GRAVITATION AND COSMOLOGY

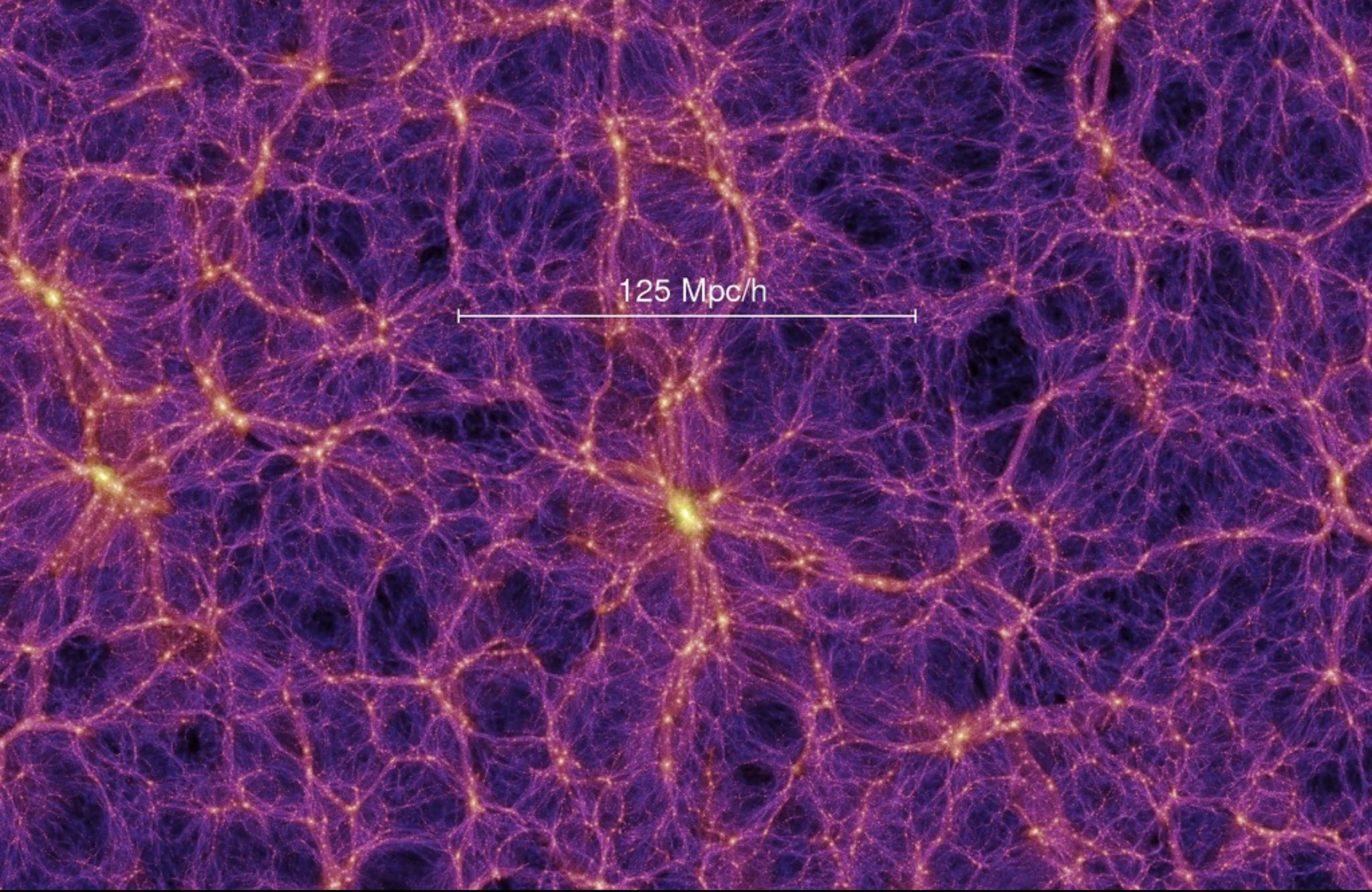
(A BIASED OVERVIEW)

TESSA BAKER, UNIVERSITY OF OXFORD.

OUTLINE

- Cosmology:
  - Cosmo. perturbation theory key results.
  - Application to observations.

- Modified gravity:
  - The panorama of theories.
  - One method of testing them.



1. COSMOLOGY — THEORY

BACKGROUND VS. PERTURBATIONS

‘Background’ ⇒ smooth, homogeneous, isotropic universe.

$$ds^2 = -c^2 dt^2 + a(t)^2\, dx^i dx_i$$

Plug into Einstein field equation :

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

⇒ Friedmann + matter conservation equations:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\left(\rho_M + \rho_R + \ldots\right)$$

$$\nabla_\mu T^\mu_\nu = 0 \qquad \Rightarrow \qquad \dot{\rho}_X = -3H\rho_X(1 + w_X)$$

BACKGROUND VS. PERTURBATIONS

Cosmological L.P.T. $\Rightarrow$ first-order description of inhomogeneity.

Linear deviations from smooth universe, valid on large scales.

Think in Fourier space, i.e. collection of modes labelled by **k** .

In **conformal Newtonian** gauge:

$$ds^2 = -dt^2\,(1 + 2\Psi) + a^2(t)\,(1 - 2\Phi)\,dx^2$$

Together with a **perturbed energy-momentum tensor** for matter:

$$\delta\rho_X = \rho_X \delta_X\,,\ v_X\,,\ \delta P_X\,,\ \sigma_X$$

00 0i ii ij

Plug into: $\delta G_{\mu\nu} = \dfrac{8\pi G}{c^4}\,\delta T_{\mu\nu}\ \ldots$

BACKGROUND VS. PERTURBATIONS

…leads to four equations, from the 00, 0i, ii and ij parts of the tensor.

00 + 3H x 0i equations leads to the **Poisson equation**:

$$\boxed{2\nabla^2\Phi = 8\pi G\sum_X \rho_X\Delta_X}$$

where $\Delta_X = \delta_X + 3H(1+w_X)v_X$

The ij component is particularly simple:

$$\Phi - \Psi = \cancel{8\pi G\sum_X \rho_X(1+w_X)\sigma_X}$$

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$$\boxed{\Phi - \Psi = 0}$$

BACKGROUND VS. PERTURBATIONS

$$\boxed{2\nabla^2\Phi = 8\pi G \sum_X \rho_X \Delta_X}$$

$$\boxed{\Phi - \Psi = 0}$$

Careful expansion of $\delta(\nabla_\mu T^{\mu}_{\nu}) = 0$ yields:

$$\boxed{\ddot{\Delta}_M + 2H\dot{\Delta}_M - \frac{3}{2}H^2\Delta_M = 0}$$

where $\Delta_X = \delta_X + 3H(1+w_X)v_X$

BACKGROUND VS. PERTURBATIONS

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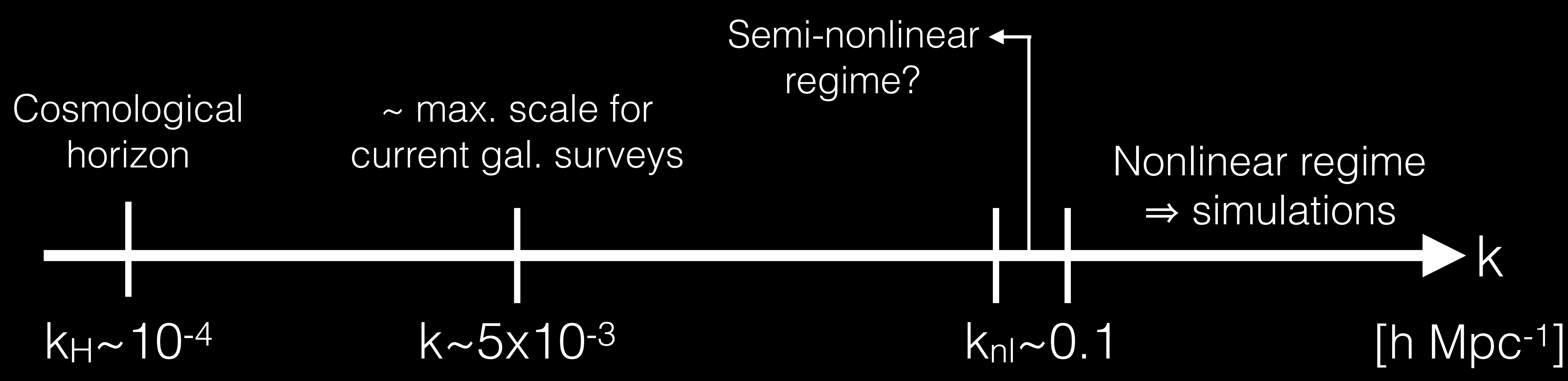
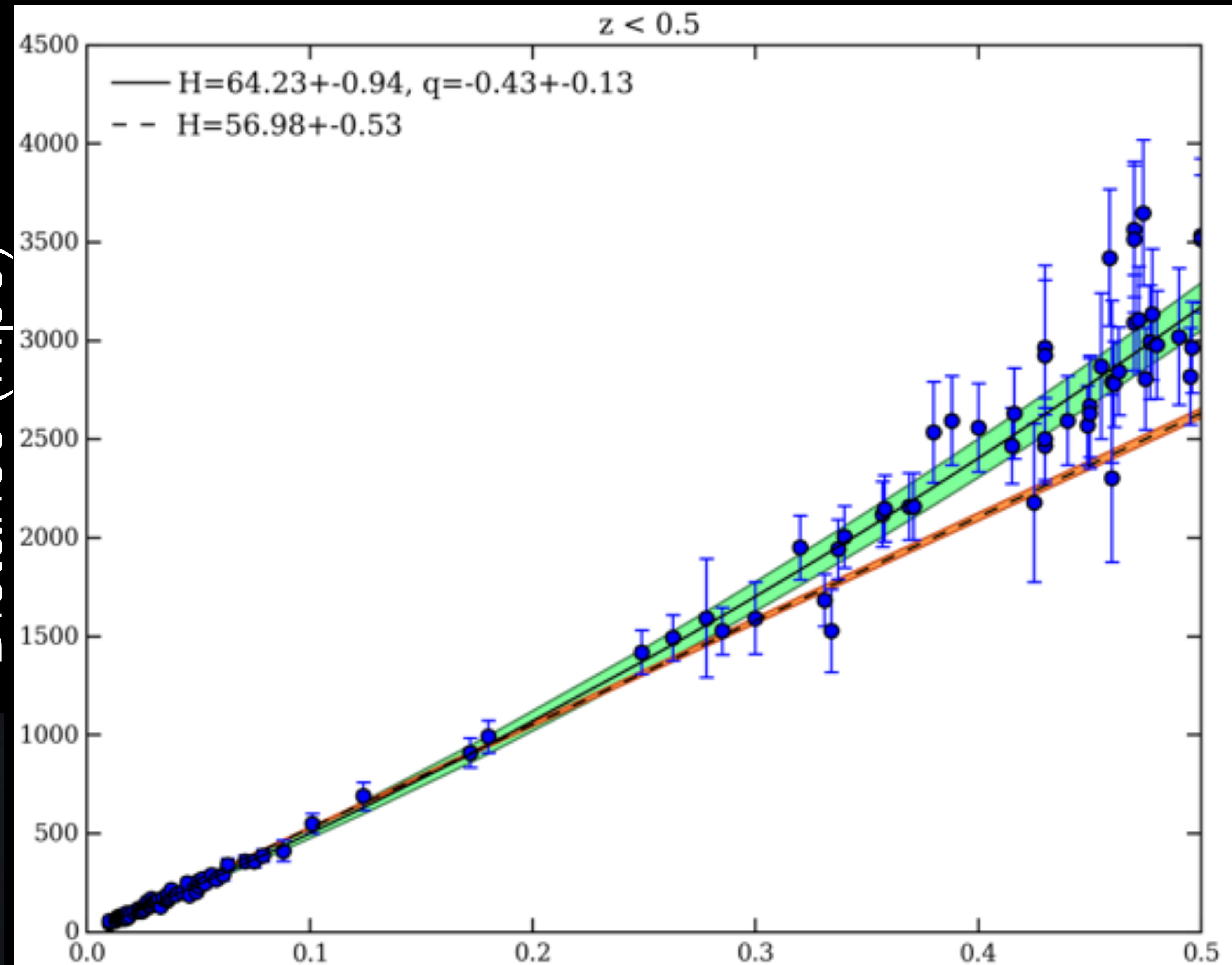
CLPT ok when

