Dark Energy’s Dual Personality

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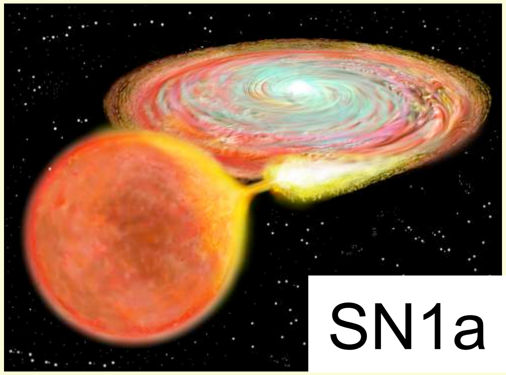
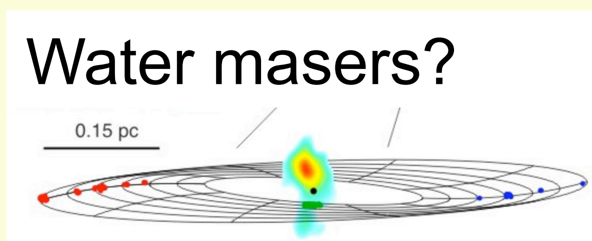
Dark energy evidence I - Geometric distance measures

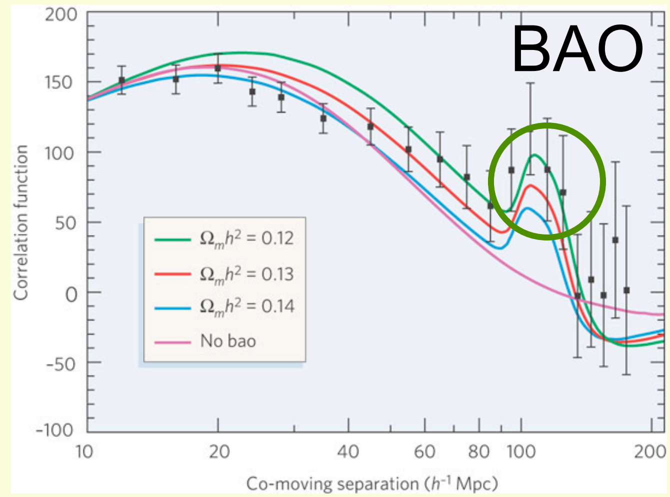
Standard Candles

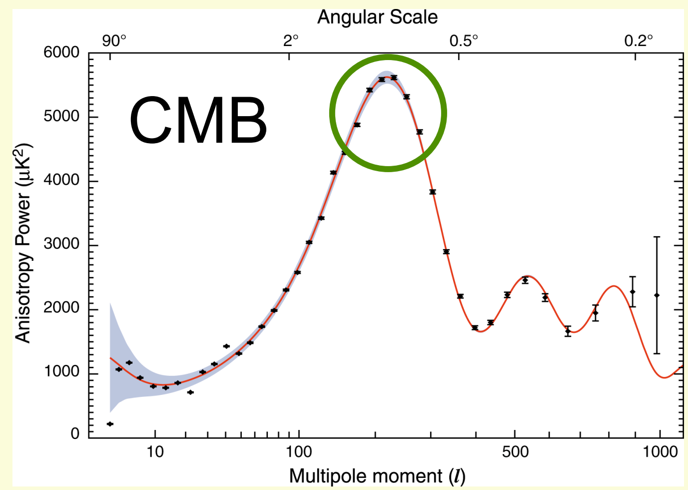


Parallax



Standard Rulers

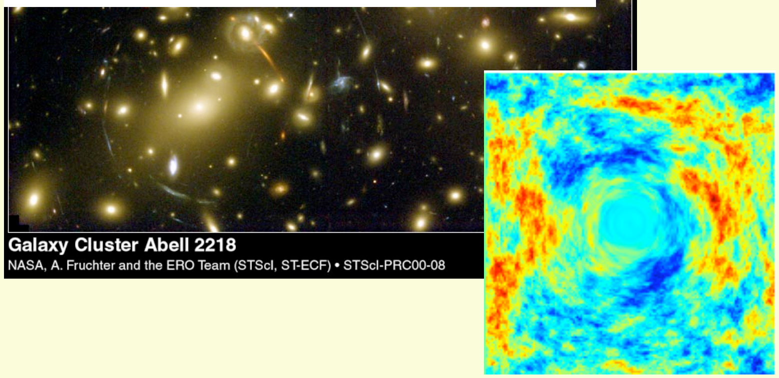




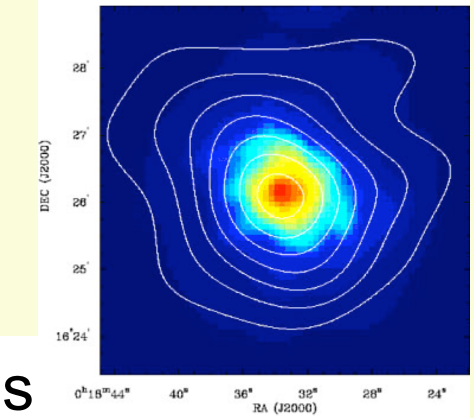
Dark Energy evidence II – Growth of structure

So far lots focus on background evolution, little on perturbations…
Yet the growth of structure provides lots of information !

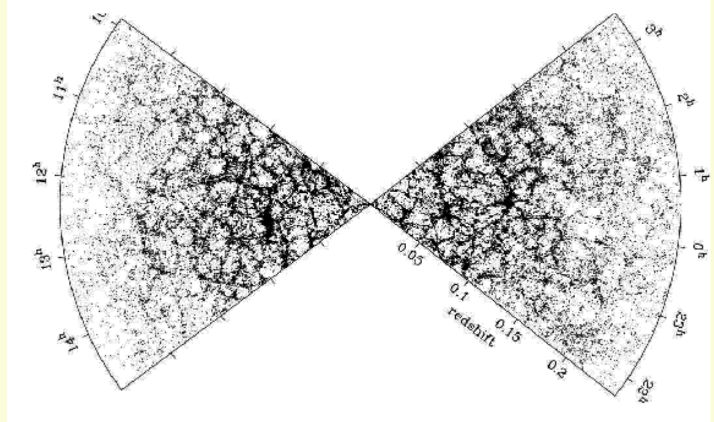
Weak lensing

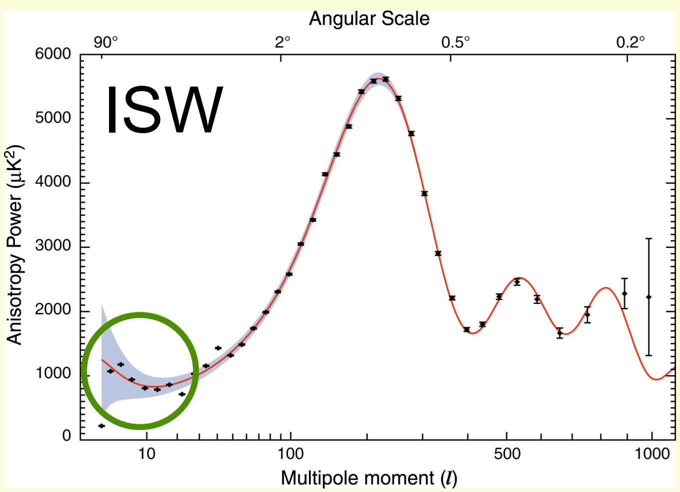


Clusters



Galaxies





How do we interpret dark energy?

Is the universe Accelerating?
No → Photons see extra dimension? Photon conversion?

$\gamma \rightarrow$?

Yes ↓

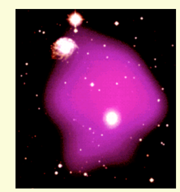
Is General Relativity correct?
No → Modified gravity?

Yes ↓

Is Dark Energy matter of some form?
No → Inhomogeneous universe: Beyond FLRW / Hubble Bubble?

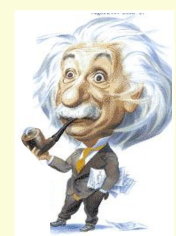
Yes ↓

Is Dark Energy constant in our observable universe?
No → New matter?



Yes ↓

Is Dark Energy constant everywhere?
No → Cosmological constant Anthropic arguments?



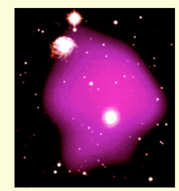
Yes ↓

Universal Cosmological Constant of unknown origin ?

How do we interpret dark energy?

Modified gravity?

New matter?



How do we interpret dark energy?

