Lecture 3

The inflation-building toolkit

Types of inflationary research

- **Fundamental physics modelling of inflation.**

  Building inflation models within the context of M-theory/braneworld/ supergravity/etc etc. Eg KKLT, D3/D7, etc.

- **Inflationary phenomenology.**

  Qualitative construction of inflationary scenarios to explore the range of phenomenology. Eg chaotic inflation, multi-field models, multiverse, reheating.

- **Deriving observational predictions.**

  For given scenarios, computing observables such as *n* and *r*, and nowadays commonly f_{NL} as well.

- **Constraining inflation with observational data.**

  Usually CMB data combined with others, either using slow-roll approximations or exact numerical calculations.

Fundamental physics models of inflation

Fundamental physics models of inflation

- *1980s: field theory models (e.g. chaotic inflation)*

Fundamental physics models of inflation

- *1980s: field theory models (e.g. chaotic inflation)*

  Typically models based on a single scalar field rolling on a flat potential. Inflation ends by failure of slow-roll.
  Phenomenology: n and r.

Fundamental physics models of inflation

- *1980s: field theory models (e.g. chaotic inflation)*

  Typically models based on a single scalar field rolling on a flat potential. Inflation ends by failure of slow-roll.
  Phenomenology: n and r.

- *1990s: supersymmetry models (e.g. hybrid inflation)*

Fundamental physics models of inflation

- *1980s: field theory models (e.g. chaotic inflation)*

  Typically models based on a single scalar field rolling on a flat potential. Inflation ends by failure of slow-roll.
  Phenomenology: *n* and *r*.

- *1990s: supersymmetry models (e.g. hybrid inflation)*

  Multiple fields, aiming to enforce $\phi \lesssim M_{Planck}$. Inflation ends by symmetry-breaking transition. Phenomenology: *n, r,* $G\mu$.

Fundamental physics models of inflation

- *1980s: field theory models (e.g. chaotic inflation)*

  Typically models based on a single scalar field rolling on a flat potential. Inflation ends by failure of slow-roll.
  Phenomenology: *n* and *r*.

- *1990s: supersymmetry models (e.g. hybrid inflation)*

  Multiple fields, aiming to enforce $\phi \lesssim M_{Planck}$. Inflation ends by symmetry-breaking transition. Phenomenology: *n, r,* $G\mu$.

- *2000s: braneworld models (e.g. KKLT/KKLMMT models)*

Fundamental physics models of inflation

- *1980s: field theory models (e.g. chaotic inflation)*

  Typically models based on a single scalar field rolling on a flat potential. Inflation ends by failure of slow-roll. Phenomenology: n and r.

- *1990s: supersymmetry models (e.g. hybrid inflation)*

  Multiple fields, aiming to enforce $\phi \lesssim M_{\mathrm{Planck}}$. Inflation ends by symmetry-breaking transition. Phenomenology: n, r, $G\mu$.

- *2000s: braneworld models (e.g. KKLT/KKLMMT models)*

  Branes moving in extra dimensions, falling down `throats', non-standard kinetic terms (DBI etc). Phenomenology: n, r, f_{NL}.

Fundamental physics models of inflation

- *1980s: field theory models (e.g. chaotic inflation)*

  Typically models based on a single scalar field rolling on a flat potential. Inflation ends by failure of slow-roll.
  Phenomenology: n and r.

- *1990s: supersymmetry models (e.g. hybrid inflation)*

  Multiple fields, aiming to enforce $\phi \lesssim M_{\rm Planck}$. Inflation ends by symmetry-breaking transition. Phenomenology: n, r, $G\mu$.

- *2000s: braneworld models (e.g. KKLT/KKLMMT models)*

  Branes moving in extra dimensions, falling down `throats', non-standard kinetic terms (DBI etc). Phenomenology: n, r, $f_{\rm NL}$.

new perturbation generation mechanisms (e.g. curvaton)

Fundamental physics models of inflation

- *1980s: field theory models (e.g. chaotic inflation)*

  Typically models based on a single scalar field rolling on a flat potential. Inflation ends by failure of slow-roll.
  Phenomenology: n and r.

- *1990s: supersymmetry models (e.g. hybrid inflation)*

  Multiple fields, aiming to enforce $\phi \lesssim M_{\mathrm{Planck}}$. Inflation ends by symmetry-breaking transition. Phenomenology: n, r, $G\mu$.

- *2000s: braneworld models (e.g. KKLT/KKLMMT models)*

  Branes moving in extra dimensions, falling down `throats', non-standard kinetic terms (DBI etc). Phenomenology: n, r, f_{NL}.

  new perturbation generation mechanisms (e.g. curvaton)

  Perturbations acquired by non-inflaton fields and processed. Phenomenology: n, isocurvature perturbations, f_{NL}.

A possible disconnect

Theory:

A possible disconnect

Theory:

first-order
PNGB
R^2
assisted
tensors
vector
branes
large-field
monodromy
monomial
3-form
stochastic
extended
fluxes
chaotic
small-field
D-term
running mass
non-gaussian
F-term
hybrid
Horava-Lifshitz
reheating
unified
GUT
old
N-flation
soft
eternal
DBI
new
modular
D3/D7
thermal
throat
hilltop
Slow-roll
curvaton
warm

A possible disconnect

Theory:

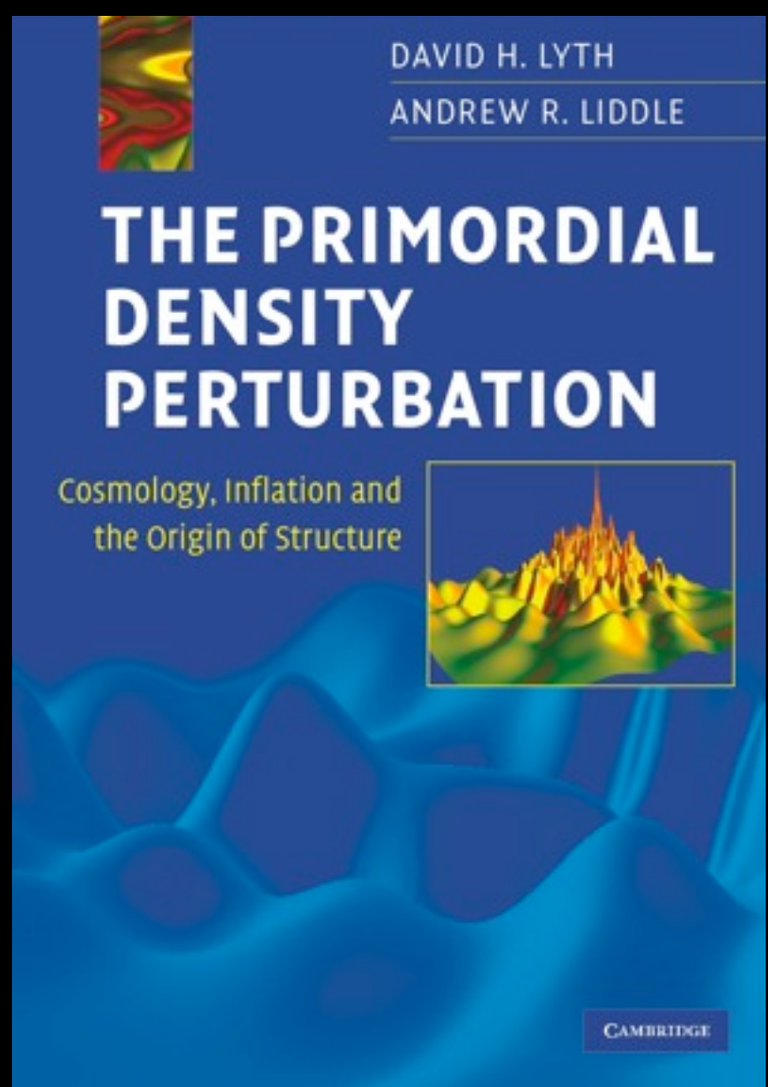
first-order
PNGB
R^2
assisted
tensors
vector
large-field
branes
monodromy
monomial
stochastic
3-form
extended
fluxes
chaotic
small-field
D-term
running mass
non-gaussian
F-term
hybrid
Horava-Lifshitz
reheating
unified
GUT
old
N-flation
soft
eternal
DBI
new
modular
D3/D7
thermal
throat
hilltop
Slow-roll
curvaton
warm

Future observations:

n probably, r maybe, α maybe, f_{NL} maybe, f_{iso} if we are lucky

inflation
potential
model
term
Eq
Vo
Slow-roll
Phys
GUT
gauge
spectral
Section
quadratic
hybrid
Eternal
one
observation
supersymmetry
value
field
contribution
hilltop
might
scale
theory
Pl
MPl
order
inflaton
models
problem
given
Also
gives
need
perturbation
horizon
observable
Universe
standard
Large
much
breaking
fields
called
MSSM
vacuum
Now
though
index
small
symmetry
D-term
Higgs
Lett
corresponds
prediction
may
consider

inflation
potential
model
term
Eq
Vo
Slow-roll
Phys
GUT
gauge
spectral
Section
quadratic
hybrid
Eternal
one
observation
supersymmetry
value
field
hilltop
contribution
scale
might
theory
Pl
MPl
order
inflaton
models
problem
given
Also
need
gives
terms
Universe
standard
Large
much
breaking
fields
case
called
MSSM
vacuum
Now
though
index
small
symmetry
D-term
Higgs
waterfall
corresponds
Lett
Taking
prediction
end
may
consider
perturbation
horizon
observable
coupling
supergravity
initial
origin
running-mass
form
non hybrid
fixed
Figure
mass
Rev
instead
string
supposed
give
CMB
GeV
pivot
Since
normalization
expected
point
Ref
φend
Lyth
D-term
first
expect
higher-order
leaves
Taking
near
Now
prediction
end
MGUT
JCAP
PNGB
m2
chaotic
means


