Unsolved Problems in Dark Energy

a.k.a. Everything

Wayne Hu

Benasque, February 2011

Said the great Spanish physicist Raul Jimenez (in Americanized paraphrase):

> “Better Lame than Late”
>
> – circa 24 hrs ago

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“Better Lame than Late”

– circa 24 hrs ago

or the A delayed Session = Cut the F***ing Time correspondence

Prolific Participants: $p+\bar{p} \rightarrow ?$ Hitoshi says 2 in billion survive!

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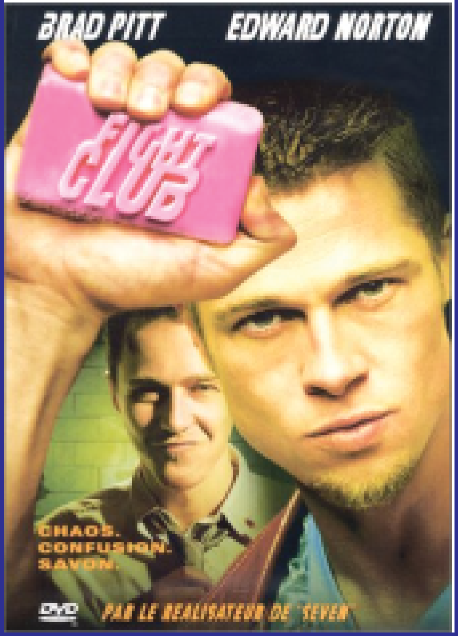
Observational to Do List

- Just 3 things (from a theorist’s perspective)
  1. Falsify (flat) ΛCDM
  2. Falsify (flat) ΛCDM
  3. Falsify (flat) ΛCDM



ΛCDM

How to Falsify

Test the consistency of ΛCDM in parameter space

- Expand parameter space or take alternate models
- MCMC set of parameters, find evidence for tension with ΛCDM
- Good - well defined, optimal if models well motivated
- Bad - there are no well motivated alternatives to Λ (cf. Sundrum's IQ Test)
- FOM (aka FML) and other elements of the Dark Energy Canon (Andrew Liddle and the New Bayesian Testament)

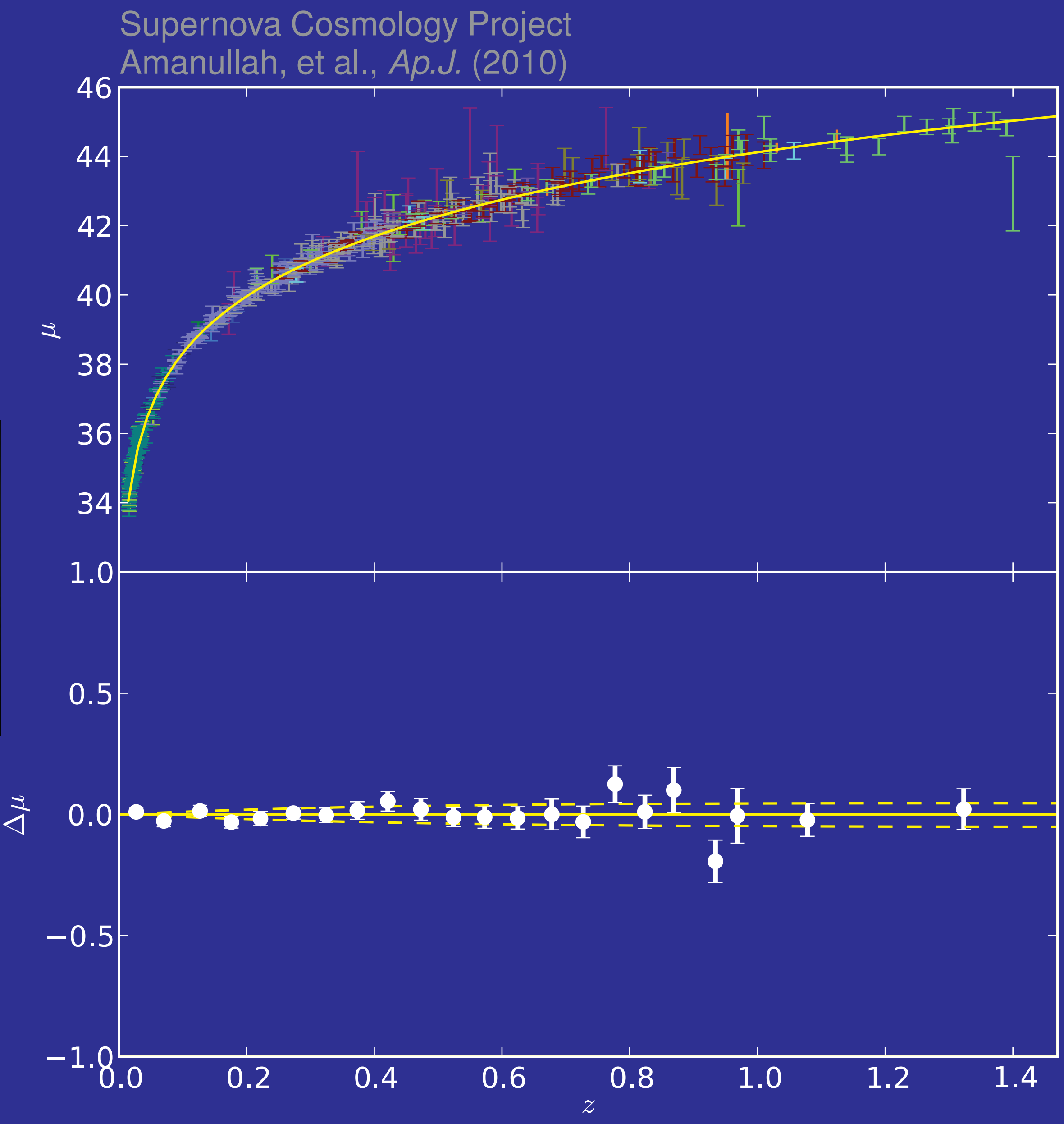
Test consistency in observable space

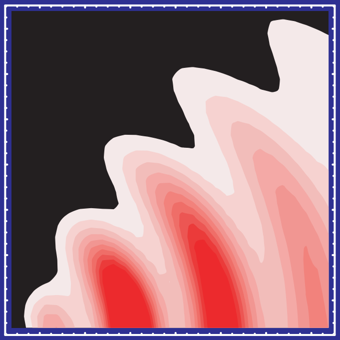
- MCMC in ΛCDM (or other complete paradigm like quintessence) and predict posteriors of new observables
- Good - theory says what best to observe to falsify ΛCDM
- Bad - falsify in favor of what?

