Cosmic Acceleration: Status and Prospects

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CosPA Symposium 2017

YITP, Kyoto, December 2017

Overview

- Motivations - brief background

- Quick comments on some possible approaches:
    - The cosmological constant
    - Dynamical dark energy
    - Modified gravity

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

- Theoretical Issues - status of models

- Modified Gravity - Observational status

- Prospects - an example - Probing a complex dark sector.

- 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

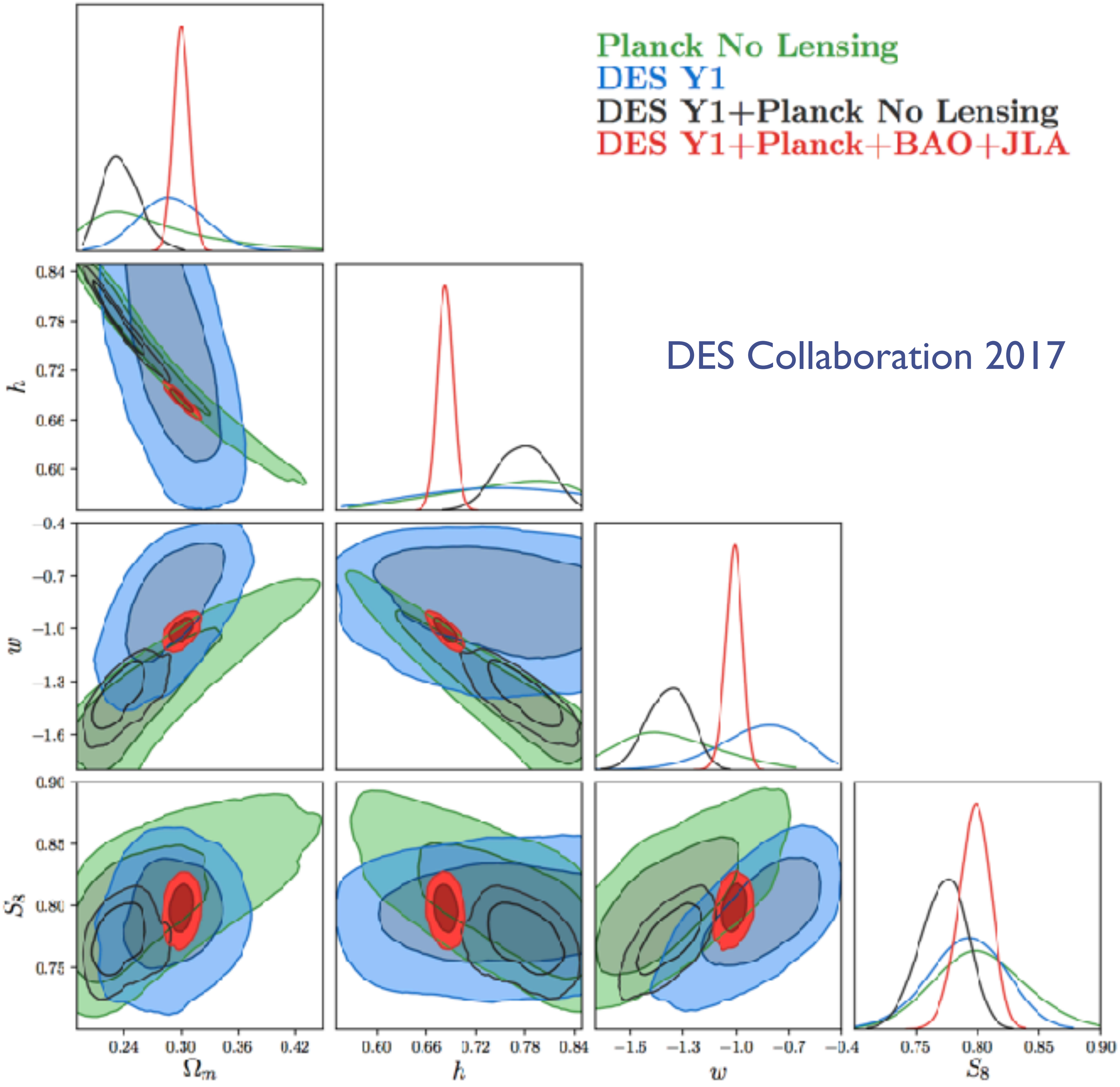
If we assume GR

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

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

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)

$$\frac{E}{\Lambda} << 1$$

(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

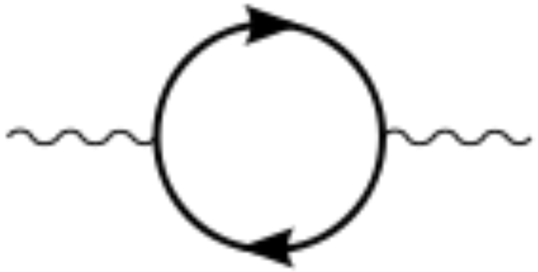
Even if your quantum mechanical corrections do not ruin your ability to trust your theory, any especially small couplings you need might be a problem.

- 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.

