Finding structure in the dark: Coupled Dark Energy Models and the Mildly Nonlinear Regime.

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Overview

- Motivations and Theoretical Considerations
    - brief background - why a coupled dark sector? The EFT approach.
    - theoretical and other constraints

"Beyond the Cosmological Standard Model"
B. Jain, A. Joyce, J. Khoury and M.T.
Phys.Rept. **568** 1-98 (2015), *[arXiv:1407.0059]*

- Prospects - an example - Probing a complex dark sector.
- Modeling dark sector interactions - fluids vs. fields
- Constraints in the mildly nonlinear regime
- Summary and discussion.
- A few comments.

"Field Theories and Fluids for an Interacting Dark Sector"
M. Carrillo González and M.T., arXiv:1705.04737
"Finding structure in the dark: coupled dark energy, weak lensing, and the mildly nonlinear regime"
V. Miranda, M. Carrillo González, E. Krause and M.T., arXiv:1707.05694

Cosmic Acceleration

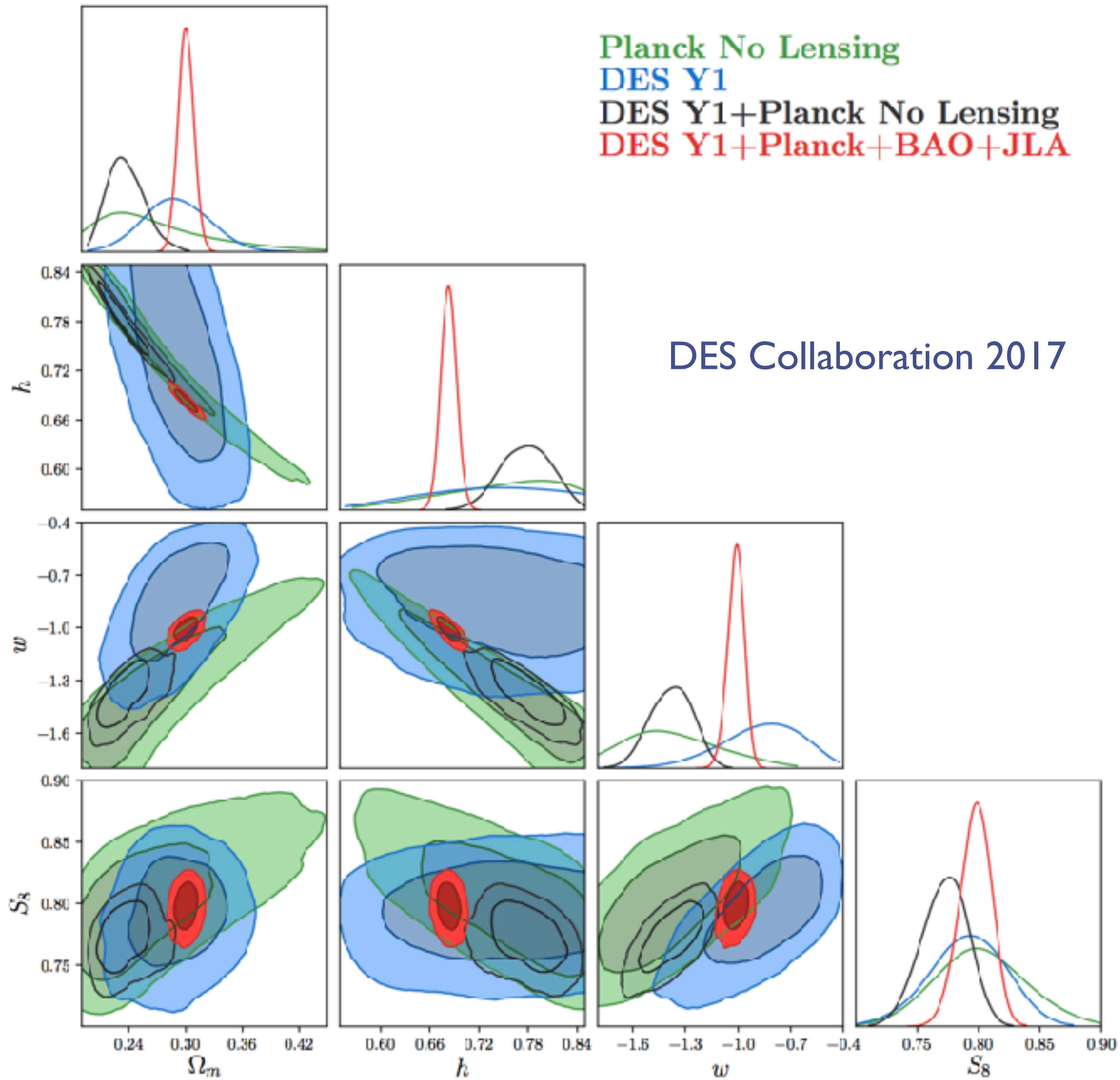
If we assume GR

$$\frac{\ddot{a}}{a} \propto -(\rho + 3p)$$

So, writing p=wρ, accelerating expansion means p<-ρ/3 or

$$\boxed{w<-1/3}$$

$$w = -1.00^{+0.04}_{-0.05}$$



DES Collaboration 2017

Logical Possibilities

There exist several seemingly distinct explanations

- **Cosmological Constant**: No good ideas to explain the size. Anthropic explanation a possibility, but requires many ingredients, none of which we are confident at this stage, and unclear how to test, even if correct.

- **Dynamical Dark Energy**: Inflation at the other end of time and energy. Challenging to present a natural model. Requires a solution to CC problem.

- **Modifying Gravity**: Spacetime responds in a new way to the presence of more standard sources of mass-energy. Extremely difficult to write down theoretically well-behaved models, hard to solve even then. But, holds out chance of jointly solving the CC problem.

A common Language - EFT

How do theorists think about all this? In fact, whether dark energy or modified gravity, ultimately, around a background, it consists of a set of interacting fields in a Lagrangian. The Lagrangian contains 3 types of terms:

- Kinetic Terms: e.g.

$$\partial_\mu\phi\partial^\mu\phi \qquad F_{\mu\nu}F^{\mu\nu} \qquad i\bar{\psi}\gamma^\mu\partial_\mu\psi \qquad h_{\mu\nu}\mathcal{E}^{\mu\nu;\alpha\beta}h_{\alpha\beta} \qquad K(\partial_\mu\phi\partial^\mu\phi)$$

- Self Interactions (a potential)

$$V(\phi) \qquad m^2\phi^2 \qquad \lambda\phi^4 \qquad m\bar{\psi}\psi \qquad m^2h_{\mu\nu}h^{\mu\nu} \qquad m^2h^\mu{}_\mu h^\nu{}_\nu$$

- Interactions with other fields (such as matter, baryonic or dark)

$$\Phi\bar{\psi}\psi \qquad A^\mu A_\mu\Phi^\dagger\Phi \qquad e^{-\beta\phi/M_p}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi \qquad (h^\mu{}_\mu)^2\phi^2 \qquad \frac{1}{M_p}\pi T^\mu{}_\mu$$

Depending on the background, such terms might have functions in front of them that depend on time and/or space.

Many of the concerns of theorists can be expressed in this language, including those of well-posedness (more later)

See talk of I. Saltas

e.g. Weak Coupling

When we write down a classical theory, described by one of our Lagrangians, are usually implicitly assuming effects of higher order operators are small. Needs us to work below the strong coupling scale of the theory, so that quantum corrections, computed in perturbation theory, are small. We therefore need.

- The dimensionless quantities determining how higher order operators, with dimensionful couplings (irrelevant operators) affect the lower order physics be <<1 (or at least <1)

$$\frac{E}{\Lambda} << 1 \qquad \text{(Energy << cutoff)}$$

But be careful - this is tricky! Remember that our kinetic terms, couplings and potentials all can have background-dependent functions in front of them, and even if the original parameters are small, these may make them large - the ***strong coupling problem***! You can no longer trust the theory!

$$G(\chi)\partial_\mu\phi\partial^\mu\phi \longrightarrow f(t)\partial_\mu\phi\partial^\mu\phi \qquad f(t) \to 0$$

e.g. Technical Naturalness

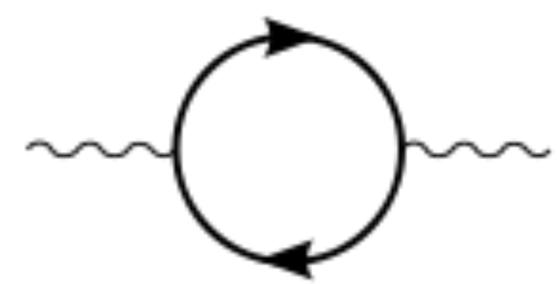
Even if your quantum mechanical corrections do not ruin your ability to trust your theory, any especially small couplings you need might be a problem.

