Growth of Cosmic Structure: Probing Dark Energy Beyond the Expansion

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- Hao-Yi Wu
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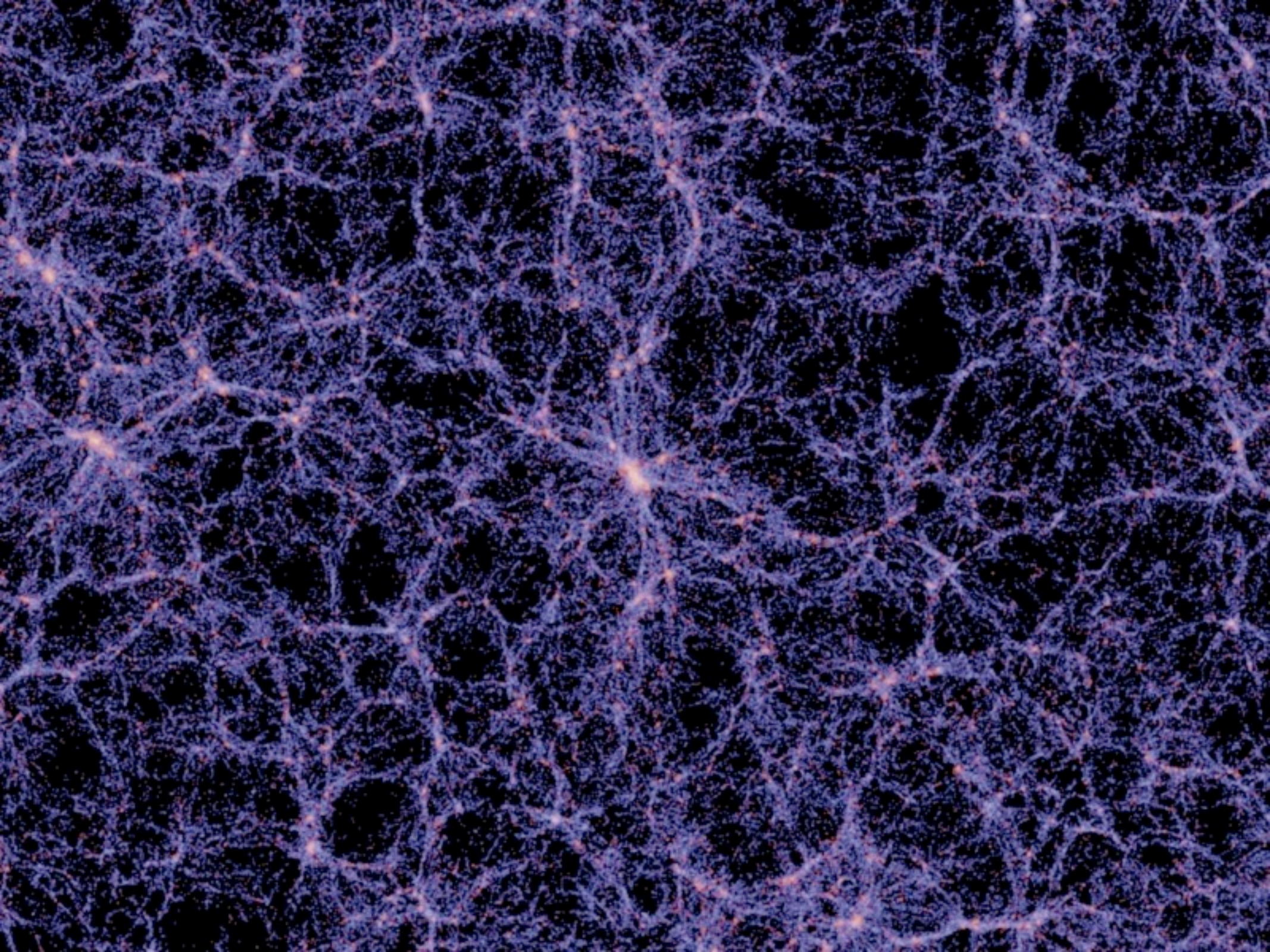


Definitions

past → $\delta(a) = D(a)\delta(a=1)$ ← today

$\delta \equiv \delta\rho/\rho$ density fluctuation in matter

D(a) is linear growth factor

a is scale factor (a=0 Big Bang, a=1 today)

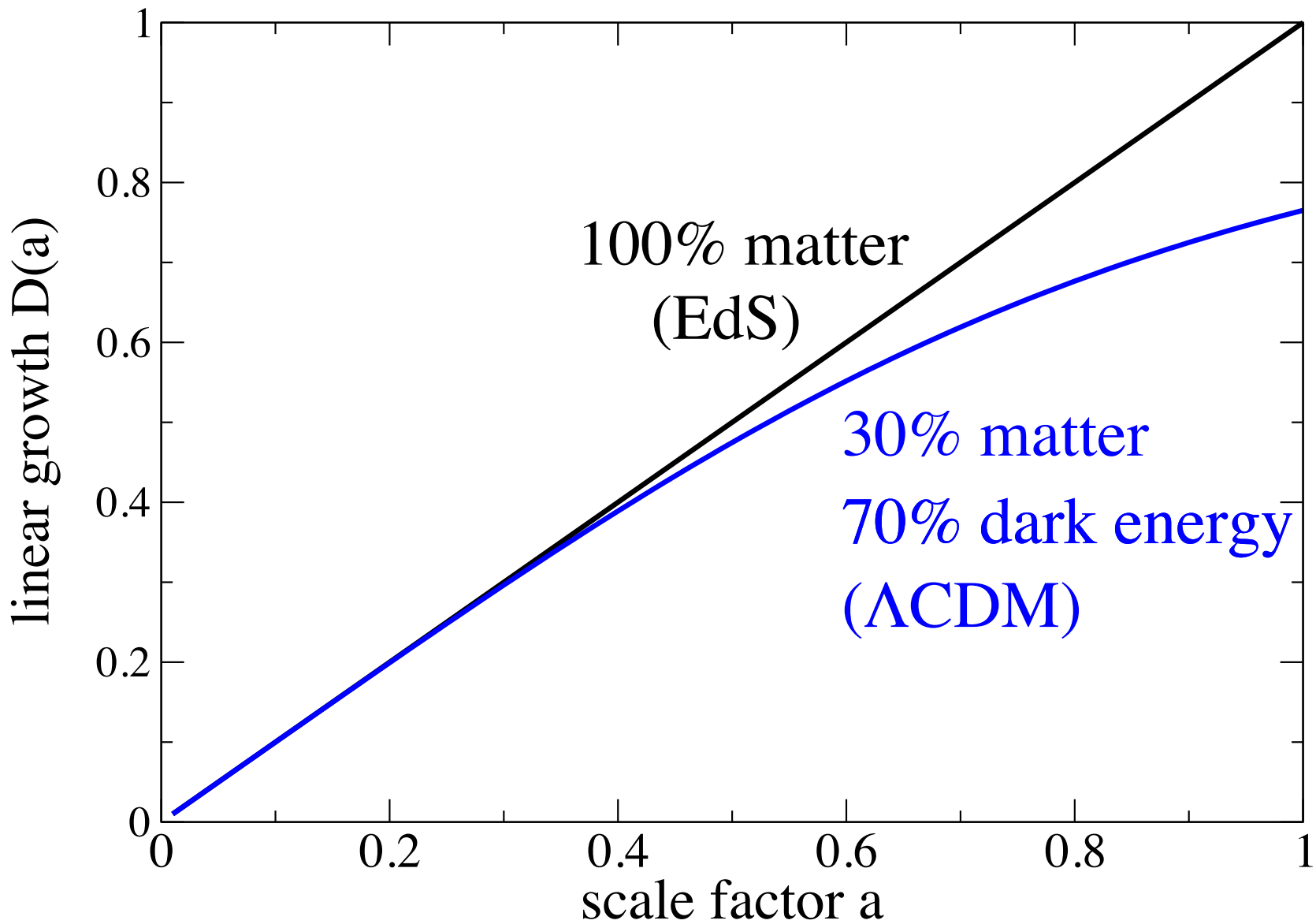
In linear theory (large scales),
δ grows at the same rate for each k-mode

