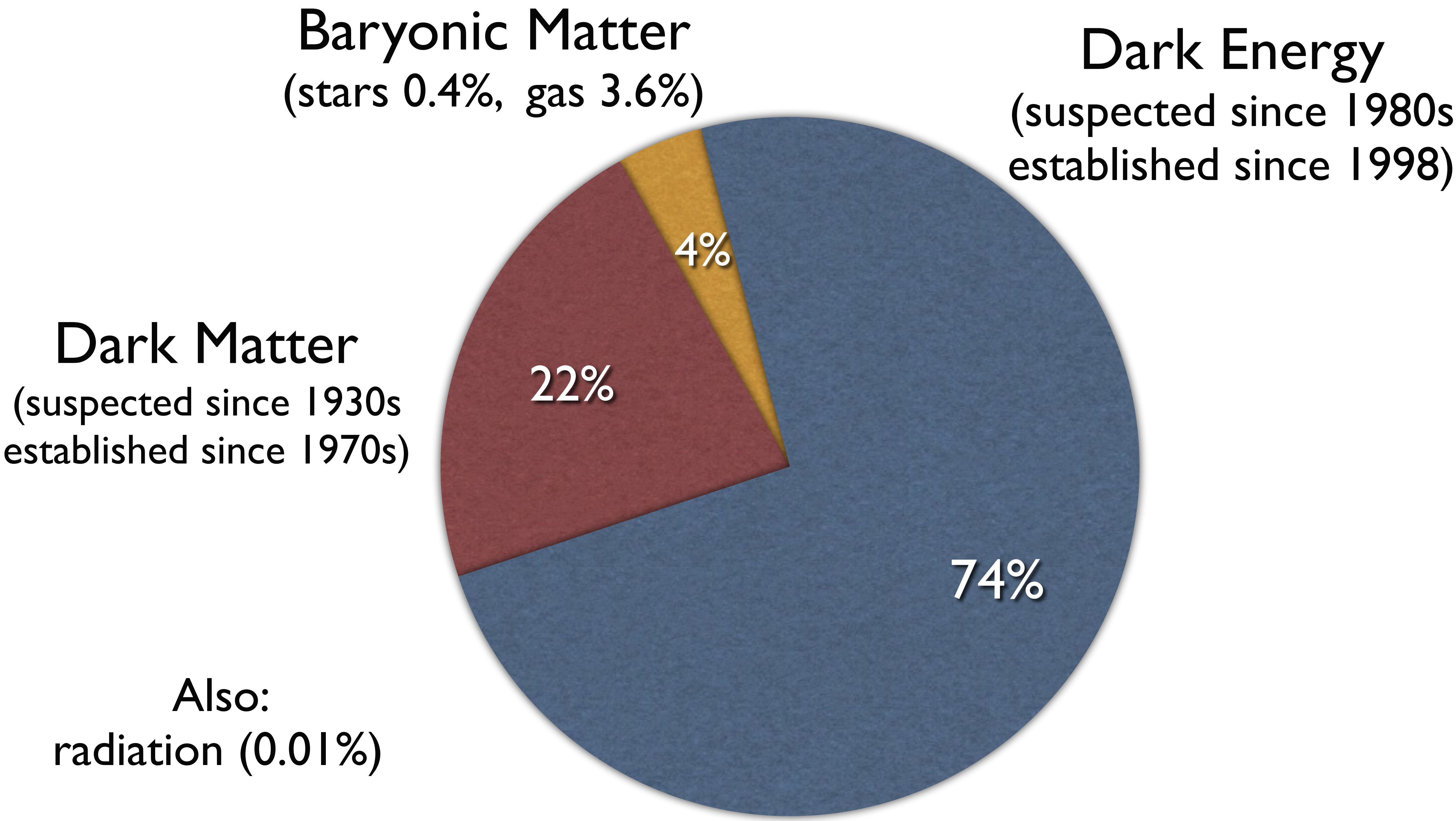
Dark Energy at the Crossroads

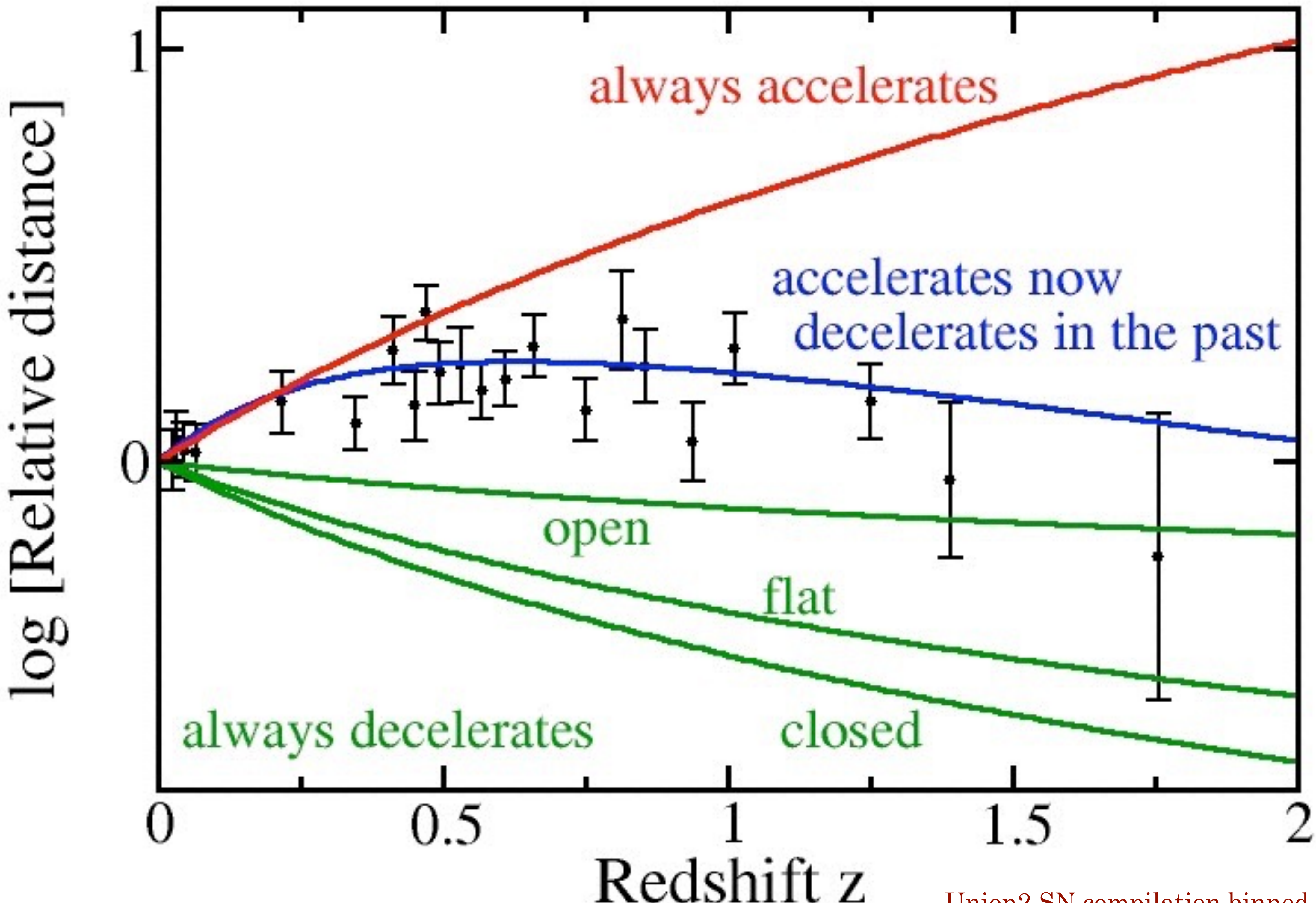
Dragan Huterer
Physics Department, University of Michigan

Key contributions from grad students:
Jessie Muir, Noah Weaverdyck (current)
Daniel Shafer, Eduardo Ruiz (former)

