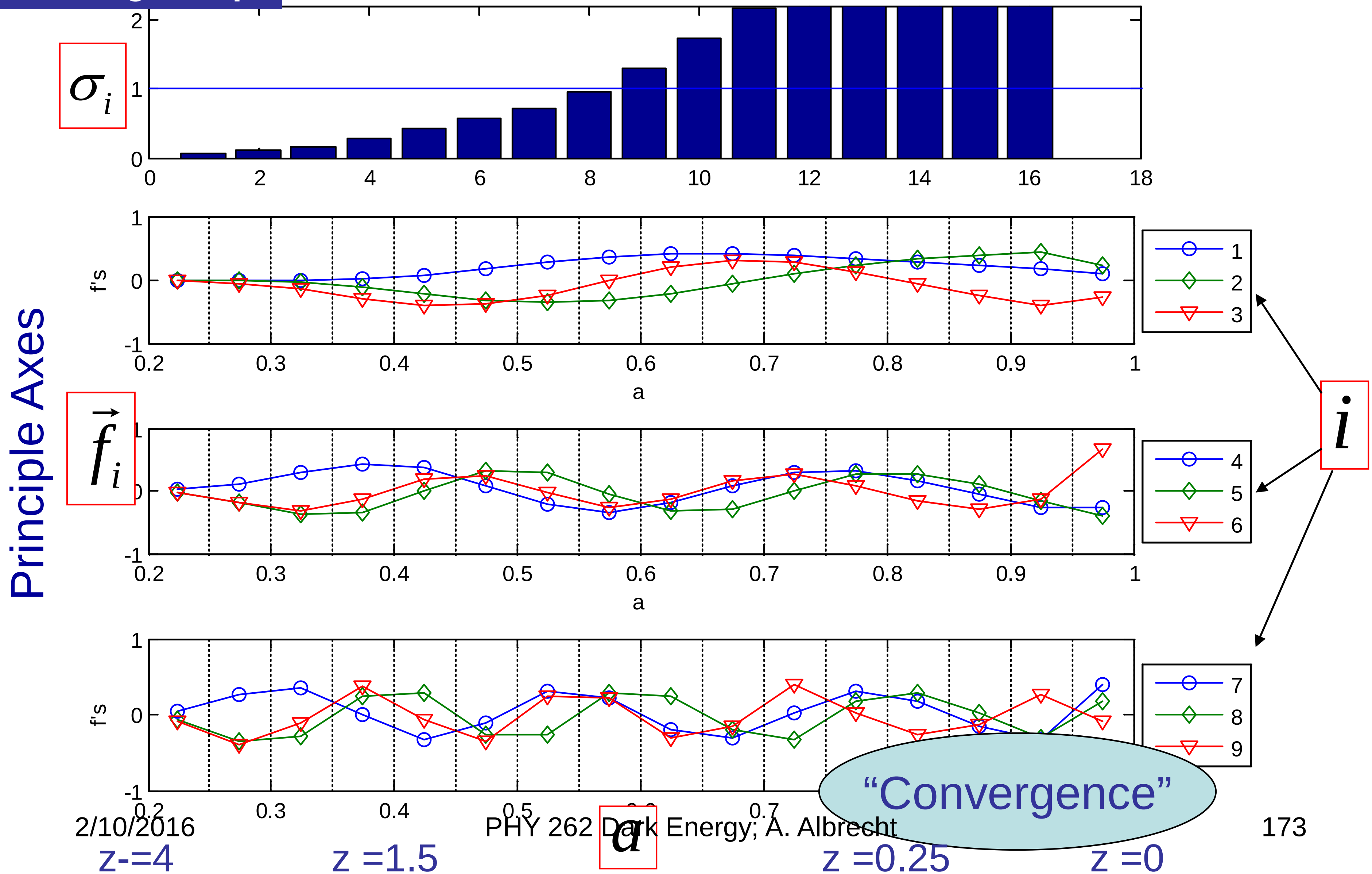
WL Stage 4 Opt



Characterizing 16D ellipses by principle axes and corresponding errors

WL Stage 4 Opt

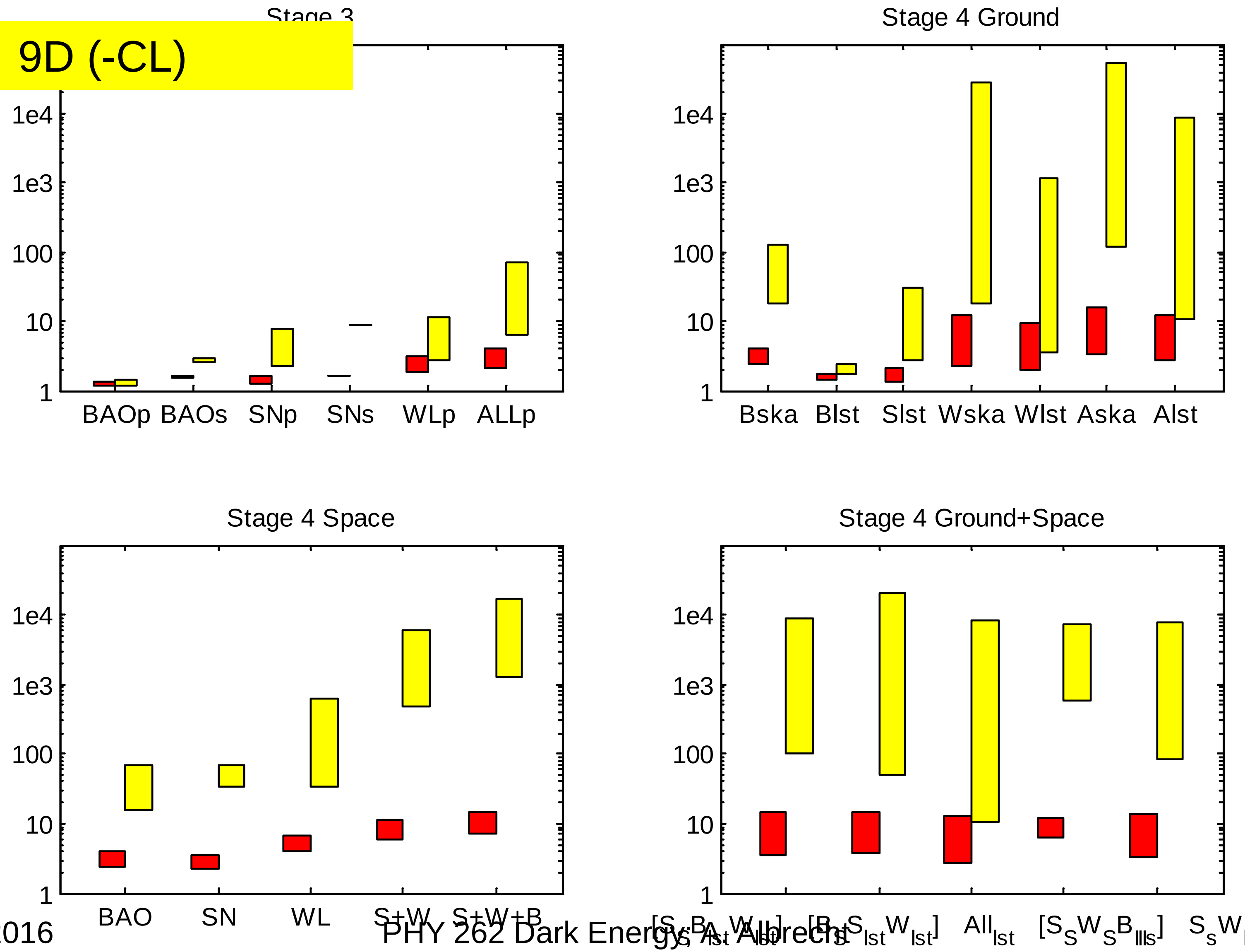


z-=4
z =1.5
z =0.25
z =0

DETF(-CL)

9D (-CL)

$\mathcal{F}_{\mathrm{DETF/9D}}$



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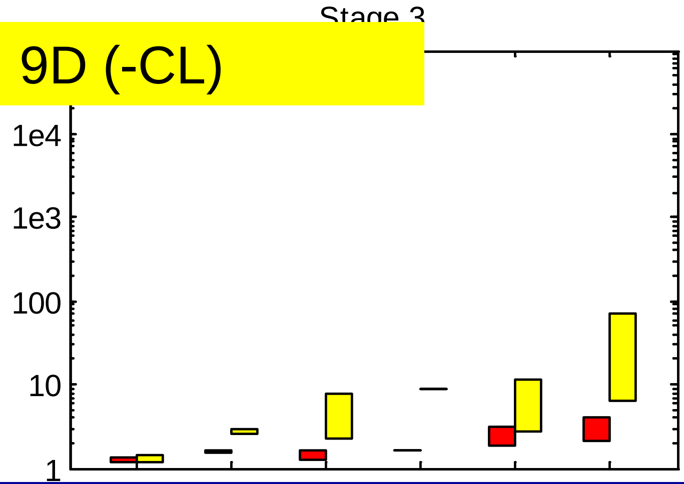
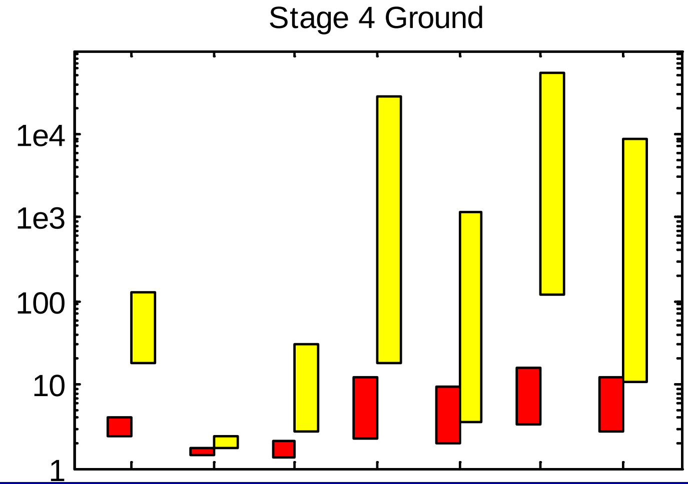
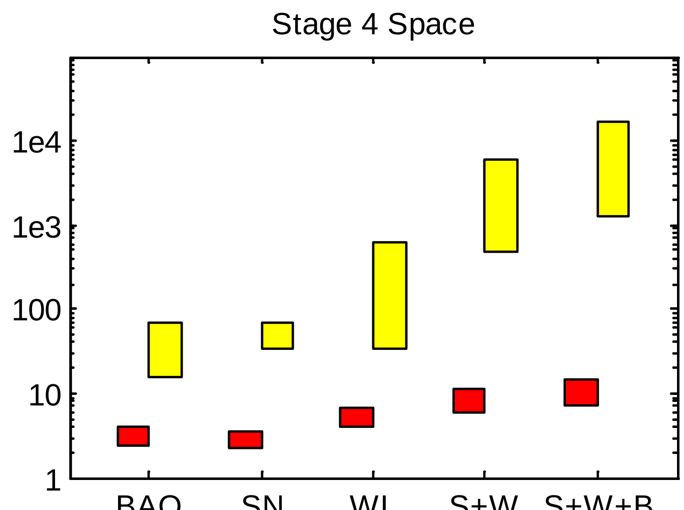
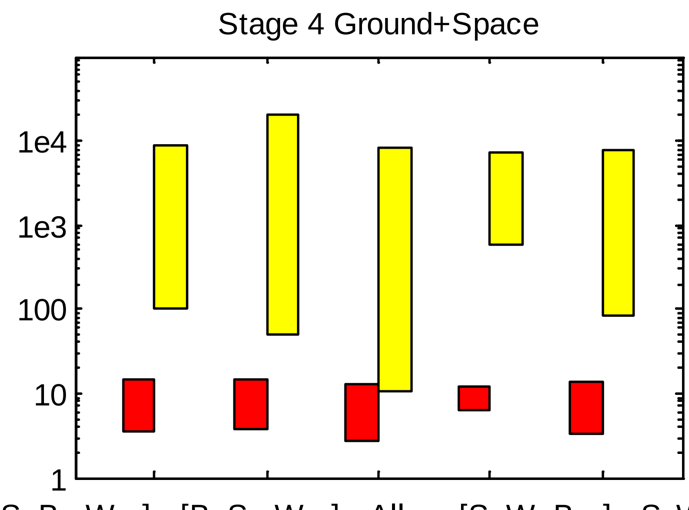




Stage 2 → Stage 3 = 1 order of magnitude (vs 0.5 for DETF)





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Upshot of *N*-D FoM:

1) DETF underestimates impact of expts
2) DETF underestimates relative value of Stage 4 vs Stage 3
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Inverts cost/FoM Estimates S3 vs S4

Summary

→ In what ways might the choice of DE parameters have skewed the DETF results?

A: Only by an overall (possibly important) rescaling

→ What impact can these data sets have on specific DE models (vs abstract parameters)?

A: Very similar to DETF results in w0-wa space

To what extent can these data sets deliver discriminating power between specific DE models?

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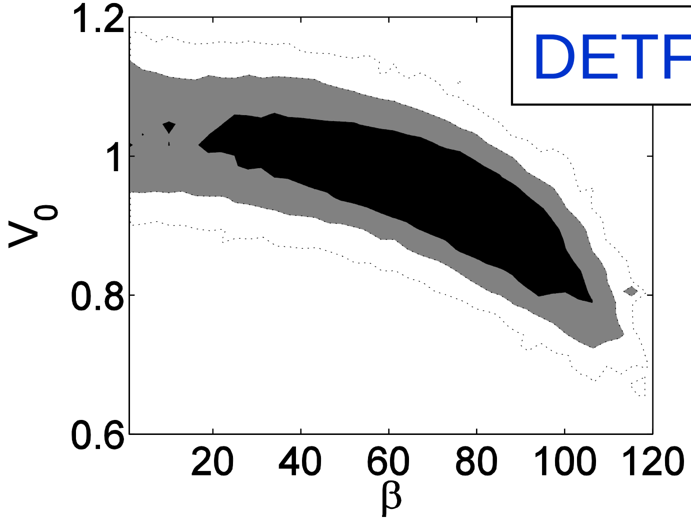

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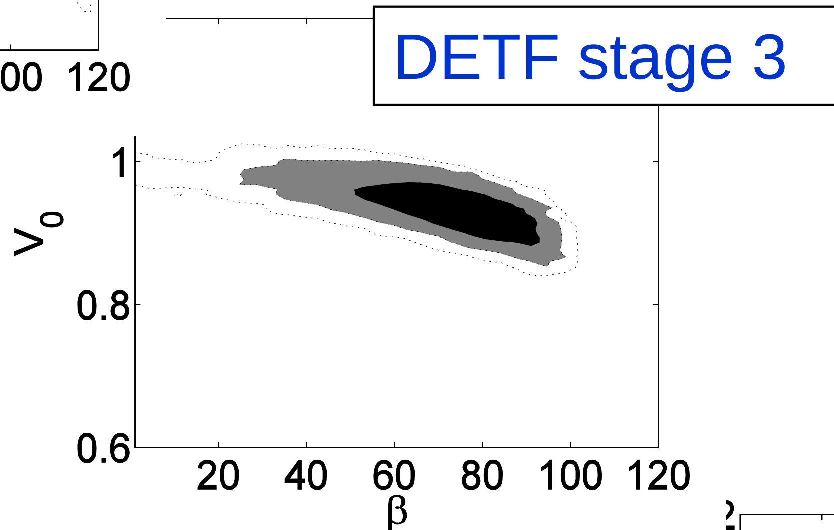

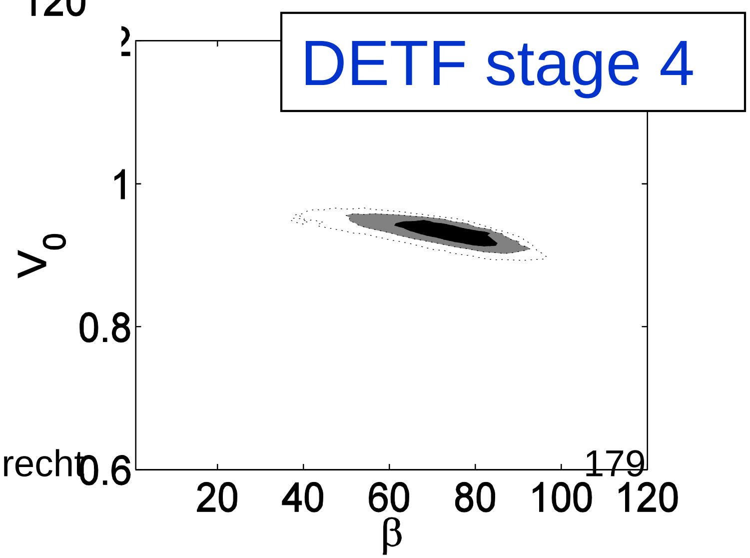

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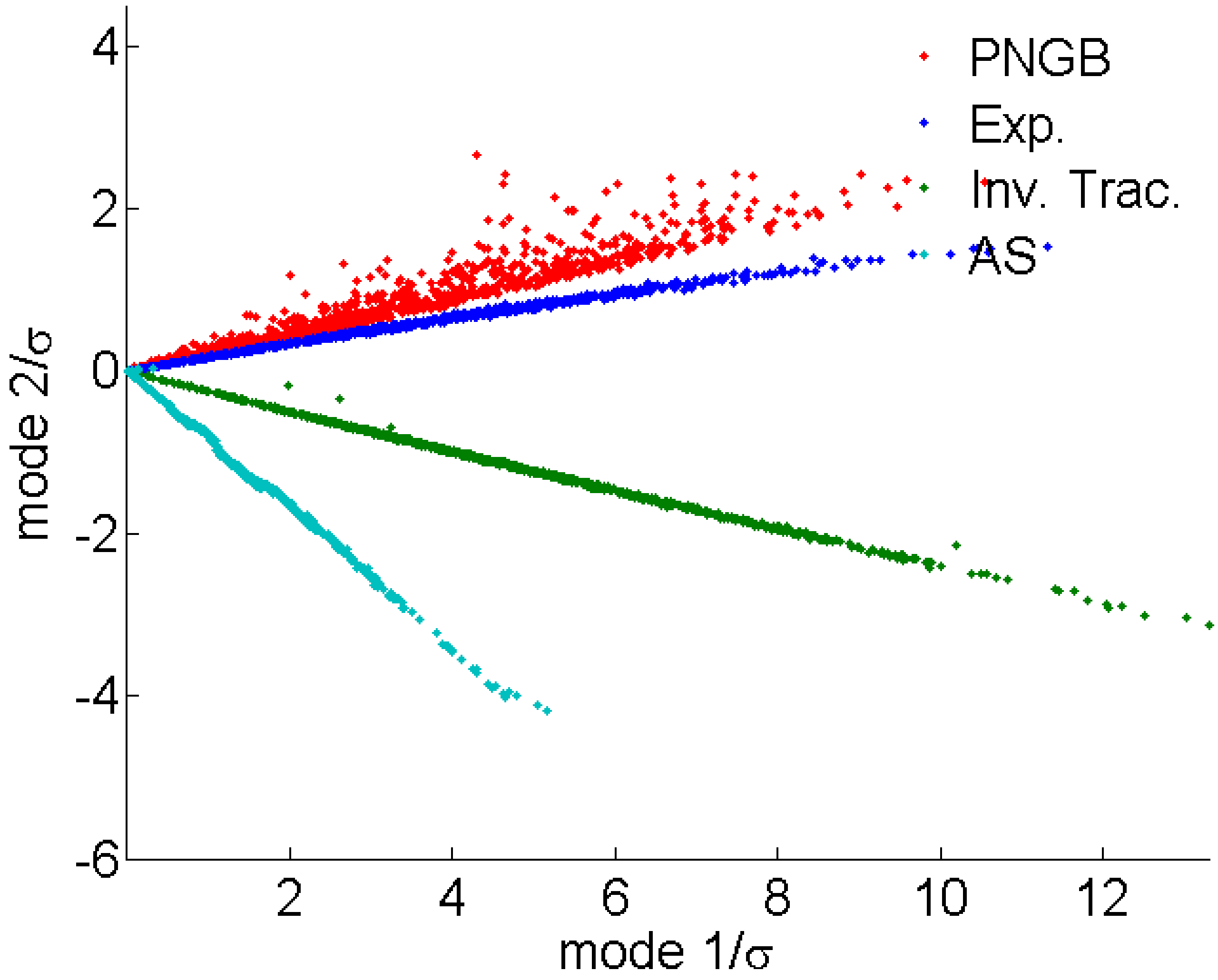
DETF Stage 4 ground [Opt]



c_2 / σ_2

c_1 / σ_1

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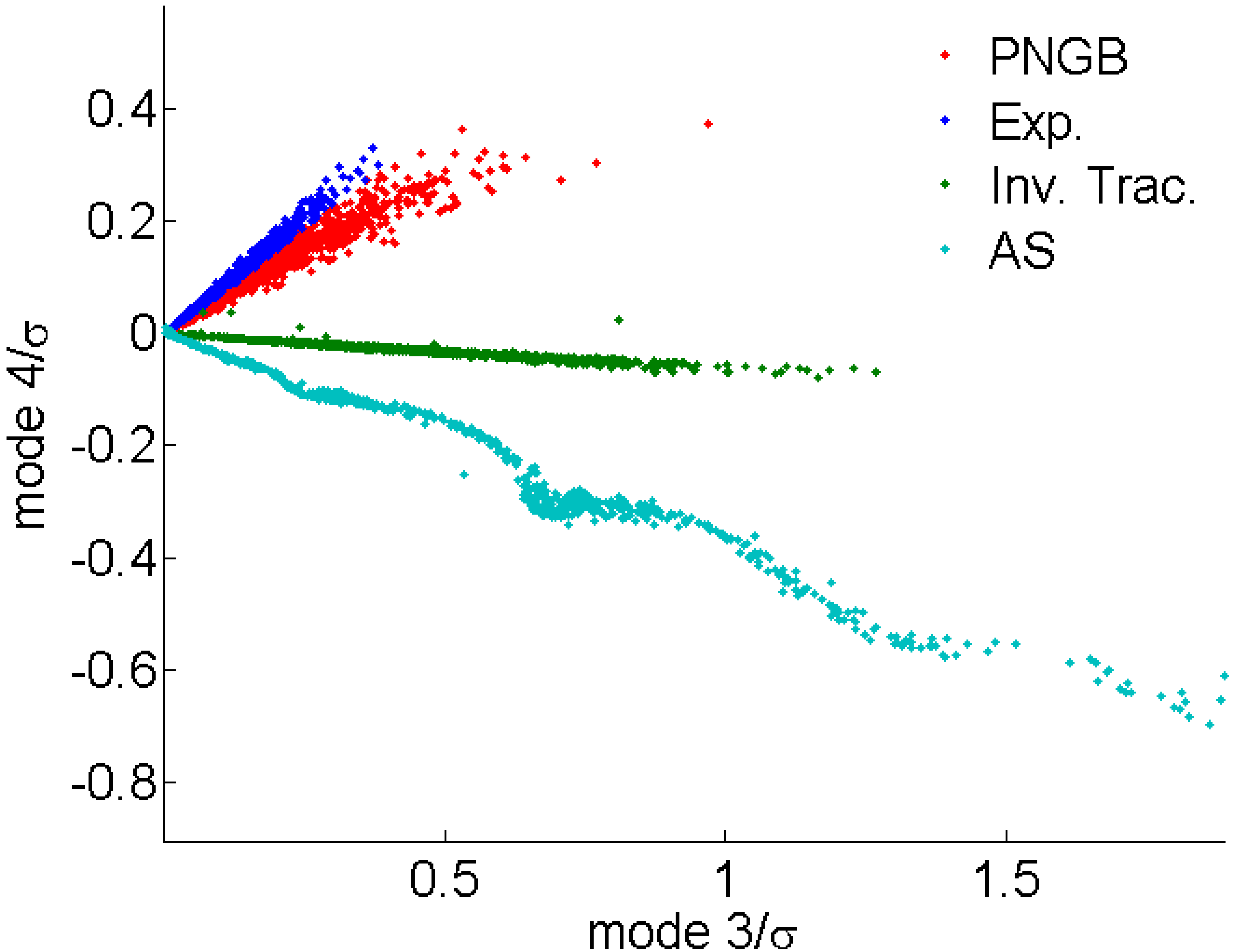
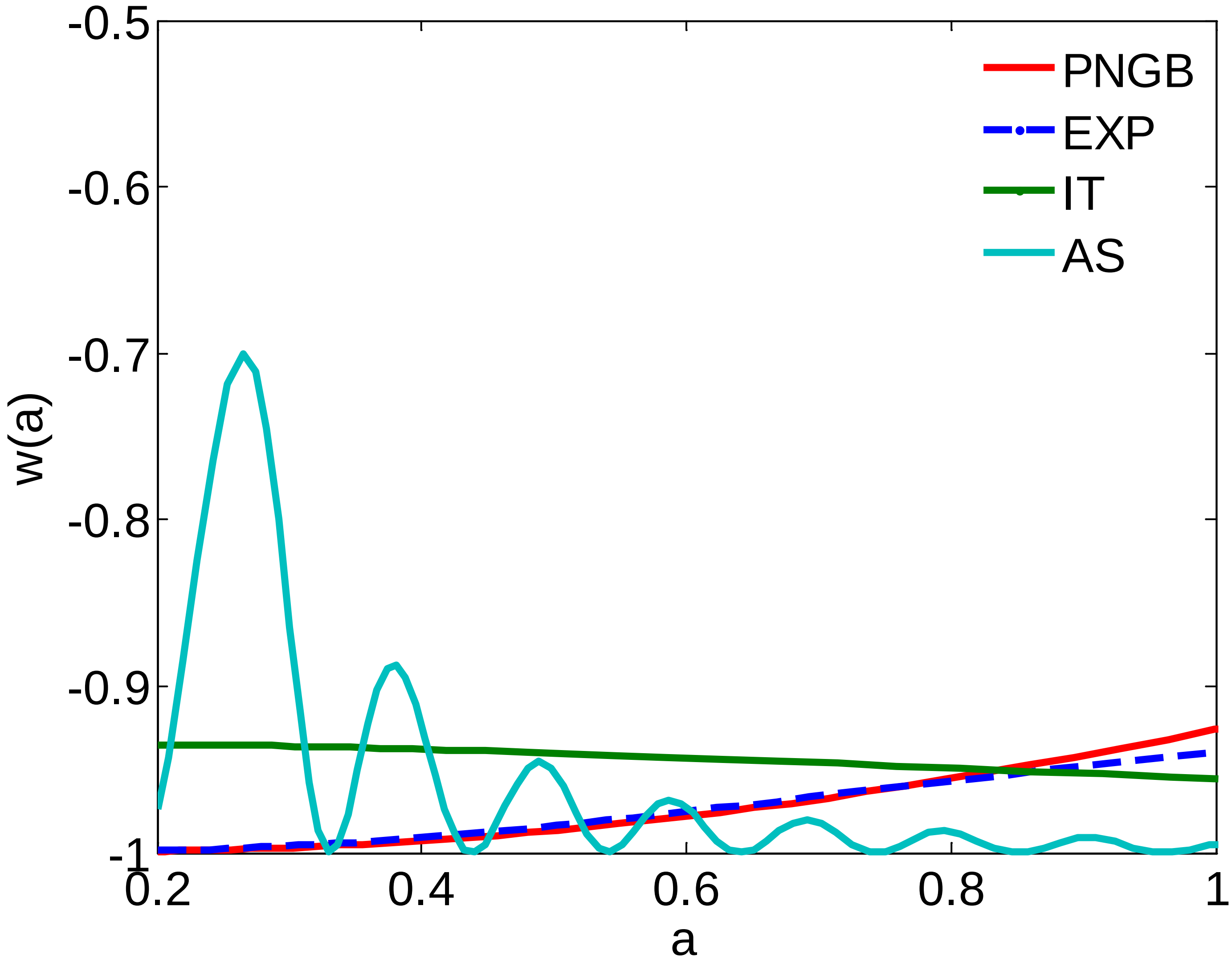
DETF Stage 4 ground [Opt]



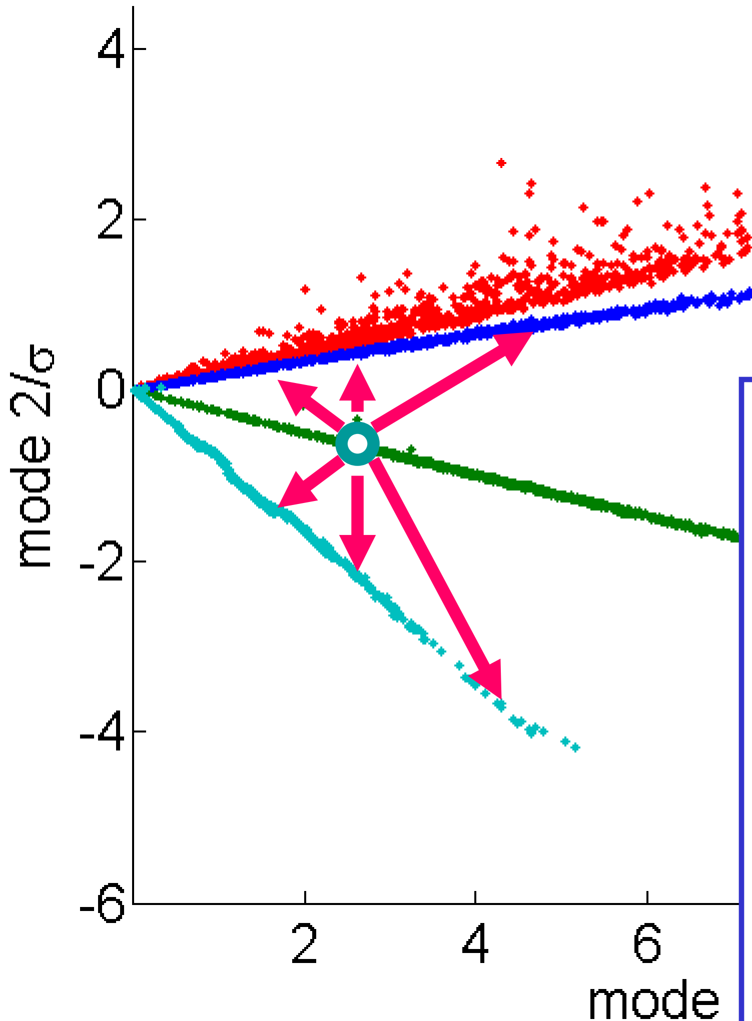
c_4 / σ_4

c_3 / σ_3

The different kinds of curves correspond to different "trajectories" in mode space (similar to FT's)



DETF Stage 4 ground



→ **Data that reveals a universe with dark energy given by " ○ " will have finite minimum "distances" χ^2 to other quintessence models**

→ **powerful discrimination is possible.**

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Interesting contribution to discussion of Stage 4 (if you believe scalar field modes)

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→ How is the DoE/ESA/NASA Science Working Group looking at these questions?

i) Using w(a) eigenmodes

ii) Revealing value of higher modes

DoE/ESA/NASA JDEM Science Working Group

➔ Update agencies on figures of merit issues

➔ formed Summer 08

➔ finished Dec 08 (report on arxiv Jan 09, moved on to SCG)

➔ Use w-eigenmodes to get more complete picture

➔ also quantify deviations from Einstein gravity

➔ For tomorrow: Something new we learned about (normalizing) modes

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This talk

Part 1:

A few attempts to explain dark energy

- Motivations, problems and other comments

→ Theme: We may not know where this revolution is taking us, but it is already underway:

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Planning new experiments

- DETF
- Next questions

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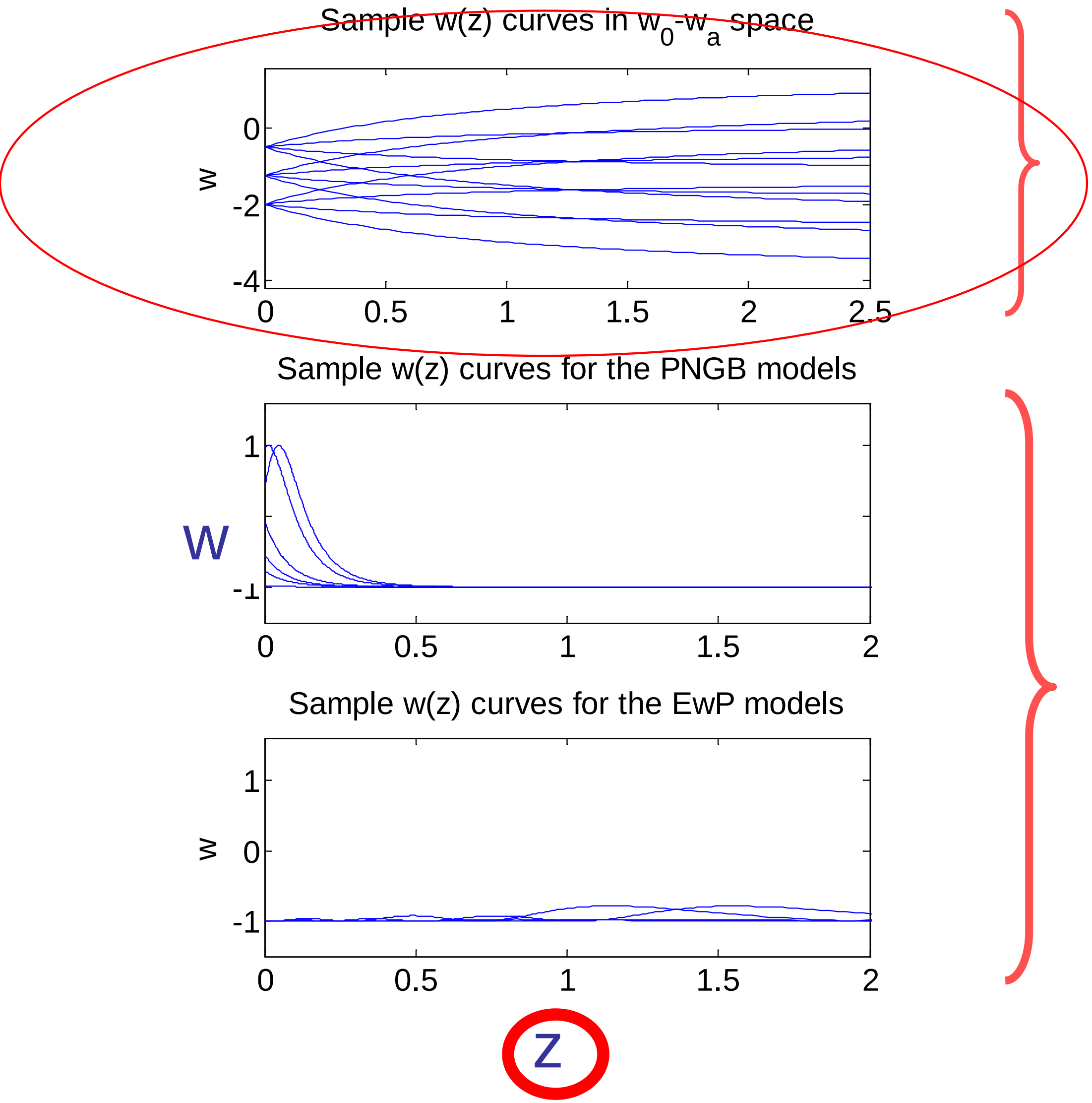
END

Additional Slides

How good is the w(a) ansatz?