Falsifying ΛCDM

- Geometric measures of distance redshift from SN, CMB, BAO

Standard(izable)
Candle
Supernovae
Luminosity v Flux

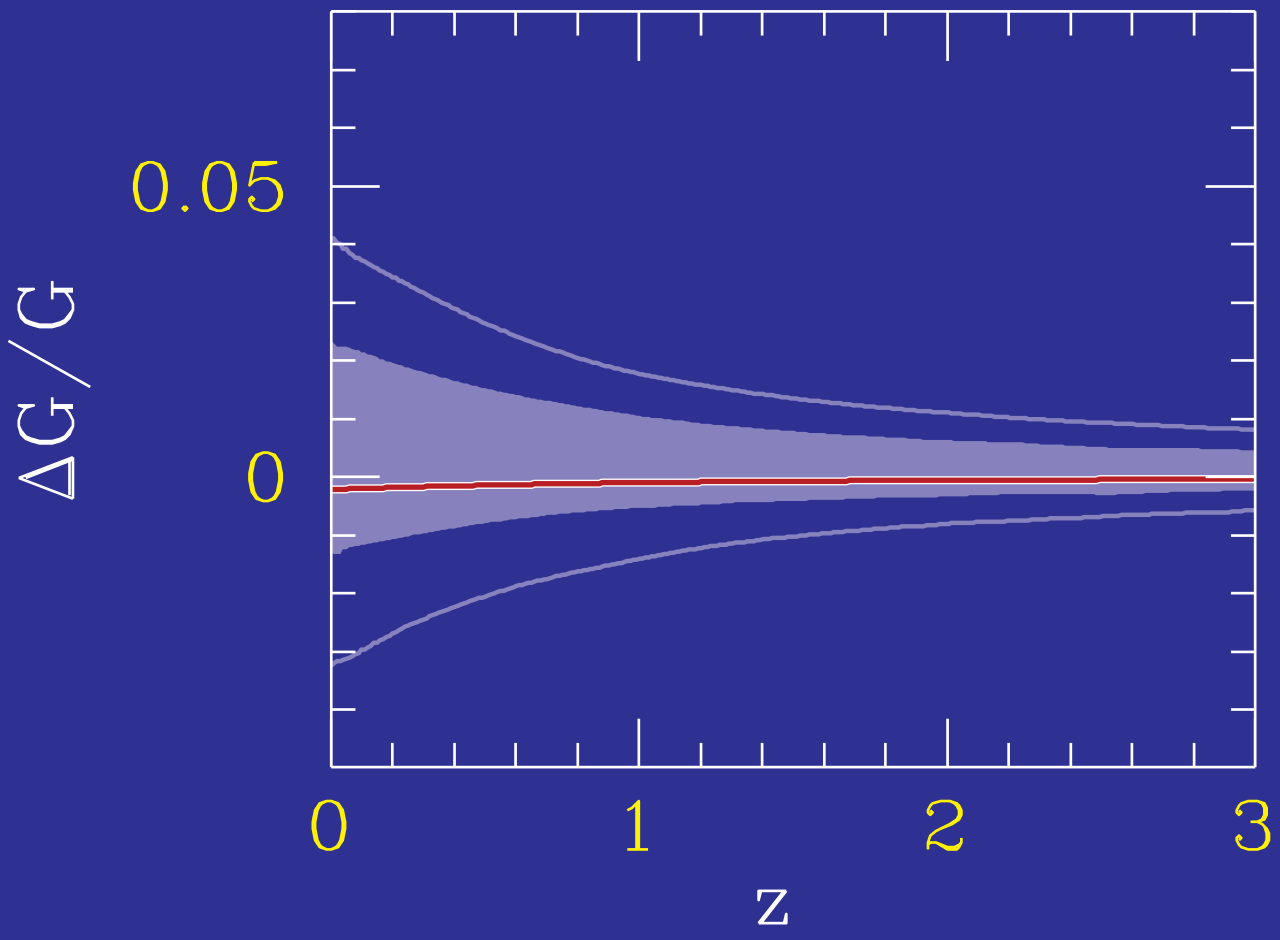




Standard Ruler
Sound Horizon
v CMB, BAO angular
and redshift separation

Falsifying ΛCDM

- Λ slows growth of structure in highly predictive way



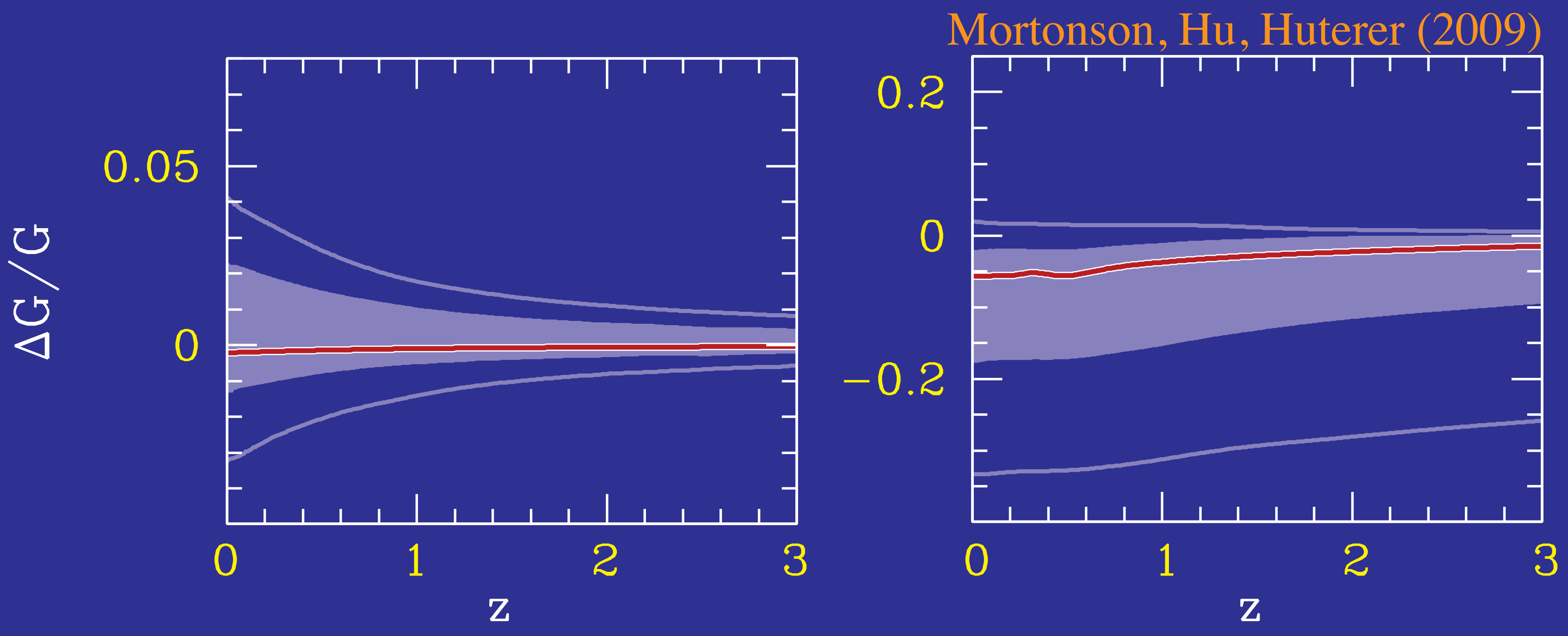
Cosmological Constant

Falsifiability of Smooth Dark Energy

- With the smoothness assumption, dark energy only affects gravitational growth of structure through changing the expansion rate
- Hence geometric measurements of the expansion rate predict the growth of structure
  - Hubble Constant
  - Supernovae
  - Baryon Acoustic Oscillations
- Growth of structure measurements can therefore falsify the whole smooth dark energy paradigm
  - Cluster Abundance
  - Weak Lensing
  - Velocity Field (Redshift Space Distortion)

Falsifying Quintessence

- Dark energy slows growth of structure in highly predictive way



Cosmological Constant

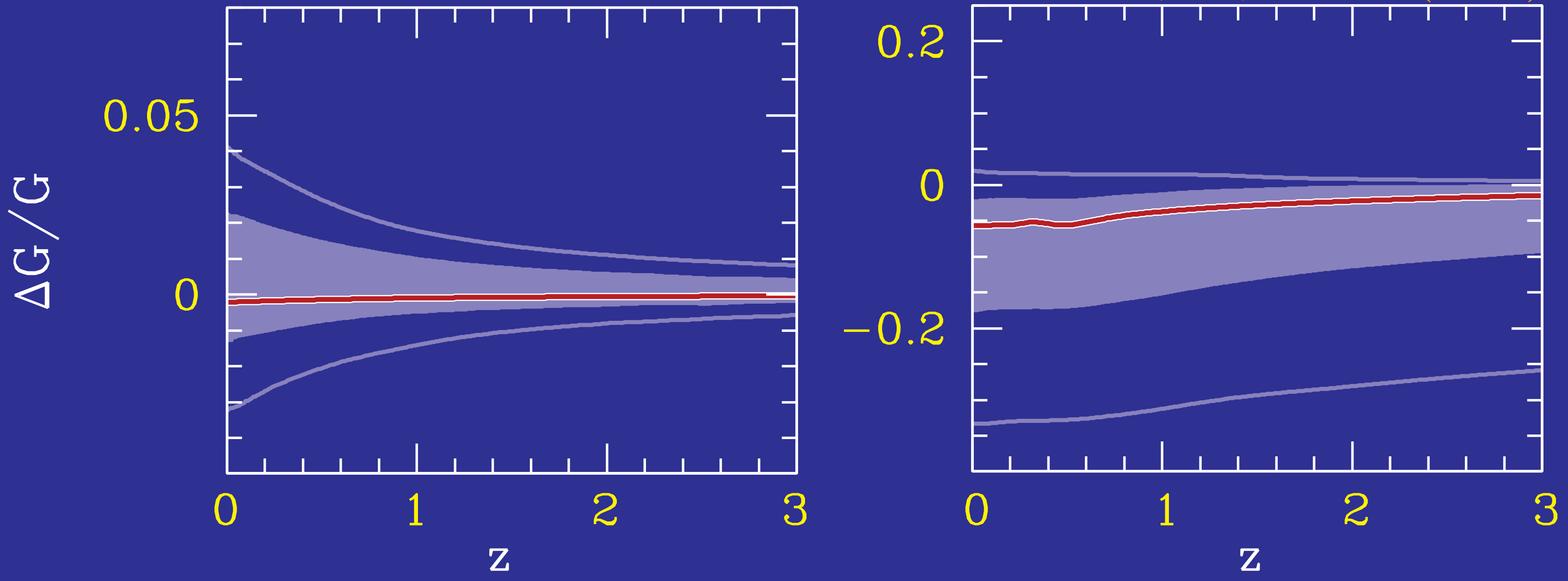
Quintessence

- Deviation significantly >2% rules out Λ with or without curvature
- Excess >2% rules out quintessence with or without curvature and early dark energy [as does >2% excess in H_0]

Dynamical Tests of Acceleration

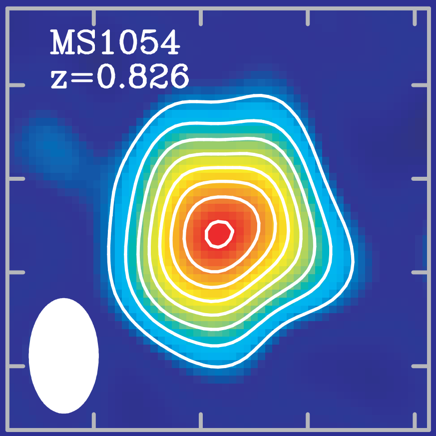
- Dark energy slows growth of structure in highly predictive way

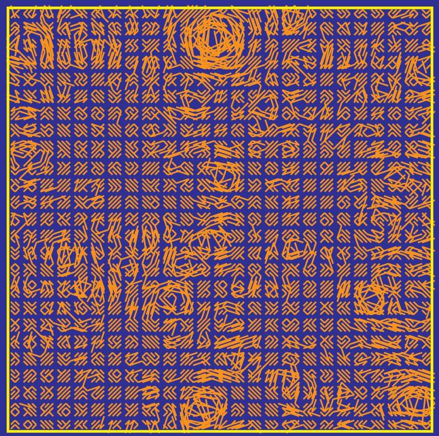
Mortonson, Hu, Huterer (2009)

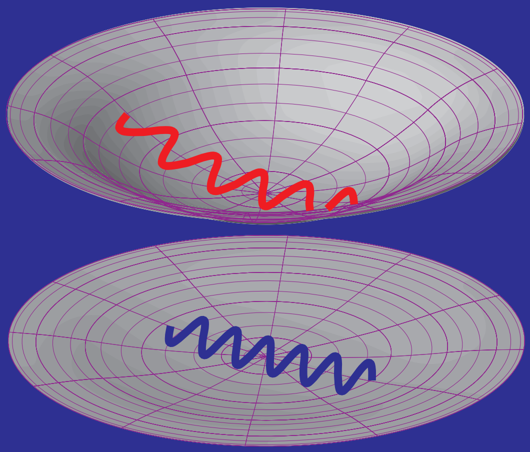


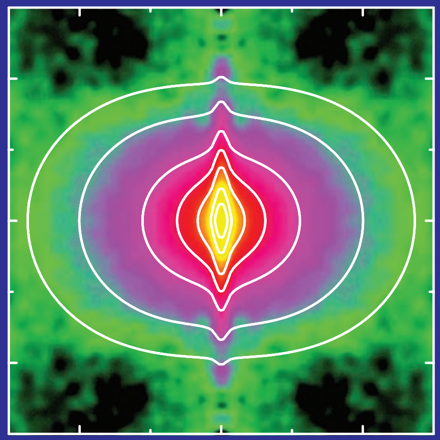
Cosmological Constant

Quintessence



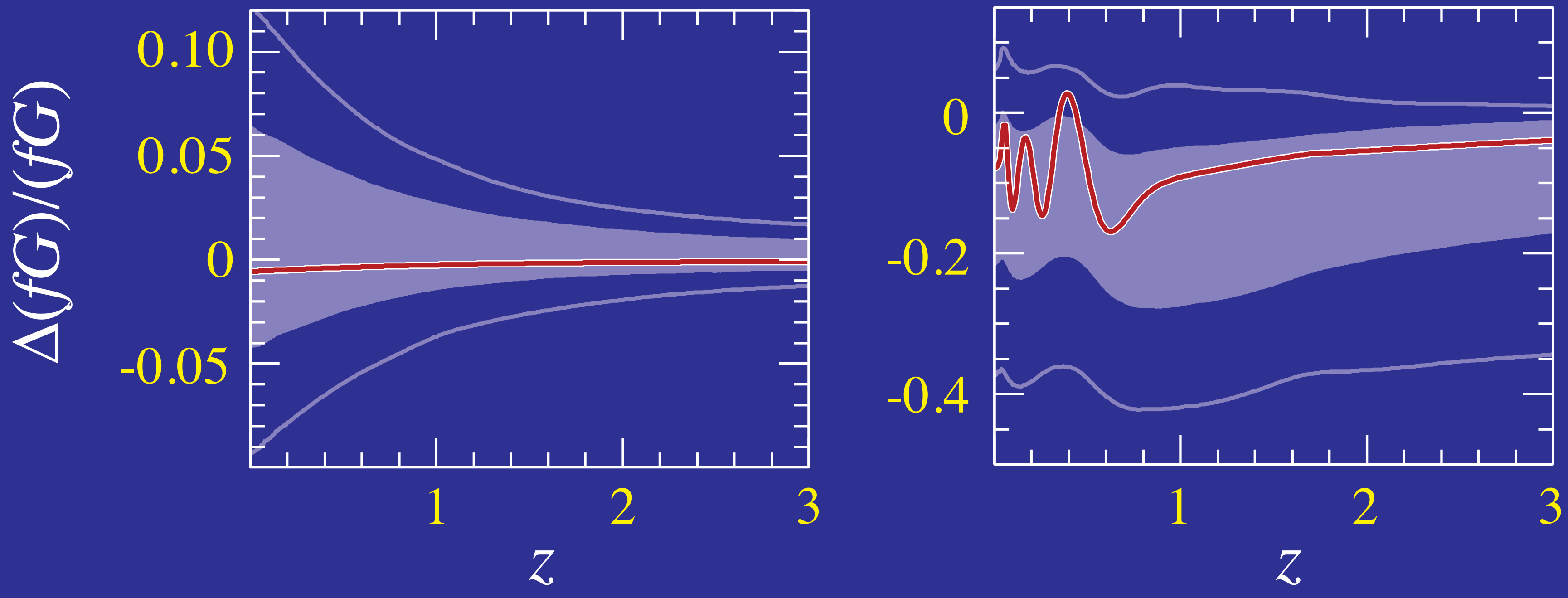






Redshift Space Distortion

- Redshift space distortions measure fG or $f\sigma_8$
- Measurements in excess of ~5% of ΛCDM would rule out quintessence

