Is Dark Energy Evolving?

Josh Frieman

Is (there evidence for) Dark Energy Evolving?

Early Inflation

- Very early epoch of cosmic acceleration motivated by flatness and horizon problems
- Theoretical context: GUTs and symmetry-breaking 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 from quantum fluctuations.
- Consistent with observations of CMB, LSS.

Late Inflation

- Current epoch of cosmic acceleration motivated by missing energy and age problems (early/mid-1990s):
  - inflation predicted $\Omega_0=1$, clusters indicated $\Omega_m=0.25$. Need for smooth component that only recently came to dominate
  - $H_0 t_0 \sim 1$ from Hubble parameter estimates and globular cluster ages
  - ΛCDM+inflation fit galaxy clustering measurements (APM, 1992).
  - SN results of 1998 made it the dominant paradigm.
- Theoretical context?
- Simplest model:

- Strong observational evidence for late acceleration from supernovae, LSS, weak lensing, CMB,...

Late Inflation

- Current epoch of cosmic acceleration motivated by missing energy and age problems (early/mid-1990s):
  - inflation predicted $\Omega_0=1$, clusters indicated $\Omega_m=0.25$. Need for smooth component that only recently came to dominate
  - $H_0t_0\sim1$ from Hubble parameter estimates and globular cluster ages
  - ΛCDM+inflation fit galaxy clustering measurements (APM, 1992).
  - SN results of 1998 made it the dominant paradigm.
- Theoretical context?
- Simplest model: weakly self-coupled scalar field that takes a cosmologically long time to reach its ground state? Or Λ
- Strong observational evidence for late acceleration from supernovae, LSS, weak lensing, CMB,...

Cosmological Dynamics

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \sum_i \rho_i \left(1 + 3w_i\right)$$

Friedmann Equation from General Relativity

- Dark Energy: dominant component of the energy density that drives cosmic acceleration ($\ddot{a} > 0$) at late times via an equation of state parameter, $w \equiv p/\rho < -1/3$.
- Special case: vacuum energy, $w = -1 \Leftrightarrow \Lambda$, cosmological constant.

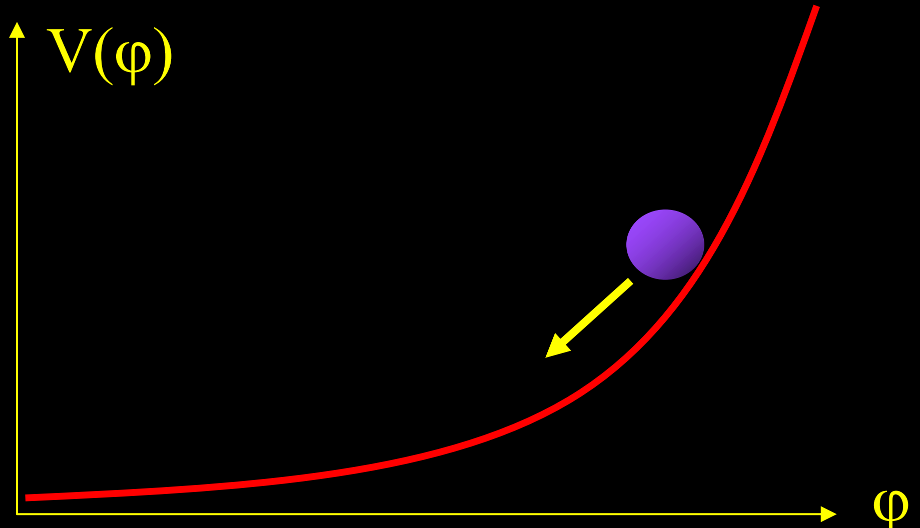
Scalar Field Dark Energy

- Dark Energy could be due to a very light scalar field φ, slowly evolving in a potential, V(φ):

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

- Density & pressure:

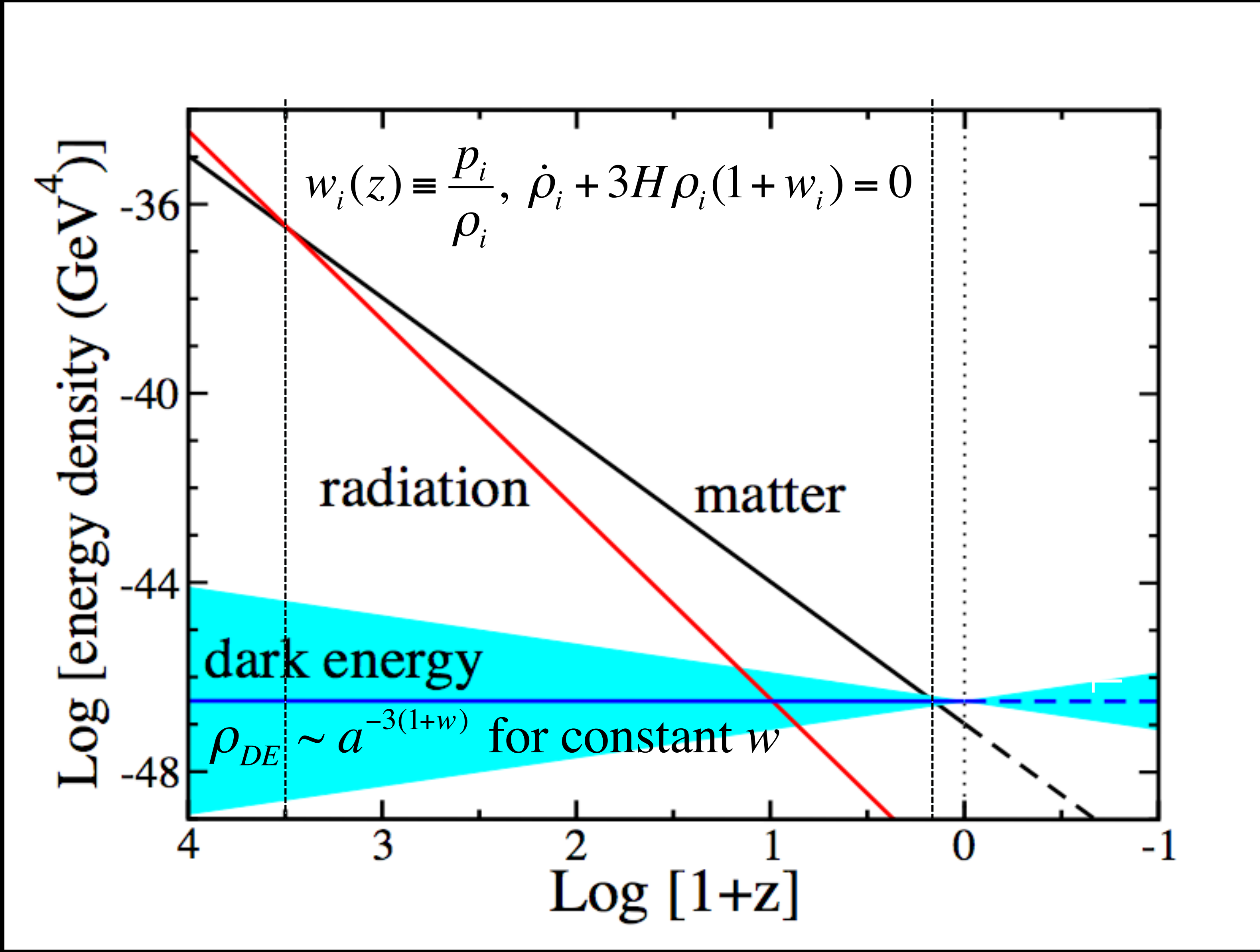
$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$
$$P = \tfrac{1}{2}\dot{\varphi}^2 - V(\varphi)$$



- Slow roll:

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

The Coincidence Problem

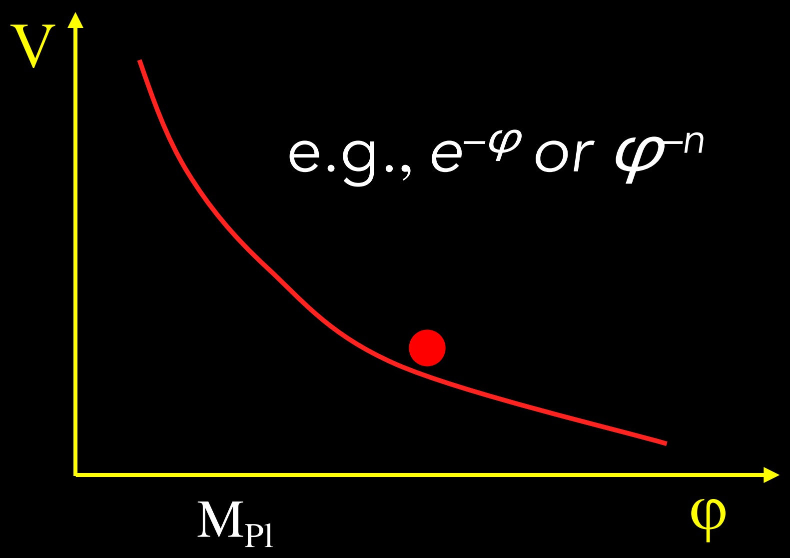


Why do we live at the `special' epoch when the matter and dark energy densities are comparable?

JF, Turner, Huterer

Scalar Field Models and Coincidence

`Dynamics' or Freezing models

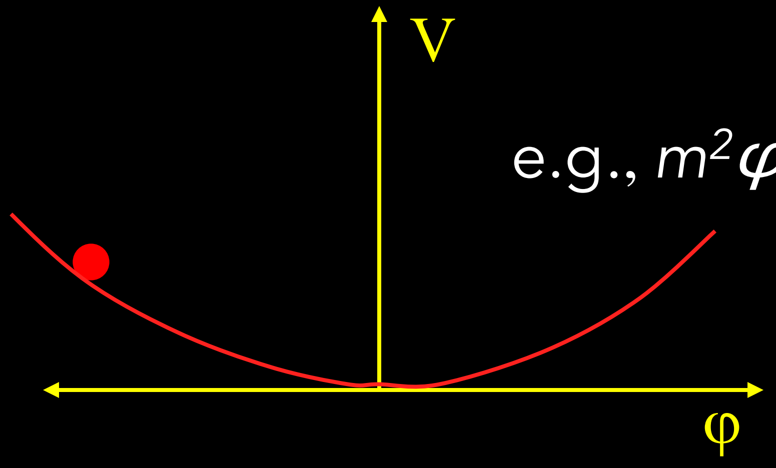


<u>Runaway potentials</u>

DE/matter ratio constant
(Tracker Solution)

