Cosmic Acceleration Then and Now

Josh Frieman
Fermilab and the University of Chicago

Progress on Old and New Themes in Cosmology
Avignon, April 18, 2014

Time	Session	Speaker	Location	Duration
09:00	**Cosmology with type-Ia Supernovae**	*Marc BETOULE*	*Chambre du Trésorier, Palais des Papes, Avignon*	09:00 - 09:45
	Cosmology with the Euclid satellite	*Valeria PETTORINO*	*Chambre du Trésorier, Palais des Papes, Avignon*	09:45 - 10:30
10:00				
	Coffee Break		*Chambre du Trésorier, Palais des Papes, Avignon*	10:30 - 11:00
11:00	**LSS and BAO: current status and prospects**	*Dr. Beth REID*	*Chambre du Trésorier, Palais des Papes, Avignon*	11:00 - 11:45
	Cosmic Acceleration Then and Now	*Josh FRIEMAN*	*Chambre du Trésorier, Palais des Papes, Avignon*	11:45 - 12:30
12:00				
	Last Lunch		*Avignon*	12:30 - 14:30
13:00				
14:00				

Last Supper
(in earlier version of program)

Cosmologists discuss BICEP2 results at PONT banquet

April, c. 33 AD

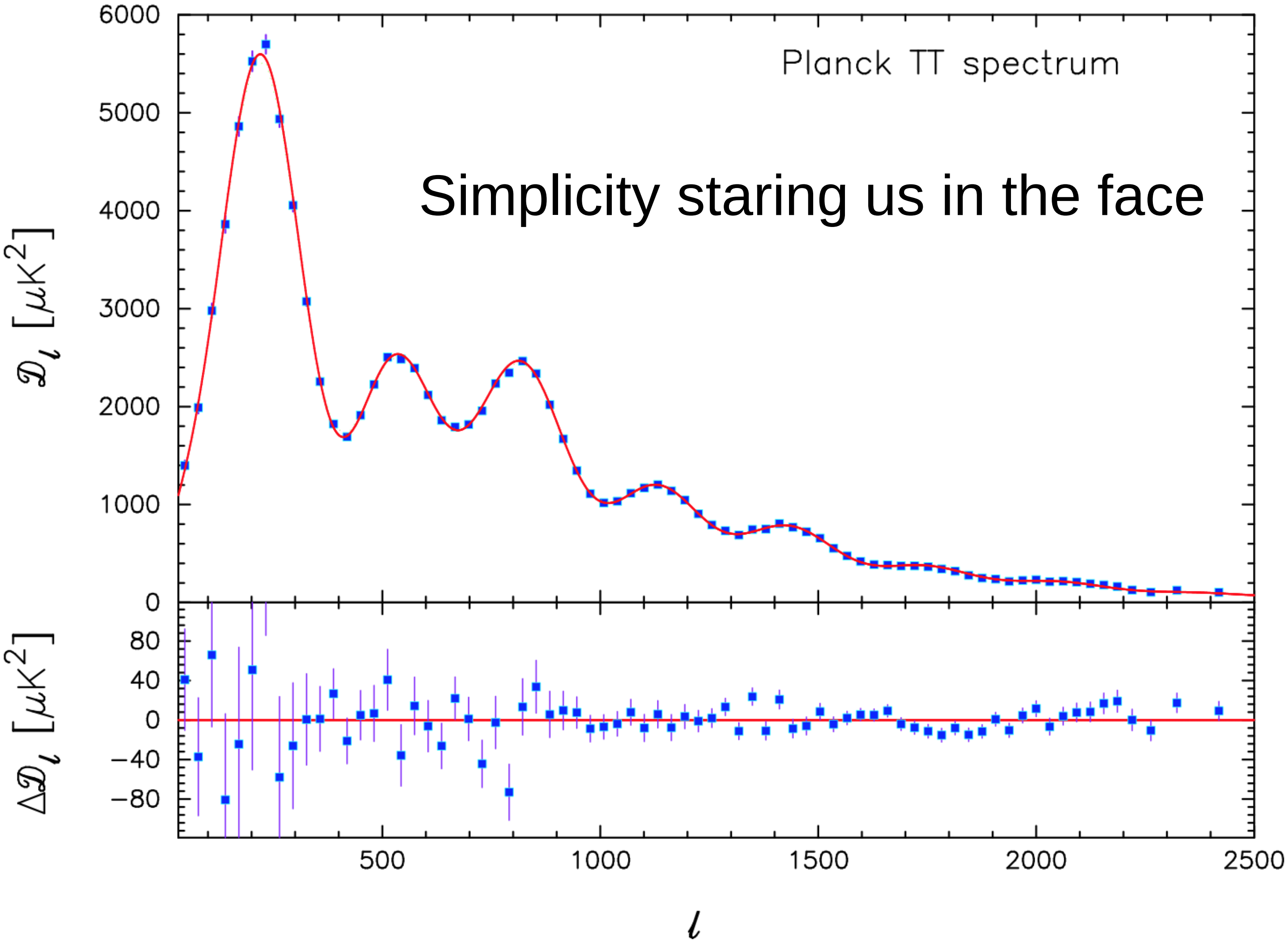
Caveats and Thoughts

- I am a recovering or lapsed theorist, depending on your point of view.
- Theoretical landscape that has developed in recent years looks very rich, but a bit overwhelming
- BICEP2 results tremendously exciting, potentially transformative upon confirmation
- Theorists should be cautious about getting overly excited about 1-2 sigma discrepancies from standard model/expectations (only small fraction of `tensions' will develop into significant inconsistencies).

We have been very lucky so far

- Over the last 20+ years, at each new stage of experimental precision, a simple (few-parameter) cosmological paradigm has been confirmed: it didn’t have to turn out that way
- Observations consistent with Λ+Cold Dark Matter in a spatially flat, initially hot Universe, with adiabatic, nearly Gaussian, slightly non-scale-invariant scalar and (now likely) tensor perturbations, as expected from inflation

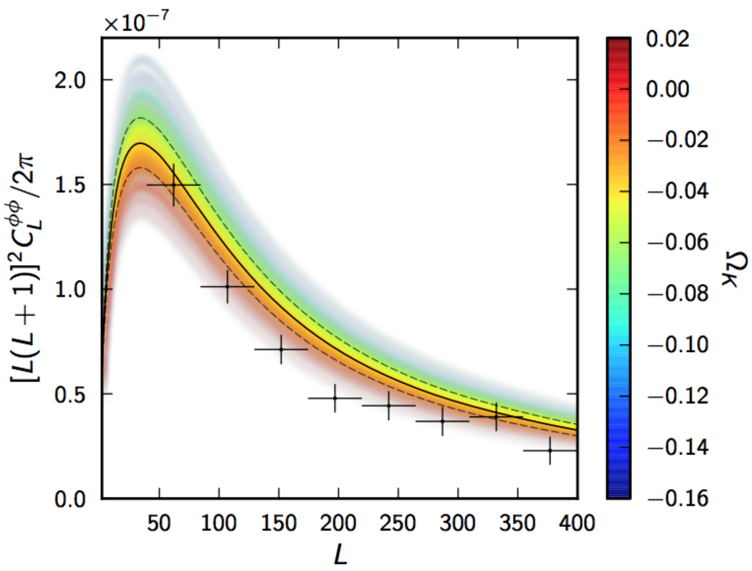
LCDM FIT

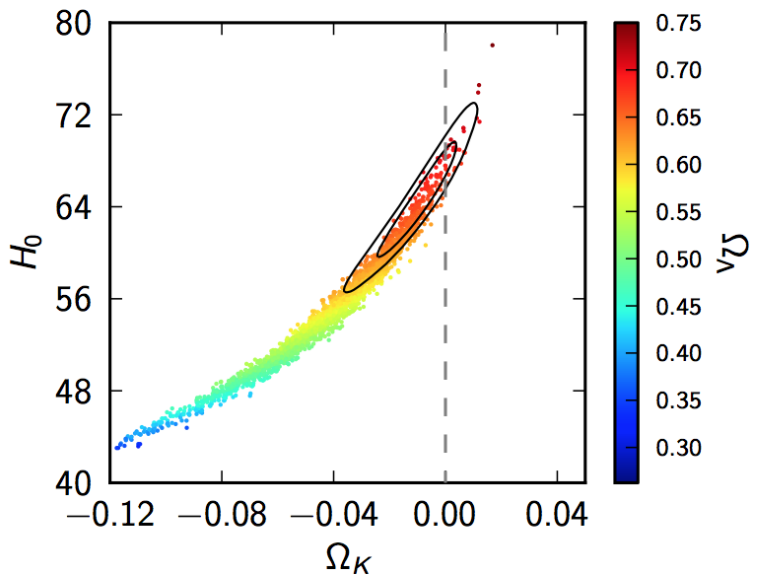


- Acceptable fit to channel spectra and composite spectrum: χ^2 compatible with LCDM to 1.6 σ

Challinor

Curvature/dark energy from the CMB alone





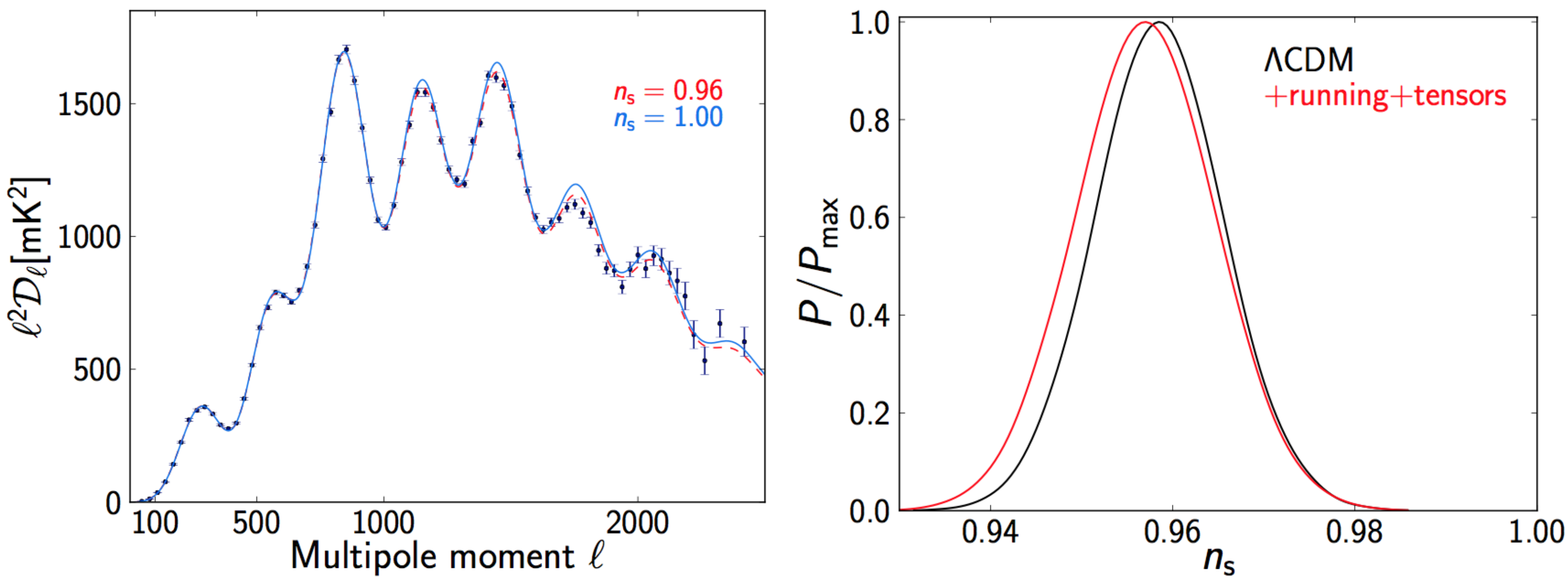
$\Omega_K = -0.0096^{+0.010}_{-0.0082}$ (68%; Planck+lensing+WP+highL)

$\Omega_\Lambda = 0.67^{+0.027}_{-0.023}$ (68%; Planck+lensing+WP+highL)

- Spatial flatness to 1% from CMB alone
  - Improves to $\Omega_K = -0.0005 \pm 0.0033$ including BAO

Challinor

CONSTRAINTS ON INFLATION: n_s

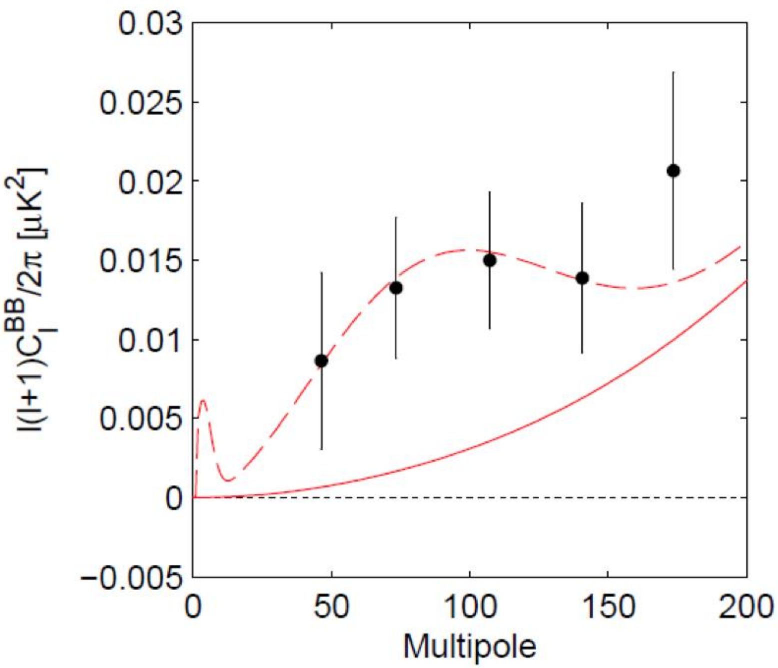


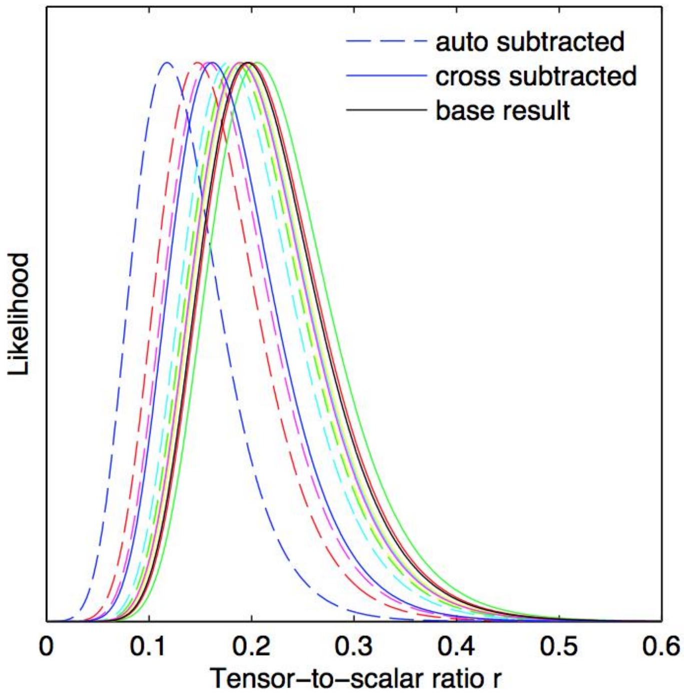
$n_s = 0.958 \pm 0.007$ (68%; Planck+WP+highL; LCDM)

- $n_s < 1$ robust to addition of running and tensors
- Robust to matter content (e.g. N_{eff} and Helium) combining Planck with BAO