DAVID H. LYTH
ANDREW R. LIDDLE
THE PRIMORDIAL DENSITY PERTURBATION
Cosmology, Inflation and the Origin of Structure
CAMBRIDGE

How to build inflation models

How to build inflation models

- *Start it!*

How to build inflation models

- *Start it!*
- *Keeping it going!*

How to build inflation models

- *Start it!*
- *Keeping it going!*
- *End it!*

How to build inflation models

- *Start it!*
- *Keeping it going!*
- *End it!*
- *Get rid of its cause and make normal stuff!*

How to build inflation models

- *Start it!*
- *Keeping it going!*
- *End it!*
- *Get rid of its cause and make normal stuff!*
- *Make the perturbations!*

Start it

How does inflation start in the first place?
There are various approaches in the literature:

Start it

How does inflation start in the first place?
There are various approaches in the literature:

- Don't ask; hope no one else does. This is the commonest strategy.

Start it

How does inflation start in the first place?
There are various approaches in the literature:

- Don't ask; hope no one else does. This is the commonest strategy.
- Assume that the pre-inflationary Universe samples possible initial conditions widely enough that some regions are suitable to start inflation.

Start it

How does inflation start in the first place?
There are various approaches in the literature:

- Don't ask; hope no one else does. This is the commonest strategy.
- Assume that the pre-inflationary Universe samples possible initial conditions widely enough that some regions are suitable to start inflation.
- Enhance the previous point by invoking eternal inflation ...

Start it

How does inflation start in the first place?
There are various approaches in the literature:

- Don't ask; hope no one else does. This is the commonest strategy.
- Assume that the pre-inflationary Universe samples possible initial conditions widely enough that some regions are suitable to start inflation.
- Enhance the previous point by invoking eternal inflation ...
- ... and/or the anthropic principle.

Start it

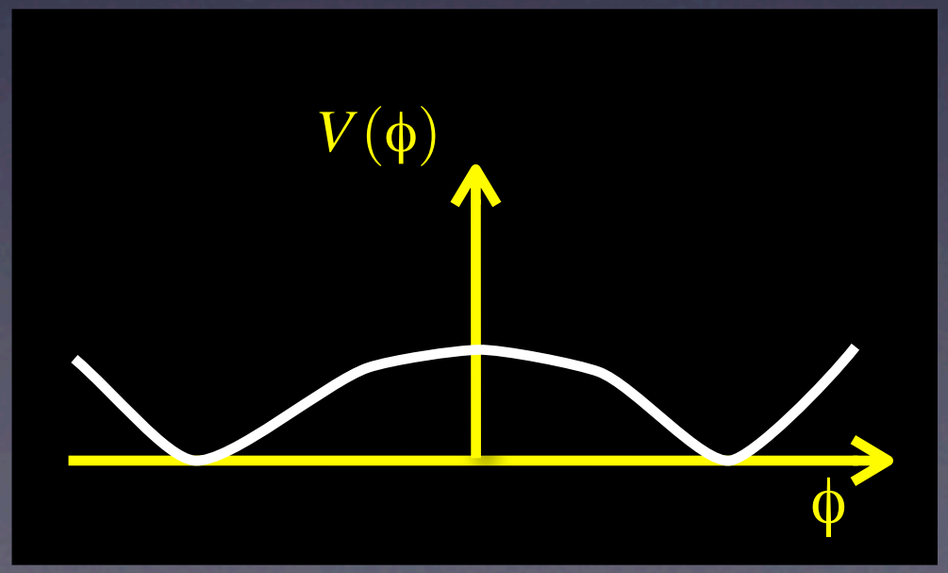
How does inflation start in the first place?
There are various approaches in the literature:

- Don't ask; hope no one else does. This is the commonest strategy.
- Assume that the pre-inflationary Universe samples possible initial conditions widely enough that some regions are suitable to start inflation.
- Enhance the previous point by invoking eternal inflation ...
- ... and/or the anthropic principle.
- Choose a potential supporting topological inflation. This might for instance emerge `naturally' out of the string landscape.

Start it

How does inflation start in the first place?
There are various approaches in the literature:

- Don't ask; hope no one else does. This is the commonest strategy.
- Assume that the pre-inflationary Universe samples possible initial conditions widely enough that some regions are suitable to start inflation.
- Enhance the previous point by invoking eternal inflation ...
- ... and/or the anthropic principle.
- Choose a potential supporting topological inflation. This might for instance emerge `naturally' out of the string landscape.



Sustain it

Almost also inflation models invoke scalar fields to drive inflation, though in some cases the fundamental origin of these scalar fields may be geometrical (eg size of an extra dimension).

Sustain it

Almost also inflation models invoke scalar fields to drive inflation, though in some cases the fundamental origin of these scalar fields may be geometrical (eg size of an extra dimension).

Occasionally people dabble with vector fields as an alternative, and more recently with 3-form fields.

Sustain it

Almost also inflation models invoke scalar fields to drive inflation, though in some cases the fundamental origin of these scalar fields may be geometrical (eg size of an extra dimension).

Occasionally people dabble with vector fields as an alternative, and more recently with 3-form fields.

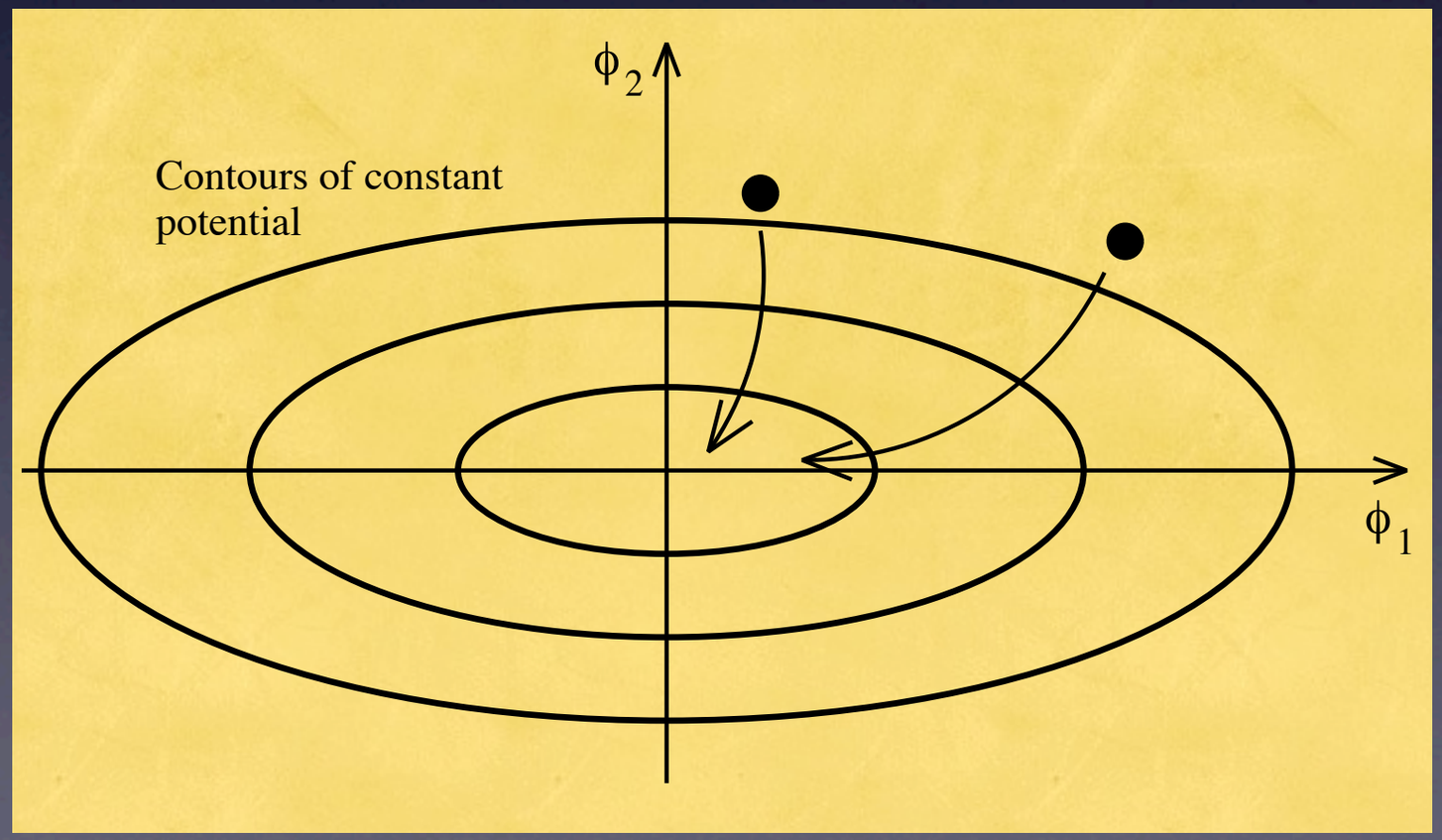
A scenario may invoke multiple scalar fields, in which case the term `inflaton' might refer to the position on the particular trajectory taken in our region of the Universe.