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

w0-wa can only do these

DE models can do this (and much more)

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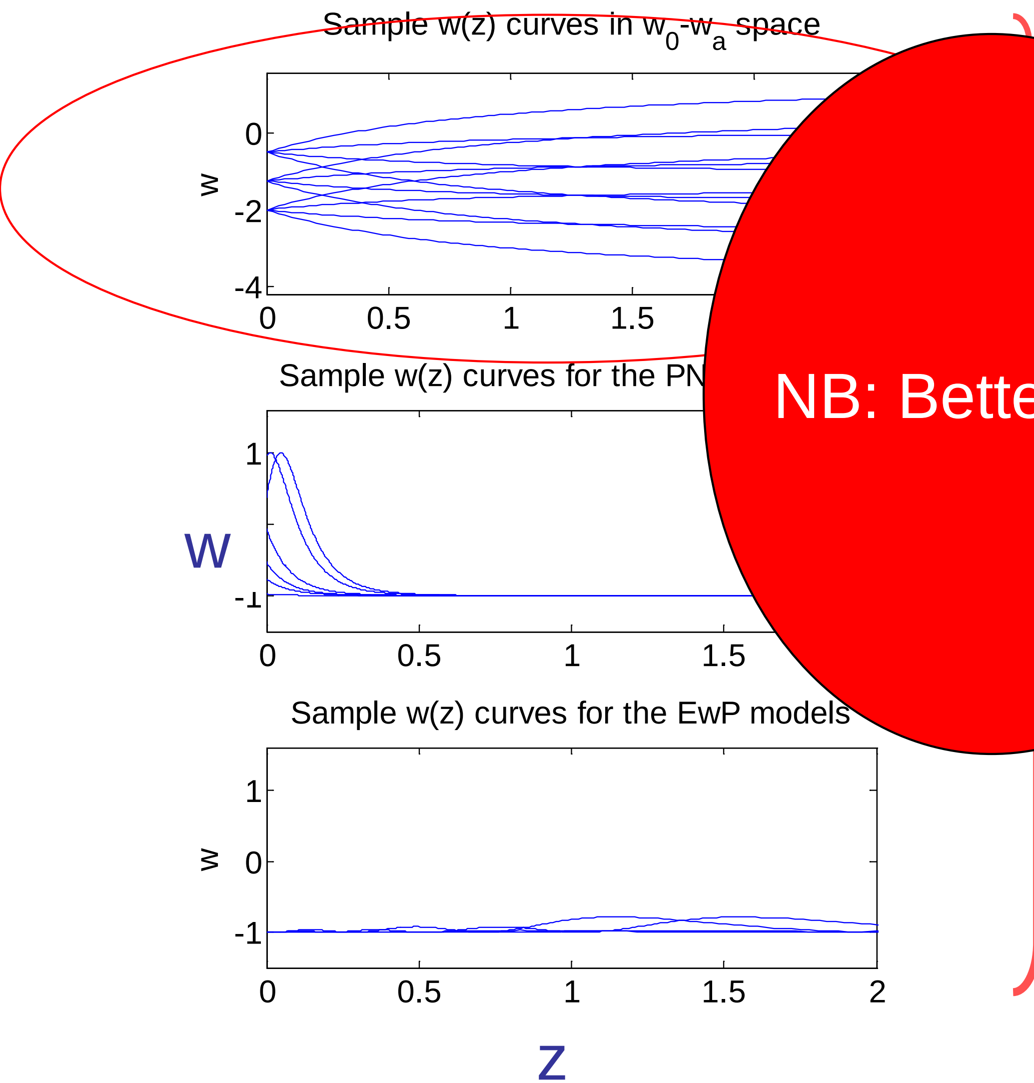

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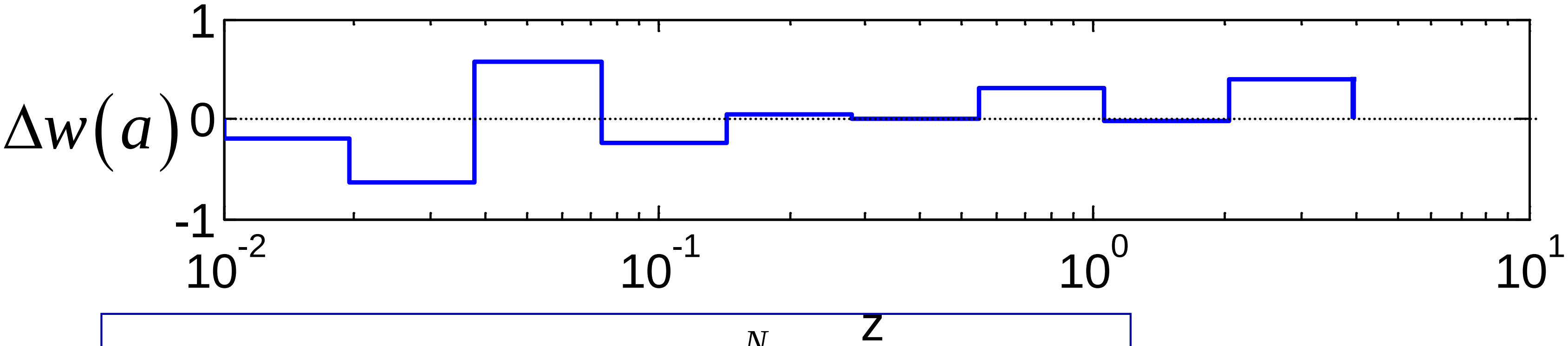
NB: Better than

$$w(a) = w_0$$

& flat

DE models can do this (and much more)

Try *N*-D stepwise constant w(a)



$$w(a) = -1 + \Delta w(a) = -1 + \sum_{i=1}^{N} \Delta w_i T(a_i, a_{i+1})$$

N parameters are coefficients of the "top hat functions" $T(a_i, a_{i+1})$

AA & G Bernstein 2006 (astro-ph/0608269). More detailed info can be found at http://www.physics.ucdavis.edu/Cosmology/albrecht/MoreInfo0608269/

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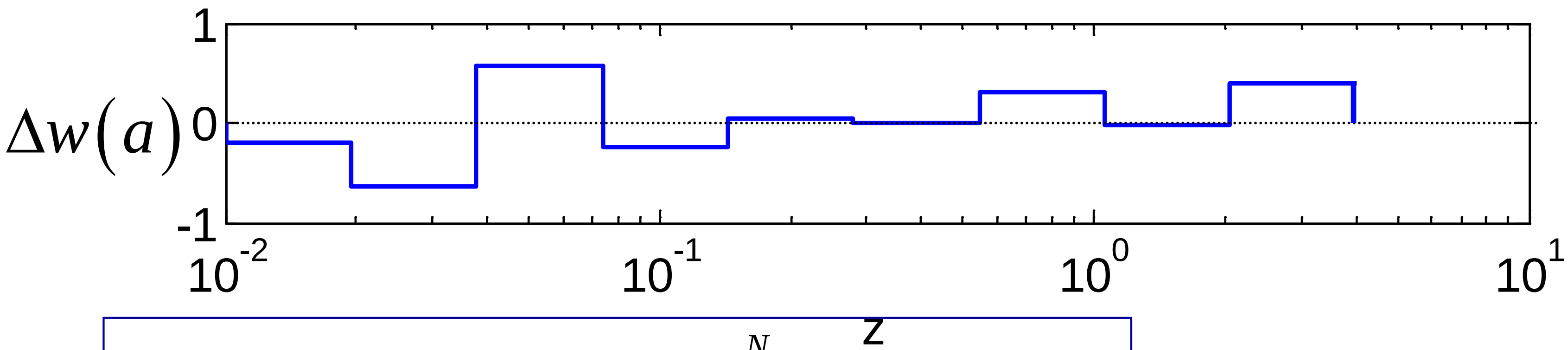

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Used by

Huterer & Turner;
Huterer & Starkman;
Knox et al;
Crittenden & Pogosian
Linder; Reiss et al;
Krauss et al
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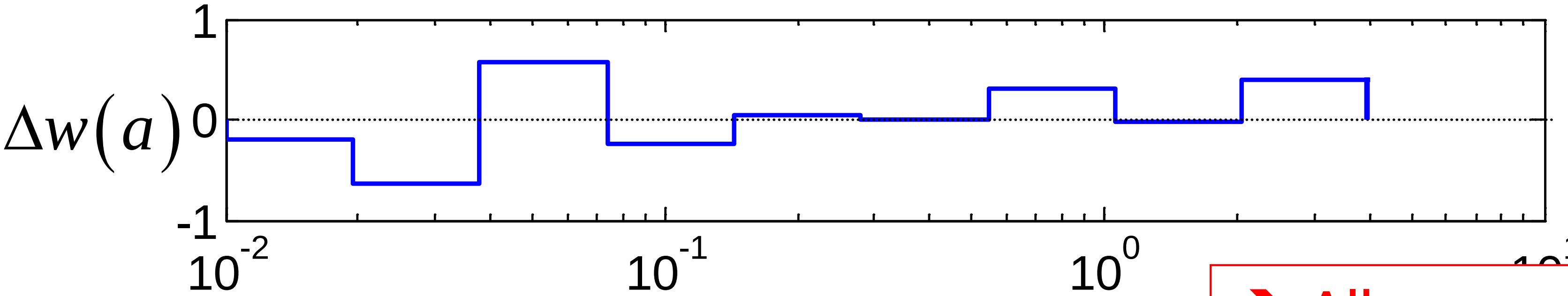

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➔ Allows each experiment to "put its best foot forward"

➔ Any signal rejects Λ

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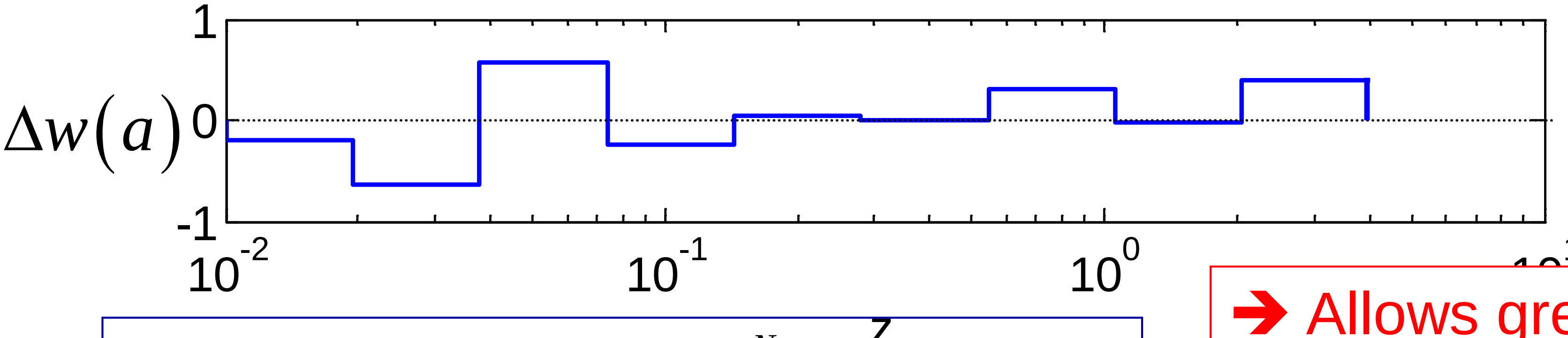

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"Convergence"

AA & G Bernstein 2006

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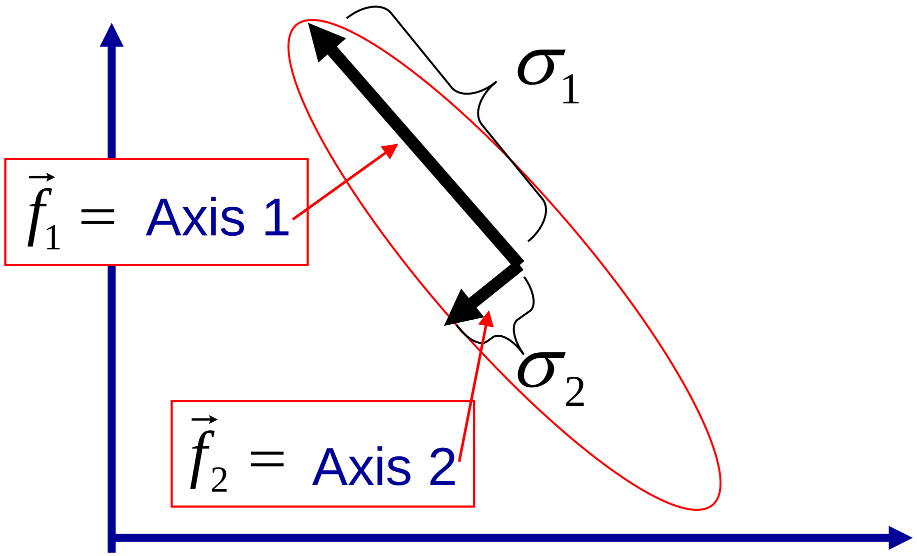
2D illustration:



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Principle component analysis

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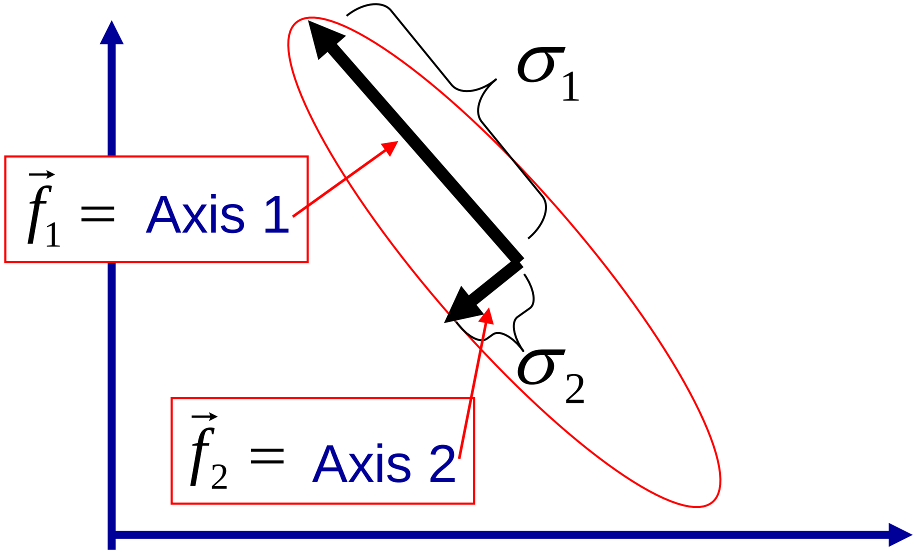

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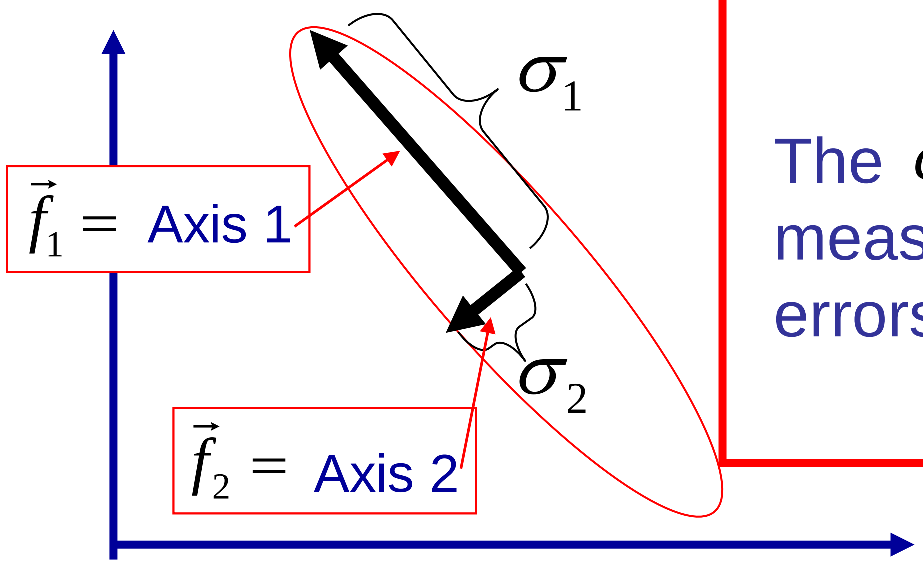

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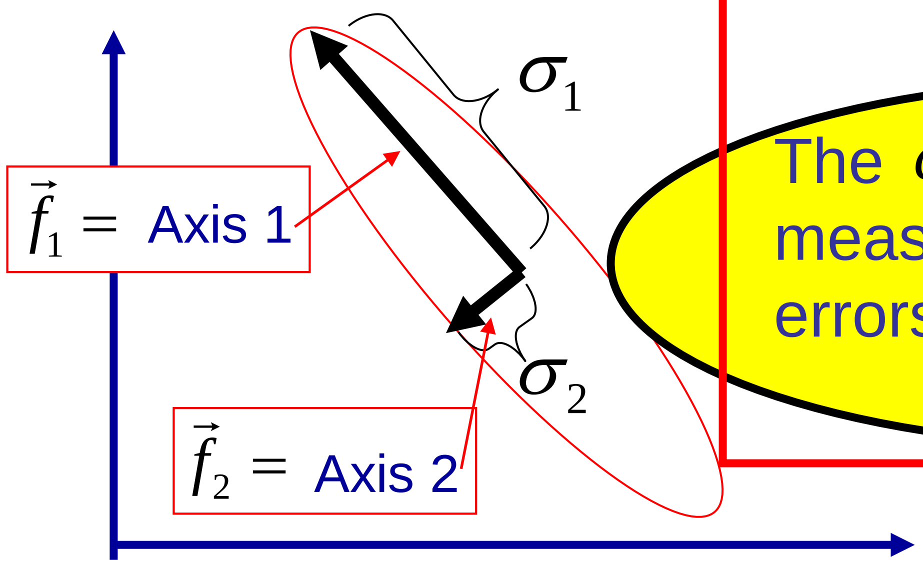

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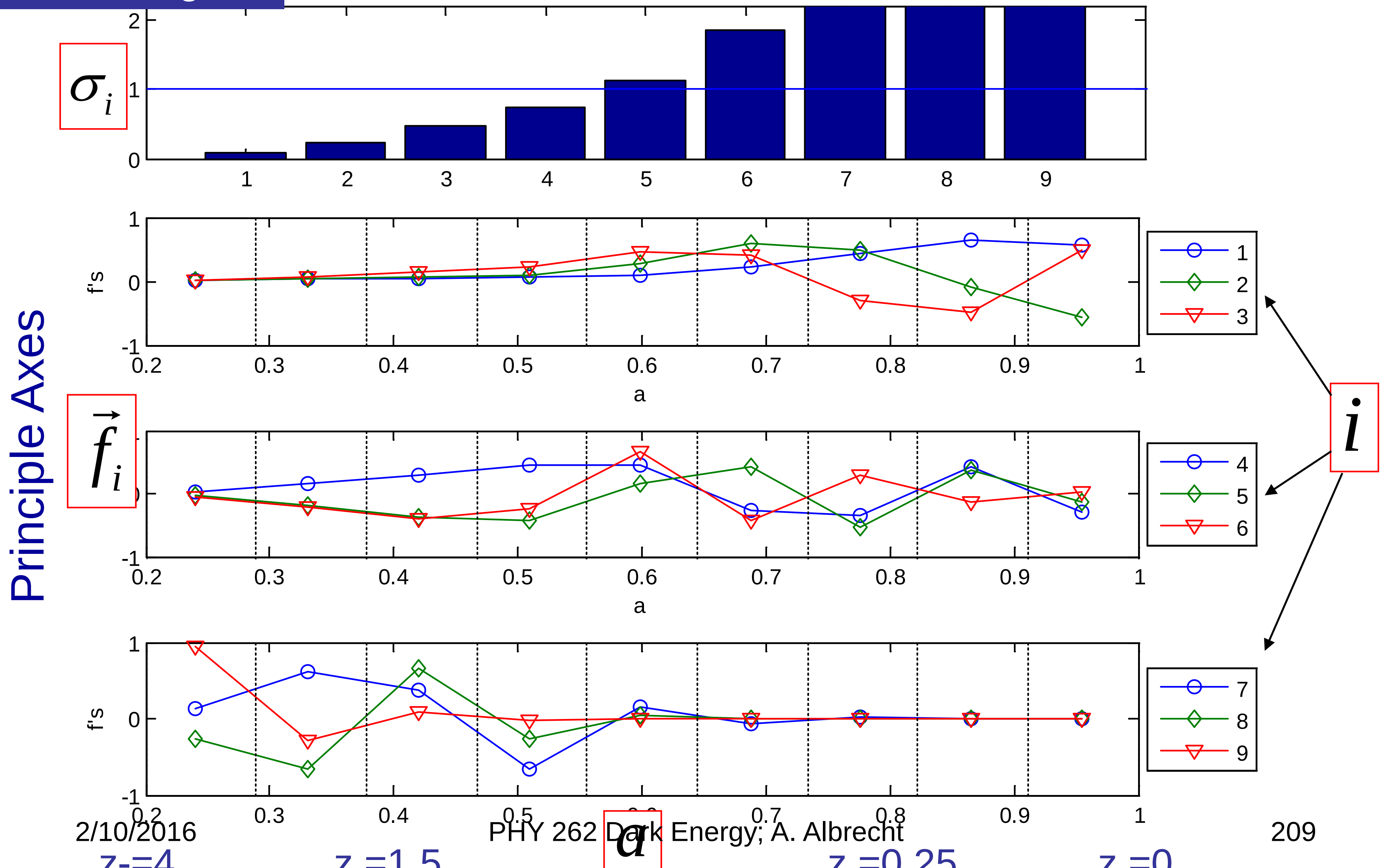

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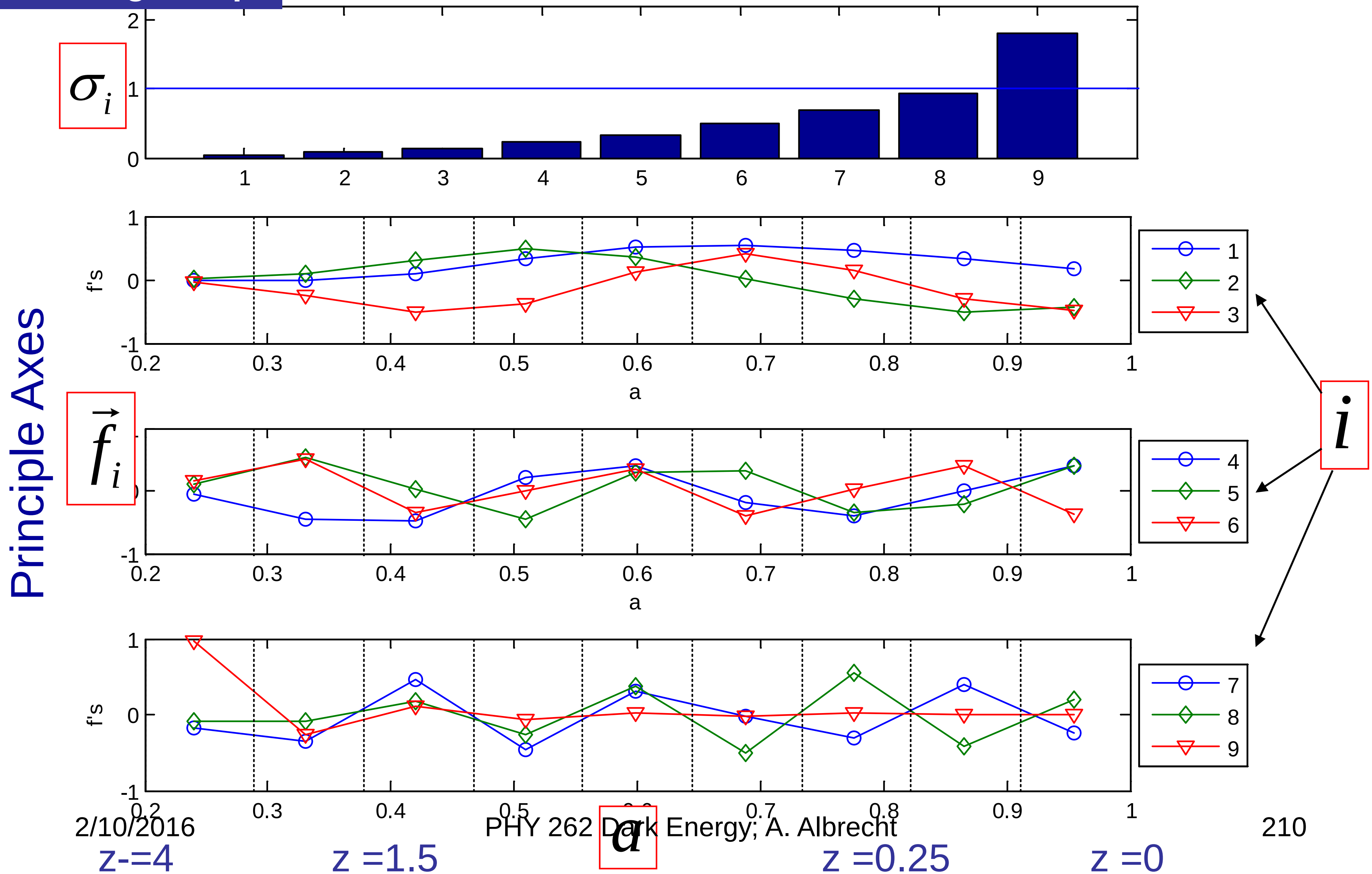

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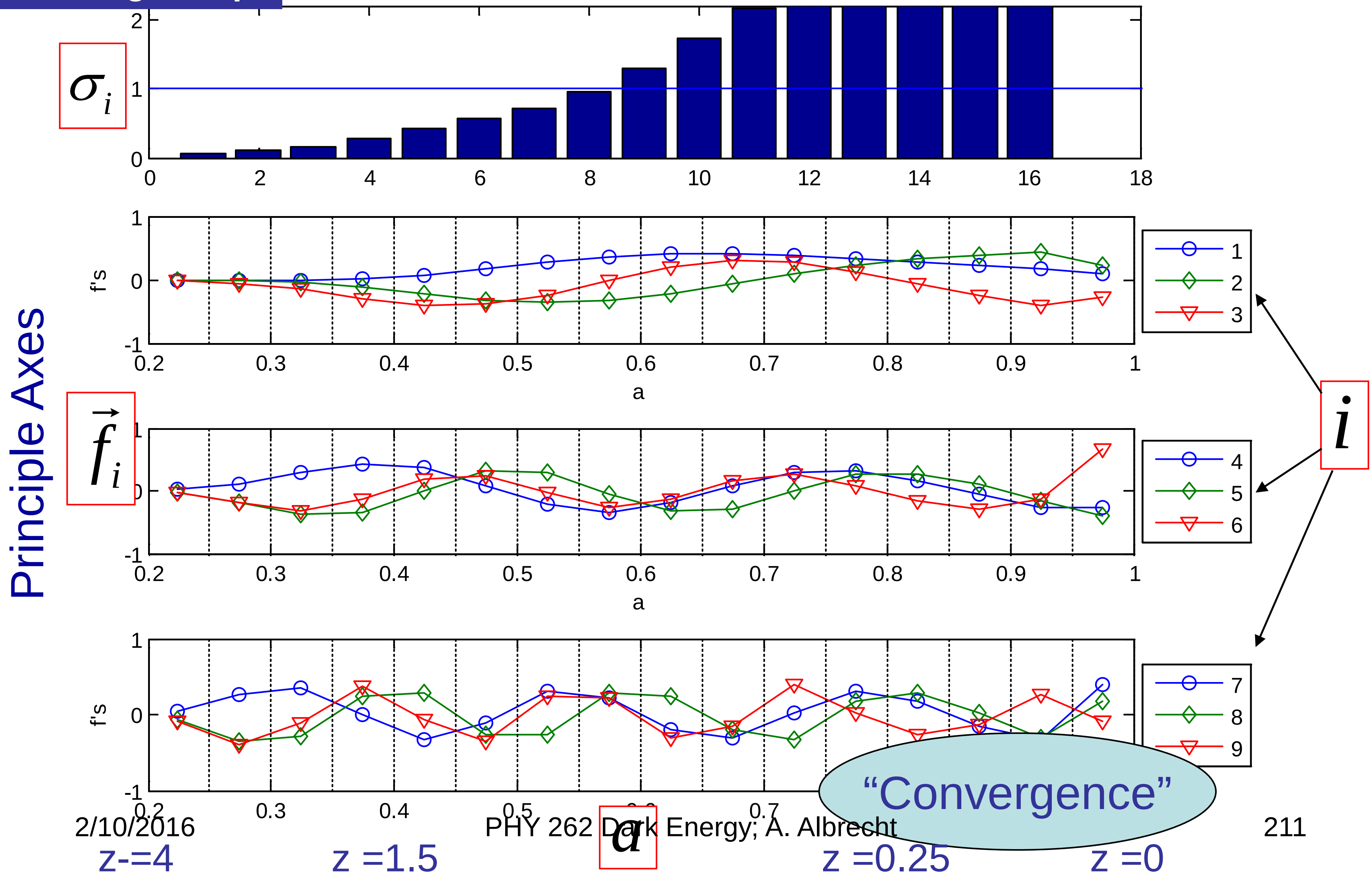

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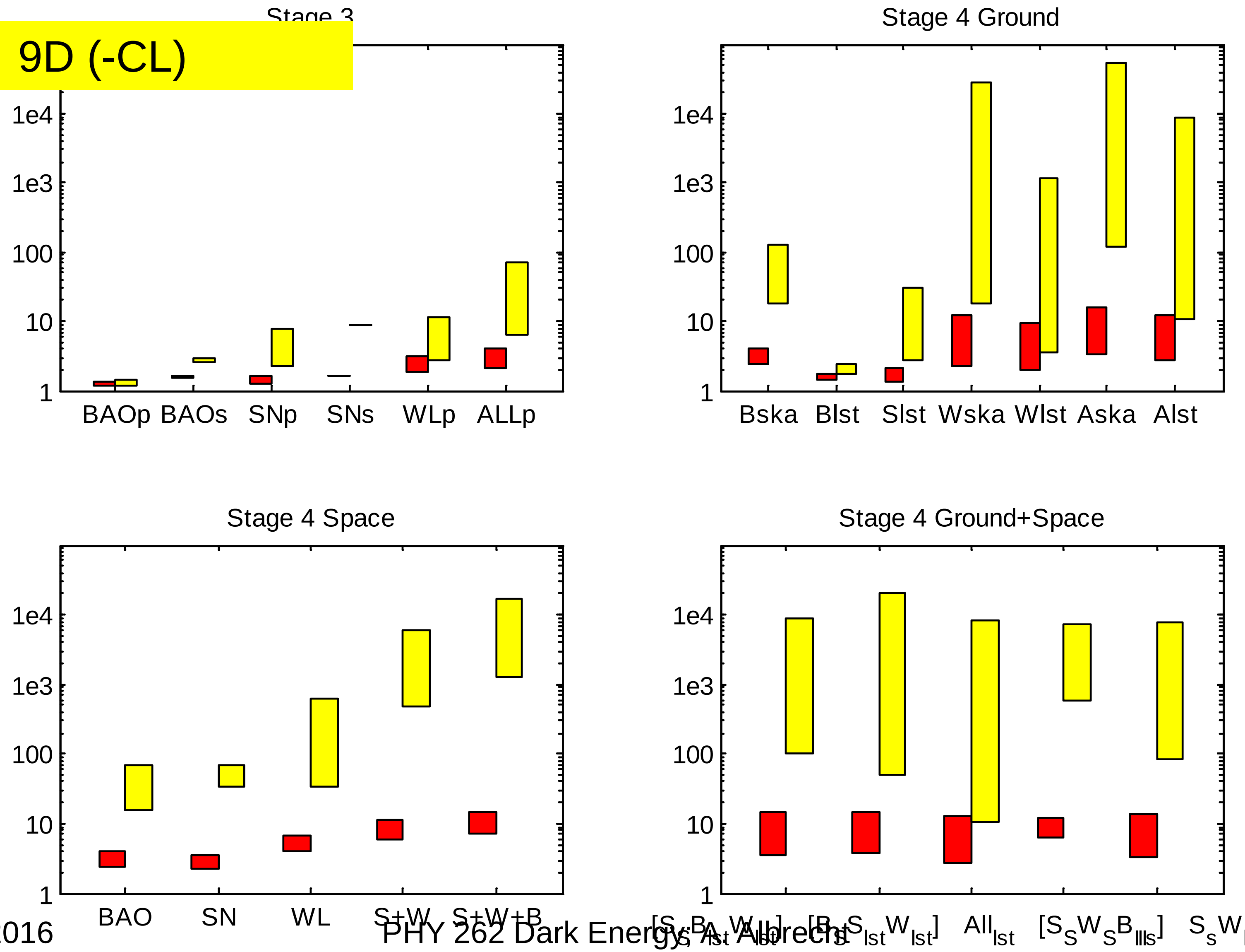