Challinor

IMPLICATIONS FOR TENSOR-TO-SCALAR RATIO



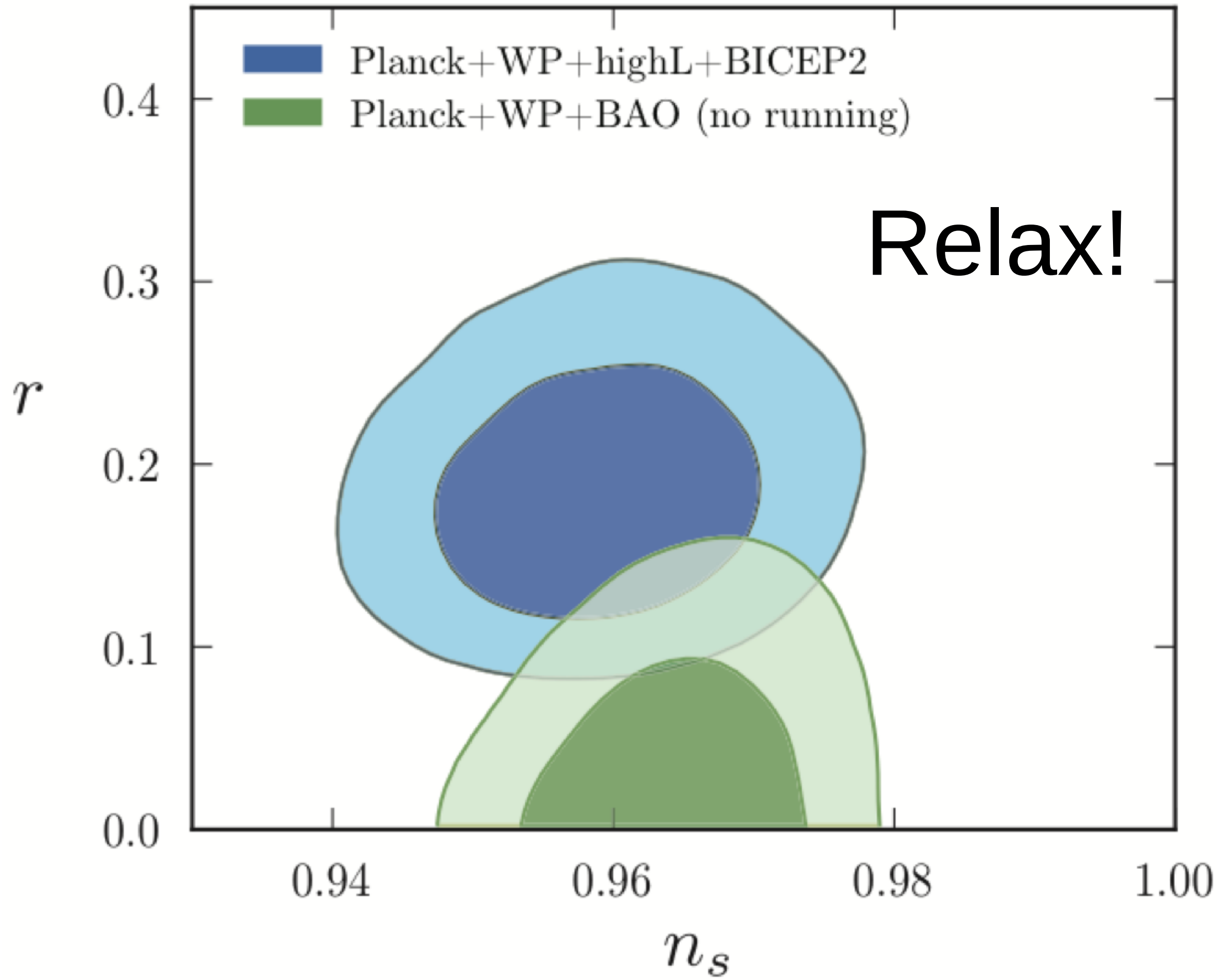


$$r = 0.20^{+0.07}_{-0.05} \quad \text{(68\%; no foreground correction)}$$

- Large spread in max. likelihood $0.12 < r < 0.21$ with foreground models

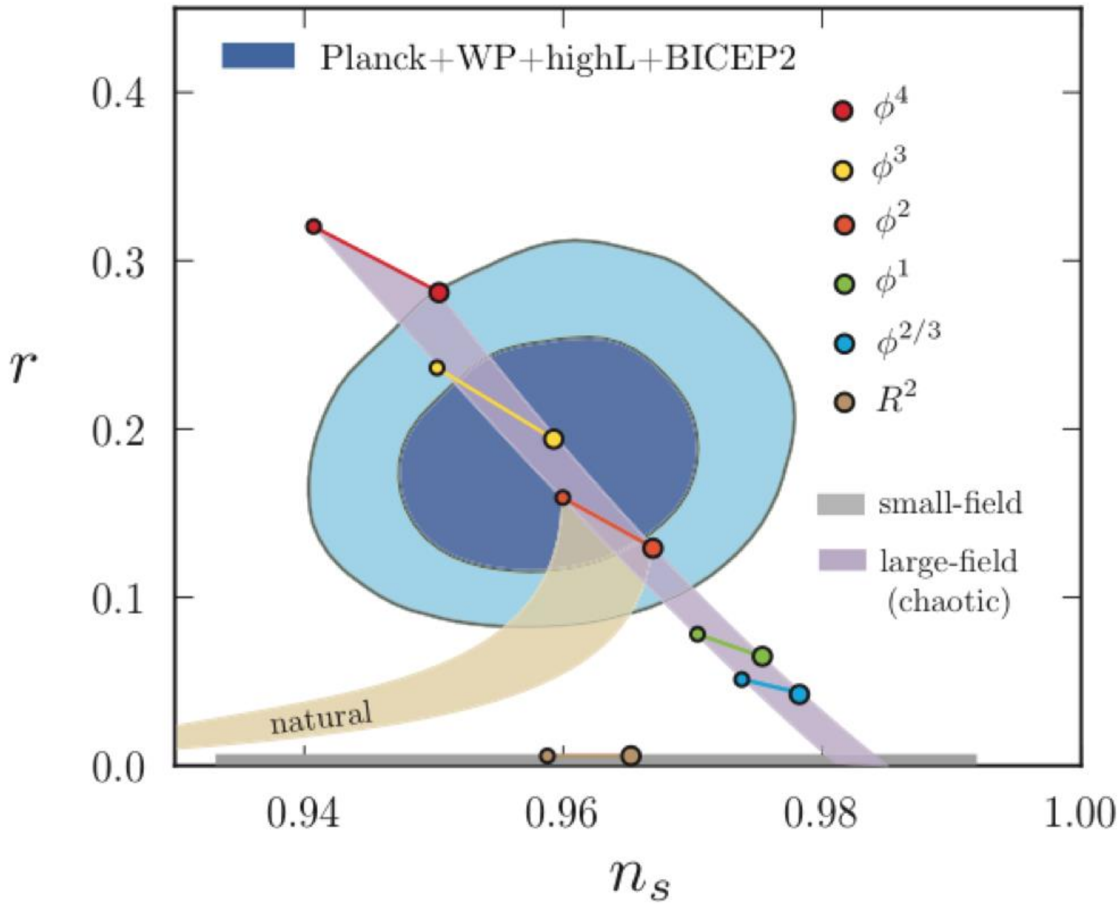
Challinor

Constraints on r=T/S



Baumann

Ruling Out Models



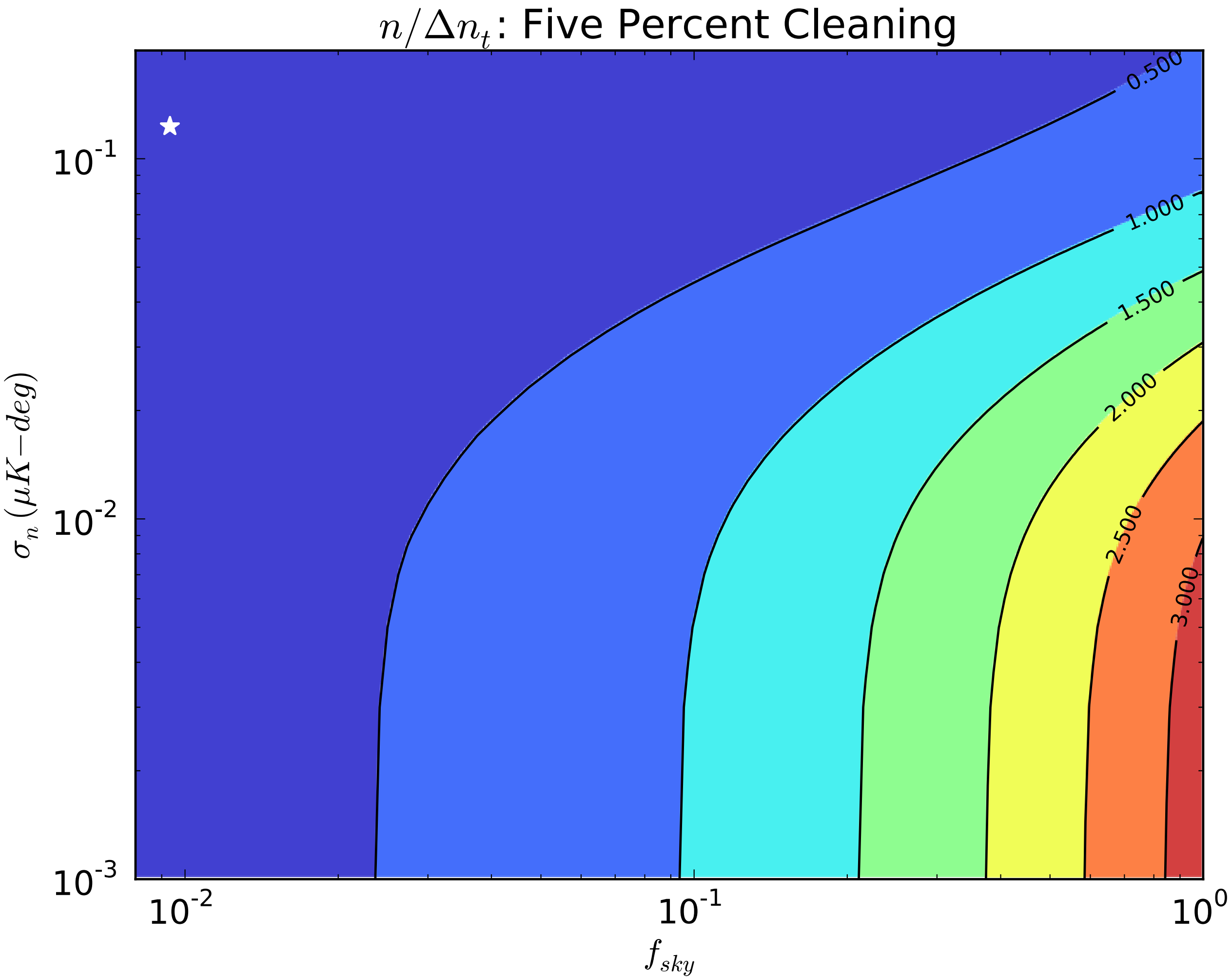
Simple models written down 25-30 years ago are consistent with the data

* careful: contours marginalize over running

contours without running shift slightly downward

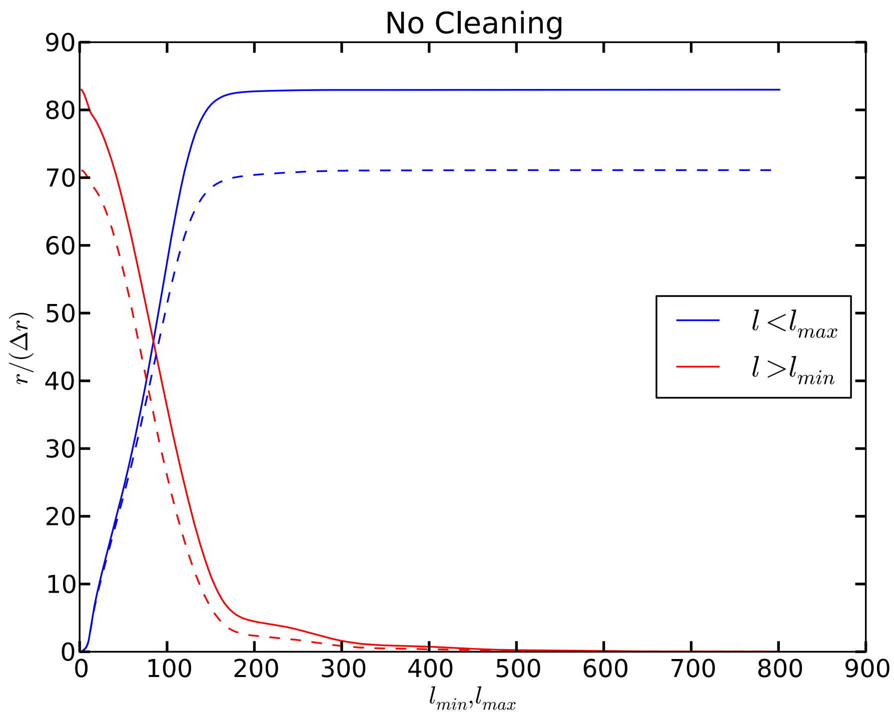
Baumann

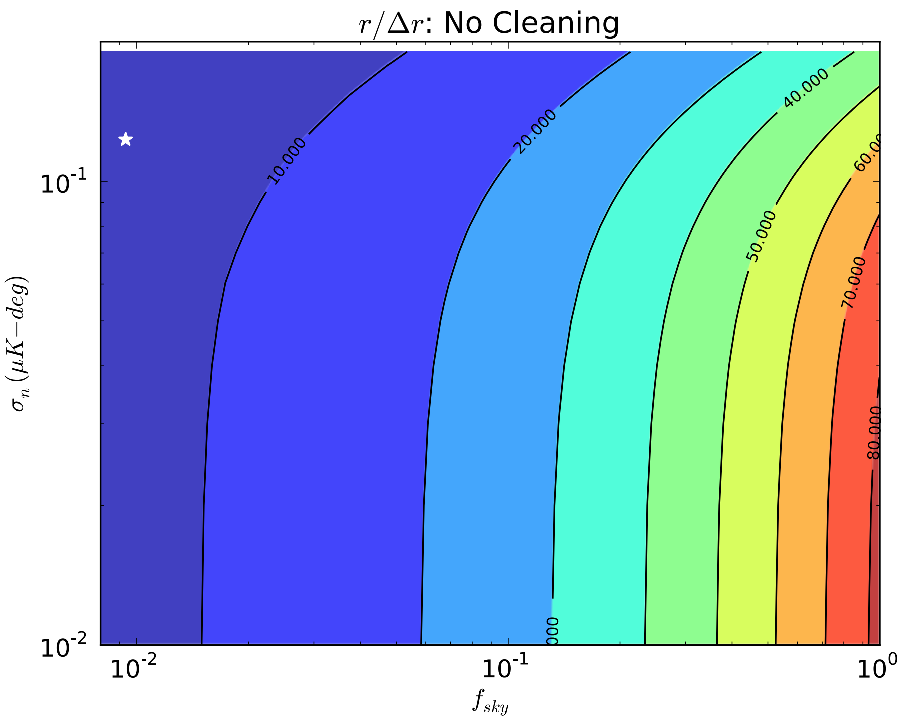
How important is it to test the consistency relation?



Dodelson

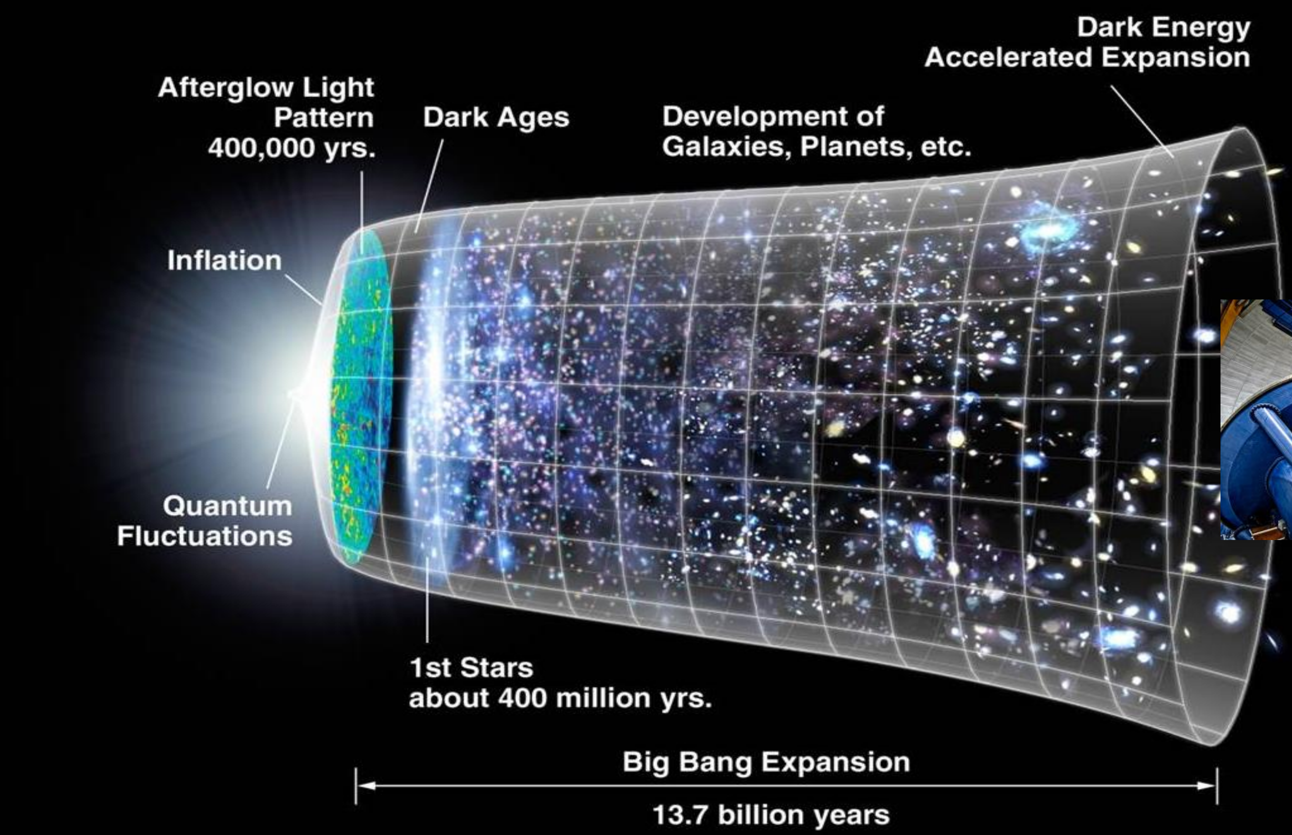
What is the best way to tighten constraints on (n_s,r)?





Dodelson

Brief History of the Universe



Dark Energy Survey

Evidence for <u>two</u> epochs of accelerated expansion
What are their physical origins?

