Dark Matter and Dark Energy: gases that dominate the Universe

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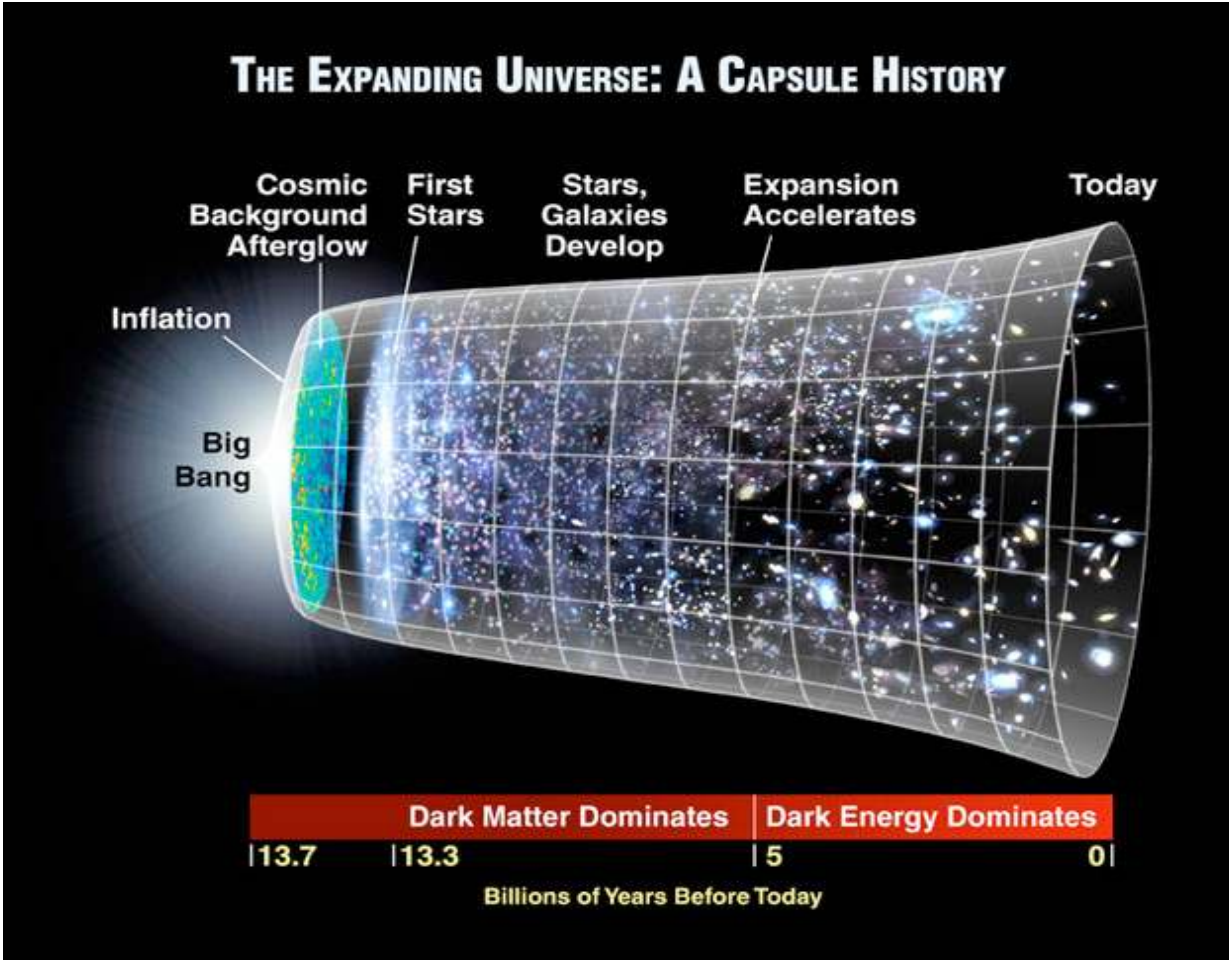


http://hetdex.org/dark_energy/

Edwin Hubble and the Expansion of the Universe (1929)

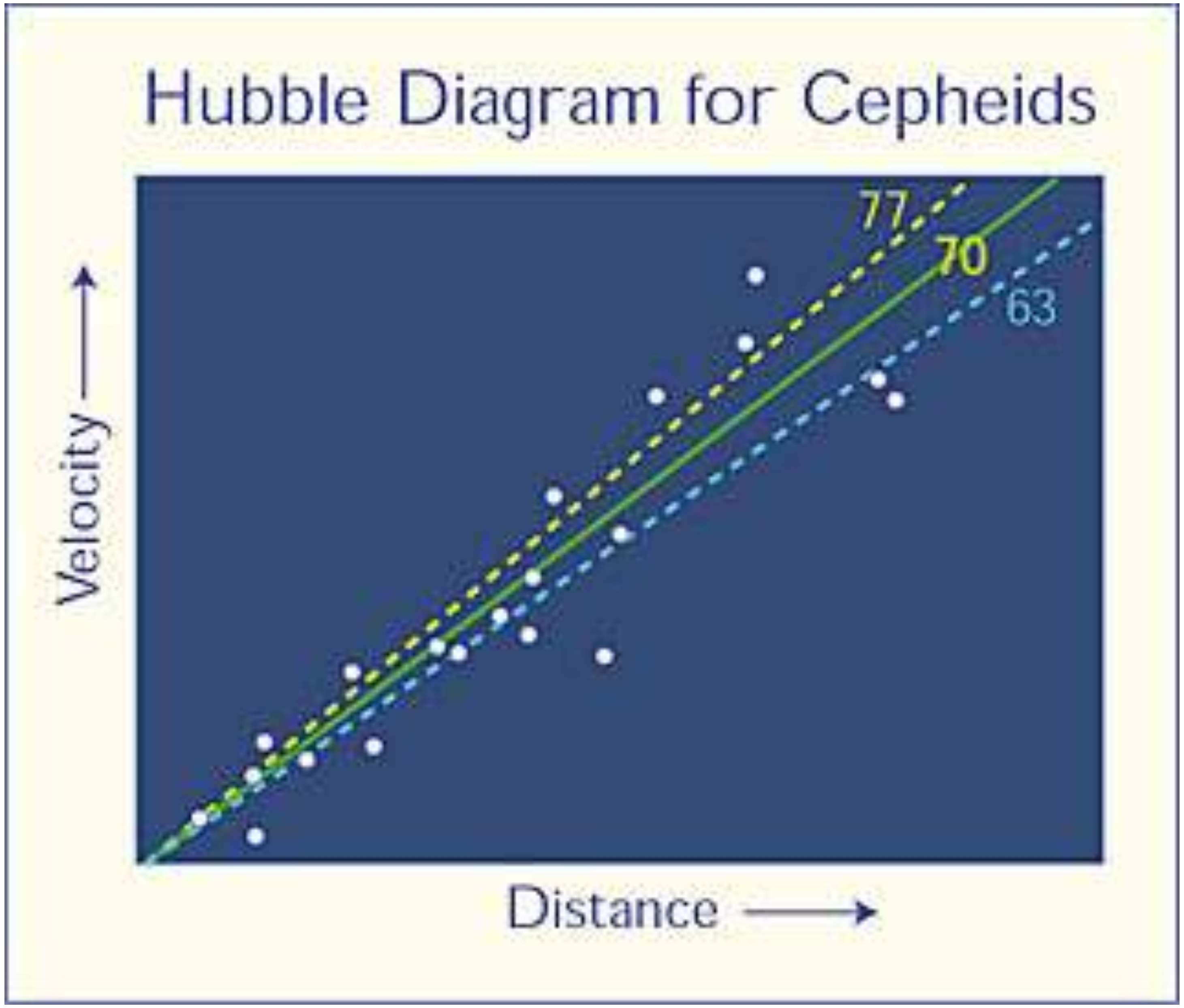
In 1929 Hubble measured the red shift (or, redshift) of nearby galaxies and found that they nearly all move away from us

$\Rightarrow$

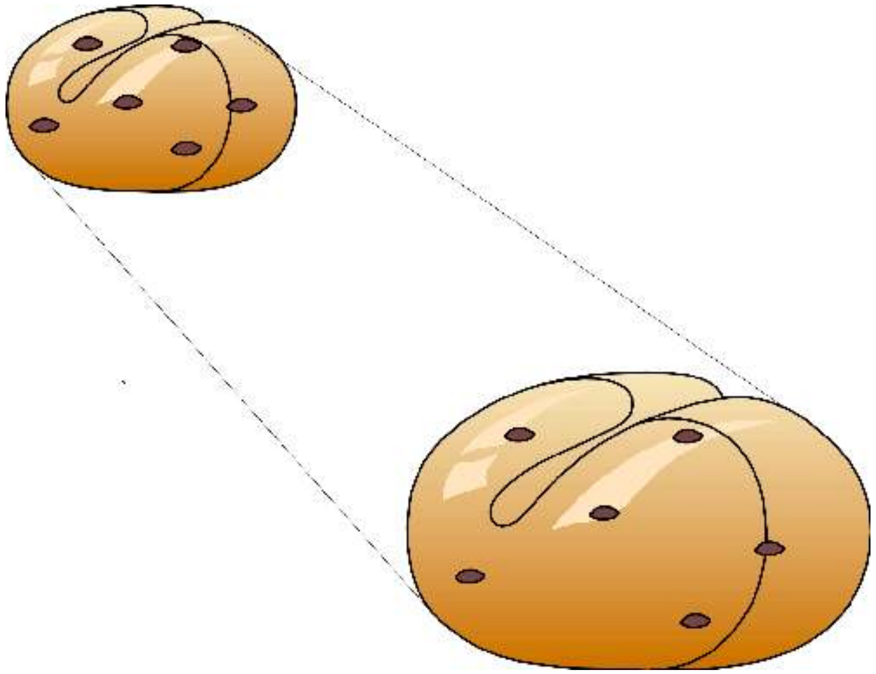
The Universe is Expanding!

100 inch Hooker telescope
(Mt Wilson, CA)

Expanding spaces: bread & universe



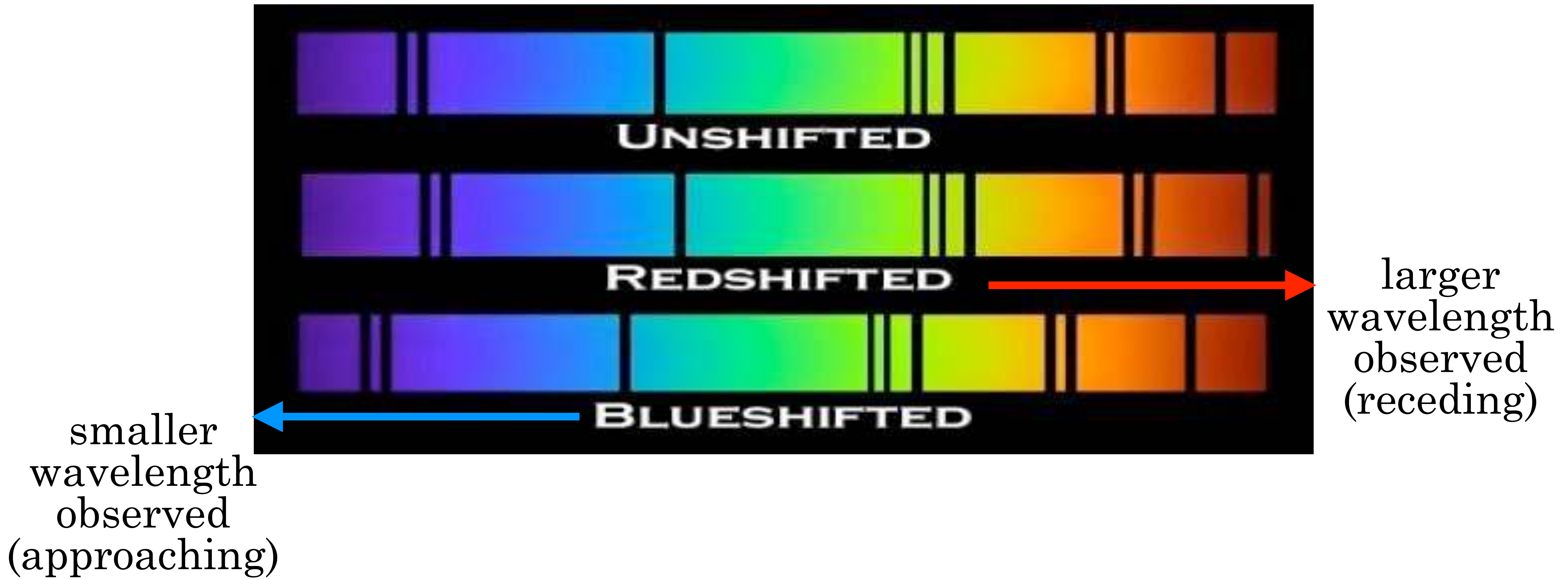
Baking the raisin bread: the **farther** two raisins are, the **faster** they are receding



- Velocity is easy: from the Doppler recession of galaxy spectra
  (first done by astronomer Vesto Slipher, whom Hubble never credited)
- Distance is hard: from Cepheid variable stars