Focus of this talk:

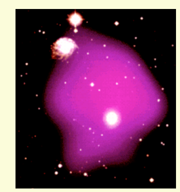
Modified gravity?

1. Can modified gravity be a viable dark energy solution?

2. Can we distinguish modified gravity from L and matter?

3. Can we constrain dark sector interactions?

New matter?



Why modify gravity?

- Many theories predict deviations from GR

- Conceivably, we don't yet have the correct large (and small?) scale theory of gravity?

- The starting point… the action describing motion in GR

$$S = \int d^4x \sqrt{-g} \left(\frac{m_p^2}{2} R + \mathcal{L}_{mat}(\psi_i, g_{\mu\nu}) \right)$$

Action for gravity (LHS of Einstein Eq)

Action for matter (LHS of Einstein Eq)

Why modify gravity?

- Simplistically modifications -> scale/ time dependent G
- Scalar tensor gravity - gravity mediated by scalar field ϕ?
  - e.g. Brans-Dicke theory

$$R \rightarrow \Phi R$$

- Higher order terms?
  - e.g. f(R) theories

$$R \rightarrow R + f(R)$$

$f(R) = A/R + \ldots$ Low curvature (late time) modifications - dark energy

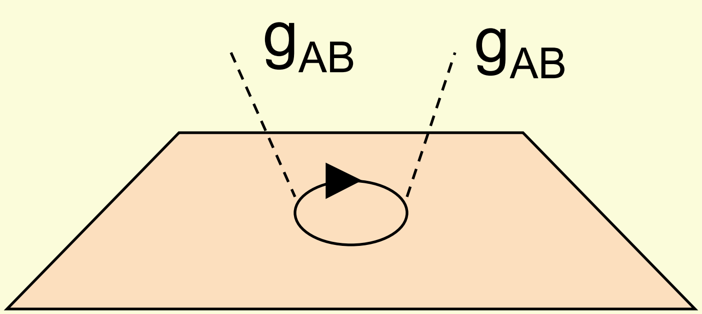
$f(R) = AR^2 + \ldots$ High curvature (early time) modifications - inflation

Why modify gravity?

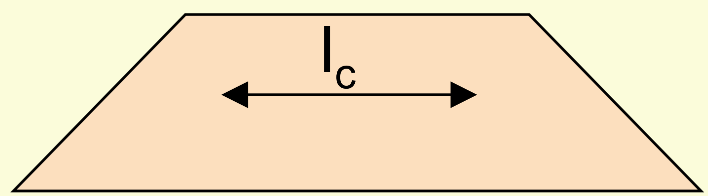
- Gravity is a higher dimensional theory?
  - e.g. Dvali, Gabadaze, Porrati PLB 485:208(2000)

$$\int d^4x\sqrt{-g}\,\frac{m_p^2}{2}R \Rightarrow \int d^5x\sqrt{-g^{(5)}}\,\frac{m_p^{(5)3}}{2}R^{(5)}$$

  - Induced intrinsic curvature on brane
  - $l >> l_c$ 5D gravity ($1/r^2$), $l >> l_c$ 4D gravity ($1/r$)

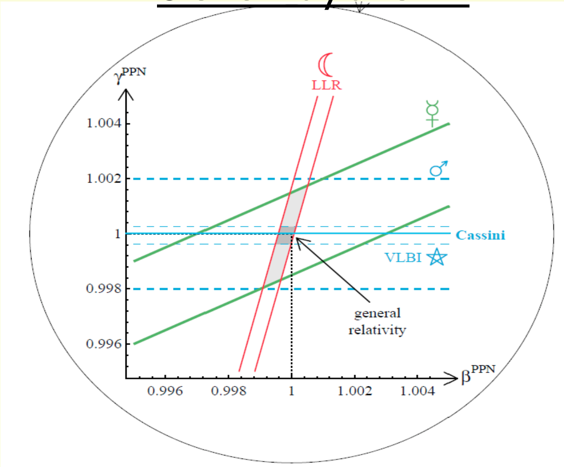


$$l_c = \frac{m_p^{(4)2}}{2m_p^{(5)3}}$$



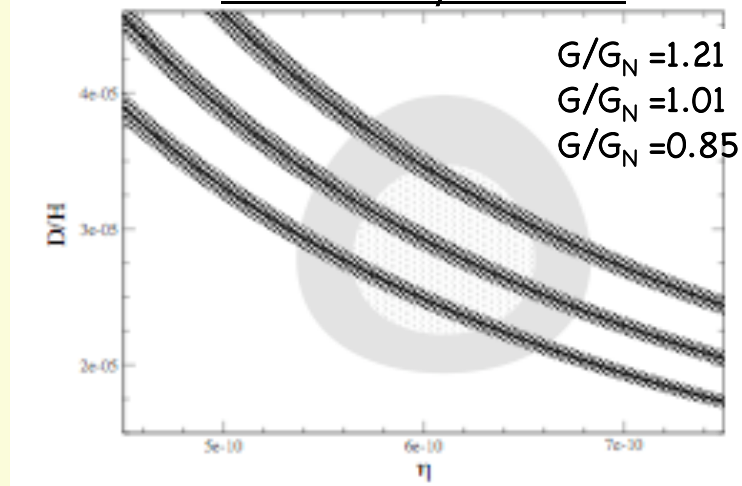
Constraining modifications to gravity

Solar system



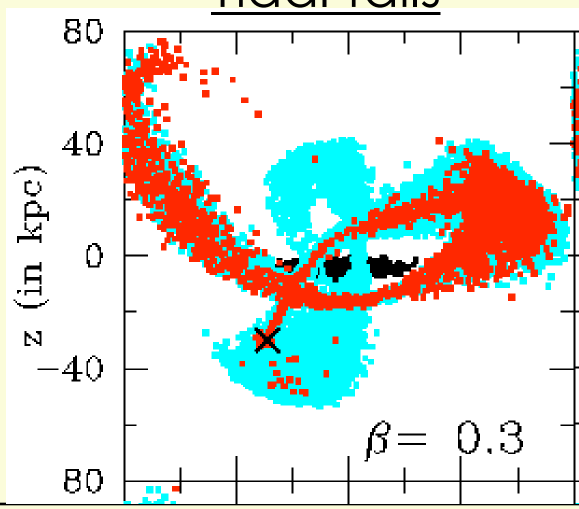
Takeshi Chiba

Nucleosynthesis



Copi, Davis, Krauss 2003

Tidal tails



Kesden & Kamionkowski 2006

What about extra galactic constraints?
- galaxy distribution?
- peculiar velocities?
- weak lensing? ….

Cosmological evolution in modified gravity

Modified Friedmann and acceleration equations

→ acceleration with normal matter (P>0)

Example: f(R) gravity

Standard GR modifications

$$\underline{H^2} + \frac{f}{\underline{6}} + \underline{H\dot{f}_R} = \frac{\kappa^2}{\underline{3}}\rho$$

$$\frac{\ddot{a}}{\underline{a}} - \underline{H^2}f_R + \frac{a^2}{6}\underline{f} + \frac{3}{2}\underline{H\dot{f}_R} + \frac{1}{2}\underline{\ddot{f}_R} = \underline{-\frac{\kappa^2}{6}(\rho + 3P)}$$

An alternative perspective

<u>"conformal transformation"</u>
Coordinate change (redefine the metric) from Jordan frame to Einstein frame

$$g_{\mu\nu}^{(J)} = e^{\sqrt{\frac{2}{3}}\kappa C\phi} g_{\mu\nu}^{(E)}$$

<u>Jordan frame</u>

- Modified gravity $F(\Phi)R$, or $F(R)$
- Minimally coupled matter
- Matter follows geodesics

<u>Einstein frame</u>

- Gravity is GR
- Matter coupled to scalar ϕ with strength C
- Matter doesn't follow geodesics
- Scalar potential $V(\phi)$ derived from F

Evolution viewed from the Einstein frame

- GR + extra matter (scalar field)

$$\frac{\ddot{a}}{a} = -\frac{\kappa^2}{6}\left(\rho + 3P + 2\dot{\phi}^2 - 2V(\phi)\right)$$

