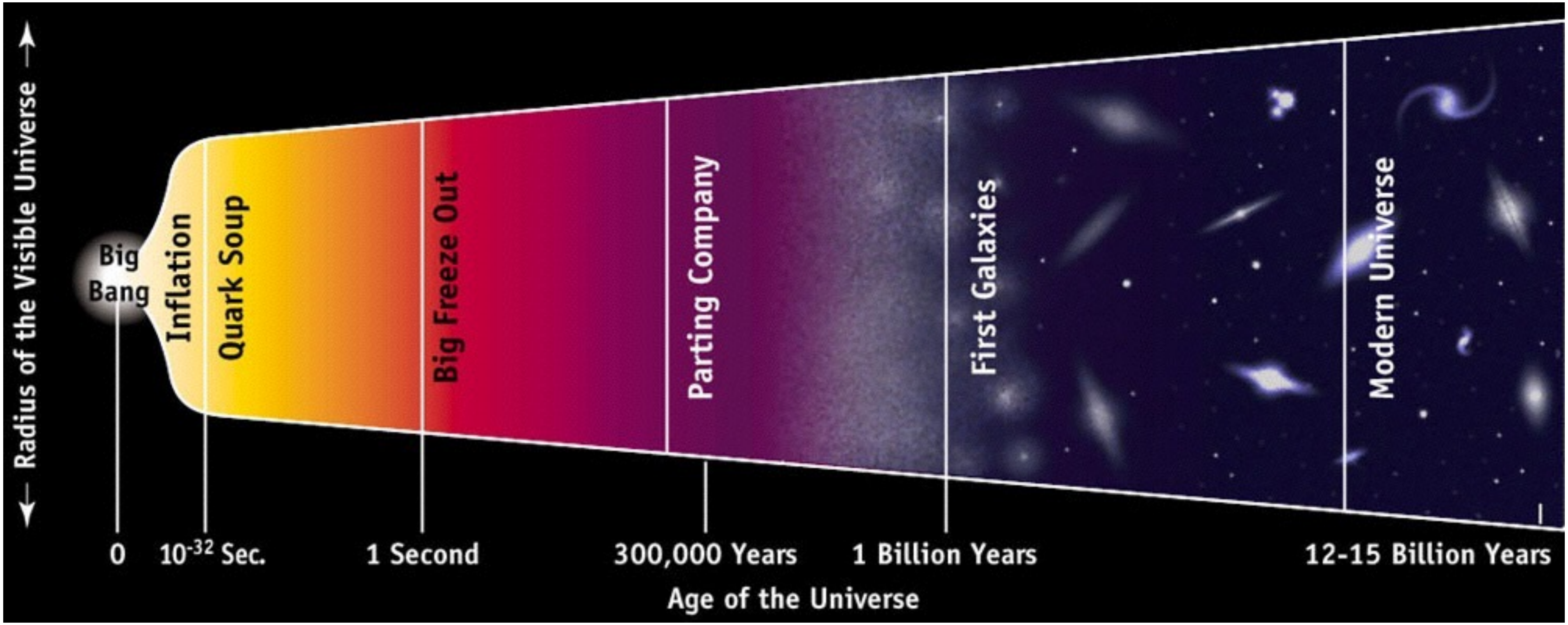
New views of the Universe

Dragan Huterer
University of Michigan

Illustris simulation

Three key questions in cosmology

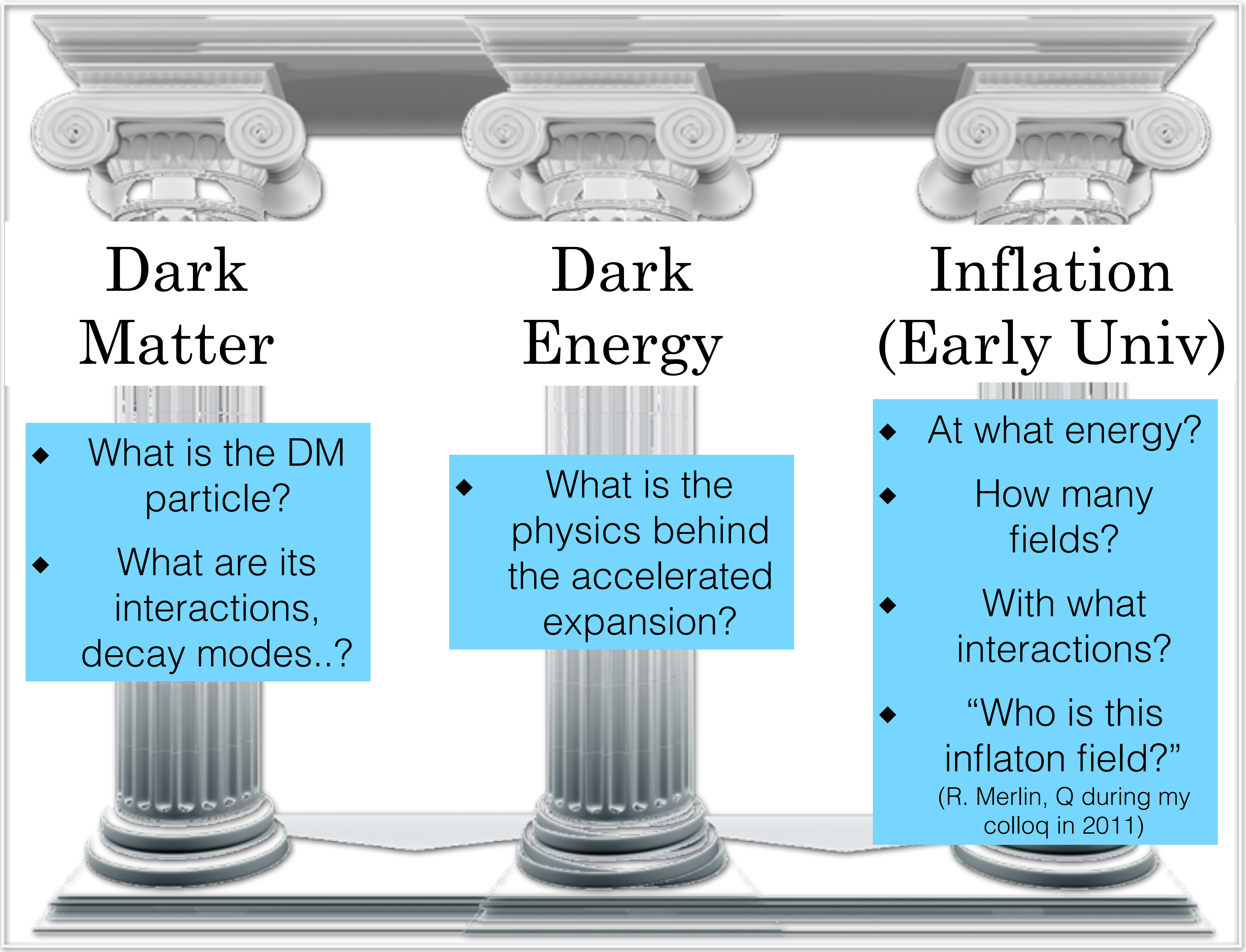


Inflation

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?” (R. Merlin, Q during my colloq in 2011)

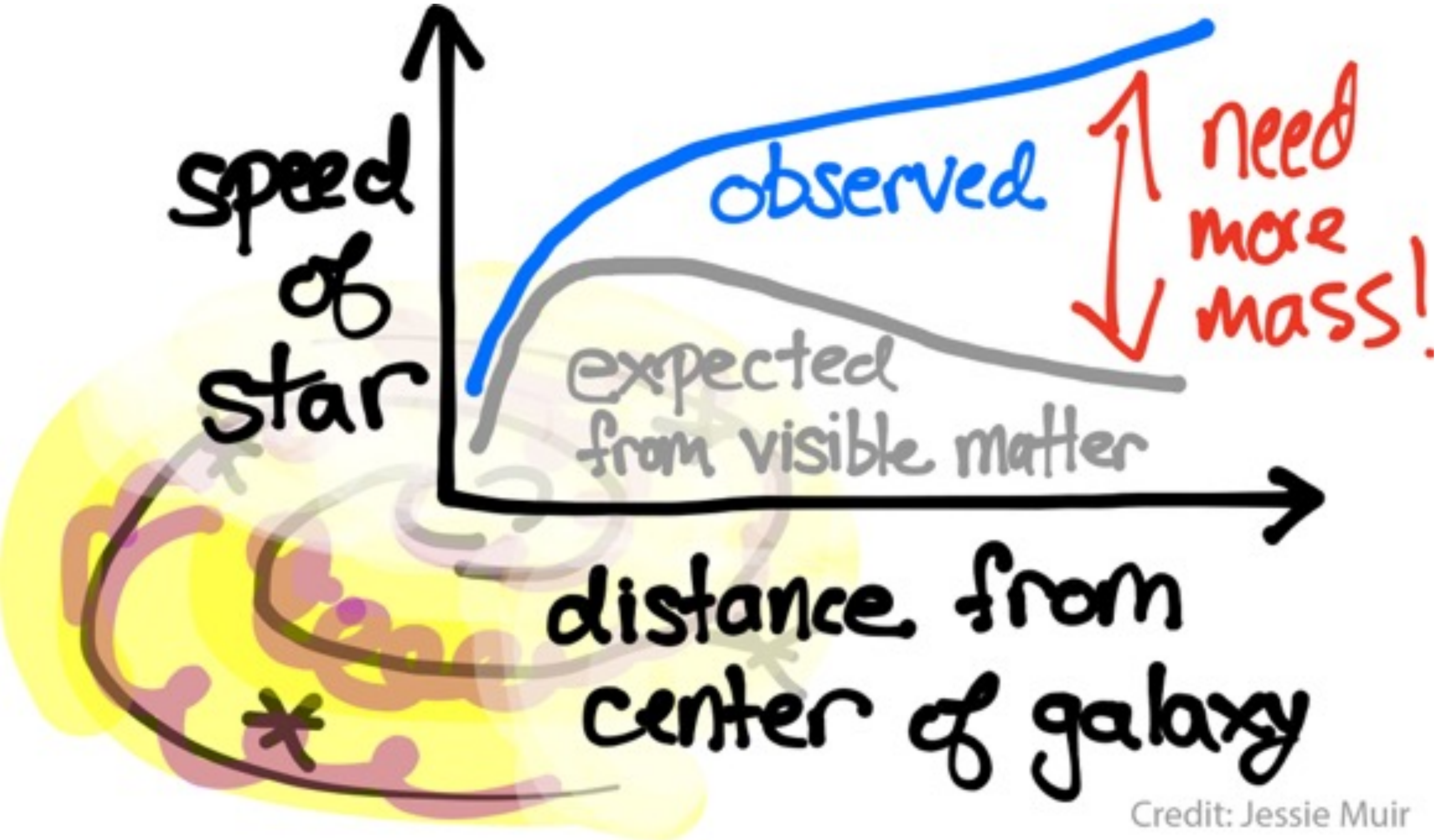
Dark Matter

Fritz Zwicky
“Dunkle Materie”,1933

Coma cluster
of galaxies

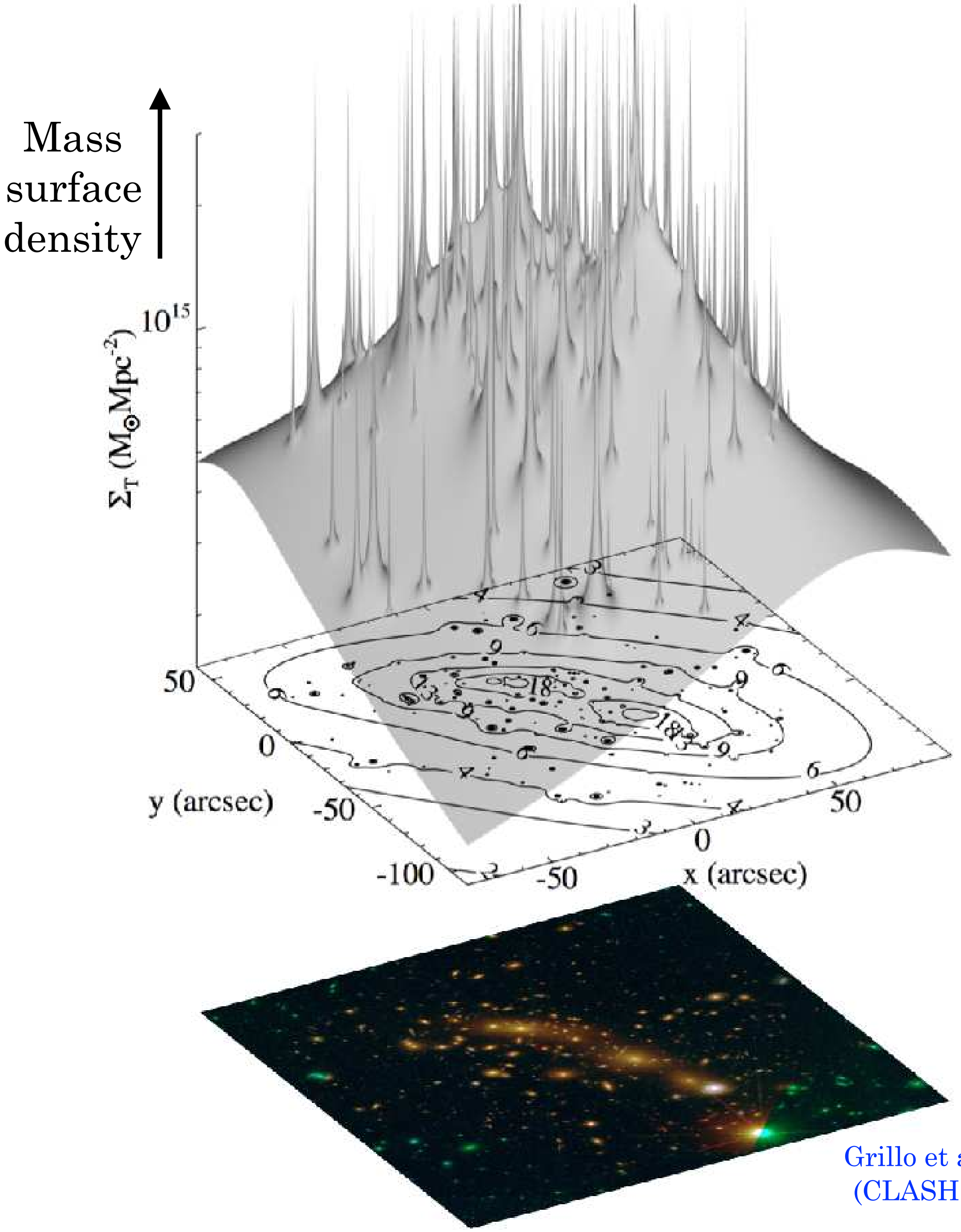
Illustration:
Jessie Muir

Vera Rubin
flat rotation curves, 1970s



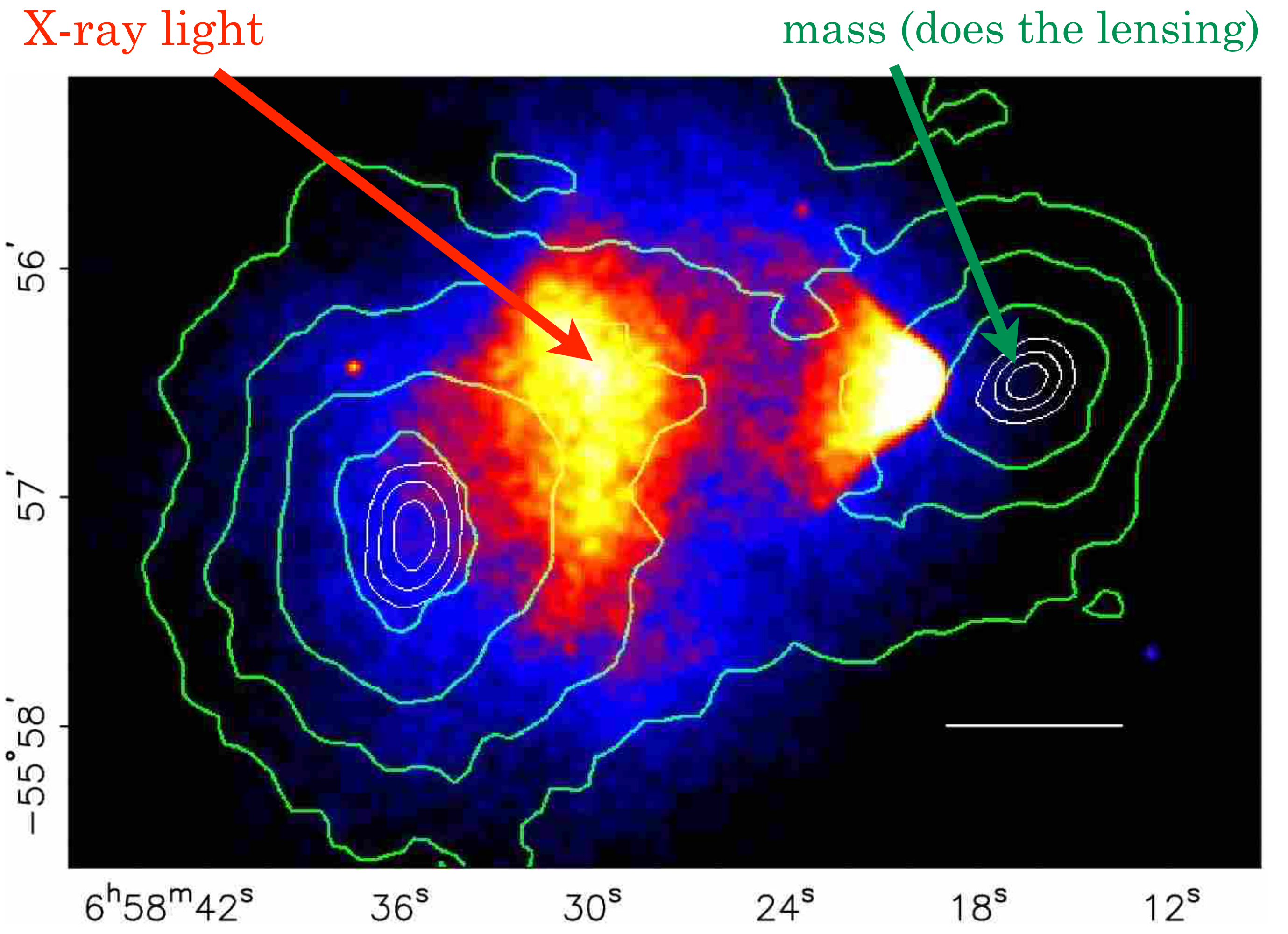
Credit: Jessie Muir

Modern evidence for Dark Matter


Mass surface density

Grillo et al 2015
(CLASH team)

