Beyond ΛCDM: Dark energy vs Modified Gravity

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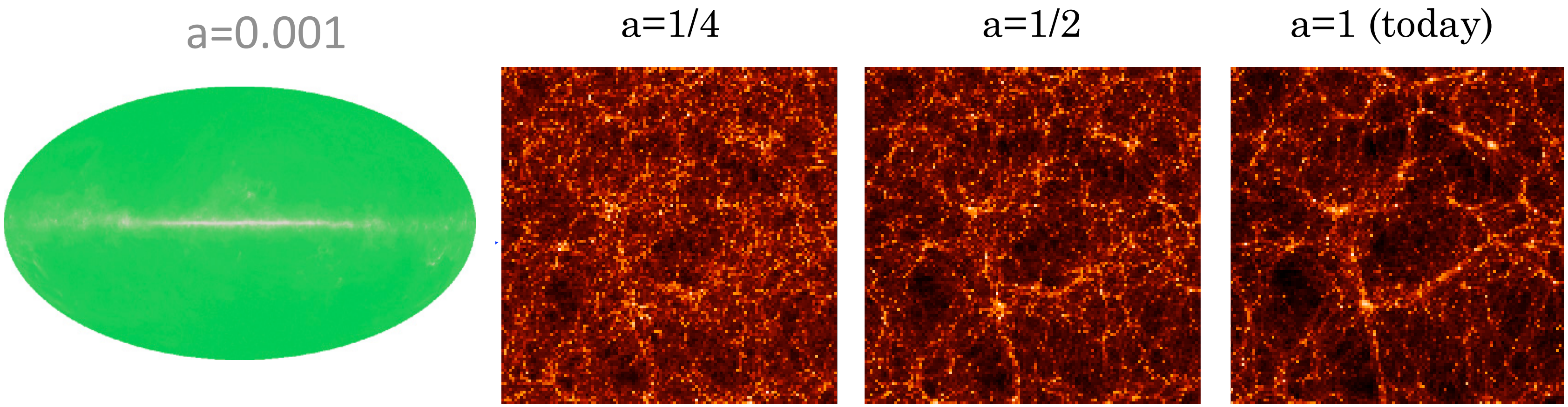
References

BJ et al, arXiv:1309.5389 (Snowmass)

Joyce, BJ, Khoury, Trodden, arXiv:1407.0059 (Review)

Cosmology probes: geometry and growth

- Geometry: Distance-Redshift relation D(z), Expansion rate H(z)
- Growth: Fluctuations in CMB, mass, gas and galaxies



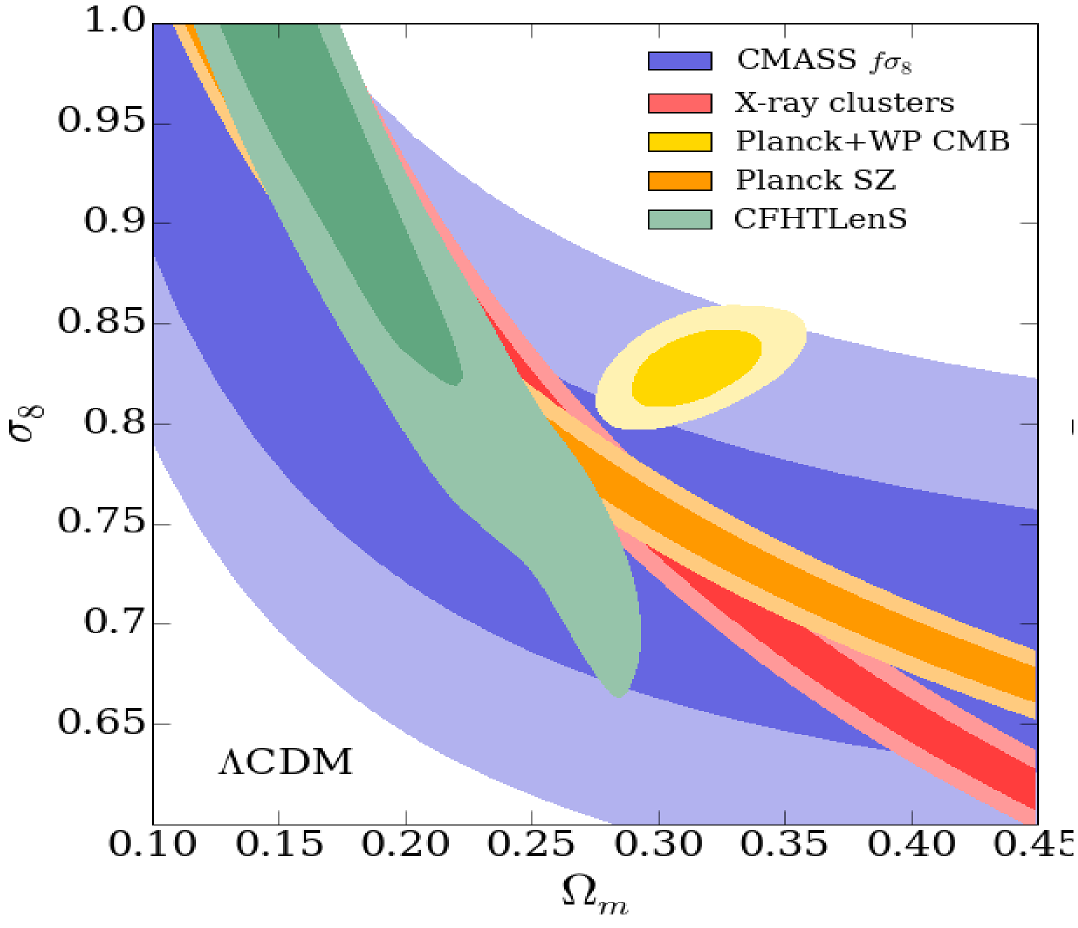
- Low-z/late time universe has several probes of geometry and growth