- Suppose you need a very flat potential, or very small mass for some reason

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m^2\phi^2 - \lambda\phi^4 \qquad m \sim H_0^{-1}$$

Then unless your theory has a special extra symmetry as you take m to zero, then quantum corrections will drive it up to the cutoff of your theory.

$$m_{\text{eff}}^2 \sim m^2 + \Lambda^2$$



- Without this, requires extreme fine tuning to keep the potential flat and mass scale ridiculously low - ***challenge of technical naturalness.***

e.g. Ghost-Free

The Kinetic terms in the Lagrangian, around a given background, tell us, in a sense, whether the particles associated with the theory carry positive energy or not.

- Remember the Kinetic Terms: e.g.

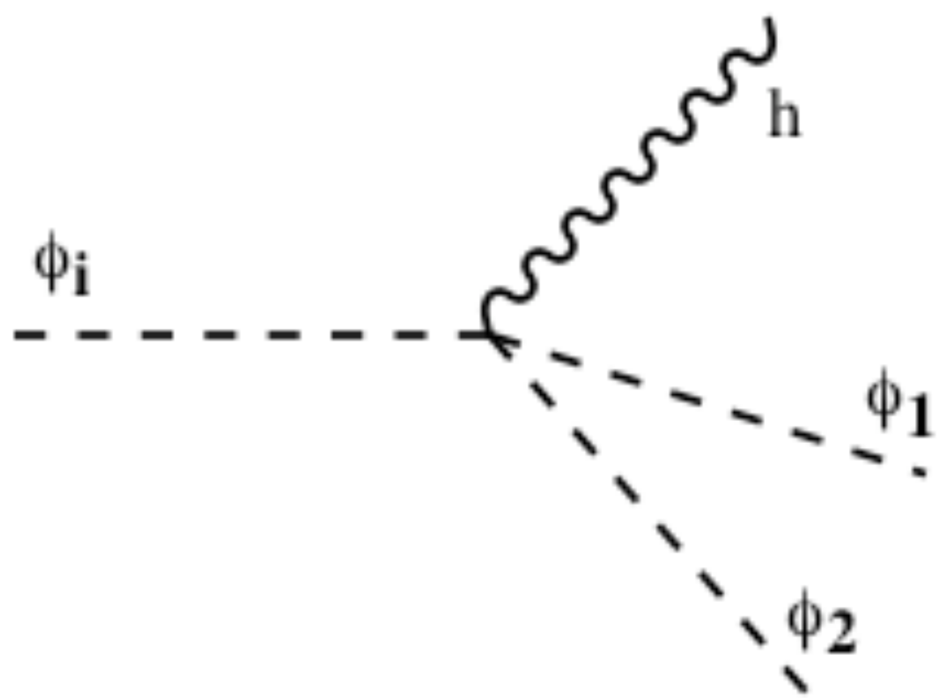
$$-\frac{f(\chi)}{2}K(\partial_\mu\partial^\mu\phi) \rightarrow F(t,x)\frac{1}{2}\dot{\phi}^2 - G(t,x)(\nabla\phi)^2$$

This sets the sign of the KE

- If the KE is negative then the theory has ***ghosts***! This can be catastrophic!

If we were to take these seriously, they'd have negative energy!!

- Ordinary particles could decay into heavier particles plus ghosts
- Vacuum could fragment



(Carroll, Hoffman & M.T.,(2003); Cline, Jeon & Moore. (2004))

e.g. Superluminality ...

Crucial ingredient of Lorentz-invariant QFT: *microcausality*. Commutator of 2 local operators vanishes for spacelike separated points as operator statement

$$[\mathcal{O}_1(x), \mathcal{O}_2(y)] = 0 \; ; \qquad \text{when} \qquad (x-y)^2 > 0$$

Turns out, even if have superluminality, under right circumstances can still have a well-behaved theory, as far as causality is concerned. e.g.

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{1}{\Lambda^3}\partial^2\phi(\partial\phi)^2 + \frac{1}{\Lambda^4}(\partial\phi)^4$$

- Expand about a background: $\phi = \bar{\phi} + \varphi$
- Causal structure set by effective metric

c.f. well-posedness

$$\mathcal{L} = -\frac{1}{2}G^{\mu\nu}(x, \bar{\phi}, \partial\bar{\phi}, \partial^2\bar{\phi}, \ldots)\partial_\mu\varphi\partial_\nu\varphi + \cdots$$

- If G globally hyperbolic, theory is perfectly causal, but *may* have directions in which perturbations propagate outside lightcone used to define theory. May or may not be a problem for the theory - remains to be seen.

But: there can still be worries here, such as analyticity of the S-matrix, ...

See talk by C. De Rham

e.g. the Need for Screening in the EFT

Look at the general EFT of a scalar field conformally coupled to matter

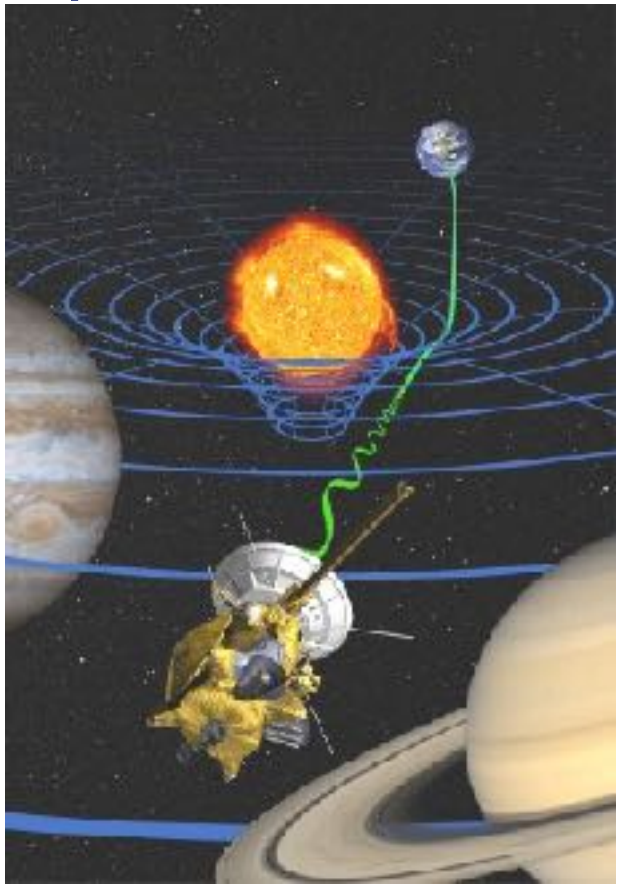
$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \ldots)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

Specialize to a point source $T^\mu_\mu \to -\mathcal{M}\delta^3(\vec{x})$ and expand $\phi = \bar{\phi} + \varphi$

$$Z(\bar{\phi})\left(\ddot{\varphi} - c_s^2(\bar{\phi})\nabla^2\varphi\right) + m^2(\bar{\phi})\varphi = g(\bar{\phi})\mathcal{M}\delta^3(\vec{x})$$

Expect background value set by other quantities; e.g. density or Newtonian potential. Neglecting spatial variation over scales of interest, static potential is

$$V(r) = -\frac{g^2(\bar{\phi})}{Z(\bar{\phi})c_s^2(\bar{\phi})} \frac{e^{-\frac{m(\bar{\phi})}{\sqrt{Z(\bar{\phi})}c_s(\bar{\phi})}r}}{4\pi r}\mathcal{M}$$



So, for light scalar, parameters O(1), have gravitational strength long range force, ruled out by local tests of GR! If we want workable model need to make this sufficiently weak in local environment, while allowing for significant deviations from GR on cosmological scales!

