Dark Energy / Modified Gravity

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Probing gravity with LSS

- LSS + CMB are unique tools for probing gravity
- Extend tests from AU scales (Solar System, pulsars) to 0.1-1000 Mpc
- With or without the puzzle of Dark Energy, we should be using the data for this purpose !
- Issue: need to know (or assume) stress-energy content of the Universe

Dark Energy

- Smooth Dark Energy (DE):
  - completely characterized by w(z)
  - unique relation between H(z) and D(z)
- Clustering & coupled Dark Energy:
  - line to modified gravity (MG) becomes blurry
- Clearly, H(z) cannot not serve as test of gravity

Tests of gravity

- Use evolution of perturbations to distinguish modified gravity (MG) from smooth DE
- Very broadly, classify gravity tests into
  - Generic *vs* targeted
  - Parametrized/consistency tests *vs* model-specific constraints

Generic vs Targeted

- *Generic tests:* use popular cosmological observables, and marginalize over non-gravity “nuisance” parameters:
  - Galaxy 2-pt function
  - Cluster abundance
  - Shear power spectrum
  - ...
- *Targeted tests:* constructed to specifically look for modifications of gravity (-> later)

Generic vs Targeted

- *Generic tests:*
  - Relatively easy to do (for a theorist)
  - Can use all information in data
  - How do we know any discrepancies are due to gravity ? (and not due to neutrinos, non-Gaussianity, ...)
- *Targeted tests:*
  - Robust to non-standard non-gravity effects
  - Work needed to implement
  - Do not use all information in data

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More work needed!

Parametrized vs Model-specific

- *Parametrized tests:* consistency tests of ΛCDM (or smooth DE) paradigm
  - $D(z) = \Omega_m(z)^\gamma$; PC analysis of D(z) given H(z)
- *Model-specific constraints:*
  - Constrain f(R), DGP, galileon, symmetron, ... model parameters

Parametrized vs Model-specific

- *Parametrized tests:* consistency tests of LCDM (or smooth DE) paradigm
  - Rely on standard paradigm around which we perturb (incl. CDM, neutrinos ?)
- *Model-specific constraints:*
  - Only constrain specific models (haha)

What do we expect from modified gravity ?

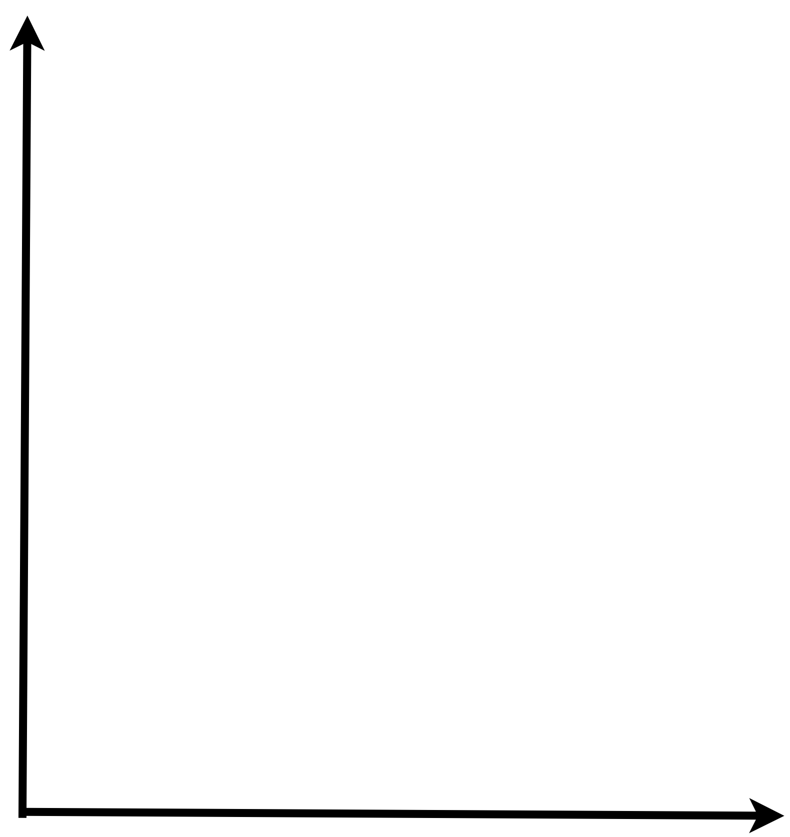
- Learned a lot over past ~7 years
- *Scalar-tensor theories* encompass wide range of models*
    - GR + universally coupled scalar with <~ gravitational strength
    - Solar System constraints: non-linear *screening mechanism* necessary to produce any interesting effect
- Want to look for this additional scalar d.o.f.