  - Combining CMB with late time data provides huge lever arm in scale and time: tests of inflation, dark energy, massive neutrinos, dark sector interactions

Cosmology probes: late times

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	Geometry and Growth
Galaxy Clusters	Abundance of massive clusters	Geometry and Growth
Type Ia Supernovae	Fluxes of standard candles	Geometry: Distance-redshift relation
Strong lensing, Lyman-alpha, 21cm…	Time delays, power spectra	Geometry and growth

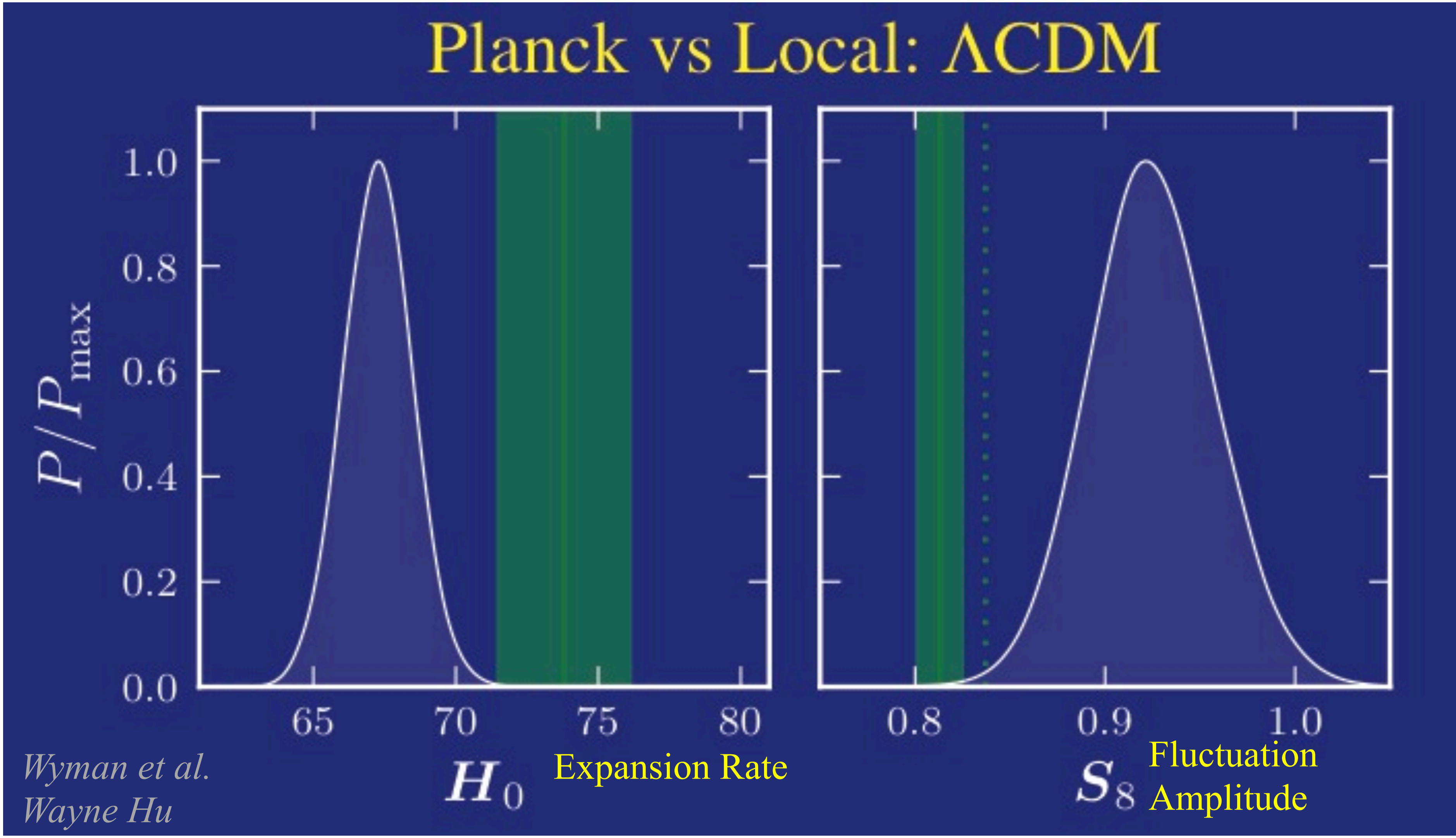
Galaxies vs. CMB



- Amplitude at late times/small scales is lower than inferred from CMB

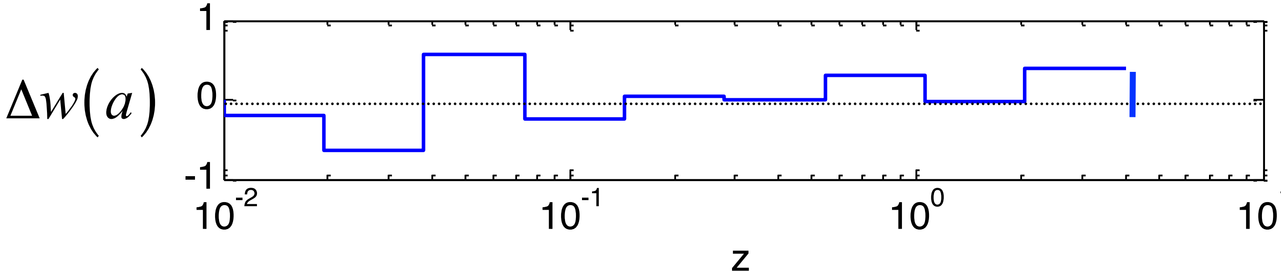
Maccrann,, Zuntz, Bridle, BJ, Becker 2014, arxiv:1408.4742

(Mild) tension in cosmology data



Extrapolation from CMB disagrees with low-z measurements

Beyond Λ



- Is dark energy constant in redshift?
- Is dark energy spatially clustered or anisotropic?
- Are there couplings between dark energy, dark matter, baryons?
- Is it dark energy or modified gravity?

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 (also arise in string theory, higher dimension theories…).
- Modified gravity (MG) theories typically invoke a scalar field coupled non-minimally to gravity. The scalar enhances the gravitational potential
  ⇨ observable effects on all scales, mm to Gpc!
- Dark energy and dark matter can also directly couple to standard model particles, leading to other 5th force-like effects.

Modified gravity and scalar fields

- Let's go beyond Λ or smooth dark energy.
- Consider a scalar $\phi = \phi_b + \delta\phi$ coupled to the energy density ρ.