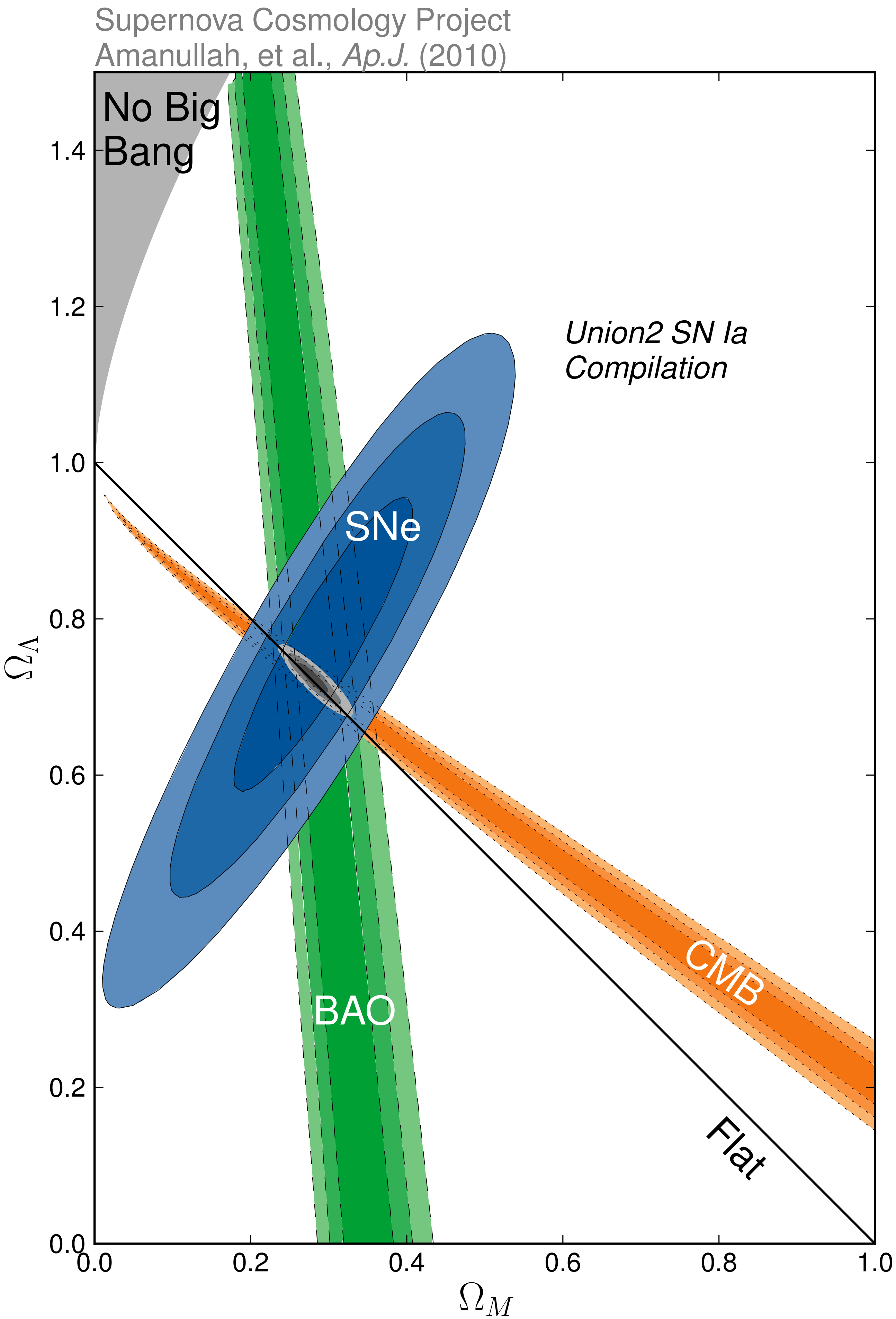
Makeup of universe today

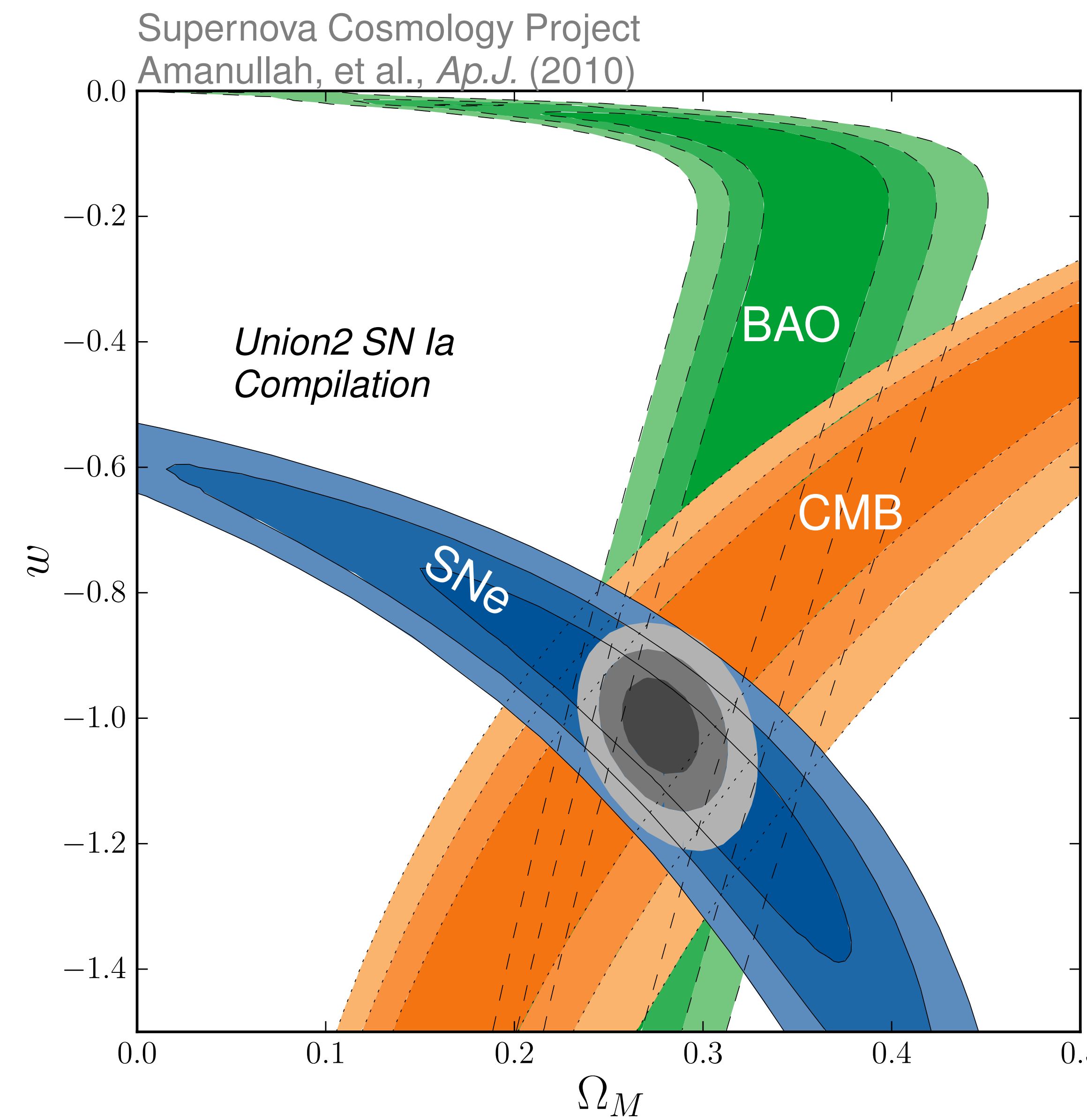


Evidence for Dark energy from type Ia Supernovae



Union2 SN compilation binned in redshift

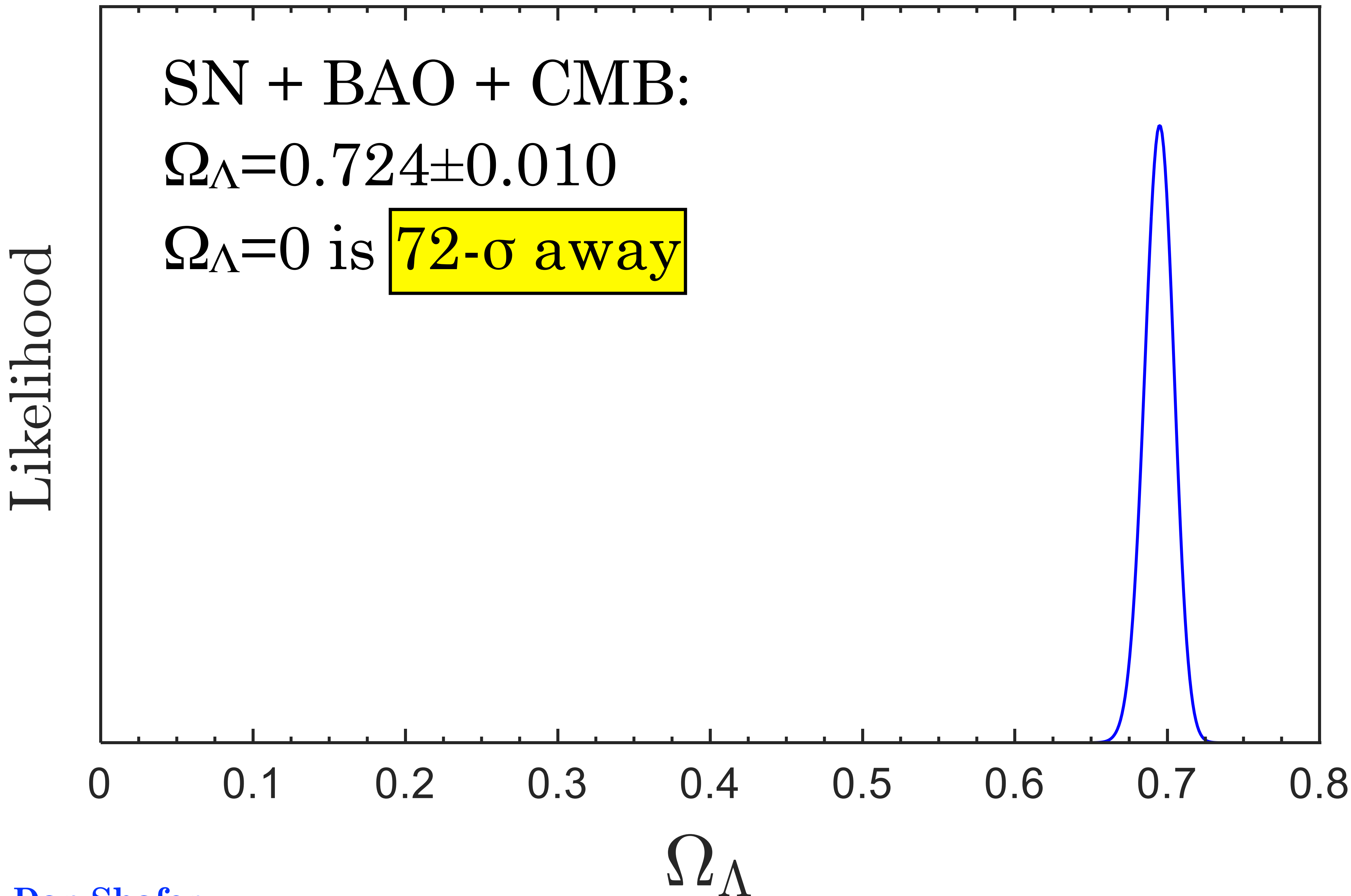




$$\Omega_{\rm DE} \equiv \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

$$w \equiv \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

Current evidence for dark energy is impressively strong



Dan Shafer

Fine Tuning Problem: "Why so small"?

Vacuum Energy: Quantum Field Theory predicts it to be determined by cutoff scale

$$\rho_{\rm VAC} = \frac{1}{2}\sum_{\rm fields} g_i \int_0^\infty \sqrt{k^2+m^2}\,\frac{d^3k}{(2\pi)^3} \simeq \sum_{\rm fields} \frac{g_i k_{\rm max}^4}{16\pi^2}$$

Measured: $(10^{-3}\mathrm{eV})^4$

SUSY scale: $(1\,\mathrm{TeV})^4$

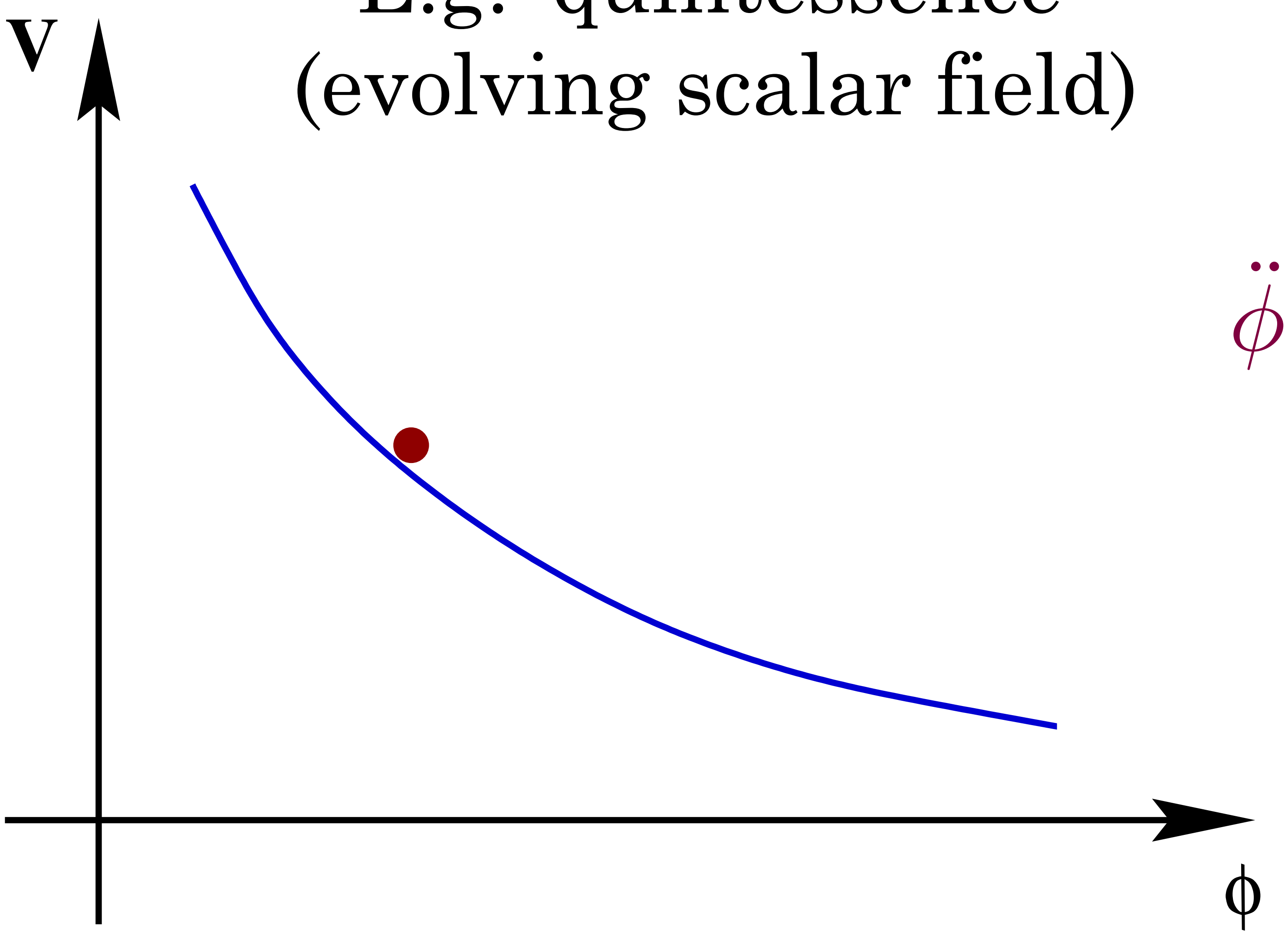
Planck scale: $(10^{19}\,\mathrm{GeV})^4$

60-120 orders of magnitude smaller than expected!

Lots of theoretical ideas, few compelling ones:

Very difficult to motivate DE **naturally**

E.g. ‘quintessence’
(evolving scalar field)



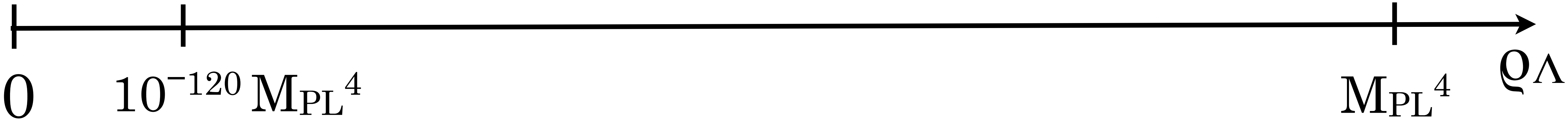
$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$$m_\phi \simeq H_0 \simeq 10^{-33}\ \mathrm{eV}$$

Ratra & Peebles, 1988
Zlatev, Wang & Steinhardt, 1999

String landscape?

⇒ A time of desperation?