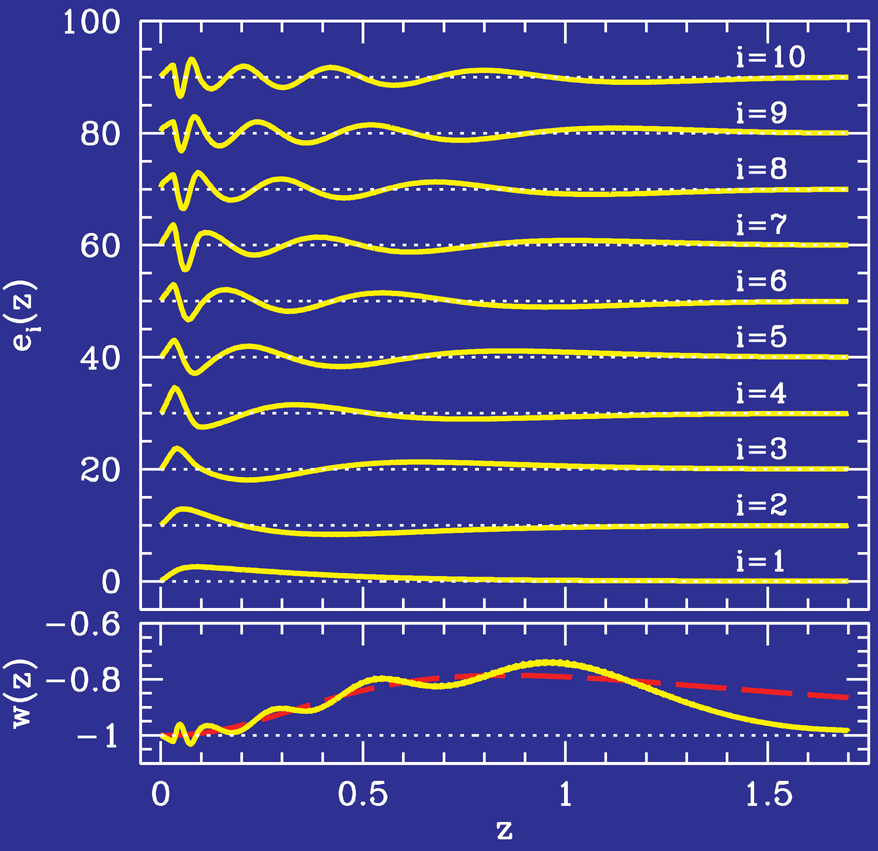


Cosmological Constant Quintessence

Mortonson, Hu, Huterer (2009)

NonPC Caveats on PCs

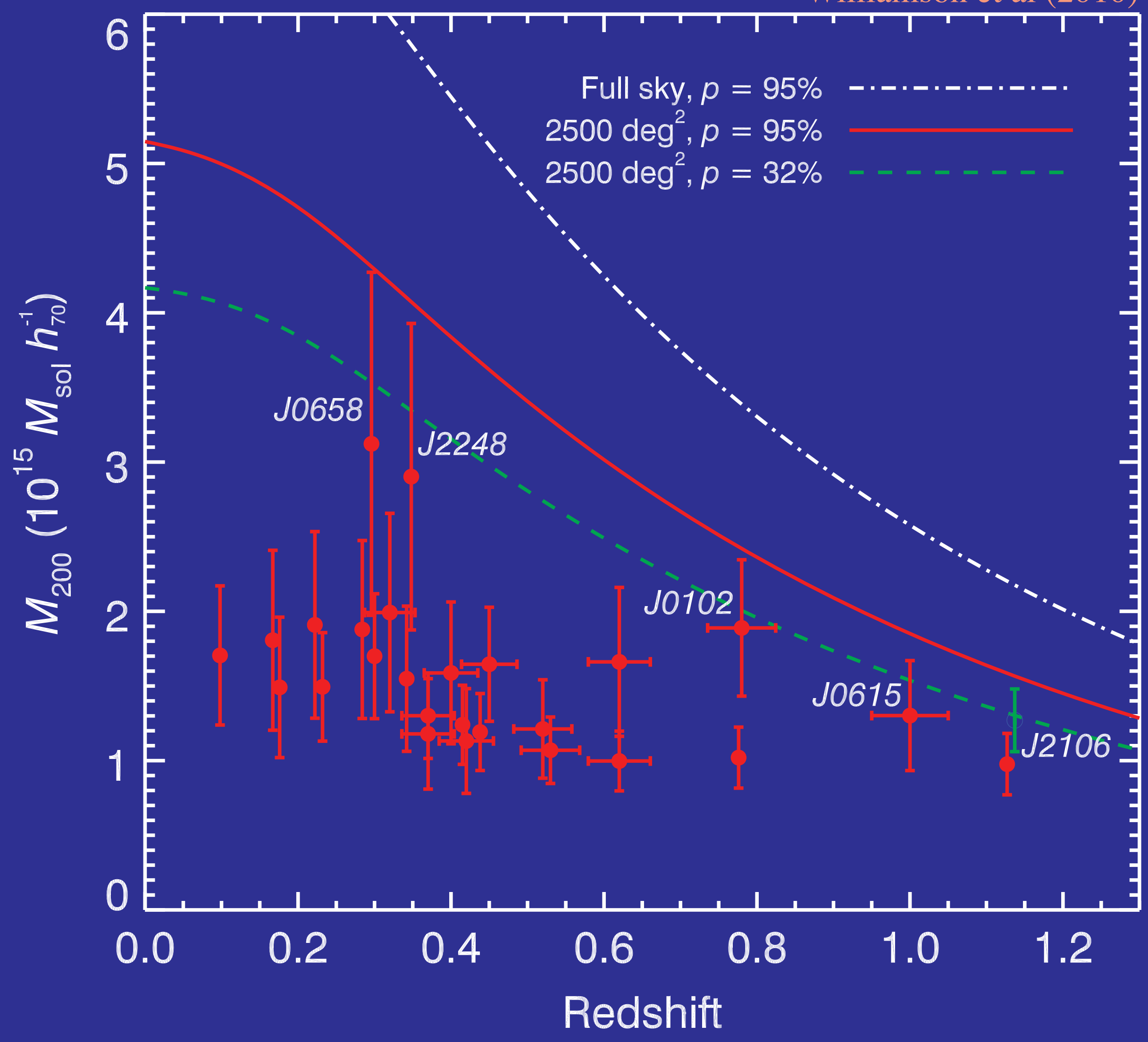
- Principal component decomposition of *w(z)* shows many components can in principle be measured (Euclid, LSST, WFirst)
- Yet even models like Albrecht-Skordis (oscillating *w*) are still dominated by first component - average *w* or pivot - plus 1-2 weaker
- Should a multidimensional parameterization be the basis for optimizing an experiment?



Pink Elephant Parade

- Too early too soon? SPT catalogue on 2500 sq degrees

Williamson et al (2010)



Falisification Criteria

Mortonson, Hu, Huterer (2010)

Holz & Perlmutter (2010)

Other Analyses

Hoyle, Jiminez, Verde (2010)

many others...

Systematics, Systematics, Systematics

- E.g.: clusters - mass calibration from X-ray, SZ, optical, lensing

Systematics, Systematics, Systematics

- Coffee talk: discuss amongst yourselves

Phenomenological To Do List

- How best to parameterize consistency tests or define theoretically predicted observables?
- How to treat baryonic effects in the non-linear regime e.g.
  - Galaxy occupation of halos [BAO, velocity field tests]
  - Concentration of clusters for cosmic shear

  Extensive simulations + modelling of gastrophysics including star formation (see Brant, Licia, Volker's talks)
- Calibrate non-linear mean and covariance of dark energy observables as function of cosmological parameters (Volker's talk)
- Simulate alternate models
  - (Kill) inhomogeneous models
  - Interacting dark matter-energy models
  - Modified gravity models

Modified Gravity = Dark Energy?

- Solar system tests of gravity are informed by our knowledge of the local stress energy content
- With no other constraint on the stress energy of dark energy other than conservation, modified gravity is formally equivalent to dark energy

$$\begin{aligned} F(g_{\mu\nu}) + G_{\mu\nu} &= 8\pi G T^{\rm M}_{\mu\nu} \\ G_{\mu\nu} &= 8\pi G [T^{\rm M}_{\mu\nu} + T^{\rm DE}_{\mu\nu}] \end{aligned} \qquad \boxed{-F(g_{\mu\nu}) = 8\pi G T^{\rm DE}_{\mu\nu}}$$

and the Bianchi identity guarantees $\nabla^\mu T^{\rm DE}_{\mu\nu} = 0$

- Distinguishing between dark energy and modified gravity requires closure relations that relate components of stress energy tensor
- For matter components, closure relations take the form of equations of state relating density, pressure and anisotropic stress

Modified Gravity $\neq$ "Smooth DE"

- Scalar field dark energy has $\delta p = \delta\rho$ (in constant field gauge) – relativistic sound speed, no anisotropic stress
- Jeans stability implies that its energy density is spatially smooth compared with the matter below the sound horizon

$$\begin{aligned} ds^2 &= -(1+2\Psi)dt^2 + a^2(1+2\Phi)dx^2 \\ \nabla^2(\Phi-\Psi) &\propto \text{matter density fluctuation} \end{aligned}$$

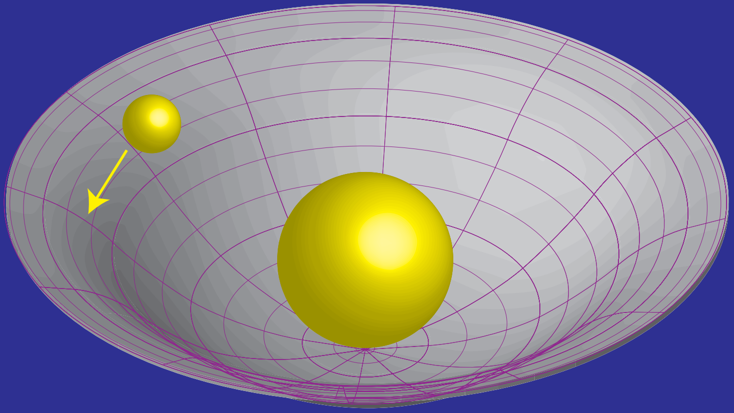
- Anisotropic stress changes the amount of space curvature per unit dynamical mass

$$\nabla^2(\Phi+\Psi) \propto \text{anisotropic stress}$$

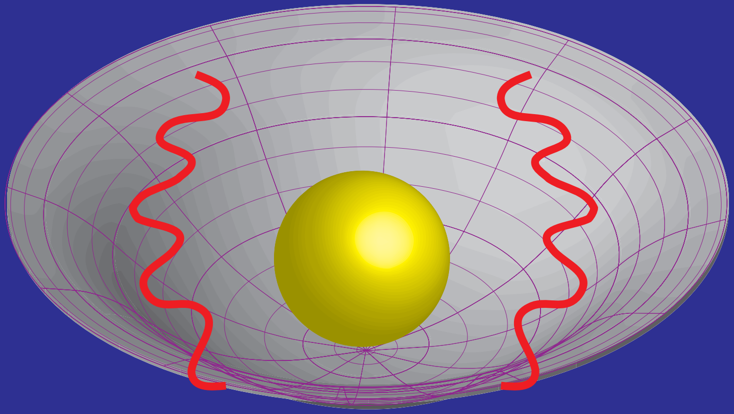
but its absence in a smooth dark energy model makes $g = (\Phi+\Psi)/(\Phi-\Psi) = 0$ for non-relativistic matter

