Dark Energy and Beyond

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LSST DESC

Dark Energy Science Collaboration

Outline

- Cosmology with LSST: the Dark Energy Science Collaboration
- Stage III Surveys -> LSST
- Beyond dark energy…and beyond cosmology: how recent theoretical work points to a program of testing fundamental physics using nearby stars and galaxies.

DESC

- The Dark Energy Science Collaboration was formed to prepare for and carry out cosmological analyses with LSST data. It came into existence at the June 2012 meeting at U Penn.
- DESC White Paper: arXiv:1211.0310
- 1st phase of work of DESC is ~2012-2015
- Sixteen Working Groups have begun work on a set of ~50 tasks for the first phase, extending to 2015 – see white paper for details.

Eternity is a long time, especially towards the end.
Woody Allen

Dark Energy Probes with LSST

Probe	**Physical Observable**	**Sensitivity to Dark Energy or Modified Gravity**
Weak Lensing	Coherent distortions in galaxy shapes	Geometry and growth of structure (projected)
Large-Scale Structure (BAO)	Power spectrum of galaxy distribution	Distance-redshift relation
Galaxy Clusters	Abundance of massive clusters	Growth of structure and geometry
Type Ia Supernovae	Fluxes of standard candles	Distance-redshift relation
Strong Lensing	Time delays of multiply lensed sources	Distance-redshift relation

DESC Working Groups

- Analysis Working Groups **Jeff Newman**
  1. Weak Lensing — Michael Jarvis, Rachel Mandelbaum
  2. Large Scale Structure — Eric Gawiser, Shirley Ho
  3. Supernovae — Alex Kim, Michael Wood-Vasey
  4. Clusters — Steve Allen, Ian Dell'Antonio
  5. Strong Lensing — Phil Marshall
  6. Combined Probes, Theory — Rachel Bean, Hu Zhan
  7. Photo-z Calibration — Jeff Newman (acting)
  8. Analysis-Computing Liaison — Rick Kessler
- Computing and Simulation Working Groups **Andy Connolly**
  1. Cosmological Simulations — Katrin Heitmann
  2. Photon Simulator — John Peterson
  3. Computing Infrastructure — Richard Dubois
  4. Software — Scott Dodelson
- Technical Working Groups **Chris Stubbs**
  1. System Throughput — Andrew Rasmussen
  2. Image Processing Algorithms — Robert Lupton
  3. Image Quality — Chuck Claver
  4. Science Operations and Calibration — Zeljko Ivezic

How do we formulate a 10 year plan for LSST dark energy?

- To develop the high-level analysis plan and to identify the key systematics it is useful to schematically break down the dark energy analysis into the following steps.
  - Observing field/band/seeing selection and cadence issues
  - The reduction of raw images
  - The production of catalogs from the processed images
  - Measurement of statistical quantities such as power spectra
  - Cosmological analysis leading to dark energy constraints.

- Identify a set of systematics that will dominate the error budget for dark energy unless advances are made by the LSST team.

- Identify critical algorithms and determine what advances are needed internally (i.e. will not be made by the outside community in the near future).

- Identify simulation and computational needs to include relevant physics, test measurement algorithms and develop methodology for controlling systematics.

- Develop a plan of work that is synergistic with precursor surveys. This requires close communication with the key surveys, identification of complementary areas and mechanisms to smoothly exchange data and software that are mutually beneficial.

Dark Energy Probes: Systematics

A few examples to illustrate the nature of systematics and uncertainties in going from pixels to dark energy:

- The starting point in analyzing an imaging survey, the identification of stars and galaxies, can introduce a number of subtle systematic errors.
  - How does one distinguish a star from a galaxy?
  - Where does one demarcate the boundary of a galaxy or the boundary between two overlapping galaxies?

- Next: measure galaxy shapes and infer the masses of galaxies & clusters.
  - The measurement of galaxy shapes, corrected for the effects of the Point Spread Function (PSF) of the atmosphere and telescope, is linked to a second set of systematic errors.
  - The relation of galaxies or clusters to their host halo masses is subject to astrophysical uncertainties and requires multi-wavelength data (for clusters).

- Finally the correlations of galaxy shapes, sizes and positions + Likelihood analysis leads to dark energy constraints.
  - Sources of spurious correlations (physical, algorithmic and instrumental) masquerade as signal
  - Photometric redshift errors can obscure the tomographic signatures of dark energy
  - How should we choose “nuisance” parameters to fit for systematics: thousands or dozens?

Systematics: the bottom line

The five dark energy probes are affected in different ways by an overlapping set of systematics that are themselves inter-connected.