NASA/WMAP Science Team

Mt. Ventoux

Tues PM

Elev. Gain
1640 m

Period of painful deceleration followed by rapid acceleration

Strong Mistral blowing

Mt. Ventoux

Elev. Gain
1640 m

Tues PM

Wed. AM

I can confirm that my energy scale during the 2nd epoch was substantially lower

Early Inflation

- Early epoch of cosmic acceleration motivated by flatness and horizon problems ($N_{e\text{-folds}}$>50-60)
- Theoretical context: GUTs and 1st order phase transitions
- Simplest model: weakly self-coupled scalar field that takes a cosmologically long time to reach its ground state
- Bonus: causal origin of density perturbations for structure formation and gravitational waves from quantum fluctuations.
- Growing observational evidence starting with COBE (April, 1992) through BICEP2 (March, 2014)

Late Inflation

- Current epoch of cosmic acceleration motivated by missing energy and age problems (early/mid-1990s)
  - inflation predicted Ω_0=1, clusters indicated Ω_m=0.25. Need a smooth component that only recently came to dominate
  - $H_0 t_0 \sim 1$ from Hubble parameter and globular cluster ages
  - ΛCDM+inflation fit galaxy clustering measurements (APM)
- Simplest model: weakly self-coupled scalar field that takes a cosmologically long time to reach its ground state
- Growing observational evidence starting with supernovae (1998) through JLA (Dec. 2013)

Late Inflation

- Current epoch of cosmic acceleration motivated by missing energy and age problems (early/mid-1990s)
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  - $H_0t_0\sim1$ from Hubble parameter and globular cluster ages
  - ΛCDM+inflation fit galaxy clustering measurements (APM)
- Simplest model: cosmological constant

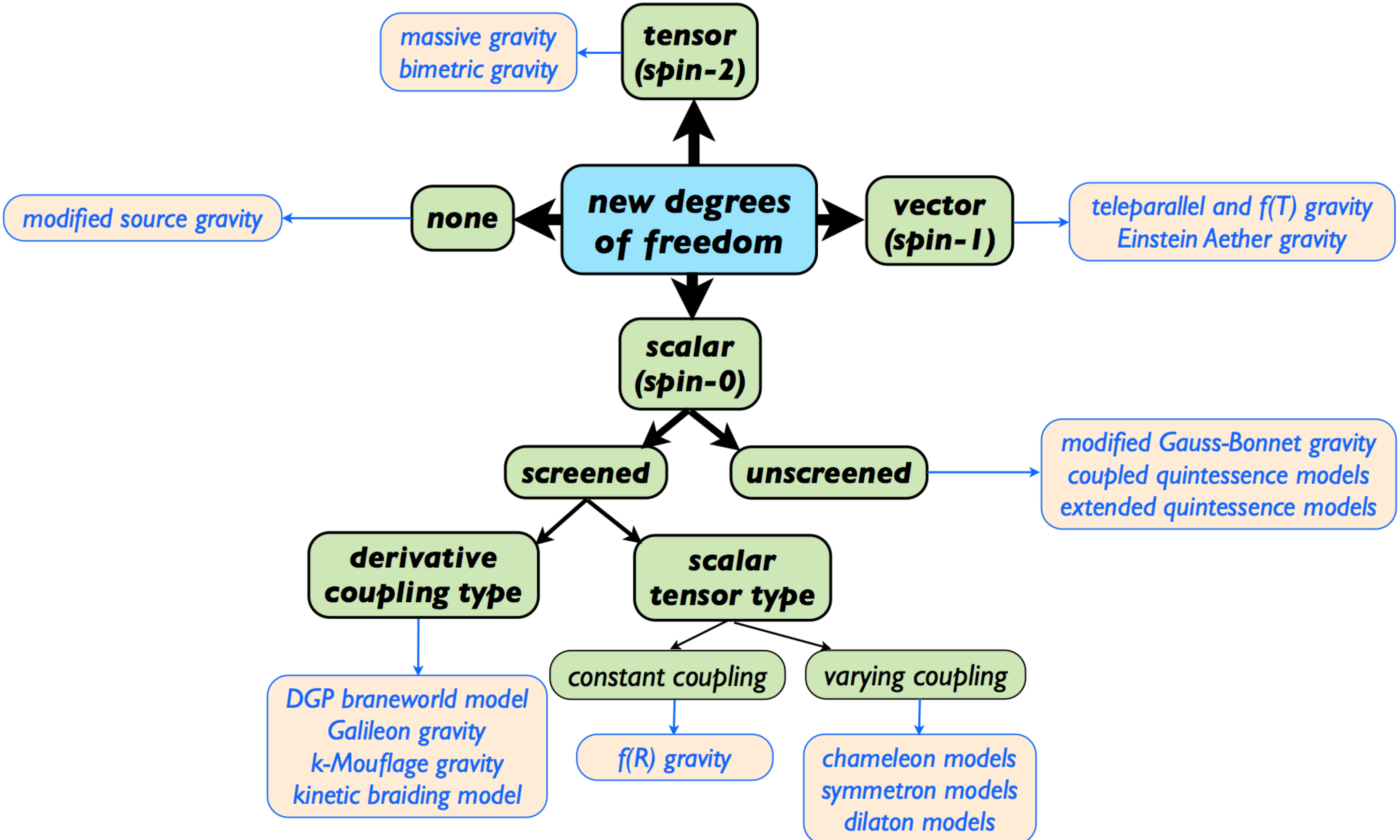
- Growing observational evidence starting with supernovae (1998) through JLA (Dec. 2013)

Cosmological Constant and Late Inflation

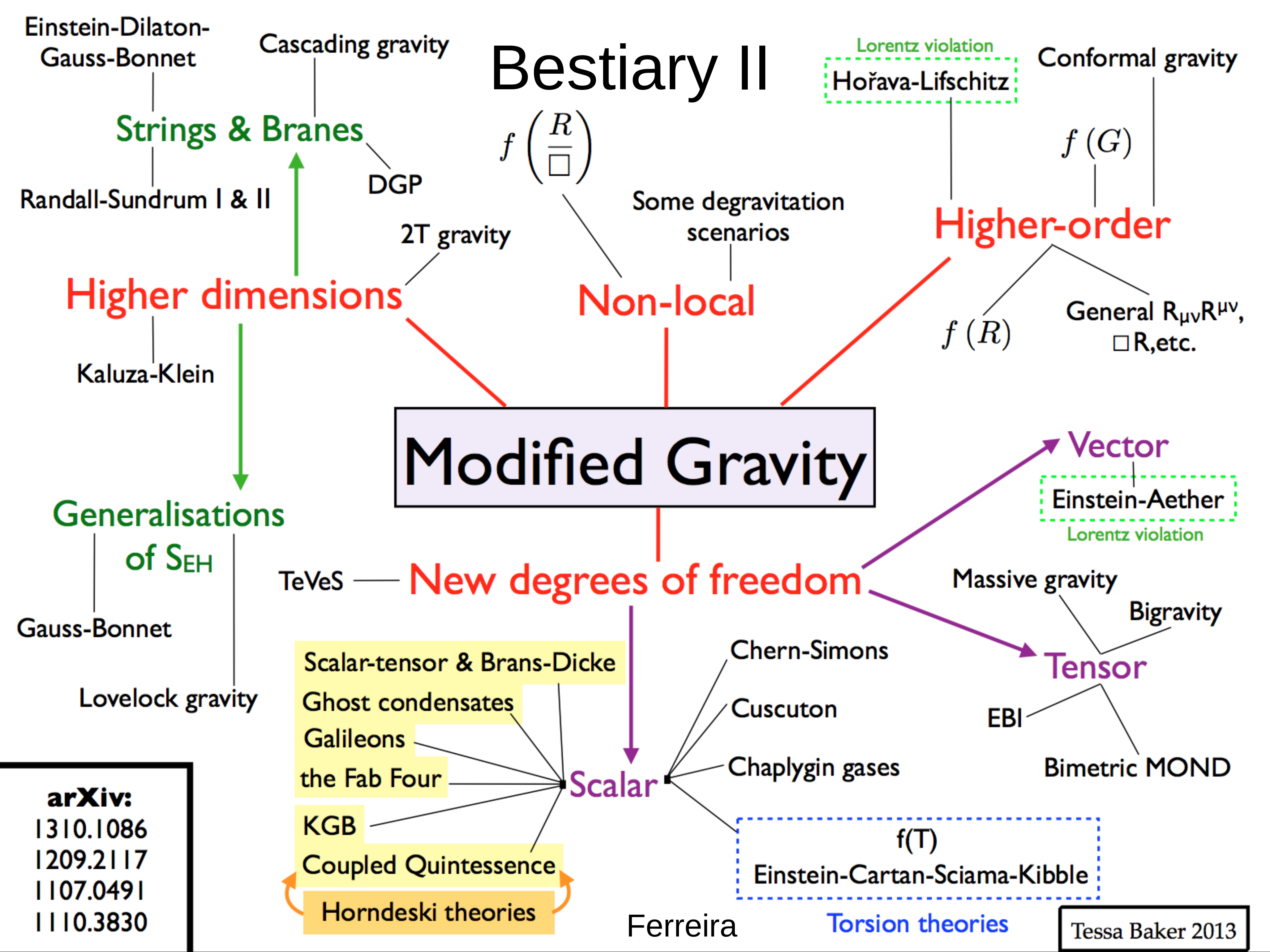
- What is the justification for theoretical prejudice in favor of Λ as origin of current acceleration?
- Imagine theorists sitting around 10^{-35} sec after the Big Bang, when inflation had just started.
  - They would have said the Universe was becoming Λ-dominated.
  - They would have been wrong.
- Being wrong once is not necessarily a strong argument in favor of it the 2nd time around.

On the Other Hand

Modified Gravity Bestiary I



Li

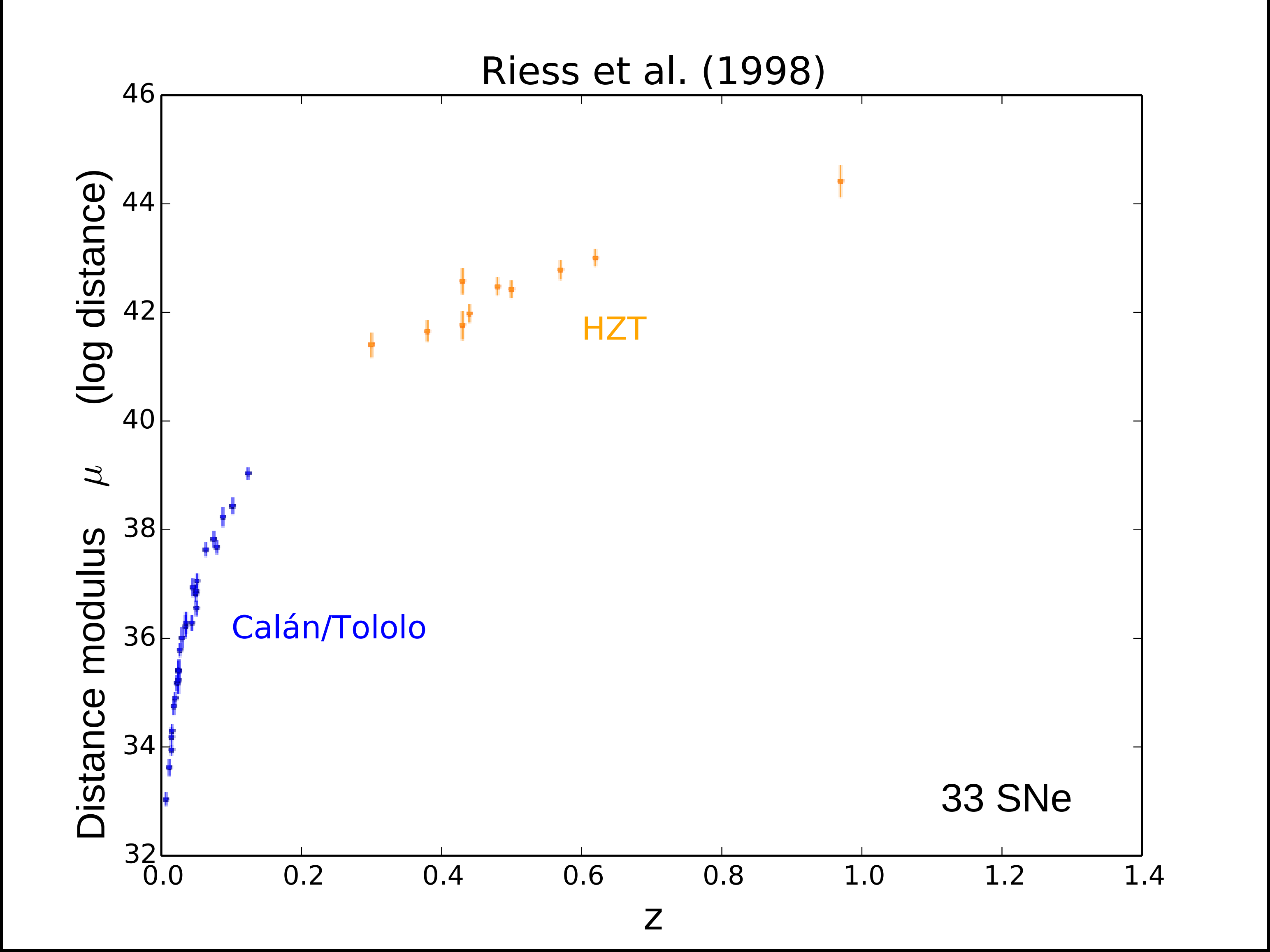

Bestiary II
Modified Gravity
Higher dimensions
Non-local
Higher-order
New degrees of freedom
Strings & Branes
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Randall-Sundrum I & II
DGP
2T gravity
Kaluza-Klein
$f\left(\frac{R}{\Box}\right)$
Some degravitation scenarios
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
TeVeS
Vector
Einstein-Aether
Lorentz violation
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Scalar
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
arXiv:
1310.1086
1209.2117
1107.0491
1110.3830
Ferreira
Tessa Baker 2013

Collective Schizophrenia?

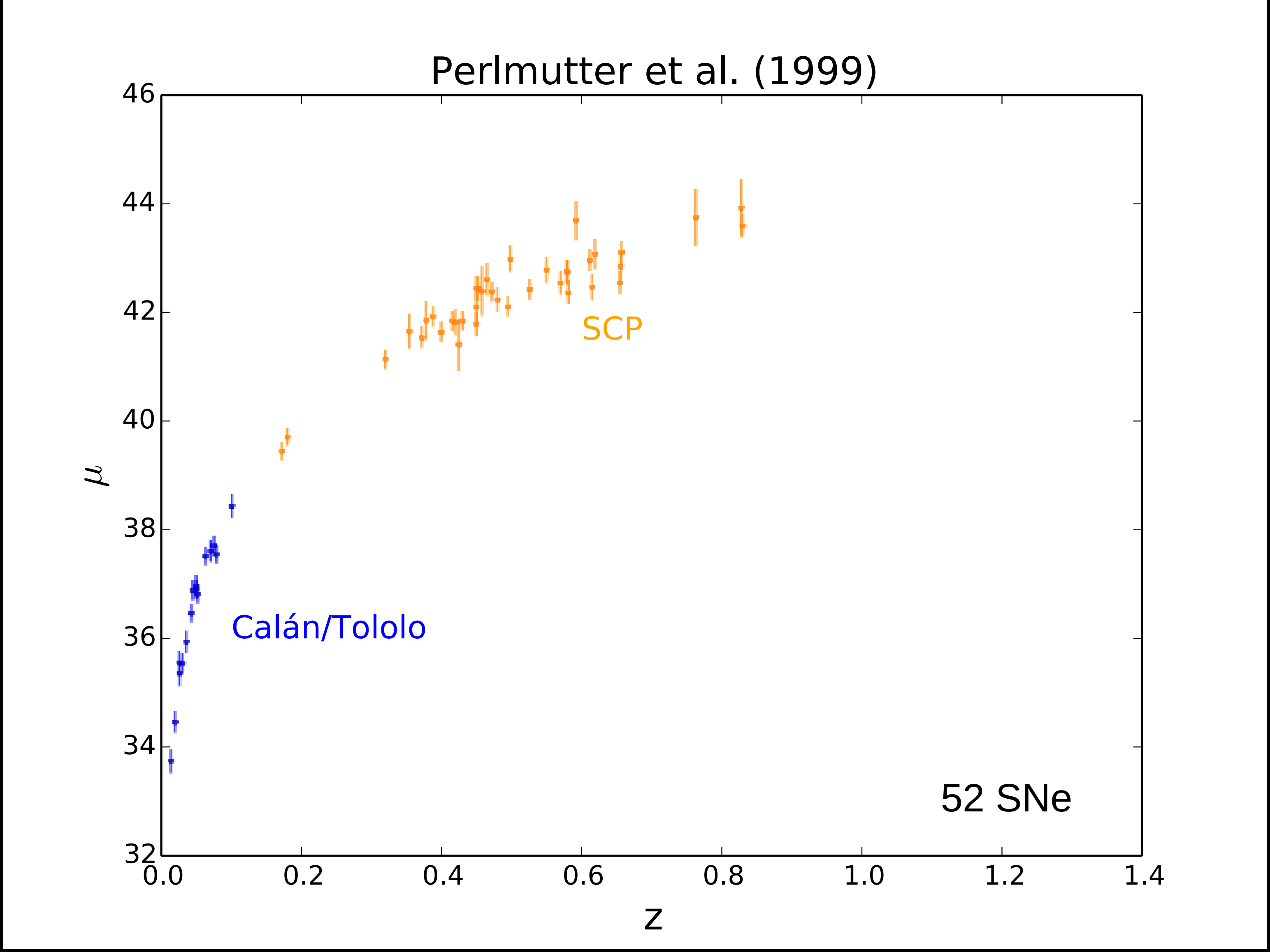
- We appear to be both less (Λ prejudice) and more (Modified Gravity bestiary) agnostic about the physical origin of late acceleration relative to early acceleration. If so, why?