Ratra & Peebles 1988
Caldwell, Dave, Steinhardt 1998

`Mass scale' or Thawing models

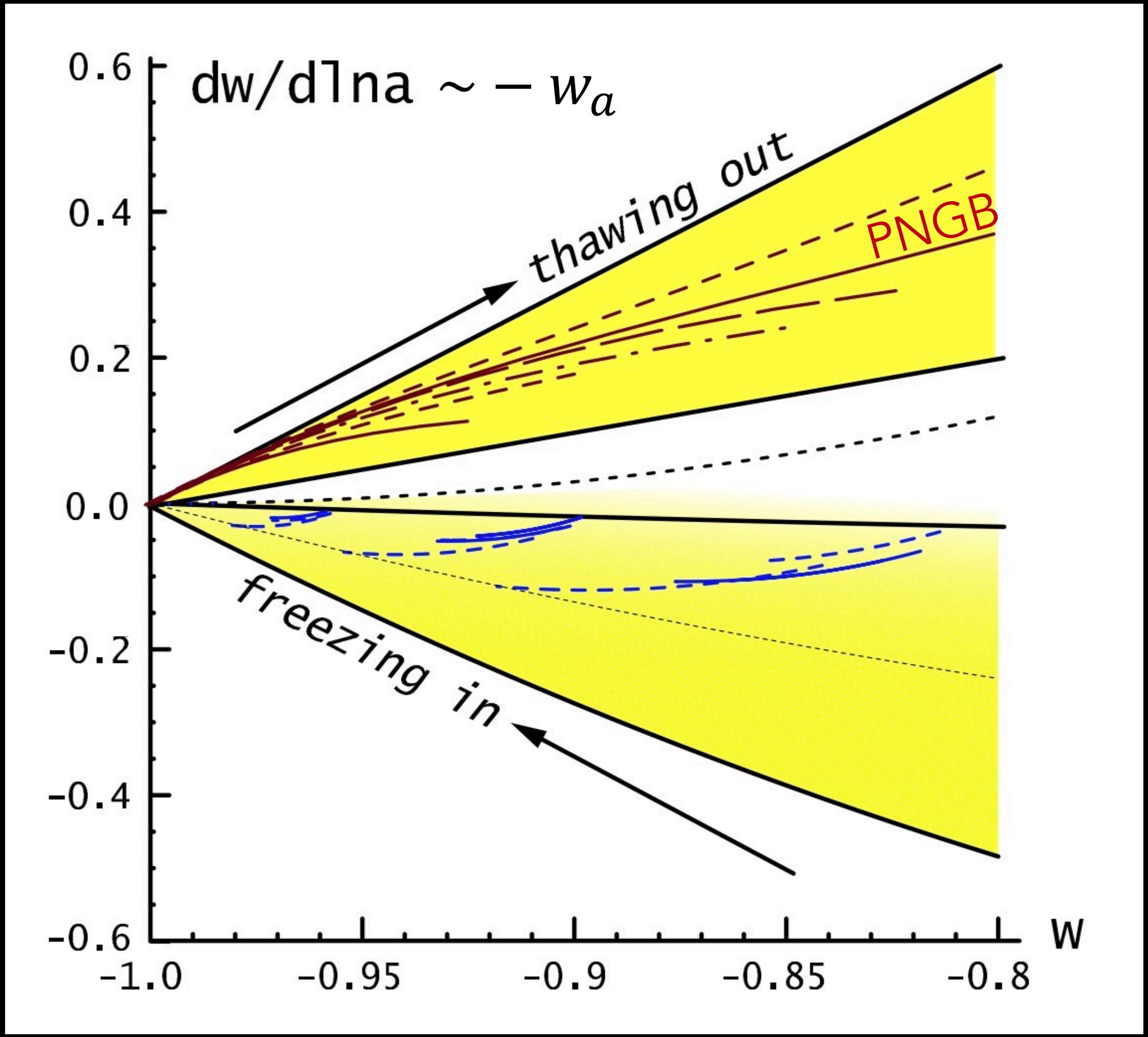


<u>Pseudo-Nambu Goldstone Boson</u>

Low mass protected by symmetry
(Cf. axion)

JF, Hill, Stebbins, Waga 1995
Coble, Dodelson, JF 1997

Constraining *w* Evolution Can Distinguish between Models



Caldwell and Linder 2005

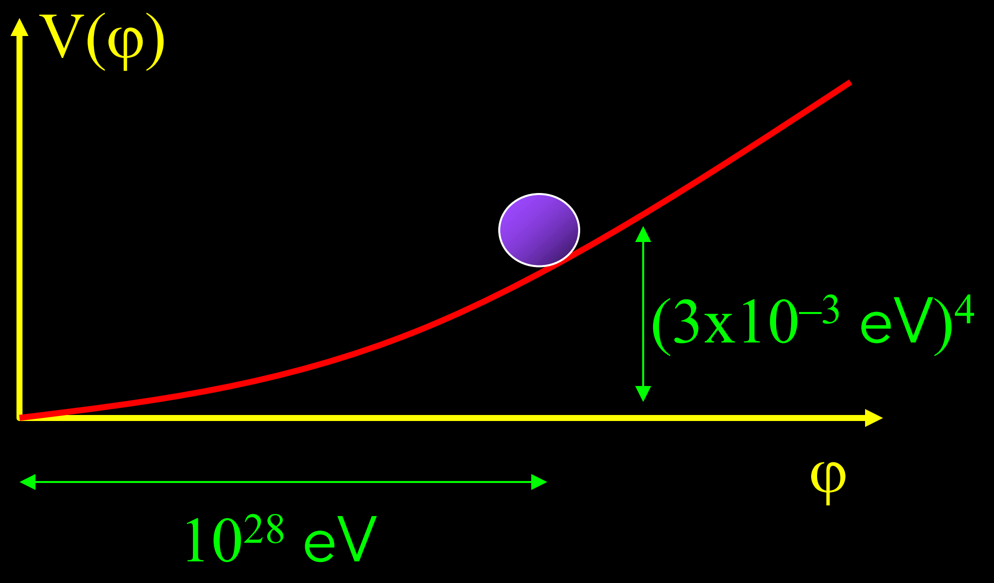
Simplest Thawing Model: Free, Massive Scalar

General features:

Field is frozen until $m \sim H$.
$m < 3H_0 \sim 10^{-33}$ eV ($w < 0$)
(Potential > Kinetic Energy)

$V \sim m^2\varphi^2 \sim \rho_{crit} \sim 10^{-10}\ \mathrm{eV}^4$

$\varphi \sim 10^{28}$ eV $\sim M_{Planck}$



Ultra-light particle: Dark Energy hardly clusters, nearly smooth
Equation of state: $w > -1$ and evolves in time from $w = -1$ (``thawing'')
Hierarchy problem: Why $m/\varphi \sim 10^{-61}$?
Weak coupling: Why quartic self-coupling $\lambda_\phi < 10^{-122}$?
Far future: Universe will again become matter-dominated