*In fact very hard to come up with viable models including vector and tensor fields

Parameter space of MG

$$\frac{\Psi}{\Psi - \Phi}$$

Relation b/w dynamics and lensing



Relation b/w lensing and matter $$\frac{\Psi - \Phi}{\rho_m}$$

Both of these to be seen as ***function of scale and redshift***

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

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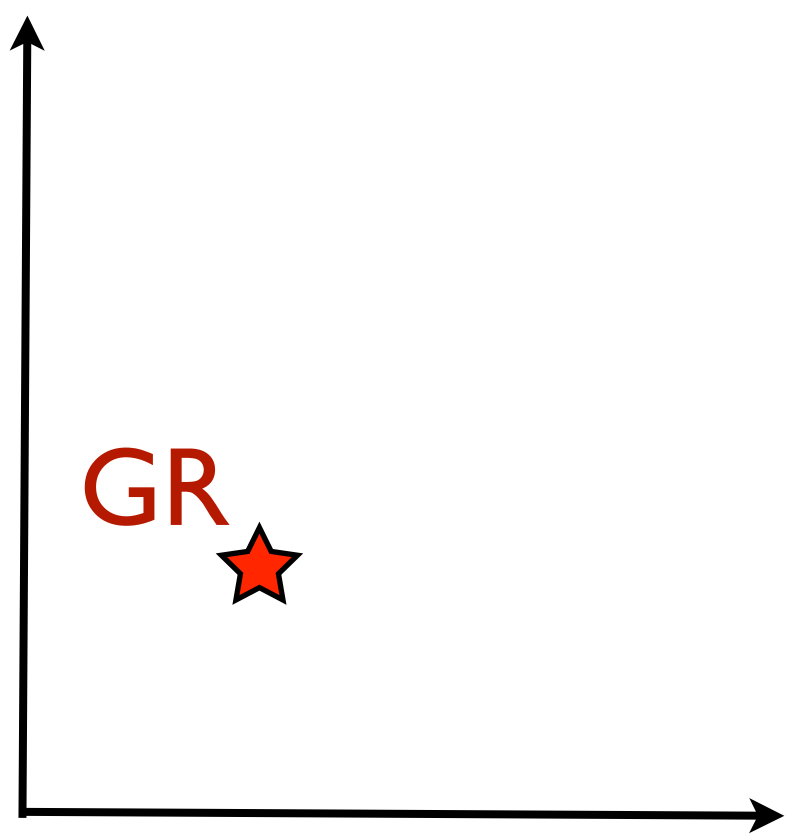

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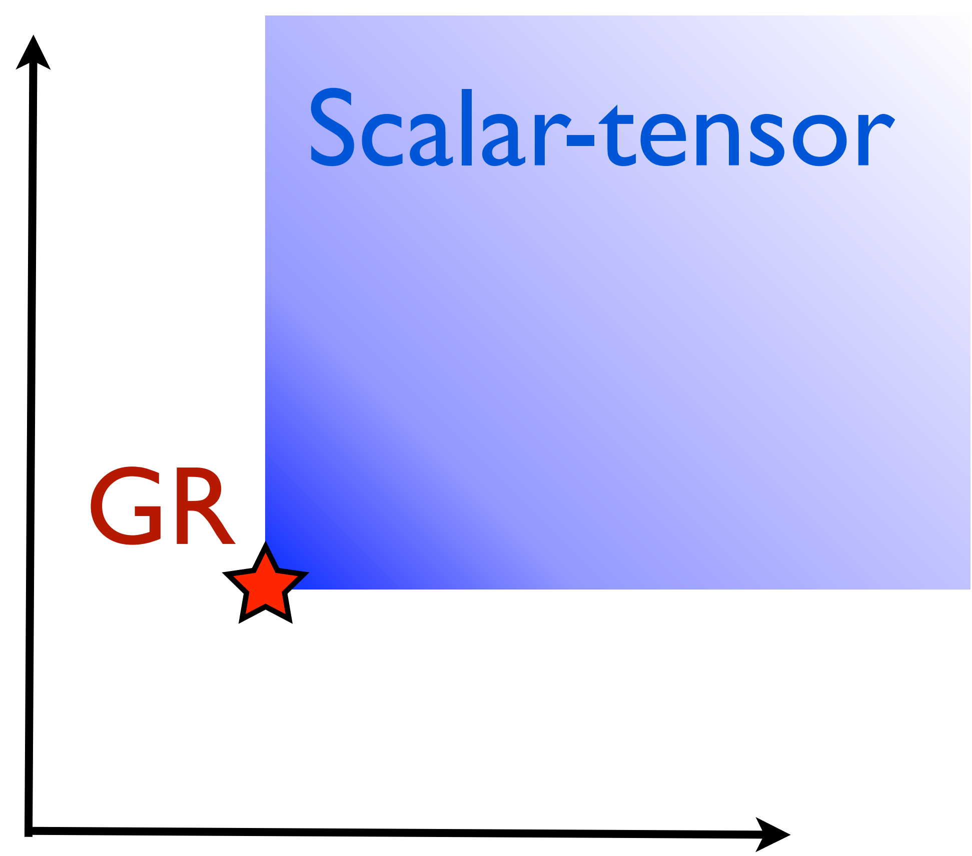