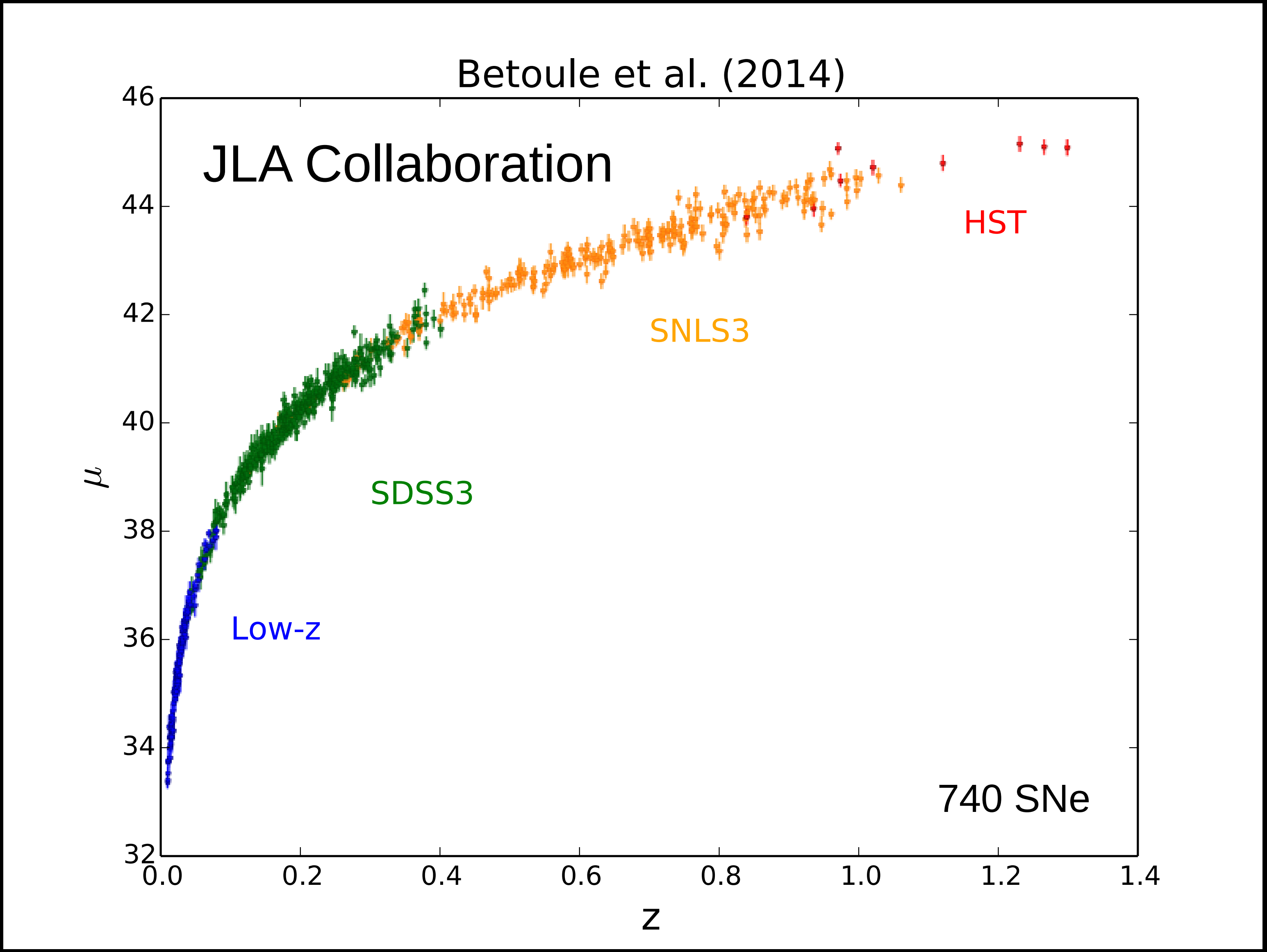
Experiments can Probe the Physics of Cosmic Acceleration

Supernova Ia Hubble Diagram



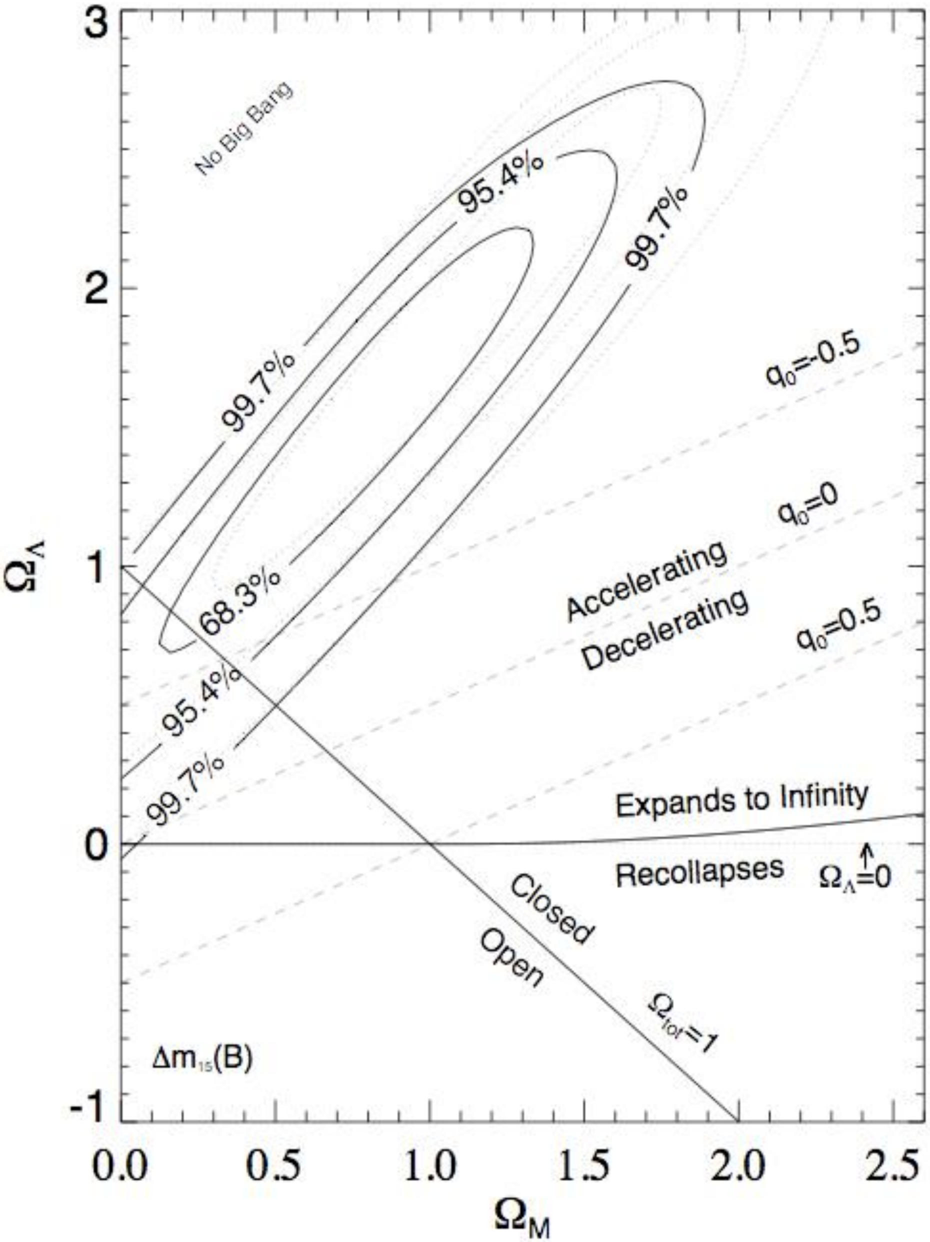
SN figures by A. Conley


Perlmutter et al. (1999)
46
44
42
40
38
36
34
32
μ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z
SCP
Calán/Tololo
52 SNe

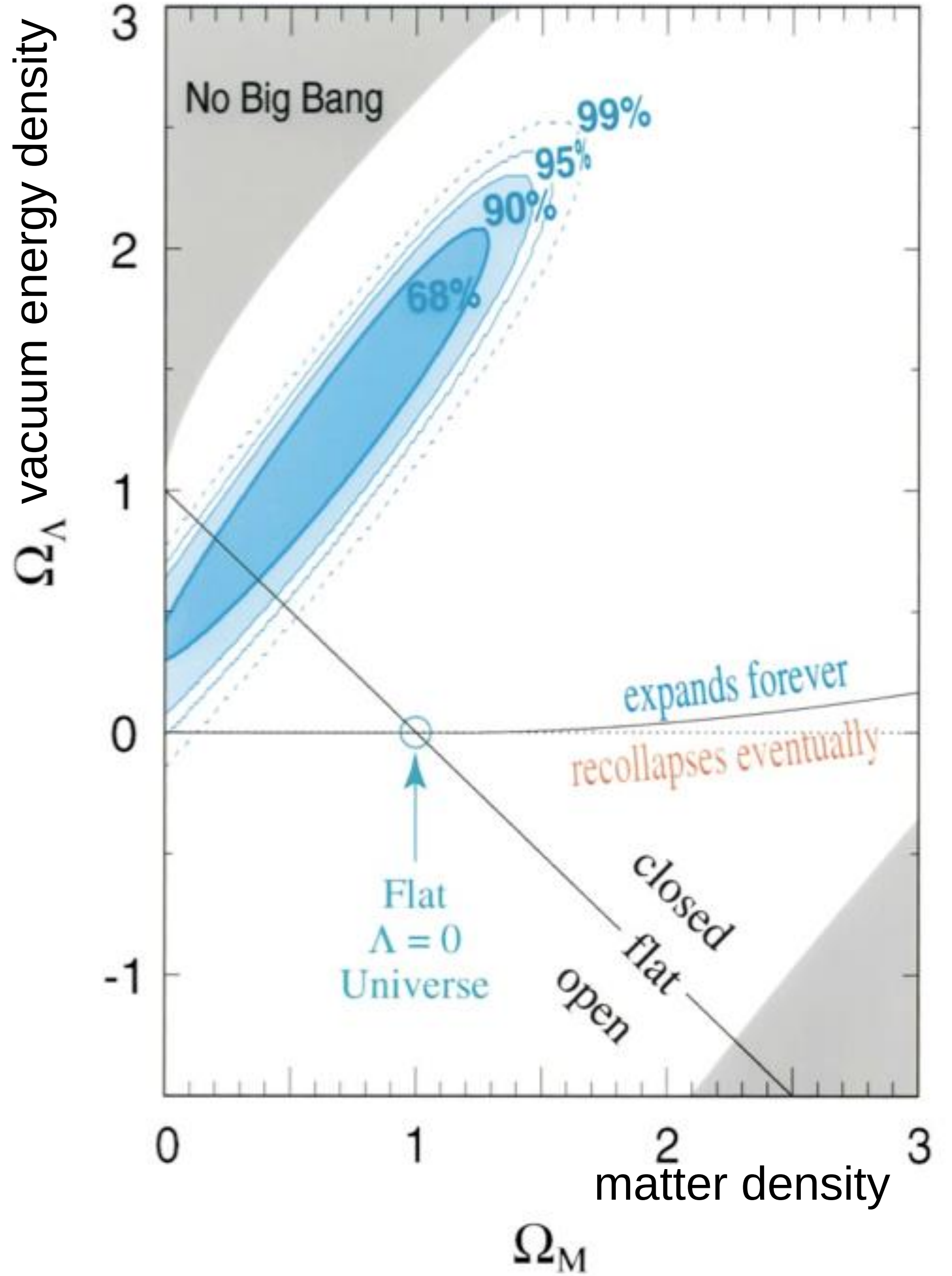


arXiv:1401.4064

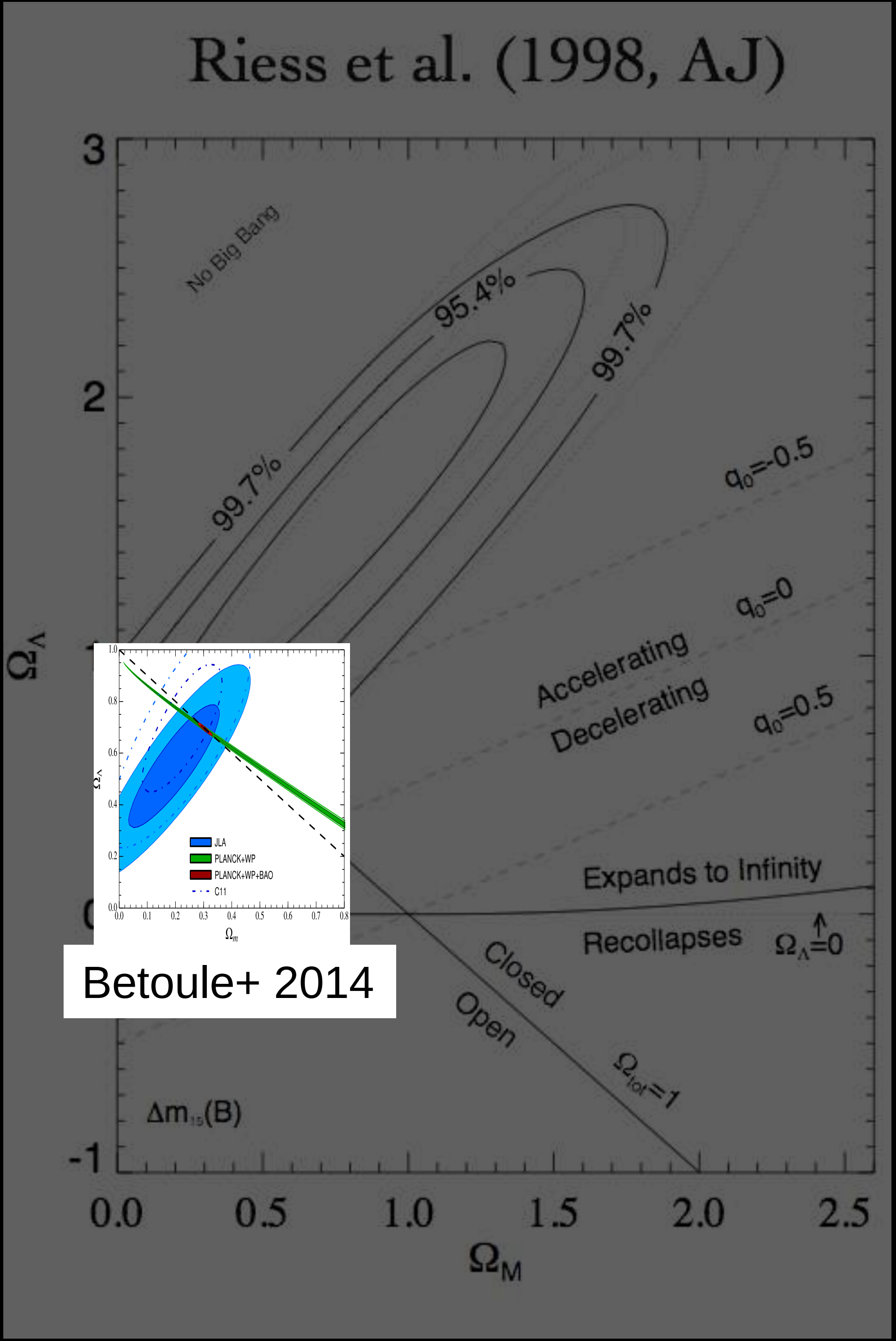
Riess et al. (1998, AJ)



Perlmutter et al. (1999, ApJ)



Progress over the last 16 years



Supernovae

Cosmic Microwave Background (Planck, WMAP)

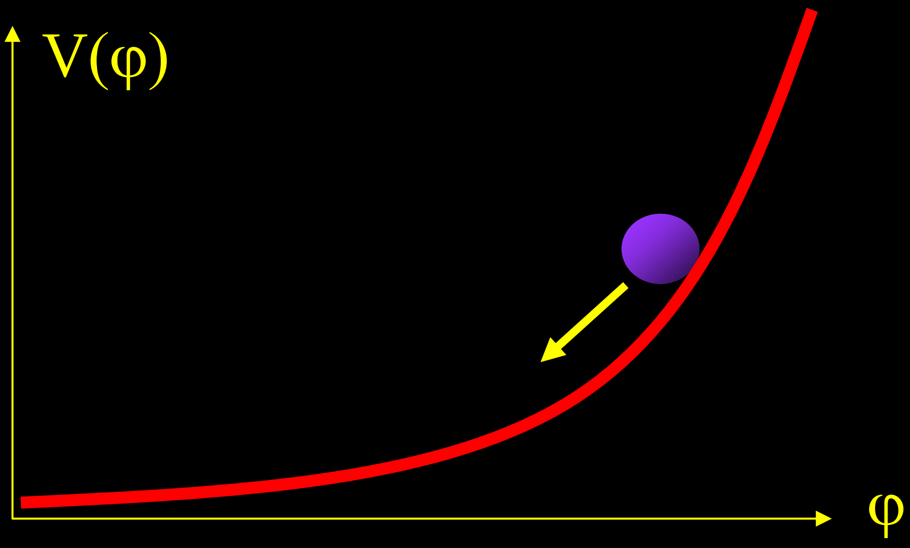
CMB+BAO

Here assuming $w=-1$

Scalar Fields and Cosmic Acceleration

- A homogeneous scalar field φ(t), slowly evolving in a potential, V(φ):

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV}{d\varphi} = 0$$



- Density & pressure:

$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$
$$P = \tfrac{1}{2}\dot{\varphi}^2 - V(\varphi)$$

- Slow roll:

$$\tfrac{1}{2}\dot{\varphi}^2 < V(\varphi) \Rightarrow \rho + 3P < 0 \Rightarrow \ddot{a} > 0$$

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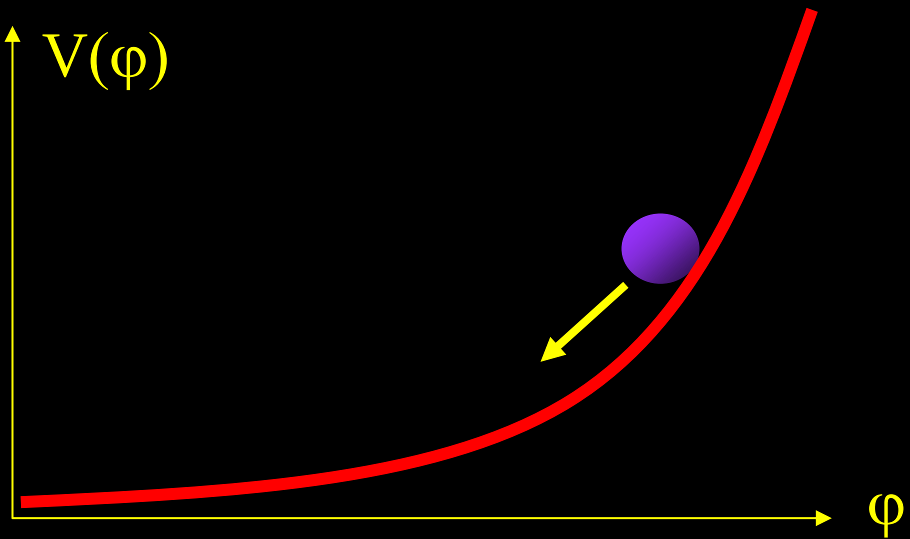
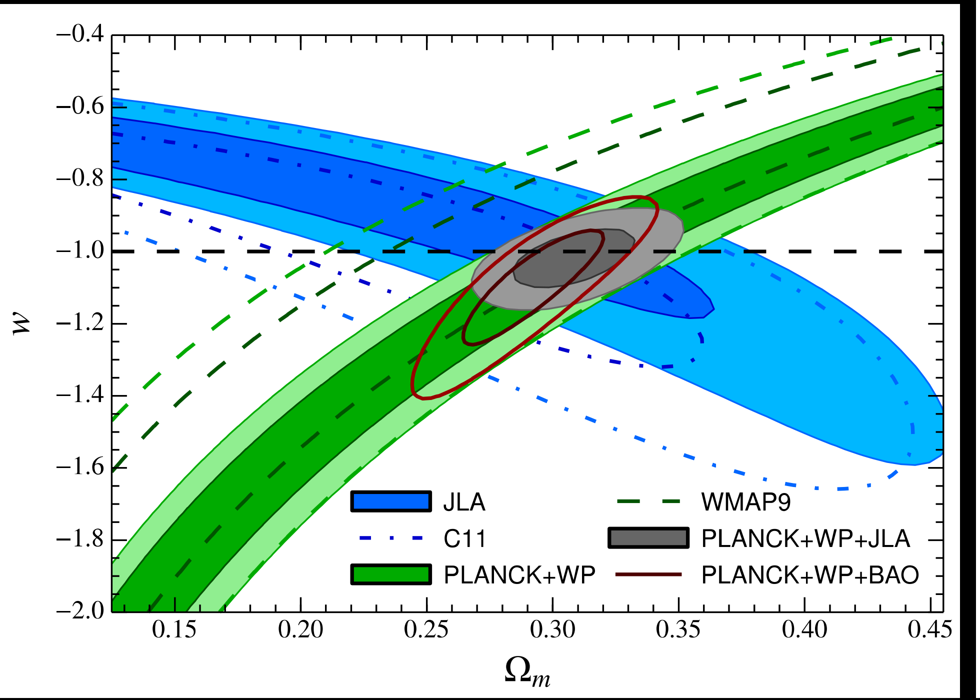