↓

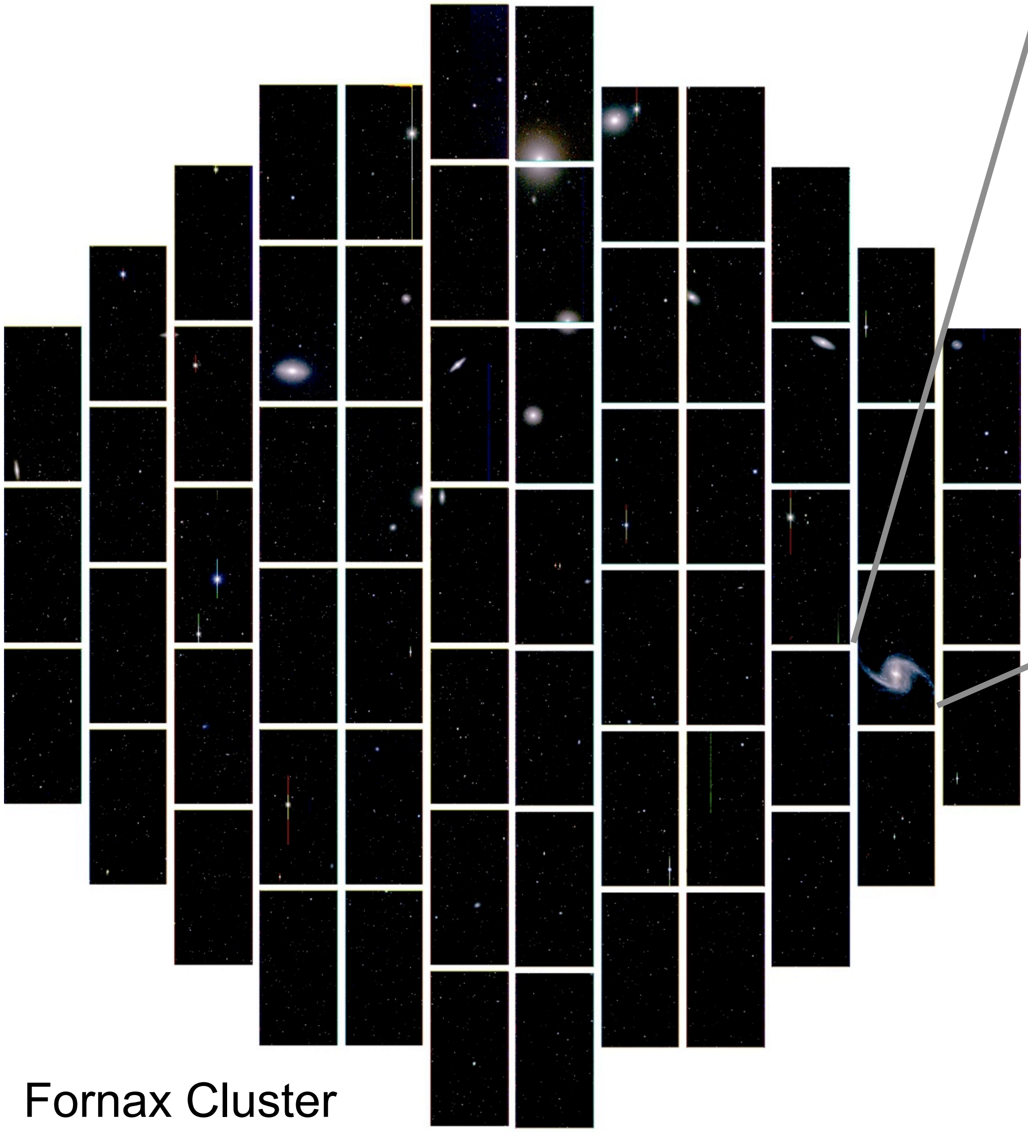
LSST will need a unified and precise understanding of a set of subtle, inter-connected observables that contain *astrophysical*, *cosmological*, *atmospheric* and *instrumental* effects.

Stage III -> IV

- Stage III imaging surveys: DES, KIDS, PanSTARRS, Subaru HSC..
- Other ongoing surveys: Spectroscopic surveys, CMB lensing..
- DESC will figure out synergies and how to exploit them. The tools and analysis we will carry out will be fed back to ongoing surveys.