Screening Mechanisms

Remember the EFT classification of terms in a covariant Lagrangian

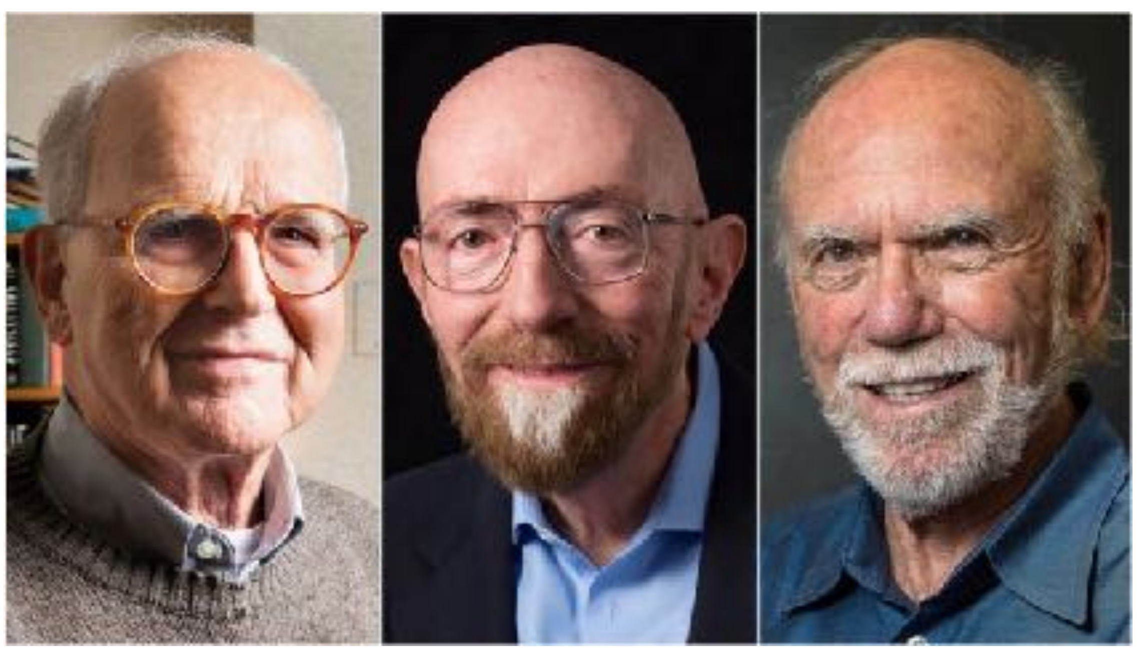
- There exist several versions, depending on parts of the Lagrangian used
  - **Vainshtein**: Uses the kinetic terms to make coupling to matter weaker than gravity around massive sources.
  - **Chameleon**: Uses coupling to matter to give scalar large mass in regions of high density
  - **Symmetron**: Uses coupling to give scalar small VEV in regions of low density, lowering coupling to matter

If one can avoid the extensive theoretical constraints, then in general, couplings in the dark sector, screened or unscreened, can now be probed in many different and complementary ways.

… and now we have New Tools!

LIGO/VIRGO +DES, etc. are already bounding many of these ideas!

Theory space is about to get narrower. How much?



e.g. Constraints from from GW170817 and GRB 170817A

A number of relevant papers (e.g. 1710.06394)
The landscape seems to be summarizable as:

$$\mathcal{L} = K(\phi, X) + G_3(\phi, X)\Box\phi + G_4(\phi)R \qquad X = -1/2(\partial\phi)^2$$

is OK, (G_3 term - trouble w/ ISW in some circumstances (e.g. cubic galileon).
Anything higher i.e.

$$G_4(\phi, X) + G_{4,X}\left((\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right) + G_5(\phi, X)\cdots$$

is in trouble unless

- the scalar is non cosmological i.e. $\dot{\phi} \ll H_0 m_p$ (similarly other time derivatives)
- there is some sort of tuning between the functions
- there is a tuning in the initial conditions so that all time-derivatives cancel near the present time
- the theories lie in the beyond Horndeski class of theories that are conformally related to the Horndeski subset where $c_T = c$

See talks by E. Berti, D. Langlois, …

Caveat: can be parameter tunings and certain initial conditions that give you a small subset of models that just get everything right. Not attractive though.

Complementary Method - Survey Cosmology - an Analogy with Particle Physics

Particle Physics

New physics discovery relies on:

- increasing energy of collisions,
  - Allows access to new events that don't appear at lower E.
- increasing accelerator luminosity
  - e.g. produce more Higgs, and measure decay modes more accurately.
  - Can allow very rare decays to be discovered at statistically significant level.

Survey Cosmology

New physics discovery relies on:

- increasing redshift of detection,
  - Allows access to new events and objects absent at lower z.
- increasing number of objects
  - detecting more objects, allows more precise measurements of inhomogeneities.
  - Can allow different signatures in shape of power spectrum to be discovered at statistically significant level.

All allow access to **a lot of** new physics!

One of primary points from Cosmic Visions White Paper:
(S. Dodelson, K. Heitmann, C. Hirata, K. Honscheid, A. Roodman, U. Seljak, A. Slosar and M.T., "Cosmic Visions Dark Energy: Science,"arXiv:1604.07626 [astro-ph.CO].)

Example - Constraining Dark Couplings

- Modern cosmology contains large unanswered questions
- Solve by:
  - Postulating new components of the energy
  - Modifying the gravitational dynamics

- In many cases, these approaches introduce interactions among different types of particles, in different sectors of the theory
  - e.g. modified gravity often needs a screening mechanism such as the chameleon mechanism.
  - These operate through non minimal couplings
  - e.g. braneworld models, with some fields in the bulk and others on the brane.
  - 4d theory can often contain non minimal couplings.

- These couplings may themselves provide answers to some of the hints of more subtle problems in cosmological data.

An Example - the H_0 Problem

See talk by F. Bouchet

- Standard cosmological model explains most observations.
- However, several anomalies and tensions have been found between cosmological and astrophysical data.
- <u>May</u> point to the presence of new physics.
- One much-discussed discrepancy is between measurements of the Hubble parameter at different redshifts.

- Local measurement obtained by observing Cepheid variables

$$H_0 = 73.24 \pm 1.79\,\mathrm{km/s/Mpc}$$

[Riess et al., Astrophys. J. 826 (2016) no. 1, 56, arXiv:1604.01424]

- Planck data estimate (LCDM, three 0.06eV neutrinos)

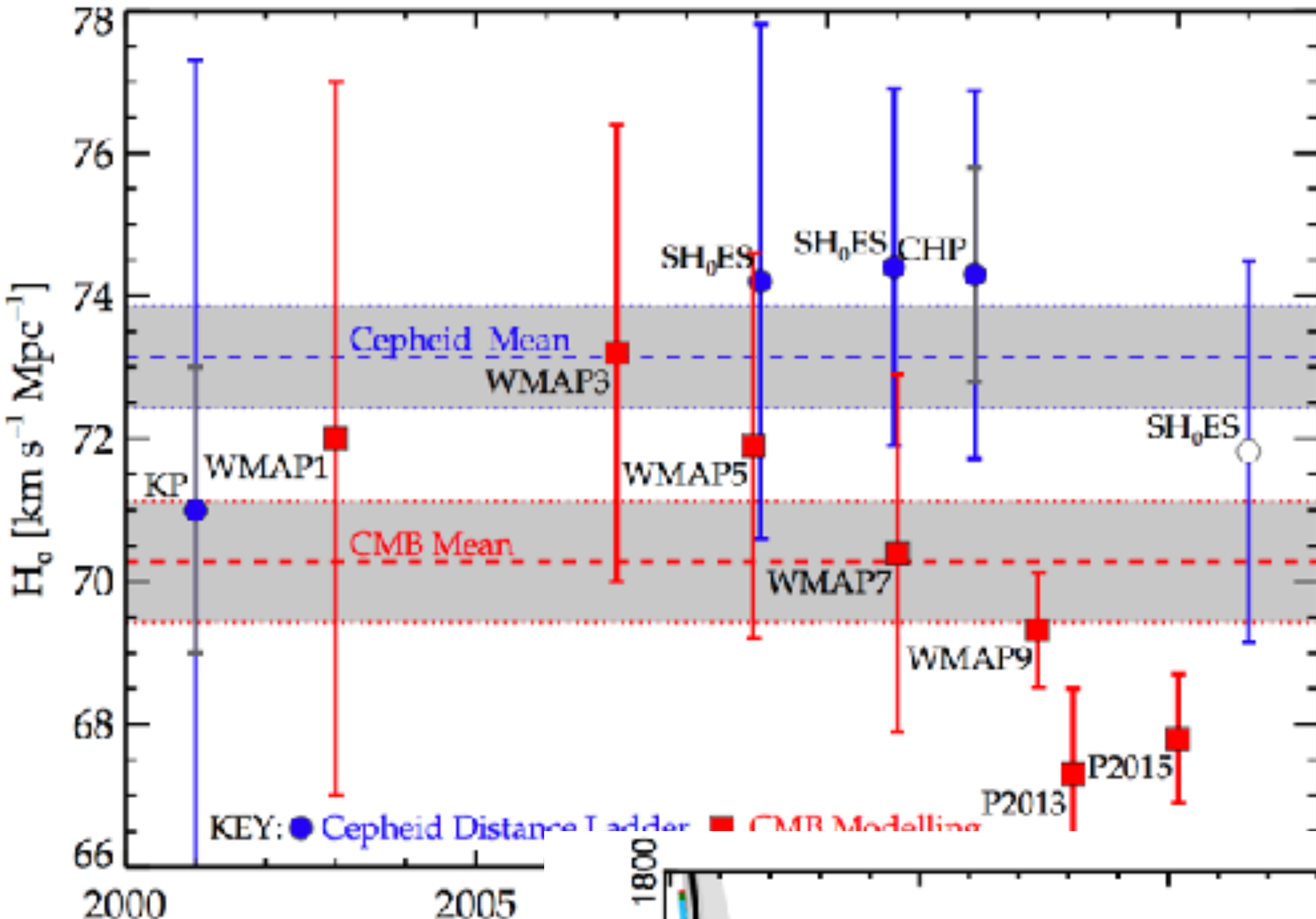
$$H_0 = 66.93 \pm 0.62\,\mathrm{km/s/Mpc}$$

