Cosmology: dark energy and beyond

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References: Snowmass reports

Kim et al, arXiv: 1309.5382

Huterer et al, arXiv: 1309.5358

BJ et al, arXiv:1309.5389

See talks by Kosowski, Kusenko, Pryke

Talk to Pitt Cosmologists!

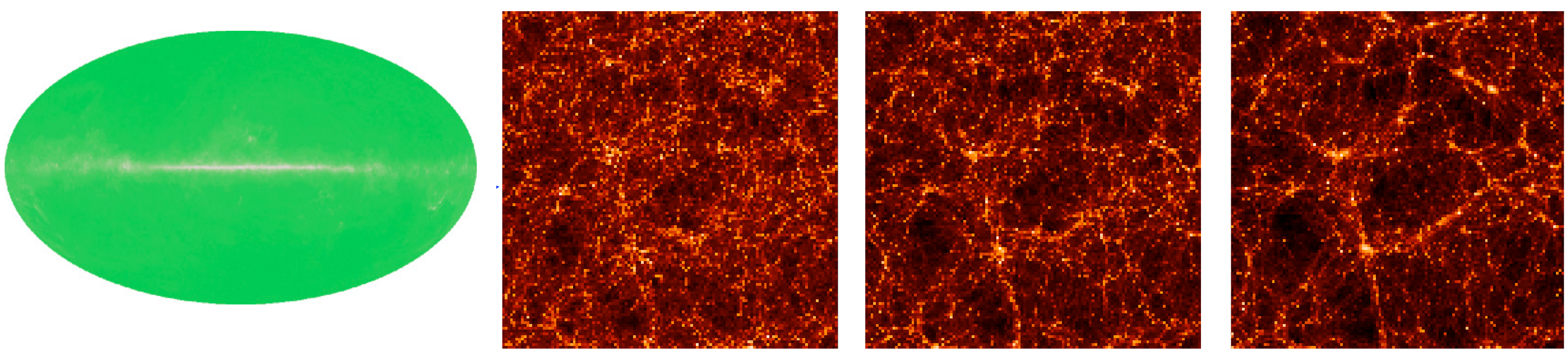
Outline

- Cosmological observations: CMB to galaxy surveys
- Beyond dark energy
- Tests of gravity from mm to Gpc scales
- Discovery space for the future

Cosmology probes: geometry and growth

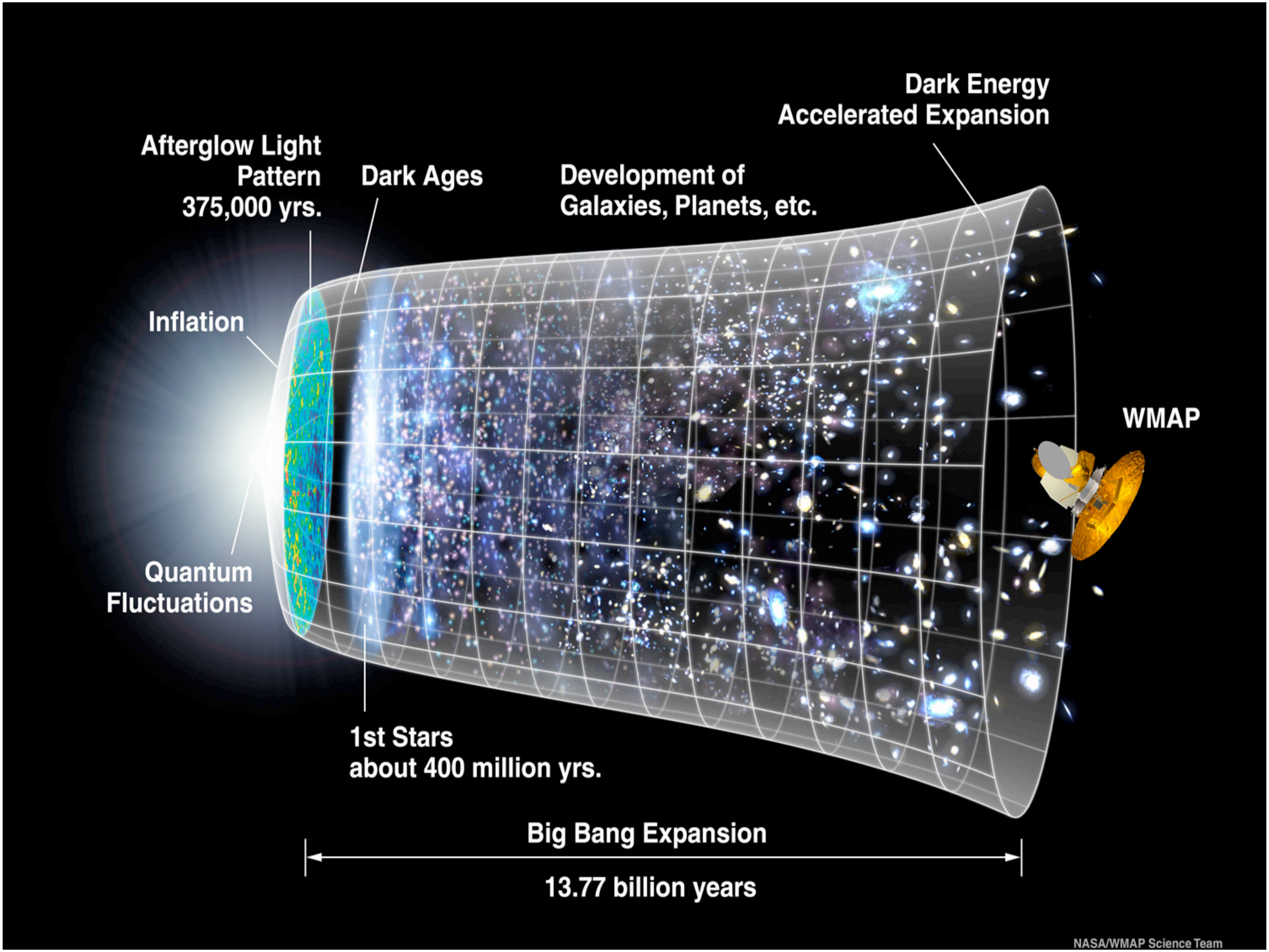
- Geometry: Distance-Redshift relation D(z), Expansion rate H(z)
- Growth: Fluctuations in temperature, mass, gas and galaxies

a=0.001 a=1/4 a=1/2 a=1 (today)



- Features in the fluctuation power spectrum
  - Tilt (inflation), locations of peaks (geometry), damping tail (neutrinos)
- Low-z/late time universe has several probes of geometry and growth