Dark Energy Survey

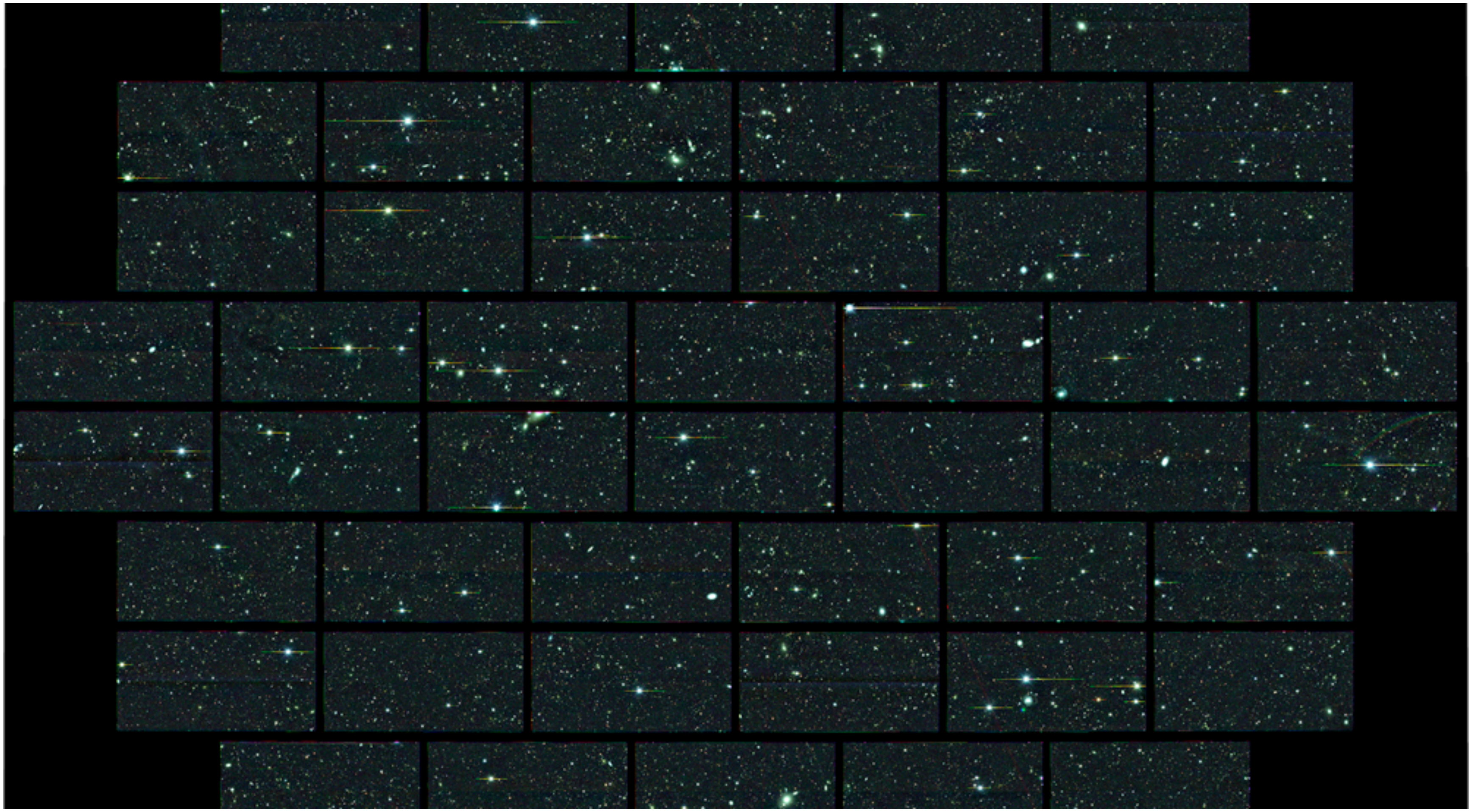
FIRST LIGHT



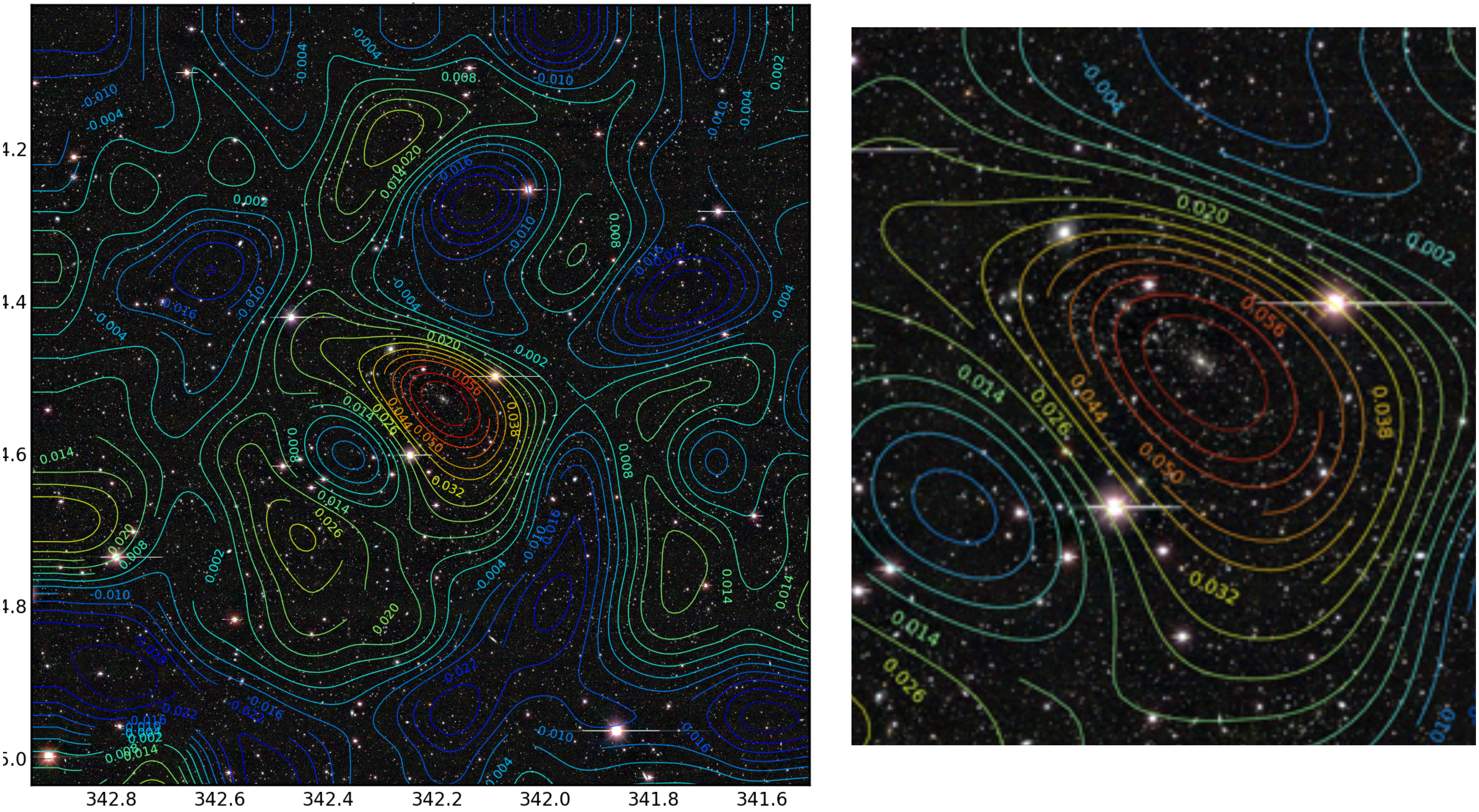
Fornax Cluster

NGC 1365

0.8” images recorded within first few nights of first light!



Dark Energy Survey: Cluster mass map



DES early data; *WLWG (teams at Penn, OSU, UCL/Manchester)*

The area, number density, survey strategy, control of systematics etc will be in a different regime with LSST! We want to work on the problems that require qualitative advances beyond the current state of the art.

beyond dark energy

Beyond Dark Energy

- Dark energy surveys will measure the geometry and growth of structure: powerful tests of dark energy and gravity.
- Here we describe new theoretical ideas that lead to novel tests of gravity and fundamental physics.
  - Snowmass: http://www.snowmass2013.org/tiki-index.php?page=Dark+Energy+and+CMB#White_Papers
- The novel tests link fundamental physics and cosmology with the astrophysics of stars, black holes and nearby galaxies.
- The power of LSST's massive multicolor time-domain surveys is that, in parallel with the classic dark energy program, a diverse suite of novel analyses and tests can be carried out.

New degrees of freedom in the universe

- Theorem: Cosmological constant is the `unique' large distance modification to GR that does not introduce any new degrees of freedom
- Dynamical models of Dark Energy or Modified Gravity invoke new degrees of freedom. New d.o.f. also arise in string theory and other contexts.
- Modified gravity (MG) theories typically invoke a scalar coupled non-minimally to gravity: it has observable effects on all scales, mm to Gpc!
  - Note: the new scalar degrees of freedom must be incredibly light: $m_{\mathrm{d.e.}} \leq 10^{-33} eV$ $m_{\mathrm{d.e.}} = \text{Hubble rate} = 1/\text{Age of universe}$
- Dark energy and dark matter can also directly couple to standard model particles: we can look for signatures in galaxies.

