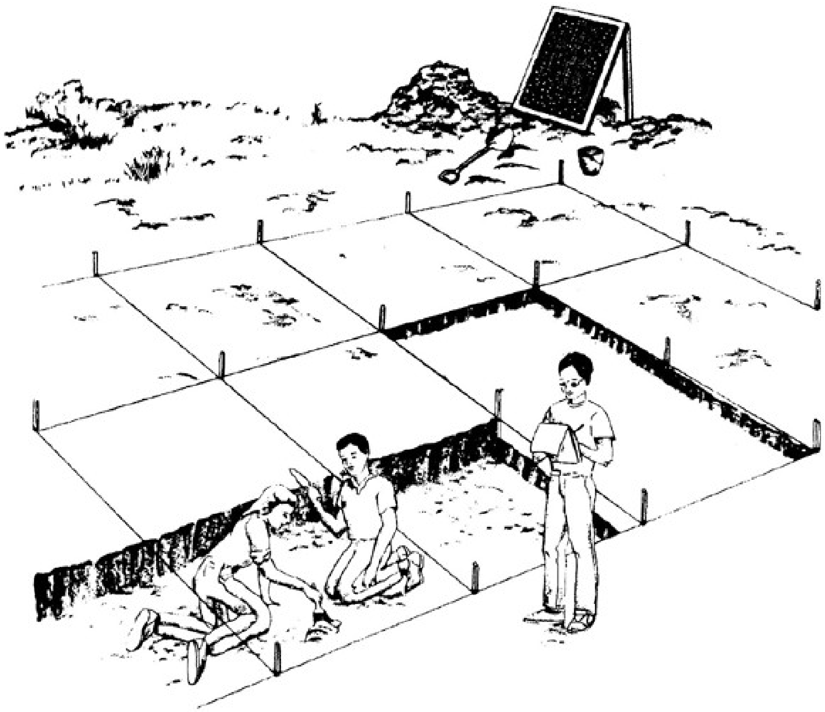
Constraining scalar field Dark Energy models



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DARKMOD

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Quintessence

For a review see S.Tsujikawa (2013)

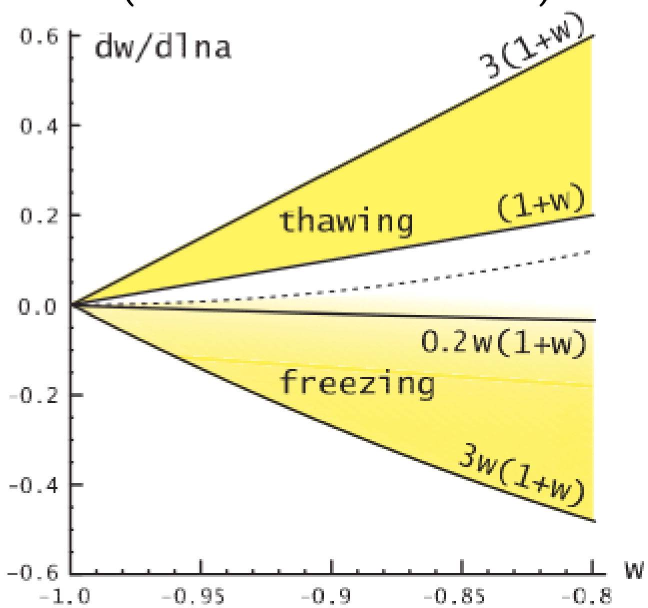
- Minimally coupled scalar field $S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_m$

Quintessence models can be classified depending on evolution of

$$w \equiv \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

→ Two classes: Thawing & Freezing

(Caldwell & Linder 2005)



- Consider approximate analytic w(a) for models:

1) Tracking Freezing
2) Scaling Freezing
3) Thawing

and put observational constraints on the parameters in w(a)

- This analysis covers most quintessence potentials

We update the constraints from T.Chiba, A.De Felice, S.Tsujikawa (2013) with the latest data

- using Boltzmann code CLASS & MonteCarlo code MontePython

- Data:
  - Planck 2015: Temperature and Polarization TT, TE & EE
  - Planck 2015: Lensing
  - Supernovae : SDSS-II/SNLS3 Joint Light-curve Analysis (JLA)
  - BAO : SDSS7 MGS, 6dFGS, BOSS LOWZ, BOSS CMASS

Note:

- For Quintessence we have the prior $w \geq -1$

- But we also extend the analysis to any value

(e.g. Dutta, Saridakis, Scherrer 2009
Chiba, Dutta, Scherrer 2009)

1) Tracking Freezing models

- Inverse power-law potential $V(\phi) = M^{4+p}\phi^{-p} \;\; (p > 0)$

- EoS: $$w(a) = w_{(0)} + \alpha_1 \Omega_\phi(a) + \alpha_2 \Omega_\phi(a)^2 + \alpha_3 \Omega_\phi(a)^3$$

(Chiba 2010)

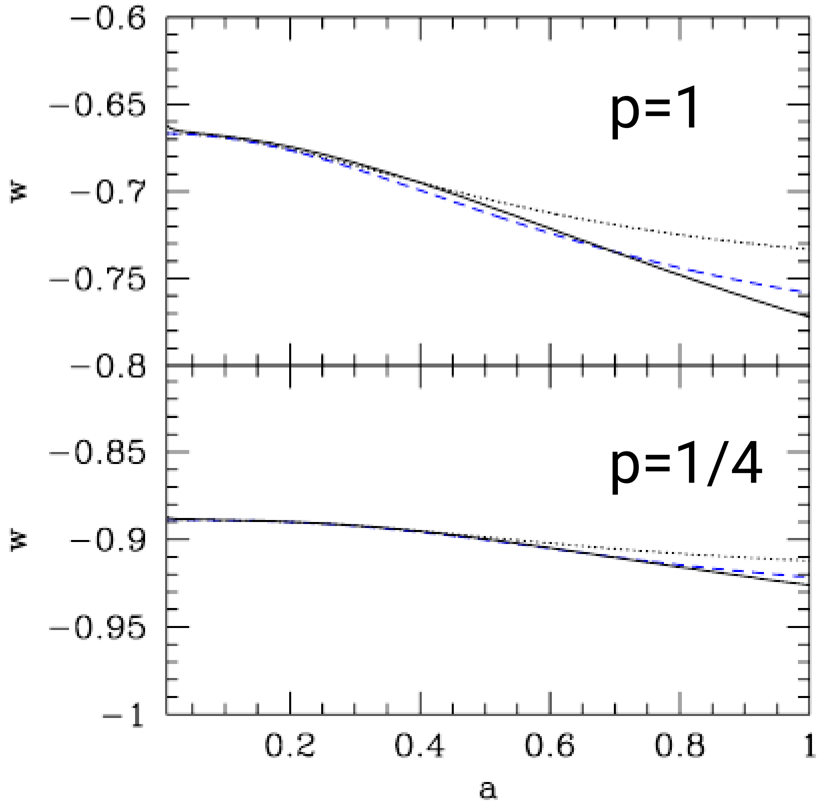
where $$\Omega_\phi(a) = \frac{\Omega_{\phi 0} a^{-3w_{(0)}}}{\Omega_{\phi 0} a^{-3w_{(0)}} + 1 - \Omega_{\phi 0}}$$