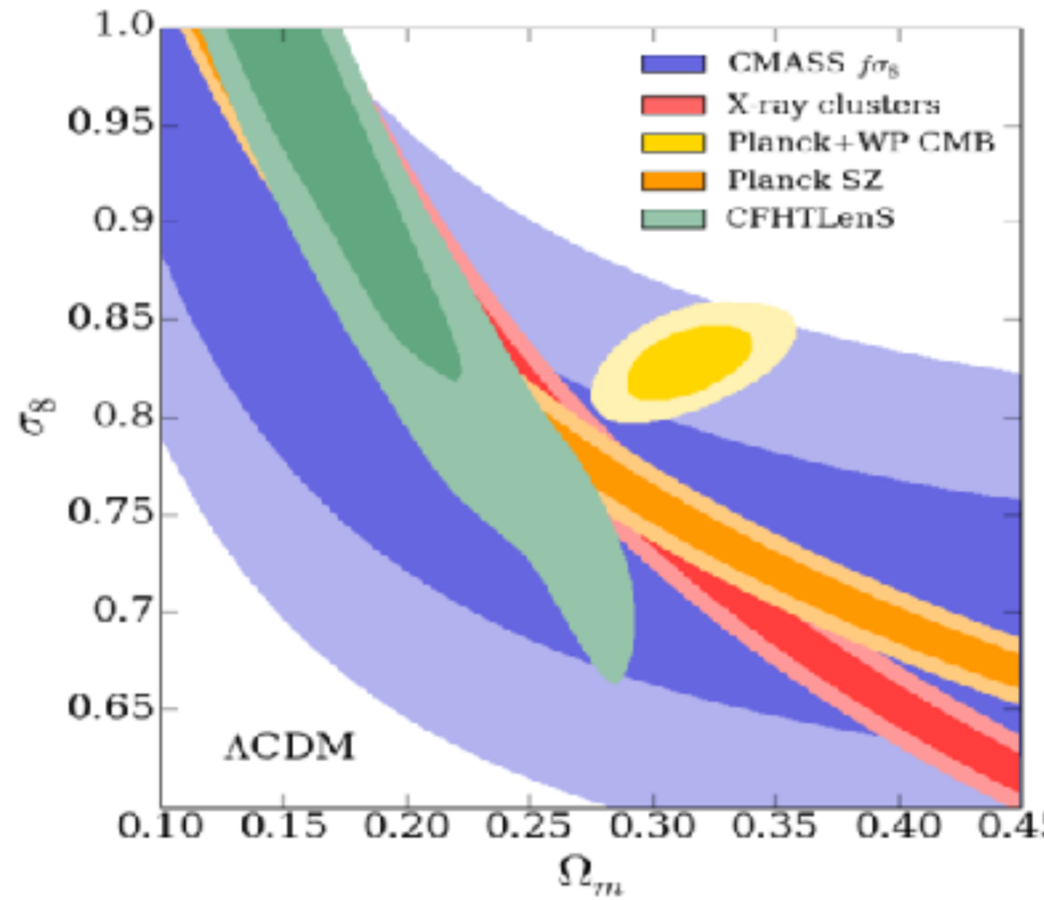
[Ade et al. (Planck Collaboration) A.A. 594, A13 (2016) arXiv:1502.01589]

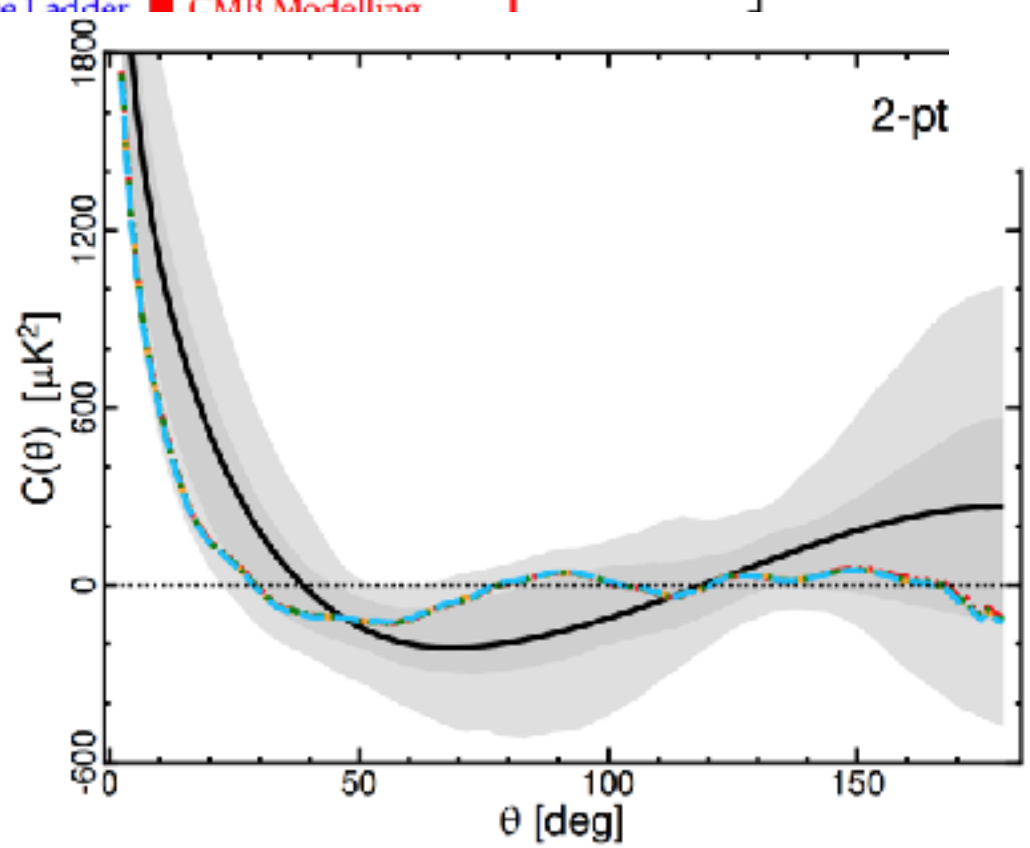
- Interactions may help this by changing the expansion history and modifying the growth of structure.

[e.g. Valentino, Melchiorri, and Mena, Phys. Rev. D96 (2017) no. 4, 043503, arXiv:1704.08342]

Moderate Tensions







Fluid Approach

- Treat dark matter and dark energy as perfect fluids.
- Energy-momentum tensors not independently conserved

$$\nabla_\mu T^{\mu\nu}_{\mathrm{cdm}} = -\nabla_\mu T^{\mu\nu}_{\mathrm{de}} = Q^\nu = \xi H u^\nu \rho_{\mathrm{cdm/de}}$$

$$\dot{\rho}_{cdm} + 3H\rho_{cdm} = Q$$
$$\dot{\rho}_{de} + 3H(1+w_{de})\rho_{de} = -Q$$

$$Q = \xi H \rho_{\mathrm{cdm/de}}$$

- Q>0 energy transfer: dark energy to dark matter
- Q<0 energy transfer: dark matter to dark energy
- DM density dilutes faster. In some models, the interaction can alleviate the H_0 tension.
- Results obtained in linear regime of theory. But: dark sector coupling can effectively change friction term in overdensity equation - dark matter feels augmented Newtonian potential.
- Can lead to important changes in the nonlinear regime.

Fluids to Fields

- Even a small coupling, resulting in small differences wrt LCDM in linear regime, could yield significant differences in nonlinear one;
- e.g. modifying the predictions for the number of clusters.
- So, appealing to have an underlying field theoretical description that is valid deep in the nonlinear regime.