Modified gravity and scalar fields

- Consider a scalar $\phi = \phi_b + \delta\phi$ coupled to the energy density ρ.
- Since it is light, the long range, scalar force inside the solar system must be suppressed to satisfy tests of the equivalence principle and GR.
- In the last decade, some natural ways to achieve this have been realized by theories designed to produce cosmic acceleration.
- The generic form of the equation of motion for $\delta\phi$ is:

$$\underset{\uparrow \atop \text{kinetic term}}{Z(\phi_b, \rho_b)} \left[\frac{d^2\delta\phi}{dt^2} - c_s^2 \frac{d^2\delta\phi}{dx^2}\right] + \underset{\uparrow \atop \text{mass term}}{m^2(\phi_b, \rho_b)}\delta\phi = \underset{\uparrow \atop \text{coupling to matter}}{\beta(\phi_b, \rho_b)} G_{\text{Newton}}\delta\rho$$

A. Tolley

Screening: how to hide enhanced gravity

$$\delta F \approx \frac{M_a M_b G}{r^2} \underline{\frac{\beta^2(\phi_b, \rho_b)}{\sqrt{Z}(\phi_b, \rho_b) c_s(\phi_b, \rho_b)} \exp(-m(\phi_b, \rho_b) r)}$$

To keep force enhancement small, this term must be small.
Only 3 options!

(a) Coupling ***β*** is small (Symmetron)
(b) Mass ***m*** is large (Chameleon)
(c) Kinetic term ***Z*** is large (Vainshtein)

- The three mechanisms of screening lead to distinct observable effects as one transitions from MG on large scales to GR well inside galaxies.
- A successful MG theory must incorporate a screening mechanism → we can pursue observable effects even before theorists agree on a theory!
- The parameters that observations constrain:
  - coupling ***β*** & mass ***m*** (the range of the scalar force ***λ***)

Signatures of modified gravity

how cosmological effects show up in galaxies

$$ds^2 = -(1+2\psi)dt^2 + (1-2\phi)a^2(\mathrm{t})d\mathbf{x}^2$$

- GR: $\Psi=\Phi$. MG: $\Psi\neq\Phi$.
- Generically in scalar-tensor theories the scalar field enhances forces on non-relativistic objects like stars and galaxies
  - *acceleration* = $-\nabla\Psi = -\nabla(\Psi_S + \Psi_N)$

➡ This enhances effective G & velocities by ~10%

- Photons respond to the sum ($\Psi+\Phi$) which is typically unaltered*:* lensing masses are true masses

➡ Dynamical masses are larger than Lensing (true) masses – on scales

- Unscreened environments in the universe will show these signatures of gravity: from cosmological scales to nearby galaxies

Signatures of modified gravity

Stars, gas, black holes: observed in time, position and velocity

- Enhanced forces can alter the luminosities, colors and ages of stars in unscreened galaxies.
  - Pulsating giant stars may feel higher G_{eff}: faster pulsations are detectable

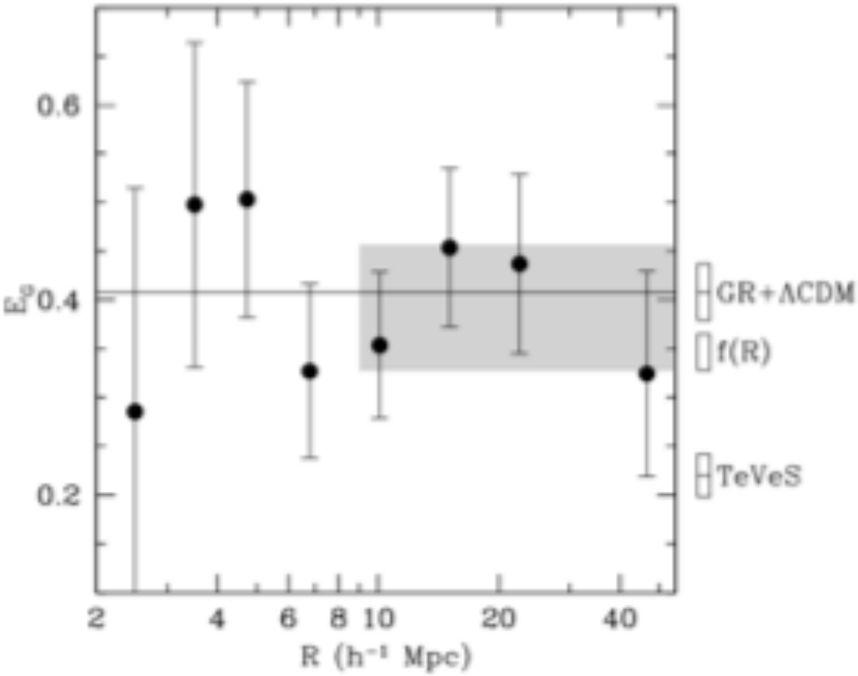
- Dark matter and gas clouds are diffuse, black holes have no hair -> they can respond differently to fifth force than stars
  - Stars rotate slower and separate from gas due to external forces
  - Black holes and stars may separate and oscillate in some scenarios

- Galaxy velocities on all scales are enhanced: Dynamical mass > Lensing mass

These novel tests deploy the full power of dedicated surveys: time evolution, spatial imaging and spectroscopy. Carrying out the tests requires close connection between theory, simulation and data analysis.

New results: gravity tests from solar system to cosmological scales

I: Lensing vs Dynamical mass



- ψ/ϕ = 1.01 with 10% accuracy from Einstein Rings + Dynamics *Schwab et al 2010*
- Analogous tests at 1-10 Mpc scales: 20% level (->2% with Stage IV) *Reyes et al 2010*
- These tests were not planned - carried out several years after SDSS survey was complete!
- Related large-scale tests: CMB, galaxy clustering, lensing, cluster counts → connect to the cosmological probes of dark energy.

