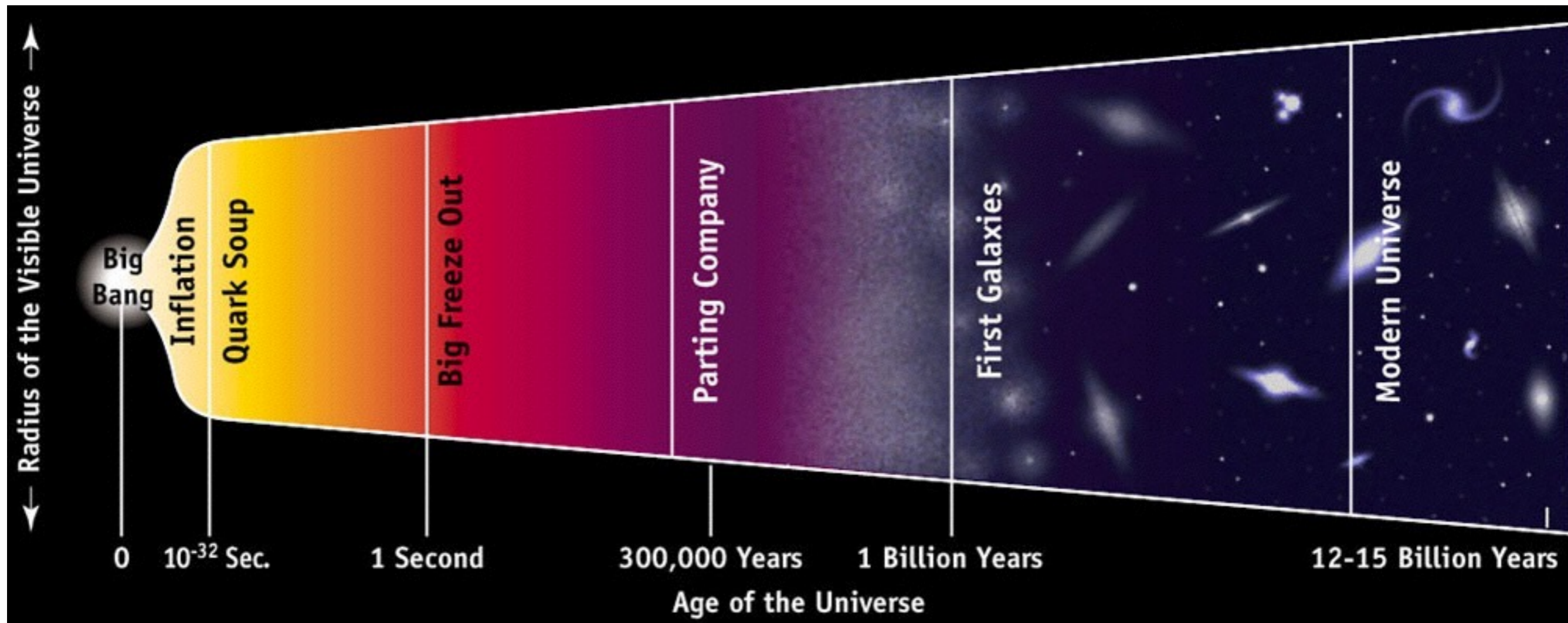


New views of the Universe

Dragan Huterer
University of Michigan

Illustris simulation
Vogelsberger et al

Three key questions in cosmology



Inflation

Dark
Matter

Dark
Energy

Three big questions in cosmology



Dark Matter

- ◆ What is the DM particle?
- ◆ What are its interactions, decay modes..?



Dark Energy

- ◆ What is the physics behind the accelerated expansion?



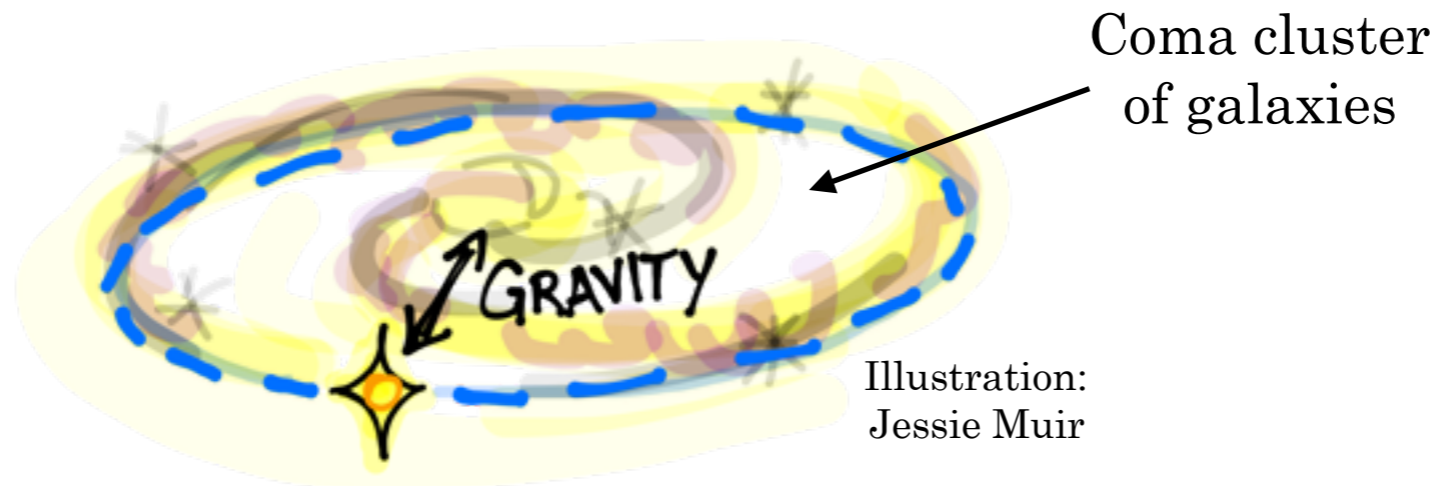
Inflation (Early Univ)

- ◆ At what energy?
- ◆ How many fields?
- ◆ With what interactions?
- ◆ “Who is this inflaton field?”