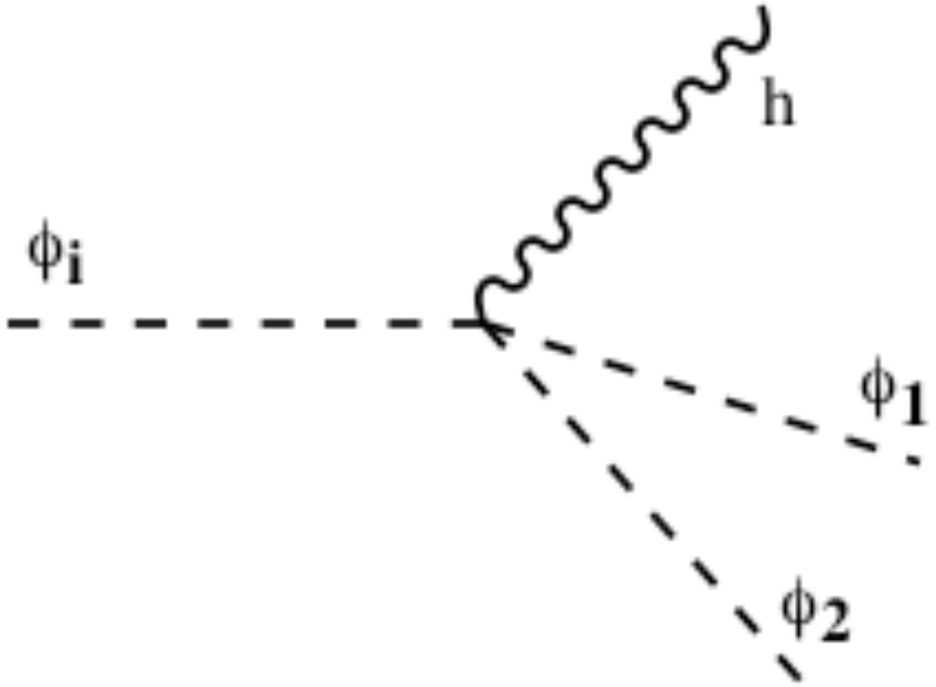
$$-\frac{f(\chi)}{2}K(\partial_\mu\partial^\mu\phi) \rightarrow F(t,x)\frac{1}{2}\dot{\phi}^2 - G(t,x)(\nabla\phi)^2$$

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

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

- 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, …

The Need for Screening in the EFT

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

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

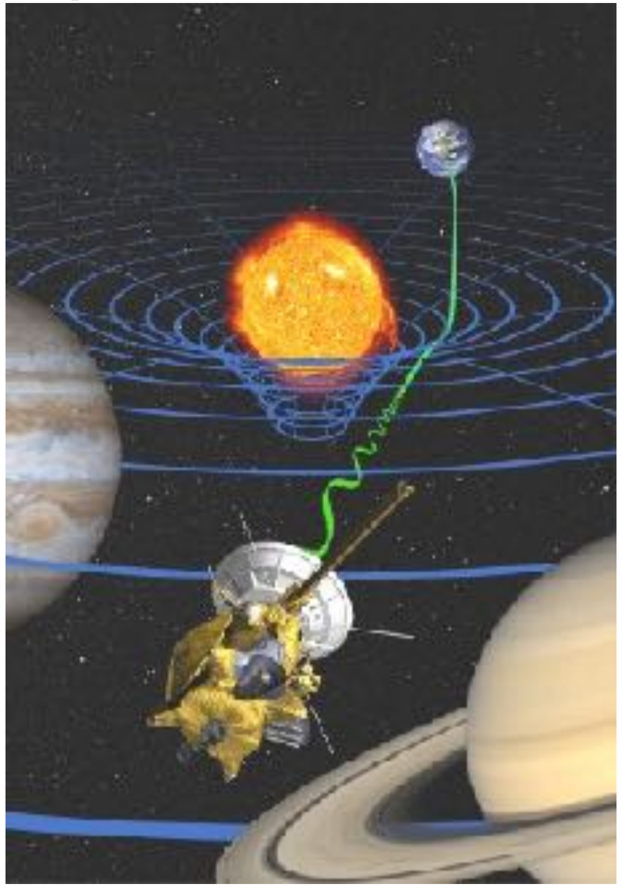
Specialize to a point source $T^\mu_\mu \to -\mathcal{M}\delta^3(\vec{x})$ and expand $\phi = \bar{\phi} + \varphi$

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

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

Massive gravity

Of particular interest - massive gravity

- Fierz and Pauli showed how to write down a linearized version of this, but...

$$\propto m^2(h^2 - h_{\mu\nu}h^{\mu\nu})$$

- ... thought all nonlinear completions exhibited the "Boulware-Deser ghost".

Over last 6 years a counterexample has been found.
This is a very new, and potentially exciting development!

[de Rham, Gabadadze, Tolley (2011]

$$\mathcal{L} = M_P^2\sqrt{-g}(R + 2m^2\mathcal{U}(g,f)) + \mathcal{L}_m$$

Proven to be ghost free, and investigations of the resulting cosmology - acceleration, degravitation, ... are underway, both in the full theory and in its decoupling limit - galileons!
(Also a limit of DGP)

[Hassan & Rosen(2011)]

The Vainshtein Effect - a Simple Example

Consider, for example, the cubic galileon, coupled to matter

$$\mathcal{L} = -3(\partial\pi)^2 - \frac{1}{\Lambda^3}(\partial\pi)^2\Box\pi + \frac{1}{M_{Pl}}\pi T$$

Now look at spherical solutions around a point mass

$$\pi(r) = \begin{cases} \sim \Lambda^3 R_V^{3/2}\sqrt{r} + const. & r \ll R_V \\ \sim \Lambda^3 R_V^3 \frac{1}{r} & r \gg R_V \end{cases} \qquad R_V \equiv \frac{1}{\Lambda}\left(\frac{M}{M_{Pl}}\right)^{1/3}$$

Looking at a test particle, strength of this force, compared to gravity, is then

$$\frac{F_\pi}{F_{\rm Newton}} = \frac{\pi'(r)/M_{Pl}}{M/(M_{Pl}^2 r^2)} = \begin{cases} \sim \left(\frac{r}{R_V}\right)^{3/2} & R \ll R_V \\ \sim 1 & R \gg R_V \end{cases}$$

So forces much smaller than gravitational strength within the Vainshtein radius - hence safe from 5th force tests.