Dynamical vs Lensing Mass

- Newtonian potential: $\Psi=\delta g_{00}/2g_{00}$ which non-relativistic particles feel



- Space curvature: $\Phi=\delta g_{ii}/2g_{ii}$ which also deflects photons

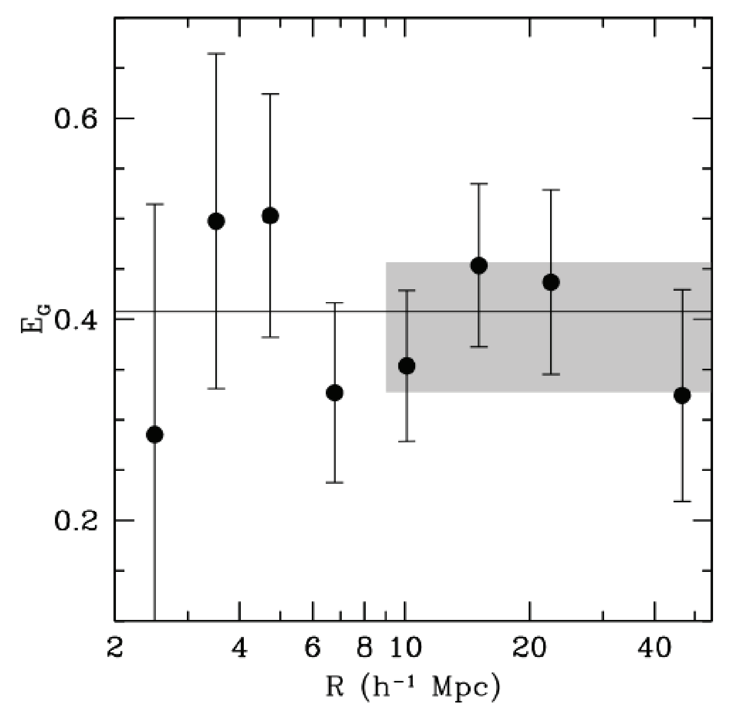


- Most of the incisive tests of gravity reduce to testing the space curvature per unit dynamical mass

Lensing v Dynamical Comparison

- Gravitational lensing around galaxies vs. linear velocity field (through redshift space distortions and galaxy autocorrelation)
- Consistent with GR + smooth dark energy beginning to test interesting models

Reyes et al (2010); Lombriser et al (2010)

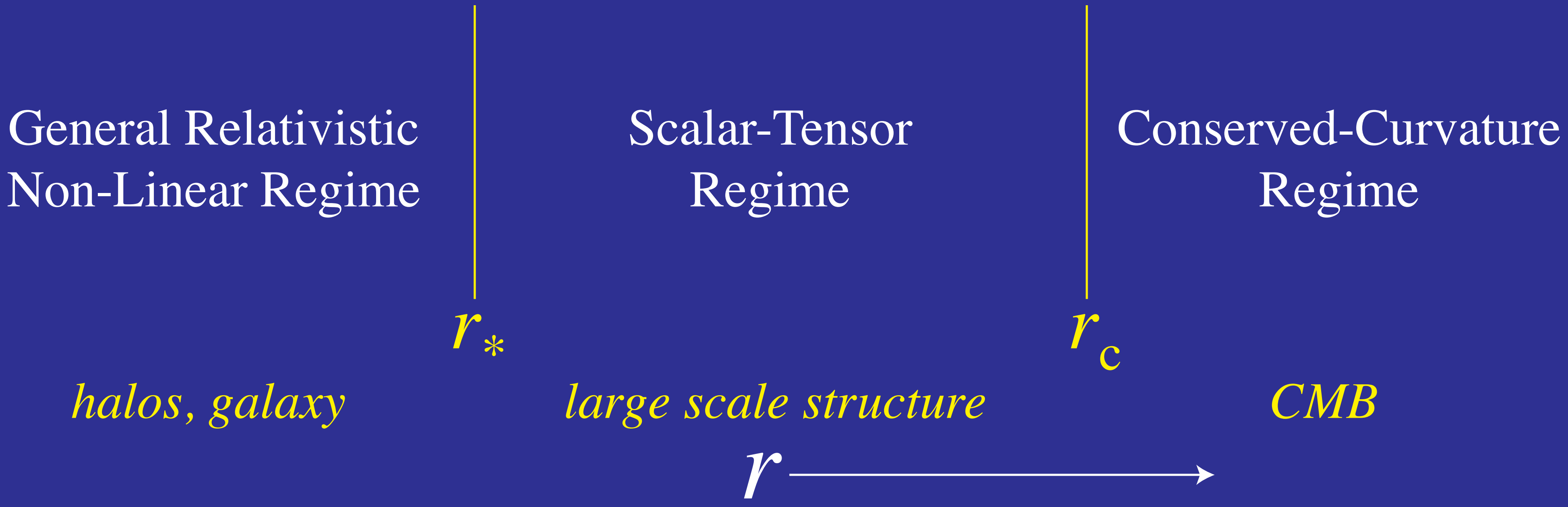


Zhang et al (2007); Jain & Zhang (2008)

Three Regimes

- Three regimes with different dynamics
- Examples *f*(*R*) and DGP braneworld acceleration
- Parameterized Post-Friedmann description

- Non-linear regime return to General Relativity / Newtonian dynamics



General Relativistic
Non-Linear Regime

r_*

Scalar-Tensor
Regime

r_c

Conserved-Curvature
Regime

halos, galaxy

large scale structure

CMB

r ⟶

Three Regimes

- Fully worked $f(R)$ and DGP examples show 3 regimes
- Superhorizon regime: ζ =const., $g(a)$
- Linear regime - closure condition - analogue of "smooth" dark energy density:

$$\begin{aligned} \nabla^2(\Phi - \Psi)/2 &= -4\pi G a^2 \Delta\rho \\ g(a, \mathbf{x}) &\leftrightarrow g(a, k) \end{aligned}$$

  G can be promoted to $G(a)$ but conformal invariance relates fluctuations to field fluctuation that is small

- Non-linear regime:

$$\begin{aligned} \nabla^2(\Phi - \Psi)/2 &= -4\pi G a^2 \Delta\rho \\ \nabla^2\Psi &= 4\pi G a^2 \Delta\rho - \frac{1}{2}\nabla^2\phi \end{aligned}$$

Nonlinear Interaction

Non-linearity in the field equation

$$\nabla^2\phi = g_{\rm lin}(a)a^2\left(8\pi G\Delta\rho - N[\phi]\right)$$

recovers linear theory if $N[\phi]\to 0$

- For $f(R)$, $\phi = f_R$ and

$$N[\phi] = \delta R(\phi)$$

a non-linear function of the field

Llinked to gravitational potential

- For DGP, ϕ is the brane-bending mode and

$$N[\phi] = \frac{r_c^2}{a^4}\left[(\nabla^2\phi)^2 - (\nabla_i\nabla_j\phi)^2\right]$$

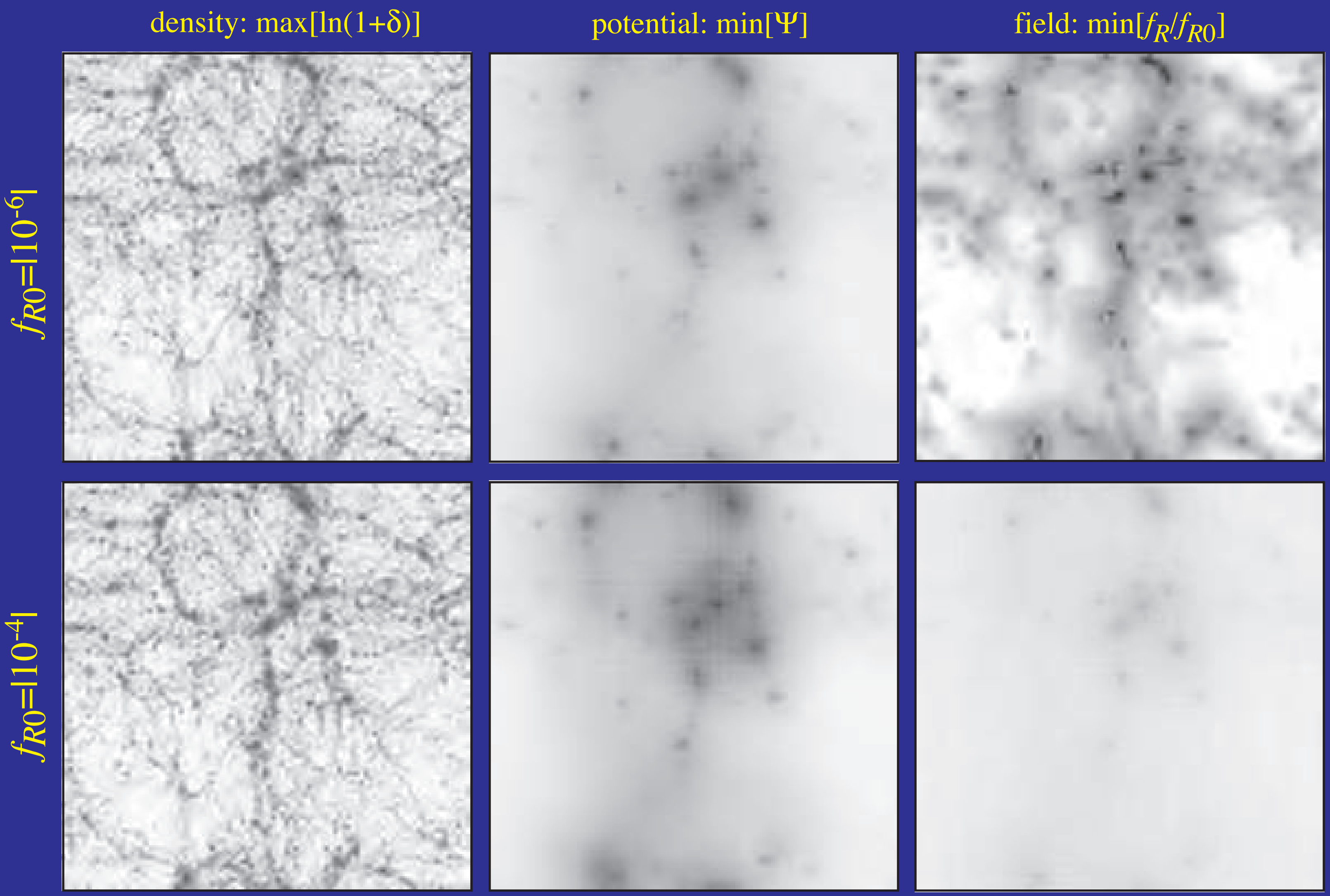
a non-linear function of second derivatives of the field

Linked to density fluctuation

Example of Galileon invariance

Environment Dependent Force

- For large background field, gradients in the scalar prevent the chameleon from appearing