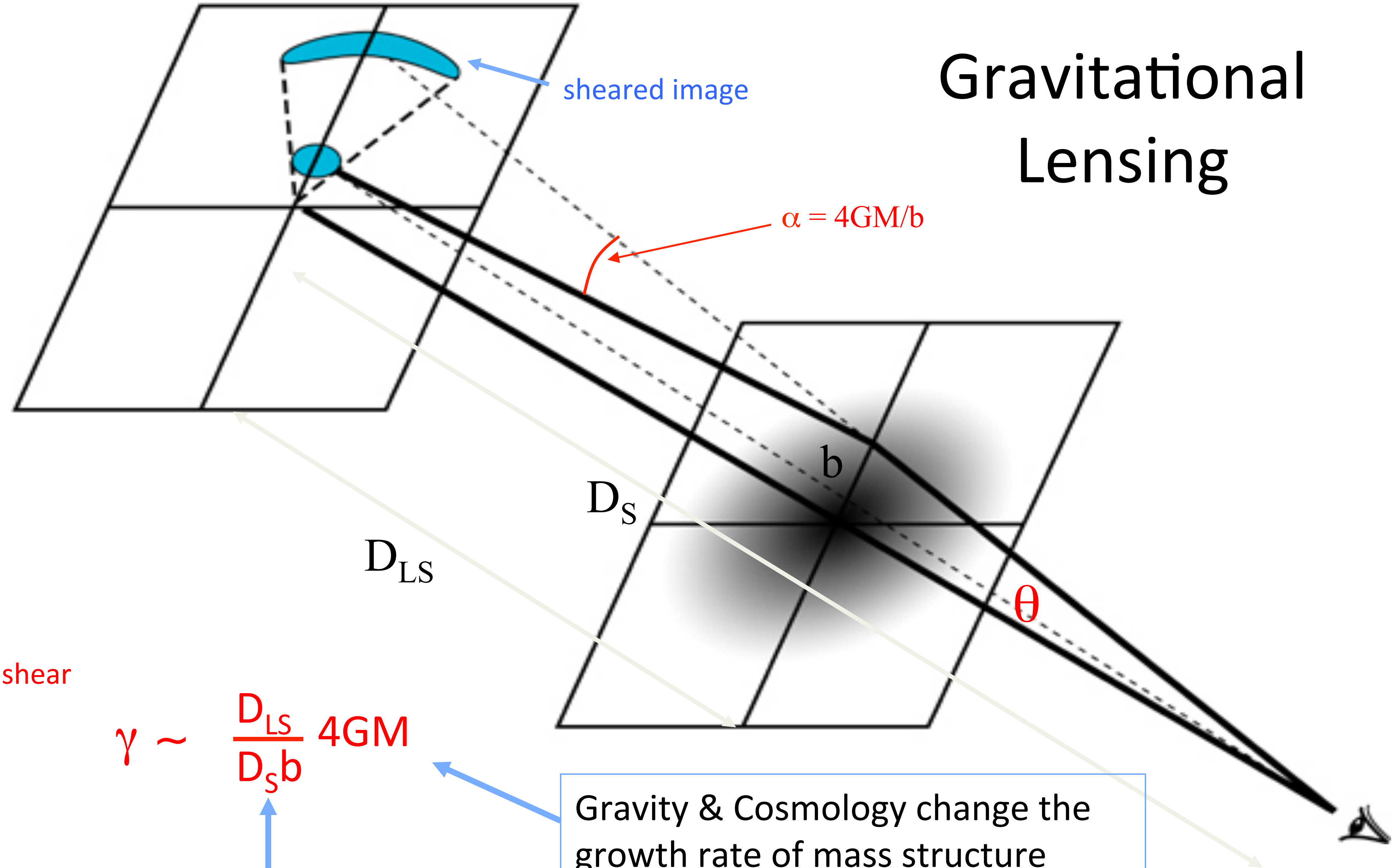
  - Combining CMB with late time data provides huge lever arm in scale and time: tests of inflation, dark energy, massive neutrinos, dark sector interactions


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

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, and others	Time delays, power spectra	Geometry and growth