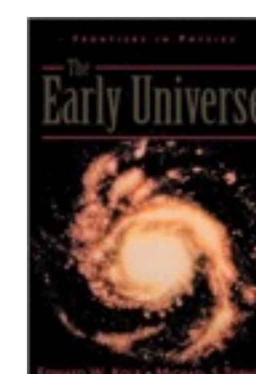


Among the ~10^{500} minima,

we live in one that allows structure/galaxies to form

(selection effect) (anthropic principle)

Landscape "predicts" the observed Ω_{DE}



Kolb & Turner, "Early Universe", footnote on p. 269:

"**It is not clear to one of the authors how a concept as lame as the "anthropic idea" was ever elevated to the status of a principle**"

A difficulty:

DE theory target accuracy, in e.g. w(z), not known *a priori*

Contrast this situation with:

1. Neutrino masses:

$$\left.\begin{array}{l}(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ \text{eV}^2 \\ (\Delta m^2)_{atm} \simeq 3\times10^{-3}\ \text{eV}^2\end{array}\right\} \quad \begin{array}{c}\sum m_i = 0.06\ \text{eV}^* \ \text{(normal)} \\ \text{vs.} \\ \sum m_i = 0.11\ \text{eV}^* \ \text{(inverted)}\end{array}$$

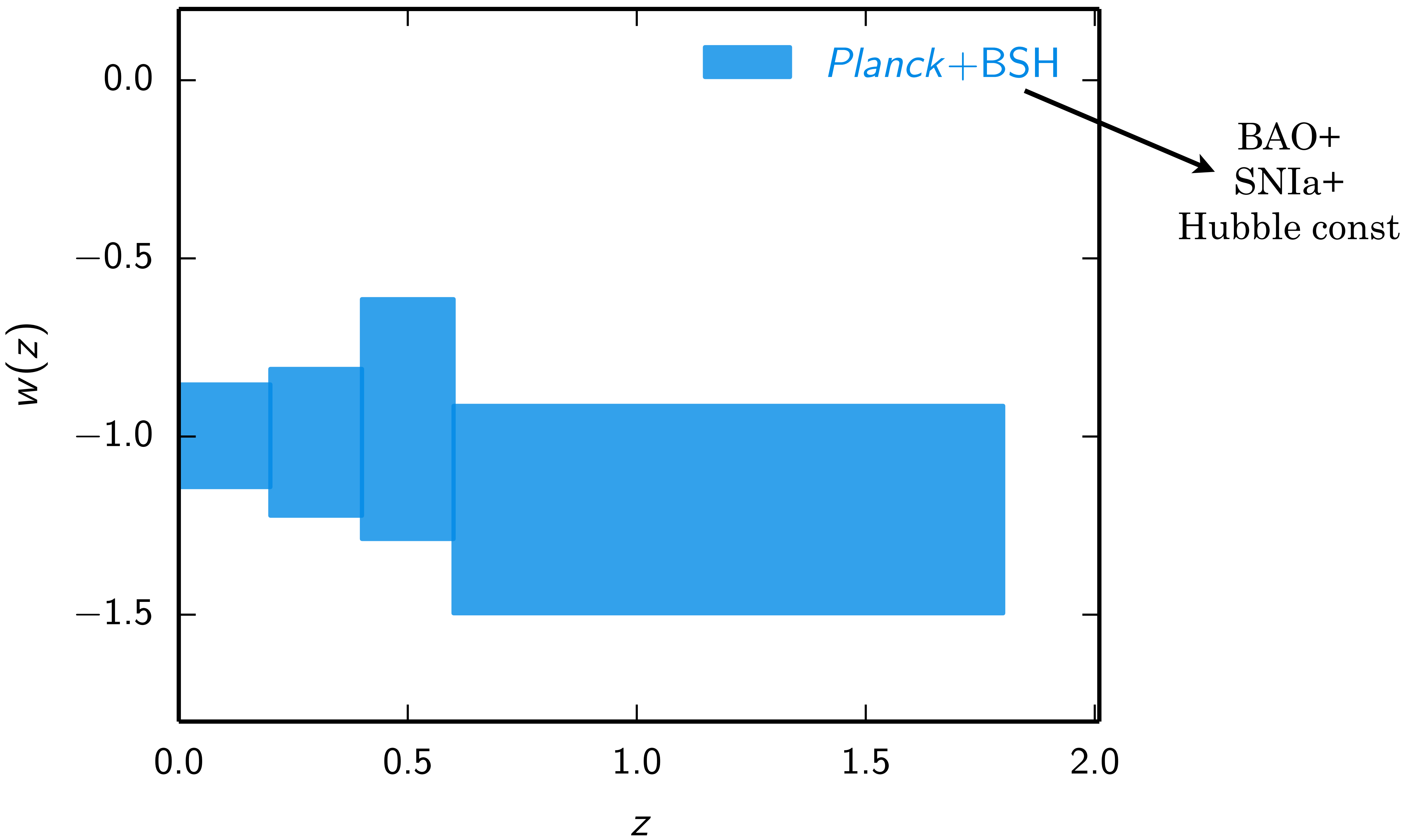
*(assuming $m_3=0$)

2. Higgs Boson mass (before LHC 2012):

$$m_H \lesssim O(200)\ \text{GeV}$$

(assuming Standard Model Higgs)

Current constraints on w(z):
largely from geometrical measures



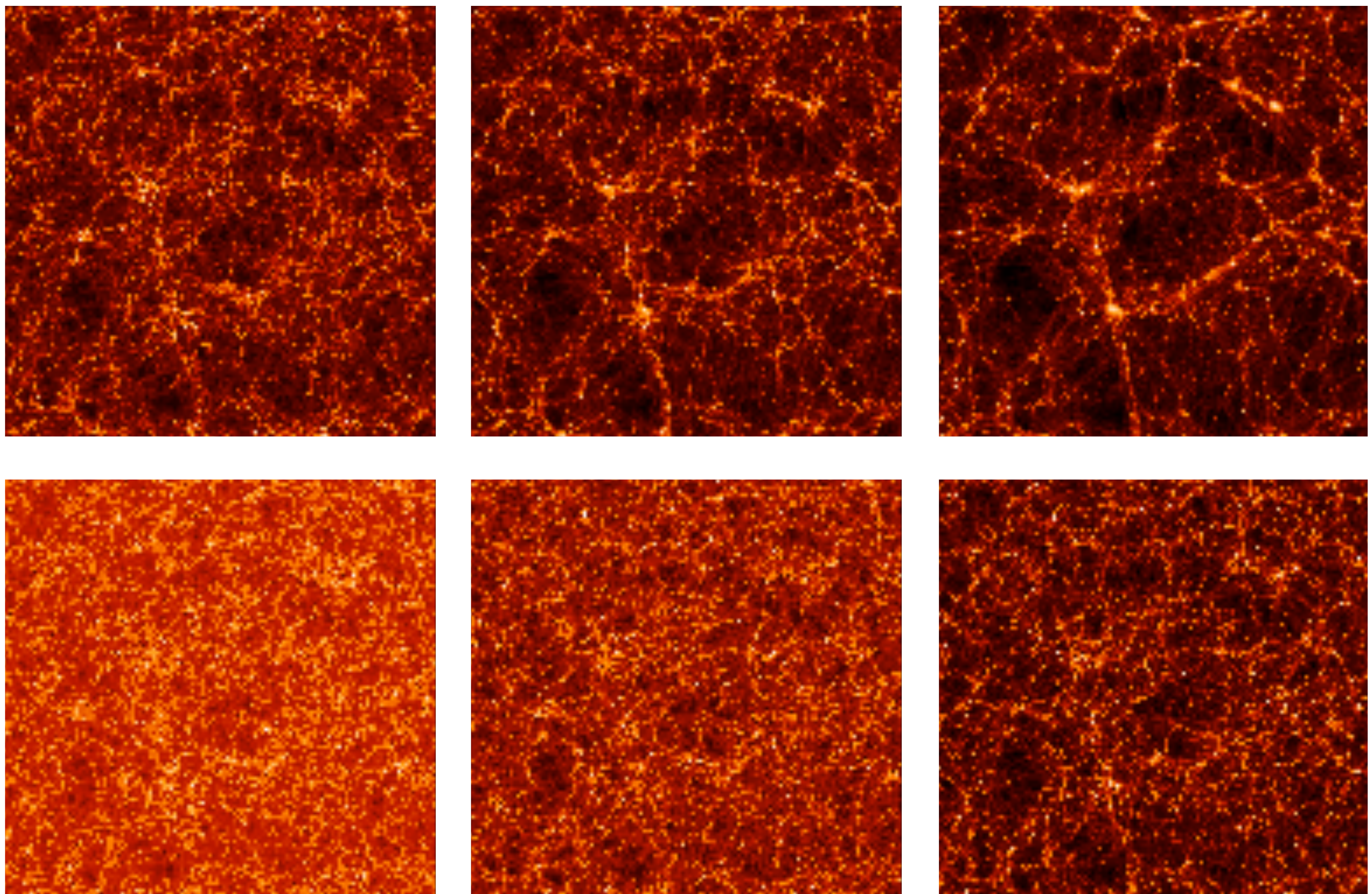
Planck XIV, "Dark Energy and Modified Gravity", arXiv:1502.01590

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



Huterer et al, Snowmass report, 1309.5385

The Virgo Consortium (1996)

Next Frontier: **Growth (+geom) from LSS**

	CMB	LSS
dimension	2D	3D
# modes	$\propto l_{max}^{2}$	$\propto k_{max}^{3}$
can slice in	λ only	λ, M, bias...
temporal evol.	no	yes
systematics?	relatively clean	relatively messy
theory modeling	easy	can be hard

Using growth to separate GR from MG:

For example:

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

↓ Modified gravity

↓ GR + dark energy

Growth of density fluctuations can decide:

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

(assuming GR)

Remainder of talk: three sets of dark energy tests with LSS

1. Separating growth from geometry using current data

2. Measuring covariance of peculiar velocities of nearby SN/gals to test LCDM

3. Blinding the DES analysis.

1. Separating geometry and growth

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$	—
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2}\, D_A(z_*)$	—
Cluster counts	$\frac{dV}{dz}$	$\frac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$	$P\left(k = \frac{\ell}{r(z)}\right)$
RSD	$F(z) \propto D_A(z) H(z)$	$f(z)\sigma_8(z)$

Ruiz & Huterer 2015

Idea: compare geometry and growth

see also: Wang, Hui, May & Haiman 2007

Our approach:

Double the standard DE parameter space

($\Omega_M = 1 - \Omega_{DE}$ and w):

$\Rightarrow \Omega_M^{geom}, w^{geom}$ $\Omega_M^{grow}, w^{grow}$

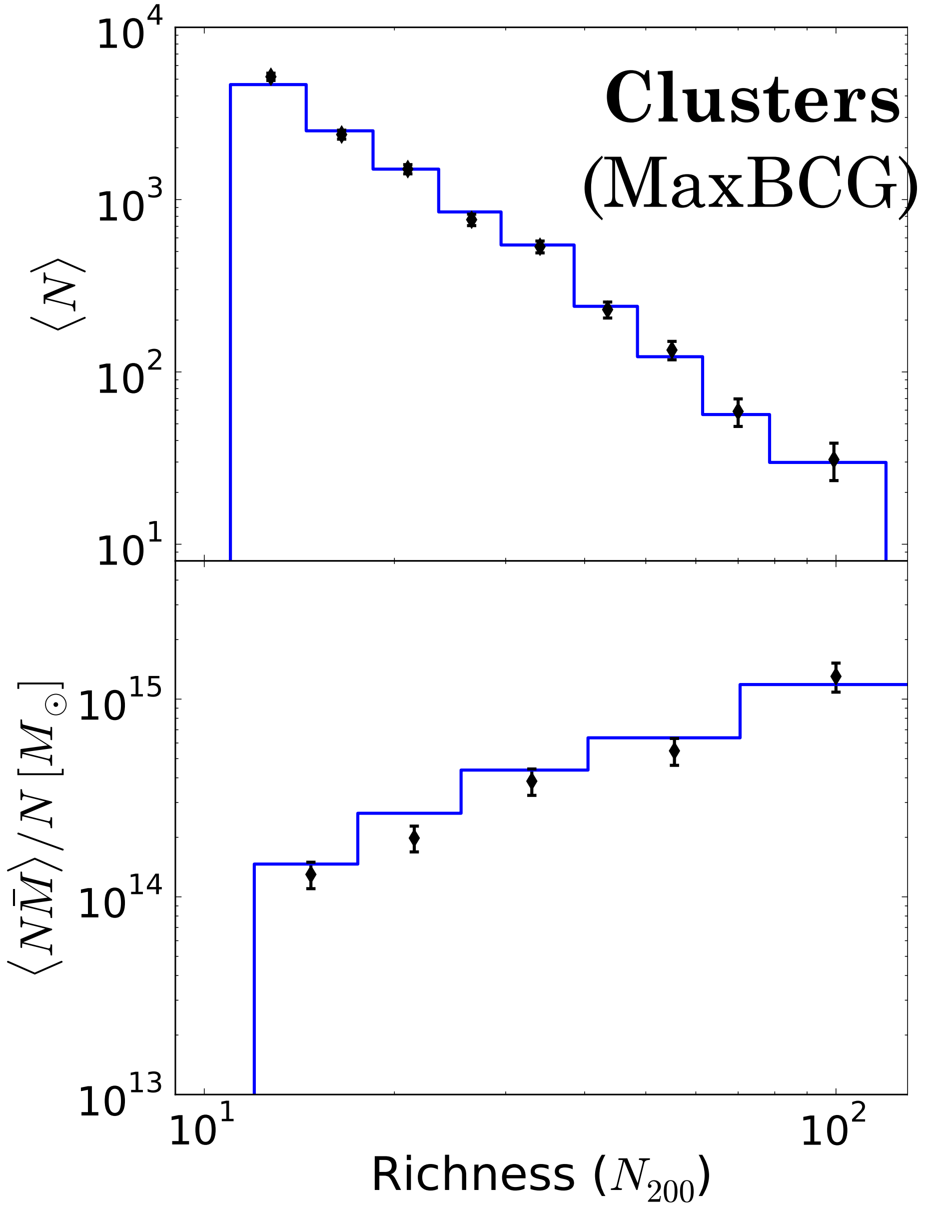
[In addition to other:

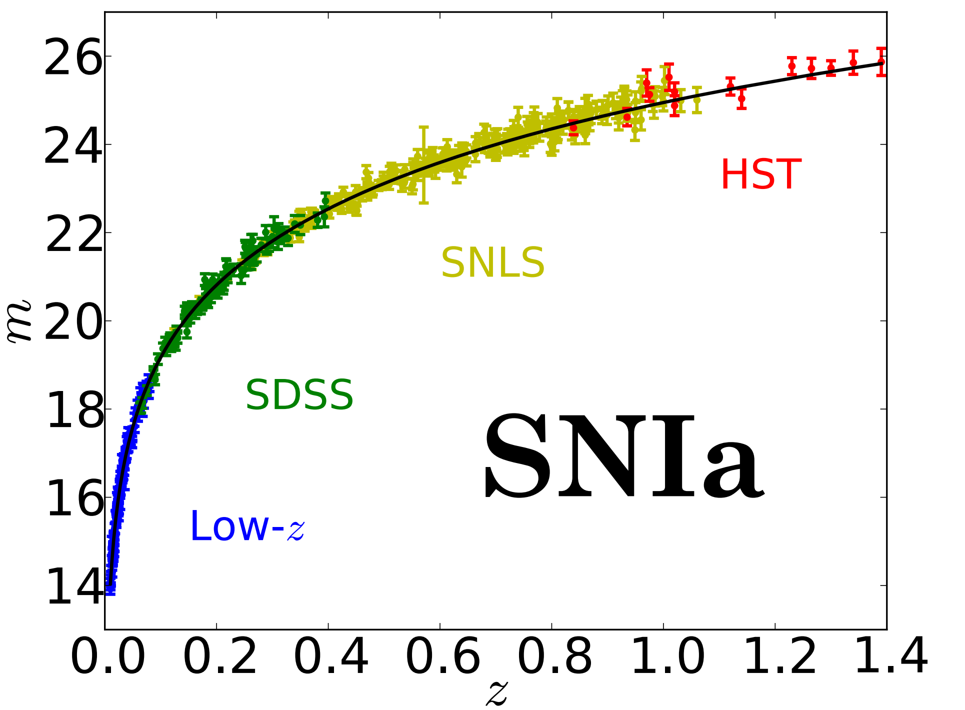
standard parameters: $\Omega_M h^2$ $\Omega_B h^2$, n_s, A)

nuisance parameters: probe-dependent]

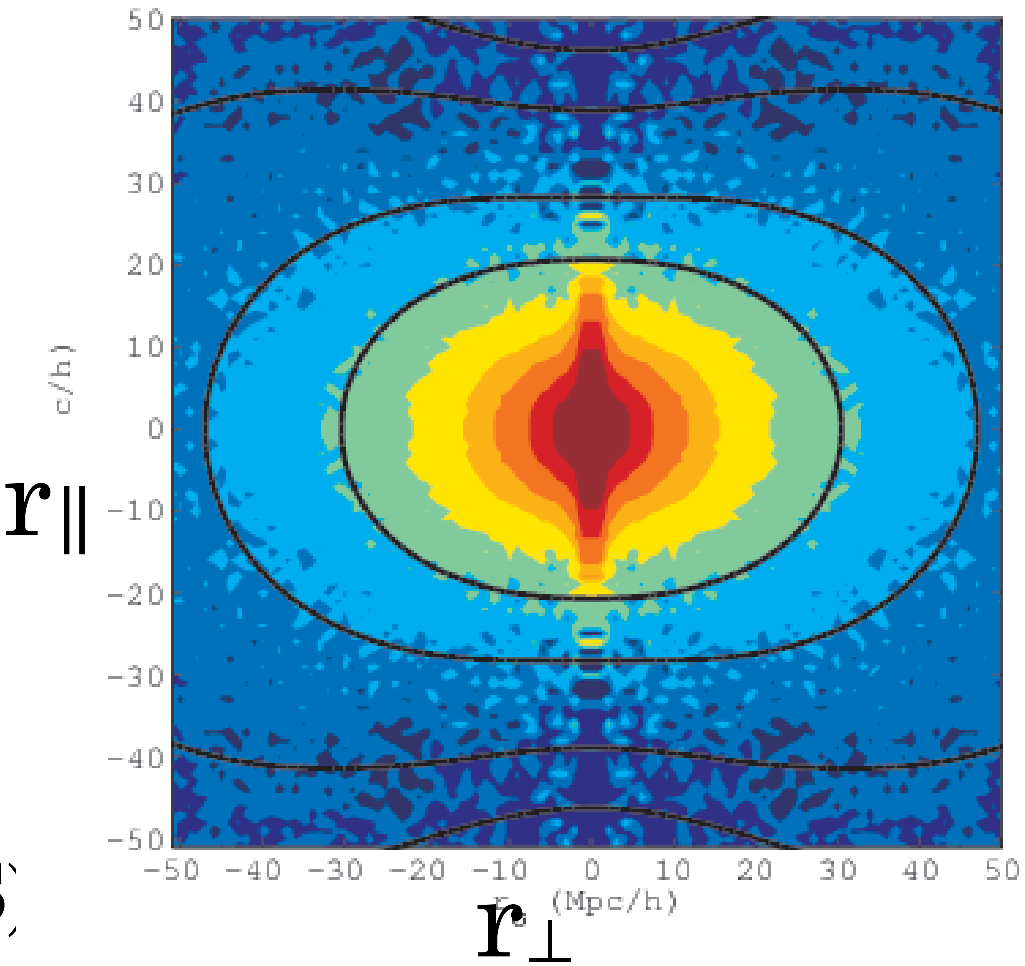
Ruiz & Huterer 2015

(Current) Data used





RSD

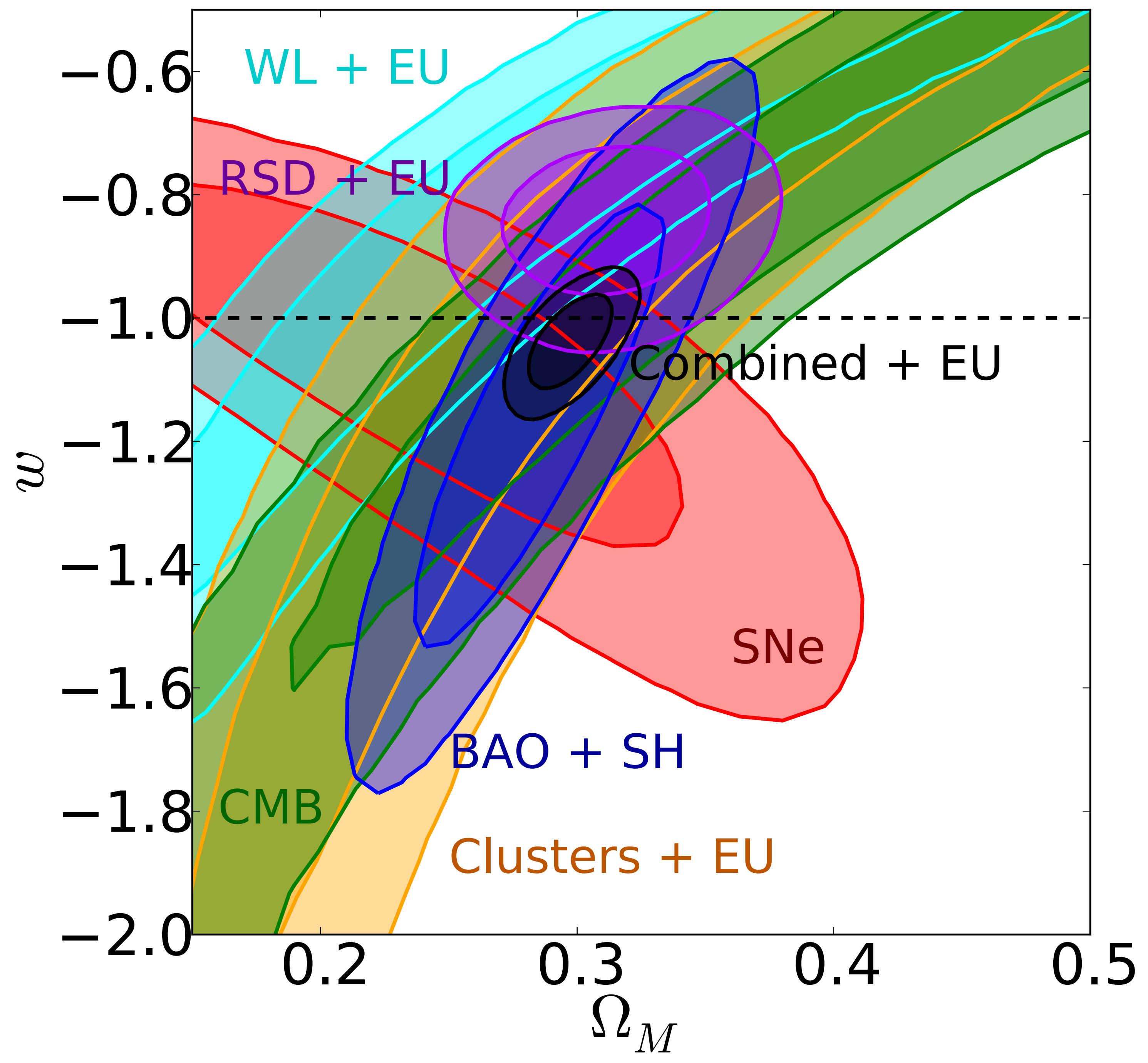


CMB (Planck peak location)

Weak Lensing (CFHTLens)

BAO (6dF, SDSS LRG, BOSS CMASS)

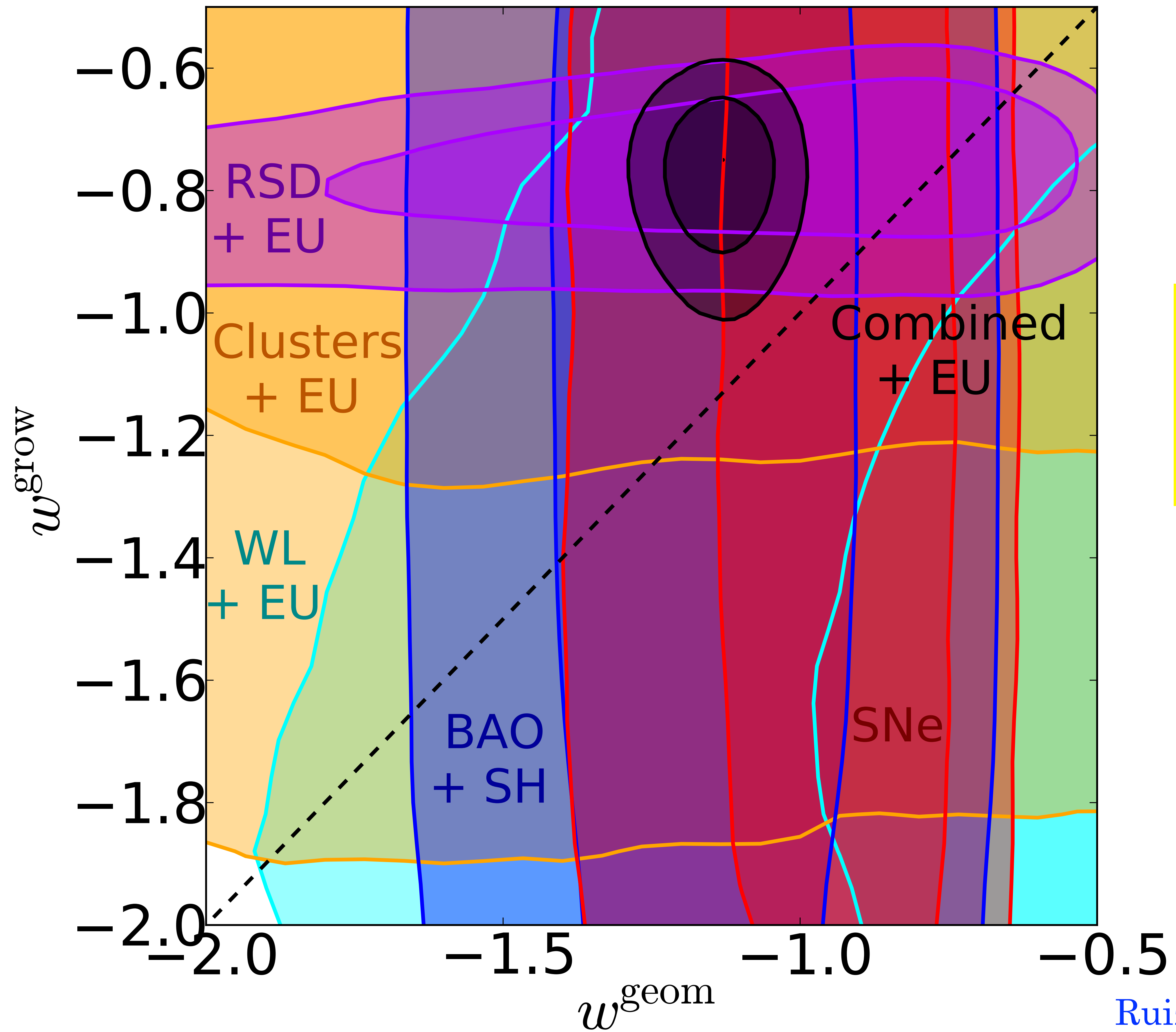
Standard parameter space



EU = Early Universe prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$, n_s, A)