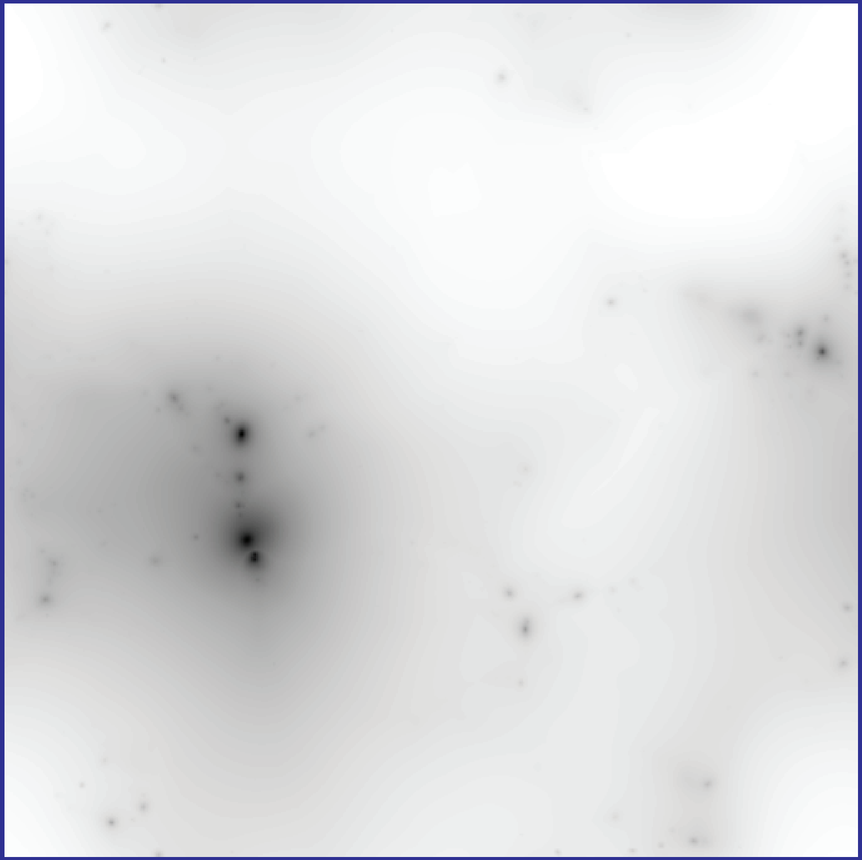


Oyaizu, Lima, Hu (2008)

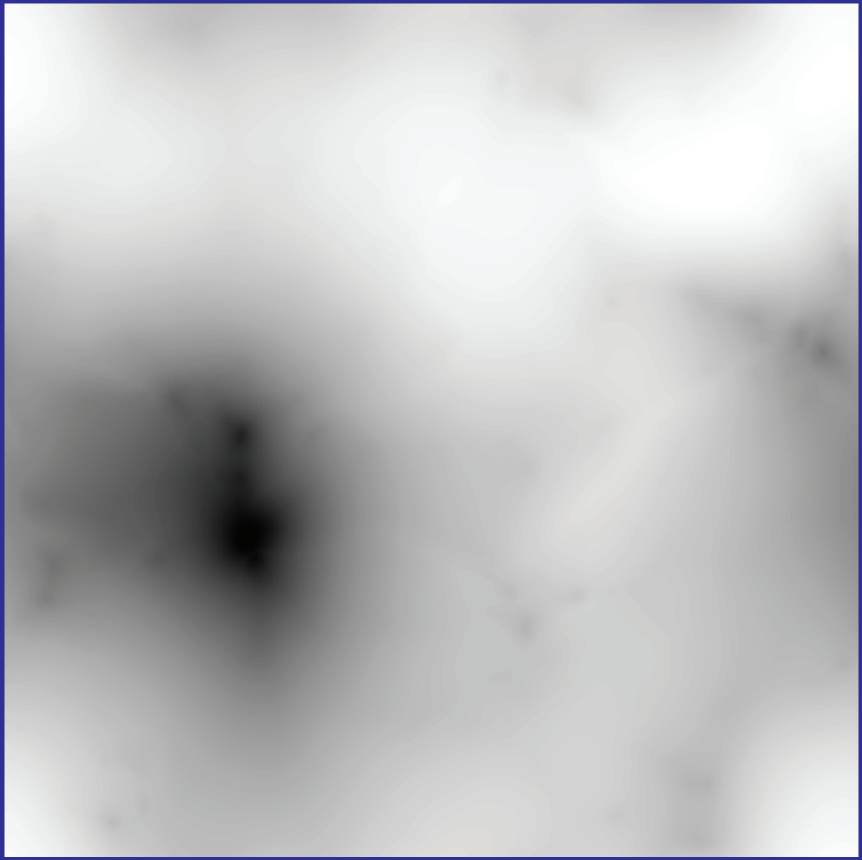
DGP N-Body

- DGP nonlinear derivative interaction solved by relaxation revealing the Vainshtein mechanism

Newtonian Potential



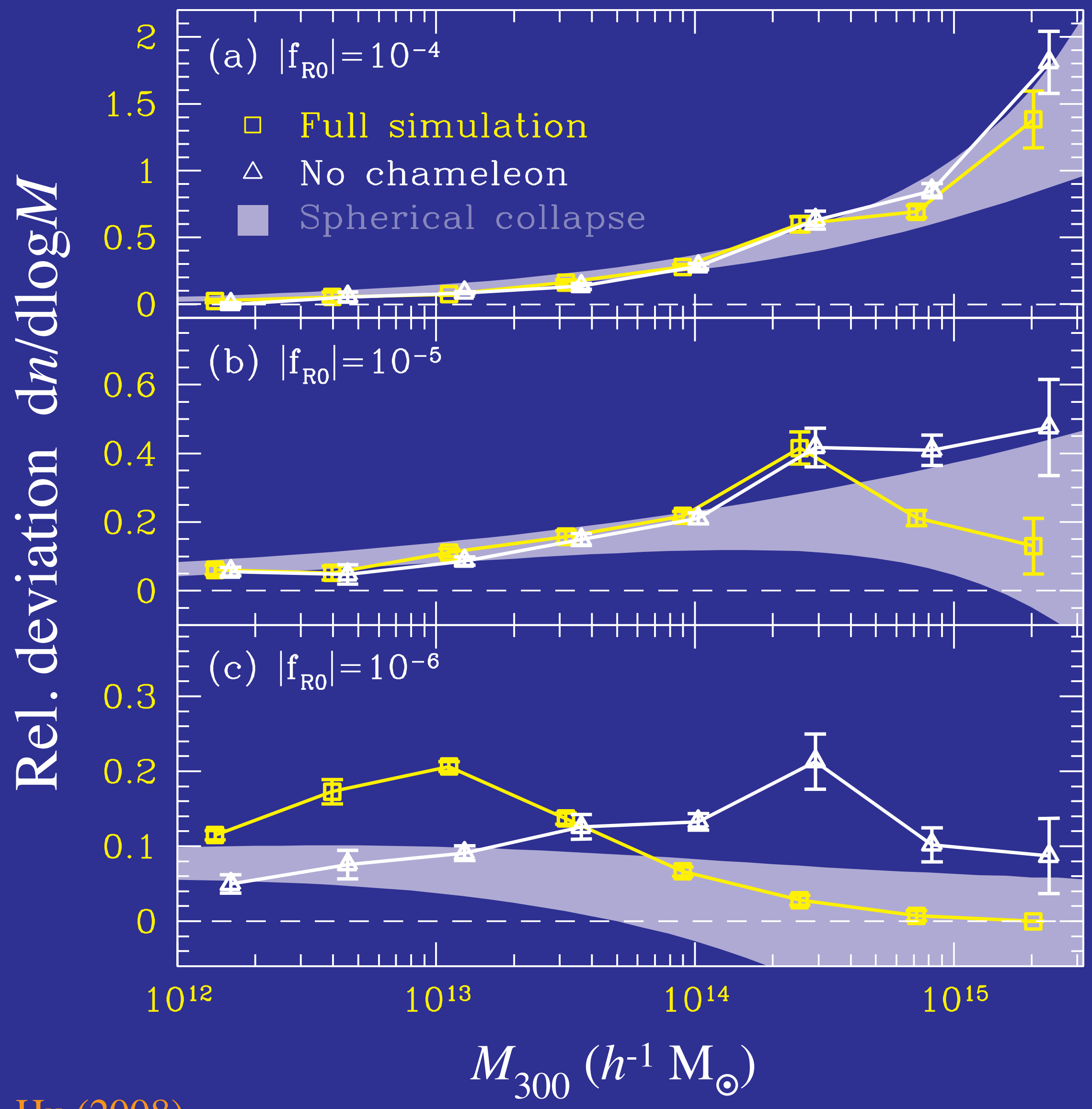
Brane Bending Mode



Schmidt (2009); Chan & Scoccimarro (2009) (cf. Khoury & Wyman 2009)

Mass Function

- Enhanced abundance of rare dark matter halos (clusters) with extra force goes away as non-linearity increases



Schmidt, Lima, Oyaizu, Hu (2008)

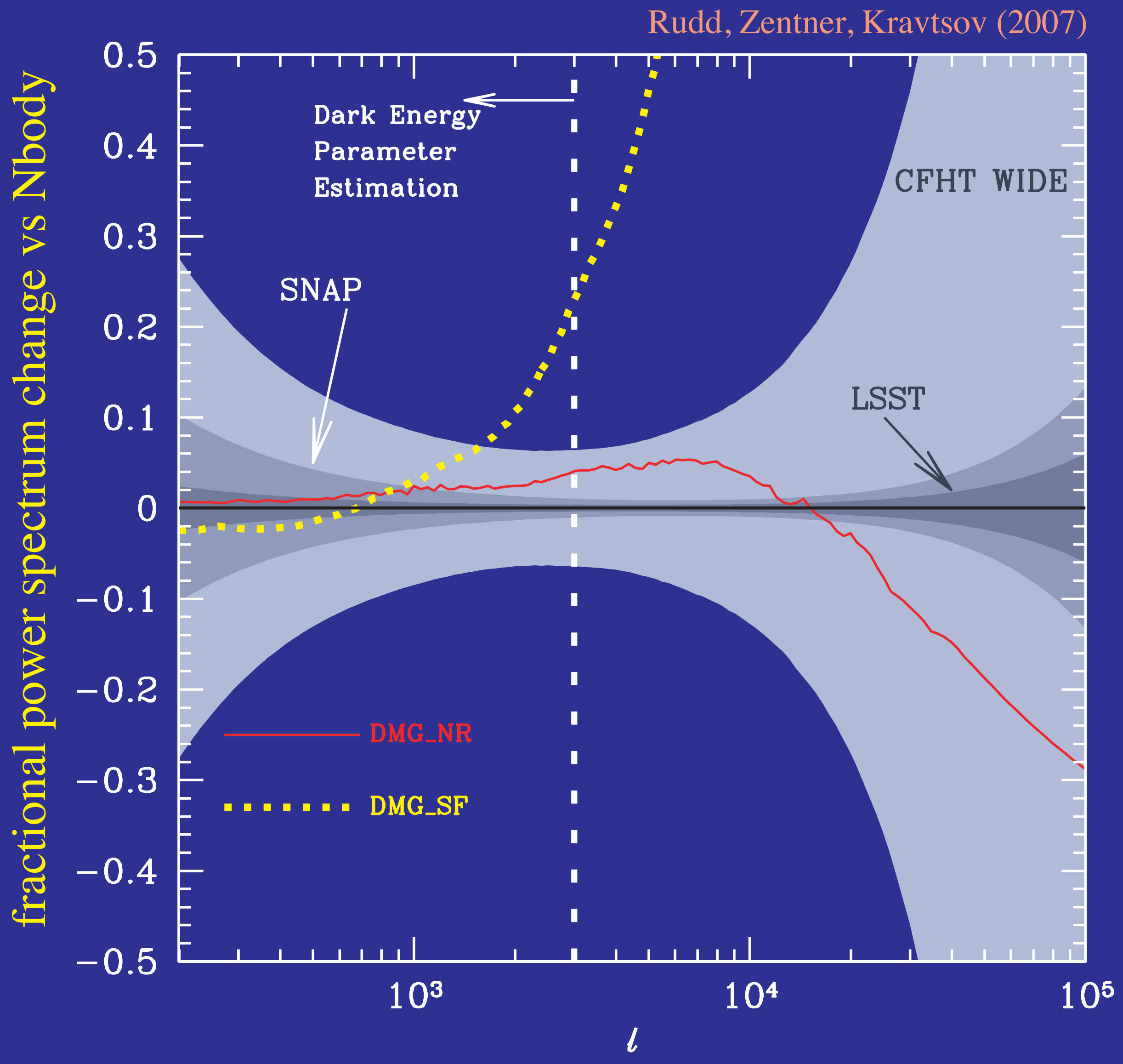
Phenomenological To Do List

- How best to parameterize consistency tests or define theoretically predicted observables?
- How to treat baryonic effects in the non-linear regime e.g.
  - Galaxy occupation of halos [BAO, velocity field tests]
  - Concentration of clusters for cosmic shear

  Extensive simulations + modelling of gastrophysics including star formation (see Brant, Licia, Volker's talks)
- Calibrate non-linear mean and covariance of dark energy observables as function of cosmological parameters (Volker's talk)
- Simulate alternate models
  - (Kill) inhomogeneous models
  - Interacting dark matter-energy models
  - Modified gravity models

Cooling/Star Formation in Clusters

- Baryonic effects can lead to false falsfication of ΛCDM



Theoretical To Do List

- Develop (discuss here) and explore known alternatives
- Dynamical Dark Energy
  - Quintessence, k-essence, phantom, effective field theoretic quintessence, vanishing sound speed k-essence, extended quintessence, coupled quintessence, electrostatic dark energy, elastically scattering dark energy, and other venial sins...
- Modified Gravity
  - braneworld, $f(R)$, $f(G)$, cascading gravity, degravitation, galileon, massive gravity, kinetic gravity braiding, TeVeS and other heresies...

