

loav's Universe

Josh Frieman
Fermilab, U. Chicago

Waga-Fest
September 28, 2018



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The Dark Energy Revolution in Cosmology

Celebrating Ioav Waga's Career

The conference in honor of professor Ioav Waga will be held on 28/Sep/2018, at Universidade Federal do Rio de Janeiro.

Professor Ioav Waga graduated at Pontifícia Universidade Católica do Rio de Janeiro (PUC, 1975), master's at from Centro Brasileiro de Pesquisas Físicas (CBPF, 1983) and PhD in Physics at UFRJ (1988). He had important contributions to the study of dark energy and of the cosmic acceleration since its discovery in 1998. He has also worked on the following subjects: Particle Physics, Cosmology, Cosmic Inflation, $f(R)$ Theories, Dark Matter and Energy, Supernovae, BAO and Gravitational Lensing. He recently retired as a full professor at UFRJ, being one of the founders of the group Astrophysics, Relativity and COSmology (ARCOS) in the Institute of Physics.

The Dark Energy Revolution in Cosmology

Celebrating Ioav Waga's Career

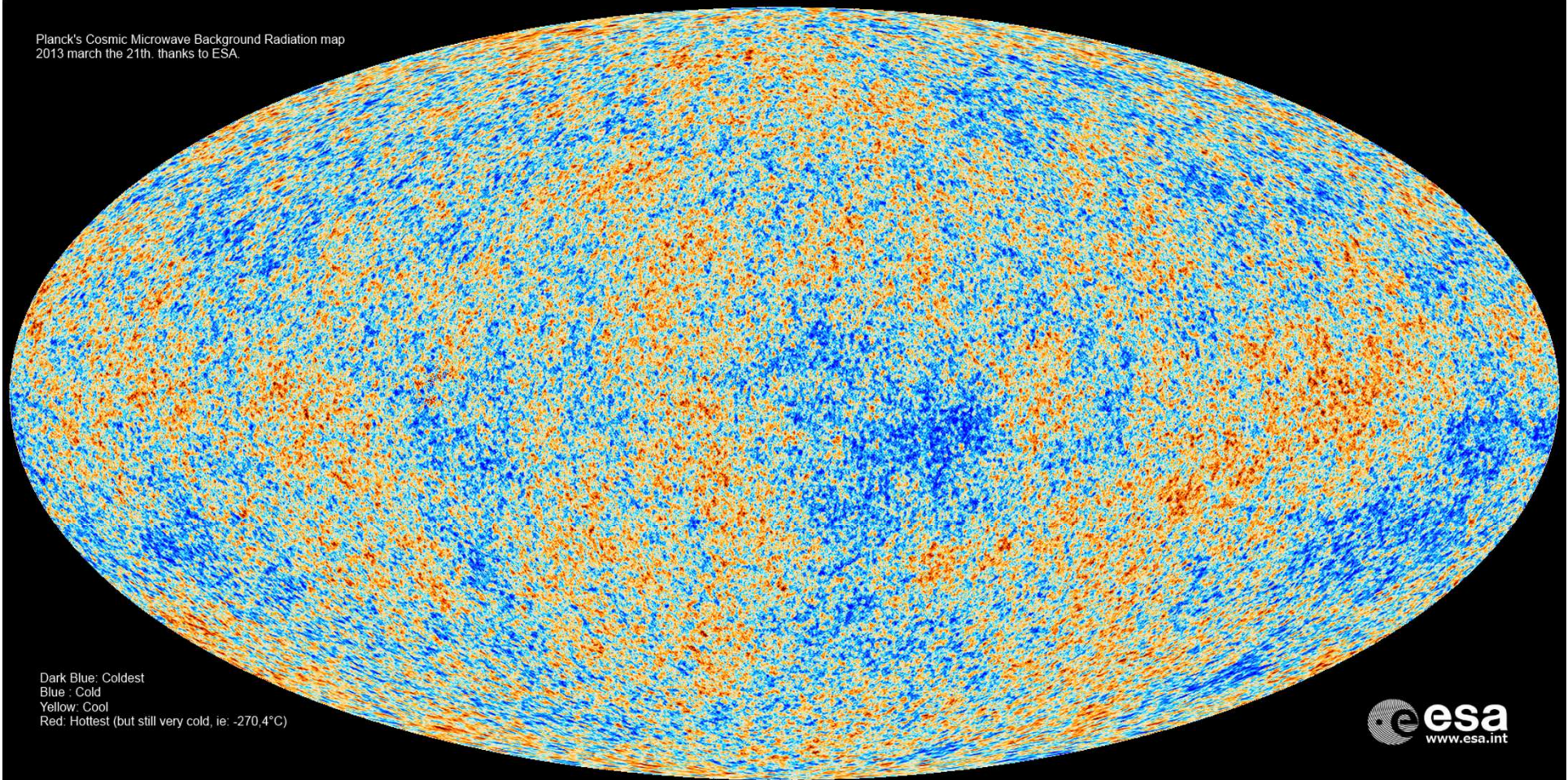
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since *before* its discovery in 1998!

Planck CMB Temperature Map

Planck's Cosmic Microwave Background Radiation map
2013 march the 21th. thanks to ESA.

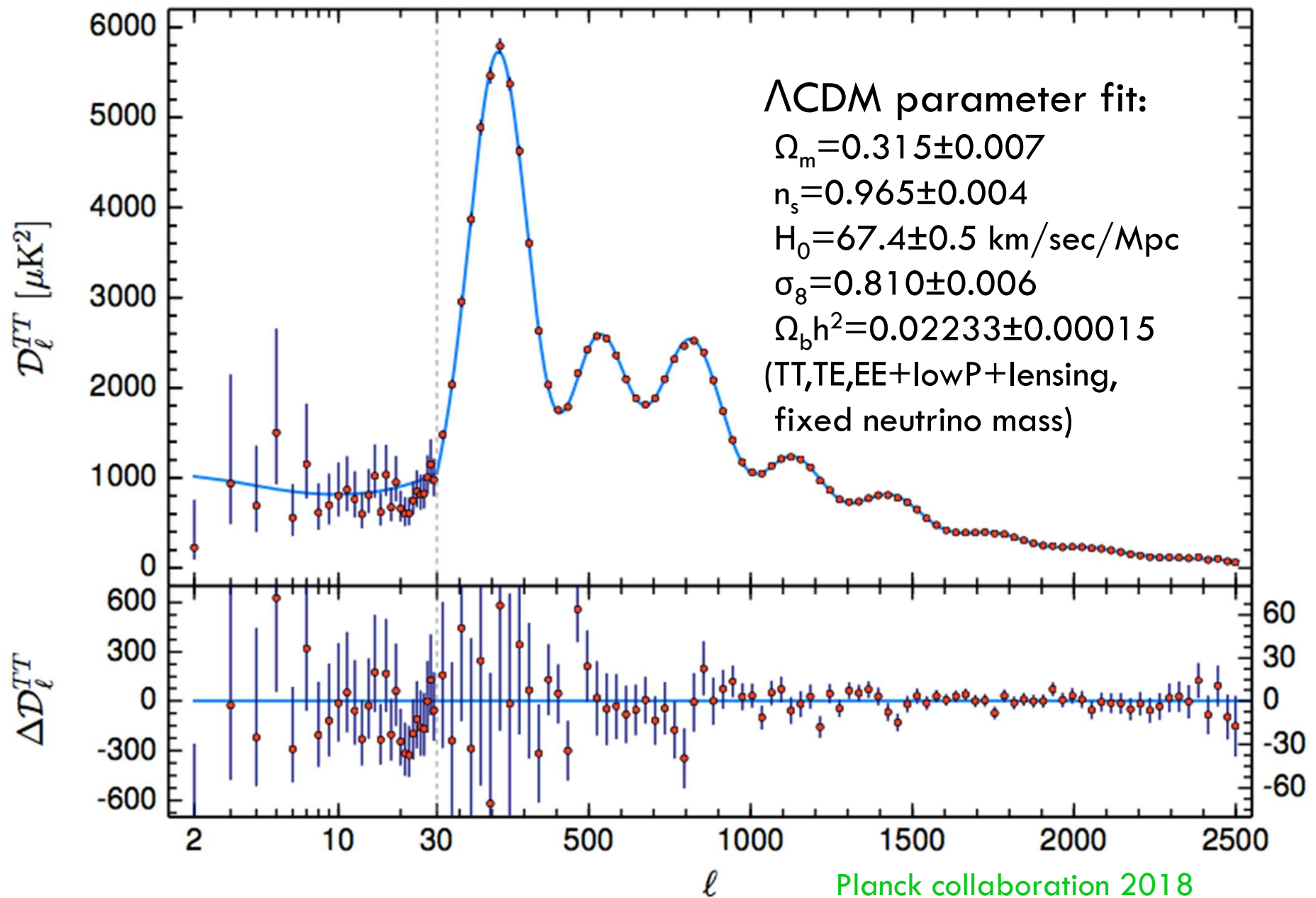


Dark Blue: Coldest
Blue : Cold
Yellow: Cool
Red: Hottest (but still very cold, ie: $-270,4^{\circ}\text{C}$)



$O(10^{-5})$ Temperature fluctuations at 380,000 years

Planck Results 2018



Cosmology 2018: Λ CDM

- A well-tested (6-parameter) cosmological model:
 - Universe is expanding from hot, dense early phase (Big Bang) 13.8 Gyr ago.
 - Early epoch of accelerated expansion (inflation) produced nearly flat & smooth spatial geometry and generated large-scale density perturbations from quantum fluctuations.
 - From these, structure formed from gravitational instability of cold dark matter (CDM, 25%) in currently Λ -dominated (70%) universe, which is again accelerating.
- Consistent with all data from the CMB, large-scale structure, lensing, supernovae, clusters, light element abundances (BBN), ...