The Vainshtein Effect

Suppose we want to know the the field that a source generates within the Vainshtein radius of some large body (like the sun, or earth)

Perturbing the field and the source

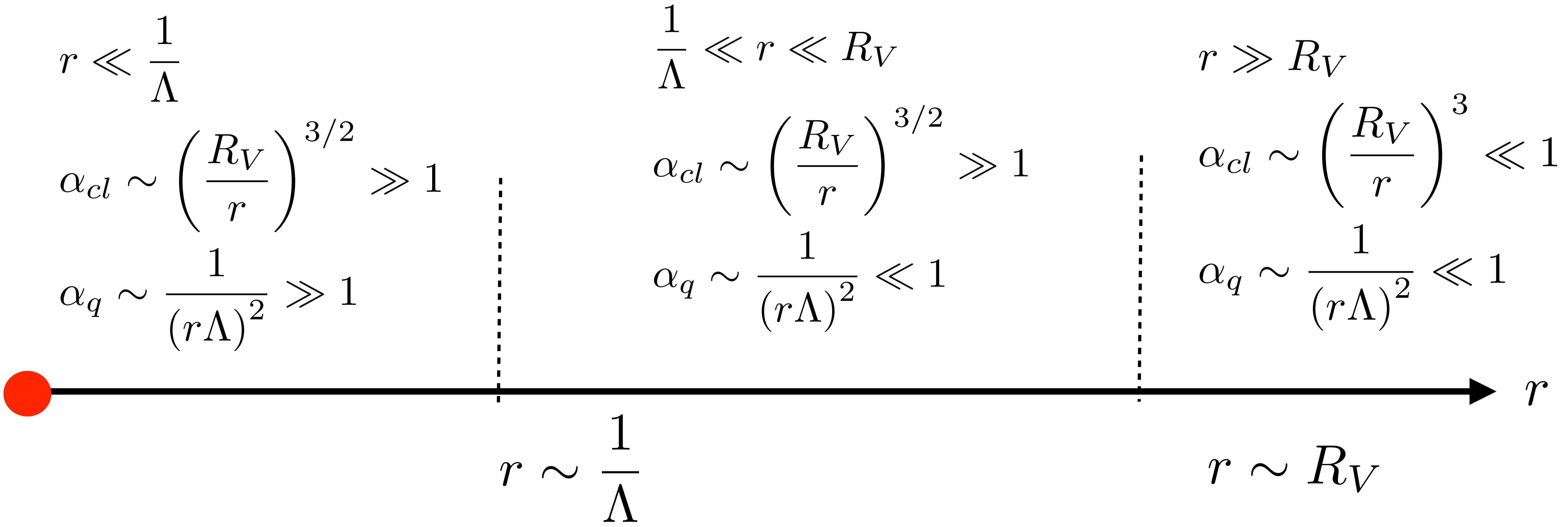
$$\pi = \pi_0 + \varphi, \quad T = T_0 + \delta T,$$

yields

$$\mathcal{L} = -3(\partial\varphi)^2 + \frac{2}{\Lambda^3}\underset{\sim\left(\frac{R_v}{r}\right)^{3/2}}{\underline{\left(\partial_\mu\partial_\nu\pi_0 - \eta_{\mu\nu}\Box\pi_0\right)}}\,\partial^\mu\varphi\partial^\nu\varphi - \frac{1}{\Lambda^3}(\partial\varphi)^2\Box\varphi + \frac{1}{M_4}\varphi\delta T$$

Thus, if we canonically normalize the kinetic term of the perturbations, we raise the effective strong coupling scale, and, more importantly, heavily suppress the coupling to matter!

Regimes of Validity



The usual quantum regime of a theory

$$r \ll \frac{1}{\Lambda}$$

$$\alpha_{cl} \sim \left(\frac{R_V}{r}\right)^{3/2} \gg 1$$

$$\alpha_q \sim \frac{1}{(r\Lambda)^2} \gg 1$$

$$\frac{1}{\Lambda} \ll r \ll R_V$$

$$\alpha_{cl} \sim \left(\frac{R_V}{r}\right)^{3/2} \gg 1$$

$$\alpha_q \sim \frac{1}{(r\Lambda)^2} \ll 1$$

The usual linear, classical regime of a theory

$$r \gg R_V$$

$$\alpha_{cl} \sim \left(\frac{R_V}{r}\right)^{3} \ll 1$$

$$\alpha_q \sim \frac{1}{(r\Lambda)^2} \ll 1$$

r

$$r \sim \frac{1}{\Lambda}$$

$$r \sim R_V$$

A new classical regime, with order one nonlinearities

The Vainshtein Effect is Very Effective!