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  - Q: e.g. do massive gravity and galileon ideas for self-acceleration without ghosts make sense beyond the decoupling limit

Theoretical To Do List

- Develop alternatives that are more than just illustrative toy models

  Floor is open to hear about them now!

- If observationally indistinguishable from Λ why does it have the value it does?

  If we fail to find something to argue about in this session we can always try landscape/anthropic

Andrew Liddle on Model Selection

What are we trying to achieve?

Goal: to define the key model tests to be carried and, where possible, to optimize survey strategies to achieve them. First we need to figure out which are the interesting models.

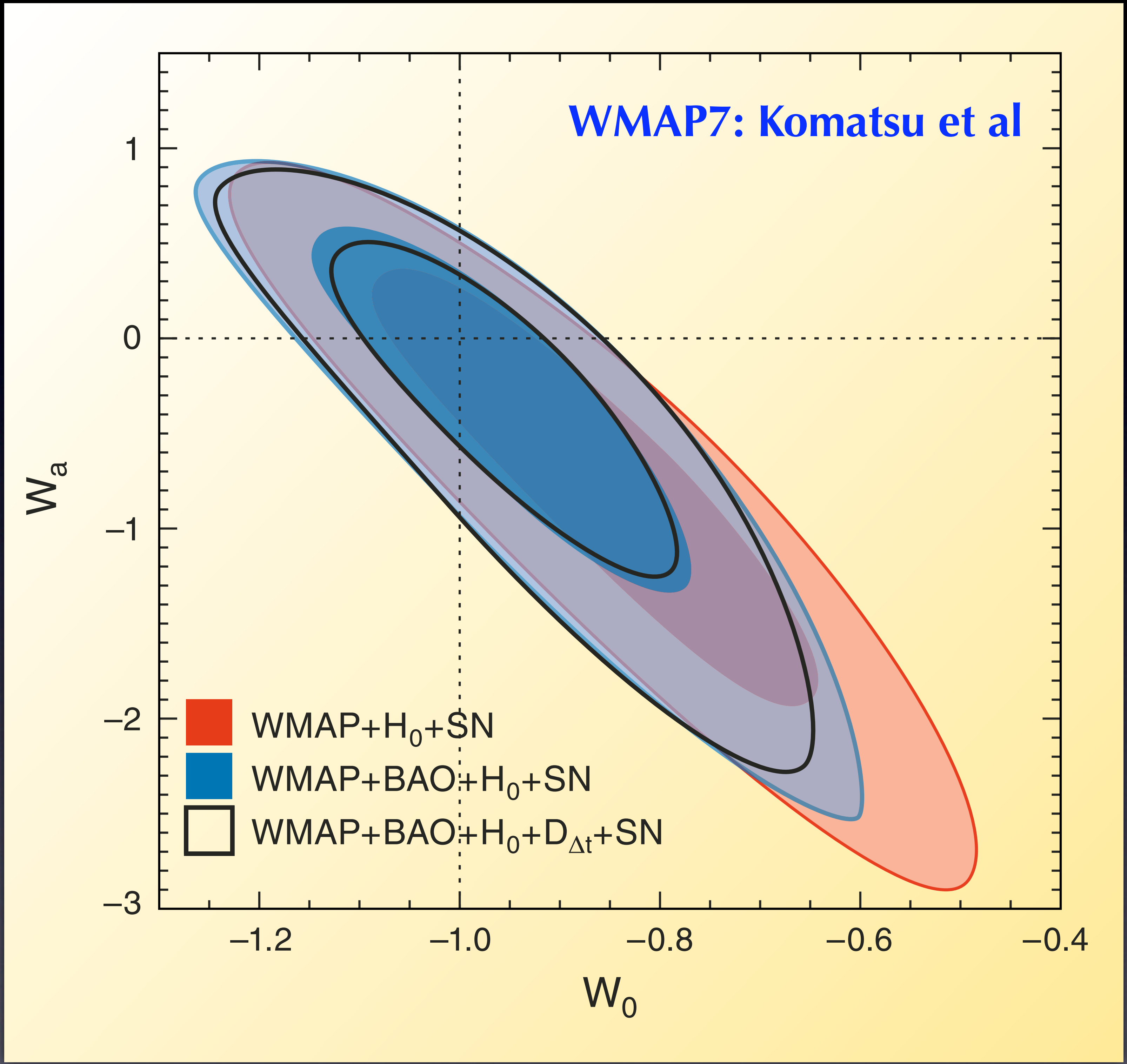
- ΛCDM: The current baseline cosmological model.
- Parameterized dark energy models, eg CPL $w = w_0+(1\text{-}a)\, w_a$

  The most common candidate alternative for dark energy studies.
- Fundamental physics dark energy models, eg inverse power-laws, Albrecht-Skordis, etc

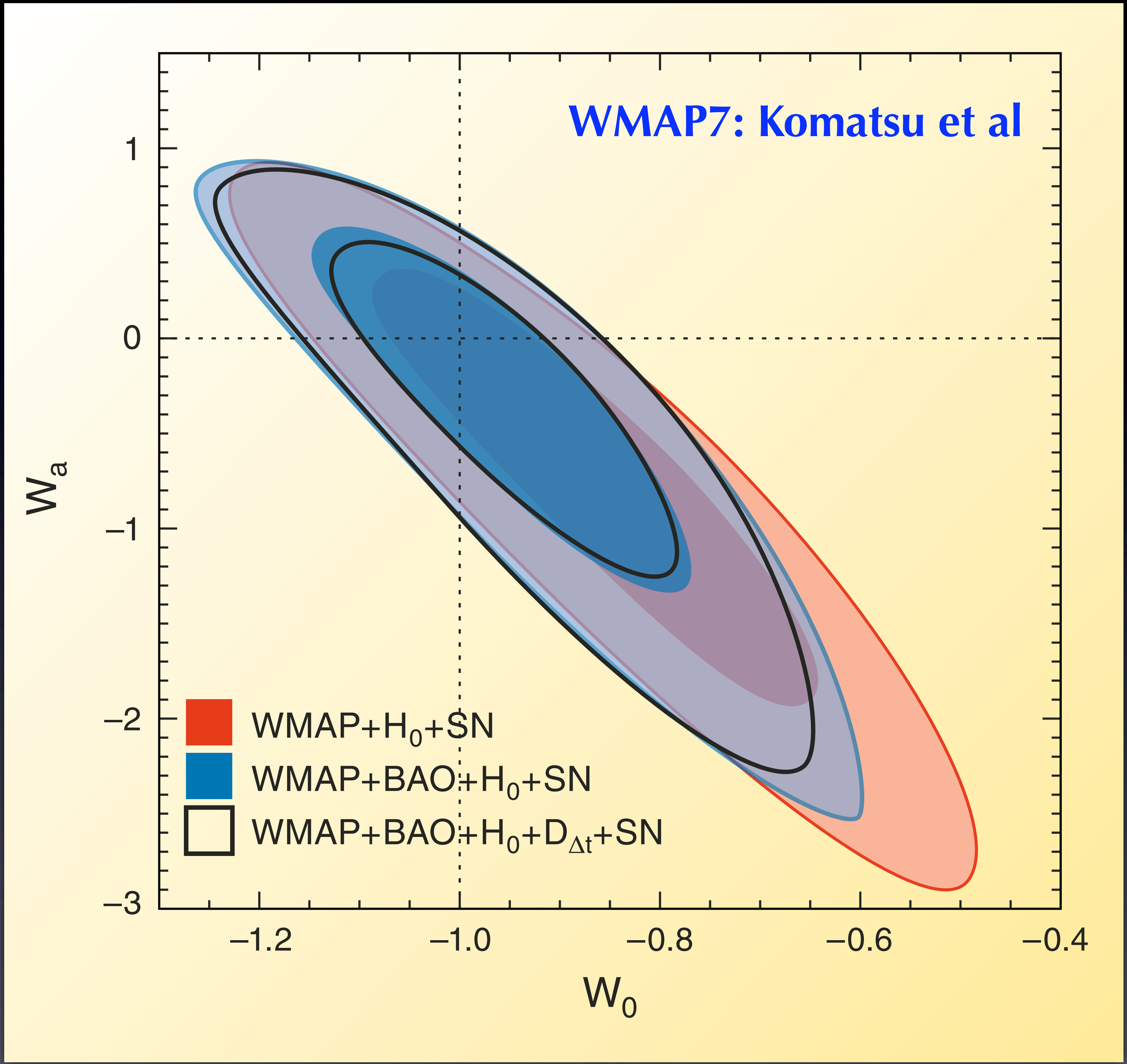
  Many candidate models in the literature though many fail to fit current data. Not clear which are best motivated.
- Modified gravity models

  Determination of best candidate modified gravity models required.

Parameter estimation tests



Parameter estimation tests



This graph answers the following question:

If we assume that the w_0-w_a dark energy model is correct, how good will our constraints on those parameters be?

Model tests

However that wasn’t the question we wanted to answer, which was:

Between the ΛCDM model and the dark energy model, which is the better description of the data?
[I.e., can one of them be ruled out with respect to the other?]

This question can only be answered with a model-level analysis, e.g. Bayesian model selection.

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Another way of expressing this: do you think that the ***prior*** probabilities of $w_0 = -1$ and of $w_0 = -0.9$ are equal?

I would argue that they are not just different in magnitude, but that the former is finite while the latter is infinitesimal.