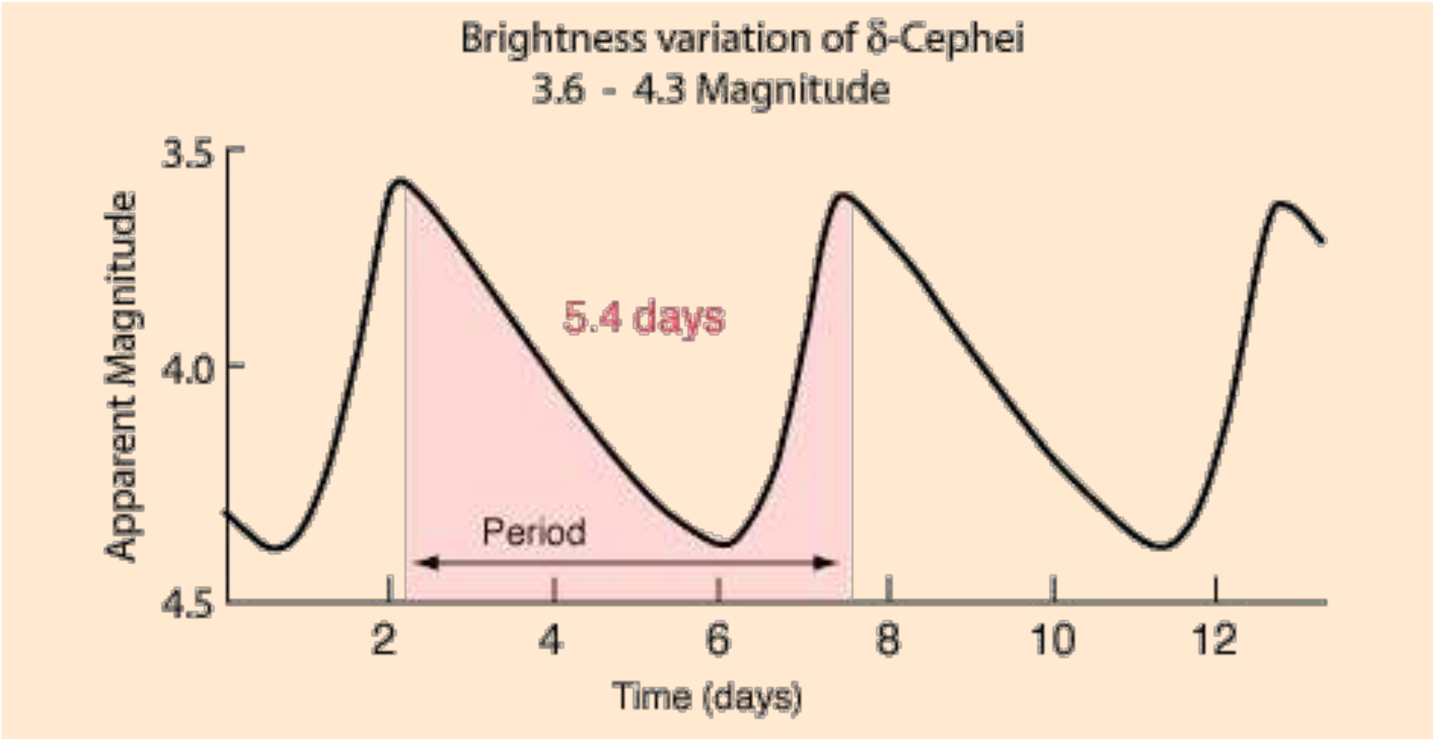
Redshift: shift of galaxy light wavelength

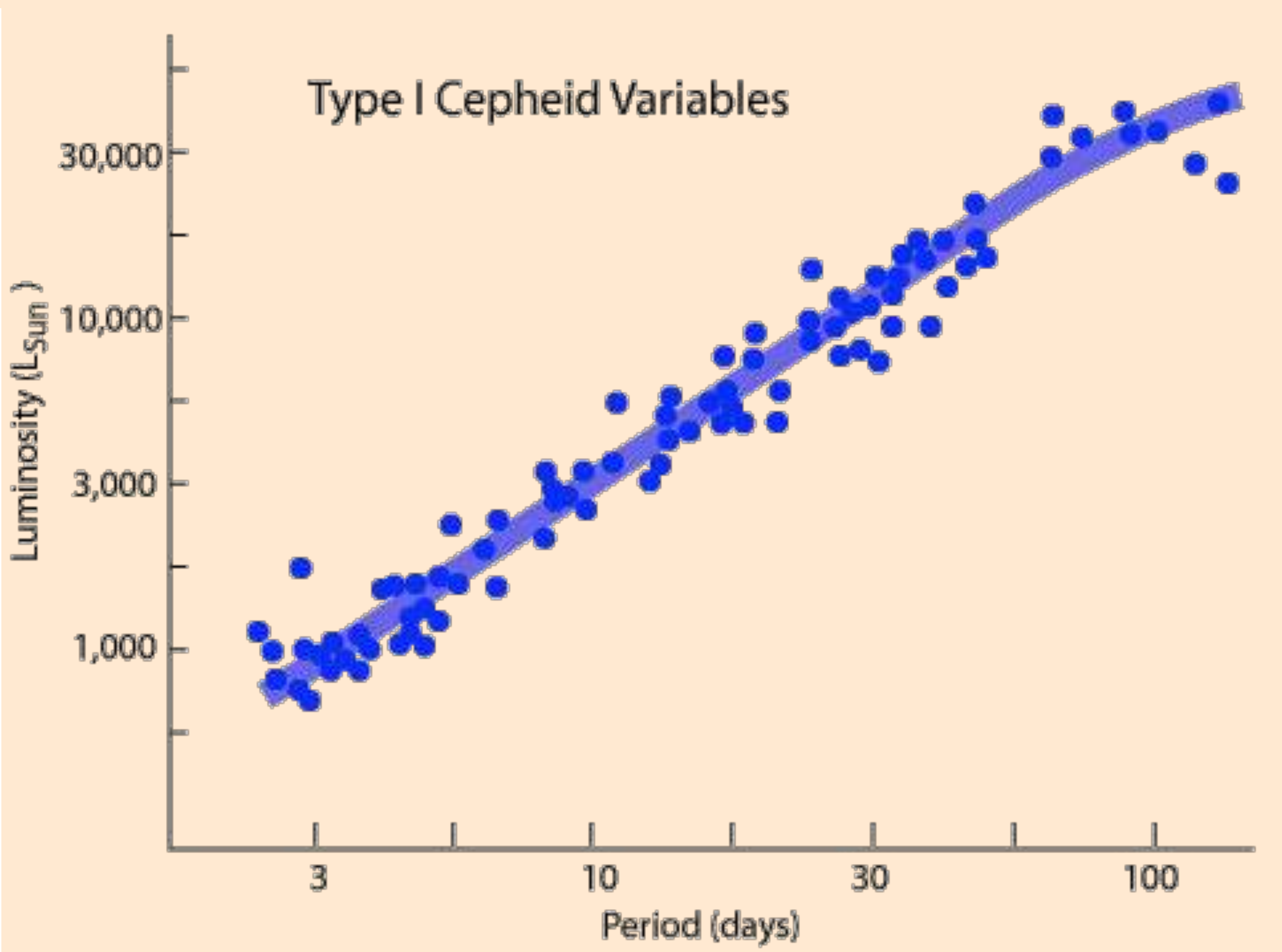
(due to galaxy's motion relative to us)



Light from almost all galaxies is redshifted (and not blueshifted)
- **the galaxies are receding away from us**!

How do you get distances to galaxies?





http://hyperphysics.phy-astr.gsu.edu/

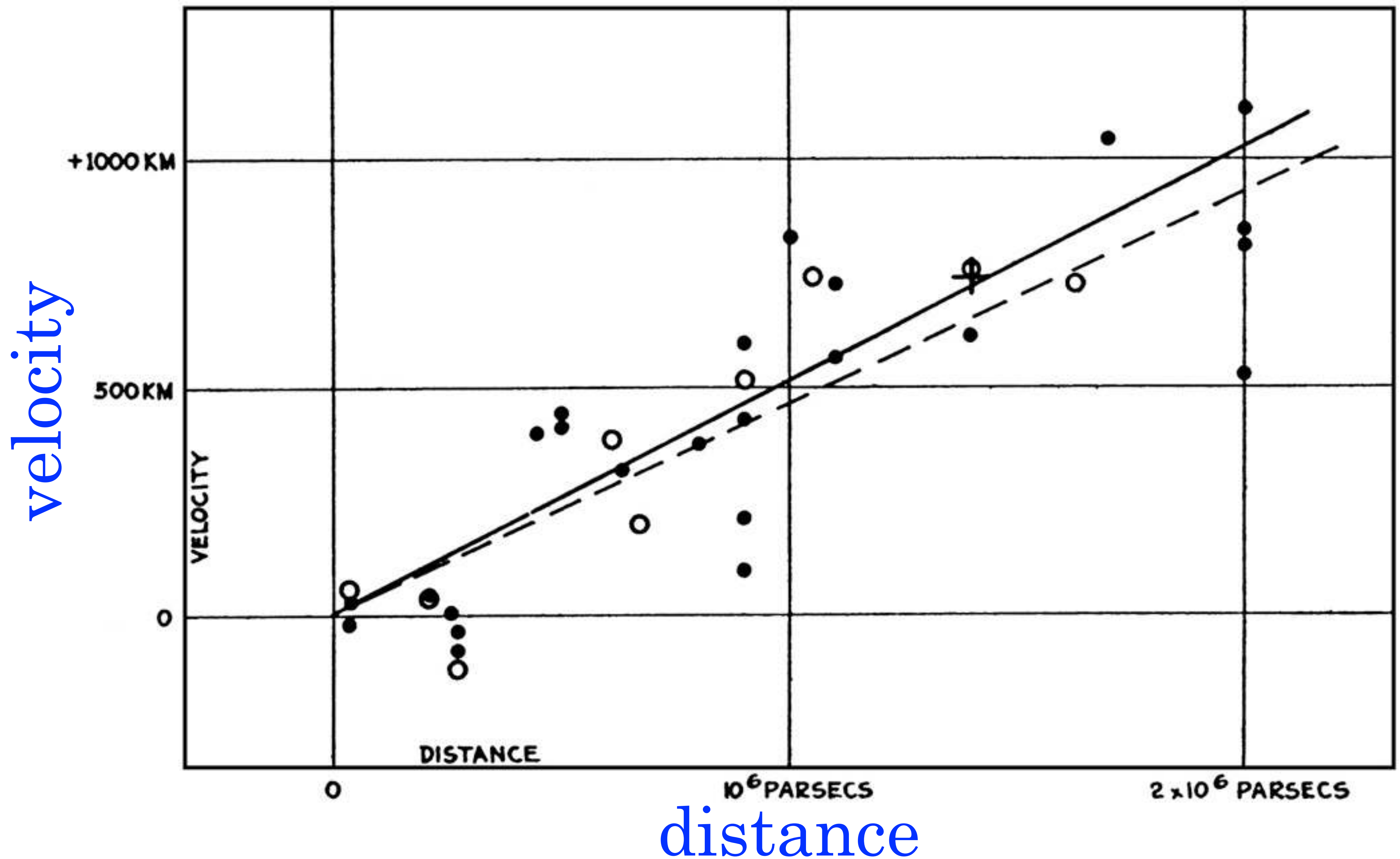
Cepheids
(variable stars)

- Empirical finding: Cepheids' period of pulsation is proportional to intrinsic luminosity
- Measure period
- Measure apparent luminosity (or, flux)
- Then, can get **distance**:

$$f = L / (4\pi d^2)$$

(f = flux
L = luminosity)

The original Hubble diagram (1929)

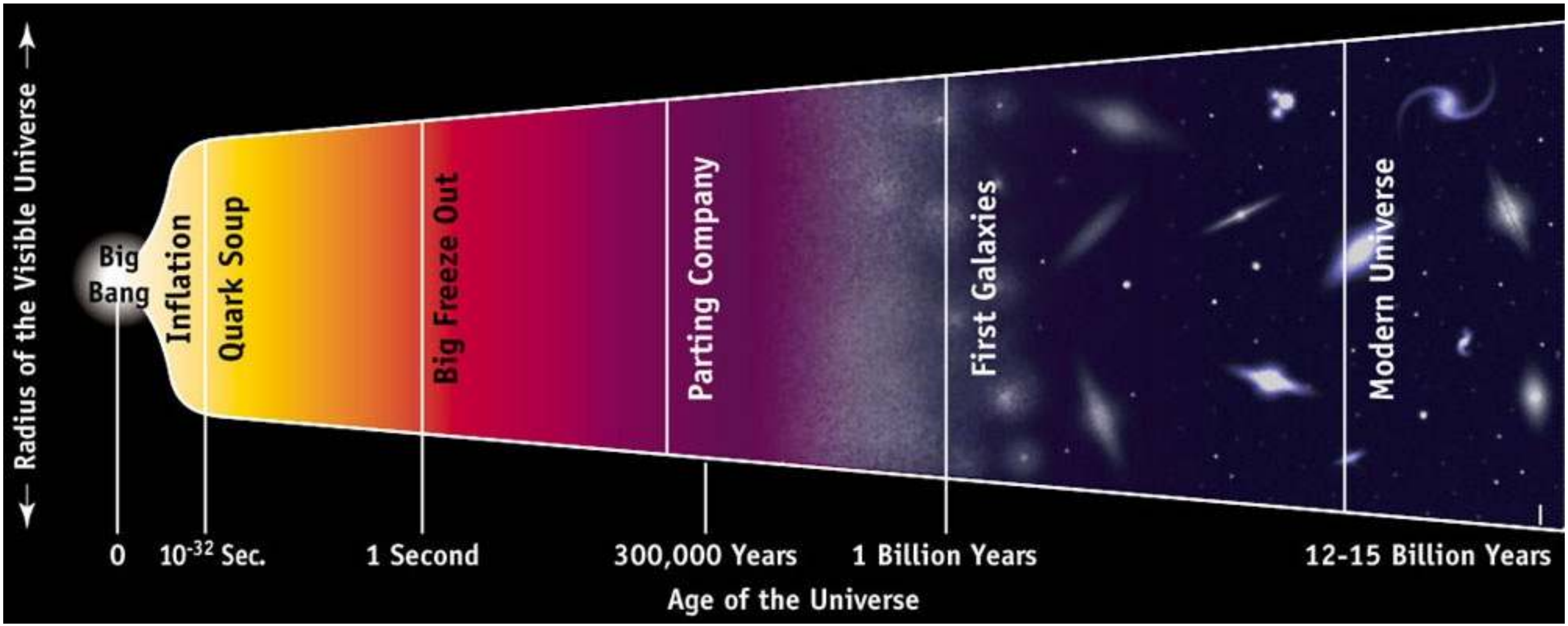


Slope of this relation (velocity vs. distance) is called the Hubble constant H_0.