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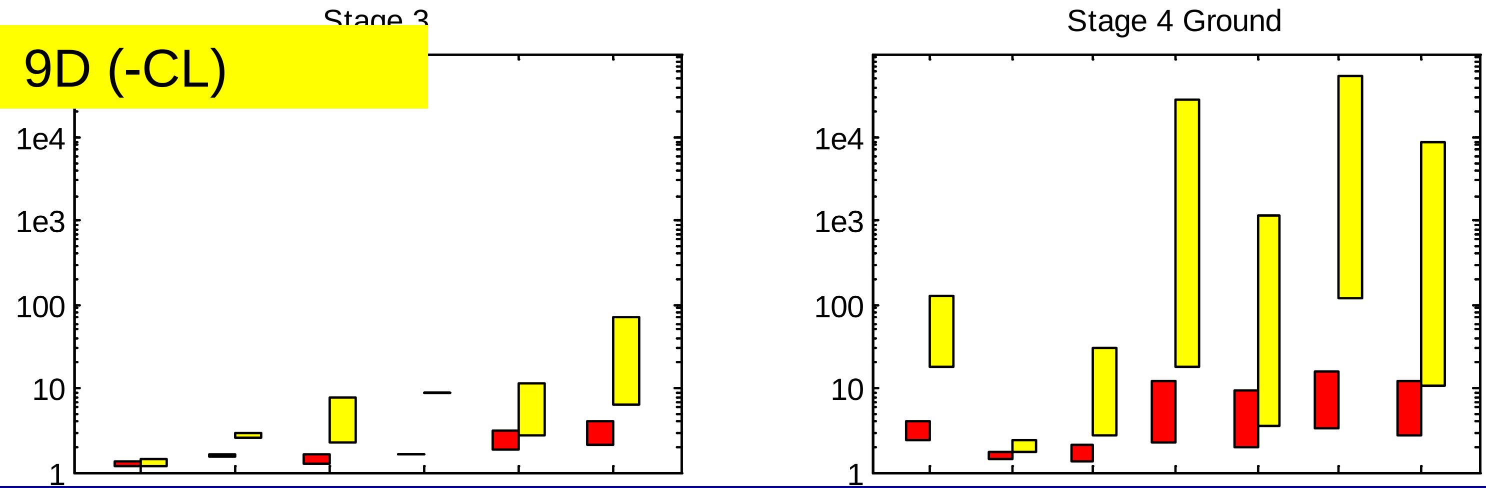

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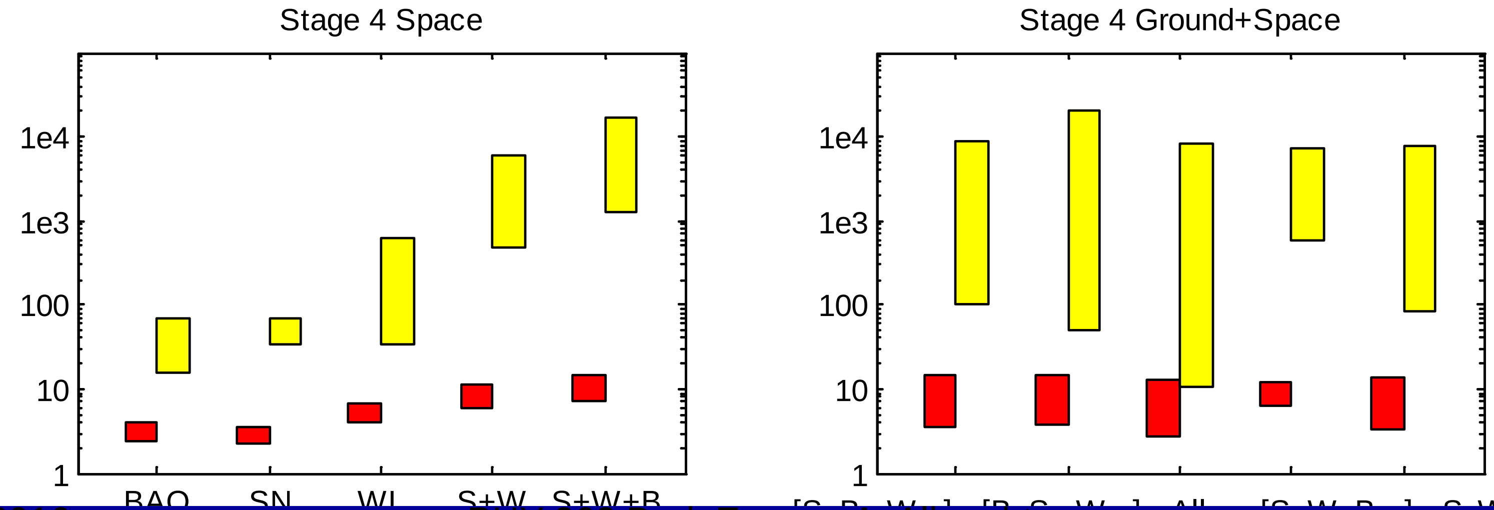

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➔ A nice way to gain insights into data (real or imagined)

Followup questions:

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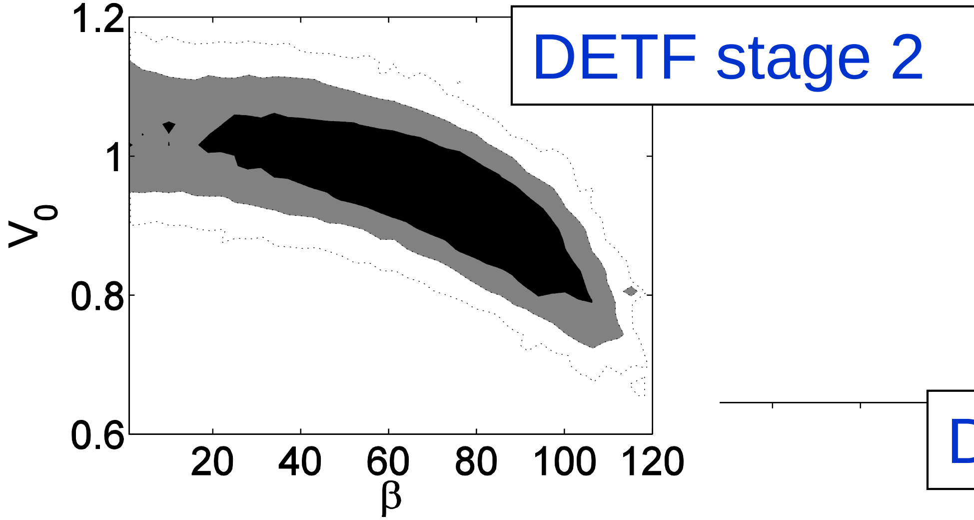

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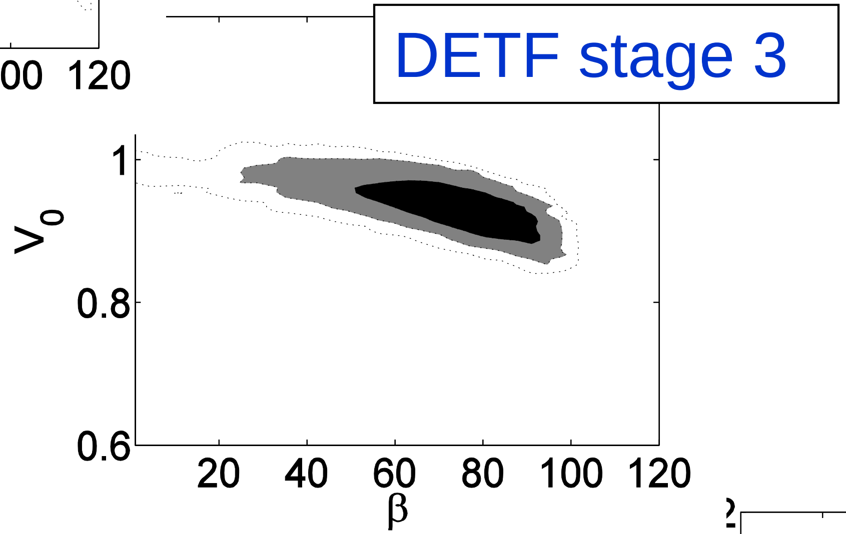
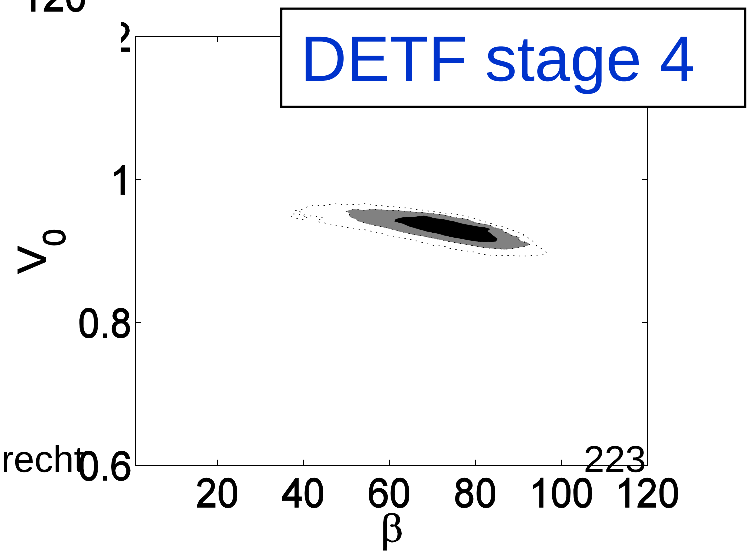
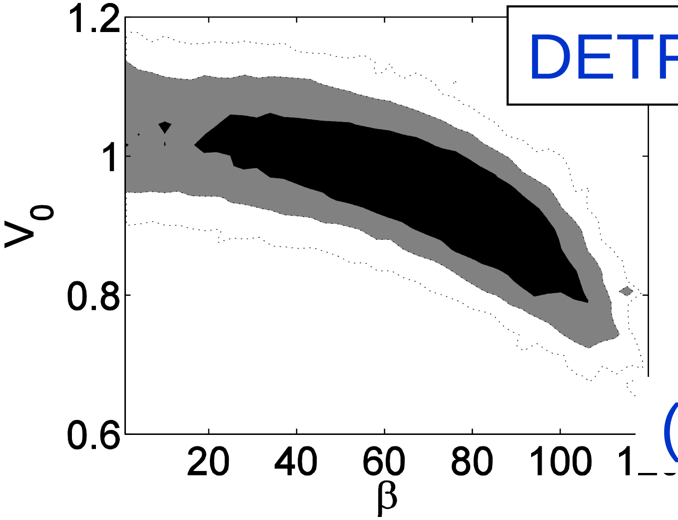




DETF stage 2



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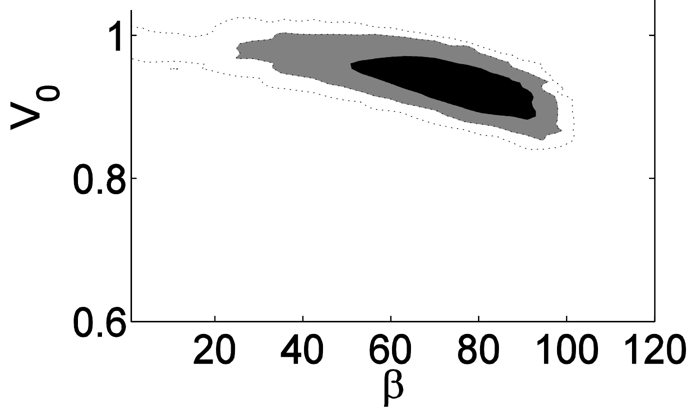
(S2/3)

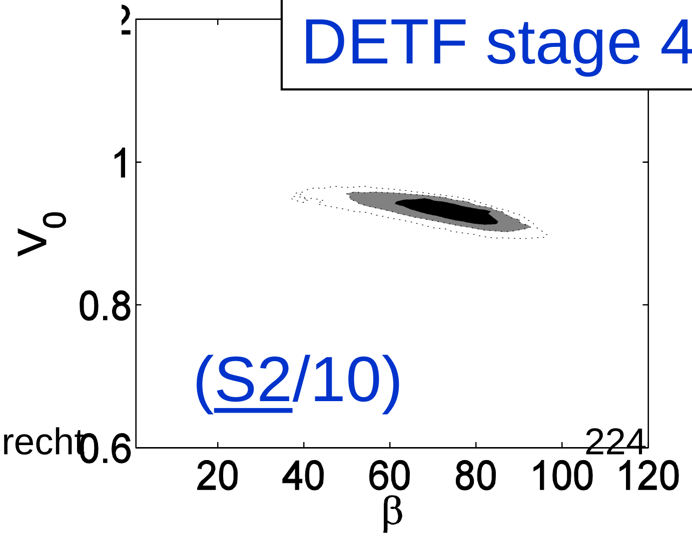
DETF stage 3



Upshot:

Story in scalar field parameter space very similar to DETF story in w0-wa space.

DETF stage 4



(S2/10)

Followup questions:

→ In what ways might the choice of DE parameters have skewed the DETF results?

→ What impact can these data sets have on specific DE models (vs abstract parameters)?

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A: Very similar to DETF results in w0-wa space

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Michael Barnard *et al* ***arXiv:0804.0413***

Problem:

Each scalar field model is defined in its own parameter space. How should one quantify discriminating power among models?

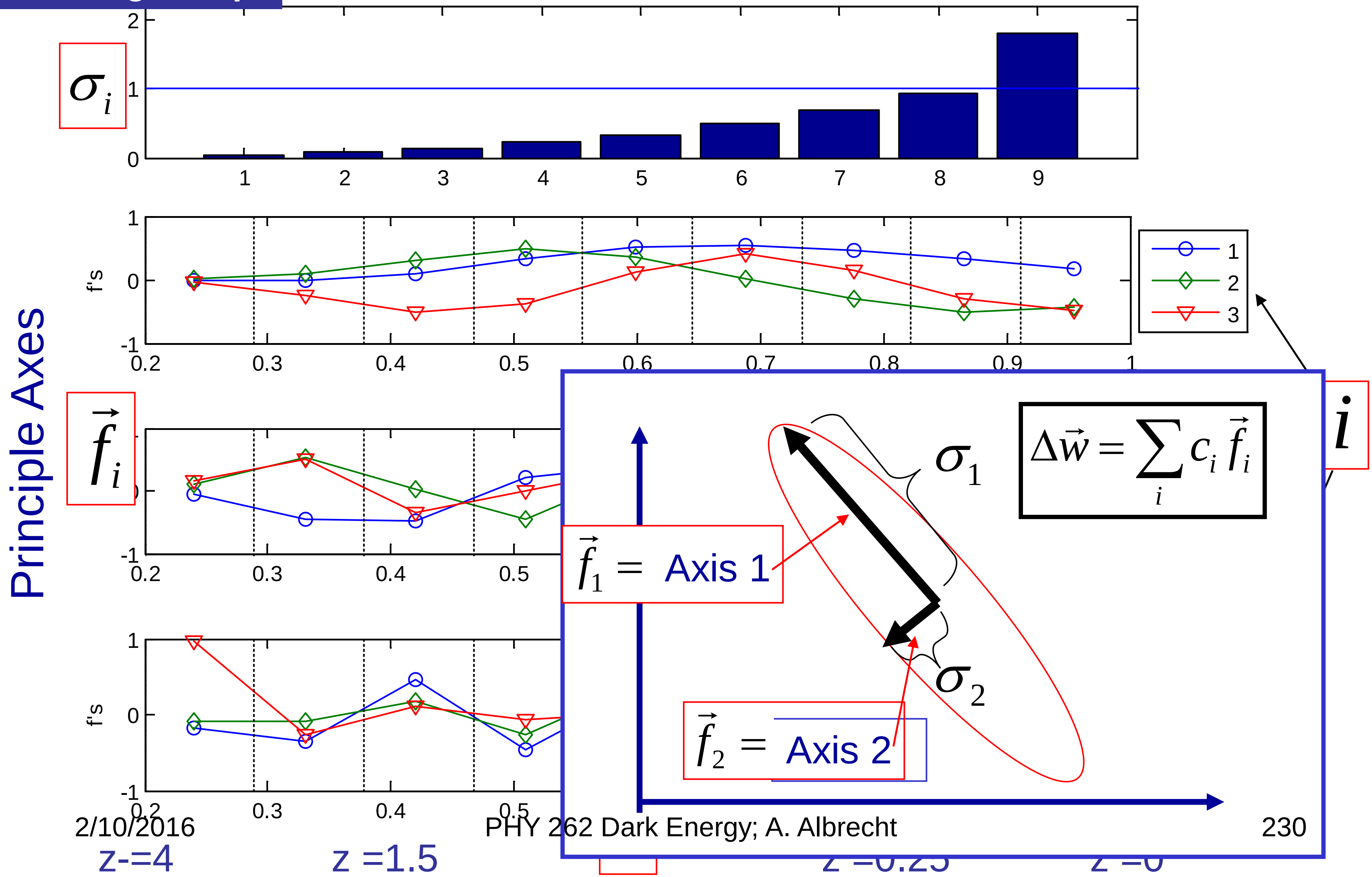
Our answer:

➔Form each set of scalar field model parameter values, map the solution into *w(a)* eigenmode space, the space of uncorrelated observables.

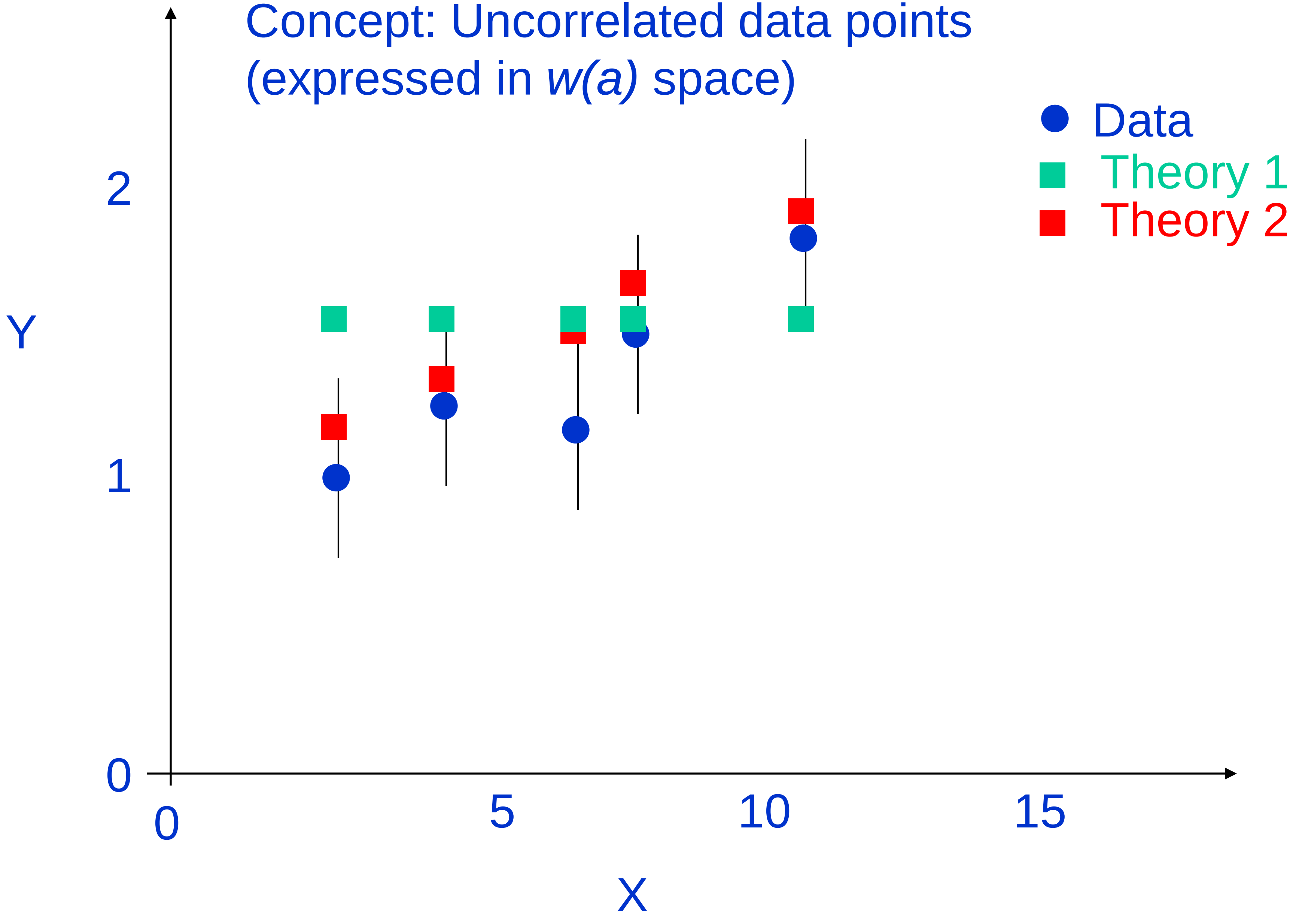
➔ Make the comparison in the space of uncorrelated observables.

Characterizing 9D ellipses by principle axes and corresponding errors

WL Stage 4 Opt



Concept: Uncorrelated data points (expressed in *w(a)* space)

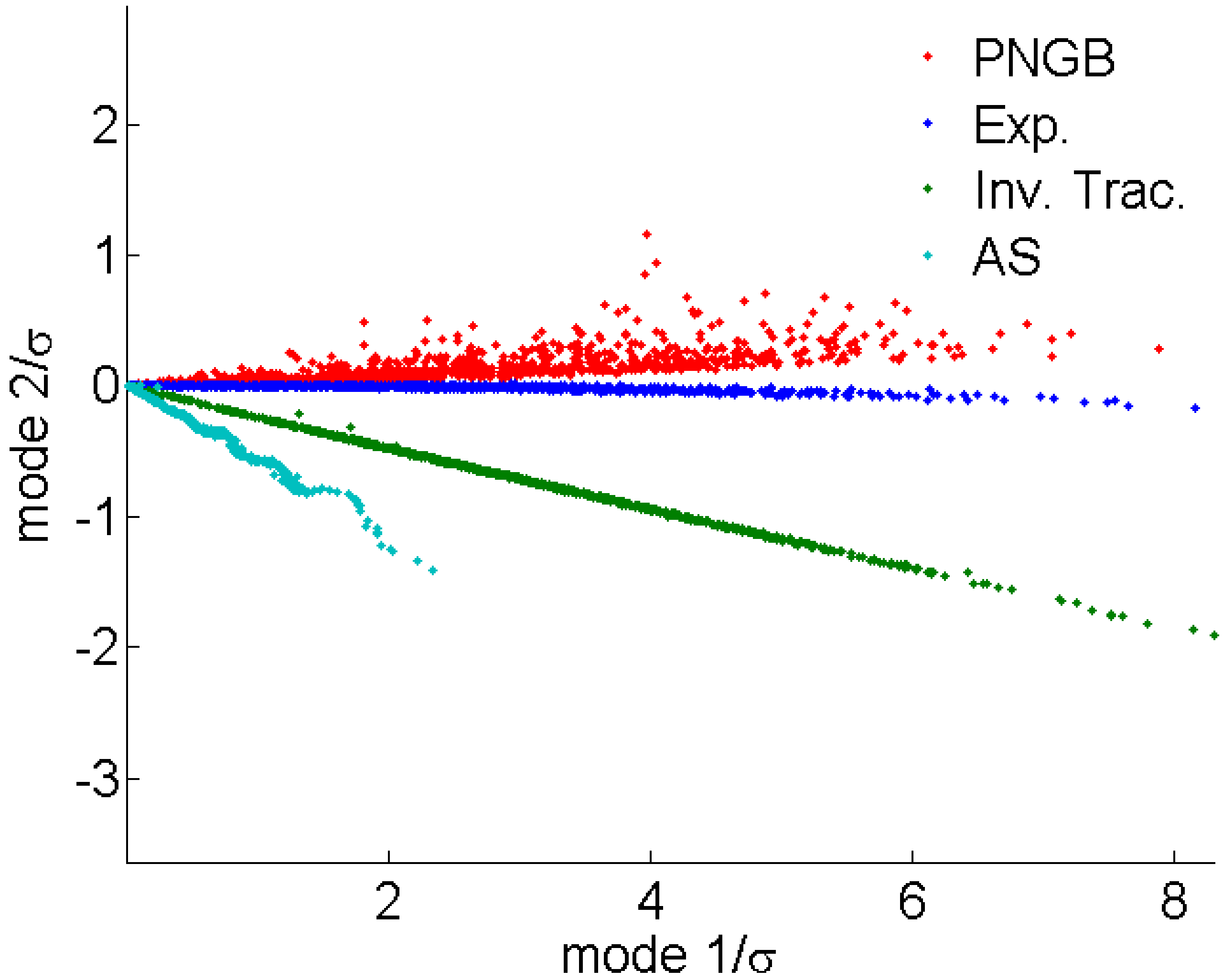


Starting point: MCMC chains giving distributions for each model at Stage 2.

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 3 photo [Opt]

c_2 / σ_2



c_1 / σ_1

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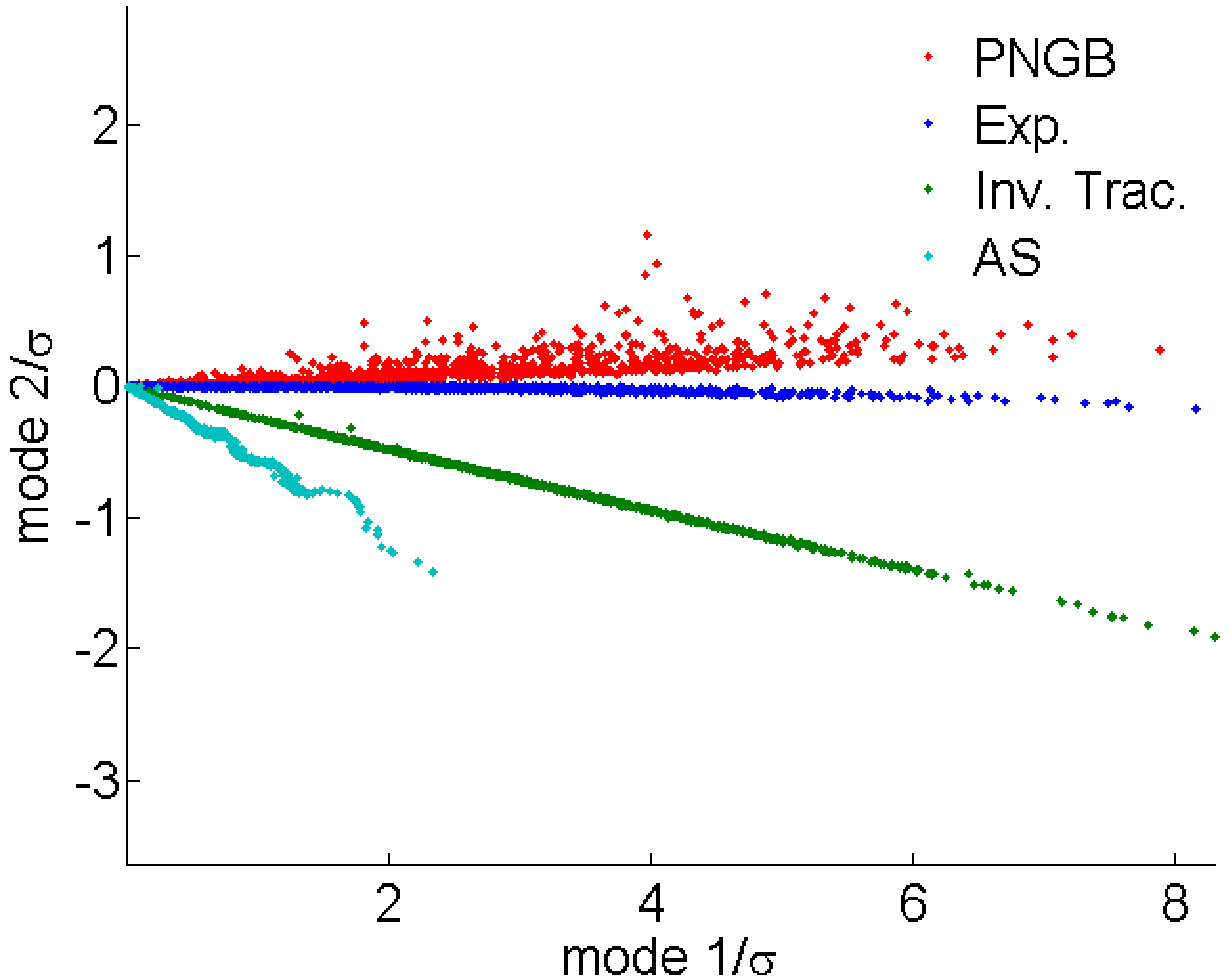
DETF Stage 3 photo [Opt]

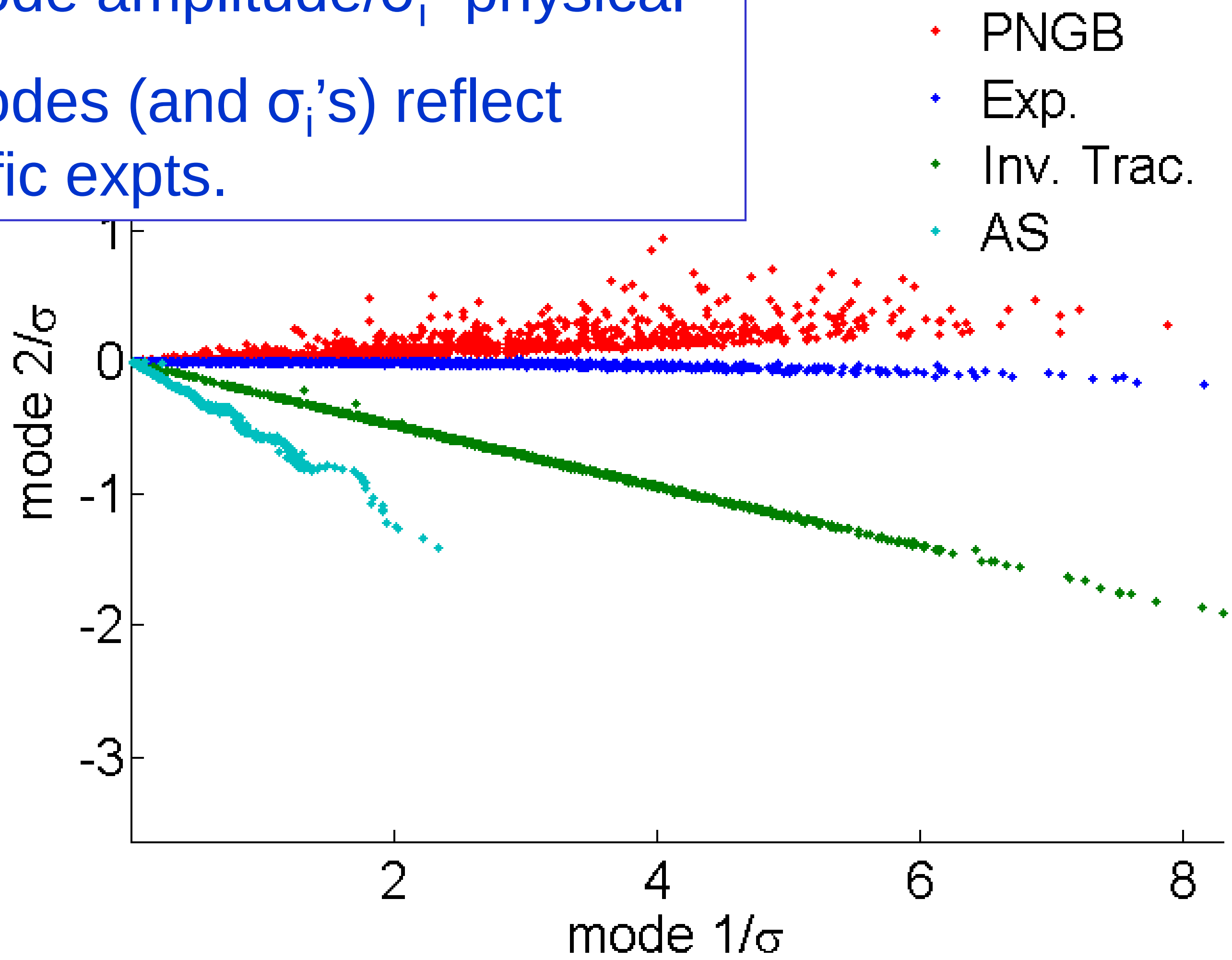
c_2 / σ_2



c_1 / σ_1

DETF Stage 3 photo [Opt]

- ➔ Distinct model locations
- ➔ mode amplitude/σ_i "physical"
- ➔ Modes (and σ_i's) reflect specific expts.



