Dark Energy: Theories and Measurements

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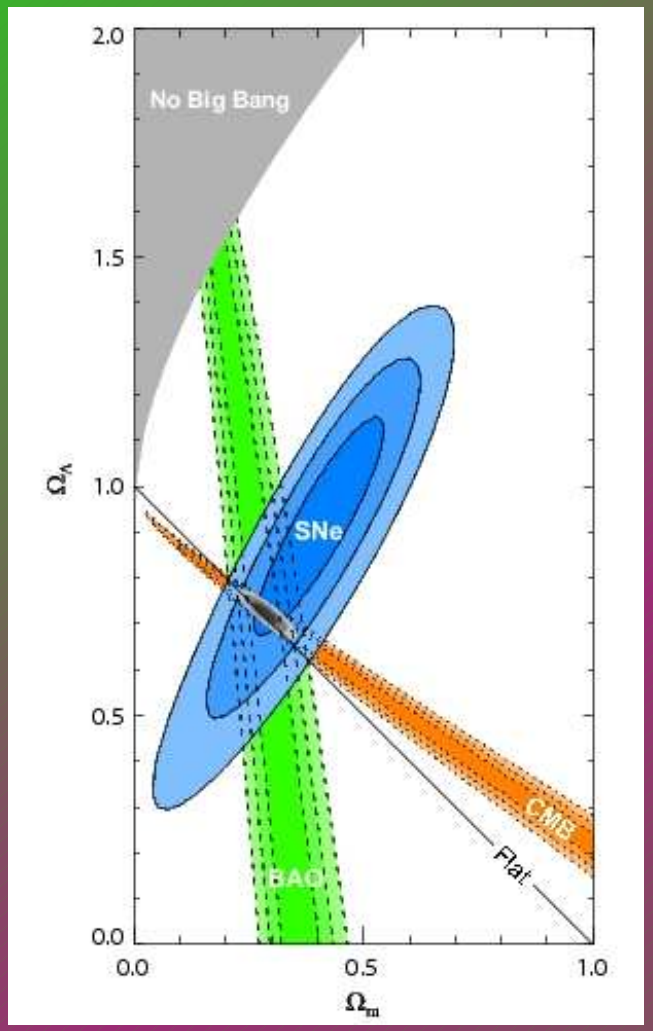
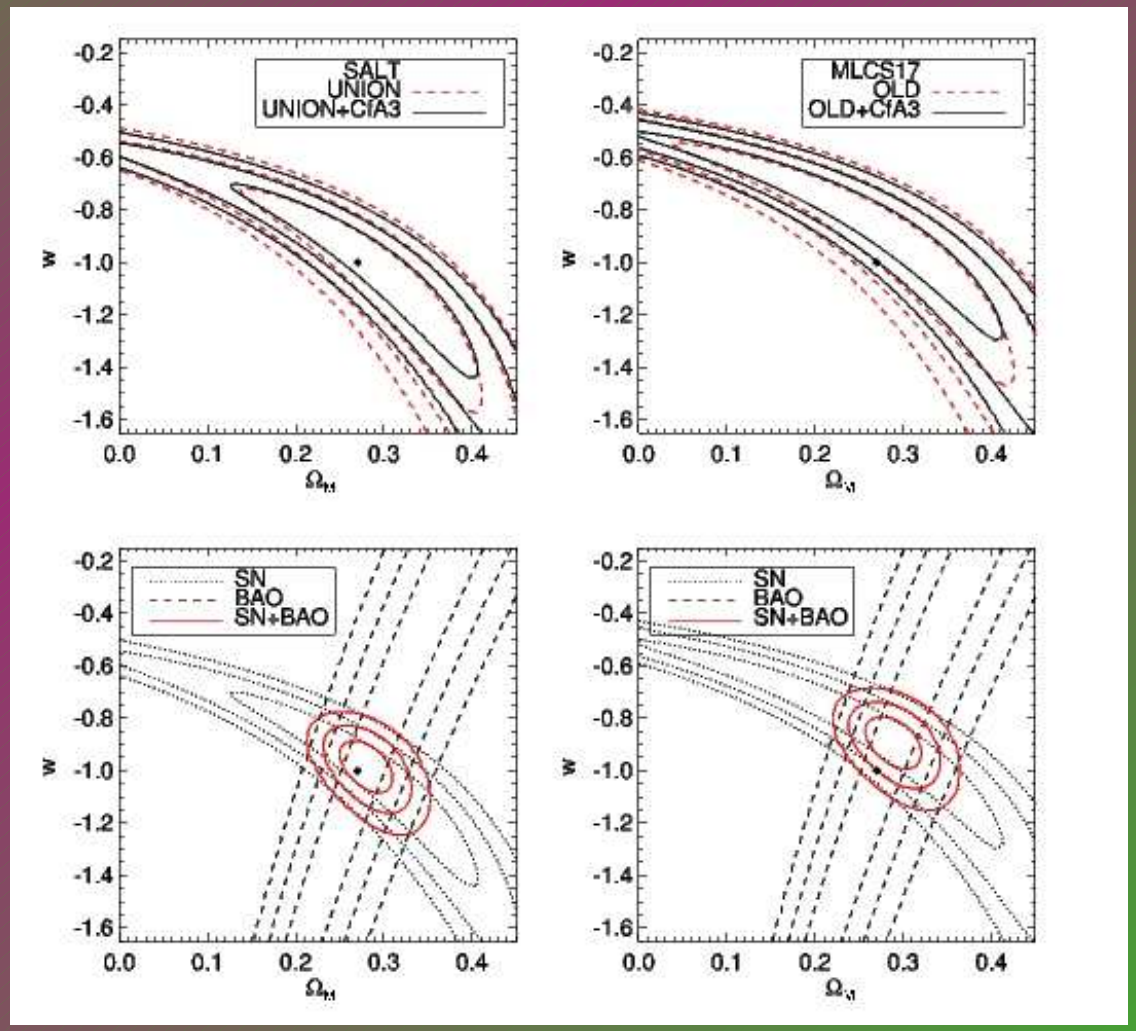
Introduction to Dark Energy