SH = Sound Horizon prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$)

w (eq of state of DE): geometry vs. growth

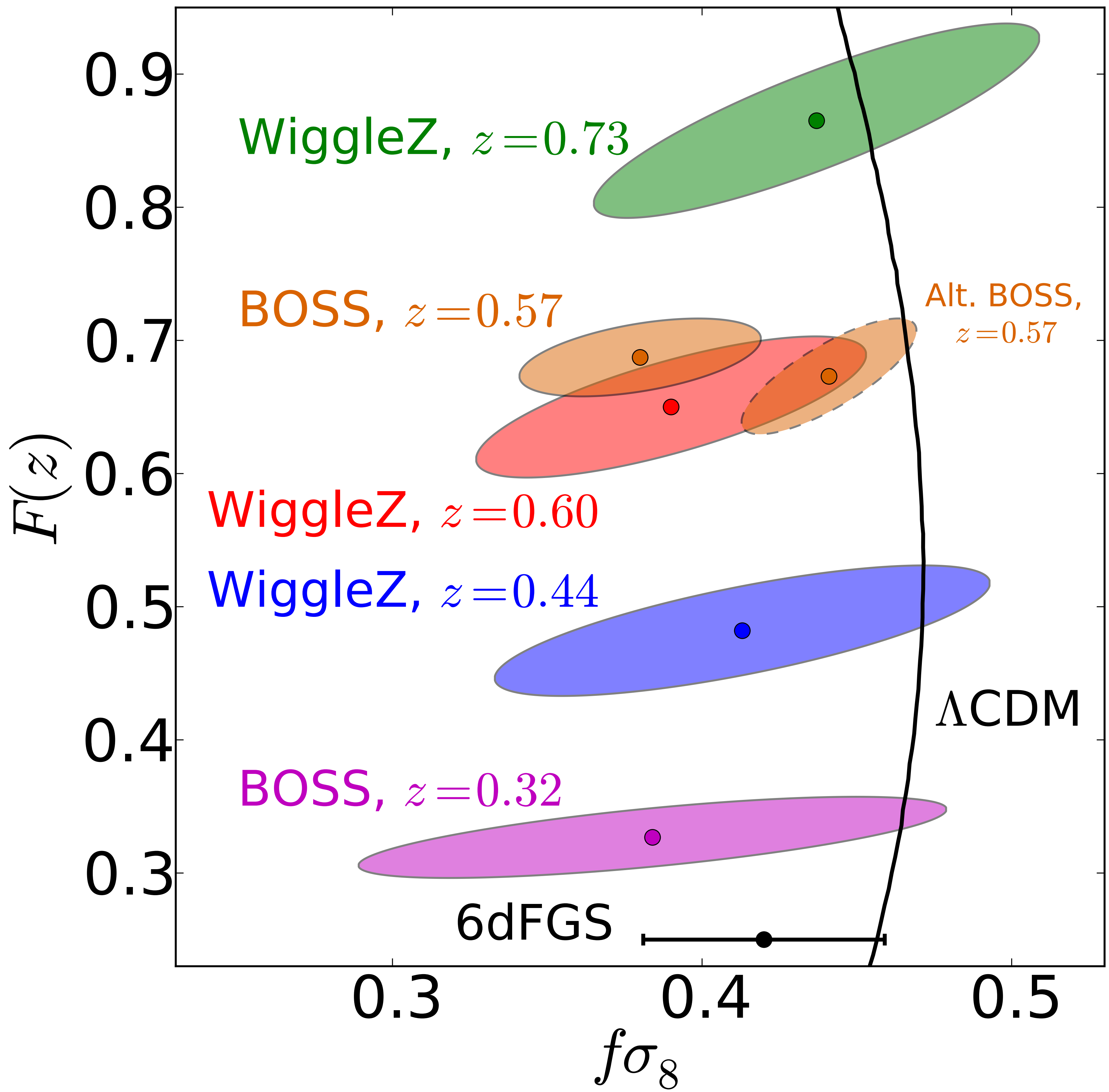


Evidence for $\mathrm{w}^{\rm grow} > \mathrm{w}^{\rm geom}$: 3.3-σ

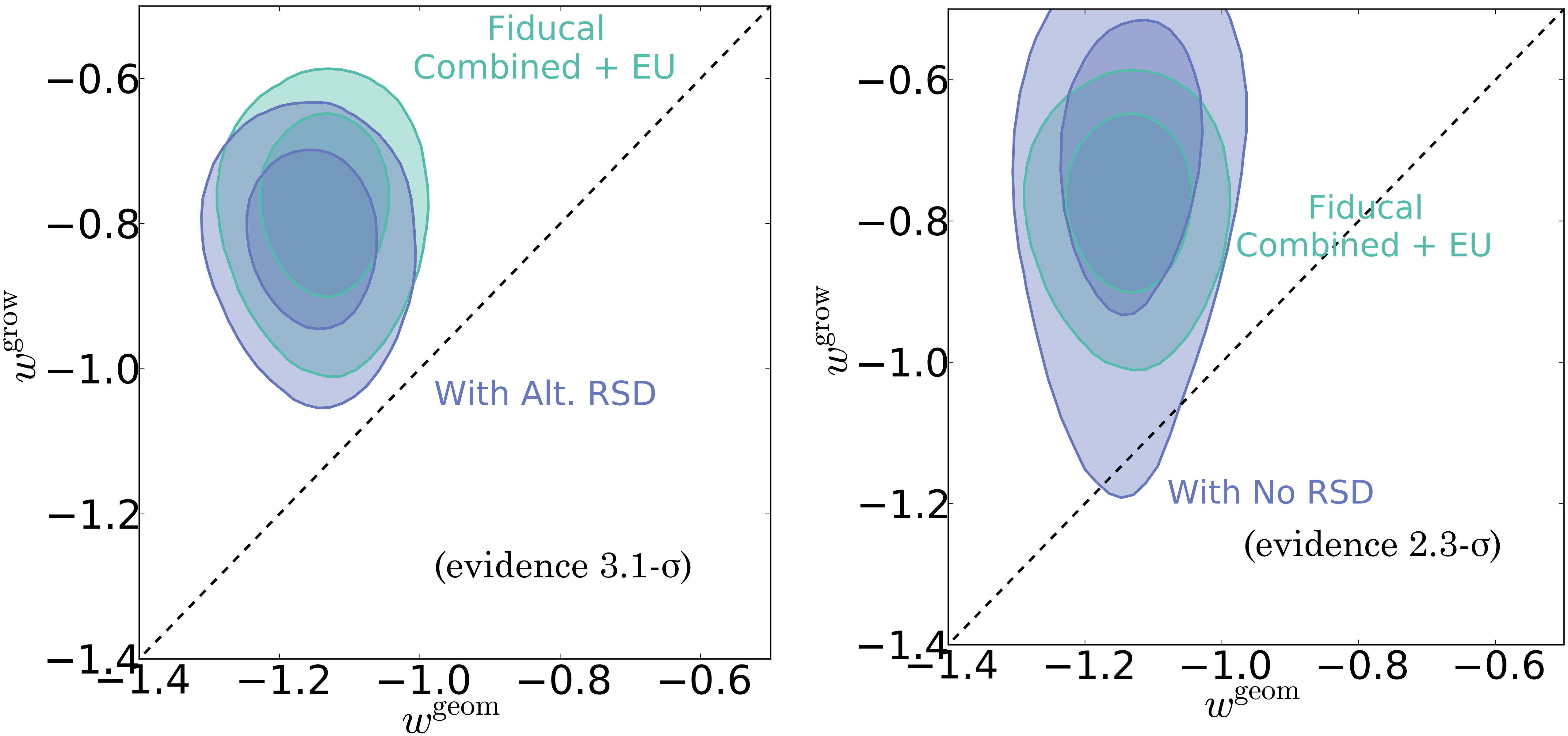
* SN not the recalibrated JLA compilation - need to update; will move $\mathrm{w}^{\rm geom}$ up

Ruiz & Huterer 2015

Redshift Space Distortion data



RSD prefer $w^{grow} > -1$ (slower growth than in LCDM)



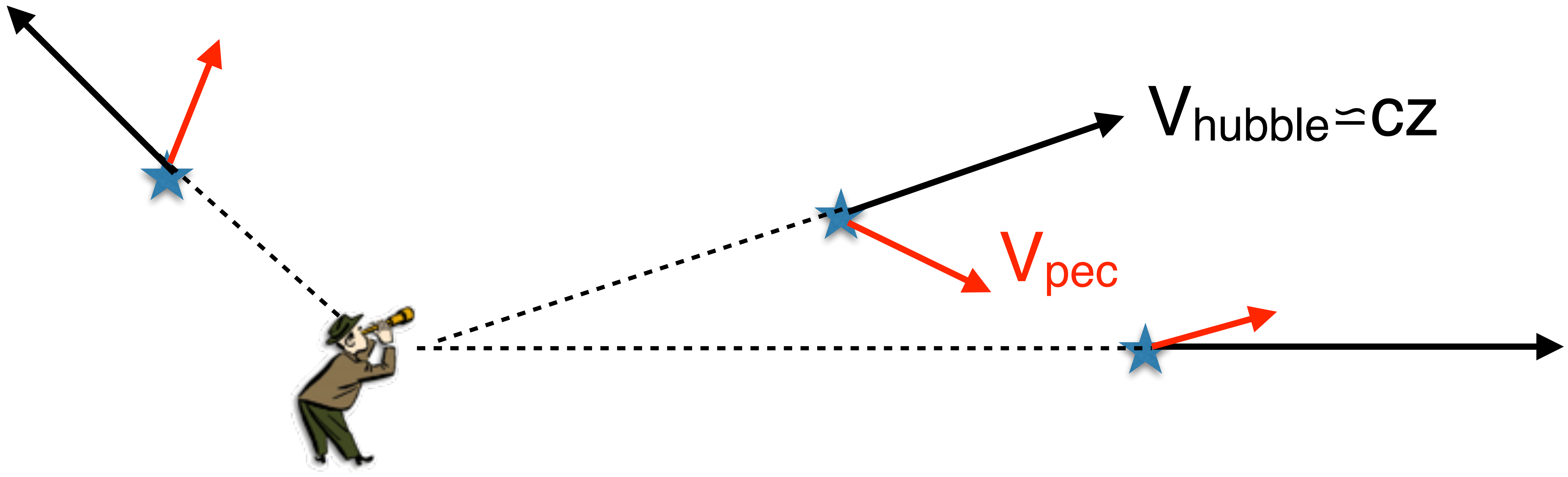
Therefore:
growth probes point to even less growth than LCDM with ~Planck parameters
(i.e. $w^{grow} > -1$)

(but the evidence is still not very strong...)

Probably equivalent to these recent findings:

- σ_8 from clusters is lower than that from CMB (eg. Chon & Bohringer, Hou et al, Bocquet et al, Costanzi et al)
- σ_8 from lensing is lower than that from CMB (eg. MacCrann et al)
- evidence for neutrino mass (eg. Beutler et al, Dvorkin et al)
- evidence for interactions in the dark energy sector (eg. Salvatelli et al)

2. Measuring peculiar velocities



$$z_{obs} = z + V_{pec,\parallel}/c$$

Typically:

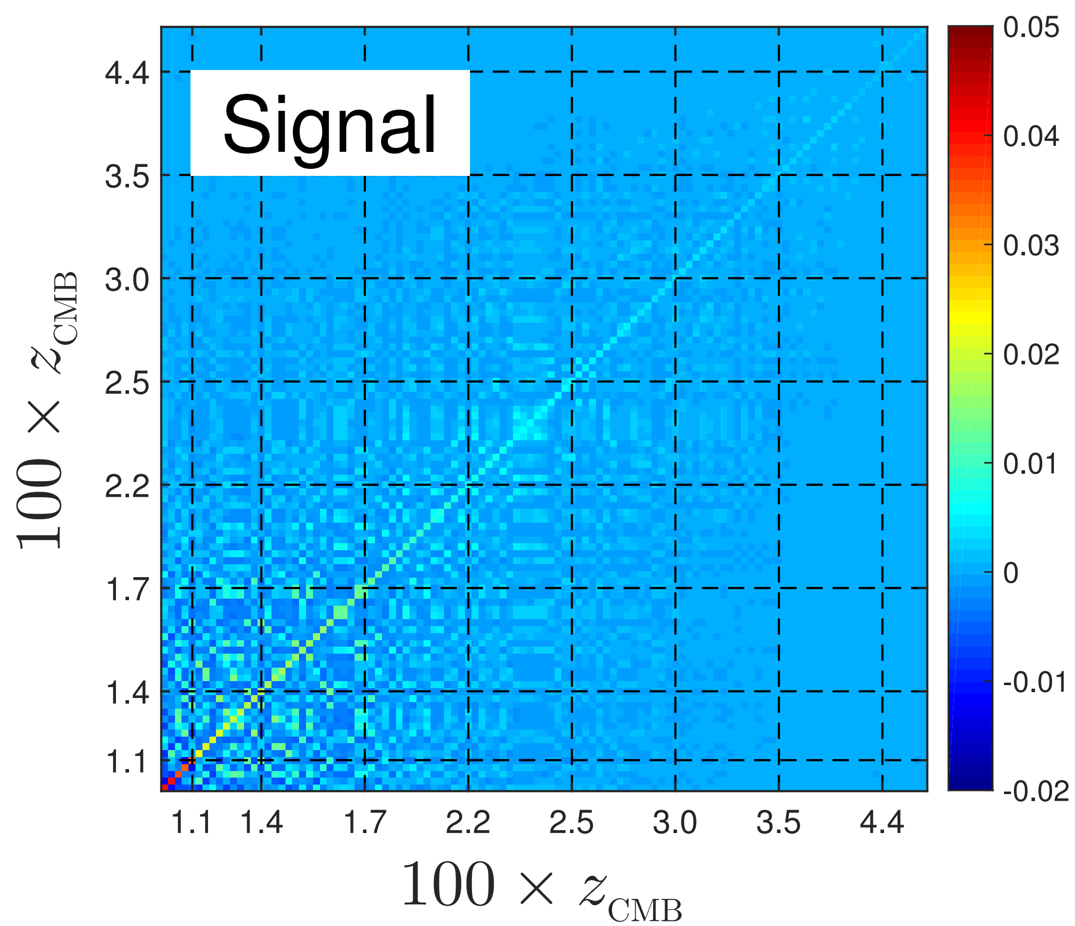
- measure z_{obs} directly (from spectrum)
- infer z from measured distance (e.g. standard candle or FP)
- $\Rightarrow$ infer $V_{pec,\parallel}$