Fix r_c to make solutions cosmologically interesting - 4000 Mpc =10^{10} ly

$$r^* = \left(\frac{2GM}{c^2} r_c^2 \right)^{1/3}$$

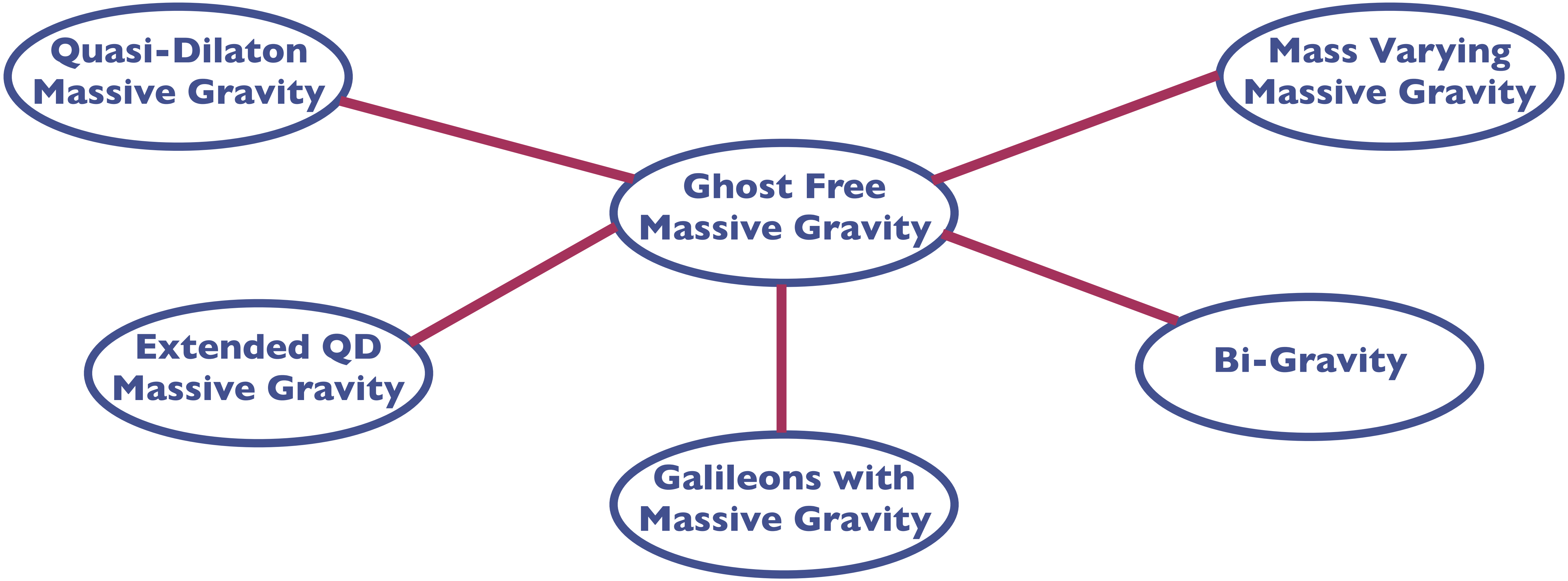
~0.1 kpc = 10^7 AU

~Mpc ~ 30 galactic radii

~10 Mpc ~ 10 virial radii

Is Massive Gravity up to the Job?

- Minimal massive gravity has fascinating features, but faces some cosmological challenges. Solutions not small modifications of GR.
- No flat isotropic accelerating cosmologies. Open ones (w/ a strong coupling problem); or anisotropic ones (not yet analyzed in detail).
- This has led to searches for extensions.



Quasi-Dilaton Massive Gravity

Mass Varying Massive Gravity

Ghost Free Massive Gravity

Extended QD Massive Gravity

Bi-Gravity

Galileons with Massive Gravity

- But so far, results are mixed - no definitive model yet in which all calculations are under control.

Status of Massive Gravity Theories

- Just to give an idea of what has been going on …

	Flat Isotropic Cosmology	Anisotropic Cosmology	Strongly-Coupled Perturbations
dRGT Massive Gravity	NO	YES	YES
Mass Varying Massive Gravity	YES	YES	NO
Quasi-Dilaton Theory	YES	YES	SOME
Extended QD Theory	YES	YES	NO
Galileons w/ Massive Gravity	NO	?	YES
BiGravity	DEPENDS	ON	FORM

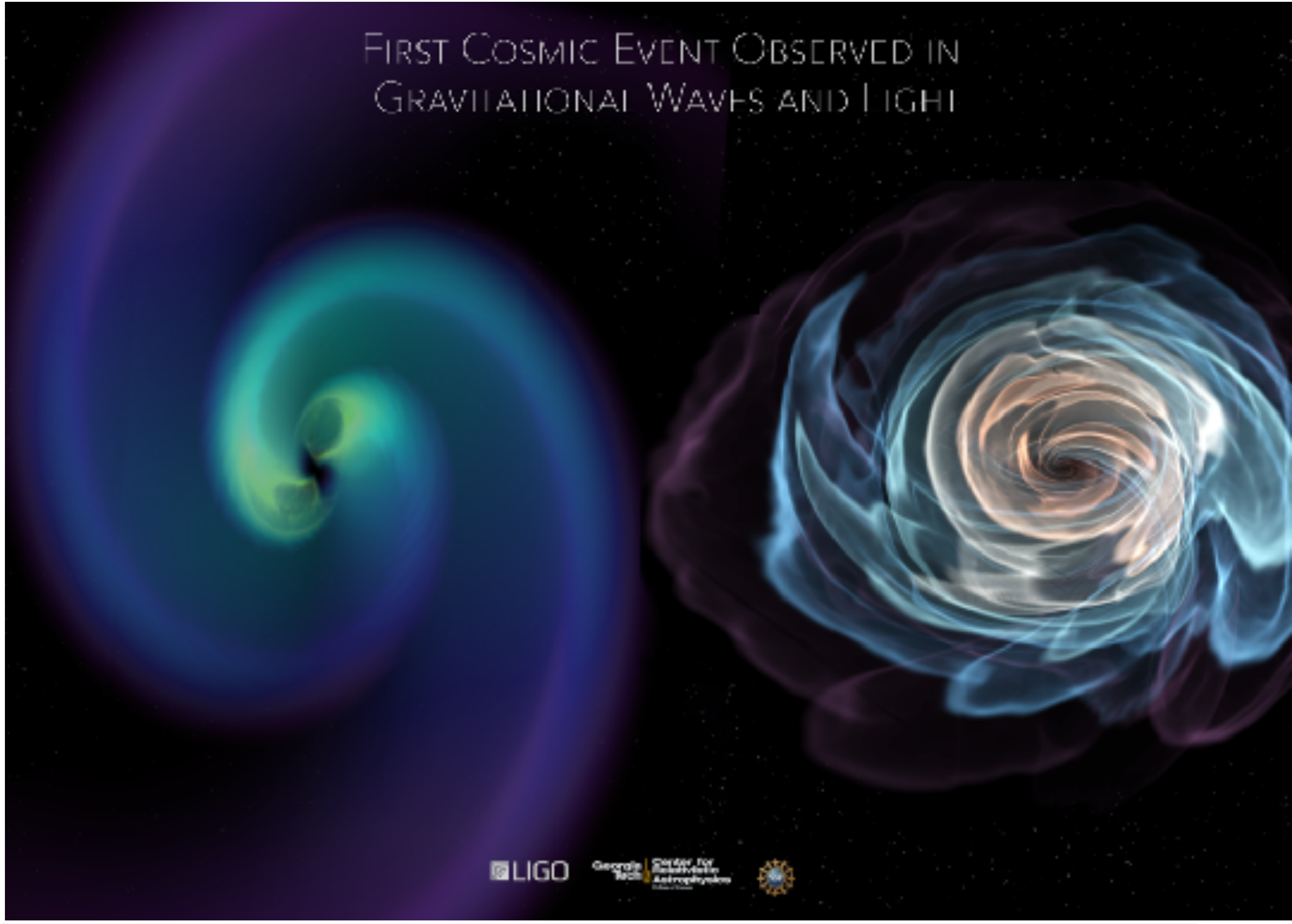
(Nice summary in Hinterbichler 1701.02873)