Sustain it

Almost also inflation models invoke scalar fields to drive inflation, though in some cases the fundamental origin of these scalar fields may be geometrical (eg size of an extra dimension).

Occasionally people dabble with vector fields as an alternative, and more recently with 3-form fields.

A scenario may invoke multiple scalar fields, in which case the term `inflaton' might refer to the position on the particular trajectory taken in our region of the Universe.



Stop it

There are quite a few choices here:

Stop it

There are quite a few choices here:

- Steepening the potential (i.e. violation of slow-roll).

Stop it

There are quite a few choices here:

- Steepening the potential (i.e. violation of slow-roll).

  This is measured by the ε slow-roll parameter. Slow-roll is automatically violated if potentials have a minimum at V=0.

Stop it

There are quite a few choices here:

- Steepening the potential (i.e. violation of slow-roll).

  This is measured by the ε slow-roll parameter. Slow-roll is automatically violated if potentials have a minimum at V=0.

- A second-order phase transition (as in hybrid inflation).

Stop it

There are quite a few choices here:

- Steepening the potential (i.e. violation of slow-roll).

  This is measured by the ε slow-roll parameter. Slow-roll is automatically violated if potentials have a minimum at V=0.

- A second-order phase transition (as in hybrid inflation).

  Here an instability in a second field direction causes inflation to end.

Stop it

There are quite a few choices here:

- Steepening the potential (i.e. violation of slow-roll).

  This is measured by the ε slow-roll parameter. Slow-roll is automatically violated if potentials have a minimum at V=0.

- A second-order phase transition (as in hybrid inflation).

  Here an instability in a second field direction causes inflation to end.

- A first-order phase transition (leading to bubble formation).

Stop it

There are quite a few choices here:

- Steepening the potential (i.e. violation of slow-roll).

  This is measured by the ε slow-roll parameter. Slow-roll is automatically violated if potentials have a minimum at V=0.

- A second-order phase transition (as in hybrid inflation).

  Here an instability in a second field direction causes inflation to end.

- A first-order phase transition (leading to bubble formation).

  As before, but now the phase transition is a first-order quantum tunnelling, promoting formation of bubbles which expand rapidly and coalesce.

Stop it

There are quite a few choices here:

- Steepening the potential (i.e. violation of slow-roll).

  This is measured by the ε slow-roll parameter. Slow-roll is automatically violated if potentials have a minimum at V=0.

- A second-order phase transition (as in hybrid inflation).

  Here an instability in a second field direction causes inflation to end.

- A first-order phase transition (leading to bubble formation).

  As before, but now the phase transition is a first-order quantum tunnelling, promoting formation of bubbles which expand rapidly and coalesce.

- Modification of gravity (e.g. braneworld gravity terms becoming unimportant).

Stop it

There are quite a few choices here:

- Steepening the potential (i.e. violation of slow-roll).

  This is measured by the ε slow-roll parameter. Slow-roll is automatically violated if potentials have a minimum at V=0.

- A second-order phase transition (as in hybrid inflation).

  Here an instability in a second field direction causes inflation to end.

- A first-order phase transition (leading to bubble formation).

  As before, but now the phase transition is a first-order quantum tunnelling, promoting formation of bubbles which expand rapidly and coalesce.

- Modification of gravity (e.g. braneworld gravity terms becoming unimportant).

  In this option the potential would not be suitable for inflation in Einstein gravity, but may promote inflation in a high-energy modified gravity regime (eg Randall-Sundrum models).

From inflation to hot big bang

At the end of inflation we still have scalar fields, which we don't want, and have to produce the material of the Hot Big Bang.

From inflation to hot big bang

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

- Bubble collisions

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

- Bubble collisions

  If inflation ends by bubble nucleation, their subsequent collisions may lead to reheating.

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

- Bubble collisions

  If inflation ends by bubble nucleation, their subsequent collisions may lead to reheating.

- A different scalar field comes to dominate and then decays

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

- Bubble collisions

  If inflation ends by bubble nucleation, their subsequent collisions may lead to reheating.

- A different scalar field comes to dominate and then decays

  An example of this is the curvaton scenario. The inflaton presumably decays separately but need not produce significant amounts of surviving material.

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

- Bubble collisions

  If inflation ends by bubble nucleation, their subsequent collisions may lead to reheating.

- A different scalar field comes to dominate and then decays

  An example of this is the curvaton scenario. The inflaton presumably decays separately but need not produce significant amounts of surviving material.

- Black hole reheating

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

- Bubble collisions

  If inflation ends by bubble nucleation, their subsequent collisions may lead to reheating.

- A different scalar field comes to dominate and then decays

  An example of this is the curvaton scenario. The inflaton presumably decays separately but need not produce significant amounts of surviving material.

- Black hole reheating

  In a variant of the above, black holes are produced whose later Hawking evaporation reheats the Universe.

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

- Bubble collisions

  If inflation ends by bubble nucleation, their subsequent collisions may lead to reheating.

- A different scalar field comes to dominate and then decays

  An example of this is the curvaton scenario. The inflaton presumably decays separately but need not produce significant amounts of surviving material.

- Black hole reheating

  In a variant of the above, black holes are produced whose later Hawking evaporation reheats the Universe.

- Gravitational particle production

From inflation to hot big bang

- Decay of the inflaton (reheating/preheating)

  One process gets rid of the inflaton and creates normal material. There may be interesting consequences if the inflaton decays are incomplete.

- Bubble collisions

  If inflation ends by bubble nucleation, their subsequent collisions may lead to reheating.

- A different scalar field comes to dominate and then decays

  An example of this is the curvaton scenario. The inflaton presumably decays separately but need not produce significant amounts of surviving material.

- Black hole reheating

  In a variant of the above, black holes are produced whose later Hawking evaporation reheats the Universe.

- Gravitational particle production

  Here particles produced quantum mechanically during the late stages of inflation later come to dominate.

From inflation to hot big bang

Amongst these various possibilities, a final question is whether the inflaton decays completely away, or whether it survives with a residual abundance.

If it survives, it might become one of the necessary ingredients of the standard cosmology, either dark matter or dark energy.

Toolkit

Toolkit

Caused by

Single scalar

Multi scalar

Vector

3-form

Toolkit

Caused by	Ended by
Single scalar	Potential steepening
Multi scalar	Hybrid
Vector	Bubble nucleation
3-form	Braneworld gravity