(Almost) current dark energy data

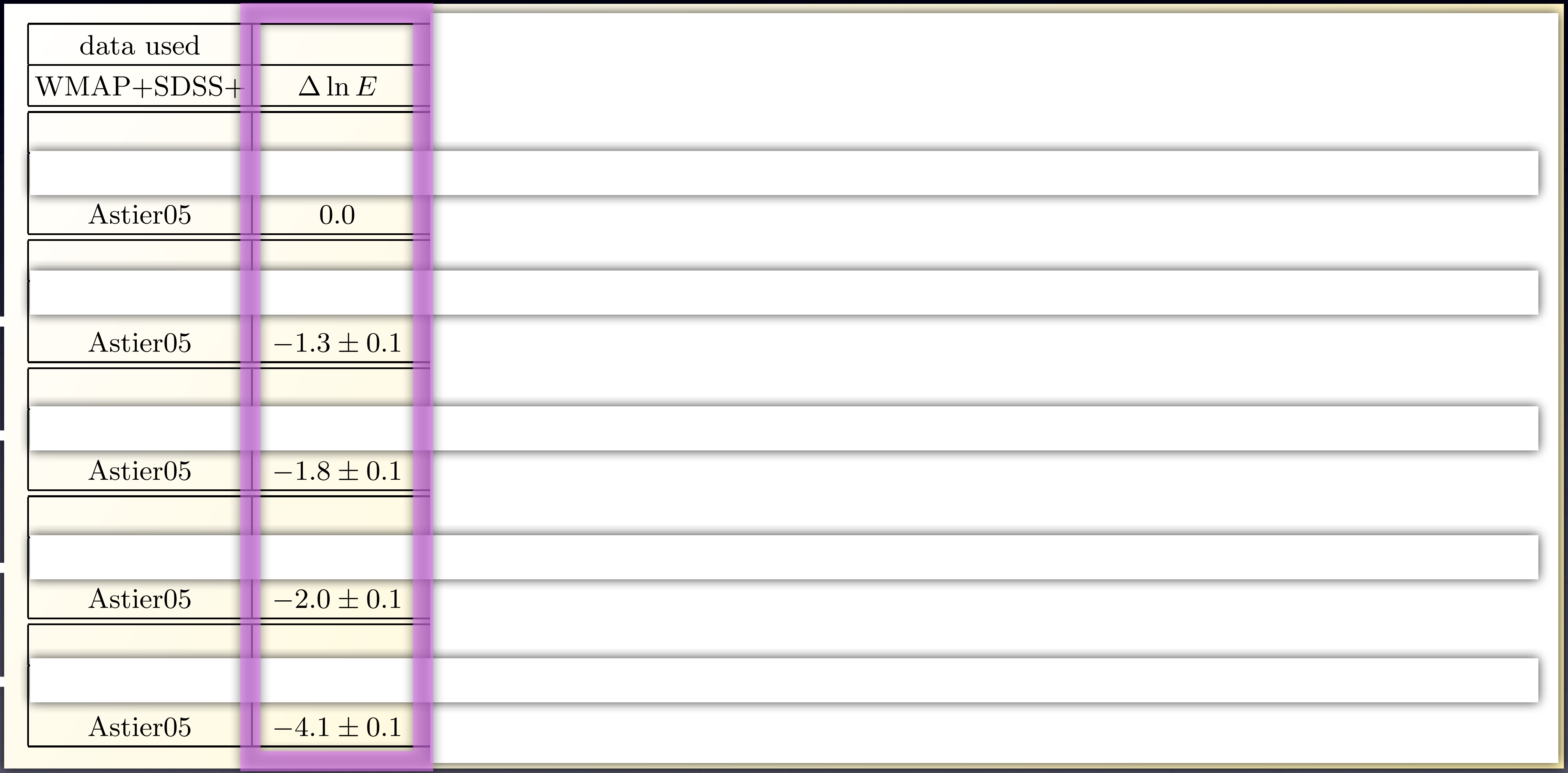
Liddle, Mukherjee, Parkinson, and Wang, PRD, astro-ph/0610126

CMB shift+BAO(SDSS)+SN

LambdaCDM

Constant W

W_0-W_a



data used WMAP+SDSS+	$\Delta \ln E$
Astier05	0.0
Astier05	-1.3 ± 0.1
Astier05	-1.8 ± 0.1
Astier05	-2.0 ± 0.1
Astier05	-4.1 ± 0.1

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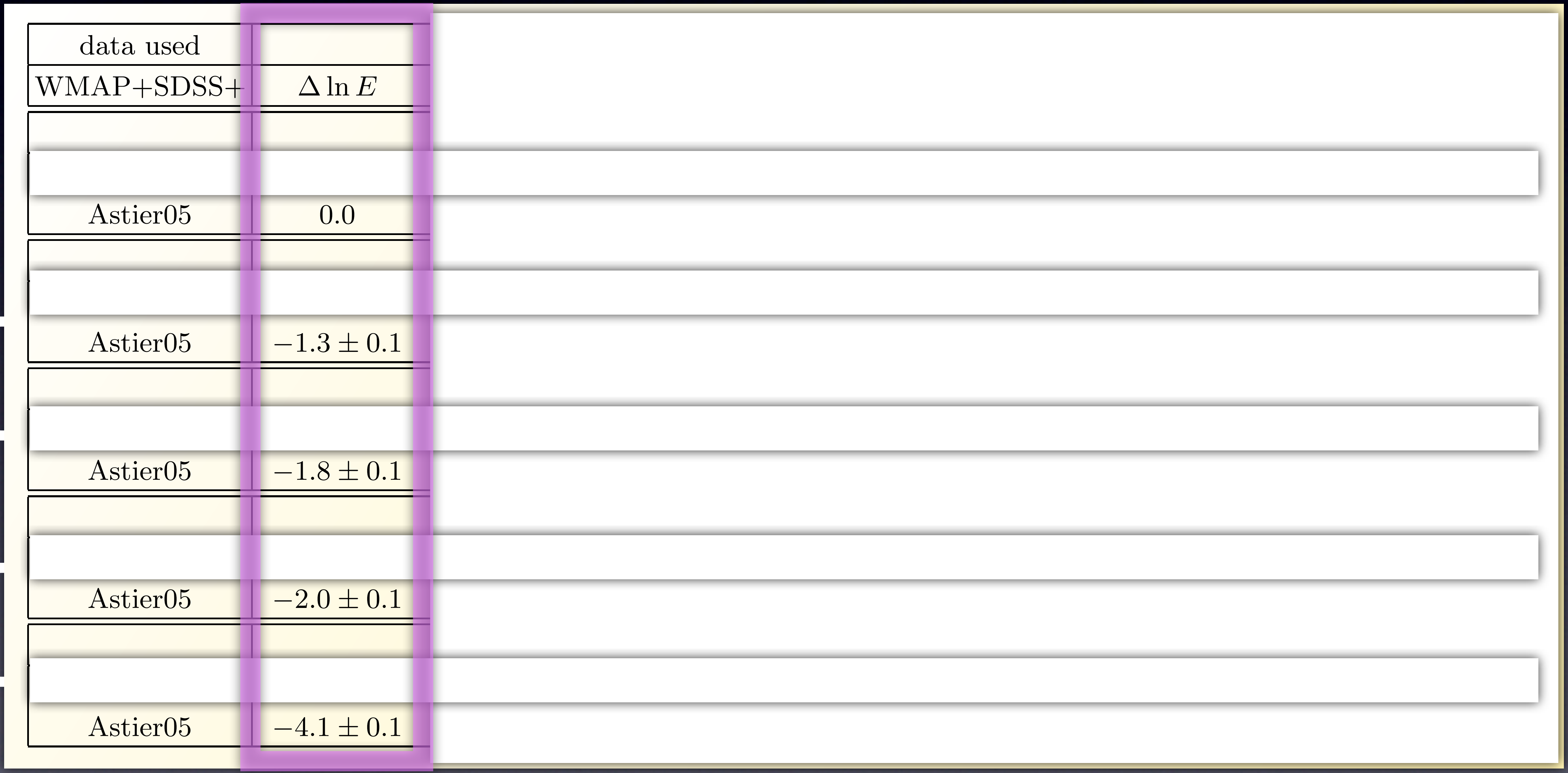
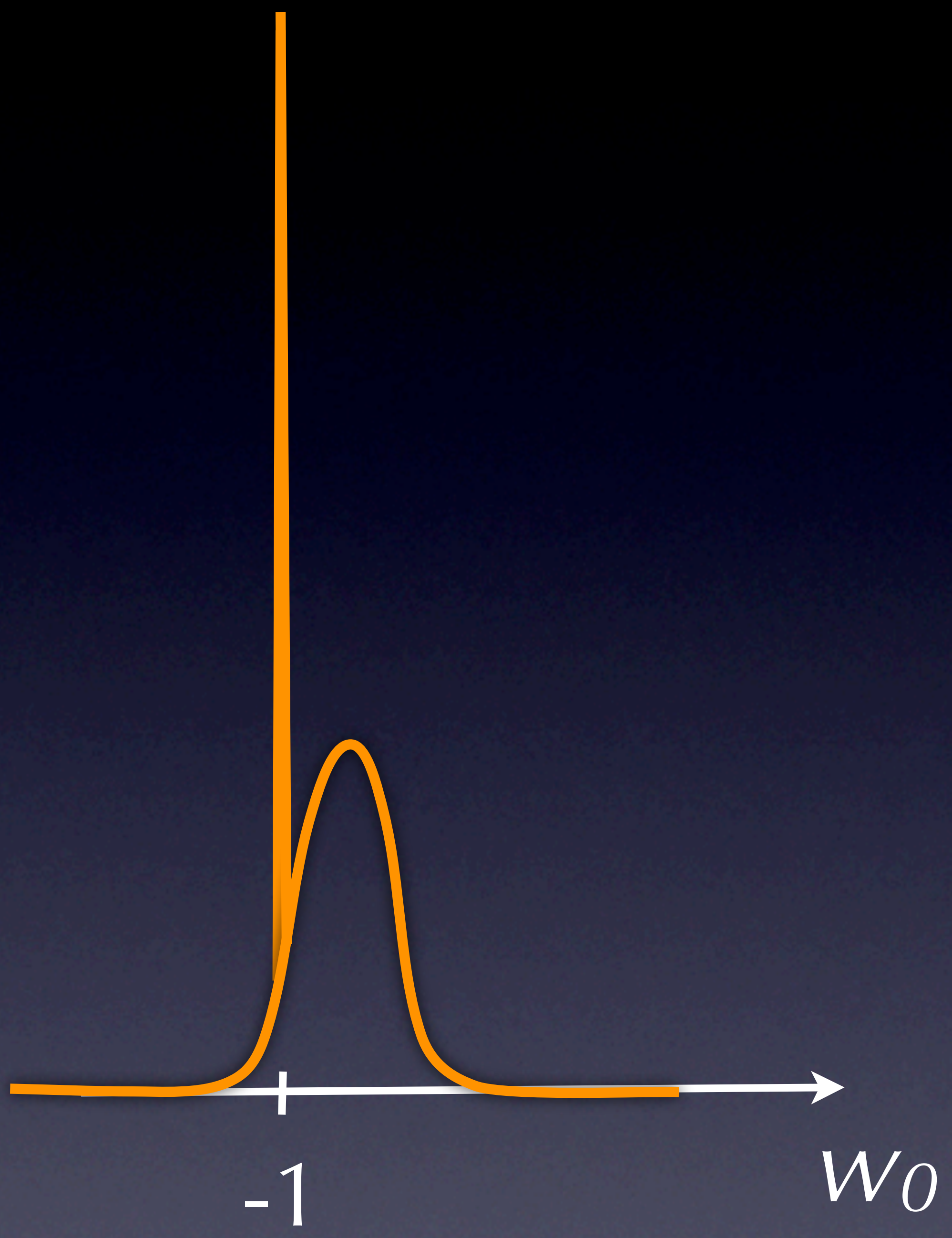


	data used WMAP+SDSS+	$\Delta \ln E$
LambdaCDM	Astier05	0.0
Constant W	Astier05	-1.3 ± 0.1
	Astier05	-1.8 ± 0.1
W_0-W_a	Astier05	-2.0 ± 0.1
	Astier05	-4.1 ± 0.1

Conclusion: If the models were originally equally likely, the data now indicates about a 75% chance that ΛCDM is correct.