Gravitational Lensing



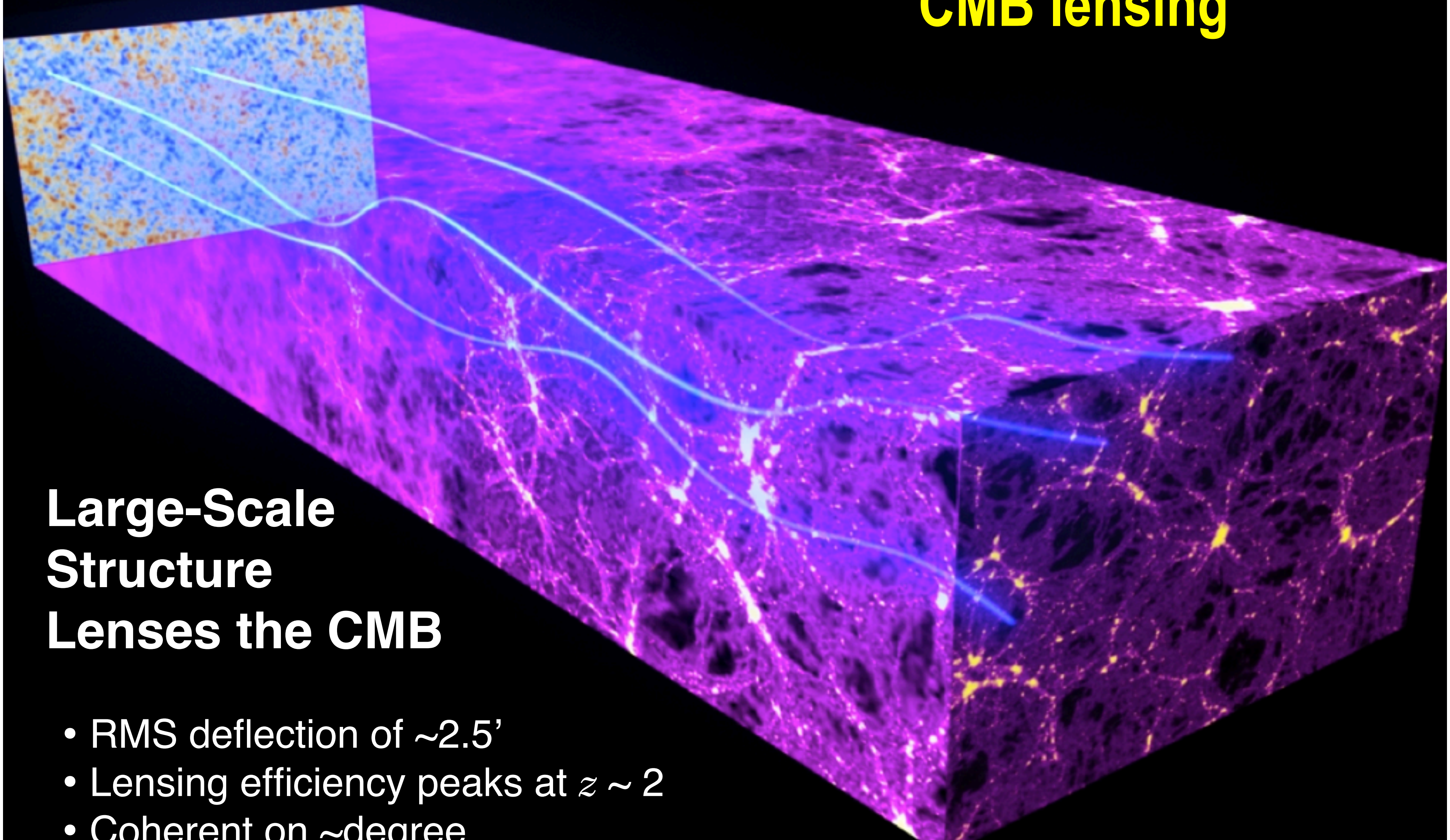
shear

$$\gamma \sim \frac{D_{LS}}{D_S b} 4GM$$

Gravity & Cosmology change the growth rate of mass structure

Cosmology changes geometric distance factors

CMB lensing

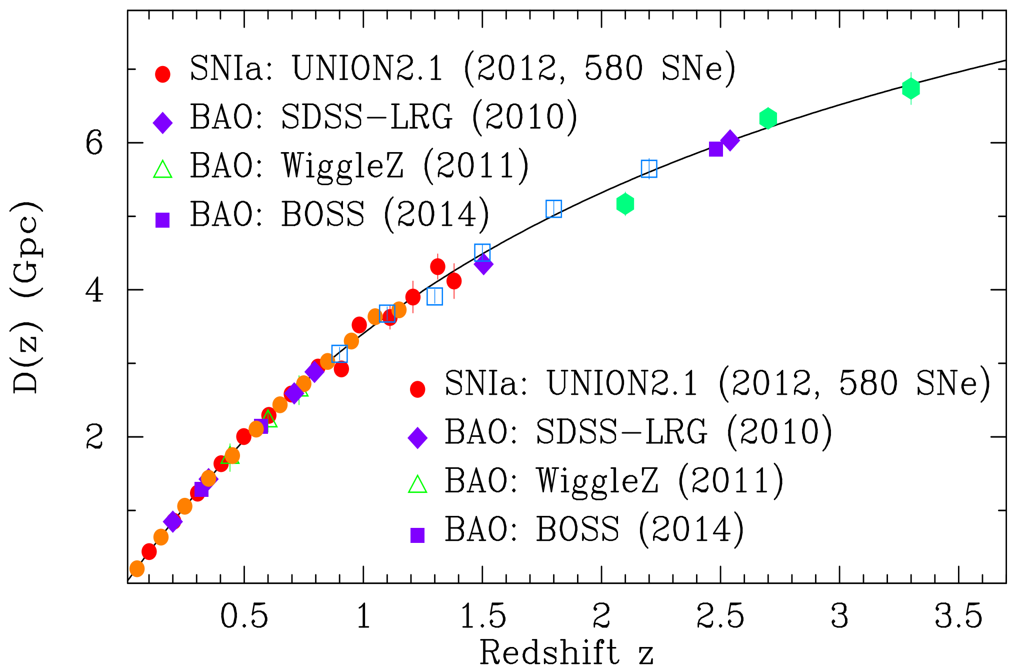


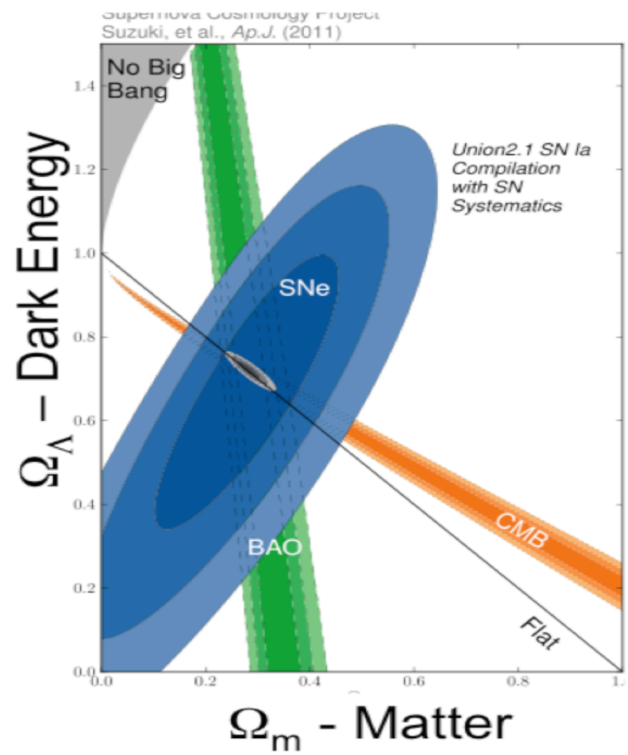
Large-Scale Structure Lenses the CMB

- RMS deflection of ~2.5'
- Lensing efficiency peaks at $z \sim 2$
- Coherent on ~degree (~300 Mpc) scales