Toolkit

Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Toolkit

Chaotic inflation

Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Toolkit

Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Toolkit

Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Curvaton scenario

Toolkit

Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Toolkit

Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Hybrid inflation

Toolkit

Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Toolkit

Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Quintessential inflation

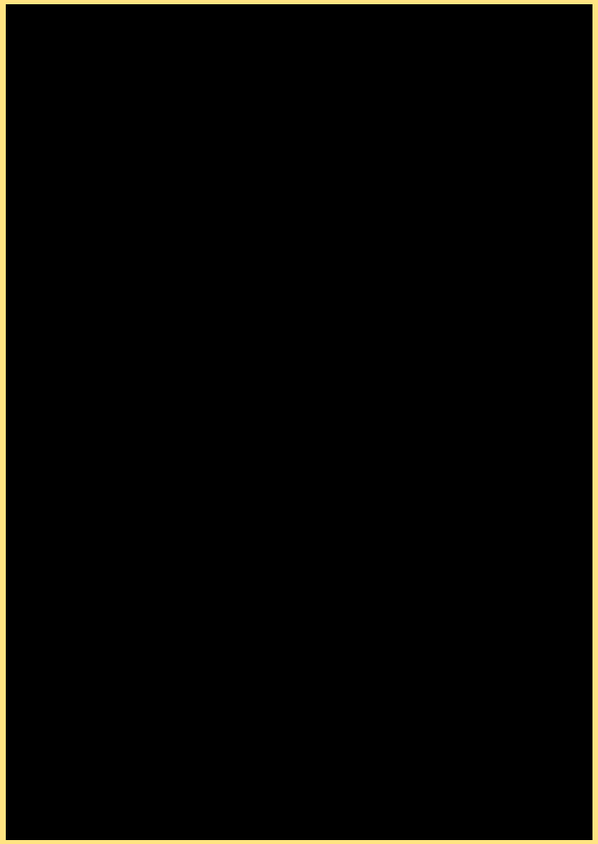
Toolkit

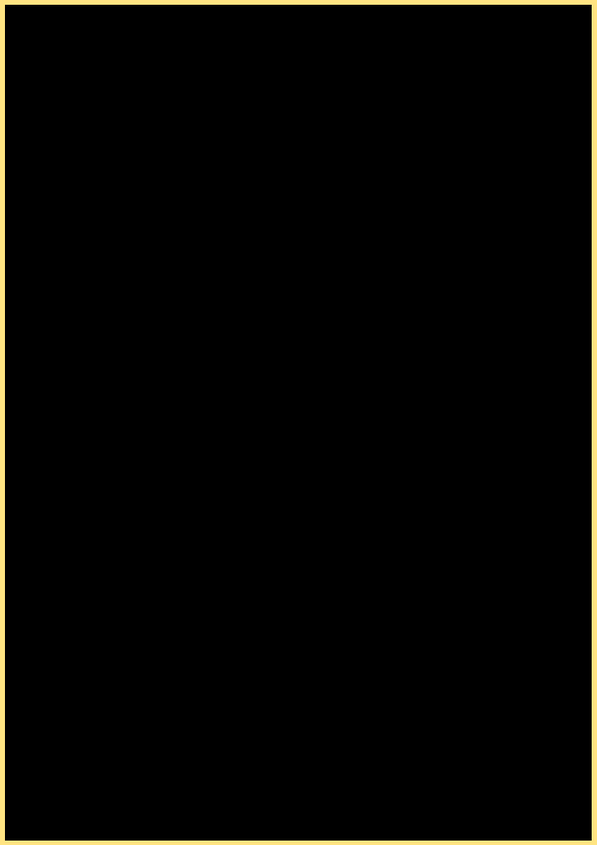
Caused by	Ended by	Reheated by
Single scalar	Potential steepening	Inflaton decays
Multi scalar	Hybrid	Curvaton decays
Vector	Bubble nucleation	Bubble collisions
3-form	Braneworld gravity	Black hole decays
		Gravitational particle production

Dark sector unification

Take the test: AmIACosmologistOrNot?

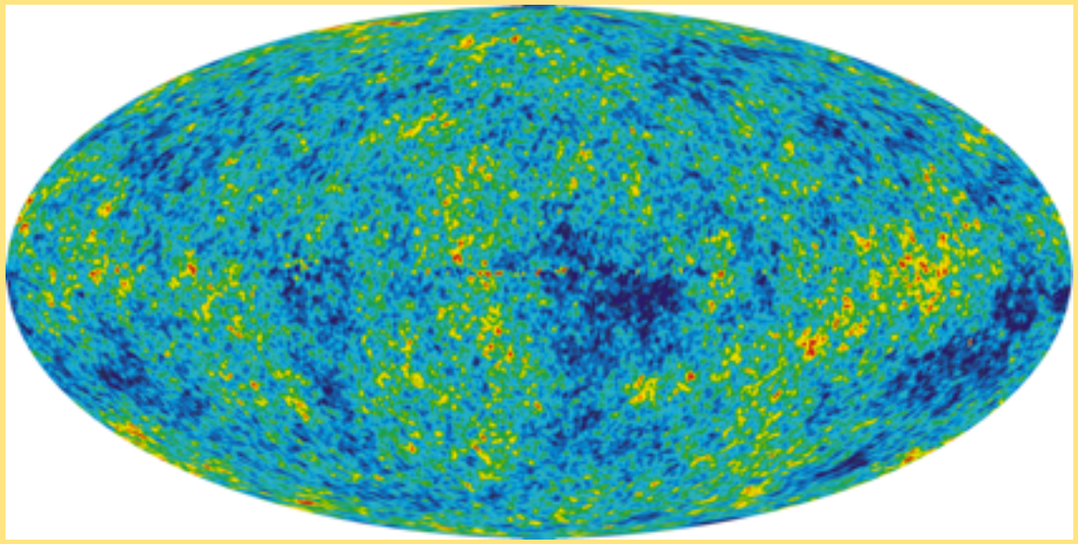
Take the test: AmIACosmologistOrNot?

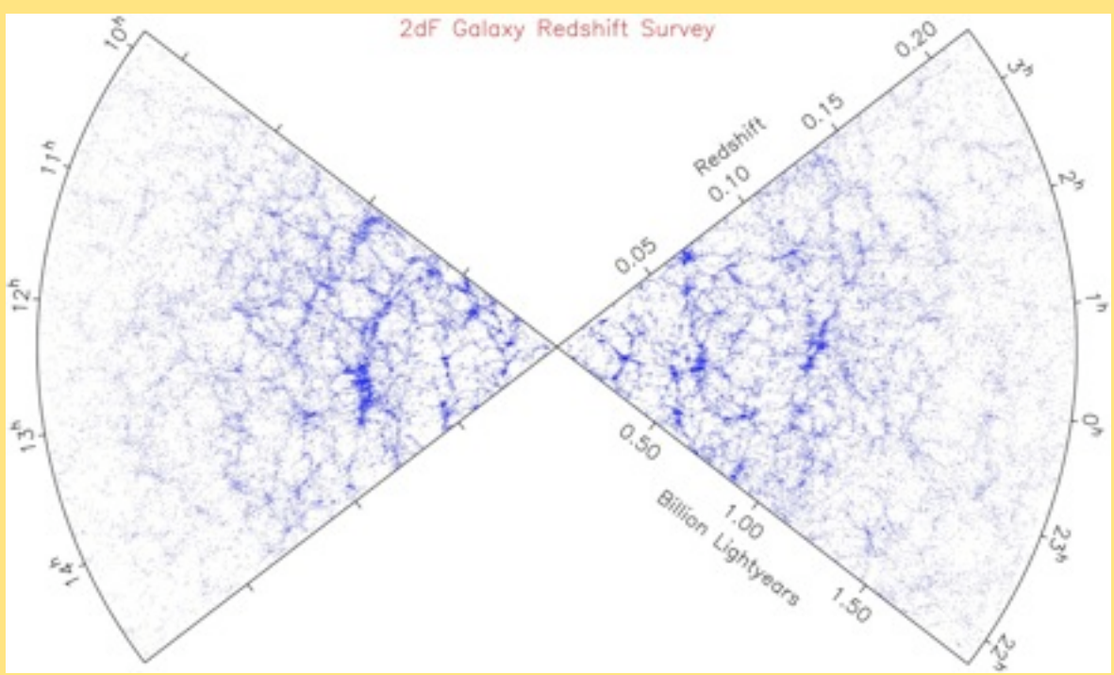


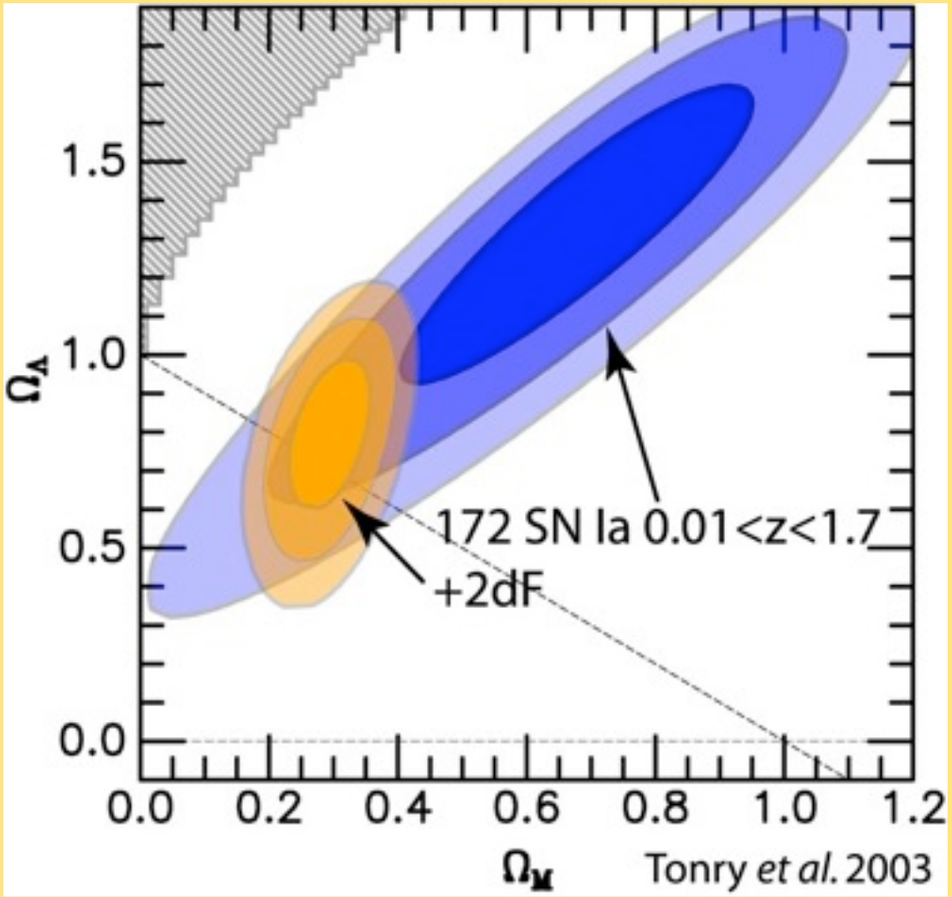


Take the test: AmIACosmologistOrNot?

Take the test: AmIACosmologistOrNot?







The Standard Cosmological Model

The Standard Cosmological Model

This model postulates that the Universe contains five different materials: baryons (including electrons), photons, neutrinos, dark matter and dark energy.