Cosmology 1995: Λ CDM?

- Conflicting hints of a cosmological model:
 - Universe is expanding from hot, dense early phase (Big Bang) $\sim 13-15$ Gyr ago (Globular cluster ages).
 - Early epoch of accelerated expansion (inflation) produced nearly flat & smooth spatial geometry and generated large-scale density perturbations from quantum fluctuations.
 - From these, structure formed from gravitational instability of cold dark matter (CDM), $20 \pm 10\%$ of $\Omega=1$ (APM galaxy clustering). $\sim 80\%$ smooth missing energy component needed for consistency with inflation.
 - Hubble constant measurements: $H_0 = 80 \pm 15$ km/sec/Mpc, indicated $H_0 t_0 \sim 1$: “age crisis”, solved by $\Omega_\Lambda \sim 0.8$.
 - But strong lensing statistics indicated $\Omega_\Lambda < 0.6-0.8$

Early Inflation

- Early epoch of cosmic acceleration
- Simplest model: weakly self-coupled scalar field that takes a cosmologically long time to reach its ground state

Late Inflation

- Current epoch of cosmic acceleration
- Simplest model: weakly self-coupled scalar field that takes a cosmologically long time to reach its ground state

Late Inflation

- Current epoch of cosmic acceleration
- Simplest model: cosmological constant Λ

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.

Cosmology with Ultra-light Pseudo-Nambu-Goldstone Bosons

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²*Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

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Rio de Janeiro, RJ, 21943 - Brasil

(May 1995)

700 citations

See also: JF, Waga 1997; Waga, JF 2000

Scalar Field Dark Energy

- Acceleration could be due to a very light scalar field φ , slowly evolving in a potential, $V(\varphi)$:

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

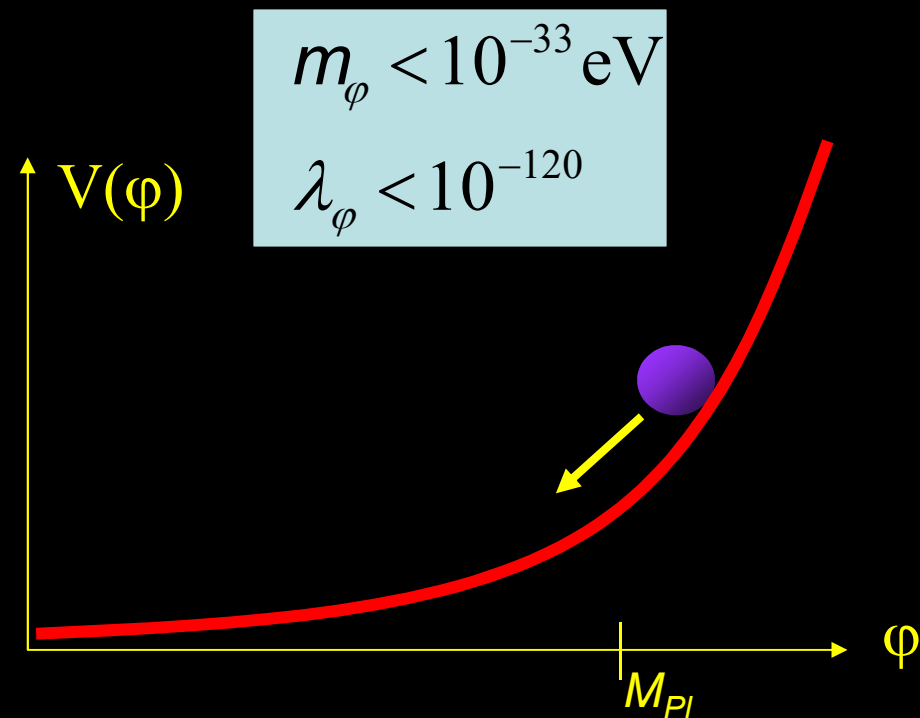
- Density & pressure:

$$\rho = \frac{1}{2} \dot{\varphi}^2 + V(\varphi)$$

$$P = \frac{1}{2} \dot{\varphi}^2 - V(\varphi)$$

- Slow roll:

$$\frac{1}{2} \dot{\varphi}^2 < V(\varphi) \Rightarrow P < 0 \Leftrightarrow w < 0 \text{ and time - dependent}$$



Scalar Field Dark Energy

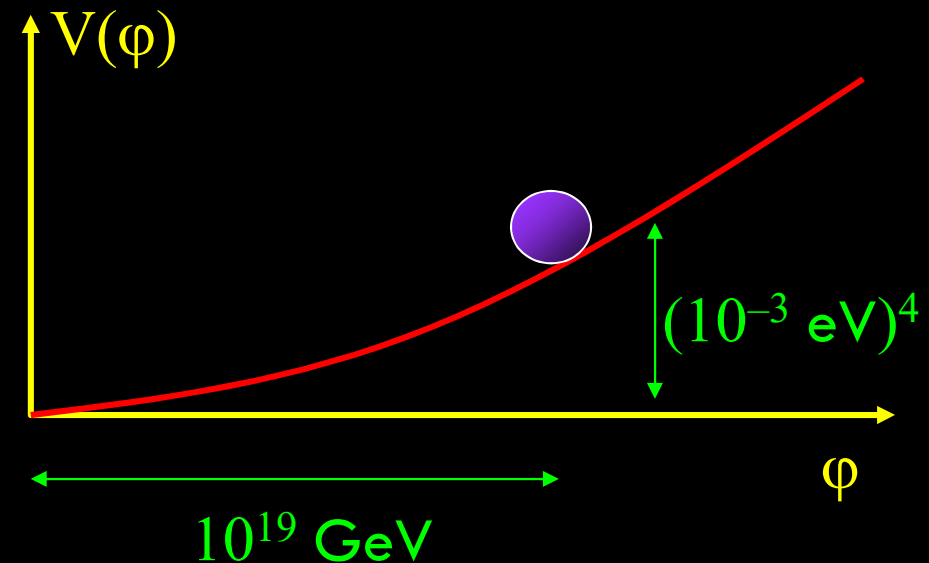
General features:

$$m < H_0 \sim 10^{-33} \text{ eV}$$

(slow roll)

$$V \sim M^4 \sim m^2 \phi^2 \sim H_0^2 M_{\text{Pl}}^2$$
$$\sim (10^{-3} \text{ eV})^4$$

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



Equation of state: $w > -1$ and evolves in time

Hierarchy: $m/\phi \sim 10^{-60}$, $H/M \sim 10^{-30}$

Weak coupling: Quartic self-coupling $\lambda_\phi < 10^{-122}$

Effective Field Theory and Scalar Field Models

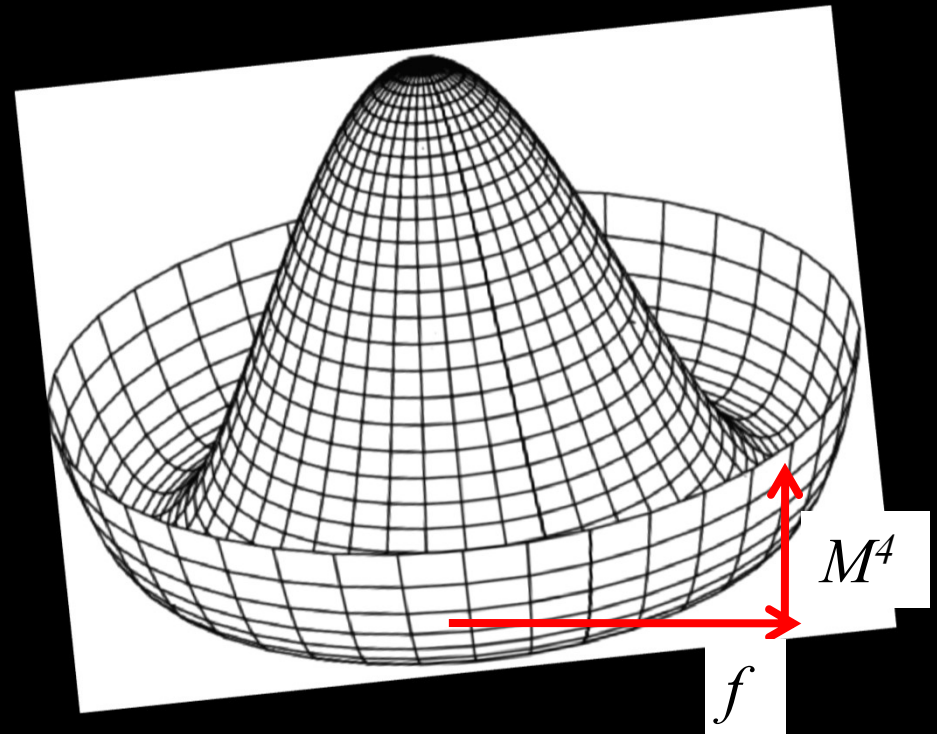
- **Technical naturalness:** small dimensionless parameters in a theory (e.g., hierarchy of mass scales or coupling constants) should be protected by symmetries from large radiative corrections (**t'Hooft**)
- **Strong naturalness:** small parameters or hierarchies should emerge dynamically in fundamental 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