Carlstrom graphic from ESA Website

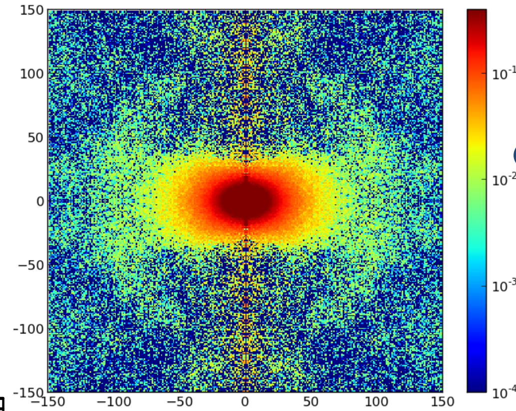
Current results: geometry



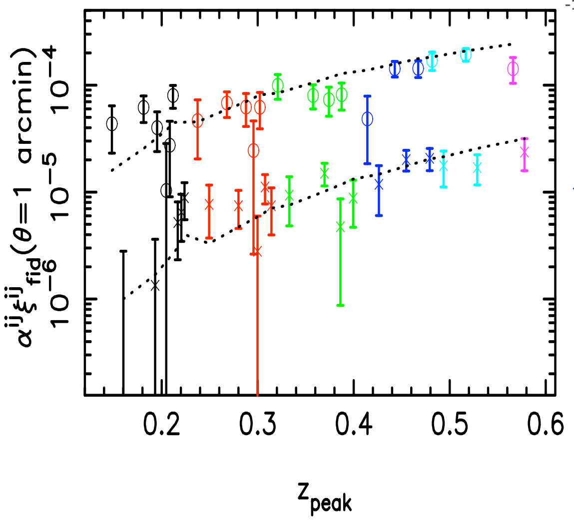


- Distance-redshift relation from SN and BAO
- Consistent with Lambda-CDM

Current results: growth of structure

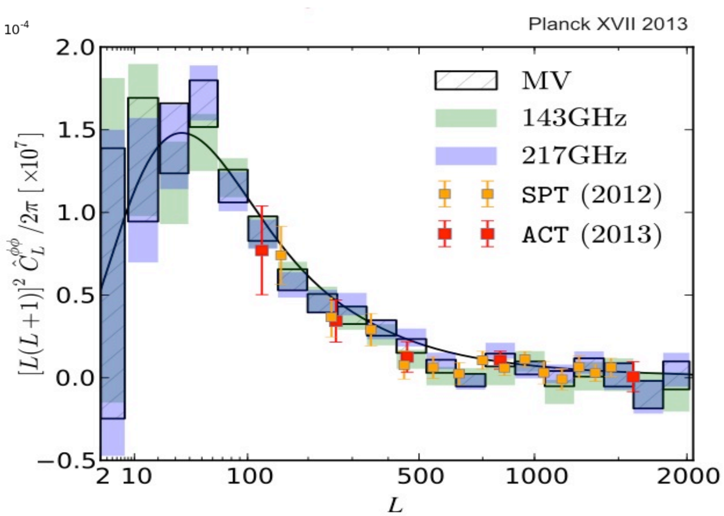


Galaxy clustering



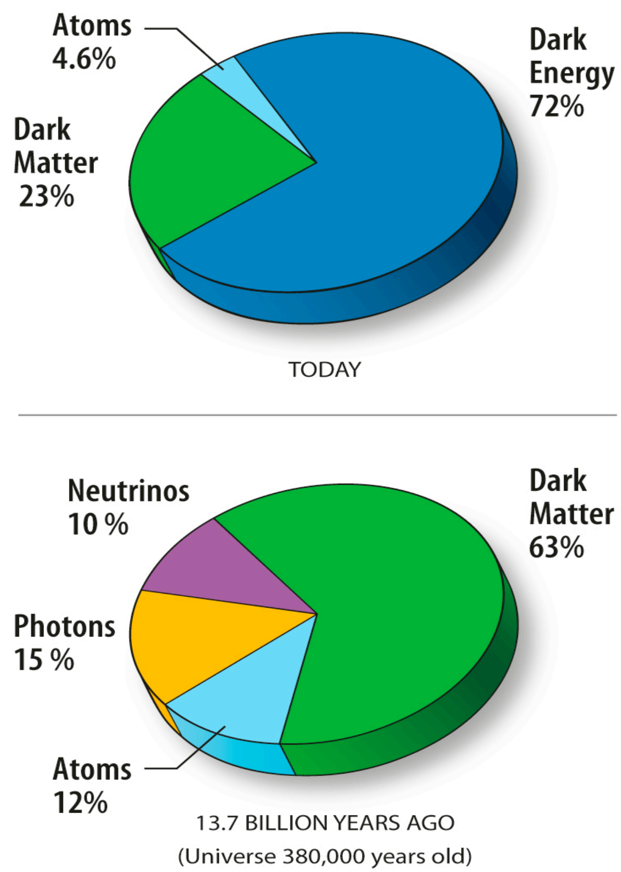
← Galaxy lensing

CMB lensing →



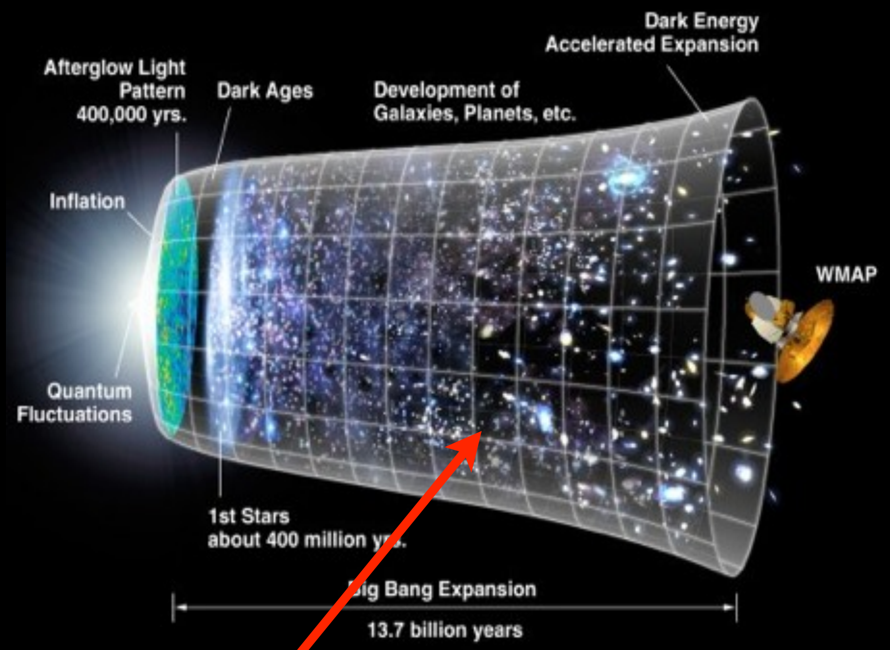
- Growth of structure: BOSS, CFHLS, Planck and SPT data (also galaxy clusters)
- CMB+late universe: consistent with inflationary fluctuations
- But…amplitude at late times lower than inferred from CMB