$$\Delta_M,\ v_M,\ \Phi,\ \Psi \ll 1$$

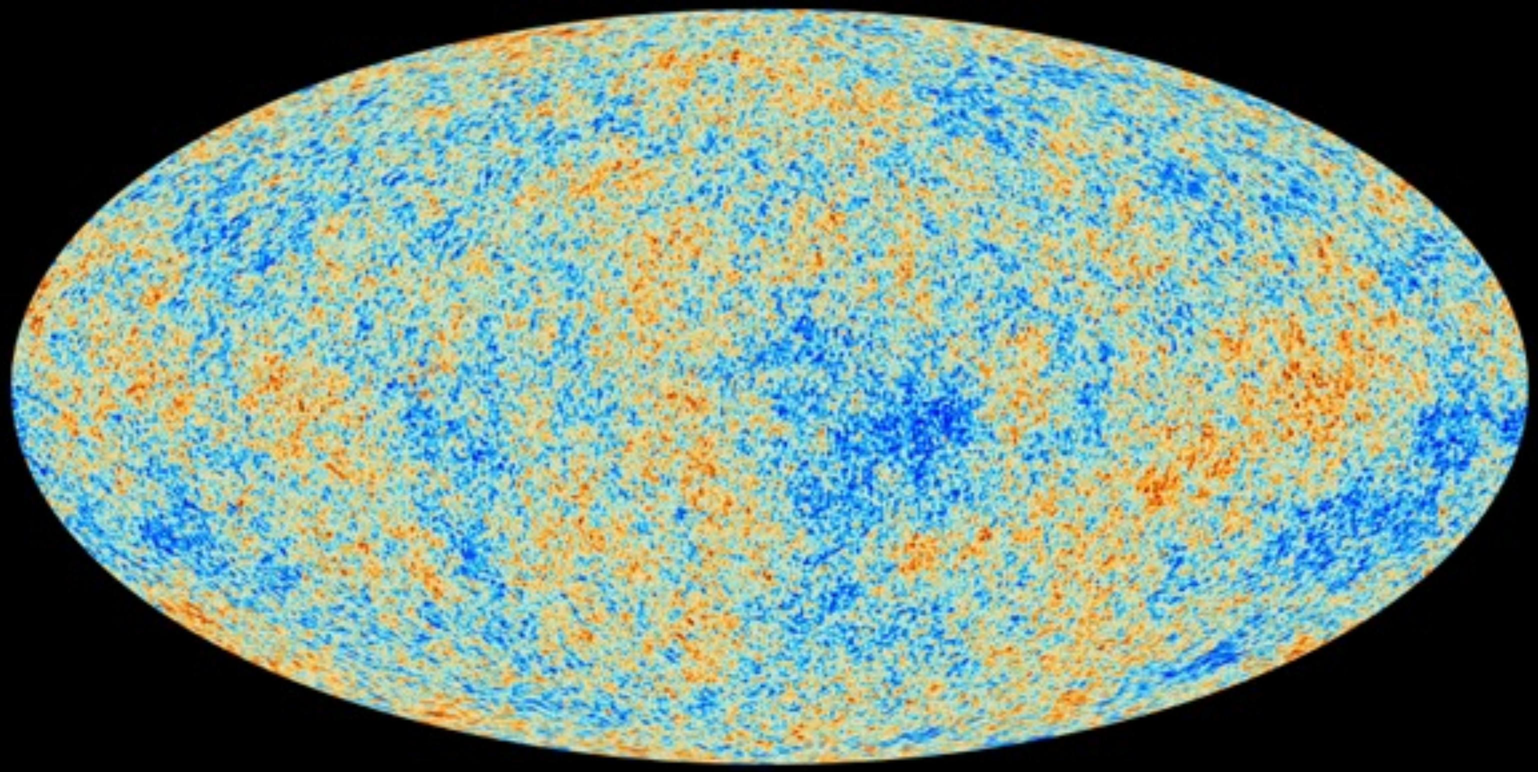


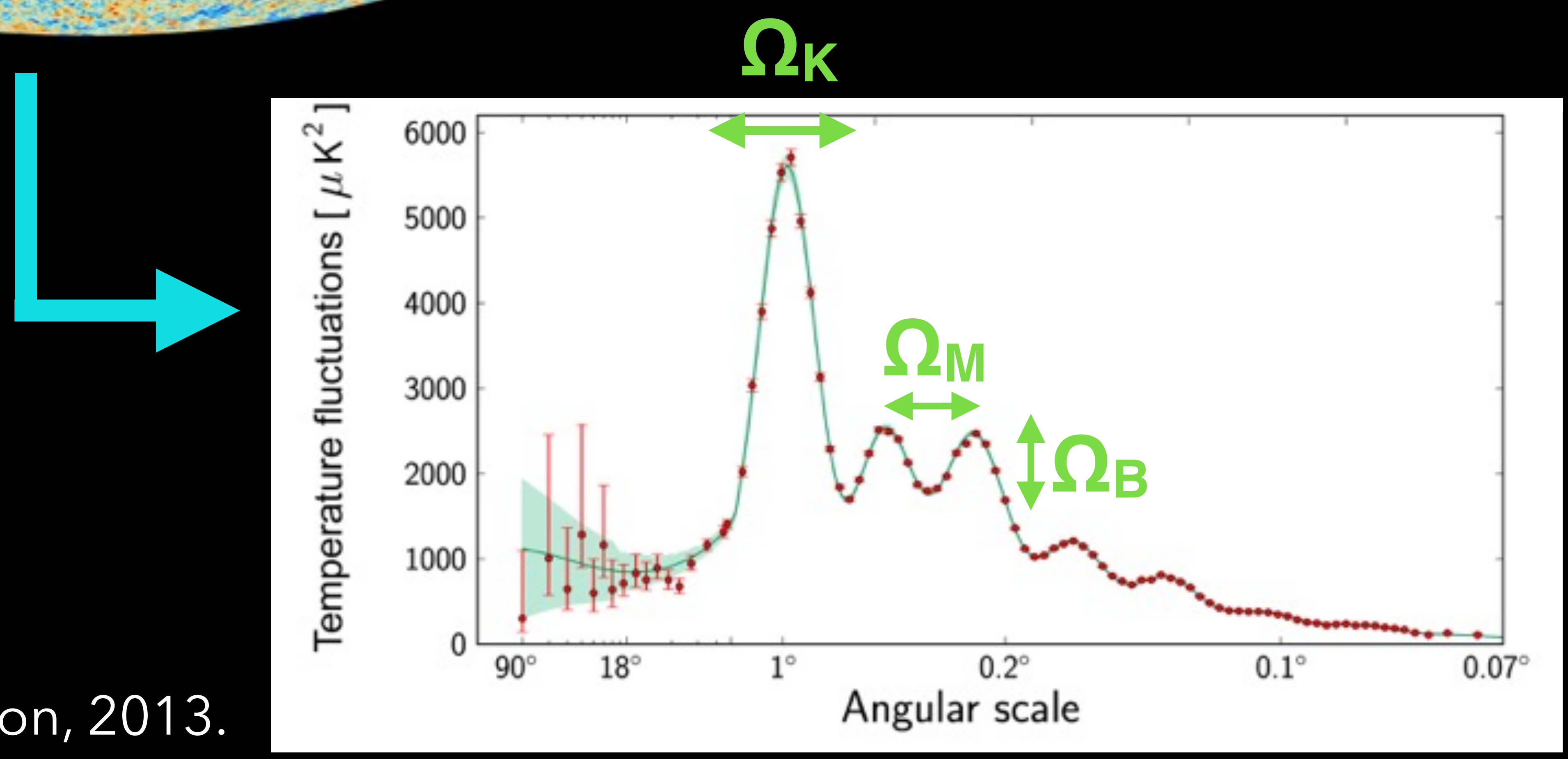
Plot: A. Dempsey.



2.COSMOLOGY — OBSERVATIONS

COSMIC ACCELERATION





Planck Collaboration, 2013.

COSMOLOGICAL TOOLBOX

'Background' ⇒ H_0, w_{DE}

Cosmic Microwave Background (CMB) (position of first peak)

Supernovae

Baryon Acoustic Oscillations (BAO)

Local H_0 measurements

Perturbations ⇒ Φ, Ψ, Δ_M

Growth rate

CMB lensing + polarisation, Integrated Sachs-Wolfe effect

Galaxy weak lensing

H1 intensity mapping

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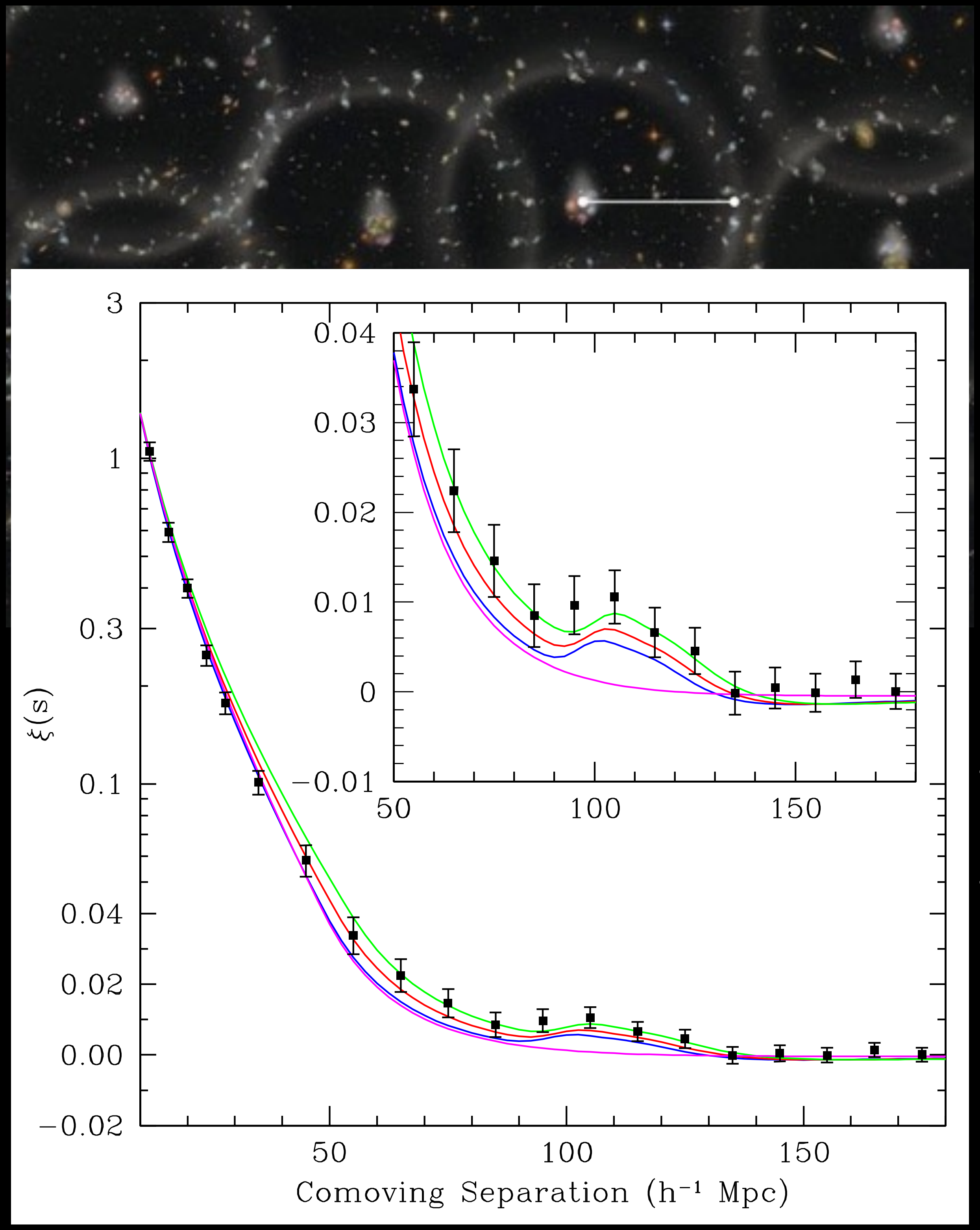