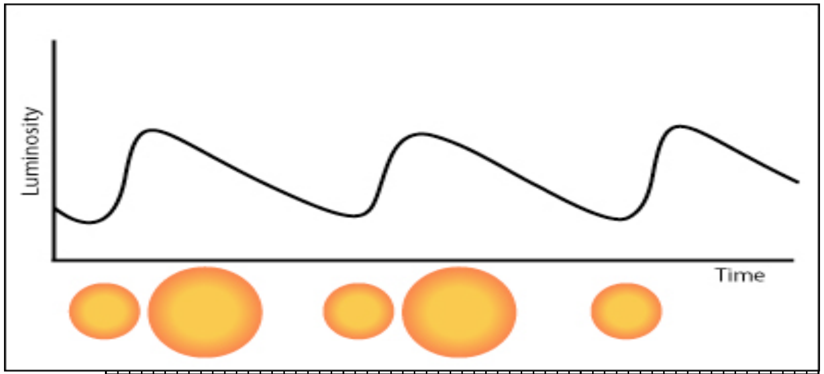
II: Astrophysical probes of gravity: Distances

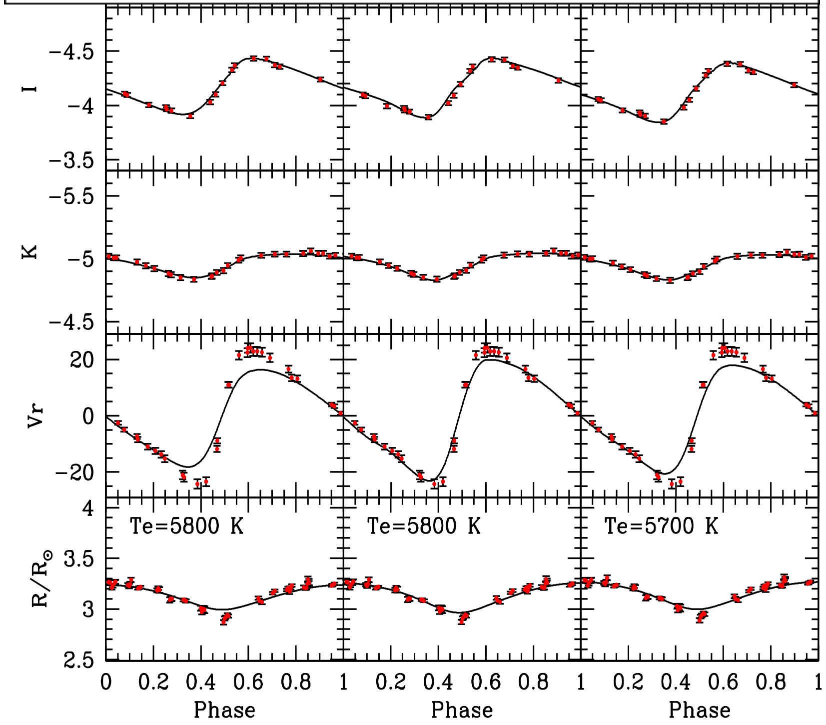
- Distances to Supernovae led to the discovery of the accelerating universe.
- Distances are calibrated in multiple steps:
    - *Milky way objects via geometric parallax, e.g. cepheids*
    - *Nearby galaxies, within 10s of Mpc, by comparison of multiple methods: e.g. SN with cepheids*
    - *Cosmological distances via calibrated SN*

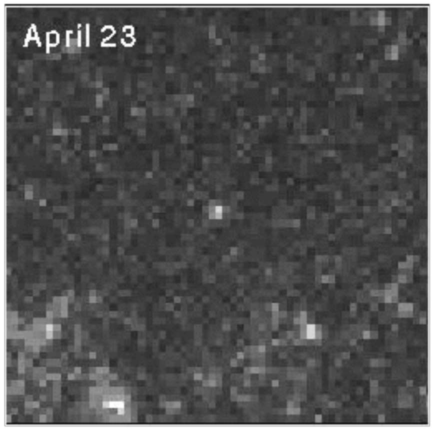
- Different distance indicators have varying gravitational potentials: giant stars, Black Hole masers, Supernovae ➡ In modified gravity, they respond differently to the fifth force ➡ the estimated distances from different tracers will disagree.

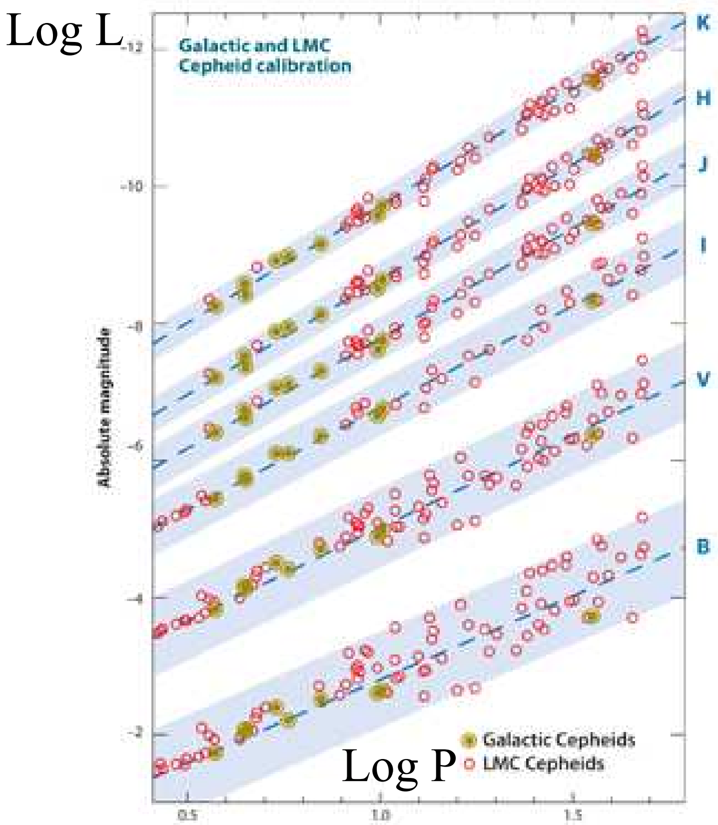
- We can slice data from the dark energy program differently to test for gravity!

Distances from pulsating giant stars









Giant stars and other distance indicators

- Cepheids are giant stars that pulsate over days to weeks. The period P and luminosity L are tightly related -> distance indicator

$$P \sim 1/\sqrt{G\rho}$$

-Scalar force enhances G -> lowers P -> underestimate distance.