A very simple example

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{Pl}^2 R - \frac{1}{2}\left(\nabla\phi\right)^2 - V(\phi)\right] + S_\chi\left[e^{2\alpha(\phi)}g_{\mu\nu}, \chi\right] + \sum_j S_j\left[g_{\mu\nu}, \psi_j\right]$$

Dark Matter Standard Model

We'll see this again later

Quantum Corrections

- Can think about quantum corrections. e.g for scalar DM

$$e^{\alpha(\phi)}V(\chi) \supset e^{\alpha(\phi)}m_\chi^2\chi\chi \qquad m_\chi^2\chi\chi + \frac{\beta}{M_{\rm Pl}}m_\chi^2\phi\chi\chi + \cdots$$

$$\alpha(\phi) \equiv \beta\phi/M_{\rm Pl} \ll 1$$

- Things we must require for the model to work:
  - χ is DM candidate - ultra-light boson never in equilibrium with thermal bath.
  - Should constitute all observed dark matter, need $m_\chi^2 > 10^{-33}\mathrm{GeV}$
  - Then indistinguishable from cold dark matter (CDM).
  - Lastly, for φ to behave as dark energy we need $m_\phi \lesssim H_0$
  - Leading quantum corrections to DE mass $\Delta m_\phi \propto \beta\frac{m_\chi^2}{M_{\rm Pl}}$
  - To be technically natural must be subdominant to bare mass

$$\Delta m_\phi \ll m_\phi \sim H_0 \qquad 10^{-24}\mathrm{eV} \ll m_\chi \ll 10^{-2}\mathrm{eV}\sqrt{\frac{10^{-2}}{\beta}}$$

Constrains coupling to be very small.

Coupled P(X) Dark Matter

Seek a field theory model that reproduces the behavior of the perfect fluid models at both the background level and that of linear perturbations.

• Divide pressure perturbations into an adiabatic and a non-adiabatic part

$$\delta P = \frac{\partial P}{\partial S}\delta S + \frac{\partial P}{\partial \rho}\delta\rho = \delta P_{\rm NA} + c_s^2\delta\rho$$

$$c_s^2 = \dot{P}/\dot{\rho}$$

Comoving gauge

$$\delta P_{\rm NA} = \left(c_\phi^2 - c_s^2\right)\delta\rho$$

$$c_\phi \equiv \frac{\delta P}{\delta\rho}$$

Minimally-coupled scalar fields with Lagrangians of form

$$\mathcal{L} = f(Xg(\phi))$$

$$X = -1/2\,\nabla_\mu\phi\nabla^\mu\phi$$

equivalent to a barotropic fluid ($c_s^2 = c_\phi^2$) - have vanishing non-adiabatic pressure to all orders in perturbation theory. Here we include a conformal coupling - insignificant violation of the adiabaticity condition.

New Model

M. Carrillo González and M.T., arXiv:1705.04737

$$\mathcal{L}_\chi = f(Xh(\chi))$$

$$X = \frac{1}{2}e^{-2\alpha(\phi)}\nabla_\mu\chi\nabla^\mu\chi$$

$$P_\chi = e^{4\alpha(\phi)} f(X\,h(\chi)),$$

$$\rho_\chi = e^{4\alpha(\phi)}\left[2X\frac{\partial f(X\,h(\chi))}{\partial X} - f(X\,h(\chi))\right]$$

$$\dot{\rho}_\chi + 3H\left(\rho_\chi + P_\chi\right) = -\alpha'\dot{\phi}\left(3\rho_\chi - P_\chi\right)$$

Consider case in which field satisfies

$$\frac{P_\chi}{\rho_\chi} \to 0, \qquad \frac{\rho_\chi + P_\chi}{2X\frac{\partial\rho_\chi}{\partial X}} \to 0$$

$$\alpha(\phi) = \beta\phi/M_{Pl}$$

$$\left|\frac{\delta P_{\mathrm{NA}}}{\delta P}\right| \lesssim \beta\left|1 - \frac{4}{3}\frac{\omega_\chi}{c_\chi^2}\right|$$

- For known P(X) Lagrangians that lead to a pressureless field, such as DBI,

$$|\omega_\chi| = |c_\chi^2|$$

and small coupling implies $\delta P_{\mathrm{NA}}/\delta P \to 0$

DBI DM coupled to DE

One of simplest examples

$$\mathcal{L} = -M^4\sqrt{1-2X}$$

With DM action

$$S_\chi = -\int d^4x\sqrt{-g}\, e^{4\alpha(\phi)} M^4 \sqrt{1-2e^{-2\alpha(\phi)}X}$$

Equation of state and speed of fluctuations

$$\omega = -\frac{1}{\gamma^2}, \qquad c_\chi^2 = \frac{1}{\gamma^2} \qquad \gamma \equiv \frac{1}{\sqrt{1-2e^{-2\alpha(\phi)}X}}$$

In relativistic limit $\gamma \gg 1$ get DM behavior

Other consistencies

$$\alpha_0 \equiv \alpha(\phi(t_0)) \lesssim 1$$

$$\rho = M^4 e^{4\alpha(\phi)}\gamma \sim M^4 e^{\alpha(\phi)}\frac{A}{a^3} \qquad A = 3\Omega_{\rm CDM}\, e^{-\alpha(\phi)}\frac{H_0^2 M_{\rm Pl}^2}{M^4} \sim 30\left(\frac{2.7\times 10^{-5}\ {\rm eV}}{M}\right)^4$$

If A=30, brane tension $M \sim 10^{-5}$ eV or smaller would give the desired behavior.
Background and linear perturbations behave as fluid case.
So, H_0 tension is alleviated in these models, by construction, for $\beta \sim 0.066$

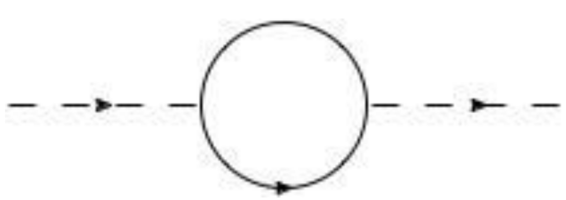
Quantum Corrections

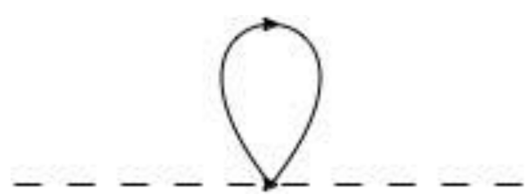
Loop corrections to n-point scattering amplitude given by

$$\mathcal{M}_\phi^{(n)} = \beta^n \frac{M^4}{M_{Pl}^n}\left(\frac{k}{M}\right)^{2L+2+\sum_m (m-2)V_m}$$

L= number of loops;
V_m = number of vertices with m lines

Largest quantum correction to the dark energy mass is





$$\Delta m_\phi = \beta \frac{k^2}{M_{Pl}}$$

Require this small

$$k < \left(\frac{m_\phi M_{Pl}}{\beta}\right)^{1/2} \sim \left(\frac{10^{-2}}{\beta}\right) 0.1 \text{ eV}$$

Self-consistency means must be below cutoff Λ_c of theory;
So, will work in regime $k \leq \Lambda_c$
As long as cutoff is such that $\Lambda_c \leq 0.1$ eV and β is not too large corrections will be under control.

Validity of Linear Regime: Fields vs. Fluids

Want to consider differences between fluid and field descriptions that may arise at nonlinear scales, when field gradients become large

Work in Newtonian gauge for weakly coupled P(X) theory that behaves as dark matter, with perturbed metric

$$ds^2 = -(1+2\Phi)\ dt^2 + (1-2\Phi)\, a^2(t)\ d\mathbf{x}^2$$

Mukhanov-Sasaki variable 

$$\frac{\nu}{z} = \frac{5\rho_\chi + 3P_\chi}{3(\rho_\chi + P_\chi)}\Phi + \frac{2\rho_\chi}{3(\rho_\chi + P_\chi)}\frac{\dot{\Phi}}{H} \qquad z = \frac{a\sqrt{\rho_\chi + P_\chi}}{c_\chi H}$$

Satisfies

$$\nu'' + \left(c_\chi^2 \nabla^2 \left(1 + \frac{2}{\nu}\int \frac{\alpha_\phi \mathcal{H}}{X\, e^\alpha}\varphi\ d\eta\right) - \frac{z''}{z}\right)\nu = 0$$

Solving

Can solve in two limits - long and short wavelengths
find that the linear regime for the field perturbations is valid as long as

$$\Phi_d(\mathbf{x})\left(\frac{\ddot{\chi}t_0}{\dot{\chi}}\left(\frac{t_0}{t}\right)^{2/3}-\frac{2}{3}\left(\frac{t_0}{t}\right)^{5/3}\right)+\nabla\Phi_d\,t_0\left(\frac{t_0}{t}\right)^{2/3}<1$$