Eisenstein et al. (2005)

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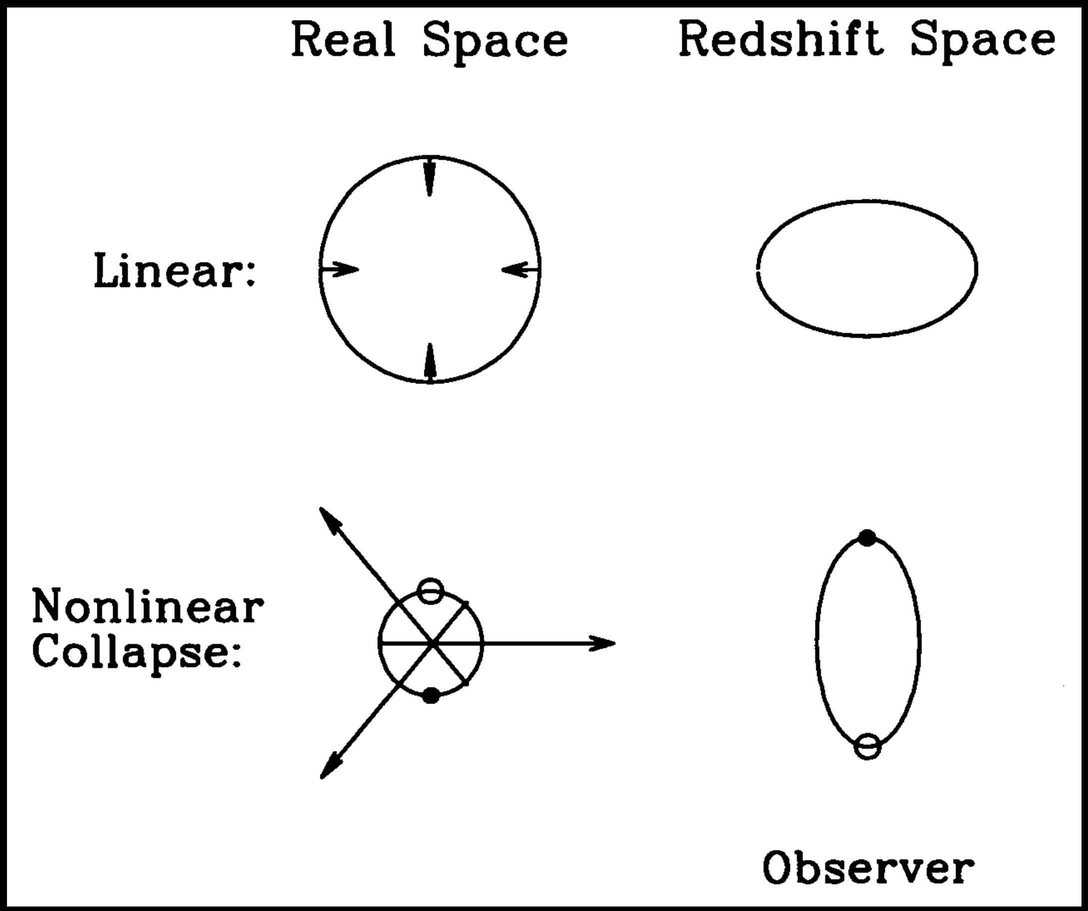
GROWTH RATE

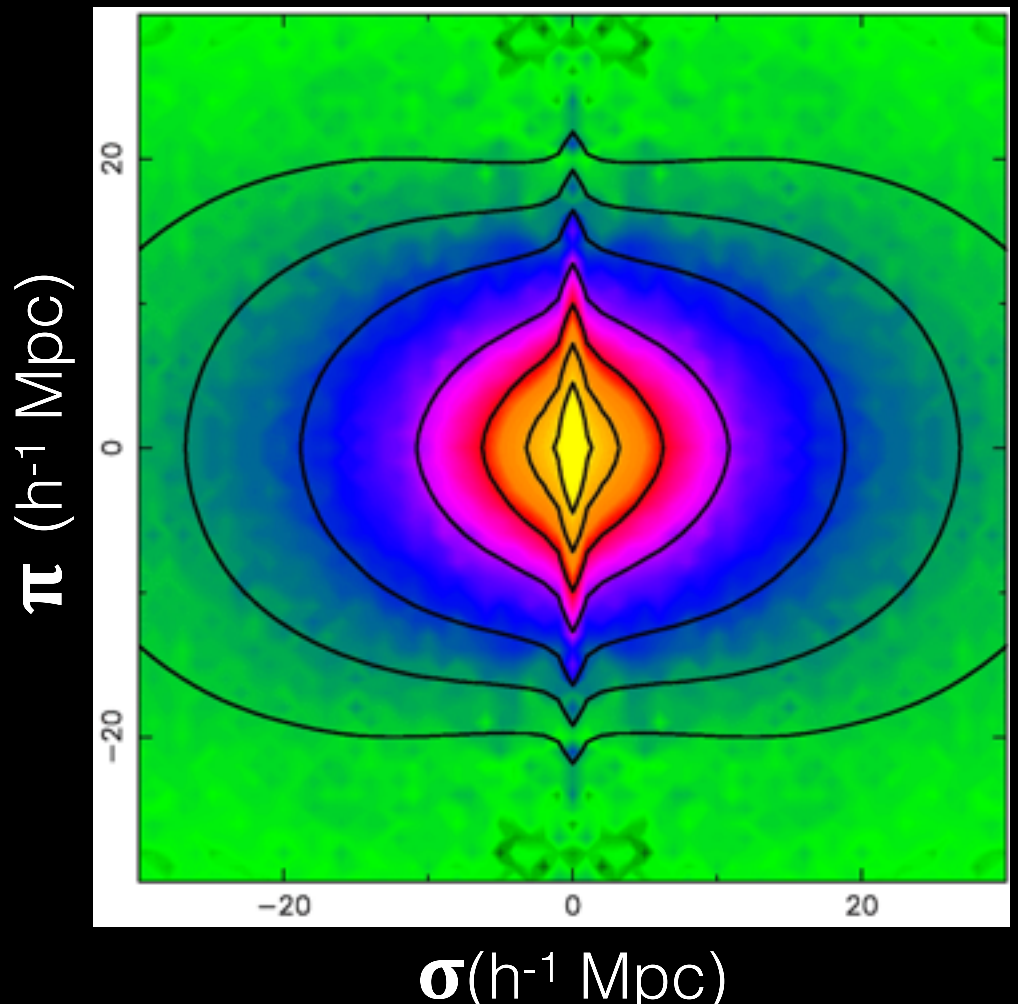
`Growth rate':

$$f(a) = \frac{\partial \ln \Delta_M}{\partial \ln a}$$

We measure redshift-space distortions (RSDs) in galaxy surveys.



Dodelson (2003)



Hawkins et al. (2002)

GROWTH RATE

`Growth rate':

$$f(a) = \frac{\partial \ln \Delta_M}{\partial \ln a} \longrightarrow f(z)\sigma_8(z) \longleftarrow \text{density normalisation}$$

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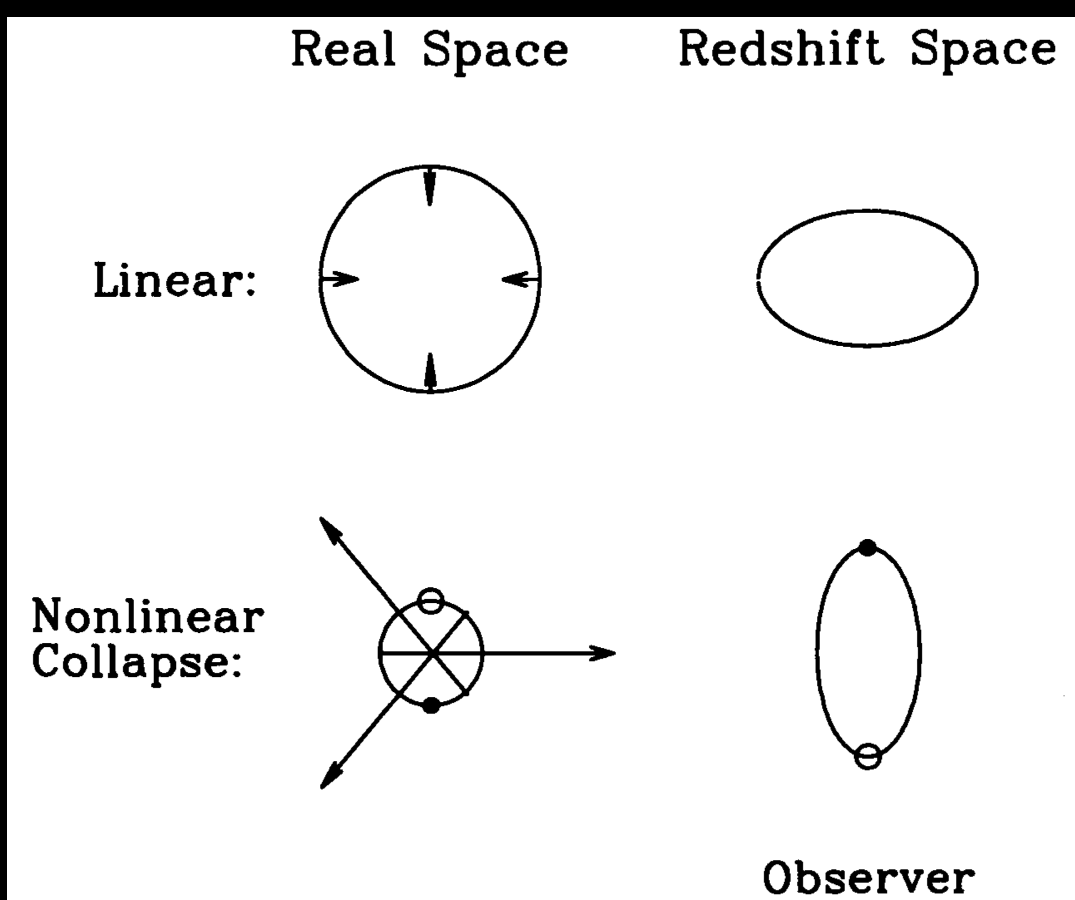