- The generic form of the equation of motion for $\delta\phi$ is:

$$Z(\phi_b, \rho_b)\left[\frac{d^2\delta\phi}{dt^2} - c_s^2\frac{d^2\delta\phi}{dx^2}\right] + m^2(\phi_b, \rho_b)\delta\phi = \beta(\phi_b, \rho_b)G_{\mathrm{Newton}}\delta\rho$$

kinetic term

mass term
(range of interaction)

coupling to matter

Screening: how to hide enhanced gravity

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

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, e.g. f(R))
(c) Kinetic term ***Z*** is large (Vainshtein, e.g. DGP and galileon)

- 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*** (equivalent to the range of the scalar force ***λ***)

Signatures of modified gravity I

how cosmological effects show up in galaxies

- Unscreened environments in the universe will show signatures of gravity: from cosmological scales to nearby 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 extra scalar field enhances forces on stars and galaxies
  - *acceleration* = $-\nabla \Psi = -\nabla (\Psi_S + \Psi_N)$
  - This enhances effective G & velocities, typically by O(10%)
- Photons respond to the sum ($\Psi+\Phi$) which is typically unaltered
  - Dynamical masses are larger than Lensing (true) masses
  - Tests from ~kpc to ~100 Mpc scales can carried out with next generation surveys!

Signatures of modified gravity II

Stars, gas , black holes and dark matter

• 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

  Chang & Hui 2010; Davis et al 2011; BJ, Vikram, Cabre 2012

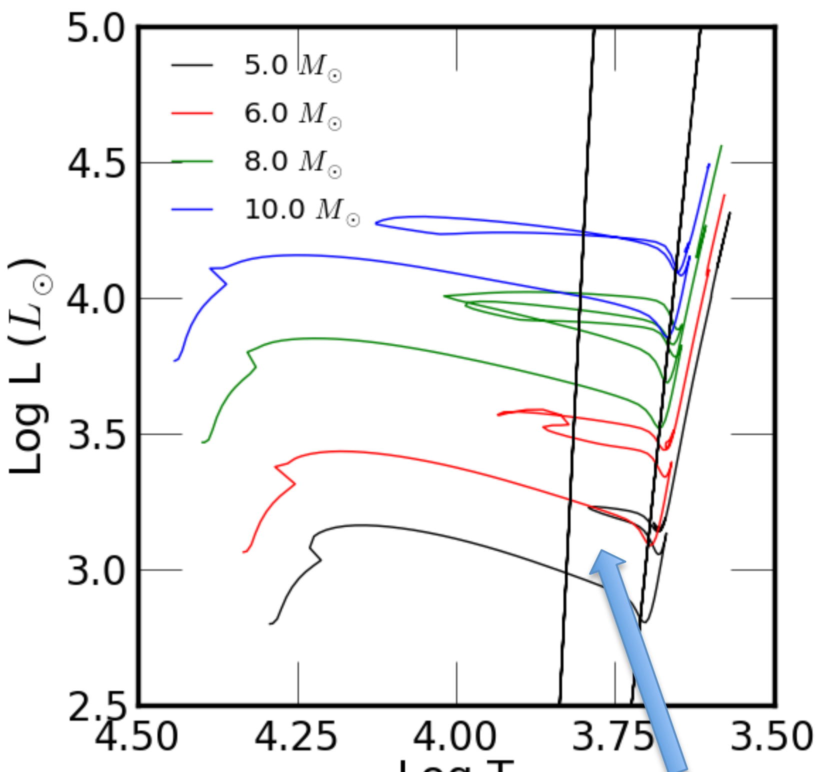
• Black holes, stars, gas clouds and dark matter-> Different levels of compactness -> respond differently to the fifth/scalar force