Evidence for dark energy is overwhelming



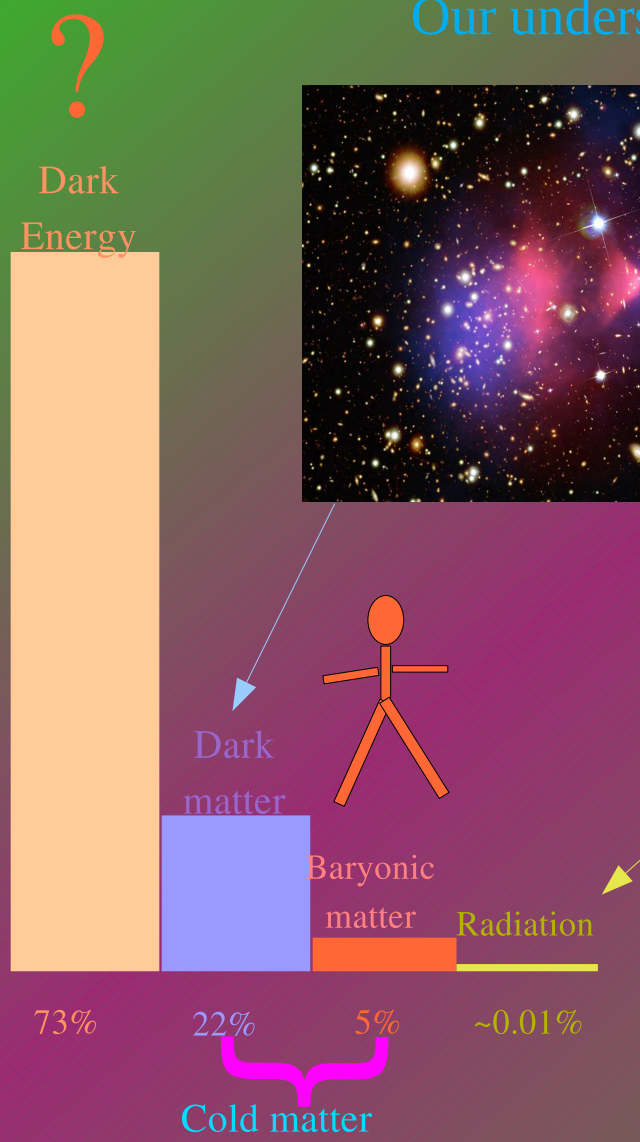


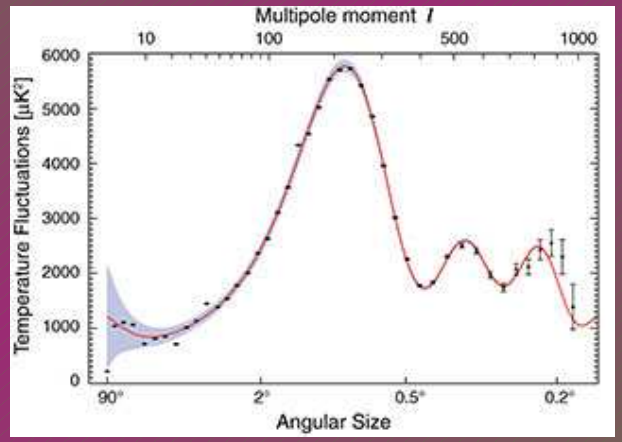
Kowlski et al. 08 (Union, Supernova Cosmology Proj.)

Hicken et al. 09 (Union + CfA)

Introduction to Dark Energy

Our understanding of the Universe





We are in the embarrassing standpoint in which we only know the nature of about 5% of the Universe

Dark Energy Models

We are not in the shortage of models !

* Quintessence
* Scaling models
* Tachyon field
* Dilaton dark energy
* Conformal symmetry breaking
* Varying coupling constants
* Brane models/DGP
* Modified gravity
* K-essence
* Coupled dark energy
* Phantom (ghost) field
* Chaplygin gas
* Effective dark energy from back-reaction of perturbations
* Neutrino mixing and varying mass
* Higher order curvature correction
* Violation of Copernican Principle

Classifying Dark Energy Models

- ⋆ Vacuum energy models: String landscape.
- ⋆ Modified gravity models:
  - Quantum gravity related models: String and brane inspired models e.g. DGP.
  - Modification of Einstein general relativity.
- ⋆ Quintessence models - models based on one or multiple scalar fields:
  - Scalar from gravity sector.
  - Scalar from matter sector.
- ⋆ False dark energy: Apparent observational signature of dark energy is considered to be due to the wrong theoretical assumptions:
  - Effect of super-horizon perturbations is seen as dark energy.
  - We live in a special place in the Universe where local average density is less than global average density of matter.

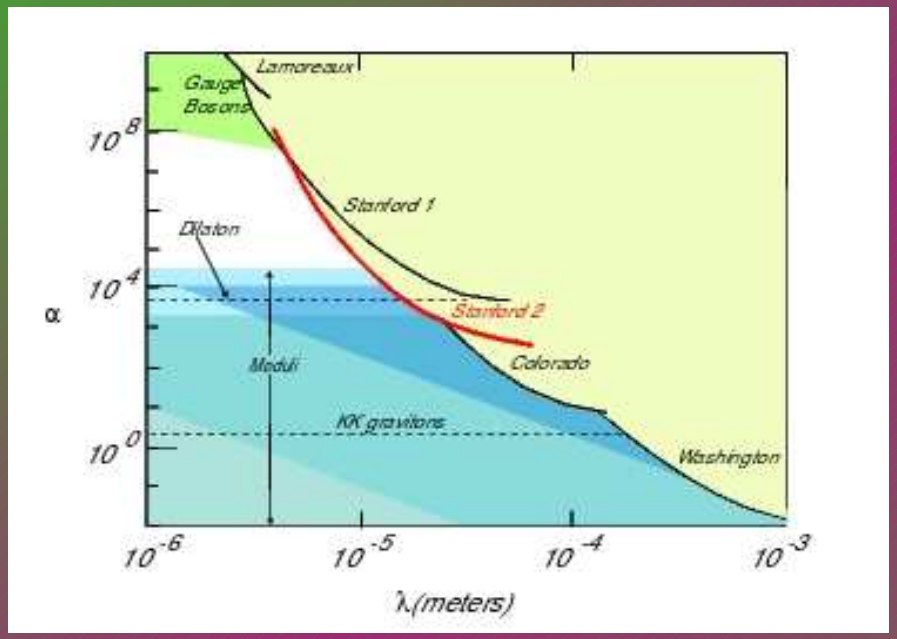
Model Making - Landscape

Depending on to which sector dark energy belongs - gravity or matter - various issues should be considered when we make a model:

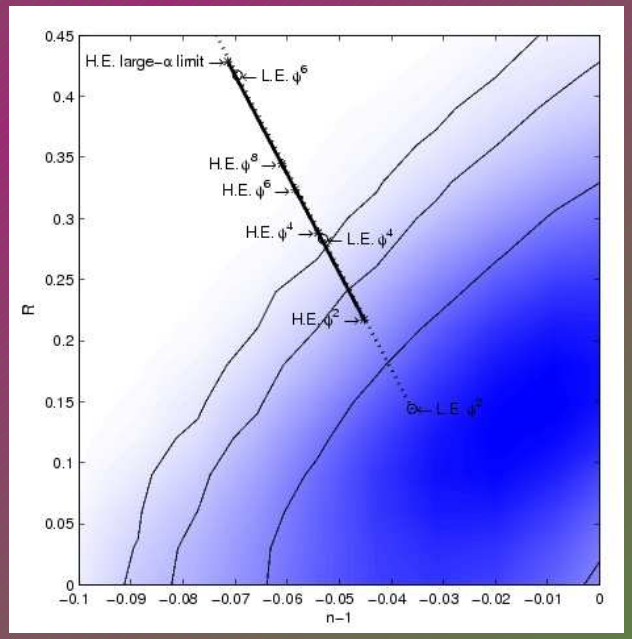
- Naturalness: Dark energy can not be incorporated easily in any of models we know.
- If we are obliged to somehow extend present models or fine-tune them, we must assess how *natural* they are.
- Ex.: In string landscape many rules for selection of vacua are suggested: anthropic Garriga, Linde, Vilenkin 03, holographic Bousso & Yang 07, tunneling Tye 06, etc.
- How can we test which one is true or at least *more natural* ?
- As gravity is a general force, physics of black hole can locally - on the landscape - constrains some parameters, but not globally and not strongly Dvali & Lüst 08.
- A global understanding of string landscape needs a nonperturbative formulation of high energy physics which does not yet exist.

Landscape - Branes

- The string models must be consistent and explain the observed low energy physics: Standard Model and Einstein gravity. Binetruy et al. 05



Constraint on Yukawa-type deviation from Einstein gravity at short distances. Smullin et al. 05



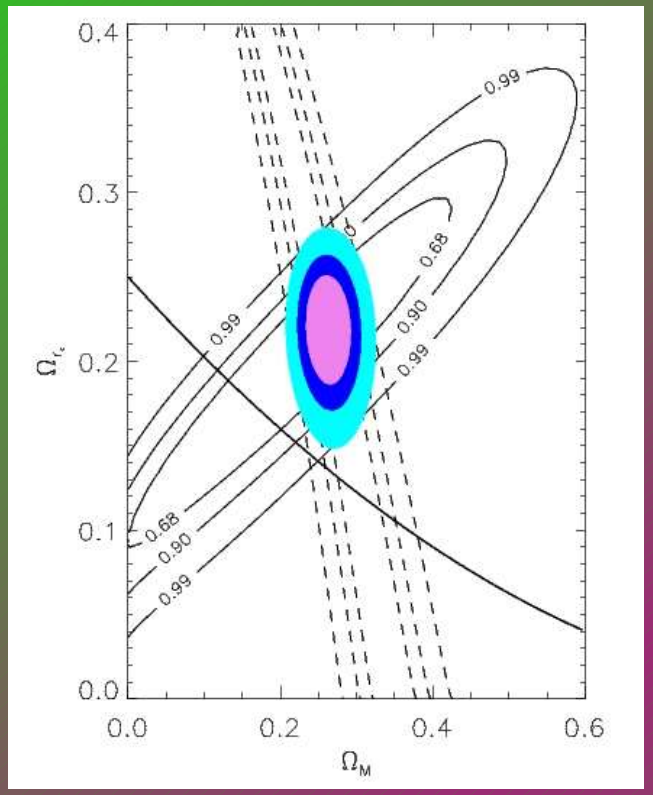
Constraint on RS-type II models. Liddle & Smith 03

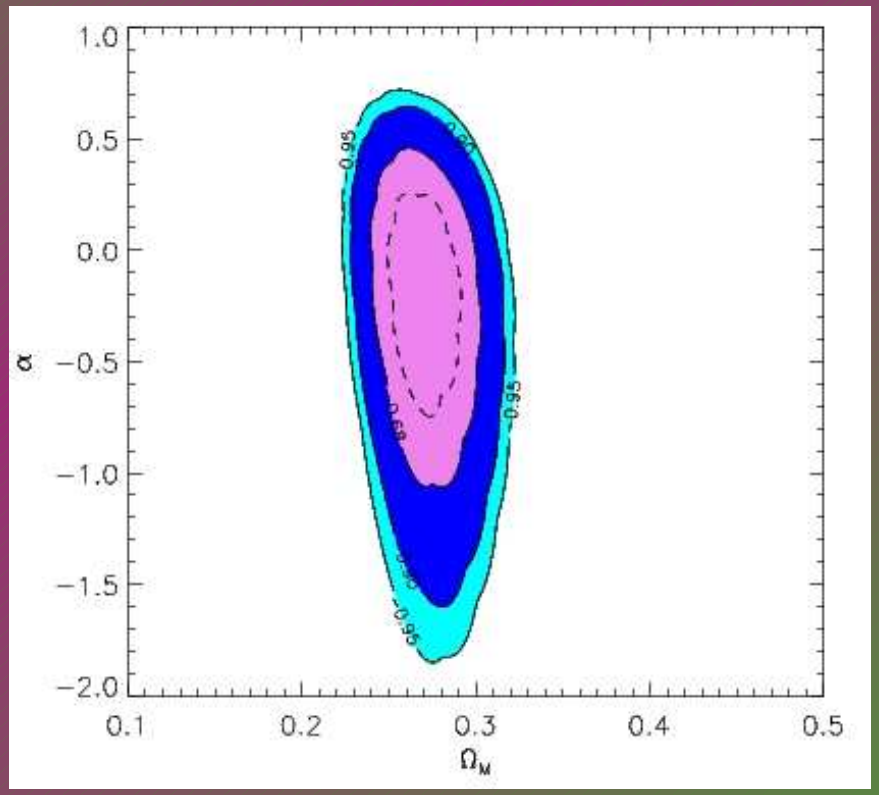
- For universal brane models, constraint from interaction of ultra high energy cosmic rays. HZ 04

Modified Gravity - DGP

- ⋆ One of the best candidate models of modified gravity is DGP model.
  Dvali, Gabadadze & Porrati 00
- ⋆ It is assumed that 5-dim gravity in the bulk induces a 4-dim mass-less graviton on the visible brane.
- ⋆ The induced gravity has a very weak Yukawa-type interaction with gravity that modifies gravity potential.
- ⋆ The characteristic distance scale of the modified potential is $r_c \equiv M_P^2/2M^3$; M is the 5-dim gravity mass scale.
- ⋆ To explain the acceleration of the Universe $r_c \approx 5$ Gpc.
- ⋆ DGP model has interesting and observable cosmological consequences for inflation and dark energy Sahni 05.
- ⋆ It induces an additional precession to planets orbits that can be measured Battat, Stubbs & Chandler 08 $\Longrightarrow r_c > 0.13$ Gpc.