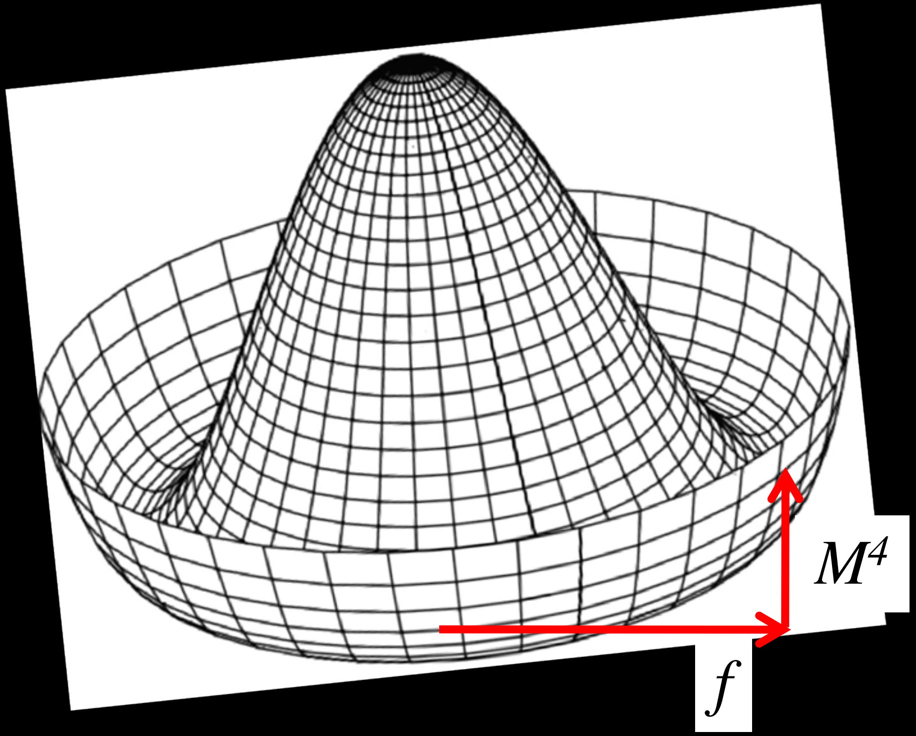
PNGB Model of Thawing Dark Energy

JF, Hill, Stebbins, Waga 1995

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

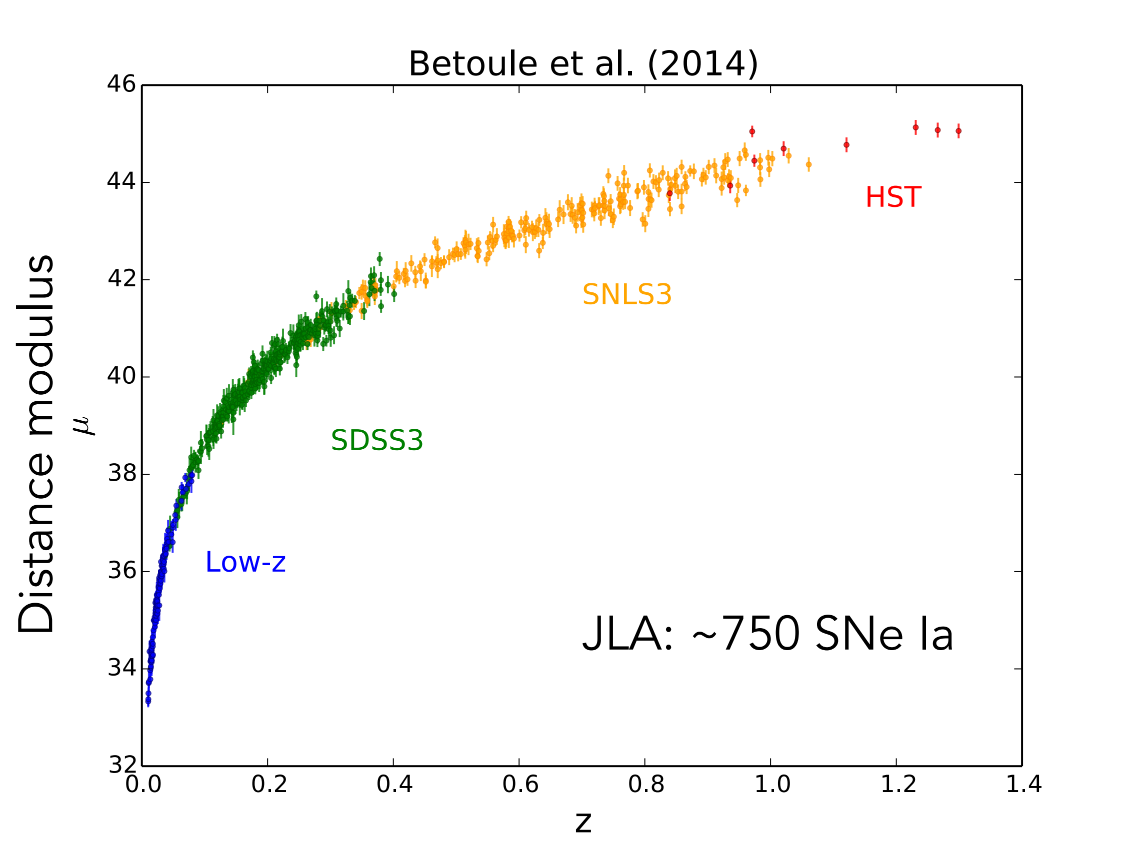
$$M \sim 10^{-3}eV,\ f \sim M_{Pl}$$

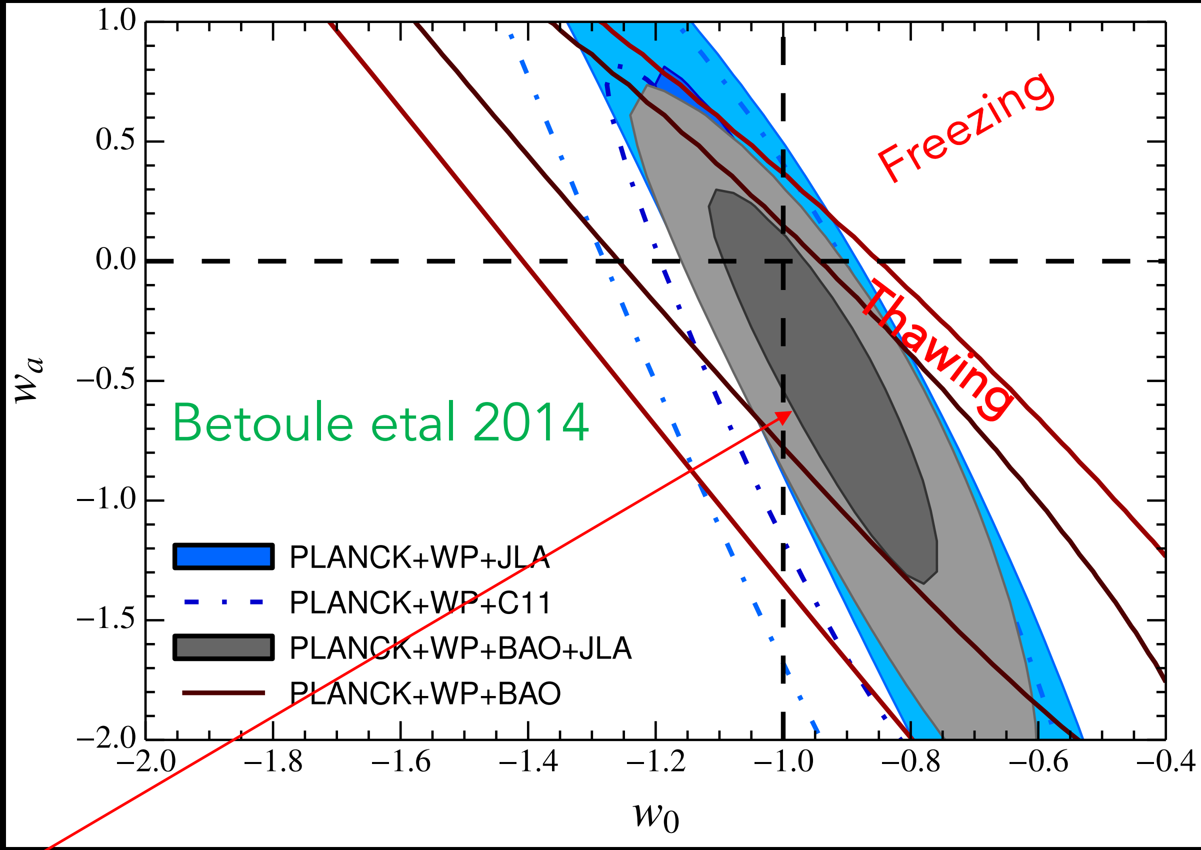
$$m_\phi = \frac{M^2}{f},\ \lambda_\phi \sim \left(\frac{M}{f}\right)^4$$



- Spontaneous symmetry breaking at fundamental scale *f*
- Explicit breaking at much lower scale *M*<<*f*
- Hierarchy between *M* and *f* protected by shift symmetry, similar to QCD axion.
- Scale *M* could be generated dynamically by non-perturbative effects (strongly natural).

Observational Constraints on Evolving DE: 2014



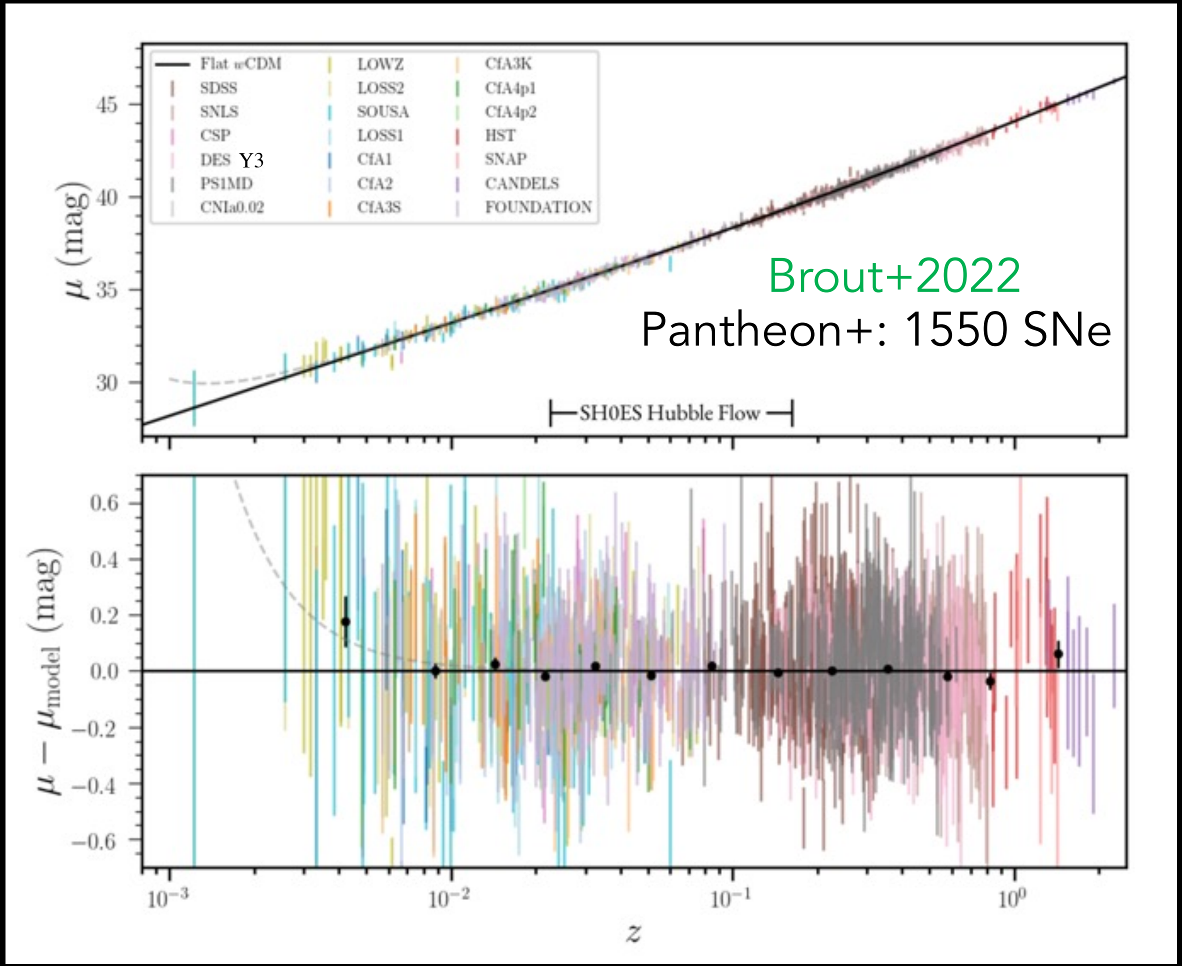


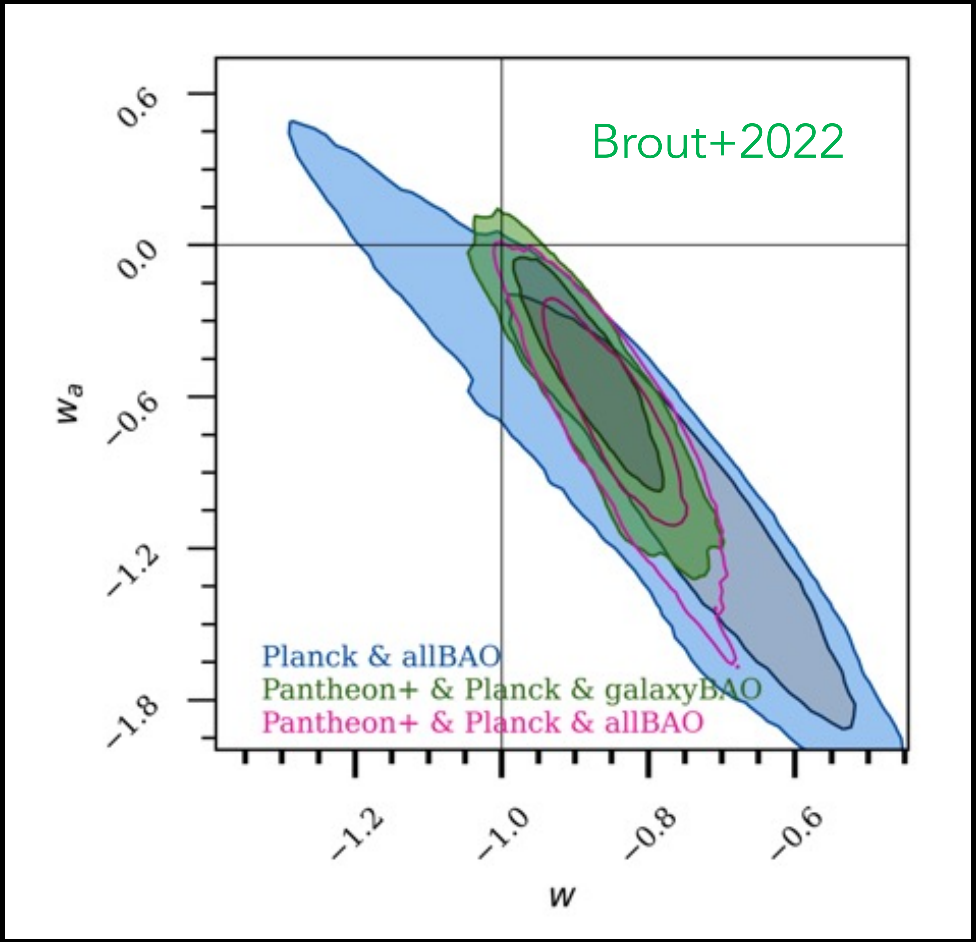
H(z) expansion history varies little along degeneracy direction

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

(Chevallier & Polarski 2001; Linder 2003)