Mass profile around a cluster

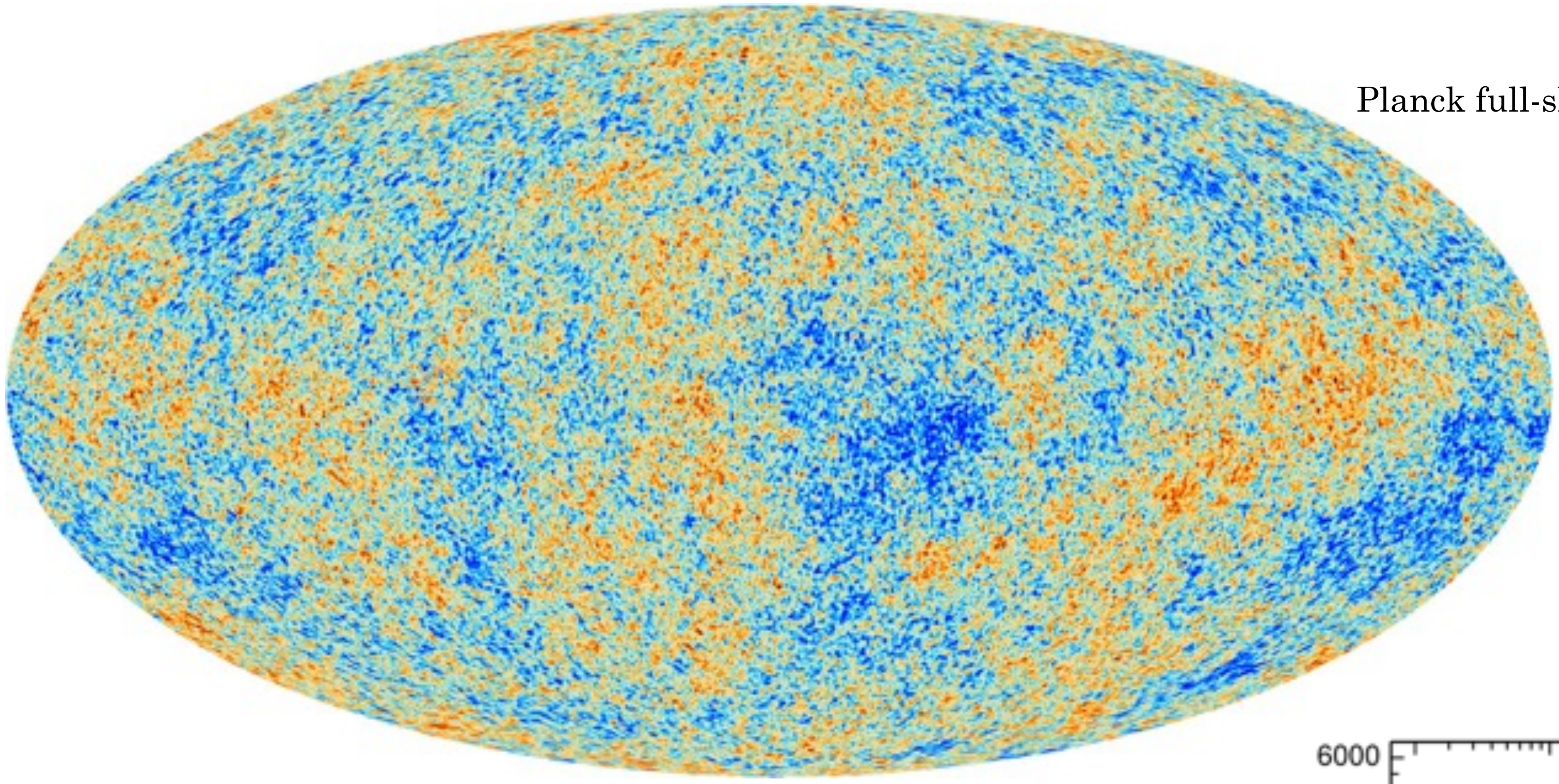

X-ray light

mass (does the lensing)

Markevitch et al
Clowe et al

Bullet cluster

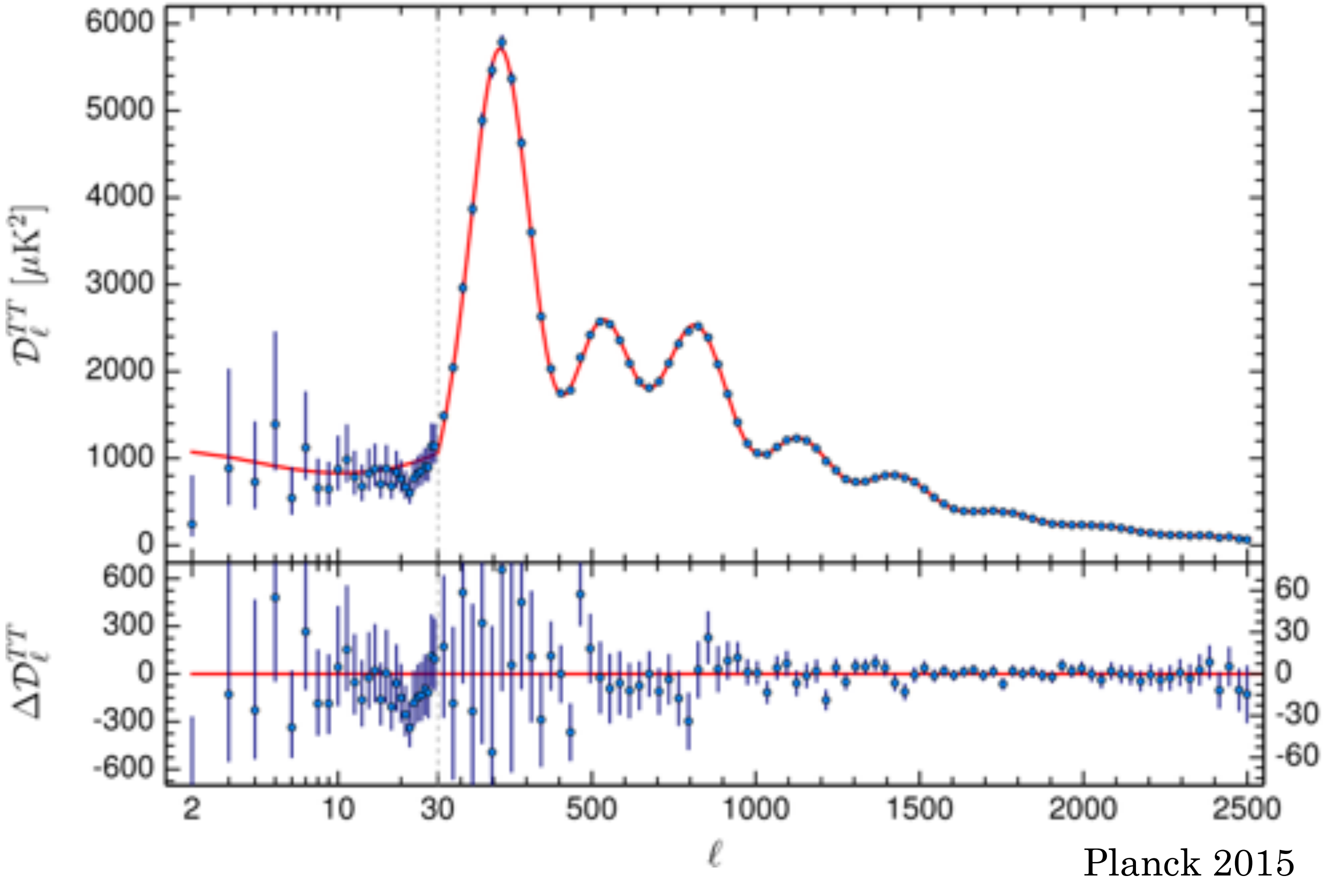
Modern evidence for Dark Matter



Planck full-sky map

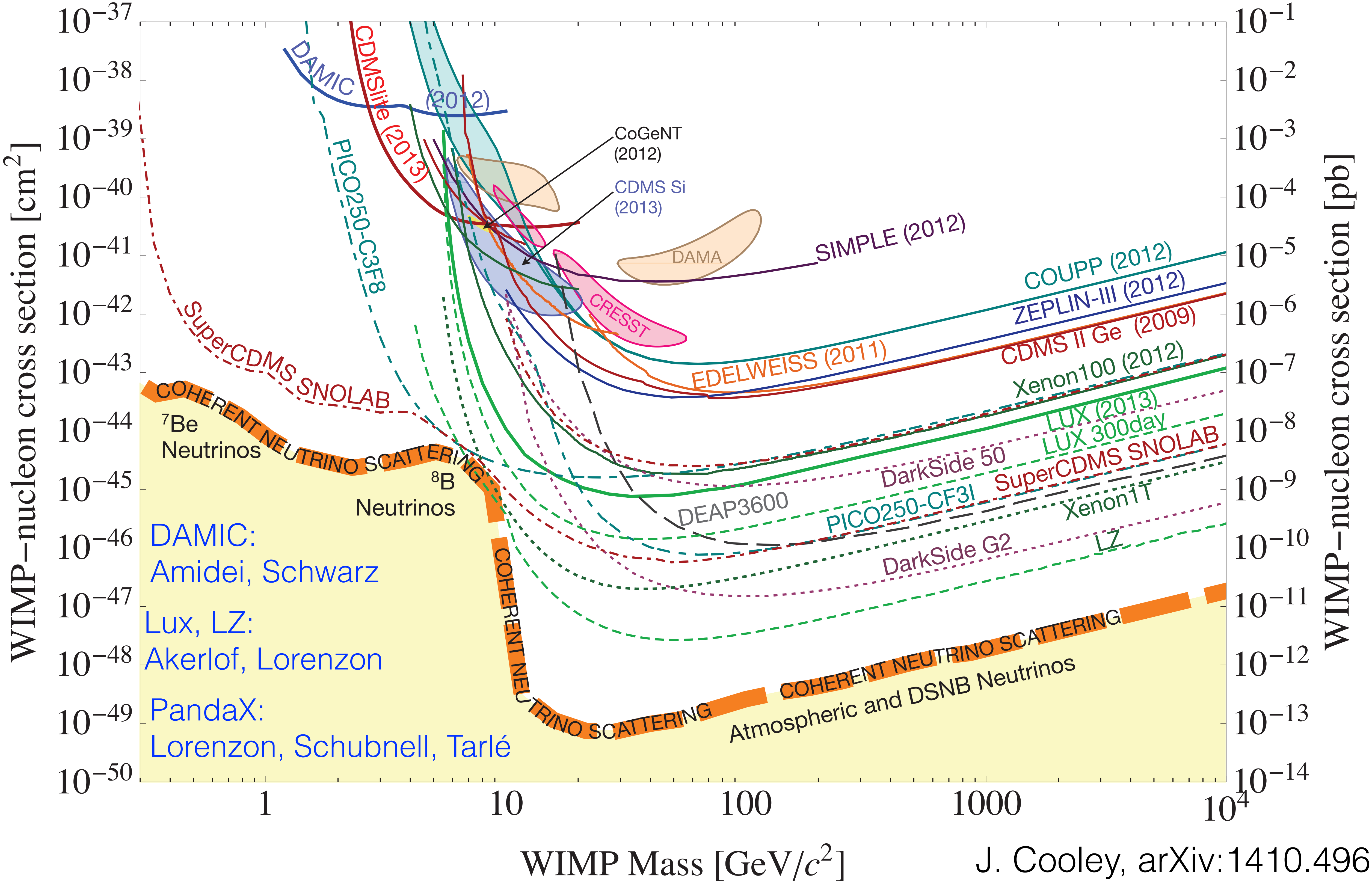
$$\Omega_{\text{dark matter}} h^2 = 0.1193 \pm 0.0014$$