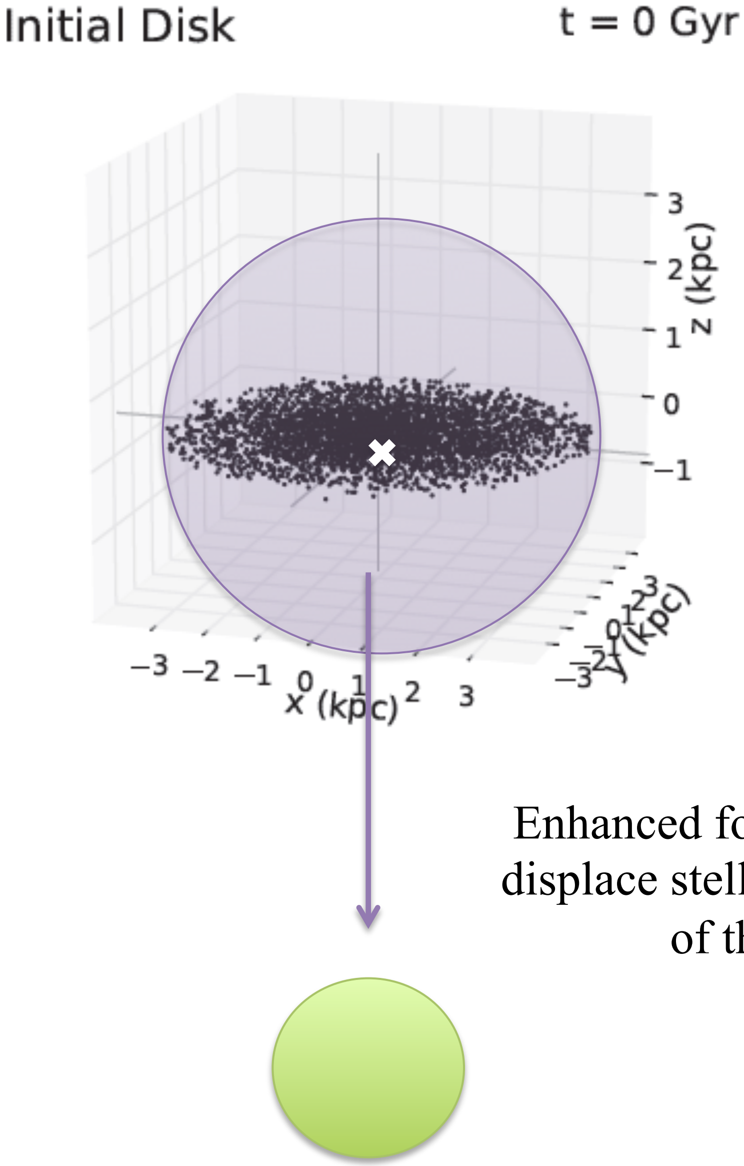
- The peak luminosity for another class of stars, TRGBs, is nearly universal for 1-2 $M_\odot$ stars -> distance indicator
  - *Distance is affected by core physics – stronger gravity – more screened + has the opposite sign from change in cepheid distance*

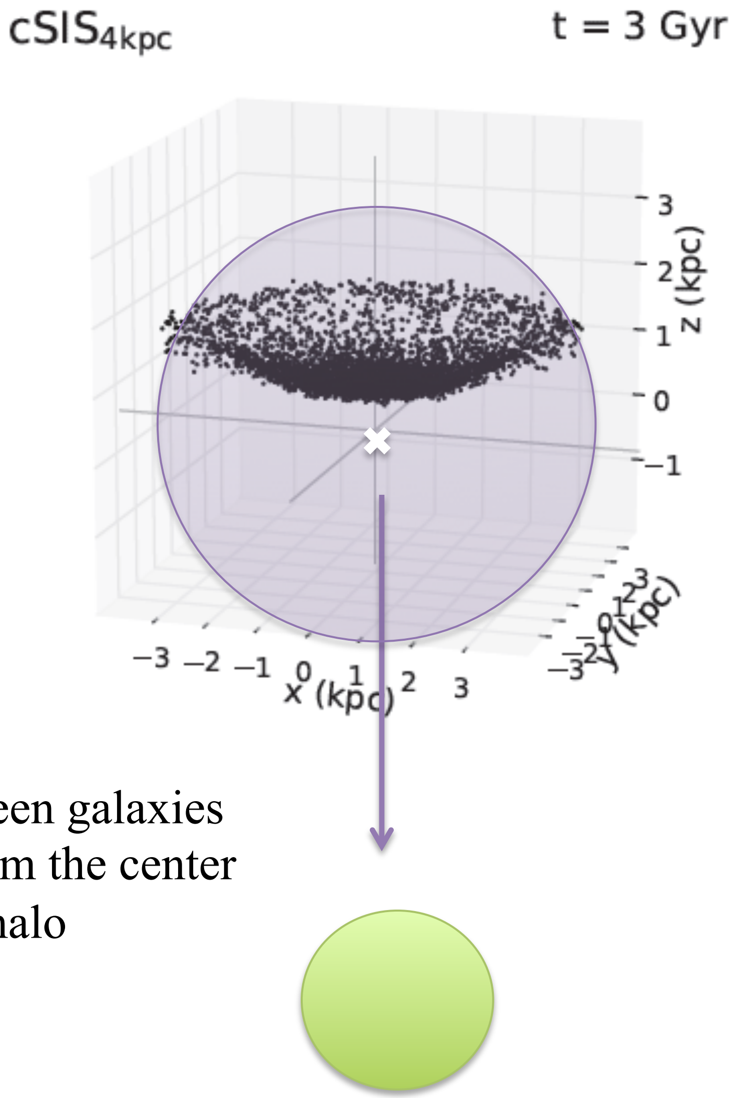
- Water masers around Supermassive Black Holes provide a geometric method: independent of G

- Type Ia Supernova distances are estimated from luminosity of shell of matter moving away from SN – stronger gravity that other indicators.

- The upper limits we obtain ($f_{R0} < 4\times10^{-7}$) superior to cosmological tests and even to solar system tests of gravity.