- Slow roll:

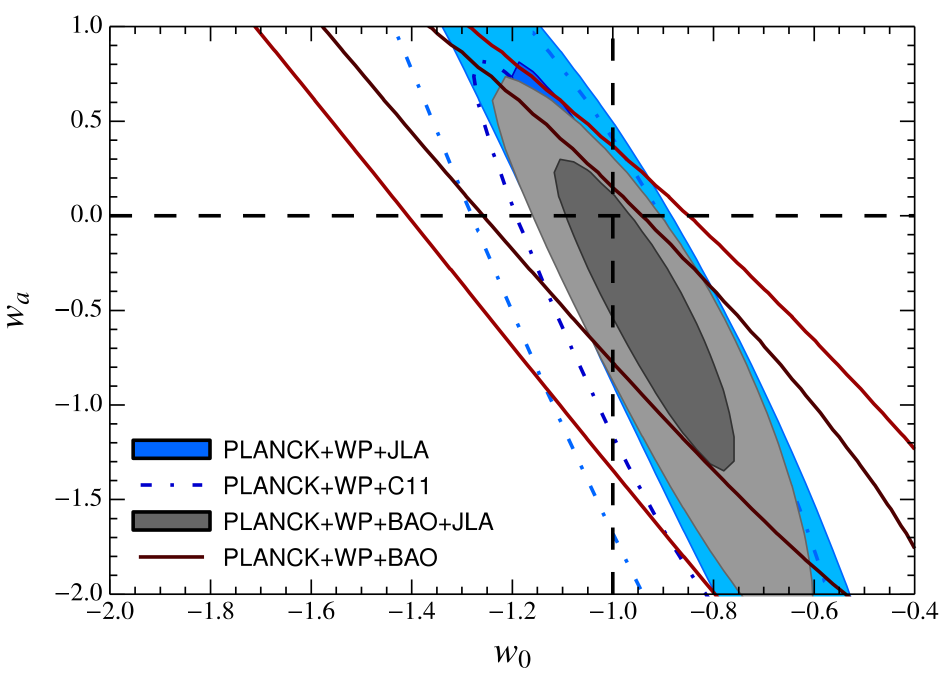
$$\tfrac{1}{2}\dot{\varphi}^2 < V(\varphi) \Leftrightarrow w \equiv P/\rho < 0 \text{ and time-dependent}$$

Current Dark Energy Constraints from Supernovae, CMB, and Large-scale Structure

Assuming constant *w*



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

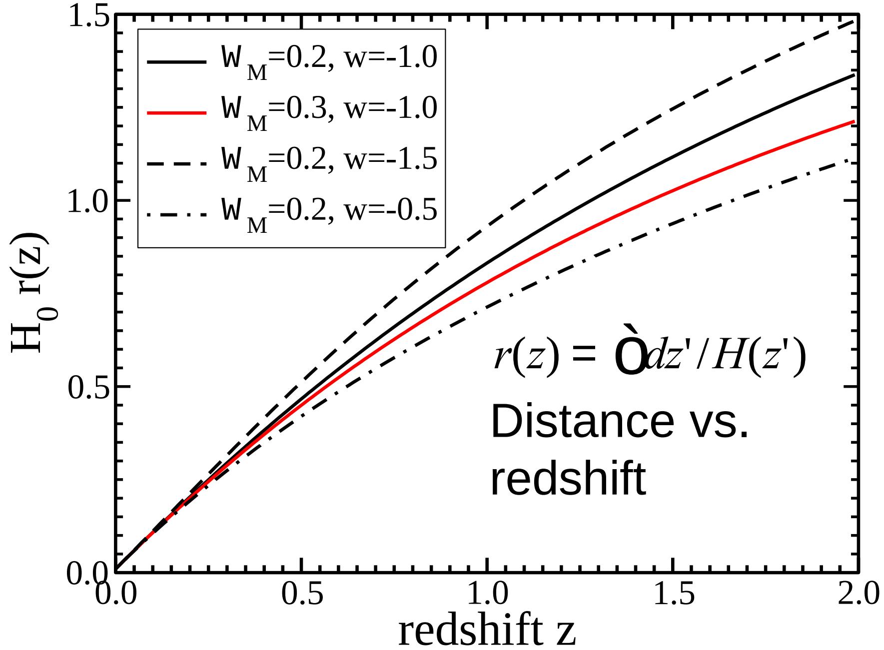


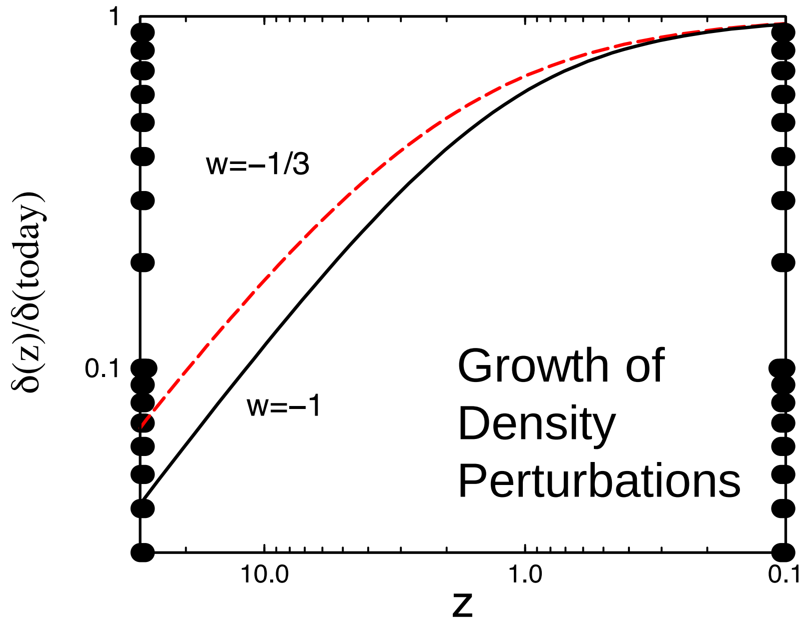
Betoule etal 2014

Consistent with vacuum energy (Λ): $w_0=-1$, $w_a=0$

What can we probe?

Require both to disentangle Dark Energy from Modified Gravity



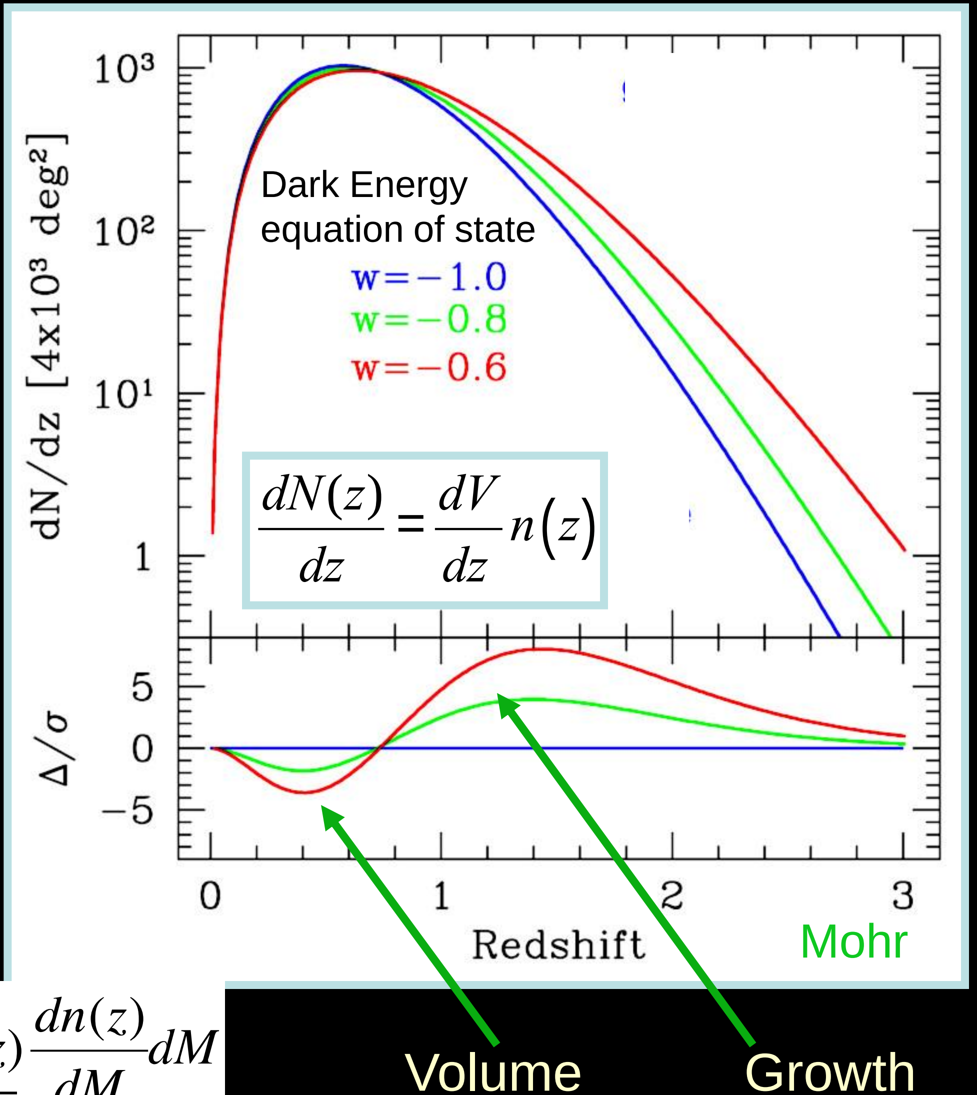


- Weak Lensing cosmic shear — Distances+growth
- Supernovae — Distances
- Baryon Acoustic Oscillations — Distances and H(z)
- Cluster counts — Distances+growth
- Redshift Distortions — Growth

I. Clusters

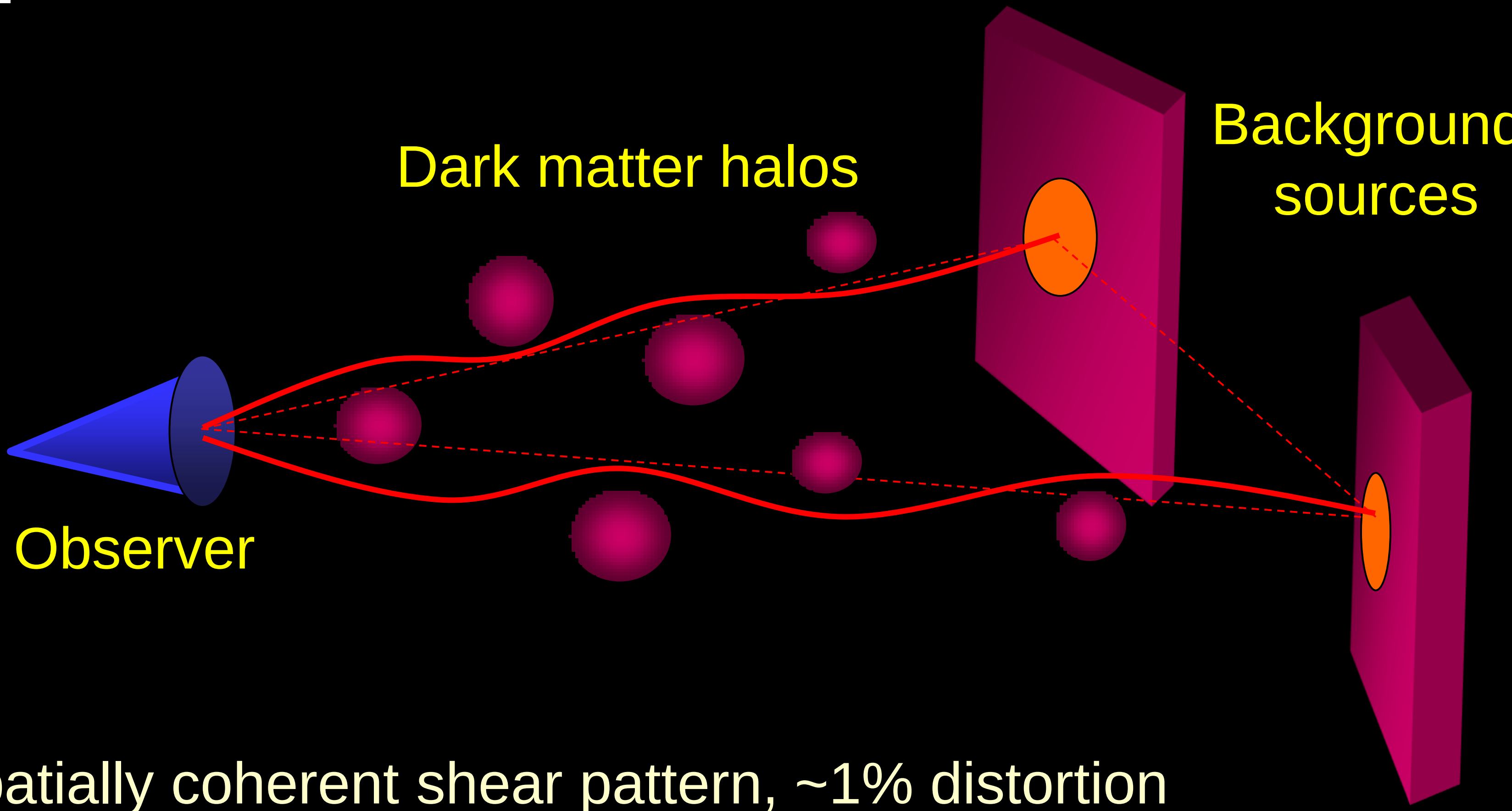
- Clusters are proxies for massive halos and can be identified to redshifts z>1
- Galaxy colors provide photometric redshift estimates for each cluster, σ(z)~0.01
- Challenge: determine mass-observable relation <u>*p(O|M,z)*</u> with sufficient precision
- Multiple observable proxies *O* for cluster mass: optical richness (DES), SZ flux (SPT), weak lensing mass (DES), X-ray flux

Number of clusters above mass threshold



$$\frac{d^2N}{dz d\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z)\, dO \int \underline{p(O\,|\,M,z)} \frac{dn(z)}{dM} dM$$

II. Weak Lensing: Cosmic Shear



- Spatially coherent shear pattern, ~1% distortion
- Radial distances depend on *expansion history* of Universe
- Foreground mass distribution depends on *growth* of structure