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



Planck 2015

Direct searches: Cross-section vs mass constraints



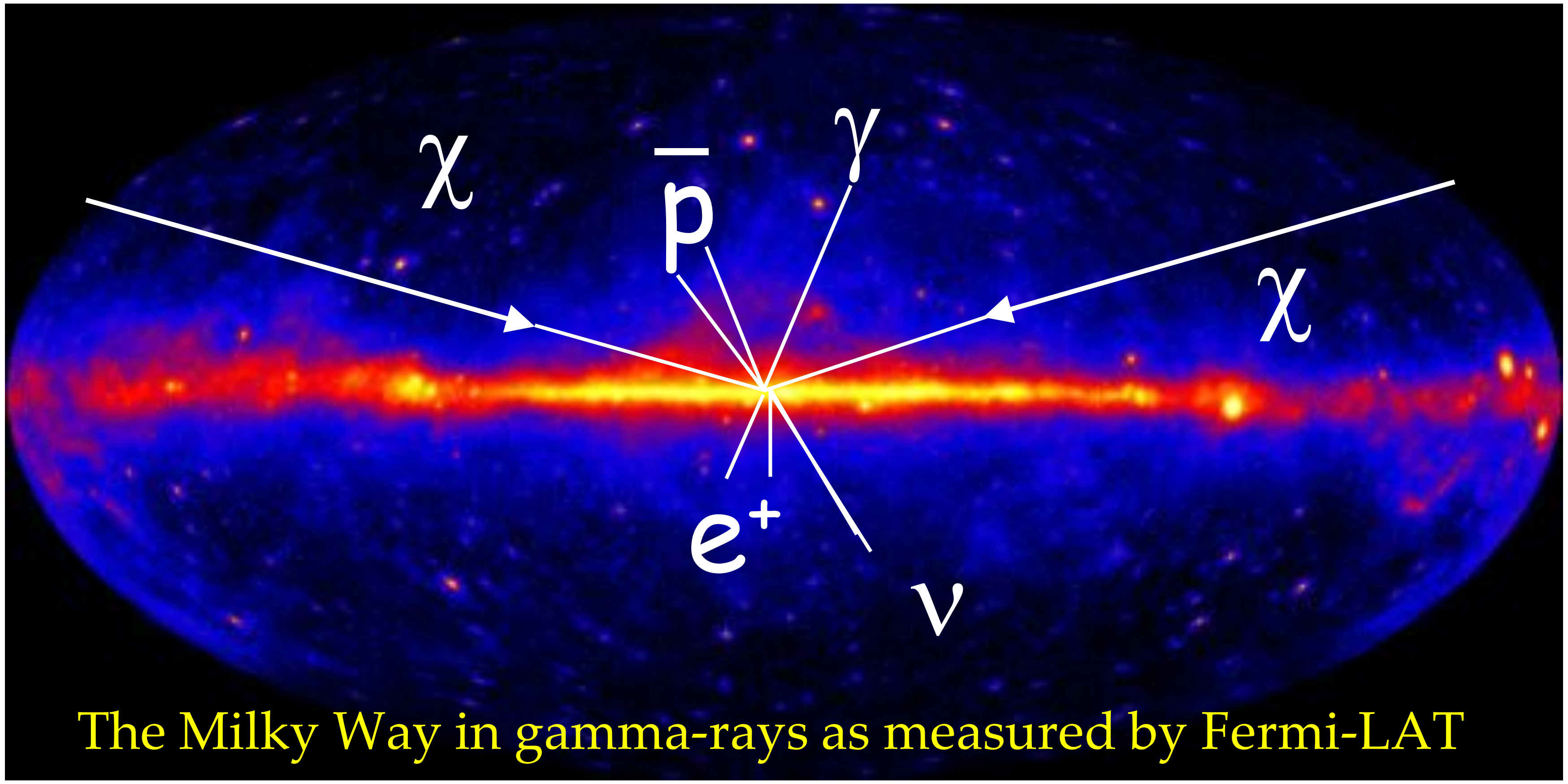
DAMIC:
Amidei, Schwarz

Lux, LZ:
Akerlof, Lorenzon

PandaX:
Lorenzon, Schubnell, Tarlé

J. Cooley, arXiv:1410.4960

Indirect detection



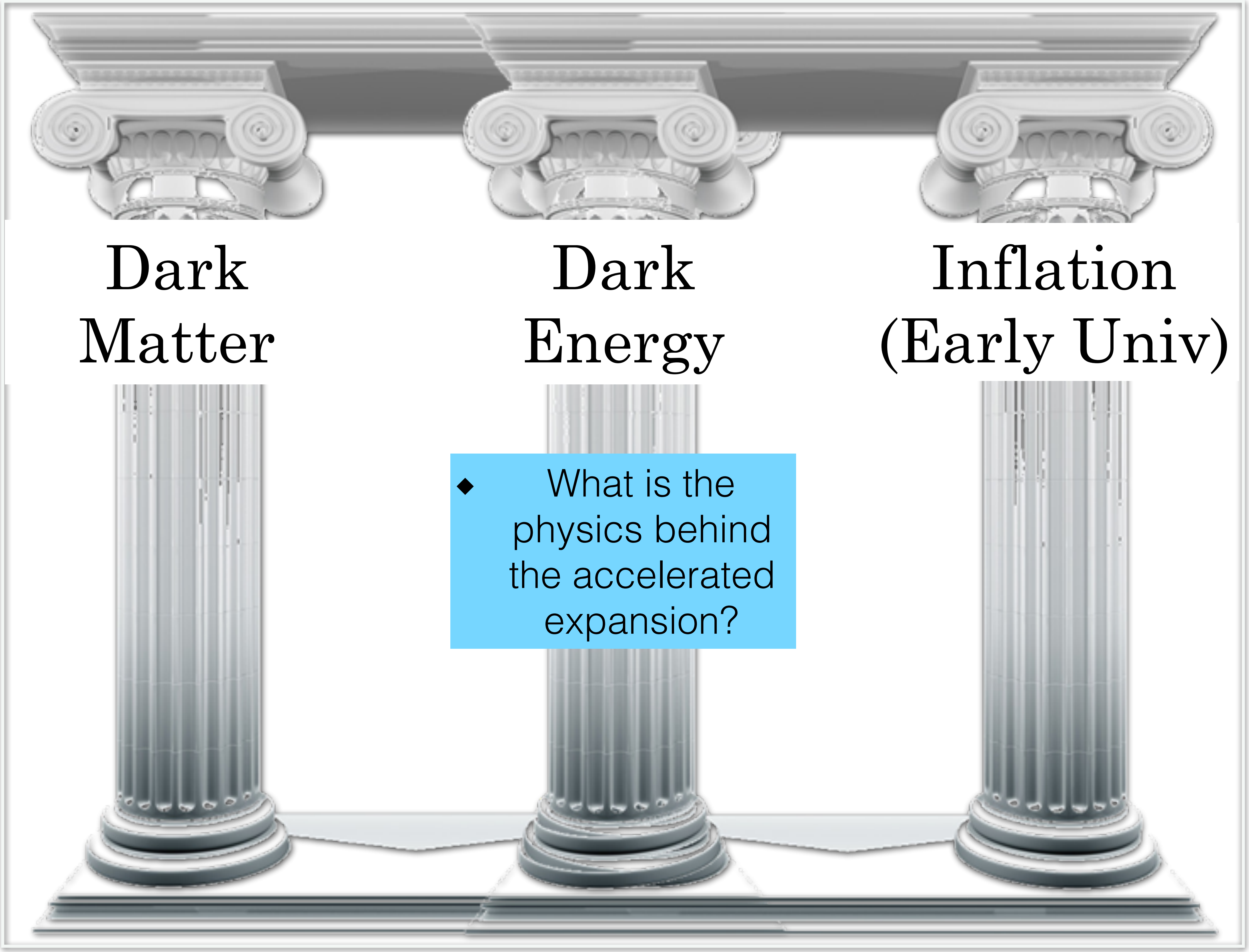
The Milky Way in gamma-rays as measured by Fermi-LAT

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



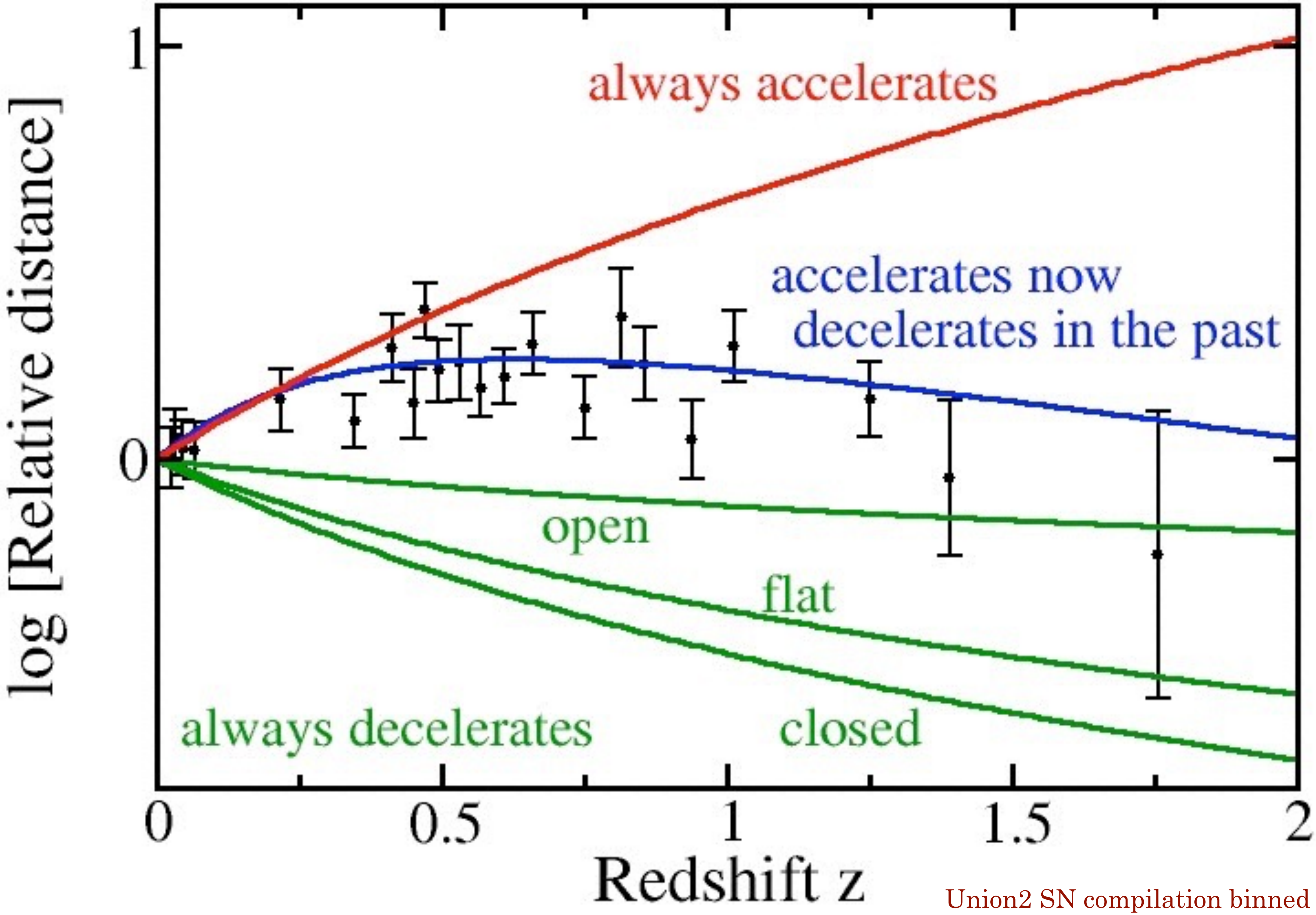
Dark Matter

Dark Energy

Inflation (Early Univ)

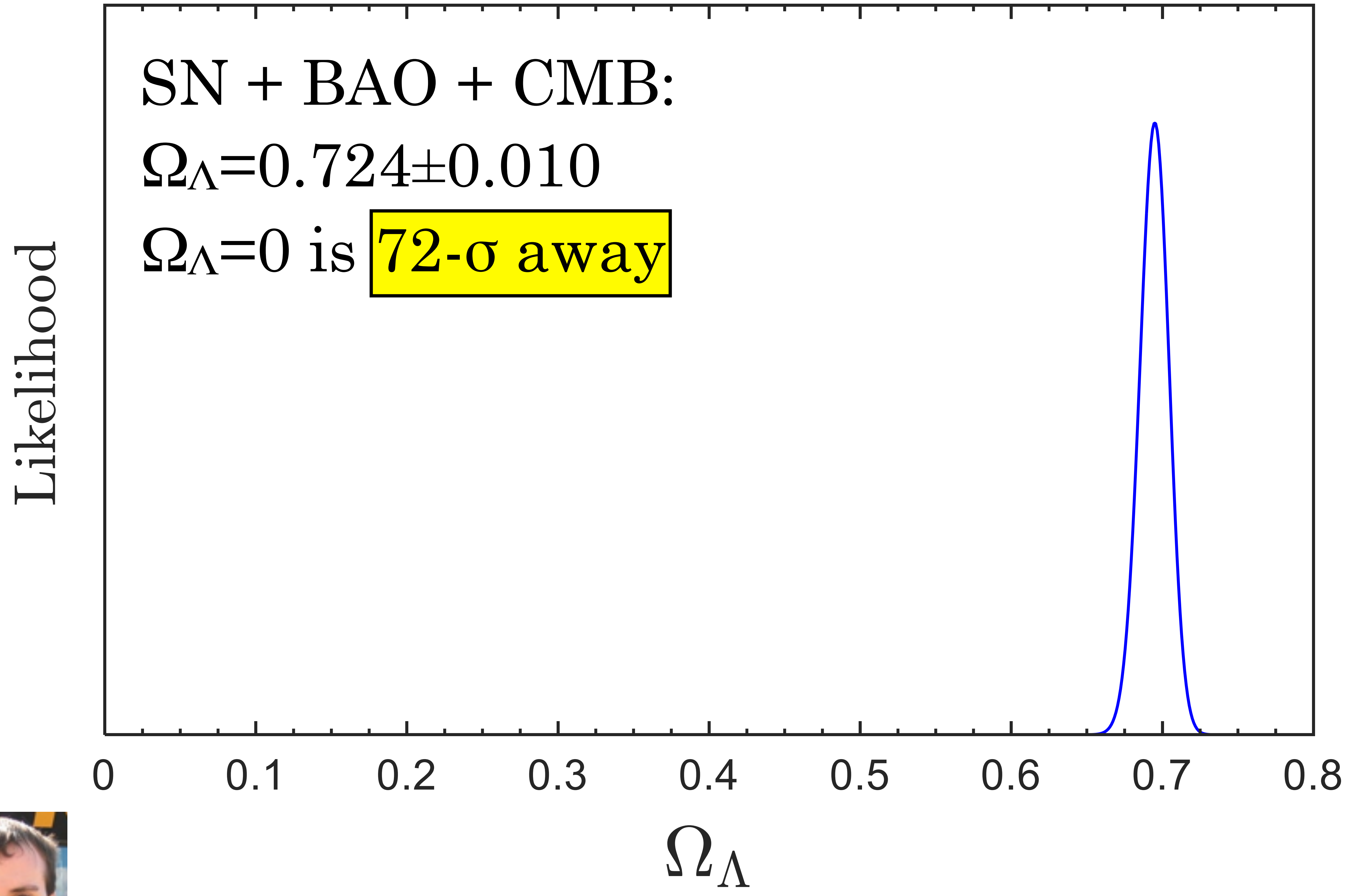
- What is the physics behind the accelerated expansion?

Evidence for Dark energy from type Ia Supernovae



Union2 SN compilation binned in redshift

Current evidence for dark energy is impressively strong

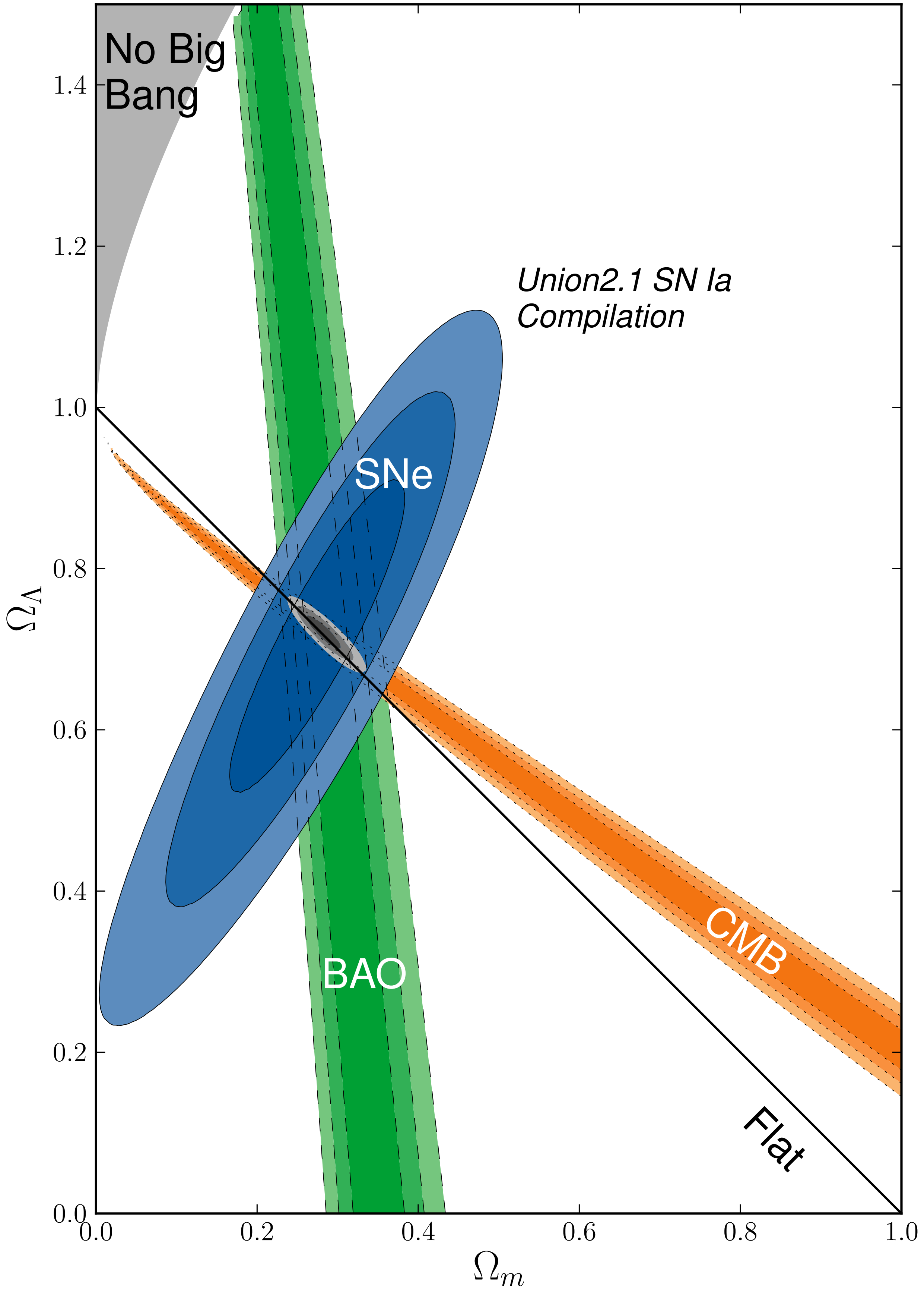


SN + BAO + CMB:

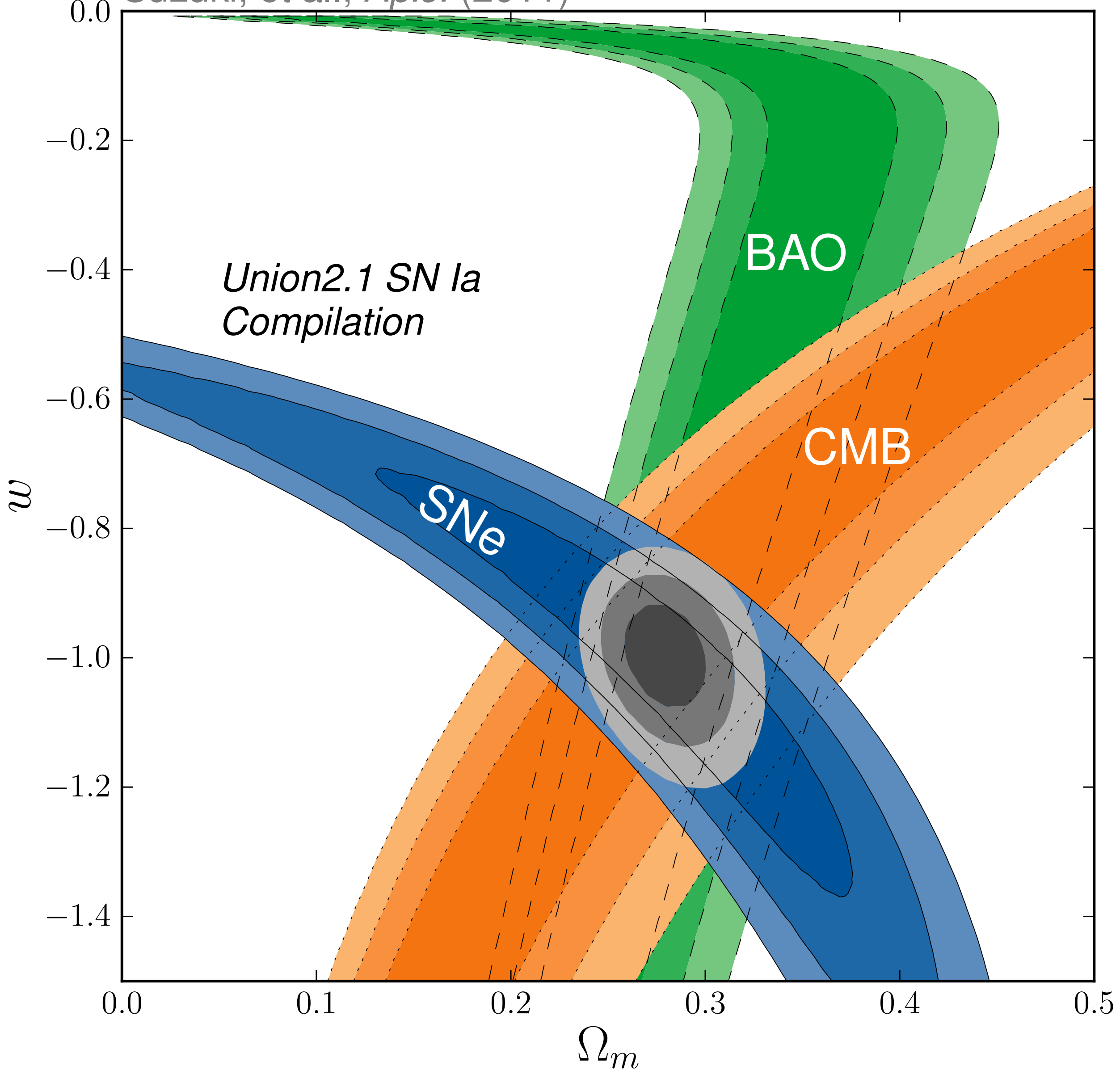
Ω_Λ=0.724±0.010

Ω_Λ=0 is 72-σ away

Daniel Shafer
PhD 2016



Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)

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

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

Fine Tuning Problem: “Why so small”?

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

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

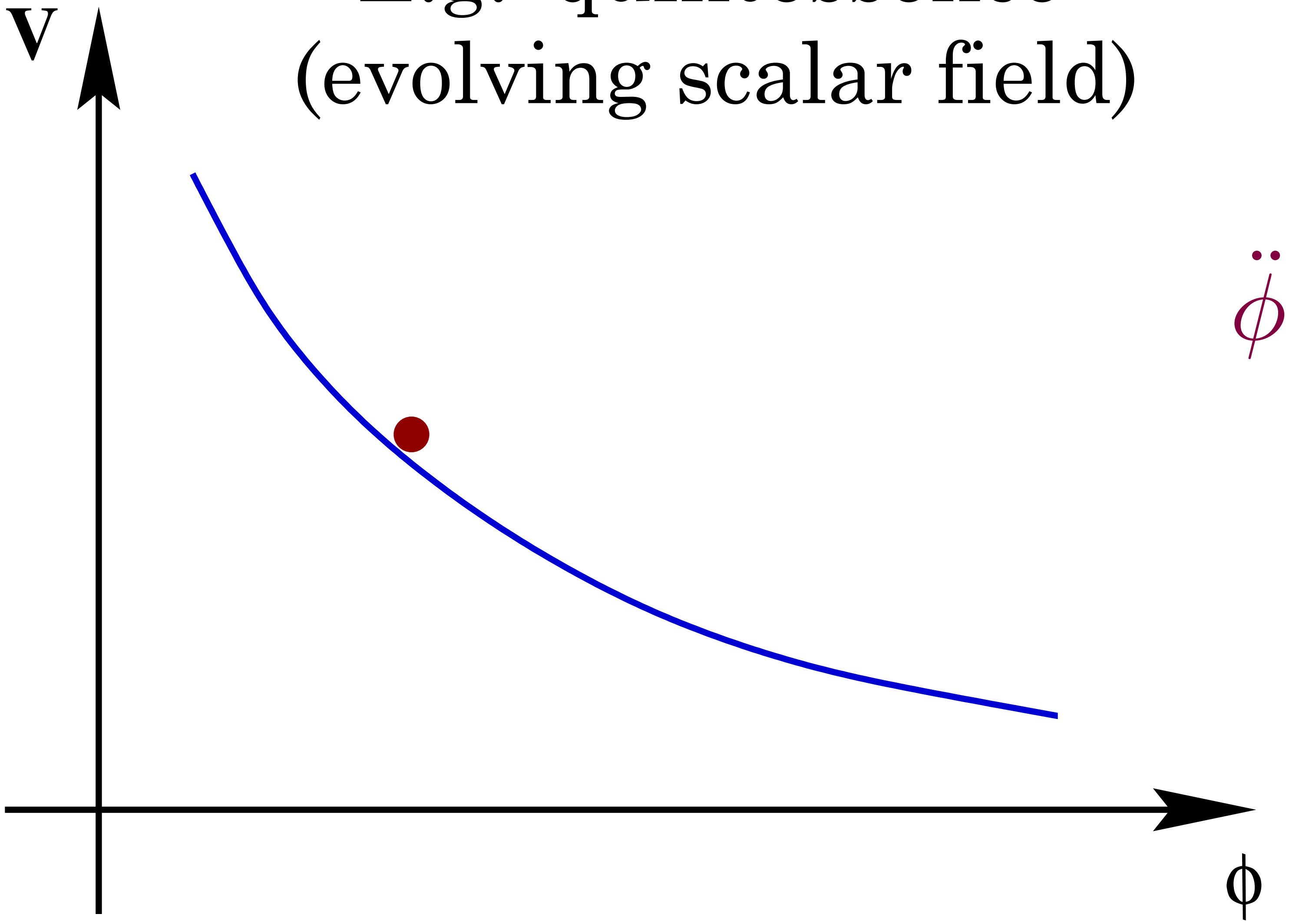
$$\left.\begin{array}{ll} \text{Measured:} & (10^{-3}\mathrm{eV})^4 \\ \text{SUSY scale:} & (1\,\mathrm{TeV})^4 \\ \text{Planck scale:} & (10^{19}\,\mathrm{GeV})^4 \end{array}\right\}$$

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)

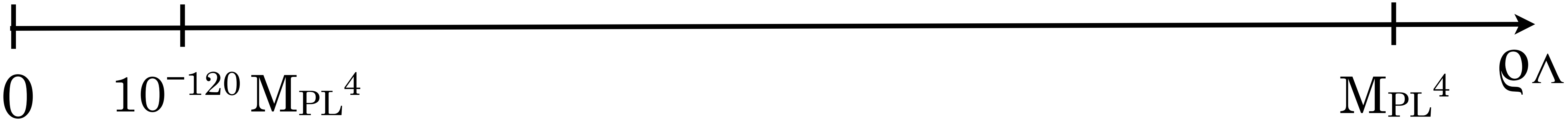


$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

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

String landscape?

$\Rightarrow$ A symptom of desperation.



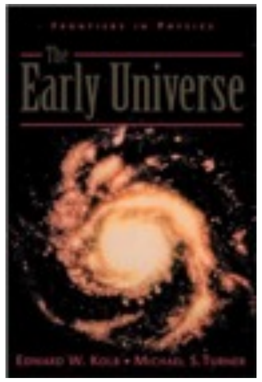
Among the $\sim 10^{500}$ minima,

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. $w=p/\varrho$, not known *a priori*

Contrast this situation with:

1. Neutrino masses:

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

*(assuming $m_3=0$)

2. Higgs Boson mass (before LHC 2012):

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

(assuming Standard Model Higgs)

What if gravity deviates from GR?

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

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)

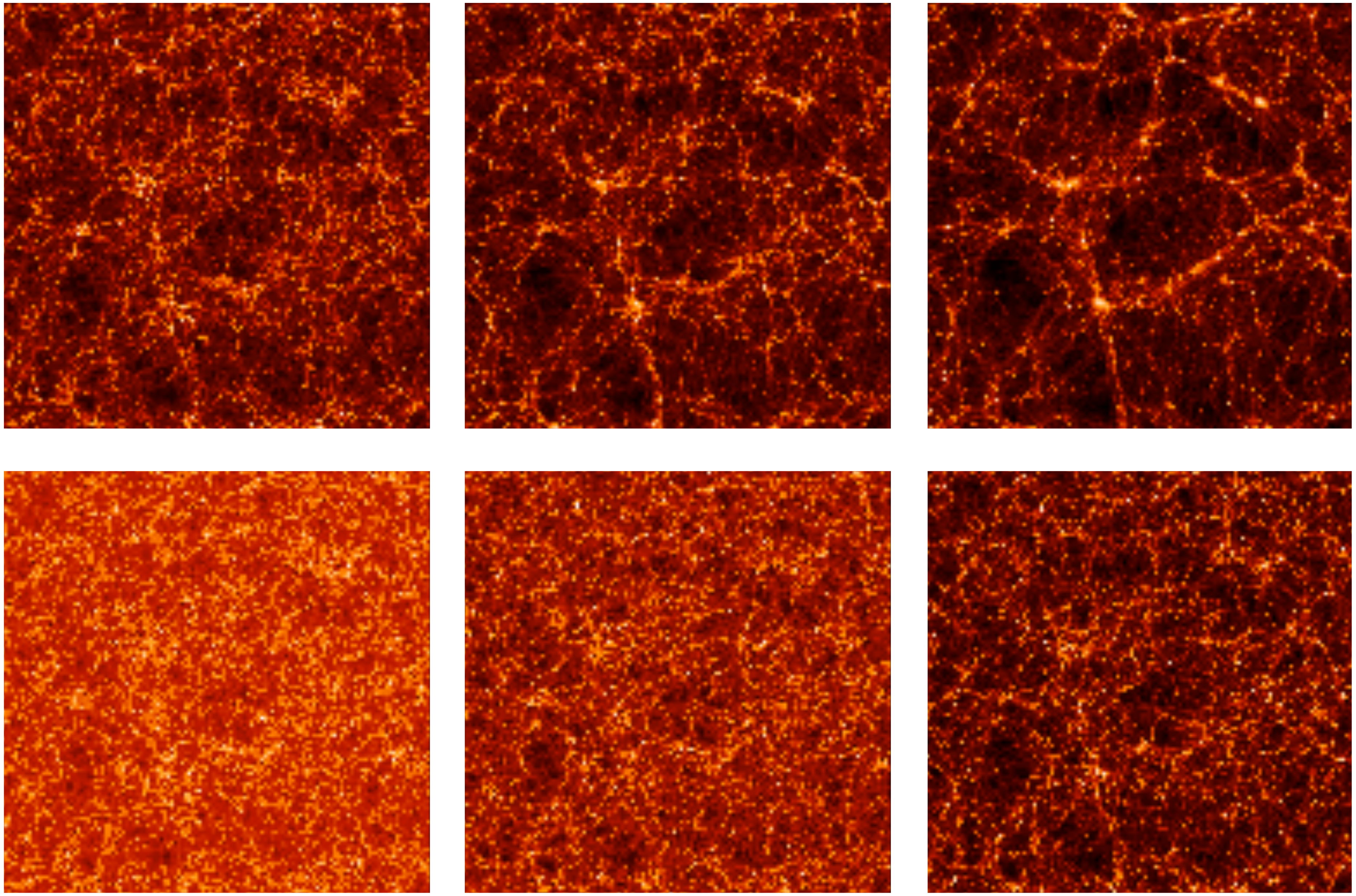
Probed by galaxy clustering,
weak lensing, cluster abundance

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)

Idea: compare geometry and growth

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, usual parameters]