Constraints on DGP Model





Constraint on DGP-like models from SN data. Fairbairn & Goobar 05

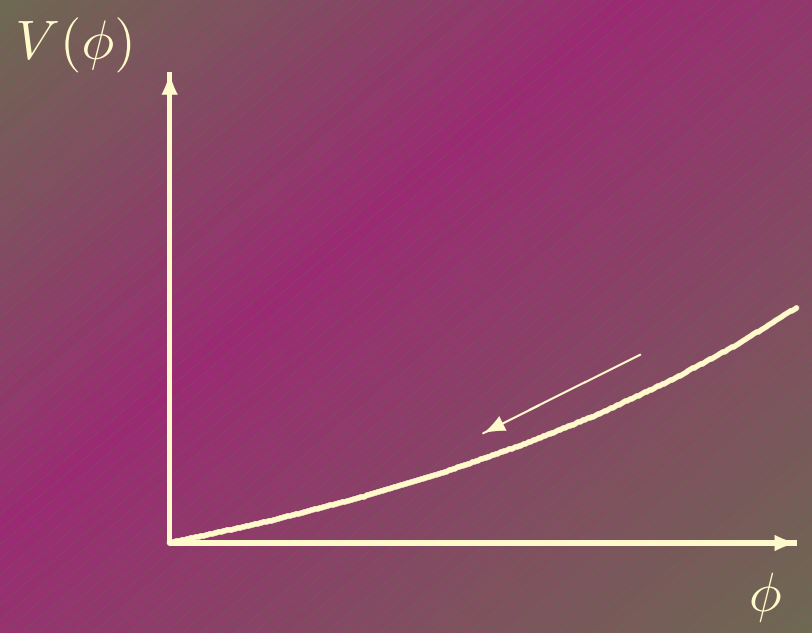
$$\left(H^2 + \frac{k}{a^2}\right)^{\alpha/2} = \frac{\kappa_*^2}{2\mu^2}\left(H^2 + \frac{k}{a^2}\right) - \frac{\kappa_*^2}{6}\rho_m \quad \text{for DGP} \quad \alpha = 2$$

Modified Gravity - Modified General Relativity

- ⋆ $f(R)$-models: Nojiri & Odintsov 06 (review)
  $\mathcal{S} = \int d^4x\sqrt{-g}\,[\frac{1}{16\pi G}R + f(R) + \mathcal{L}_m]$
- ⋆ Gauss-Bonnet gravity: Cognola et al. 06
  $\mathcal{S} = \int d^4x\sqrt{-g}\,[\frac{1}{16\pi G}R + f(G) + \mathcal{L}_m]$
  $G = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$
- ⋆ Additional curvature-dependent terms behave similar to a scalar field $\Longrightarrow$ scalar-tensor models.
- ⋆ Scalar-tensor gravity models:
  $\mathcal{S} = \int d^4x\sqrt{-g}\,[\frac{1}{16\pi G}(R + g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi) - V(\phi) + \mathcal{L}_m(\Psi, A^2(\phi)g_{\mu\nu}))]$
- ⋆ These models behave very similar to quintessence models. Faulkner et al. 06
- ⋆ Strong constraints from solar system S. Davis 07, galaxy clusters Rapetti et al. 08.

Quintessence

- This is a generic name given to all the models in which dark energy is due to condensation of an scalar field $\Longrightarrow$ Including phantom and varying neutrino mass models
- Similar to inflation it is assumed that the scalar field roles down the potential very slowly.
- The challenge is to find models in which at late times the potential be very small but not zero.



Under certain conditions for the potential *Tracking* solutions with necessary behaviour at late times without (or almost) fine-tuning of the initial conditions exist.

Wetterich 88, Peebles & Rata 88

$V(\phi) = e^{-\alpha\phi}$ or ϕ^{-n} (In SUGRA & string models more sophisticated $V(\phi)$ potentials with tracing solutions are possible.) Brax & Martin 99

$$w = \frac{P}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} > -1$$

Gravity Sector - String Dilaton

In the case of a gravitational origin for dark energy:

- As gravity is a general force, the model should not violate Equivalence Principle or keeps the violation at the level consistent with observations.
- Dilaton is assumed an effective field originated from full loop corrected/nonperturbative high energy physics - presumably string theory. Damour & Polyakov 94
- It should have the same coupling to gravity and visible matter - to preserve Equivalence Principle - but can have a different coupling to for dark matter Bean & Magueijo 00.

Gravity Sector - String Dilaton

- In string frame:

$$\mathcal{S} = \int d^4x\sqrt{-\hat{g}}\,[\hat{B}_g(\Phi)(\hat{R}/2-2\hat{\Lambda})-\hat{B}_\Phi(\Phi)\partial_\mu\Phi\partial^\mu\Phi+\sum_i \hat{B}_i(\Phi)\mathcal{L}^{(i)}]$$

- When transferred to Einstein frame -$g = \hat{B}_g(\Phi)\hat{g}$ - the model has the general form of interacting scalar field:

$$\mathcal{S} = \int d^4x\sqrt{-g}\,[\frac{R}{2} + \mathcal{L}^{visible} + \mathcal{L}^{\phi} + f(\phi)\mathcal{L}^{CDM}]$$

Matter Sector - Axion

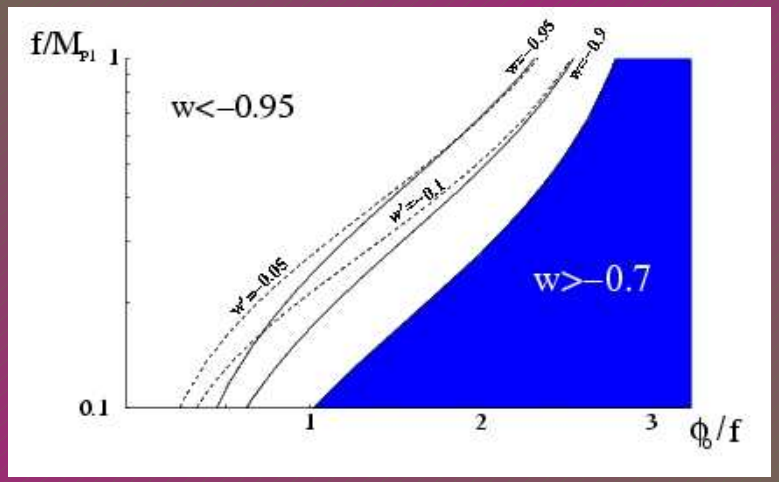
The advantage of matter sector is that a nongravitational interaction with dark matter can solve the coincidence problem.