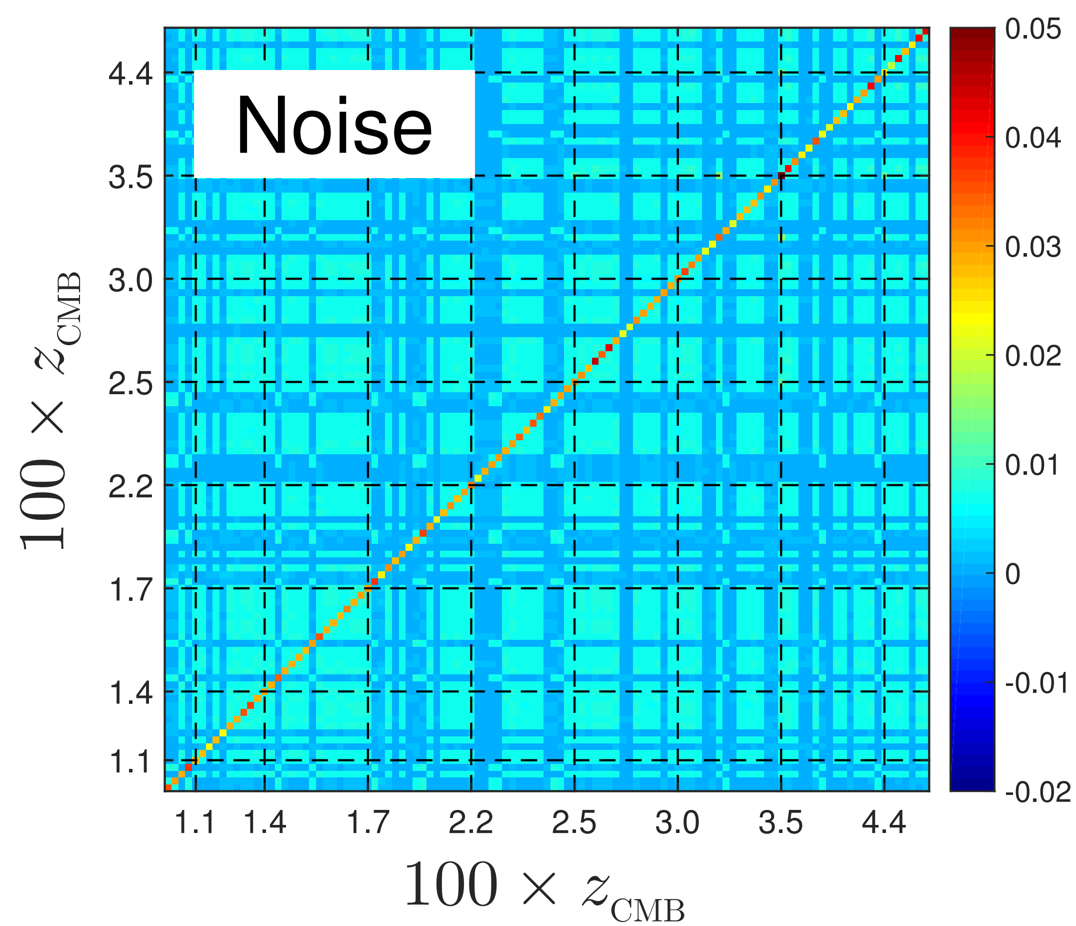
Signal and noise covariance

$$C_{ij} = S_{ij} + N_{ij}$$

$$S_{ij} \equiv \langle \delta m_i \, \delta m_j \rangle = \left[\frac{5}{\ln 10}\right]^2 \frac{(1+z_i)^2}{H(z_i) d_L(z_i)} \frac{(1+z_j)^2}{H(z_j) d_L(z_j)} \xi_{ij}$$

$$\xi_{ij} \equiv \langle (\mathbf{v}_i \cdot \hat{\mathbf{n}}_i)(\mathbf{v}_j \cdot \hat{\mathbf{n}}_j) \rangle = \frac{dD_i}{d\tau} \frac{dD_j}{d\tau} \int \frac{dk}{2\pi^2} P(k, a=1) \sum_\ell (2\ell+1) j'_\ell(k\chi_i) j'_\ell(k\chi_j) P_\ell(\hat{\mathbf{n}}_i \cdot \hat{\mathbf{n}}_j)$$





Using v_{pec} to test cosmology

This is a mature subject Kaiser 1989, Gorski et al 1989, Willick & Strauss 1995, Hui & Greene 2005, Watkins et al 2012,…

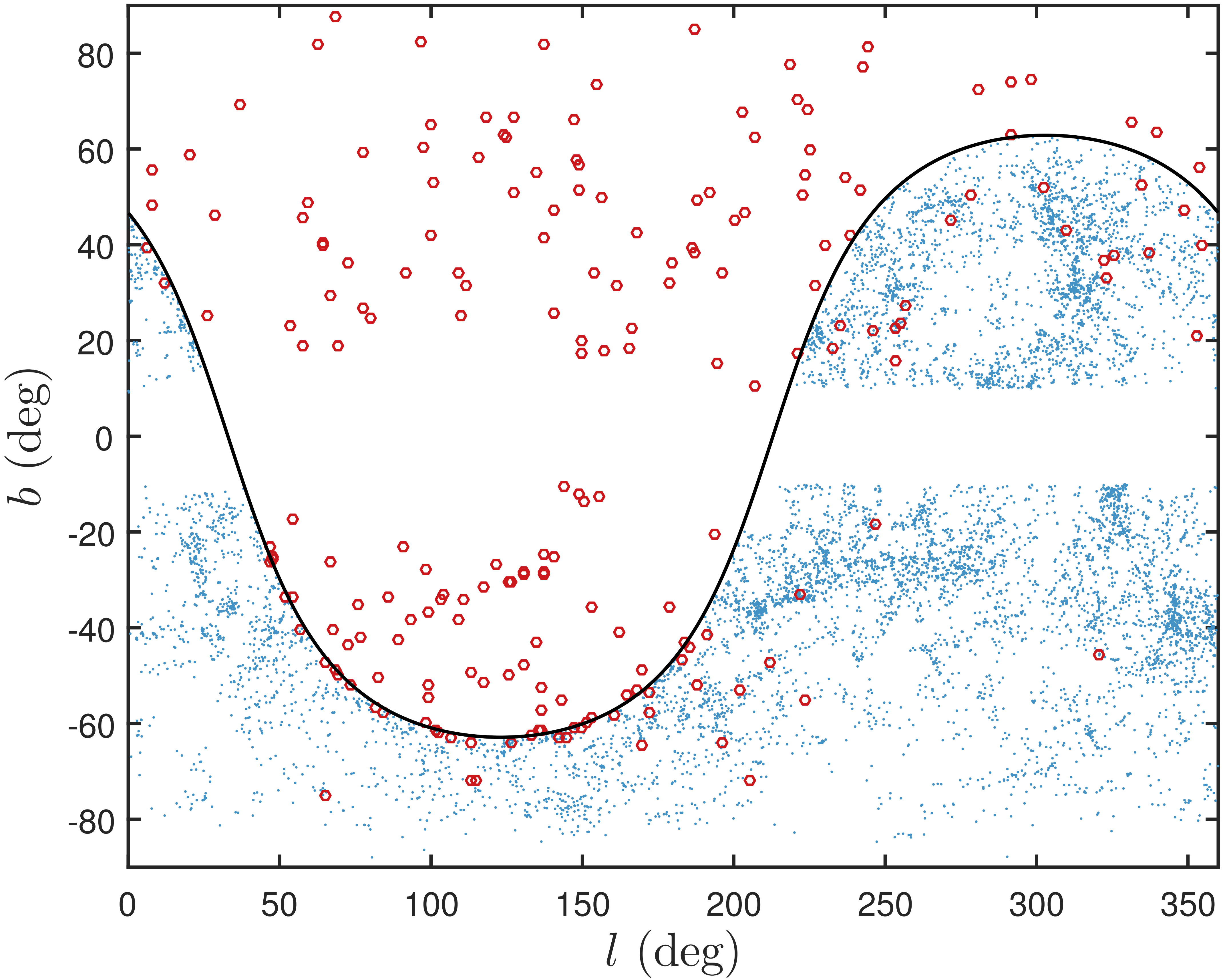
Our contribution:

- Significantly **streamlined and simplified** analysis/likelihood approach
- Using **best SN sample to date** (Supercal; 208 objects at $z<0.1$): all objects fitted and calibrated using the same technology (Scolnic et al 2015)
- Analysis is **robust**: we marginalize over systematic parameters, check alternate assumptions in fits. [Note: systematics *still* a concern.]

Huterer, Shafer & Schmidt, JCAP, 2016

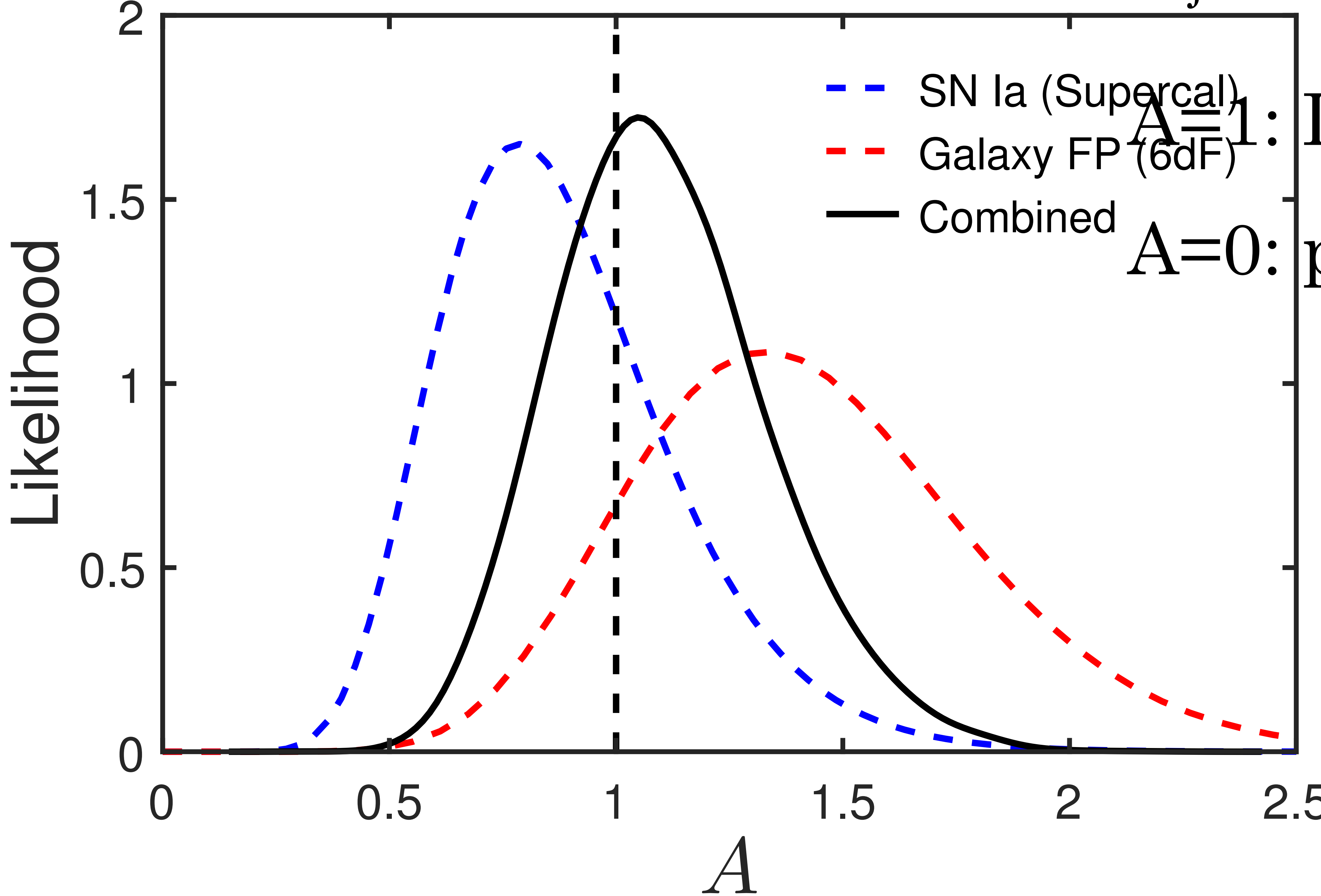
Huterer, Shafer, Scolnic & Schmidt, on arXiv soon

Supercal SNe and 6dF galaxies



Do the SN and galaxy data prefer signal covariance?