and

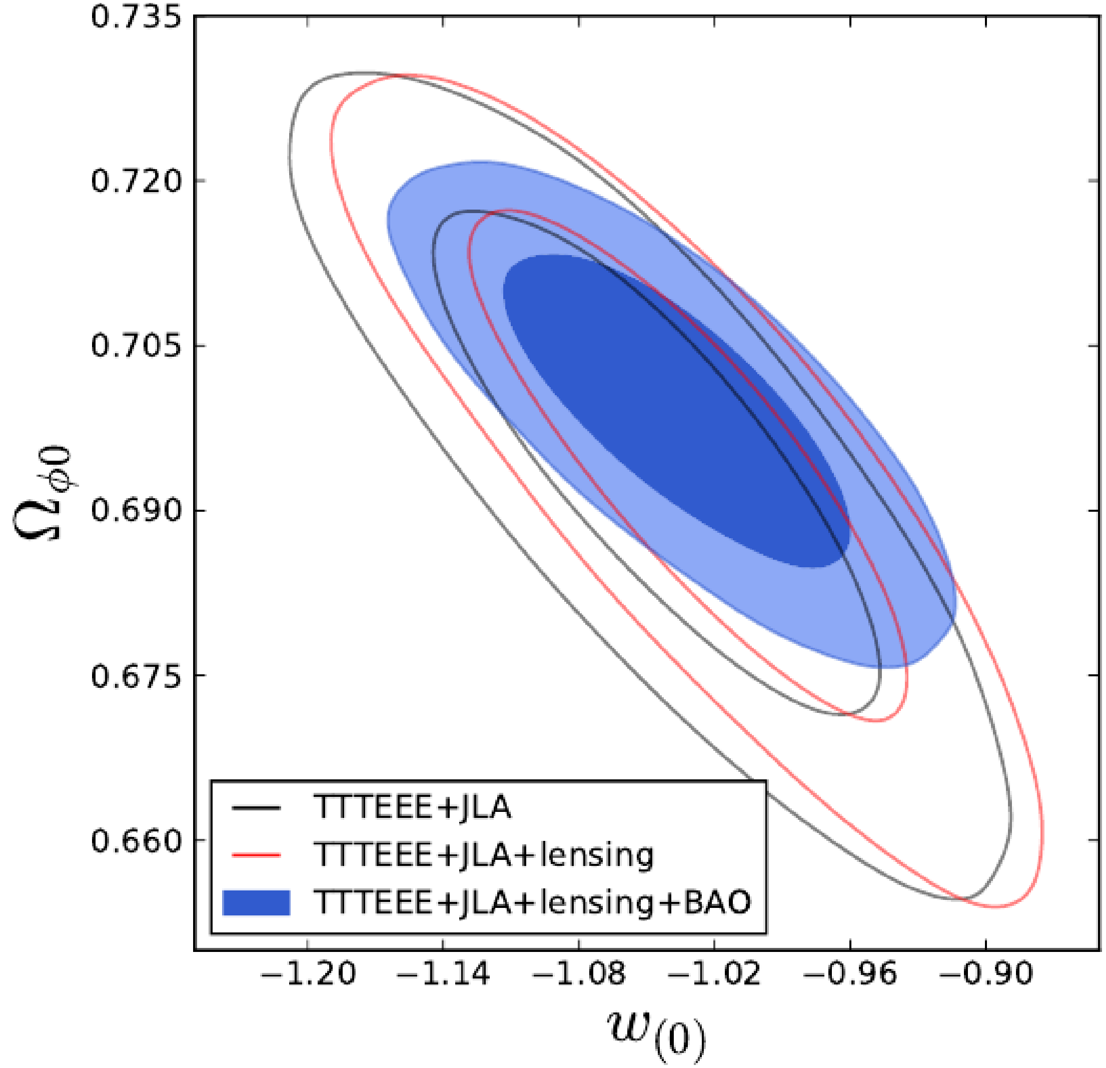
$$\begin{cases} \alpha_1 = \frac{(1-w_{(0)}^2)w_{(0)}}{1-2w_{(0)}+4w_{(0)}^2} \\ \alpha_2 = \frac{(1-w_{(0)}^2)w_{(0)}^2(8w_{(0)}-1)}{(1-2w_{(0)}+4w_{(0)}^2)(1-3w_{(0)}+12w_{(0)}^2)} \\ \alpha_3 = \frac{2(1-w_{(0)}^2)w_{(0)}^3(4w_{(0)}-1)(18w_{(0)}+1)}{(1-2w_{(0)}+4w_{(0)}^2)(1-3w_{(0)}+12w_{(0)}^2)(1-4w_{(0)}+24w_{(0)}^2)} \end{cases}$$

→ Two parameters: $w_{(0)}$ and $\Omega_{\phi 0}$

Chiba 2010



1) Tracking Freezing models



- Constraints: (95% C.L.)

No prior:

$$0.680 < \Omega_{\phi 0} < 0.718$$

$$-1.141 < w_{(0)} < -0.933$$

With prior:

$$0.675 < \Omega_{\phi 0} < 0.703$$

$$-1 < w_{(0)} < -0.923$$

(corresponds to $p < 0.17$)