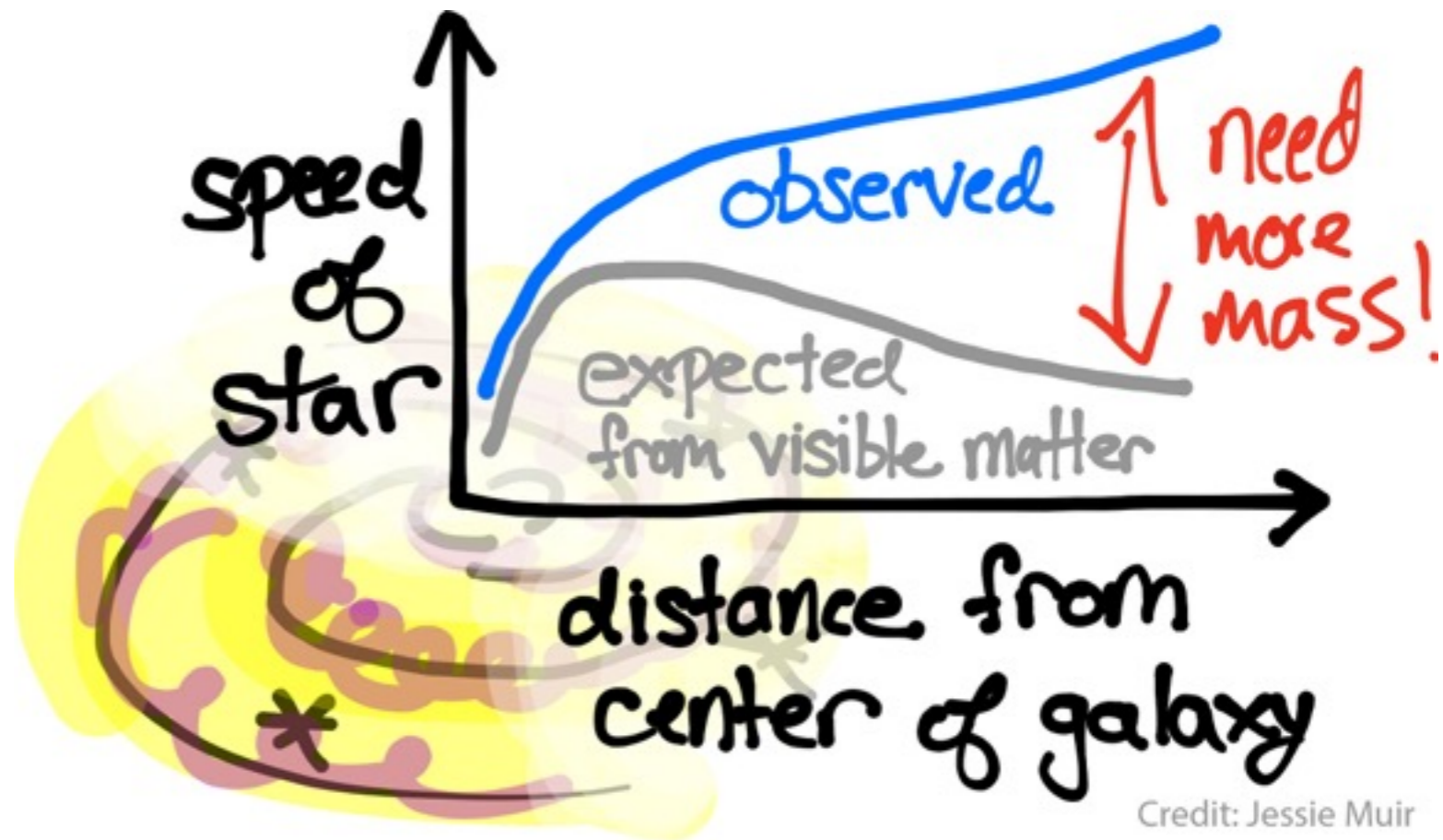
Dark Matter



Fritz Zwicky
“Dunkle Materie”, 1933

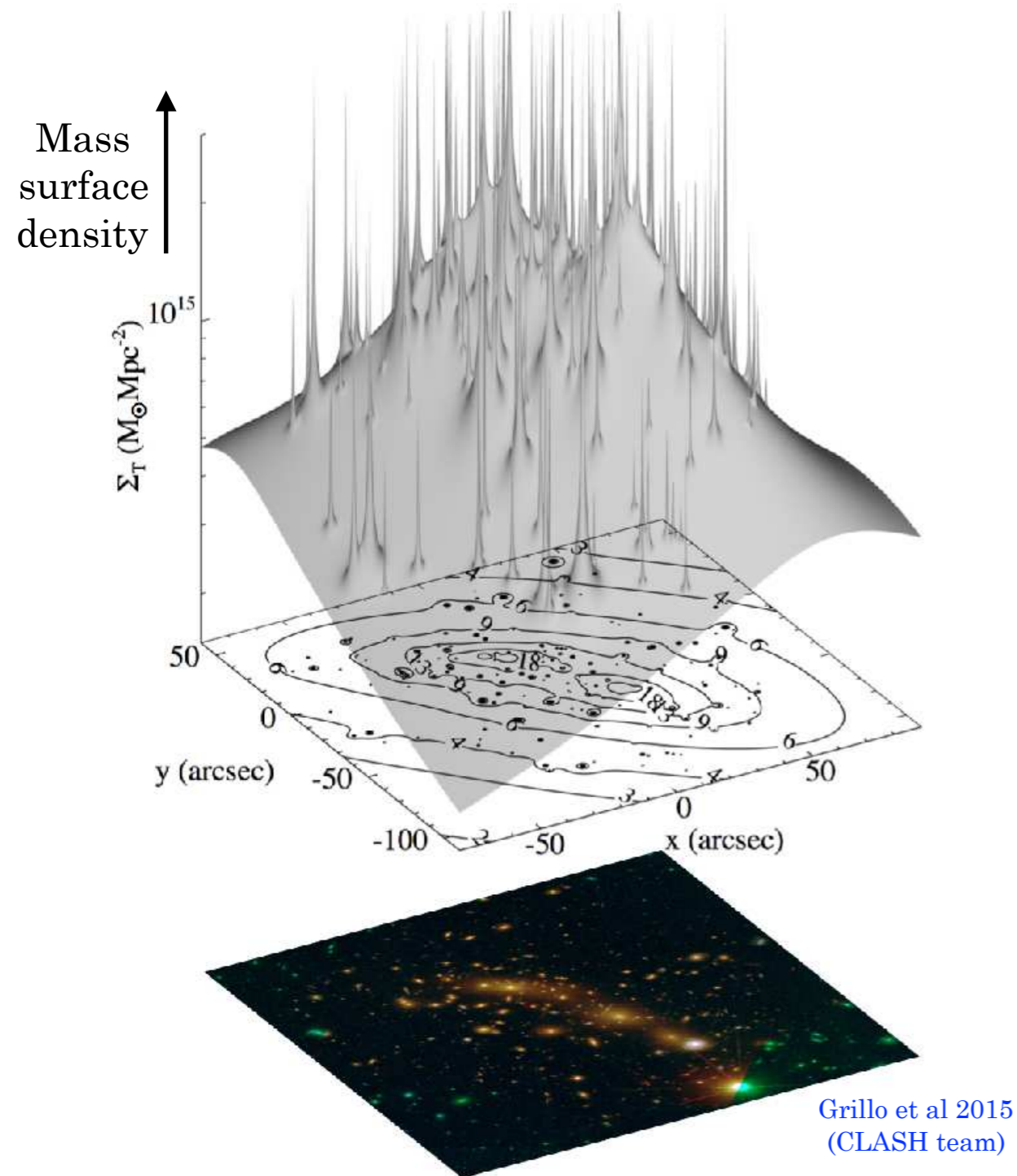


Vera Rubin
flat rotation curves, 1970s

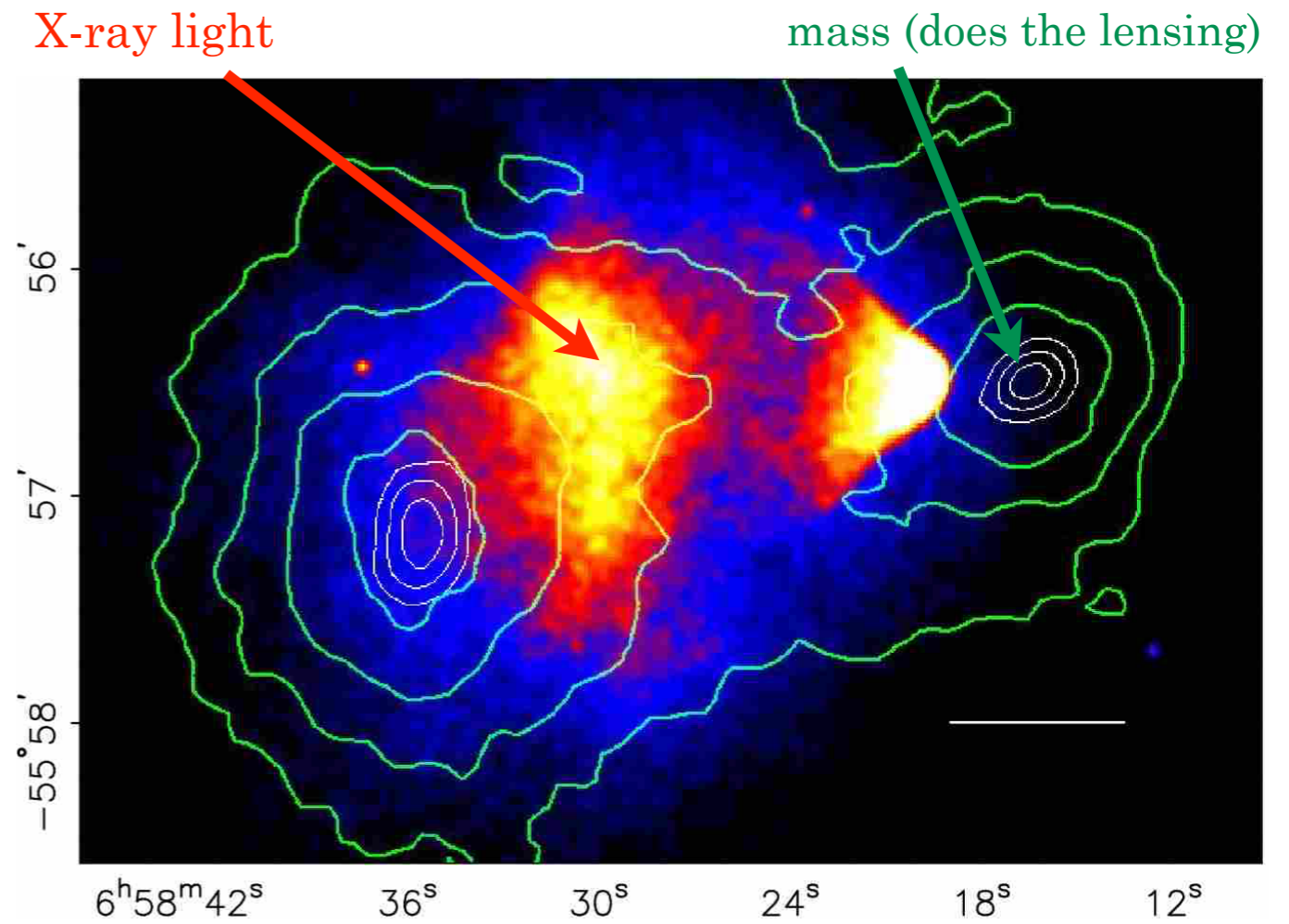


Credit: Jessie Muir

Modern evidence for Dark Matter

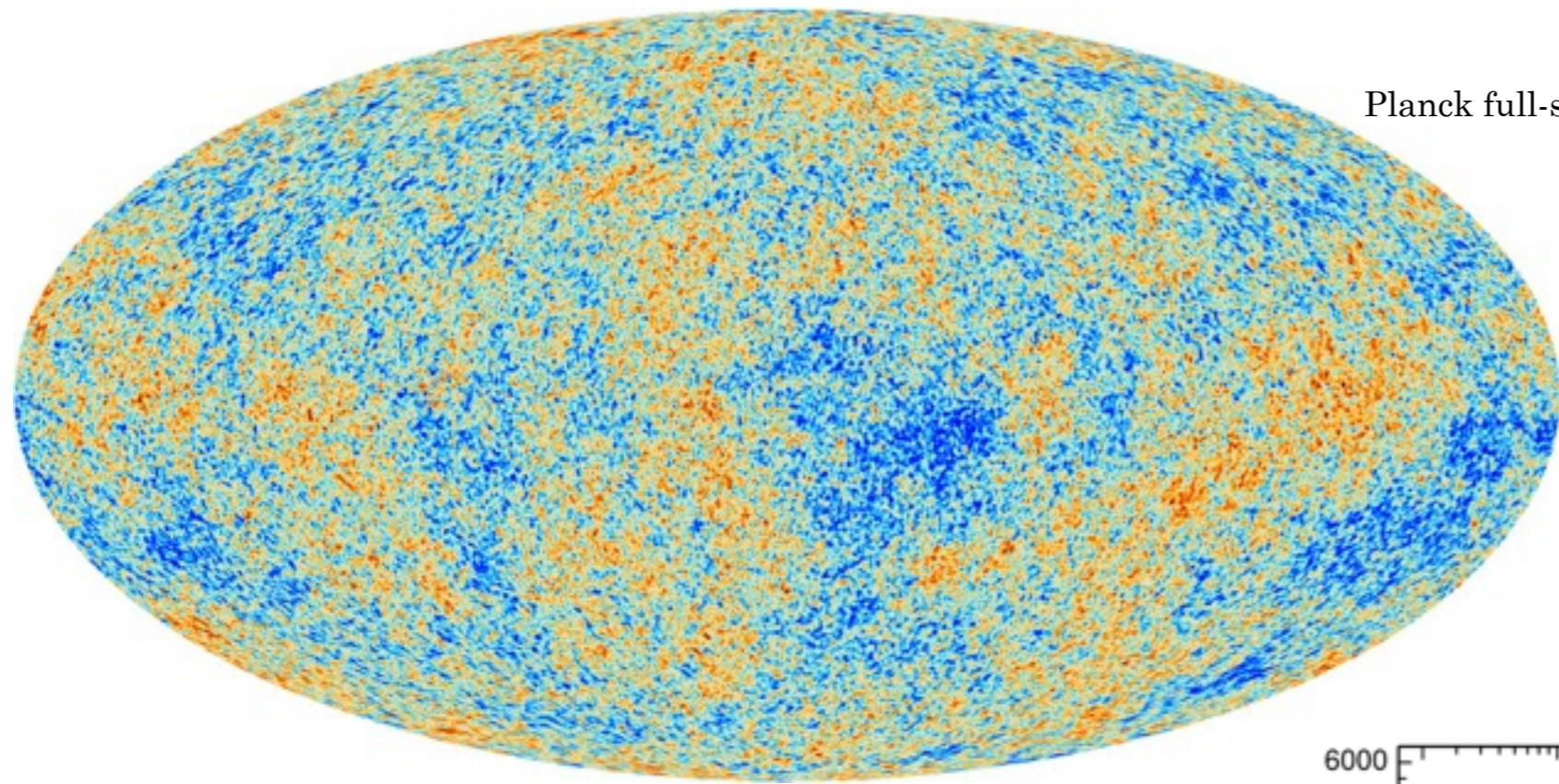


Mass profile around a cluster



Bullet cluster

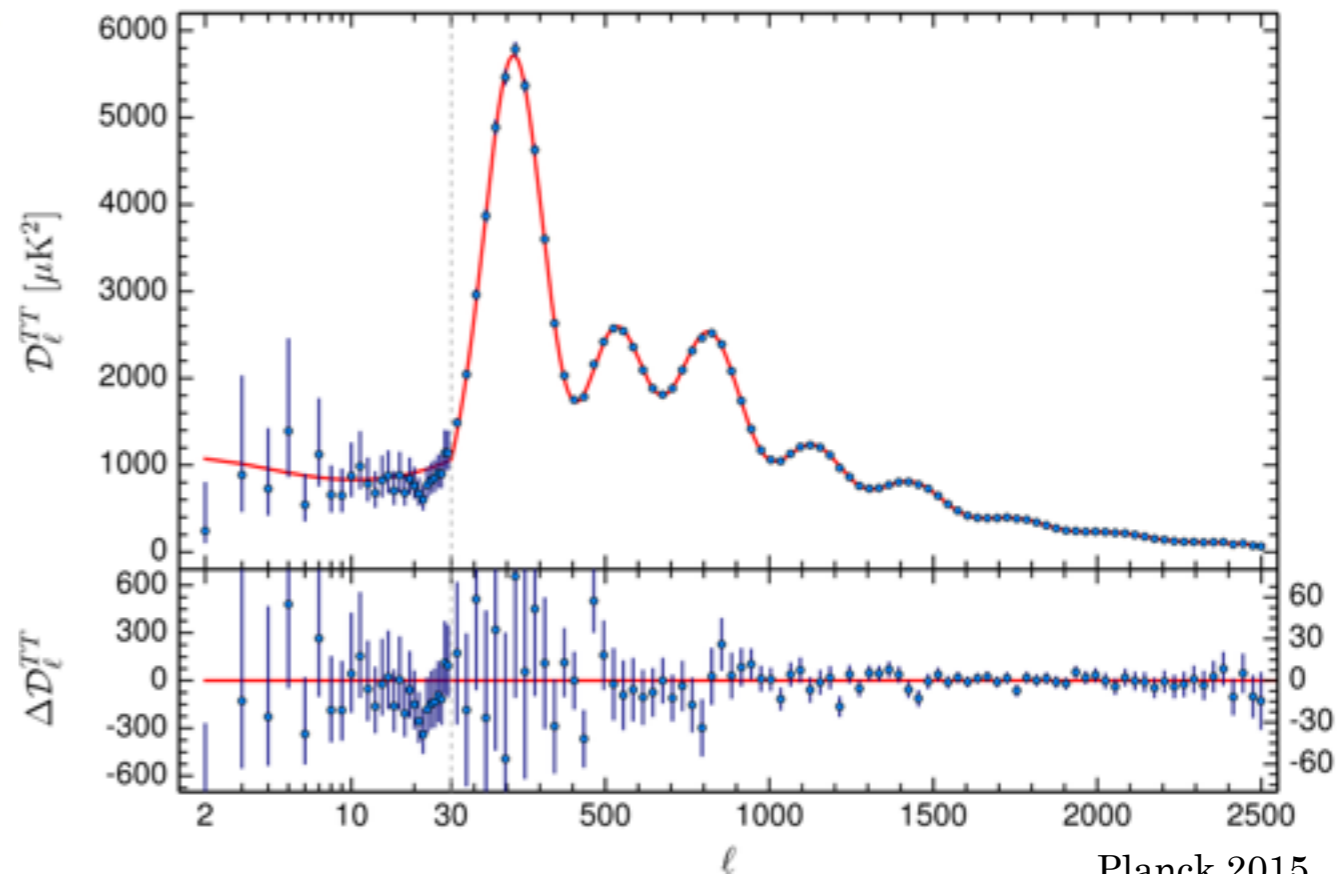
Modern evidence for Dark Matter



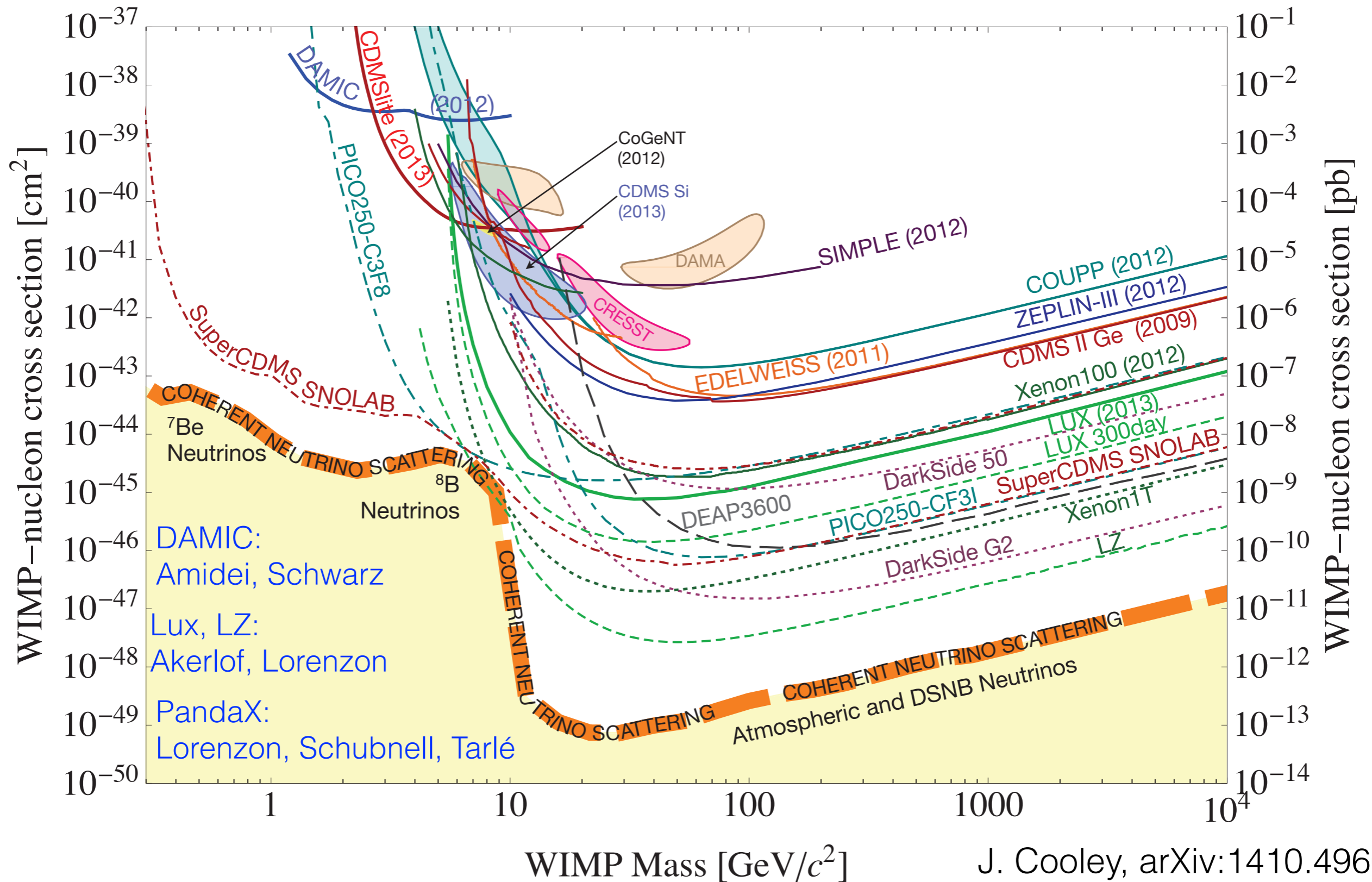
Planck full-sky map

$$\Omega_{\text{dark matter}} h^2 = 0.1193 \pm 0.0014$$