- Again: results are mixed - no definitive model yet in which all calculations are under control.

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?



Constraints from from GW170817 and GRB 170817A

A number of relevant papers (particularly https://arxiv.org/pdf/1710.06394.pdf)
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 $c_T = c$

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.

In General, for all models, can look for cosmological signals

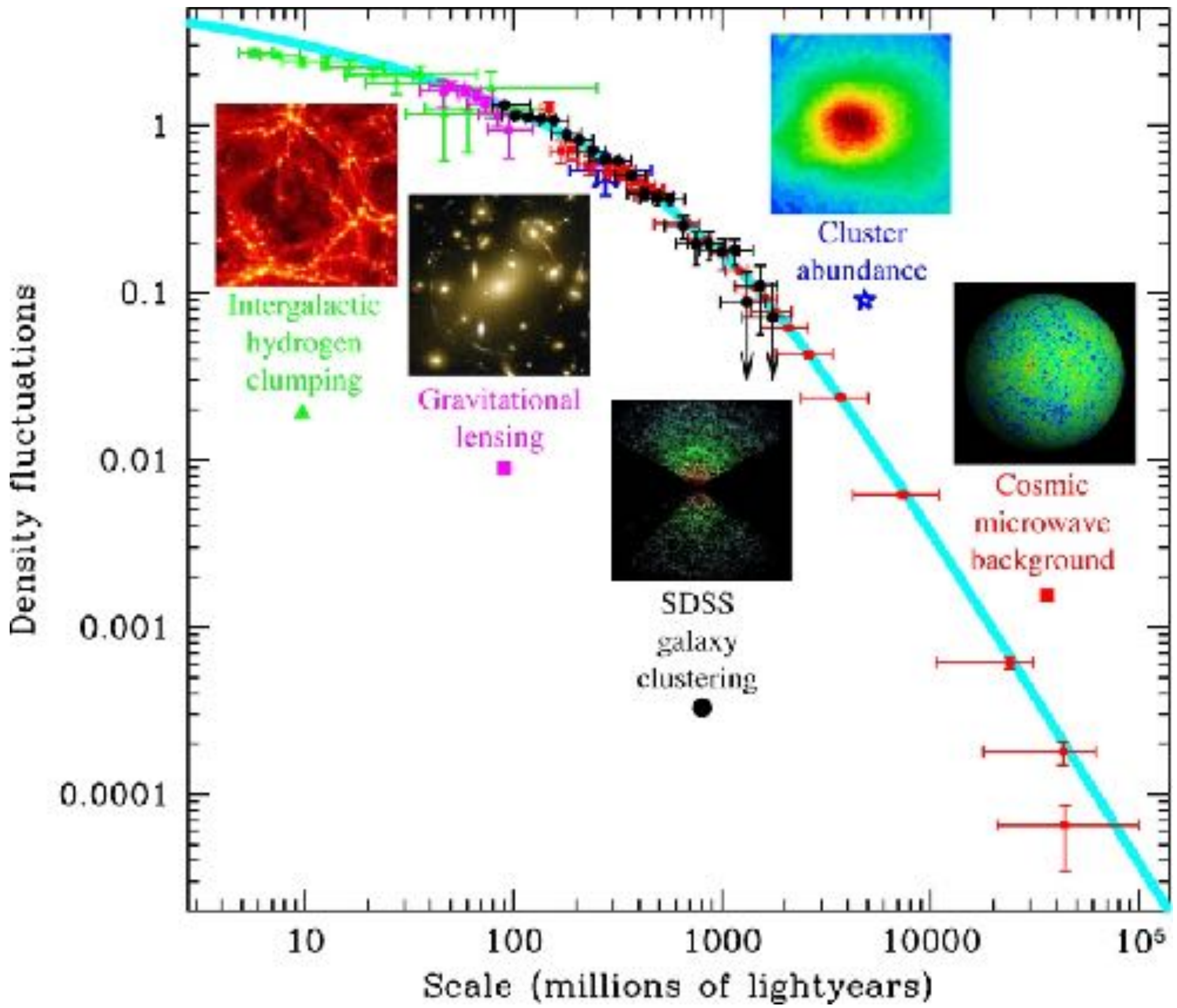
- Weak gravitational lensing
- CMB lensing and the ISW effect
- Redshift space galaxy power spectra
- Combining lensing and dynamical cross-correlations
- The halos of galaxies and galaxy clusters

- Very broadly: Gravity is behind the expansion history of the universe

- But it is also behind how matter clumps up - potentially different.

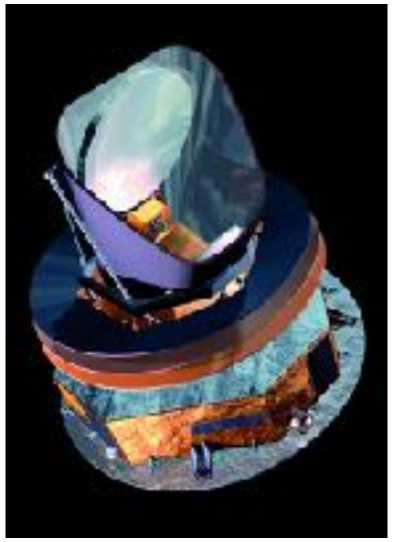
- This could help distinguish a CC from dark energy from other possibilities

- <u>Much</u> work remains here!