PNGB Model for Acceleration

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

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

$$m_\phi = \frac{M^2}{f}, \lambda_\phi \sim \left(\frac{M}{f} \right)^4$$

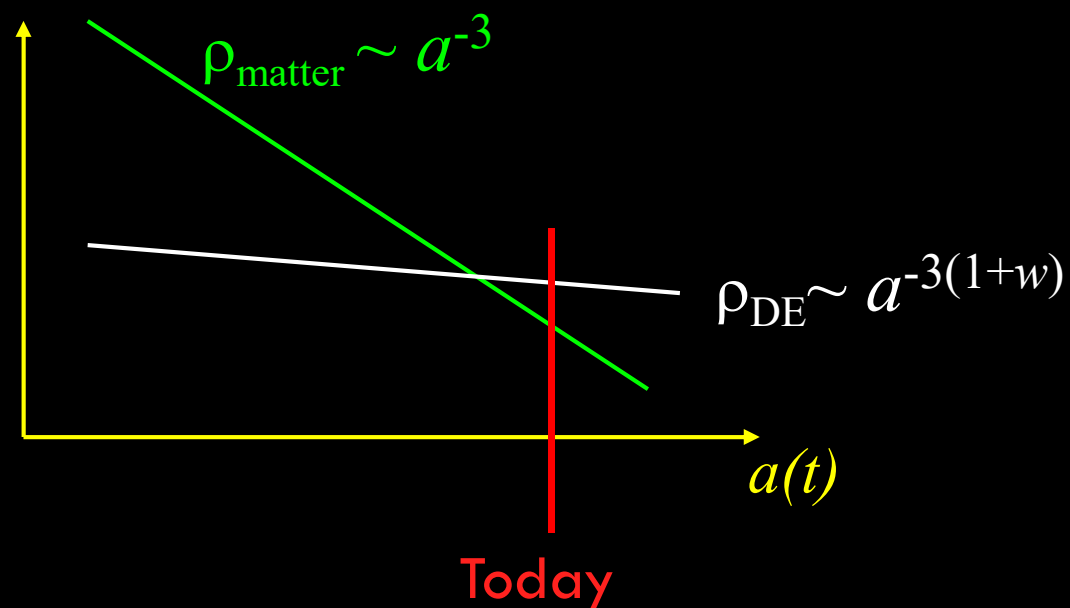


- Spontaneous symmetry breaking at fundamental scale f
- Explicit breaking at lower scale $M \ll f$
- Hierarchy between M and f protected by shift symmetry (technically natural), similar to QCD axion
- Lower scale M could be generated dynamically by non-perturbative effects (strongly natural)

JF, Hill, Stebbins, Waga 1995

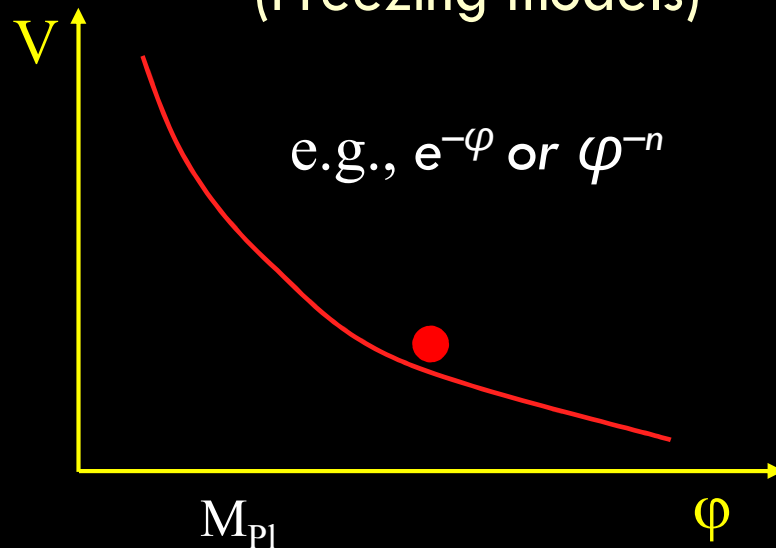
The Coincidence Problem

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)

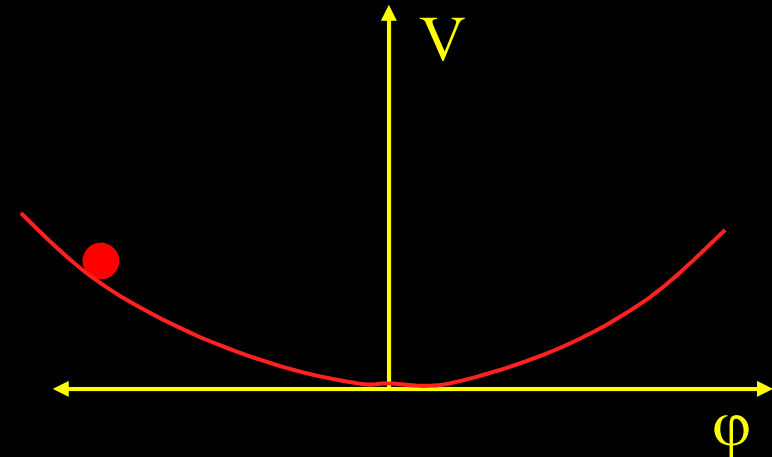


Runaway potentials

DE/matter ratio constant
(Tracker Solution)

Ratra & Peebles; Caldwell, et al

'Mass scale' models
(Thawing models)



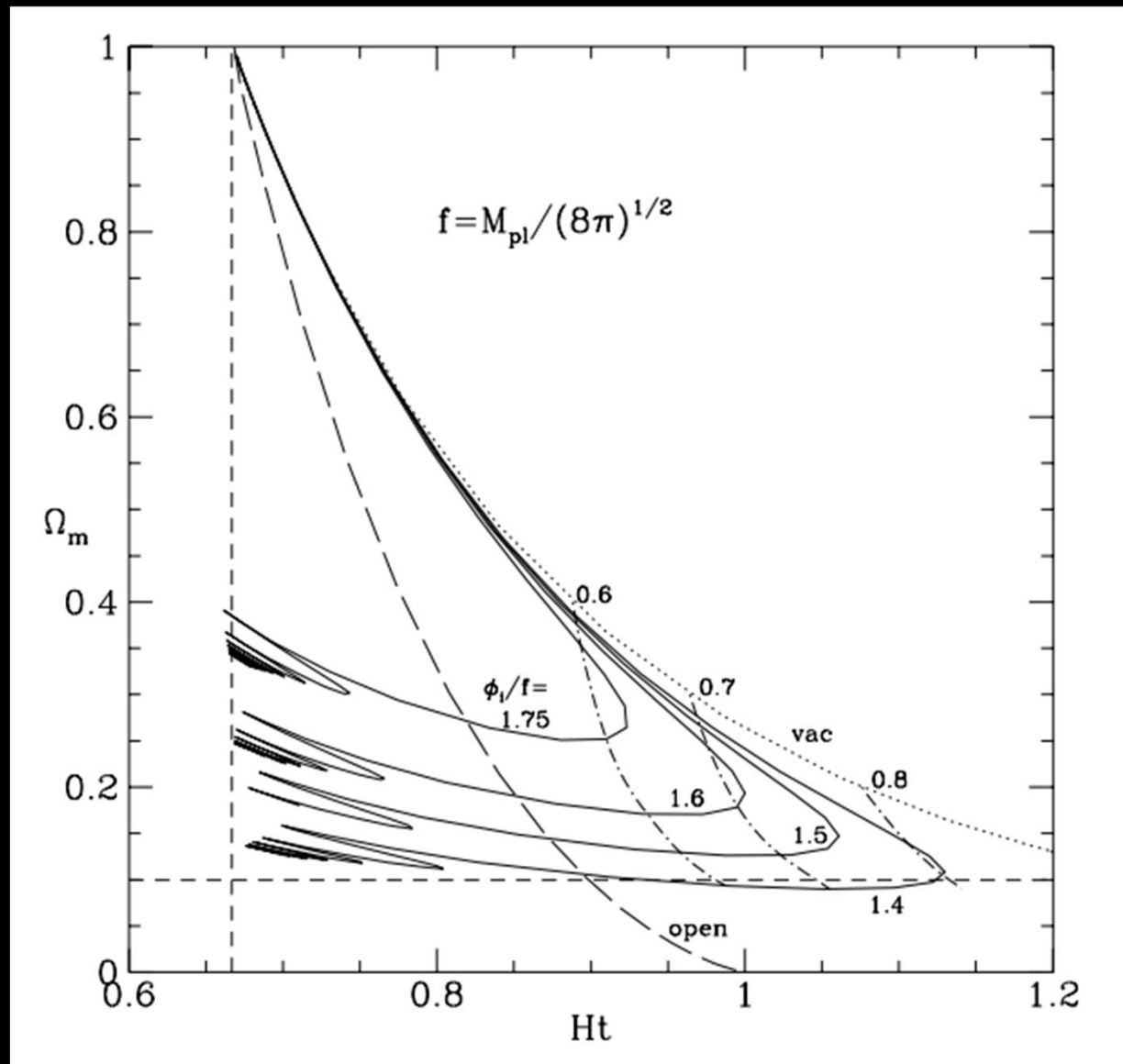
Pseudo-Nambu Goldstone Boson

Low mass protected by symmetry
(Cf. axion, natural inflation)