amount of fluctuation over a sphere of radius R usually calculated as

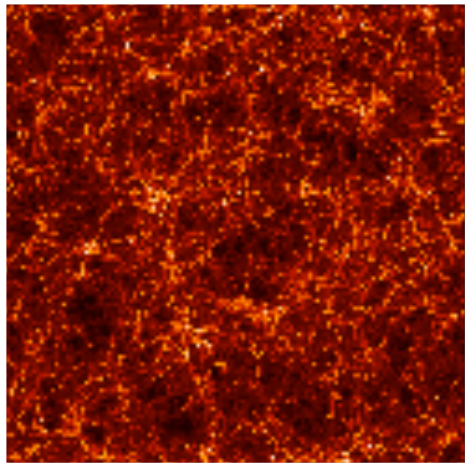
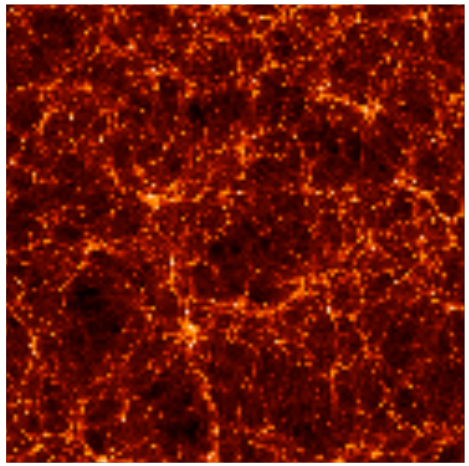
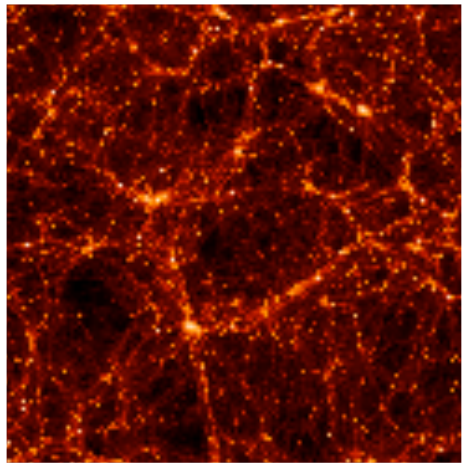
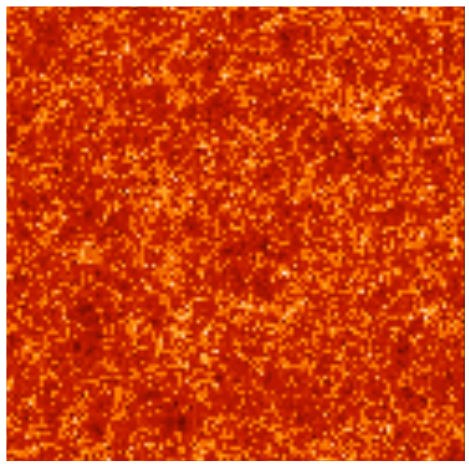
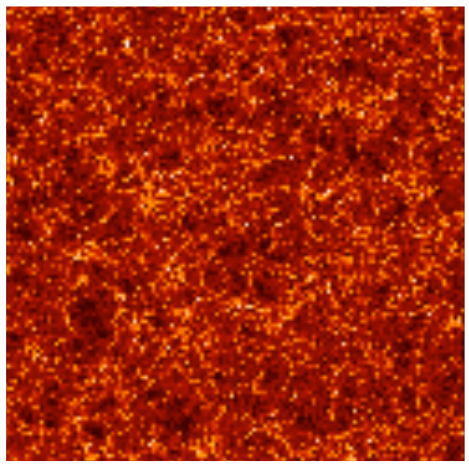
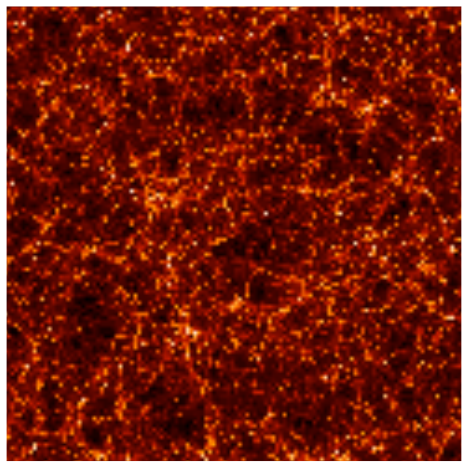
$$\sigma_R^2(a) = \int_0^\infty \frac{k^3 P_{\rm linear}(k,a)}{2\pi^2} W^2(kR)\, d\ln k$$

For historical reasons,
σ_8 (so R=8 h^{-1} Mpc) is popular to gauge "how much structure"

Dark Energy suppresses the growth of density fluctuations



Dark Energy suppresses the growth of density fluctuations

	(a=1/4 or z=3) 1/4 size of today	(a=1/2 or z=1) 1/2 size of today	(a=1 or z=0) Today
with DE			
without DE			

The Virgo Consortium (1996)

What if gravity deviates from GR?

For example, in the Friedmann equation:

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \qquad \text{or} \qquad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

Modified gravity

Dark energy

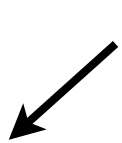
Notice: there is no way to distinguish these two possibilities just by measuring expansion rate H(z)!

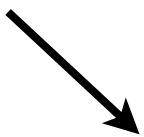
Can we distinguish between DE and MG?

- In standard GR, H(z) determines distances and growth of structure

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi\rho_M\delta = 0$$

  - So check if this is true by measuring separately





Geometry

(as known as kinematic probes)
(a.k.a. 0^{th} order cosmology)