- Matter and scalar coupled together as fifth force with strength C

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \sqrt{\frac{2}{3}}C\kappa(\rho - 3P)$$

$$\rho \propto e^{-\sqrt{\frac{2}{3}}\kappa C\phi} a^{-3(1+w)}$$

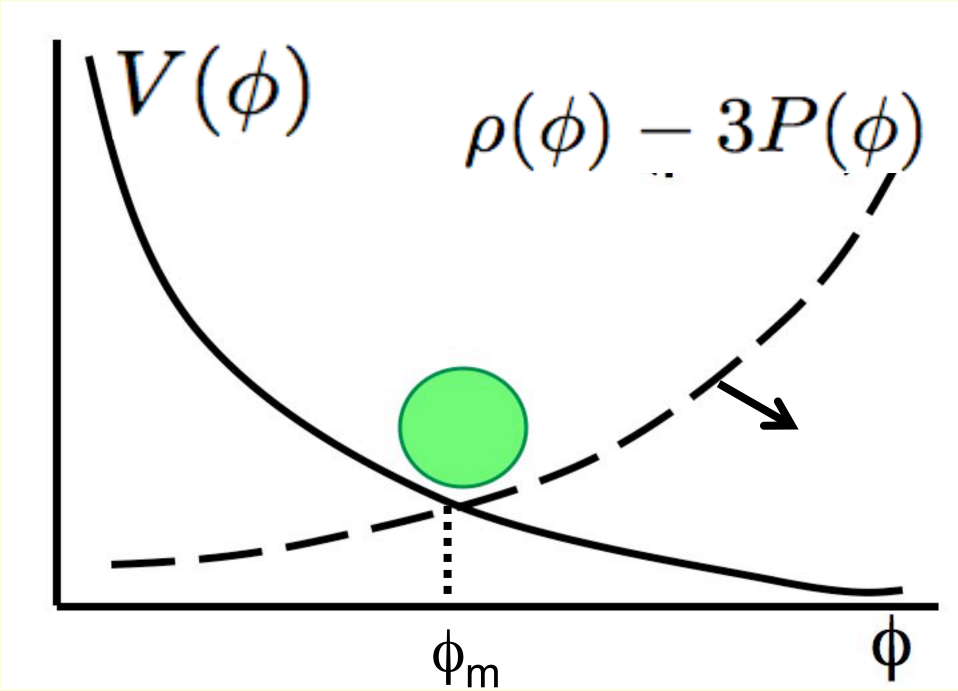
Strength of coupling C determined by theory

$$\begin{cases} \text{GR} \longrightarrow C = 0 \\ \text{F(R)} \longrightarrow C = 1/2 \\ \text{F}(\Phi)\text{R} \longrightarrow \text{C can take range of values} \end{cases}$$

Acceleration in the Einstein frame perspective

- Acceleration when scalar sits in minimum of effective potential

$$\cancel{\ddot{\phi}} + 3\cancel{H\dot{\phi}} + V'(\phi) \quad = \quad \sqrt{\frac{2}{3}} C\kappa(\rho - 3P)$$



EF shows possible instabilities in structure growth

- Jean's instability in a general fluid undergoing gravitational collapse

$$\delta = \frac{\delta\rho}{\rho} \qquad \ddot{\delta} + 2H\dot{\delta} + (c_s^2 k^2 - 4\pi G\rho)\delta = 0$$

- If coupling too strong (minimum too steep) get catastrophic instabilities
  - Jean's instability in matter growth with negative speed of sound

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_{eff}\rho\delta = 0$$

$$\frac{G_{eff}}{G_N} = e^{-2\kappa\beta\phi}\left[1 + \frac{k^2\beta^2}{4\pi\left(k^2 + V''e^{-\kappa\beta\phi}\right)}\right]$$

N. Afshordi et al. PRD 2005 (MaVaNs)
RB, E. Flanagan and M. Trodden PRD 2007

Which frame to use, Jordan or Einstein?

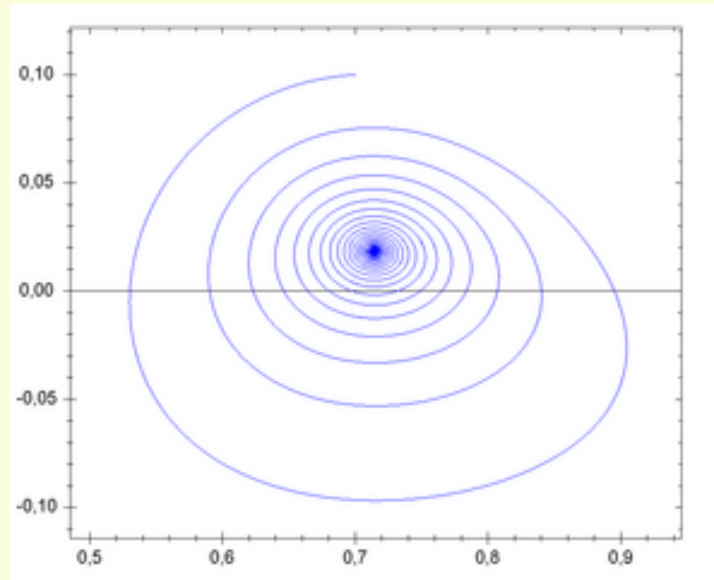
- Benefits of Einstein frame
  - Equations more intuitive (at least to me) in this frame
  - Evolution also easier to understand

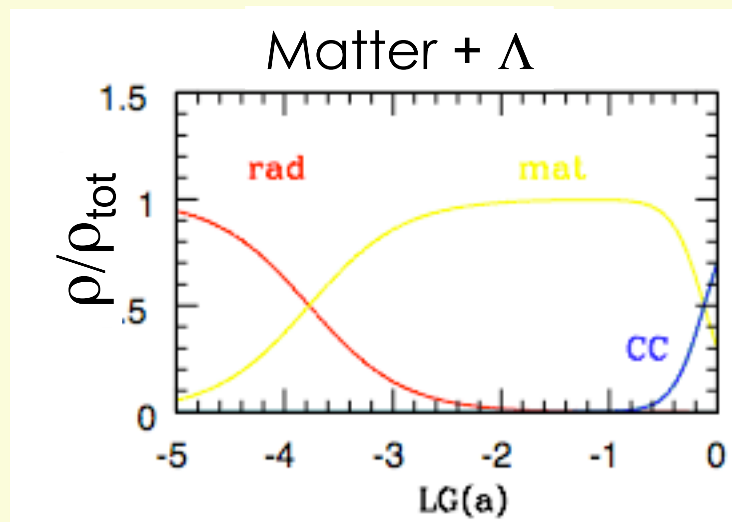
- Benefits of Jordan frame
  - Observations e.g. redshifts typically interpreted in Jordan frame
  - Assumes atomic physics in distant galaxy/ supernovae or the CMB is the same as on Earth (I.e. minimally coupled)

- No frame more `physical' than the other
  - all a matter of convenience

Dynamical attractors powerful in classifying viable models

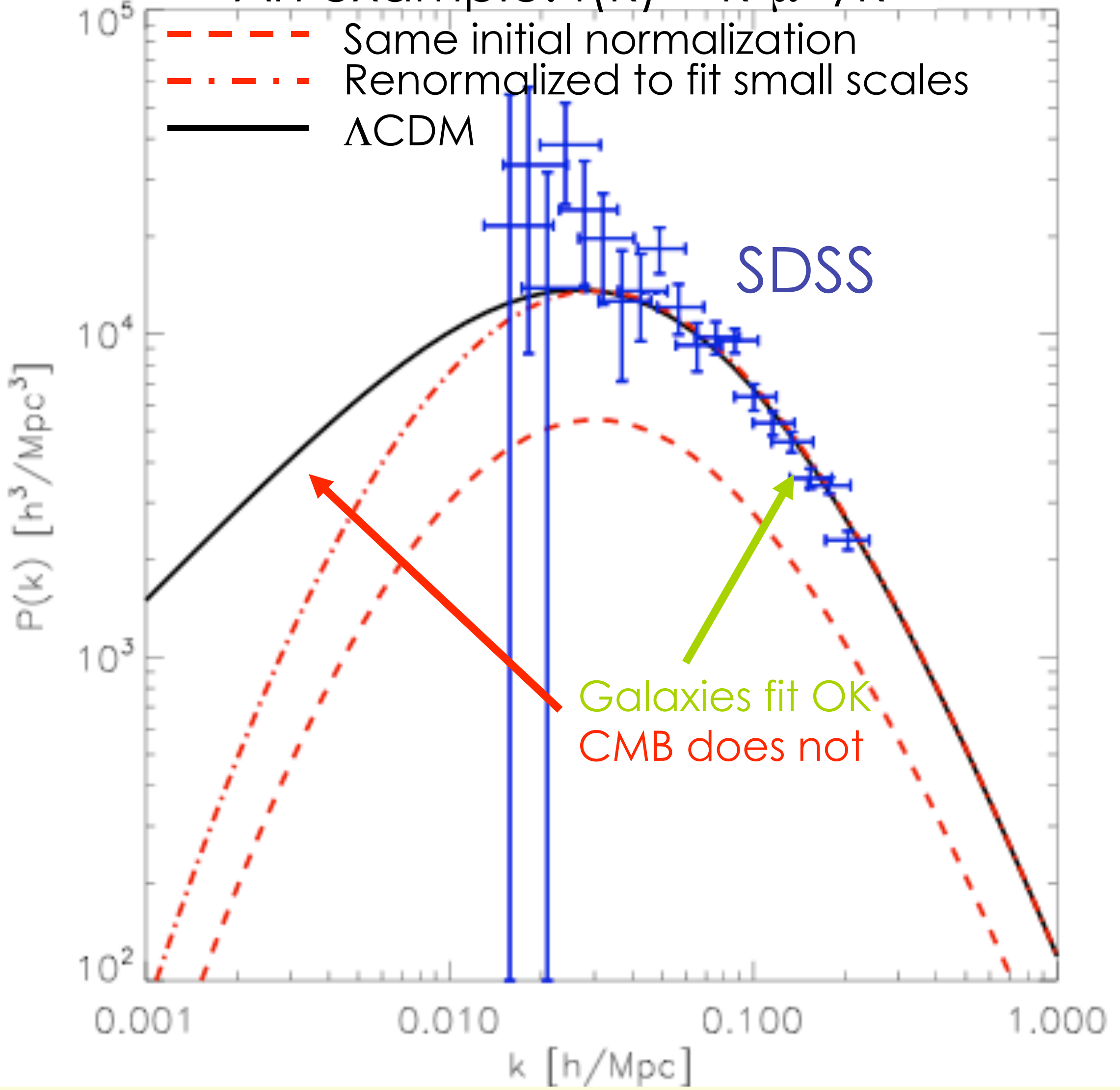
- Finds stable,saddle and unstable fixed points
- Evolution tends to fixed points largely independent of initial conditions
- Gives conditions on theory for viable evolution
  - Matter dominated era - Saddle point
  - late time acceleration- Stable or saddle point
- Behavior often generic irrespective of the specific form of the action