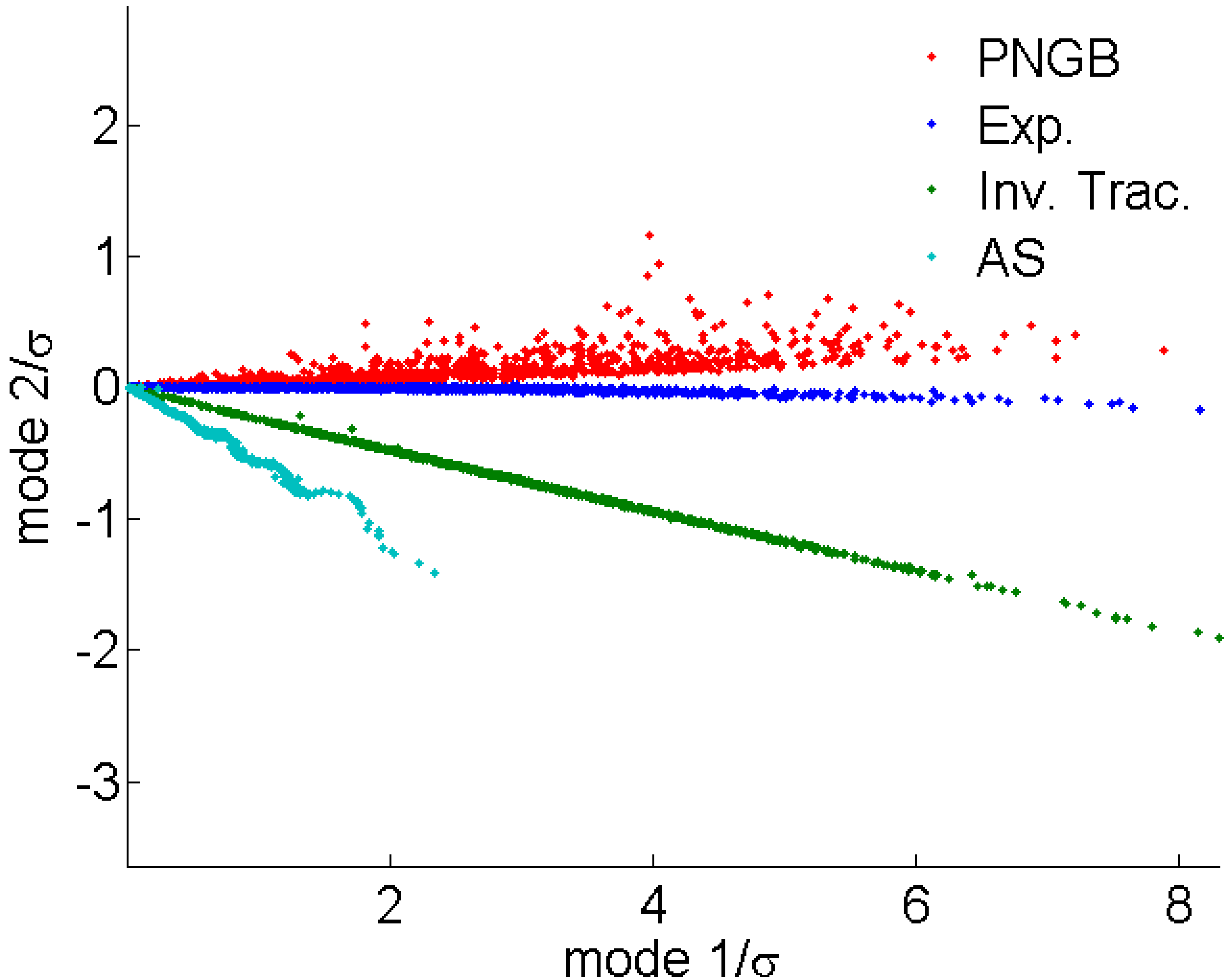
c_2 / σ_2

c_1 / σ_1

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 3 photo [Opt]

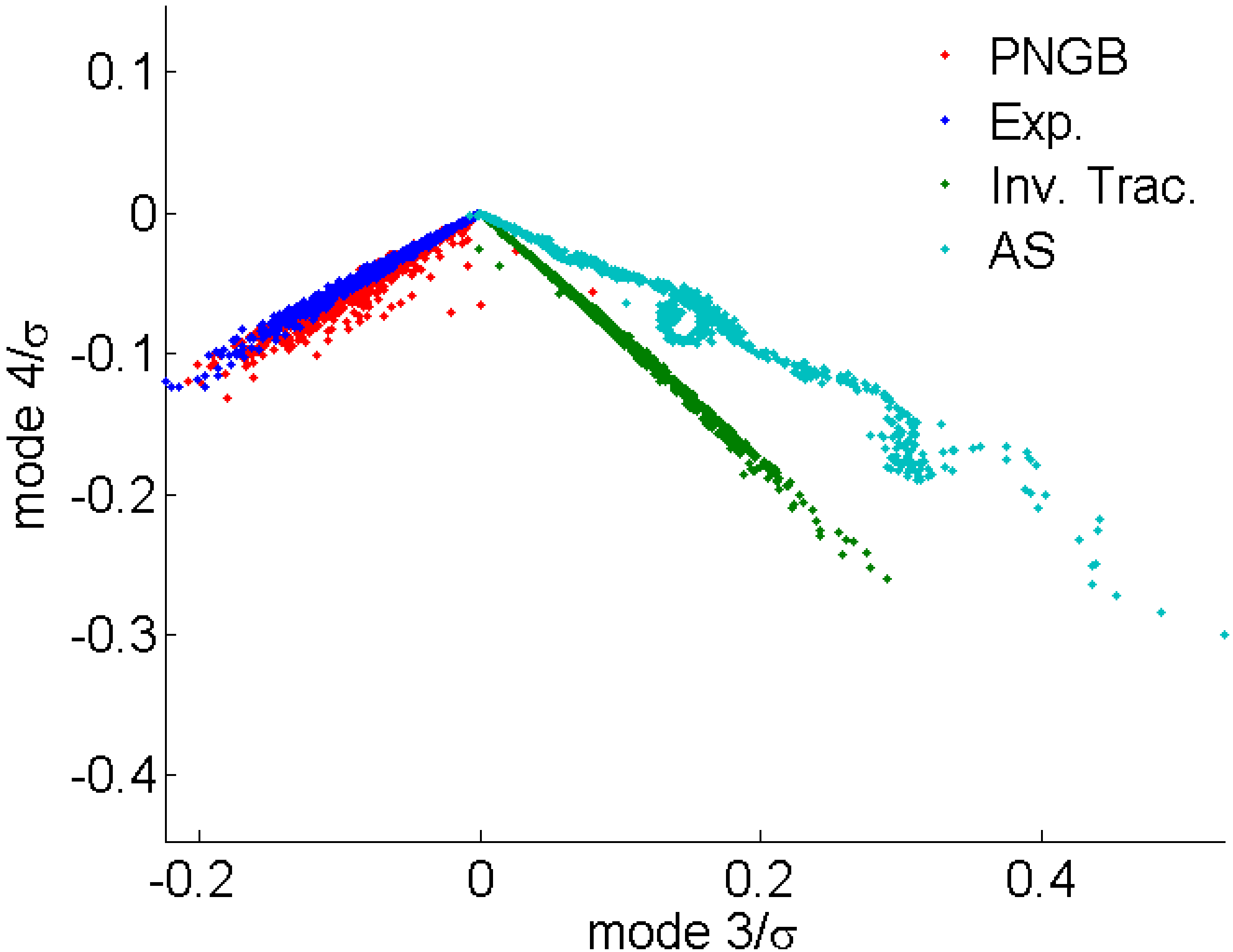
c_2/σ_2



c_1/σ_1

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

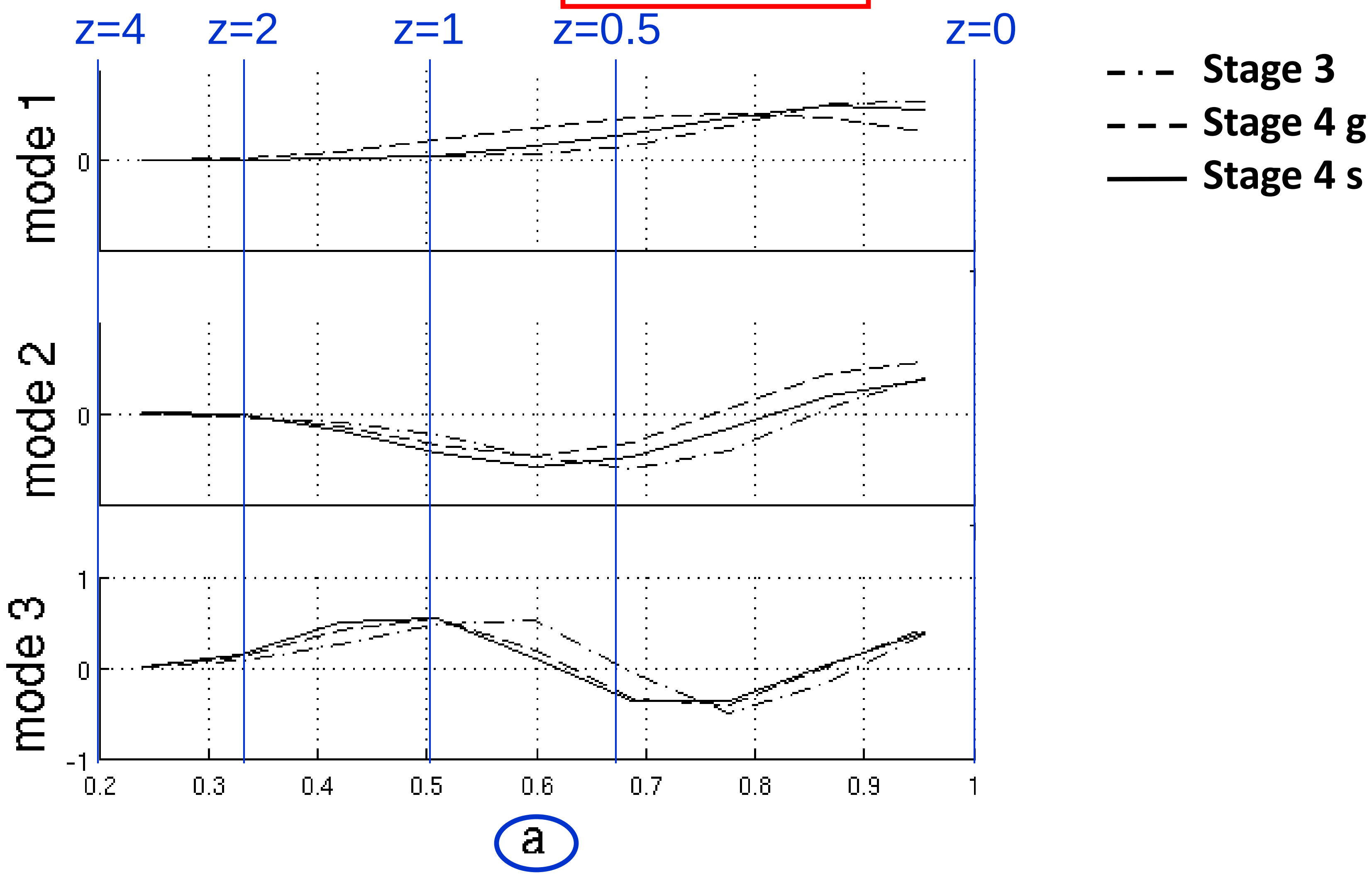
DETF Stage 3 photo [Opt]



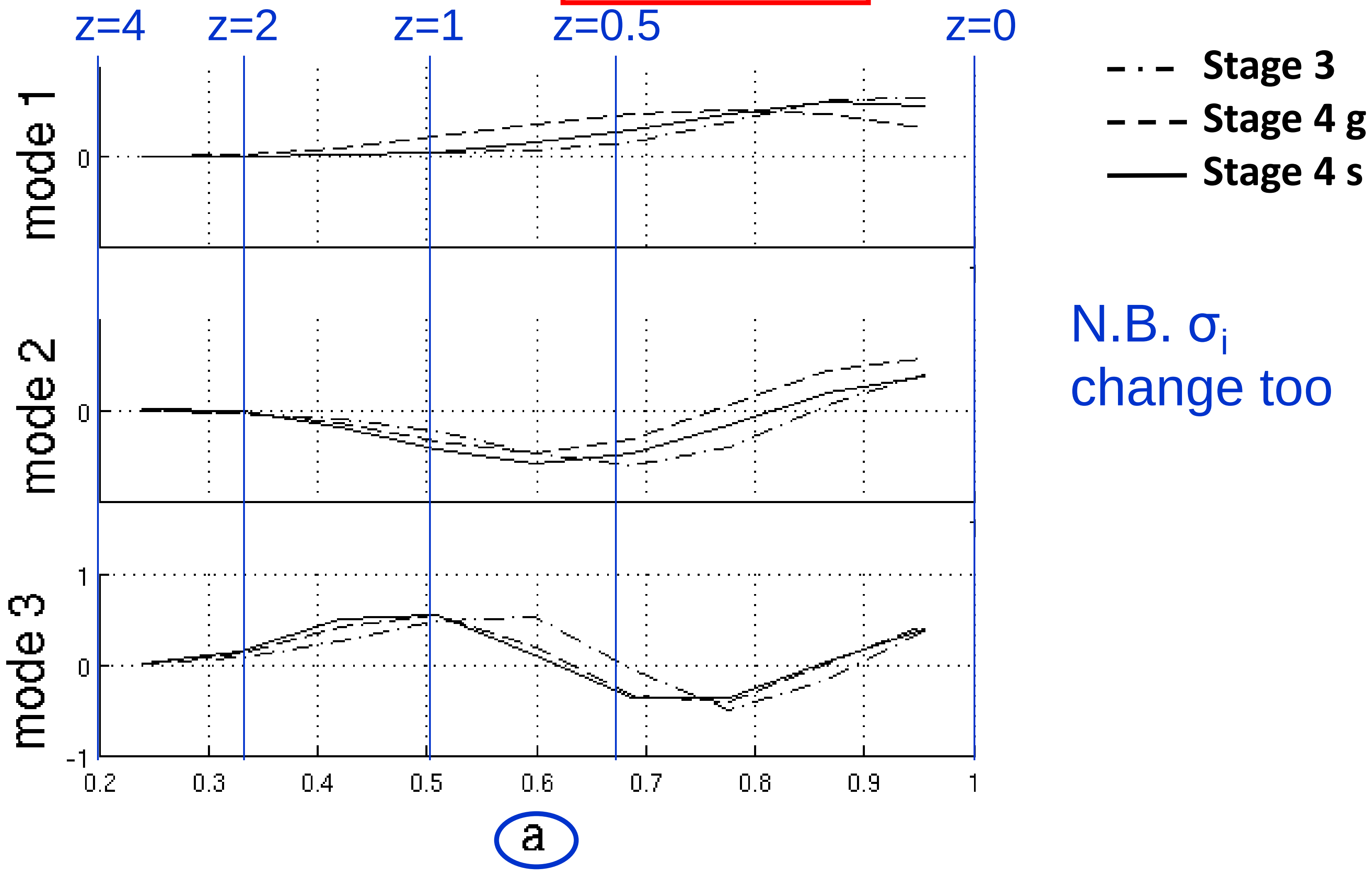
c_4 / σ_4

c_3 / σ_3

Eigenmodes:


z=4
z=2
z=1
z=0.5
z=0
mode 1
mode 2
mode 3
0
0
1
0
-1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
a
Stage 3
Stage 4 g
Stage 4 s

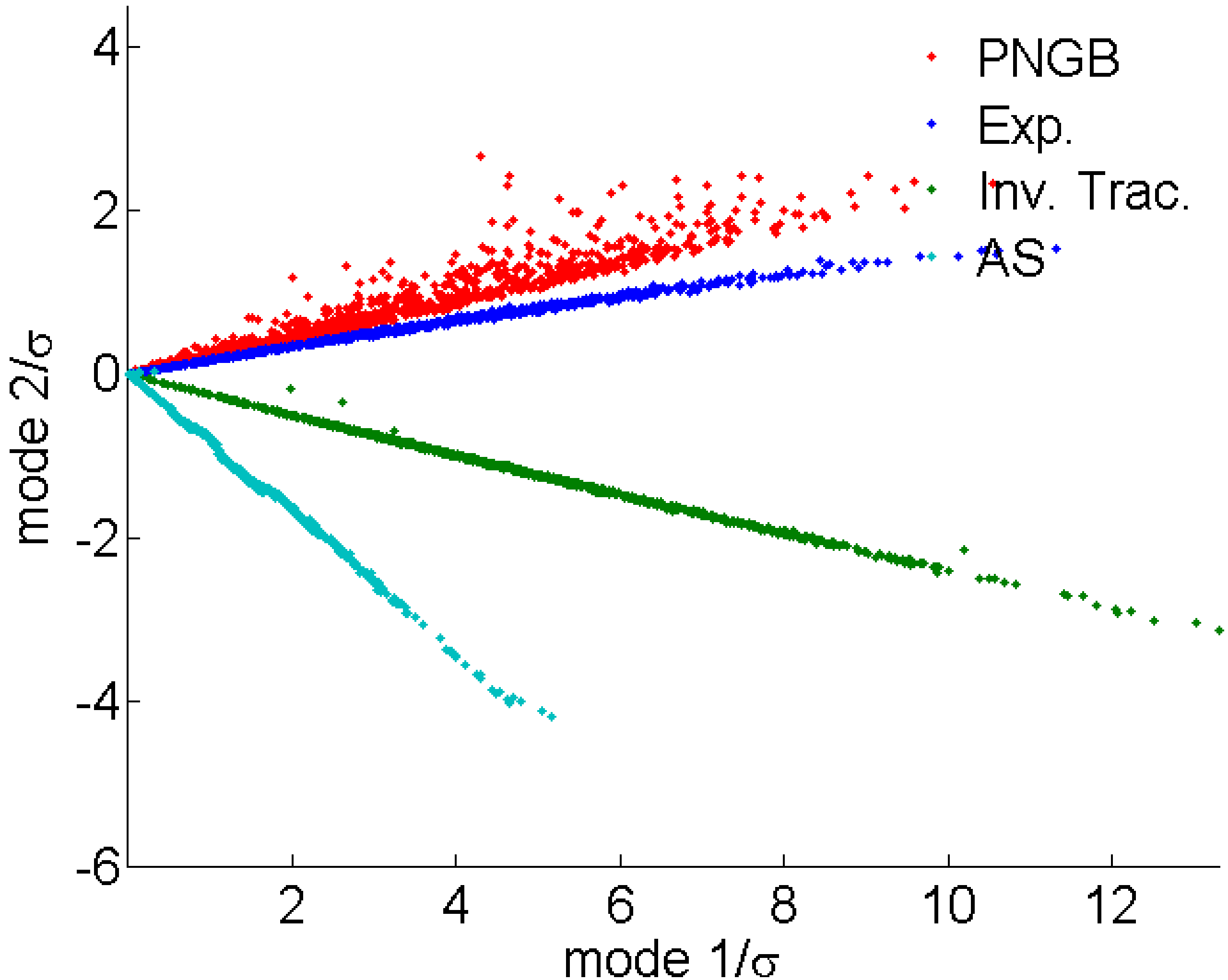
Eigenmodes:



N.B. σ_i change too

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 4 ground [Opt]

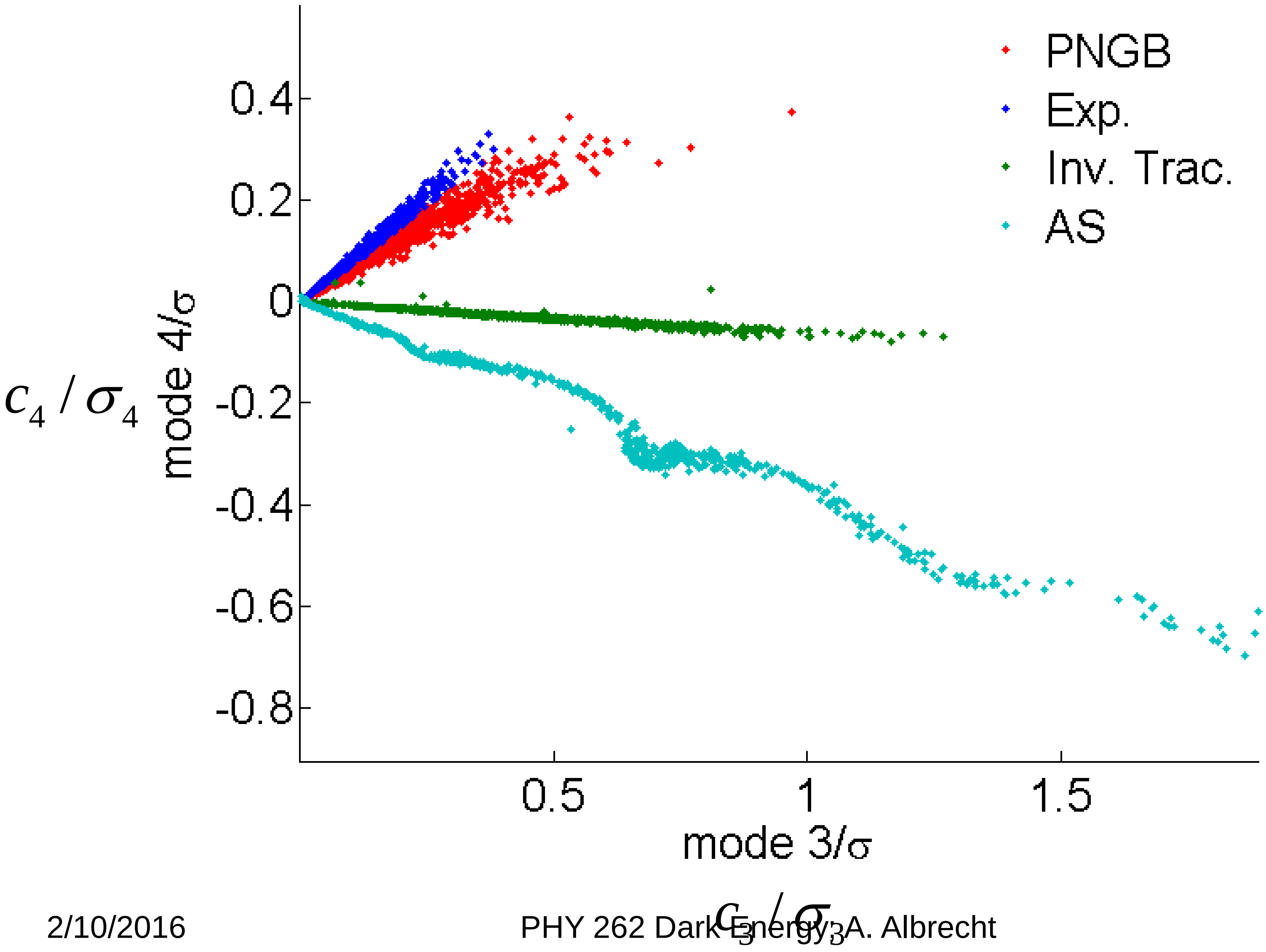


c_2 / σ_2

c_1 / σ_1

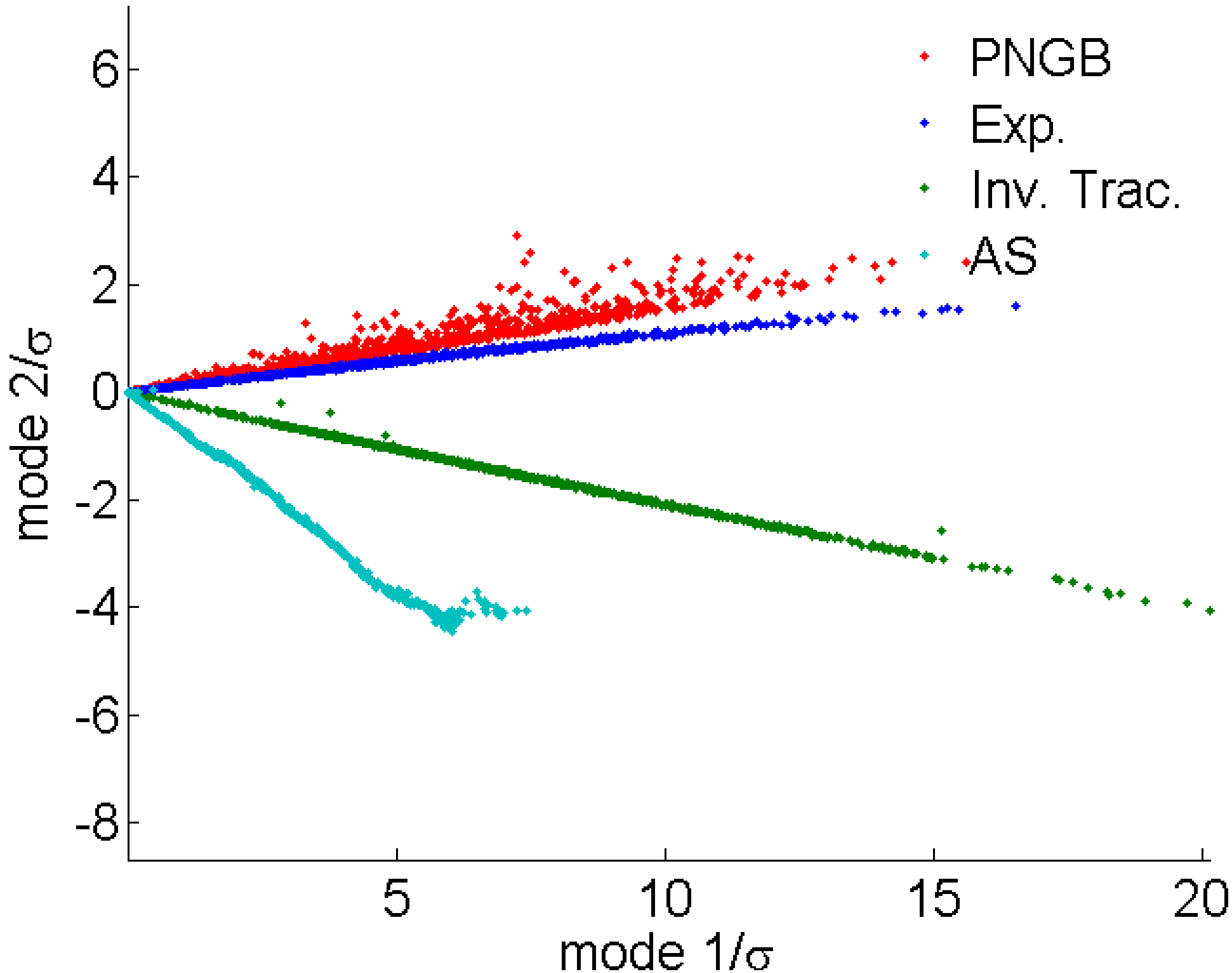
$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 4 ground [Opt]



$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 4 space [Opt]

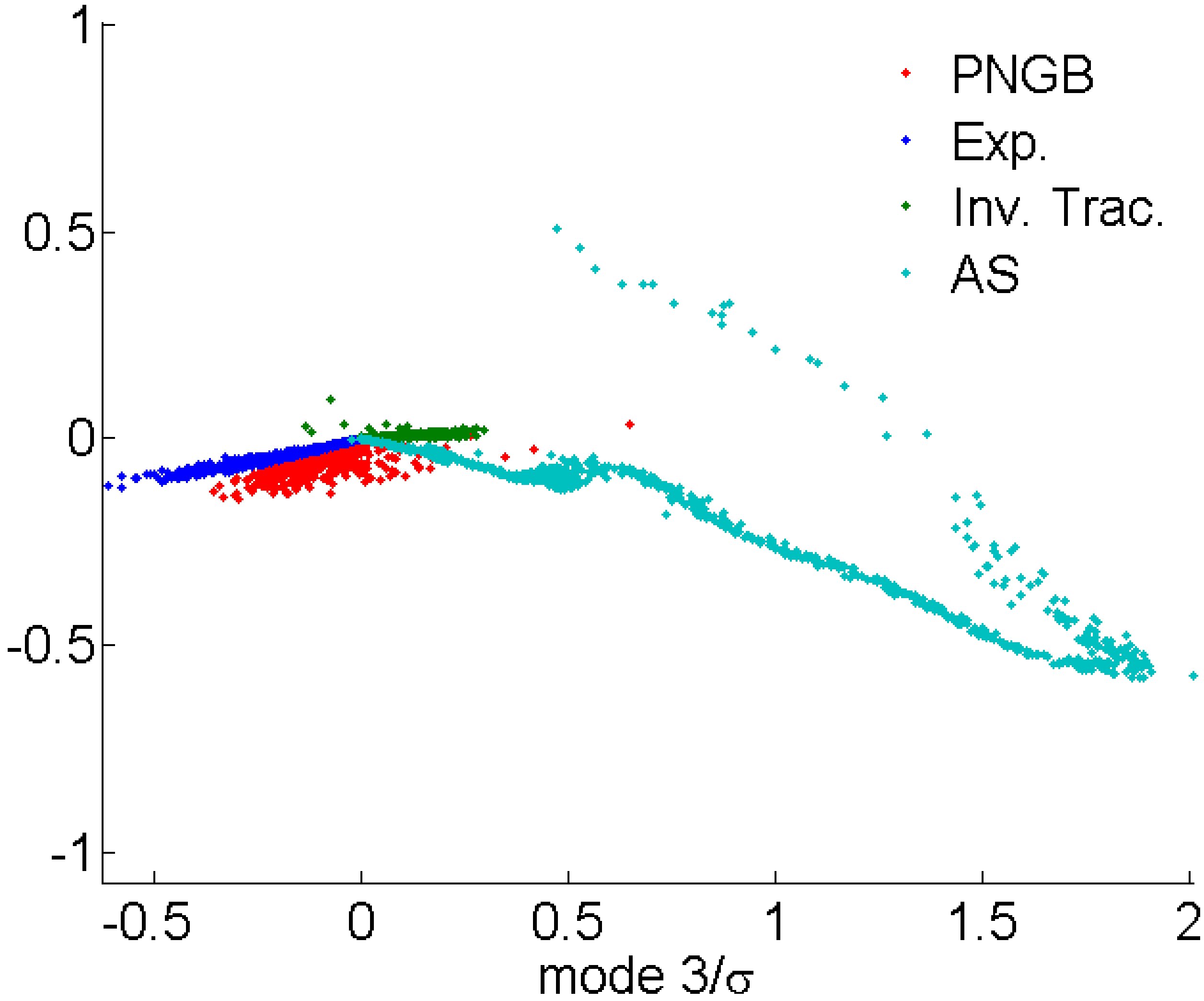


c_2 / σ_2

c_1 / σ_1

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

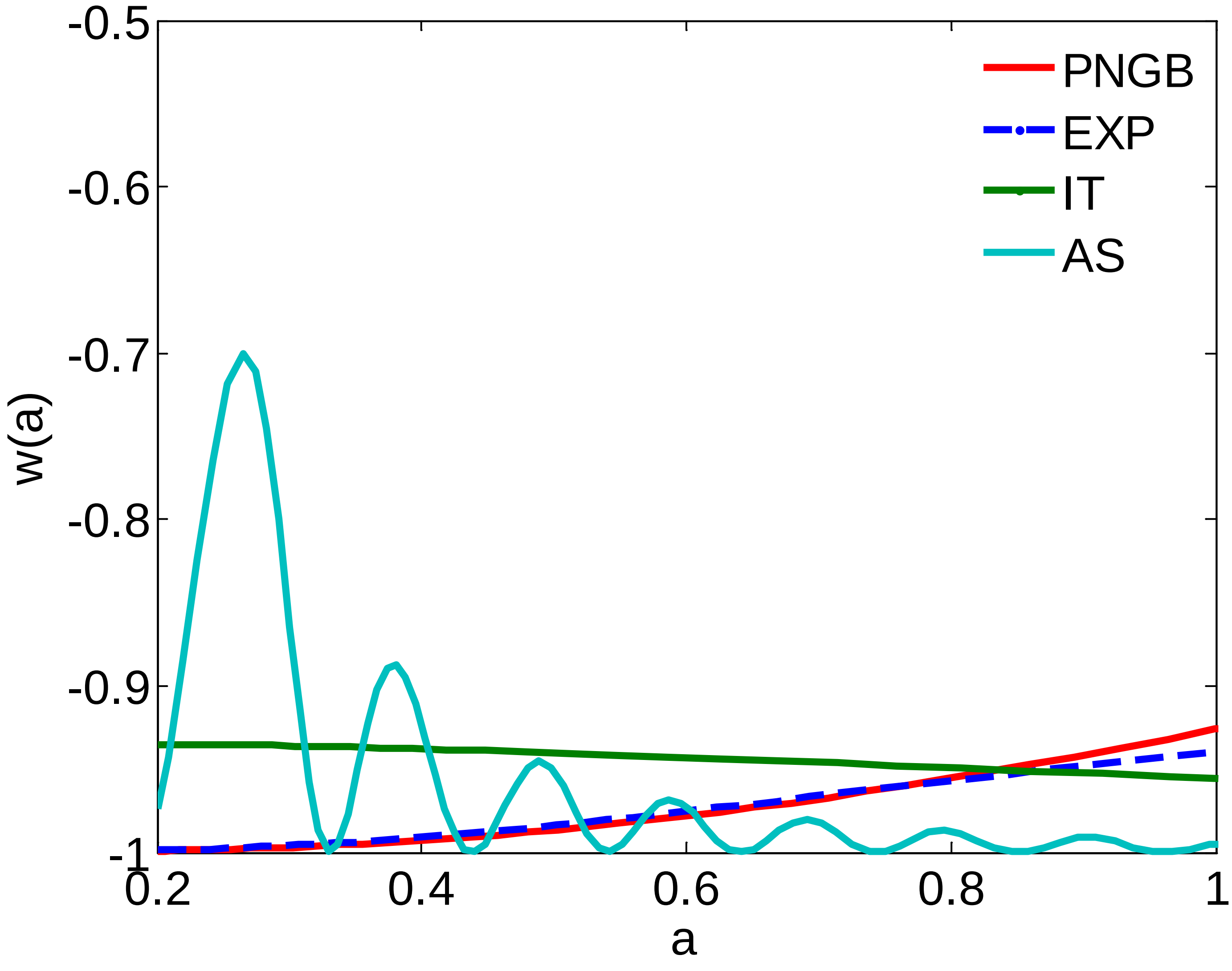
DETF Stage 4 space [Opt]