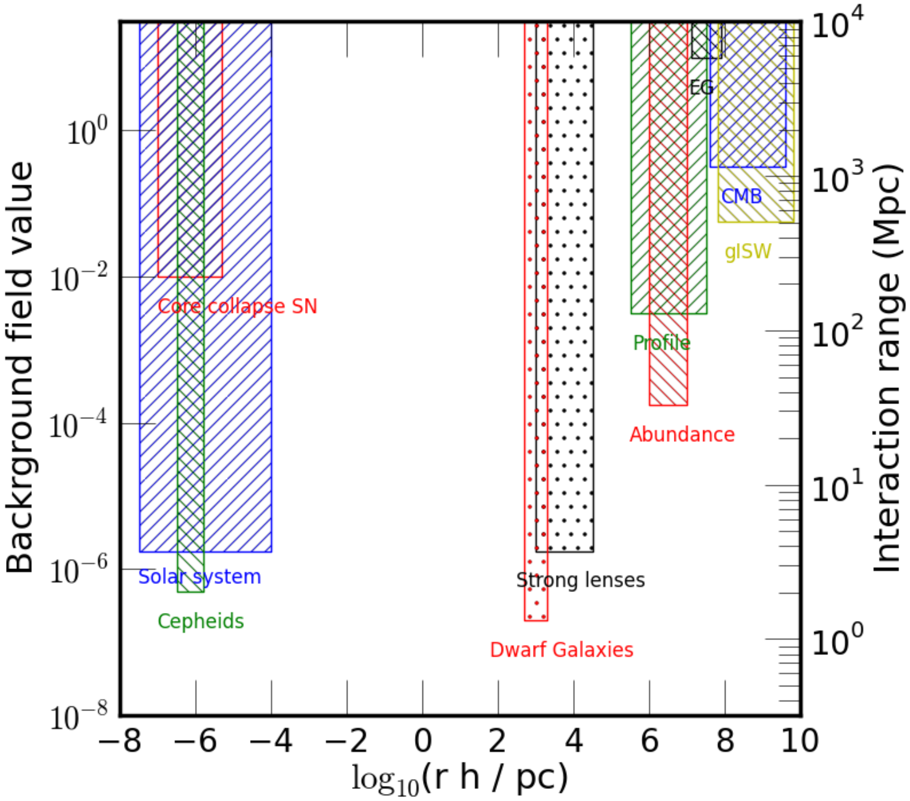
III: Astrophysical probes of gravity: galaxies





Enhanced forces between galaxies
displace stellar disk from the center
of the galaxy halo

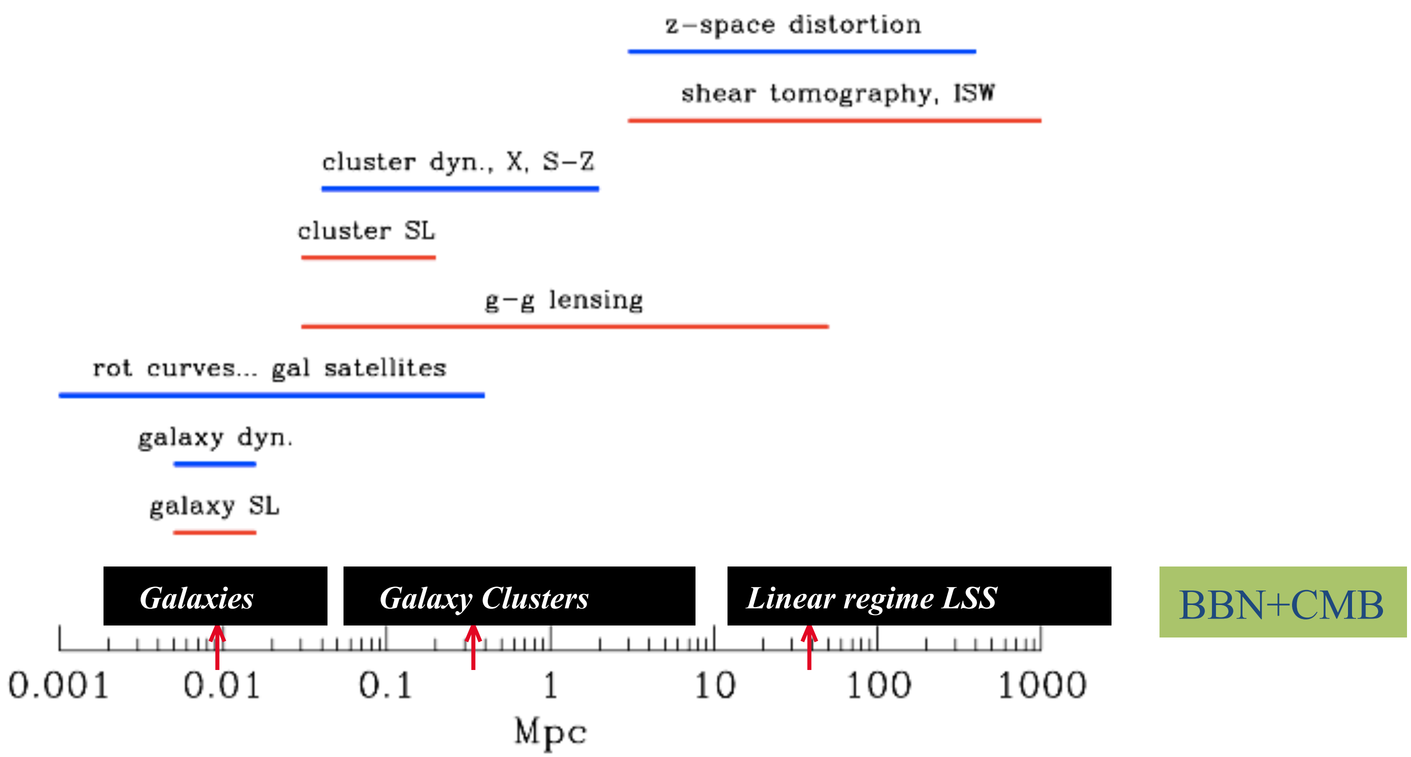
Current limits on gravity theories



- Nearly all these limits have been obtained in the last 5 years.