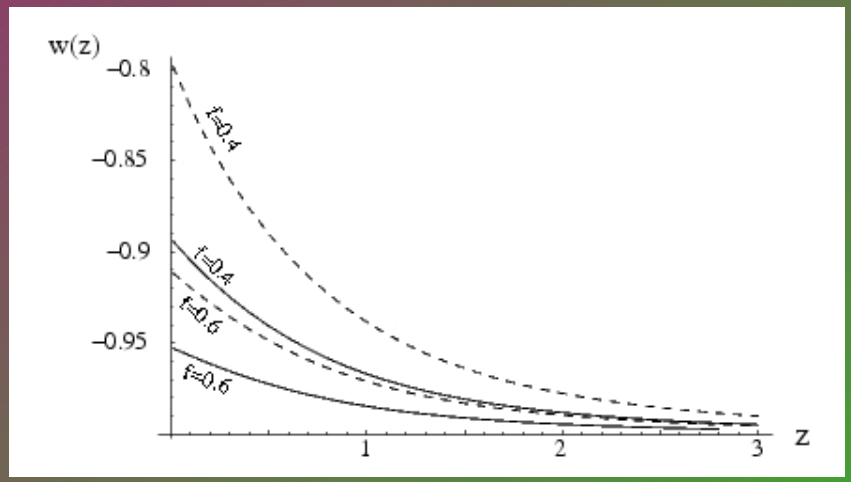
- ⋆ Due to their small mass and weak interaction, axions are one of the most favorite candidates for a quintessence field.
- ⋆ For both quintessence axion and dilaton, the mass of the scalar field must be very small $m_\phi \sim 10^{-33}$ eV.
- ⋆ Protecting such a small mass against high energy radiative corrections is very difficult.
- ⋆ The best candidate is Pseudo-Nimbau-Goldston Boson (PNGB) with a cyclic potential generated by a $SU(2)$ gauge symmetry instantons. Choi 99, Namura, Watari & Yanagida 00, Hill & Leibovich 02, Kim & Nilles 02, 09

$$V(\phi) = \mu^4(1 - \cos(\frac{\phi}{f_a}) \qquad f_a \gtrsim M_P$$

Matter Sector - Axion

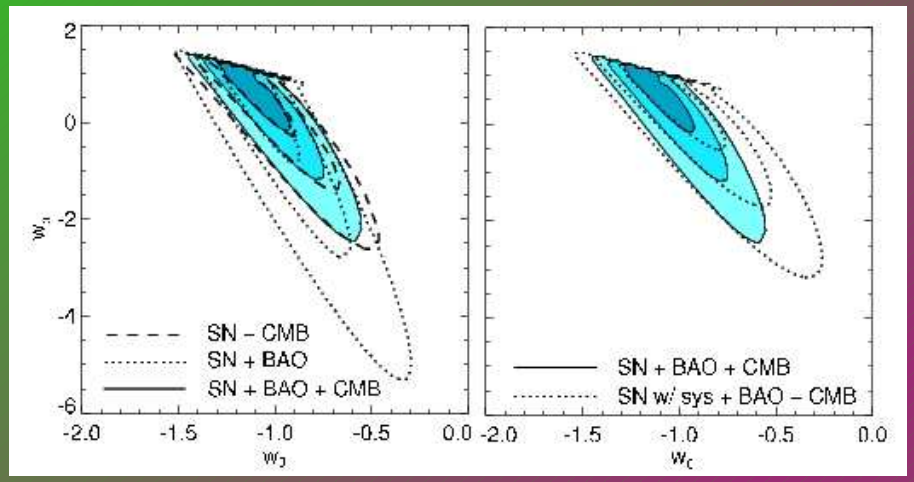
- ⋆ Dark matter can be also related to PNGB axions, either as a QCD axion Miniani, Colombo & Bonometto 05, 07, or a heavy bosonic super-partner of PNGB axion. Takahashi & Yanagida 05
- ⋆ Interaction of quintessence axion with leptons can strongly constraint neutrino physics. Barberi et al. 05
- ⋆ To release the extreme condition of $f_a \gtrsim M_P$ multiple axions should be considered. Kaloper & Sorbo 05

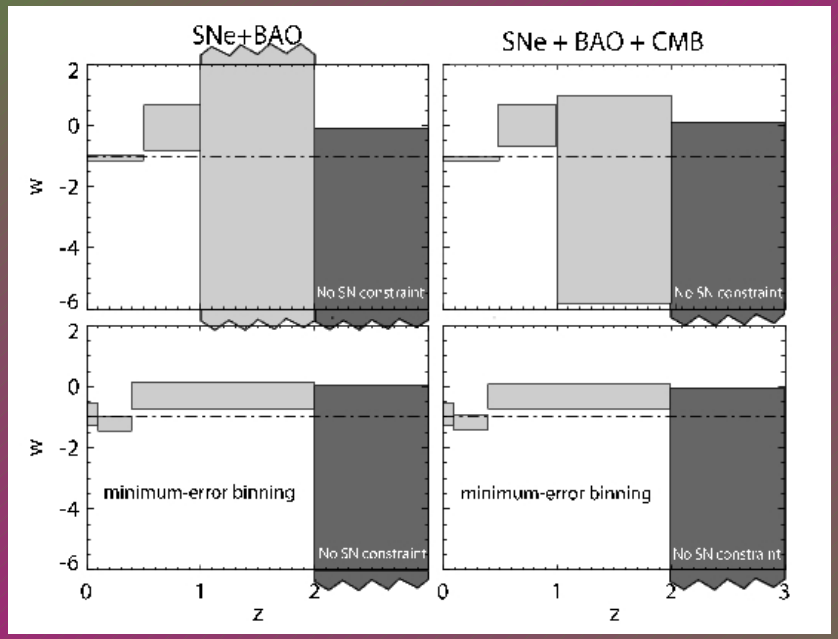




ϕ_0 is the present value of quintessence field. Hall, Nomura & Oliver 05

Observations





Large variation of w with redshift is ruled out and $w < -1$ is yet possible.