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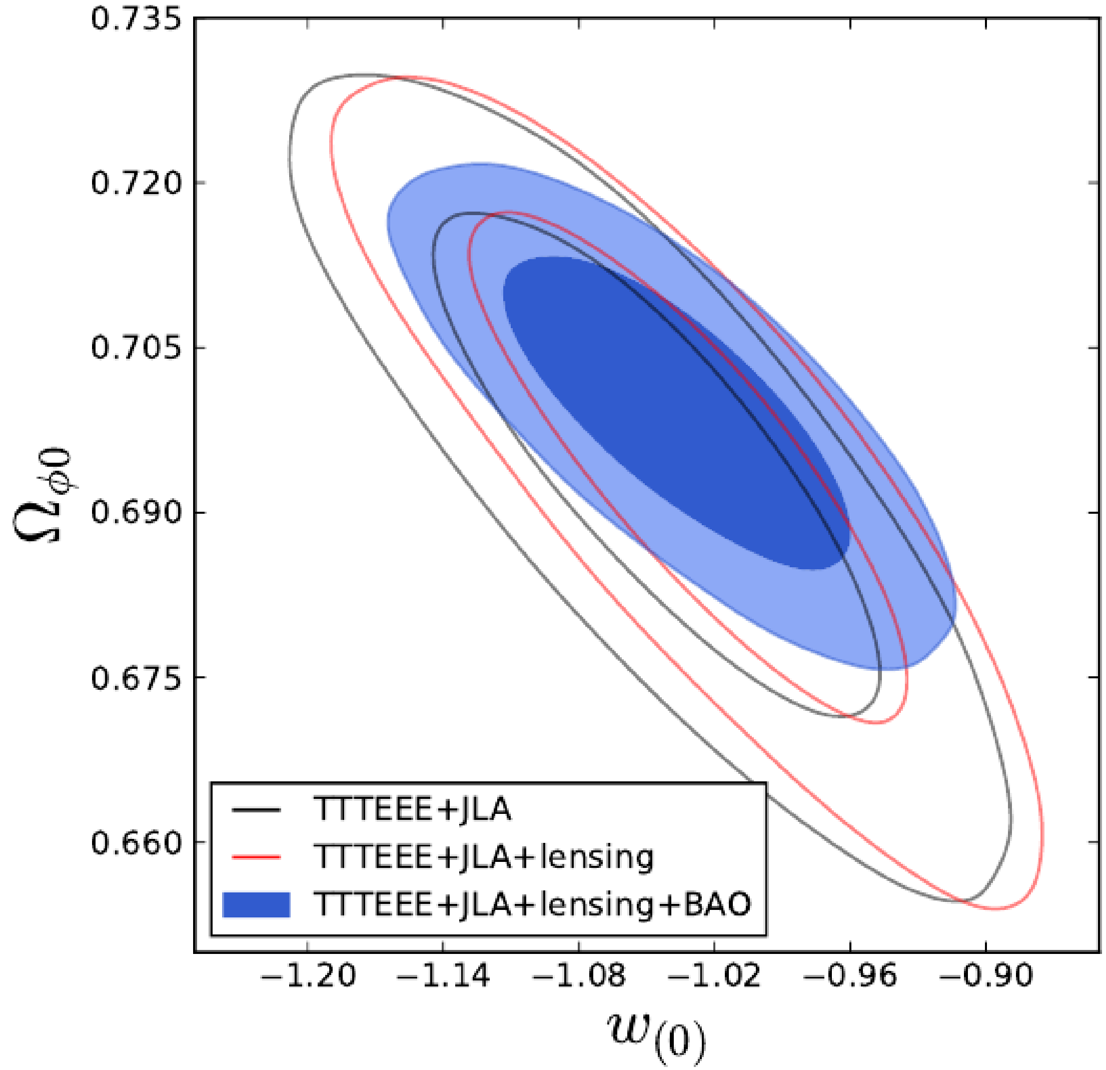

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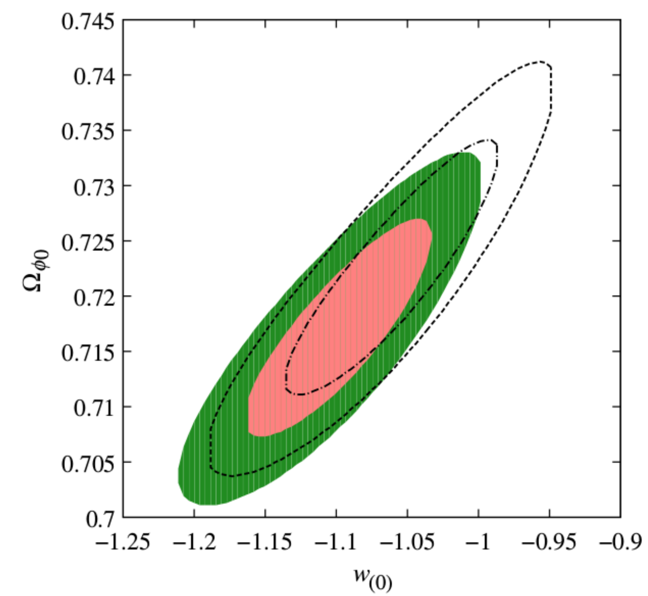

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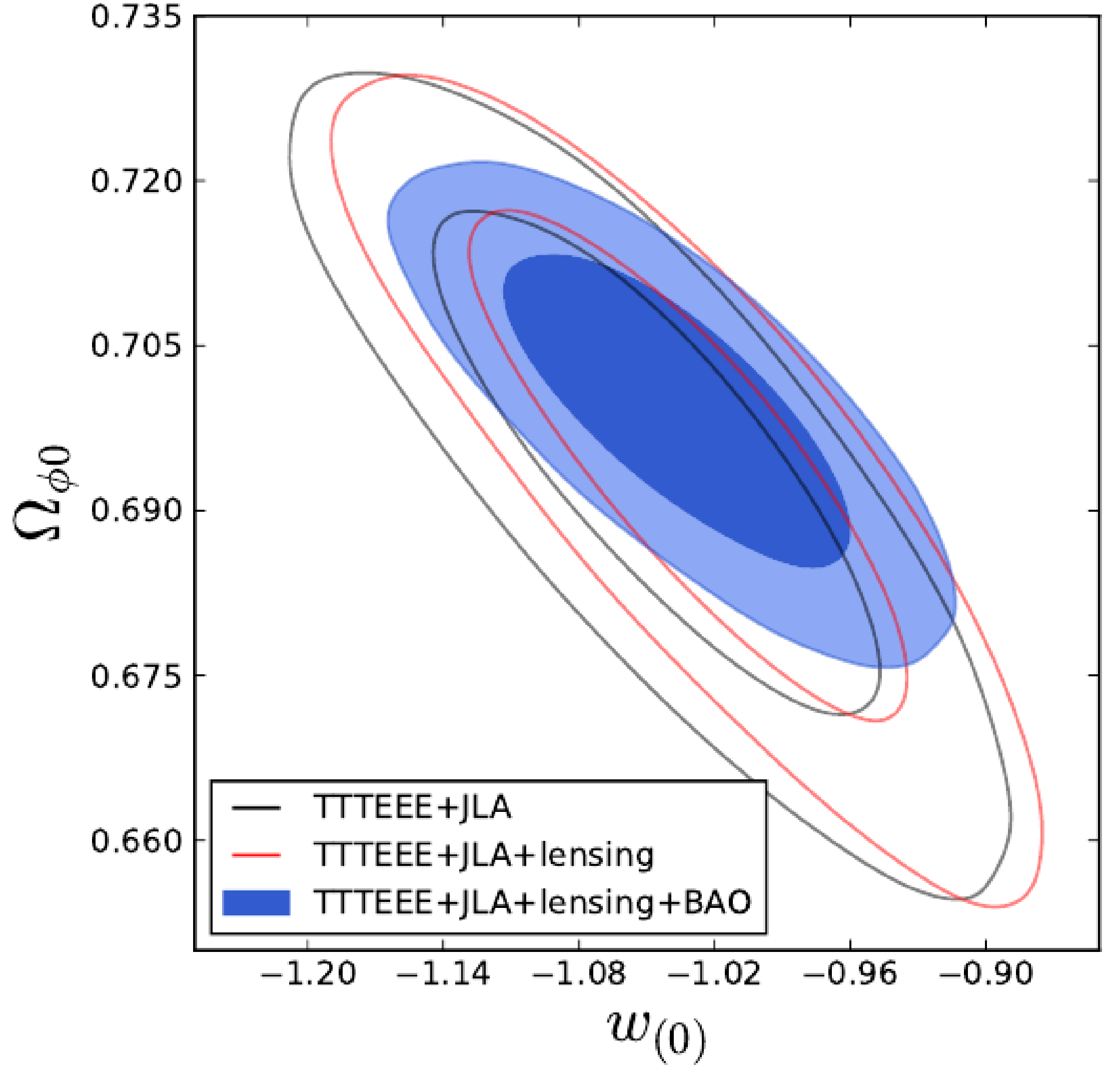