The Standard Cosmological Model

This model postulates that the Universe contains five different materials: baryons (including electrons), photons, neutrinos, dark matter and dark energy.

$$G_{\mu\nu} = T_{\mu\nu}^{\text{baryon-photon-neutrino}} + T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}}$$

The Standard Cosmological Model

This model postulates that the Universe contains five different materials: baryons (including electrons), photons, neutrinos, dark matter and dark energy.

$$G_{\mu\nu} = T_{\mu\nu}^{\text{baryon-photon-neutrino}} + T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}}$$

Observational probes of dark matter and dark energy are presently entirely gravitational, and amount to

The Standard Cosmological Model

This model postulates that the Universe contains five different materials: baryons (including electrons), photons, neutrinos, dark matter and dark energy.

$$G_{\mu\nu} = T_{\mu\nu}^{\text{baryon-photon-neutrino}} + T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}}$$

Observational probes of dark matter and dark energy are presently entirely gravitational, and amount to

$$T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}} = G_{\mu\nu} - T_{\mu\nu}^{\text{baryon-photon-neutrino}}$$

The dark degeneracy

$$T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}} = G_{\mu\nu} - T_{\mu\nu}^{\text{baryon-photon-neutrino}}$$

In general, there is no unique decomposition of the `dark fluid' energy-momentum tensor into `dark matter' and `dark energy' components.

Eisenstein & Hu 1999
Wasserman 2002
Rubano & Scudellaro 2002
Kunz 2007

The dark degeneracy

$$T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}} = G_{\mu\nu} - T_{\mu\nu}^{\text{baryon-photon-neutrino}}$$

In general, there is no unique decomposition of the `dark fluid' energy-momentum tensor into `dark matter' and `dark energy' components.

Eisenstein & Hu 1999
Wasserman 2002
Rubano & Scudellaro 2002
Kunz 2007

If we model the dark sector as cold dark matter and a cosmological constant, we can get strong constraints on each.

The dark degeneracy

$$T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}} = G_{\mu\nu} - T_{\mu\nu}^{\text{baryon-photon-neutrino}}$$

In general, there is no unique decomposition of the `dark fluid' energy-momentum tensor into `dark matter' and `dark energy' components.

Eisenstein & Hu 1999
Wasserman 2002
Rubano & Scudellaro 2002
Kunz 2007

If we model the dark sector as cold dark matter and a cosmological constant, we can get strong constraints on each.

If we model the dark energy more generally, e.g. equation of state $w = w_0 + (1-a)\, w_a$, we can still measure Ω_{dm}, though not as well.

The dark degeneracy

$$T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}} = G_{\mu\nu} - T_{\mu\nu}^{\text{baryon-photon-neutrino}}$$

In general, there is no unique decomposition of the `dark fluid' energy-momentum tensor into `dark matter' and `dark energy' components.

Eisenstein & Hu 1999
Wasserman 2002
Rubano & Scudellaro 2002
Kunz 2007

If we model the dark sector as cold dark matter and a cosmological constant, we can get strong constraints on each.

If we model the dark energy more generally, e.g. equation of state $w = w_0 + (1-a)\, w_a$, we can still measure Ω_{dm}, though not as well.

But if we model the dark energy equation of state arbitrarily through $w(a)$, then we cannot measure Ω_{dm} at all.

The dark degeneracy

$$T_{\mu\nu}^{\text{dark matter}} + T_{\mu\nu}^{\text{dark energy}} = G_{\mu\nu} - T_{\mu\nu}^{\text{baryon-photon-neutrino}}$$

Another powerful result (Kunz 2007) is that for any model of interacting dark matter and dark energy, there is always a model of non-interacting dark matter and dark energy that gives precisely the same predictions.

Possible context: Suppose we have a model of dark energy that is flexible enough that we may be able to do away with the dark matter altogether.

With Martin Kunz (Sussex), David Parkinson (Sussex), Changjun Gao (Beijing)
arXiv:0908.3197, Phys Rev D

Constraining the dark fluid

In this study we consider only kinematic data, which means that the equation of state $w_{dark}(a)$ is the only parameter. The dark degeneracy applies to structure formation data as well, but the sound speed $c_s(a)$ then also needs to be constrained.

Example

In the standard cosmological model, we have

Example

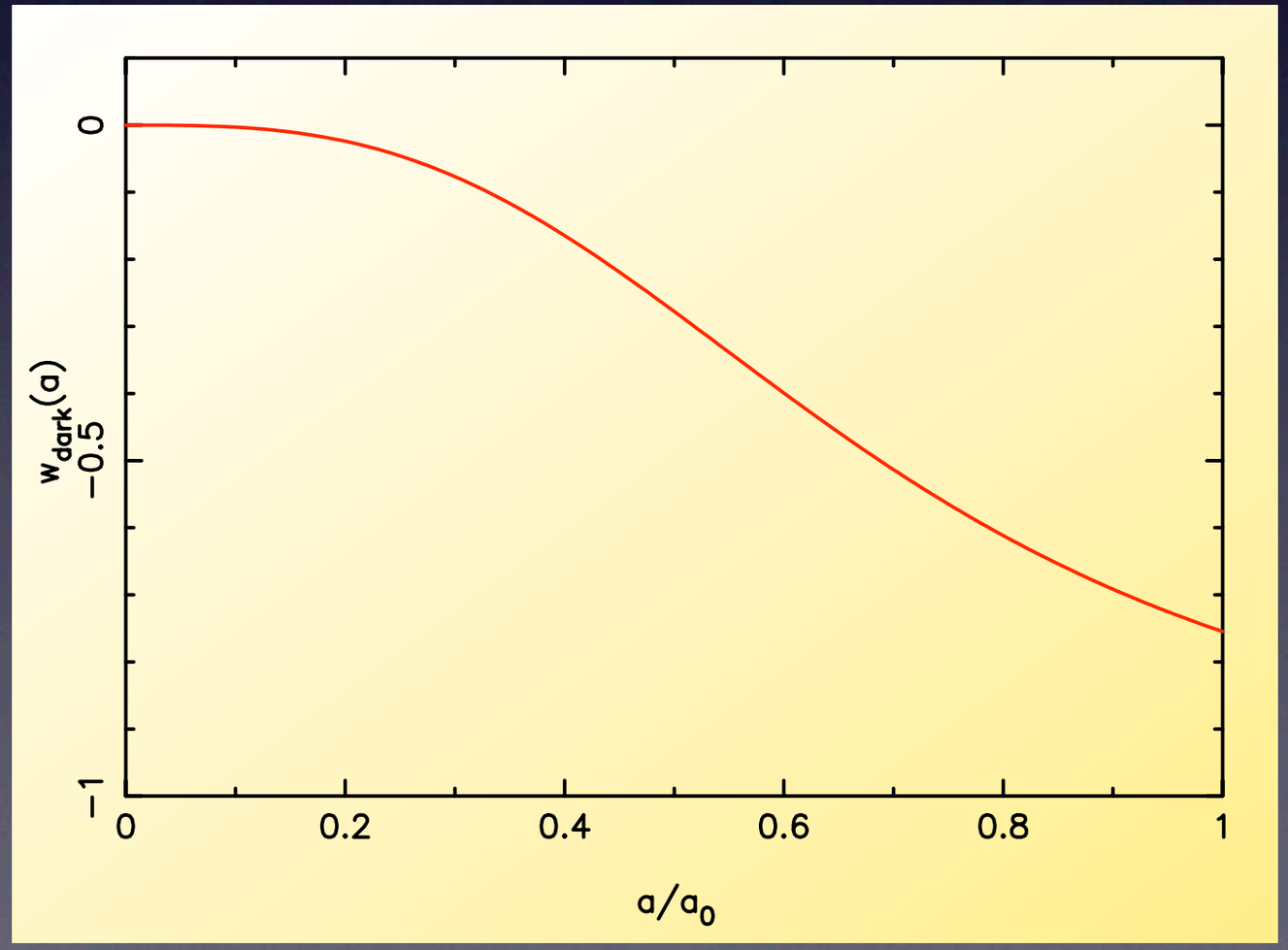
In the standard cosmological model, we have

$$
\begin{aligned}
w_{\rm dark}^{\rm SCM}(z) &= -\frac{1-\Omega_{\rm m,0}}{1-\Omega_{\rm m,0}+(\Omega_{\rm m,0}-\Omega_{\rm b,0})\,(1+z)^3}\,, \\
&\simeq -\frac{1}{1+13(1+z)^3/40}\,.
\end{aligned}
$$

Example

In the standard cosmological model, we have

$$
\begin{aligned}
w_{\rm dark}^{\rm SCM}(z) &= -\frac{1-\Omega_{\rm m,0}}{1-\Omega_{\rm m,0}+(\Omega_{\rm m,0}-\Omega_{\rm b,0})\,(1+z)^3}\,, \\
&\simeq -\frac{1}{1+13(1+z)^3/40}\,.
\end{aligned}
$$



Constraining the dark fluid

We simply parametrize the complete dark fluid by expanding $w_{dark}(a)$, for instance as a Taylor series, up to cubic order, possibly with some low derivatives set to zero (the `constrained' expansions).