Probed by SN Ia, BAO, CMB, weak lensing, cluster abundance

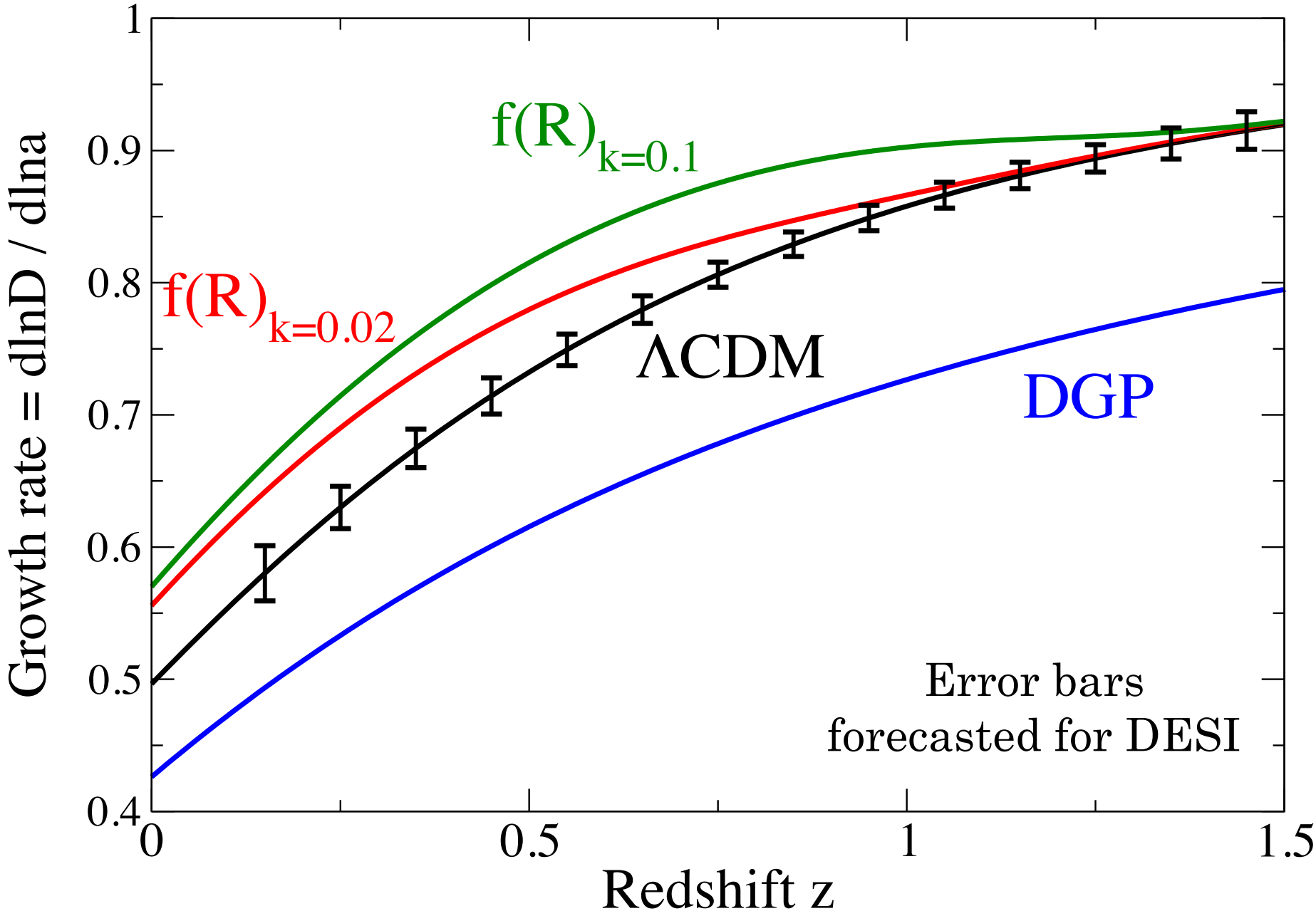
Growth

(a.k.a. dynamical probes)
(a.k.a. 1^{st} order cosmology)

Probed by galaxy clustering, weak lensing, cluster abundance

Growth distinguishes MG from "new-stuff" DE

E.g. all models below have identical expansion history H(z)



Principal probes of the growth of structure

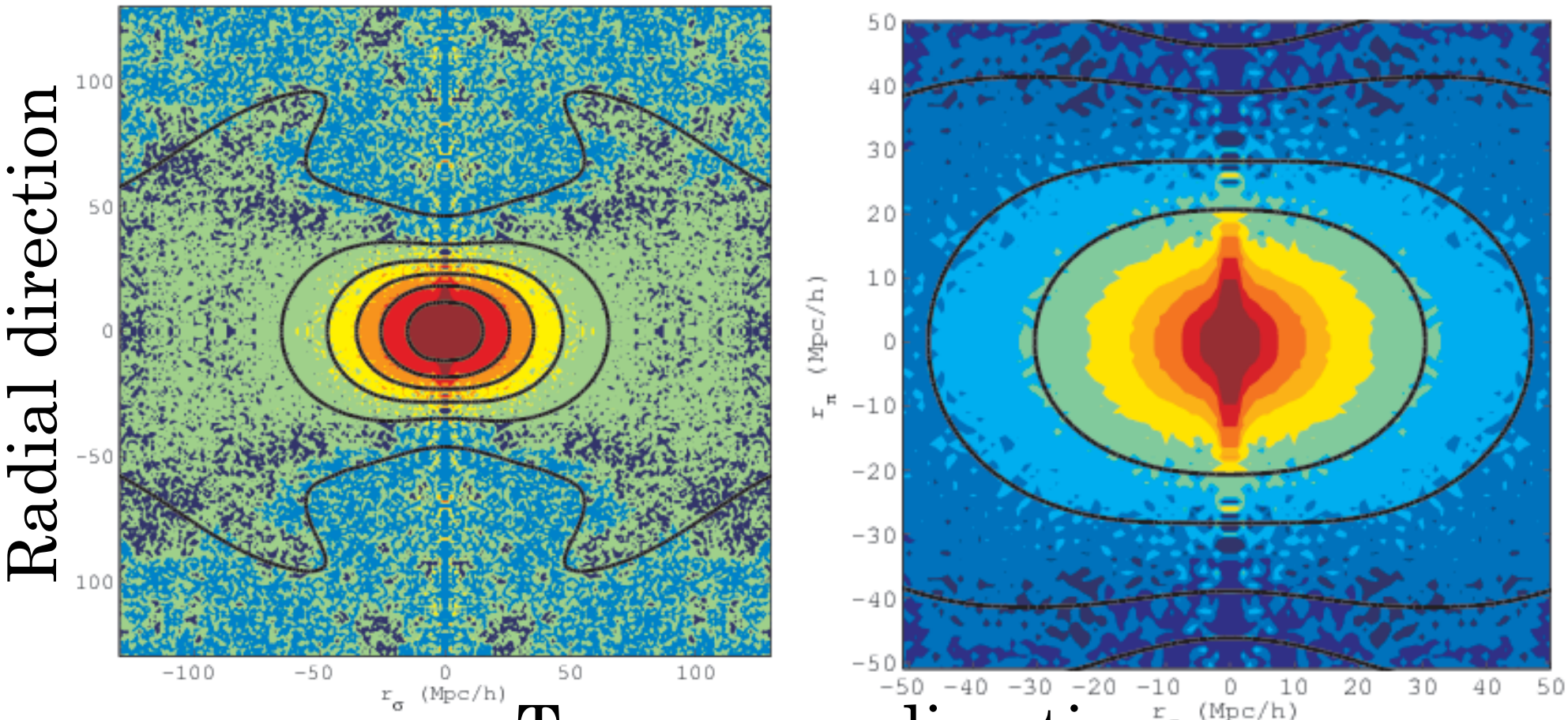
- Redshift-space distortions (RSD)
- Counts of clusters of galaxies
- Weak gravitational lensing (WL)
  including CMB lensing

vs. Powerful probes of cosmology
but geometry aspect only:

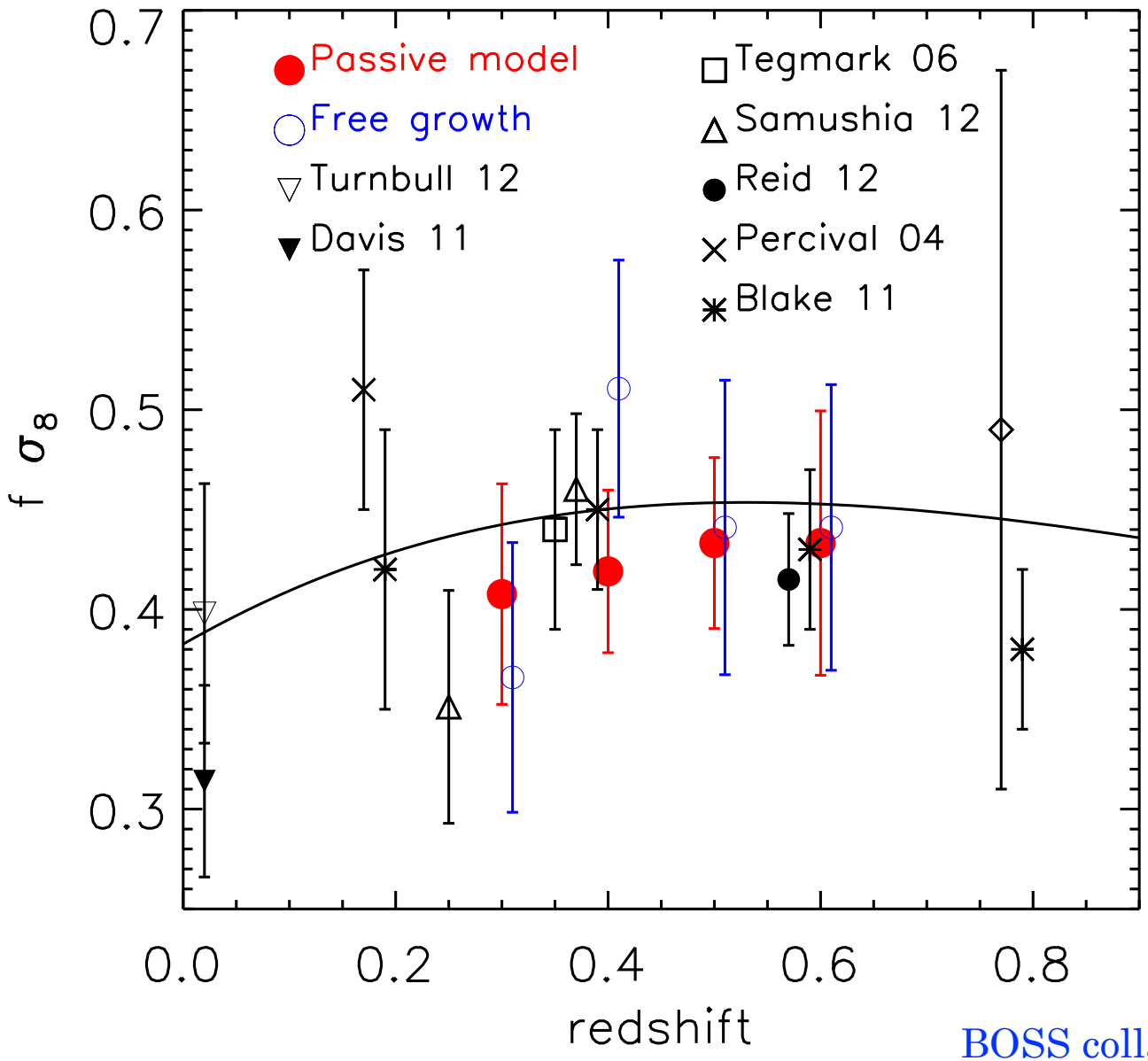
- type Ia supernovae
- Baryon Acoustic Oscillations (BAO)
- Cosmic Microwave Background (CMB)

Redshift-Space Distortions (RSD)

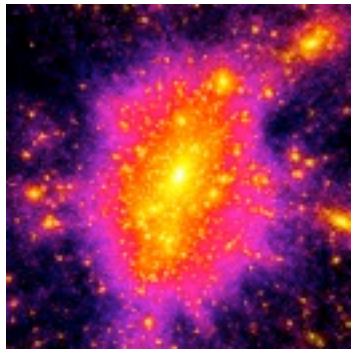
- **anisotropic** clustering of galaxies due to grav infall
- sensitive to $f(a)\sigma_8(a) \propto dD/d\ln a$
- readily measured (2dF, BOSS, Wiggles; future: eBOSS, PFS, DESI)



Current constraints from various spectroscopic surveys



BOSS collab (Tojeiro et al 2012)



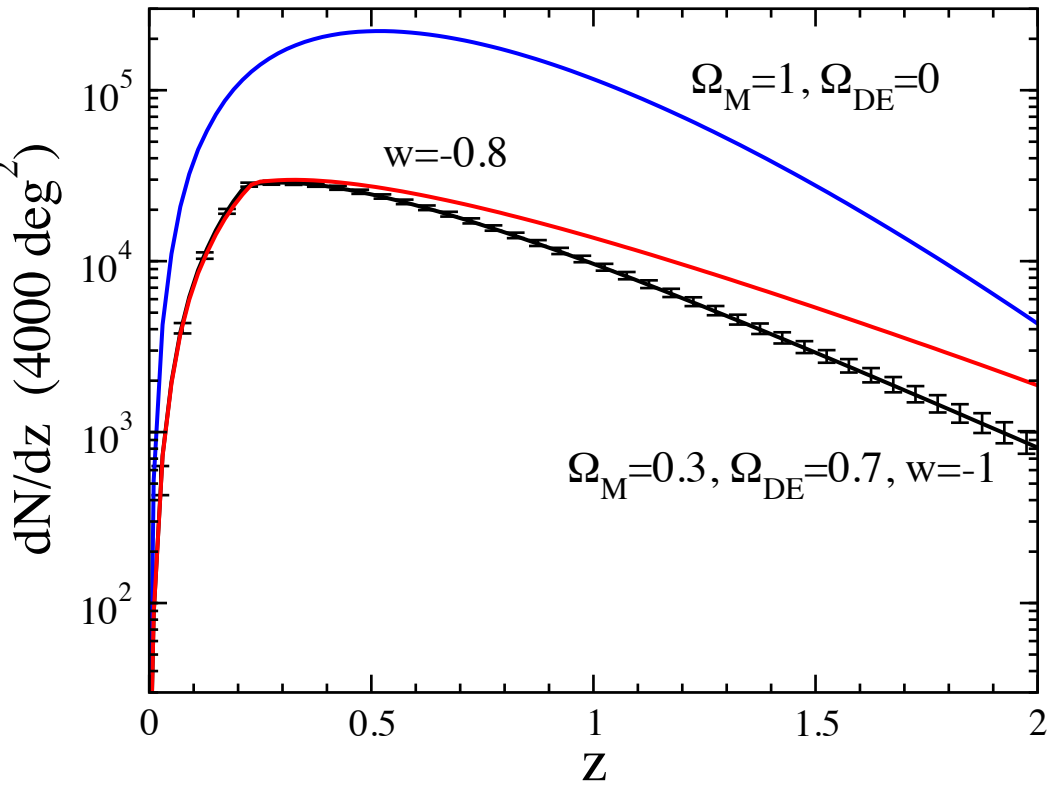
Counting galaxy clusters

cluster number
(measure)