the next decade

Astrophysical probes of gravity



Dynamical probes (blue) measure Newtonian potential ψ

Lensing and ISW (red) measures $\phi + \psi$ *Jain & Khoury 2010*

Beyond smooth dark energy: tests

Test	Theories Probed	Current Status	Prospects for next decade	MG Signal
Growth vs. Expansion: 100Mpc-1Gpc	Test of GR + smooth dark energy	10% accuracy	2-4% accuracy by combining probes[1]	MG signal is model-dependent
Lensing vs. Dynamical mass[2]: 0.01-100Mpc	Test of GR	20% accuracy[3]	5% accuracy	MG signal at 10% level
Astrophysical Tests: 0.01AU-1Mpc	MG Screening Mechanisms	Few tests at the 10% level	Several tests with factor of 10 or more improvement	Chameleon and Vainshtein theories predict detectable signal for several tests
Lab and Solar System Tests: 1mm-1AU	PPN → MG parameters	Mass & Range of 5th force[4]	Up to a factor of 10 improvement	Model-dependent[5]

Beyond Dark Energy

- Cosmic acceleration and fundamental physics motivations → multi-scale tests of gravity and dark sector couplings.
- Novel tests of gravity and the dark sector will be be carried out in the next decade+. By bridging local tests of gravity with cosmological observations we will probe many failure modes of the standard model of cosmology.

- Backup slides

DESC science: introduction

- The accelerated expansion of the universe can be attributed to a new component of energy density, “dark energy”, that makes up 70% of the energy density of the universe.
- What is the nature of dark energy?
  - Vacuum energy: Λ
  - Dynamical scalar field?
  - Modified gravity?
  - Understanding
- dark energy requires multiple techniques that have different systematics and differing sensitivities to the new physics.
  - Expansion history of the universe is sensitive to the time evolution of dark energy
  - Comparison of expansion history and growth of structure tests for breakdown of General Relativity
- Understanding dark energy is closely connected to other questions in cosmology and fundamental physics: the mission of DESC includes these questions as well. The research program of DESC is geared towards a complete cosmological analysis of LSST data.

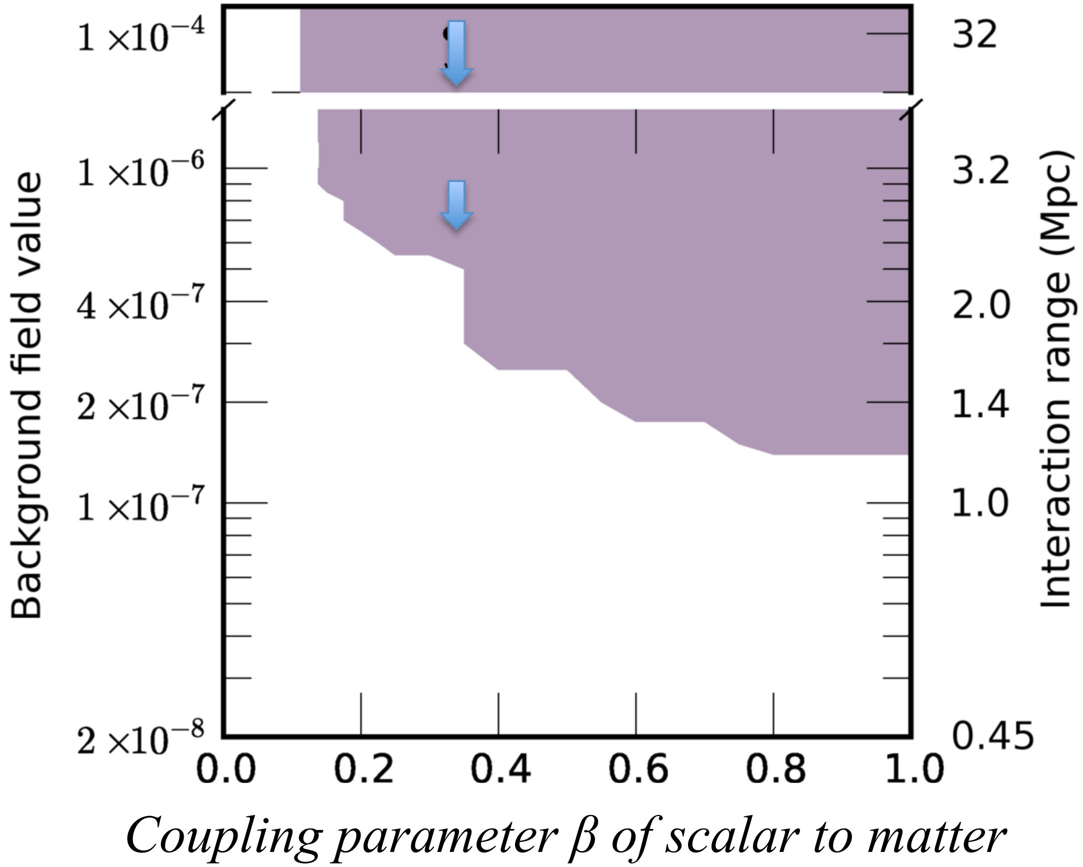
Interactions with the project

- The technical coordination group (Stubbs, Rasmussen, Lupton, Claver, Ivezic) is the primary venue for studying the connections of the cosmological analyses to the detailed system design.

- Phosim and the other simulators are the primary tools for studying this connection. Several analysis working groups have begun using the simulators; versatile implementations of phosim are being made available to the working groups.

- Recent examples of interactions between DESC and the project include:
  - Connecting atmospheric effects on the PSF with existing data and quantification of systematic contributions for LSST.
  - Scoping out the impact of a ring-like structure produced by the chips in LSST images.
  - Quantifying (once and for all!) the effective number density achieved by LSST for weak lensing science.
  - Useful lessons and interactions with ongoing surveys as well.

Prospects for astrophysical tests of modified gravity parameters



The entire parameter space for chameleon theories is testable in the coming decade

Vainshtein theories are the other interesting class of theories:
only beginning to be tested on small scales