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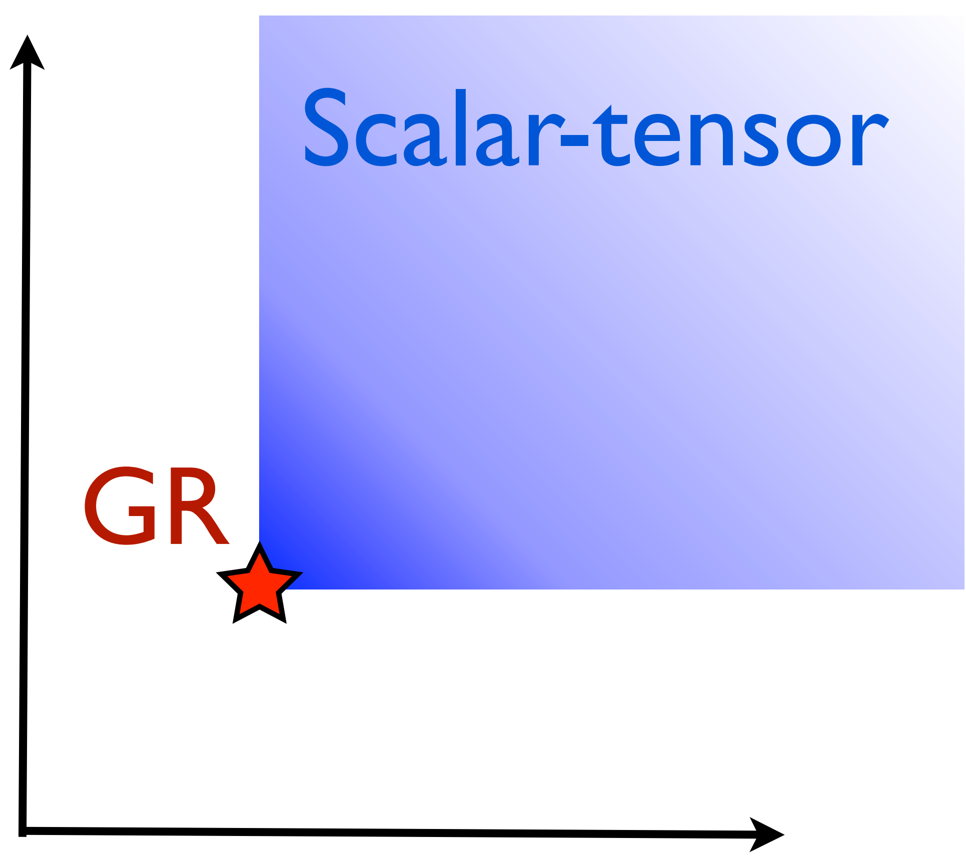

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Tricky - degenerate with anything else that modifies growth