Modern value:

$H_0 \approx 70$ km/sec/megaparsec (will return to H_0 later!)

Three key questions in cosmology



Inflation

Dark Matter

Dark Energy

Cosmological components as fluids

Pressure p, energy density ρ

The continuity equation is $\dot{\rho} + 3H(p + \rho) = 0$

with $H \equiv \dot{a}/a$ the Hubble parameter and a is scale factor

or: $\frac{d \ln \rho}{d \ln a} + 3(1 + w) = 0$ with eq. of state $w = p/\rho$

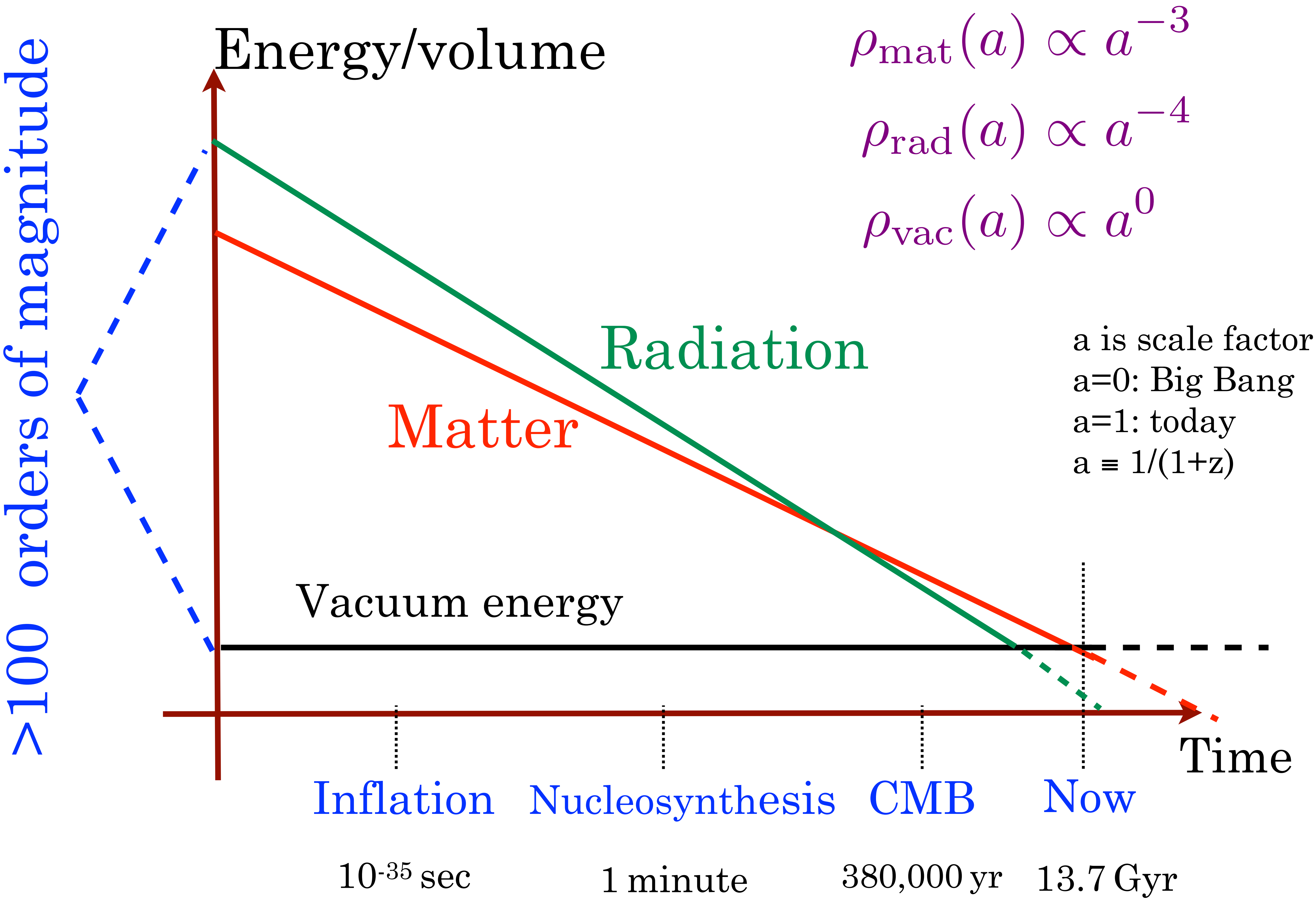
Solutions for w = const:

$\rho(a) \propto a^{-3} \quad (w = 0;\ \text{matter})$

$\rho(a) \propto a^{-4} \quad (w = +1/3;\ \text{radiation})$

$\rho(a) \propto \text{const} \quad (w = -1;\ \text{vacuum energy})$

How components scale with time

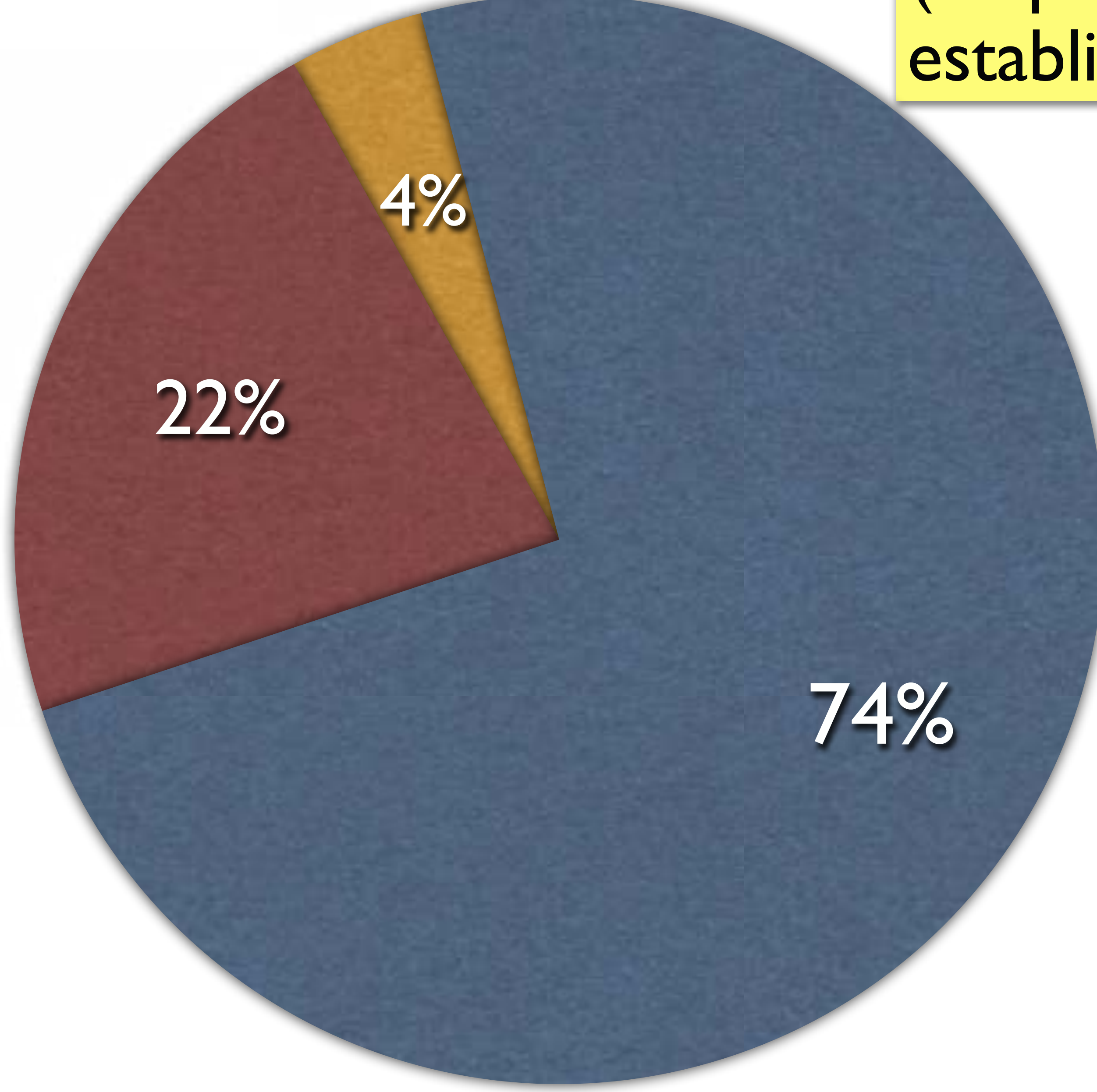


Makeup of universe today

Baryonic Matter
(stars 0.4%, gas 3.6%)

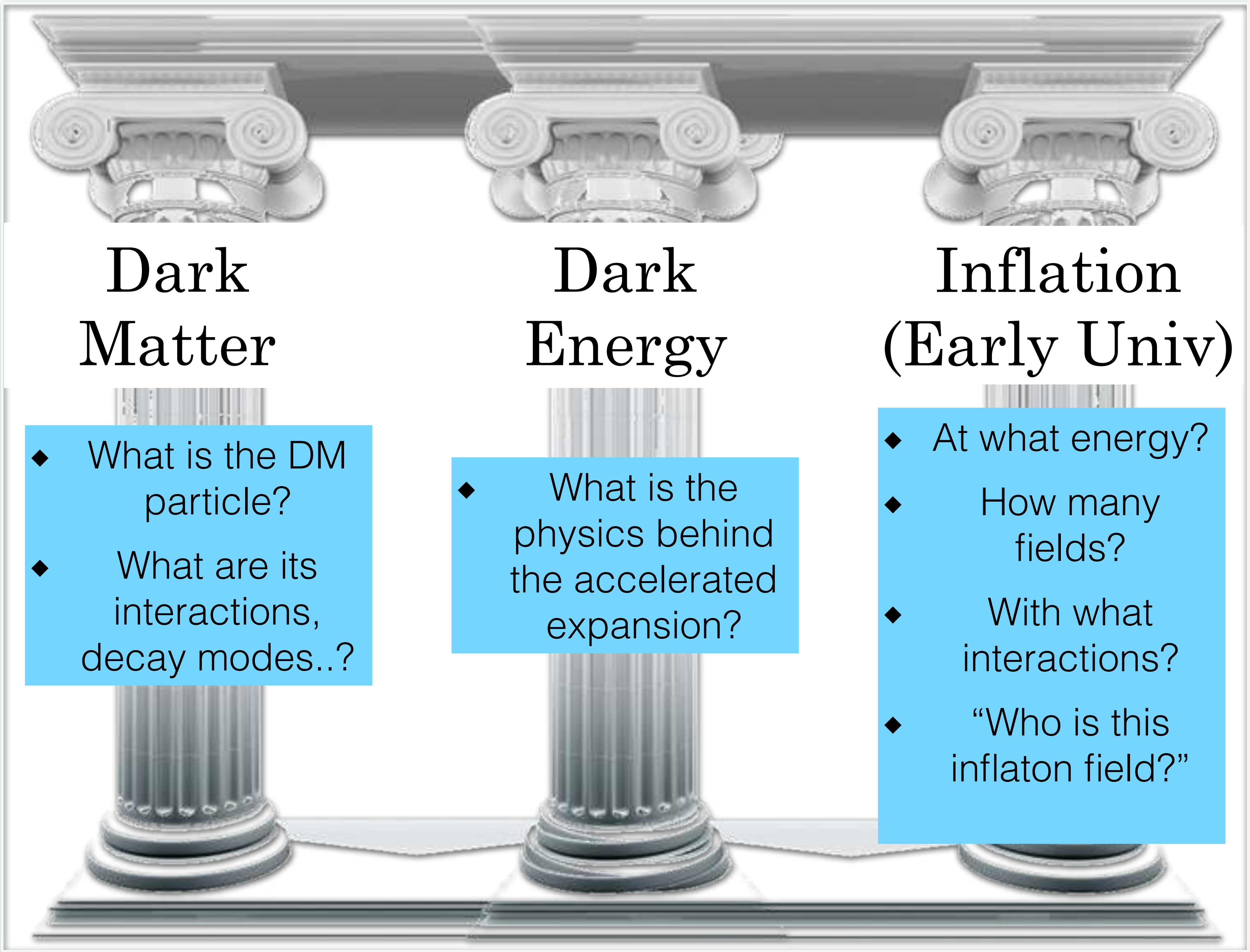
Dark Energy
(suspected since 1980s
established since 1998)