Constraining the dark fluid

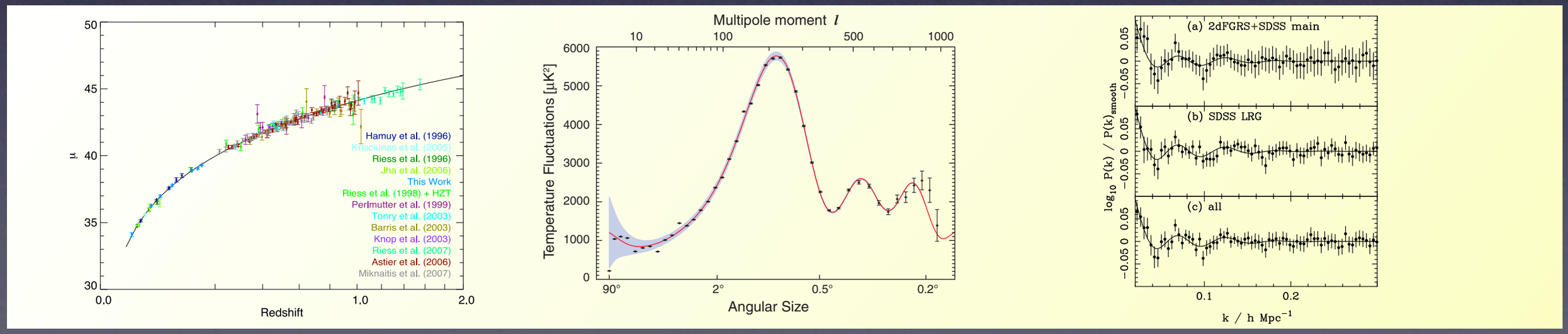
We simply parametrize the complete dark fluid by expanding $w_{dark}(a)$, for instance as a Taylor series, up to cubic order, possibly with some low derivatives set to zero (the `constrained' expansions).

Data used: Supernova luminosity distances (Union sample, 307 SN)
Cosmic microwave background peak positions (WMAP5)
Baryon acoustic oscillation peak positions (SDSS+2dFGRS)
Hubble parameter (SHOES)

Constraining the dark fluid

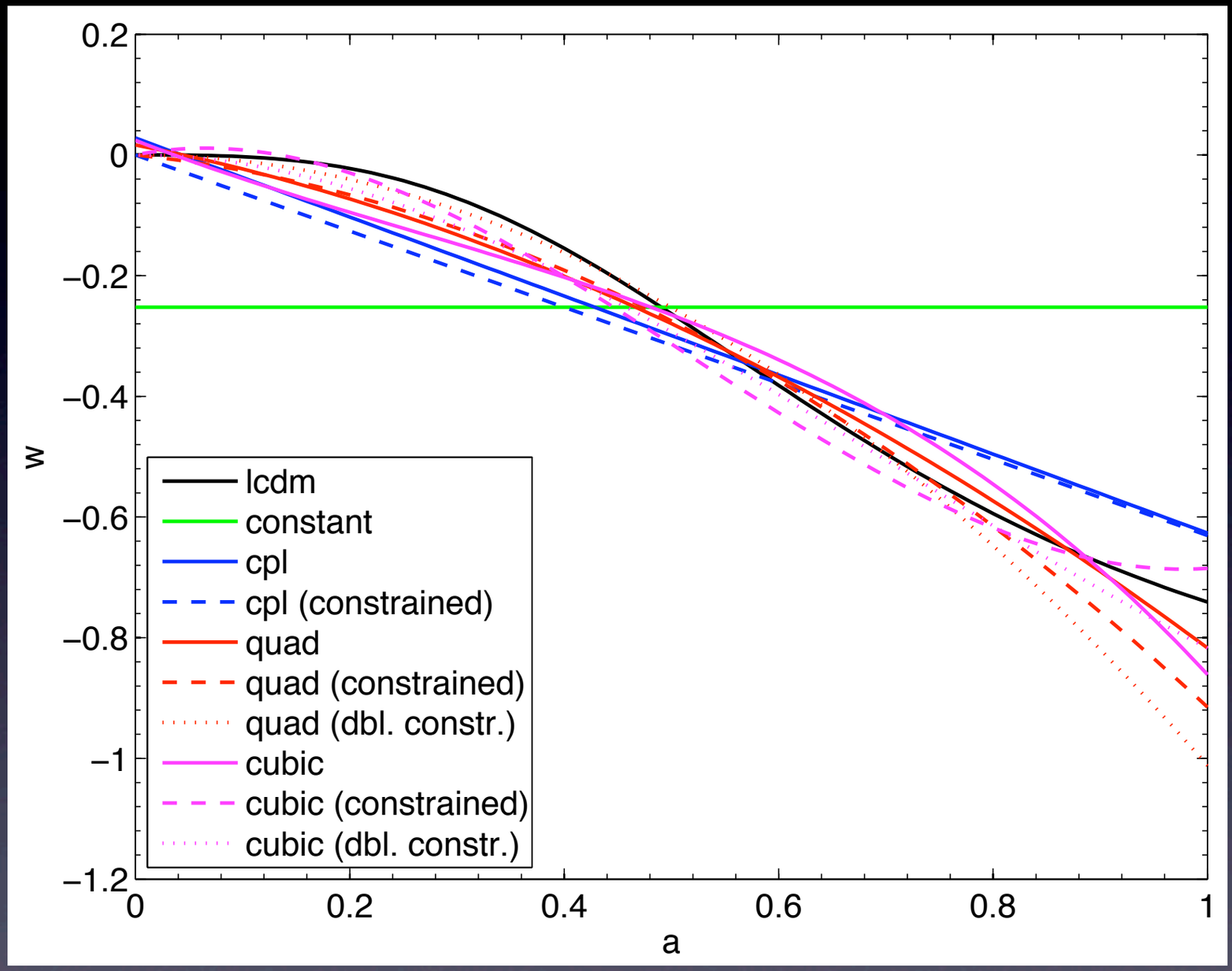
We simply parametrize the complete dark fluid by expanding $w_{dark}(a)$, for instance as a Taylor series, up to cubic order, possibly with some low derivatives set to zero (the `constrained' expansions).

Data used: Supernova luminosity distances (Union sample, 307 SN)
Cosmic microwave background peak positions (WMAP5)
Baryon acoustic oscillation peak positions (SDSS+2dFGRS)
Hubble parameter (SHOES)



Constraining the dark fluid

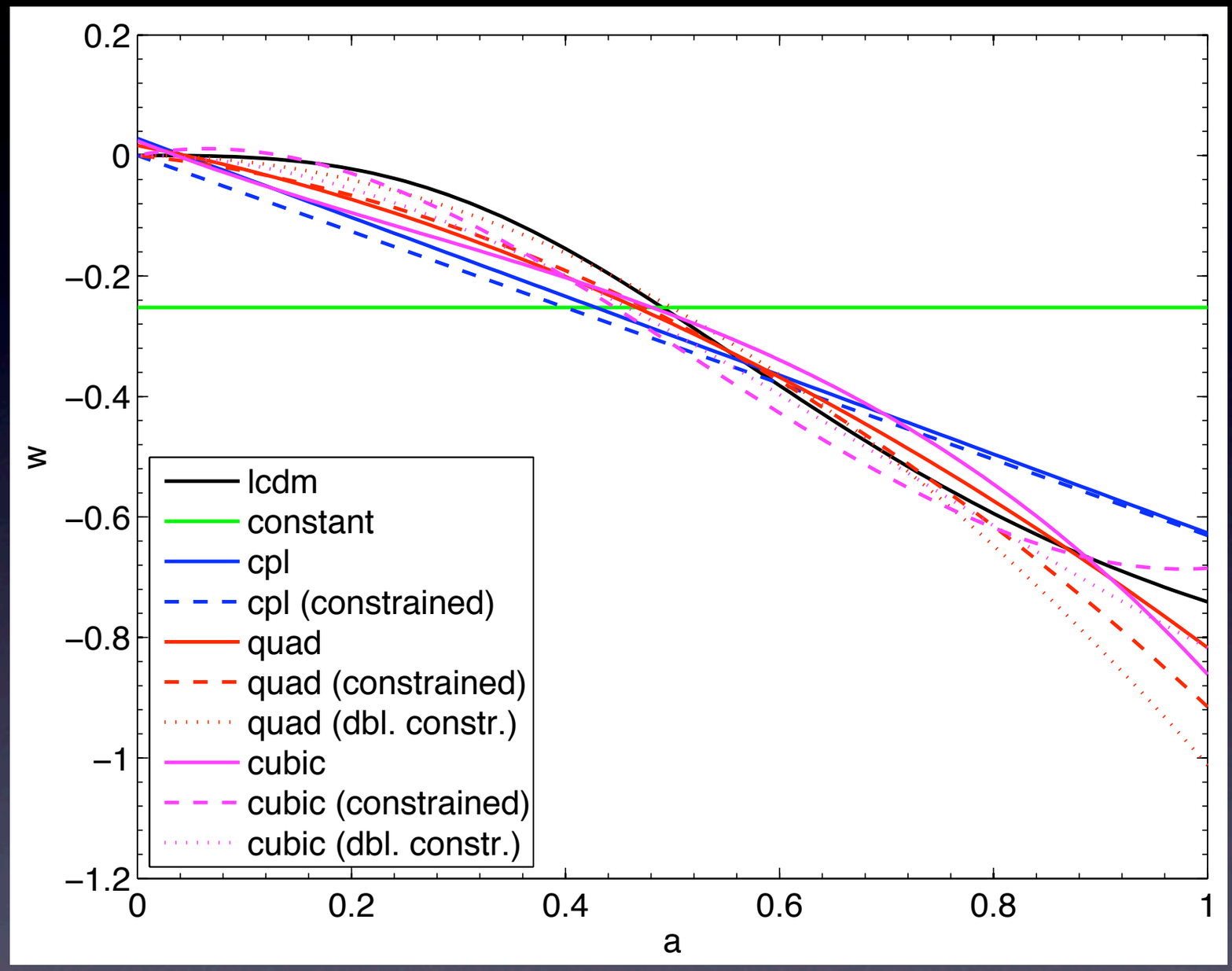
Constraining the dark fluid



Here are the best fits for different parameterizations.