$$\frac{d^2N}{d\Omega\, dz} = n(z)\,\frac{r(z)^2}{H(z)}$$

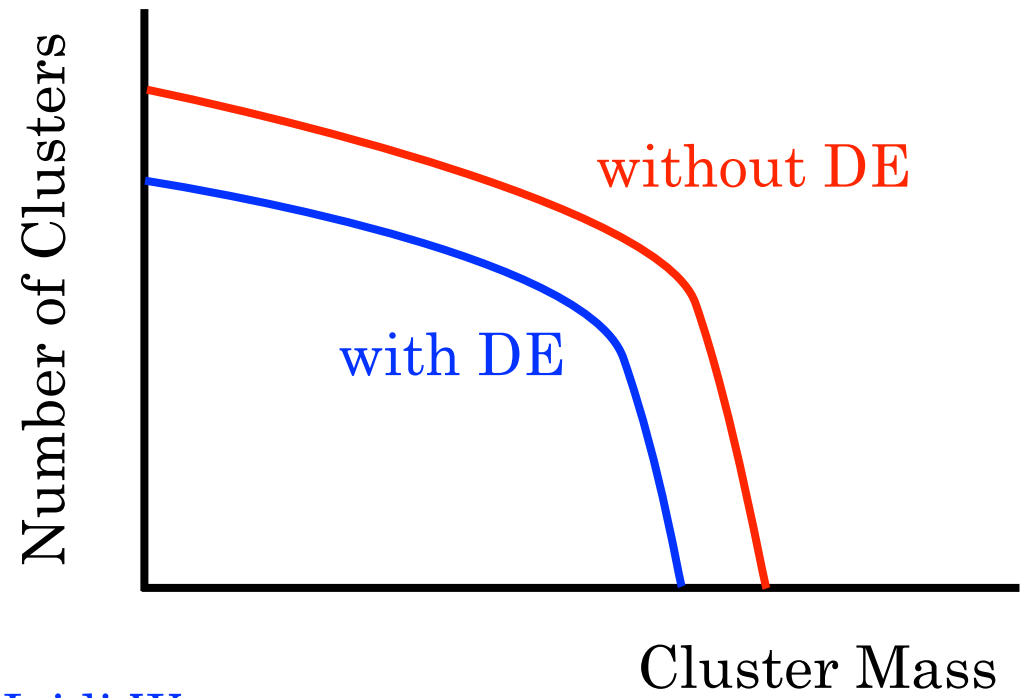
cluster num. density
(simulations→DE)

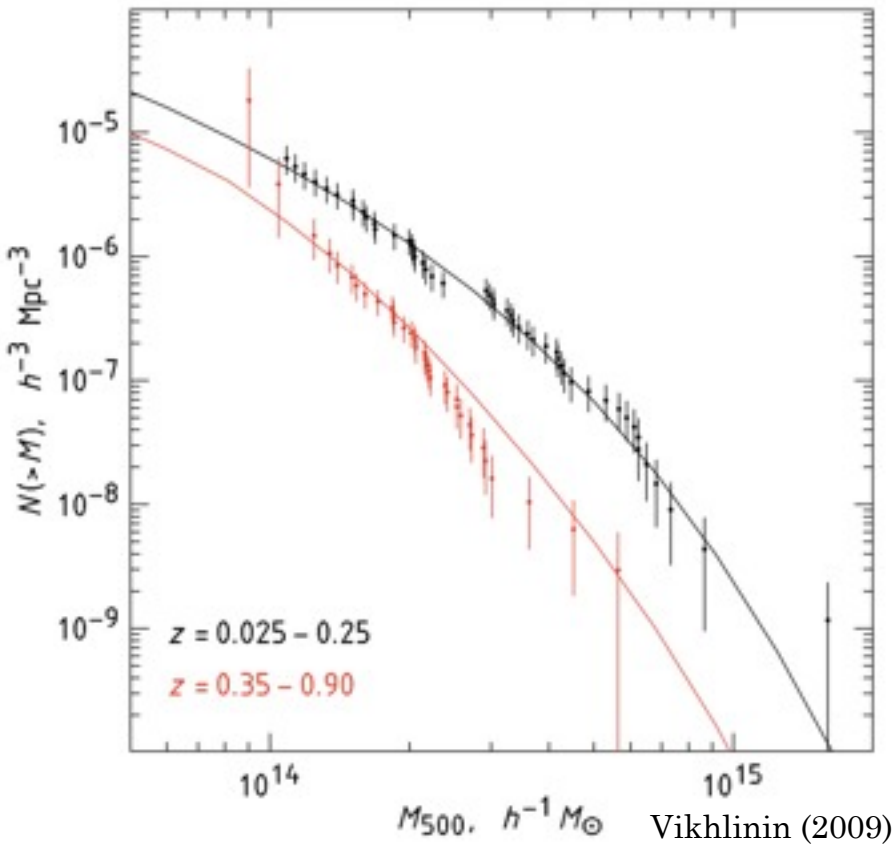
distance factors
(theory→DE)