Attractors and observational implications

An example: $f(R) = R - \mu^4/R$



RB, D. Bernat, L. Pogosian, S. Silvestri, M. Trodden PRD 2007

Dynamical attractors in scalar-tensor theories F(Φ)R

- Perform dynamical analysis in Jordan or Einstein frame

$$x_1 = -\frac{d\ln F}{d\ln a}, \quad x_2 = -\frac{\int F d\Phi}{6FH^2}, \quad x_3 = \frac{\Phi}{6H^2}$$

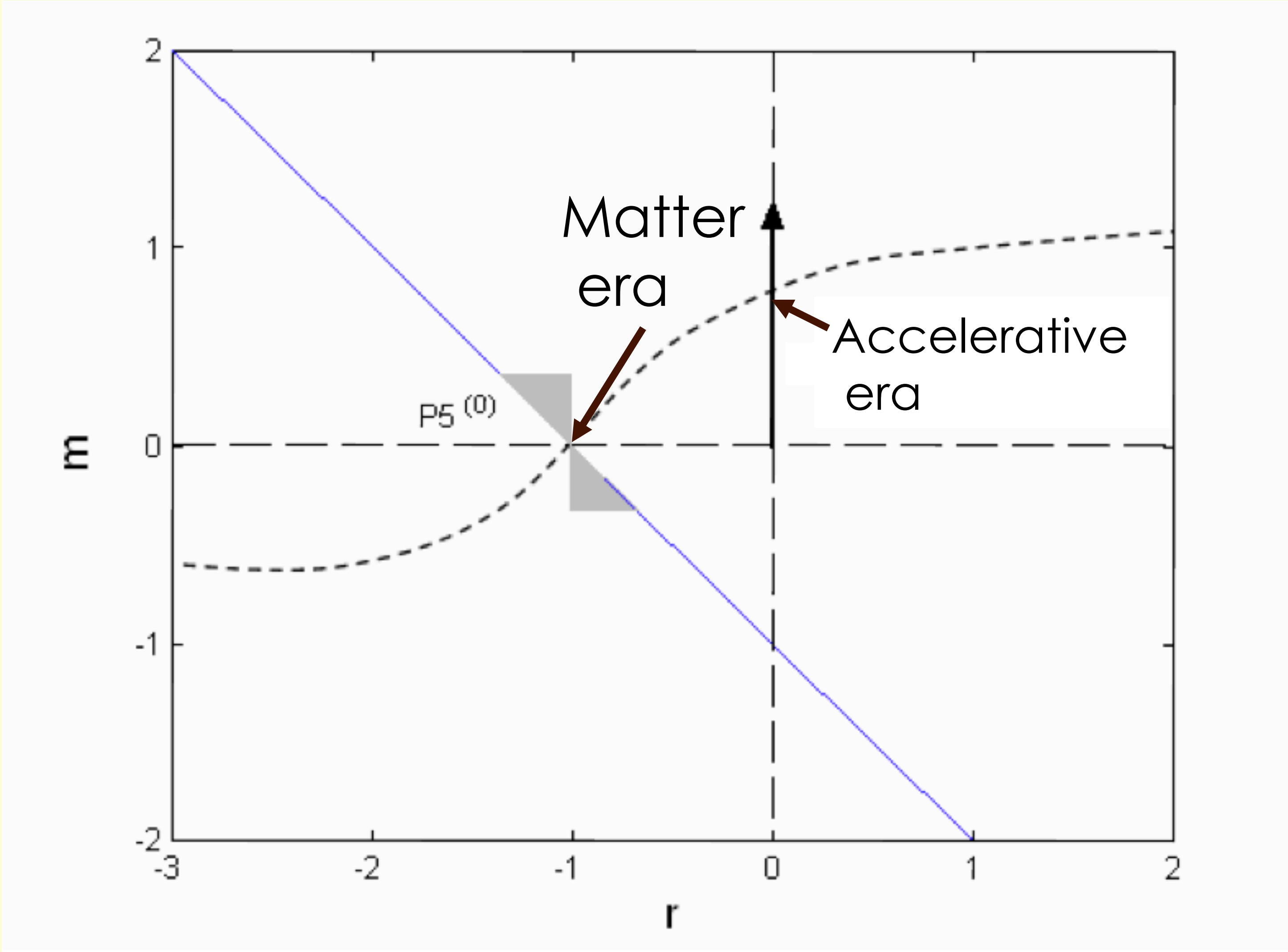
- Require evolution to satisfy
  - 1) CDM dominated era with $w^{(J)}\sim 0$ - saddle point
  - 2) Late time accelerated era - saddle point or stable

- Dynamical attractor solutions place restrictions on
  - Size of coupling C In Einstein frame
  - Allowed trajectories in Jordan frame of two variables, m and r

$$m = \frac{\Phi}{F}\frac{dF}{d\Phi} \qquad r = -\frac{\Phi F}{\int F d\Phi}$$

Amendola et al PRD 2006 (f(R) theories)
Nishant Agarwal and RB CQG 2008

A viable trajectory



Nishant Agarwal and RB CQG 2008

Can observations distinguish between modified gravity & Λ?

- Yes, look at how structure (galaxies, cluster of galaxies) grows…

$$\rho(x,a) = \bar{\rho}(a)\left[1+\delta(x,a)\right]$$

- Growth in δ related to gravitational metric perturbations (Φ and Ψ)

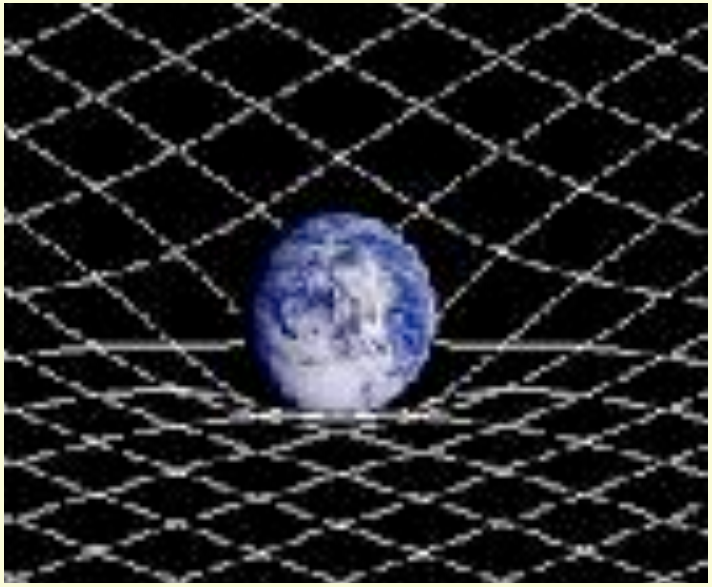
$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)dx^2$$