DARK ENERGY SURVEY

Large Synoptic Survey Telescope



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.

Simple Field Theory Models

- 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 into the nonlinear regime.

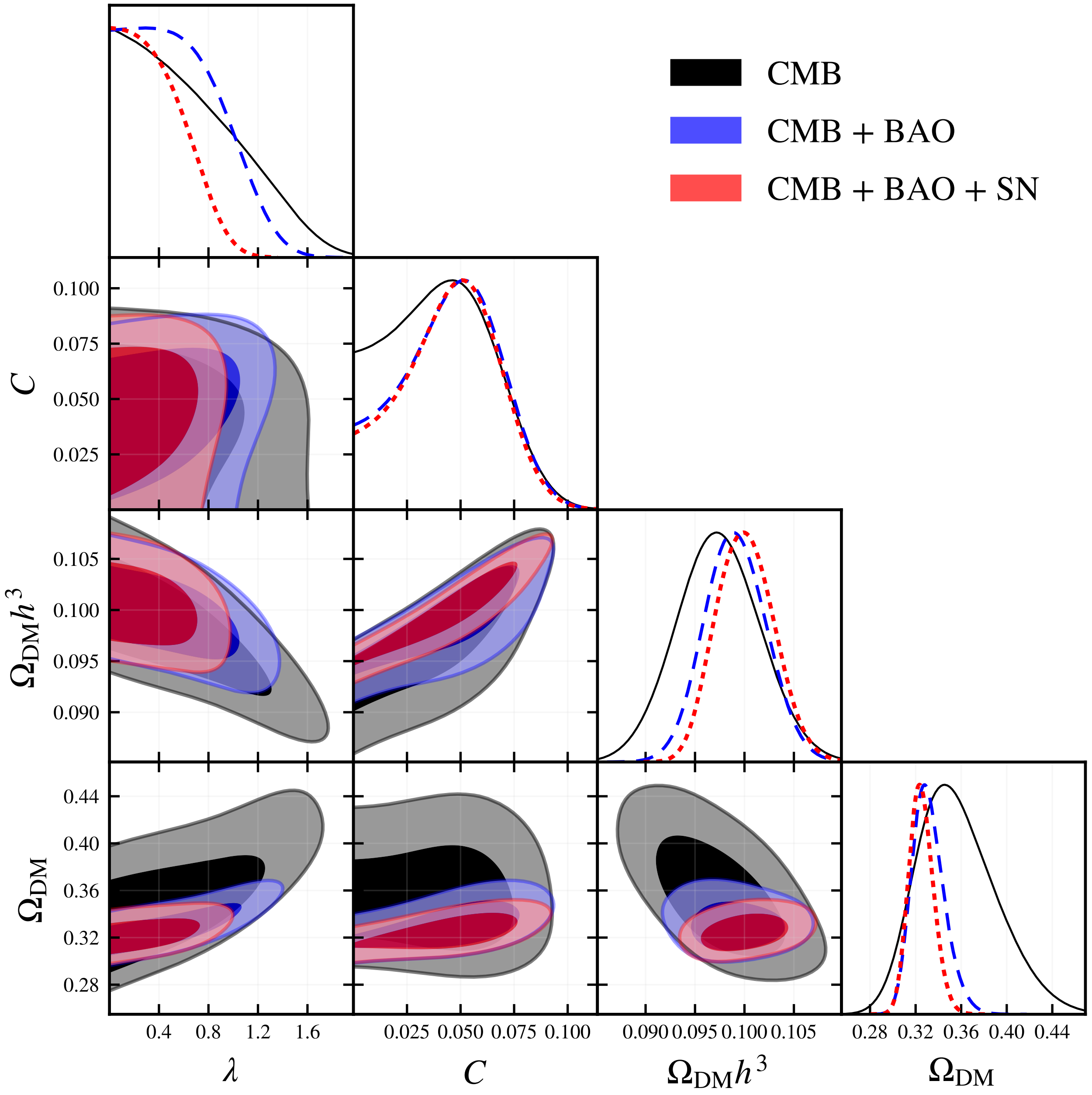
A very simple example

(c.f. talks by Rong-Gen Cai and Bin Wang)