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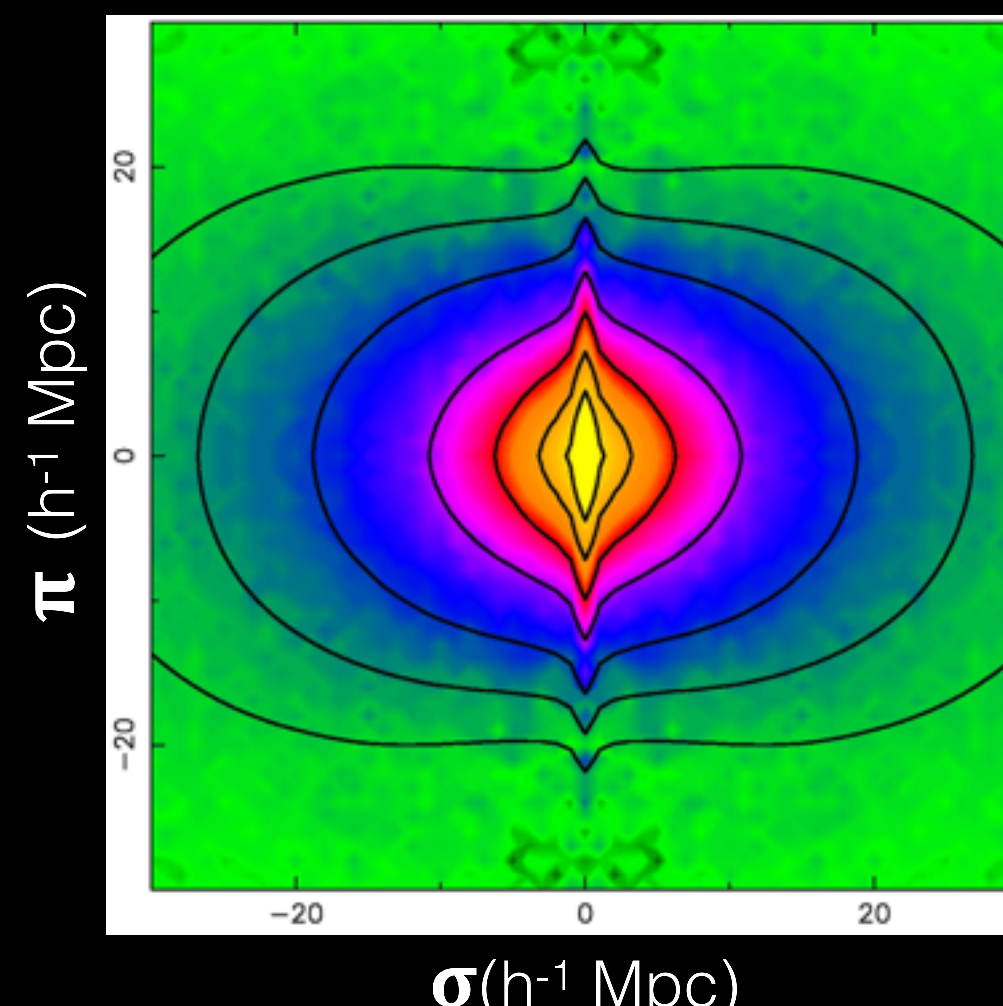

Hawkins et al. (2002)

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density normalisation

Recall:

$$\boxed{\ddot{\Delta}_M + 2H\dot{\Delta}_M - \frac{3}{2}H^2\Delta_M = 0}$$

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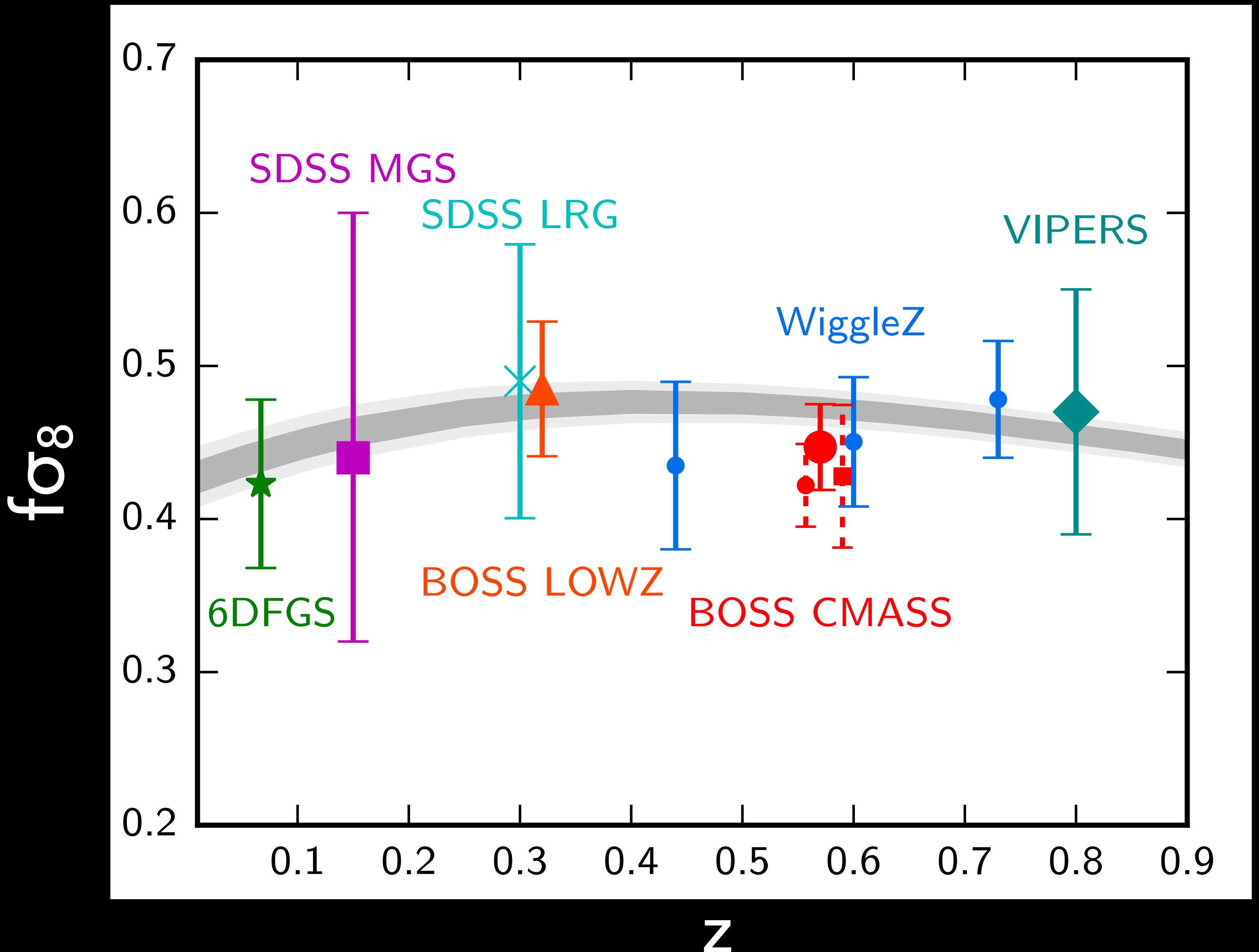
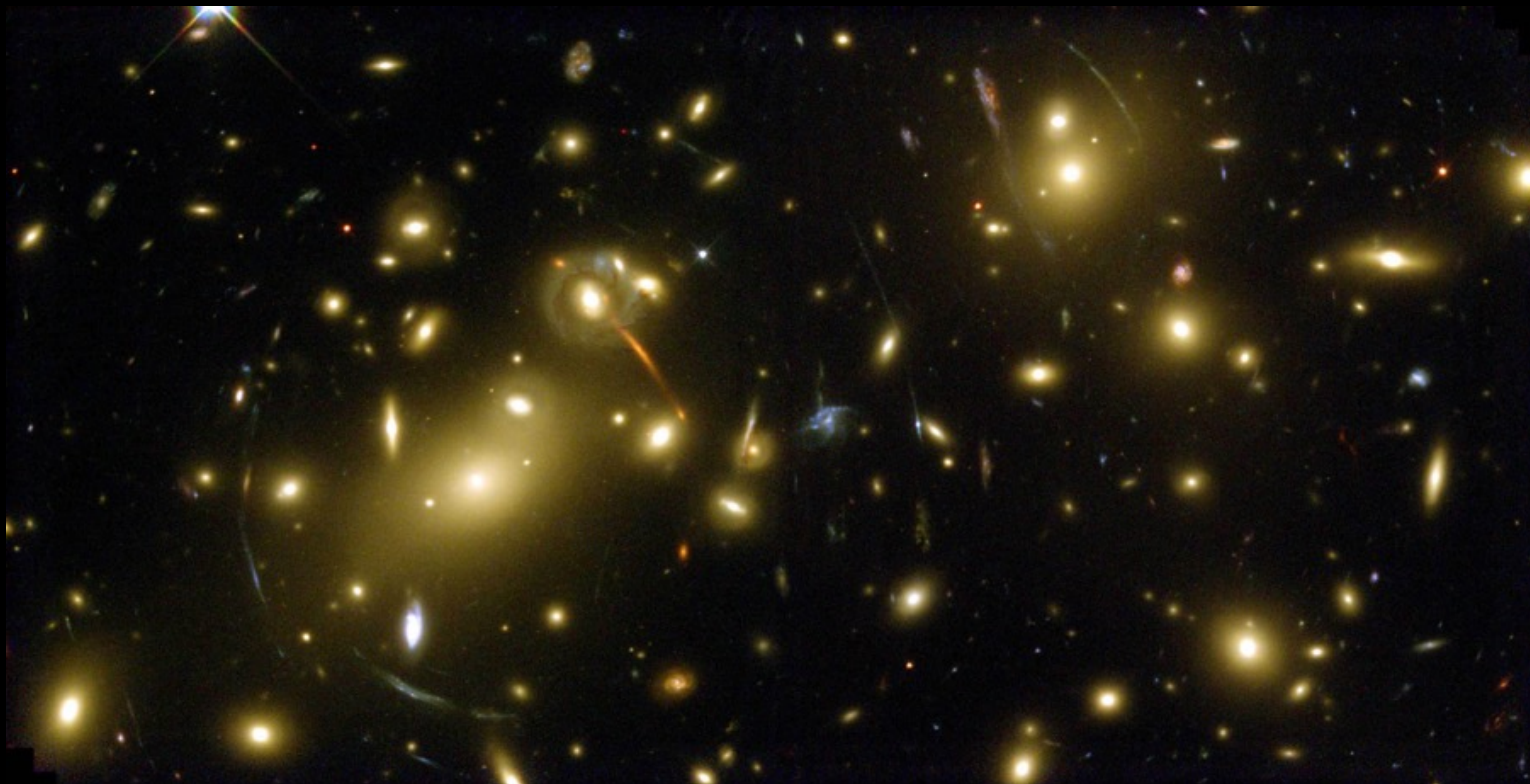


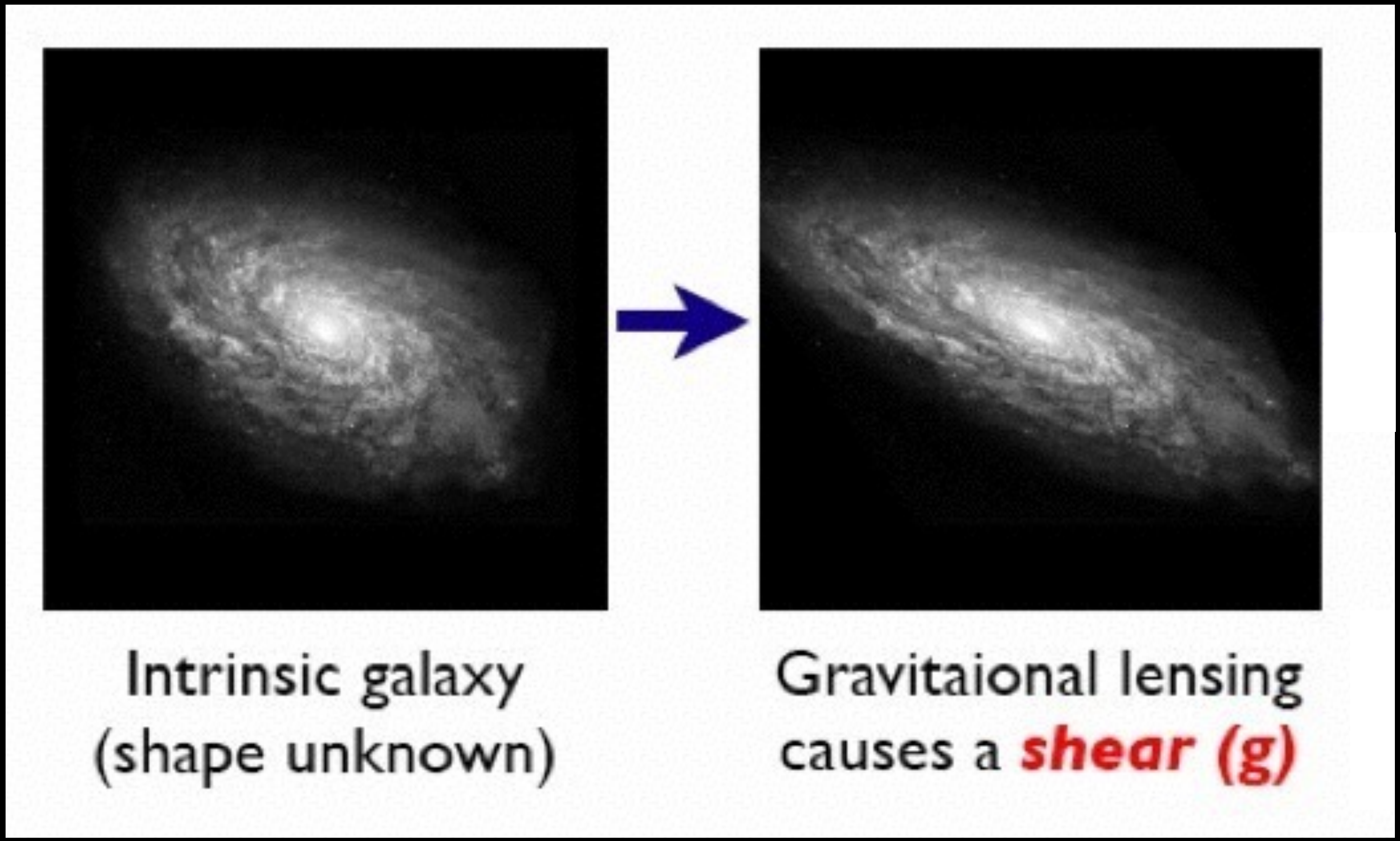
Planck Collaboration, 2015.