Counting galaxy clusters helps us understand dark energy

Number as a function of mass

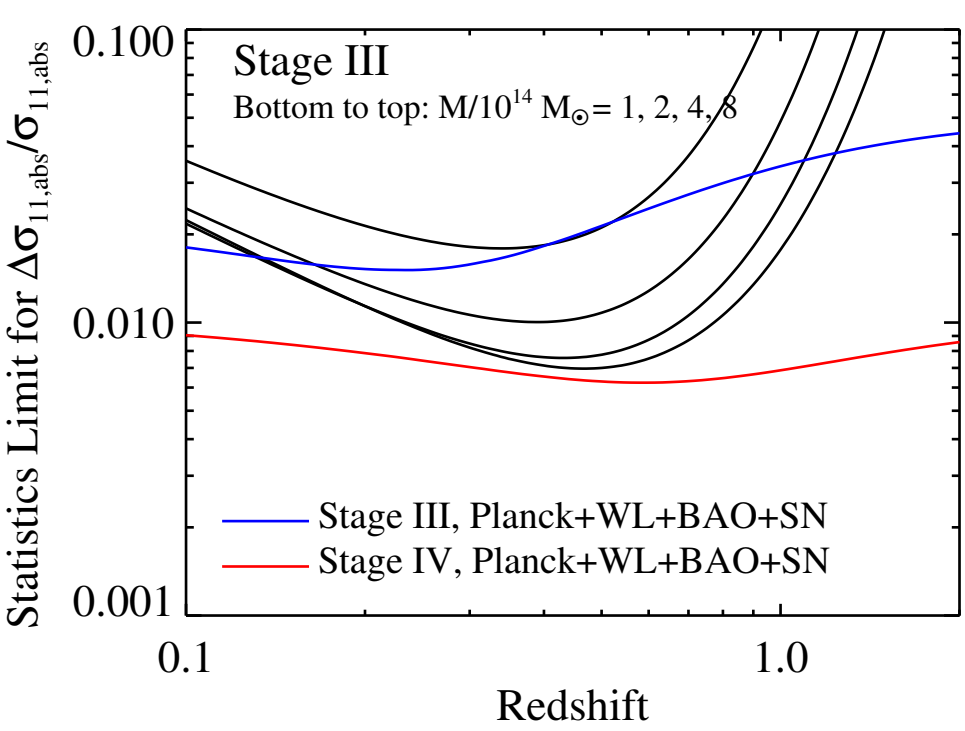


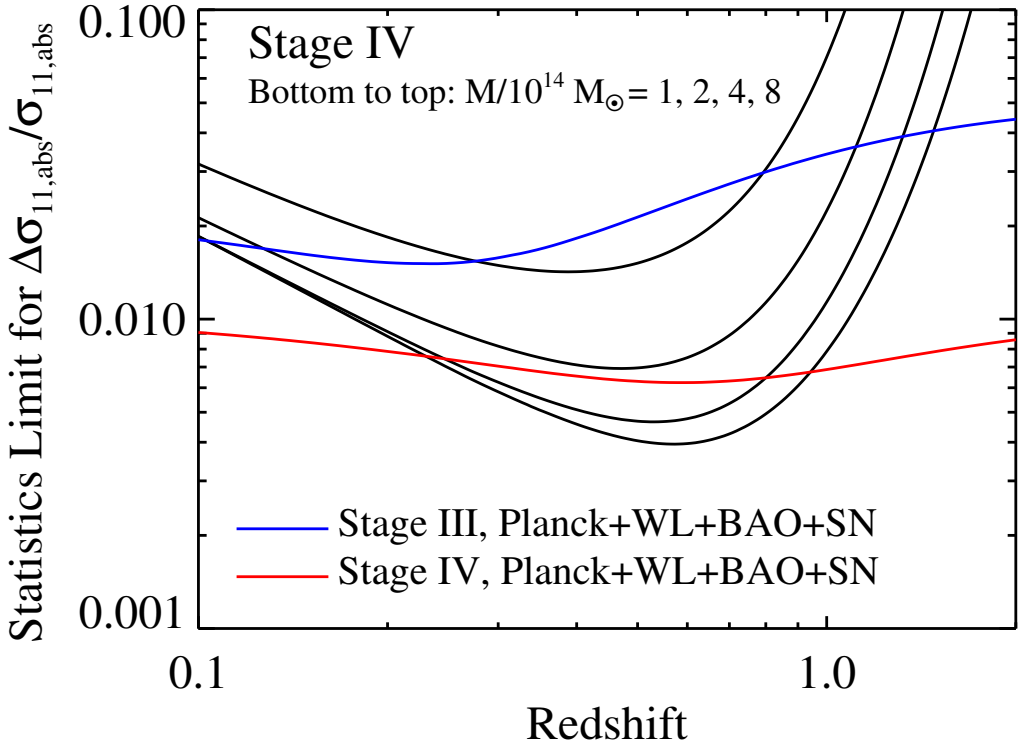


Vikhlinin (2009)