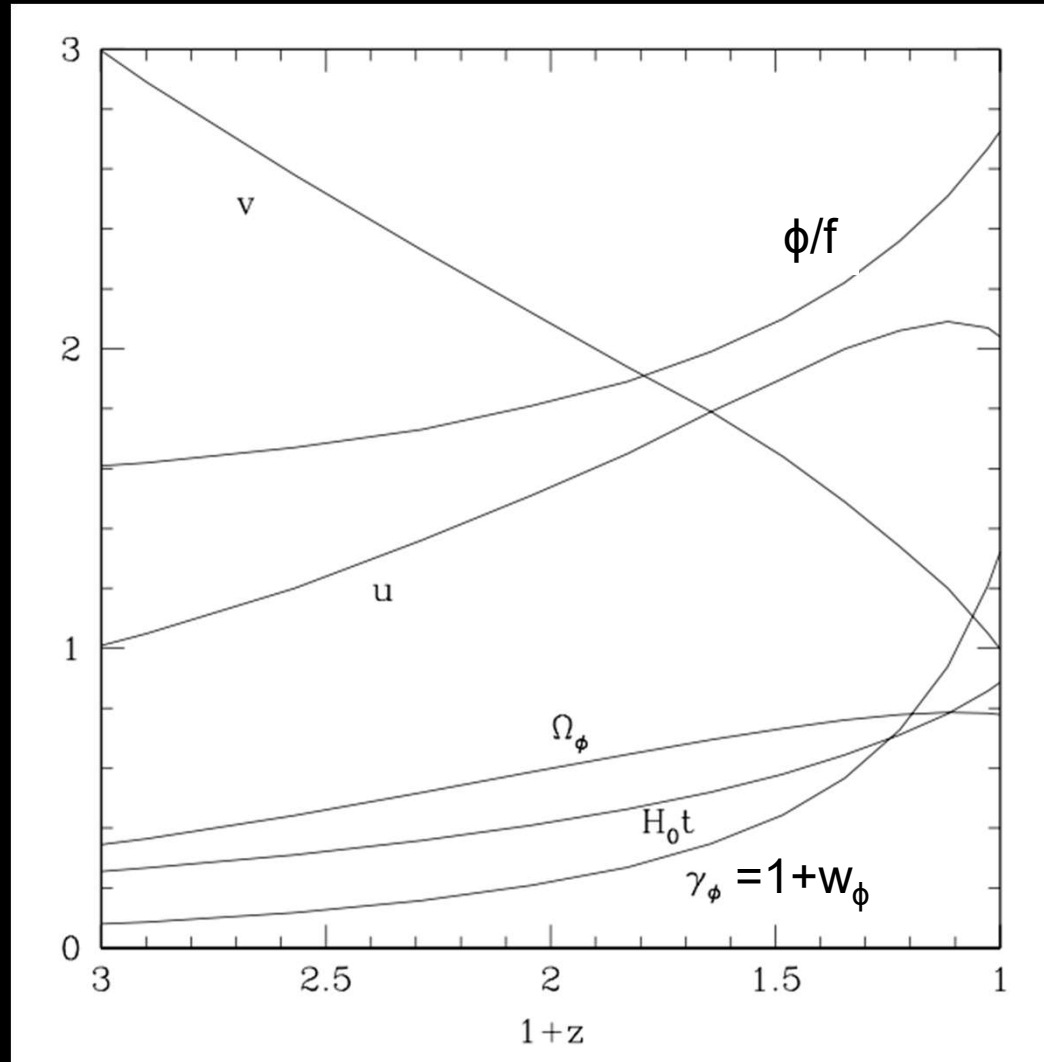
$$M \sim 10^{-3} \text{ eV}$$

JF, Hill, Stebbins, Waga

PNGB Dark Energy

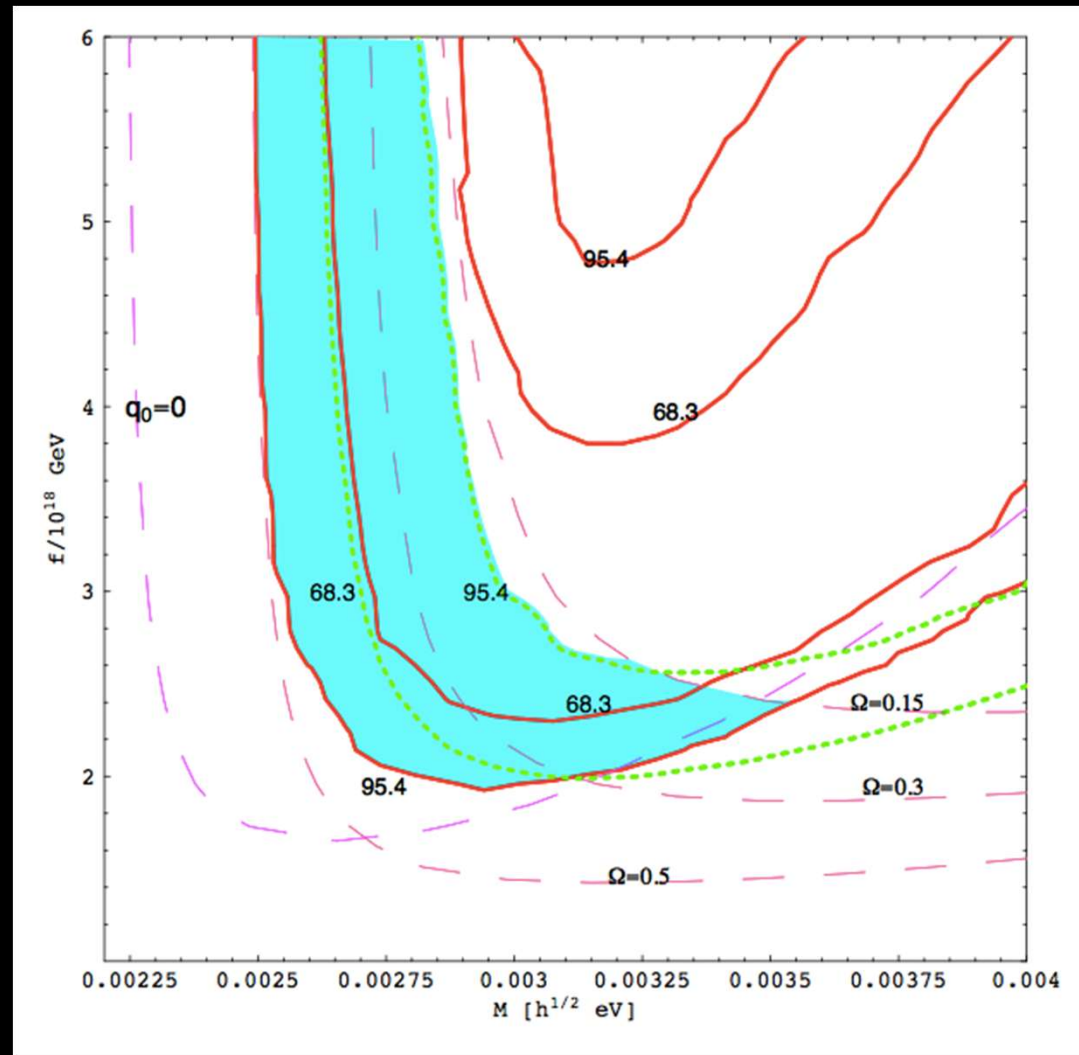


PNGB Dark Energy