Distinguishing between modified gravity and Λ

Interactions between matter and gravitational potential

- 1) Poisson equation:
  How potential related to local density

$$\nabla^2\Phi(x,a) = \frac{\bar{\rho}(a)}{2m_p^2}\delta(x,a)$$



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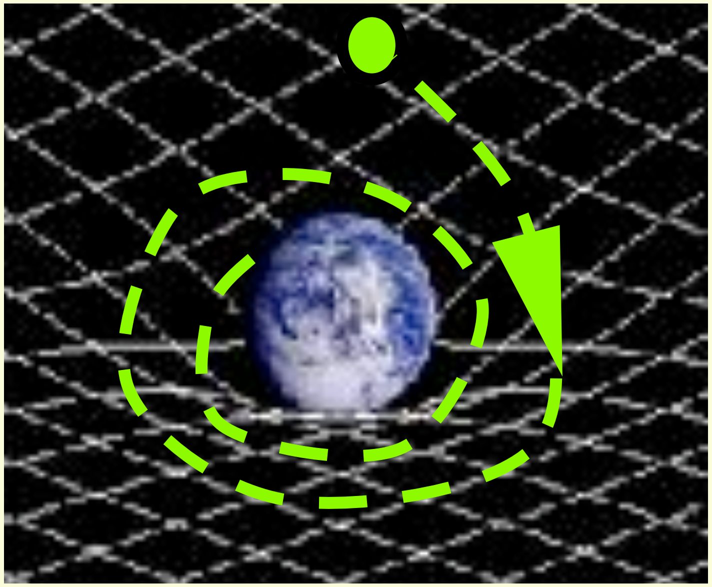
- 2) Peculiar acceleration equation:
  How matter responds to potential

$$g_i = \nabla_i \Psi$$



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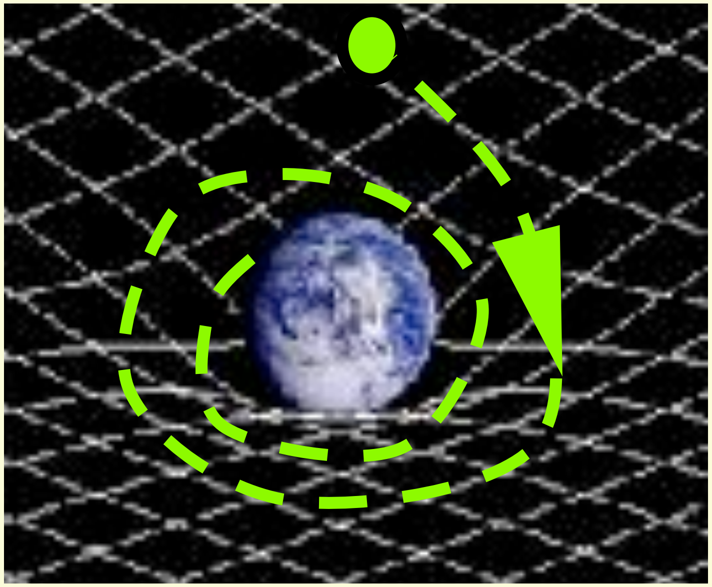
- 2) Peculiar acceleration equation:
  How matter responds to potential

$$g_i = \nabla_i \Psi$$

- 3) Relationship between two potentials:
  Presence of shear stresses

$$\Phi = \Psi$$



Distinguishing between modified gravity and Λ

These equations alter in modified gravity:

1) Can modify how potential is related to density (Poisson's equation)

$$\nabla^2\Phi = \frac{\bar{\rho}}{2m_p^2}Q(\underline{x,a})\delta$$

2) Can introduce intrinsic shear stress

$$\Psi = [1+\eta(\underline{x,a})]\Phi$$

Shear stress alters how matter responds to the potential (peculiar accel^n)

$$g_i = \nabla_i(1+\eta)\Phi$$

Example : DGP

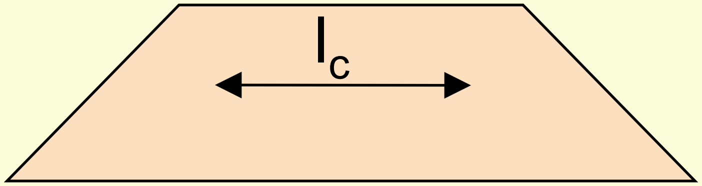
- Scale independent modifications

$$Q(a) = 1 - \frac{1}{3\beta(a)}$$

$$\eta(a) = \frac{2}{3\beta(a) - 1}$$

$$\beta(a) \equiv 1 - \frac{2H(a)^2 l_c^2}{2H(a) l_c - 1}$$

$$l_c = \frac{m_p^{(4)2}}{2m_p^{(5)3}}$$



Distinguishing between modified gravity and Λ

- Different observations measure different quantities
  - Weak lensing distortions - $\Phi+\Psi$ -> $Q(1+\eta/2)$
  - Galaxy number counts - Φ -> Q
  - Peculiar velocities - Ψ -> $Q(1+\eta)$

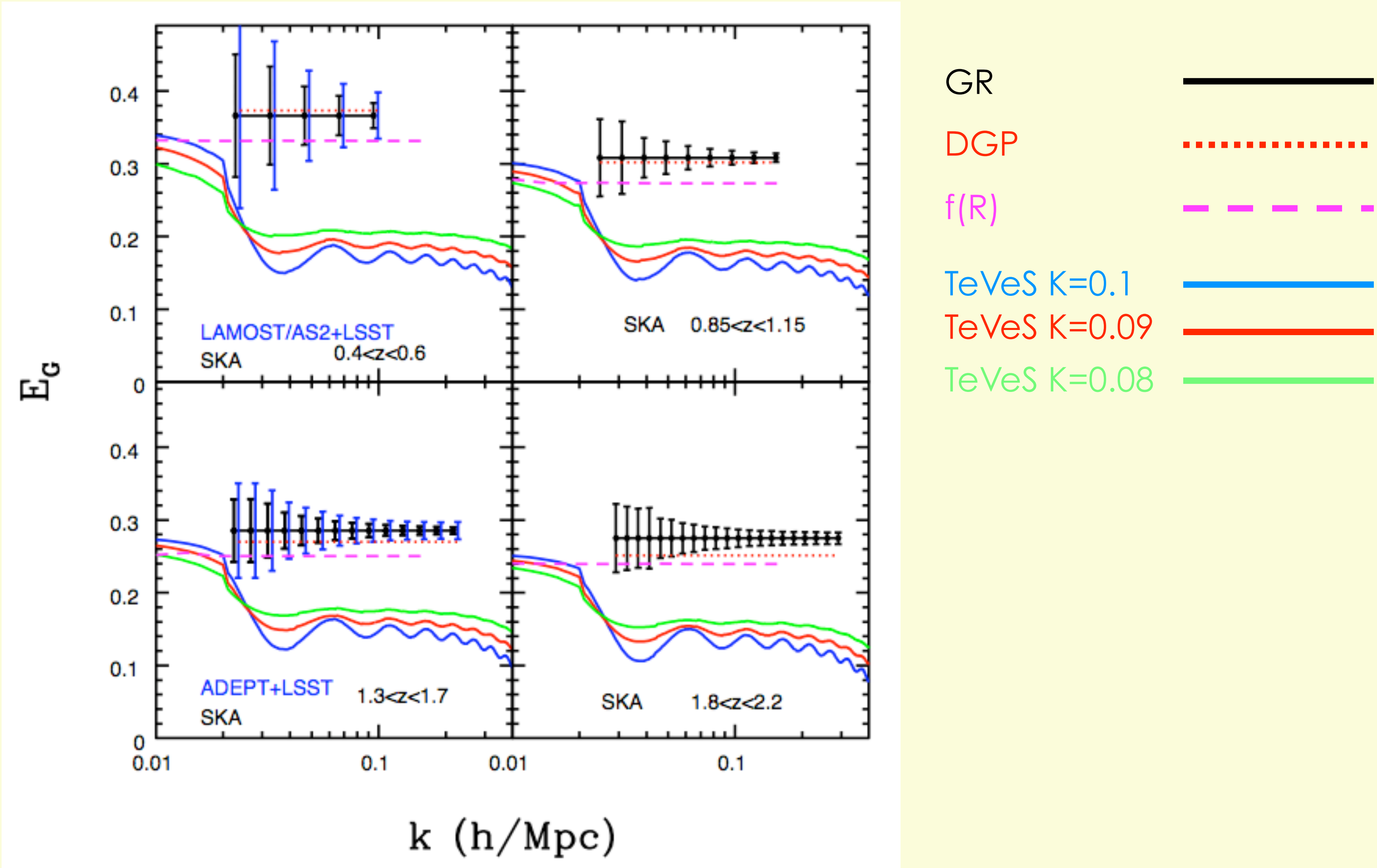
- By comparing observations we can distinguish modifications from GR

$$\hat{E}_G \propto \frac{\mathrm{lensing-galaxy\ correlation}}{\mathrm{velocity-galaxy\ correlation}}$$

$$\hat{E}_G = \left. \frac{\nabla^2(\Psi+\Phi)}{3H_0^2 \frac{d\delta}{d\ln a}} \right|_{k=\frac{l}{\chi},\bar{z}}$$