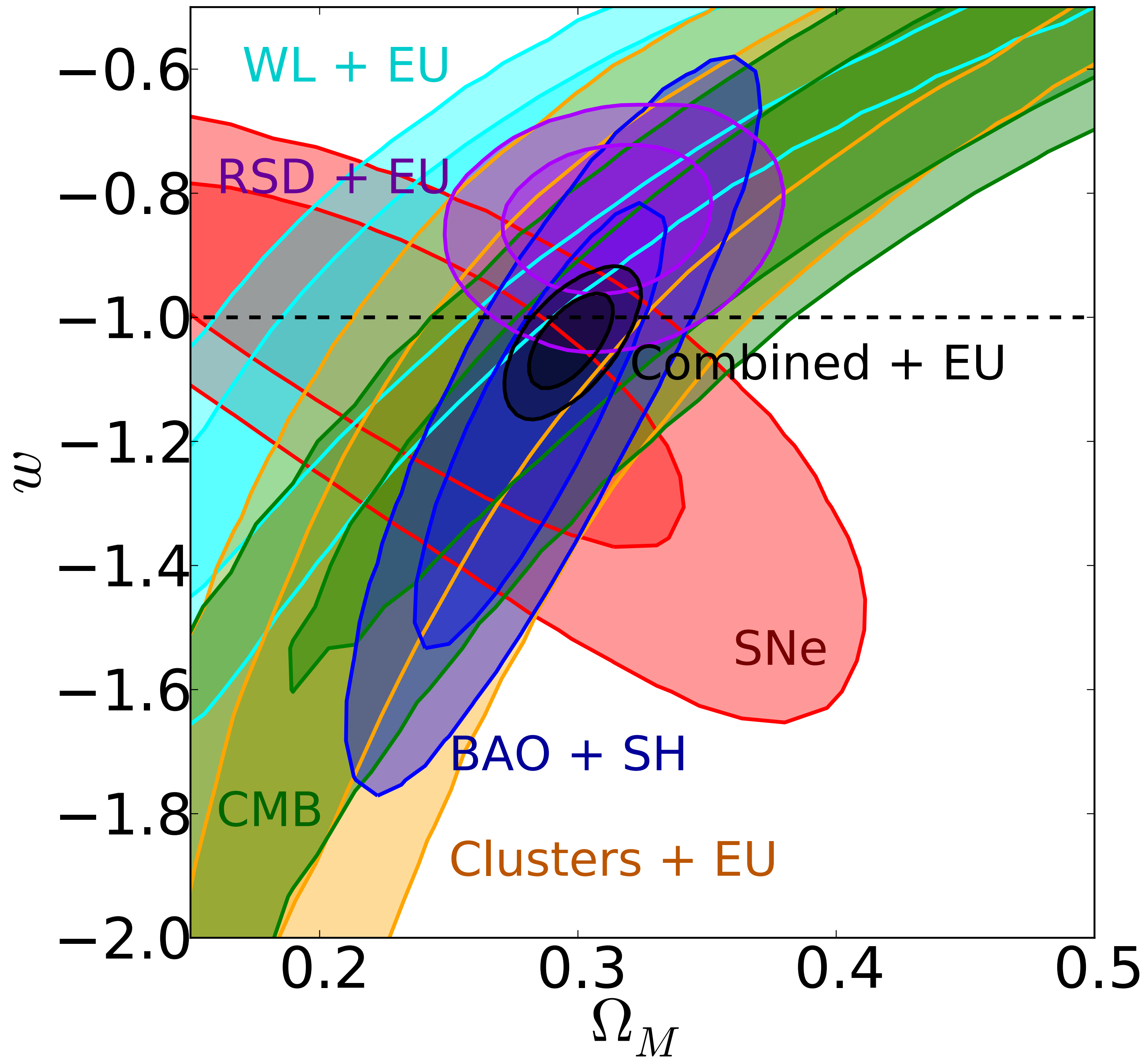
Eduardo Ruiz, PhD 2014

Ruiz & Huterer, PRD 2015

Sensitivity to geometry and growth

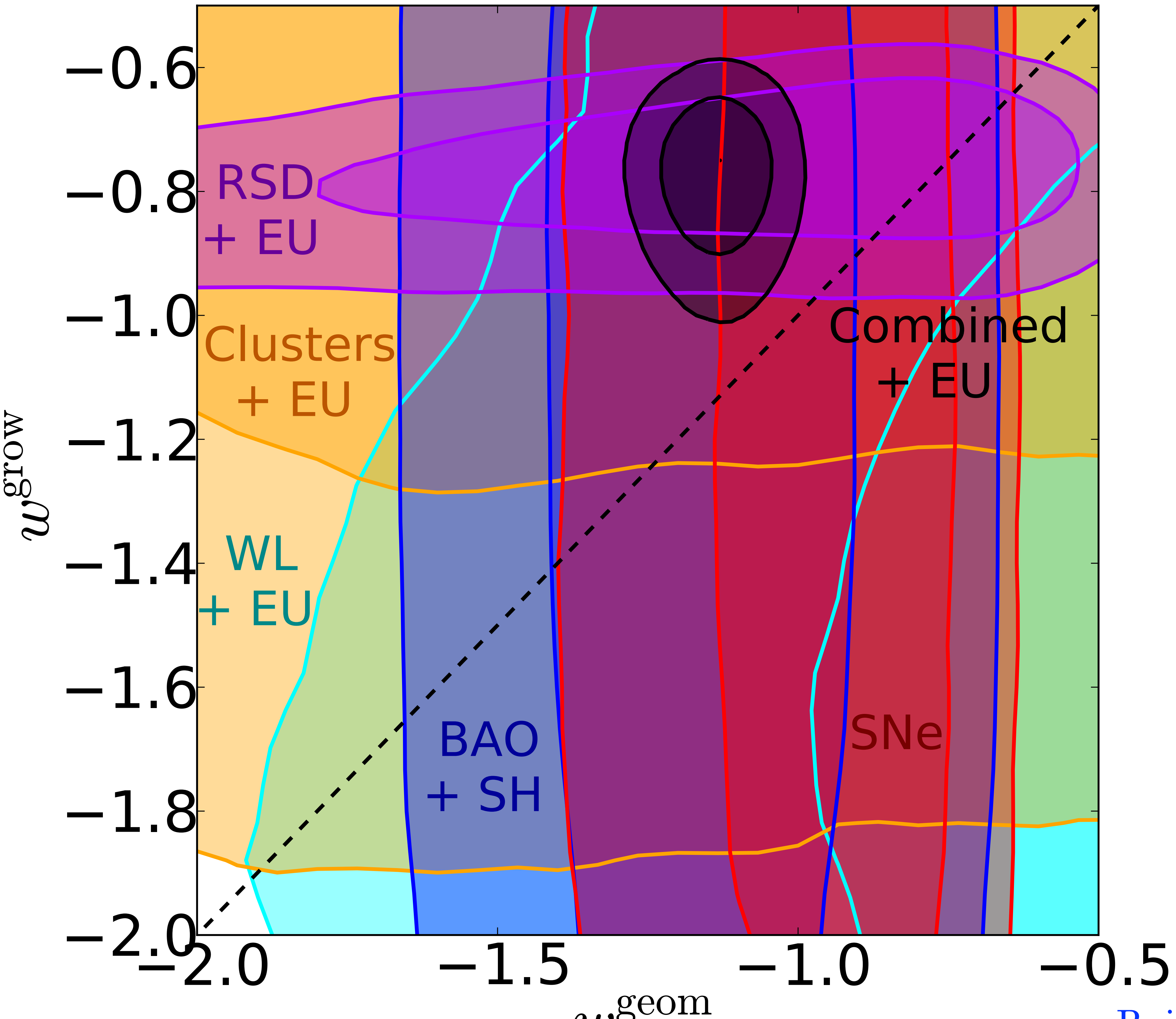
Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$	—
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2}\, D_A(z_*)$	—
Cluster counts	$\frac{dV}{dz}$	$\frac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$	$P\left(k = \frac{\ell}{r(z)}\right)$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



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

Ruiz & Huterer 2015

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)

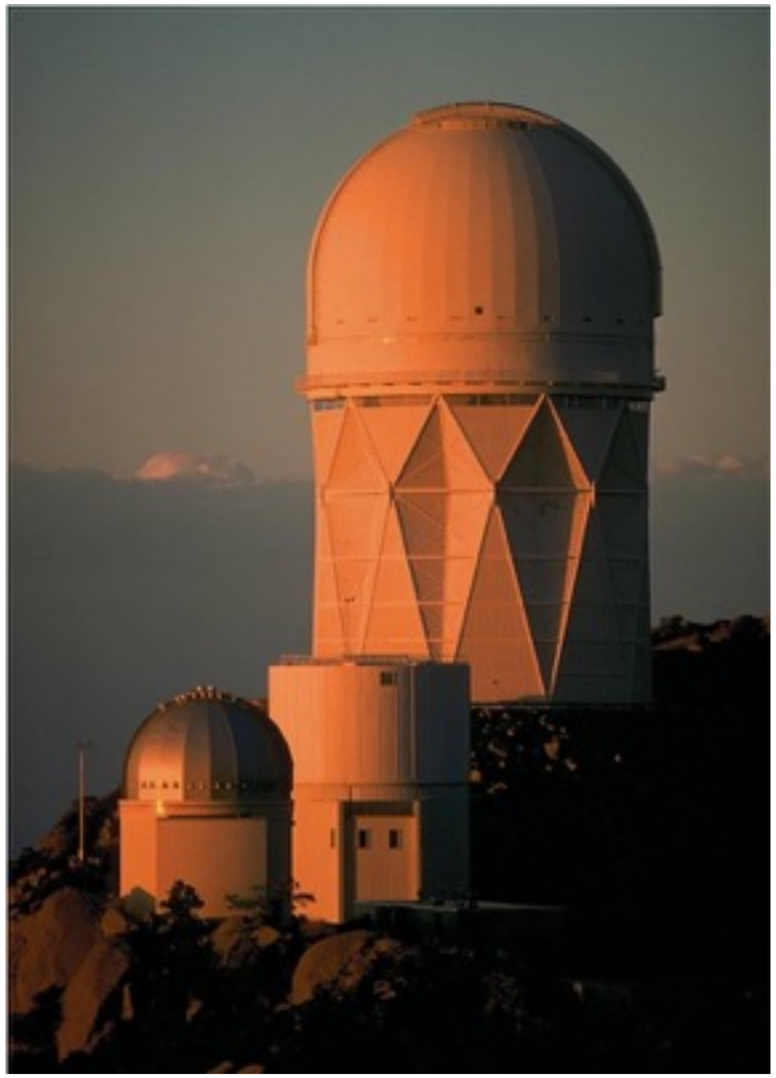
Dark Energy Survey (DES)

Evrard, Gerdes, Huterer, McKay, Miller, Schubnell, Tarlé

Cerro Blanco, Chile

Dark Energy Spectroscopic Instr. (DESI)

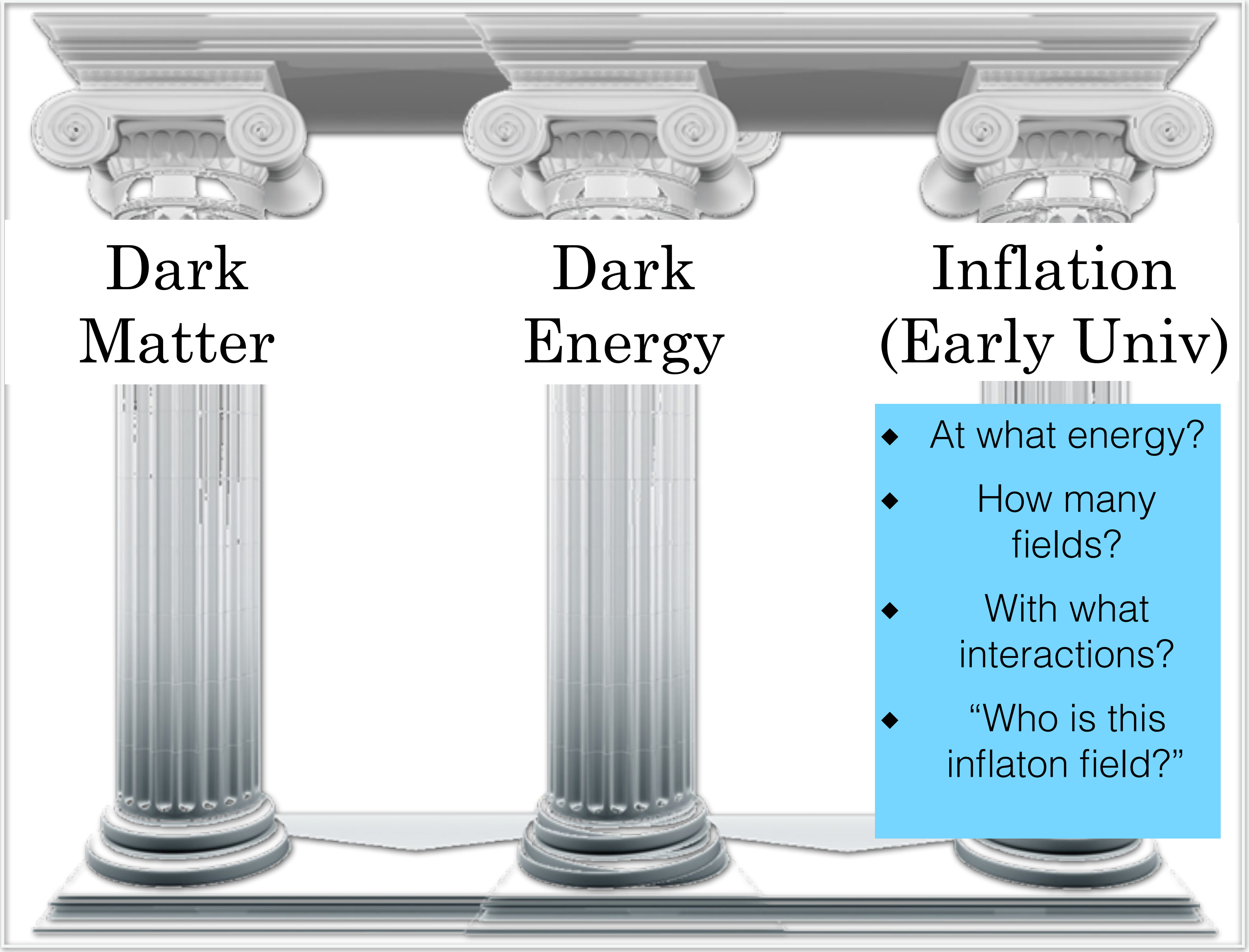
Gerdes, Huterer, Miller, Schubnell, Tarlé



Kitt Peak, Arizona

Fiber positioner
@UM (×5000)

Three big questions in cosmology



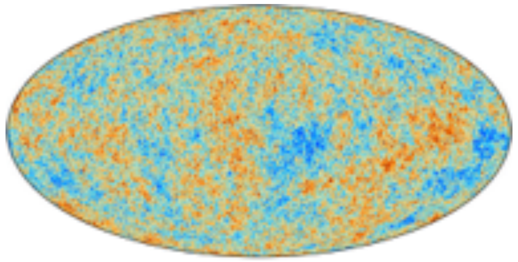
Dark Matter

Dark Energy

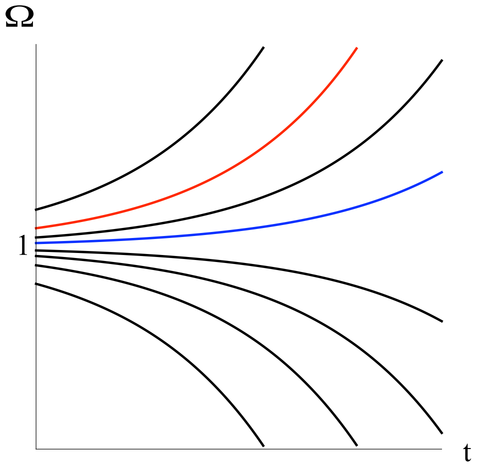
Inflation (Early Univ)

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

But: in the 1970s, it is known 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

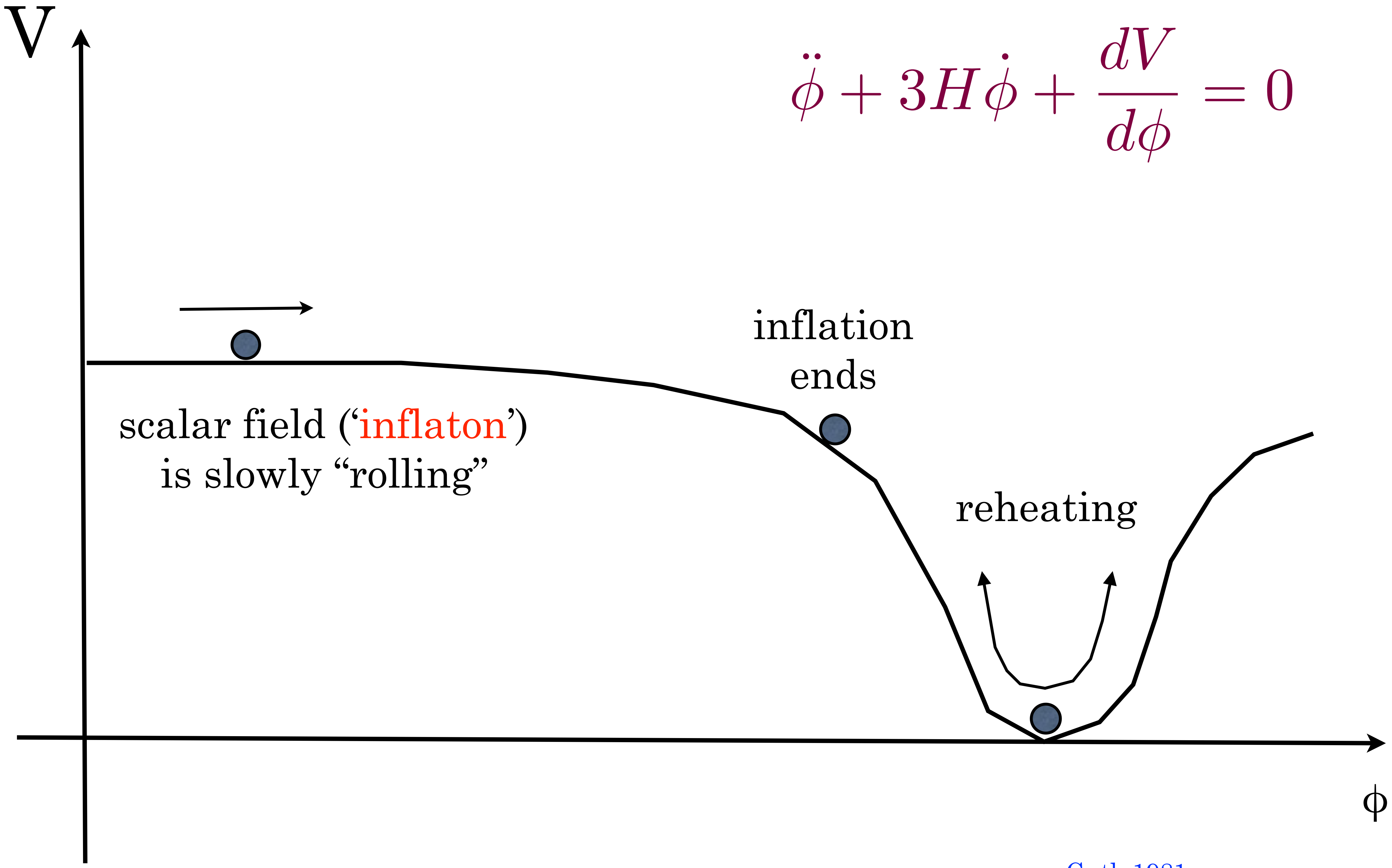


- **Flatness problem**: the universe is close to flat (flat geometry), while, if you work out basic equations, it tends to diverge from flat. Therefore, present-day flatness implies extreme fine tuning (to flat) in early universe