$$C_{ij} = AS_{ij} + N_{ij}$$



A=1: LCDM

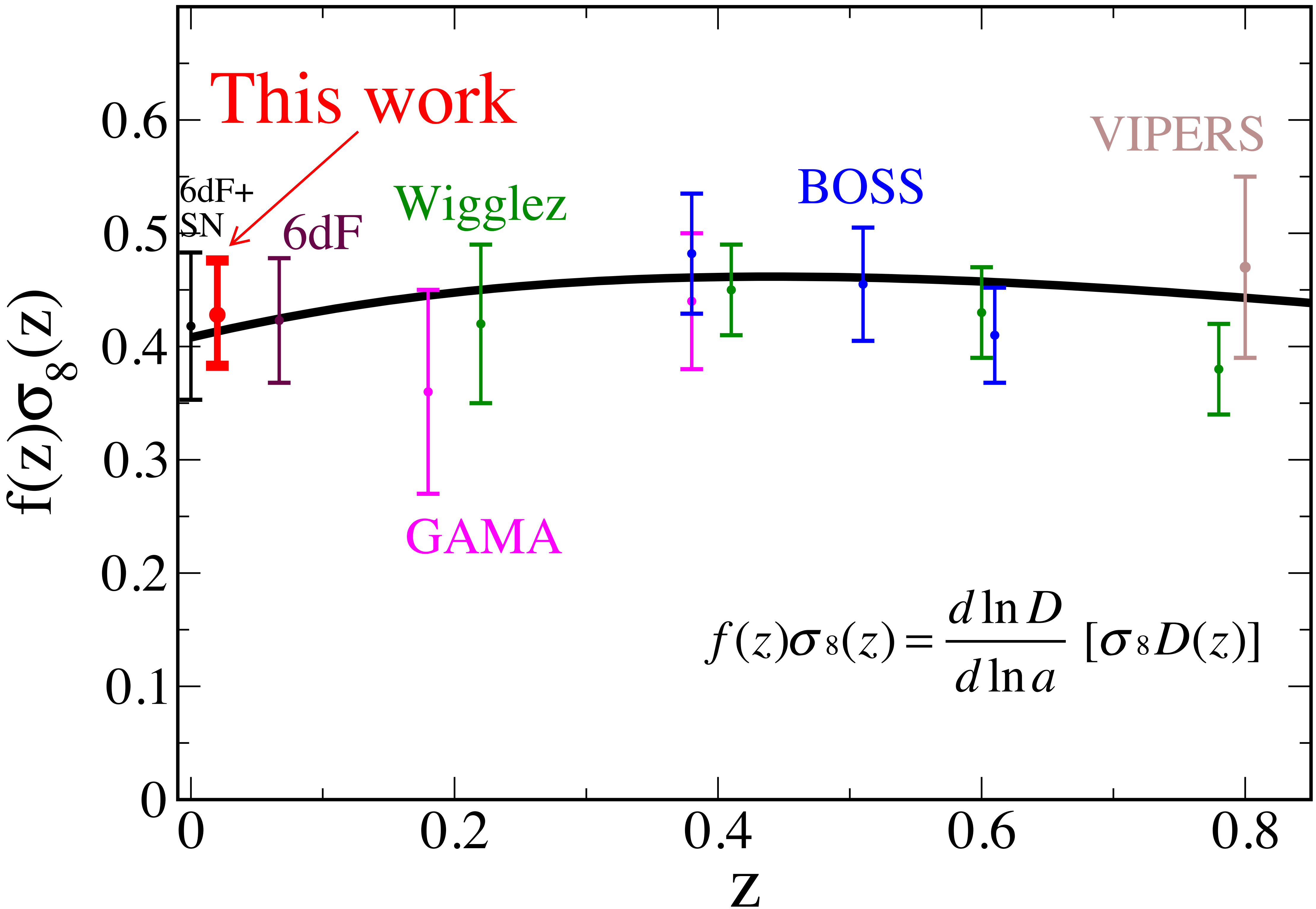
A=0: pure noise

11-σ detection of covariances; $A=1.05^{+0.25}_{-0.21}$

Huterer, Shafer, Scolnic & Schmidt, on arXiv soon

Equivalently, we have a 11% meas. of fσ8

$$f\sigma_8 = 0.428^{+0.048}_{-0.045}$$ @ z≃0.02



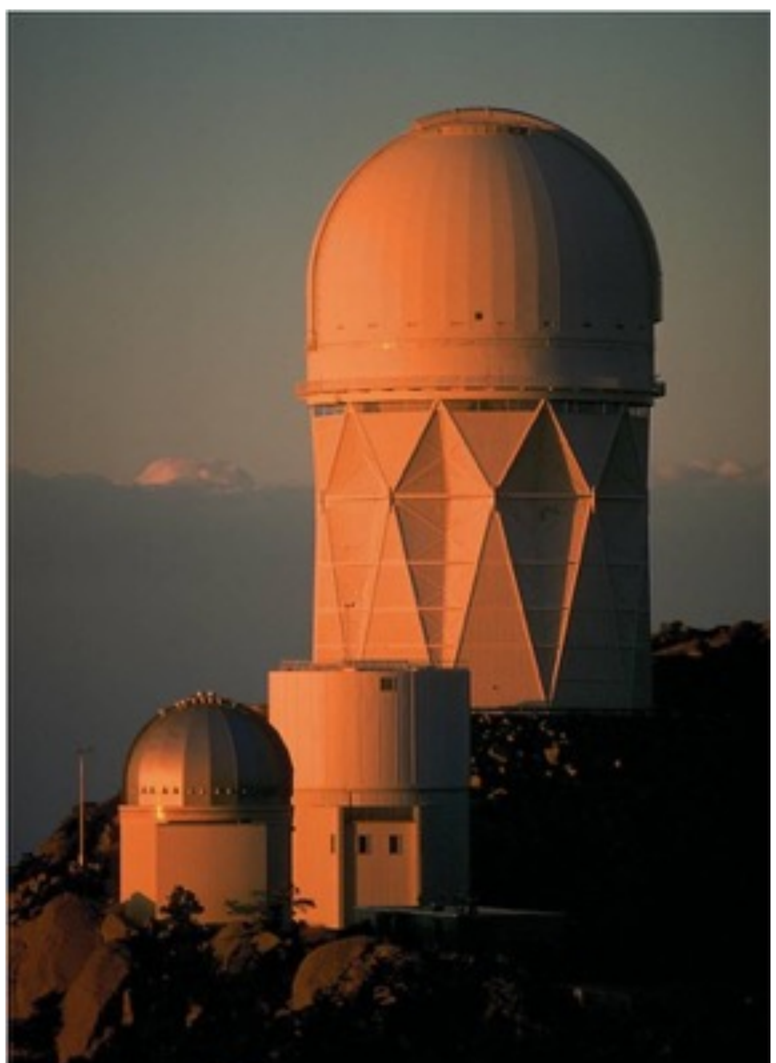
Ongoing or upcoming DE experiments:

- **Ground photometric:**
  - Dark Energy Survey (DES)
  - Pan-STARRS
  - Hyper Suprime Cam (HSC)
  - Large Synoptic Survey Telescope (LSST)
- **Ground spectroscopic:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Prime Focus Spectrograph (PFS)
  - Dark Energy Spectroscopic Instrument (DESI)
- **Space:**
  - Euclid
  - Wide Field InfraRed Space Telescope (WFIRST)

Blanco telescope at Cerro Tololo, Chile

Dark Energy Survey (DES)

Imaging survey over 5000 sq deg



Mayall telescope at Kitt Peak, Arizona

Dark Energy Spectroscopic Instr. (DESI)

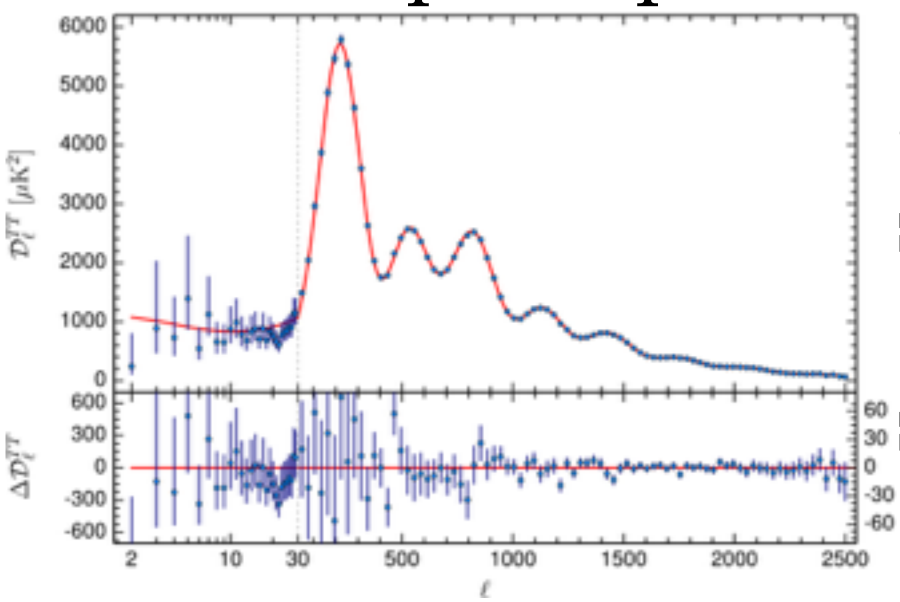
Spectroscopic survey over 15,000 sq deg

Story so far:

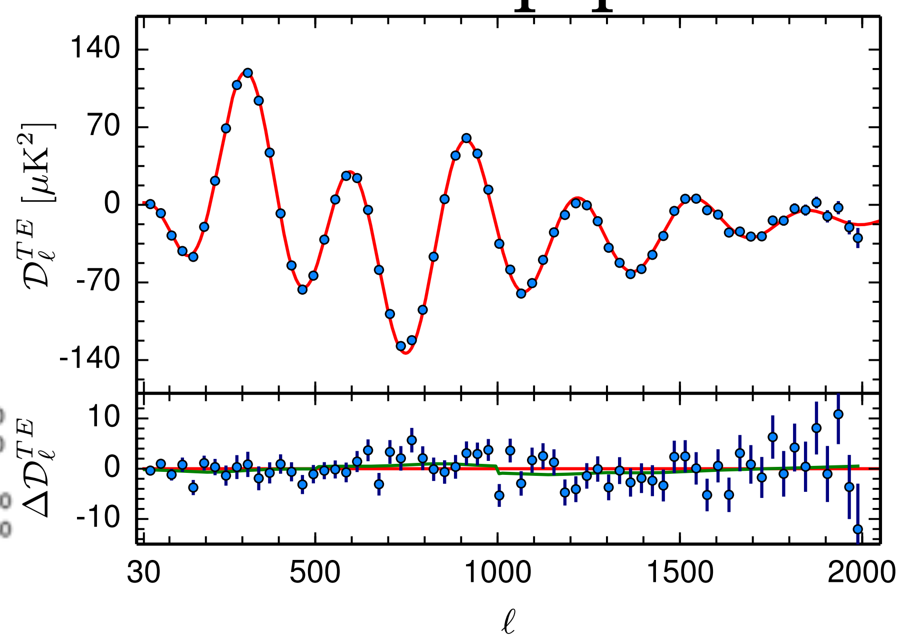
- Dark energy measurements definitely in the precision regime - impressive constraints…
- …but the really big questions (nature of DE) unanswered
- Potential to improve constraints from upcoming surveys

But are Planck++ constraints *so* good that they bias us?

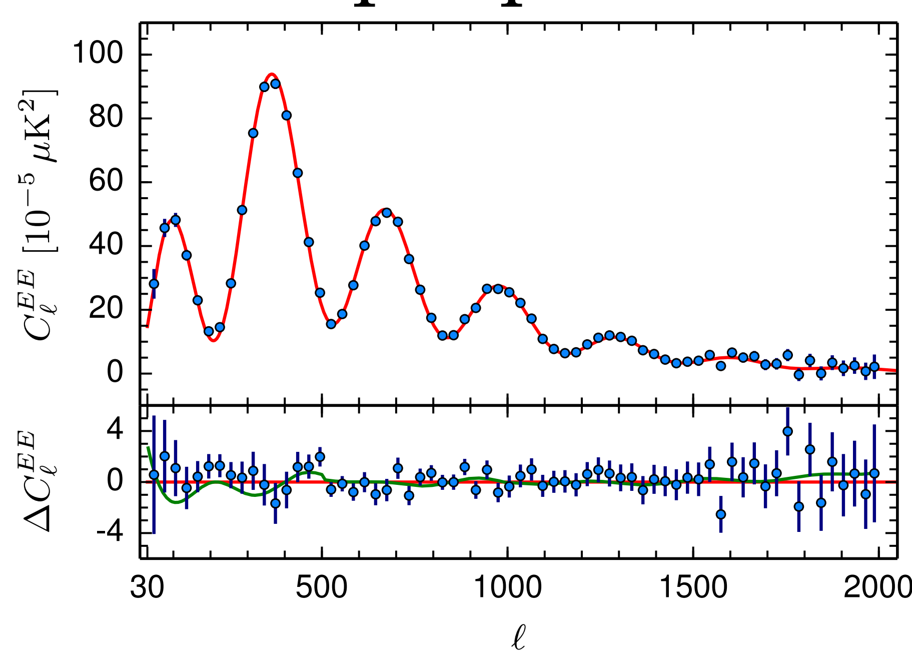
temp-temp



temp-pol



pol-pol



Danger of declaring currently favored model to be the truth

$\Longrightarrow$ **blinding new data is key**

3. Blinding the DES analysis

Muir, Elsner, Bernstein,
Huterer, Peiris and DES collab.