Decaying mode

t at end of matter domination

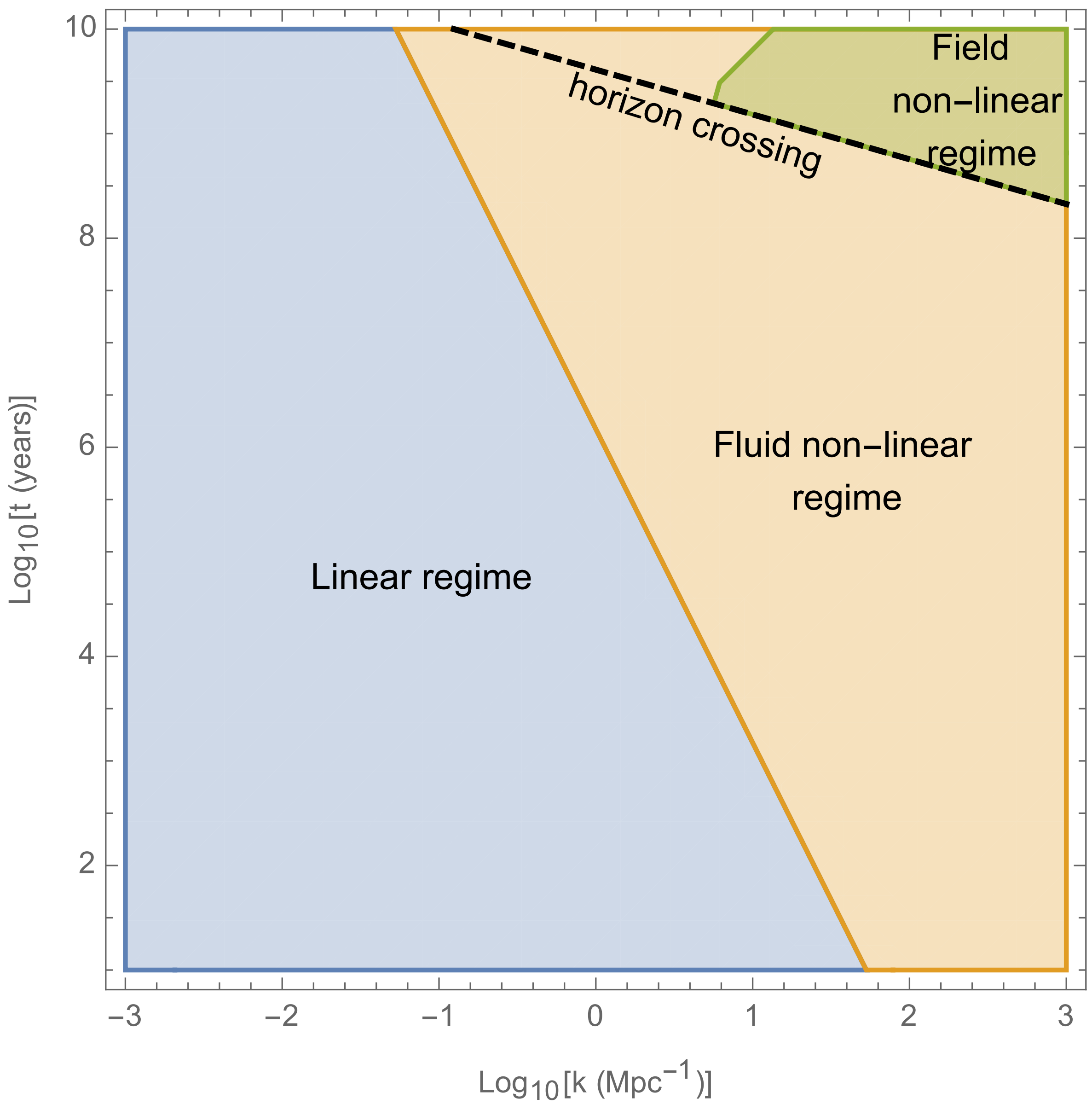
Compare with fluid point of view

$$\delta=\frac{2M_{Pl}^2}{\rho}\left[\frac{1}{a^2}\nabla^2\Phi-\frac{3H}{2M_{Pl}^2}(\rho_\chi+P_\chi)\frac{\xi}{\dot{\chi}}\right]$$

$$\delta=\frac{3}{2a_0^2}t_0^{4/3}\nabla^2\Phi t^{2/3}-2\Phi+\text{decaying modes}$$

Can see that validity of fluid linear regime is same as in CDM

Combined Constraints



Approximate linear and nonlinear regimes in k-t plane for coupled DBI model with A=30. The dotted line shows horizon crossing: Fluid nonlinear regime starts when

$$3/2\, k^2 \Phi a_0^{-2} t_0^{4/3} t^{2/3} > 1$$

Field nonlinear regime starts when physical wavelength of perturbation is smaller than sound horizon and

$$k\Phi\, t_0^{5/3} t^{-2/3} > 1$$

Fluid nonlinear regime reached before field gradients grow large. So field theory can be trusted in fluid nonlinear regime without worrying about e.g. formation of caustics. In the DBI case, for scales satisfying $k\Phi\, t_0^{5/3} t^{-2/3} > 1$ inside sound horizon, caustics could form and cannot trust any conclusions.

Go back to the Simple Model

Would like to now bring the powerful methods of structure formation measurements to bear on these exotic models. In particular have shown lensing in surveys is particularly powerful. Full exotic coupled models coming in the future, for now …

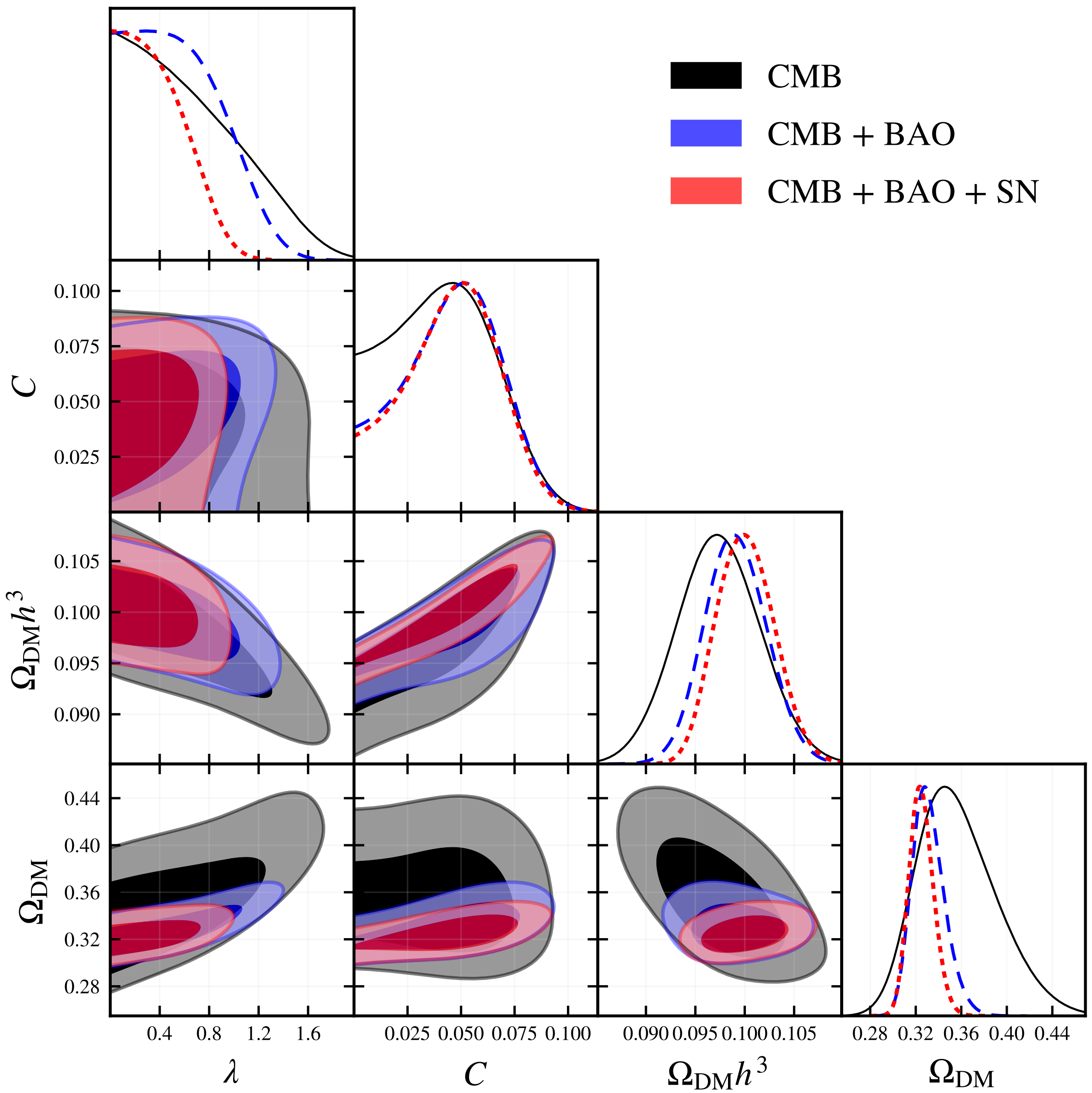
Recall the very simple example

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{Pl}^2 R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right] + S_\chi\left[\underbrace{e^{2\alpha(\phi)}g_{\mu\nu}, \chi}_{\text{Dark Matter}}\right] + \sum_j S_j\left[\underbrace{g_{\mu\nu}, \psi_j}_{\text{Standard Model}}\right]$$

We'd like to see how current and future surveys might constrain our complicated coupled models. For now, start with this simple one again, and eventually work ourselves up in future work to very complicated ones.