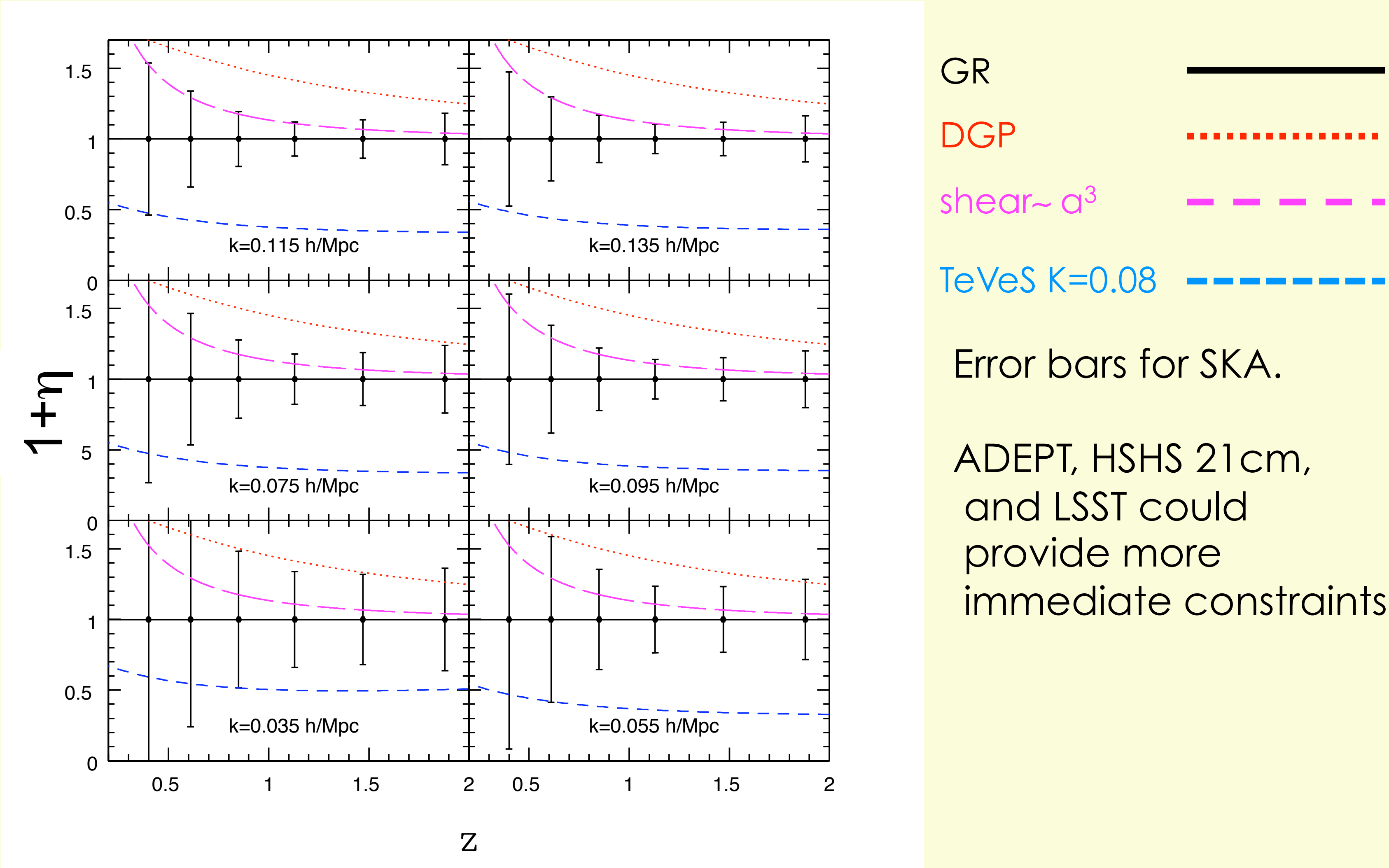
Zhang, Liguori, RB, Dodelson PRL 2007

Distinguishing between modified gravity and Λ



Zhang, Liguori, RB, Dodelson PRL 2007

Measuring η



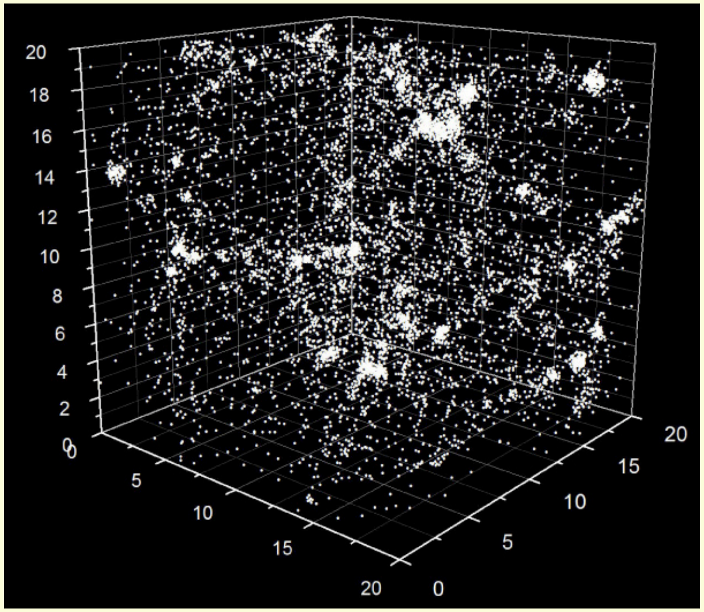
Error bars for SKA.

ADEPT, HSHS 21cm, and LSST could provide more immediate constraints

Zhang, RB, Liguori, Dodelson in preparation

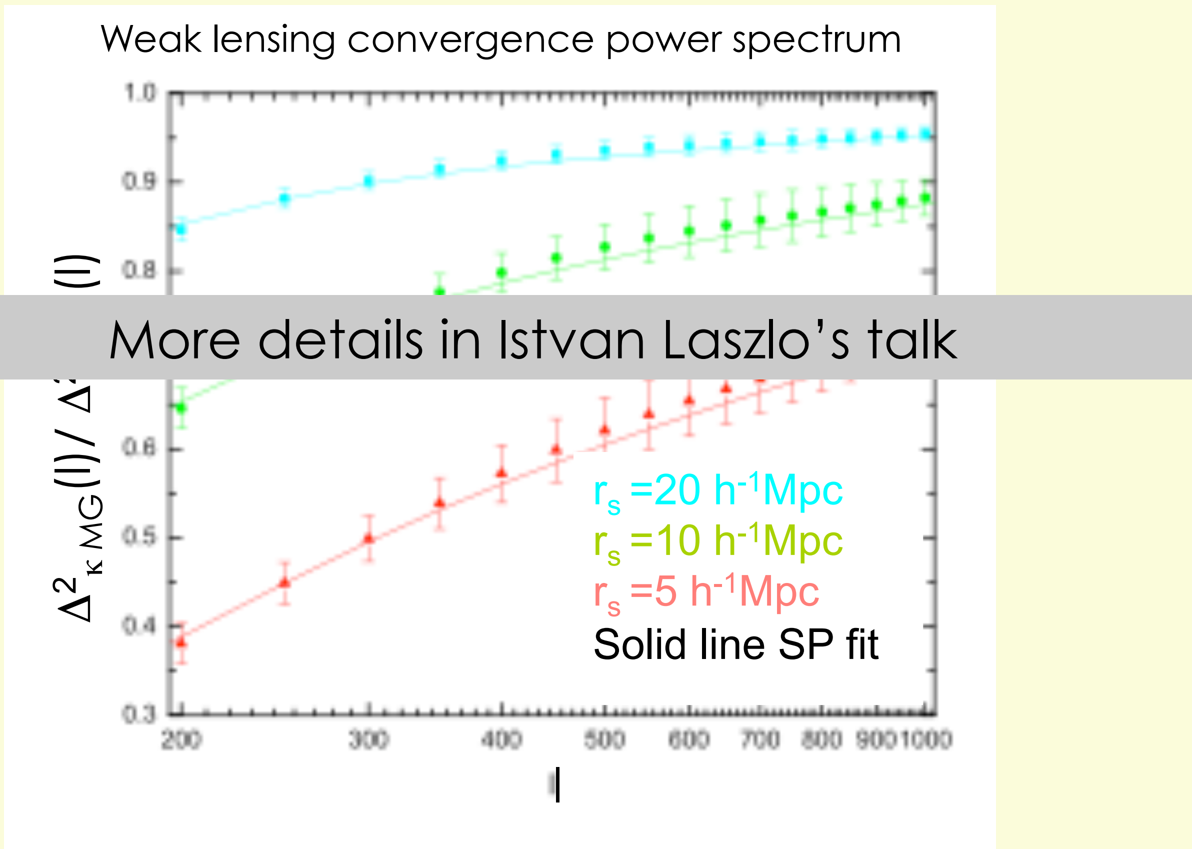
Accurate non-linear growth predictions

- Weak lensing and galaxy correlations measured when over-densities large
  - "non- linear growth"
- N-body simulations needed to model growth numerically
- Analytical fits done of GR simulations
  - Smith and Peacock
  - Peacock and Dodds
- Need simulations of non-linear growth in modified gravity theories to accurately predict effect on weak lensing and galaxy surveys