Likelihood of w_0 given all models



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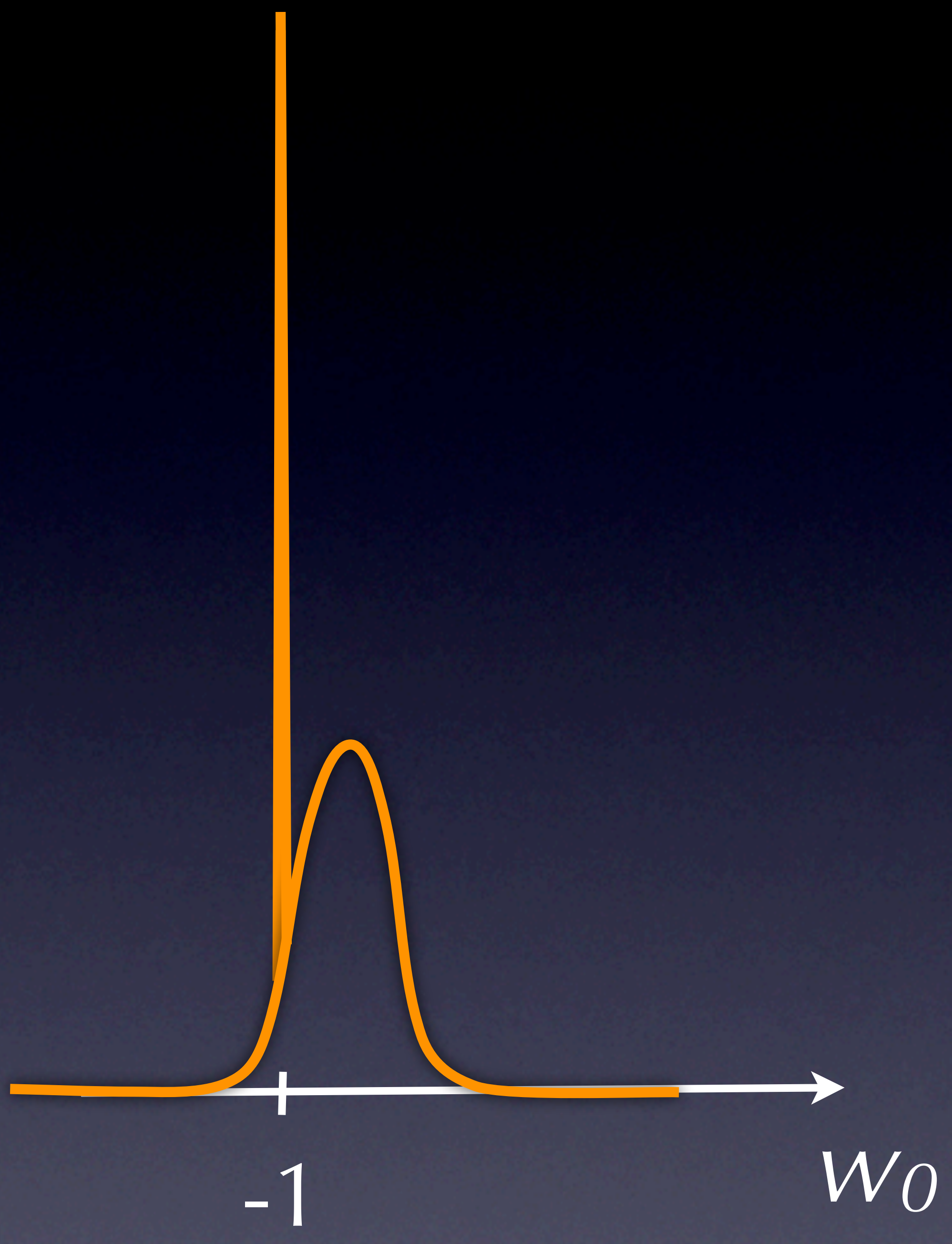
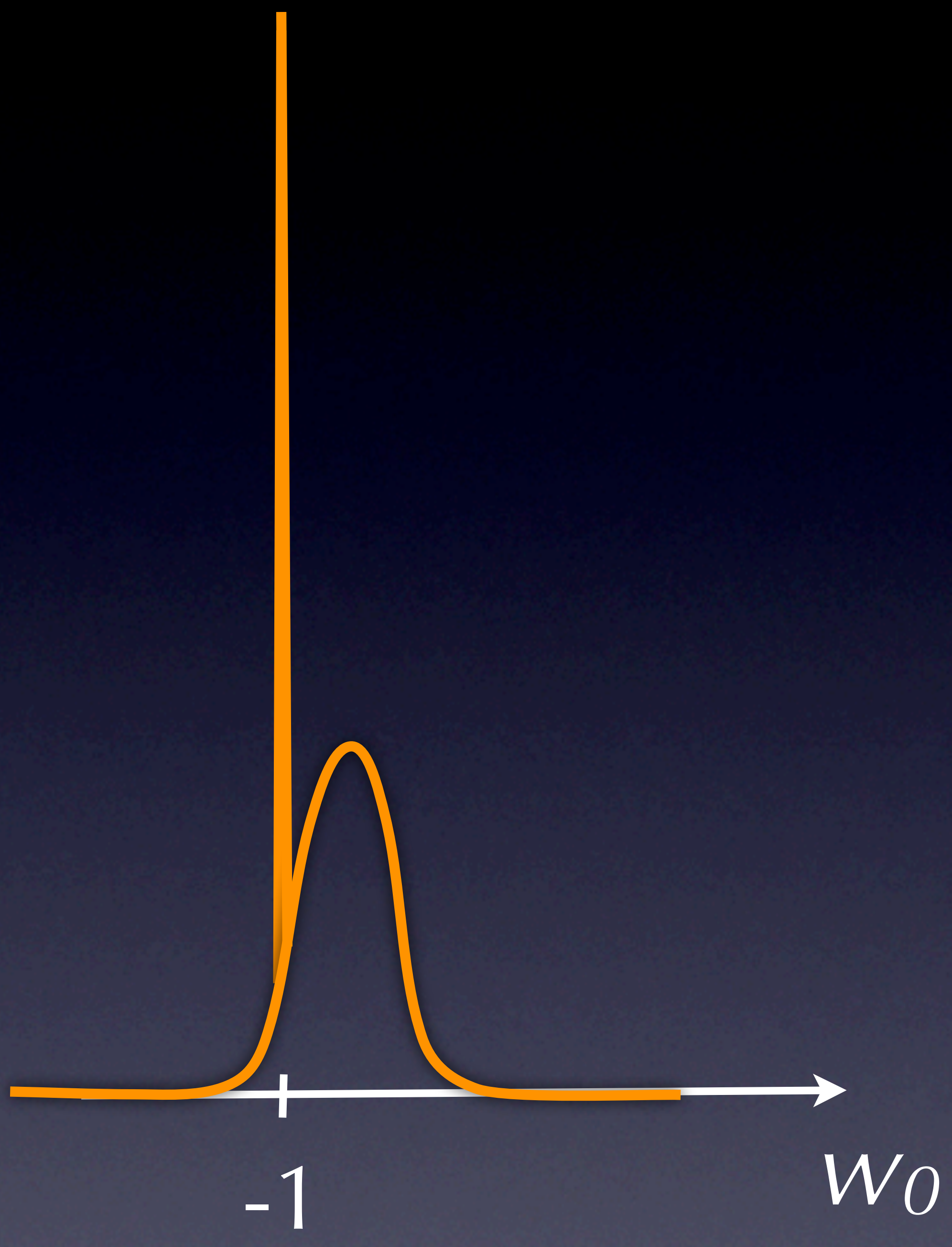
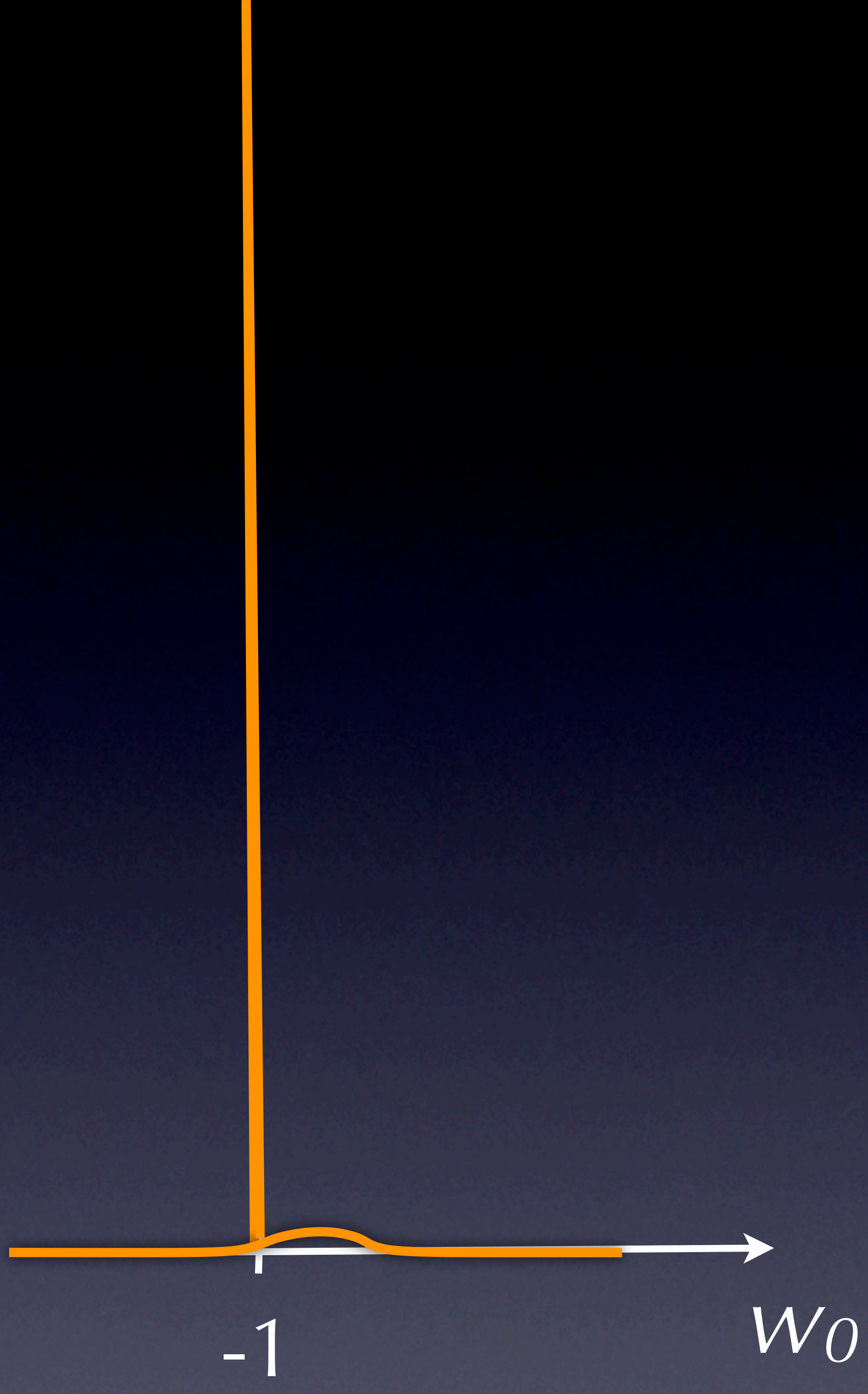


Low IQ version

Likelihood of w_0 given all models



Low IQ version



High IQ version

Model tests/inference

Model-level inference can be used at several levels:

- Model-level tests

  Deploy Bayesian model selection tools to compare model classes.

- Model selection forecasting

  Evaluate the capability of proposed experiments to answer model selection questions, by defining model selection FoMs. Explore outcomes contingent on each model class (including ΛCDM) being correct.

- Survey optimization

  Vary survey configurations in order to optimize ability to carry out identified model test priorities.