V. Miranda, M. Carrillo González, E. Krause and M.T., arXiv:1707.05694

Existing Constraints in the Mildly Nonlinear Regime



$$V(\phi) = V_0 \exp\left(-\lambda \frac{\phi}{M_{\rm pl}}\right)$$

$$\alpha(\phi) = -C\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm pl}}$$

- Dark matter dilutes faster, implying smaller matter density
- Acoustic peaks move to larger multipoles
- Radiation-matter equality takes place later

- Planck data reveals a preference for low power on large scales
- Implies a weak preference for C>0
- But, doesn't solve other tensions simultaneously.

Coupling Affects the Linear Power Spectrum

- Matter linear power spectrum defined by

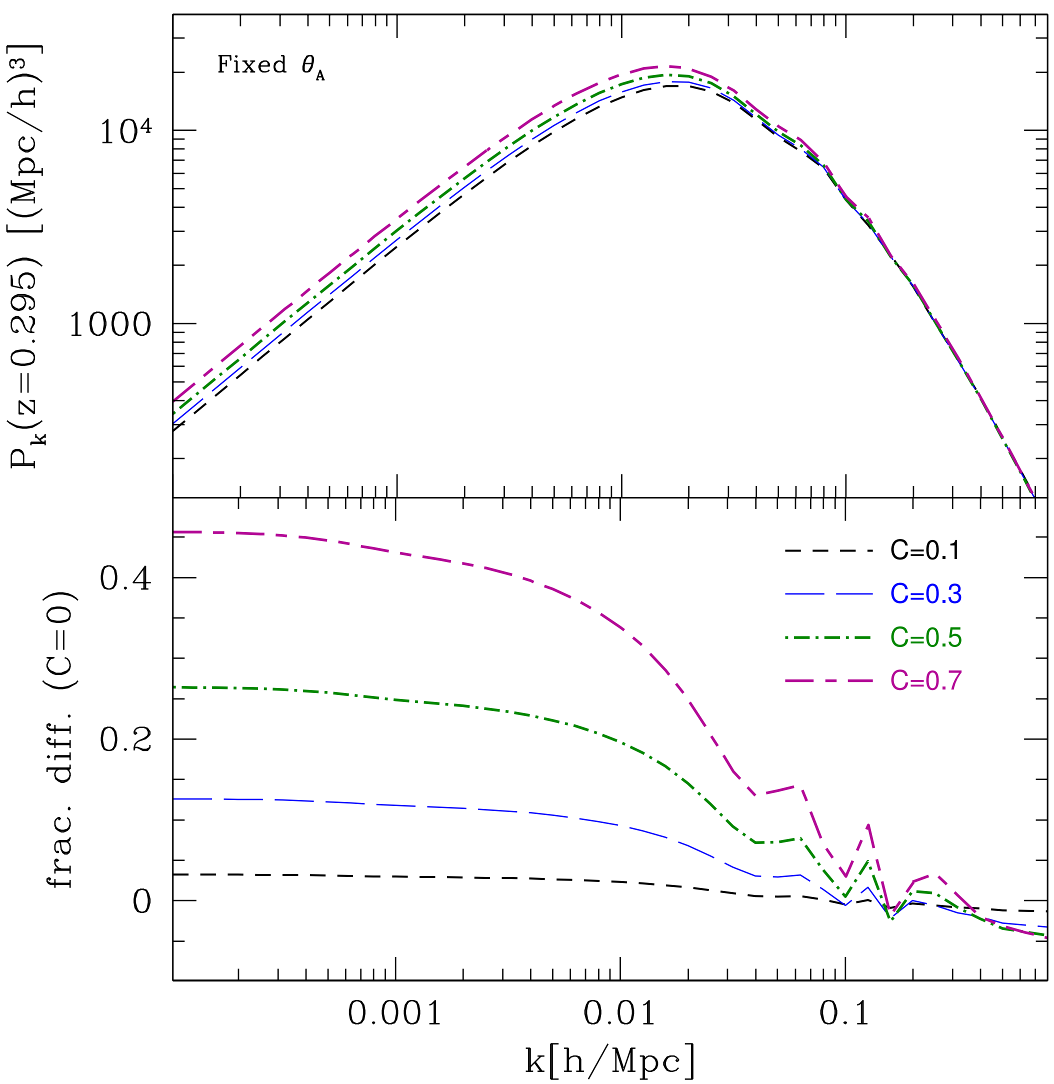
$$\frac{k^3}{2\pi^2}P_k = \frac{4}{25}A_s\left(\frac{G(a)a}{\bar{\Omega}_m}\right)^2\left(\frac{k}{H_0}\right)^4\left(\frac{k}{k_{\rm norm}}\right)^{n_s-1}T^2(k)$$