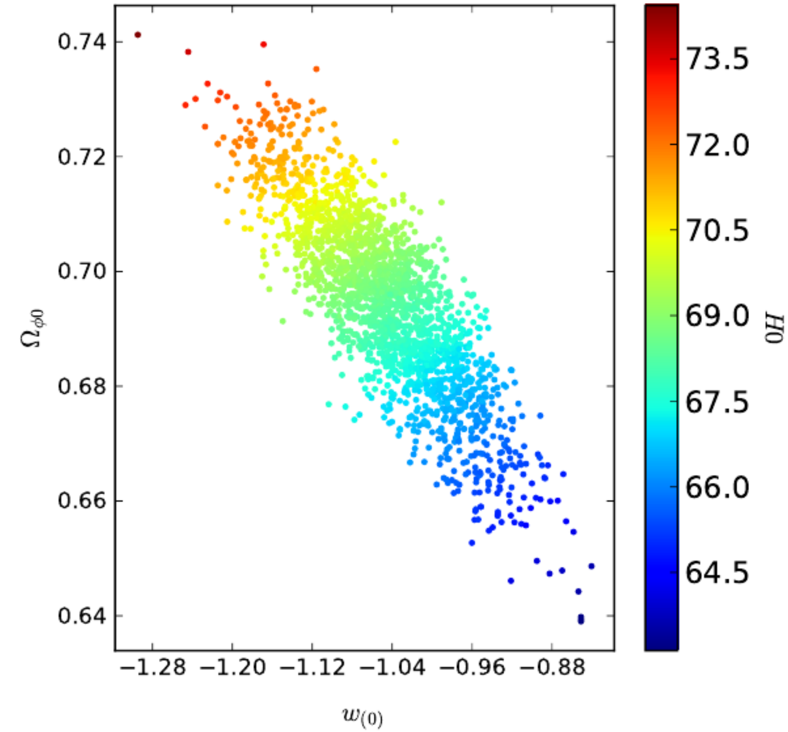

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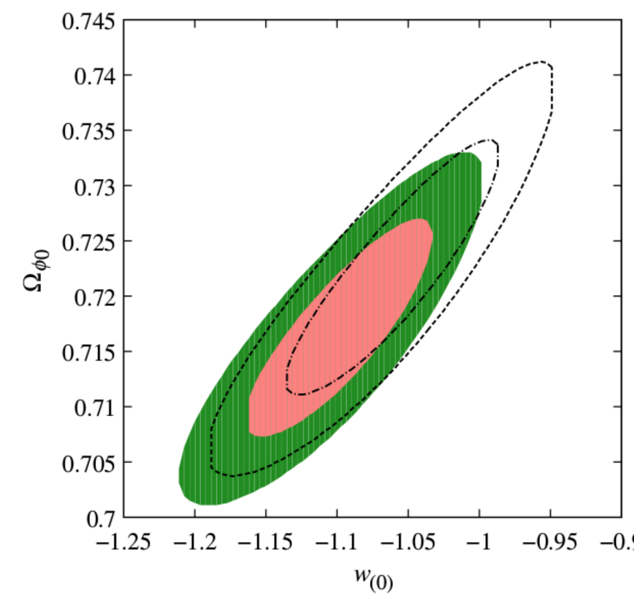


2) Scaling Freezing models

- Double exponential potential: $V(\phi) = V_1 e^{-\lambda_1 \phi / M_{\rm pl}} + V_2 e^{-\lambda_2 \phi / M_{\rm pl}}$

- with $\lambda_1 \gg 1$ and $\lambda_2 \ll 1$

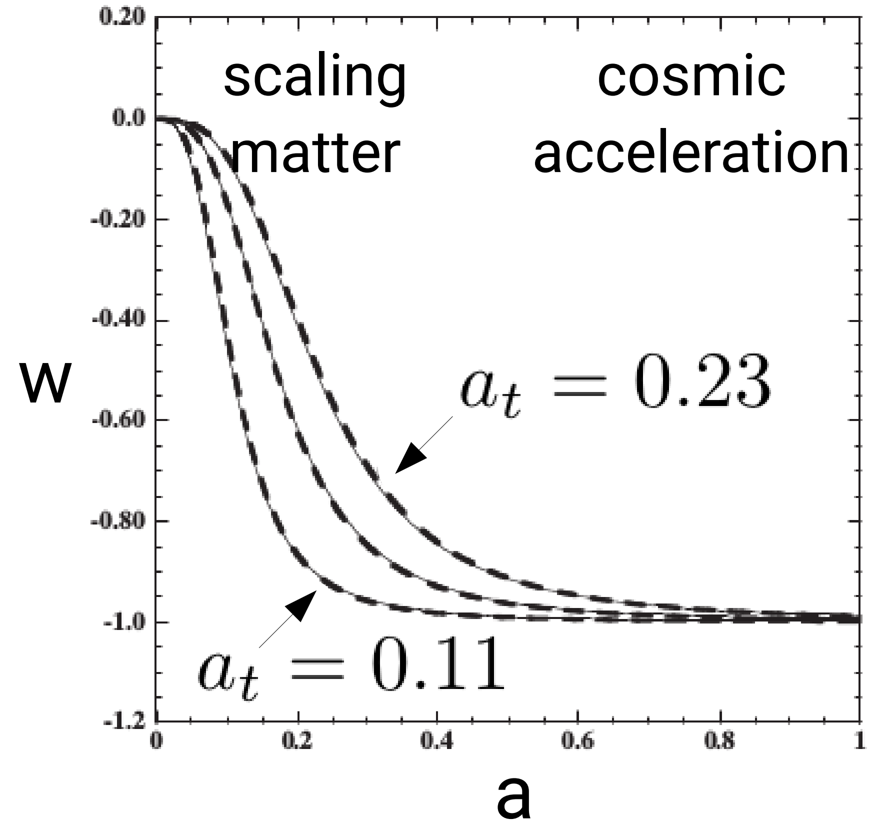
EoS: (Linder & Huterer 2005)