Dark Matter
(suspected since 1930s
established since 1970s)

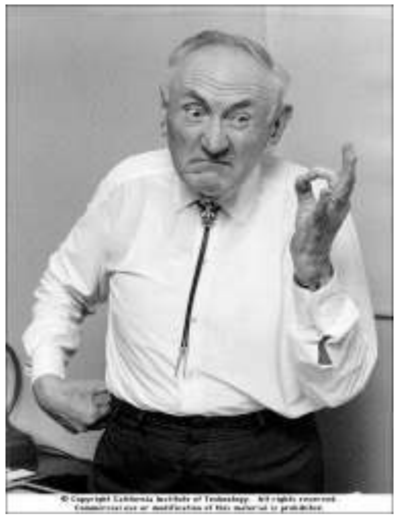


Also:
radiation (0.01%)

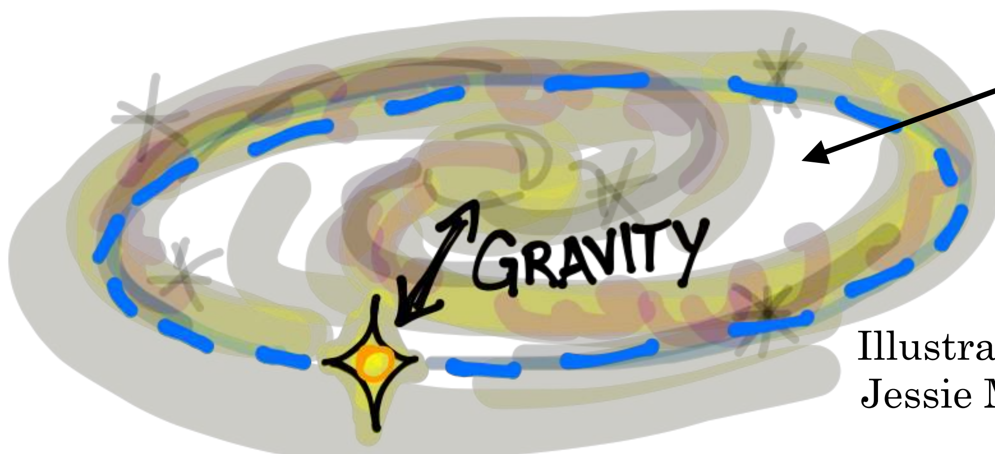
Three big questions in cosmology



Dark Matter



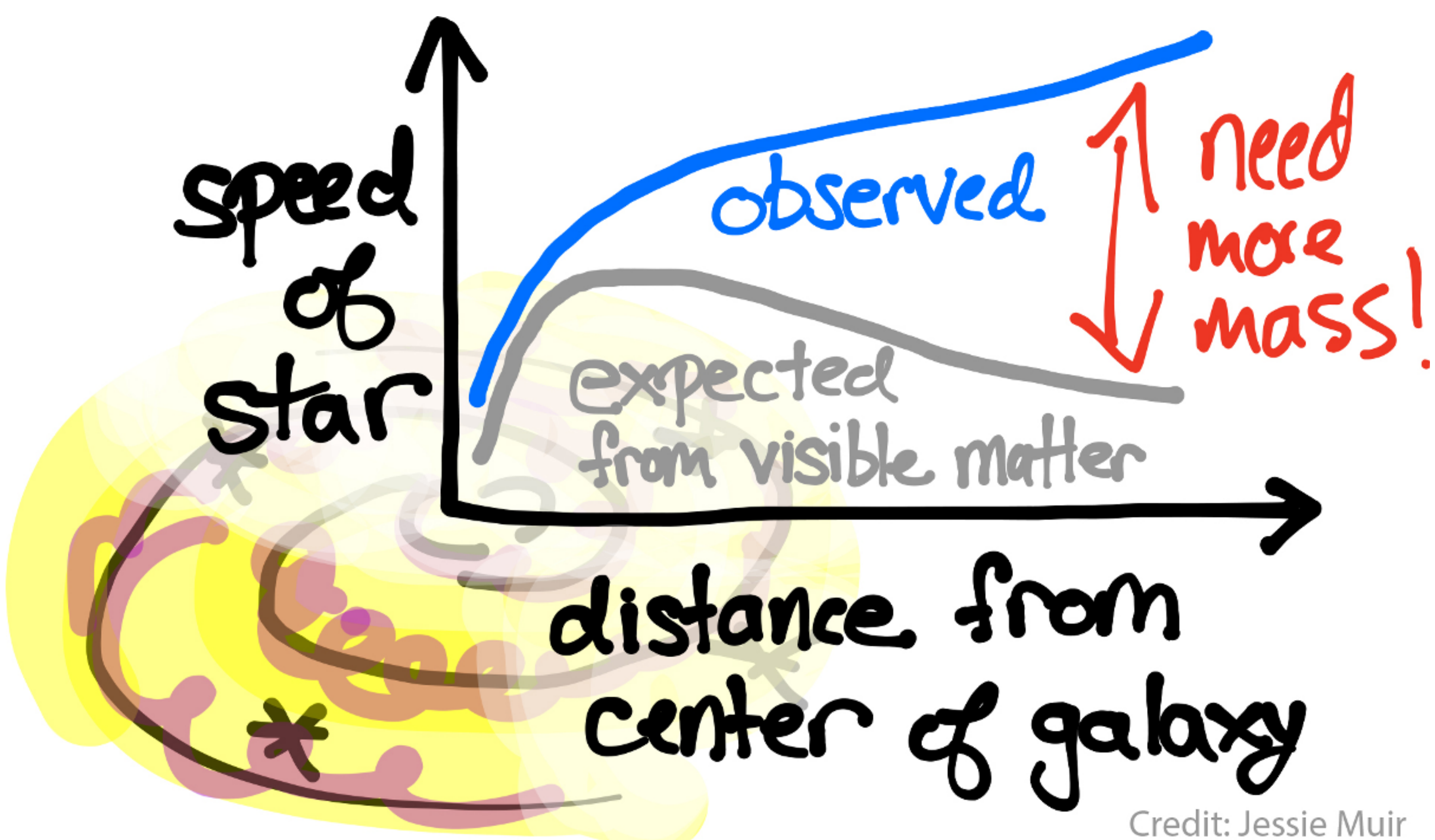
Fritz Zwicky
"Dunkle Materie",1933



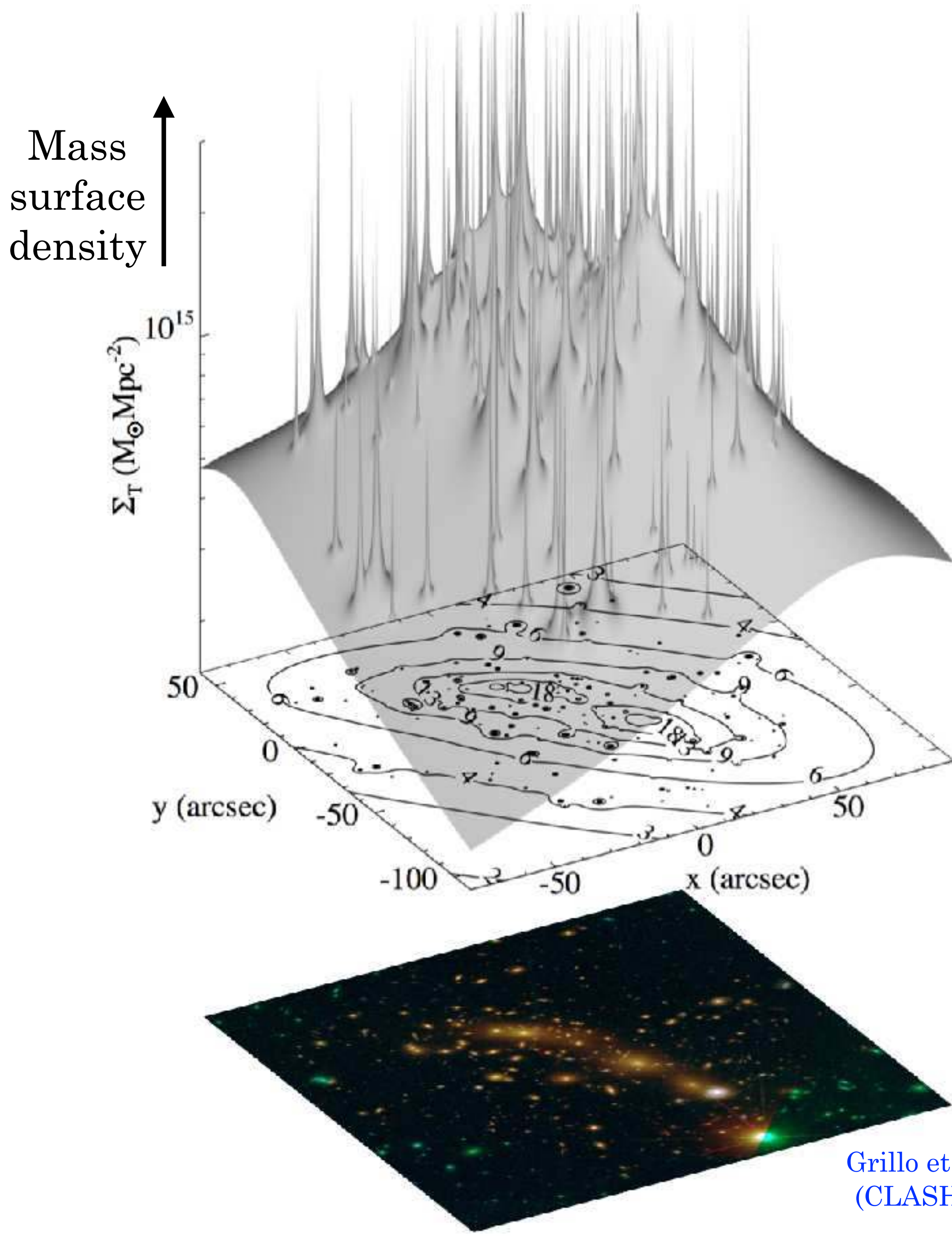
Coma cluster
of galaxies

Illustration:
Jessie Muir

Vera Rubin
flat rotation curves, 1970s

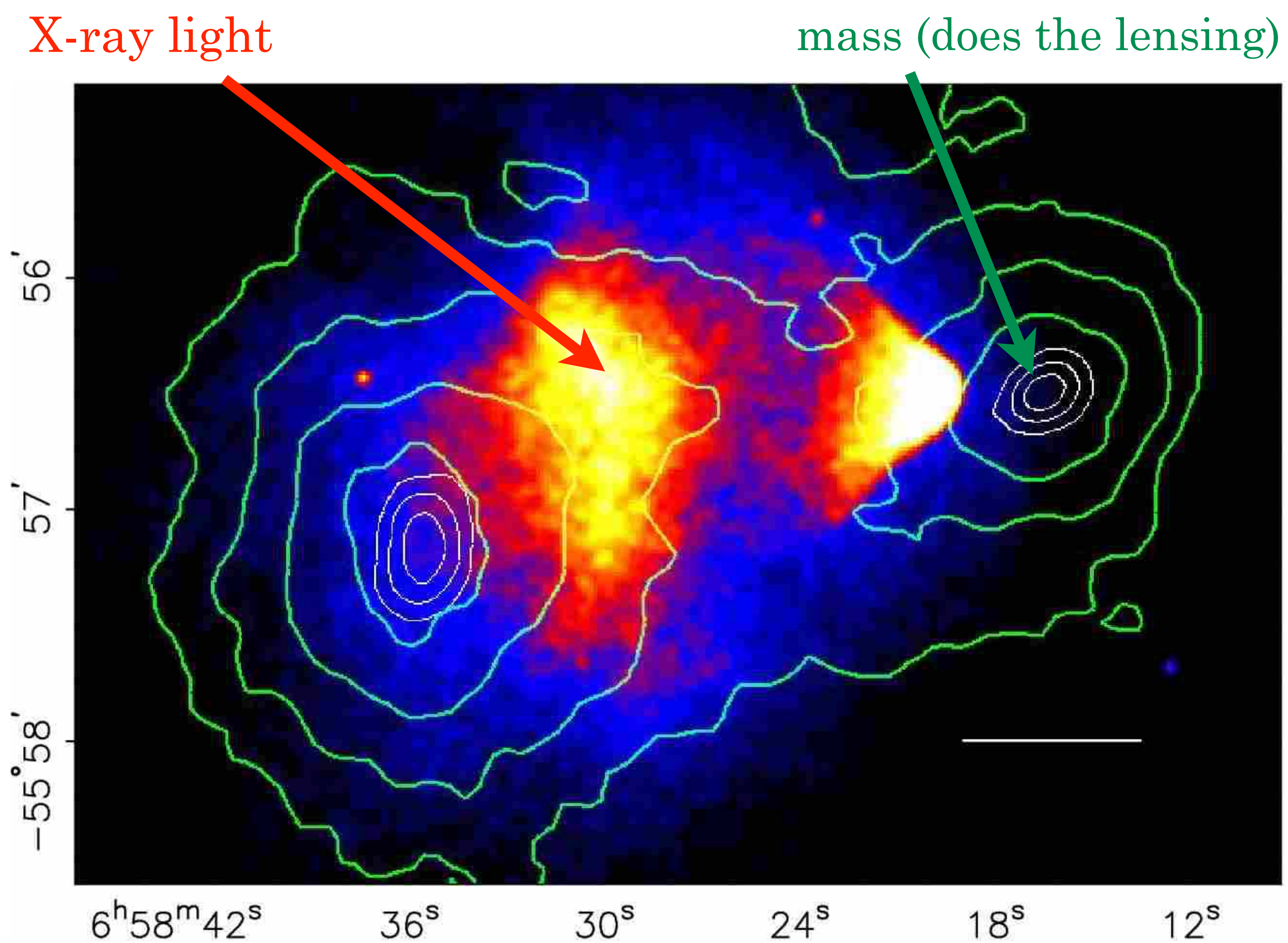


Modern evidence for Dark Matter



Grillo et al 2015
(CLASH team)