Observational Constraints on Evolving DE: 2022

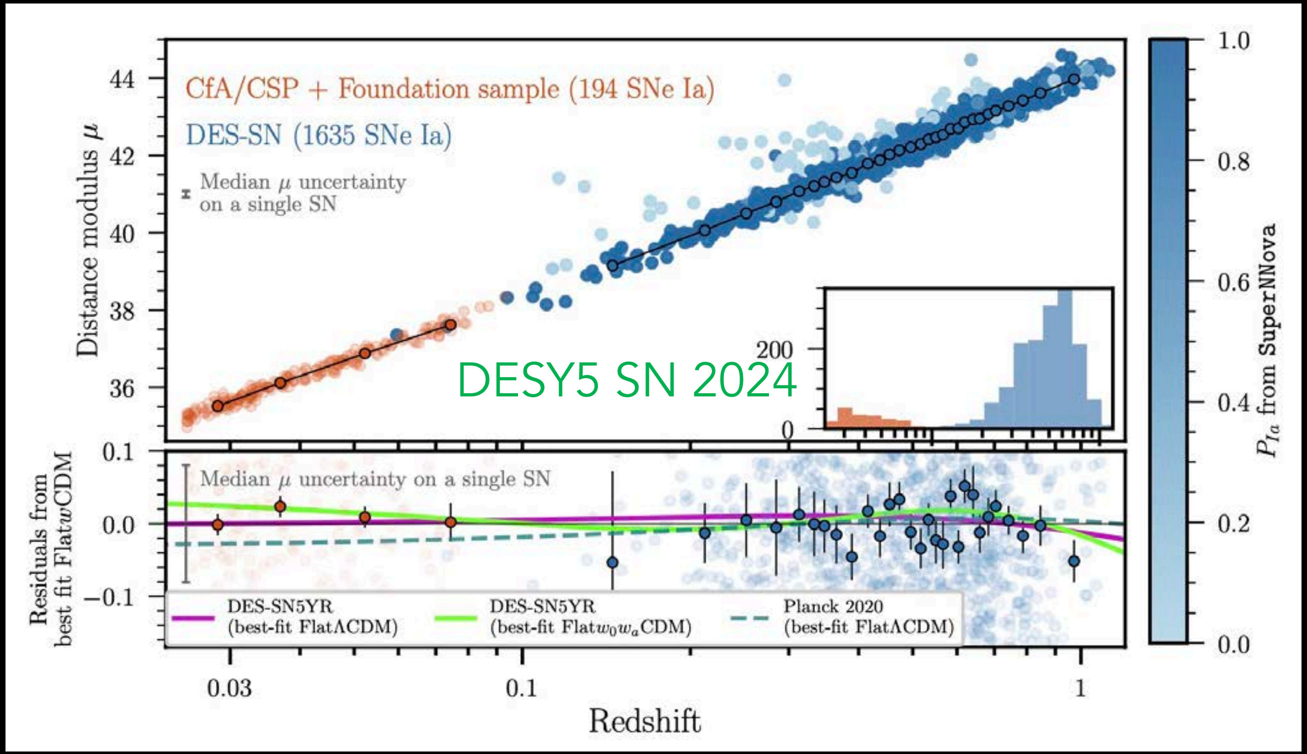


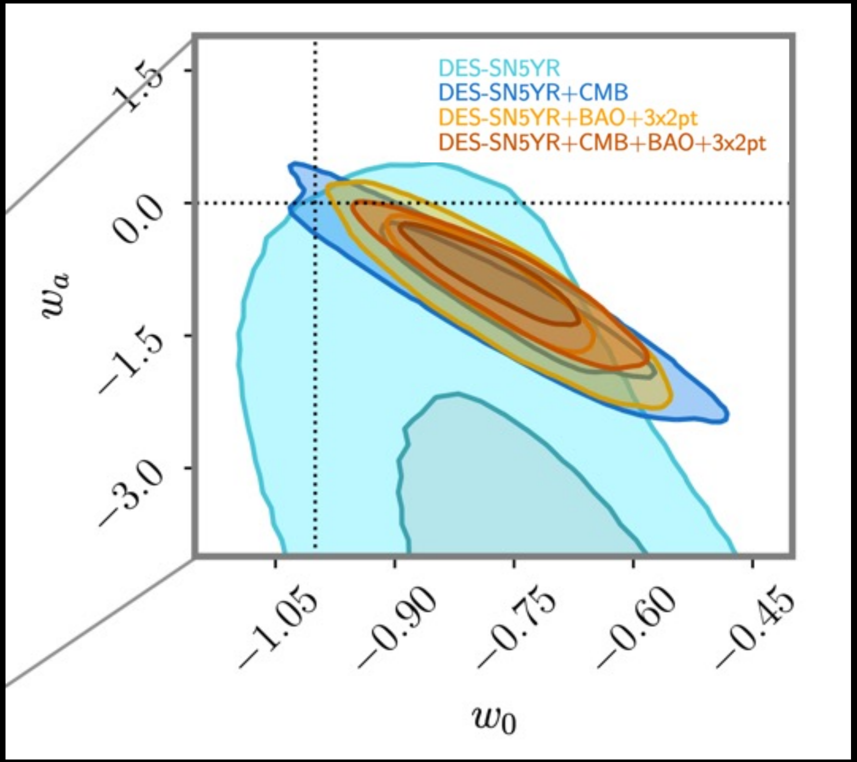


$\sim 2\sigma$ from ΛCDM

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

Observational Constraints on Evolving DE: 1/2024





DESY5 SN 2024

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

Using SDSS (Pre-DESI) BAO

Combined constraints:

$$w_0 = -0.773^{+0.075}_{-0.067}$$
$$w_a = -0.83^{+0.33}_{-0.42}$$

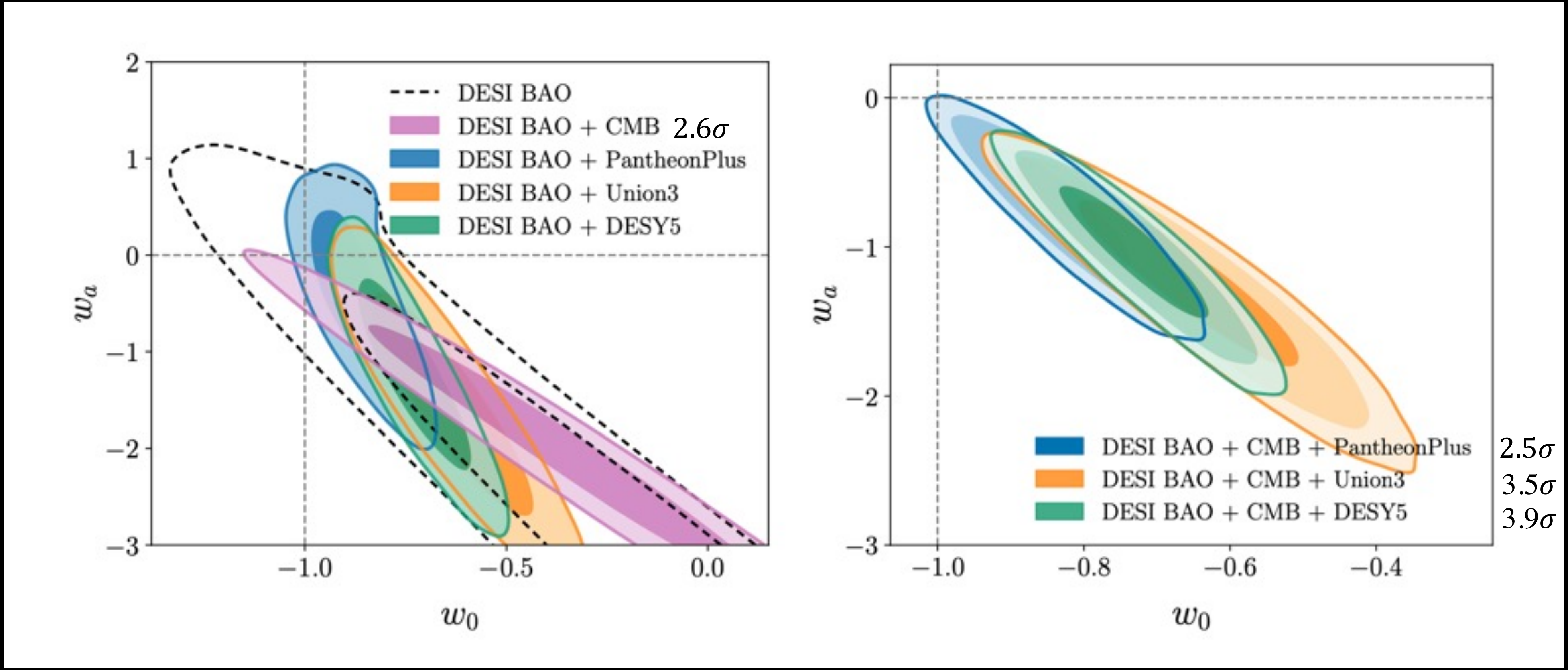
~3σ from ΛCDM

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

Overbye 2024

Observational Constraints on Evolving DE: 4/2024



3.9σ from ΛCDM

Combined constraints:

$$w_0 = -0.727 \pm 0.067$$

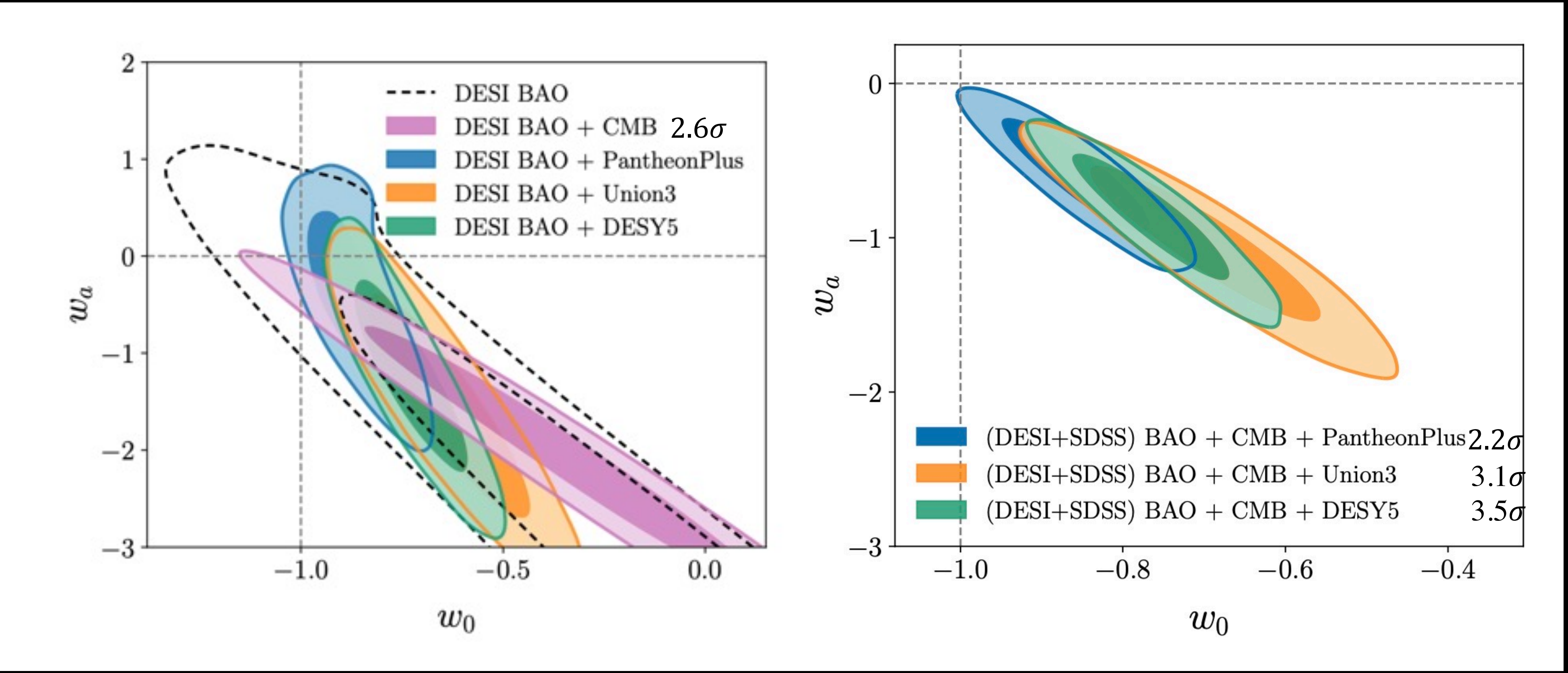
$$w_a = -1.05^{+0.31}_{-0.27}$$

using DESY5 SN

DESI 2024

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

Observational Constraints on Evolving DE: 4/2024



3.5σ from ΛCDM

Combined constraints:

$w_0 = -0.761 \pm 0.064$

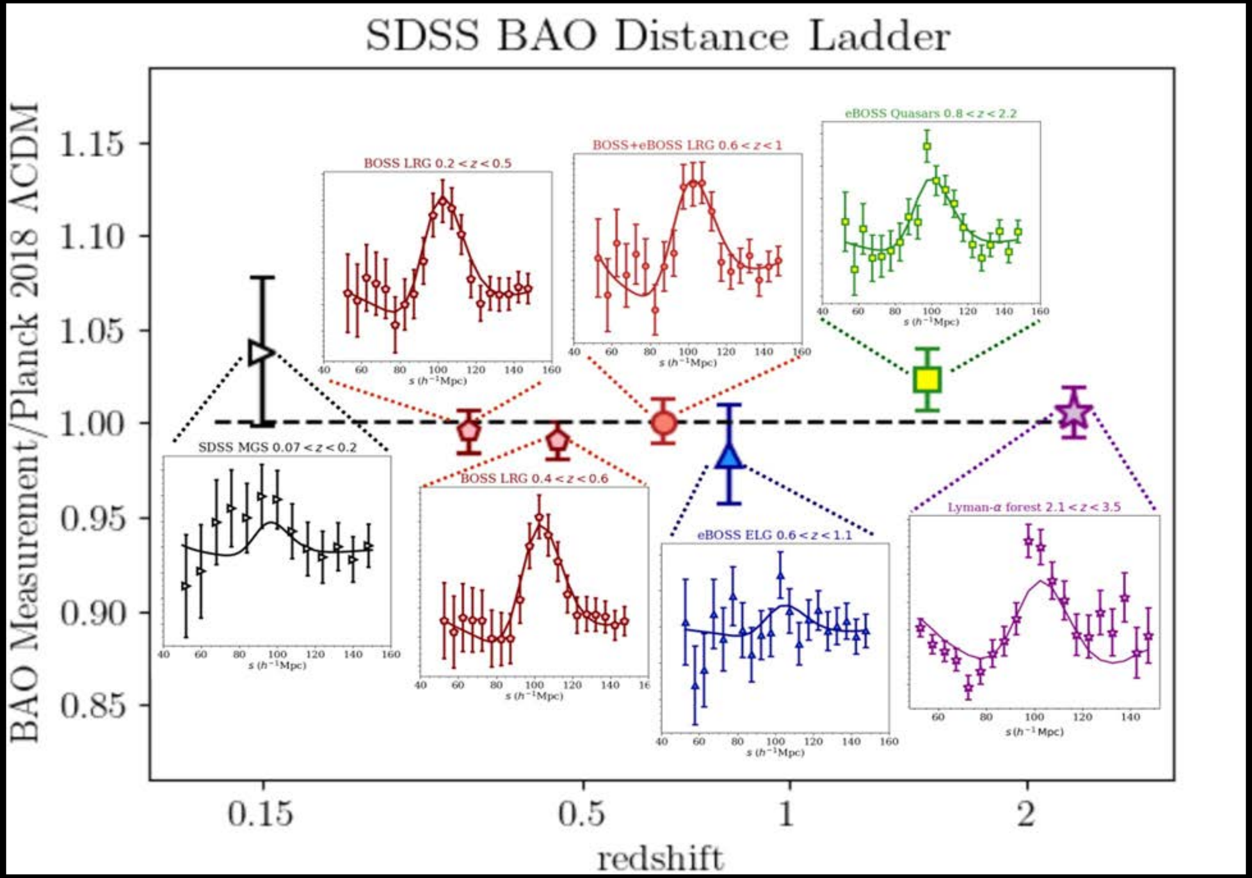
$w_a = -0.88^{+0.29}_{-0.25}$

using DESY5 SN

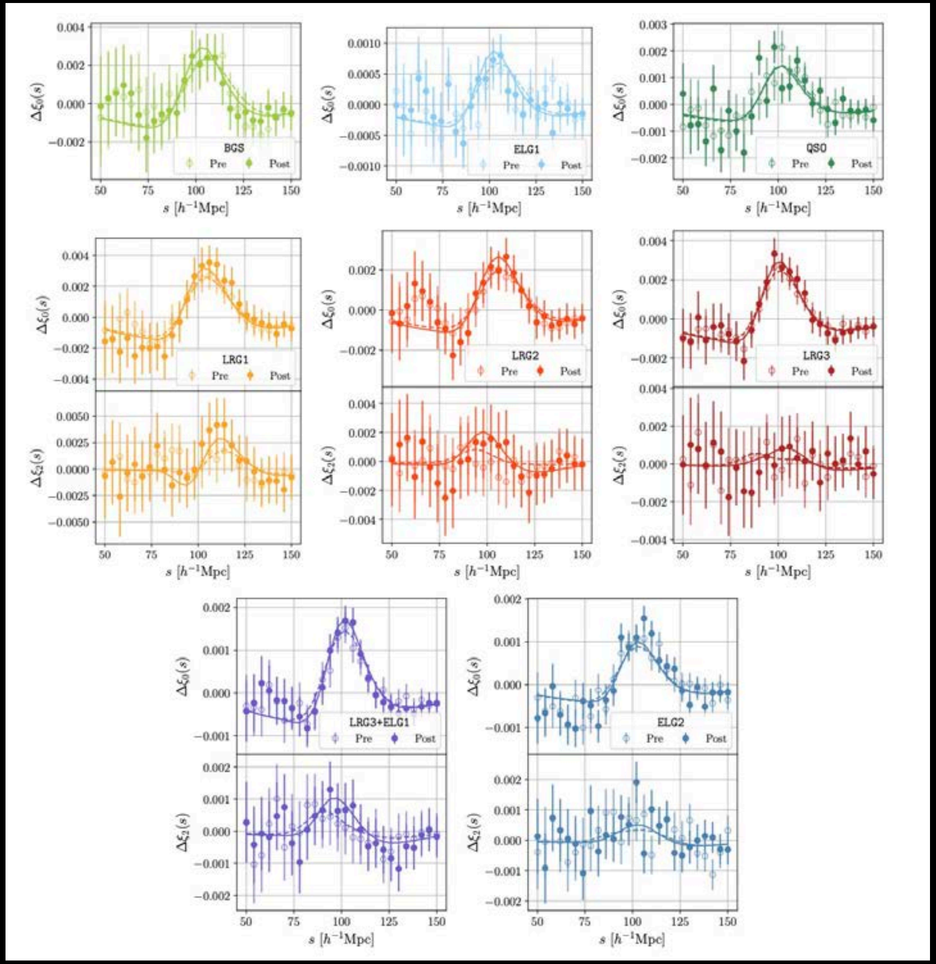
DESI 2024

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

Baryon Acoustic Oscillations (BAO)



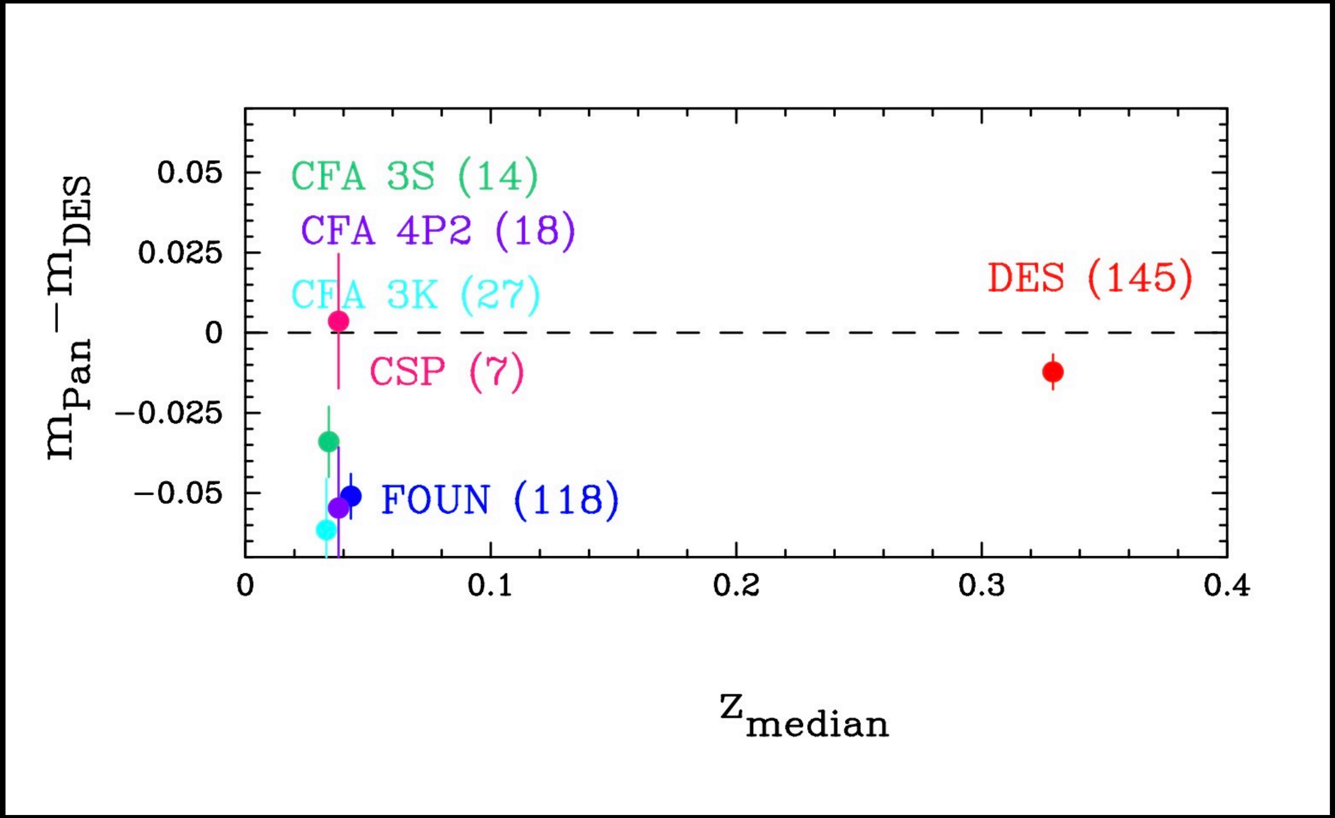
Alam+ 2021



DESI 2024

DESI+SDSS uses most precise BAO measurement in each z bin

Is it SN Systematics?