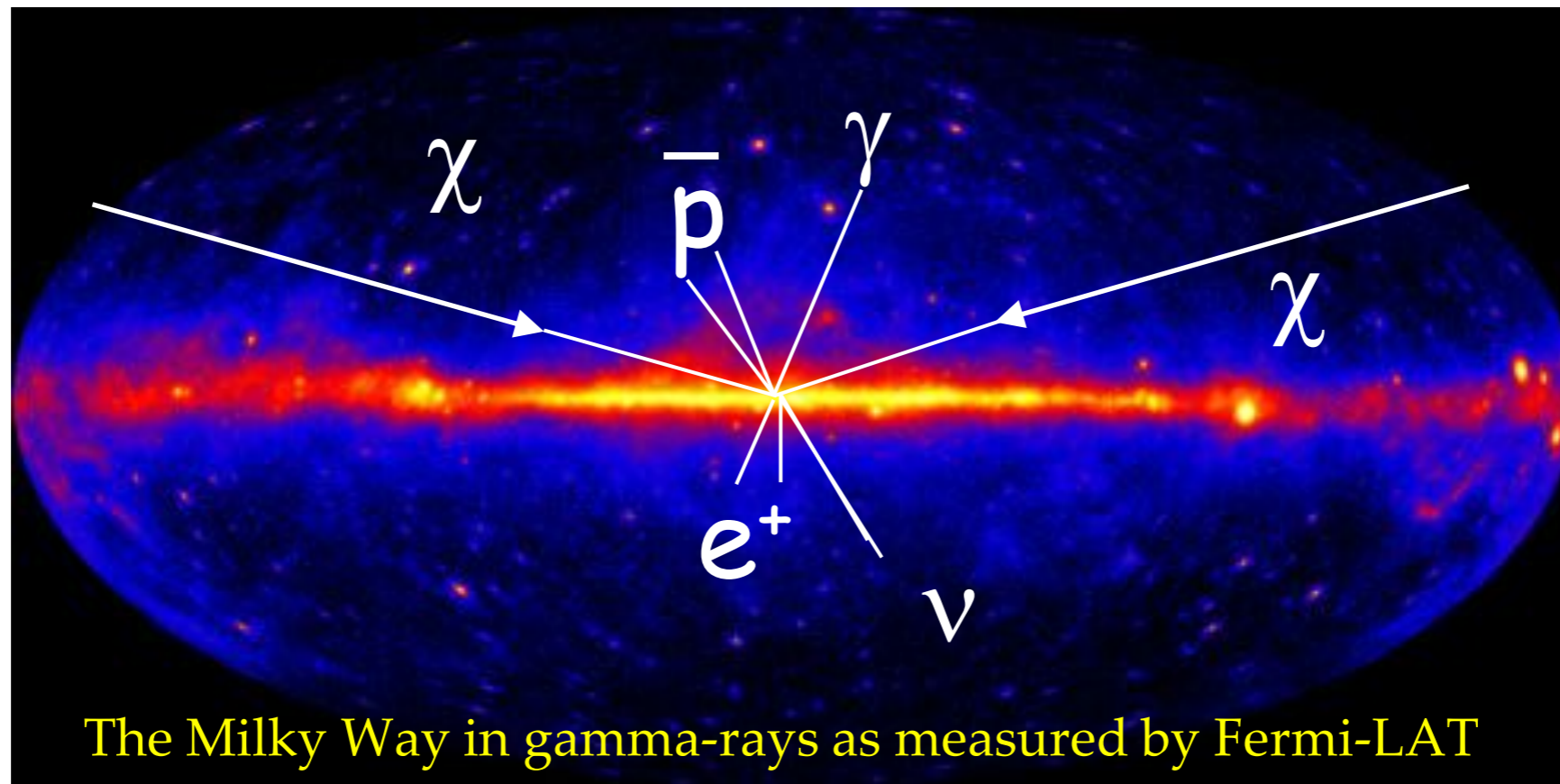
$$\Omega_{\text{baryons}} h^2 = 0.0222 \pm 0.0001$$



Direct searches: Cross-section vs mass constraints



Indirect detection

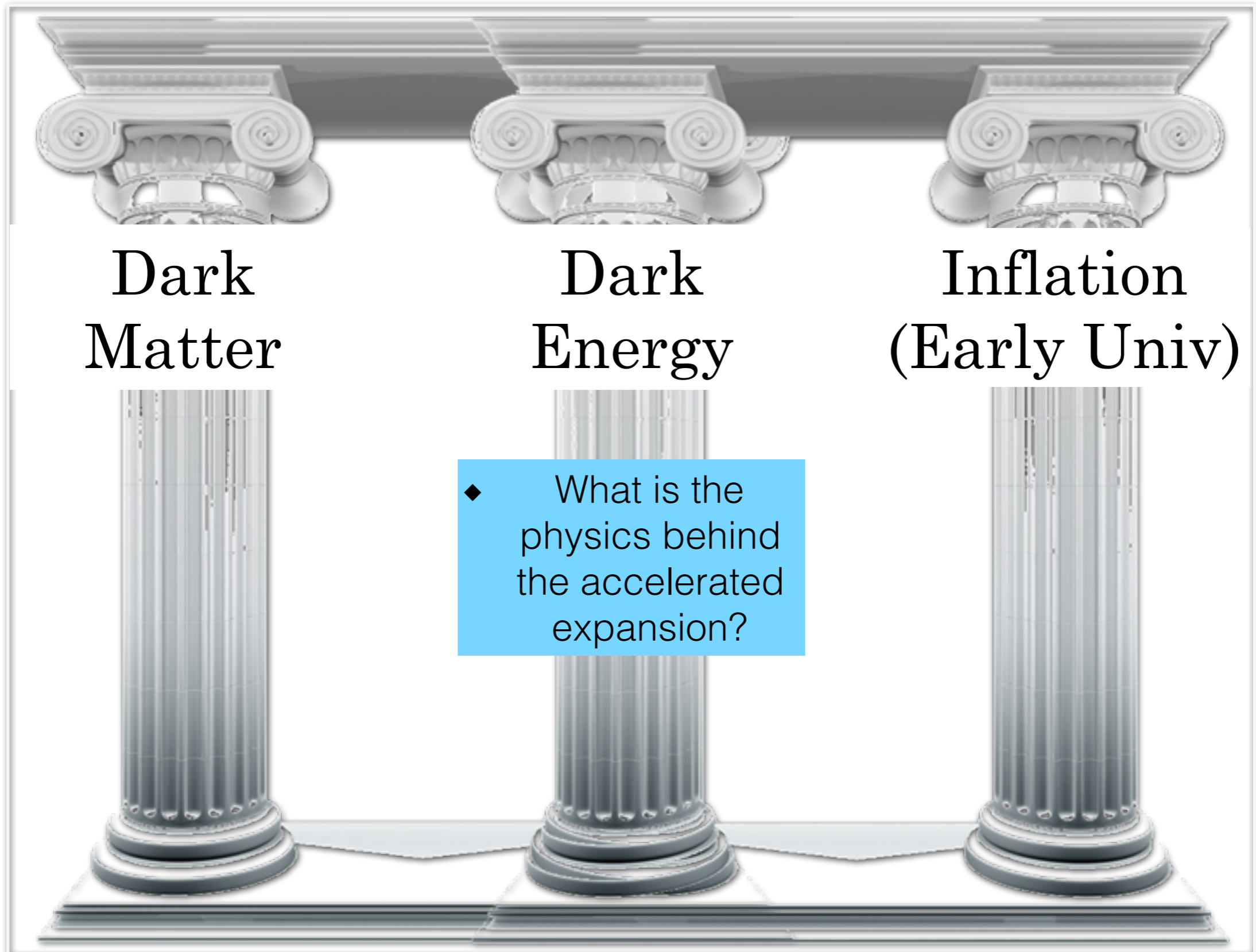


Numerous alarms about “bumps” in spectra seen from Galaxy, and from dwarf galaxies (Reticulum, etc)

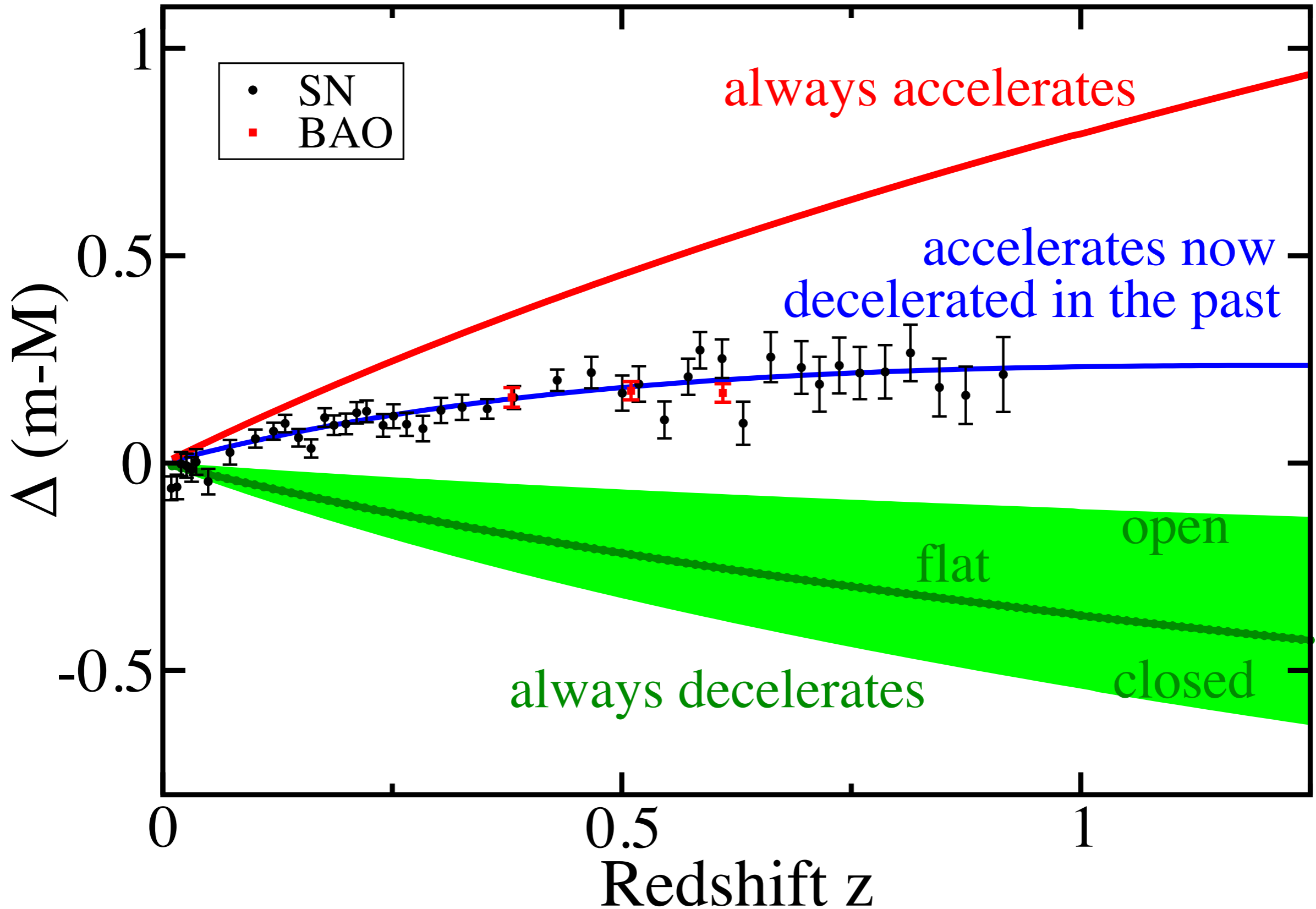
So far, none are convincing or truly statistically significant

Exciting and fast-developing field, but will be **hard to have a convincing detection of DM just from indirect detection**