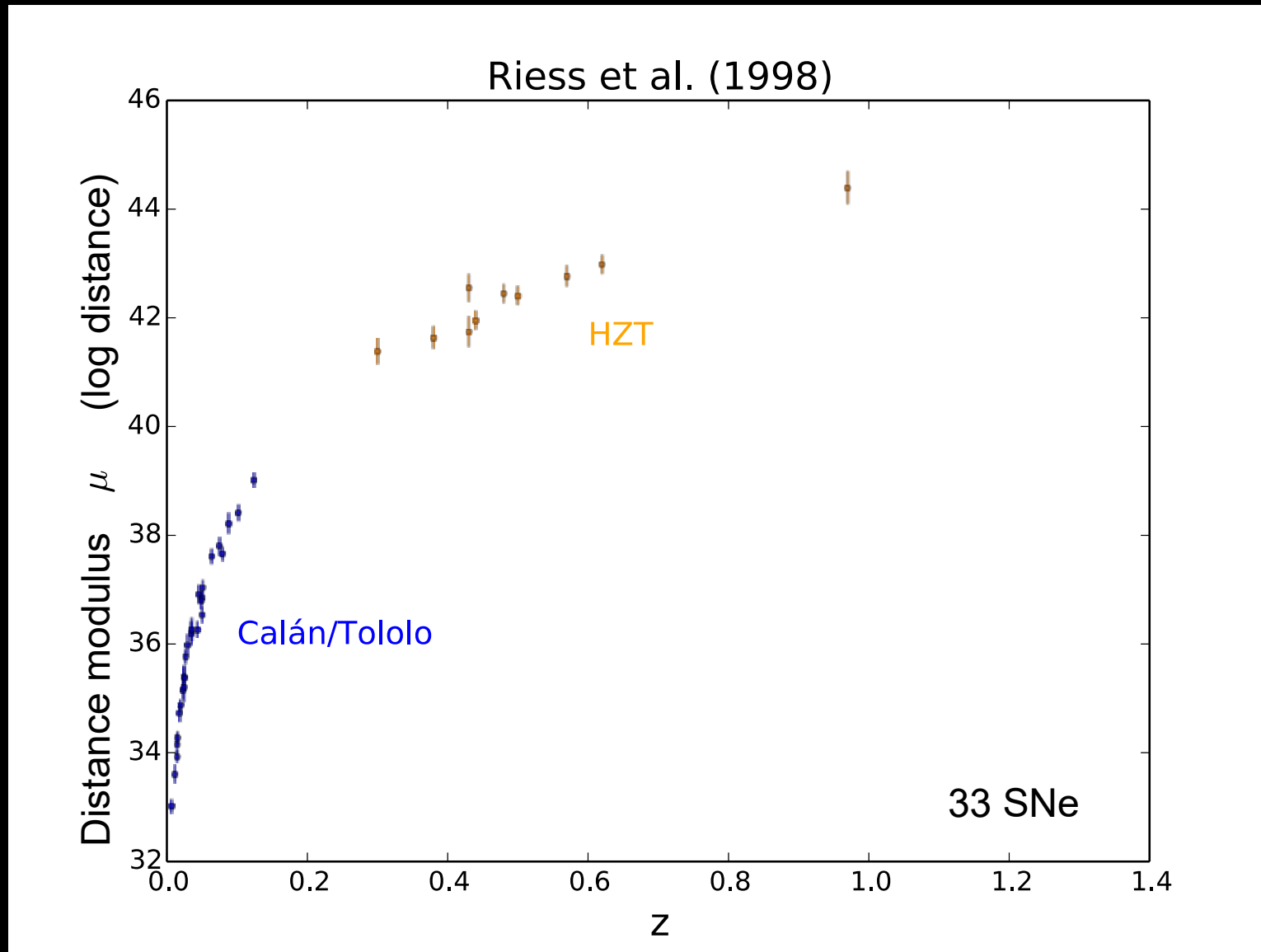


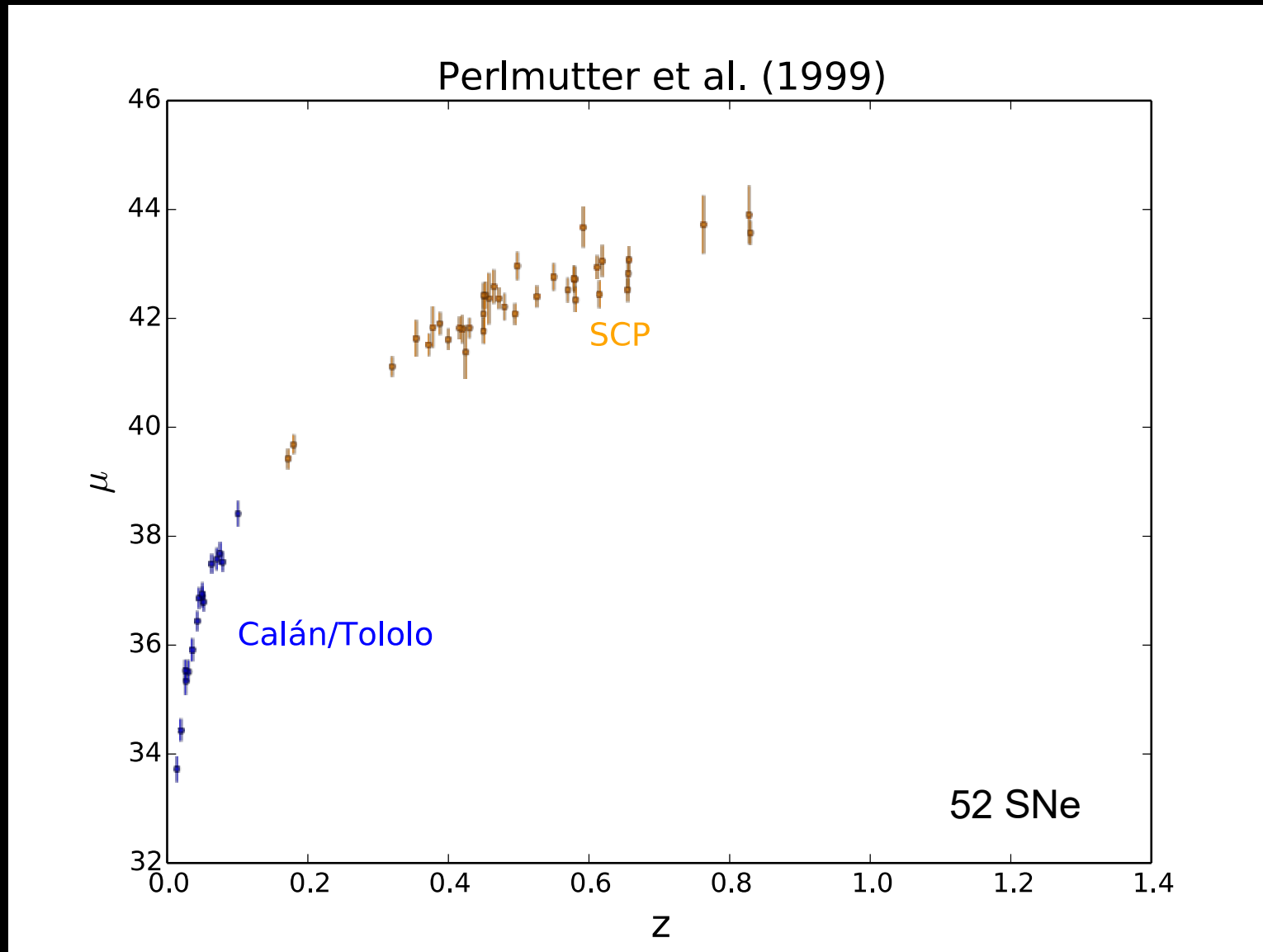
PNGB Dark Energy

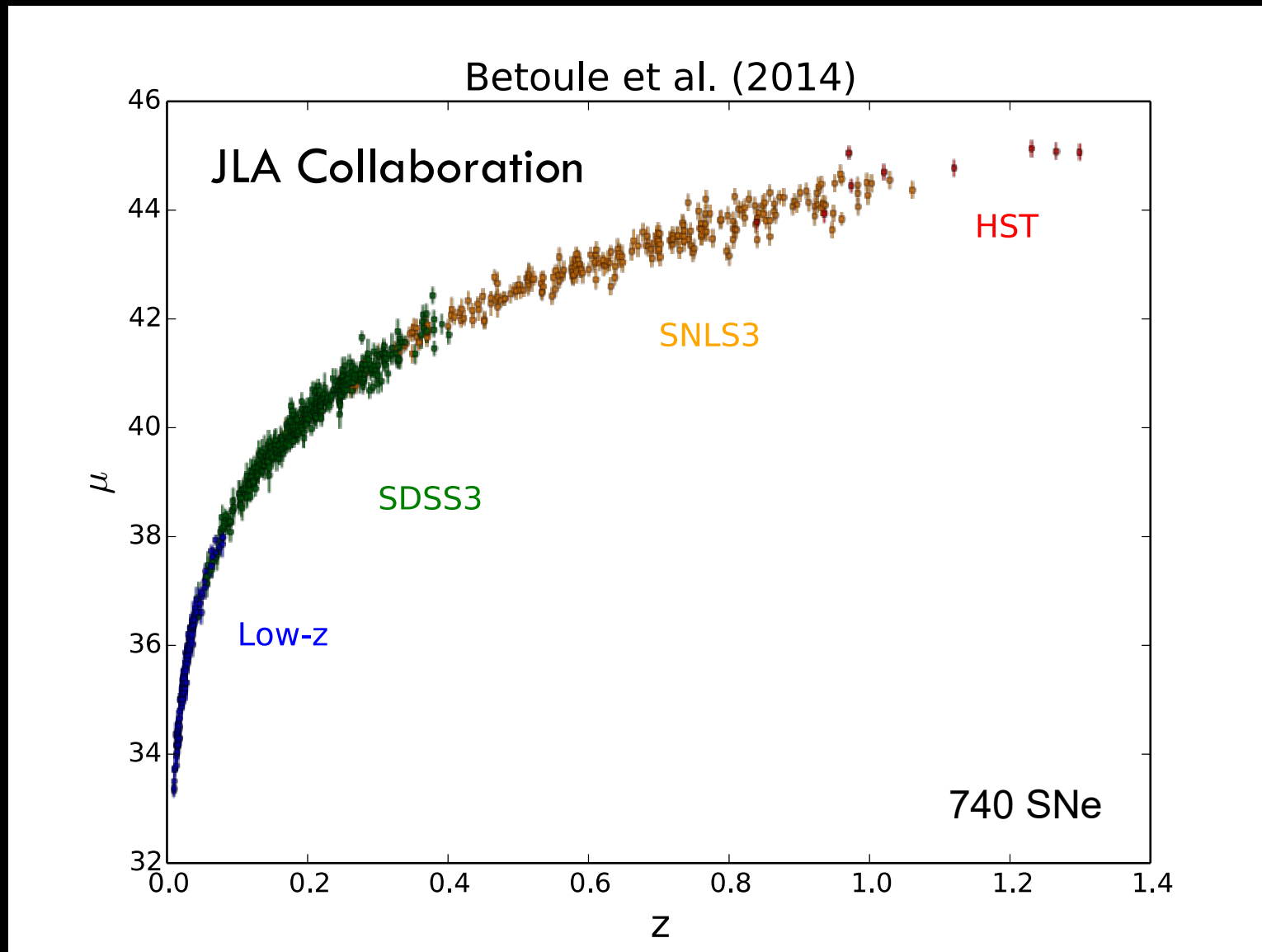
Constraints
from
supernovae,
strong lensing,
and clusters