Mass profile around a galaxy cluster

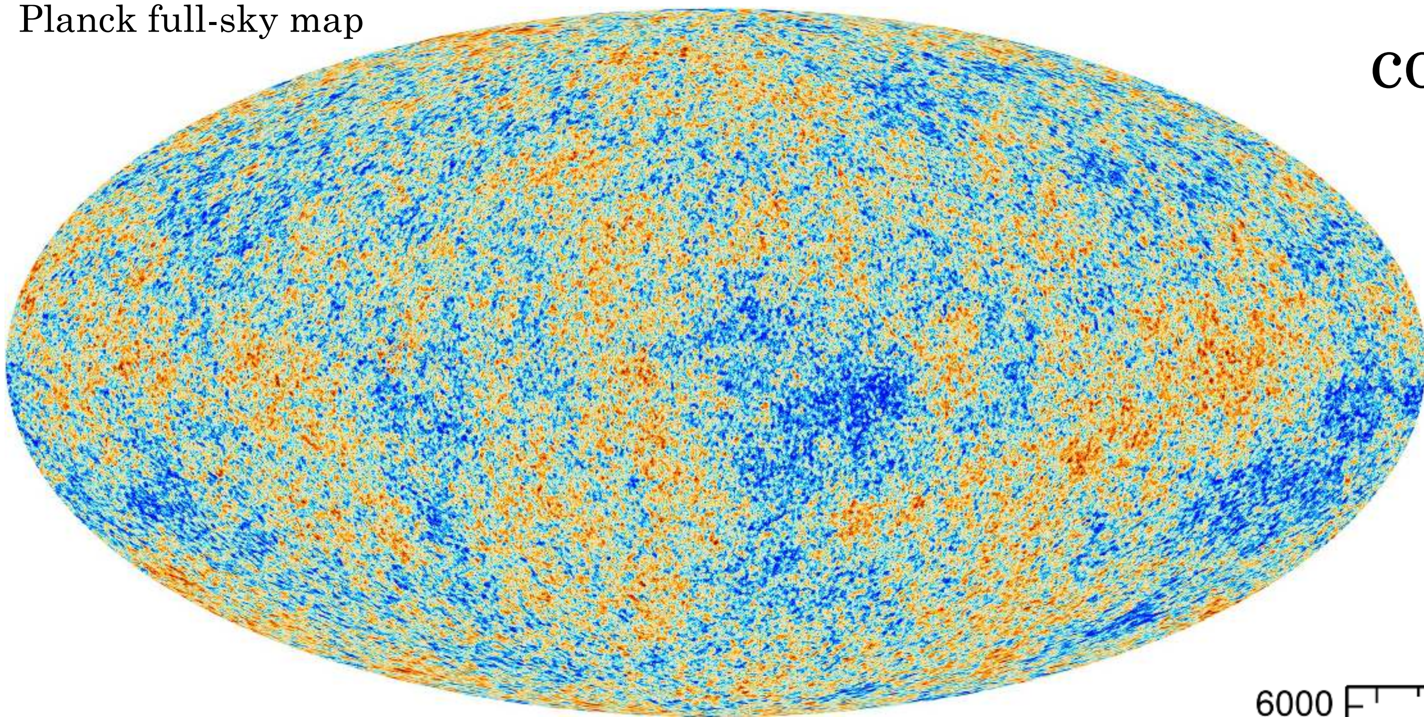


Markevitch et al
Clowe et al

Bullet cluster

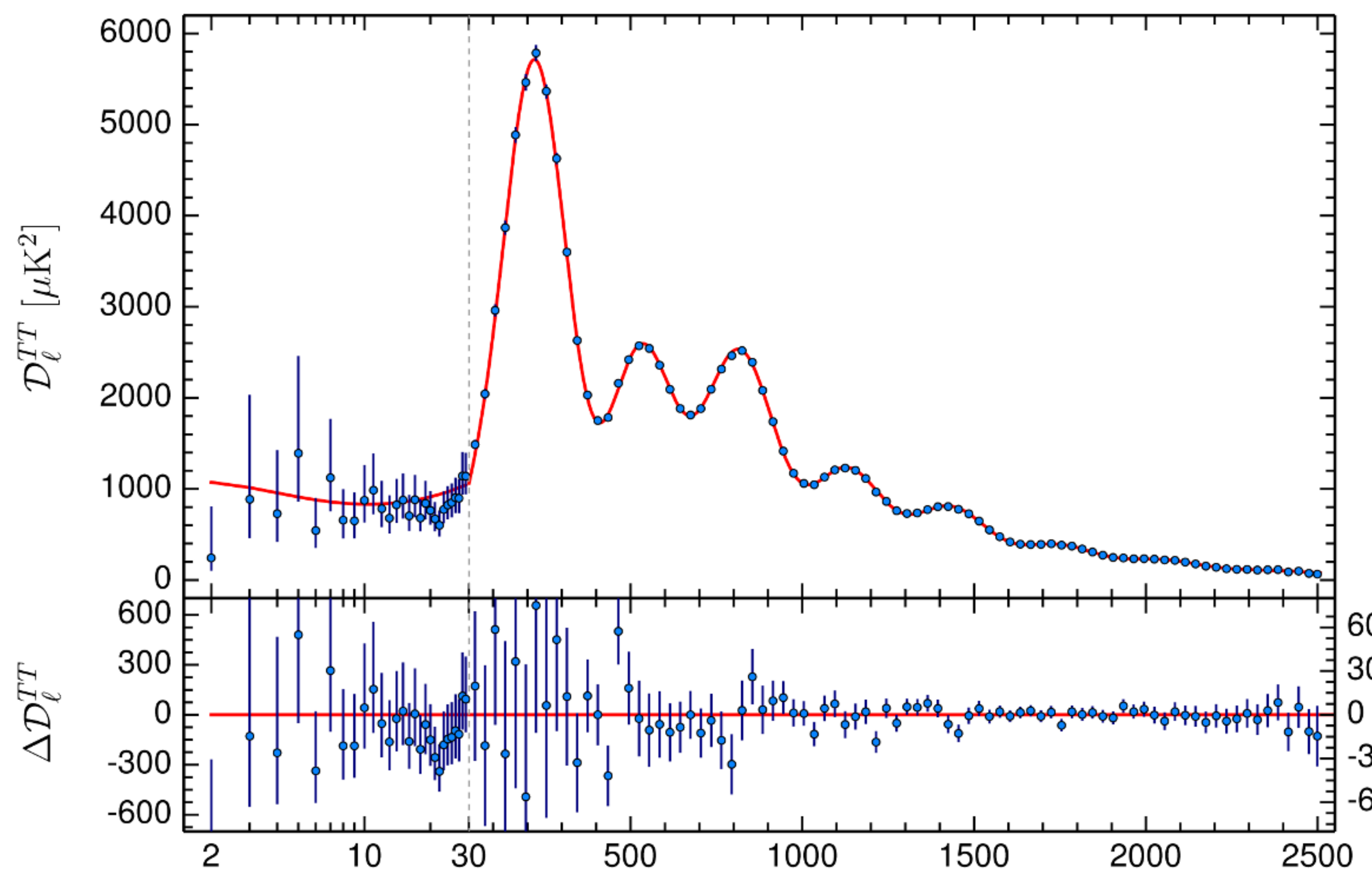
Strongest evidence for Dark Matter

Planck full-sky map



cosmic microwave background (CMB) anisotropy sky map

its angular power spectrum



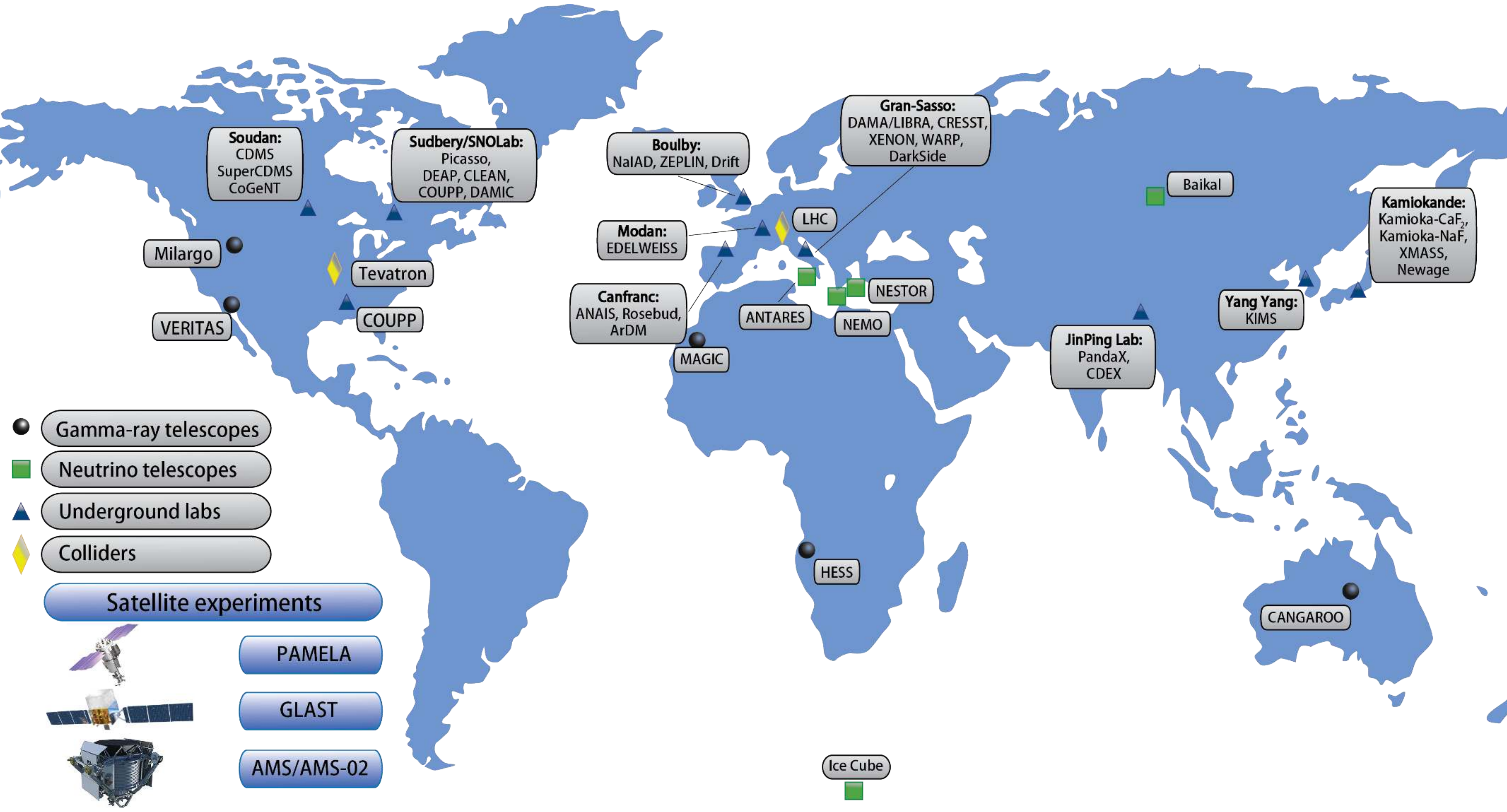
Planck 2015

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

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

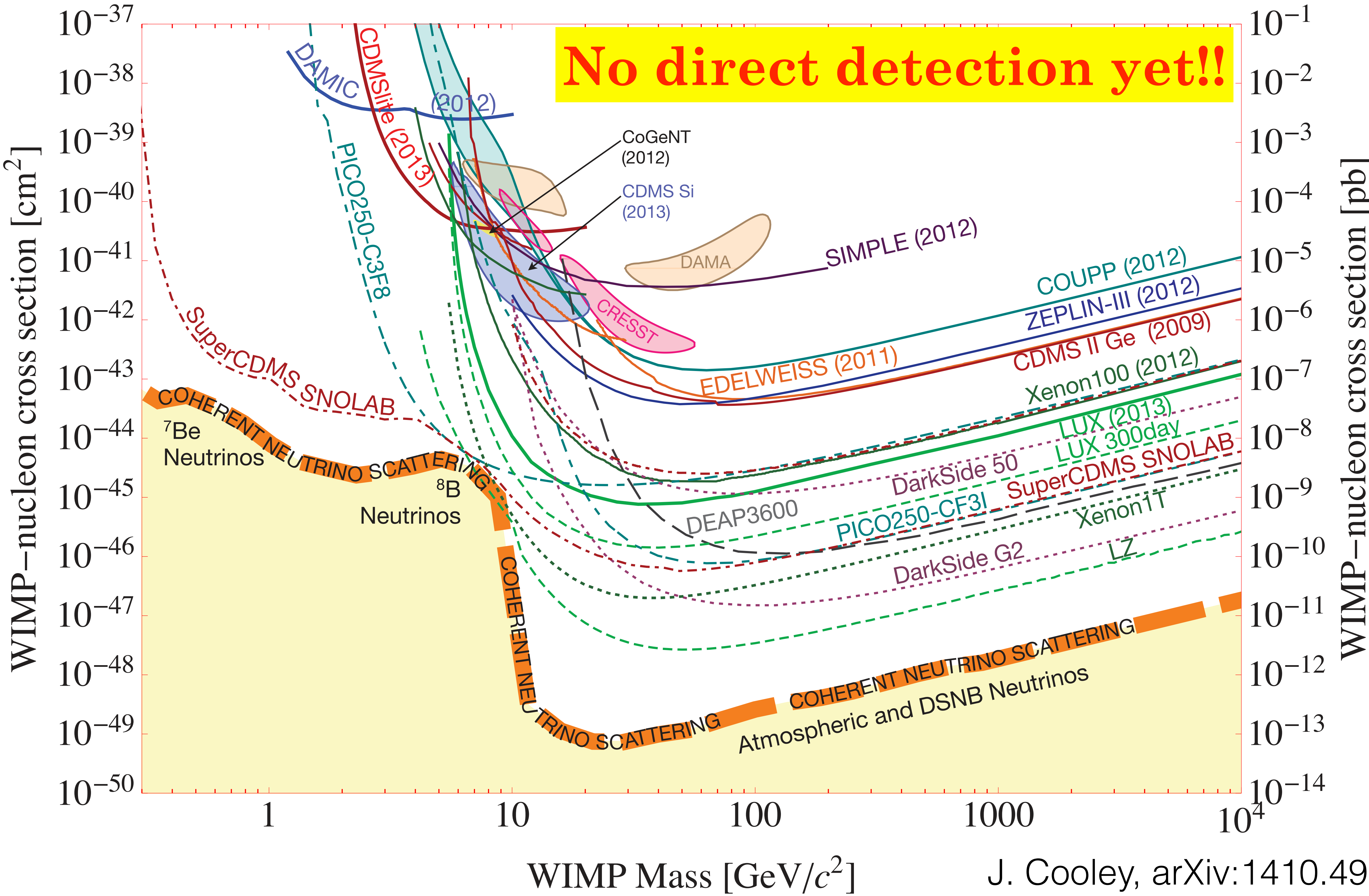
baryons ≠ dark matter
at ~50 sigma!

Worldwide quest to (in)directly detect DM



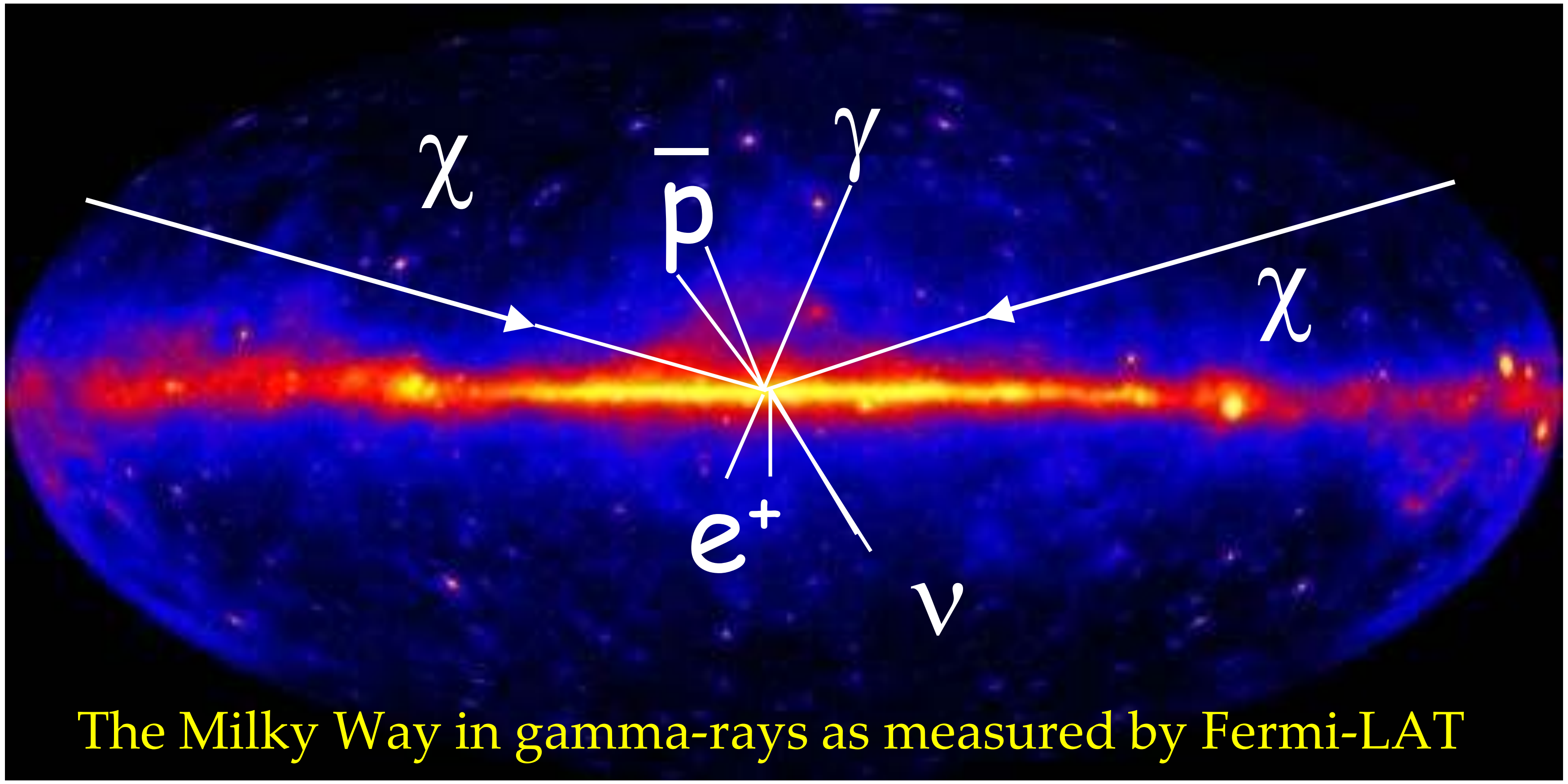