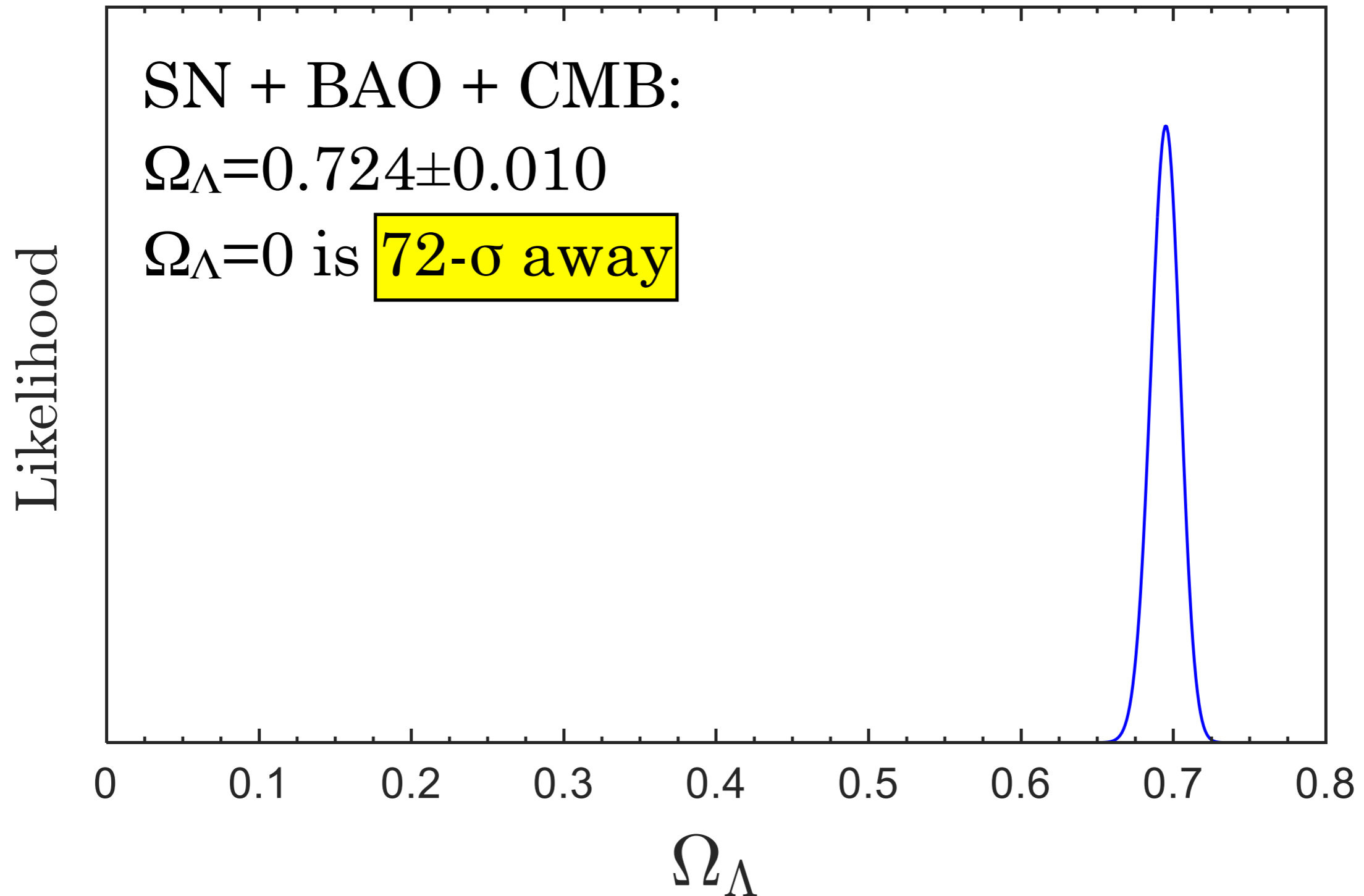
Three big questions in cosmology

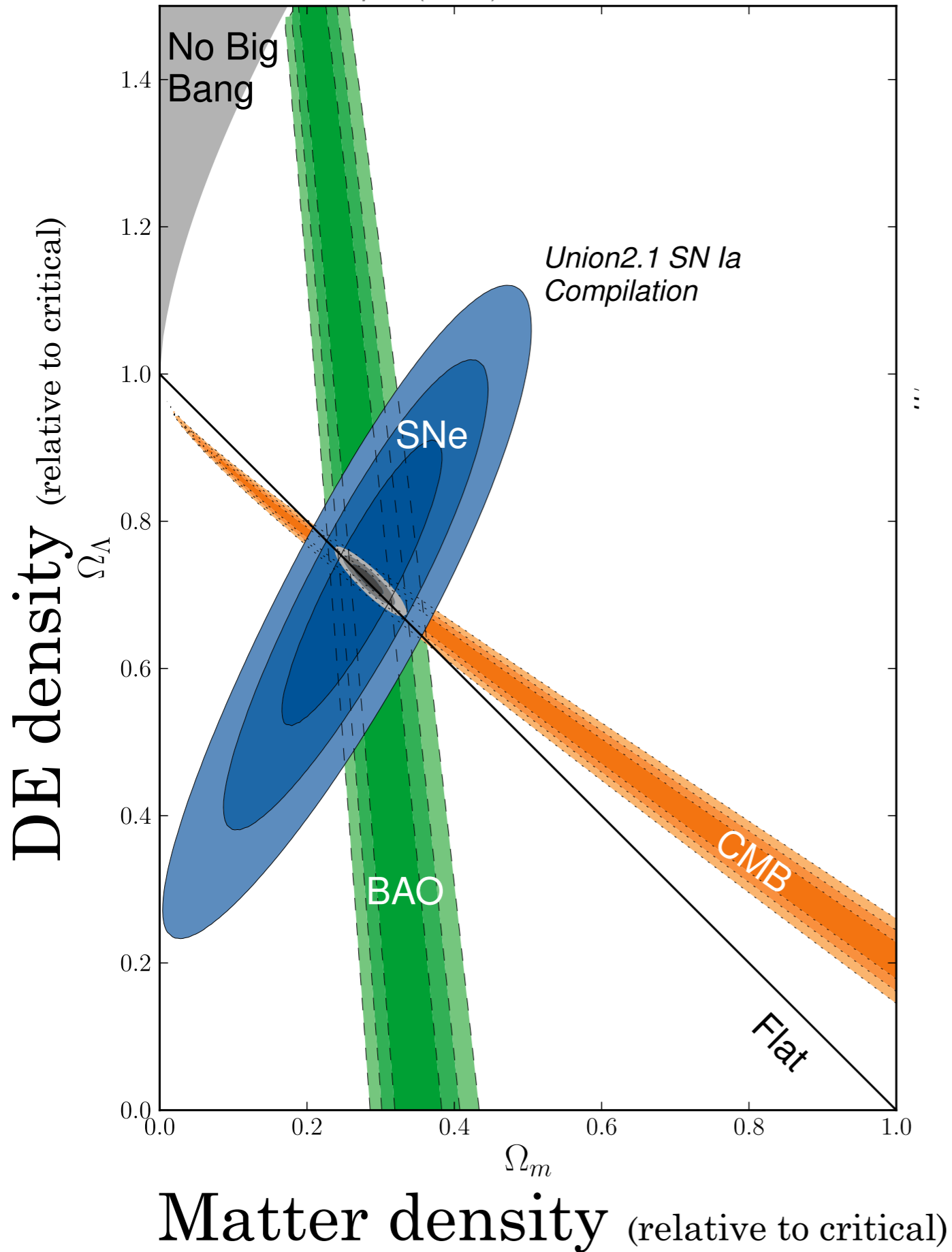


Evidence for Dark energy from type Ia Supernovae

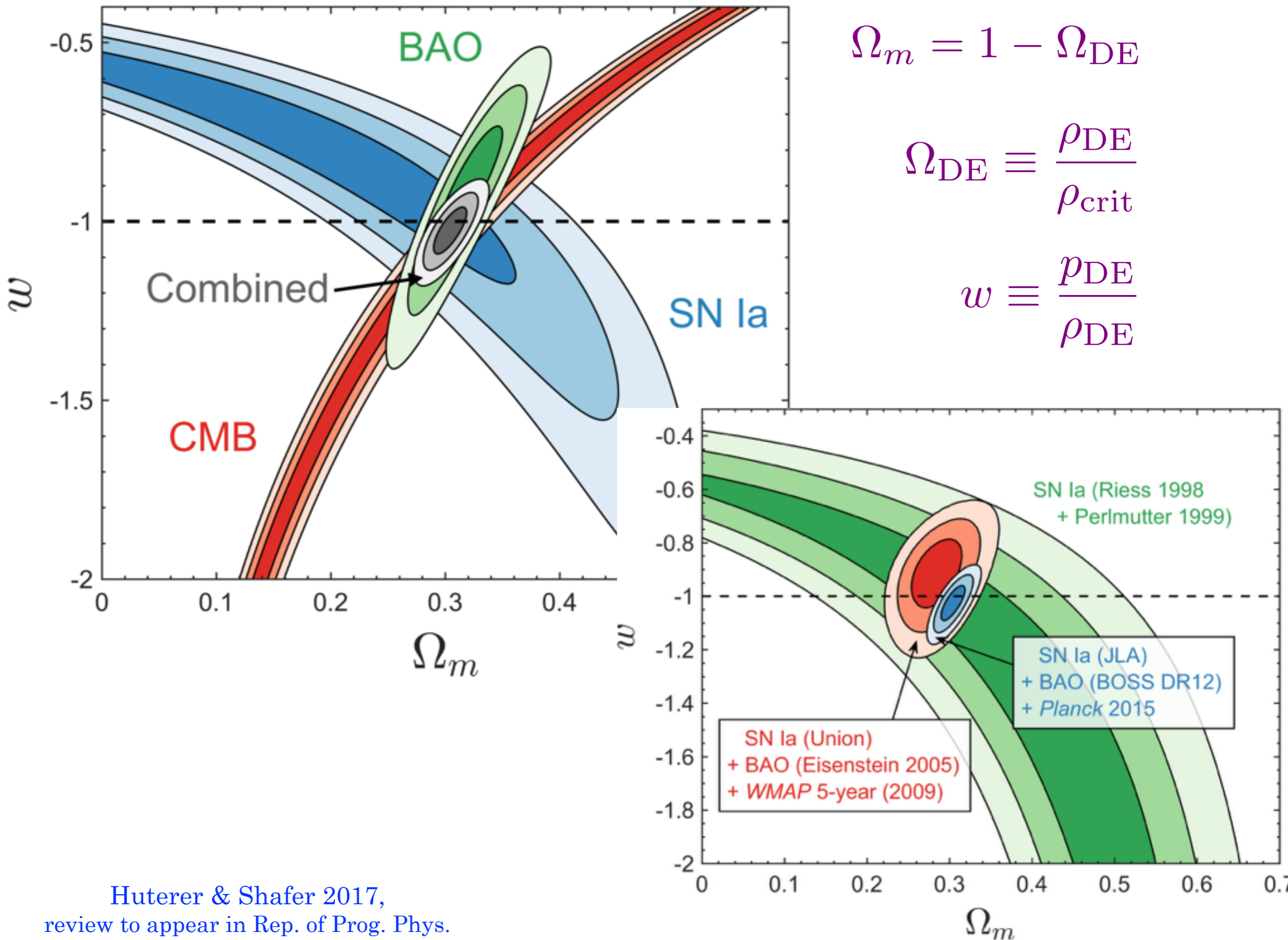


Current evidence for dark energy is
impressively strong

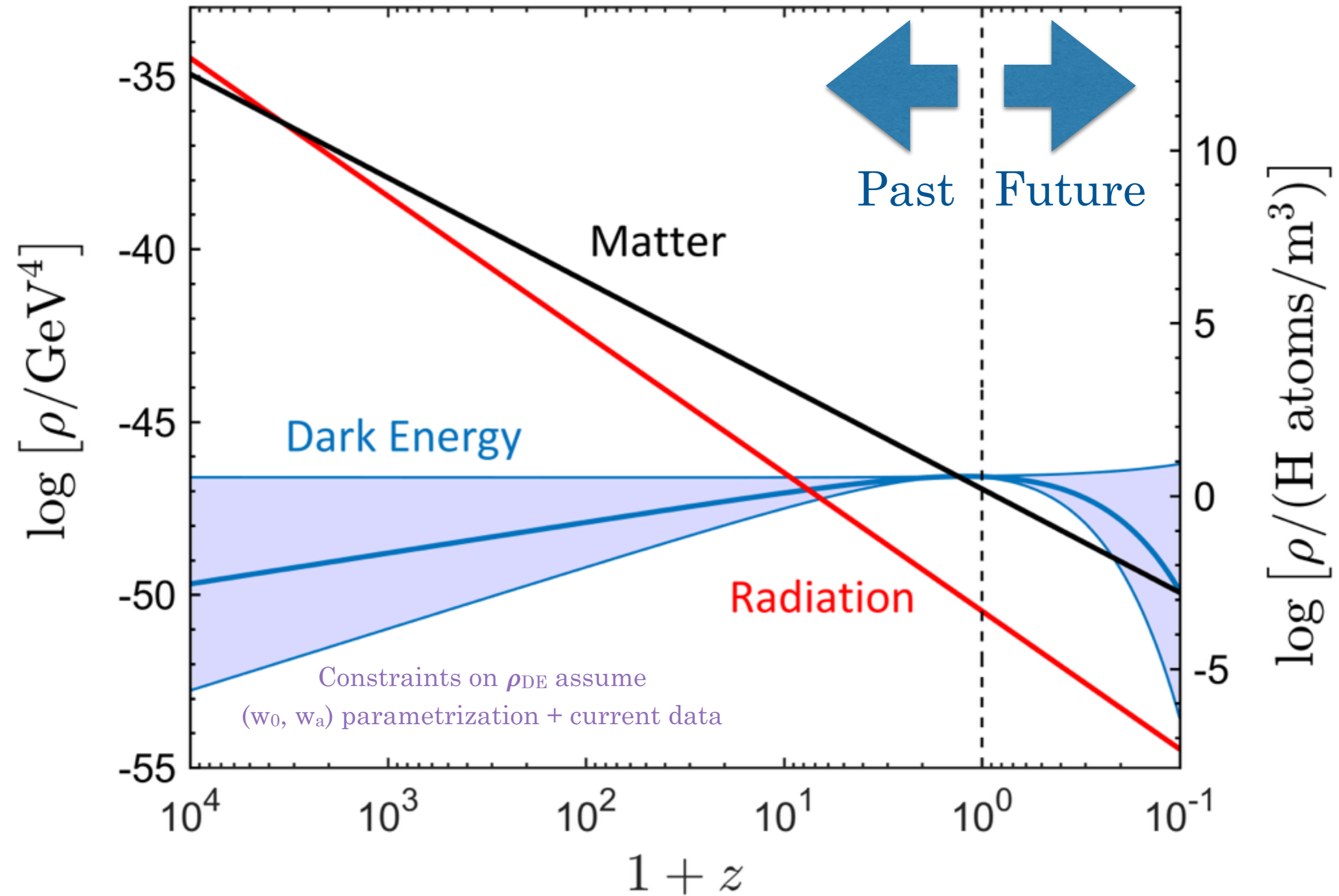




Recent (2011) constraints on dark energy density



Huterer & Shafer 2017,
 review to appear in Rep. of Prog. Phys.



Fine Tuning Problem: “Why so small”?

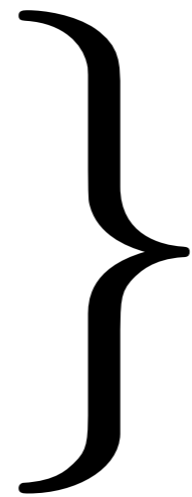
Vacuum Energy: Quantum Field Theory predicts it to be determined by cutoff scale

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

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

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

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

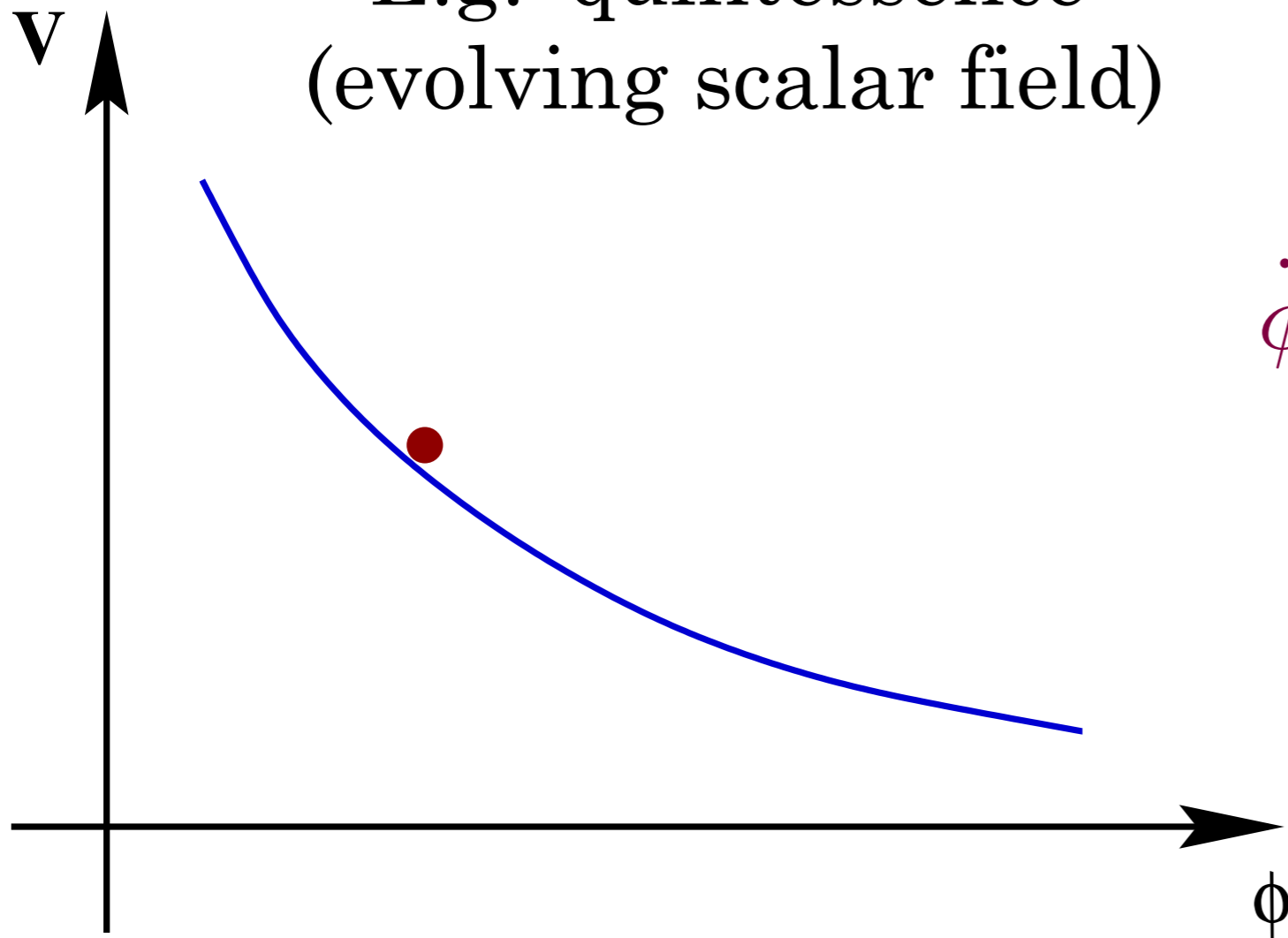


60-120 orders of magnitude smaller than expected!

Lots of theoretical ideas, few compelling ones:

Very difficult to motivate DE naturally

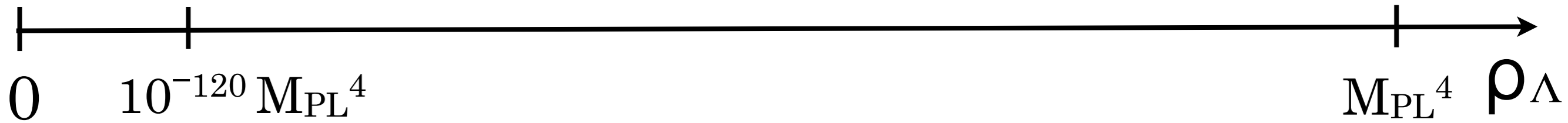
E.g. 'quintessence'
(evolving scalar field)



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

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

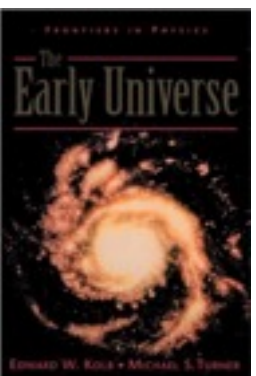
String landscape?