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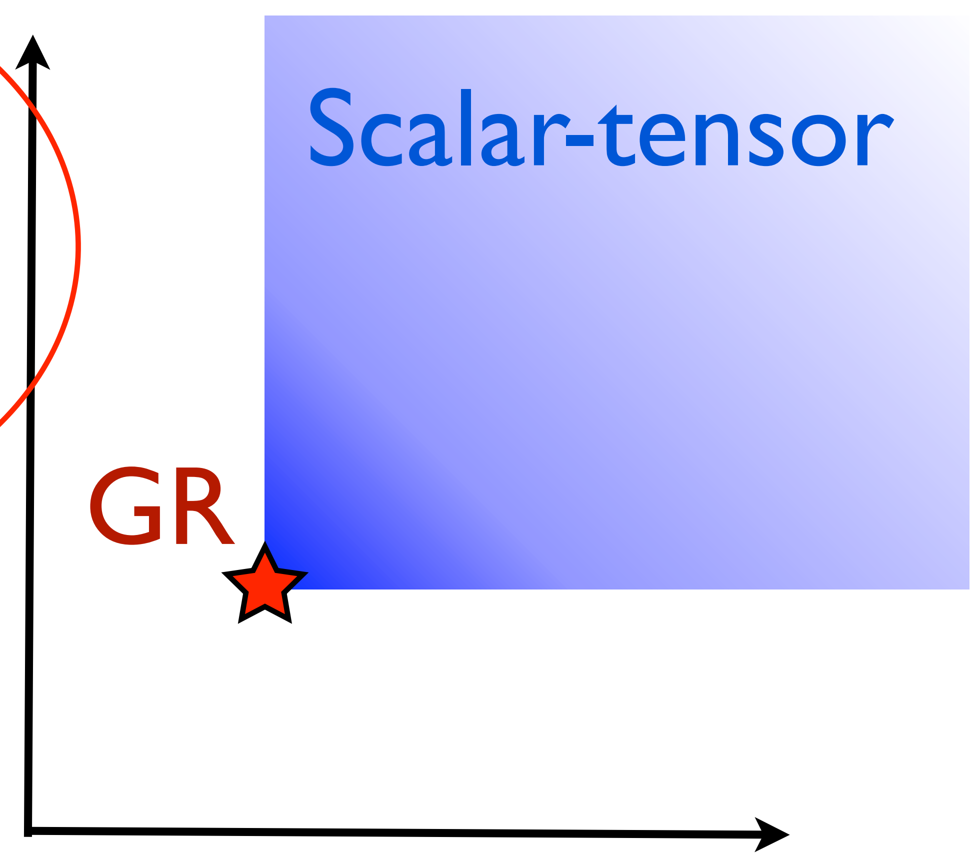

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What do we expect from modified gravity ?

- Scalar field generically leads to *discrepancies between dynamics and lensing*
  - RSD vs lensing — 50 - 150 Mpc
  - Phasespace of clusters — 5 - 20 Mpc
  - Velocity dispersions within clusters and galaxies — < 3 Mpc
- This is a *targeted test of gravity*
  - cf PPN tests in the Solar System

*In fact very hard to come up with viable models including vector and tensor fields

Screening mechanisms

- Important for constraints on non-linear scales
  - Chameleon / symmetron mechanisms: depth of potential
  - Vainshtein mechanism: mean enclosed density
  - ... more ?

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  - Vainshtein mechanism: mean enclosed density
  - ... more ?
- Rich phenomenology:

cf Bhuv Jain's talk

  - Sharp transition in mass function
  - Dynamics of gas vs stars within galaxies
  - Equivalence principle violation

Screening mechanisms

- Hard to parametrize - gravity tests on non-linear scales necessarily either *consistency checks of ΛCDM* or *model-specific tests*
- However, tests of screening mechanisms probe *non-linear aspects of entire classes of models*
  - From theoretical standpoint, perhaps more interesting than linear-regime constraints

Non-vanilla DE

- If w != -1, DE might have perturbations
    - Amplitude depends on w and c_s, but generally relevant on large scales
    - We will likely detect 1+w before we see the perturbations...
- DE could be coupled to dark matter and/or neutrinos
    - Interesting LSS signatures
    - Degenerate with MG in generic tests, but probably not in targeted tests

Benchmark models

- Want to cover as much of theory space as possible
  - Scale- and redshift-dependence
  - Type of screening mechanism
- Suggestion: one chameleon model (e.g., *f(R)*) and one Vainshtein model (e.g., effective galileon model)
  - Come up with models with "medium z" phenomenology ?

When do we believe “it’s Λ” ?

- Dark matter as analogy: there is no true gravitational alternative
  - *Constraints from entire range of scales (0.1-1000 Mpc)* force us to introduce some form of dark matter - even ignoring “smoking gun” like bullet cluster

When do we believe "it's Λ" ?

- Dark matter as analogy: there is no true gravitational alternative
    - *Constraints from entire range of scales (0.1-1000 Mpc)* force us to introduce some form of dark matter - even ignoring "smoking gun" like bullet cluster
- Can we eventually get to the same conclusion for Λ ?
    - Need constraints from all scales
    - And maximally expanded theory space (more models !)

Conclusions

- Generic and parametrized tests well developed (at least for forecasting & survey design)
- *Targeted tests* (dynamics vs lensing) and *model-specific tests* (screening mechanisms) warrant more work
  - Forecasts & study of systematics
  - Can and should these tests influence survey design ? E.g., overlap between spec and imaging surveys ?
- We want to cover the *entire accessible range of scales & redshifts*