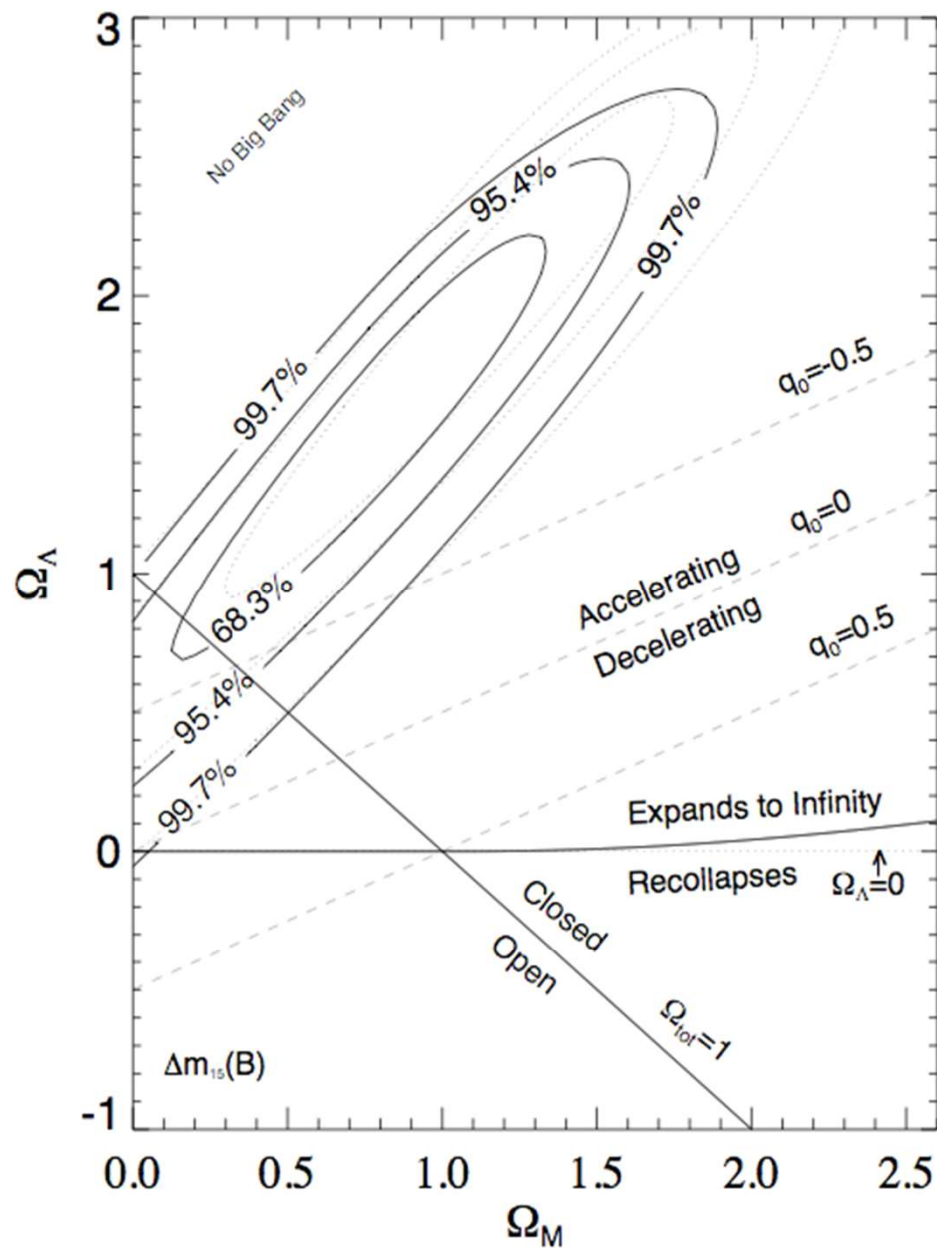
Supernova Ia Hubble Diagram



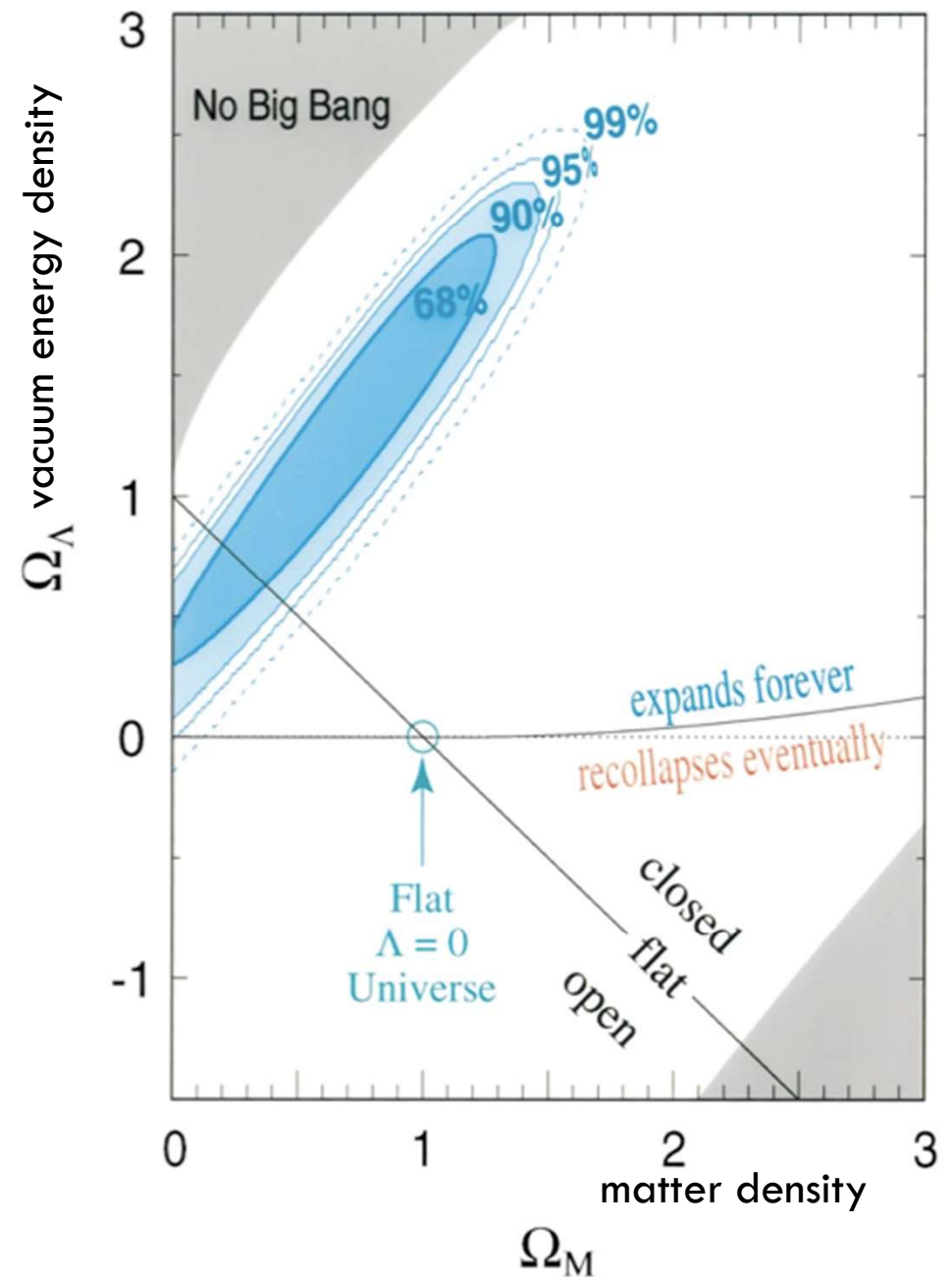




Riess et al. (1998, AJ)