GALAXY WEAK LENSING



NASA/ESA

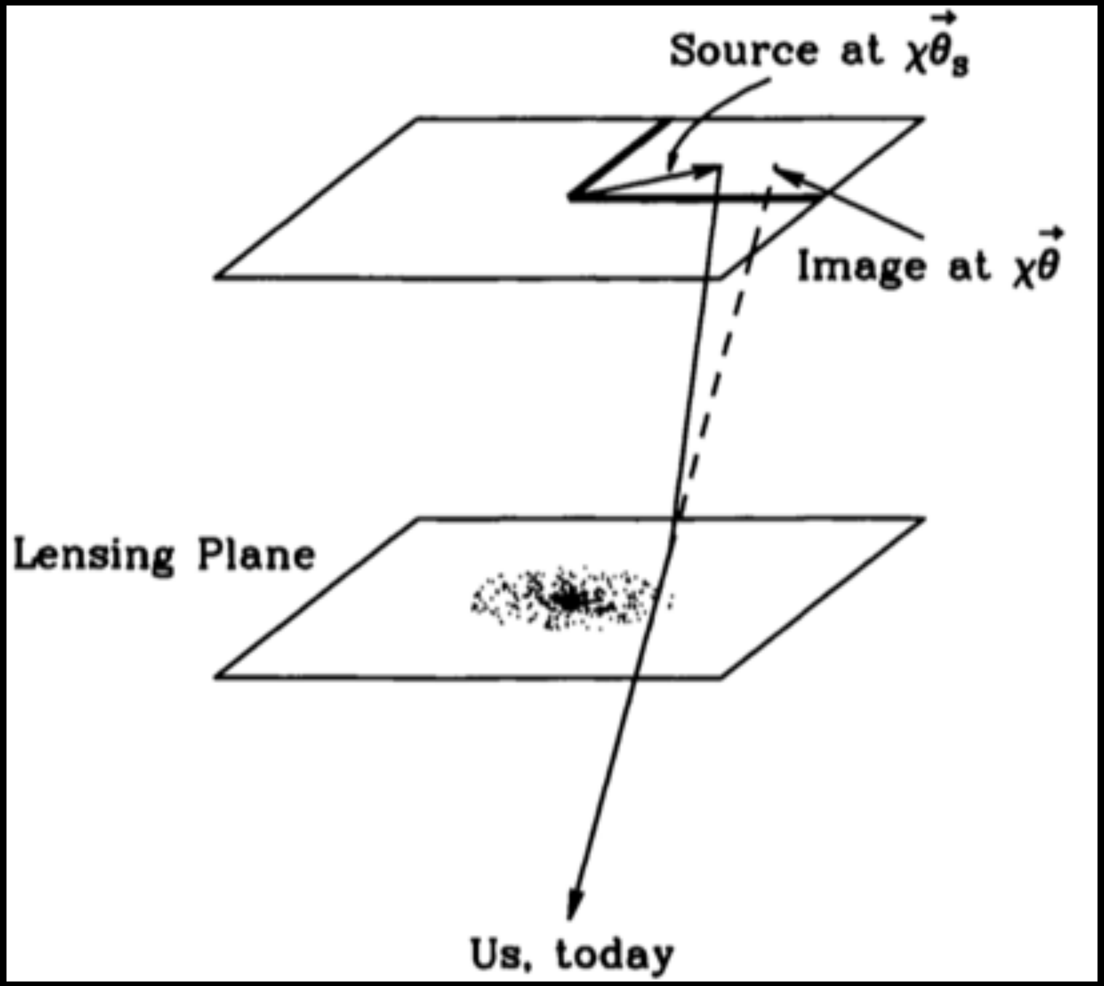
GALAXY WEAK LENSING



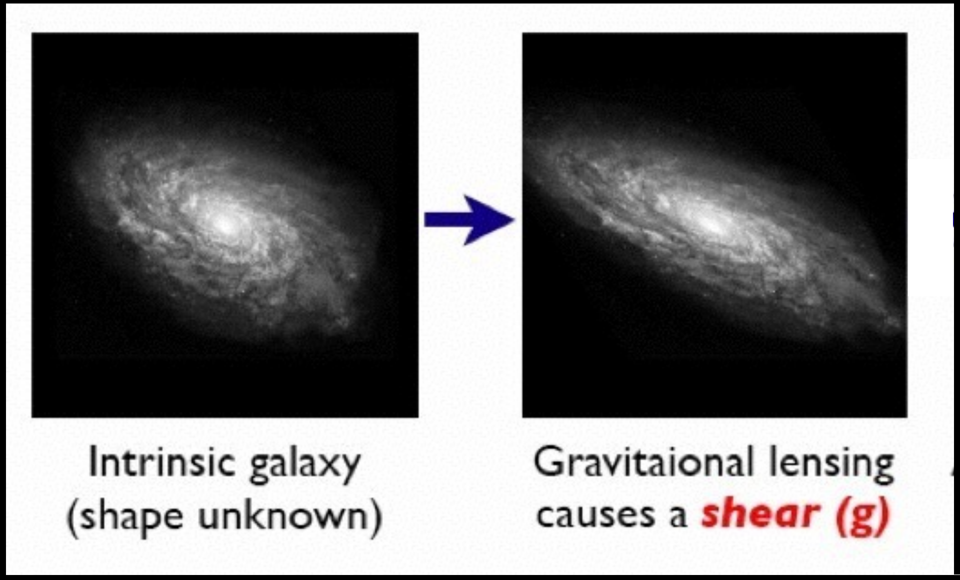
S.Bridle

GALAXY WEAK LENSING

S.Dodelson



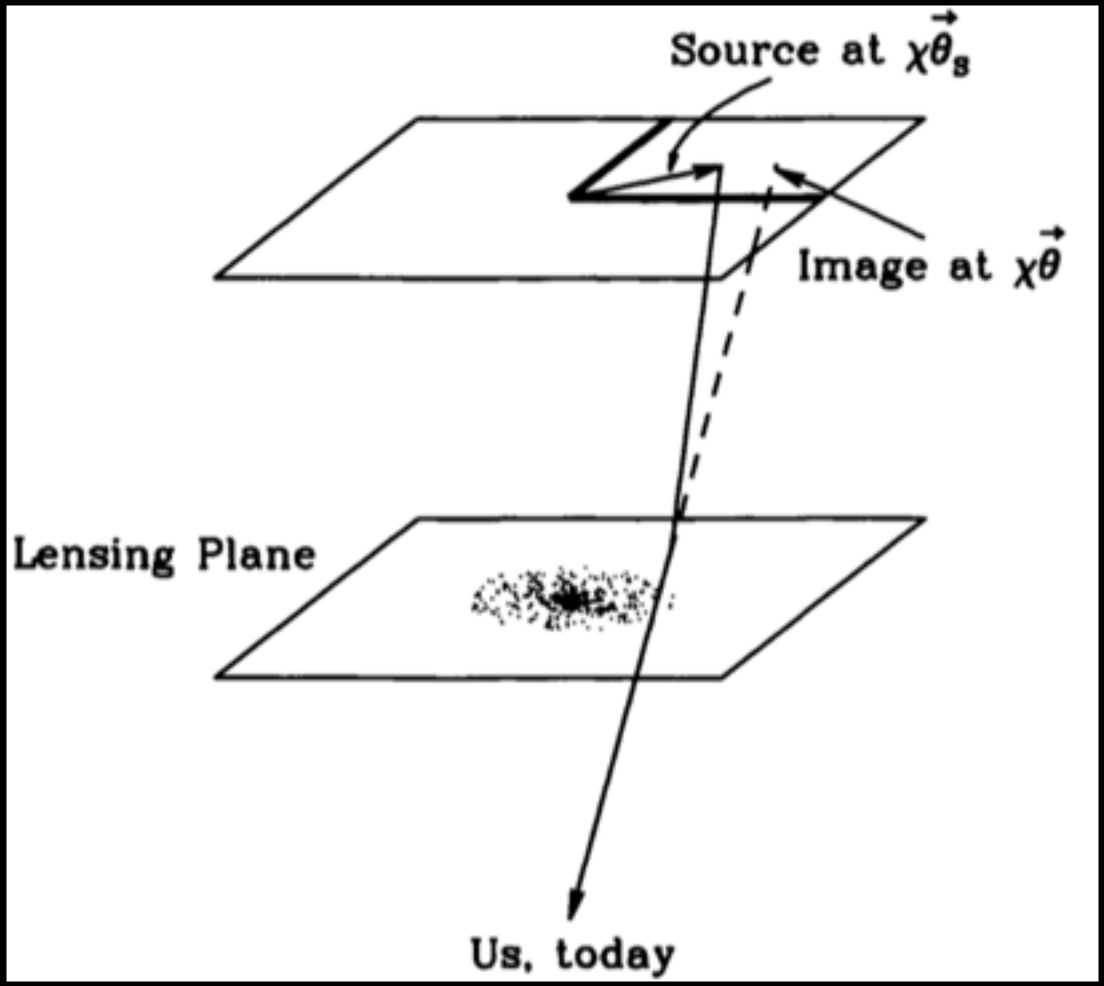
S.Bridle



Tensor relating true and apparent image positions:

$$\mathcal{A}_{ij} = \frac{\partial \theta_S^i}{\partial \theta^j}$$

GALAXY WEAK LENSING



S.Dodelson

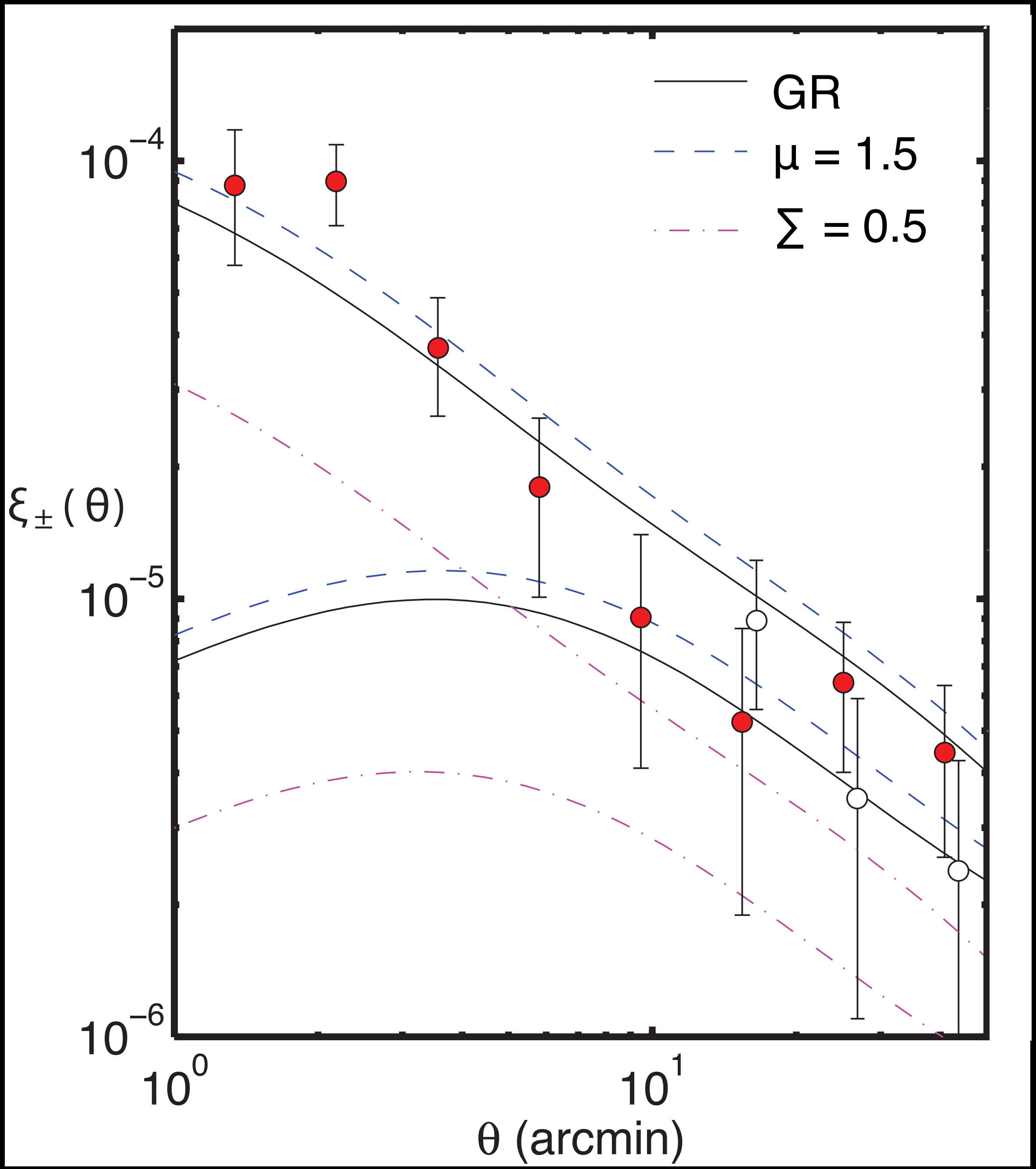
Tensor relating true and apparent image positions:

$$\mathcal{A}_{ij} = \frac{\partial \theta_S^i}{\partial \theta^j}$$

$$\mathcal{A}_{ij} - \delta_{ij} = \frac{1}{2} \int_0^{\chi_\infty} d\chi \, \partial_i \partial_j \left(\Phi + \Psi \right) \, g(\chi)$$

contains cosmological distances + number density of galaxies

GALAXY WEAK LENSING



Simpson et al. (2012)

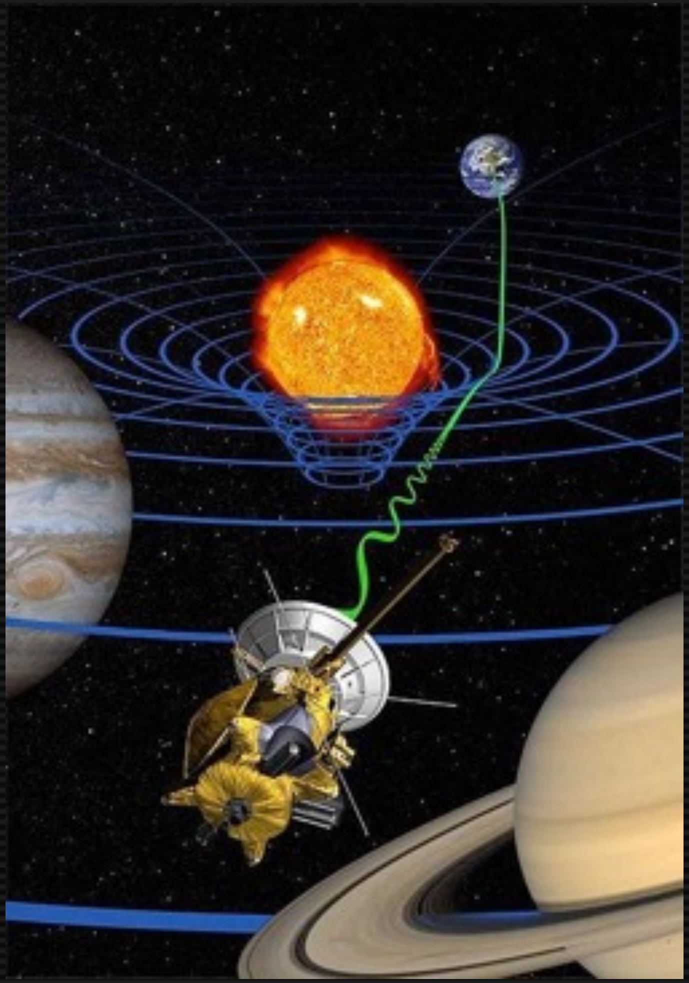
$$\mathcal{A}_{ij} - \delta_{ij} = \frac{1}{2} \int_0^{\chi_\infty} d\chi \, \partial_i \partial_j \left(\Phi + \Psi \right) \, g(\chi)$$

3. MODIFIED GRAVITY

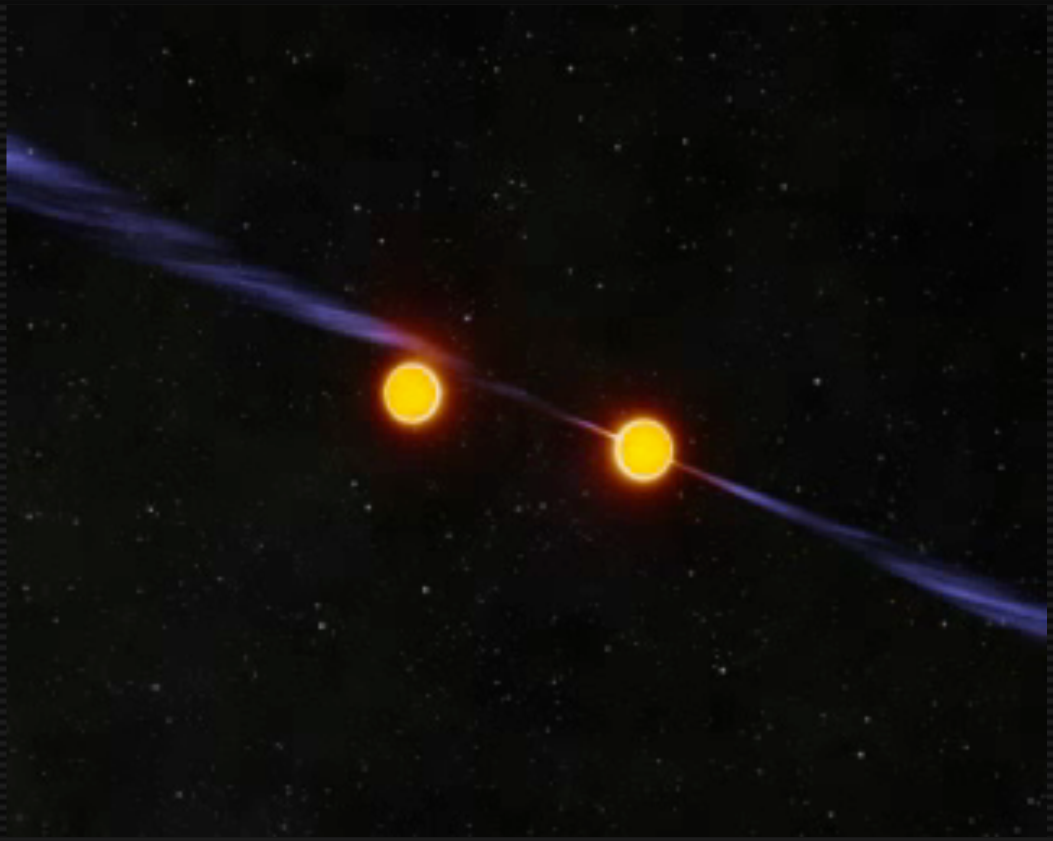
ISN'T GR SUPER WELL-TESTED?

Yes!

Shapiro time delay:



Binary pulsars:



Credit: John Rowe Animation/Australia Telescope National Facility, CSIRO.

`Screening mechanisms' protect the GR limit in modified gravity models.

LOVELOCK'S THEOREM

"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."

$$S_{\rm grav} = \frac{M_{Pl}^2}{2}\int\sqrt{-g}\,d^4x\,\Big[\,R\,\Big]$$

Five options:

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$$S_{\rm grav} = \frac{M_{Pl}^2}{2}\int \sqrt{-g}\, d^4x \left[\phi R - \frac{\omega(\phi)}{\phi}\left(\nabla\phi\right)^2 - 2V(\phi)\right]$$

Five options:

1. Add new field content.

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"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."

$$S_{\text{grav}} = \frac{{M_D}^2}{2} \int \sqrt{-\gamma}\, d^D x \left[\mathcal{R} + \alpha\, \mathcal{G} \quad \right]$$

Five options:

1. Add new field content.
2. Higher dimensions.

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$$S_{\rm grav} = \frac{M_{Pl}^2}{2}\int \sqrt{-g}\, d^4x \Big[R + \beta_1 R \nabla_\mu \nabla^\mu R + \beta_2 \nabla_\mu R_{\beta\gamma} \nabla^\mu R^{\beta\gamma}\Big]$$

Five options:

1. Add new field content.
2. Higher dimensions.
3. > 2nd order derivatives in the field equations.

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$$S_{\rm grav} = \frac{M_{Pl}^2}{2}\int \sqrt{-g}\, d^4x \left[R + f\left(\frac{1}{\Box}R\right) \right]$$

Five options:

1. Add new field content.
2. Higher dimensions.
3. > 2nd order derivatives in the field equations.
4. Non-locality.

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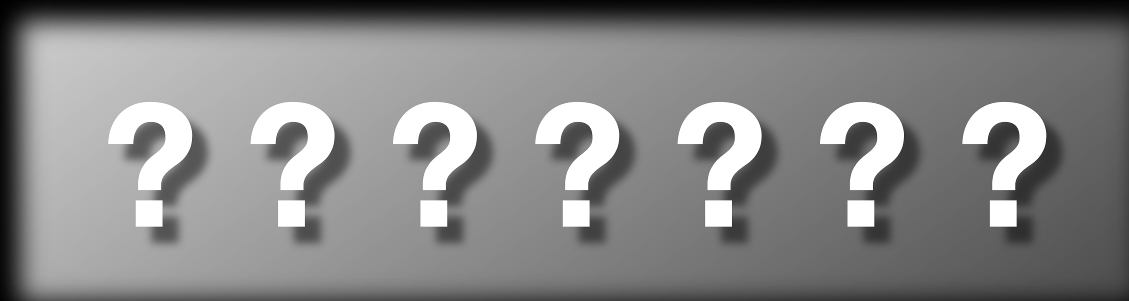
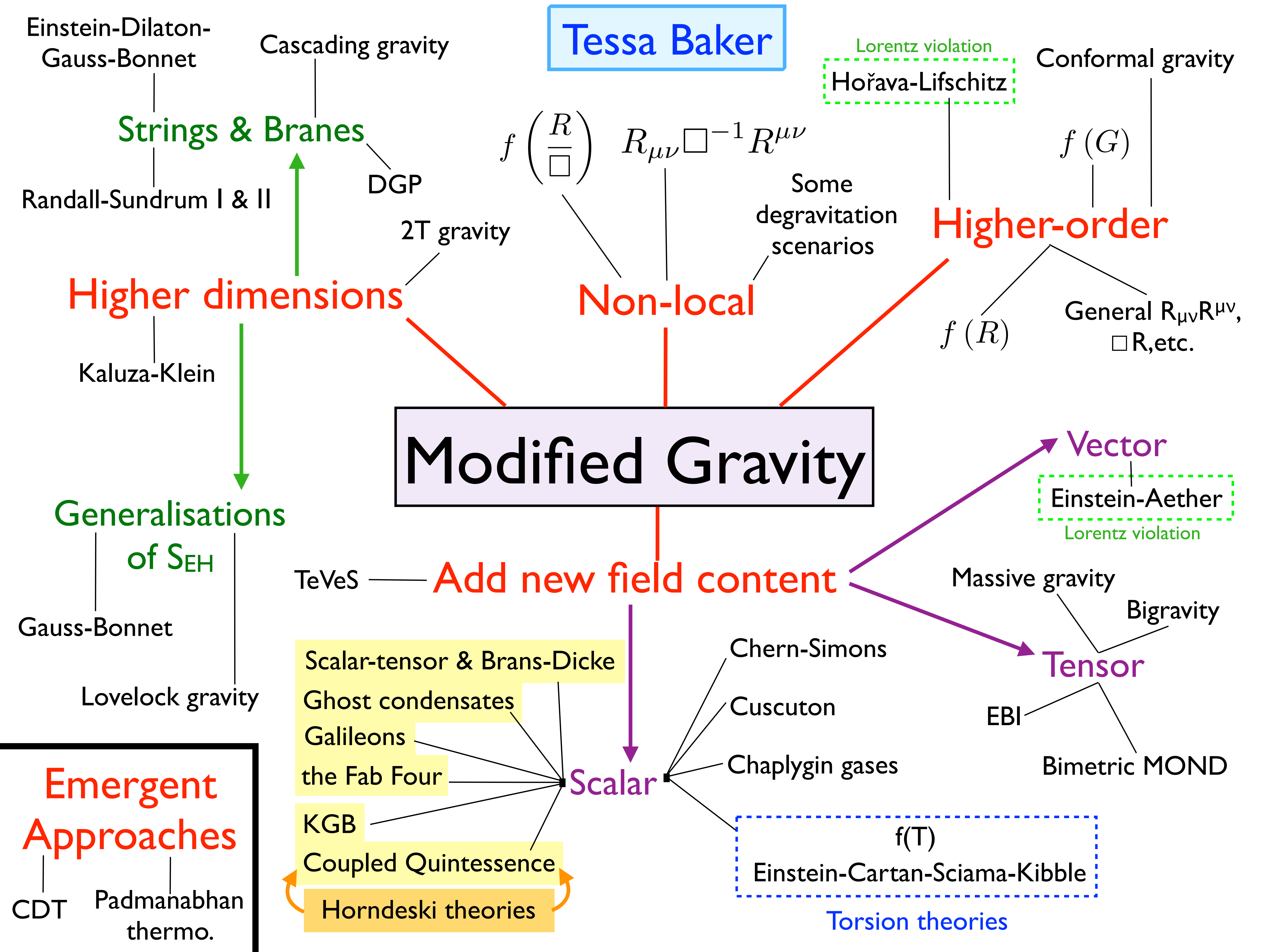


Five options:

1. Add new field content.
2. Higher dimensions.
3. > 2nd order derivatives in the field equations.
4. Non-locality.
5. Radically change our action principle (emergence).



Tessa Baker
Modified Gravity
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Strings & Branes
DGP
Randall-Sundrum I & II
2T gravity
Higher dimensions
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
Some degravitation scenarios
Non-local
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
Higher-order
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Vector
Einstein-Aether
Lorentz violation
TeVeS
Add new field content
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Chern-Simons
Cuscuton
Chaplygin gases
Scalar
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Emergent Approaches
CDT
Padmanabhan thermo.

MODIFIED PERTURBATIONS

$$2\nabla^2\Phi = 8\pi G \sum_X \rho_X \Delta_X$$

$$\Phi - \Psi = 0$$

These relations change in alternative theories of gravity.

MODIFIED PERTURBATIONS

$$2\nabla^2 \Phi = 8\pi G \mu(a) \sum_X \rho_X \Delta_X$$

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These relations change in alternative theories of gravity.

MODIFIED PERTURBATIONS

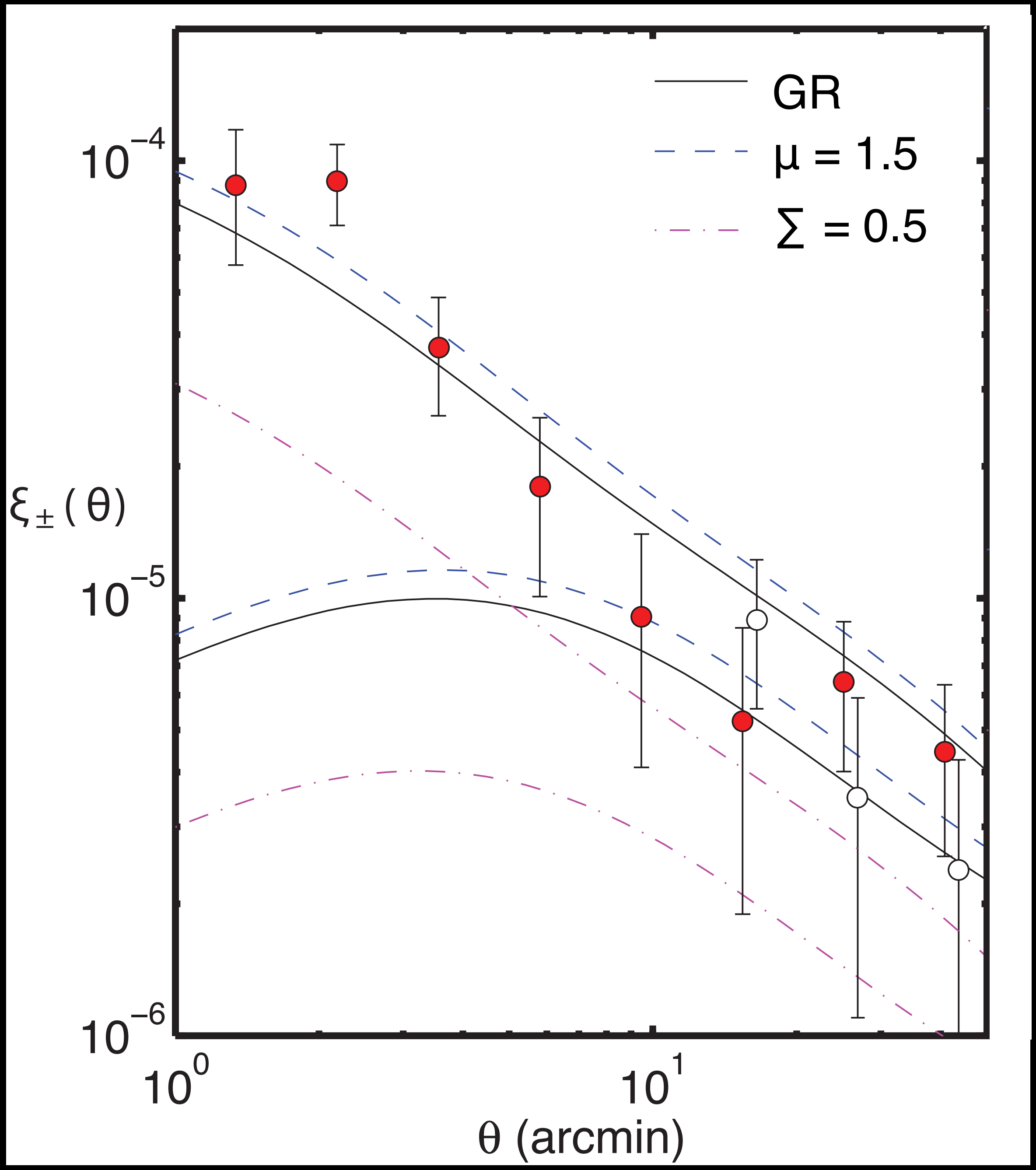
$$2\nabla^2\Phi = 8\pi G\,\mu(a)\sum_X \rho_X \Delta_X$$

$$\frac{1}{2}\left(\Phi + \Psi\right) = \Sigma(a)\Phi$$

These relations change in alternative theories of gravity.

Rerun all the previous linear P.T. calculations with μ & ∑ folded in.

MODIFIED PERTURBATIONS



Simpson et al. (2012)

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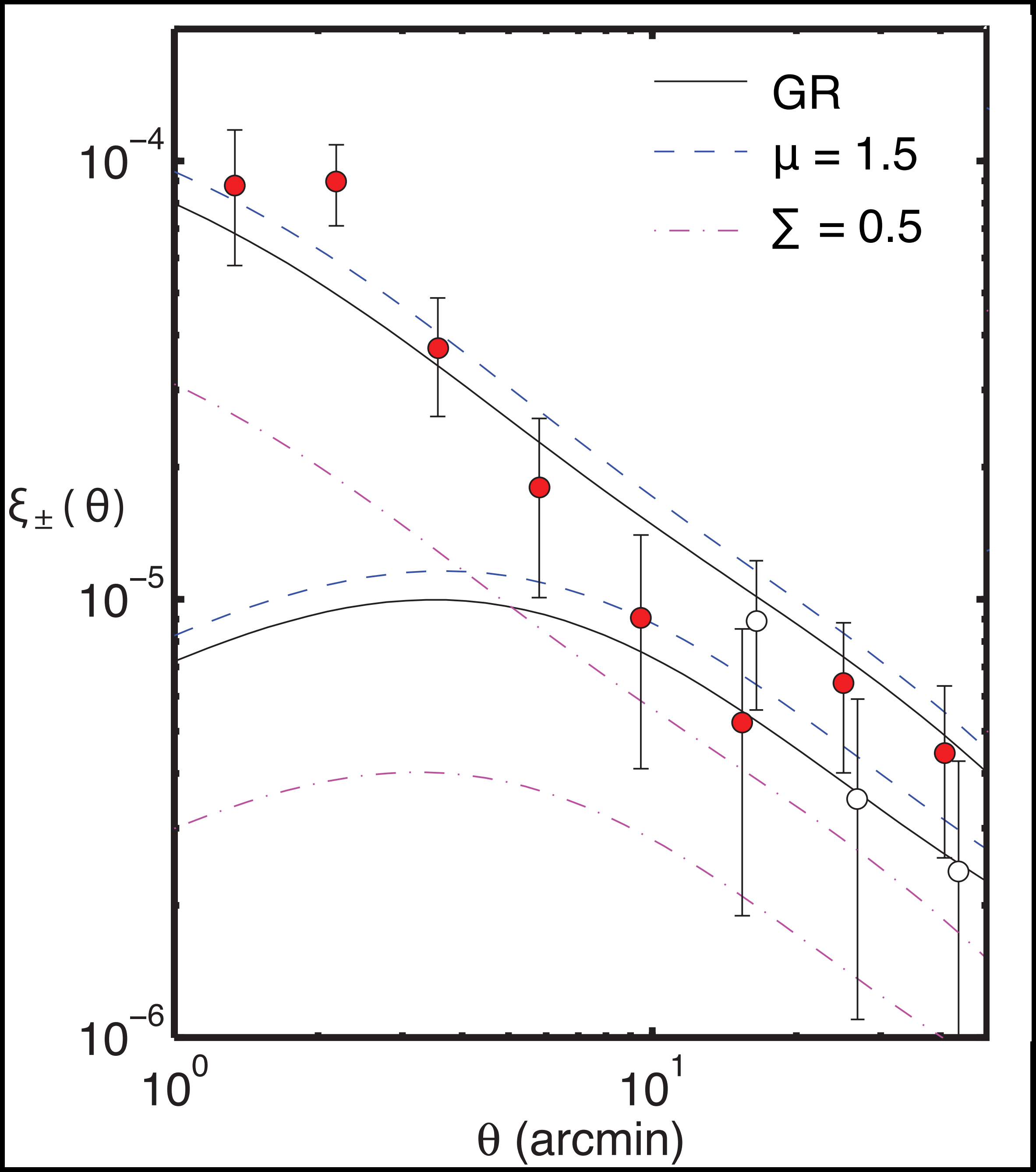
MODIFIED PERTURBATIONS