Among the $\sim 10^{500}$ minima,
we live in one that allows structure/galaxies to form
(selection effect) (anthropic principle)



Landscape
“predicts” the
observed Ω_{DE}



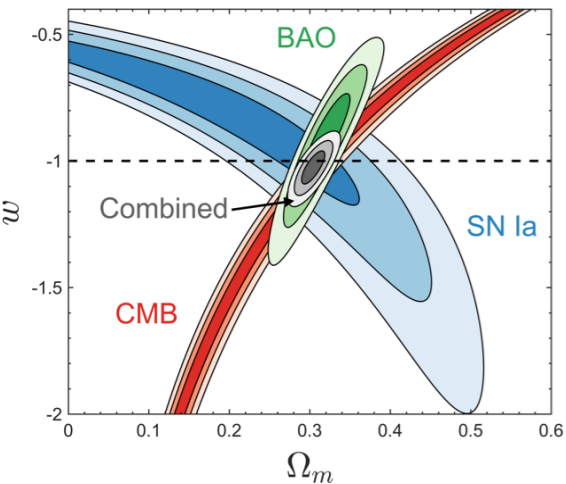
Kolb & Turner, “Early Universe”, footnote on p. 269:

“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. $w=p/\rho$,
not known *a priori*

Contrast this situation with:



1. Neutrino masses:

$$(\Delta m^2)_{\text{sol}} \simeq 8 \times 10^{-5} \text{ eV}^2$$

$$(\Delta m^2)_{\text{atm}} \simeq 3 \times 10^{-3} \text{ eV}^2$$

$$\left. \begin{array}{l} (\Delta m^2)_{\text{sol}} \simeq 8 \times 10^{-5} \text{ eV}^2 \\ (\Delta m^2)_{\text{atm}} \simeq 3 \times 10^{-3} \text{ eV}^2 \end{array} \right\} \sum m_i = 0.06 \text{ eV}^* \text{ (normal)}$$

vs.

$$\sum m_i = 0.11 \text{ eV}^* \text{ (inverted)}$$

*(assuming $m_3=0$)

2. Higgs Boson mass (before LHC 2012):

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

(assuming Standard Model Higgs)

What if gravity deviates from GR?

For example:

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



Modified gravity



Dark energy

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

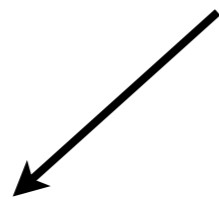
Can we distinguish between DE and MG?

Yes; here is how:

- 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. 0th order cosmology)

Probed by supernovae, CMB,
weak lensing, cluster abundance



Growth

(a.k.a. dynamical probes)
(a.k.a. 1st order cosmology)

Probed by galaxy clustering,
weak lensing, cluster abundance

Idea: compare geometry and growth

Our approach:

Double the standard DE parameter space

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

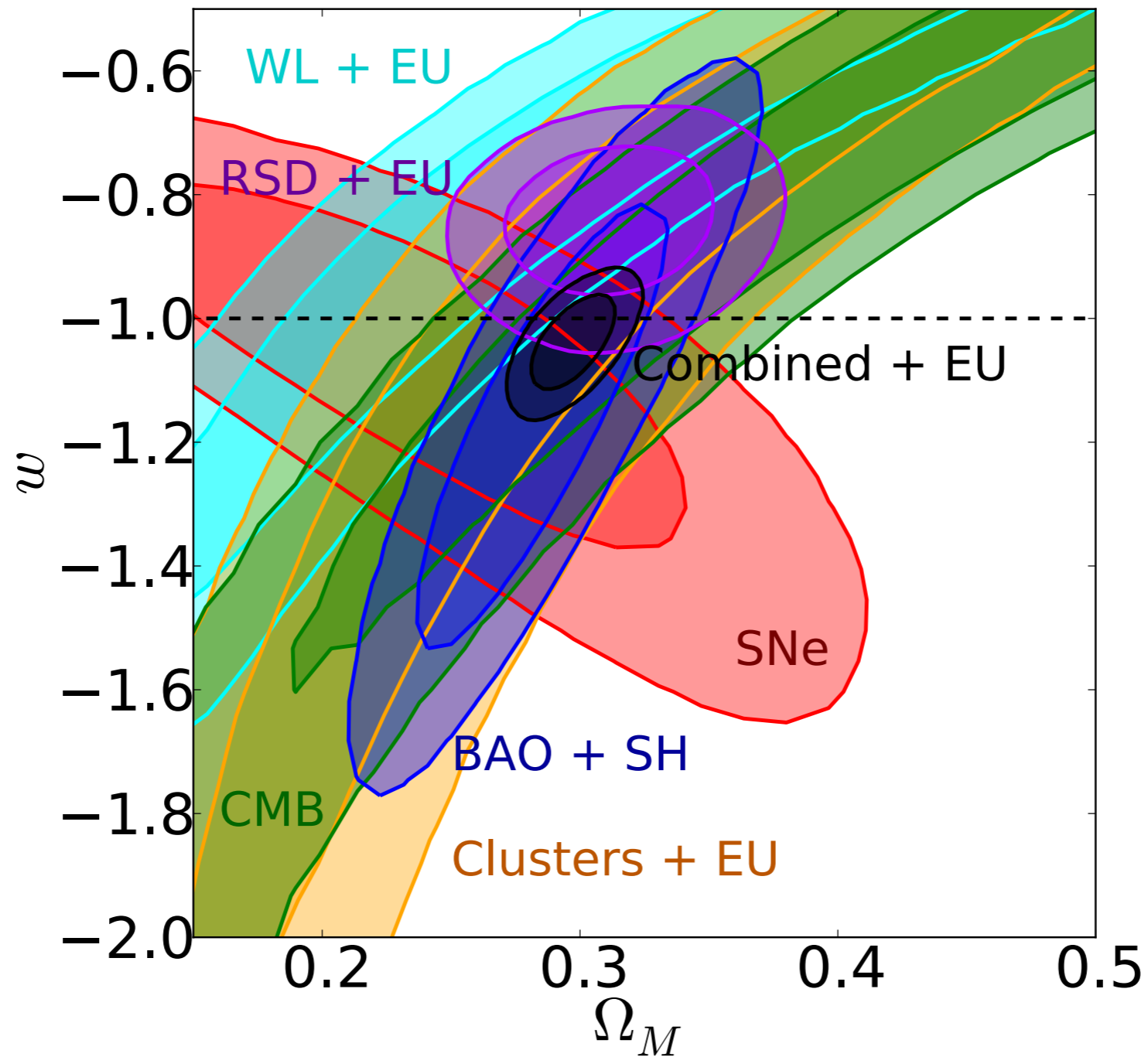
$\Rightarrow \Omega_M^{\text{geom}}, w^{\text{geom}} \quad \Omega_M^{\text{grow}}, w^{\text{grow}}$

[In addition to other, usual parameters]

Sensitivity to geometry and growth

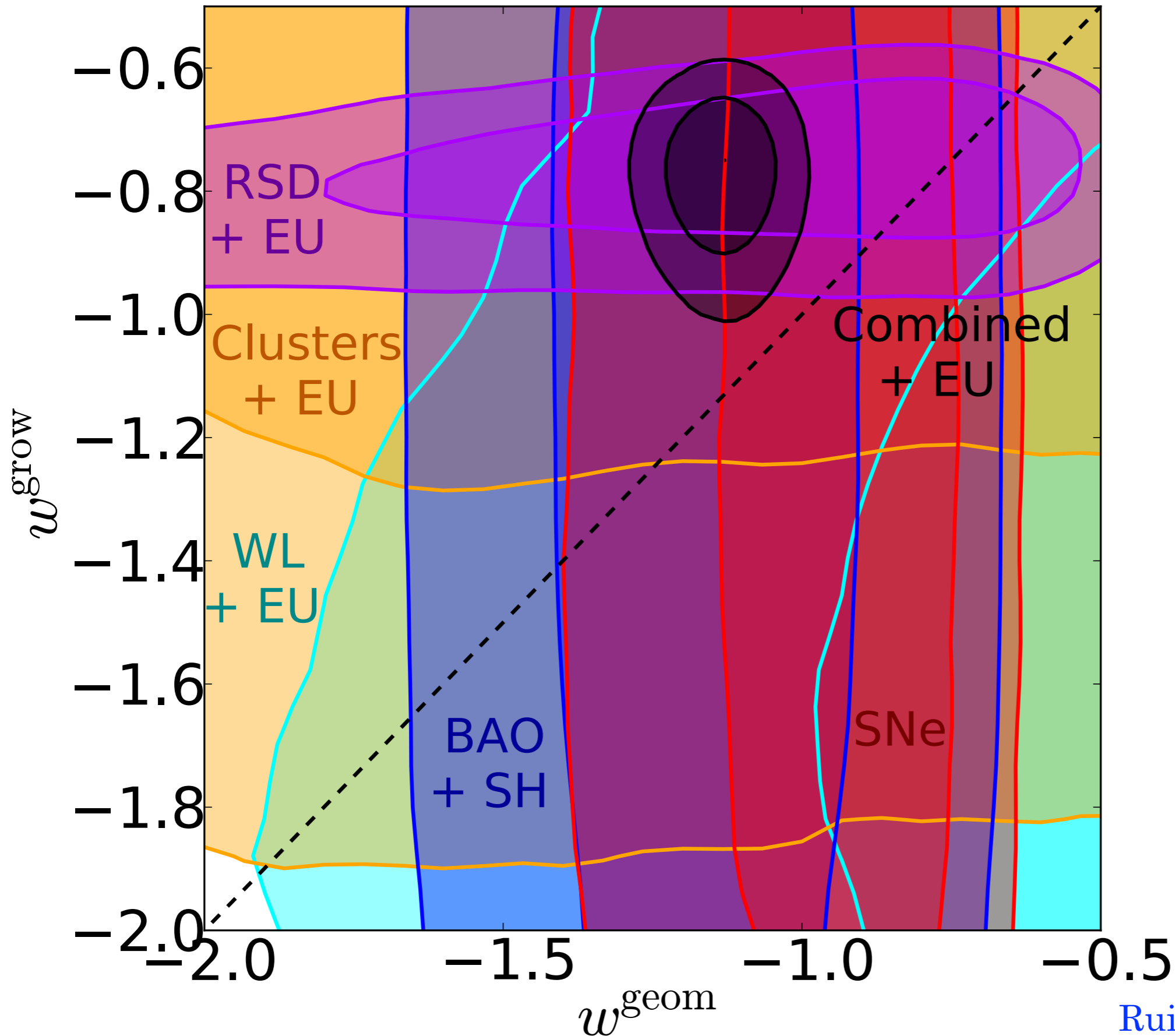
Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$	—
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2} D_A(z_*)$	—
Cluster counts	$\frac{dV}{dz}$	$\frac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$	$P \left(k = \frac{\ell}{r(z)}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

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



Ongoing or upcoming DE experiments:

- **Ground photometric:**

- ▶ Dark Energy Survey (DES)
- ▶ Pan-STARRS
- ▶ Hyper Supreme 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)

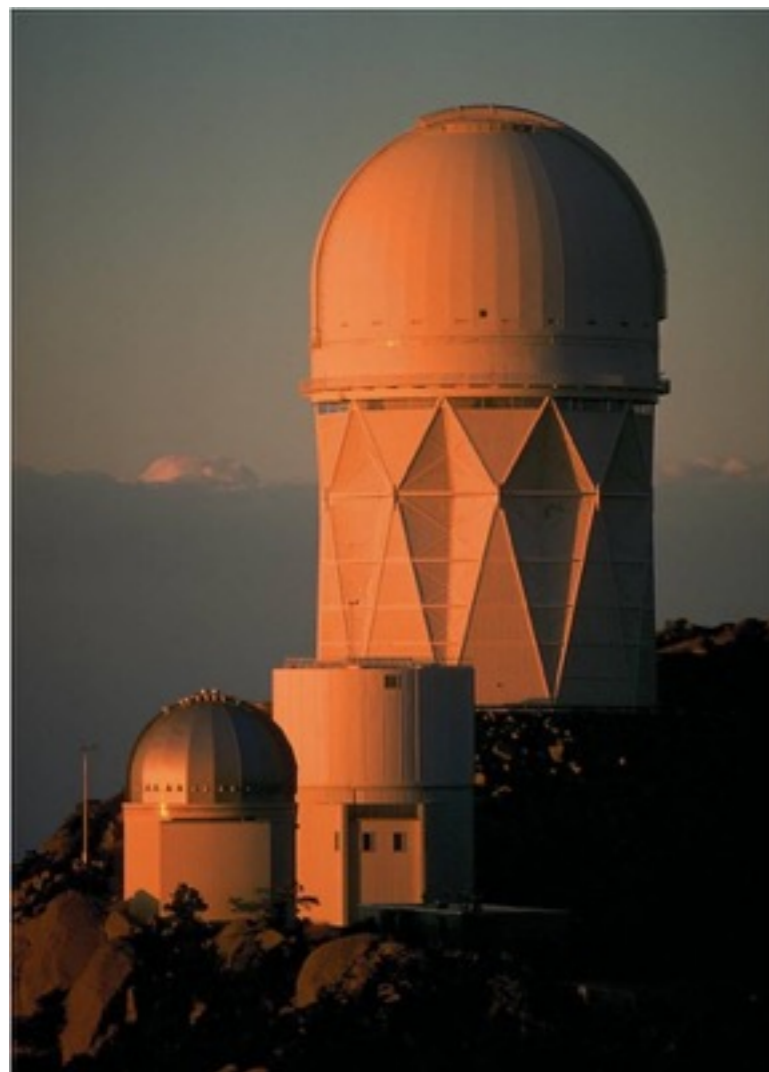
Dark Energy Survey (DES)