Heidi Wu

Future prospects





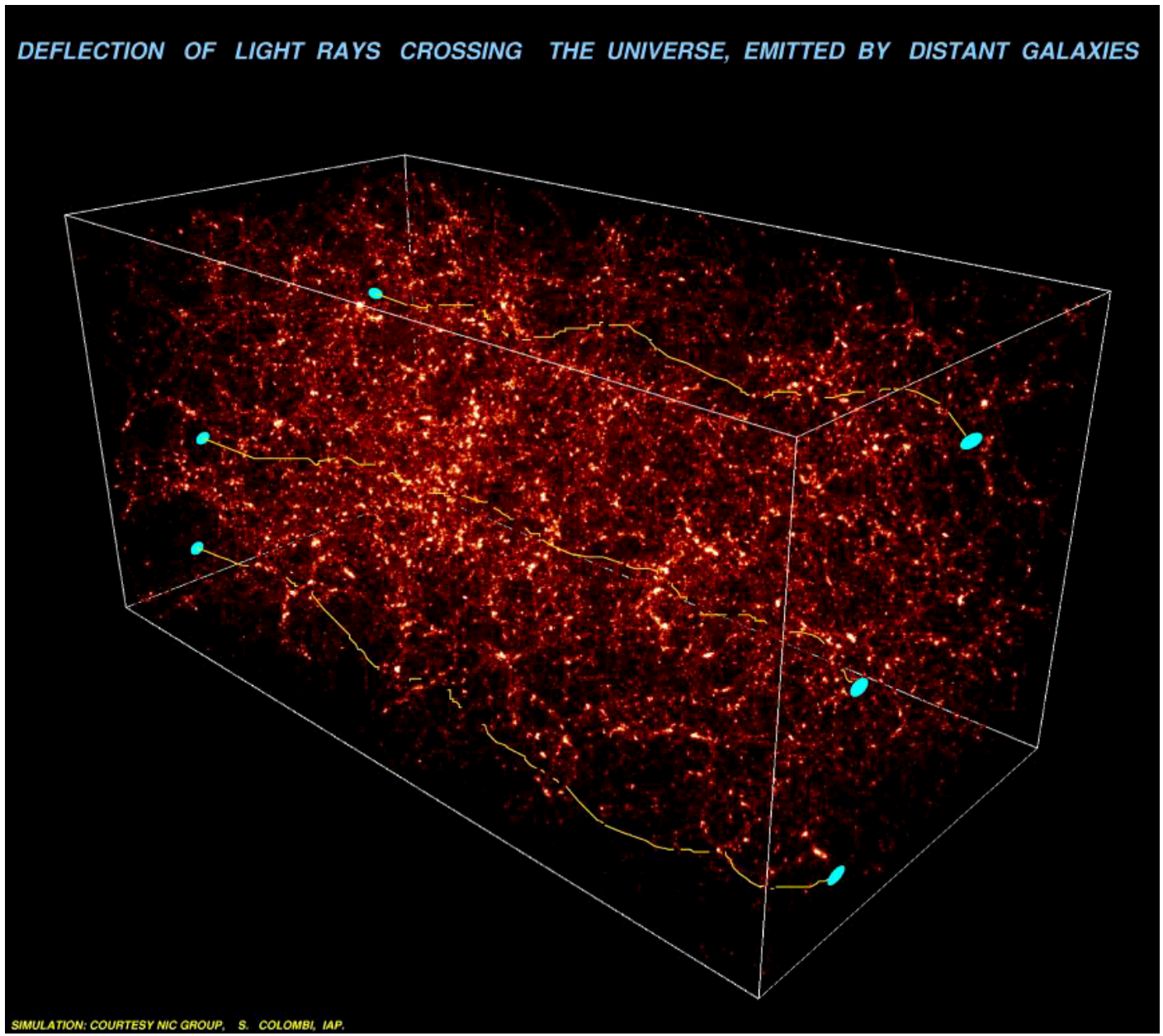
Weinberg et al. 2012

Current/future: ACT, SPT, DES;
Future: HSC, LSST, WFIRST, eROSITA

Weak Gravitational Lensing

Galaxy shapes appear **sheared** due to **all matter** along line-of-sight

Measure **correlations** of those shears - not random



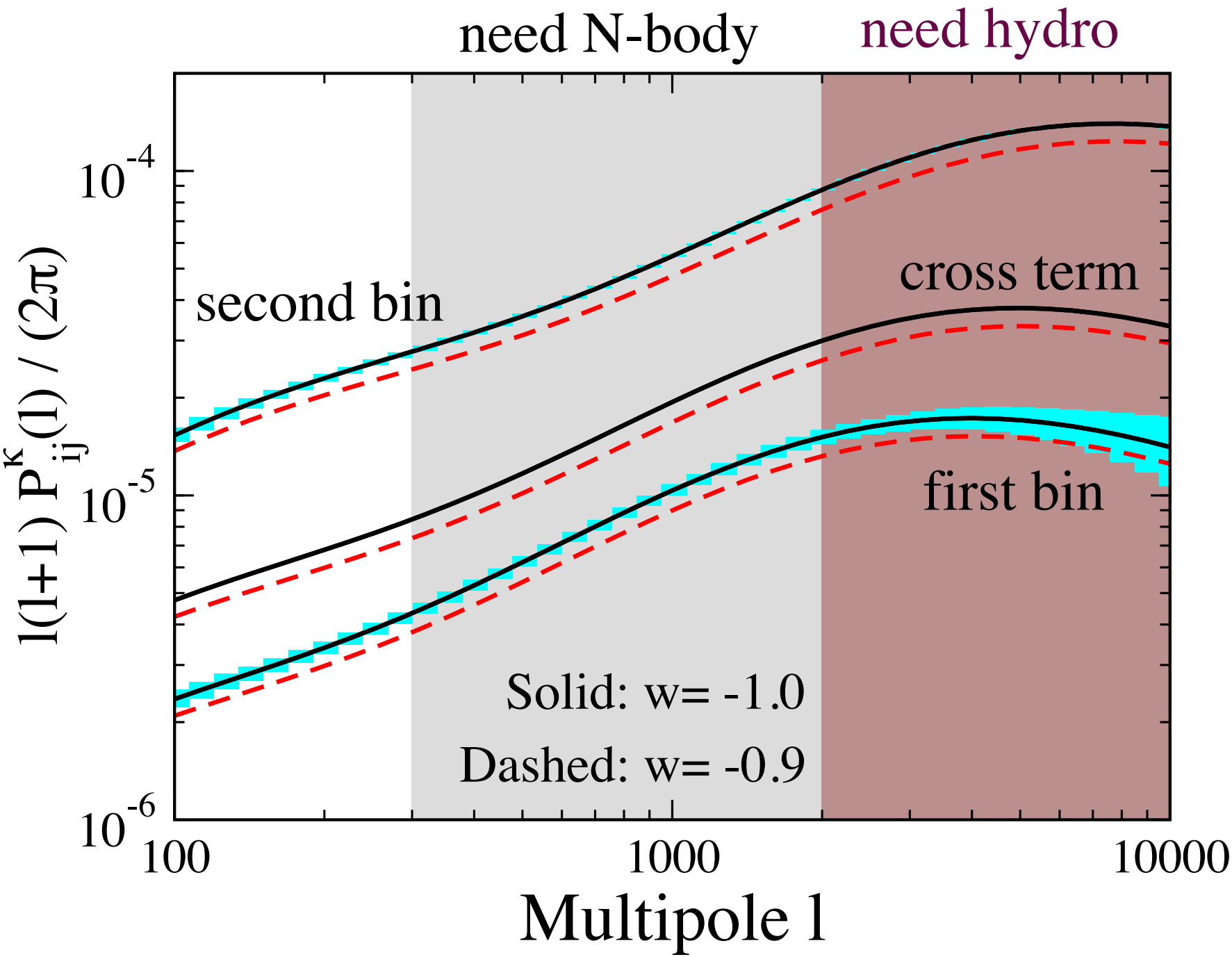
Weak Lensing and Dark Energy

Shear-shear correlation function:
integral along the line of sight

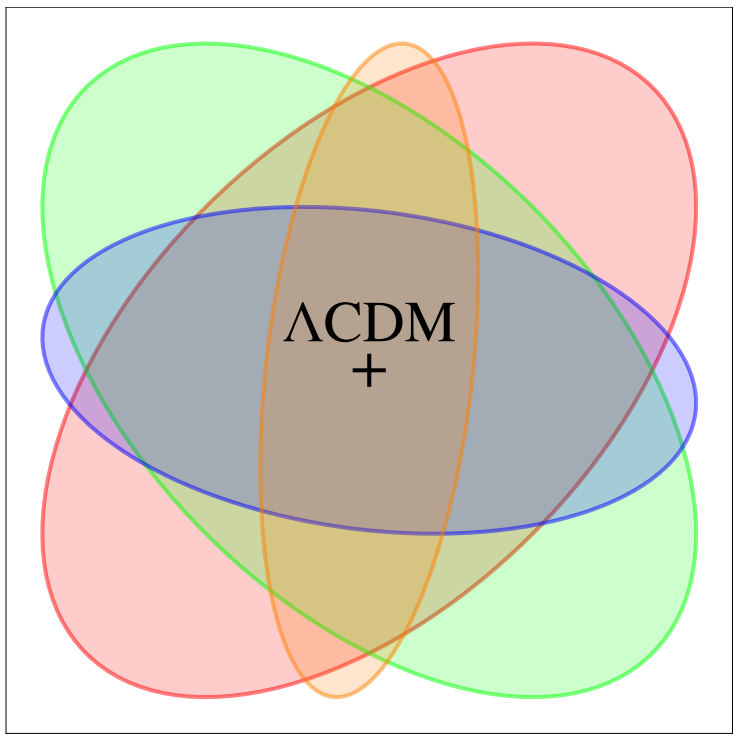
$$P_{ij}^{\kappa}(\ell) = \int_0^\infty dz \, \underbrace{\frac{W_i(z)\, W_j(z)}{r(z)^2\, H(z)}}_{\text{geometry}} \, \underbrace{P\left(\frac{\ell}{r(z)}, z\right)}_{\text{growth}}$$

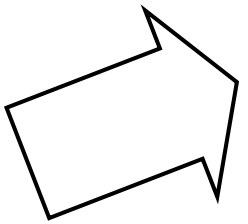
$$\Delta P_{ij}^{\kappa}(\ell) = \sqrt{\frac{2}{(2\ell+1)\, f_{\rm sky}}} \left[\underbrace{P_{ij}^{\kappa}(\ell)}_{\text{cosmic var}} + \underbrace{\delta_{ij} \frac{\langle \gamma_{\rm int}^2 \rangle}{\bar{n}_i}}_{\text{shot noise}} \right]$$