$$w(a) = -1 + \frac{1}{1+(a/a_t)^{1/\tau}}$$

with

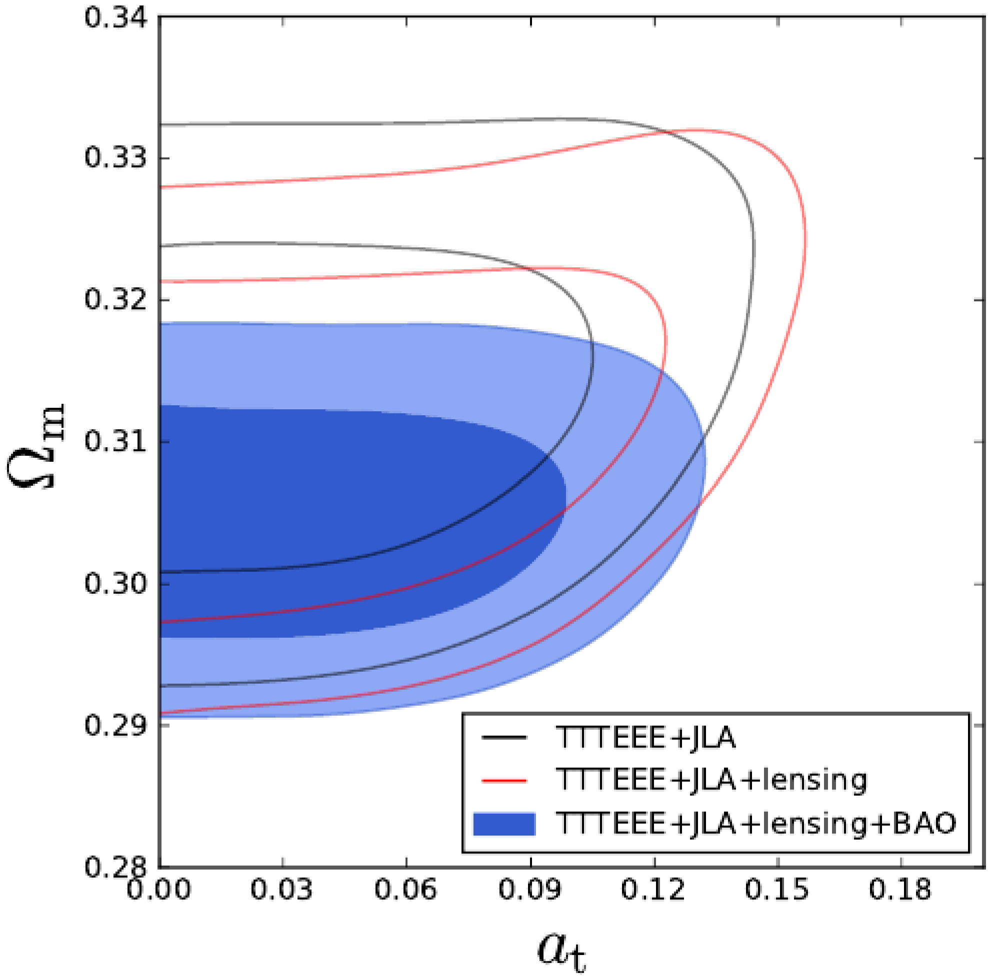
a_t scale factor at transition

$\tau \simeq 0.33$ thickness of transition



→ Two parameters: a_t and Ω_{m0}

2) Scaling Freezing models



- Constraint: $a_t < 0.11$ i.e. $z_t > 8.1$ (95% C.L.)

The transition to the EoS close to w = -1 needs to occur at a very early cosmological epoch

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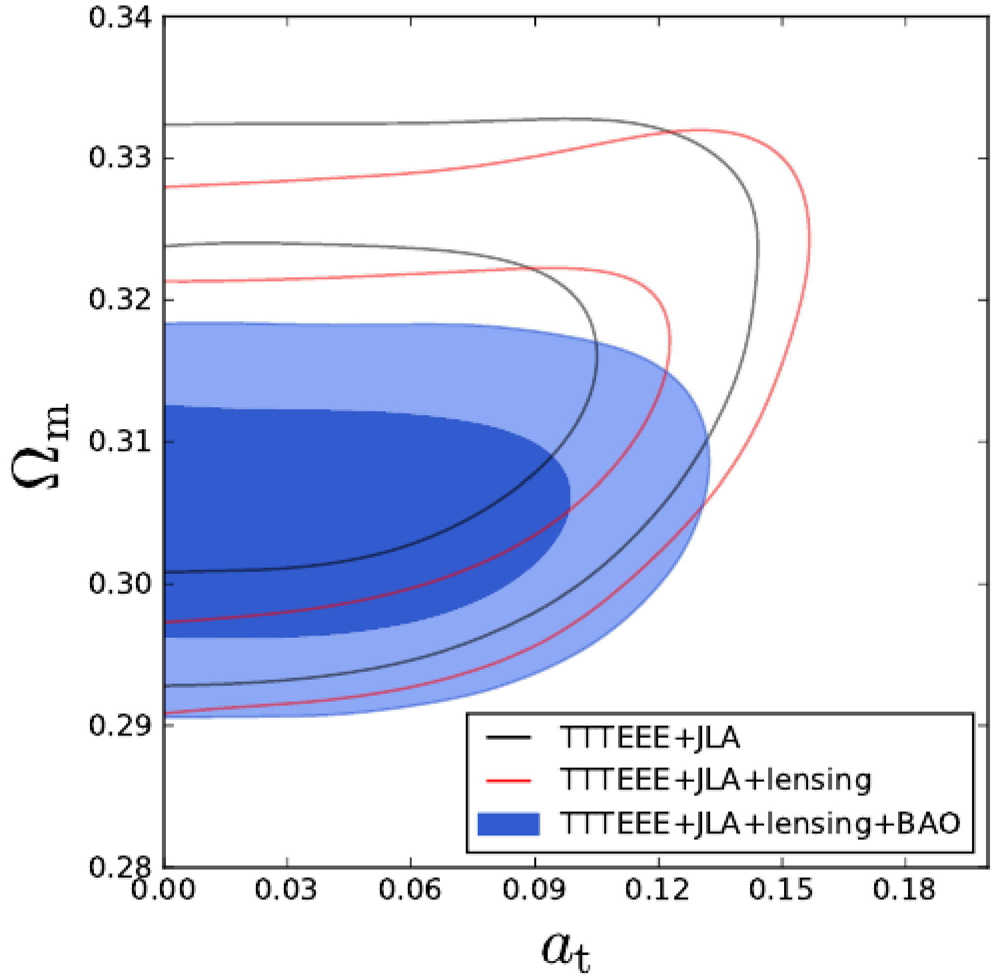