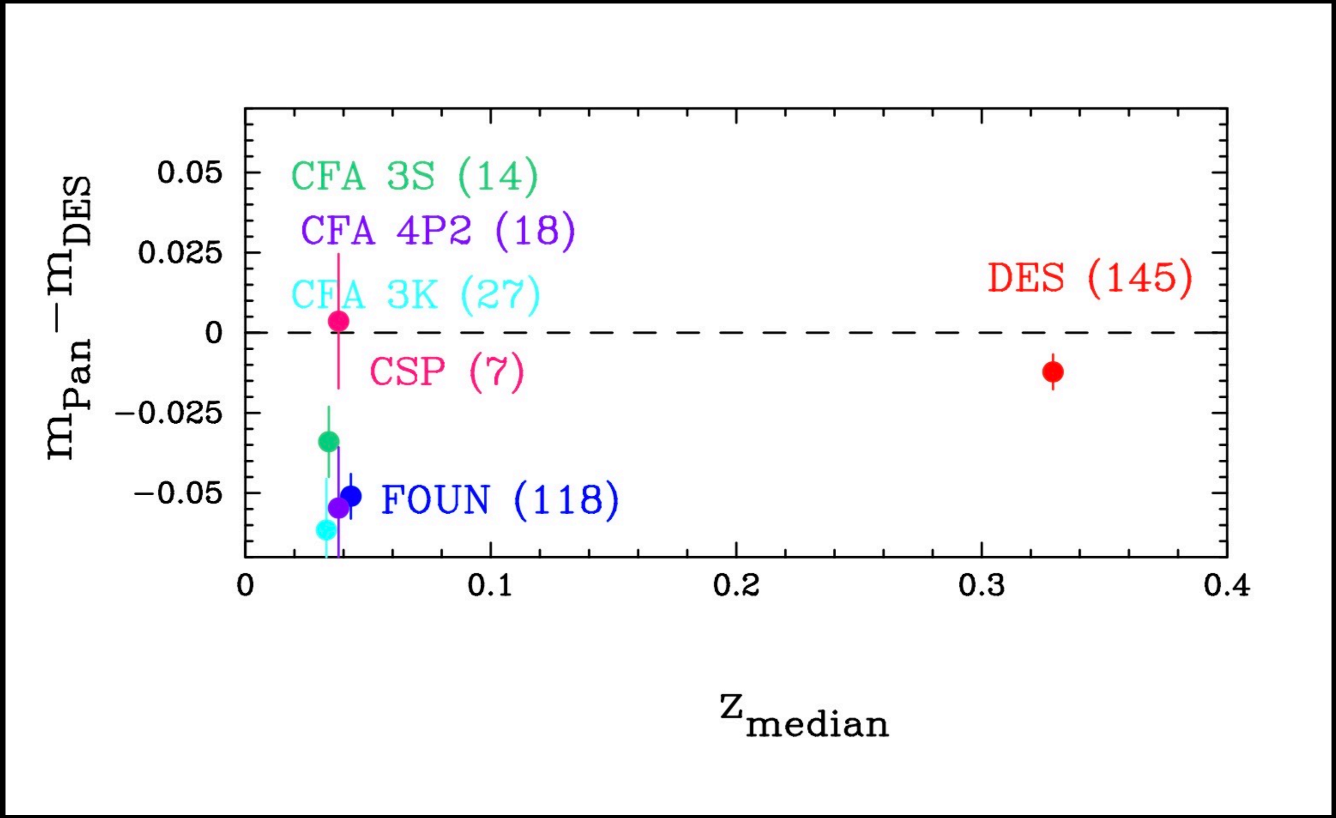


Efstathiou 2024

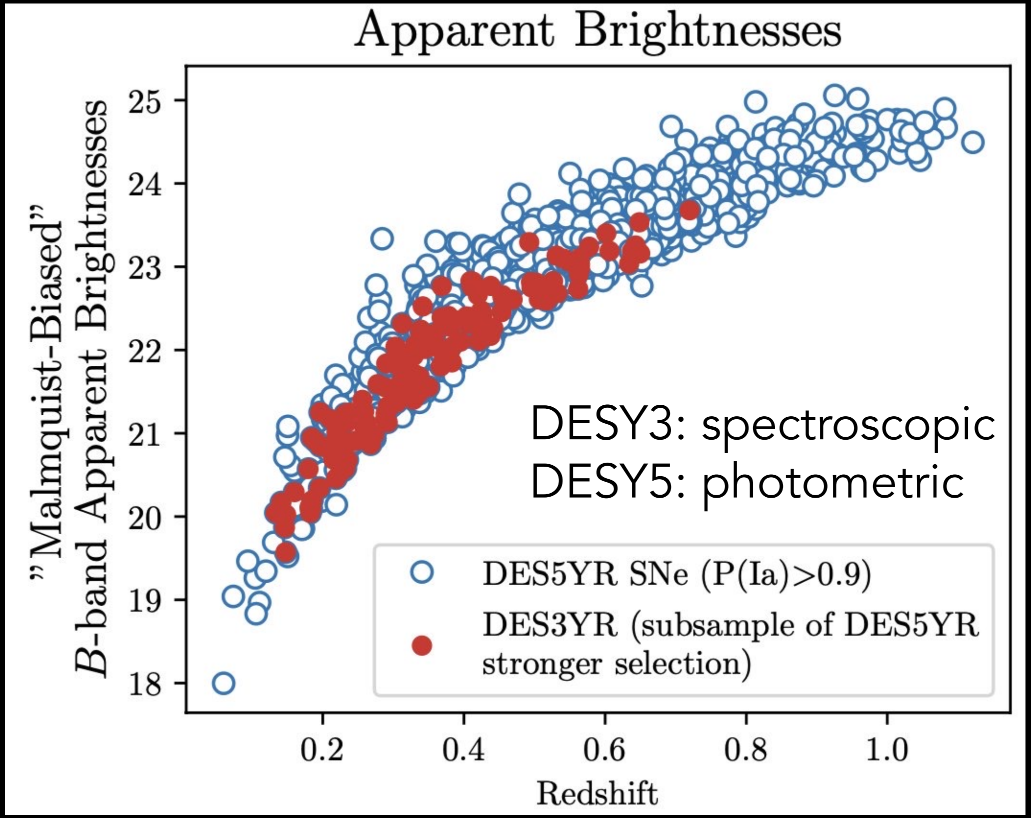
~0.04 mag offset low- vs. high-redshift for SNe in common between Pantheon and DESY5.

Recall DESI+Pantheon closer to Planck ΛCDM. "Correcting" DESY5 SN would make $3.9\sigma \rightarrow 2.5\sigma$

Is it SN Systematics? We don't think so.



Efstathiou 2024



DES 2024 in preparation

0.04 mag offset low- vs. high-redshift for SNe in common between Pantheon and DESY5.

DESY3(Pantheon) selection effects and bias corrections very different from DESY5 SN.

$w_0 w_a$ and Expansion History

- Supernovae measure luminosity distance vs. redshift:

$$D_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{E(z')}$$

where expansion history

$$E^2(z) = \frac{H^2(z)}{H_0^2} = \Omega_{m,0}a^{-3} + (1-\Omega_{m,0})\exp\left(3\int_a^1 \frac{1+w(a)}{a}da\right)$$

- $w_0 w_a$ parameterization

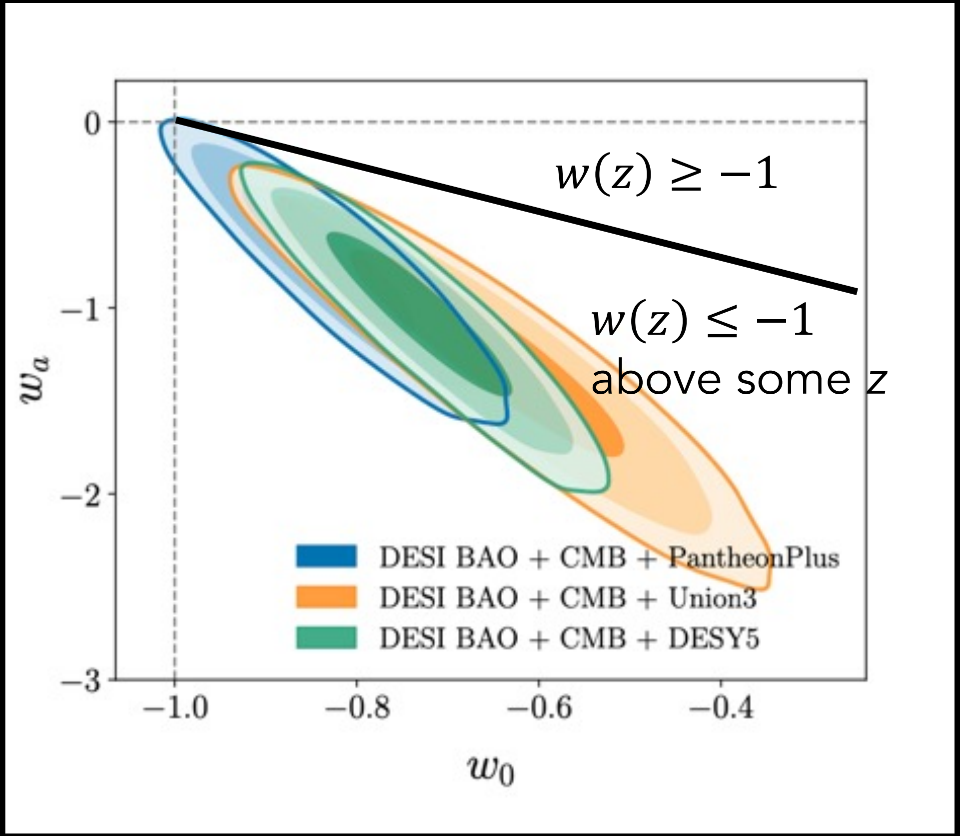
$$w(a) = w_0 + w_a(1-a) = w_0 + w_a\left(\frac{z}{1+z}\right)$$

provides parametrized expansion history $E(z;\Omega_{m,0},w_0,w_a)$ that can fit $E(z)$ of scalar models with *different* $w(a)$ behavior:

$$\exp\left(3\int_a^1 \frac{1+w(a)}{a}da\right) = a^{-3(1+w_0+w_a)}e^{-3w_a(1-a)}$$

Issues with $w_0 w_a$

- Much of the parameter space naively violates the Null Energy Condition (NEC) $w(z) \geq -1\ \forall z$
- Can approximate thawing scalar field EOS $w(z)$ at low redshift but not high redshift.
- Can approximate $H(z)$ expansion history for many scalar field models, but resulting $w(z)$ doesn't match the true $w(z)$.



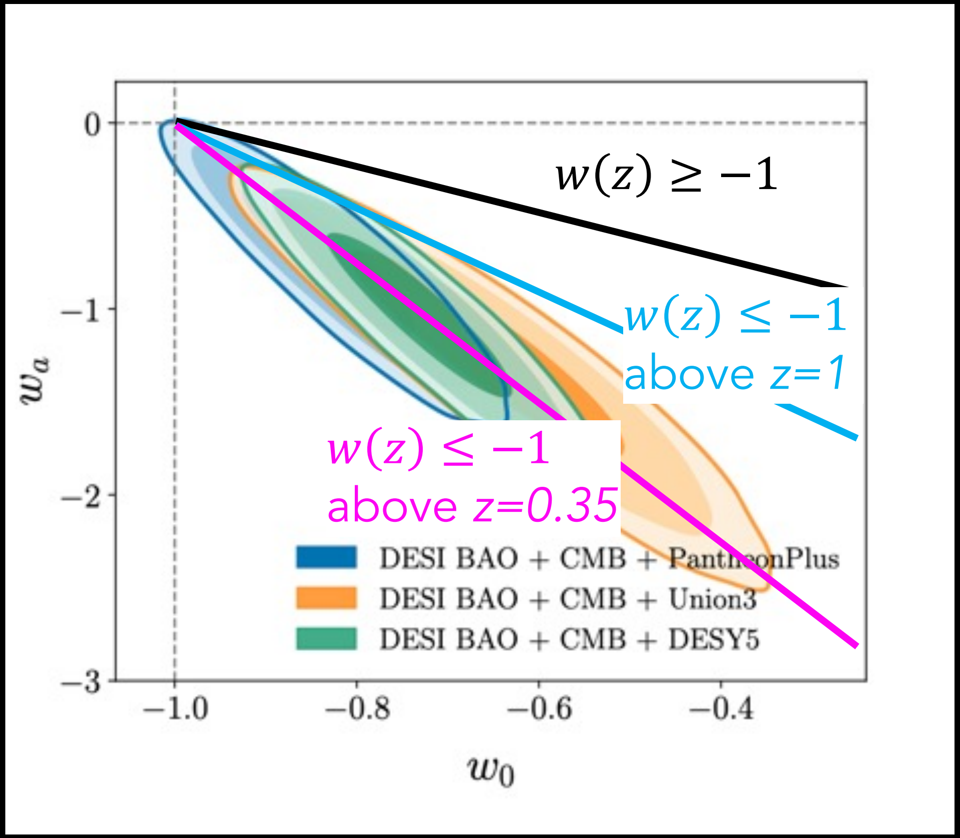
$w(a)=w_0+w_a(1-a)$

$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right)$$

Shlivko and Steinhardt 2024

Issues with $w_0 w_a$

- Much of the parameter space naively violates the Null Energy Condition (NEC) $w(z) \geq -1 \; \forall z$
- Can approximate thawing scalar field EOS $w(z)$ at low redshift but not high redshift.
- Can approximate $H(z)$ expansion history for many scalar field models, but resulting $w(z)$ doesn't match the true $w(z)$.