F. Stabenau and B. Jain PRD 2006
I. Laszlo and RB PRD 2007

A simple 5D gravity model



I. Laszlo and RB, PRD 2007

Constraining a coupling between dark energy and dark matter?

- What if purely dark sector interactions? Just couple scalar to CDM.

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \sqrt{\frac{2}{3}} C\kappa(\rho - 3P)$$

$$\rho \propto e^{-\sqrt{\frac{2}{3}}\kappa C\phi} a^{-3(1+w)}$$

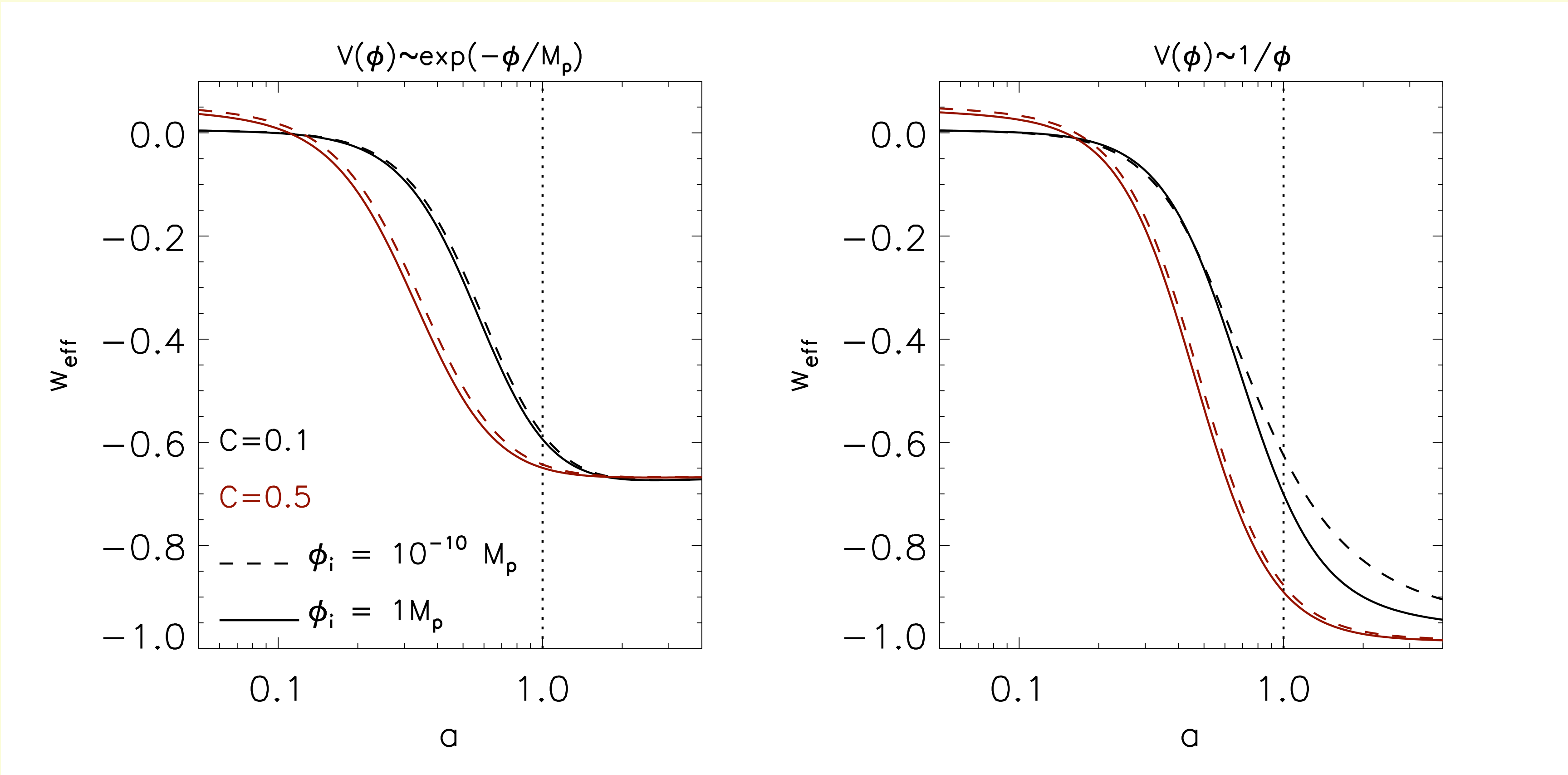
- Interaction acts as species dependent G

$$\frac{G_{cc}G_{bb}}{G_{bc}^2} = 1 + \frac{4}{3}C^2$$

RB, E. Flanagan, I. Laszlo, M. Trodden, arxiv: 0808.1105

Constraining a coupling between dark energy and dark matter?

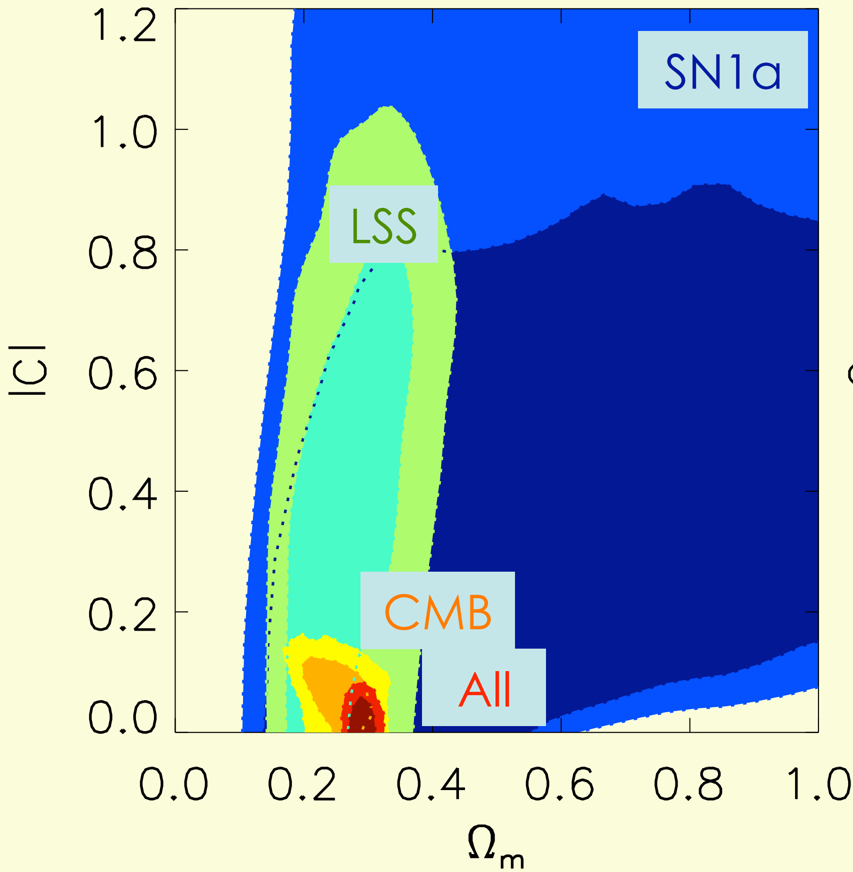
Attractor and tracker solutions again important