- **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

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



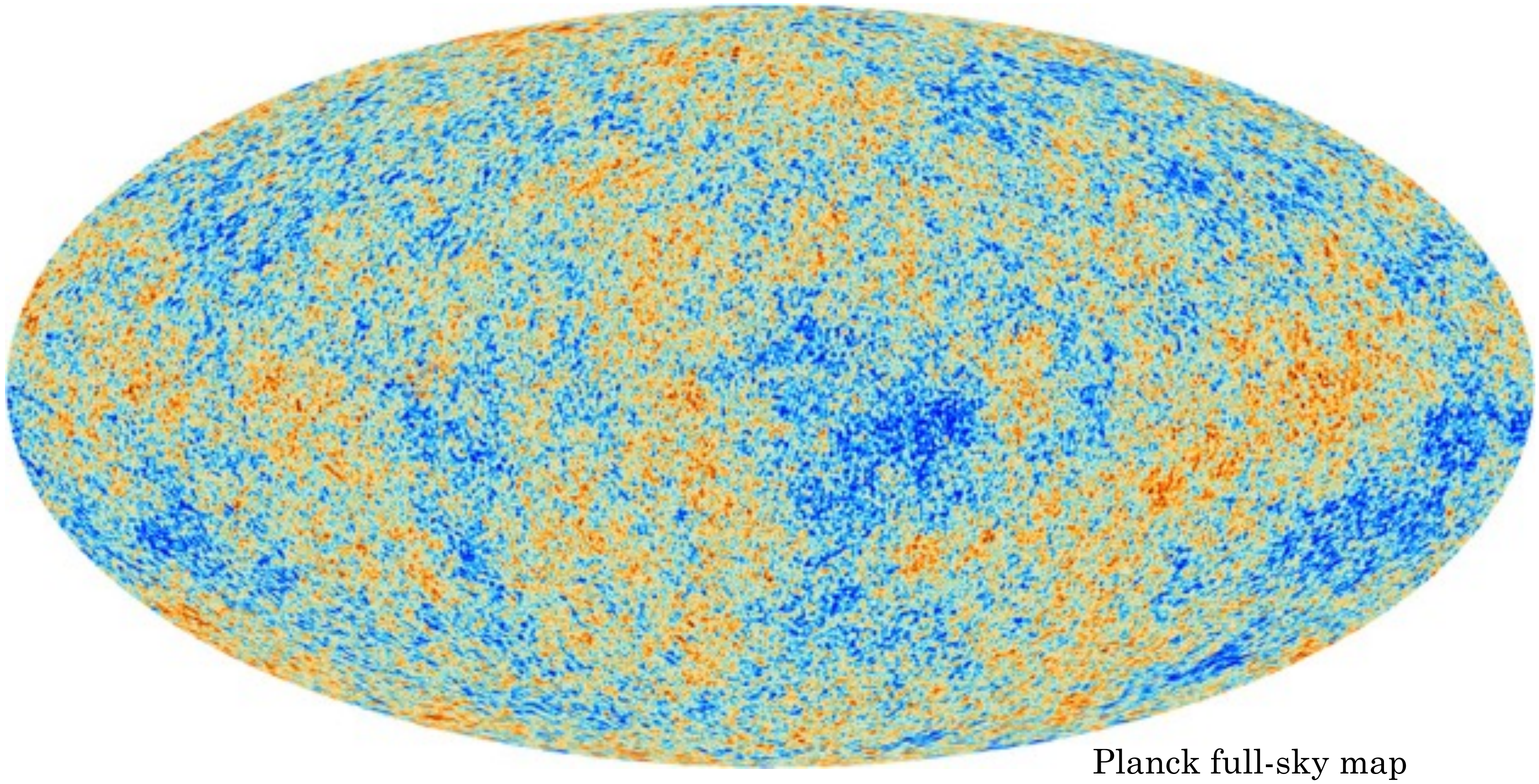
scalar field (‘inflaton’)
is slowly “rolling”

inflation
ends

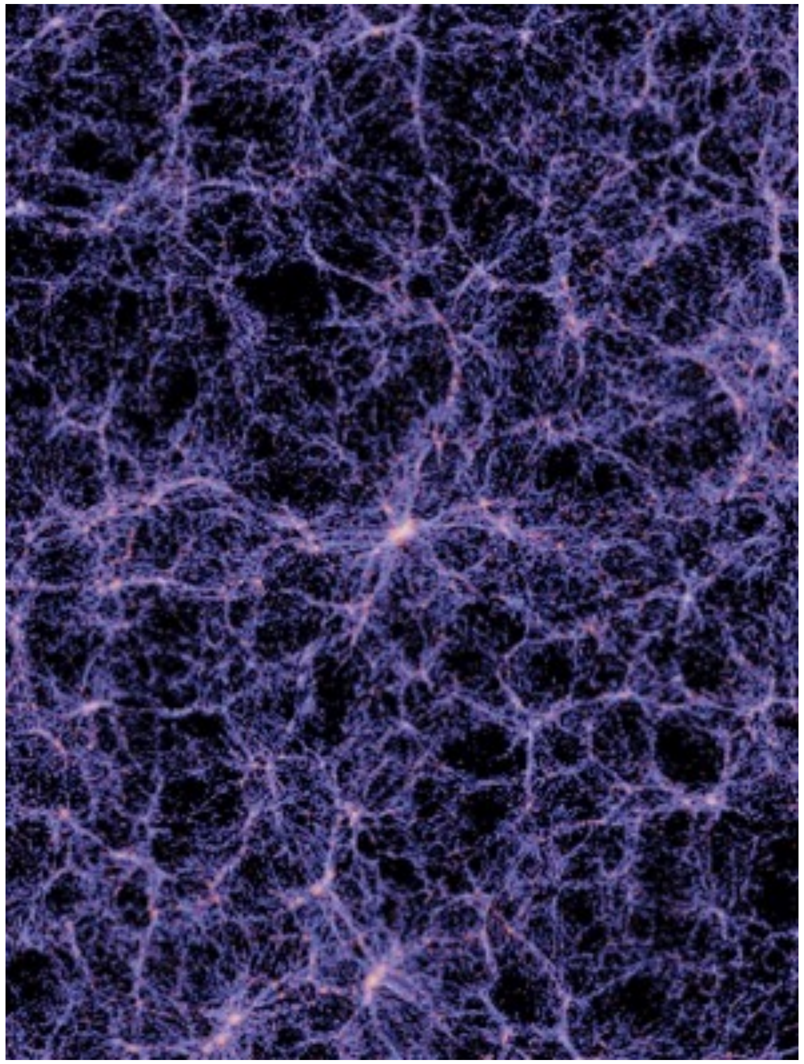
reheating

Guth 1981;
Linde 1982; Albrecht & Steinhardt 1982

Generic Inflationary Predictions:



Planck full-sky map



Millenium simulation

- Flat spatial geometry; $\Omega_K = 0.000 \pm 0.005$ √
- **Nearly scale-inv spectrum;** $n_s = 0.965 \pm 0.005$ √
- Background of gravity waves $(r \lesssim 0.1)$?
- (Nearly) gaussian ICs $f_{NL} = 0.8 \pm 5.0$

- What energy scale?
- How many fields?
- What interactions?

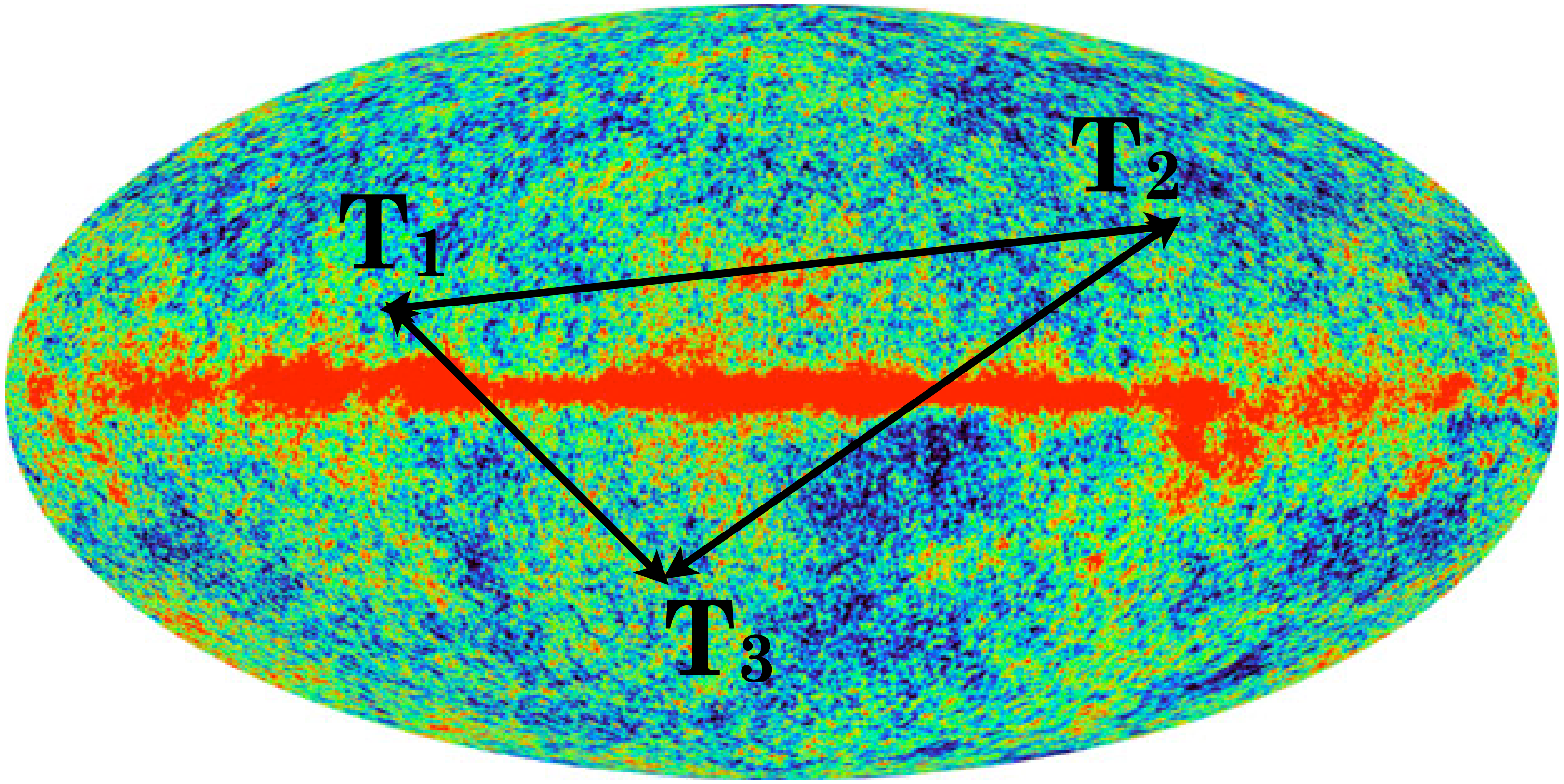
Standard Inflation, with...

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

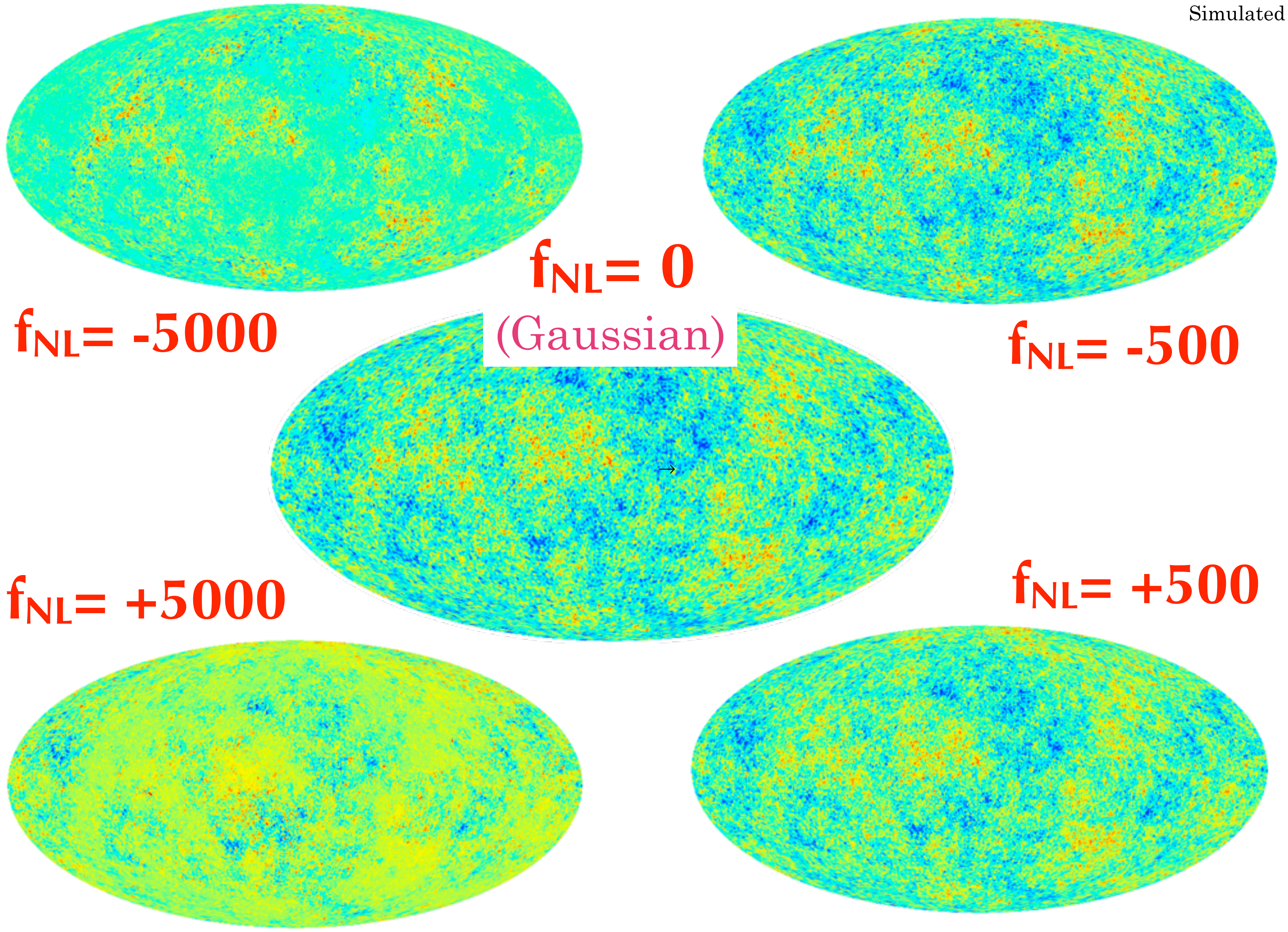
$$\Phi = \Phi_G + f_{\rm NL}\left(\Phi_G^2 - \langle\Phi_G^2\rangle\right)$$

"Local", "Equilateral", "orthogonal" $f_{\rm NL}$ - refers to triangle shapes
⇒ test number of fields & their interactions

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

Alvarez et al, arXiv:1412.4671

Simulated maps



$f_{NL} = -5000$

$f_{NL} = 0$

(Gaussian)