Our requirements:

- Preserve inter-consistency of cosmological probes
- Preserve ability to test for systematic errors

Our choice is specifically:

$$\xi_{ij}^{\text{blinded}}(k) = \xi_{ij}^{\text{measured}}(k) \left[\frac{\xi_{ij}^{\text{model 1}}(k)}{\xi_{ij}^{\text{model 2}}(k)} \right]$$

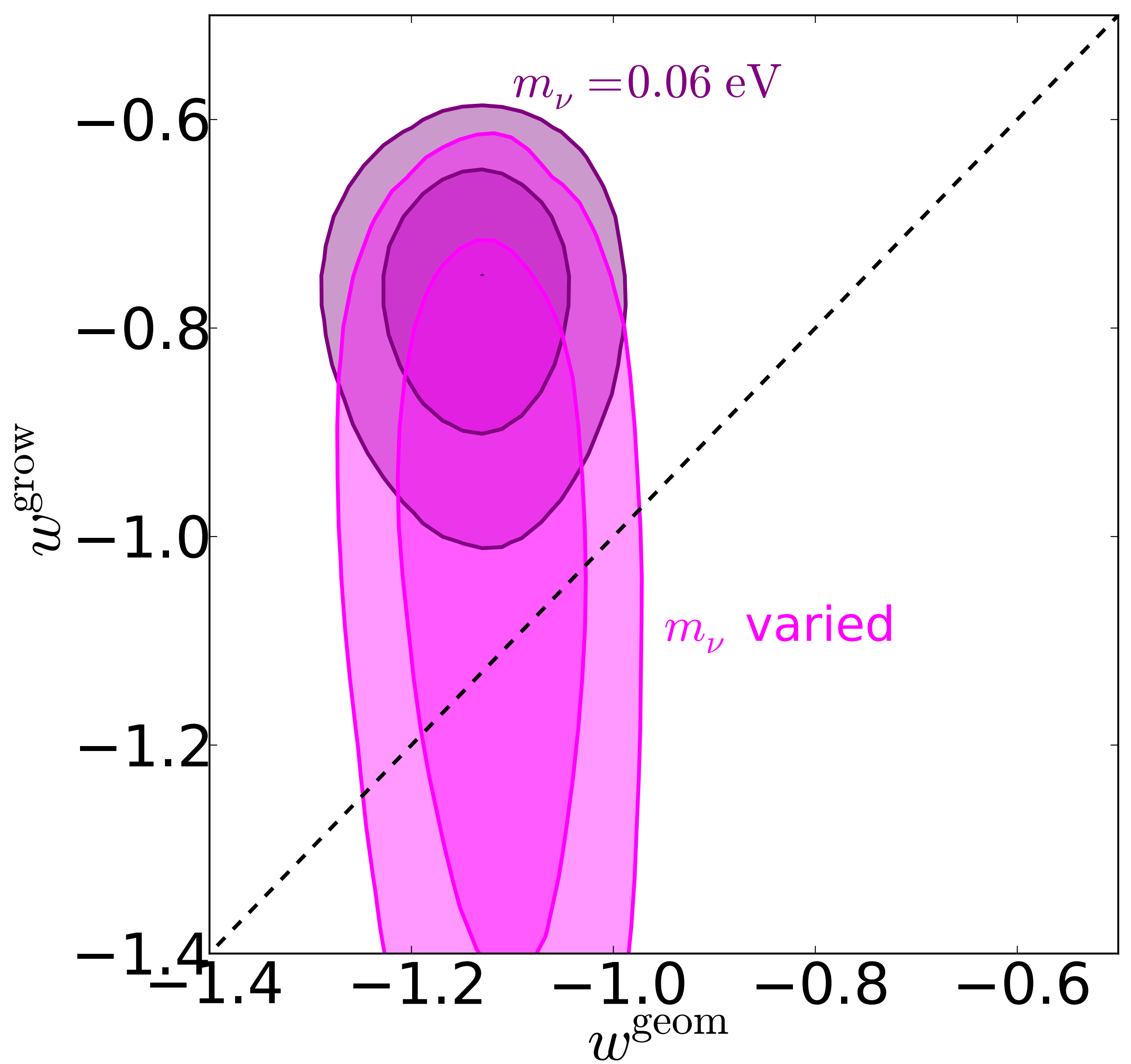
Tests passed, black-box code ready.
First application expected for clustering measurements in DES year-3 data.

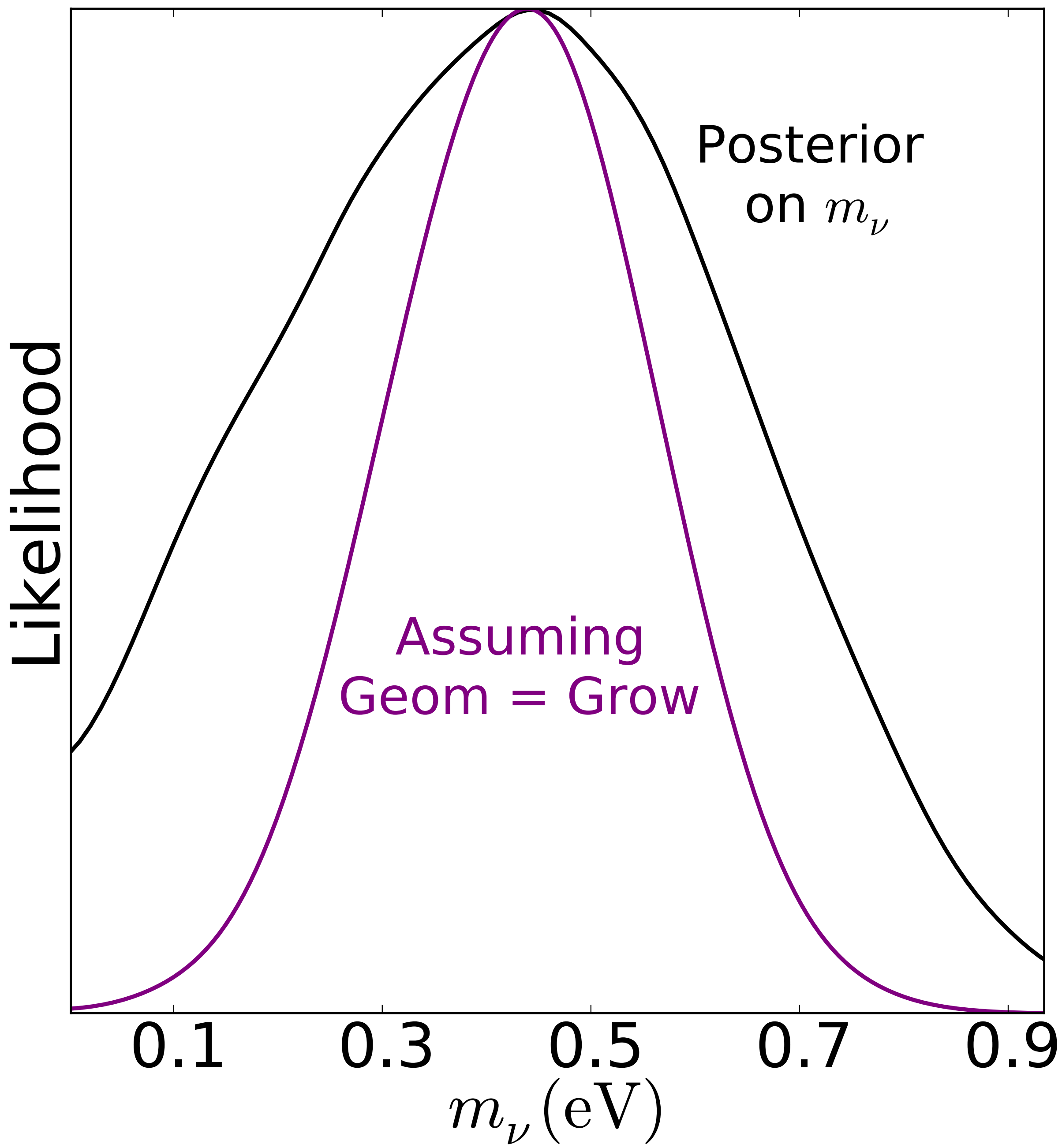
Conclusions

- Huge variety of new observations probing dark energy, particularly with the large-scale structure
- Current status of DE: excellent consistency with Lambda
- Blinding in analysis (along with sophisticated statistical tools + systematics control) will be key
- Like particle physicists, we would really like to see some "bumps" in the data
- In that regard, **internal consistency tests with data** (e.g. geometry/growth split) can help

EXTRA SLIDES

(Pretty high) neutrino mass can relieve the tension





Ruiz & Huterer, arXiv:1410.5832

Likelihood

"Admixture" of signal: C = AS+N

Excess (on top of LCDM) bulk vel.

LCDM predicts: A=1, v_{bulk}=0

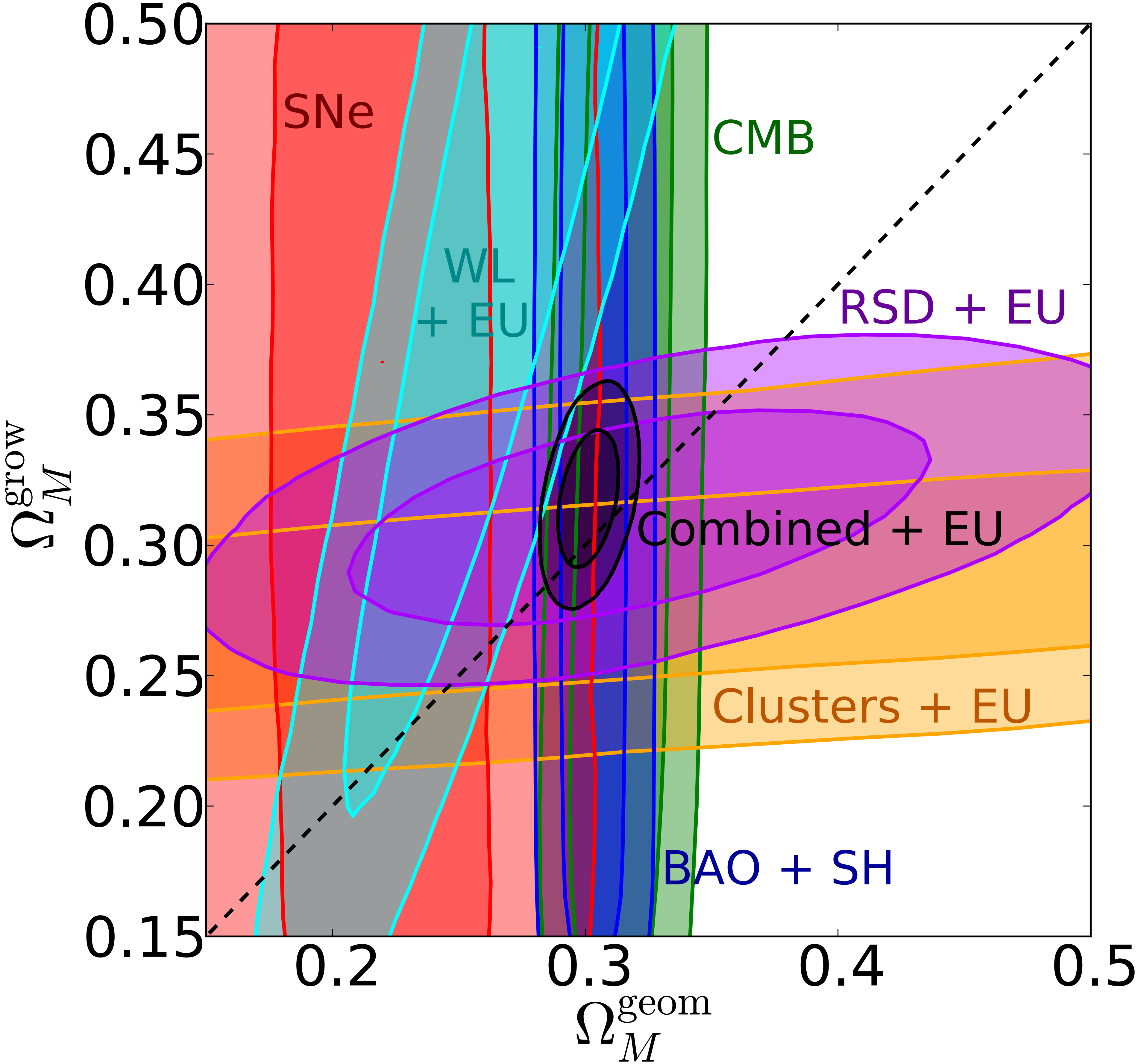
$$\mathcal{L}(A, v_{\rm bulk}) \propto \frac{1}{\sqrt{|\mathbf{C}|}} \exp\left[-\frac{1}{2}\mathbf{\Delta m}^{\intercal}\mathbf{C}^{-1}\mathbf{\Delta m}\right]$$

$$(\mathbf{\Delta m})_i = m_i^{\rm corr} - m^{\rm th}(z_i, \mathcal{M}, \Omega_m) - \Delta m_i^{\rm bulk}(v_{\rm bulk})$$

$$\Delta m_i^{\rm bulk} \equiv \Delta m^{\rm bulk}(v_{\rm bulk}; z_i, \hat{\mathbf{n}}_i) = -\left(\frac{5}{\ln 10}\right) \frac{(1+z_i)^2}{H(z_i) d_L(z_i)} \; \hat{\mathbf{n}}_i \cdot v_{\rm bulk} \, ,$$

Very simple.

Omega matter: geometry vs. growth



* SN not the recalibrated JLA compilation - need to update; will move Ω_M^{geow} up