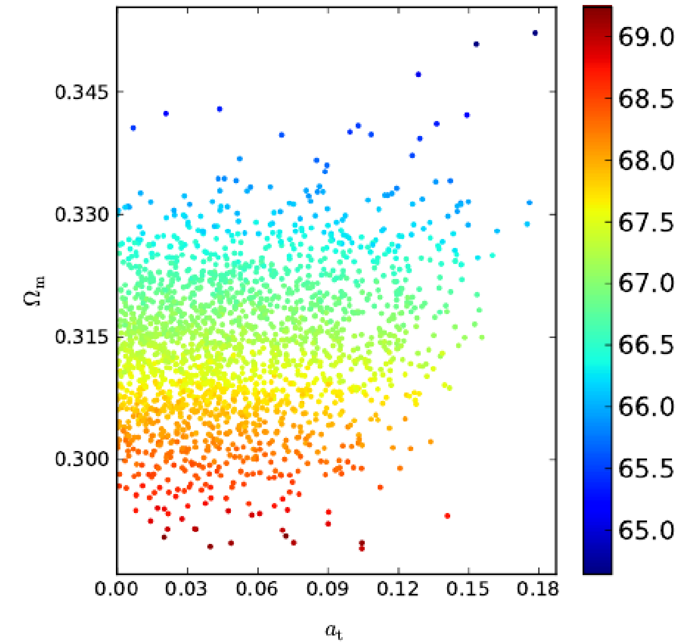

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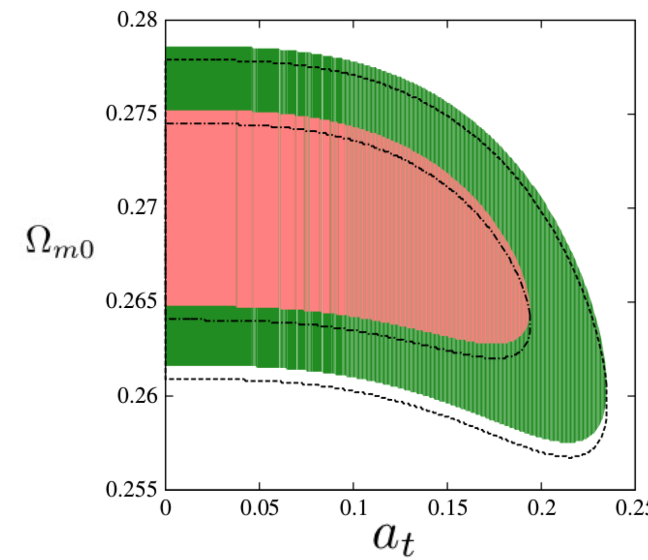
Chiba et al 2013



$a_t < 0.23 \text{ i.e. } z_t > 3.4 \text{ (95\% C.L.)}$

3) Thawing models

- Hilltop potential: $V(\phi) = \Lambda^4[1 + \cos(\phi/f)]$ (e.g. pseudo-Nambu-Goldstone boson or axions)

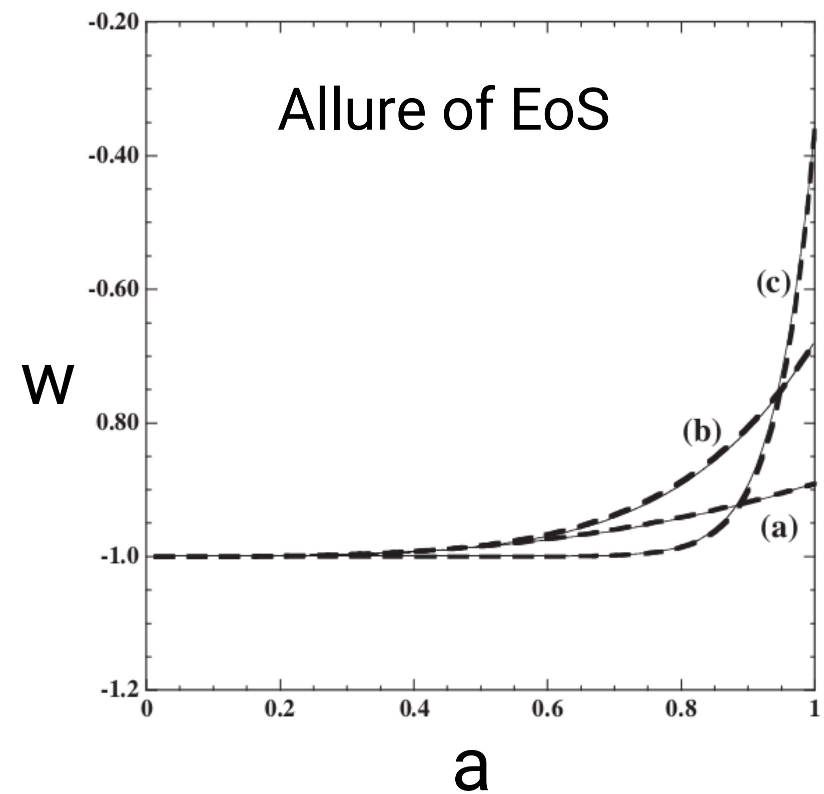
- EoS: (Chiba 2009)

$$w(a) = -1 + (1 + w_0)a^{3(K-1)}\left[\frac{(K - F(a))(F(a) + 1)^K + (K + F(a))(F(a) - 1)^K}{(K - \Omega_{\phi 0}^{-1/2})(\Omega_{\phi 0}^{-1/2} + 1)^K + (K + \Omega_{\phi 0}^{-1/2})(\Omega_{\phi 0}^{-1/2} - 1)^K}\right]^2$$

where $F(a) = \sqrt{1 + (\Omega_{\phi 0}^{-1} - 1)a^{-3}}$

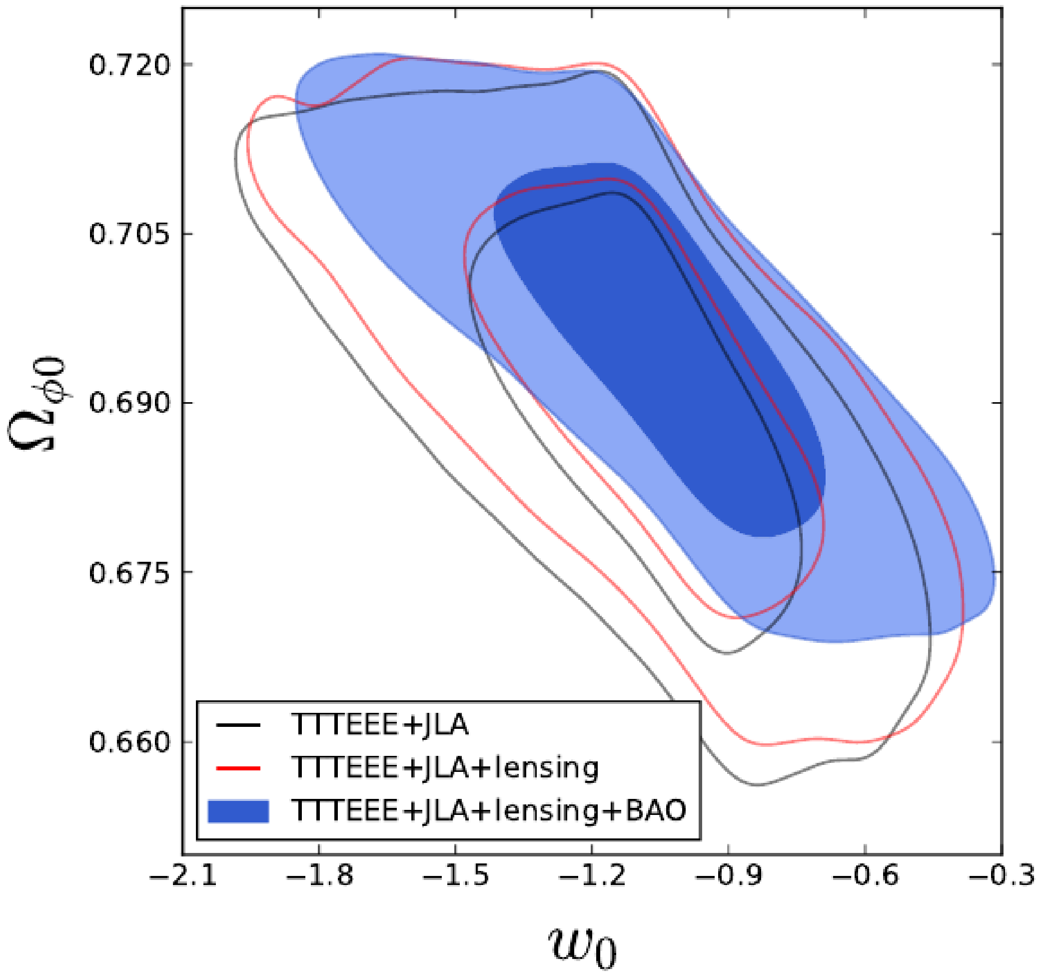
and $K = \sqrt{1 - \frac{4M_{pl}^2 V_{,\phi\phi}(\phi_i)}{3V(\phi_i)}}$