$f_{NL} = -500$

$f_{NL} = +5000$

$f_{NL} = +500$

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

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

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

cosmologists measure

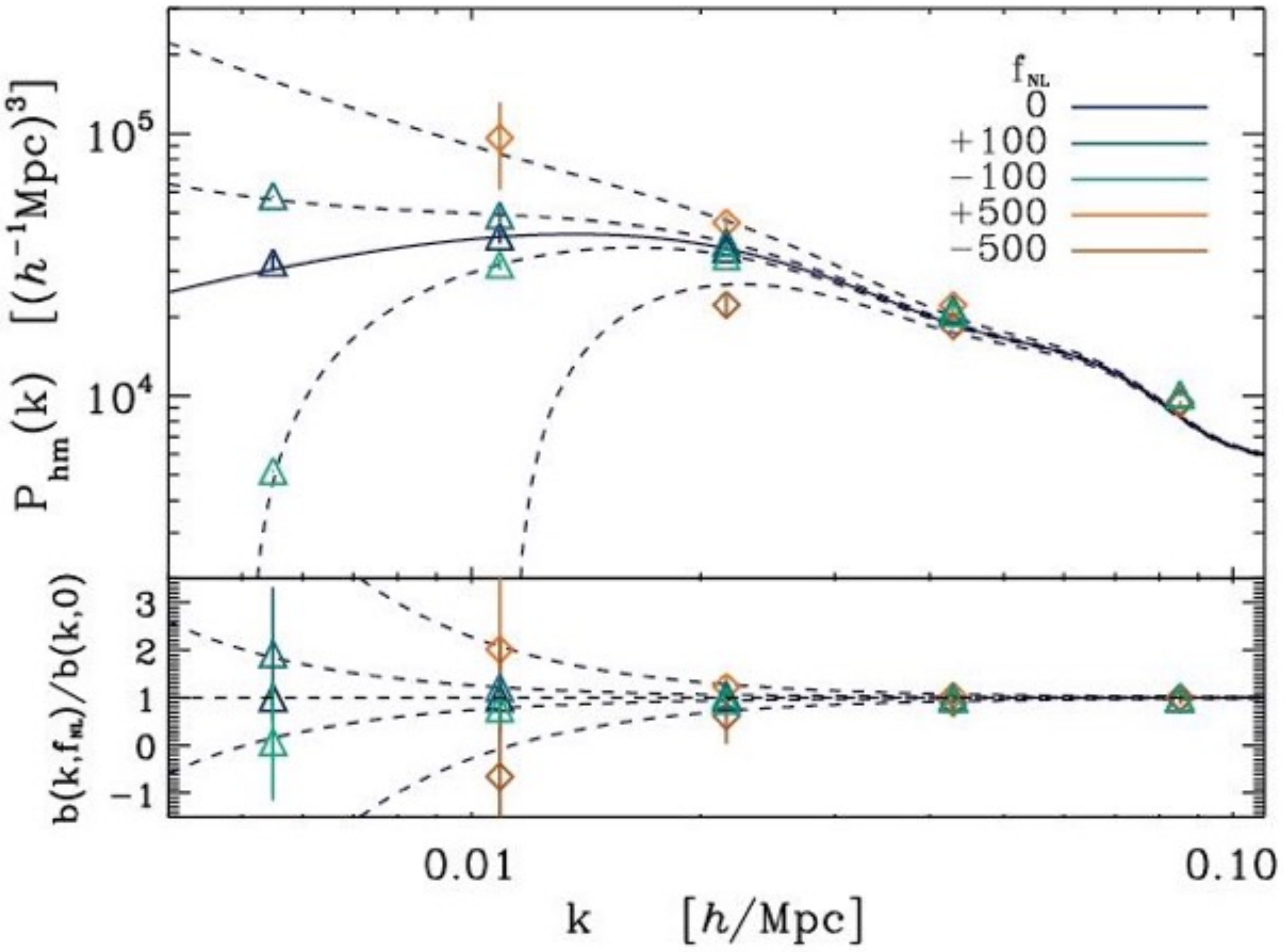
theory predicts

usually nuisance parameter(s)

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

(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



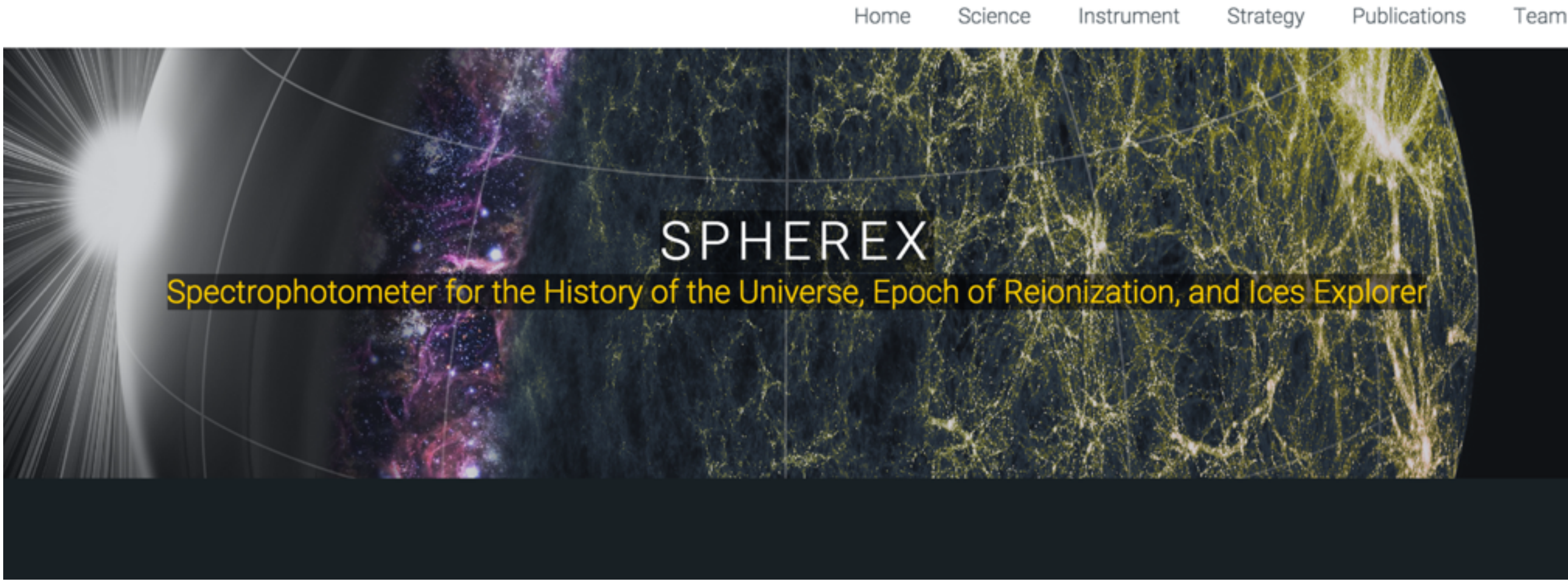
$$b(k) = b_{\rm G} + f_{\rm NL}\,\frac{\rm const}{k^2}$$

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

Dalal, Doré, Huterer & Shirokov 2008

SPHEREx

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



SPHEREX

Spectrophotometer for the History of the Universe, Epoch of Reionization, and Ices Explorer

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~1
- **goal: $\sigma(f_{NL}) \lesssim 1$**

Non-Gaussianity vs inflation recap:

If we find:

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

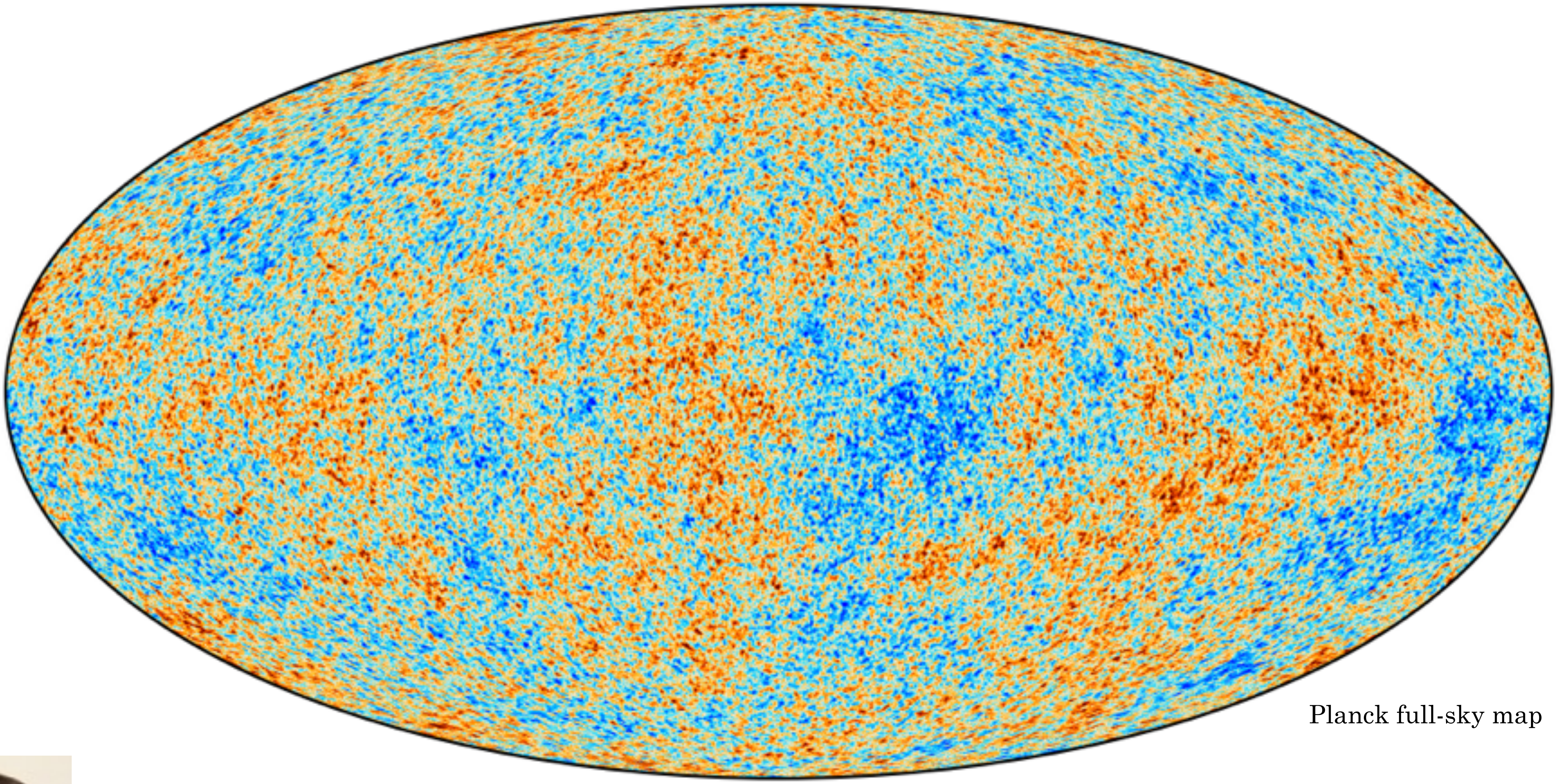
$f_{NL}{}^{\text{equil}} \gtrsim O(1) \Rightarrow$ strong coupling (non-slow roll)

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

Connecting the early and late universe

(inflation and dark energy):

Which part of the CMB signal comes from the **late** universe?



Planck full-sky map

Jessie Muir

Integrated Sachs-Wolfe effect

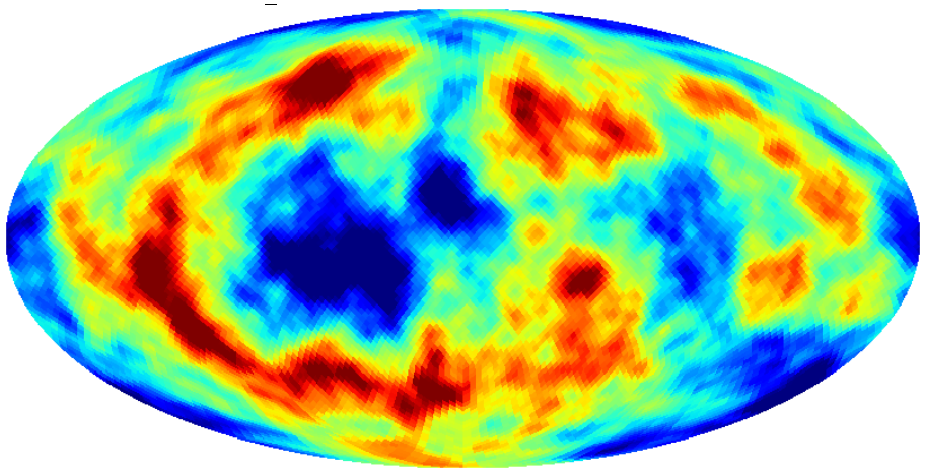
$$\left.\frac{\Delta T}{\bar{T}}\right|_{\rm ISW}(\hat{n}) = \frac{2}{c^2}\int_{t_*}^{t_0} dt\, \frac{\partial\Phi(\vec{r},t)}{\partial t},$$

Sachs & Wolfe, 1967

Nonzero when universe is *not* matter-dominated, so:

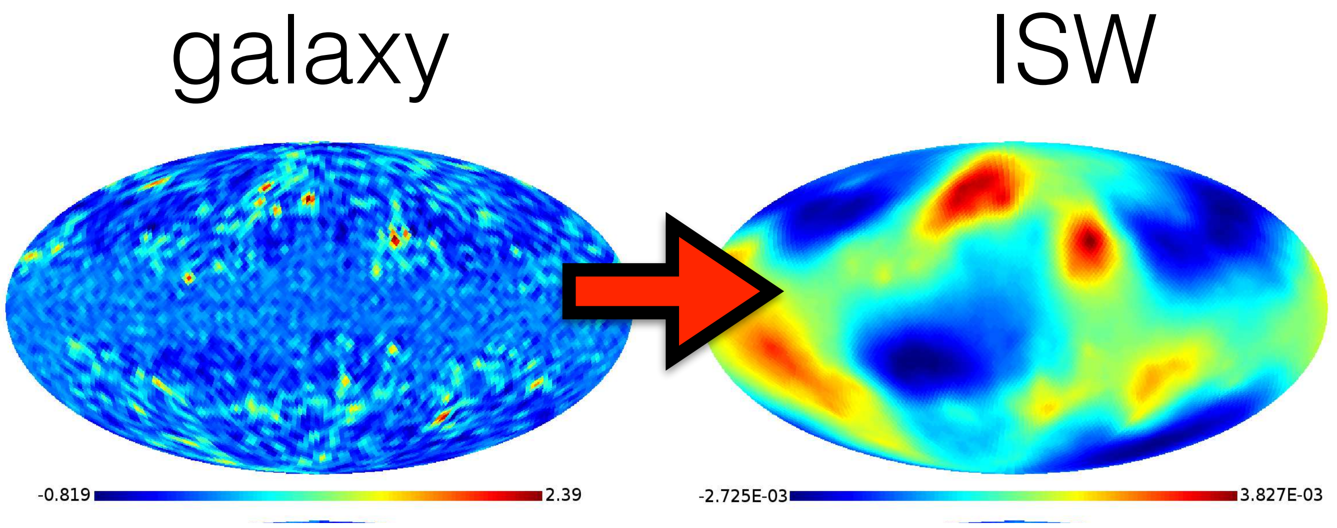
- right after recombination (`early ISW’)
- **when dark energy starts to dominate (`late ISW’)**

$$\frac{\Delta T}{\bar{T}}(\hat{n}) = \left.\frac{\Delta T}{\bar{T}}\right|_{\rm prim}(\hat{n}) + \left.\frac{\Delta T}{\bar{T}}\right|_{\rm ISW}(\hat{n}) \rightarrow$$



Idea: use a galaxy survey to map out dΦ/dt, then get $(dT/T)_{\rm ISW}$

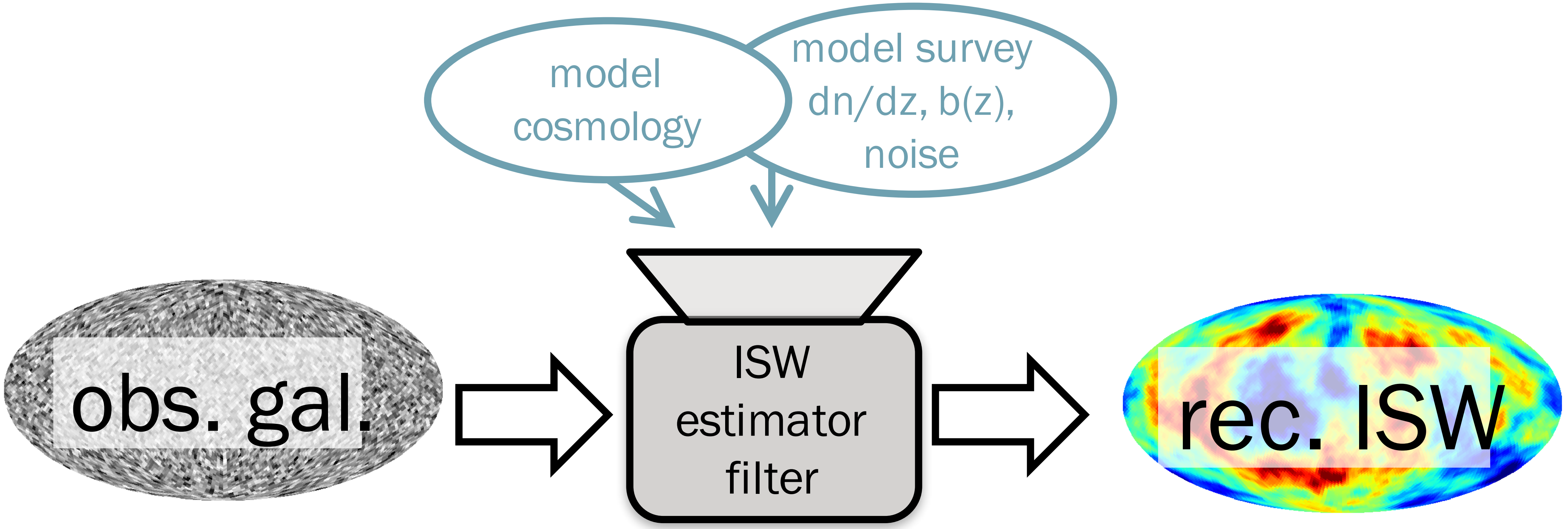
Real-data of ISW reconstruction:
(Peacock & Francis 2010)



But what about systematic errors??