Constraining the dark fluid

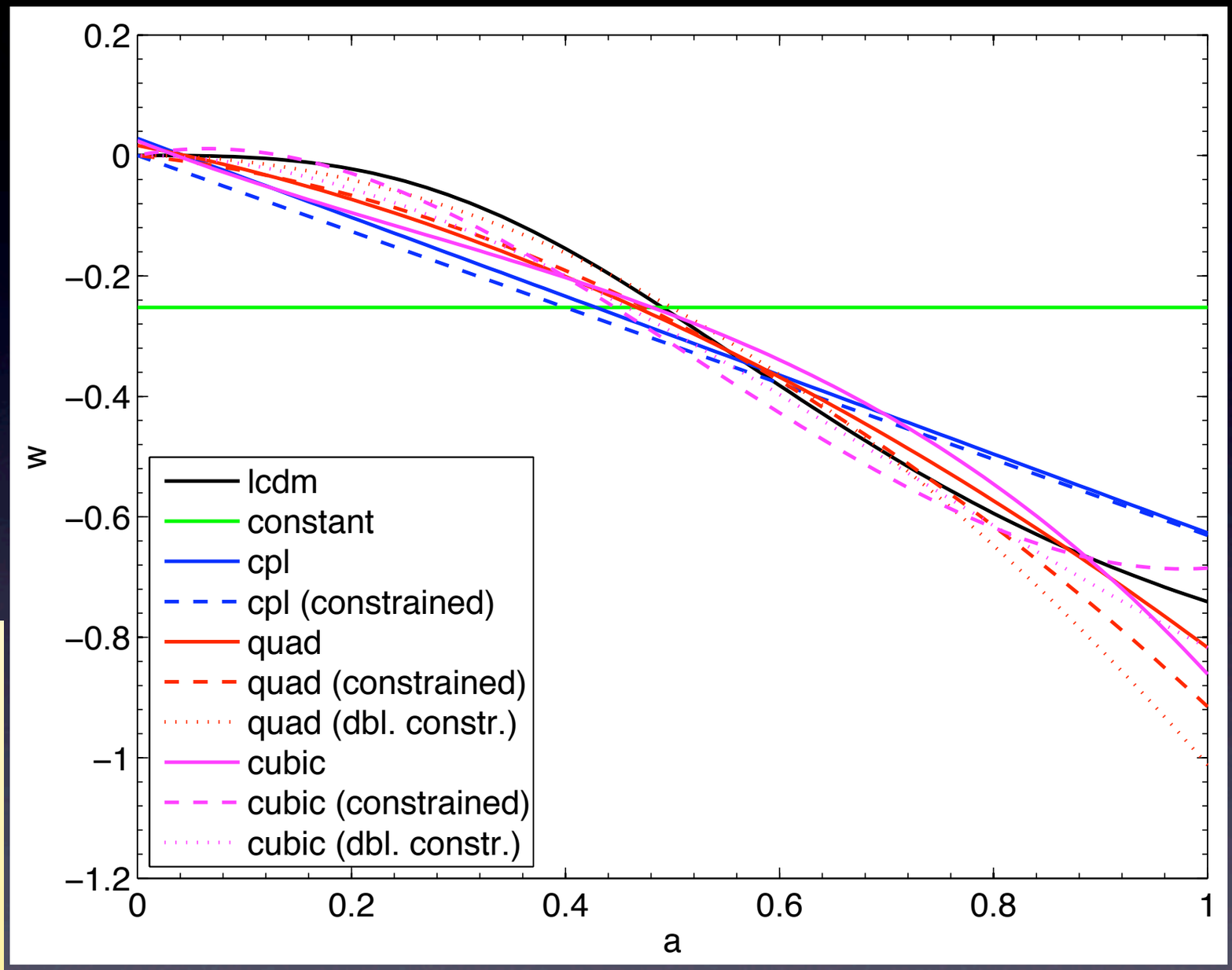
The data alone enforce that w=0 at early times, i.e. dark matter behaviour. This motivates enforcing this condition in the models.



Here are the best fits for different parameterizations.

Constraining the dark fluid

The data alone enforce that w=0 at early times, i.e. dark matter behaviour. This motivates enforcing this condition in the models.



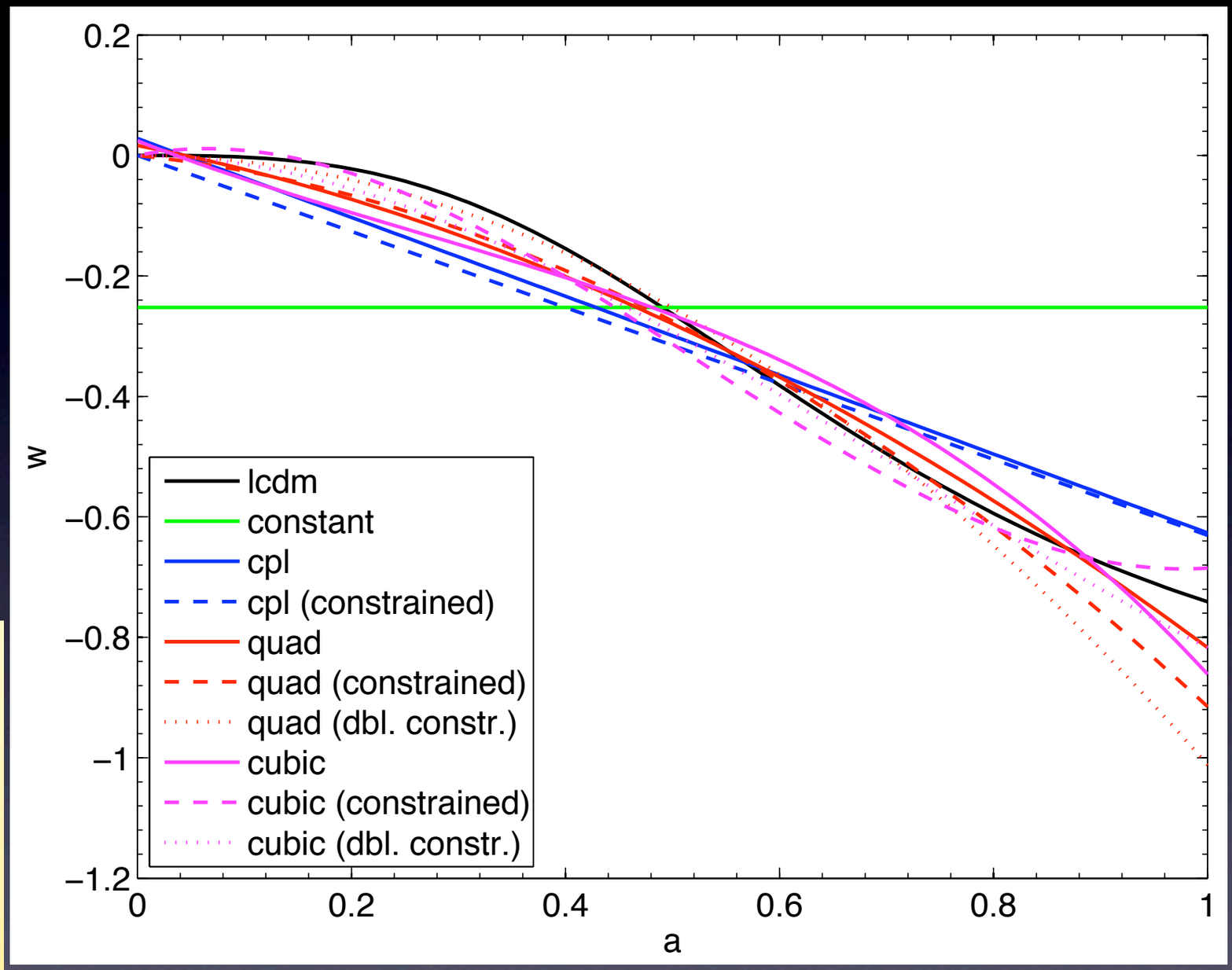
Model	Dark sector parameters	$\chi^2_{\rm min}$
ΛCDM	1	311.9
Constant w	1	391.3
Linear (CPL)	2	312.1
Constrained linear	1	320.5
Quadratic	3	309.8
Constrained quadratic	2	311.9
Doubly-constrained quadratic	1	313.5
Cubic	4	309.6
Constrained cubic	3	311.1
Doubly-constrained cubic	2	311.5

Here are the best fits for different parameterizations.