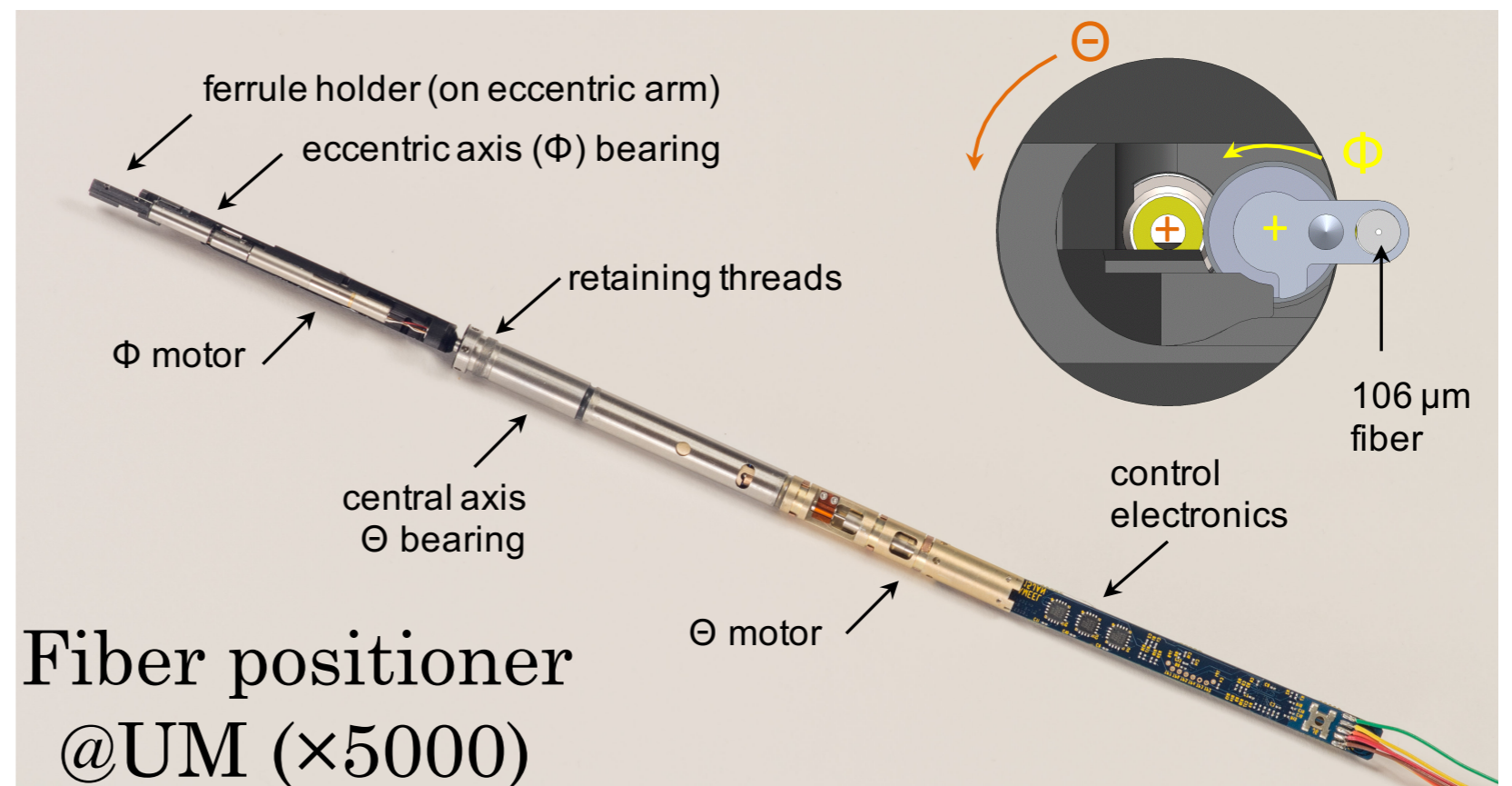
Cerro Tololo, Chile



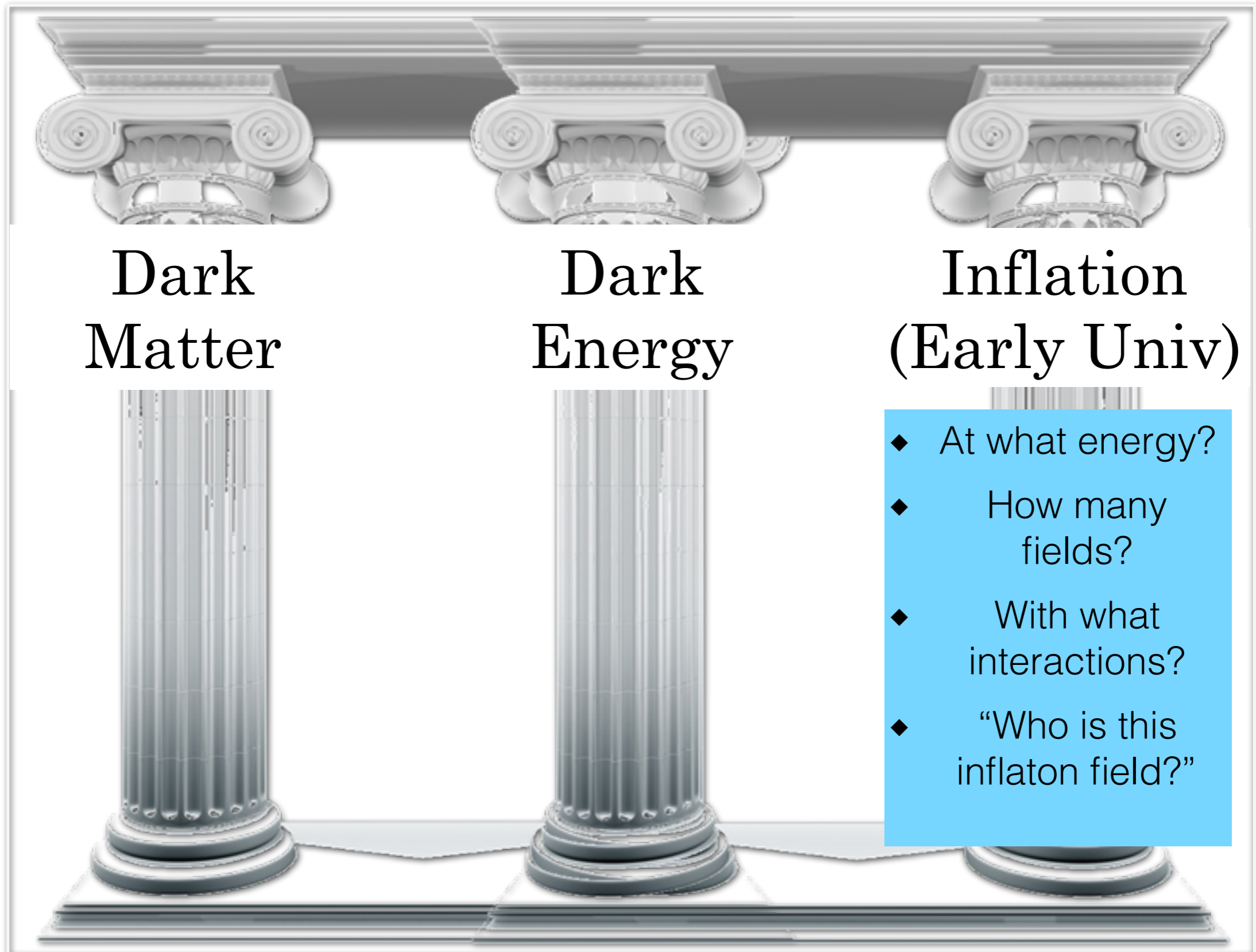
Dark Energy Spectroscopic Instr. (DESI)



Kitt Peak, Arizona

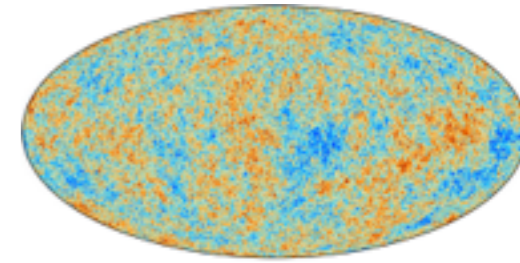


Three big questions in cosmology

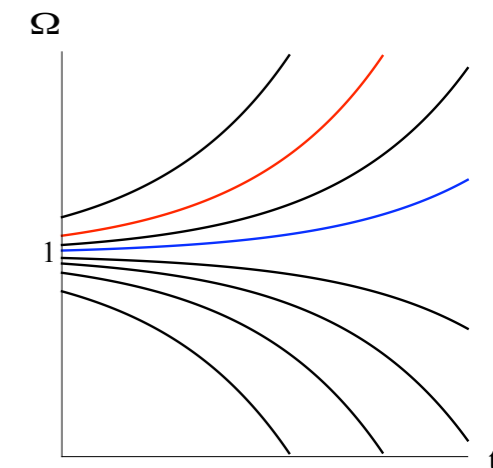


In the 1970s, it was established that standard cosmological model has some problems

▶ **Horizon problem:** the CMB is (very nearly) uniform, while we can show that **regions greater than about 1° apart could not have been in a causal contact**



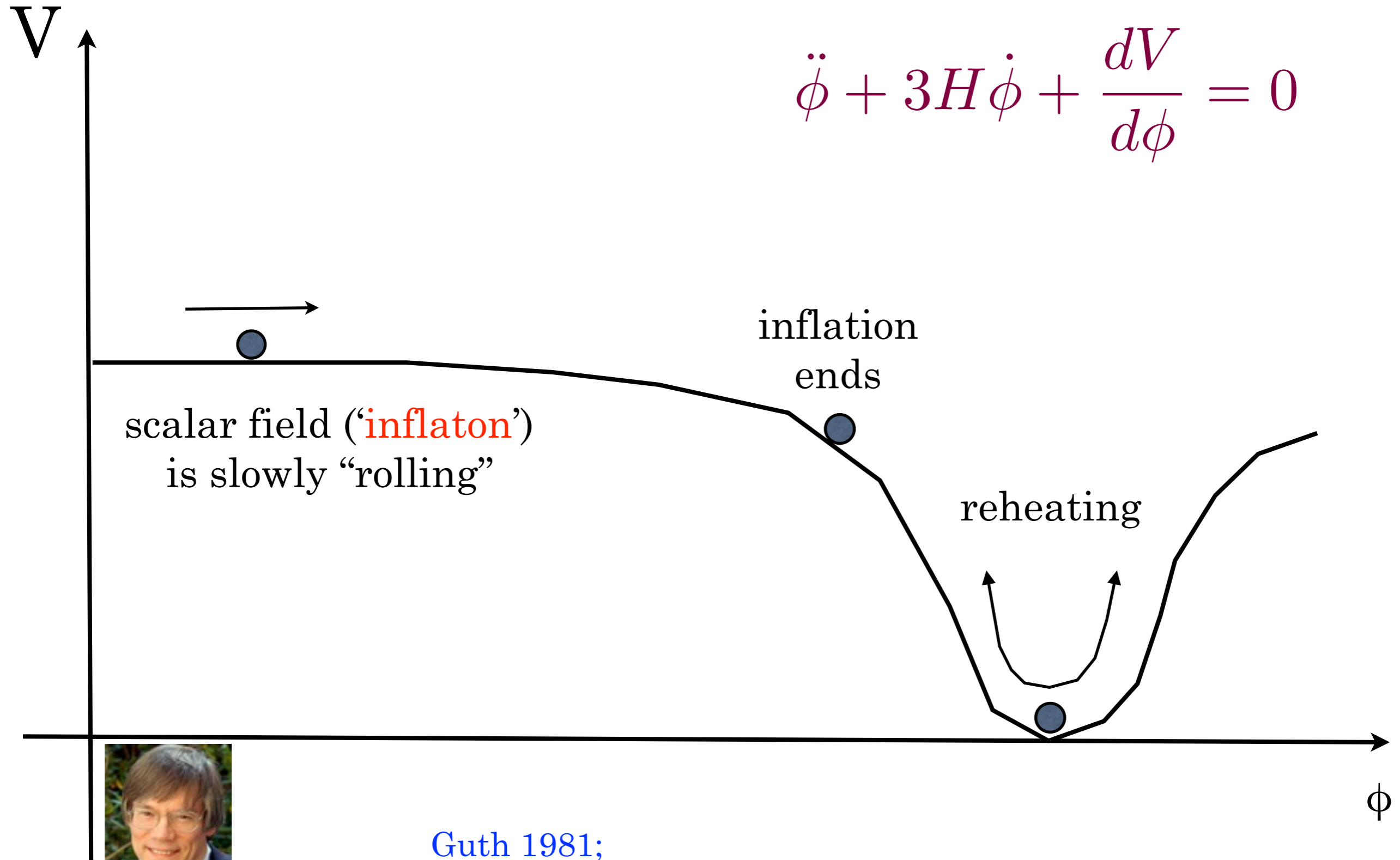
▶ **Flatness problem:** the universe is close to flat (flat geometry), while, if you work out basic equations, it tends to diverge from flat. Therefore, present-day flatness implies **extreme fine tuning (to flat) in early universe**



▶ **Origin of Structure:** the CMB (and our sky) show structures: hot and cold spots first, and then later galaxies etc. CMB shows that you **need a seed density perturbation of $\delta\rho/\rho \approx 10^{-5}$** (ρ is density)