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

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

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

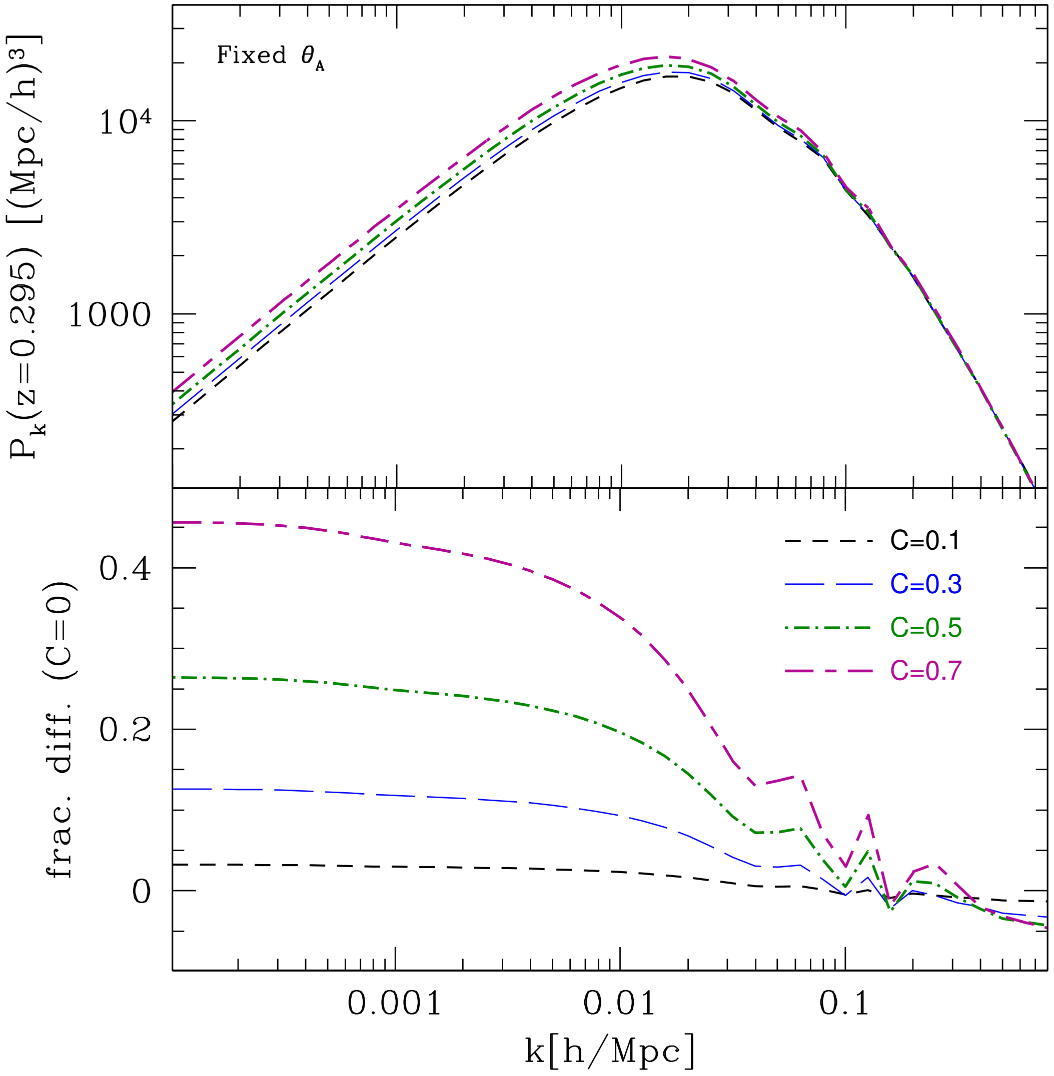
$$\frac{k^3}{2\pi^2}P_k = \frac{4}{25}A_s\left(\frac{G(a)a}{\bar{\Omega}_m}\right)^2\left(\frac{k}{H_0}\right)^4\left(\frac{k}{k_{\rm norm}}\right)^{n_s-1} T^2(k)$$