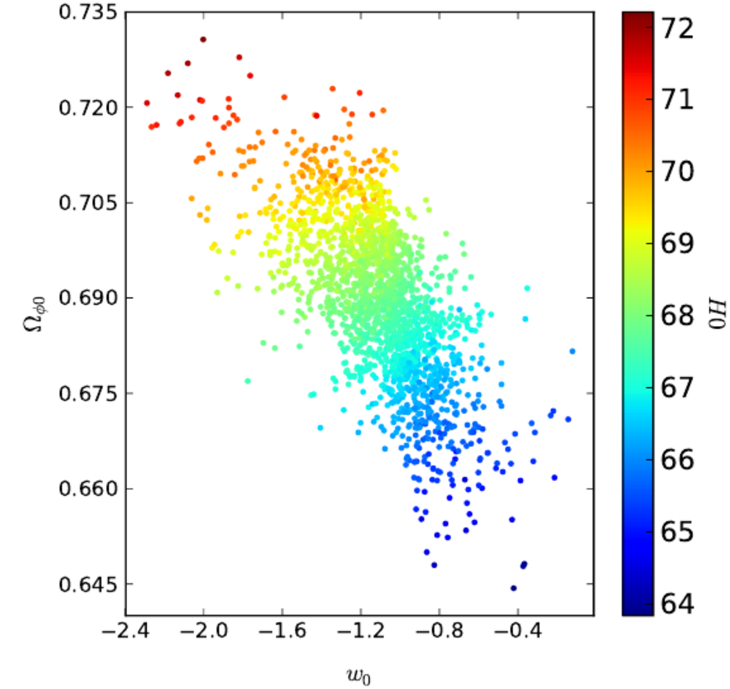
→ Three parameters: w_0, $\Omega_{\phi 0}$ and K



- Constraints with prior $0.1 < K < 10$ for approximate w(a) to be reliable

3) Thawing models





- Constraints: (95% C.L.)

No prior:

$$0.674 < \Omega_{\phi 0} < 0.719$$

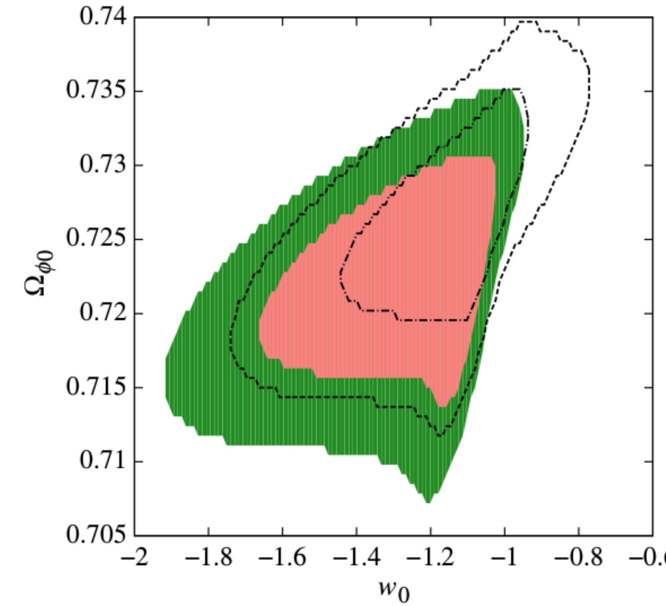
$$-1.69 < w_0 < -0.46$$

With prior:

$$0.670 < \Omega_{\phi 0} < 0.704$$

$$-1 < w_0 < -0.471$$

Chiba et al 2013



$$0.703 < \Omega_{\phi 0} < 0.735 \text{ (95\% C.L.)}$$

$$-2.18 < w_0 < -0.89 \text{ (95\% C.L.)}$$

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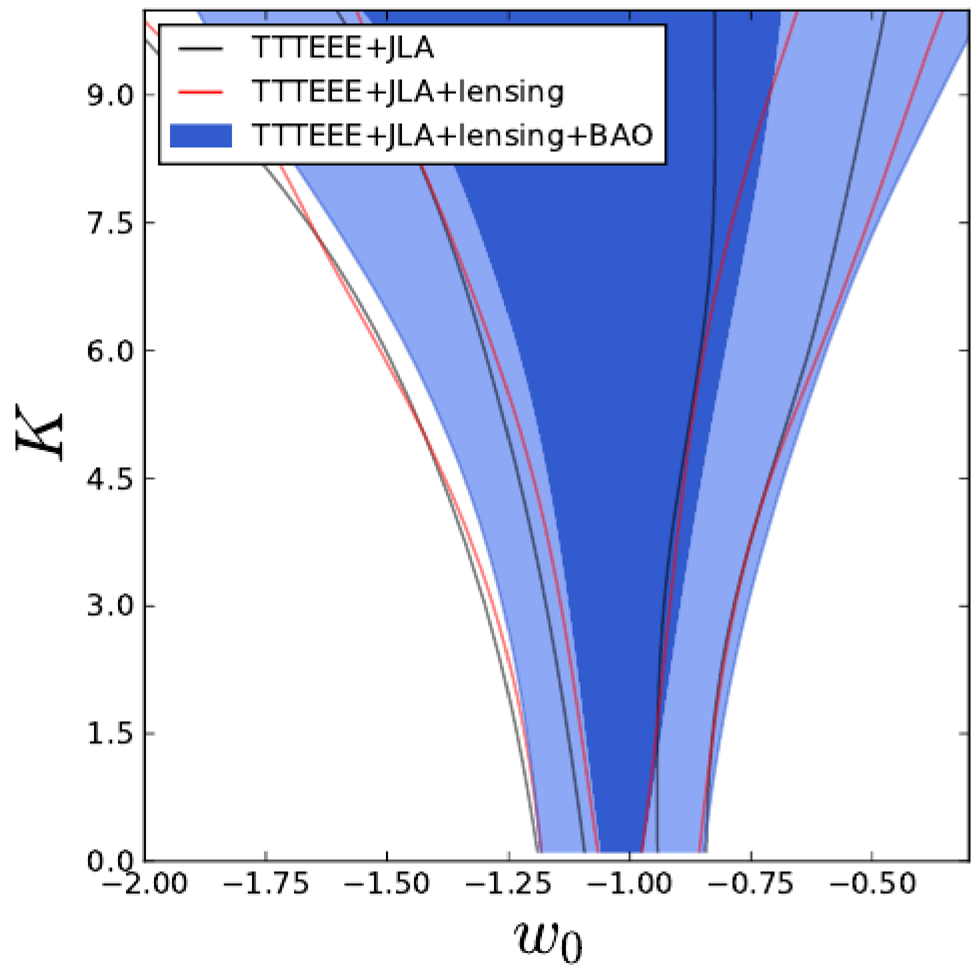