M. Deliyergiyev, 2016

Direct searches:
Cross-section vs mass constraints



J. Cooley, arXiv:1410.4960

Indirect detection

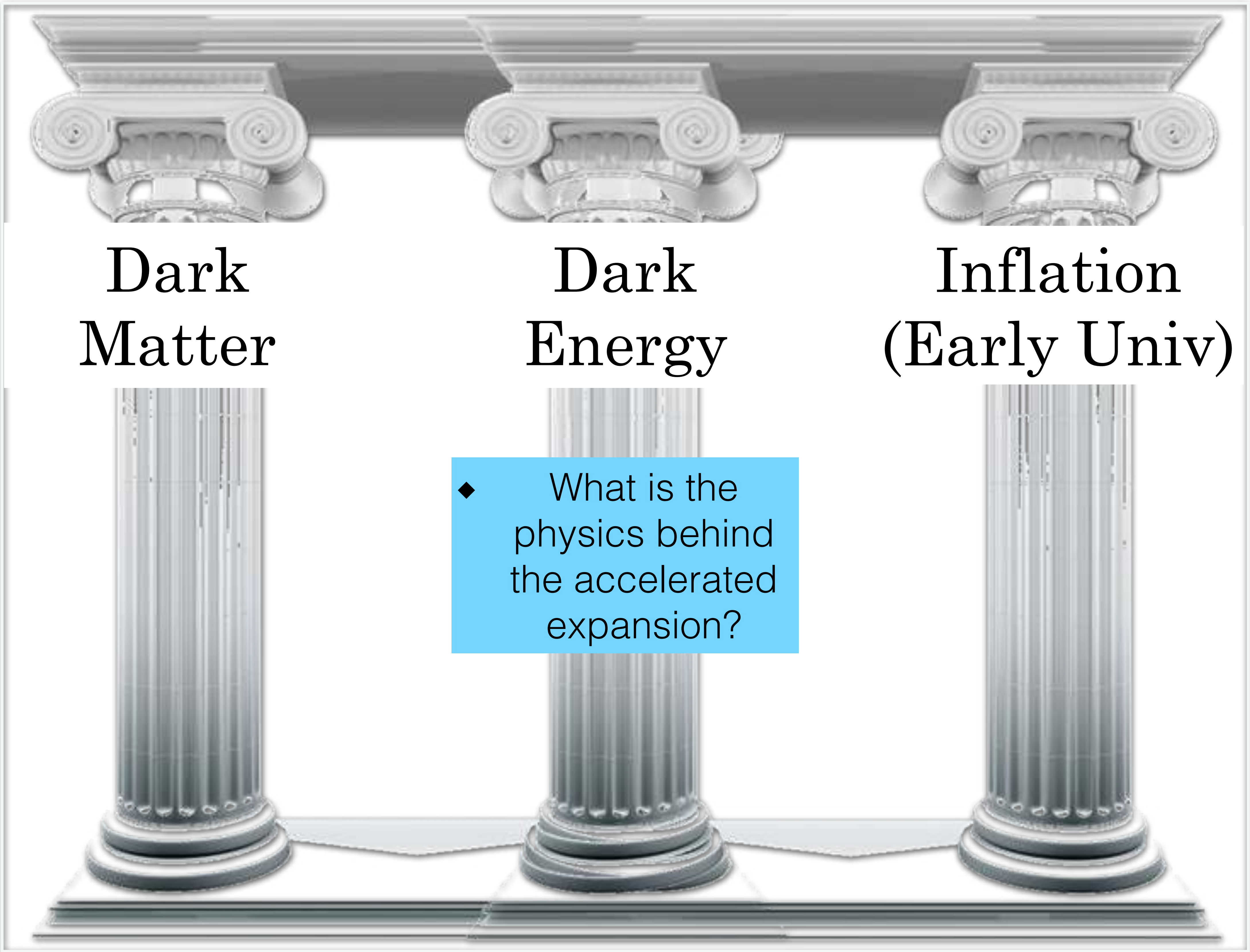


Numerous alarms about "bumps" in spectra seen from Galaxy, and from dwarf galaxies (Reticulum, etc)

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



SNe Ia are "Standard Candles"

(car headlights example)

If you know the intrinsic brightness of the headlights, you can estimate how far away the car is

A way to measure (relative) distances to objects far away

But how do you find SNe?

Rate: 1 SN per galaxy per 500 yrs!