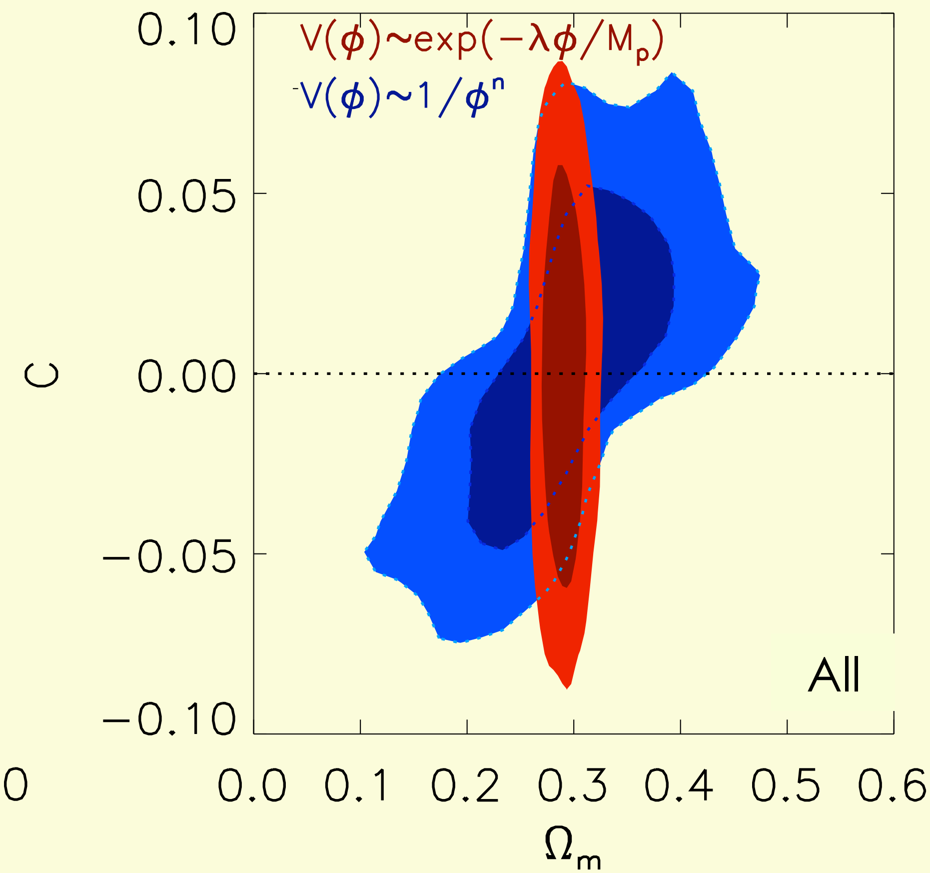


RB, E. Flanagan, I. Laszlo, M. Trodden, arxiv: 0808.1105

CMB, LSS and SN observations place very tight constraints on any such interaction

Coupling < 0.07 at 95% confidence level





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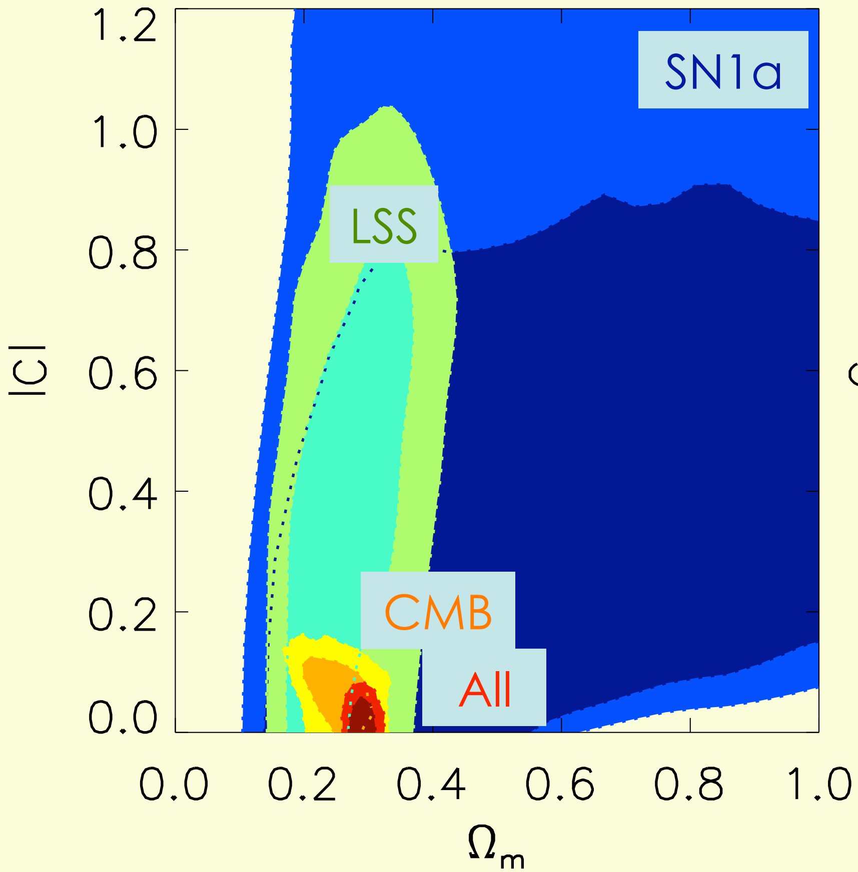

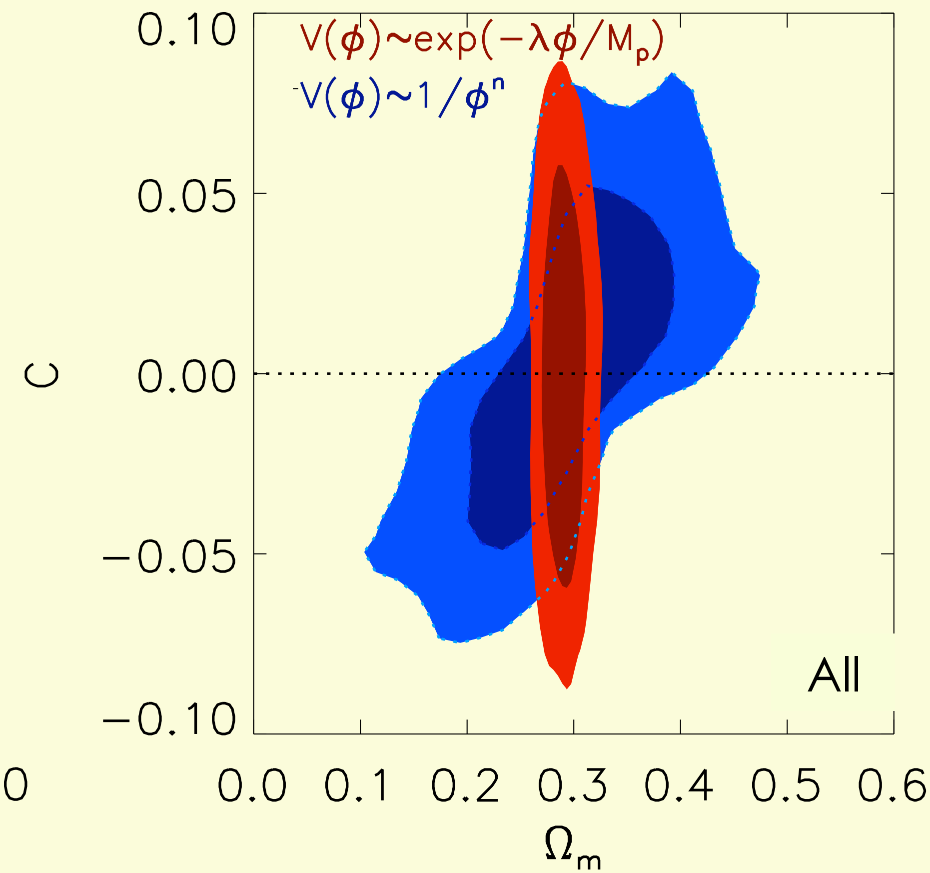

See Istvan's talk for constraints on dark matter self interactions

RB, E. Flanagan, I. Laszlo, M. Trodden, arxiv: 0808.1105

Conclusions

1. We should establish empirically if dark energy caused by Λ, or not
   - Late time acceleration can arise in matter or gravity based theories
   - Can affect the growth of structure differently

2. Dynamical attractor analysis powerful for establishing conditions for viability
   - Constrain broad properties of modified gravity and coupled theories

3. We *can* hope to differentiate between modified gravity and Λ
   - By contrasting different observations of large scale structure

4. Theorists should also aim to minimize systematic errors
   - Shouldn't assume a priori that fits to GR simulations hold here
   - However, weakly non-linear growth well fit by current analytical fits