- Stars rotate slower and separate from gas due to external forces
- Galaxies and clusters show signatures in morphology and dynamics
- Black holes and stars may separate in some scenarios

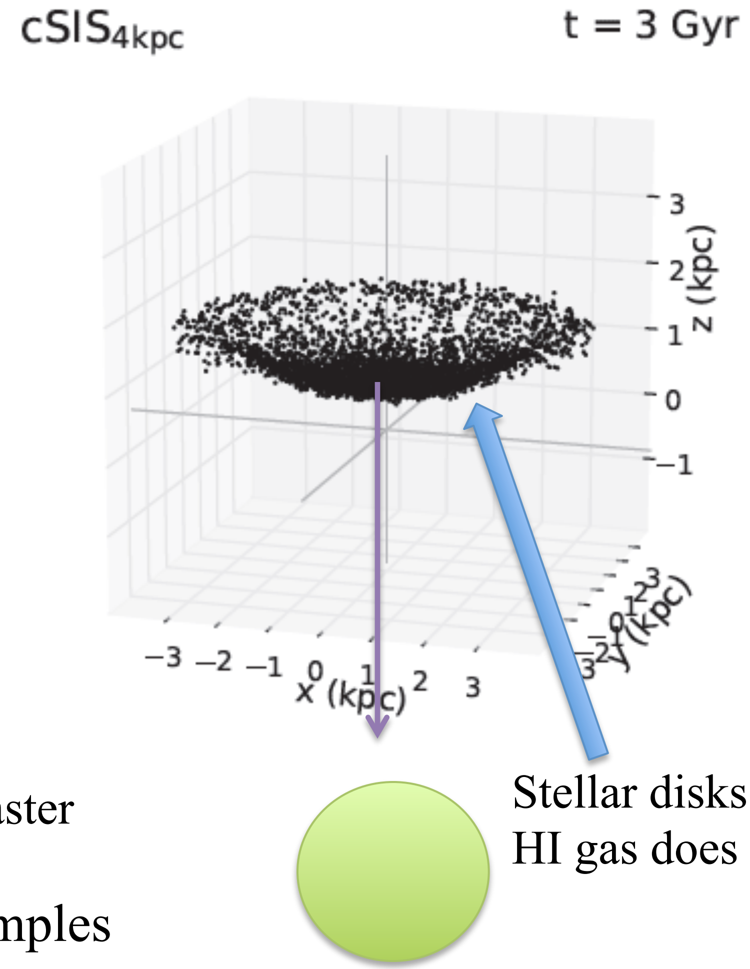
  Hui, Nicolis & Stubbs 2009; BJ & VanderPlas 2011; Hui &Nicolis 2012