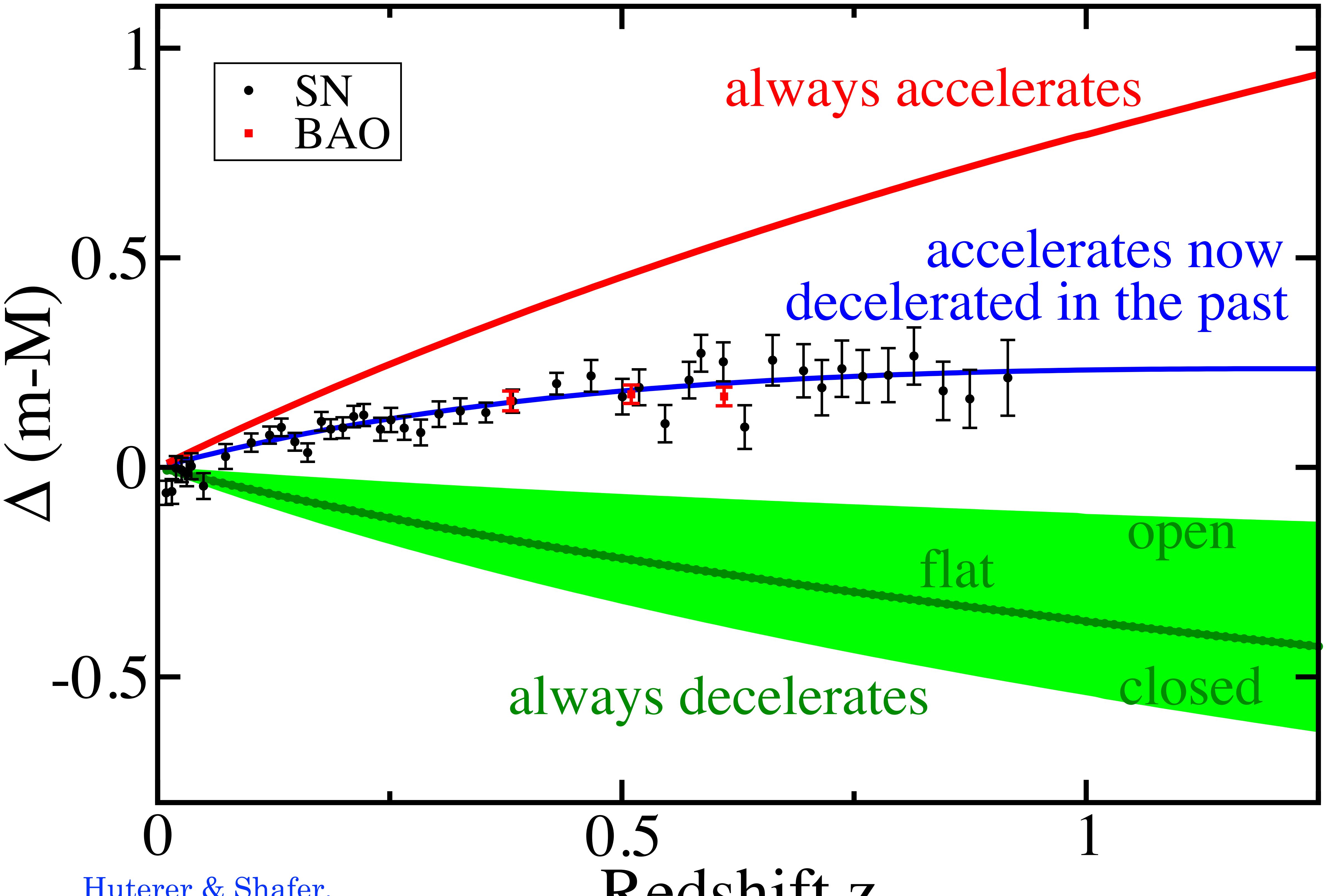
Solution:

1. use world's large telescopes,
2. schedule them to find, then "follow-up" SNe
3. put in heroic hard work

Motivation: to measure geometry of the universe

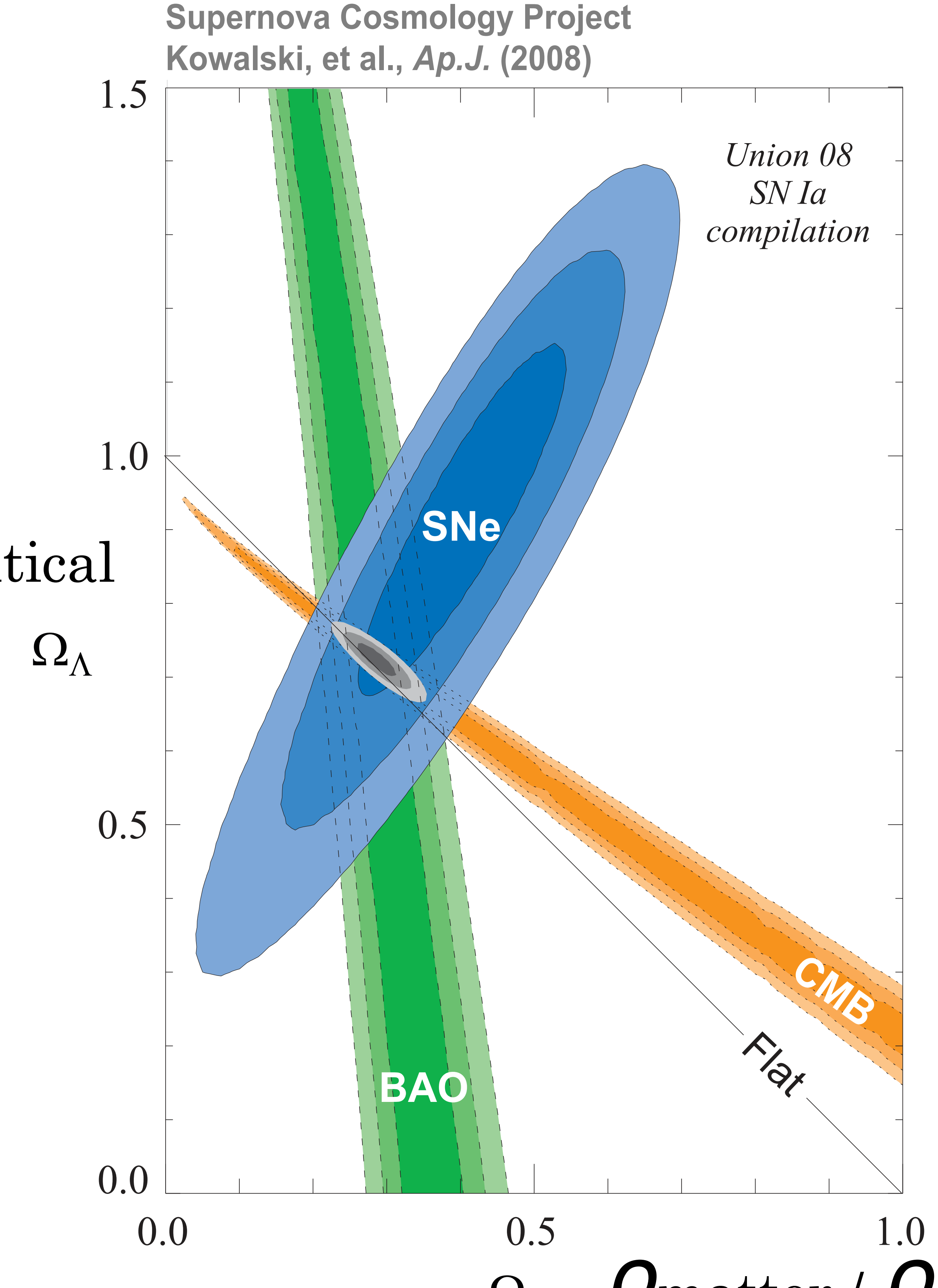
2011 Physics Nobel Prize (Perlmutter, Riess, Schmidt)

Evidence for Dark energy from type Ia Supernovae



Huterer & Shafer,
Rep. Prog. Phys.; arXiv:1709.01091

Constraints on dark energy

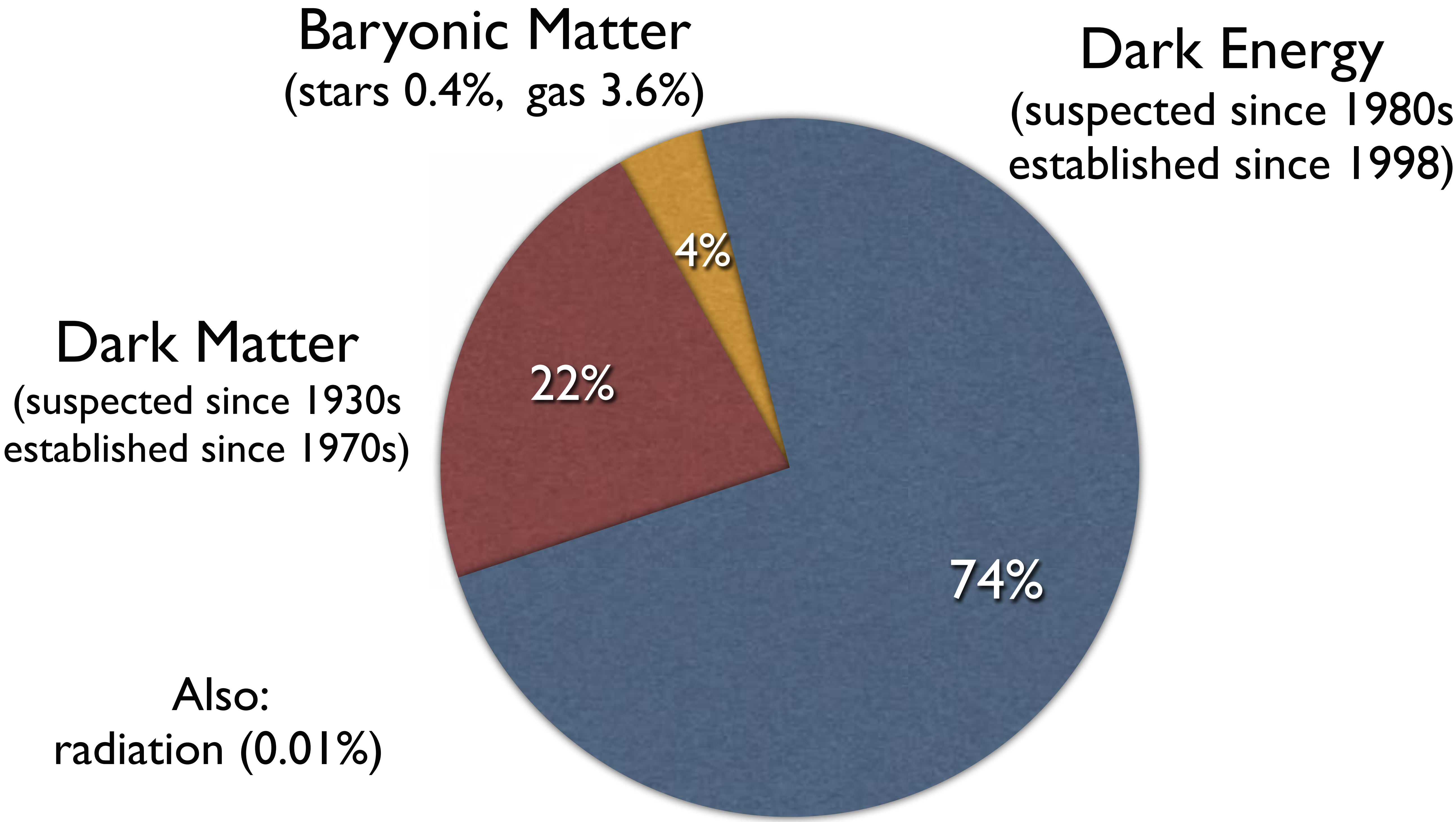


$\rho_{DE} / \rho_{critical}$

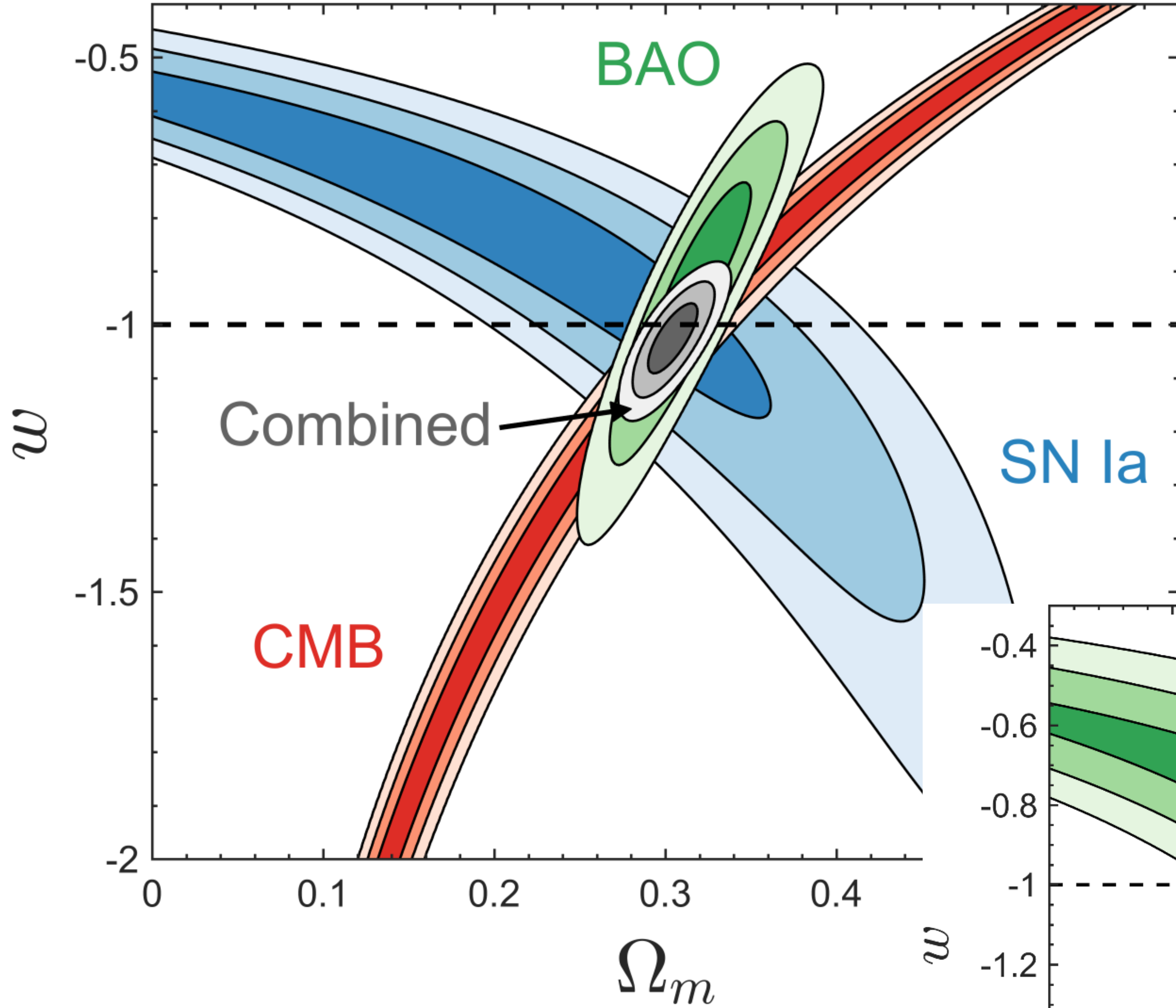
$\rho_{matter} / \rho_{critical}$

Diverse methods agree!