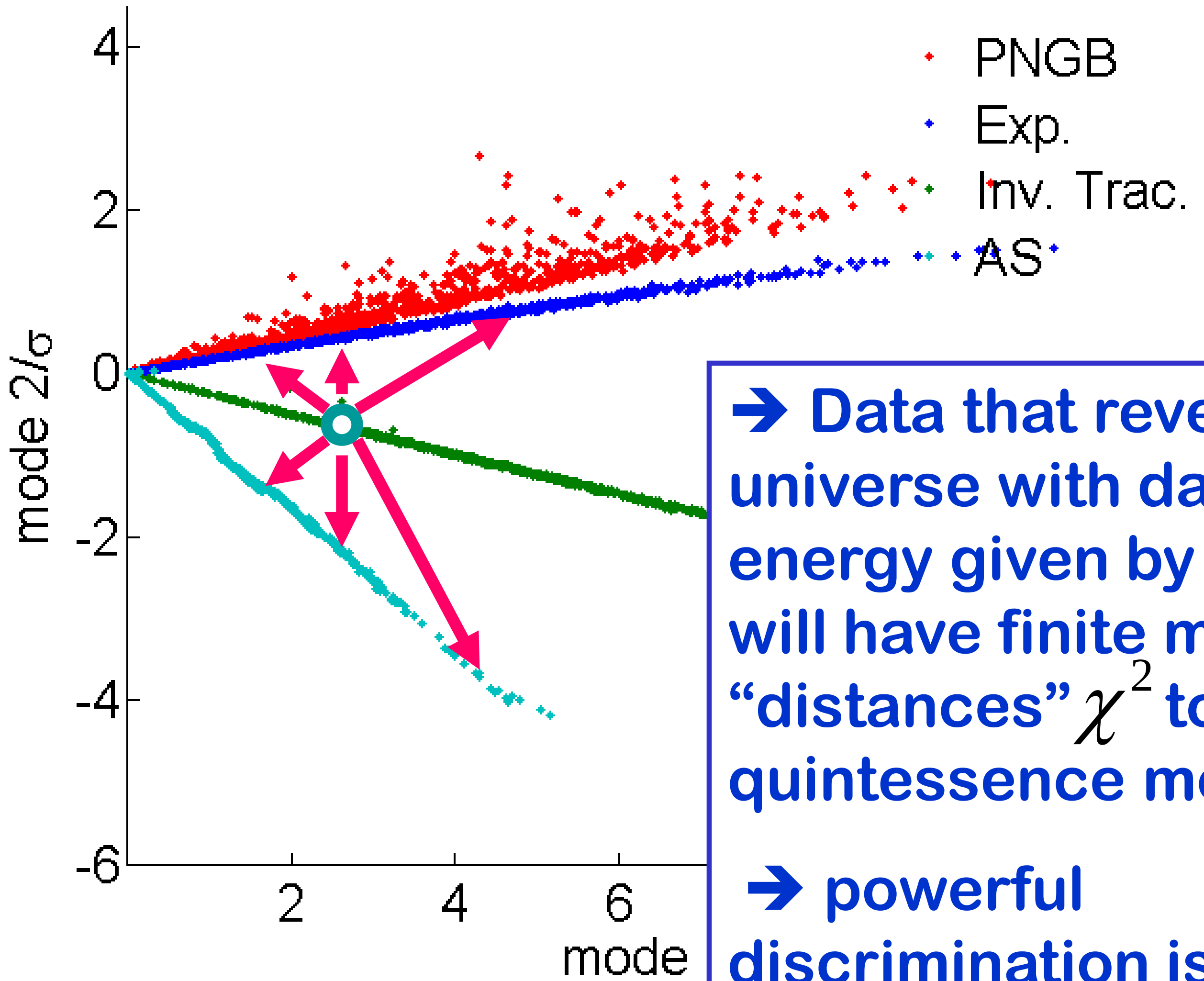
c_4 / σ_4

c_3 / σ_3

The different kinds of curves correspond to different "trajectories" in mode space (similar to FT's)



DETF Stage 4 ground



➔ Data that reveals a universe with dark energy given by " o " will have finite minimum "distances" χ^2 to other quintessence models

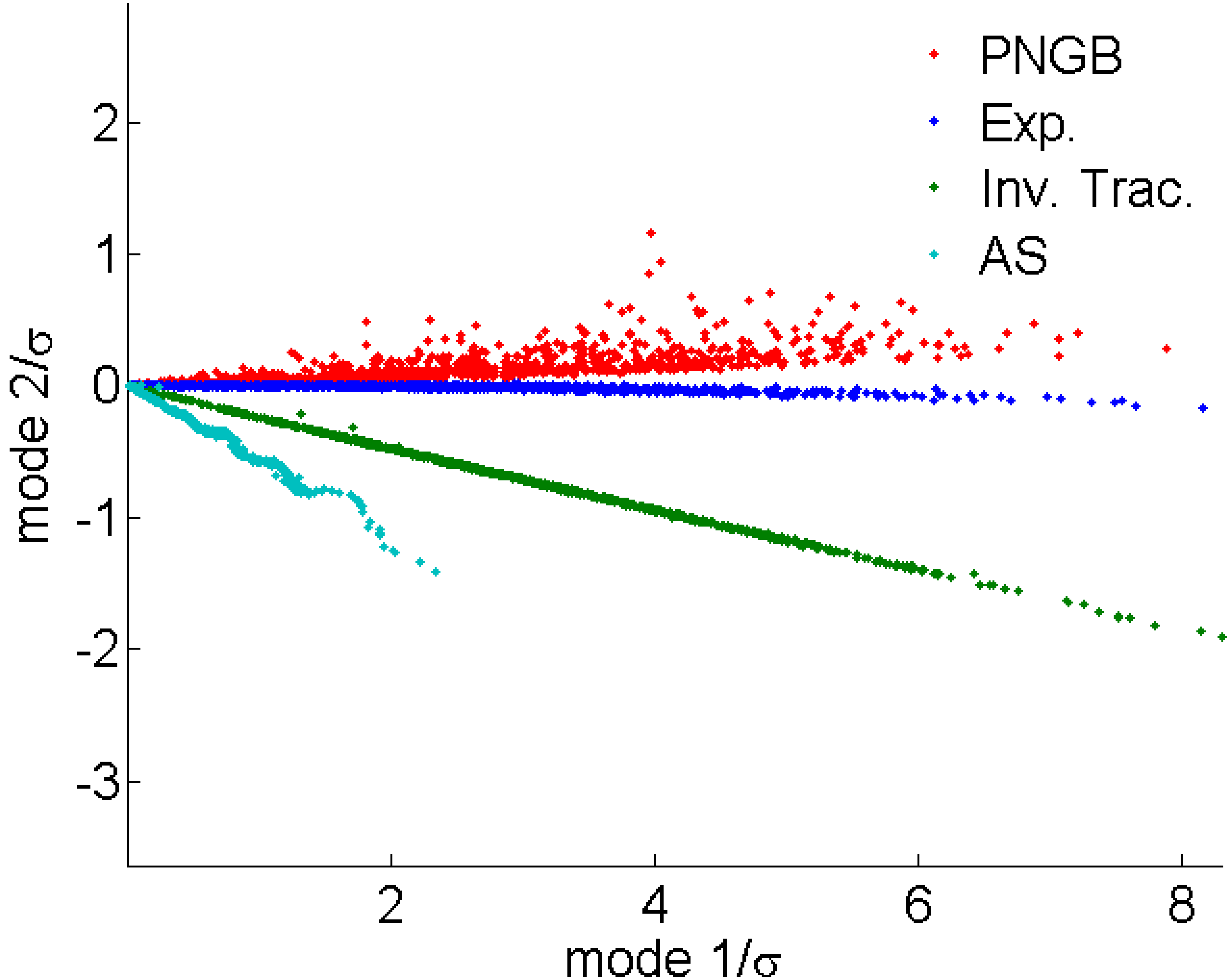
➔ powerful discrimination is possible.

Consider discriminating power of each experiment (→look at units on axes)

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 3 photo [Opt]

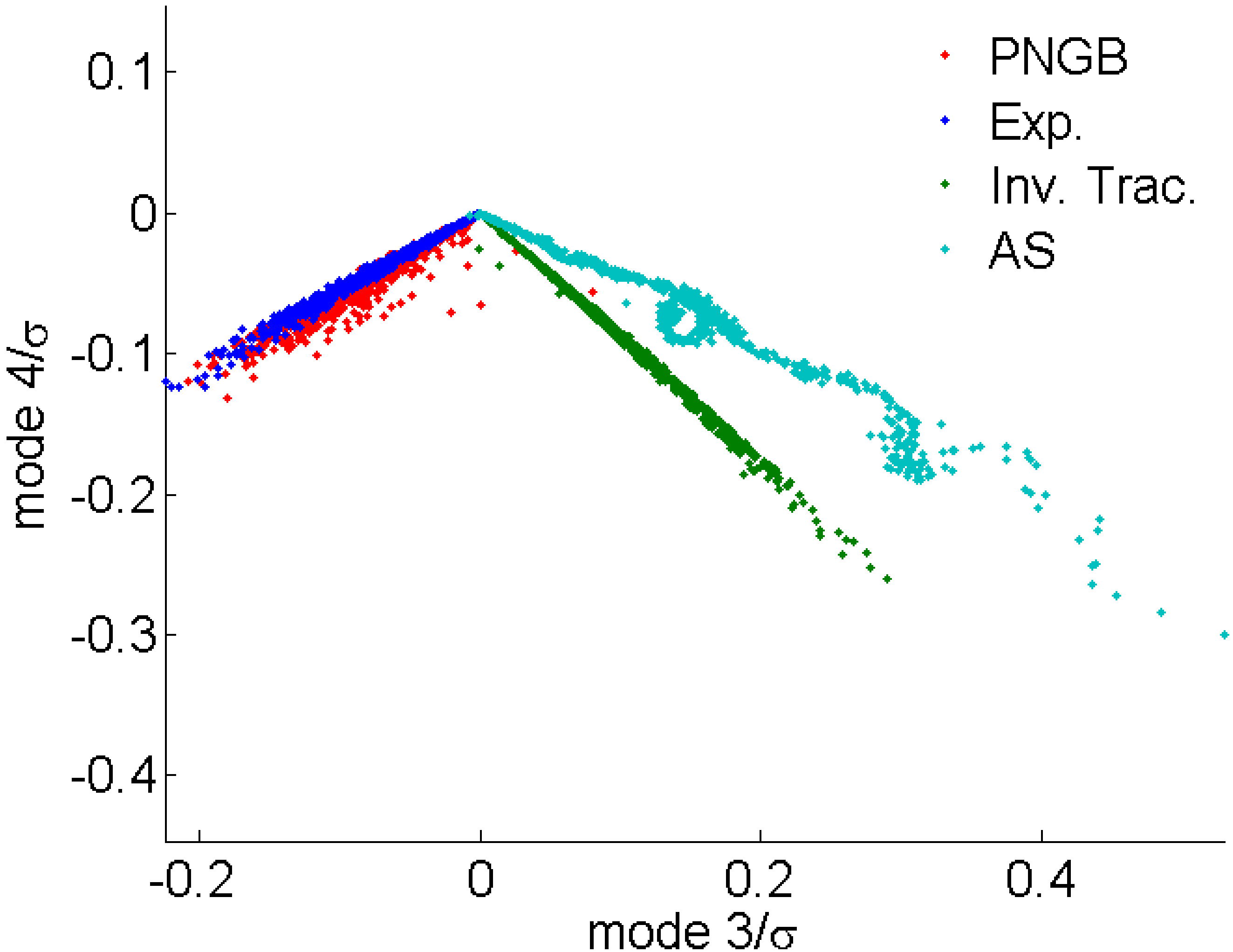
c_2 / σ_2



c_1 / σ_1

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 3 photo [Opt]



c_4 / σ_4

c_3 / σ_3

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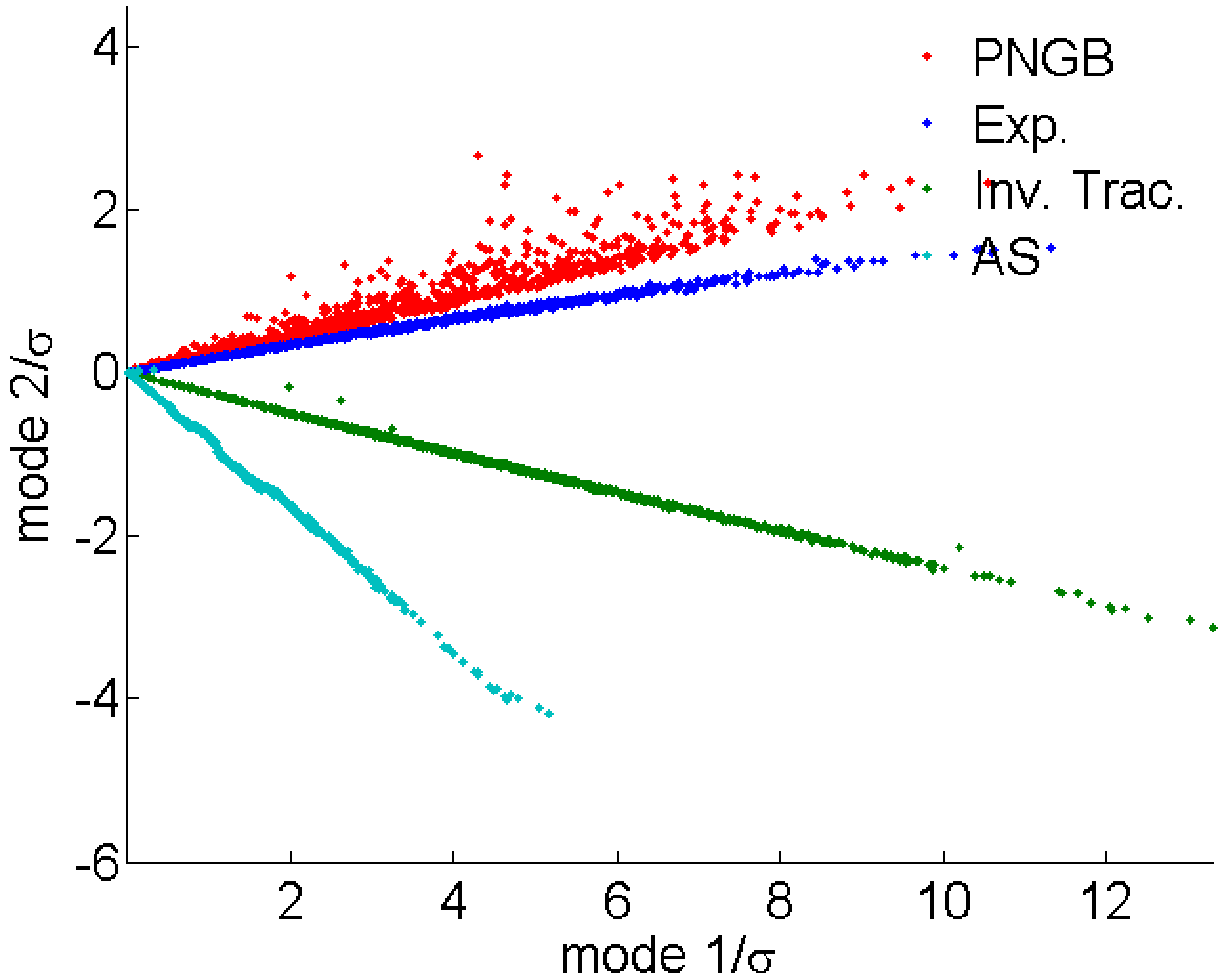
DETF Stage 4 ground [Opt]

c_2 / σ_2



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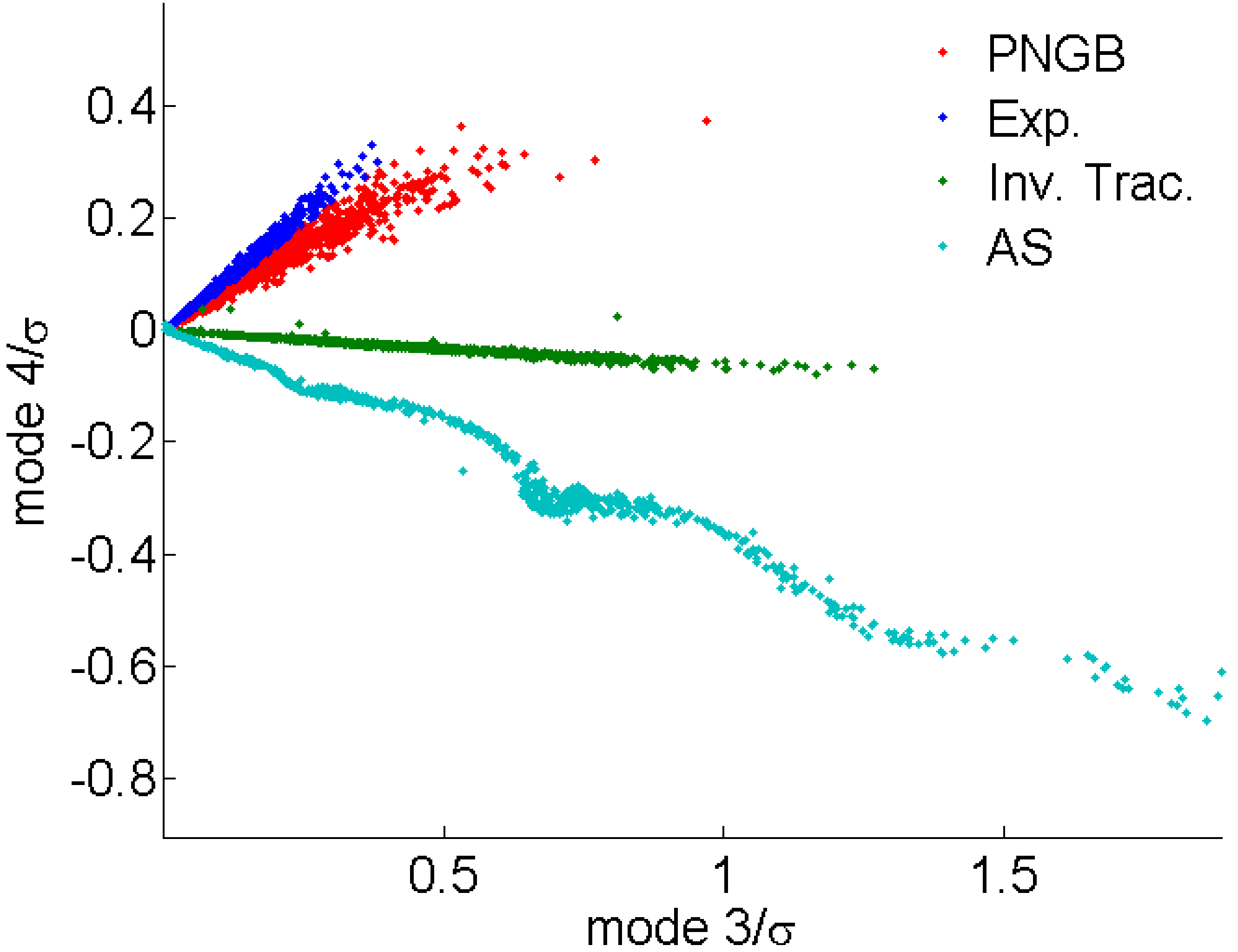

c_4 / σ_4

c_3 / σ_3

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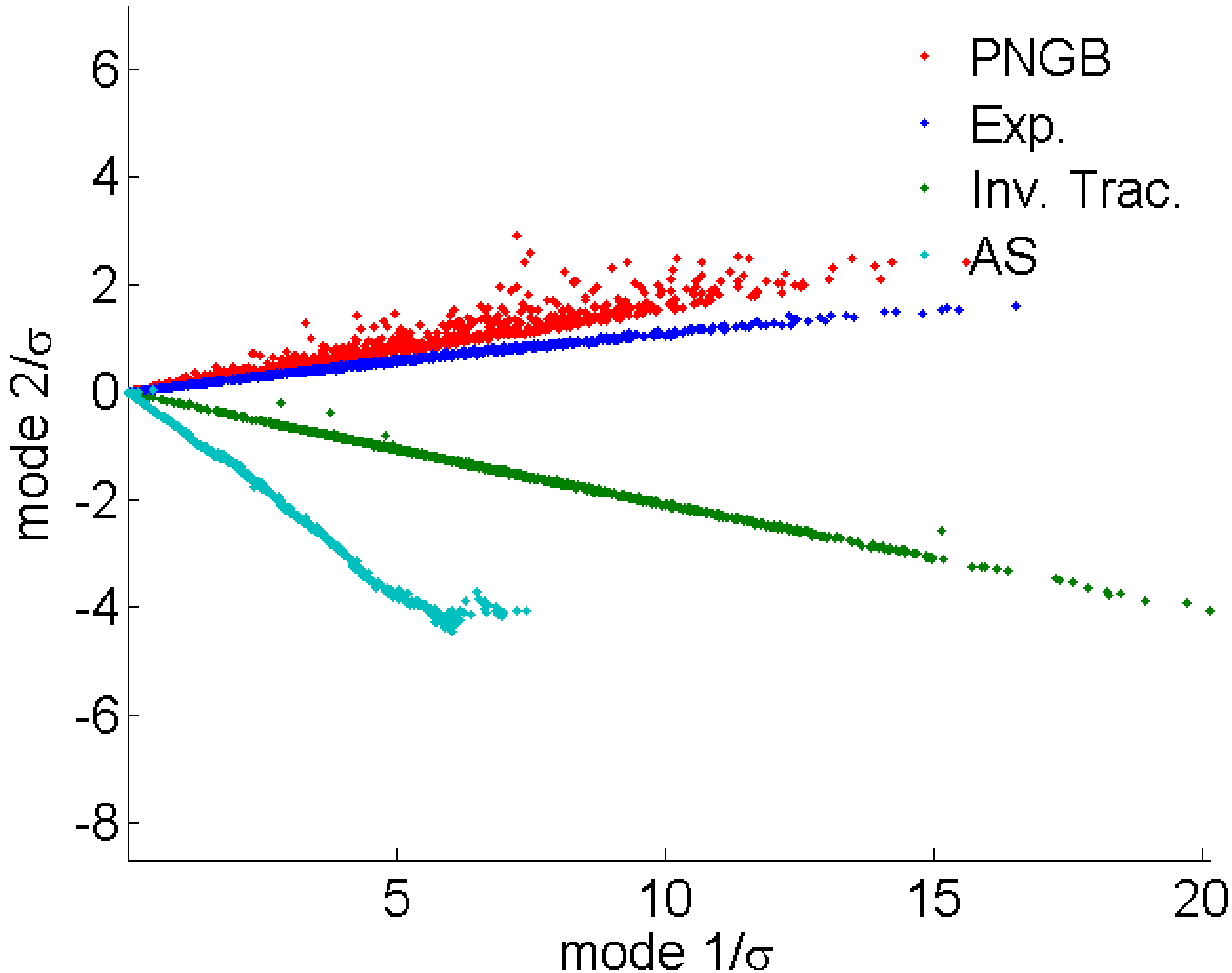
DETF Stage 4 space [Opt]



c_2 / σ_2

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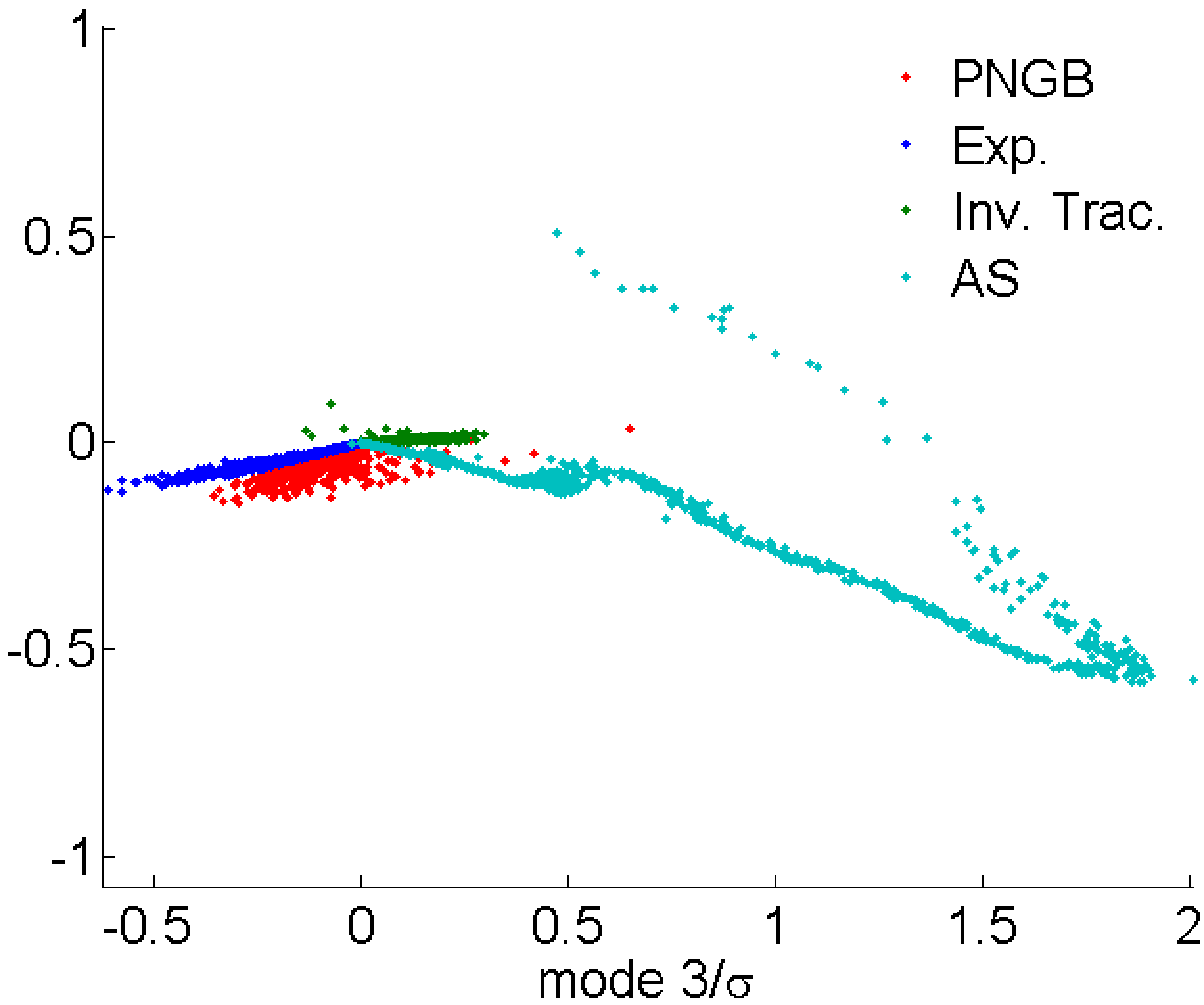
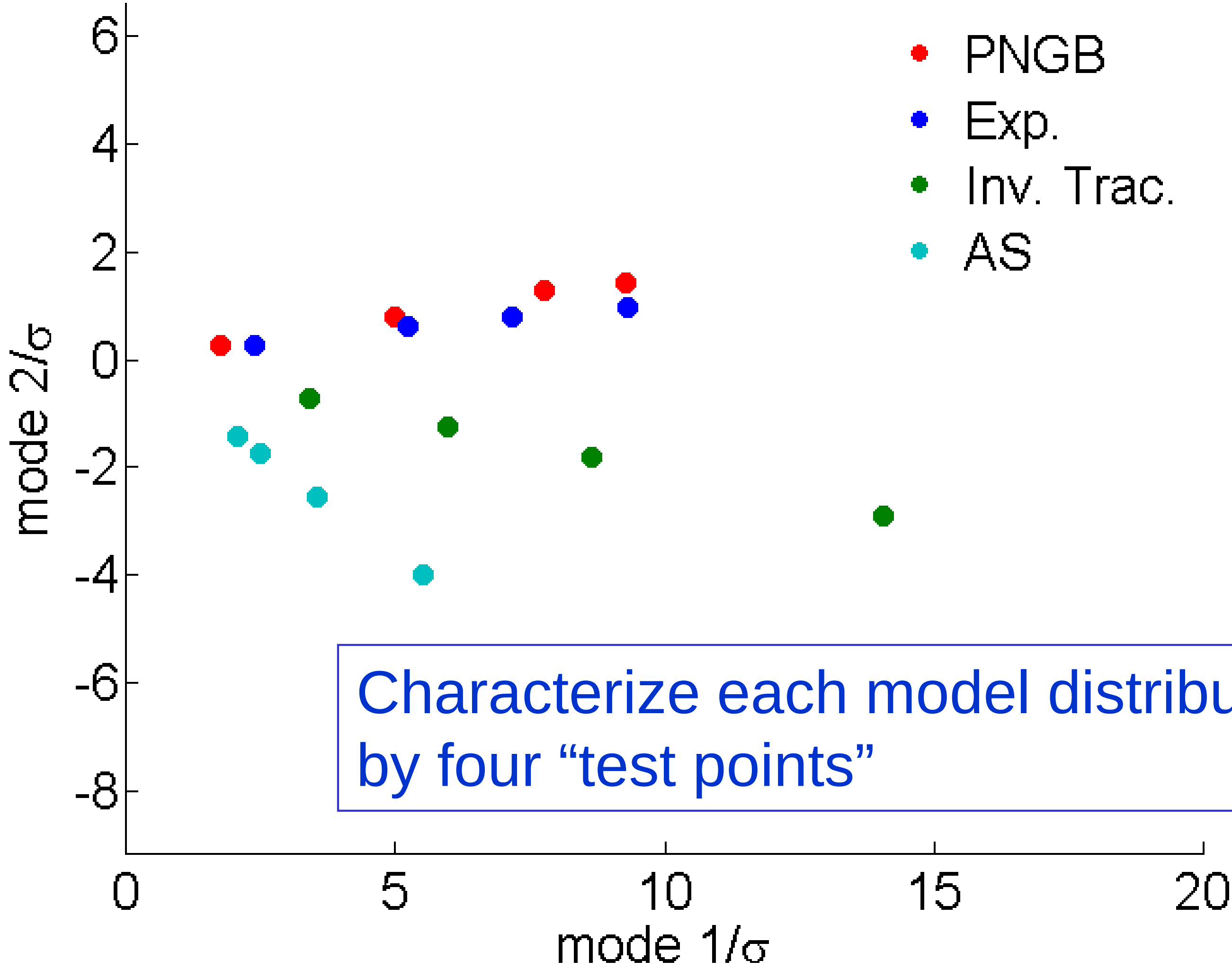


c_4/σ_4

c_3/σ_3

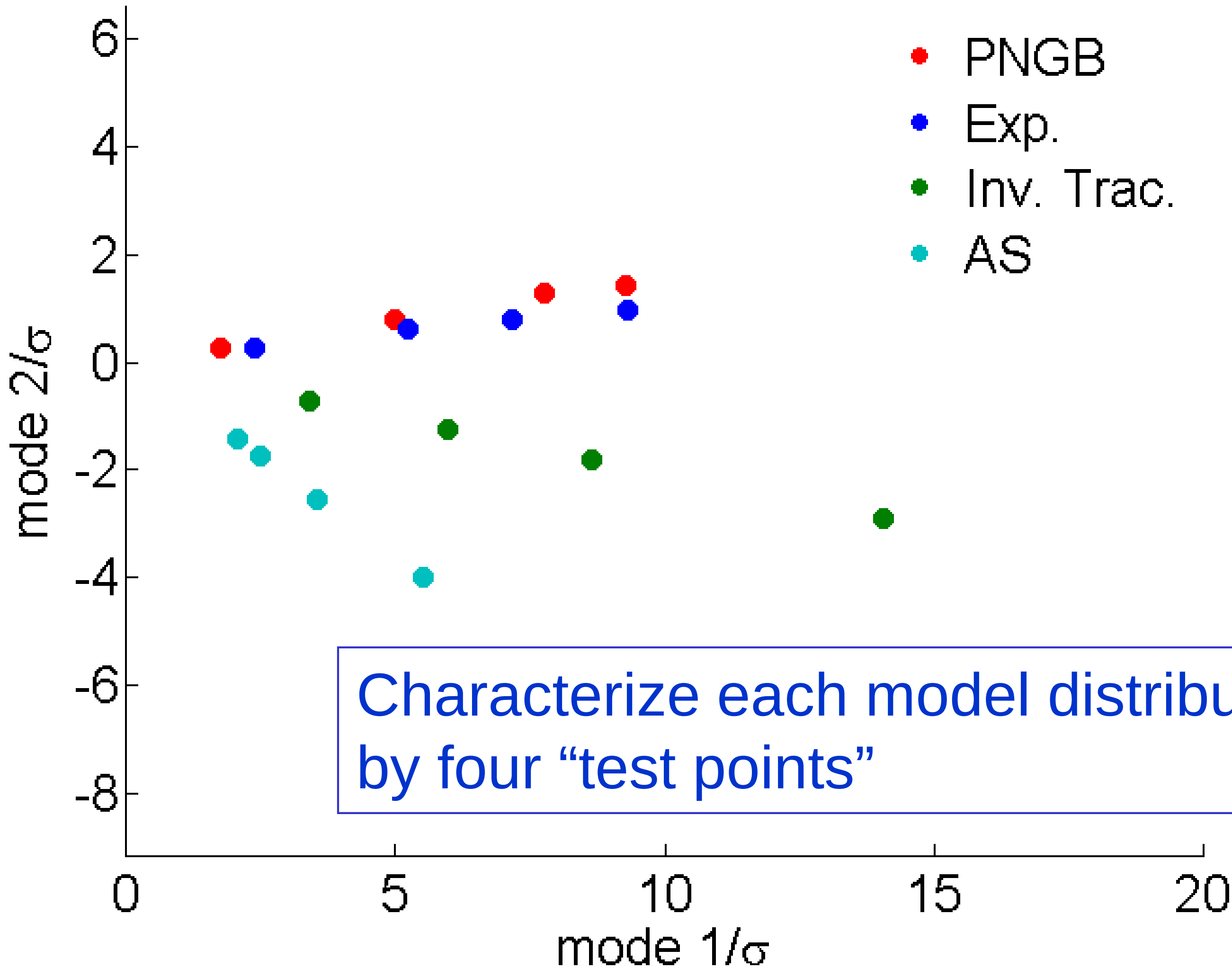
Quantify discriminating power:

Stage 4 space Test Points



Characterize each model distribution by four “test points”

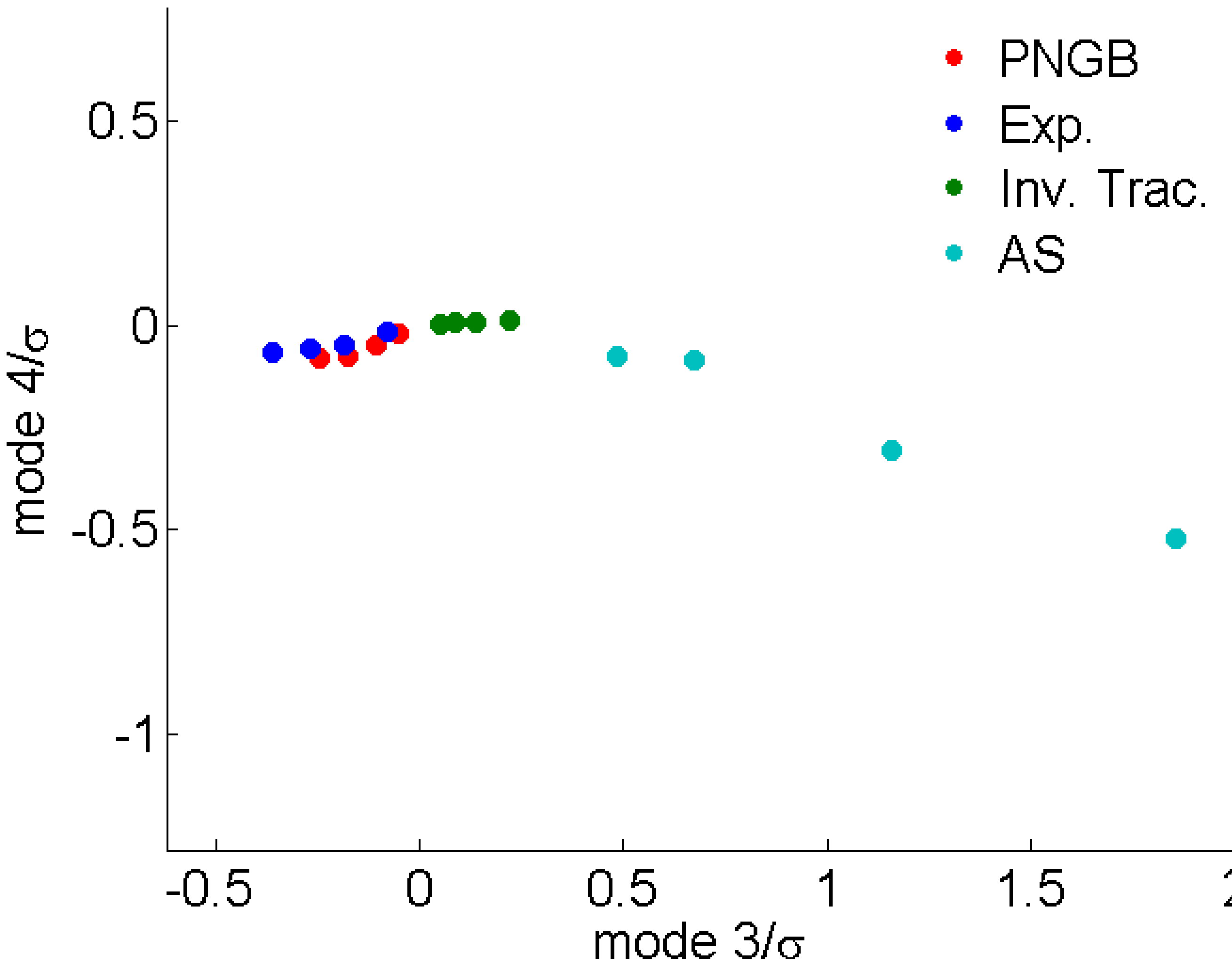
Stage 4 space Test Points



Characterize each model distribution by four "test points"

(Priors: Type 1 optimized for conservative results re discriminating power.)