Supernova Cosmology Project - Union compilation, Kowalski et al. 08.

Matter Sector - Interacting / Decaying dark energy

Interacting dark energy models are interesting specially because they can solve coincidence problem: Why does dark energy become dominant after galaxy formation ?

- ⋆ Interaction between quintessence and other fields exists in all particle-physics motivated models.
- ⋆ In interacting models the interaction with other fields dominates over self-interaction.
- ⋆ Under certain conditions they can induce an effective $w_{eff} < -1$.

Equivalent cosmologies

- Phenomenological field equation for an interacting quintessence field:
  HZ 00 & 03, Das et al. 05

$$\dot{\rho}_{dm} + 3H\rho_{dm} = -\mathcal{F}(\phi)\rho_{dm} \qquad \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \frac{\mathcal{F}_{,\phi}}{\mathcal{F}(\phi_0)}\rho_{dm}$$

$$H^2 = \frac{8\pi G}{3}(\rho_{0dm}(1+z)^3\frac{\mathcal{F}(\phi)}{\mathcal{F}(\phi_0)} + \rho_q)$$

- Equivalent quintessence cosmology without interaction: Das et al. 05

$$\begin{aligned} H^2(z) &= \frac{8\pi G}{3H_0^2}((1-\Omega_{eff})(z+1)^3 + \Omega_{eff}(z+1)^{3(w_{eff}+1)}) \\ w_{eff}(z) &= \frac{w_q}{1+\frac{\rho_{dm}(z)}{\rho_q(z)}(\mathcal{F}(\phi)-\mathcal{F}(\phi_0))} \end{aligned}$$

- If $w_q \sim -1$ and $\mathcal{F}(\phi) < \mathcal{F}(\phi_0)$, $w_{eff}(z \neq 0) < -1$.

An Explicit Case: Decay of Dark Matter

- Assuming that dark energy is a Cosmological Constant and dark matter decays to relativistic particles: HZ 00

$$\frac{\rho(z)}{\rho_c} \approx \Omega_M(1+z)^3 \exp(\frac{\tau_0 - t}{\tau}) + \Omega_{Hot}(1+z)^4 + \Omega_M(1+z)^4\left(1 - \exp(\frac{\tau_0 - t}{\tau})\right) + \Omega_\Lambda$$

If $3H_0\sqrt{\Omega_\Lambda}\tau \gg 1$, τ age of the Universe:

$$\frac{\rho(z)}{\rho_c} \approx \Omega_M(1+z)^3 + \Omega_{Hot}(1+z)^4 + \Omega_q(1+z)^{3\gamma_q}$$

$$\Omega_q(1+z)^{3\gamma_q} \equiv \Omega_\Lambda(1 + \frac{\Omega_M}{\alpha\tau\Omega_\Lambda} z(1+z)^3 \ln C)$$

$$w_{eff} \equiv \gamma_{eff} - 1 \approx \frac{\Omega_M(1+4A)(1-\sqrt{2A})}{3\alpha\tau\Omega_\Lambda B} - 1.$$

$A(\Omega_\Lambda)$, $B(\Omega_\Lambda)$, $C(\Omega_\Lambda, z)$. If $\Omega_\Lambda > \frac{1}{3} \Longrightarrow w_{eff} < -1$

stant

A decaying dark matter producing quintessence field: HZ 03, 04

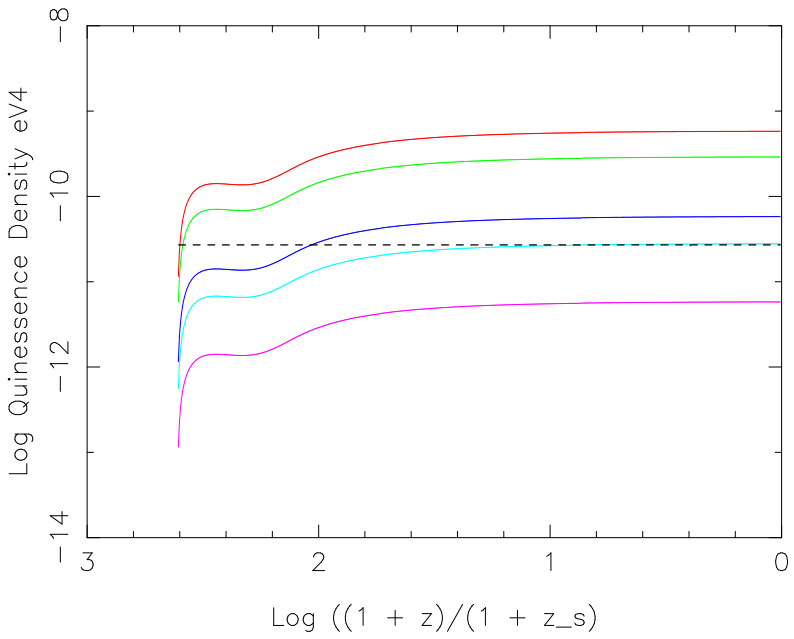
- ⋆ ϕ: quintessence condensate, ϕ_x: scalar dark matter

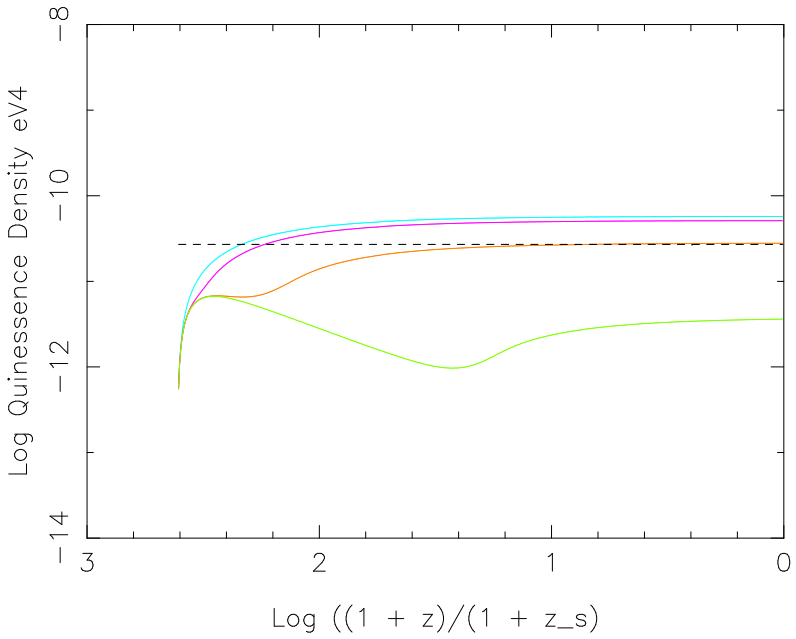
$$\mathcal{L} = \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi_x\partial_\nu\phi_x + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi_x,\phi,J)\right] + \mathcal{L}_J$$

$$V(\phi_x,\phi,J) = V(\phi) + V(\phi_x) + g{\phi_x}^2\phi^2 + W(\phi_x,\phi,J)$$