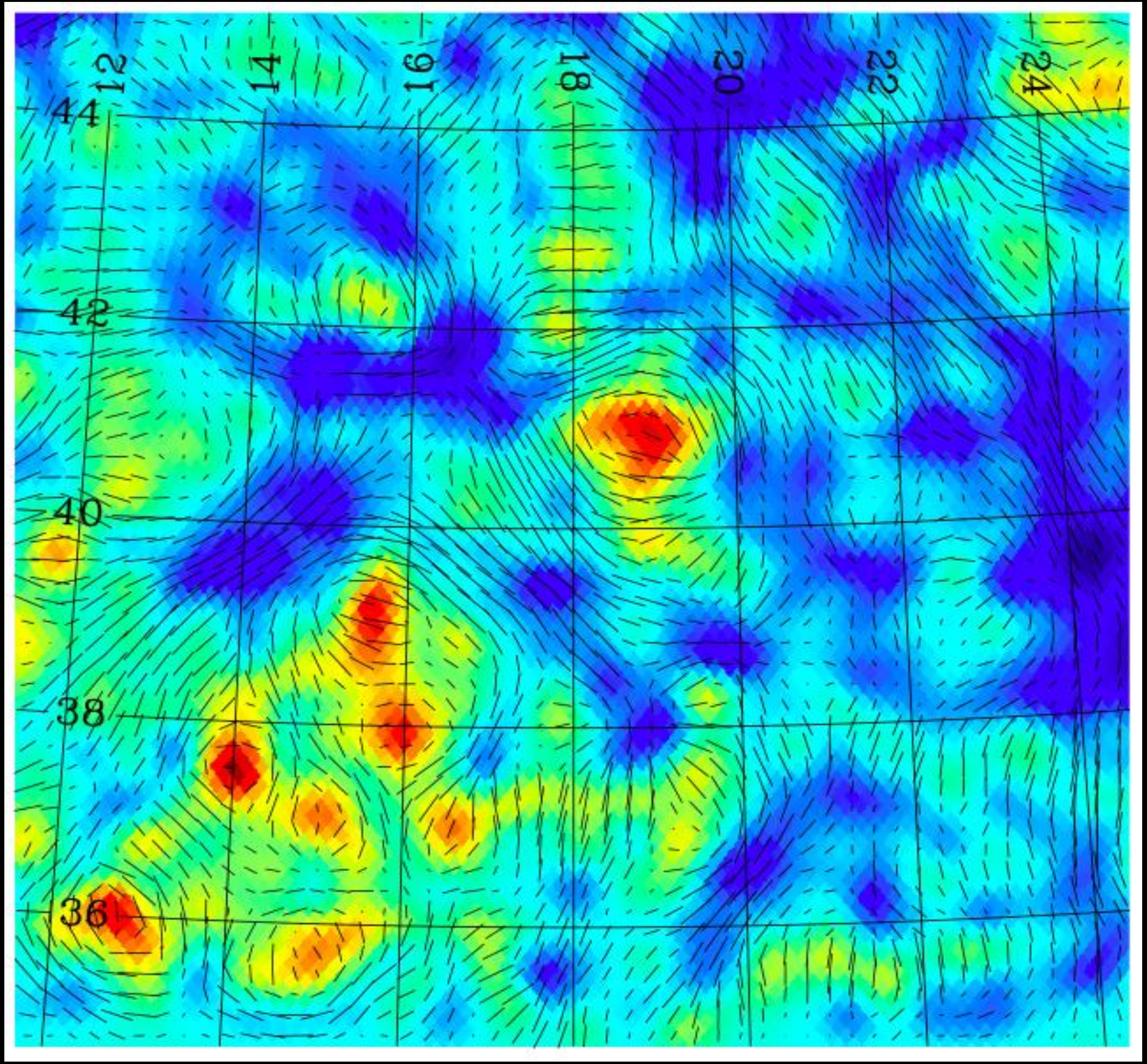
Weak Lensing Mass and Shear

DES Simulation

Tick marks: shear

Colors: projected mass density

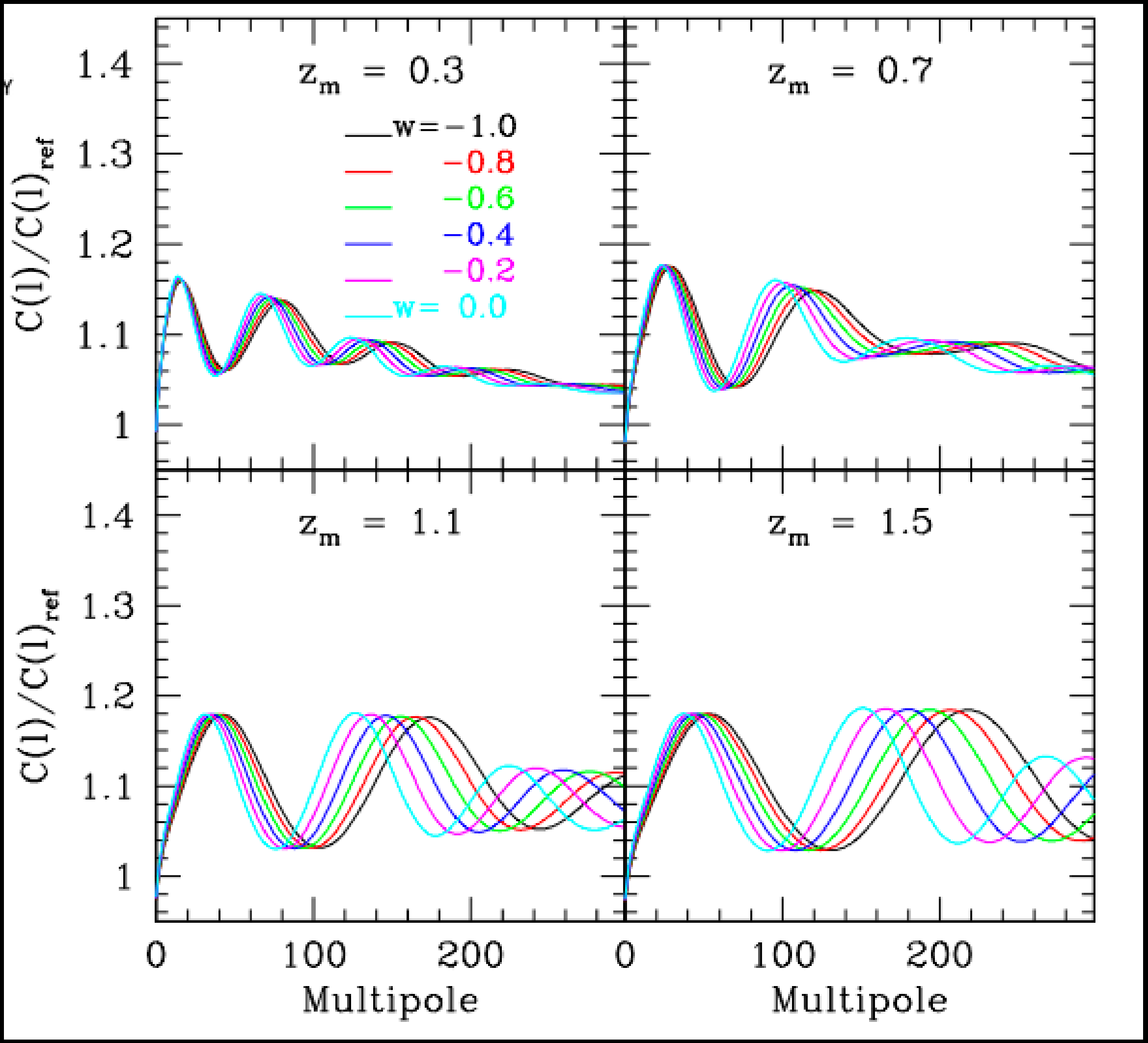
Becker, Kravtsov, etal



III. Baryon Acoustic Oscillations

Galaxy angular power spectrum in photo-z bins
(relative to model without BAO)

Photometric surveys provide this angular measure



Fosalba & Gaztanaga

IV. Supernovae

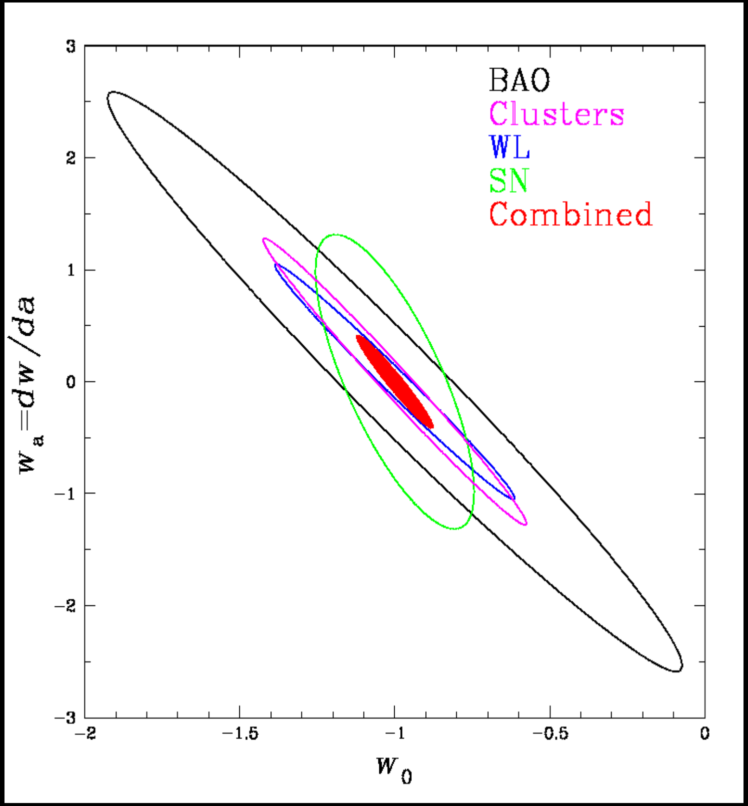
B. Dilday

SDSS-II: 500 spectroscopically confirmed SNe Ia, >1000 with host redshifts from SDSS-III

Dark Energy Survey

Forecast Constraints on DE Equation of State

$$w(a) = w_0 + w_a(1 - a(t)/a_0)$$



DES forecast

Four Probes of Dark Energy

- Galaxy Clusters
  - Tens of thousands of clusters to z~1
  - Synergy with SPT, VHS
- Weak Lensing
  - Shape and magnification measurements of 200 million galaxies
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
- Supernovae
  - 30 sq deg time-domain survey
  - 3500 well-sampled SNe Ia to z ~1

See Gus Evrard's talk

Dark Energy Survey

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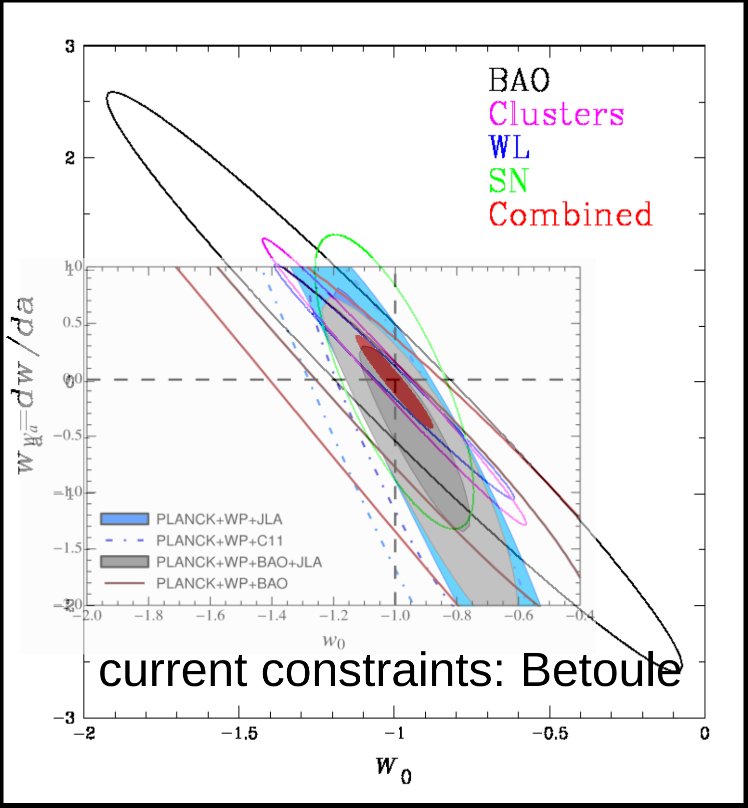
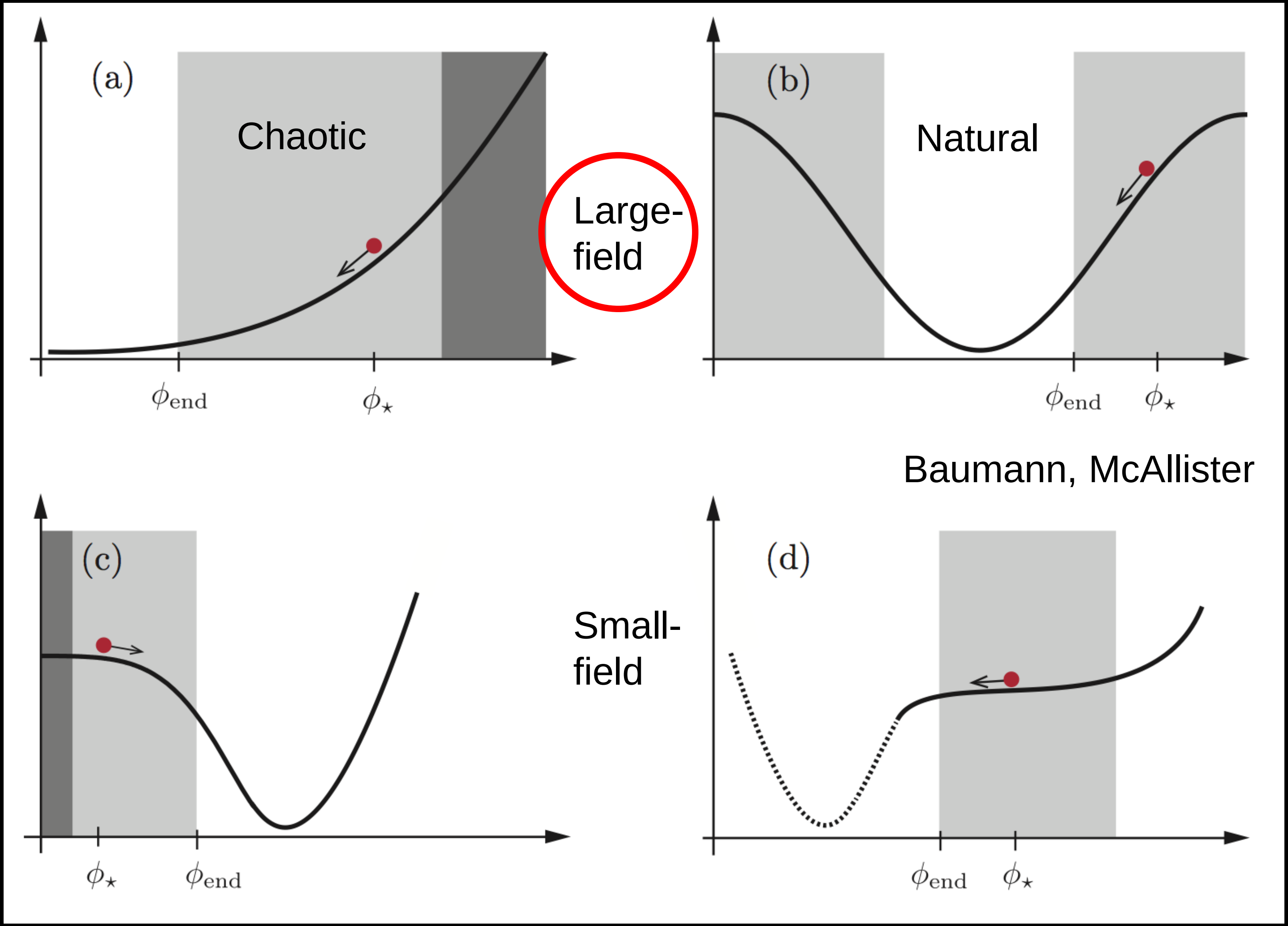


DES forecast

Inflation Models



$\Delta\Phi/M_{Pl}>3(r/0.1)^{1/2}$ BICEP r~0.2 favors large-field models

Scalar Field Inflation

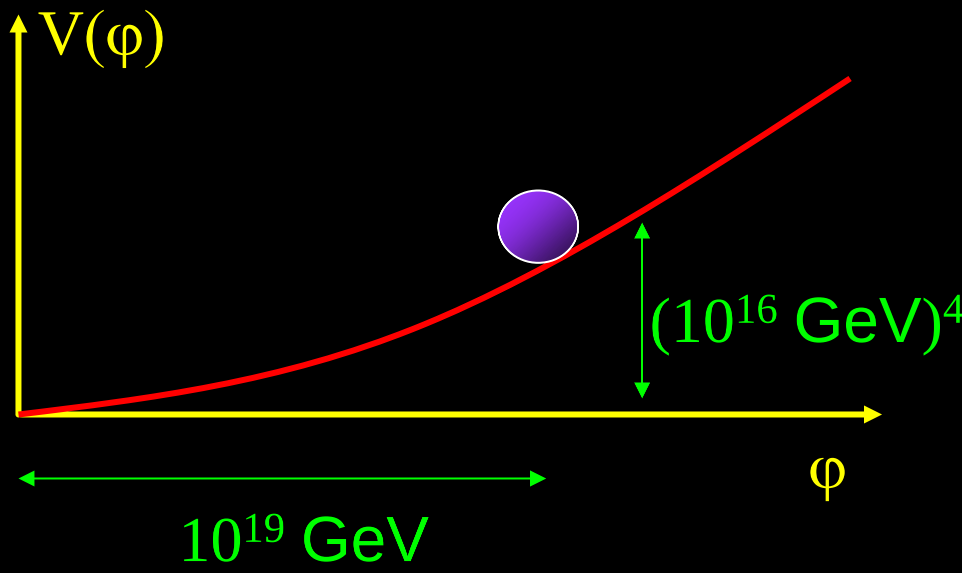
(for large-field models favored by BICEP)

General features:

$m \sim H_{inf} \sim 6\text{x}10^{14}$ GeV
(slow roll) (BICEP)

$V \sim M^4 \sim m^2\varphi^2 \sim H^2_{inf}M^2_{Pl}$
$\sim (2\text{x}10^{16}\ \text{GeV})^4$

$\varphi_i > M_{Pl} \sim 10^{19}$ GeV



Equation of state: $w > -1$ and evolves in time
Hierarchy: $m/\varphi \sim 10^{-5}$, $H/M \sim 10^{-2}$
Weak coupling: Quartic self-coupling $\lambda_\phi \sim 10^{-10}$

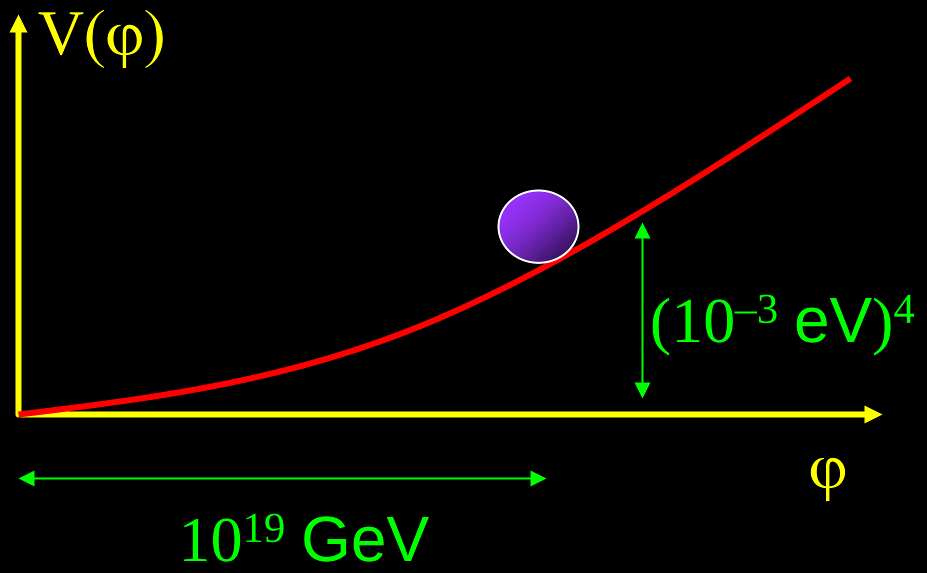
Scalar Field Dark Energy

General features:

$m < H_0 \sim 10^{-33}$ eV
(slow roll)

$V \sim M^4 \sim m^2\varphi^2 \sim H^2_0 M^2_{Pl}$
$\sim (10^{-3}\text{ eV})^4$

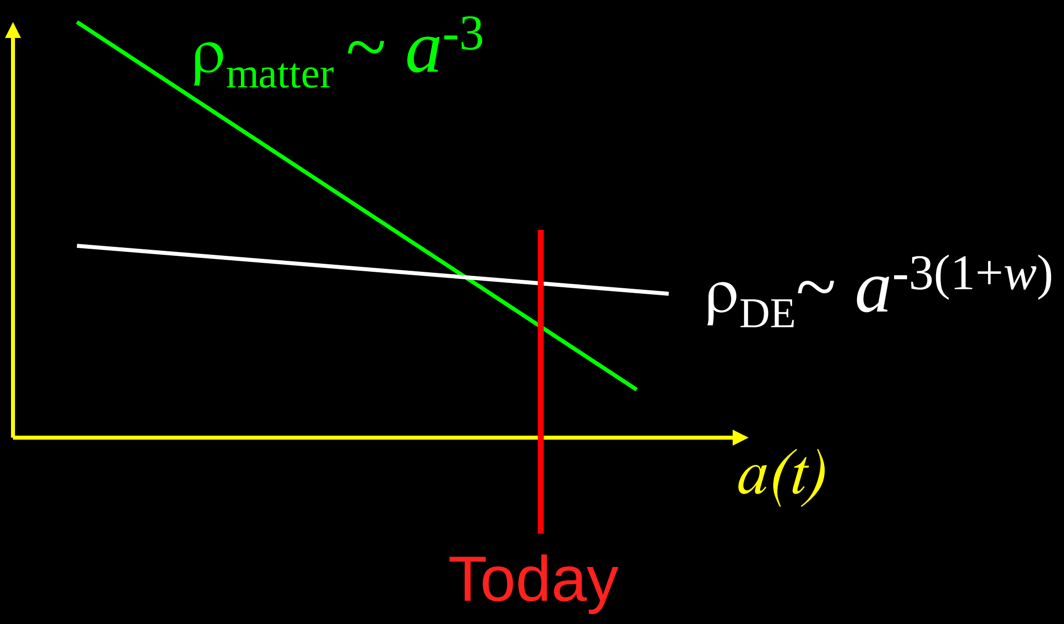
$\varphi_i > M_{Pl} \sim 10^{19}$ GeV



Equation of state: $w > -1$ and evolves in time
Hierarchy: $m/\varphi \sim 10^{-60}$, $H/M \sim 10^{-30}$
Weak coupling: Quartic self-coupling $\lambda_\phi < 10^{-122}$

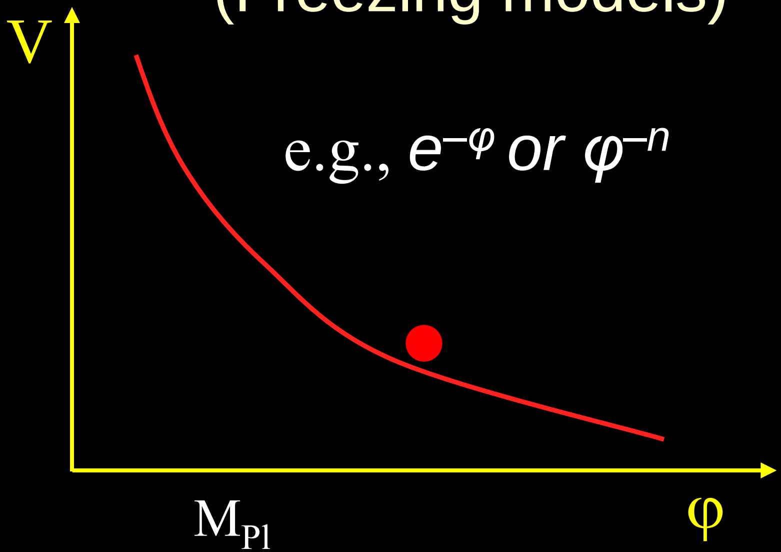
The Coincidence Problem

Why do we live at the `special' epoch when the dark energy density is comparable to the matter energy density?



Scalar Field Models and Coincidence

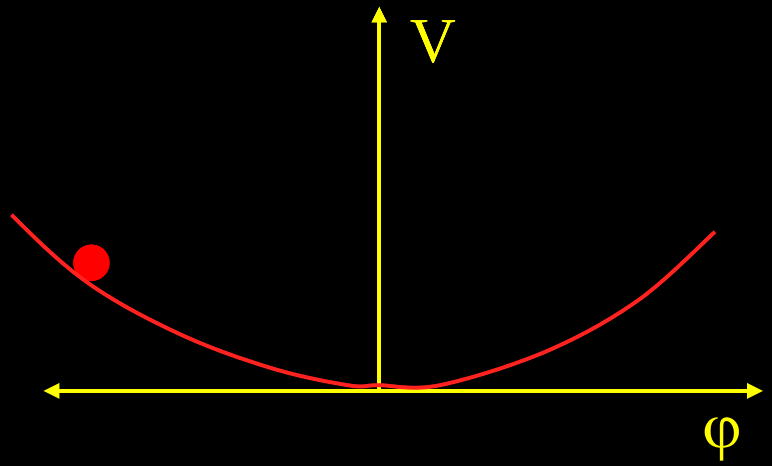
`Dynamics' models
(Freezing models)



Runaway potentials
DE/matter ratio constant
(Tracker Solution)

Ratra & Peebles; Caldwell, etal

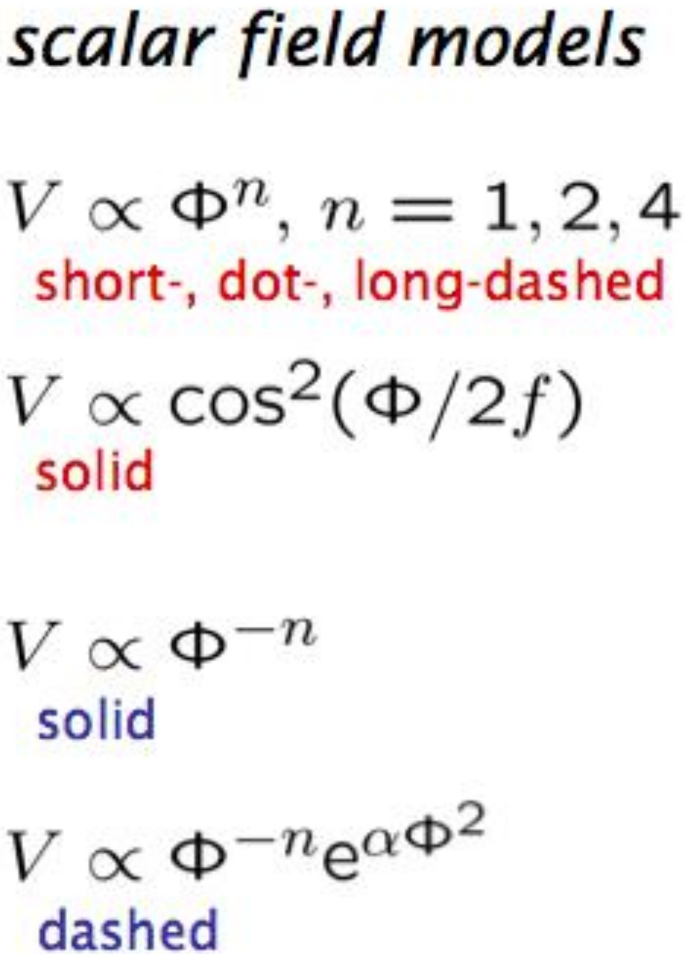
`Mass scale' models
(Thawing models)

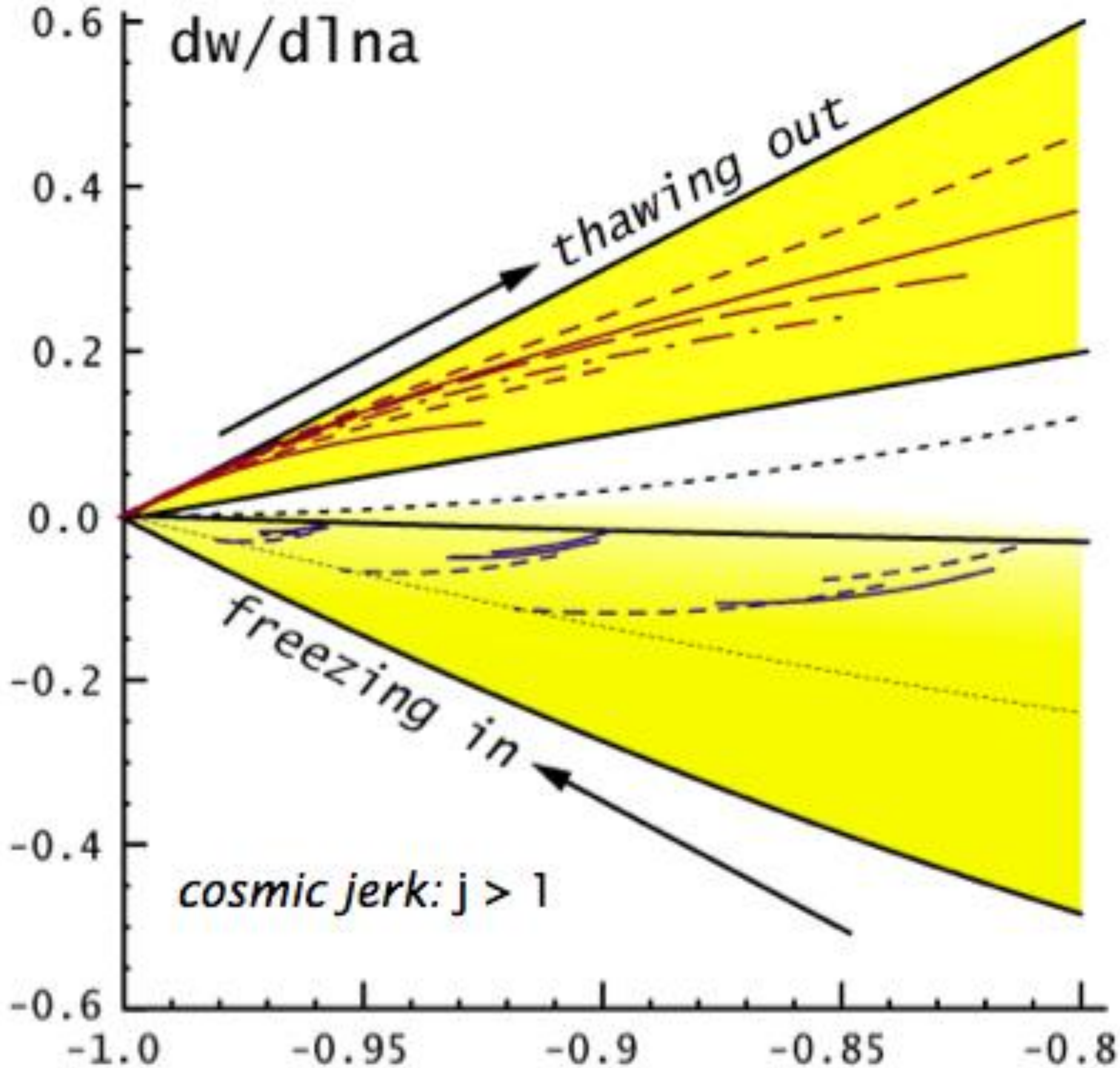


Pseudo-Nambu Goldstone Boson
Low mass protected by symmetry
(Cf. axion, natural inflation)
$M \sim 10^{-3}$ eV

JF, Hill, Stebbins, Waga

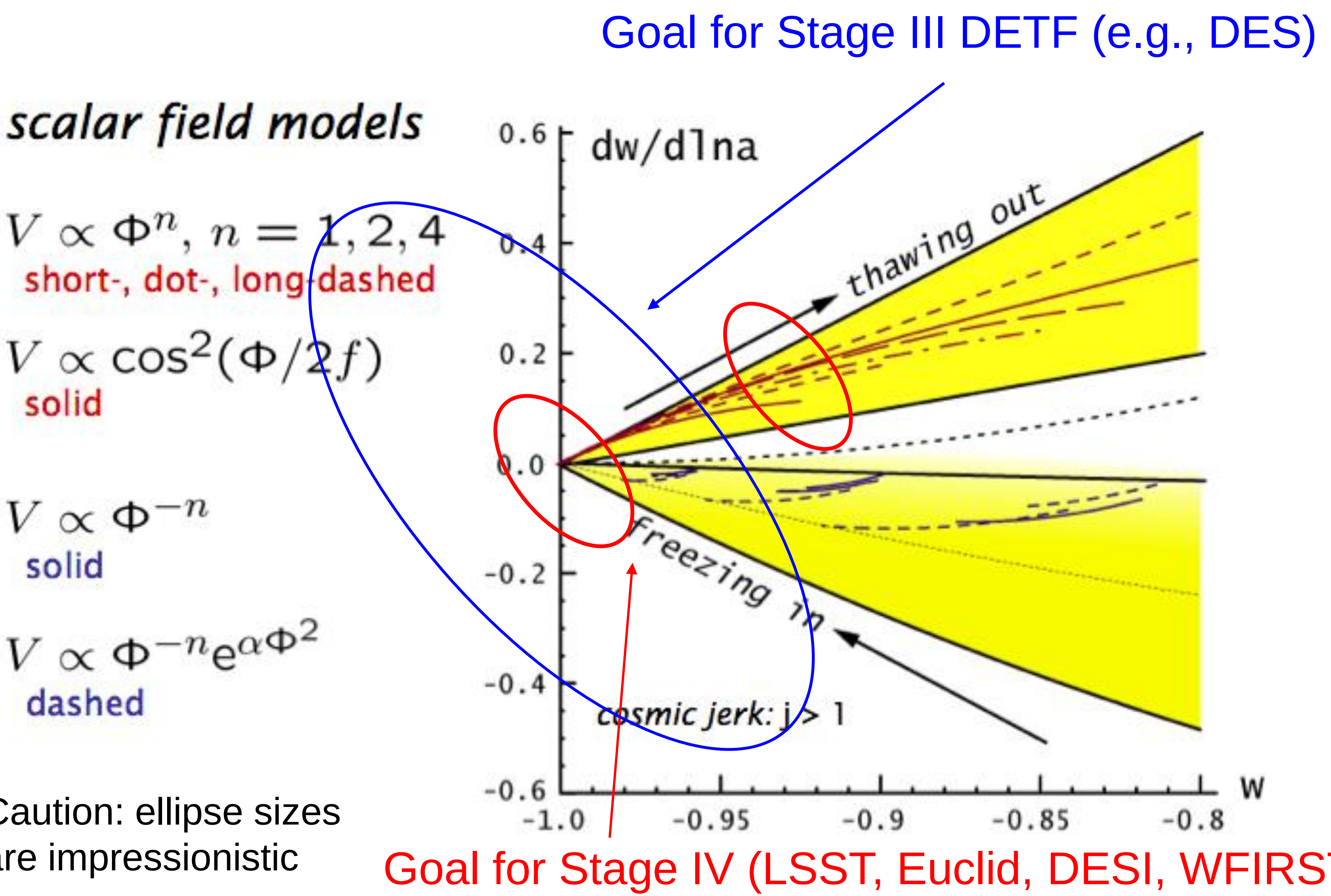
Dynamical Evolution of Freezing vs. Thawing Models





Caldwell & Linder

Measuring *w* and its evolution can potentially distinguish between physical models for acceleration



Caution: ellipse sizes
are impressionistic

Effective Field Theory and Acceleration Models

- Technical naturalness: small dimensionless parameters in a theory (e.g., hierarchy of mass scales or coupling constants) should be protected by symmetries from large radiative corrections (t'Hooft)
- NOTE: small ≠ fine-tuned
- Strong naturalness: small parameters or hierarchies should emerge dynamically in fundamental theories without small parameters (e.g., QCD scale from logarithmic running of strong coupling)
- Inflation model-builders, coming out of hep-th, adopted EFT framework
- Dark Energy model-builders (astro-ph) not so much
- In absence of such framework, not clear what physics one learns from writing down arbitrary functions $V(\Phi)$