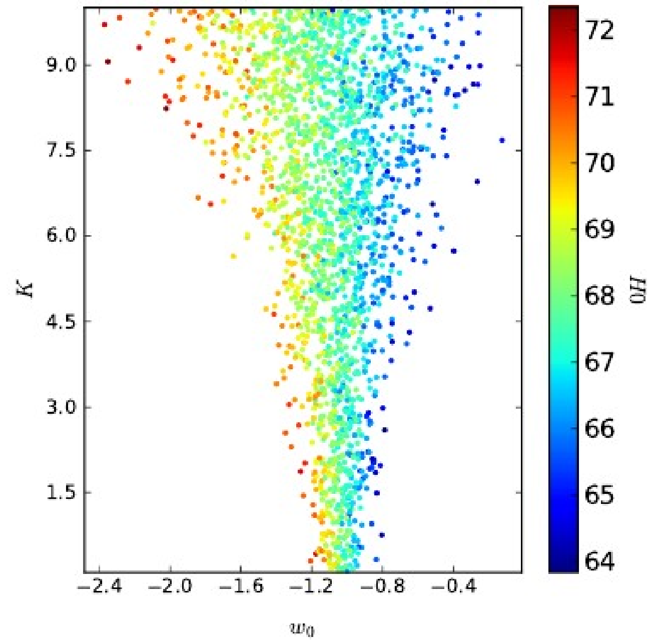

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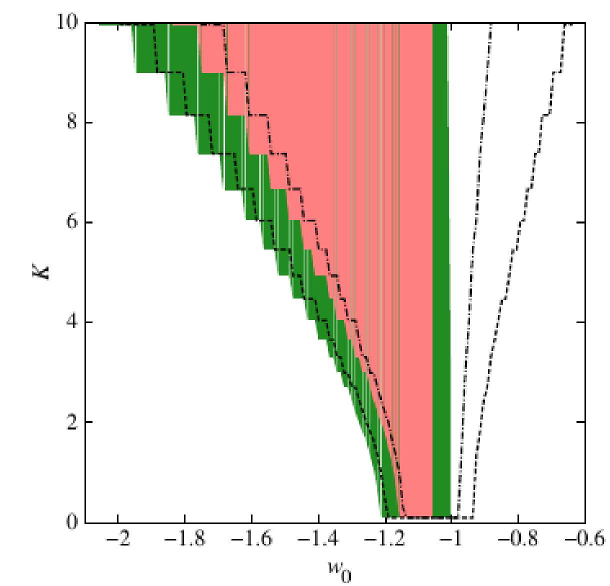

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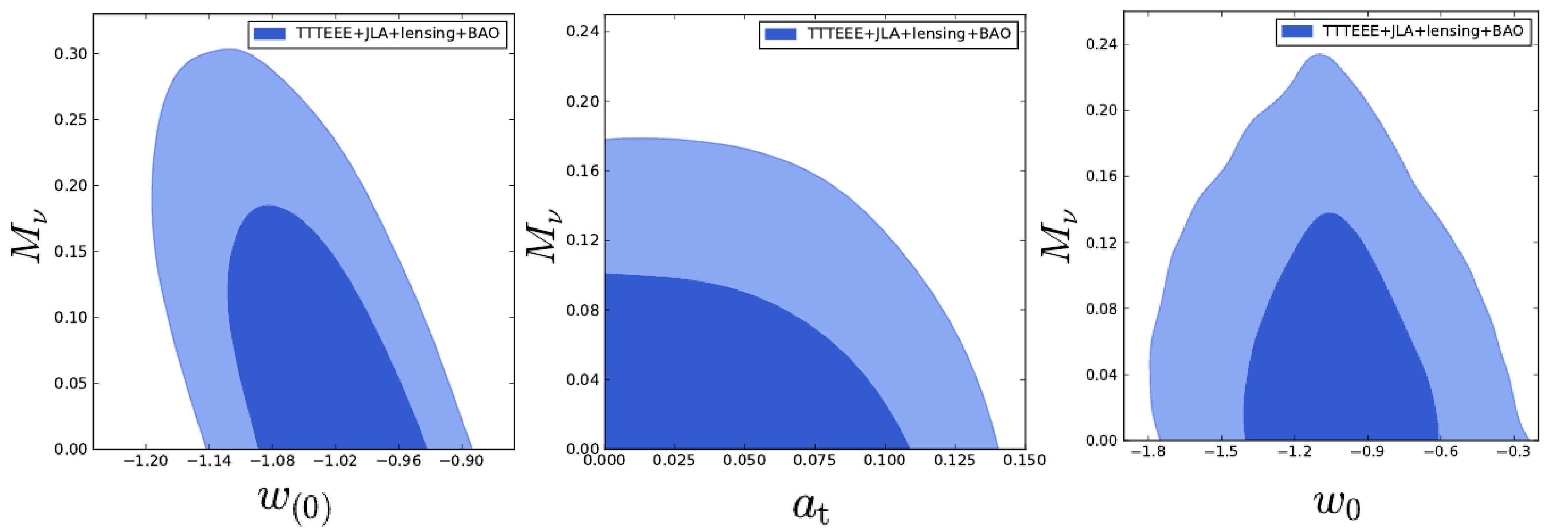
In the above we assumed massless neutrinos.

Considering massive neutrinos (total mass M_ν) we get:

Tracking Freezing | Scaling Freezing | Thawing



- Constraints: (95% C.L.)

Tracking Freezing:
$M_\nu < 0.25$ eV (no prior)
$M_\nu < 0.15$ eV (with prior)

Scaling Freezing:
$M_\nu < 0.16$ eV

Thawing:
$M_\nu < 0.17$ eV (no prior)
$M_\nu < 0.15$ eV (with prior)

Thank you for your attention