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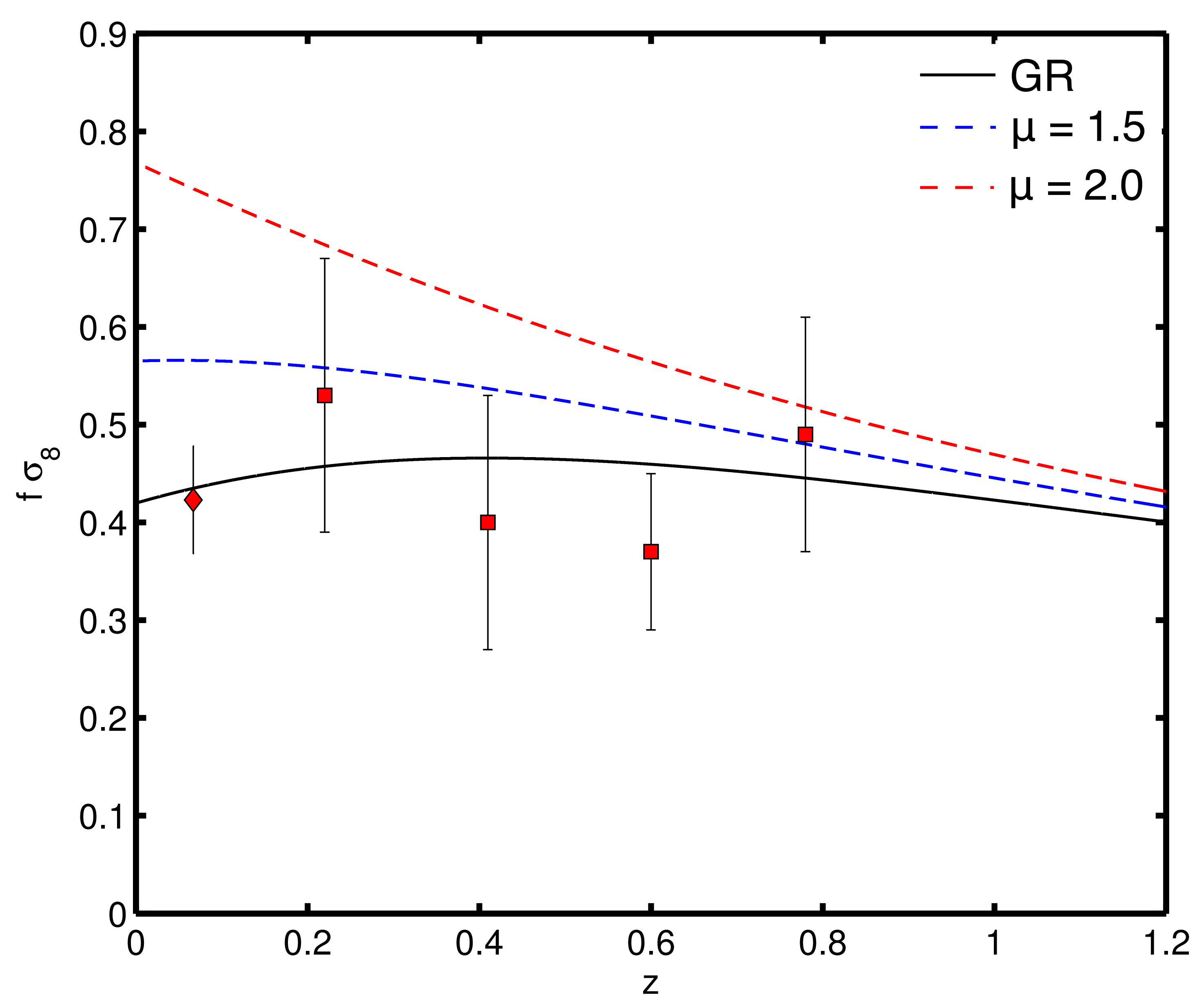

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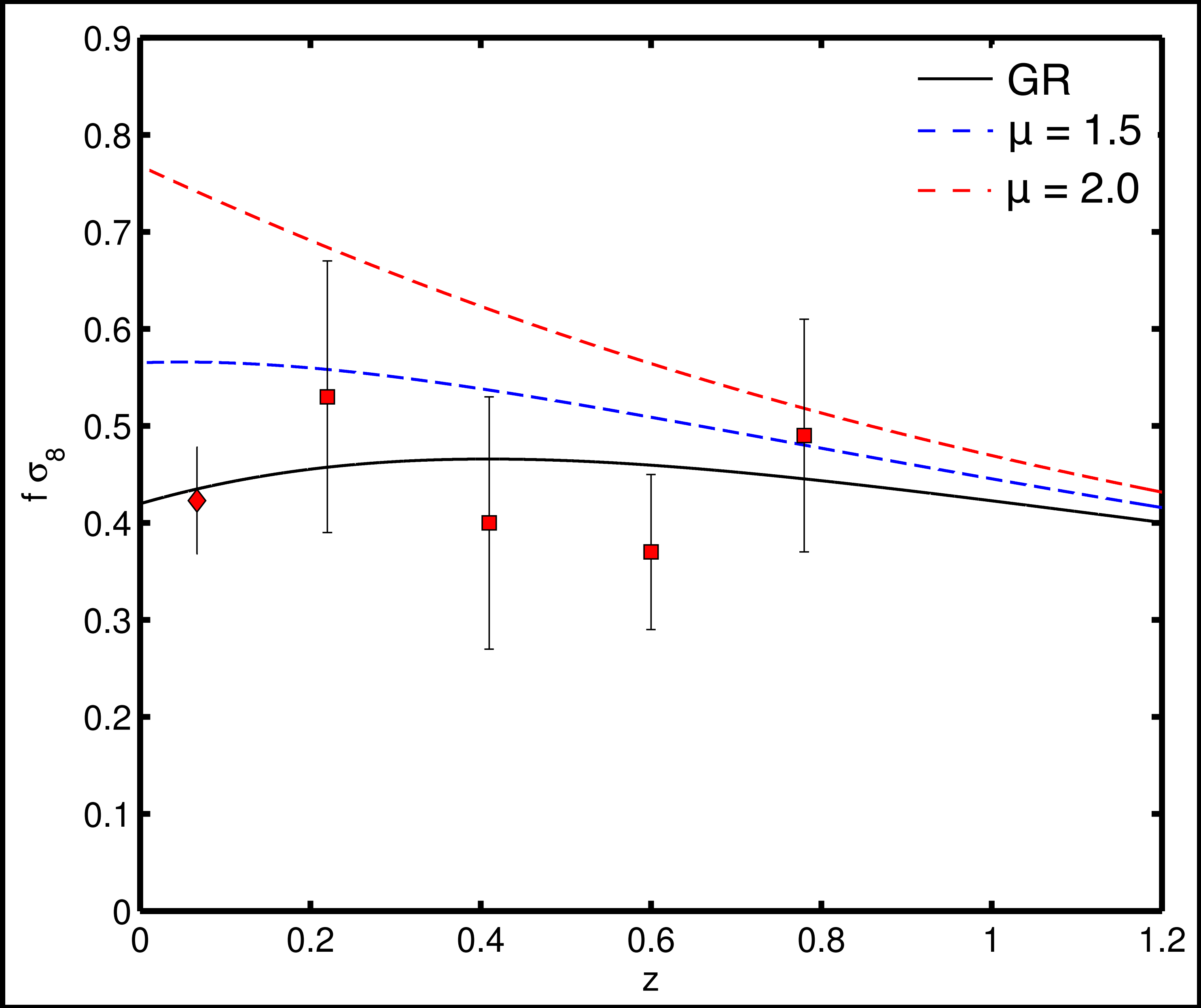

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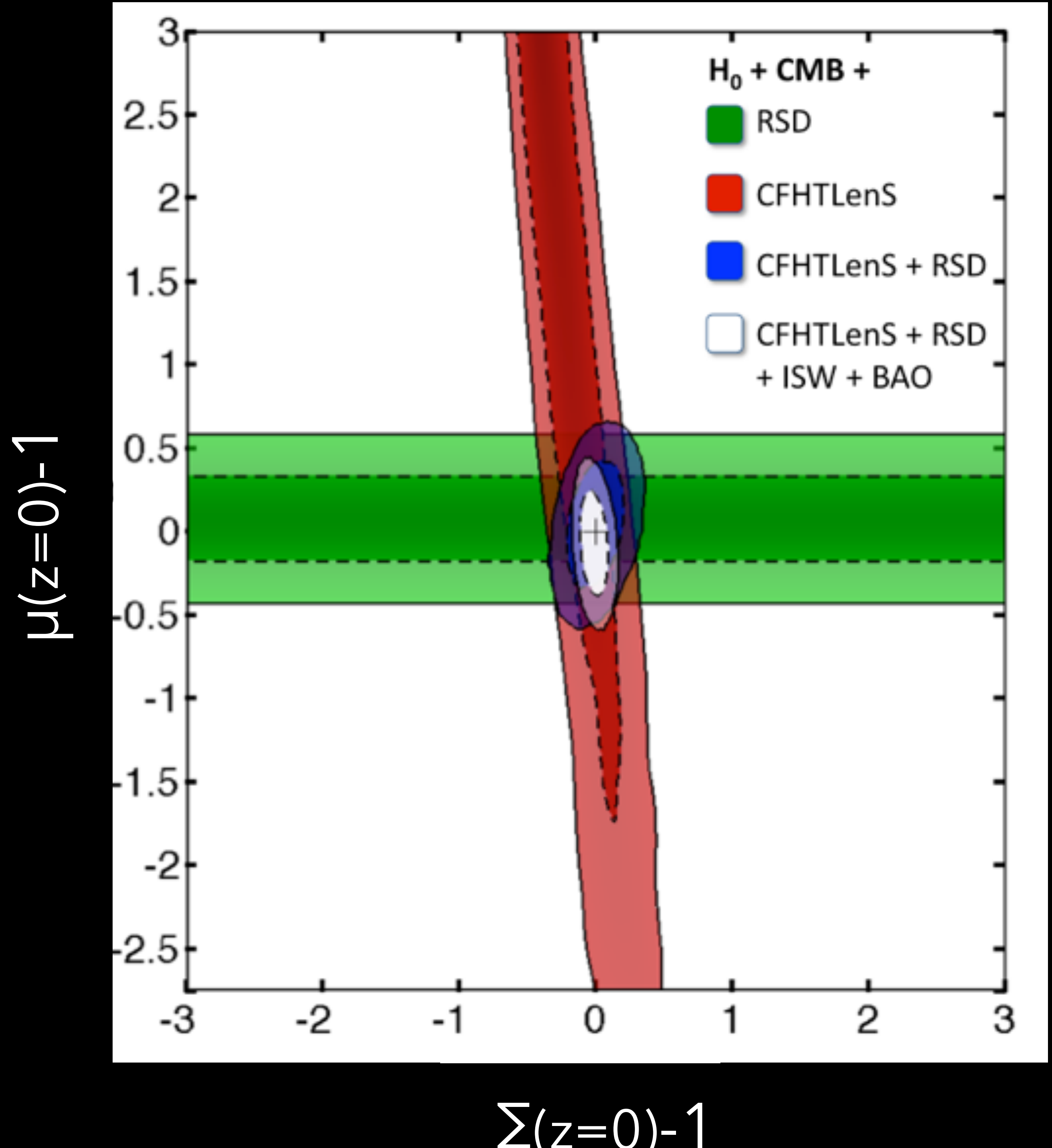

Simpson et al. (2012)

SUMMARY

- Cosmo. linear perturbation theory.
- Observables: supernovae, CMB, growth rate, weak lensing.
- Modified gravity: Lovelock's theorem.
- Putting it all together: testing parameterised deviations from GR.

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