Stage 4 space Test Points



•Measured the χ^2 from each one of the test points (from the "test model") to all other chain points (in the "comparison model").

•Only the first three modes were used in the calculation.

•Ordered said χ^2's by value, which allows us to plot them as a function of what fraction of the points have a given value or lower.

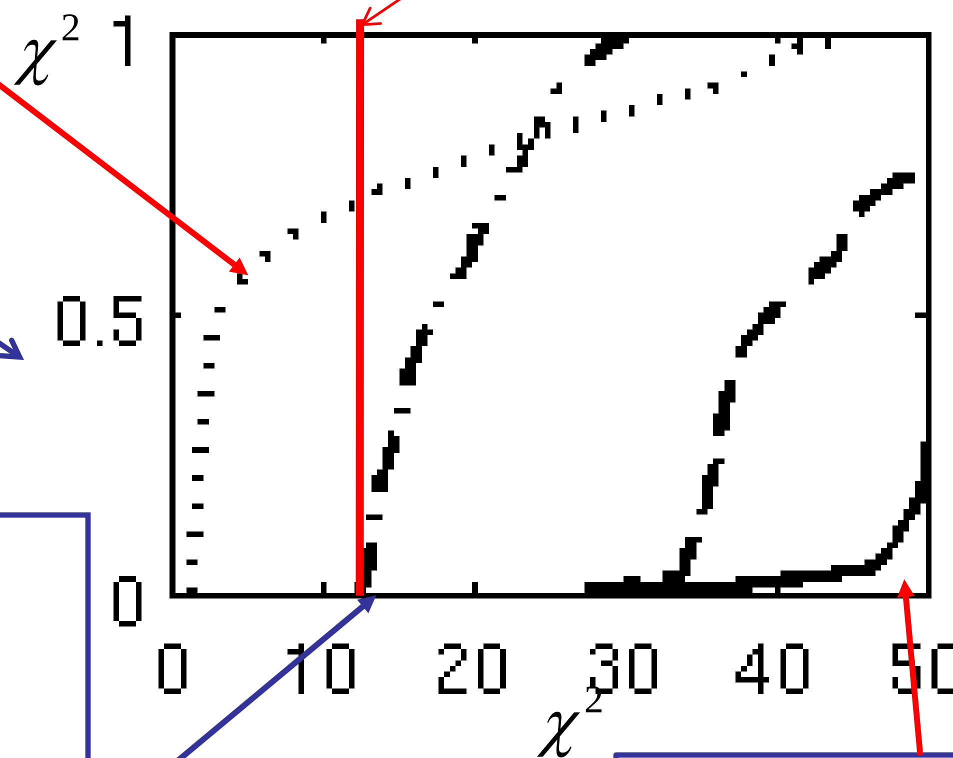
•Looked for the smallest values for a given model to model comparison.

Model Separation in Mode Space

99% confidence at 11.36

Test point 1

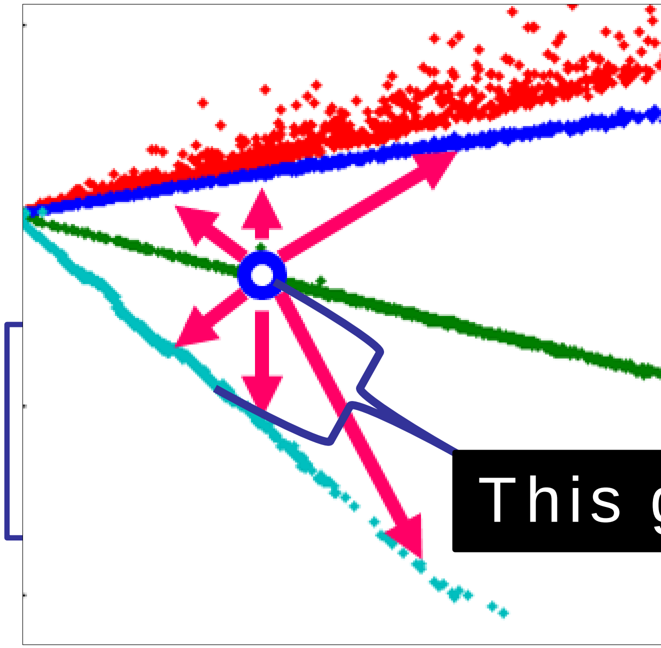
Fraction of compared model within given χ^2 of test model's test point



Where the curve meets the axis, the compared model is ruled out by that χ^2 by an observation of the test point. This is the separation seen in the mode plots.

Test point 4

Model Separation in Mode Space



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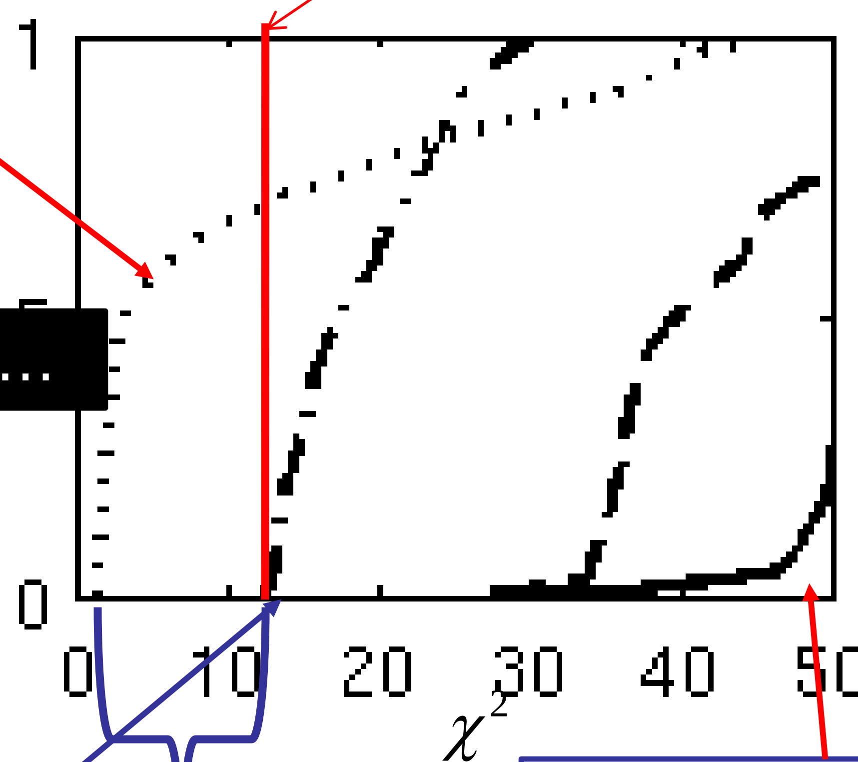

This gap…

…is this gap

Test point 4

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Comments on model discrimination

- Principle component w(a) “modes” offer a space in which straightforward tests of discriminating power can be made.

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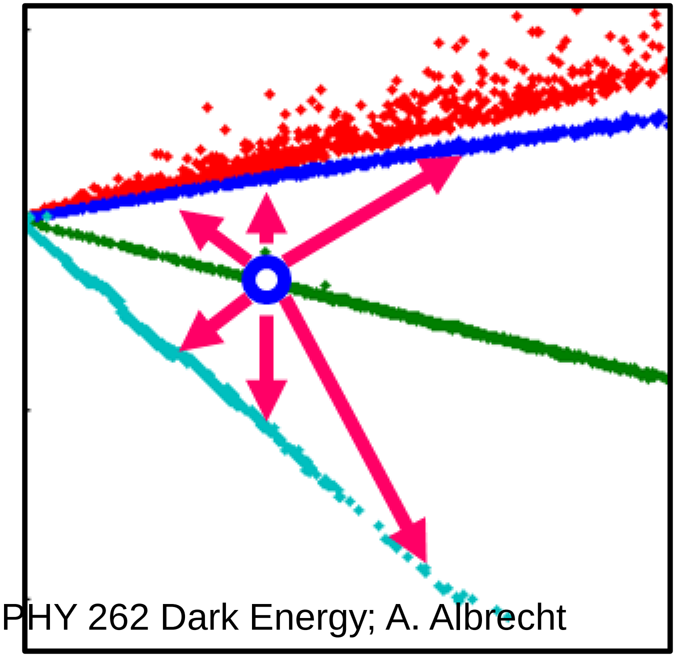

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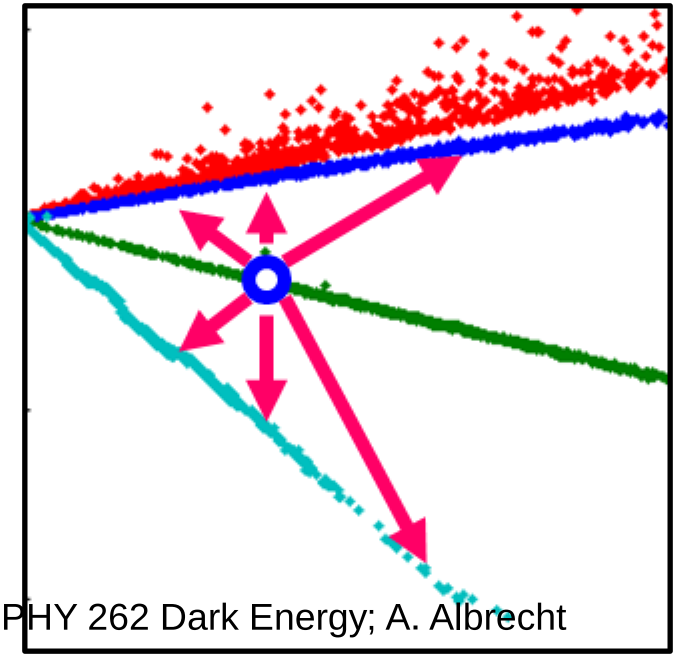

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A:

- DETF Stage 3: Poor
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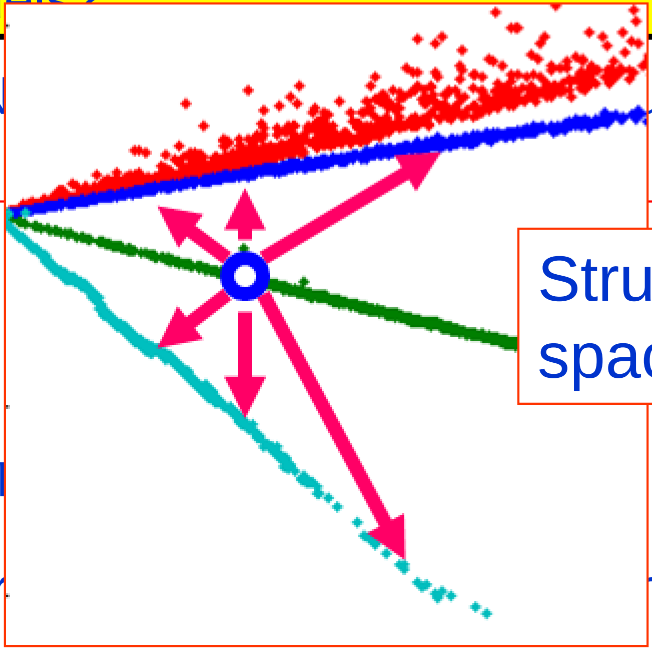

Structure in mode space

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DoE/ESA/NASA JDEM Science Working Group

➔ Update agencies on figures of merit issues

➔ formed Summer 08

➔ finished ~now (moving on to SCG)

➔ Use w-eigenmodes to get more complete picture

➔ also quantify deviations from Einstein gravity

➔ For today: Something new we learned about (normalizing) modes

NB: in general the $\vec{f}_i$s form a complete basis:

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

The c_i are independently measured qualities with errors σ_i

Define

$$\vec{f}_i^{\,D} \equiv \vec{f}_i / \sqrt{\Delta a}$$

which obey continuum normalization:

$$\sum f_i^D(k) f_j^D(k) \Delta a = \delta_{ij}$$

then

$$\Delta\vec{w} = \sum_i c_i^D \vec{f}_i^{\,D}$$

where

$$c_i^D \equiv c_i \times \sqrt{\Delta a}$$

Q: Why?

A: For lower modes, f_j^D has typical *grid independent* "height" O(1), so one can more directly relate values of $\sigma_i^D \equiv \sigma_i \times \sqrt{\Delta a}$ to one's thinking (priors) on $\Delta\vec{w}$

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i = \sum_i c_i^D \vec{f}_i^D$$

Define

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which obey continuum normalization:

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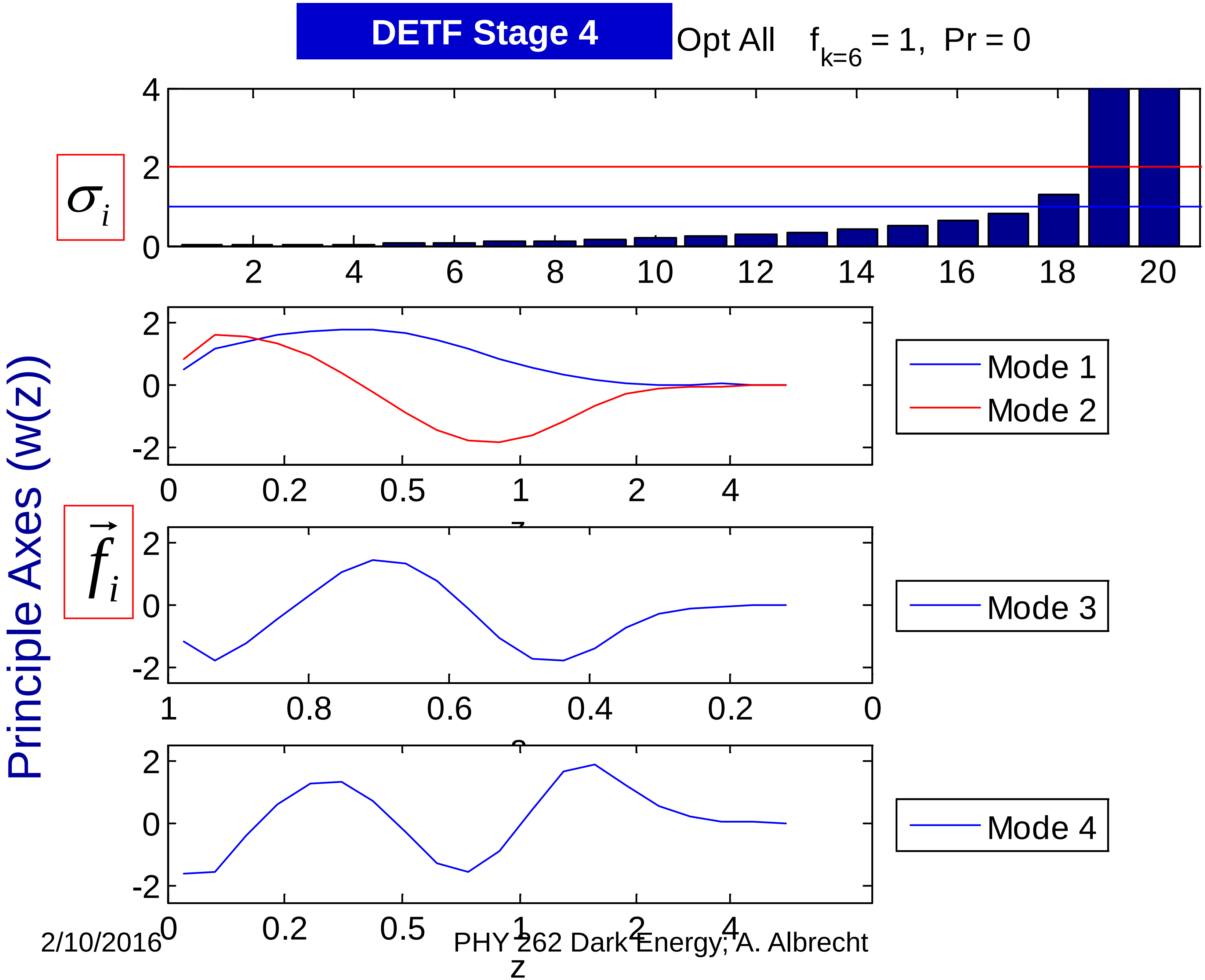
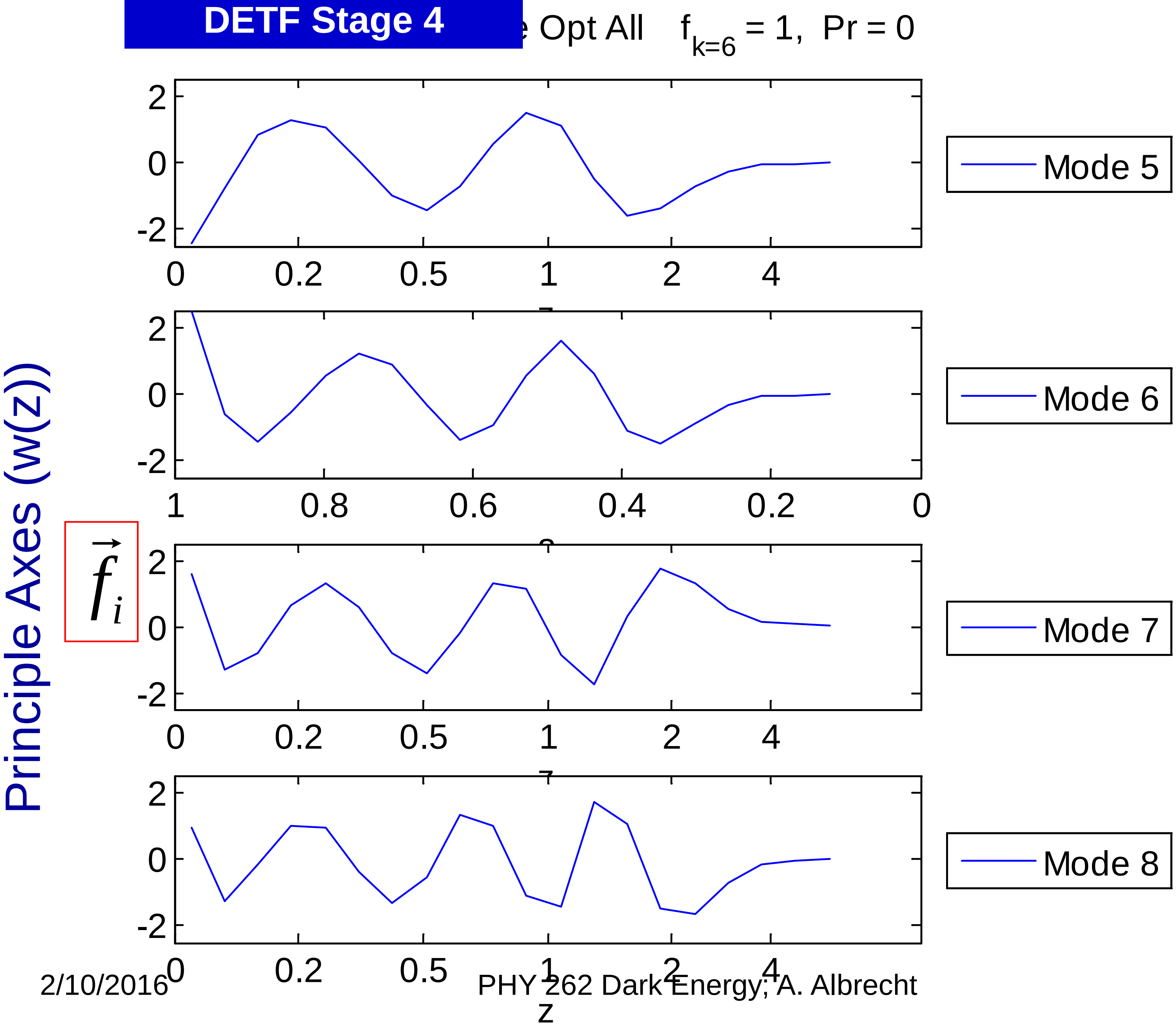
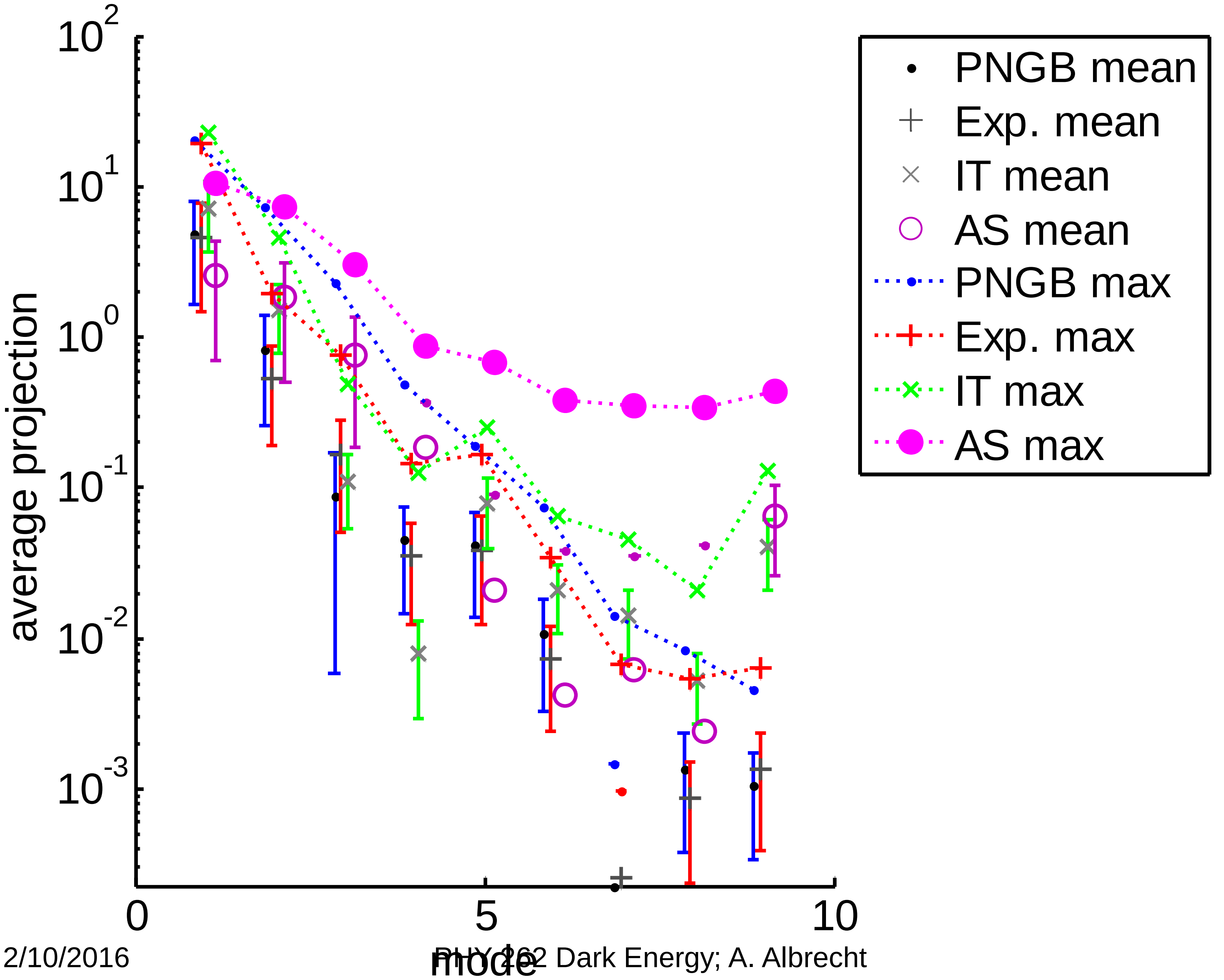


DETF Stage 4
Opt All $f_{k=6}$ = 1, Pr = 0
σ_i
Principle Axes (w(z))
$\vec{f}_i$
Mode 1
Mode 2
Mode 3
Mode 4
z

DETF Stage 4


e Opt All f k=6 = 1, Pr = 0
Principle Axes (w(z))
$\vec{f}_i$
2
0
-2
0
0.2
0.5
1
2
4
Mode 5
1
0.8
0.6
0.4
0.2
0
Mode 6
Mode 7
Mode 8
z

Upshot: More modes are interesting ("well measured" in a grid invariant sense) than previously thought.

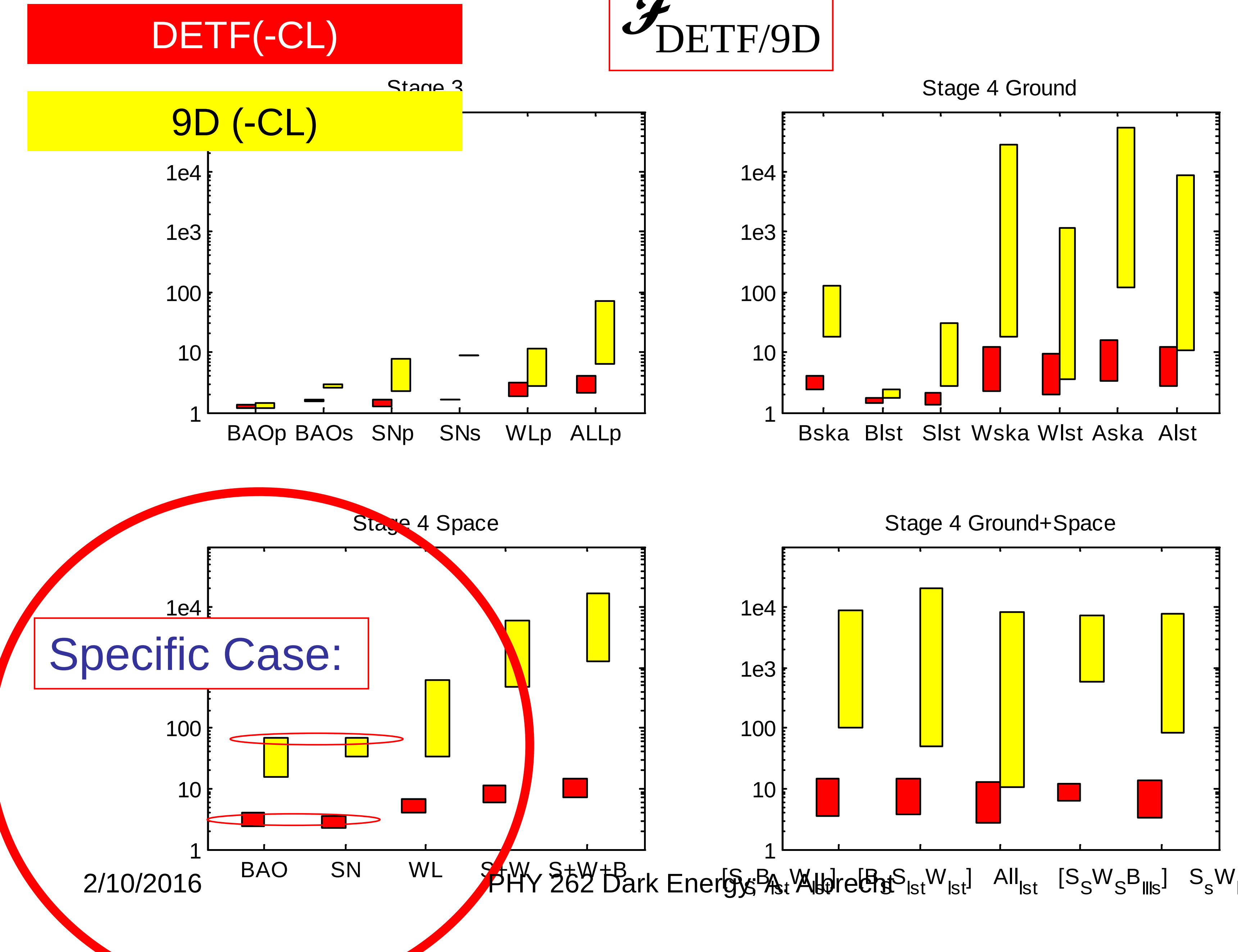


average projection
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
5
10
mode
PNGB mean
Exp. mean
IT mean
AS mean
PNGB max
Exp. max
IT max
AS max

An example of the power of the principle component analysis:

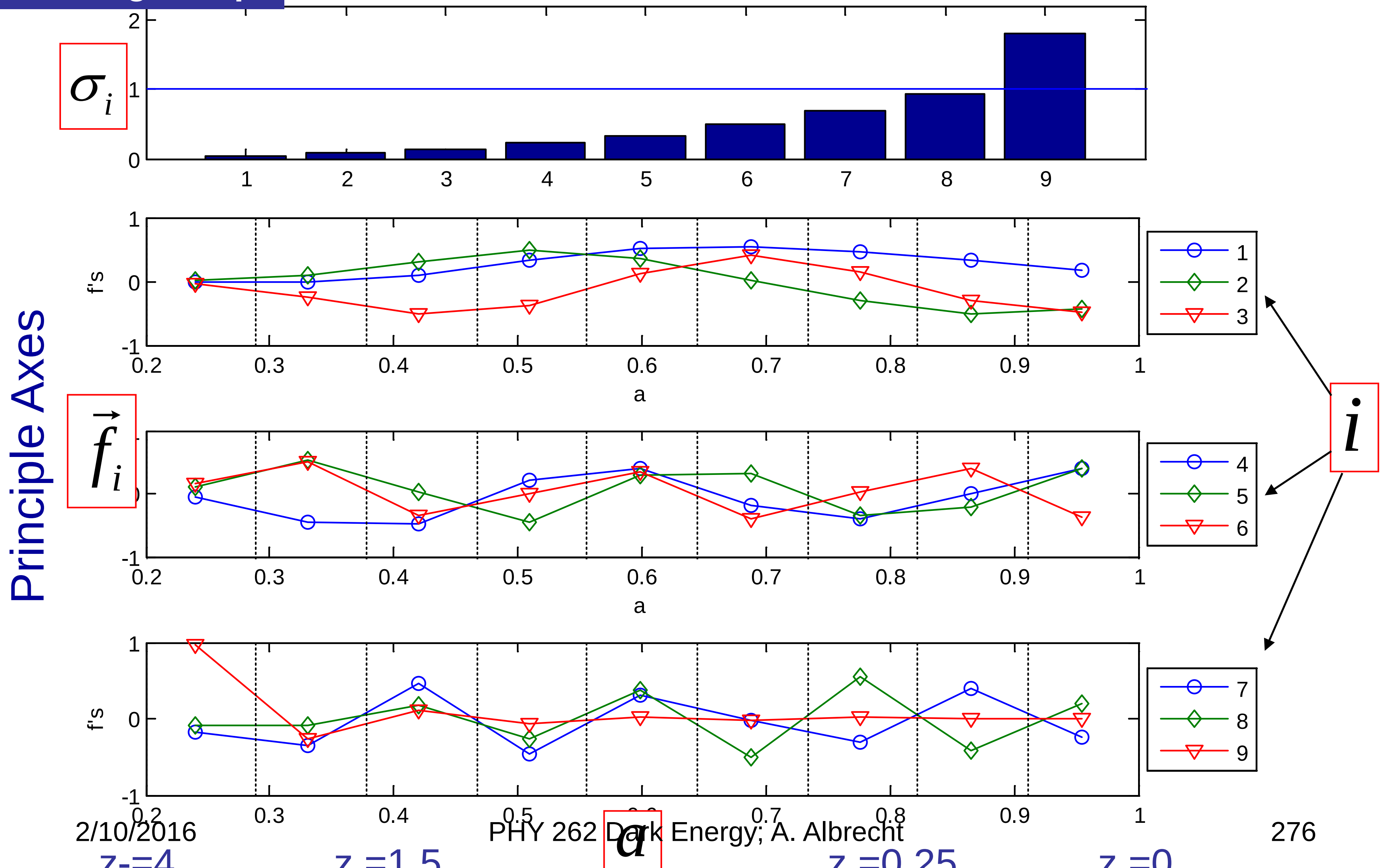
Q: I’ve heard the claim that the DETF FoM is unfair to BAO, because w0-wa does not describe the high-z behavior to which BAO is particularly sensitive. Why does this not show up in the 9D analysis?