Signatures of modified gravity

Two examples



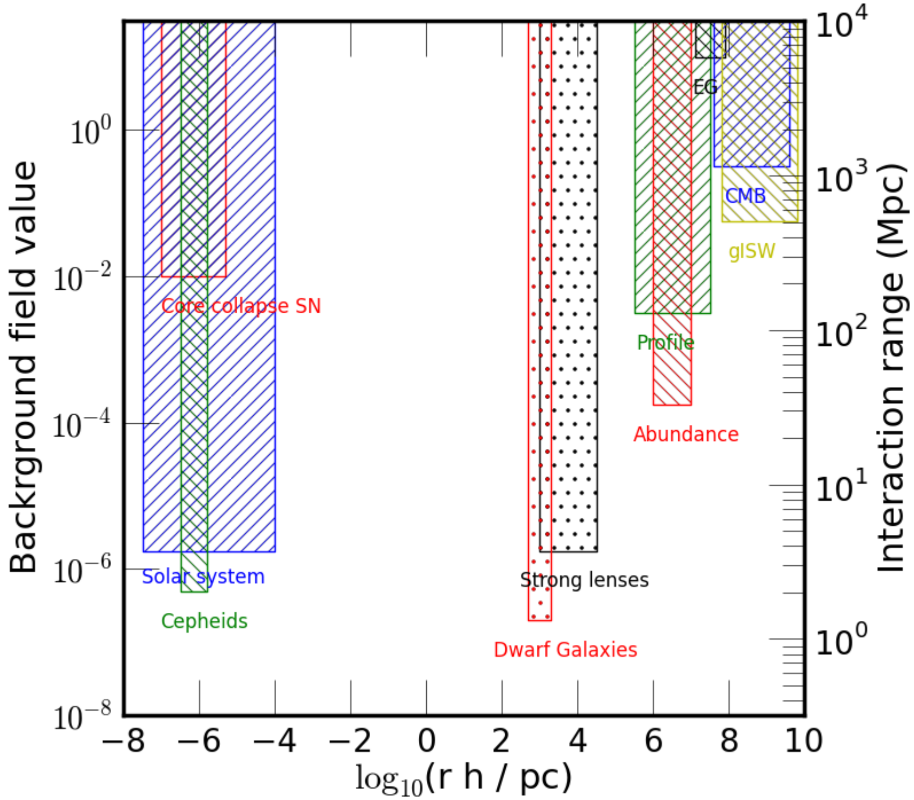
Cepheids pulsate faster



Stellar disks warp
HI gas does not

Giant stars and disk galaxies: use control samples to distinguish astrophysical effects

Current limits on gravity theories



- Nearly all these limits on chameleon/f(R) gravity theories have been obtained in the last 5 years.
- A broad class of gravity theories is essentially ``ruled out''

BJ, Vikram, Sakstein 2012; Lombriser et al 2012; BJ et al 2013 (Snowmass)

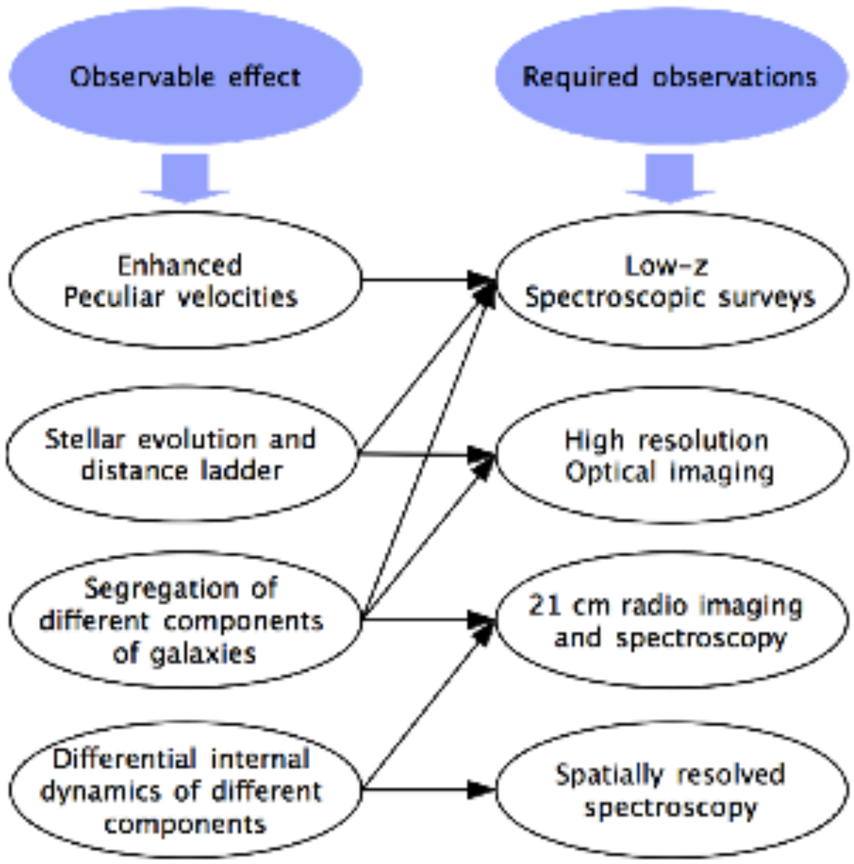
Beyond smooth dark energy: experimental prospects

Gravity Test	Length scale	Telescope/Experiment
Consistency of growth and expansion	100 Mpc – 1 Gpc	Dark energy (DE) surveys: Ongoing + Stage IV surveys
Lensing vs. Dynamics	1 kpc – 100 Mpc	Imaging + Spectroscopy on common sample of galaxies/clusters: DE Surveys supplemented by 4-8m telescope observations
Astrophysical Tests	0.01 AU – 100 kpc	Low-z* spectroscopy + imaging: DE Surveys + supplementary data from diverse telescopes
Lab and Solar System Tests	1mm – 10 AU	A variety of experiments: EotWash, CHASE, Lunar Laser Ranging

How do we plan for and integrate information from different regimes?

These and other questions are being figured out, while theories are evolving!

How to think about surveys



We need a set of mini-surveys for astrophysical tests of gravity

Beyond Dark Energy

- Cosmic acceleration and fundamental physics motivations ➡ multi-scale tests of gravity and dark sector couplings.
- By bridging local and astrophysical tests of gravity with cosmological observations we will probe many failure modes of the standard model of cosmology.
- The new experimental program makes life interesting!
  - Multi-scale, multi-wavelength imaging + spectroscopy, and innovative analysis
  - Several combinations of LSST and WFIRST with other datasets are of interest!