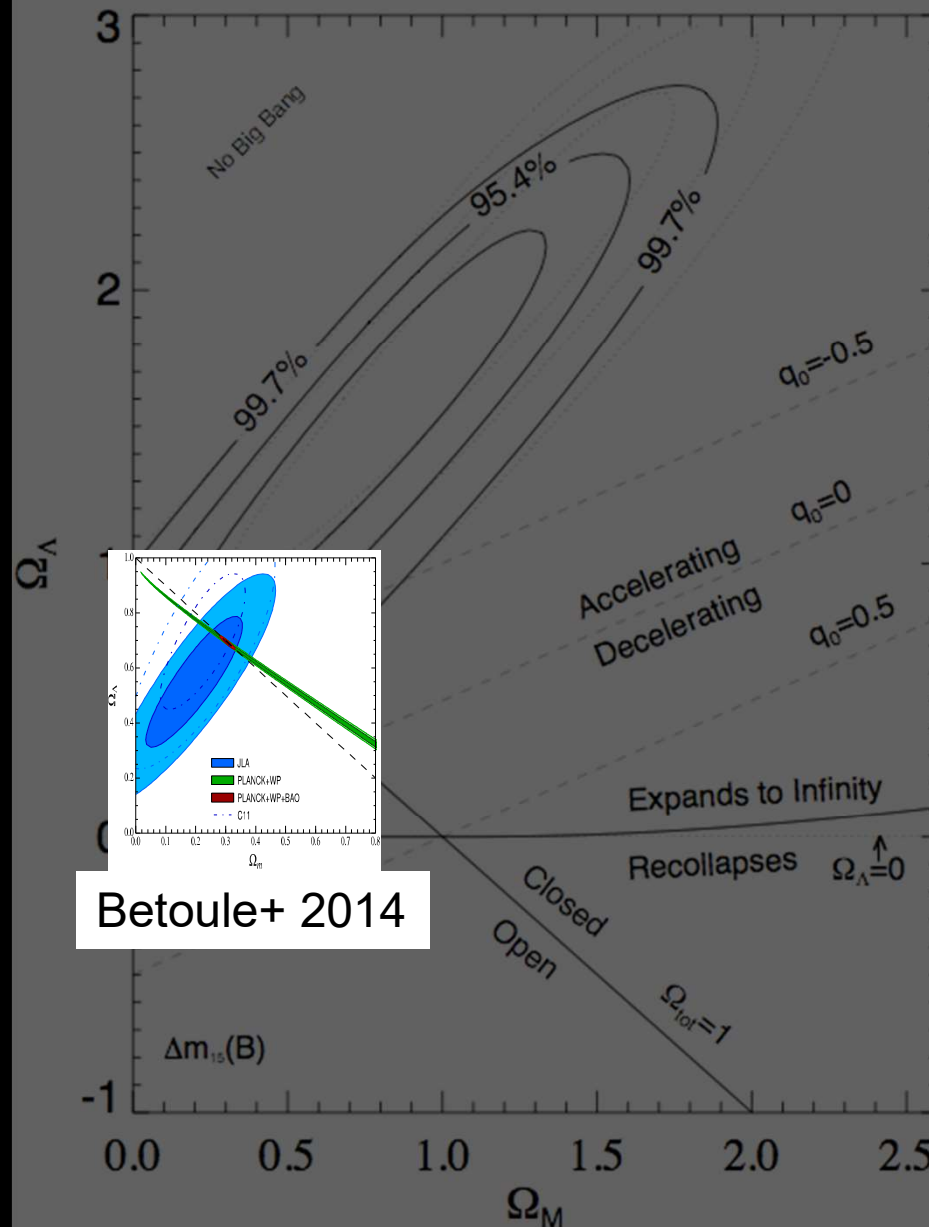


Perlmutter et al. (1999, ApJ)



Progress
over 16
years

Riess et al. (1998, AJ)



Betoule+ 2014

Supernovae

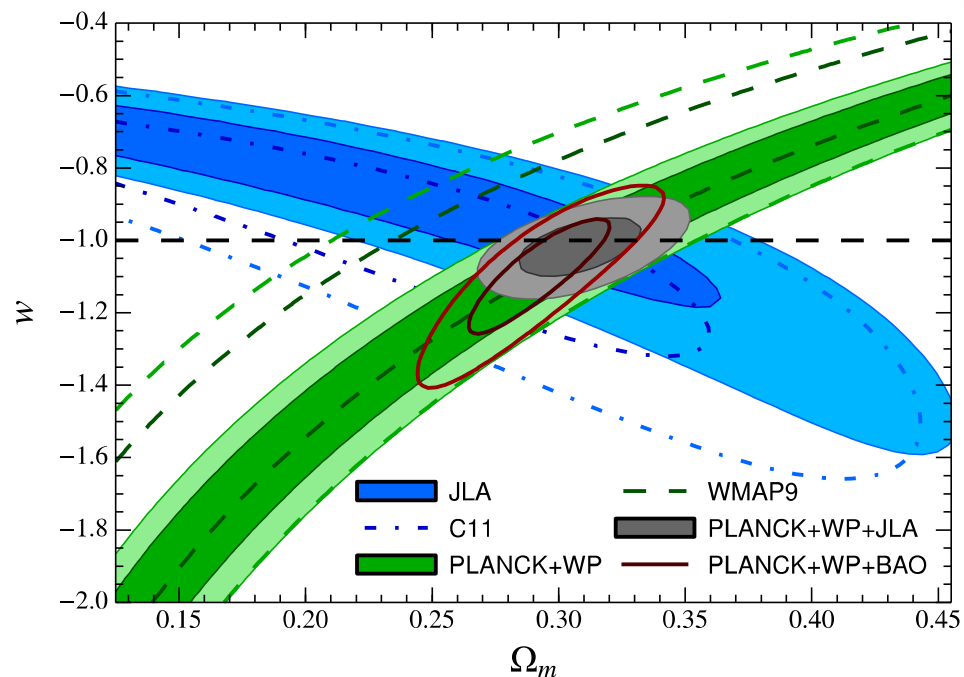
Cosmic Microwave
Background
(Planck, WMAP)