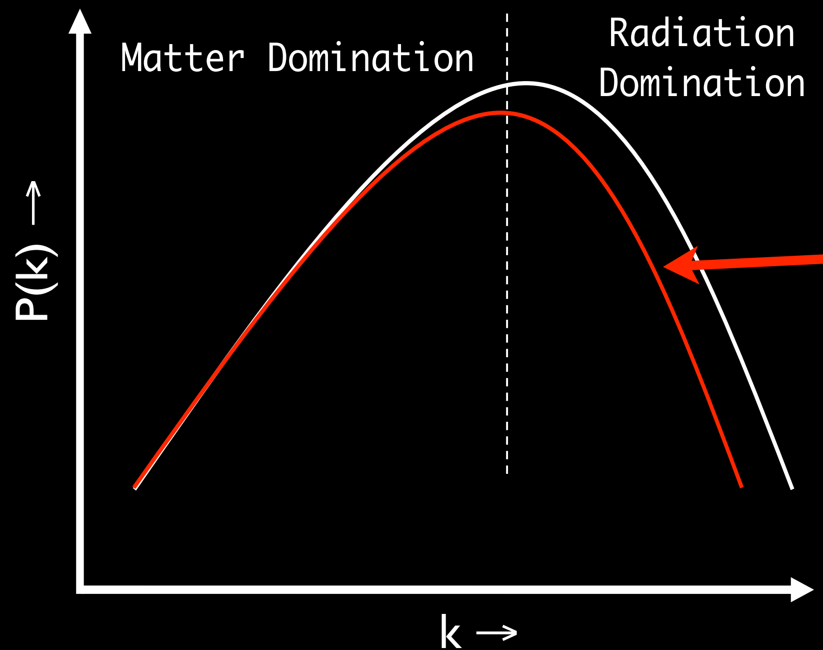
Energy budget over cosmic time



WMAP web site

Neutrinos





$\Sigma m_\nu > 0$

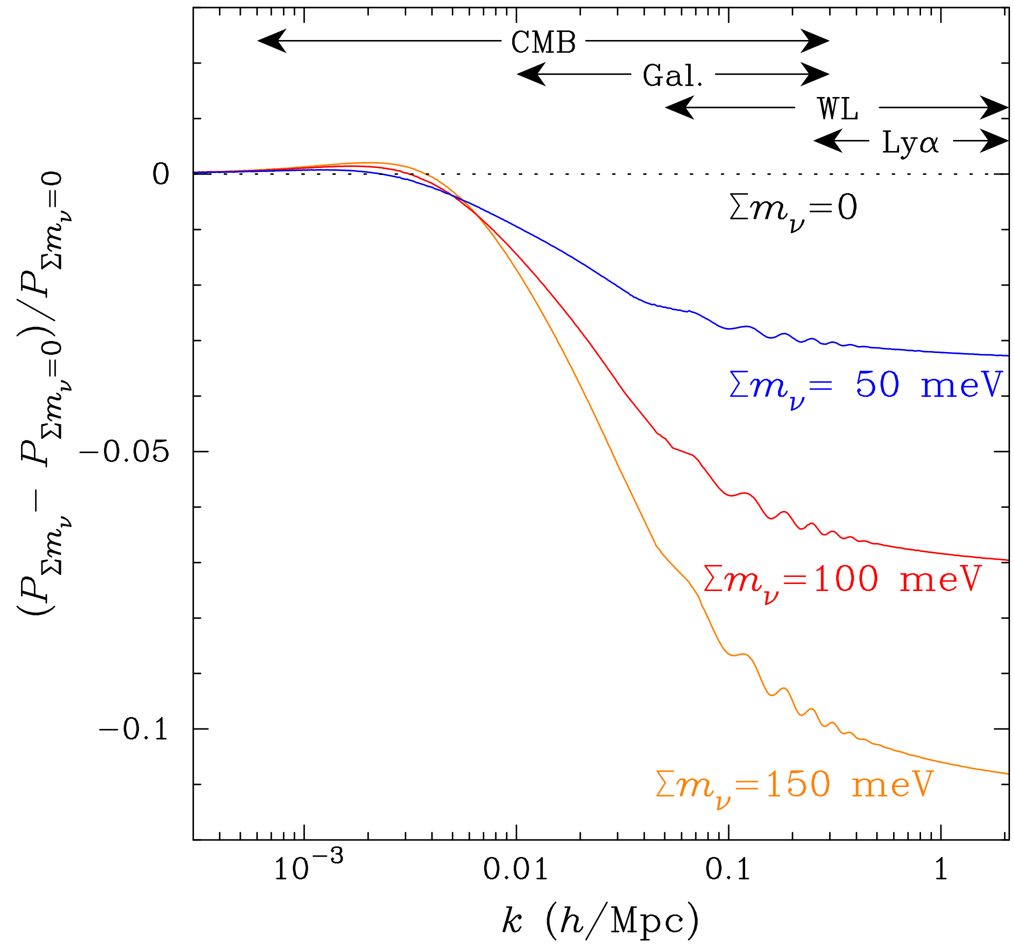
Sum of the neutrino masses
impacts growth of large scale structure,
i.e., the matter power spectrum
Probed by CMB lensing

Carlstron

graphic from NASA/WMAP

Multi-component dark matter and neutrinos

- Neutrinos as a known hot component of dark matter
- Changes matter-radiation equality: impact on CMB
- Suppress growth of structure in a scale dependent way
- Note: Data also sensitive to other features in primordial power spectrum.



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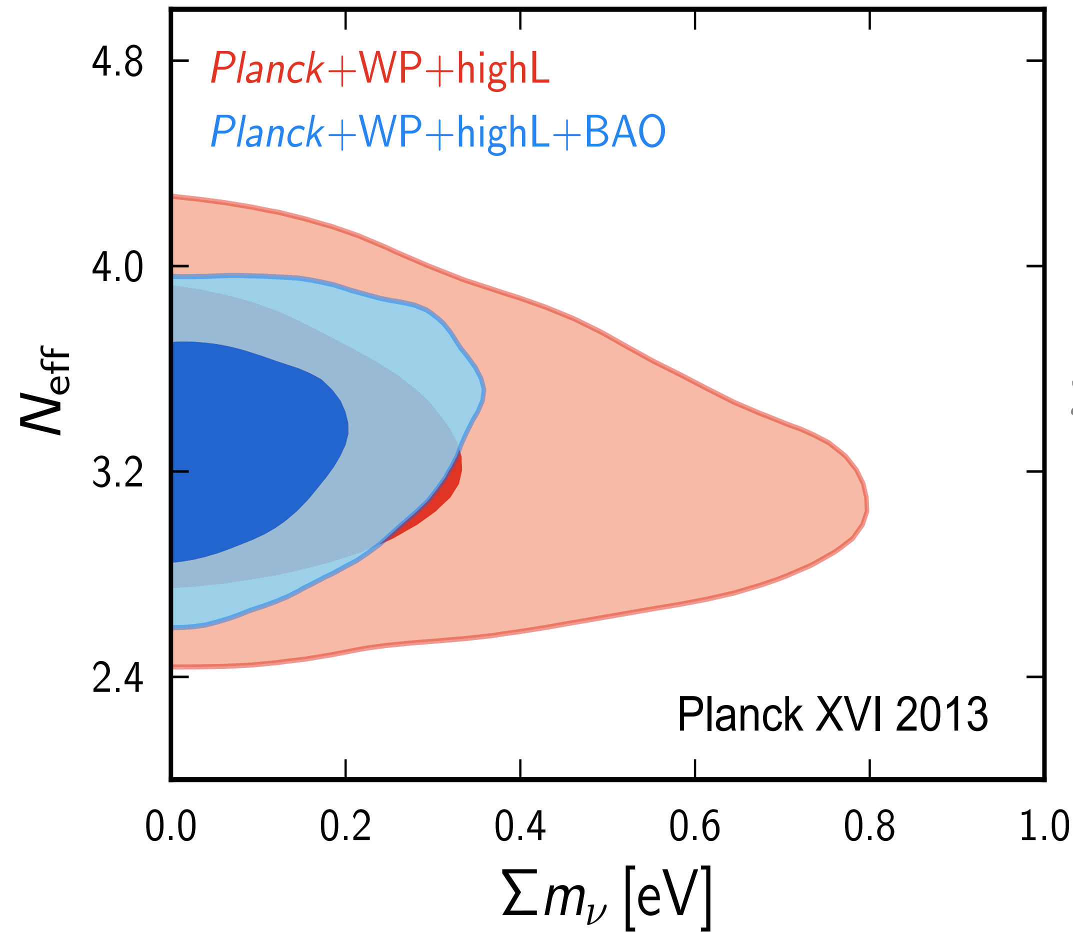
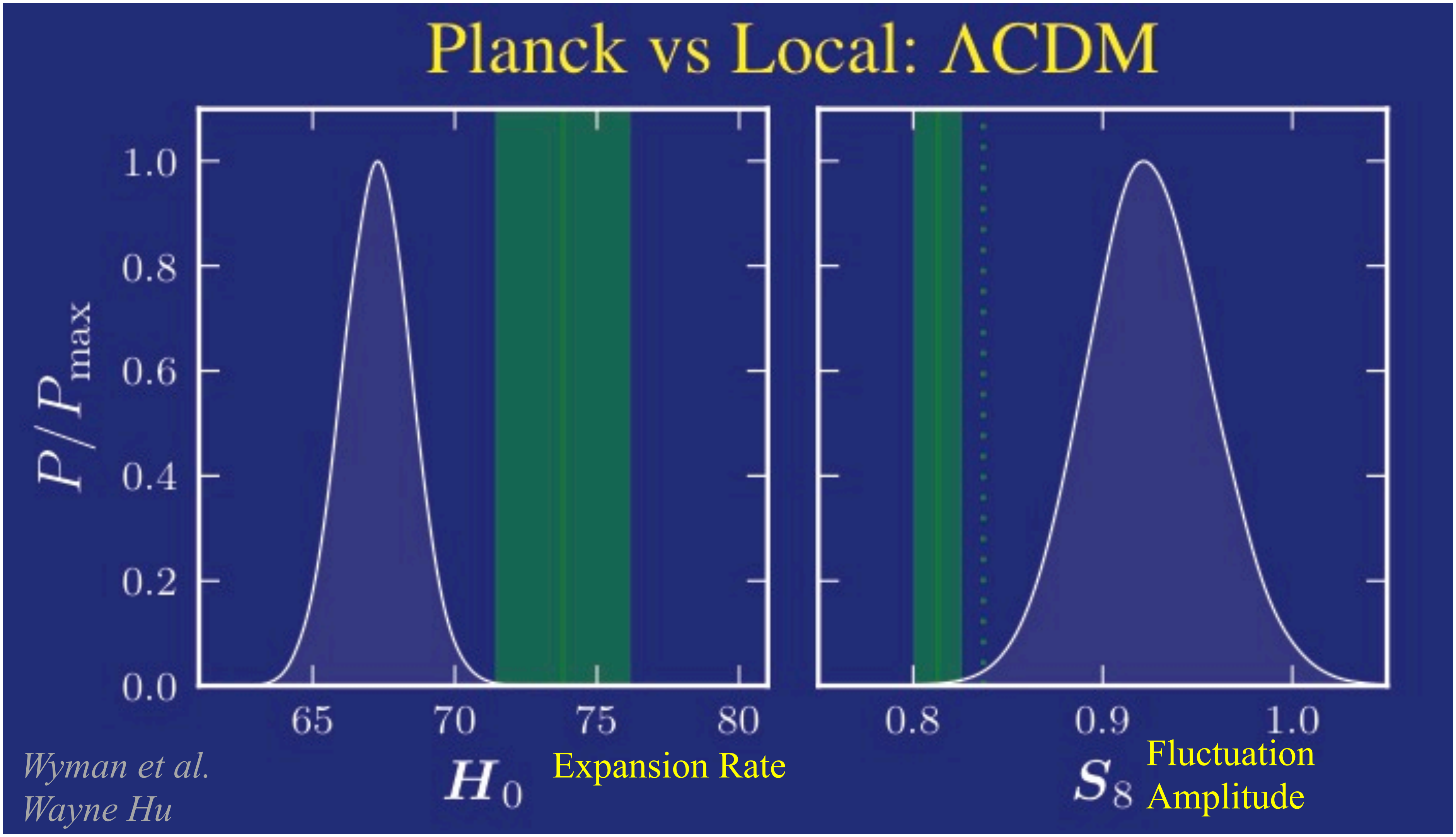