$\mathcal{F}_{DETF/9D}$



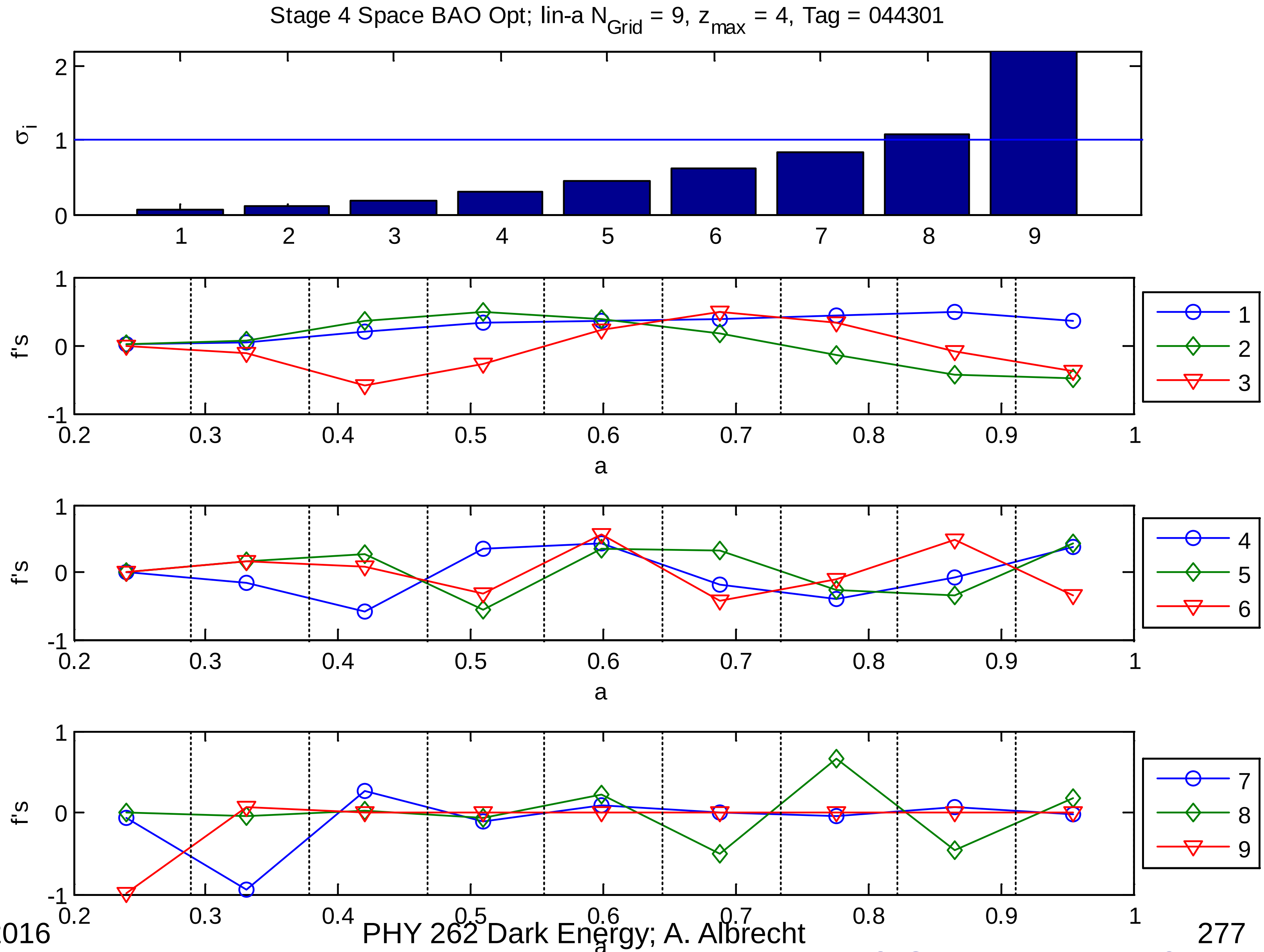
Characterizing 9D ellipses by principle axes and corresponding errors

WL Stage 4 Opt



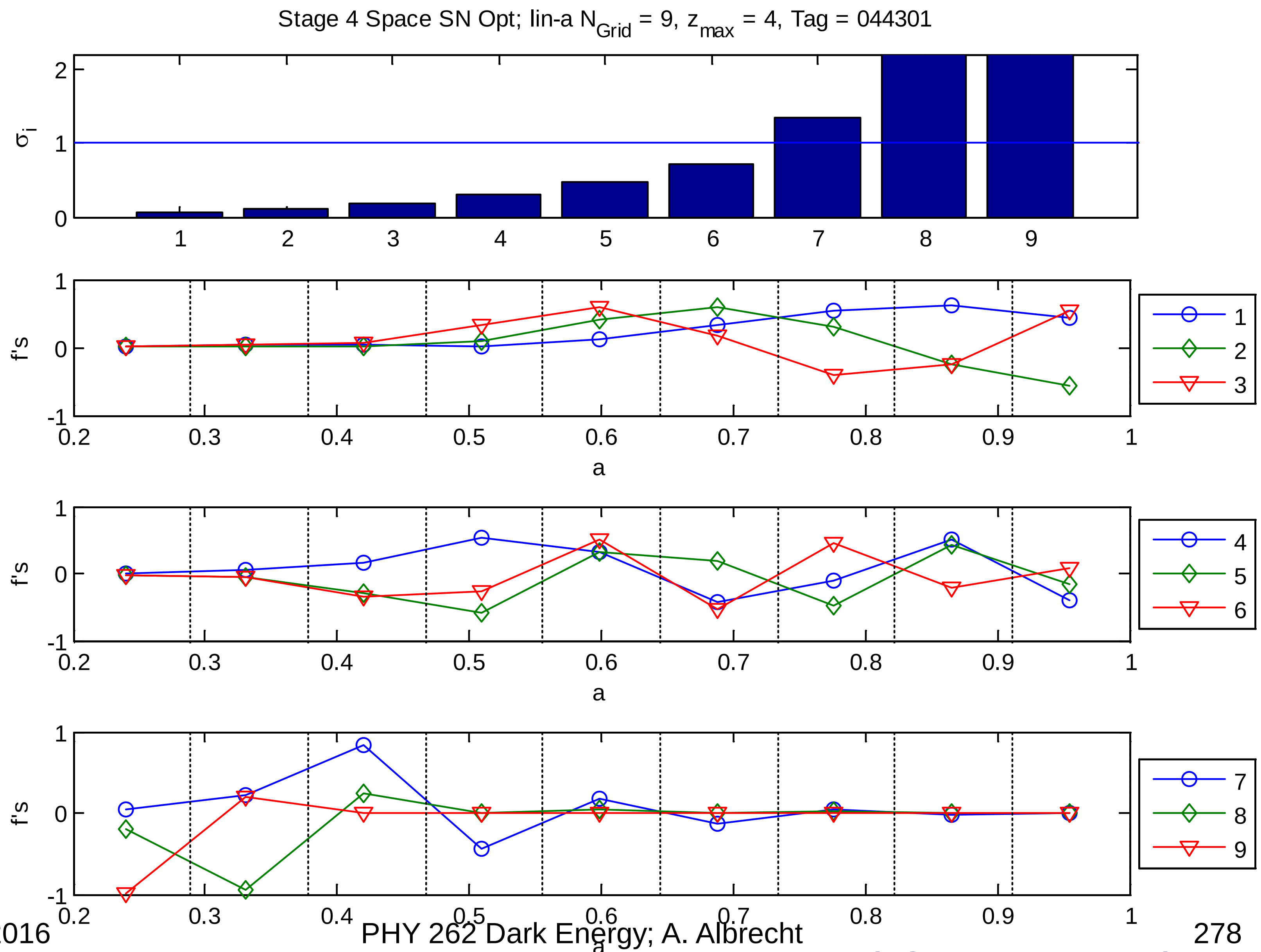
z-=4 z =1.5 z =0.25 z =0

BAO



z-=4 z =1.5 z =0.25 z =0

SN



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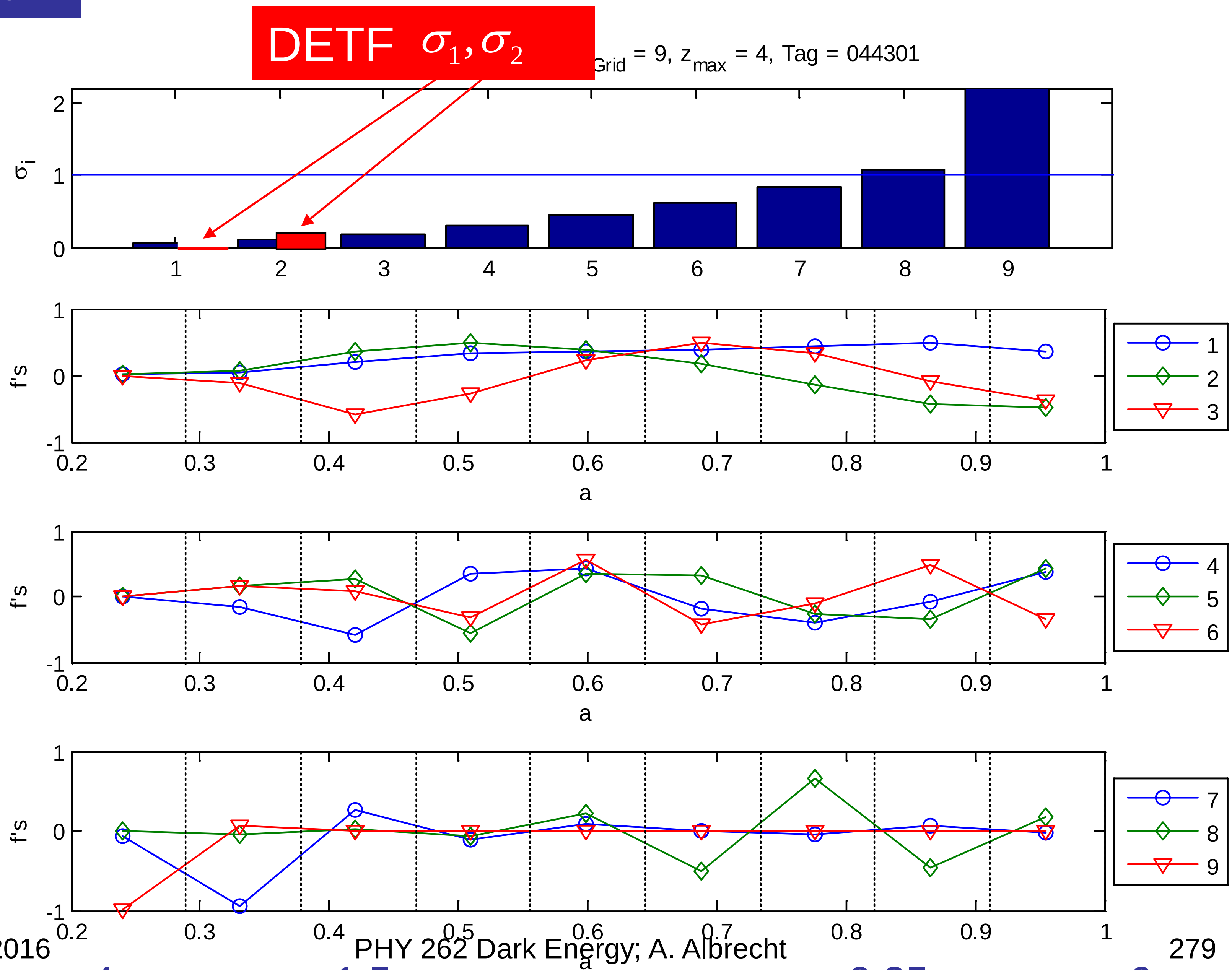
BAO



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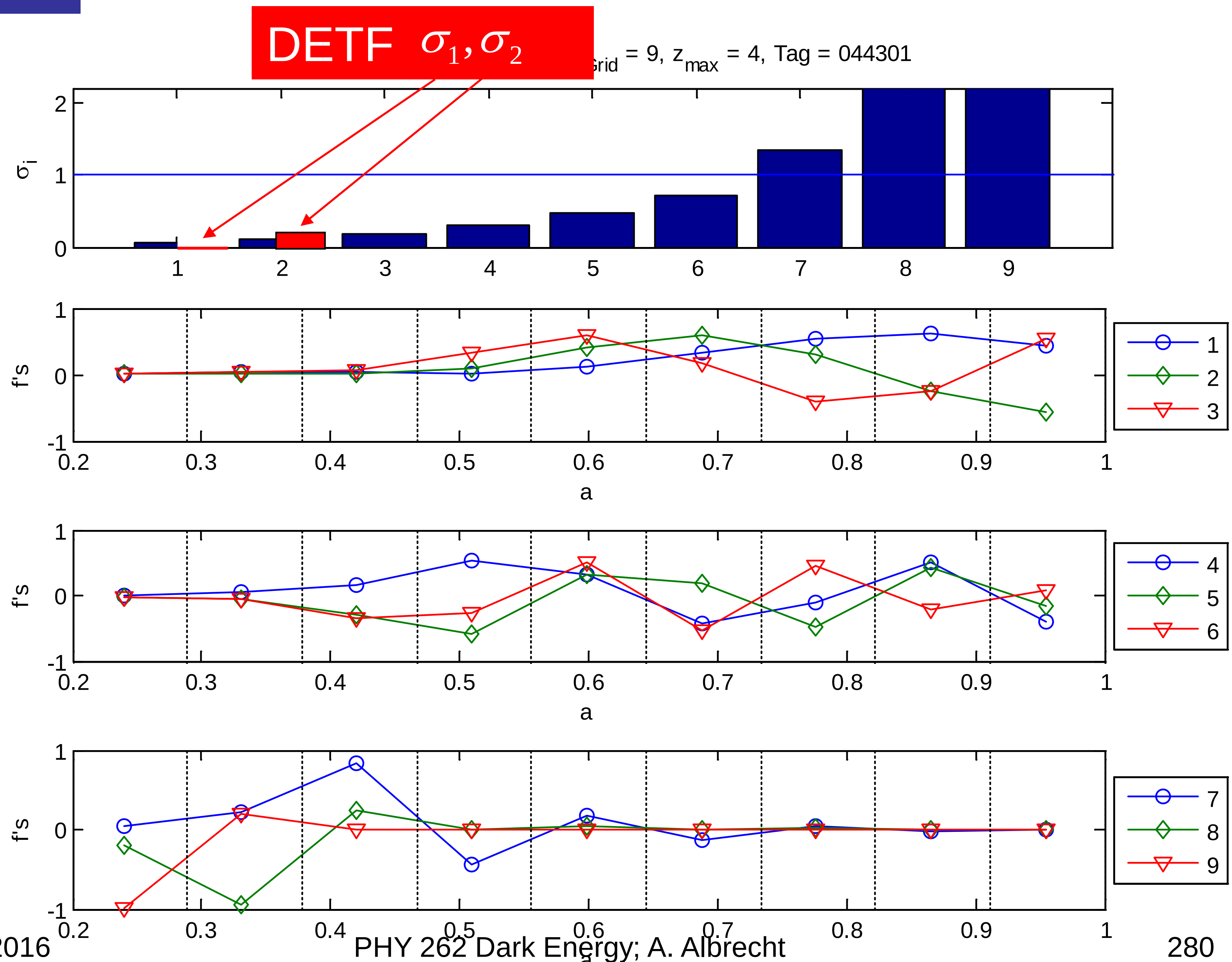
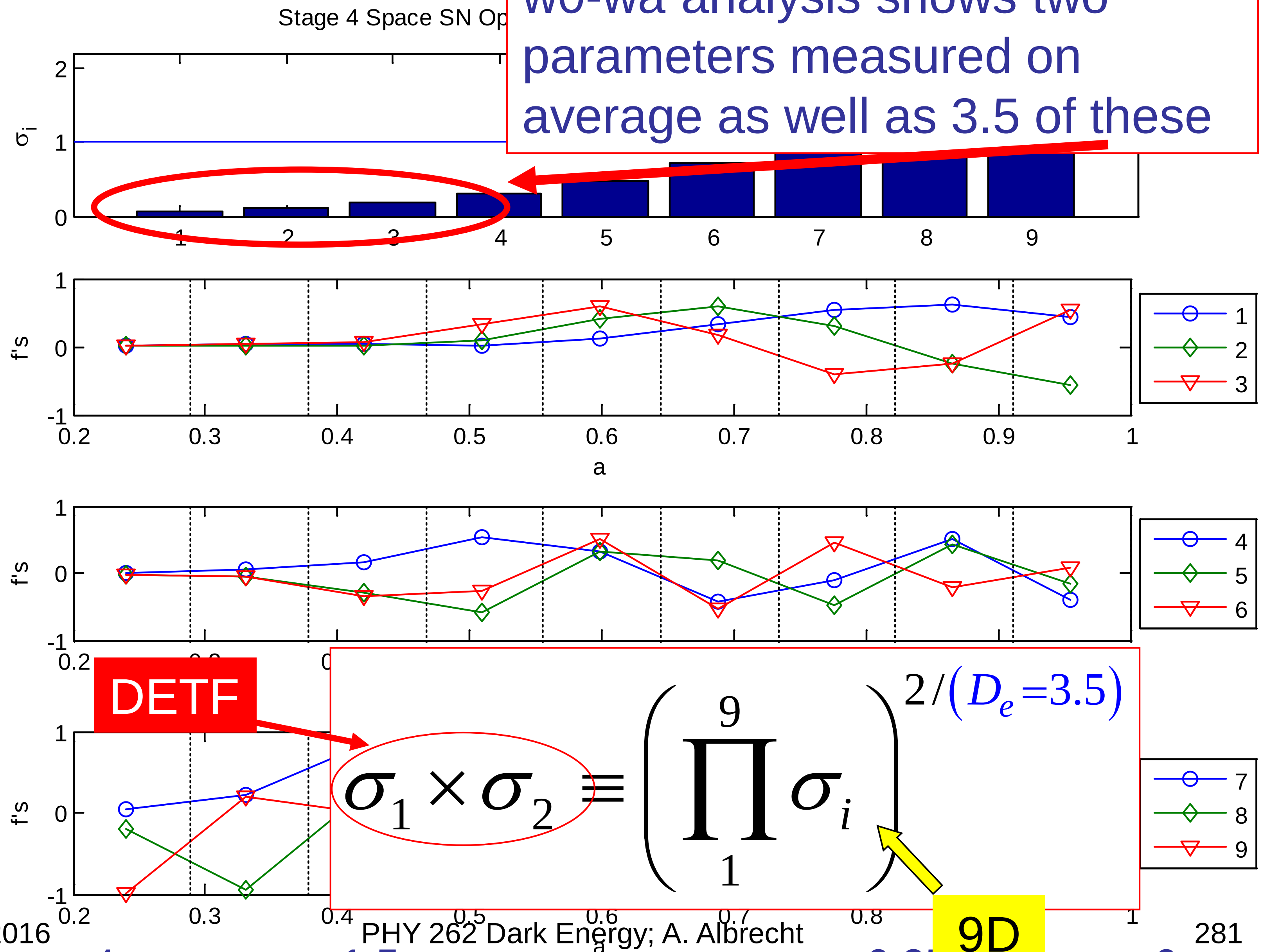
SN



z-=4 z =1.5 z =0.25 z =0

SN

w0-wa analysis shows two parameters measured on average as well as 3.5 of these

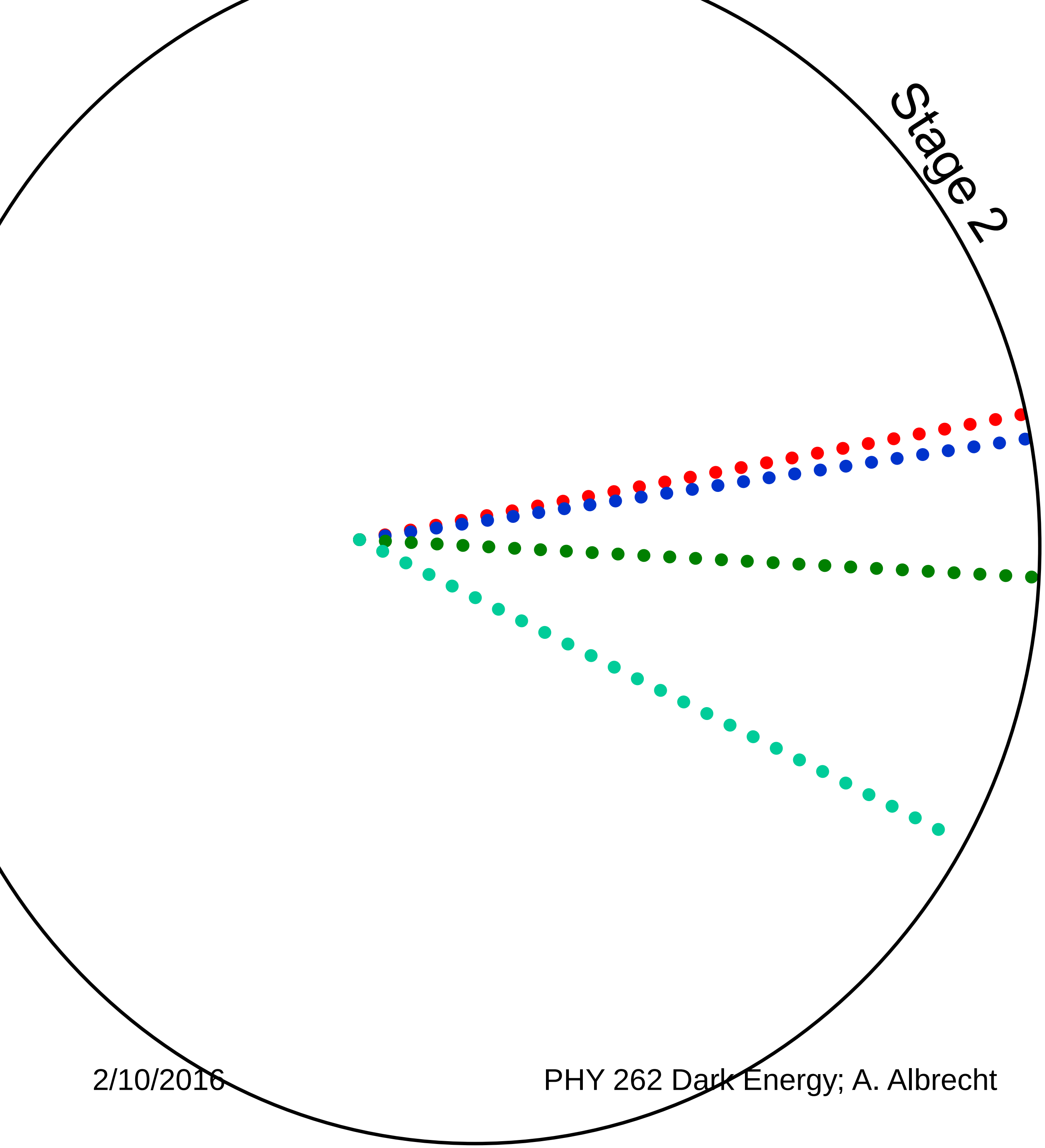


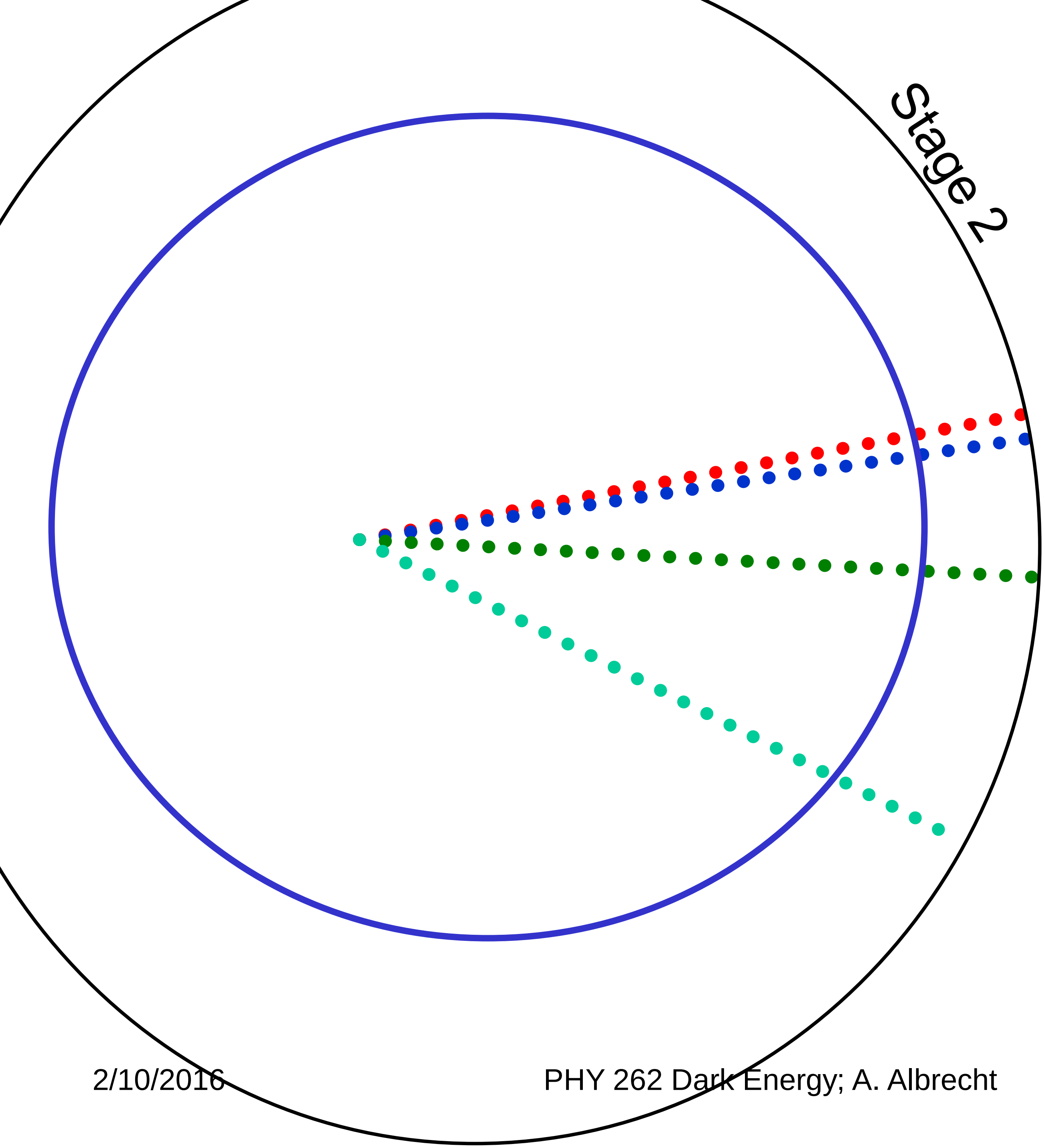
DETF

$$\sigma_1 \times \sigma_2 \equiv \left(\prod_1^9 \sigma_i \right)^{2/(D_e = 3.5)}$$