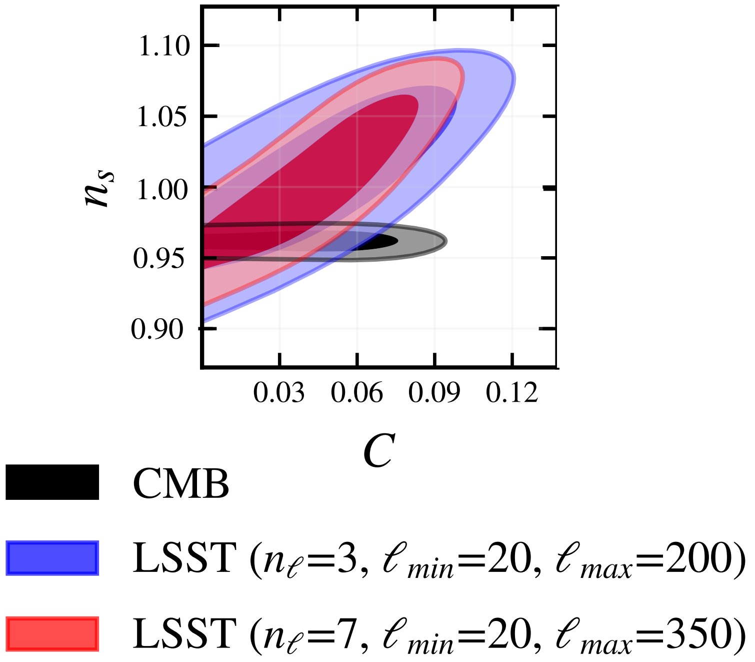
Inflationary amplitude

Growth rate relative to
During matter dom in LCDM

Inflationary spectral
index

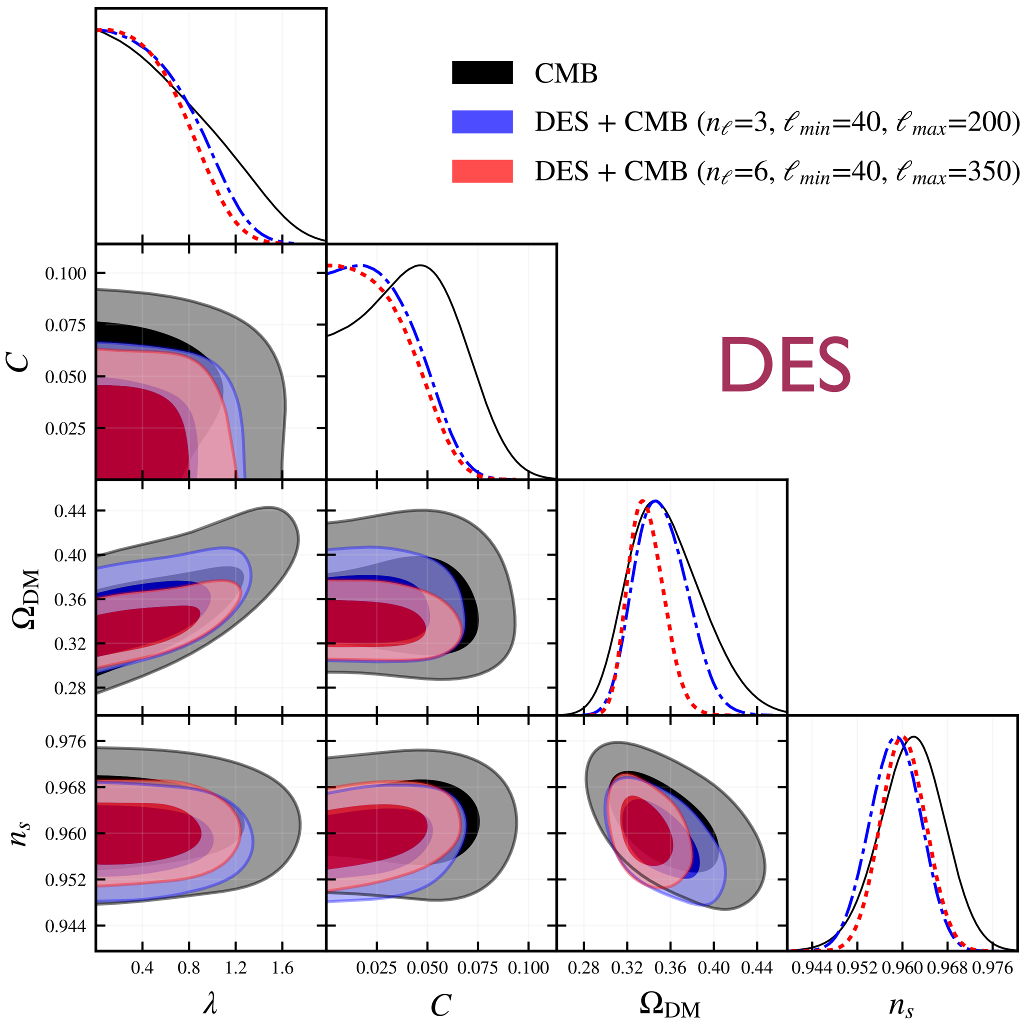
Transfer function

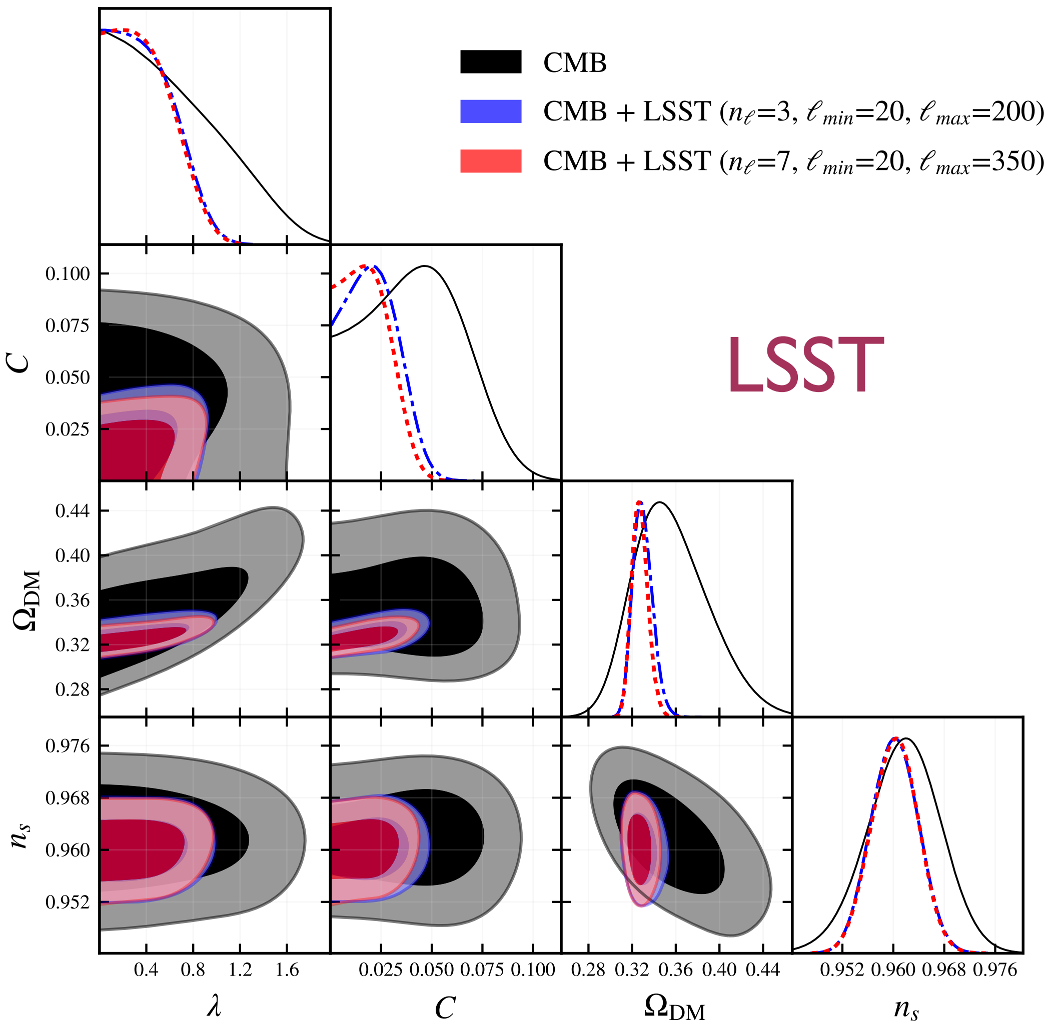




- Effect of coupling is to mimic changing spectral index at DES and LSST scales

Lensing Forecasts and Constraints





- DES LSS forecasts rule out C >0.12.

Summary

- 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.***)

Conclusions

- Have revisited simple realization of interacting dark sector 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.

- Planck data rules out C > 0.1, and have shown low redshift information from BAO and type IA Sne doesn't change this limit.

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

Conclusions

- 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.

Thank You!