Snowmass report presents these ideas: BJ et al, arXiv:1309.5389

Review article: Joyce, BJ, Khoury, Trodden, arxiv:1407.0059

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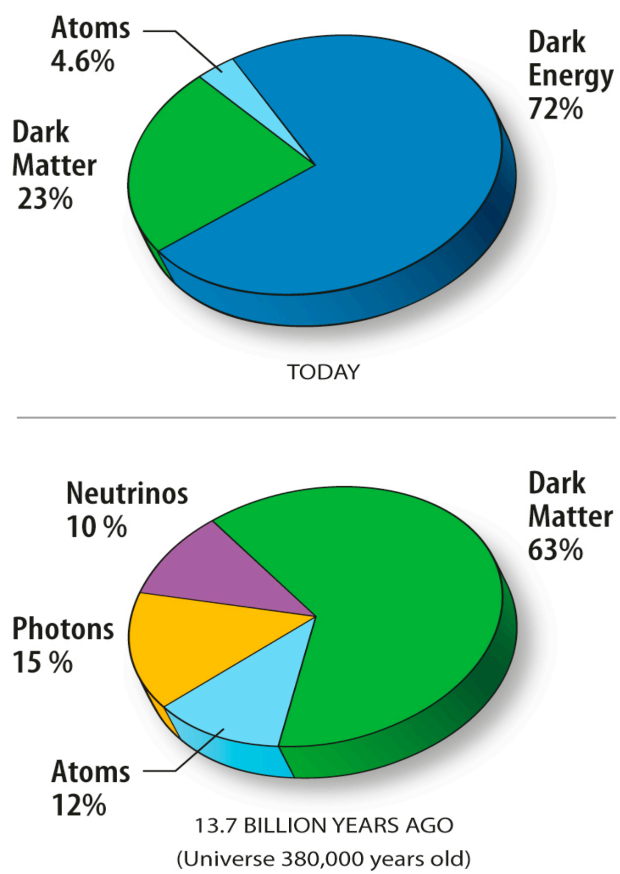
Spare slides