- ⋆ General behavior of this model is controlled by a feedback between the density of dark matter and the production rate of quintessence condensate. $\Longrightarrow$ No fine-tuning of the quintessence potential or relative initial abundance which is necessary in interacting models.
- ⋆ A tracking solution exists for orders of magnitude variation in parameters.

Decaying Super Heavy Dark Matter and Quintessence





$\Gamma_0 = \Gamma_q/\Gamma = 10^{-16}$, $5\Gamma_0$, $10\Gamma_0$, $50\Gamma_0$, $100\Gamma_0$. $m_q = 10^{-6}eV, \lambda = 10^{-20}$.

$m_q = 10^{-3}eV$, $m_q = 10^{-5}eV$, $m_q = 10^{-6}eV$, $m_q = 10^{-8}eV, \lambda = 10^{-20}$;

⋆ An important issue in this model as well as other interacting quintessence model is the microphysics of condensate evolution. HZ 06

Dark Energy Measurements

- Definition of $H(z)$ used for data analysing:

$$\frac{H^2(z)}{H_0^2} = \frac{\rho(z)}{\rho_0} = \Omega_m(1+z)^3 + \Omega_{hot}(1+z)^4 + \Omega_{de}(1+z)^{3\gamma(z)}$$

- When $\gamma = cte.$, $\gamma = w + 1$, $w \equiv p/\rho$.
- Cosmological constant: $\gamma = 0$.
- Quintessence models: $\gamma > 0$.
- Phantom models: $\gamma < 0$.

In this definition if $\mathbf{w} < -1$, the null energy condition $\rho_{de} + p_{de} > 0$ is violated.

Most Recent Estimation of w

Fit	Ω_M	Ω_k	w
SNe	$0.287^{+0.029+0.039}_{-0.027-0.036}$	0 (fixed)	-1 (fixed)
SNe+BAO	$0.285^{+0.020+0.011}_{-0.020-0.009}$	0 (fixed)	$-1.011^{+0.076+0.083}_{-0.082-0.087}$
SNe+CMB	$0.265^{+0.022+0.018}_{-0.021-0.016}$	0 (fixed)	$-0.955^{+0.060+0.059}_{-0.066-0.060}$
SNe+BAO+CMB	$0.274^{+0.016+0.013}_{-0.016-0.012}$	0 (fixed)	$-0.969^{+0.059+0.063}_{-0.063-0.066}$
SNe+BAO+CMB	$0.285^{+0.020+0.011}_{-0.019-0.011}$	$-0.009^{+0.009+0.002}_{-0.010-0.003}$	-1 (fixed)
SNe+BAO+CMB	$0.285^{+0.020+0.010}_{-0.020-0.010}$	$-0.010^{+0.010+0.006}_{-0.011-0.004}$	$-1.001^{+0.069+0.080}_{-0.073-0.082}$

- ⋆ The sign of $\gamma \equiv w + 1$ and its redshift dependence have a crucial role in discriminating between models.
- ⋆ Although strong variation of w at low redshifts is practically ruled out Riess, et al. 06, small evolution is yet possible.
- ⋆ There is a large degeneracy between cosmological parameters and data analysis depends on the parametrization of w.
- ⋆ Fitting methods probably can never achieve enough precision to discriminate a dark energy from a Cosmological Constant Krauss et al. 07.
- ⋆ We must find a direct method to measure w and its evolution.

Direct Measurement of γ

- Assuming a constant w, we define $A(z)$: HZ 06

$$A(z) \equiv \frac{1}{3(1+z)^2\rho_0}\frac{d\rho}{dz} - \Omega_m = \gamma\Omega_{de}(1+z)^{3(\gamma-1)}$$

Properties of $A(z)$:

- It is proportional to γ.
- From observations:
  $|\gamma| \ll 1 \sim 0 \Longrightarrow \{|A(z)|\}_{max} = A(z=0)$
- Less low redshift SN - smaller volume - but more precise measurements.
- The sign of $dA(z)/dz$ is opposite to the sign of $\gamma \Longrightarrow A(z)$ is concave or convex function of redshift, respectively for positive or negative γ.
- Small uncertainties on the measurement of Ω_m shift $A(z)$ but does not change its geometry.

Direct Measurement of γ

- If the equation of state of the dark energy depends on redshift: HZ 07

$$\gamma(z) = \frac{1}{\ln(1+z)} \int_0^z dz' \frac{1+w(z')}{1+z'}$$

$$w(z) = \frac{p_{de}(z)}{\rho_{de}(z)}$$ (Valid if no interaction with other fields)

- Observations show that at low redshifts $w(z)$ is constant or varies slowly. Riess et al. 06, Serra et al. 07

$$w(z) = w_0 + w_1 z \quad , \quad A(z) \approx \Omega_{de} \left(\gamma(z) + w_1 (\frac{z^2}{2} + \ldots) \right) (1+z)^{3(\gamma-1)}$$

- If w_1 is small, the effect of redshift dependence on the sign of $A(z)$ would be small.