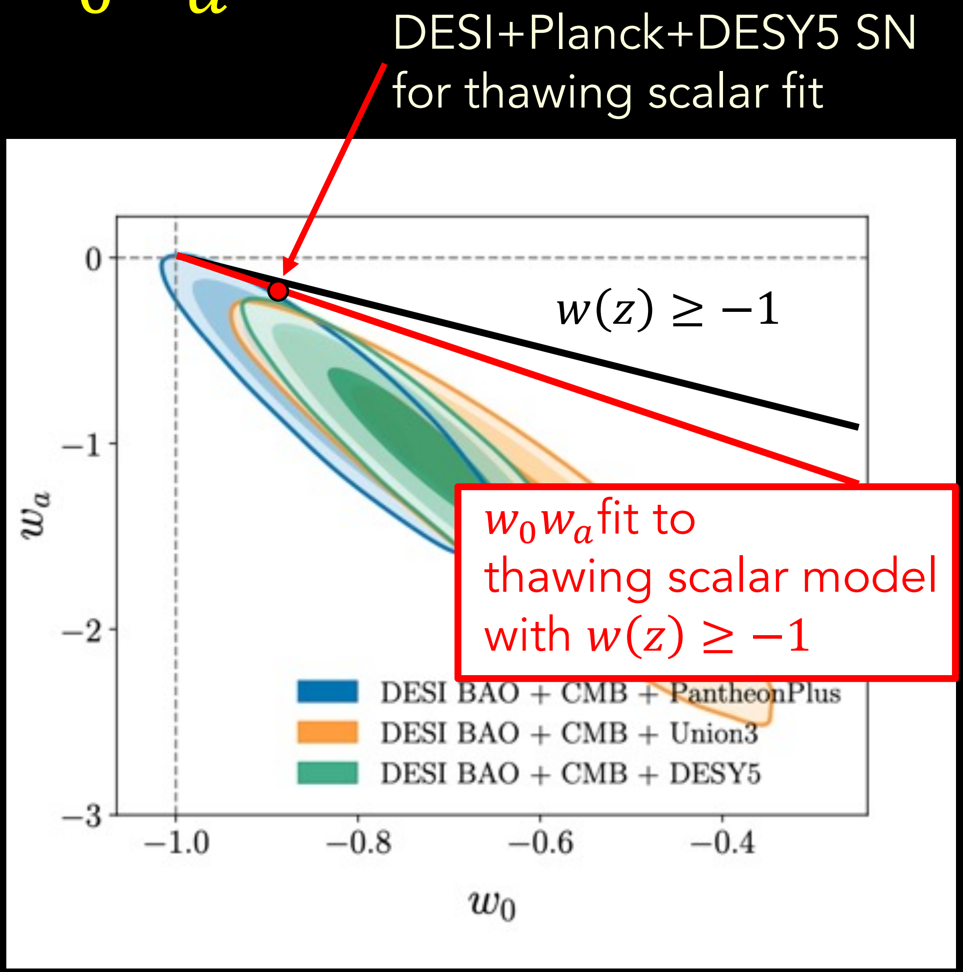
$w(a)=w_0+w_a(1-a)$

$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right)$$

Shlivko and Steinhardt 2024

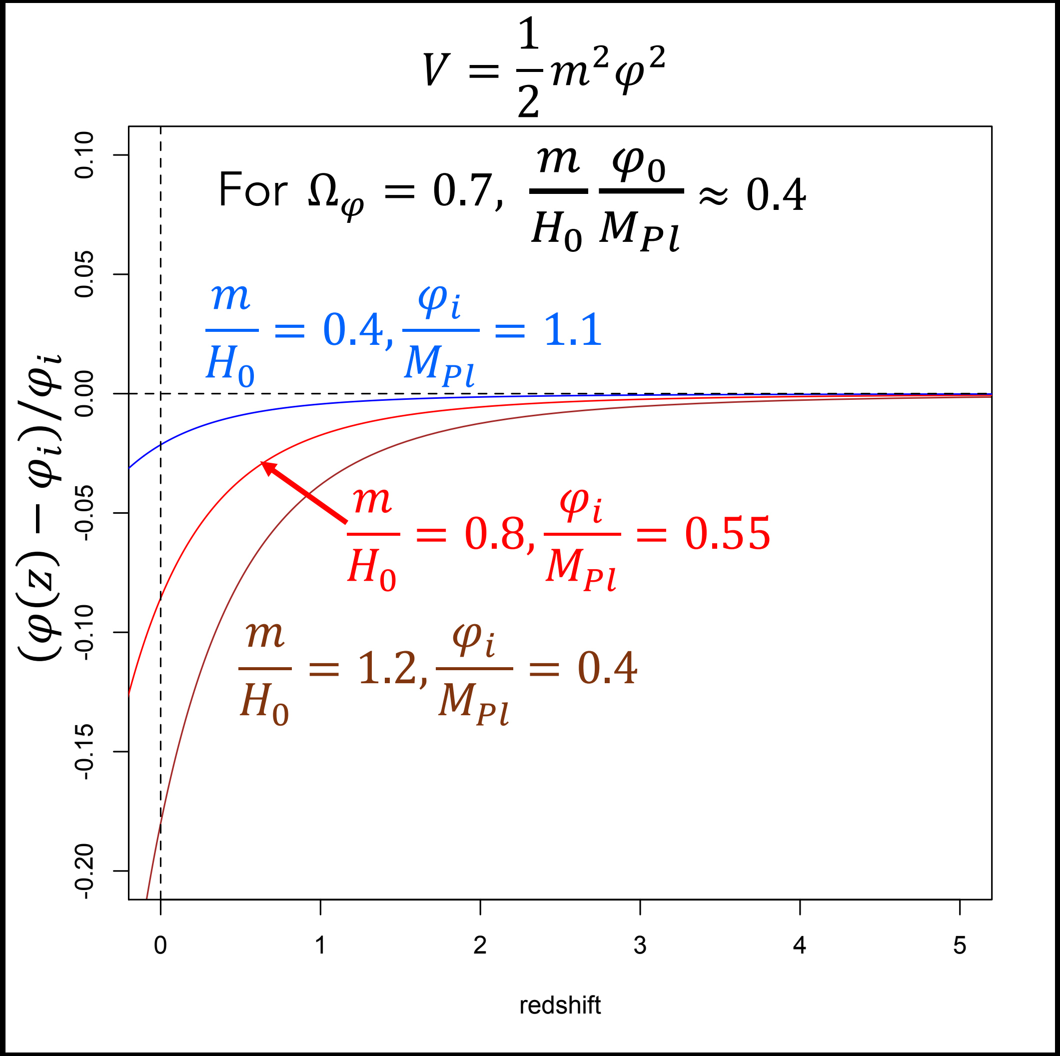
Issues with $w_0 w_a$

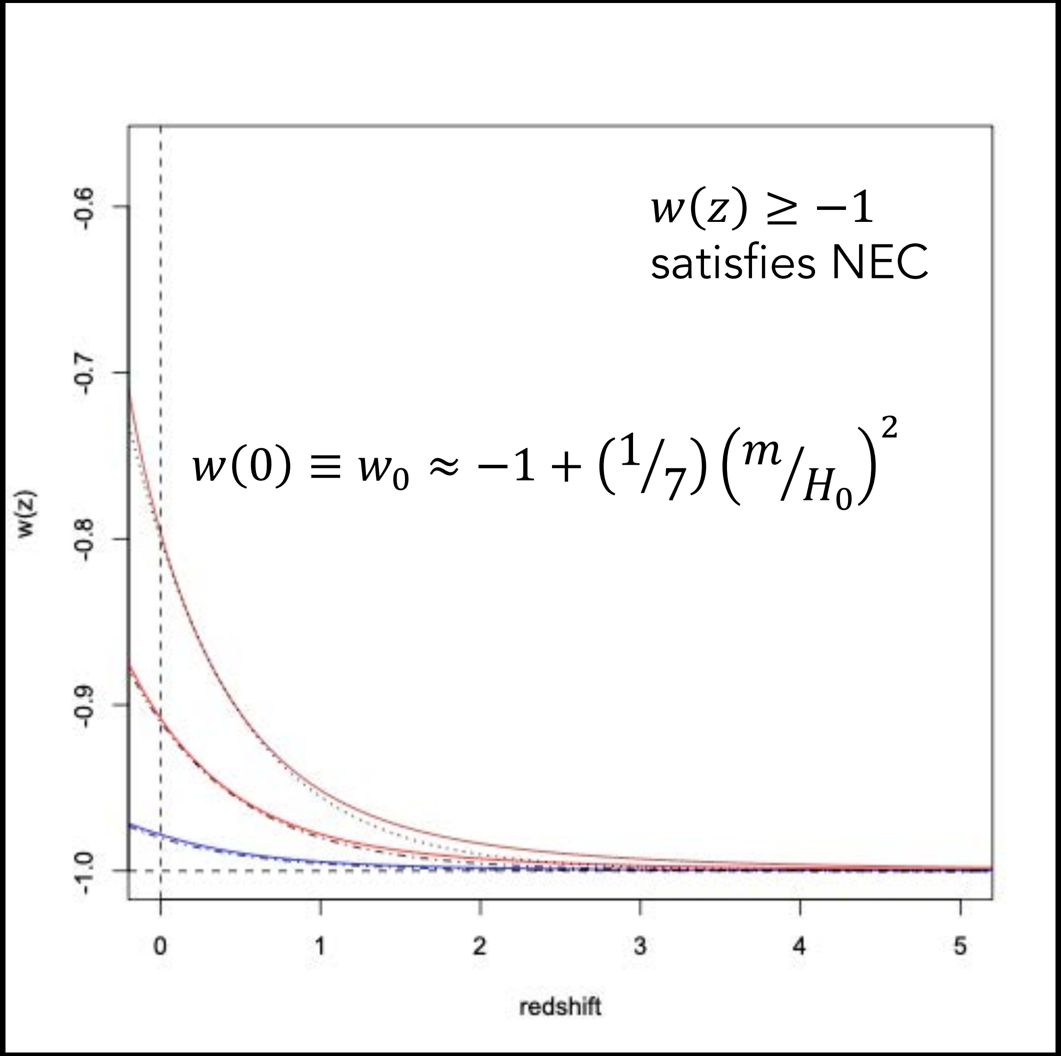
- Much of the parameter space naively violates the Null Energy Condition (NEC) $w(z) \geq -1\ \forall z$
- Can approximate thawing scalar field EOS $w(z)$ at low redshift but not high redshift.
- Can approximate $H(z)$ expansion history for many scalar field models, but resulting $w(z)$ doesn't match the true $w(z)$.
- Therefore, recent data do *not* indicate violation of NEC.



Shlivko and Steinhardt 2024
Lodha+ 2024

How do thawing scalar fields actually evolve?