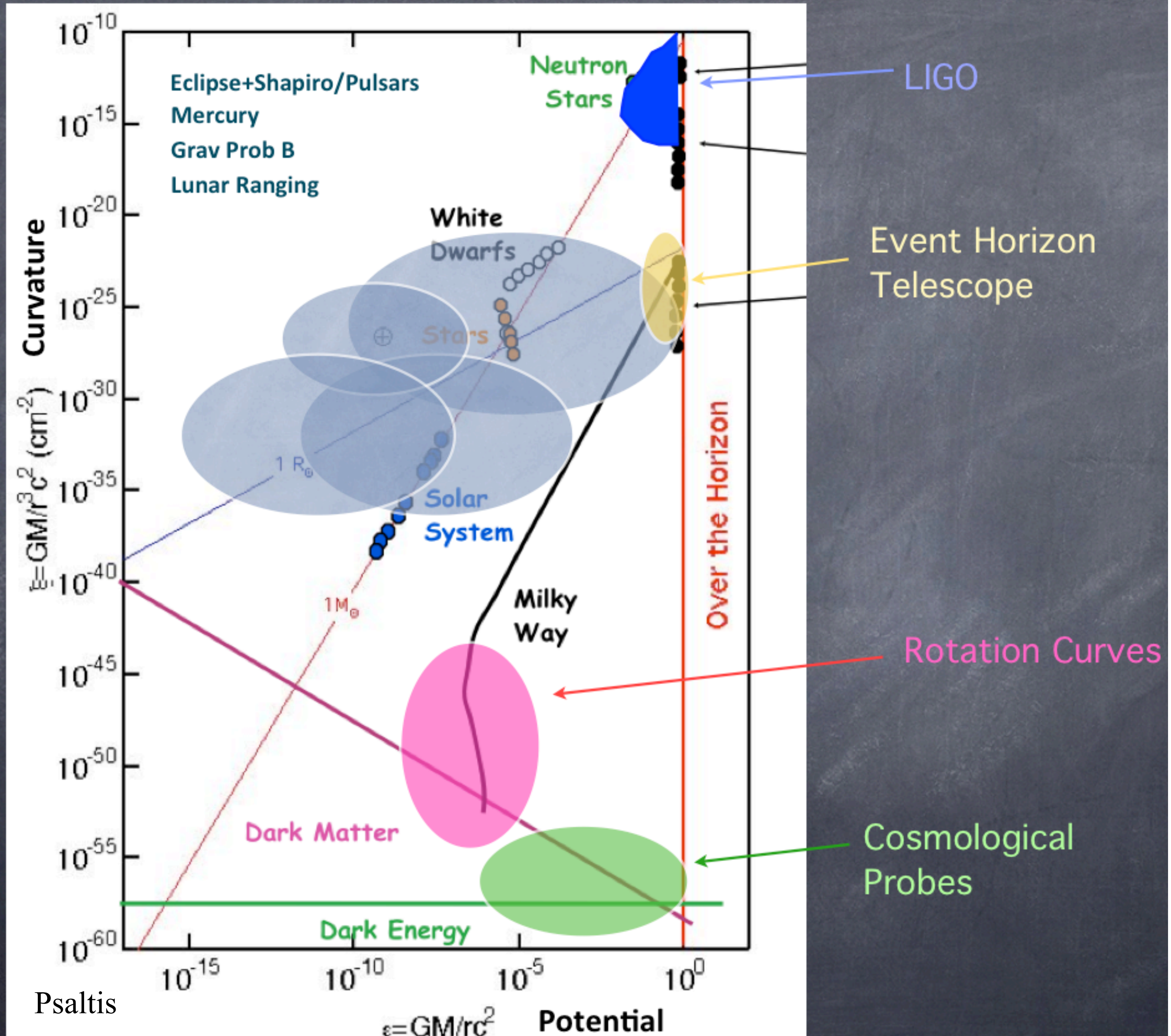
Energy budget over cosmic time



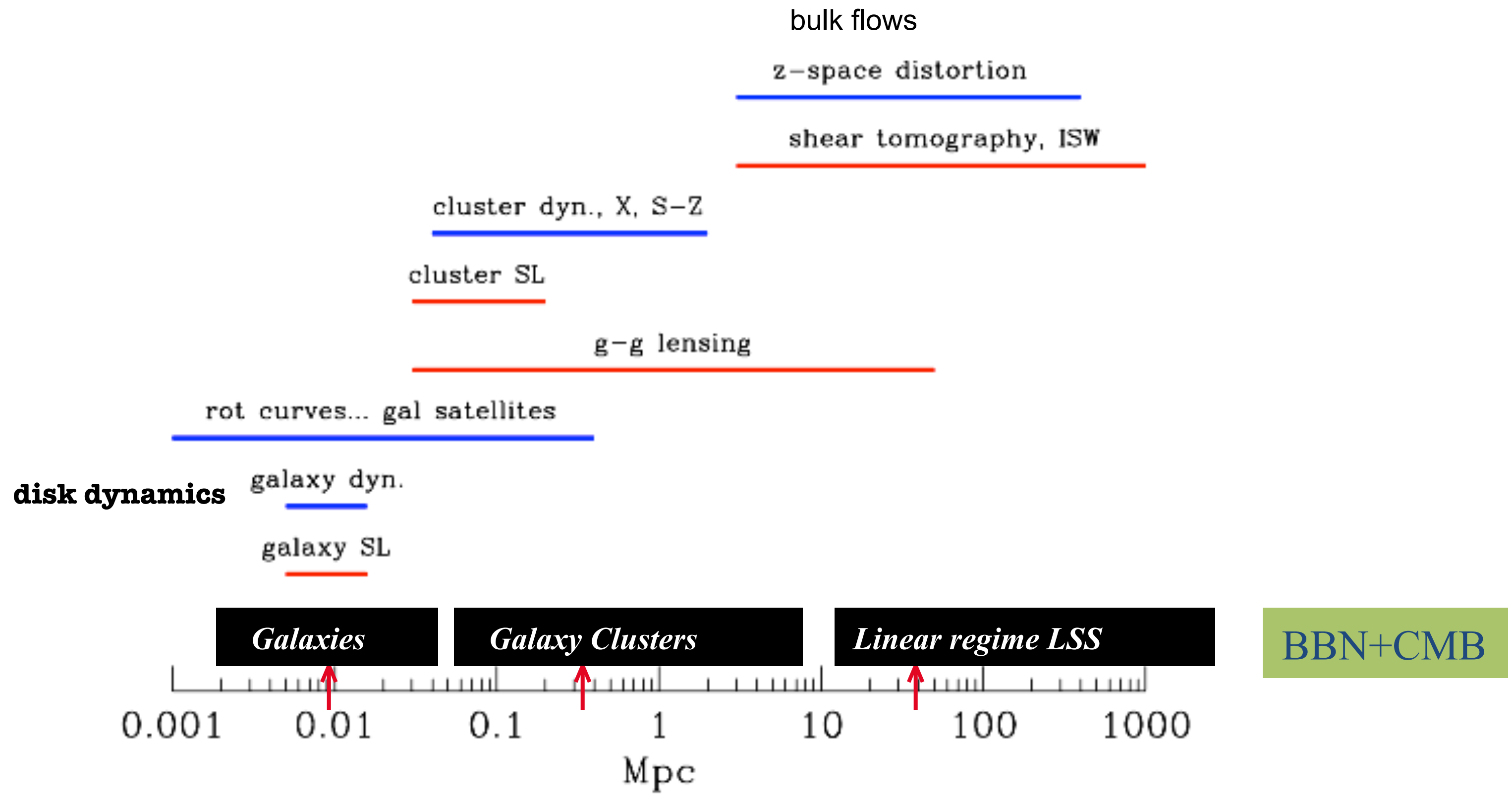
WMAP web site

Discovery Space

- Cosmic acceleration and fundamental physics motivations ⇨ multi-scale tests of dark energy, gravity and dark sector couplings.
- The ``discovery space'' spans:
  - Early universe
  - Evolution of the universe at late times
  - Dark sector interactions