Application to Observations

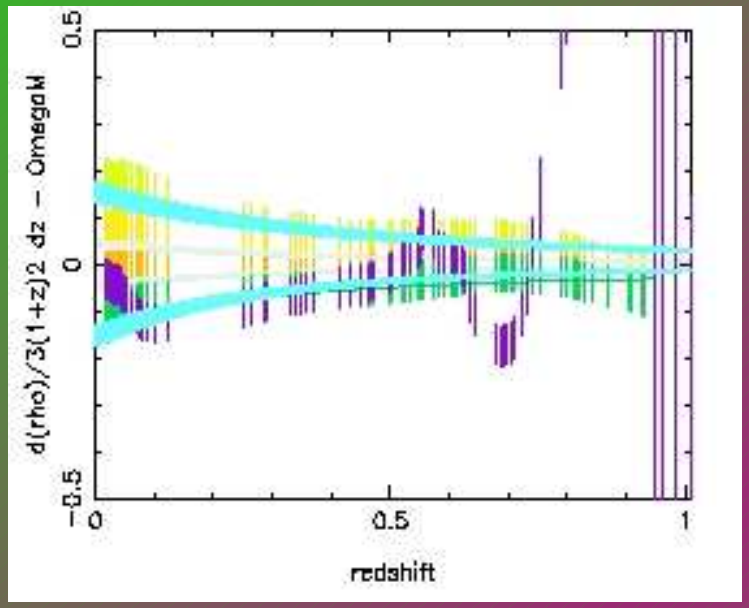
- $A(z) + \Omega_m$ can be determined from Luminosity distance, itself measurable from the peak luminosity of SN Type Ia (or from LSS):

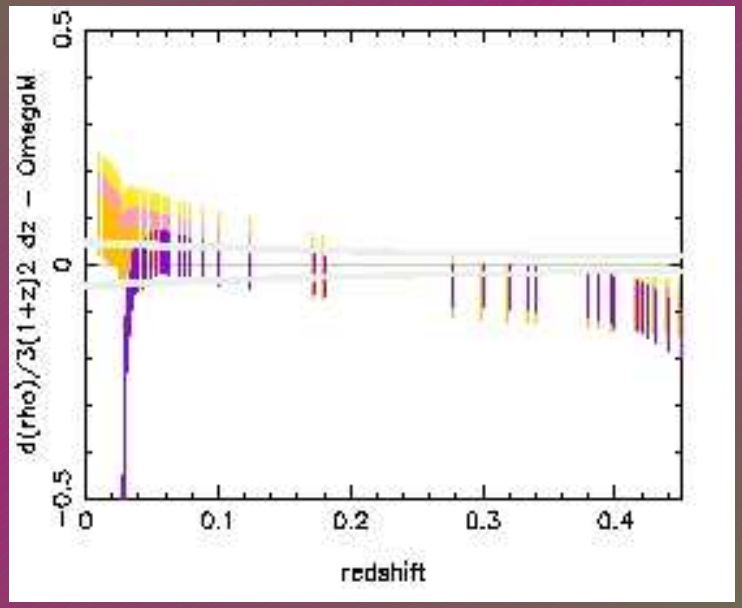
$$A(z) + \Omega_m \equiv \frac{1}{3(1+z)^2 \rho_0} \frac{d\rho}{dz} = \frac{\frac{2}{1+z}\left(\frac{dD_l}{dz} - \frac{D_l}{1+z}\right) - \frac{d^2 D_l}{dz^2}}{\frac{3}{2}\left(\frac{dD_l}{dz} - \frac{D_l}{1+z}\right)^3}$$

$$D_l = (1+z) H_0 \int_0^z \frac{dz}{H(z)}$$

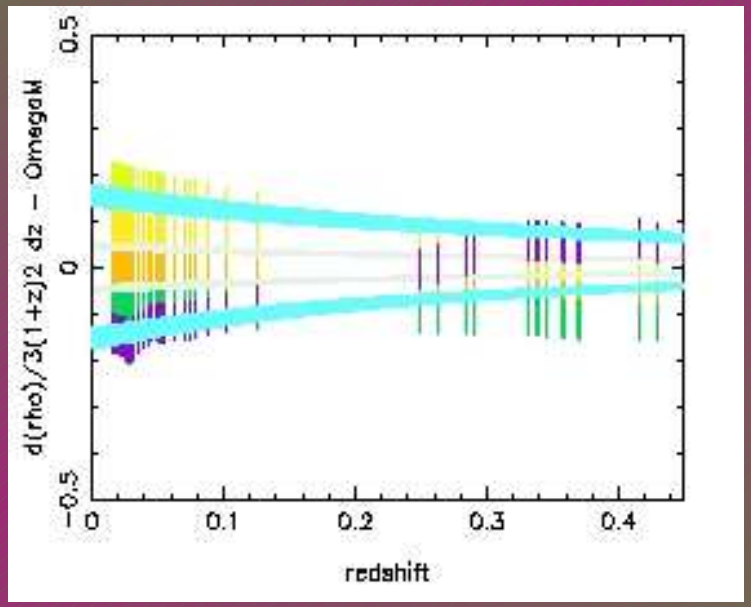
- Uncertainties in H_0 scale $A(z) + \Omega_m$, but don't change its geometry.
- No switching from concave to convex or vis-versa.
- This method is less sensitive to other uncertainties of cosmological parameters than fitting methods.
- This method can be used for SN and LSS data. It may be possible to find similar relations for CMB. HZ, in preparation

Application to Observations





Riess et al. compilation ($z < 0$ only)



HZ 07 Top: SNLS data 05; Bottom: SNLS data ($z < 0.45$ only)

Classification of Models and their Observables

- As the particle physics of dark energy is unknown, we can phenomenologically classify models as:
  - Dark energy is a cosmological constant and dark matter decays or has self-interaction.
  - Dark energy is a scalar field produced by the decay of dark matter.
  - Dark energy is a scalar and has interaction with dark matter of a sector of visible matter e.g. neutrinos.

Classification of dark energy models and their discriminating observables.

Distinguishing between Models

Direct observation of effects related to dark energy:

- ⋆ Anisotropy of dark energy.
  In the case of a decaying dark matter to a quintessence:

$$\partial^i(\delta\phi) \approx -\frac{\Gamma_q \bar{\rho}_x \delta {u_x}^i}{V'(\bar{\phi}, \bar{\rho}_x)}$$

- ⋆ For a metastable dark matter this quantity is very strongly suppressed except in the very early Universe. (HZ 03
- ⋆ It can change the transfer function or spectrum index. (Mainini & Bonometto 07)
- ⋆ If other fields/particles are involved in decay/interaction, they produce a hot dark matter and cosmic rays.
- ⋆ If quintessence field does not condensate at late times, it contributes to HDM.

Outline

- ⋆ We have a long way to go to understand the nature of dark energy.
- ⋆ Present data seems to prefer $w \lesssim -1$, but uncertainties are yet too large to make a definitive conclusion.
- ⋆ What will (or will not) be found by LHC - Higgs, supersymmetry, any other extension to the Standard Model - is crucial as a hint to the nature of dark energy.
- ⋆ Constraints on the HDM and its evolution can be important for understanding dark energy.
- ⋆ No single observation can select a unique model. We need to investigate both cosmological and particle physics aspects of dark energy.