PNGB Models for Acceleration

$$V(f) = M^4\left(1 + \cos(f / f)\right)$$

- Natural Inflation:

$$M \sim 10^{16}\, GeV,\ f \sim M_{Pl}$$

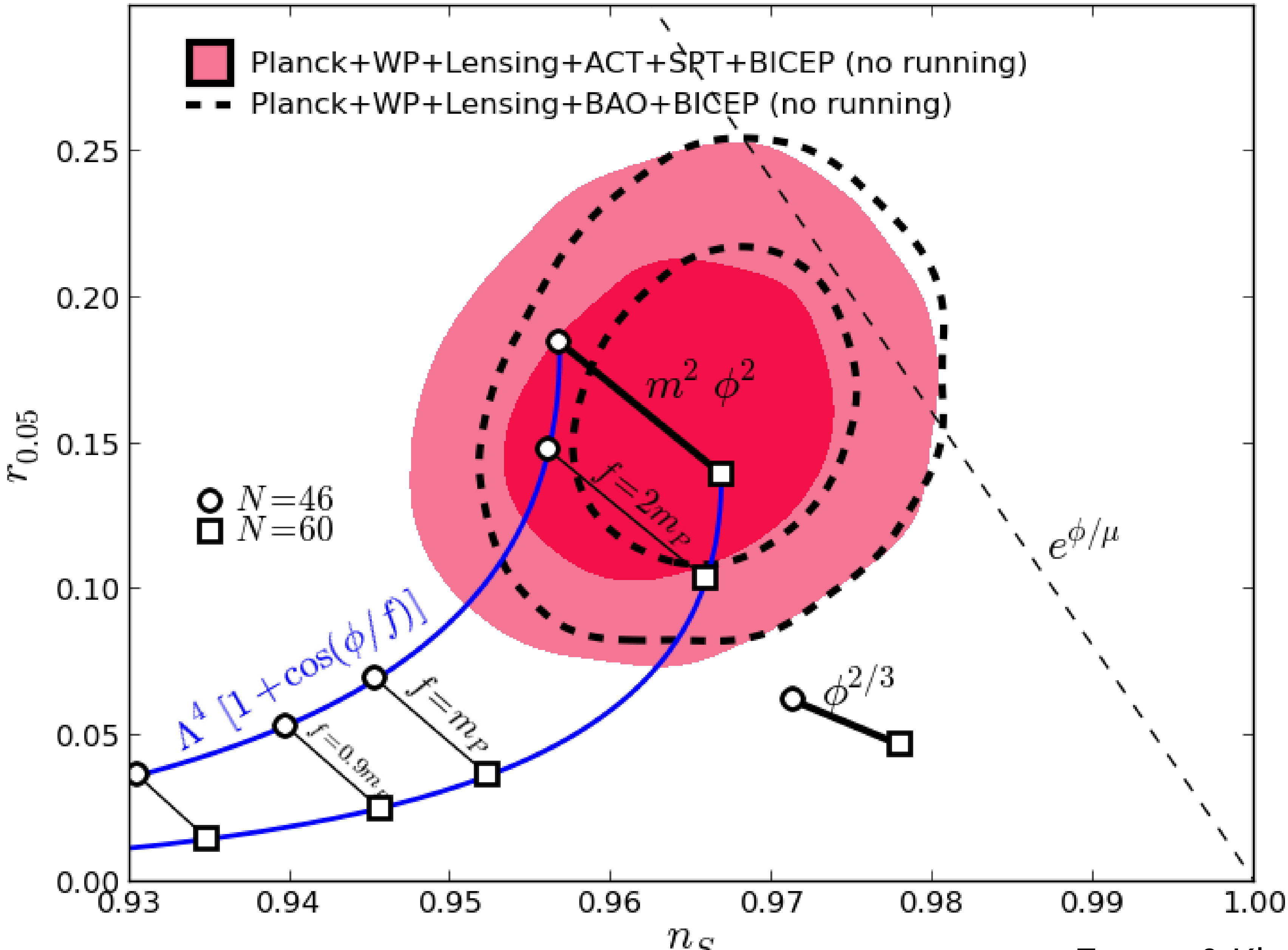
Freese, JF, Olinto 1990

- Dark Energy:

$$M \sim 10^{-3}\, eV,\ f \sim M_{Pl}$$

JF, Hill, Stebbins, Waga 1995

- Spontaneous symmetry breaking at fundamental scale *f*
- Explicit breaking at lower scale *M*
- Hierarchy protected by shift symmetry (technically natural)
- Lower scale *M* might be generated dynamically by non-perturbative effects (strongly natural)



Freese & Kinney

Quintessential Inflation

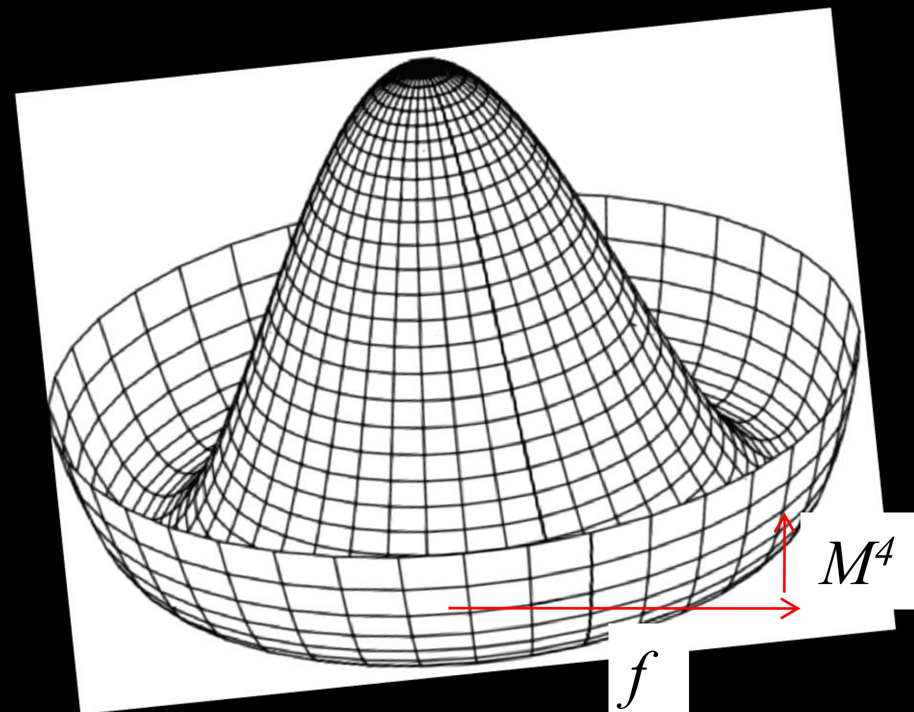
Rosenfeld, JF 2005, 2006

- Tilted Mexican hat:

$$V(F) = /\left(F F^* - \frac{f^2}{2}\right)^2 + M^4\left(\cos(Arg(F) - 1\right)$$

$$M \sim 10^{-3} eV << f \sim M_{Pl}$$

$$/ \sim 10^{-10}$$



•Radial mode: inflaton

•Angular mode: dark energy

•Simplest model with 2 epochs of acceleration that unifies the trans-Planckian scalar field amplitudes/excursions

Quintessential Inflation

Rosenfeld, JF 2005, 2006

f	ϕ_e	ϕ_{50}	ϕ_{60}	n_{50}	n_{60}	r_{50}	r_{60}
0.1	0.581	4.04	4.41	0.941	0.951	0.313	0.262
1.0	1.32	4.48	4.84	0.946	0.955	0.280	0.237
3.0	3.40	6.17	6.49	0.954	0.961	0.229	0.195
5.0	5.29	8.06	8.37	0.956	0.963	0.207	0.176

in Planck mass units

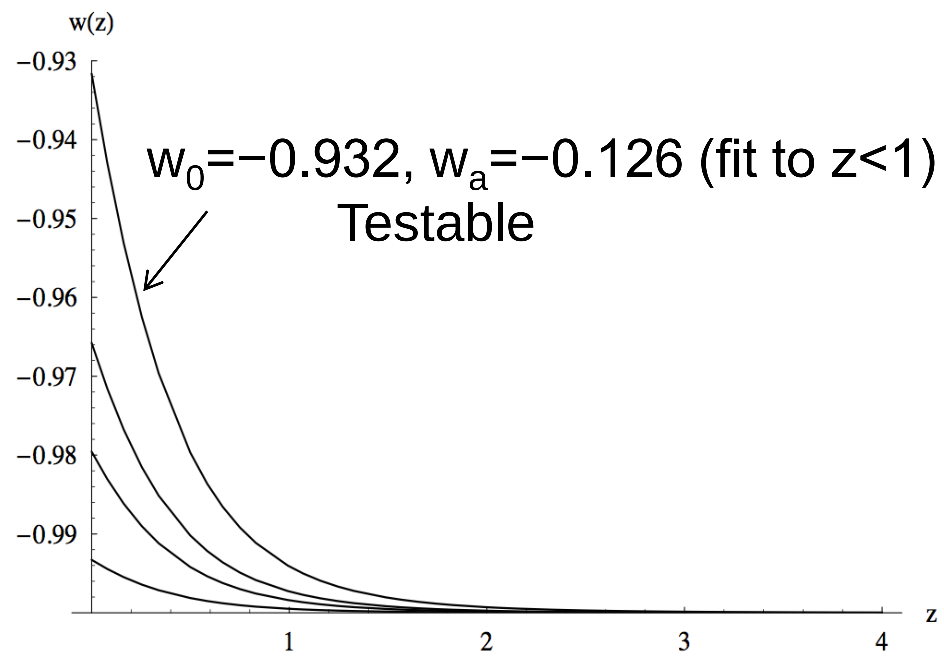
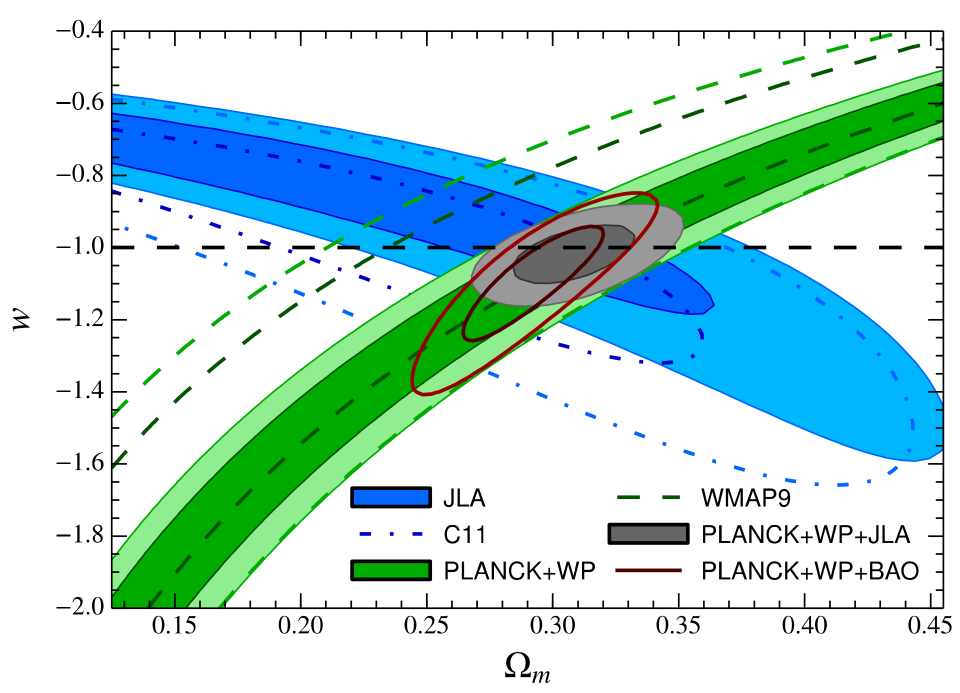


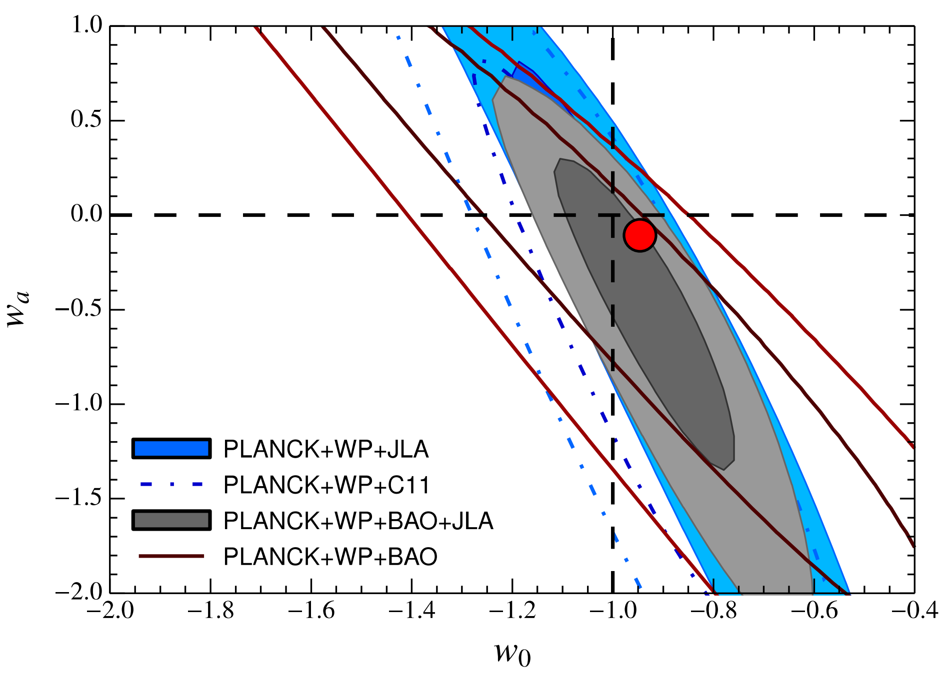
FIG. 2: Evolution of the quintessence equation of state parameter $w(z)$ as a function of redshift for $f = 5\ M_{Pl}$, $\Omega_\varphi = 0.7$, and $M^4 = 10(5.4), 30(3.2), 50(2.5)$, and $100(1.8)$ times $\rho_c^{(0)}$ (from bottom to top curves). The numbers in parentheses are the initial values of the field φ_i in Planck mass units for the corresponding value of M.

Current Dark Energy Constraints from Supernovae, CMB, and Large-scale Structure

Assuming constant *w*



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

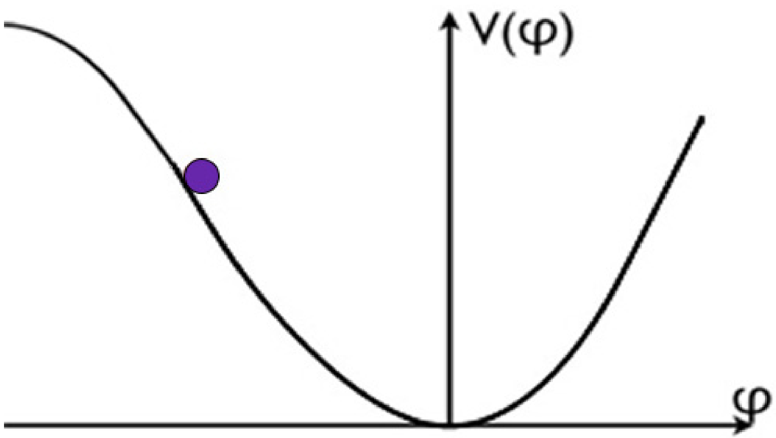


Betoule etal 2014

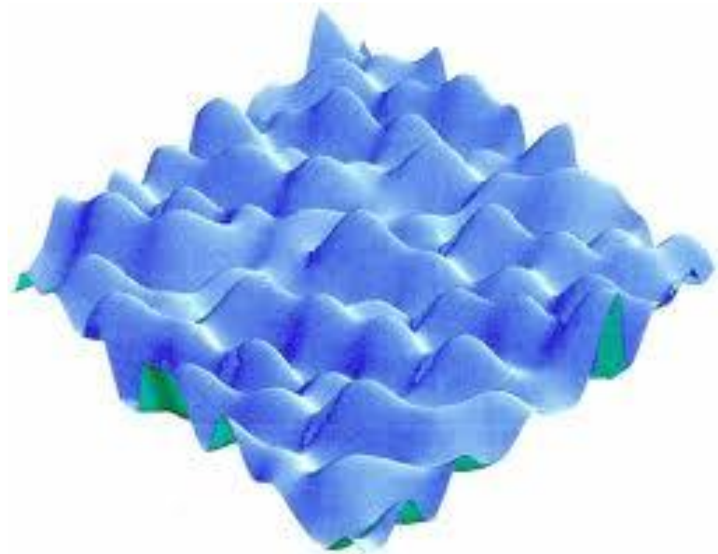
Consistent with vacuum energy (Λ): $w_0 = -1$, $w_a = 0$

Large-r Problem: Suppressing Higher order terms in EFT

This works



This doesn't but is what you expect when ϕ is of order m_{Pl}



Shift symmetry, axion monodromy, natural inflation,…?

Extranatural Inflation

- Models with $\Delta\Phi > M_{Pl}$ (BICEP2) and/or $f > M_{Pl}$ go beyond domain of validity of Effective Field Theory (Lyth)
- Expect global shift symmetry to be broken by Quantum Gravity corrections $\sim(\Phi/M_{Pl})^n$
- Inflaton as component of 5-d gauge field compactified on circle of radius R
- QG corrections under control if $R > 1/M_{Pl}$
- Estimated n_s=0.96, r=0.11

Arkani-Hamed, Cheng, Creminelli, Randall 2003

Inflation and Equation of State

- Slow Roll parameters:
- $\varepsilon_V = (M^2_P/2)(V'/V)^2 = r/16$
- $\eta_V = M^2_P(V''/V)$
- Scalar spectral index: $n_s - 1 = 2\eta_V - 6\varepsilon_V$
- Translation to Equation of State parameter: $1 + w = 2\varepsilon_V/3 = r/24$
- $d\ln(1+w)/d\ln a = -2\eta_V + 4\varepsilon_V = 1 - n_s - r/8$
- Planck (n_s=0.96)+BICEP (r=0.2):

$\varepsilon_V = 0.0125$, $w = -0.992 \pm 0.003$, $\eta_V = 0.0175$,

$d\ln(1+w)/d\ln a = 0.015 \pm 0.008$

(50-60 e-folds before end of inflation)

Ilic, Kunz, Liddle, JF 2010

What do we know?

- First epoch of acceleration ended
- It lasted at least N=50-60 e-folds
- Observations probe ~10 e-folds range
- Planck (n_s=0.96)+BICEP (r=0.2):

  $w=-0.992\pm0.003$, $d\ln(1+w)/d\ln a=0.015\pm0.008$

  (50-60 e-folds before end of inflation)
- 2nd epoch has lasted N~0.4 e-folds so far
- JLA:

  $w_0=-0.957\pm0.124$, $w_a=-0.336\pm0.552$
- Stage IV DE uncertainties: w_0~0.01, w_a~0.1

Where do we go from here?

- On-going and near-future CMB experiments will test BICEP results
- Probe physics of Inflation:
  - $n_T = -r/5$ consistency relation (challenging)
  - Primordial non-Gaussianity constraints
  - Higher-precision measurements of r, n_s
- Probe physics of Late Acceleration:
  - Expansion history
  - Growth of structure
  - Surveys underway and planned

PONT c’est merveilleux!
(S’marvelous)

Merci beaucoup Chiara,
Geraldine, Marco, Philippe!