(Mild) tension in cosmology data



Extrapolation from CMB to Present disagrees with low-z measurements

(Mild) tension in cosmology data

- BICEP2
- CMB vs low-z measurements of H_0
- Amplitude of fluctuations

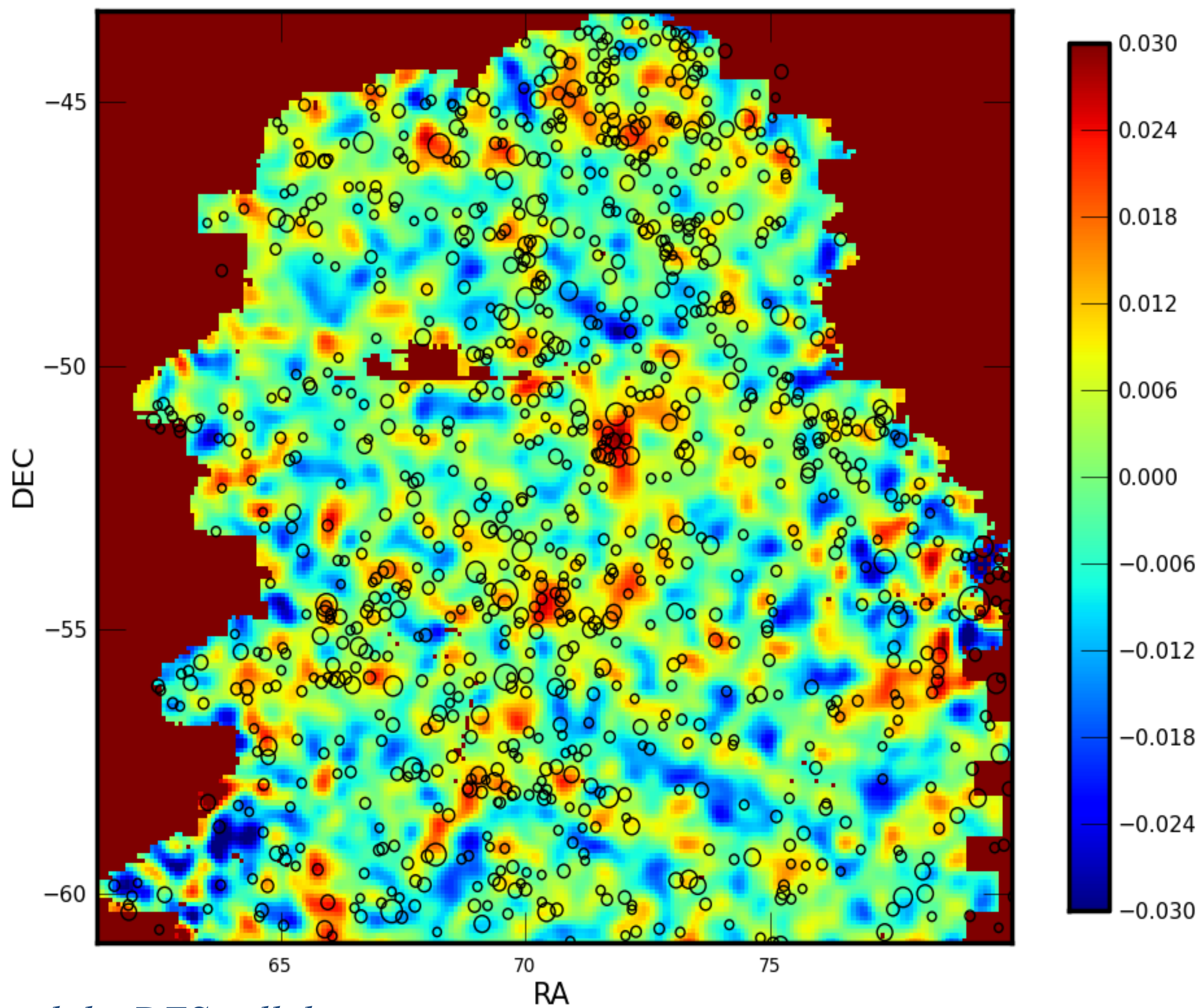
Resolution?

- Tilt+running of primordial spectral index,
- evolving dark energy,
- sterile neutrinos,
- ??