CMB+BAO

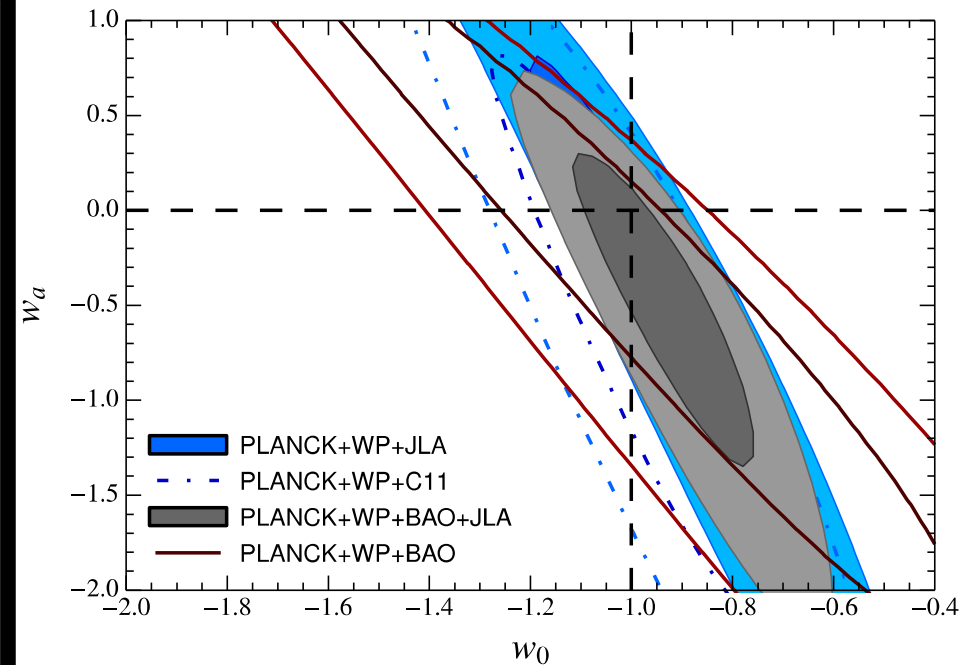
Here assuming
 $w = -1$

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

Assuming constant w



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

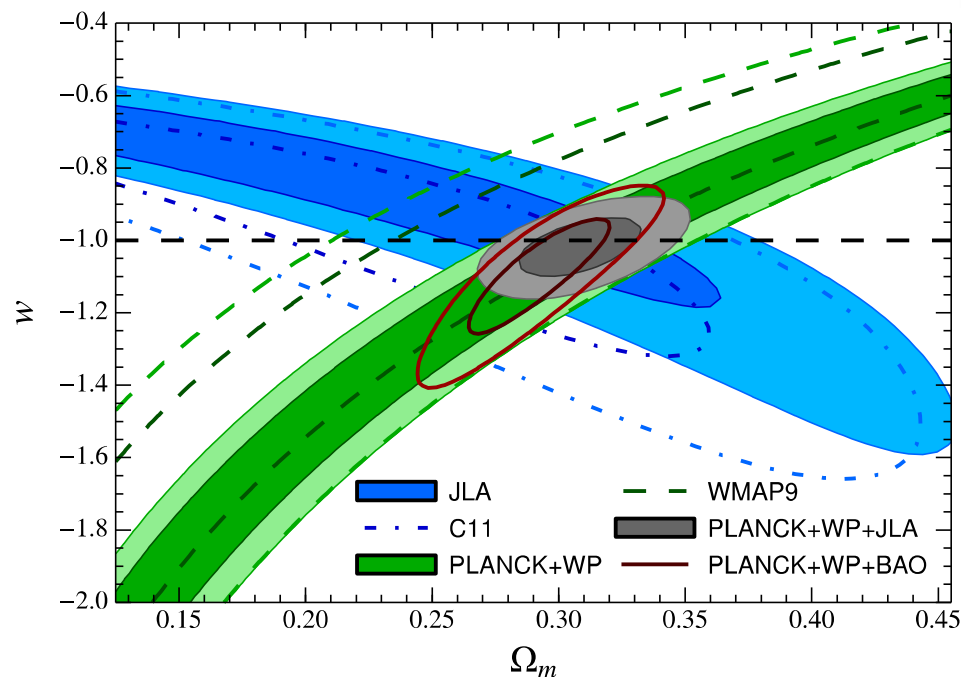


Betoule et al 2014

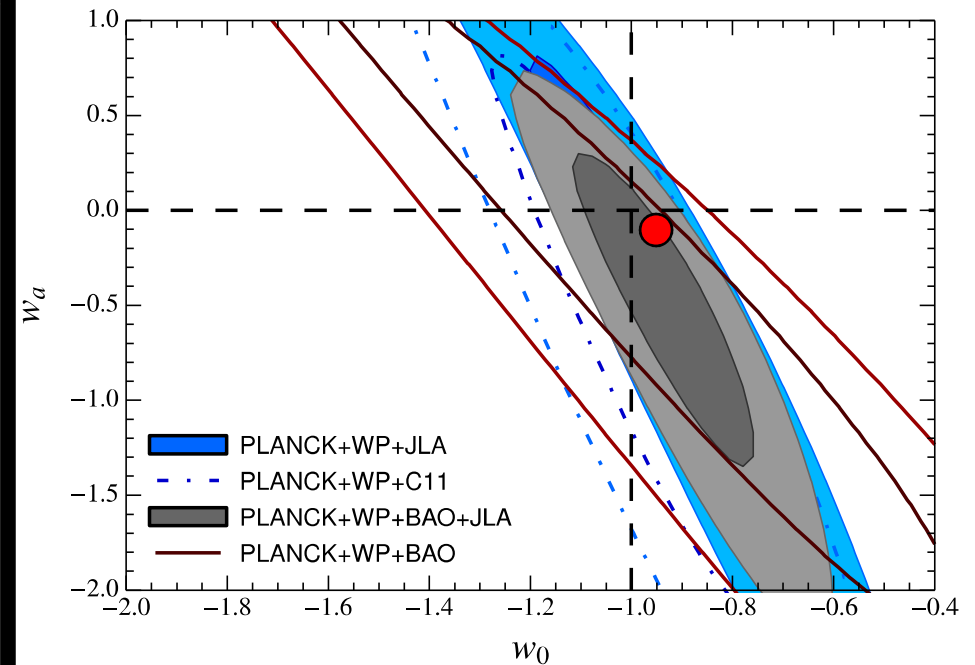
Consistent with vacuum energy (Λ): $w_0=-1$, $w_a=0$

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

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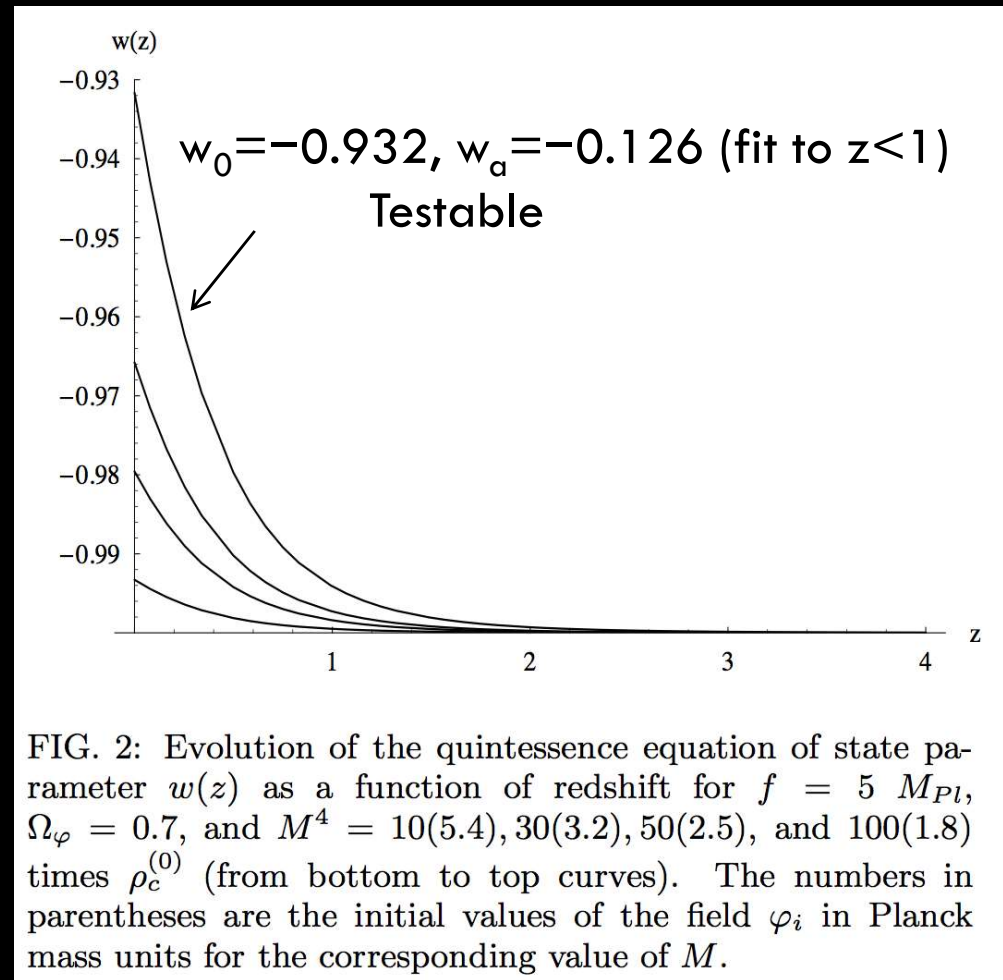
Assuming $w=w_0+w_a(1-a)$



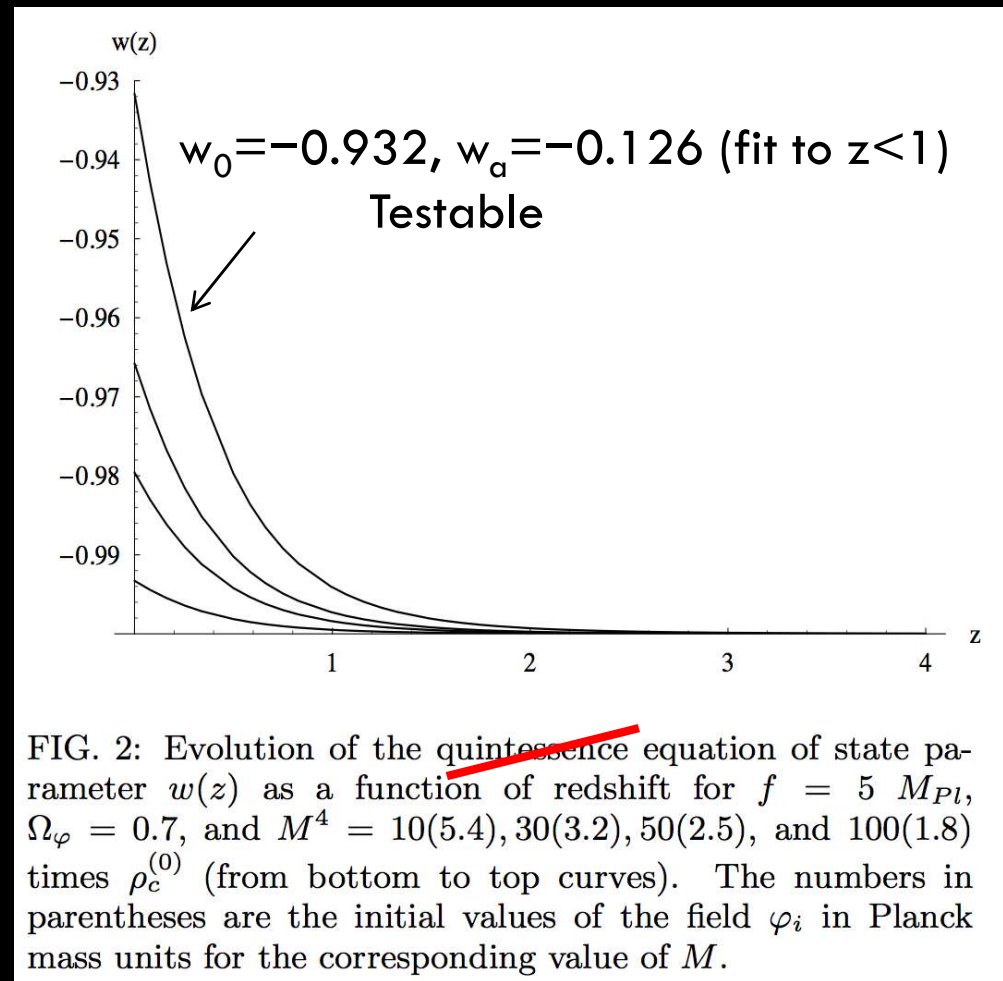
Betoule et al 2014

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

Evolving Dark Energy and PNGBs



Evolving Dark Energy and PNGBs



Cosmological Physics

- Despite the remarkable success of Λ CDM, we don't understand the *physics* of dark matter, dark energy, or inflation.
- What is the Dark Matter?
- Who is the Inflaton?
- What is the origin of Cosmic Acceleration?
 - Dark Energy or Modified Gravity?
 - Nature of Dark Energy: Λ or dynamical component?

Discoveries around the Corner?

- In next year or less: results from DES Y3, KiDS-900, HSC,...
- In the coming years, Stage IV Dark Energy experiments: DESI, Subaru PFS, LSST, Euclid, WFIRST,...plus CMB-S4, plus large numbers of NS-NS binaries from LIGO/Virgo.
- We should be able to test a variety of dark energy models and learn more about the Universe.

Best Wishes loav!



Perhaps a future in politics?