Constraining the dark fluid

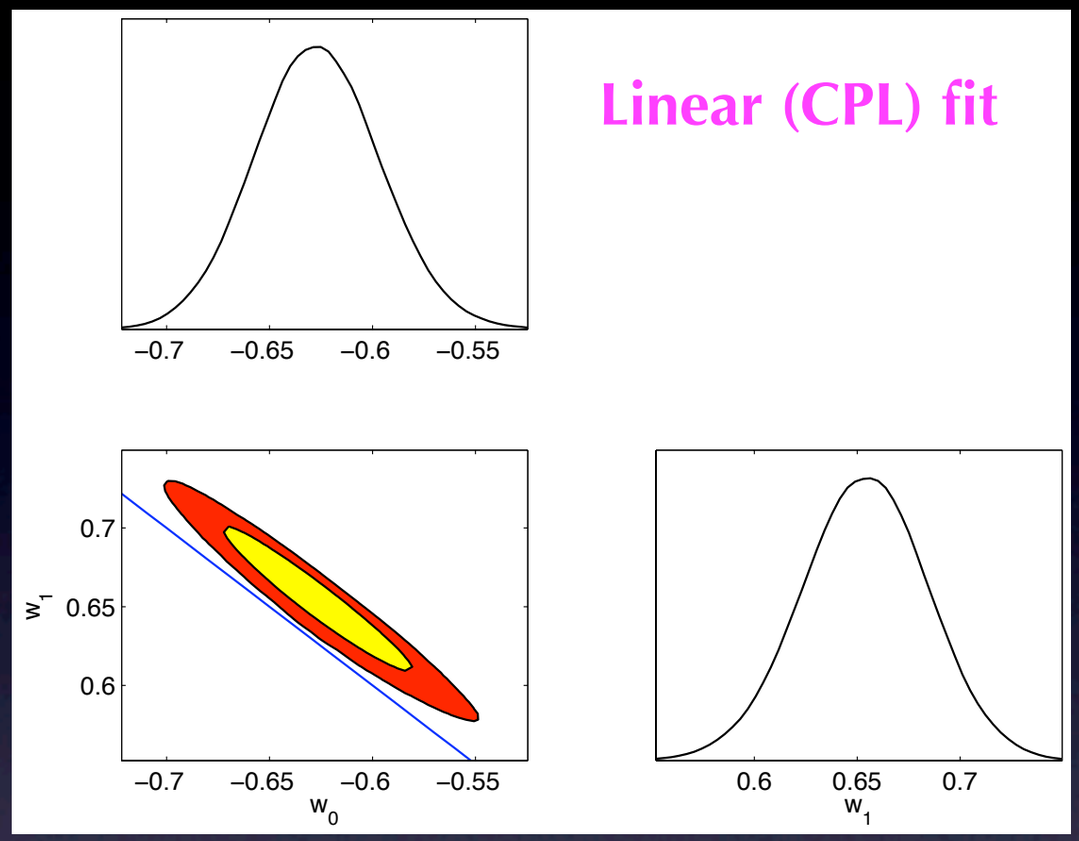
The data alone enforce that w=0 at early times, i.e. dark matter behaviour. This motivates enforcing this condition in the models.

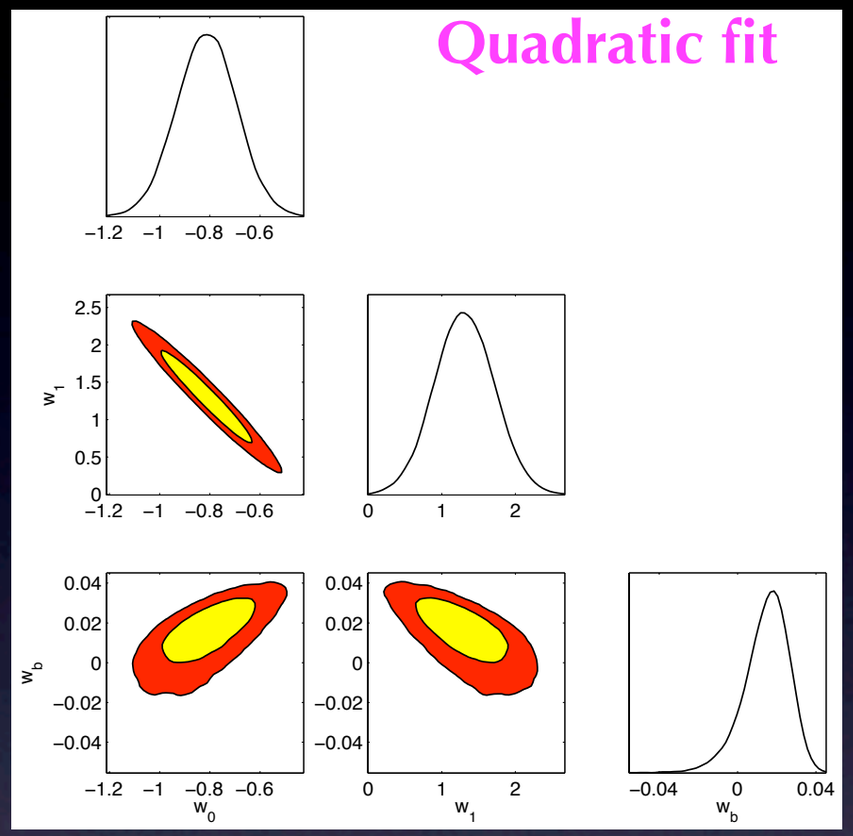
Model	Dark sector parameters	$\chi^2_{\min}$
ΛCDM	1	311.9
~~Constant w~~	~~1~~	~~391.3~~
Linear (CPL)	2	312.1
Constrained linear	1	320.5
Quadratic	3	309.8
Constrained quadratic	2	311.9
Doubly-constrained quadratic	1	313.5
Cubic	4	309.6
Constrained cubic	3	311.1
Doubly-constrained cubic	2	311.5

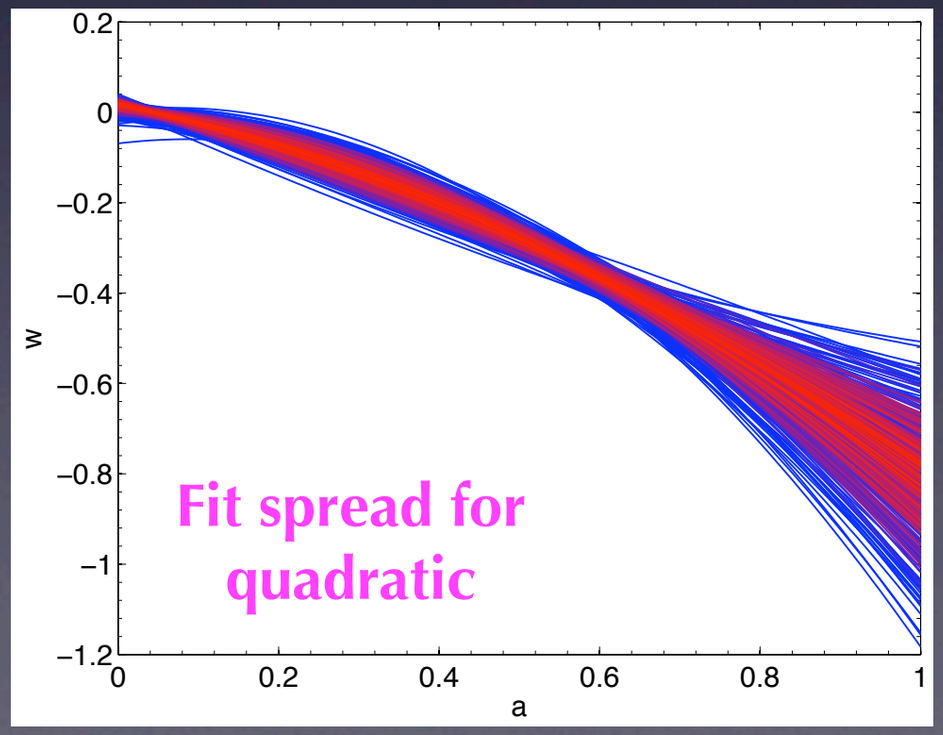


Here are the best fits for different parameterizations.

Constraining the dark fluid







Dark fluid conclusions

Dark fluid conclusions

- At present there is no unique decomposition of the dark fluid into components, i.e. no model-independent determination of the dark matter or dark energy densities.

Dark fluid conclusions

- At present there is no unique decomposition of the dark fluid into components, i.e. no model-independent determination of the dark matter or dark energy densities.
- In order to test unified dark sector scenarios, a generalized data analysis is required which does not assume this split.

Dark fluid conclusions

- At present there is no unique decomposition of the dark fluid into components, i.e. no model-independent determination of the dark matter or dark energy densities.
- In order to test unified dark sector scenarios, a generalized data analysis is required which does not assume this split.
- This does show that the dark sector must behave as dark matter at early epochs.

Dark fluid conclusions

- At present there is no unique decomposition of the dark fluid into components, i.e. no model-independent determination of the dark matter or dark energy densities.
- In order to test unified dark sector scenarios, a generalized data analysis is required which does not assume this split.
- This does show that the dark sector must behave as dark matter at early epochs.
- Despite the above, the standard assumption of separate dark matter and cosmological constant components is the simplest satisfactory explanation of present data.