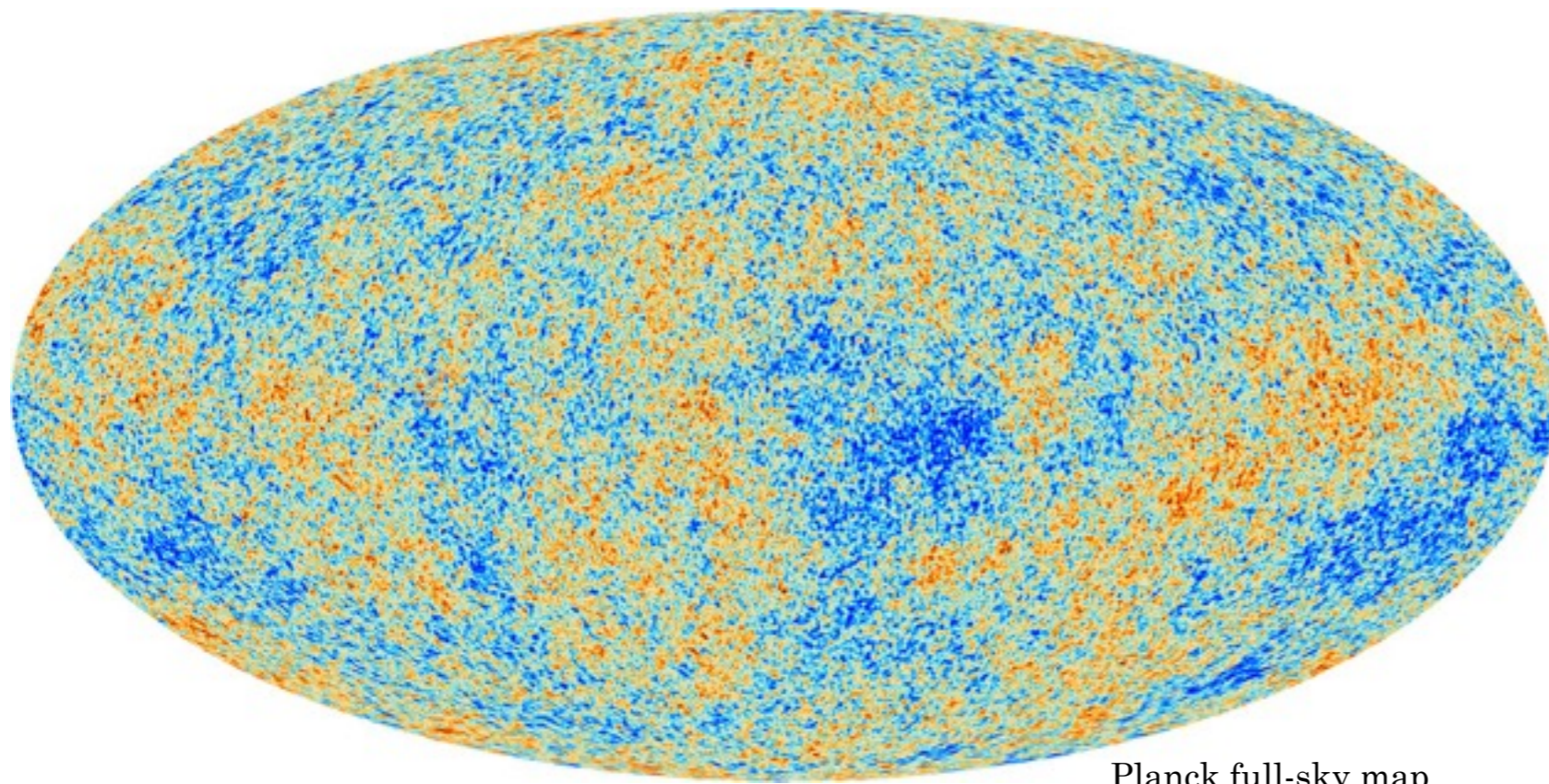


Inflation: basic picture

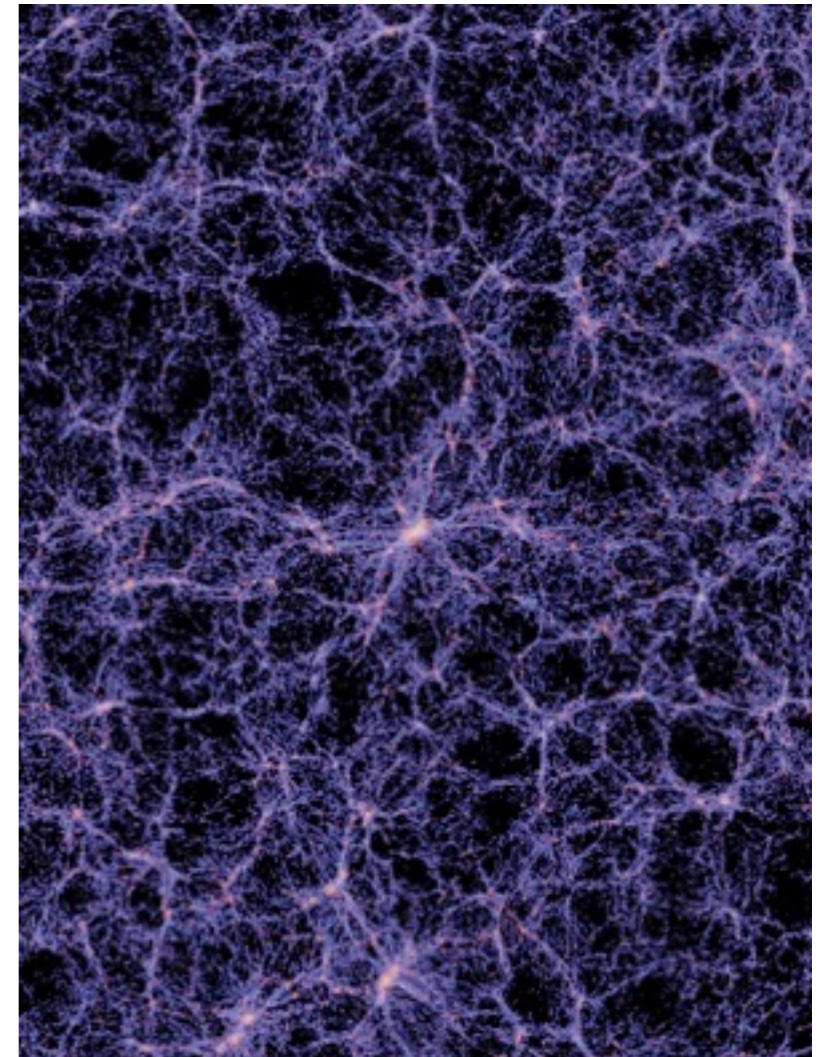


Guth 1981;
Linde 1982; Albrecht & Steinhardt 1982

Generic Inflationary Predictions:



Planck full-sky map



Millennium simulation

- Flat spatial geometry; $\Omega_K = 0.000 \pm 0.005 \sqrt{}$
 - Nearly scale-inv spectrum; $n_s = 0.965 \pm 0.005 \sqrt{}$
 - Background of gravity waves ($r \approx 0.1$)?
 - (Nearly) gaussian ICs $f_{NL} = 0.8 \pm 5.0$
- What energy scale?
 - How many fields?
 - What interactions?

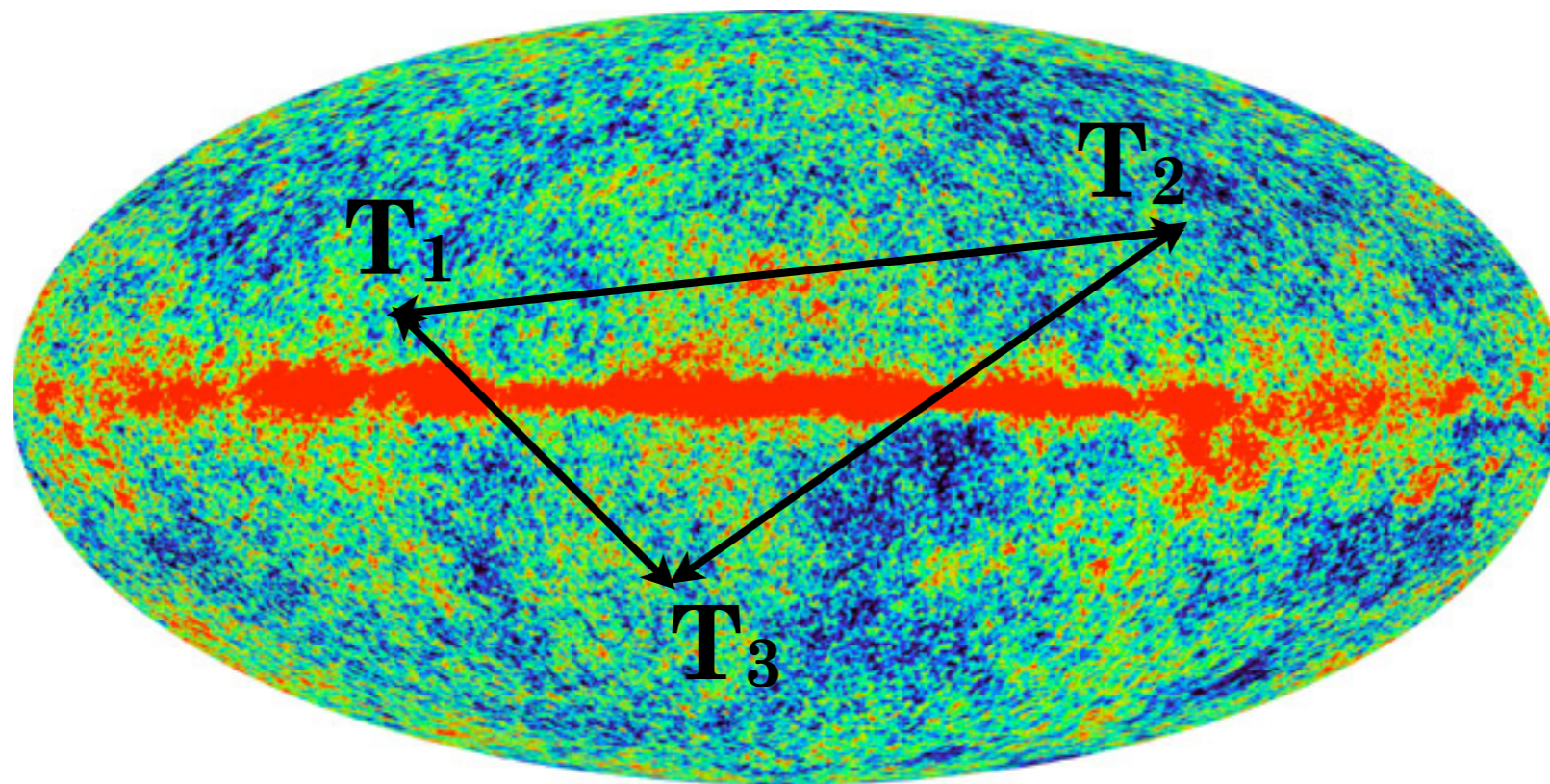
Standard Inflation, with...

1. a single scalar field
2. the canonical kinetic term
3. always slow rolls
4. in Bunch-Davies vacuum
5. in Einstein gravity

produces **unobservable** NG

Therefore, measurement of nonzero NG would point to a **violation** of one of the assumptions above

NG from 3-point correlation function



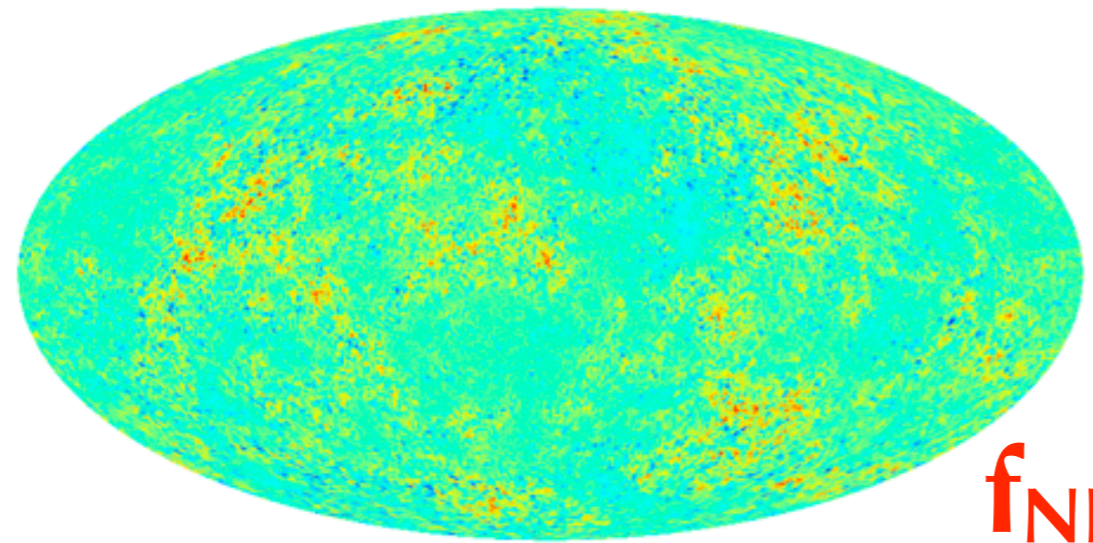
“Local NG” (squeezed triangles) is defined as

$$\Phi = \Phi_G + f_{\text{NL}} \left(\Phi_G^2 - \langle \Phi_G^2 \rangle \right)$$

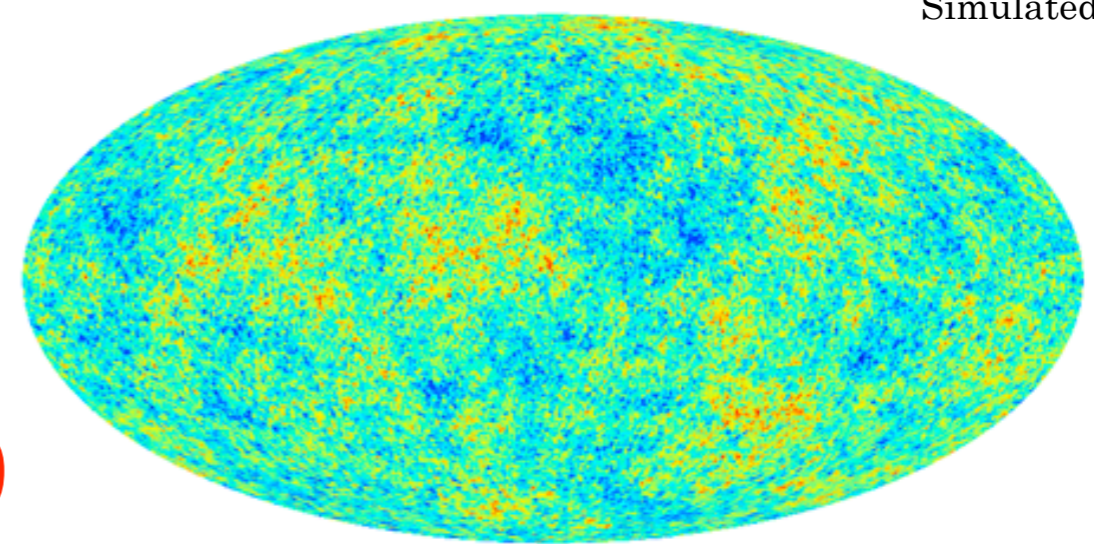
“Local”, “Equilateral”, “orthogonal” f_{NL} - refers to triangle shapes
 \Rightarrow test number of fields & their interactions

Threshold for new physics: $f_{\text{NL}}^{\text{any kind}} \gtrsim \mathcal{O}(1)$