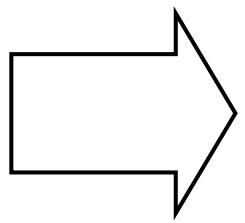
Weak lensing shear correlation function

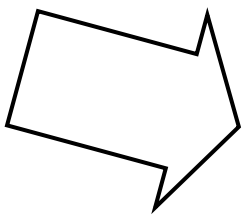


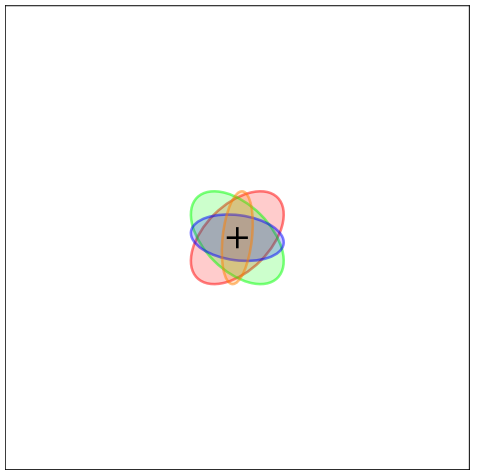
Stage III



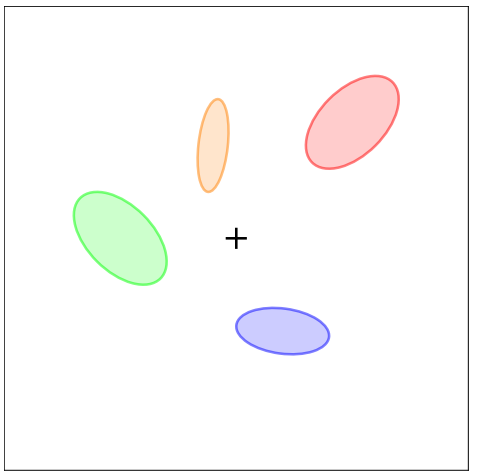




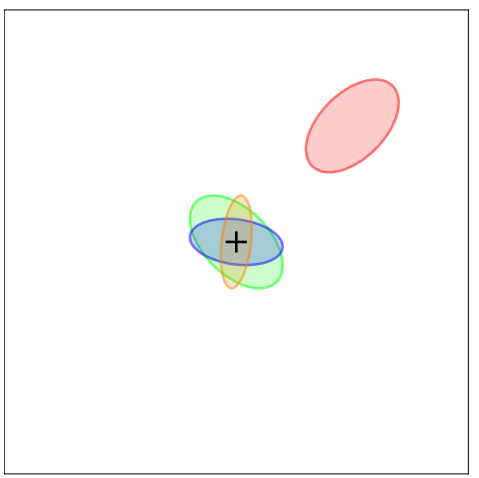




Stage IVa



Stage IVb



Stage IVc

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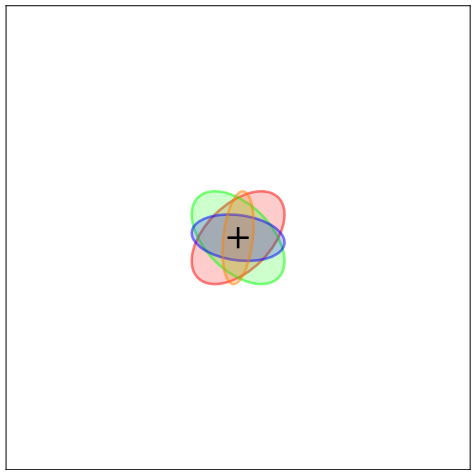
Stage IVa



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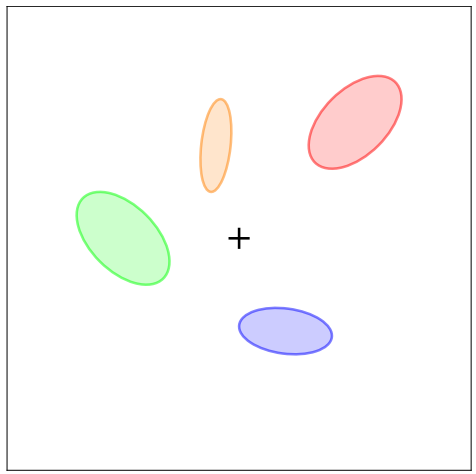

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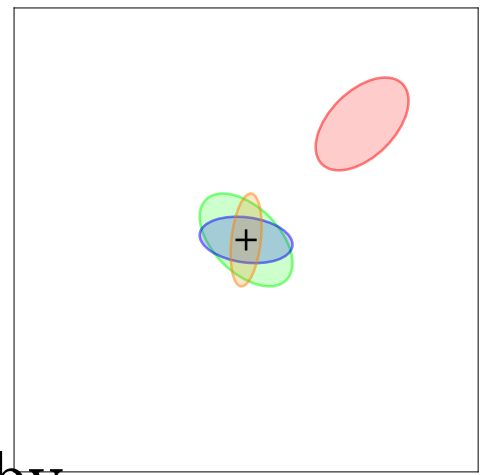

Is there a compelling new theory that has not been excluded?

YES: proceed to stage V

NO: done for now?

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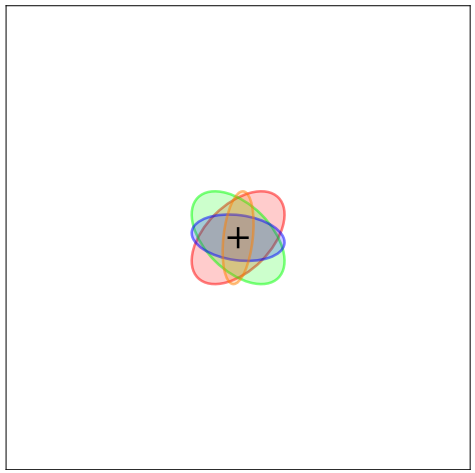
Stage IVa



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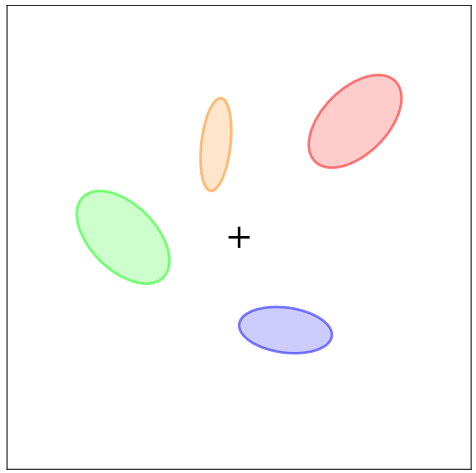
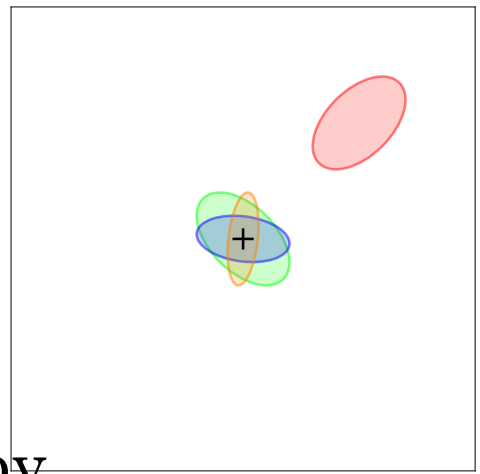


We need a new theory. Find it, then proceed to stage V for validation and refinement.

Stage IVc



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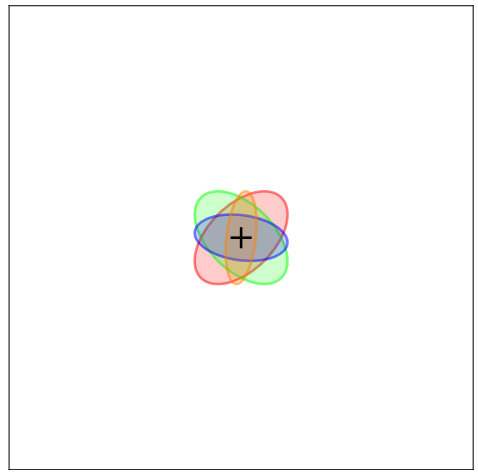
Stage IVa



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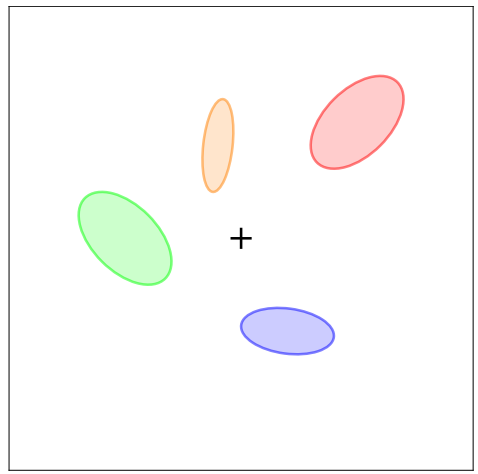

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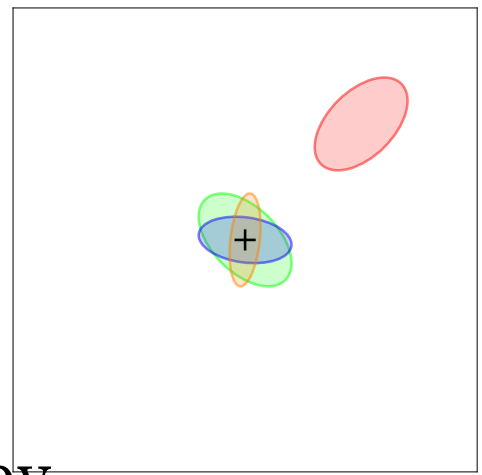

Do we really understand our systematics? Limited scope stage IV.5 to clarify picture.

David Kirkby

Growth distinguishes MG from "new stuff" DE