Quasi-Universal Behavior of Thawing Scalar Models

Thawing models very well fit by:

$$\boxed{w(z) \cong -1 + (1 + w_0)e^{-\alpha z}}$$

where $w(0) = w_0$, and

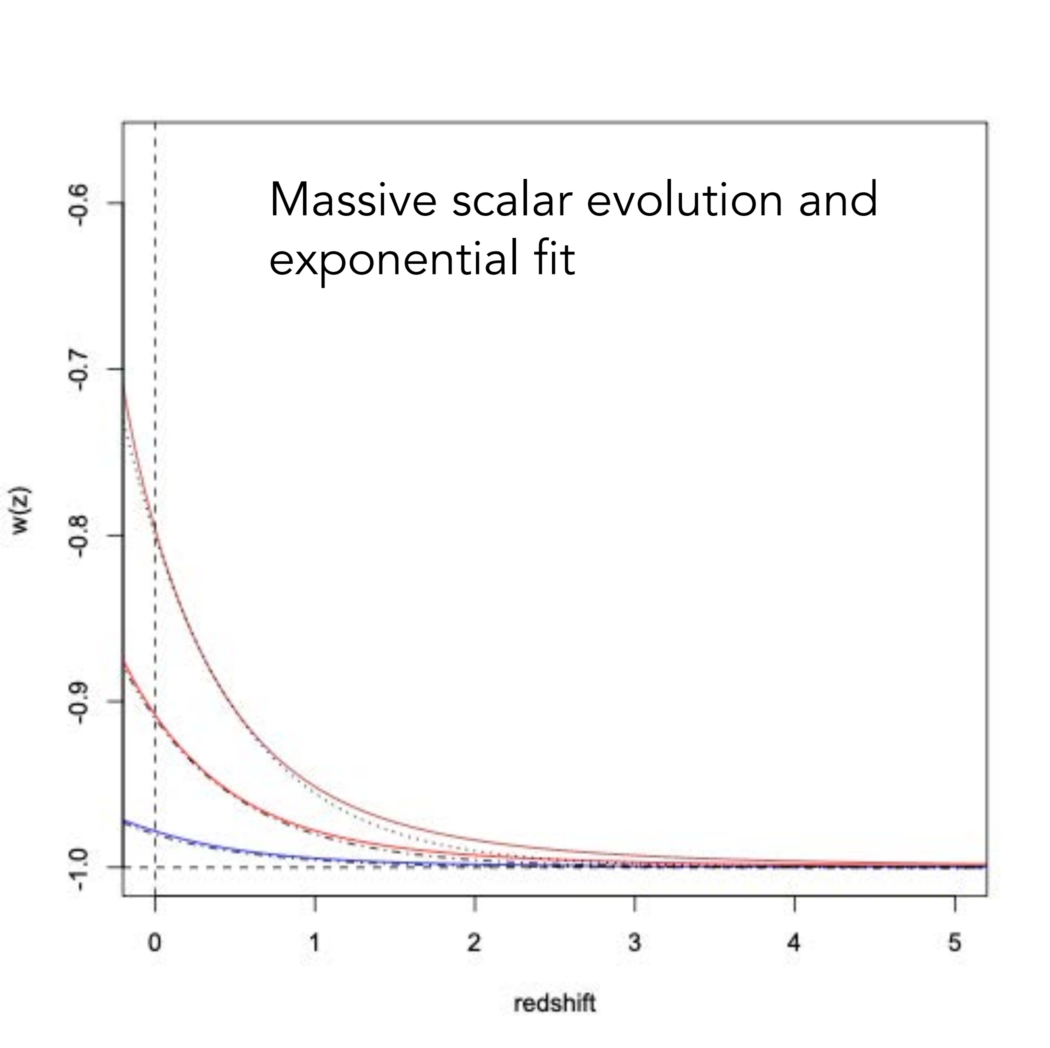
$$\alpha = 1.35 - 1.55$$

depends *very weakly* on $V(\varphi)$ and w_0.

Note that:

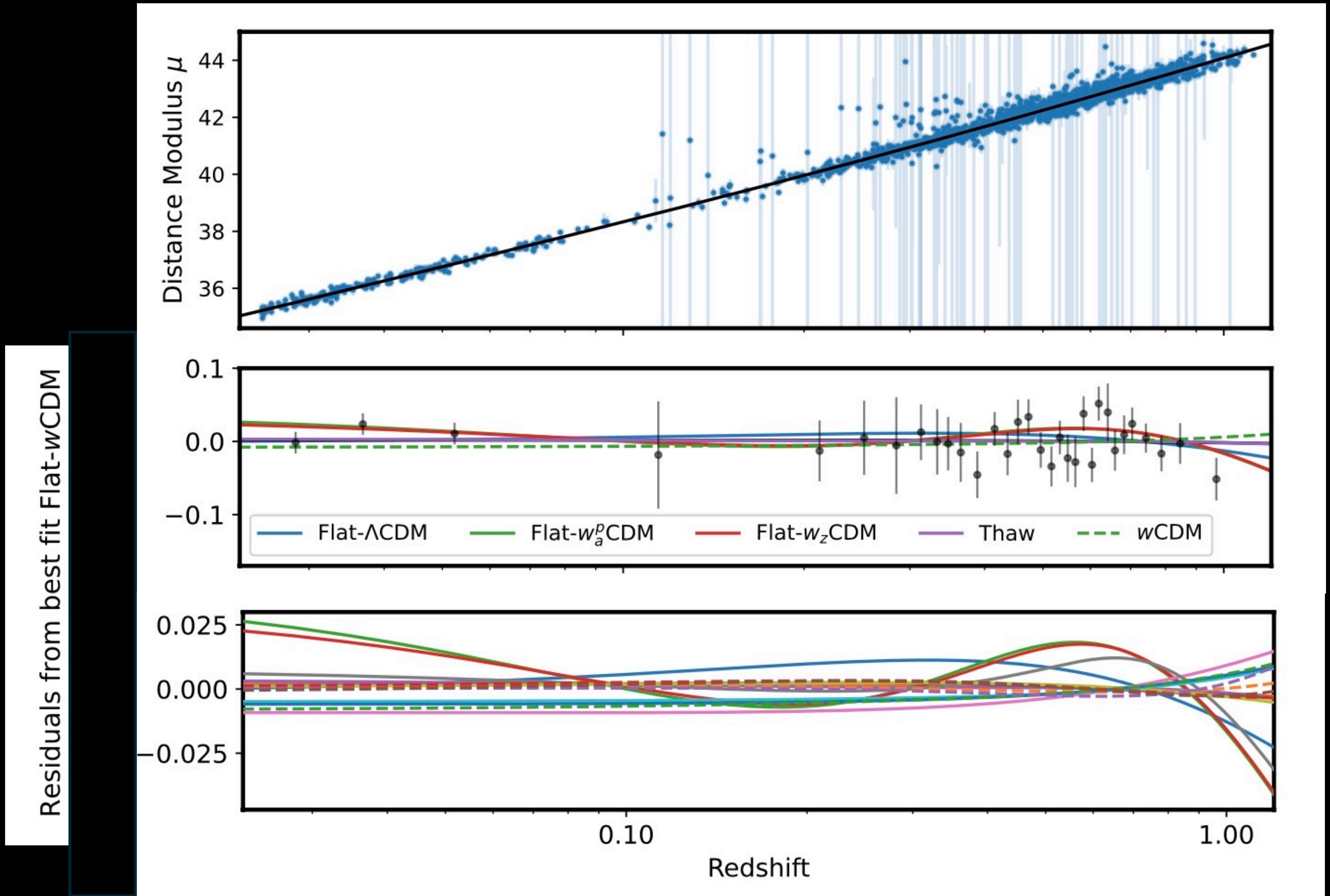
$$\alpha = 0 \Leftrightarrow w\text{CDM}$$

$$\alpha \gg 1 \Leftrightarrow \Lambda\text{CDM}$$



Linder 2008, Shlivko 2024, Camilleri+ 2024

DESY5 SN Hubble Diagram



SNe with inflated error bars are likely non-Ia contaminants

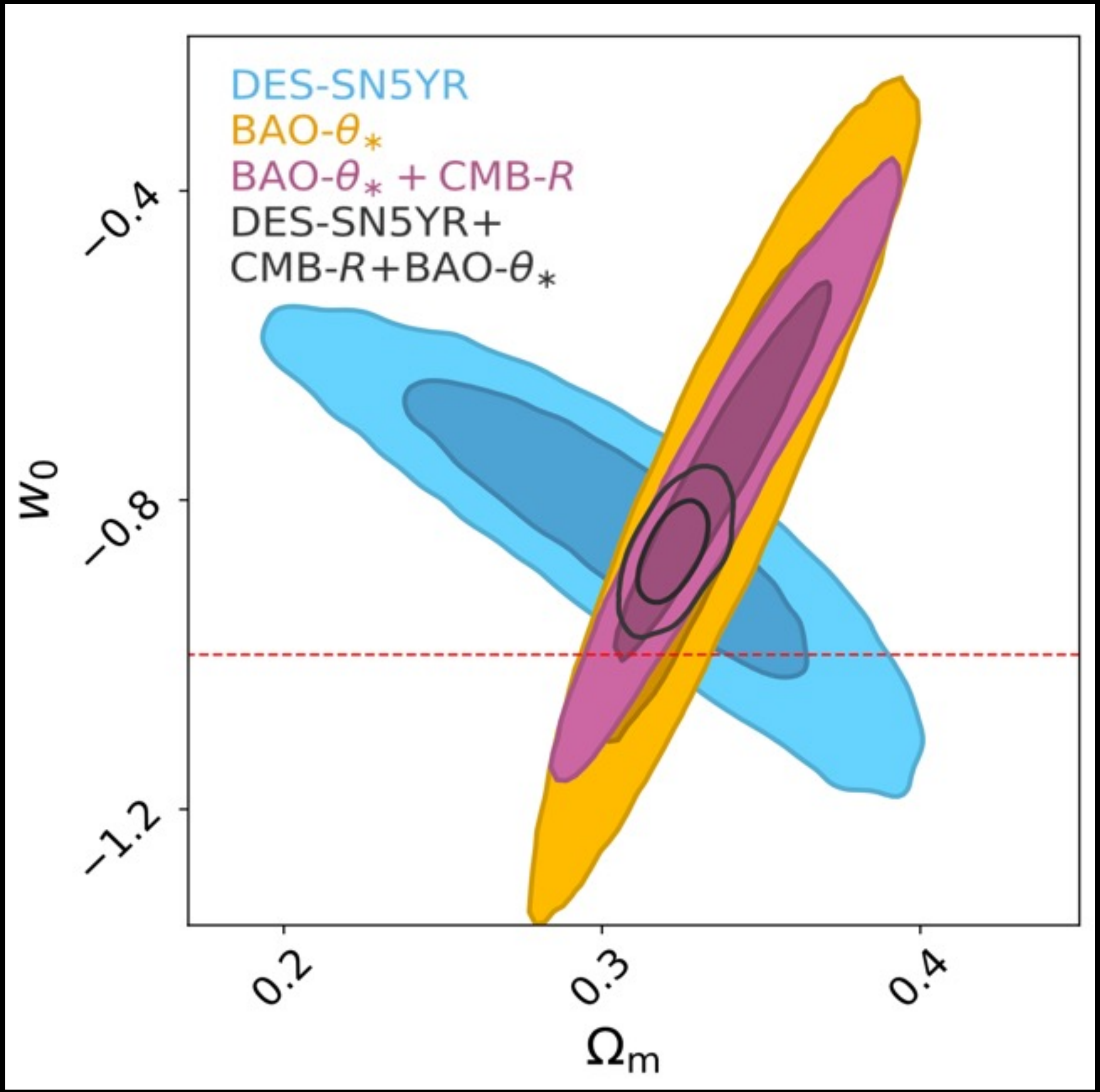
Relative distances for best-fit thawing model ~2% less than for Planck ΛCDM at z~0.5

Camilleri+ 2024

Observational Constraints on Thawing Models

$$w(z) \cong -1 + (1 + w_0)e^{-\alpha z}$$

- Constraints marginalized over
$$\alpha = 1.35 - 1.55$$
- Best fit parameters:
$$w_0 = -0.867 \pm 0.040$$
$$\Omega_m = 0.323 \pm 0.007$$
- 3.3σ from ΛCDM
- Using SDSS (pre-DESI) BAO and DESY5 SN.
- $\frac{1}{2}\Delta\mathrm{AIC} = -3.2$ (moderate preference vs ΛCDM but not vs wCDM)
- Inferred scalar mass $m \approx H_0$ with 2% uncertainty



Camilleri+ 2024

The Precision Cosmic Frontier

- Cosmic surveys can test evolving Dark Energy and may break ΛCDM.
- Current results are tantalizing, but we should be cautious about moderate-significance results and potentially unmodelled systematics.
- Physically-motivated thawing scalar field models from 30 years ago are consistent with the recent results (freezing models are disfavored). Time to stop trying to fit them into the round hole of $w_0 w_a$.
- Near-future results from DES Y6 3x2pt, DESI Y3, DESI-extension, DESI-II, Vera Rubin Observatory LSST, Euclid, Nancy Grace Roman Space Telescope,…will help determine if DE evolves.
- Quasi-universality of thawing models will make it difficult to distinguish between them in the near term.
- In the long term (~10^9 years), the transition to another matter-dominated epoch will provide further clues about Dark Energy.