2-3 theory papers per day since BICEP2 -> we need more data!

Dark Energy Survey: 150 sq deg mass map

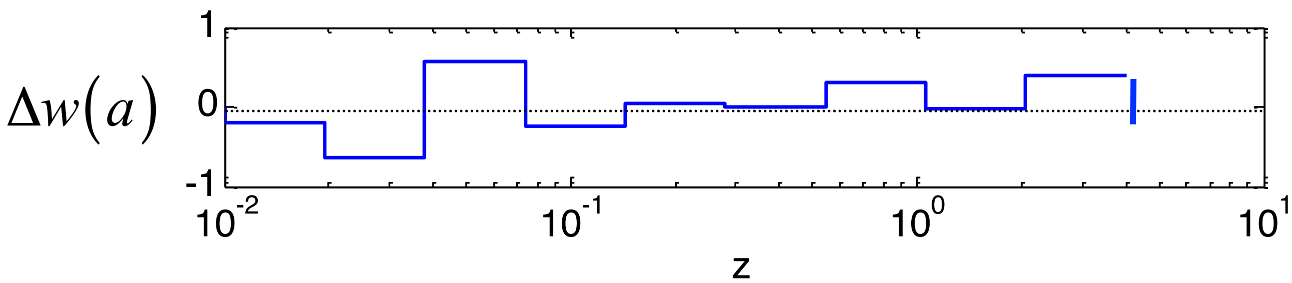
- Convergence map from DES: largest mass map to date
- Overlaid with with galaxy clusters
- Preliminary!



Vikram, Chang, BJ, Bacon and the DES collaboration, in prep.

Beyond dark energy

Beyond Lambda



- 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

- 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:

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

A. Tolley

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)
(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

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

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

- 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 by ~10%
- Photons respond to the sum ($\Psi+\Phi$) which is typically unaltered
  - Dynamical masses are larger than Lensing (true) masses

Modified Gravity

Stars, gas 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

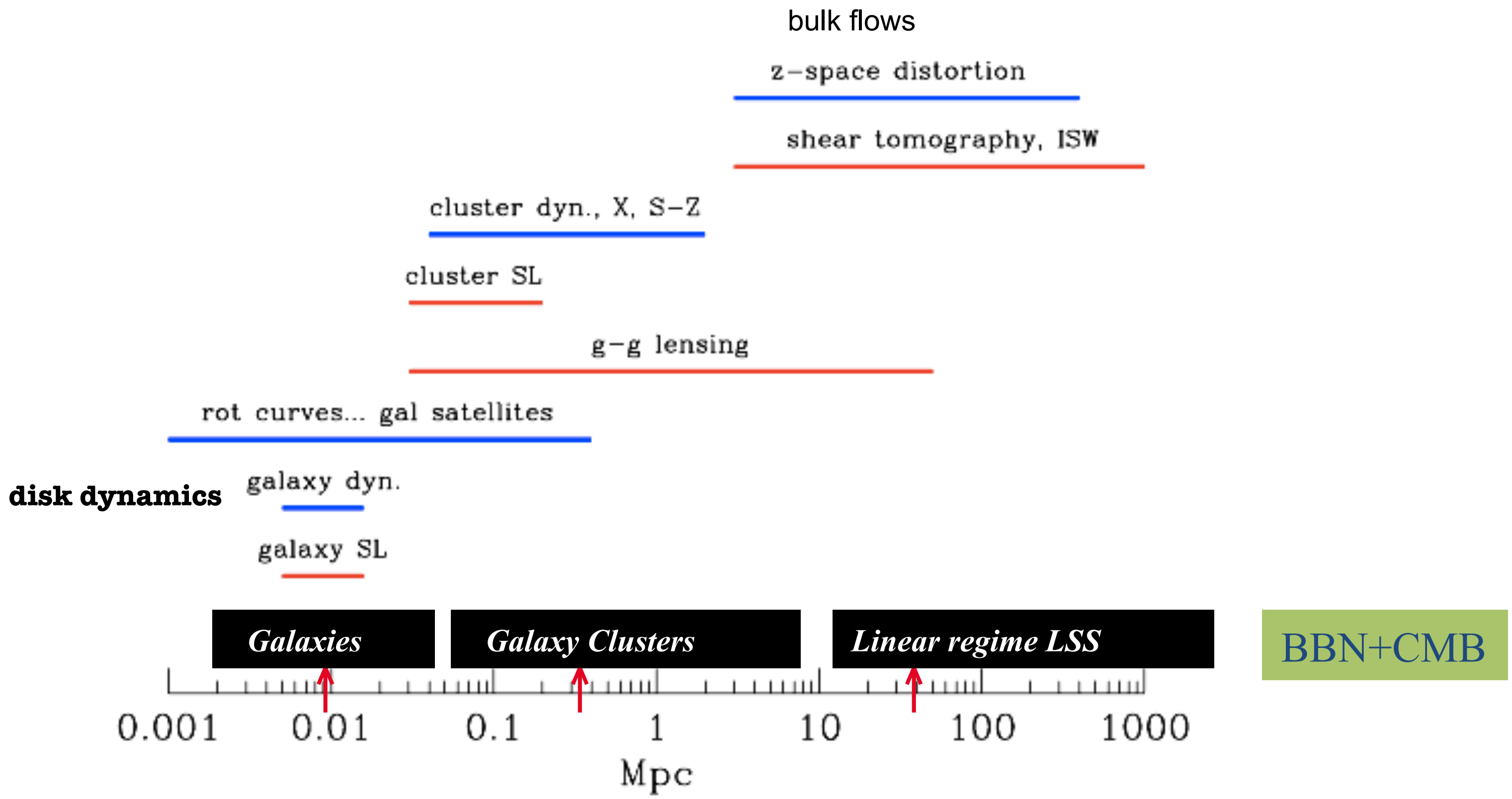
  Chang & Hui 2010; Davis et al 2011; BJ, Vikram, Cabre 2012

• Dark matter and gas clouds are diffuse -> should feel the fifth/scalar force if their host galaxy is unscreened.

- Stars rotate slower and separate from gas due to external forces
- Black holes and stars may also separate in some scenarios

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

Astrophysical and cosmological probes of gravity



Dynamical probes (blue) measure Newtonian potential ψ

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

Cosmological tests with nearby galaxies

Pulsating stars and nearby distances

• Cepheids are 3-10 $M_{\odot}$ giant stars that pulsate over days to weeks. The period P and luminosity L are tightly related -> distance indicator