Astrophysical - instrumental - theoretical

We performed end-to-end simulation to answer this:


model cosmology

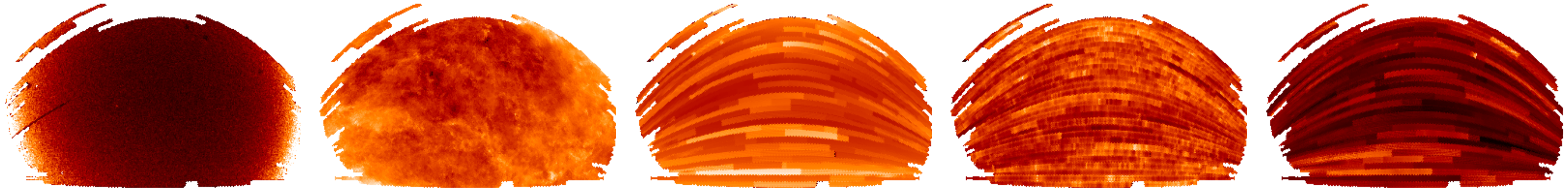
model survey dn/dz, b(z), noise

obs. gal.

ISW estimator filter

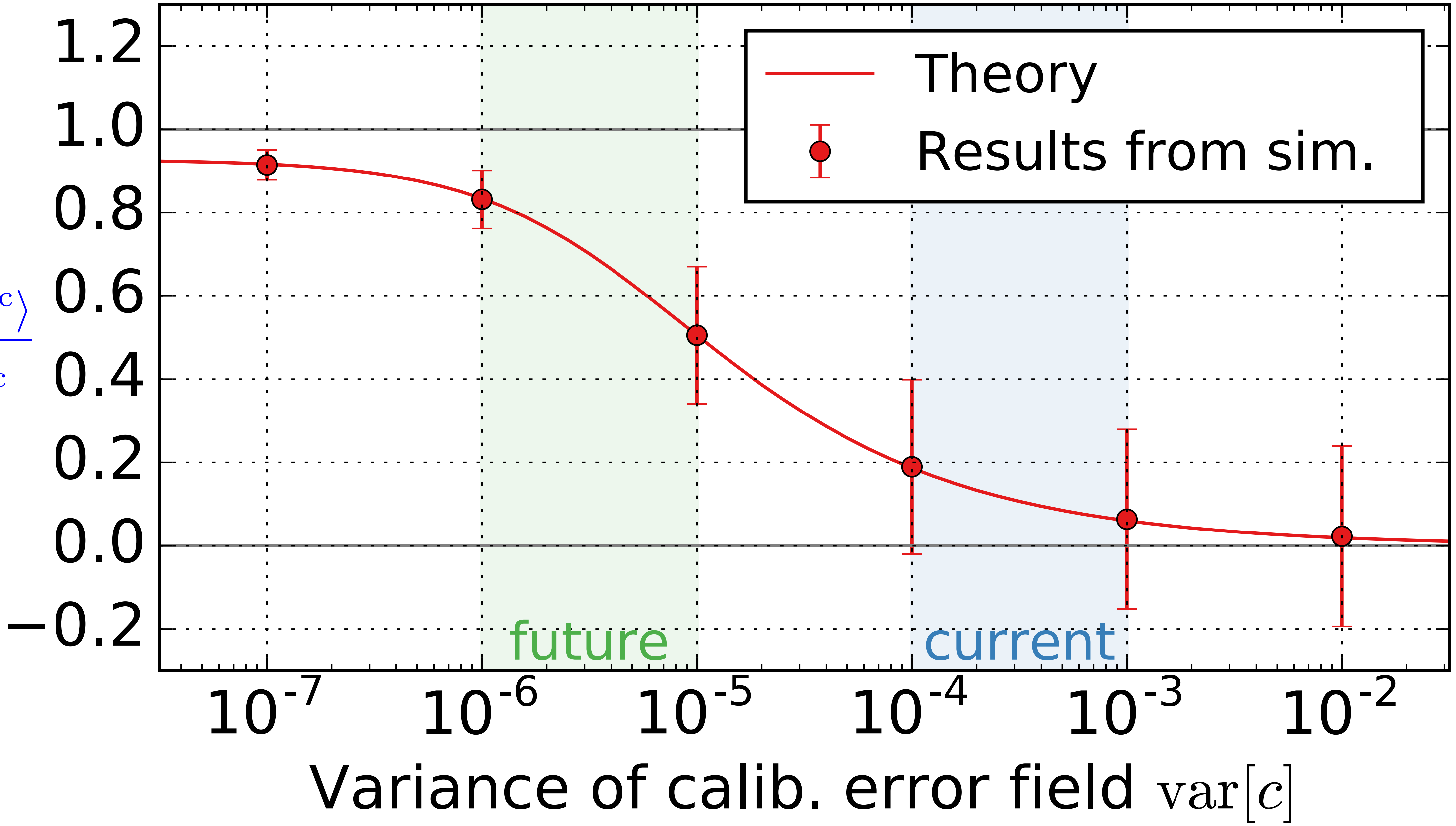
rec. ISW

Main conclusion: in reconstructing ISW maps, direction-dependent calibration errors can be devastating


(a) Stellar density (b) Extinction (c) Airmass (d) Seeing (e) Sky brightness

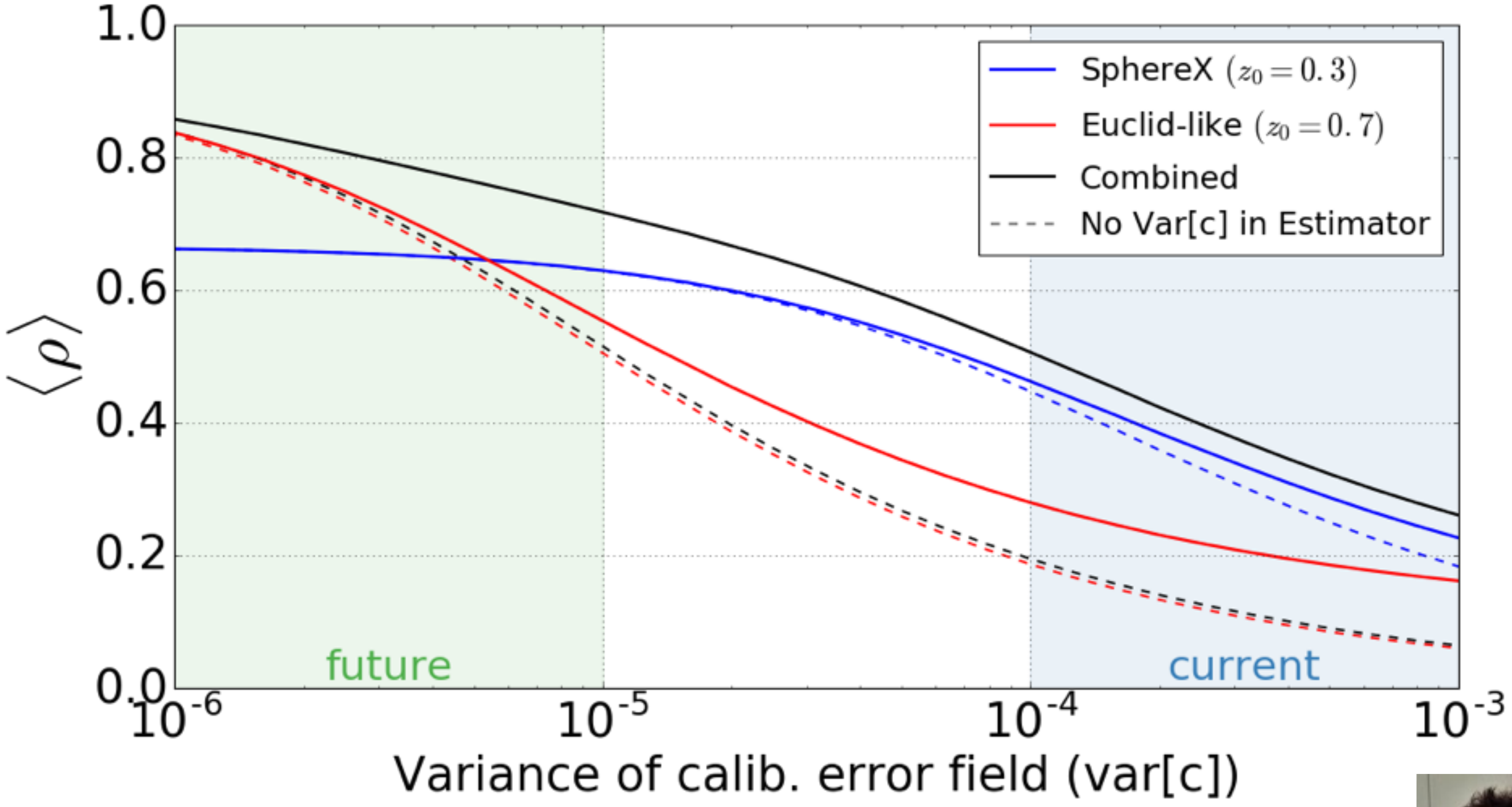
Leistedt et al

$$\rho = \frac{\langle T^{\rm ISW}\, T^{\rm rec}\rangle}{\sigma_{\rm ISW}\, \sigma_{\rm rec}}$$



Muir & Huterer, Phys Rev D, 2016

Quality of ISW map reconstruction with multiple surveys



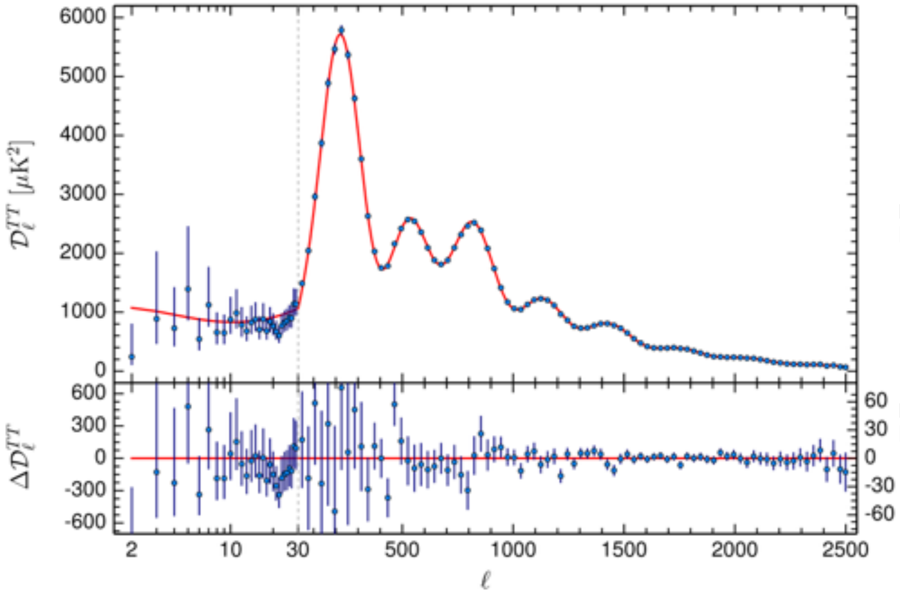
Weaverdyck, Muir & Huterer

Story so far:

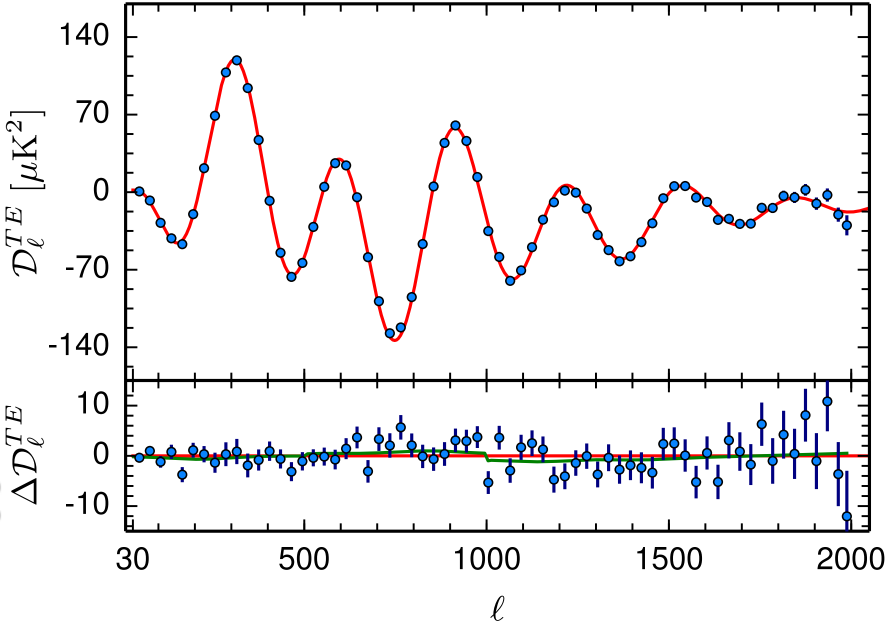
- Cosmology definitely in the precision regime
- Impressive constraints on DM, DE and inflation…
- …but some big questions unanswered
- Lots of potential from upcoming surveys

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

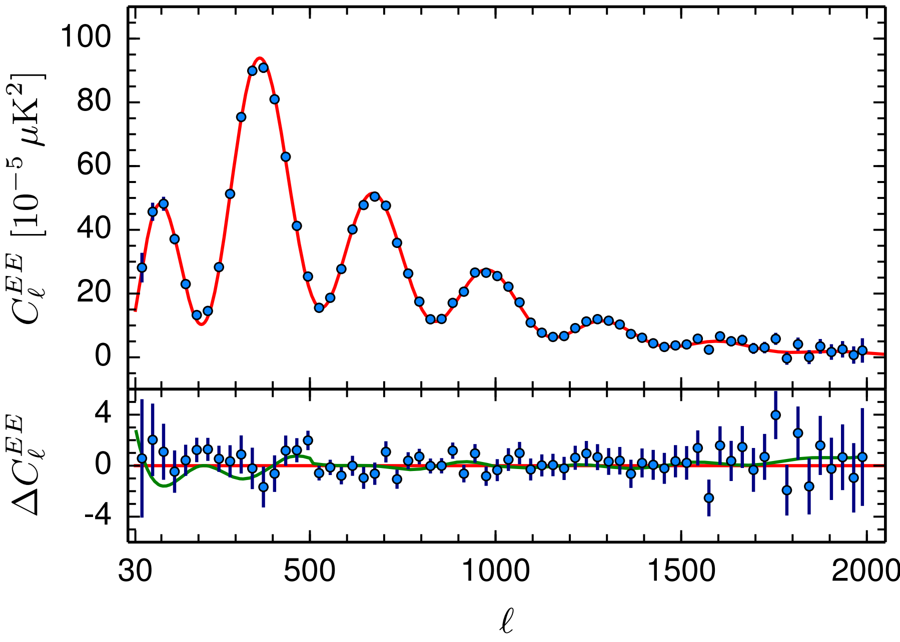
temp-temp



temp-pol



pol-pol



Danger of declaring currently favored model to be the truth

$\Longrightarrow$ **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