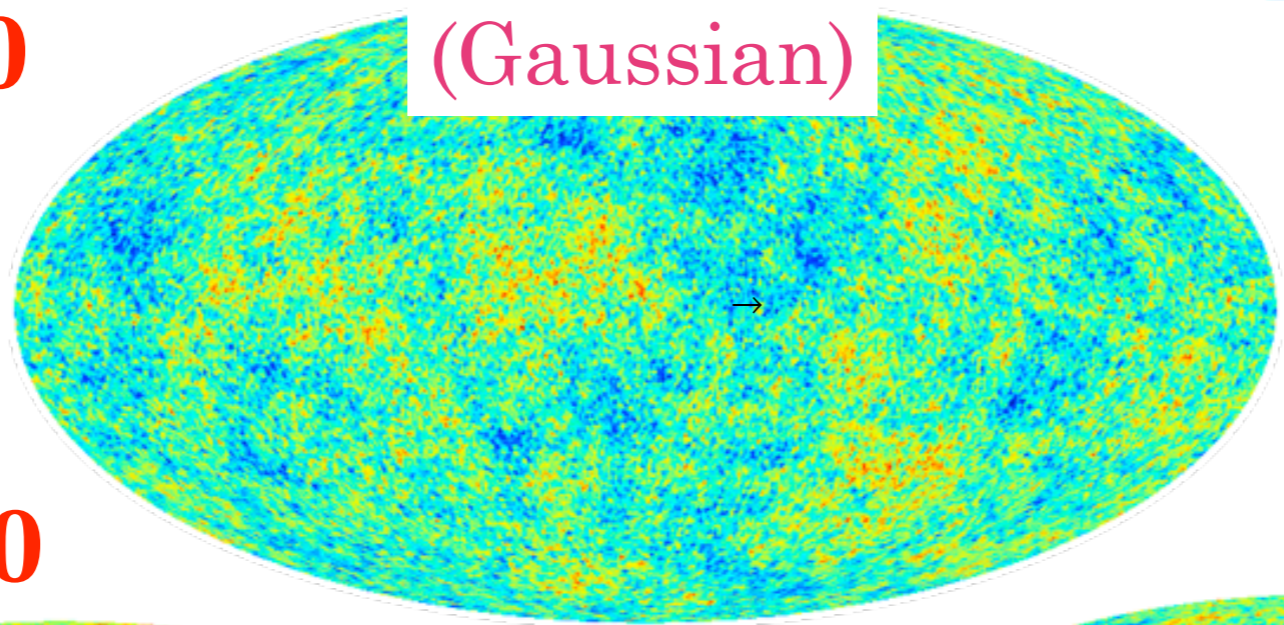
Simulated maps



$f_{NL} = -5000$

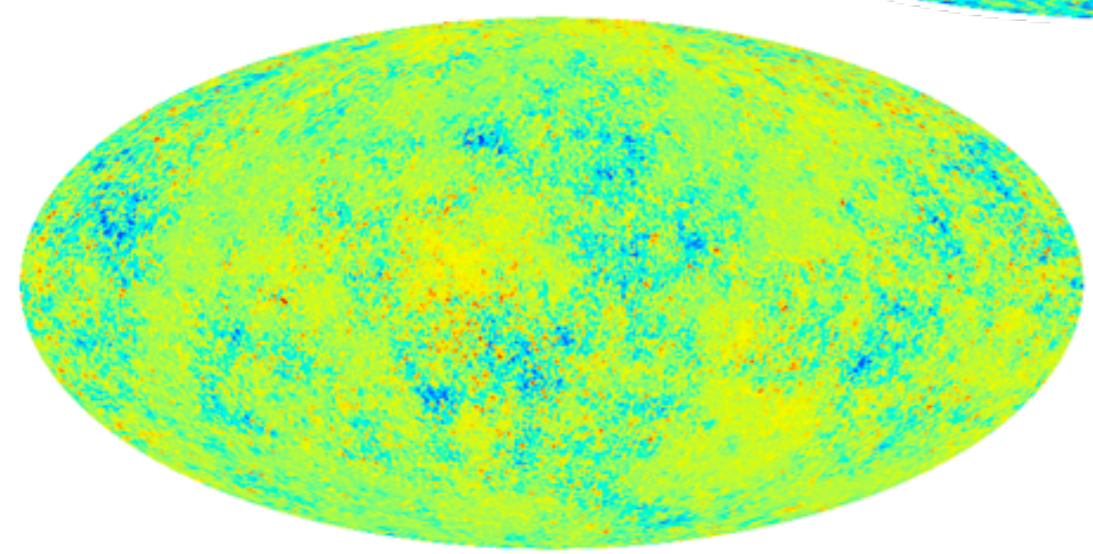


$f_{NL} = -500$

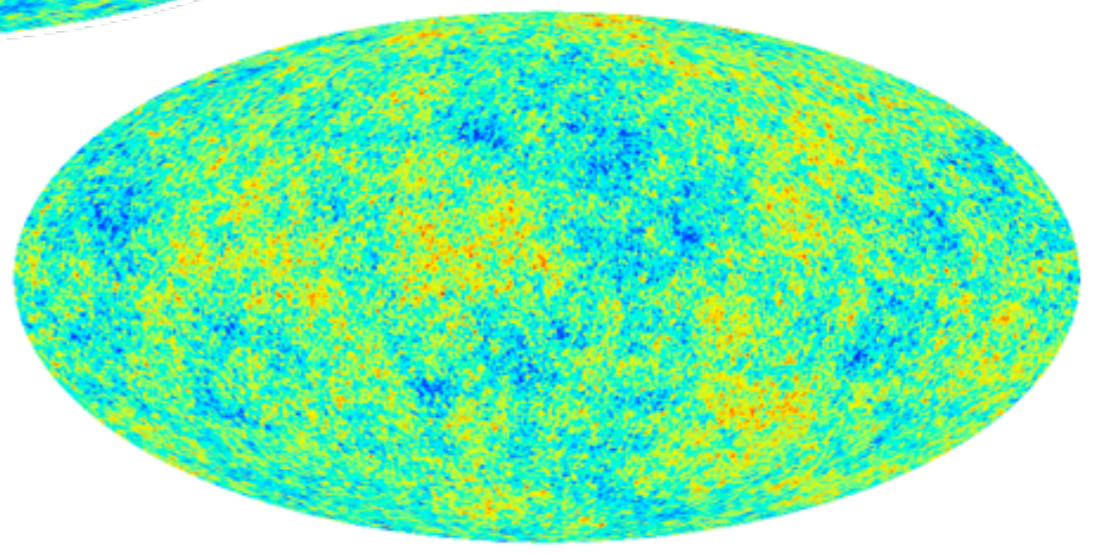


$f_{NL} = 0$
(Gaussian)

$f_{NL} = +5000$



$f_{NL} = +500$



Planck Temp + Pol: $f_{NL} = 0.8 \pm 5.0$

Does galaxy/halo **bias** depend on NG?

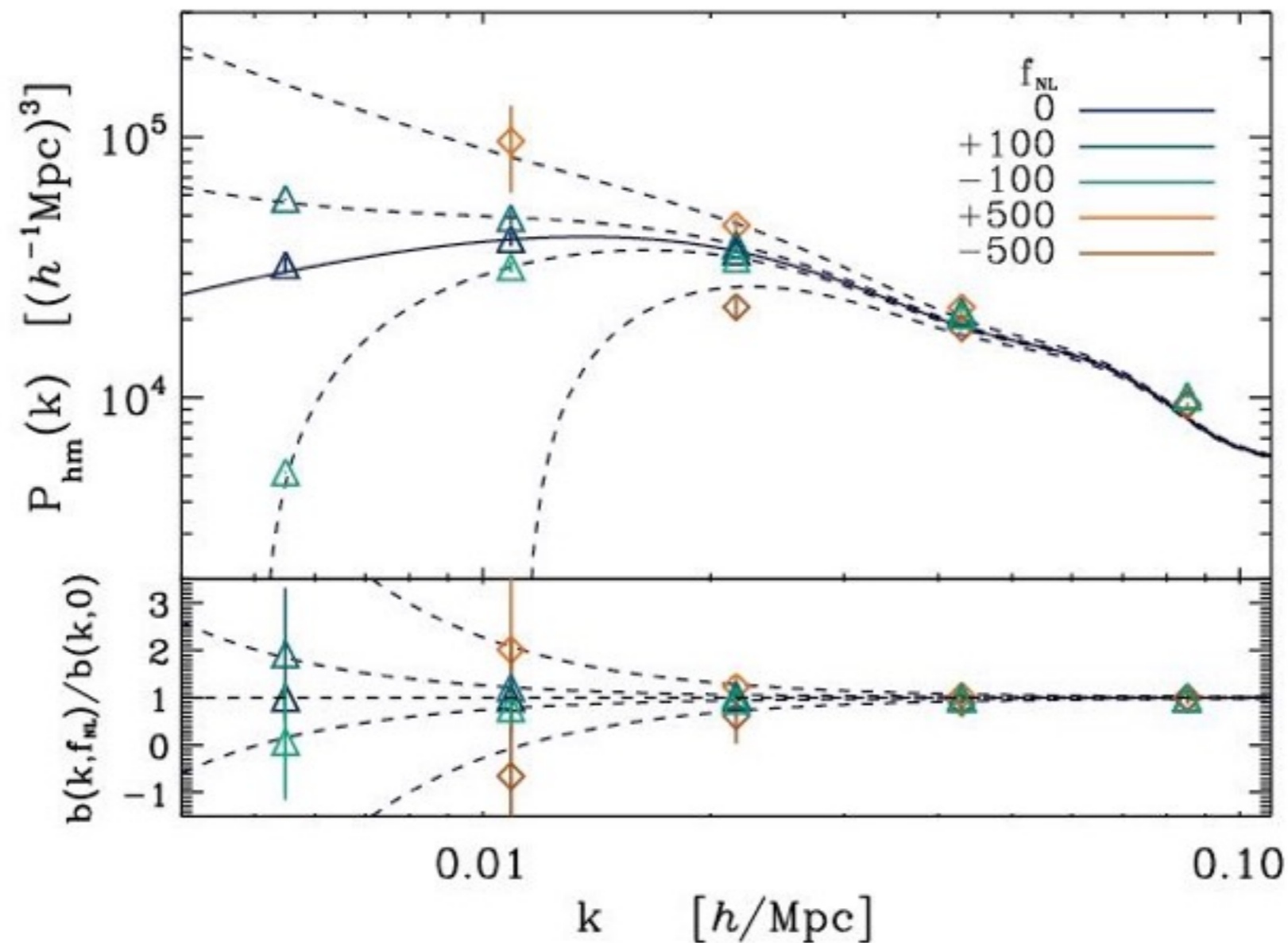
$$\text{bias} \equiv \frac{\text{clustering of galaxies}}{\text{clustering of dark matter}} = \frac{\left(\frac{\delta\rho}{\rho}\right)_{\text{halos}}}{\left(\frac{\delta\rho}{\rho}\right)_{\text{DM}}}$$

usually nuisance parameter(s) cosmologists measure theory predicts

$$P_h(k, z) = b^2(k, z) P_{\text{DM}}(k, z)$$

(theorem:) Large-scale bias is scale-independent (**b doesn't depend on k**)
if the short and long modes are uncorrelated
that is, **if structure distribution is Gaussian**

Scale dependence of NG halo bias



$$b(k) = b_G + f_{\text{NL}} \frac{\text{const}}{k^2}$$

Verified using a variety of theory and simulations.
 ~500 papers on subject so far.

SPHEREx

proposal for telescope dedicated to measuring NG (and other science)

[Home](#)

[Science](#)

[Instrument](#)

[Strategy](#)

[Publications](#)

[Team](#)



spherex.caltech.edu

- 97 bands (!) with Linearly Variable Filters (LVF)
- λ between 0.75 and 4 μm
- small (20cm) telescope, big field of view
- whole sky out to $z \sim 1$
- **goal: $\sigma(f_{\text{NL}}) \lesssim 1$**

Non-Gaussianity vs inflation recap:

If we find:

$f_{\text{NL}}^{\text{local}} \gtrsim O(1) \Rightarrow$ multiple fields

$f_{\text{NL}}^{\text{equil}} \gtrsim O(1) \Rightarrow$ strong coupling (non-slow roll)

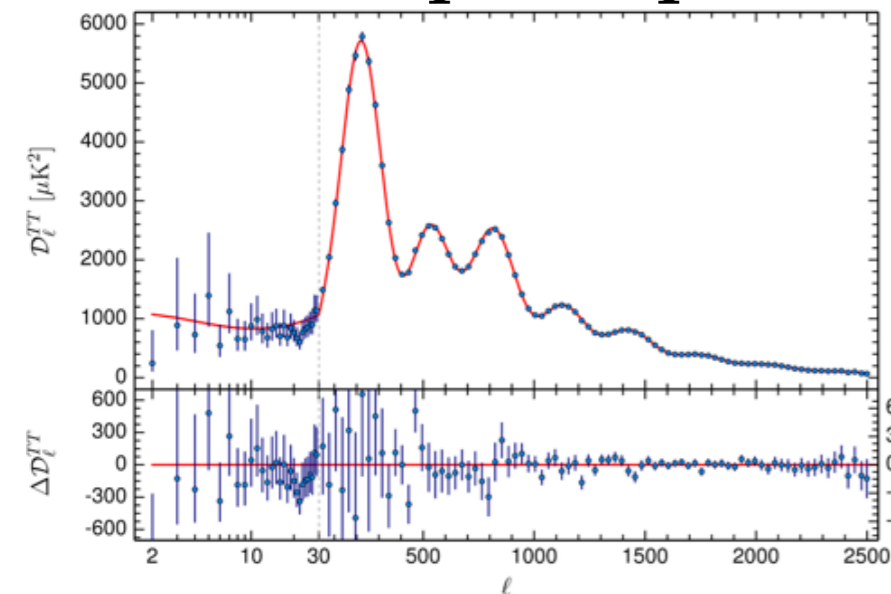
$f_{\text{NL}}^{\text{any kind}} < O(1)$ [no detection] \Rightarrow
consistent with slow-roll, weakly coupled single field

Story so far:

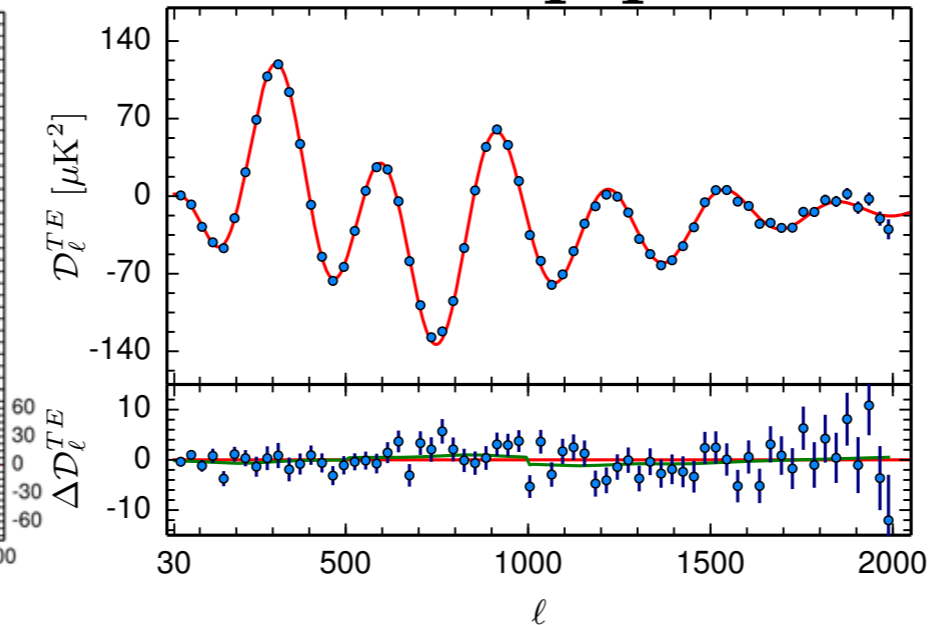
- Cosmology definitely in the precision regime
- Impressive constraints on DM, DE and inflation...
- ...but some big questions unanswered
- Lots of potential from upcoming surveys

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

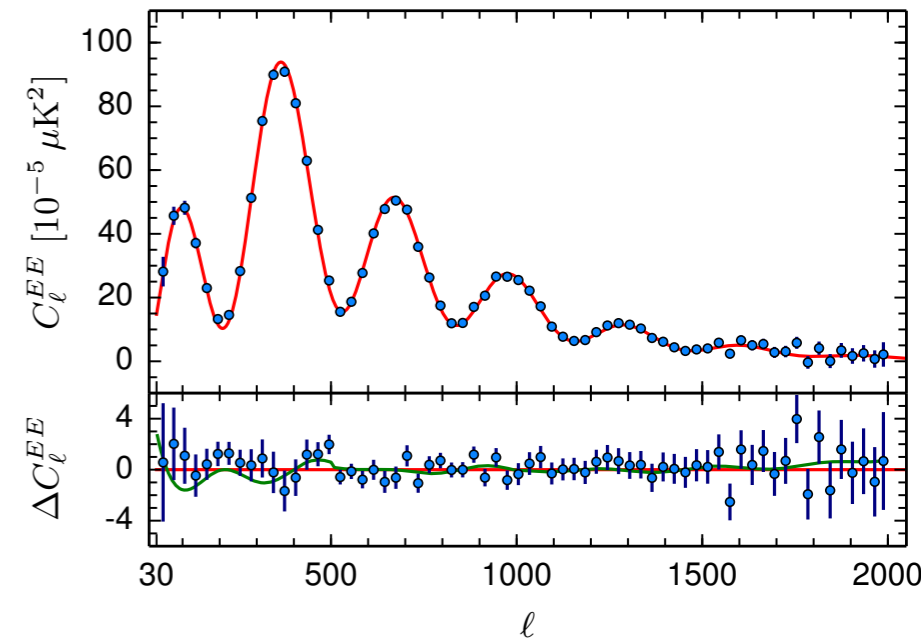
temp-temp



temp-pol



pol-pol



Danger of declaring currently favored model to be the truth

\Rightarrow **blinding new data is key**

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 in cosmology, particularly in the large-scale structure
- 3 big questions: dark matter, dark energy, inflation
- Ability to measure parameters, test theories, at the 1% level
- Blinding in analysis (along with sophisticated statistical tools) will be key
- Like particle physicists, we would really like to see some “bumps” in the data