-*Newtonian potential in oscillating envelope of star ~ 10^{-7}*

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

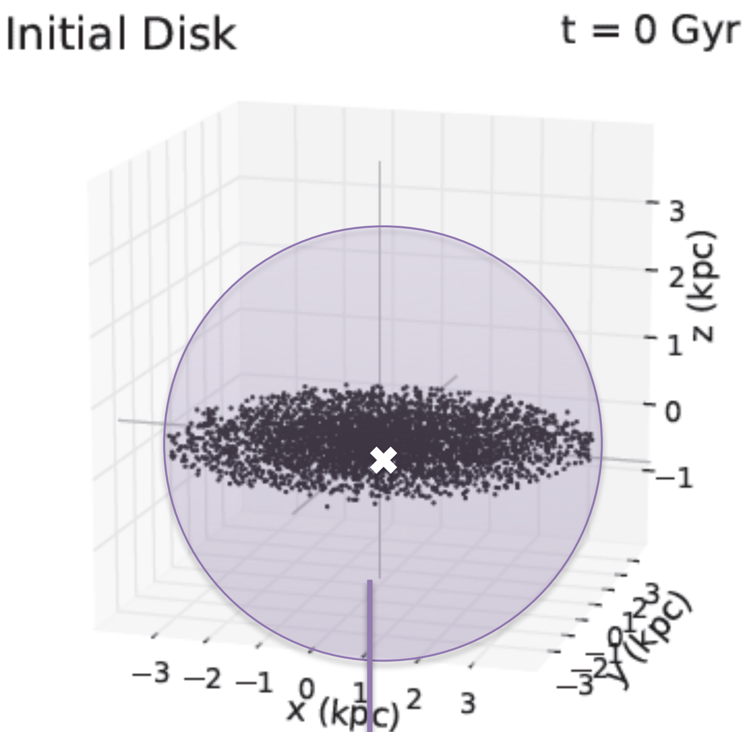
-*Scalar force enhances G -> lowers P -> underestimate distance.*

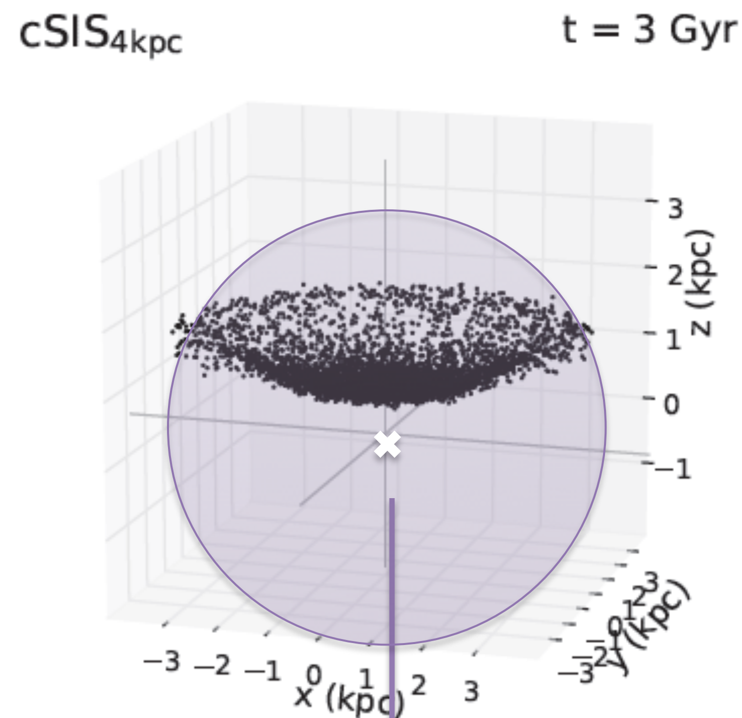
• The peak luminosity at the TRGB (tip of the red giant branch) is nearly universal for 1-2 $M_{\odot}$ stars -> distance indicator

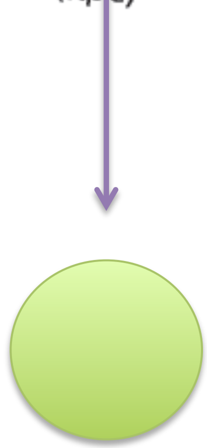
- *Distance estimate is insensitive to gravity theory, and has the opposite change from cepheid distance*

• Water masers around SMBHs provide a geometric method: independent of G!

Disk Galaxy Tests

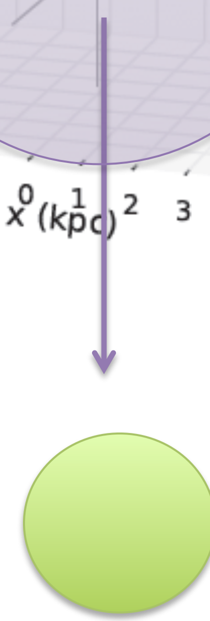




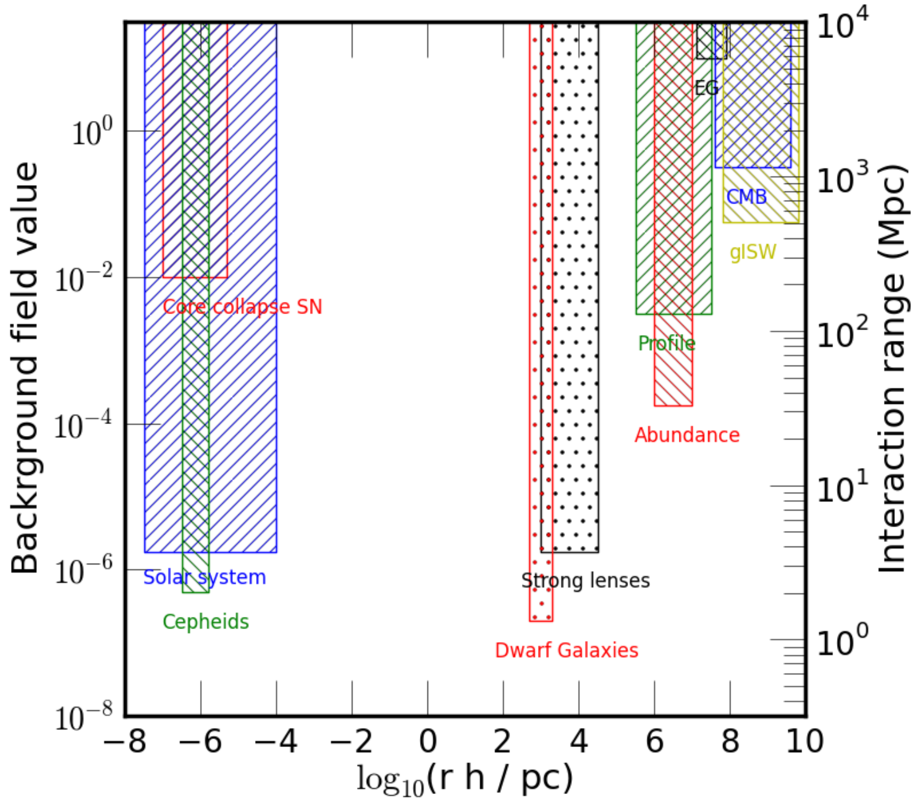


- Enhanced forces between dwarf galaxies can displace stellar disk from halo center
- The gas disk tracks the dark matter halo -> observable offsets

BJ & VanderPlas 2011



Current limits on gravity theories



- Nearly all these limits have been obtained in the last 5 years.
- A broad class of gravity theories ``ruled out”

Einstein ring test of gravity

ψ/ϕ = 1.01+/-0.05 from Einstein Rings + velocity dispersion

Bolton et al 2006; Schwab, Bolton, Rappaport 2010

A suite of tests on large scales will be carried out with upcoming surveys

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