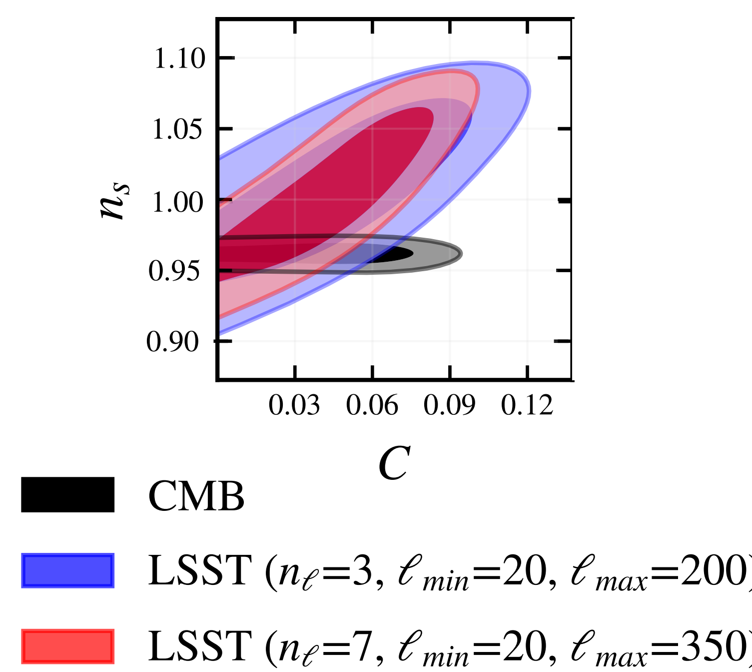
Inflationary amplitude

Growth rate relative to During matter dom in LCDM

Inflationary spectral index

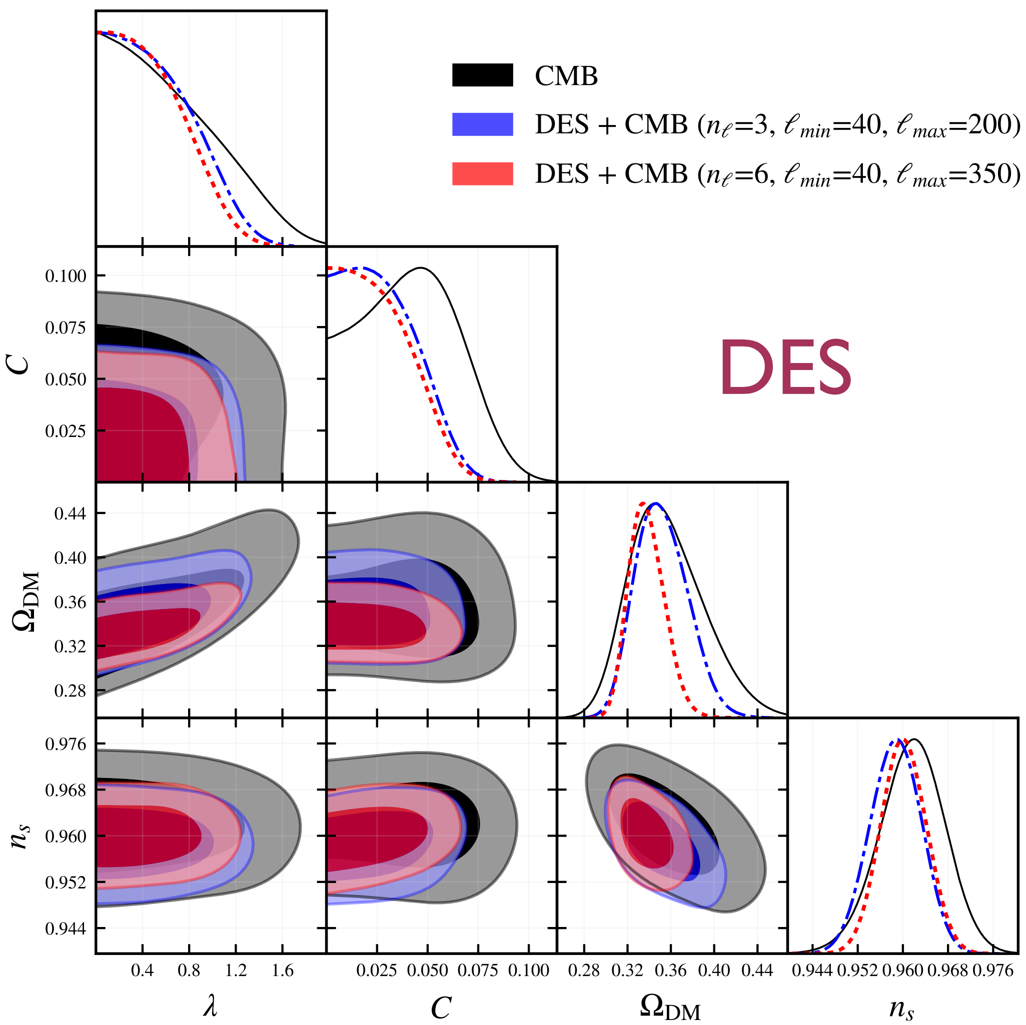
Transfer function

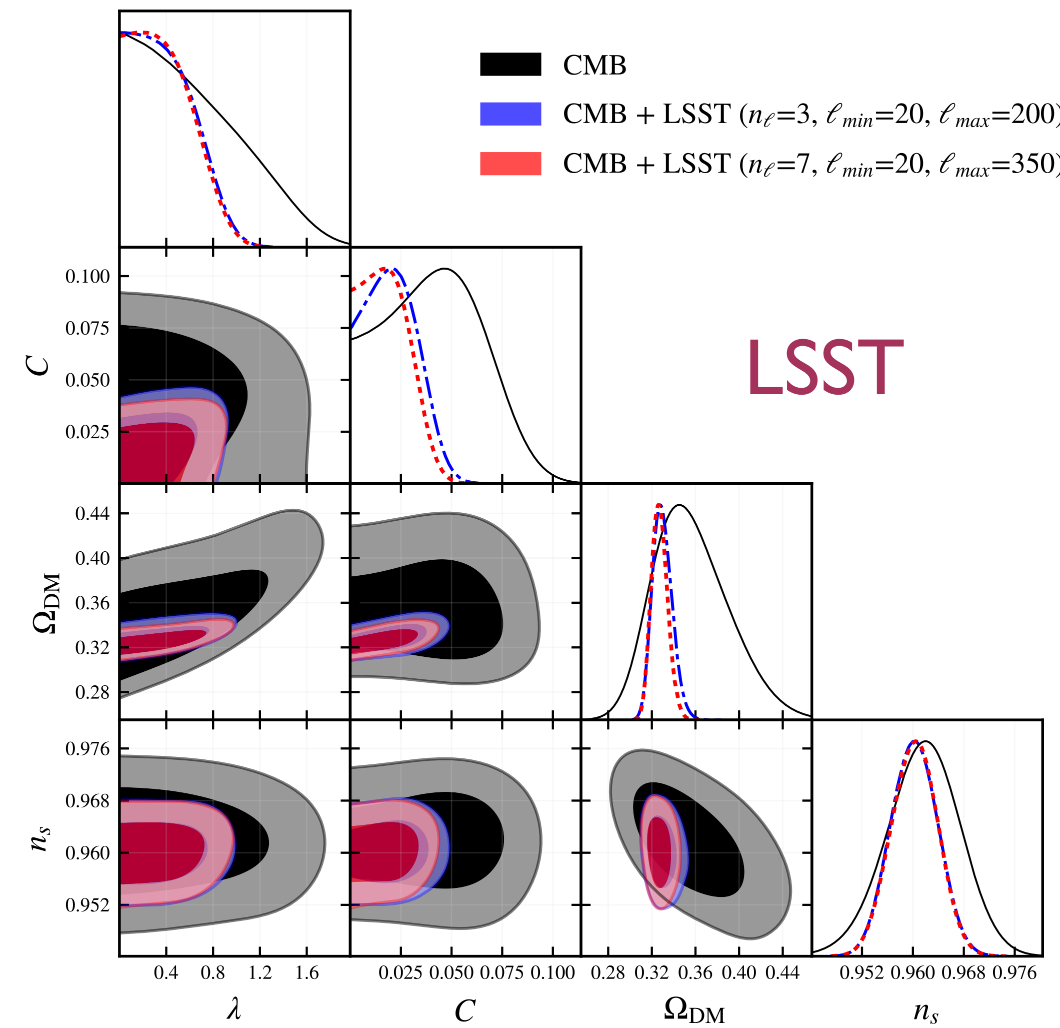




- Effect of coupling is to mimic changing spectral index at DES and LSST scales

Lensing Forecasts and Constraints





- DES LSS forecasts rule out C >0.12.
- More k-modes - better constraints on direction perpendicular to n_s-C degeneracy, if linear power spectrum is good approximation.
- BUT, on nonlinear scales, the matter power spectrum becomes less sensitive to changes in spectral index - therefore see less improvement in direction perpendicular to n_s-C degeneracy.

Summary I

- Cosmic acceleration: one of our deepest problems
- Questions posed by the data need to find a home in fundamental physics, even if a cosmological constant is the right answerand many theorists are hard at work on this. Requires particle physicists and cosmologists to work together.
- We still seem far from a solution in my opinion, but some very interesting ideas have been put forward in last few years.
- Many ideas (and a lot of ugly ones) being ruled out or tightly constrained by these measurements. And fascinating new theoretical ideas are emerging (even without acceleration)
- Serious models only need apply - theoretical consistency is a crucial question. We need (i) models in which the right questions can be asked and (ii) A thorough investigation of the answers. (***Beware of theorists' ideas of likelihood.***)

Summary II

• Interacting dark sector, perhaps even mimicking the complexity of the visible sector, motivated both through candidate models of high energy physics and by the considerations of effective field theory.
•Modern cosmological data allows for constraints on such proposals through the combination of multiple datasets relevant to physics at many different scales.

•Have revisited simple realization of this idea - single component of dark matter interacts with single dark energy field through coupling described by single dimensionless parameter C.
•Previous work using CMB data has shown that energy transfer from dark matter to dark energy (C>0) preferred at small statistical significance by current observations, mainly because of lower power in T-T power spectrum at large scales observed in Planck data.

Summary III

- Preference for a smaller DM fraction when CMB included slightly increases the posterior for C > 0.05.

- BUT: Planck data rules out C > 0.1, and have shown that addition of low redshift information from BAO and type IA SNe doesn't change this upper limit.

- Have used weak lensing and galaxy clustering in data forecasts for both DES and LSST to demonstrate correlation between the inflationary spectral index and the dark sector coupling,

- At redshifts probed by large-scale structure effect of positive C in the matter power spectrum is similar to changing the tilt.

Summary IV

•Combination of lensing and clustering of galaxies and CMB data has allowed us to demonstrate an improvement on the constraints on the coupling strength without entering the deeply nonlinear regime.

•The tightest constraint on the coupling strength from combining CMB and LSST data. $C \lesssim 0.03$

•Further improvement on this constraint could be achieved by better modeling the matter power spectrum deep into the nonlinear regime, but this option requires expensive N-body simulations.

•Models are not able to address the Hubble and sigma-8 tensions between CMB and low redshift data at the same time.

•Constraints at level of $C \lesssim 0.03$ already diminish significantly the appeal of such models.

And Congratulations to Misao!

It is clear that there is a great deal of work to do by brilliant, creative researchers, unencumbered by time-consuming administrative and even teaching requirements.

Thank You!