Curvature
ξ=GM/r³c² (cm⁻²)
ε=GM/rc²
Potential
Eclipse+Shapiro/Pulsars
Mercury
Grav Prob B
Lunar Ranging
Neutron Stars
White Dwarfs
Stars
Solar System
Milky Way
Dark Matter
Dark Energy
Over the Horizon
1 R⊙
1M⊙
LIGO
Event Horizon Telescope
Rotation Curves
Cosmological Probes
Psaltis

Astrophysical and cosmological probes of gravity

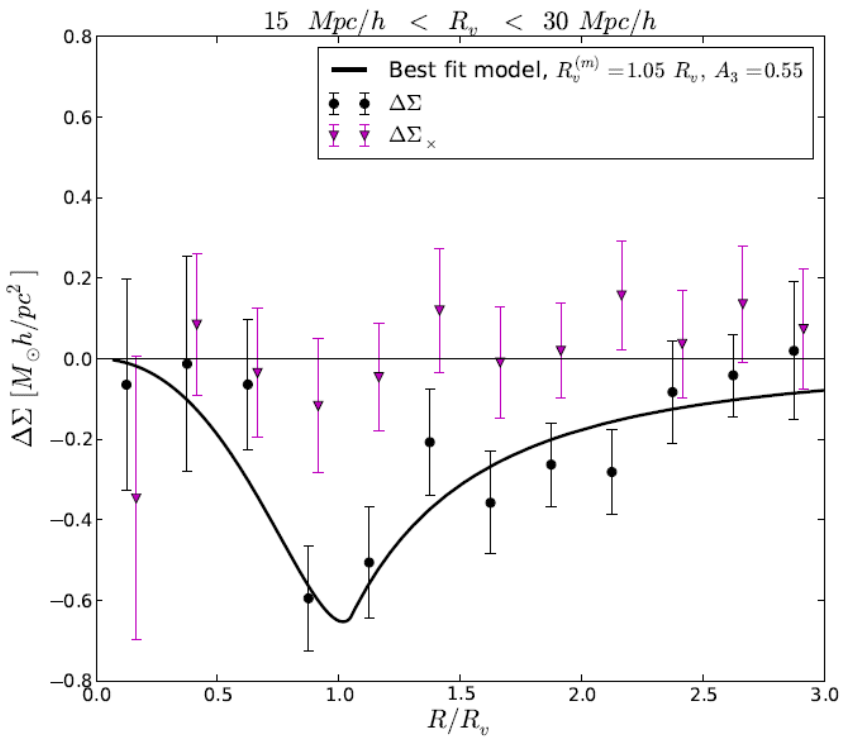


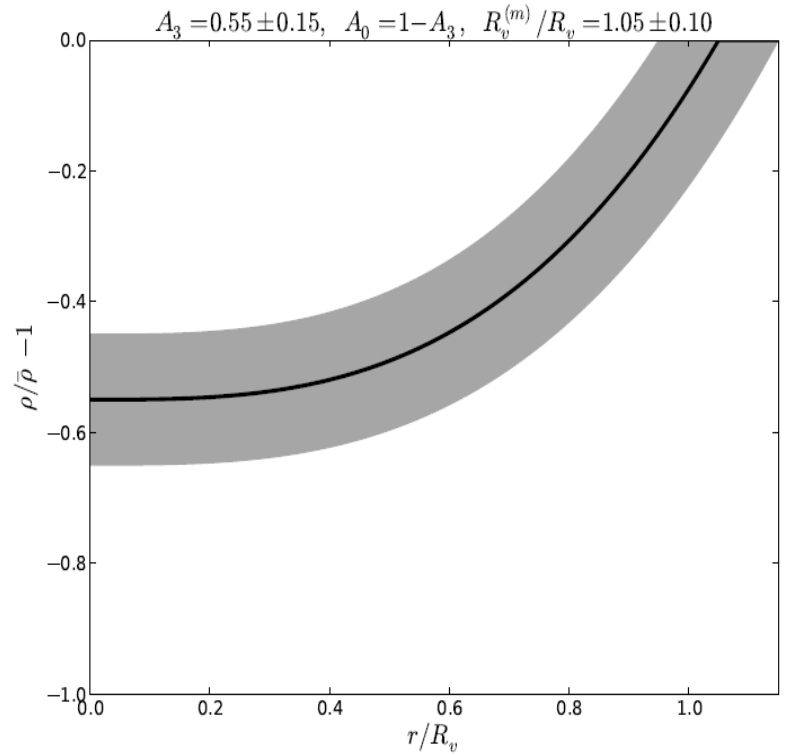
Dynamical probes (blue) measure Newtonian potential ψ

Lensing and ISW (red) measures $\phi + \psi$

BJ & Khoury 2010

Void lensing detection from the SDSS





- 16-sigma detection of void lensing: *Clampitt & BJ, arxiv: 1404.1834*
- For the first time can measure the mass content of cosmic voids