9D

z-=4 z =1.5 z =0.25 z =0


Stage 2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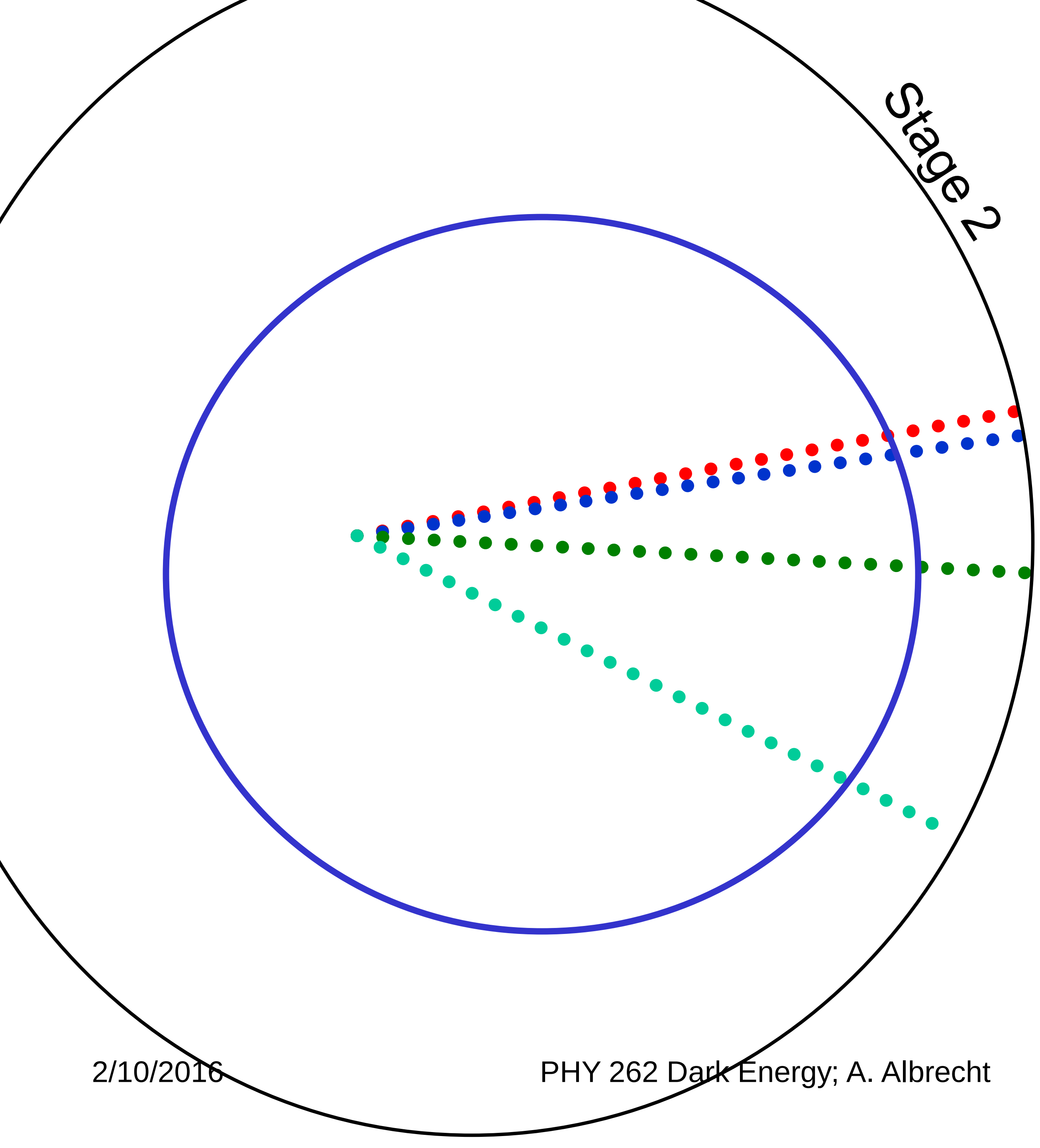
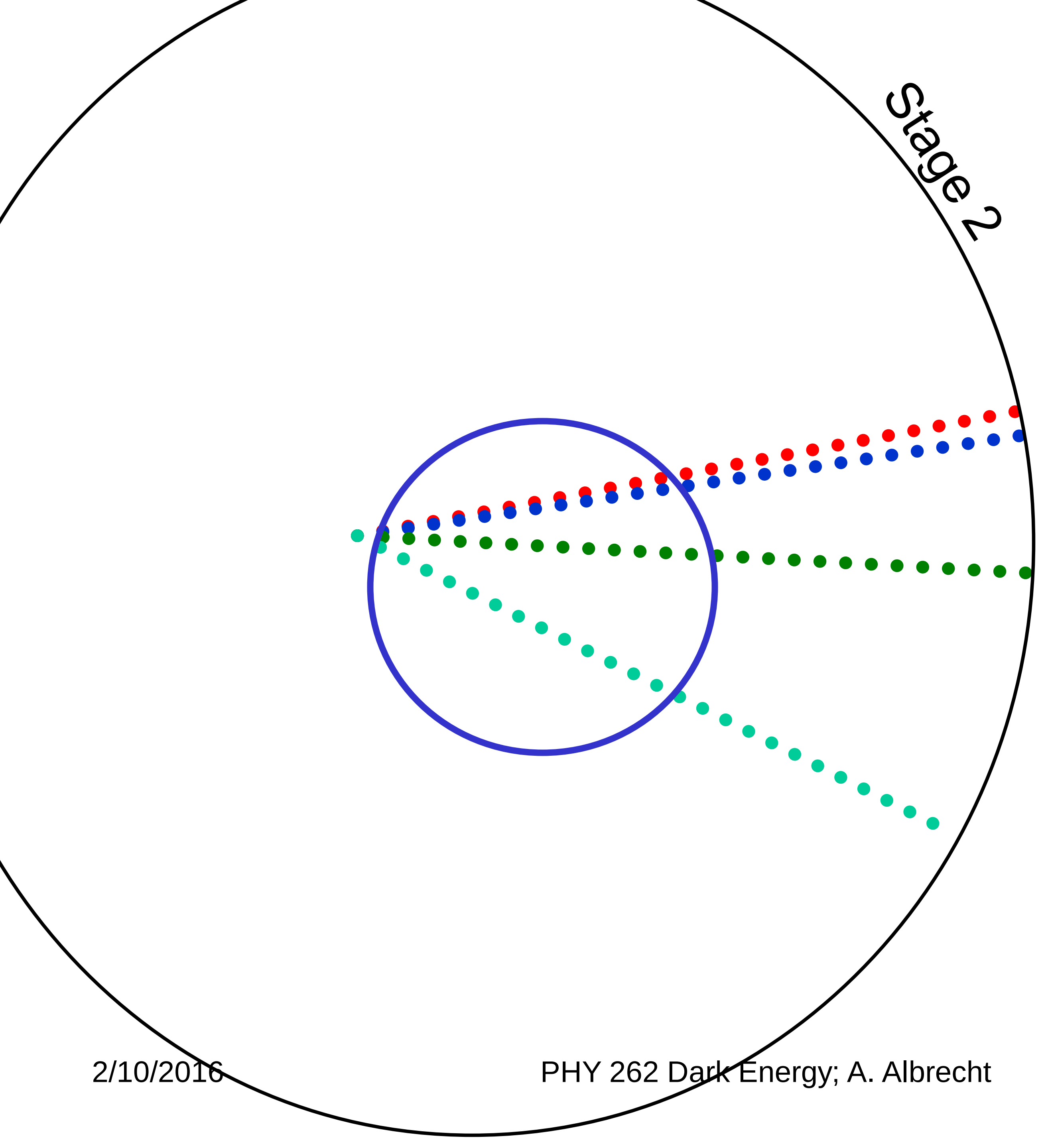
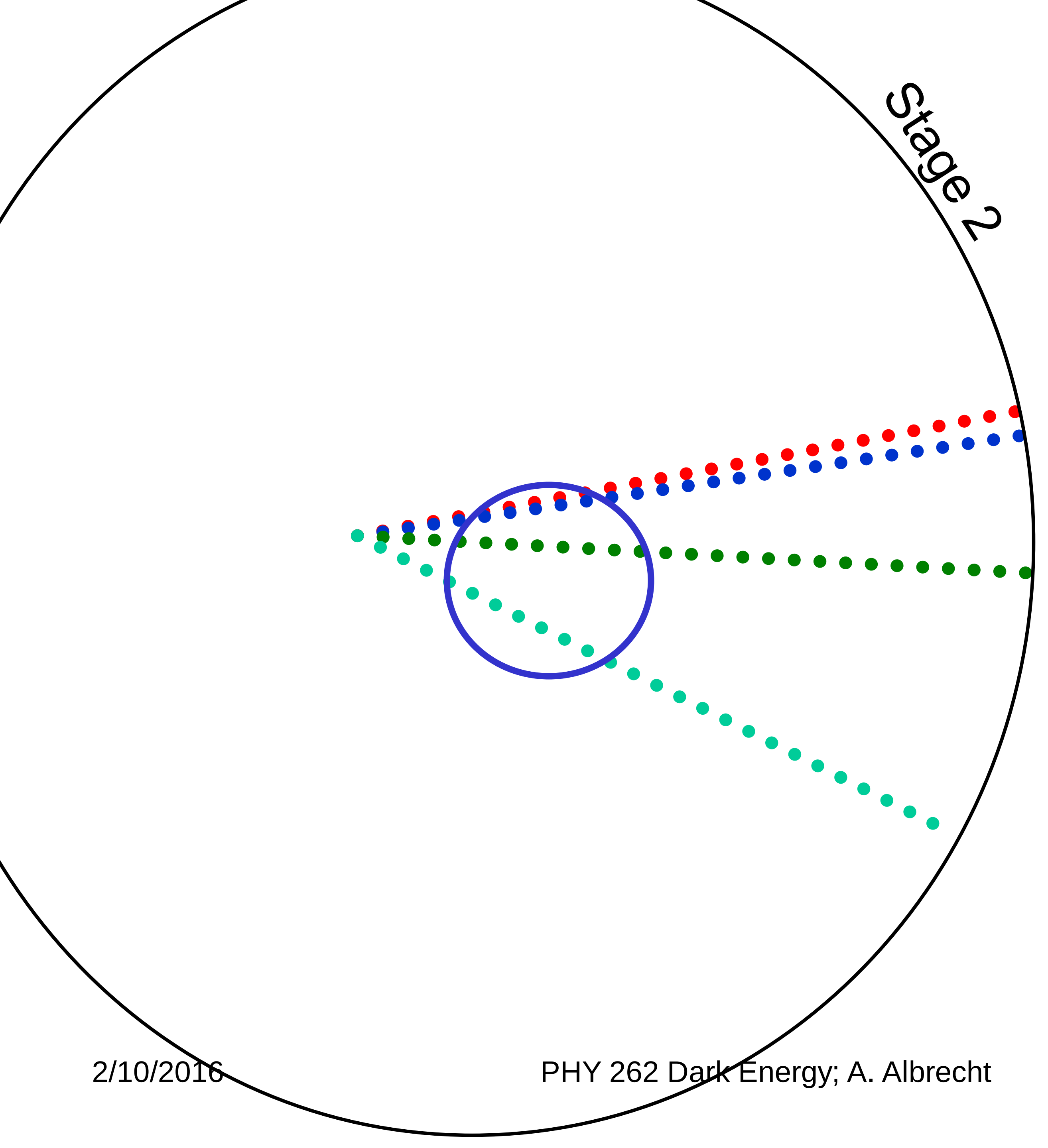
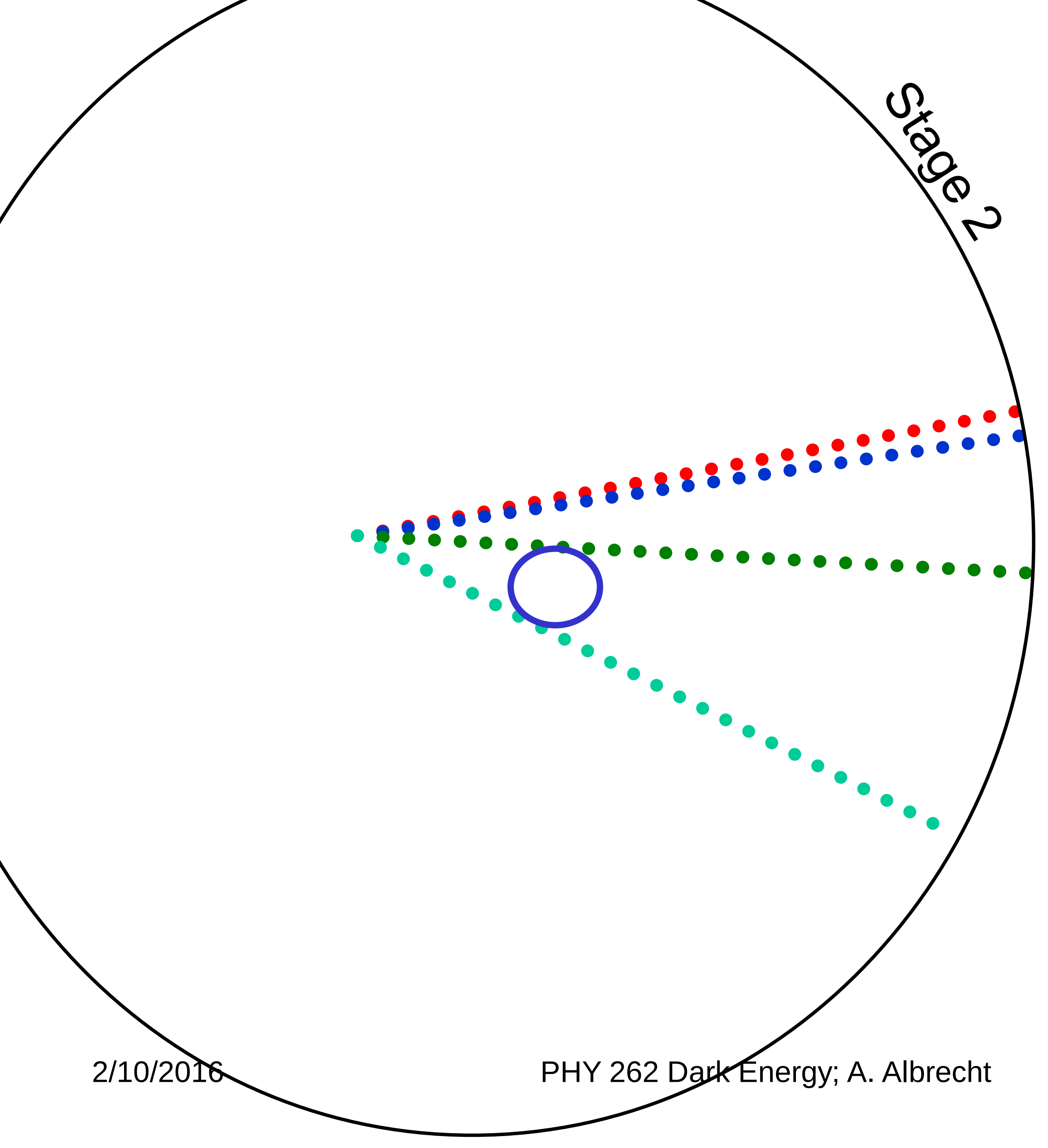
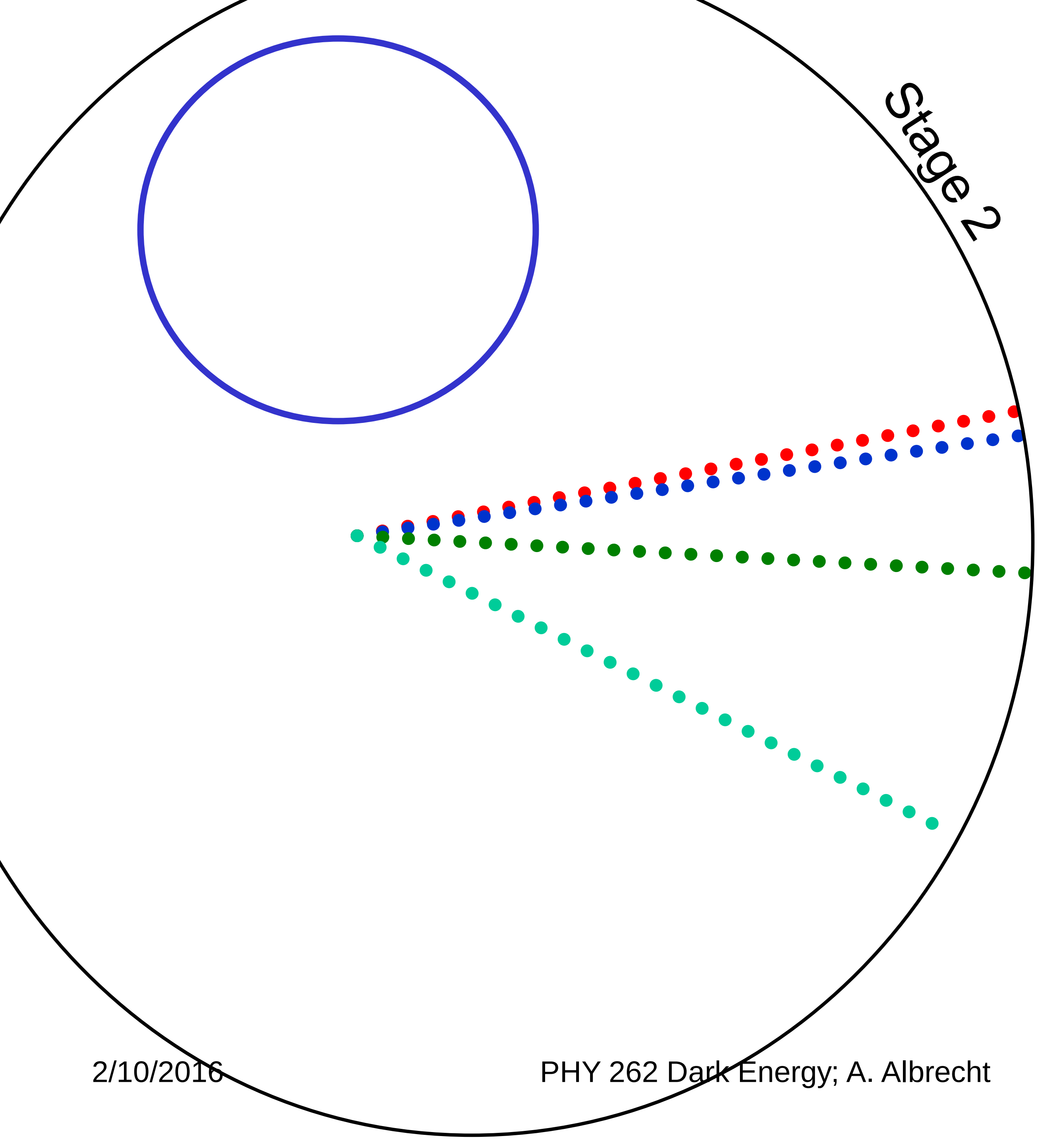

Stage 2


Stage 2

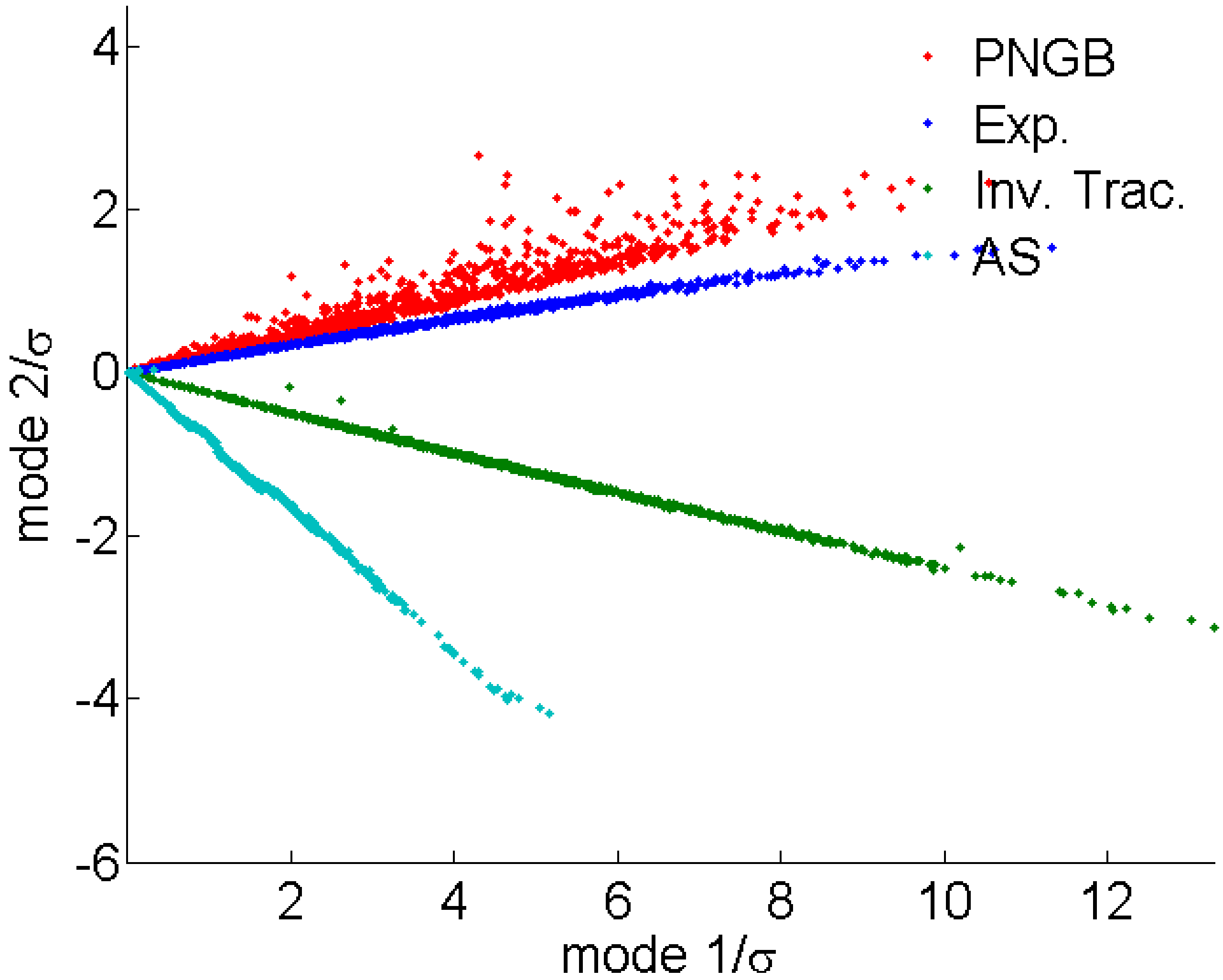

Stage 2


Stage 2


Stage 2

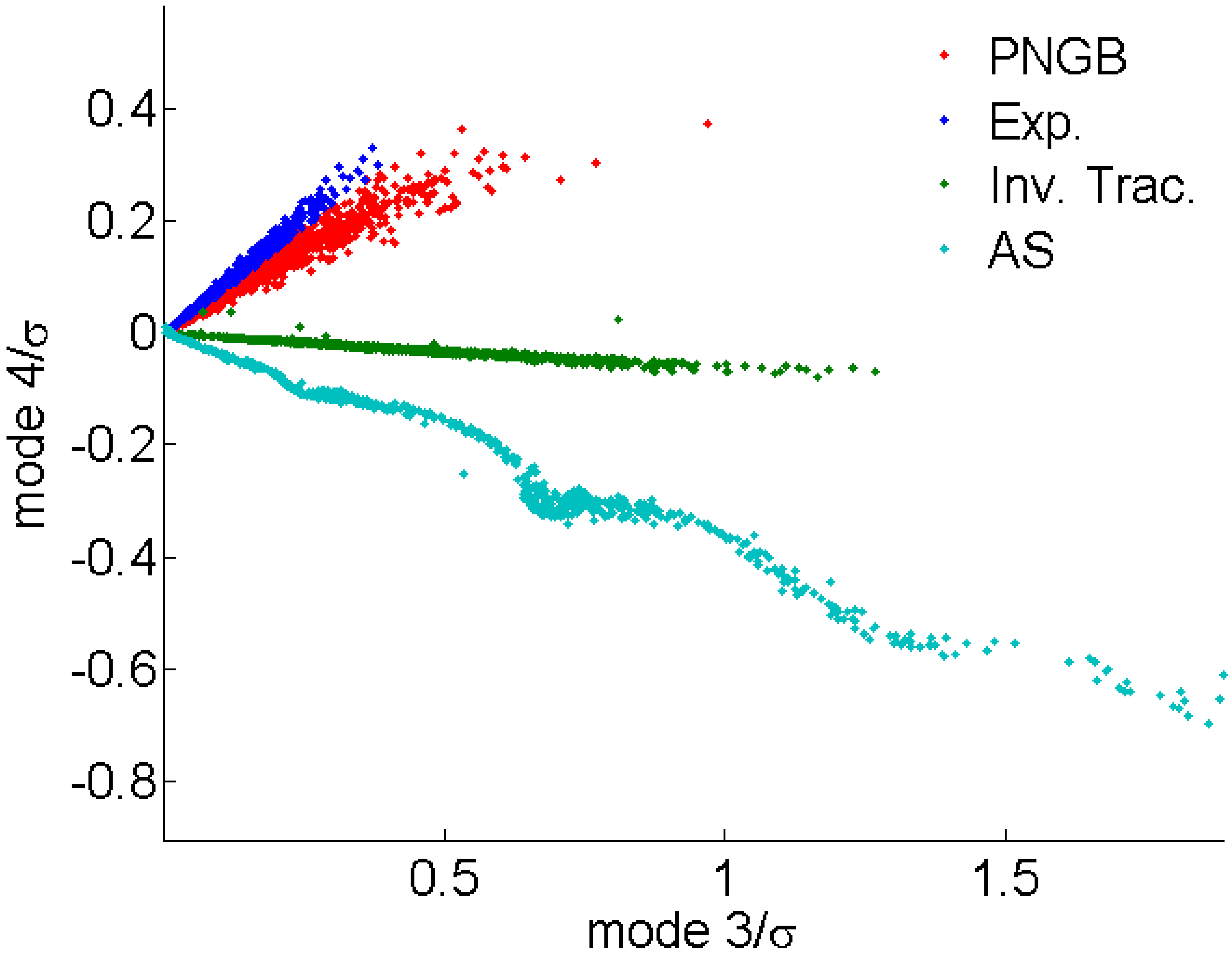
Detail: Model discriminating power

DETF Stage 4 ground [Opt]

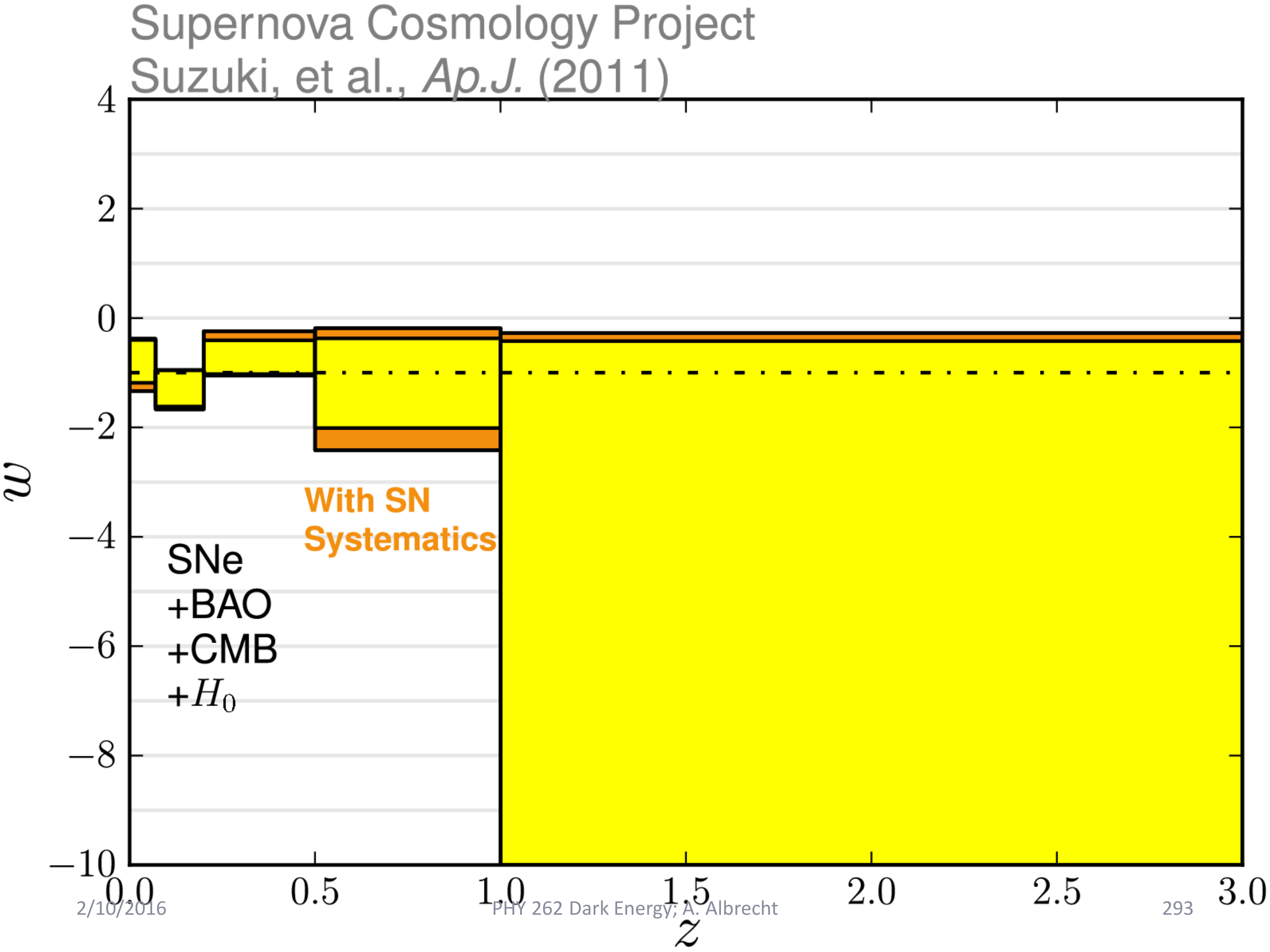


Axes: 1st and 2nd best measured w(z) modes

DETF Stage 4 ground [Opt]



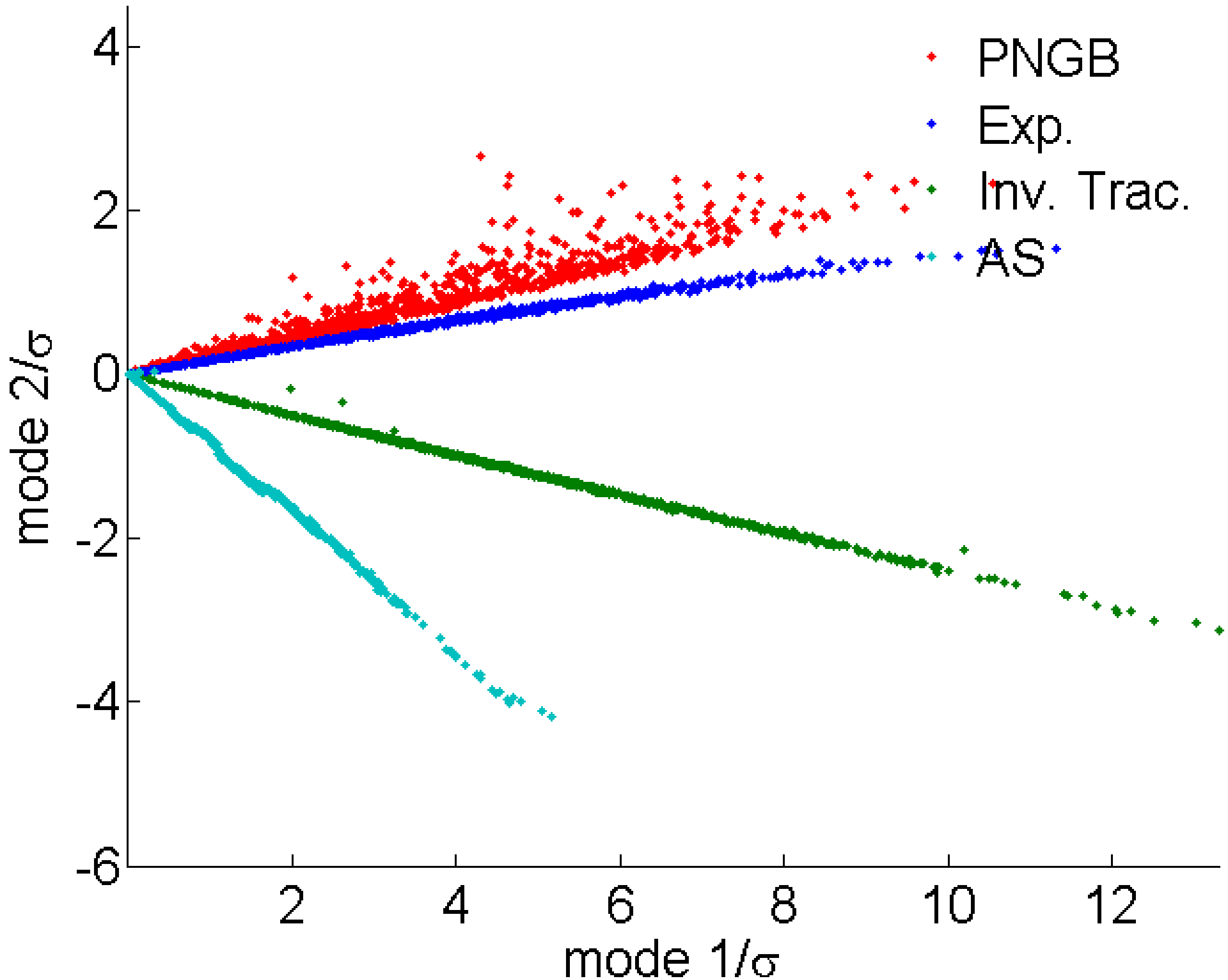
Axes: 3rd and 4th best measured w(z) modes


Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)
With SN Systematics
SNe
+BAO
+CMB
$+H_0$
w
z
4
2
0
−2
−4
−6
−8
−10
0.0
0.5
1.0
1.5
2.0
2.5
3.0

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 4 ground [Opt]

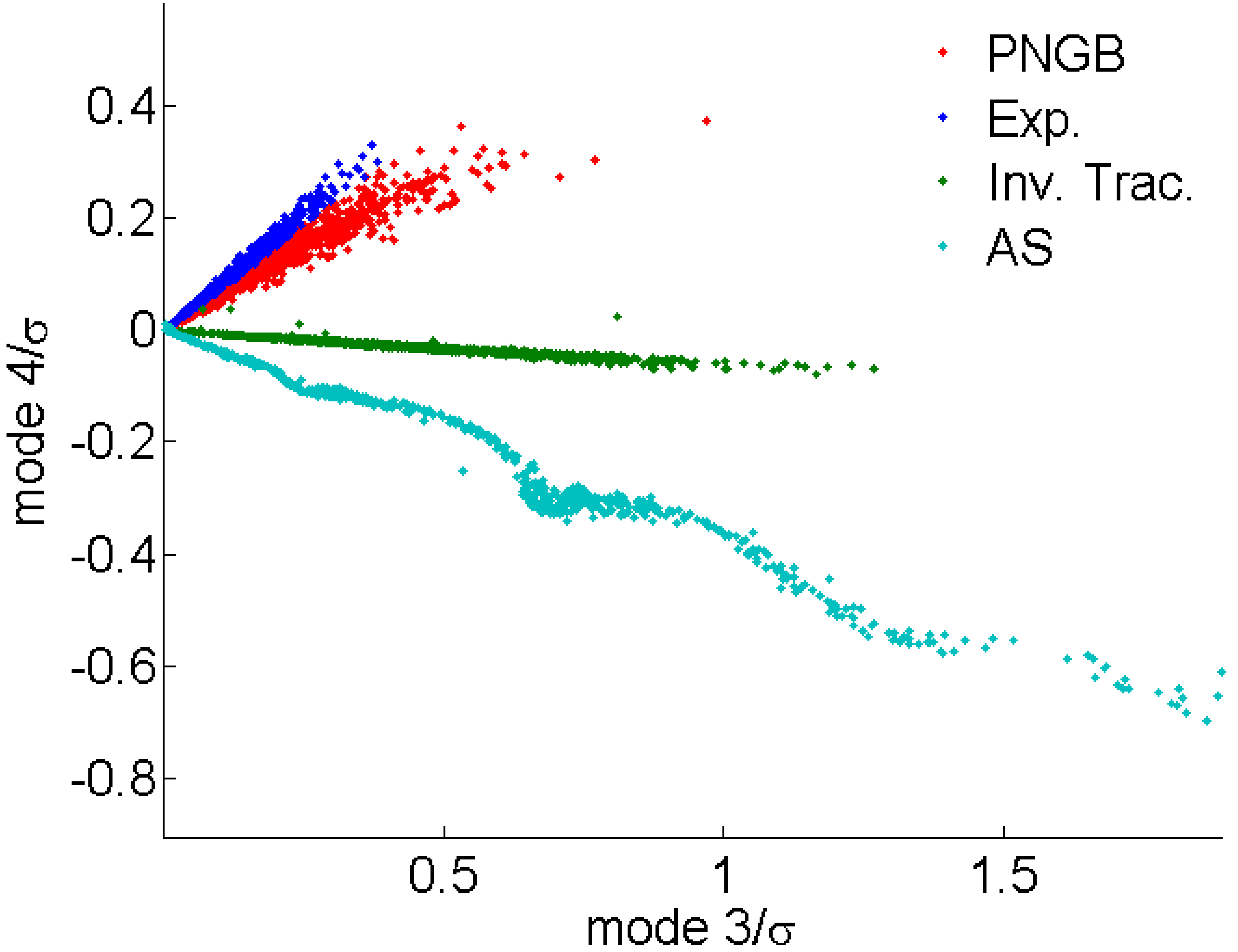
c_2 / σ_2



c_1 / σ_1

$$\Delta\vec{w} = \sum_i c_i \vec{f}_i$$

DETF Stage 4 ground [Opt]



c_4 / σ_4

c_3 / σ_3