Makeup of universe today



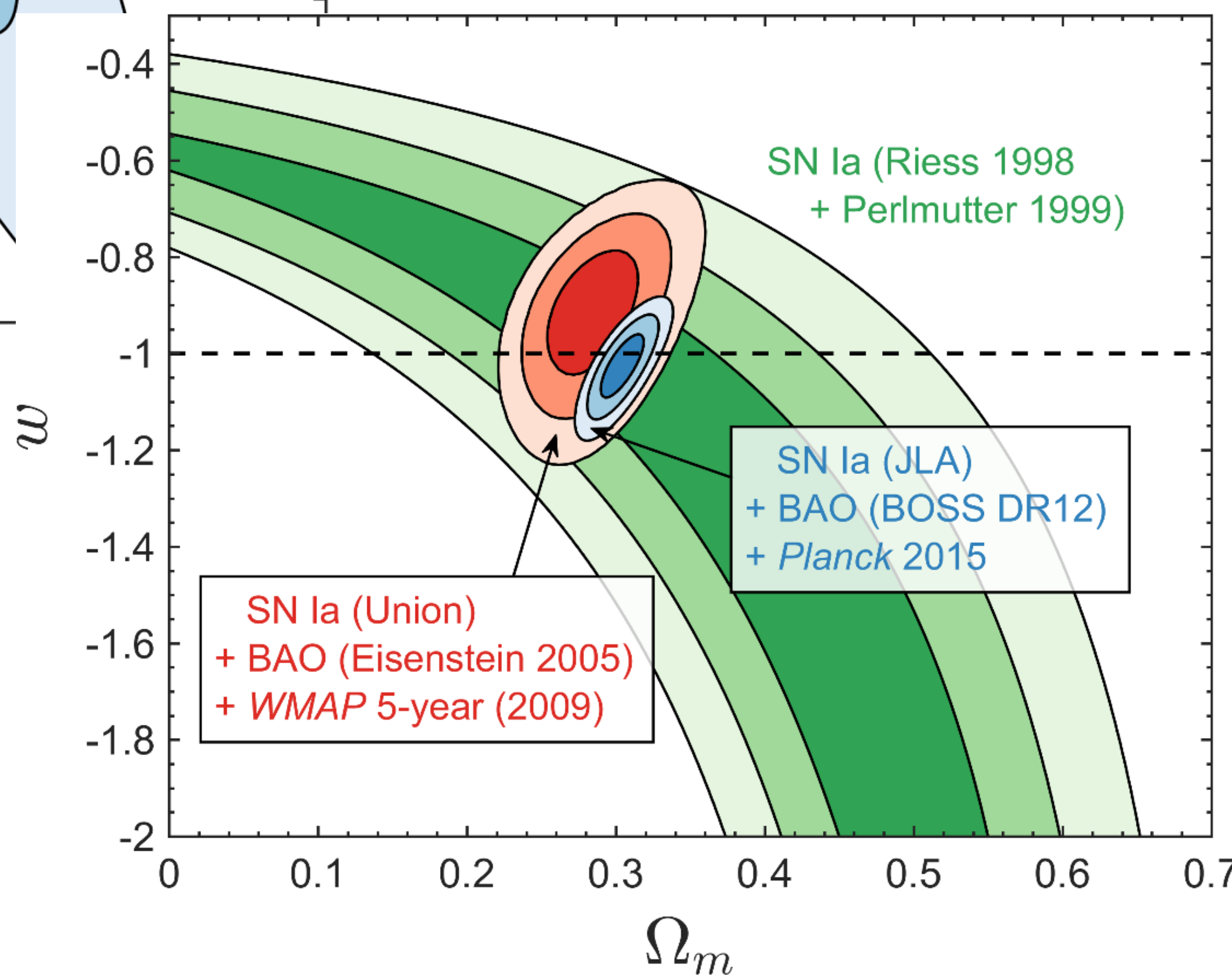
Also:
radiation (0.01%)



$$\Omega_m = 1 - \Omega_{\rm DE}$$

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

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



Huterer & Shafer,
Rep. Prog. Phys.; arXiv:1709.01091

Fine Tuning Problem: "Why so small"?

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

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

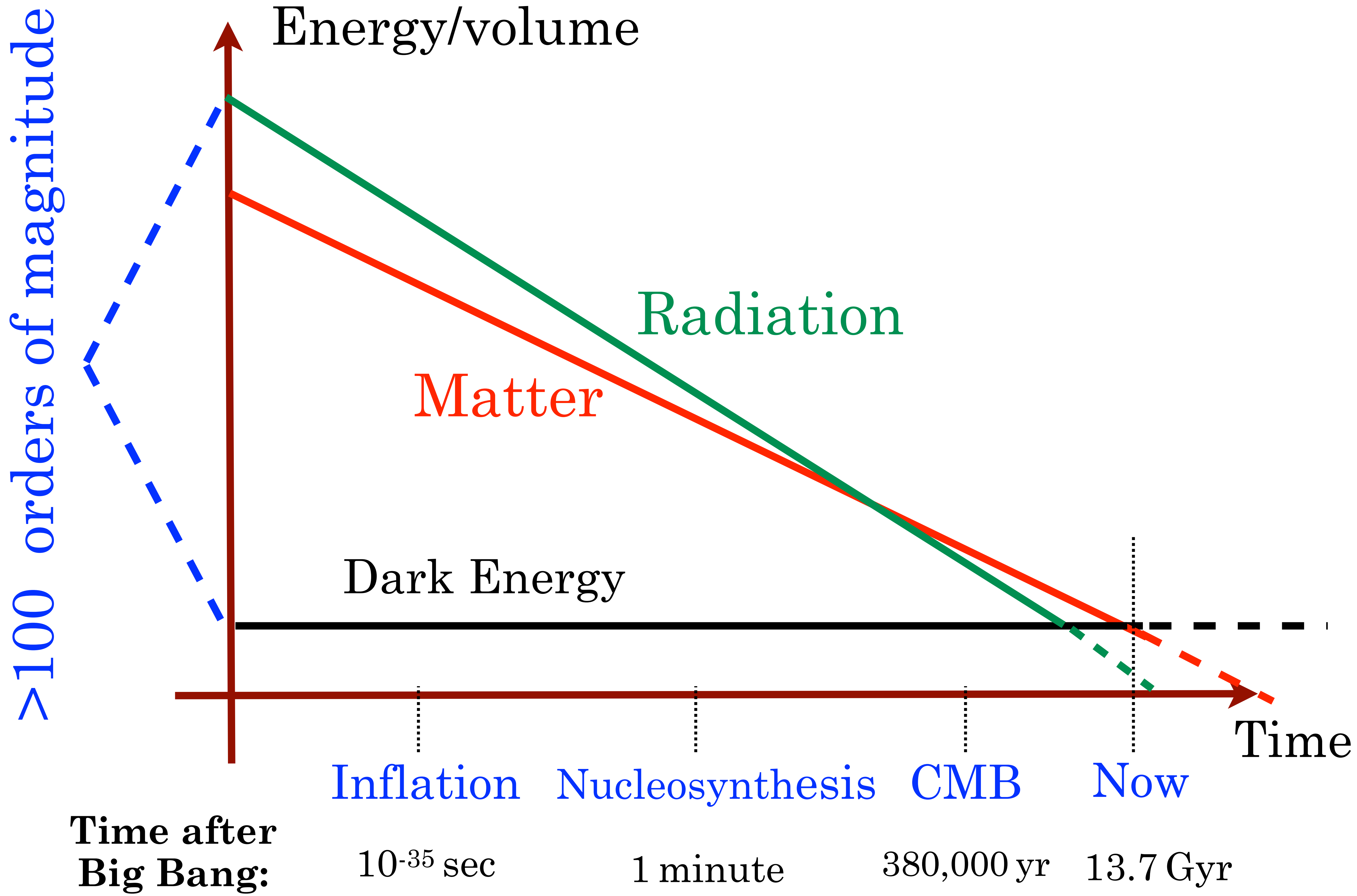
Measured: $(10^{-3}\mathrm{eV})^4$

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

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

} 60-120 orders of magnitude smaller than expected!

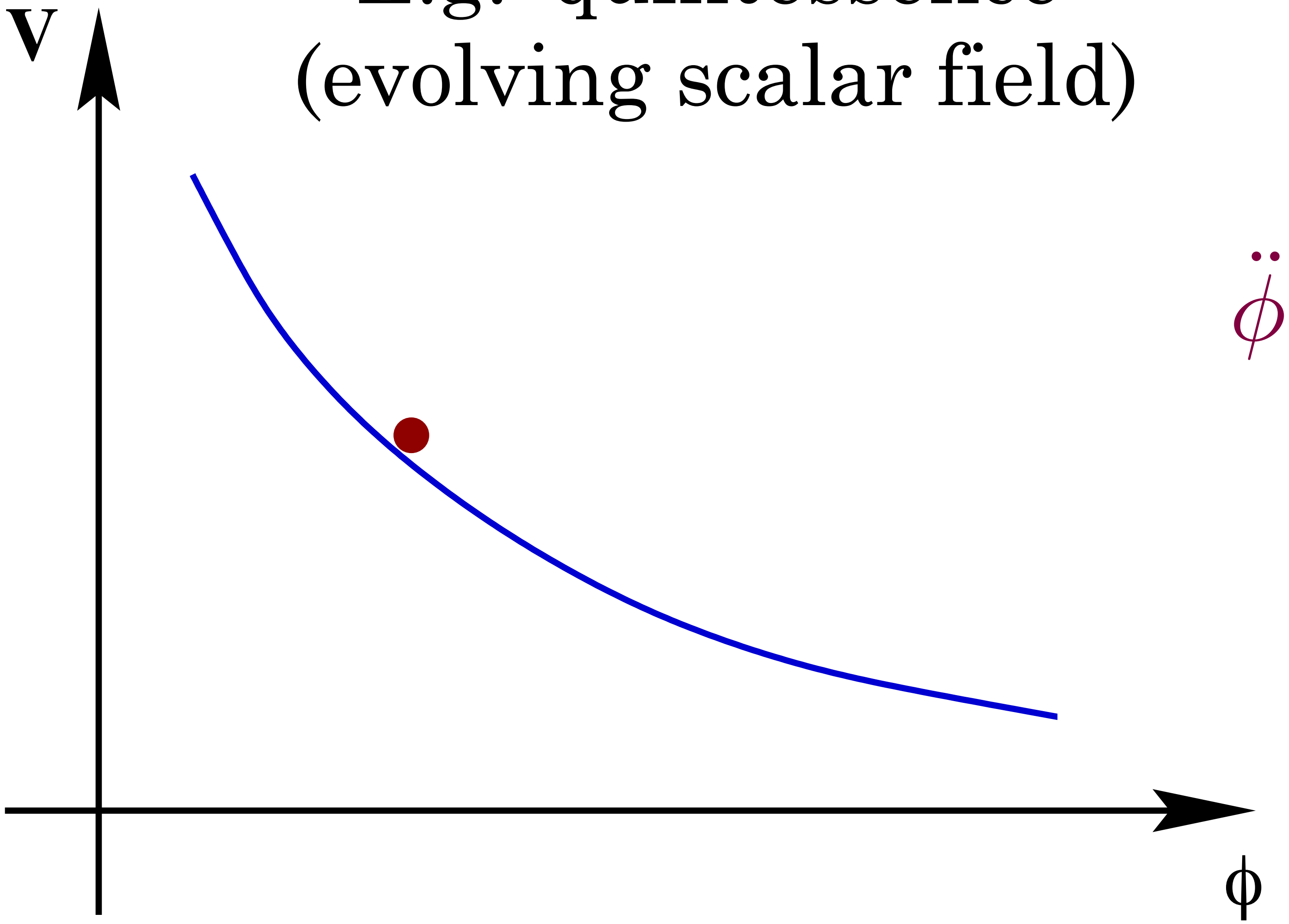
The coincidence problem



Lots of theoretical ideas, few compelling ones:

Very difficult to motivate DE **naturally**

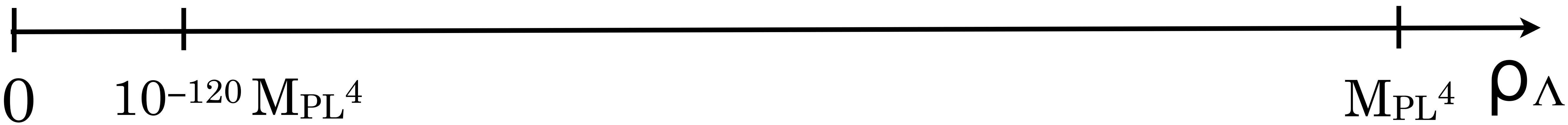
E.g. 'quintessence'
(evolving scalar field)



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

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

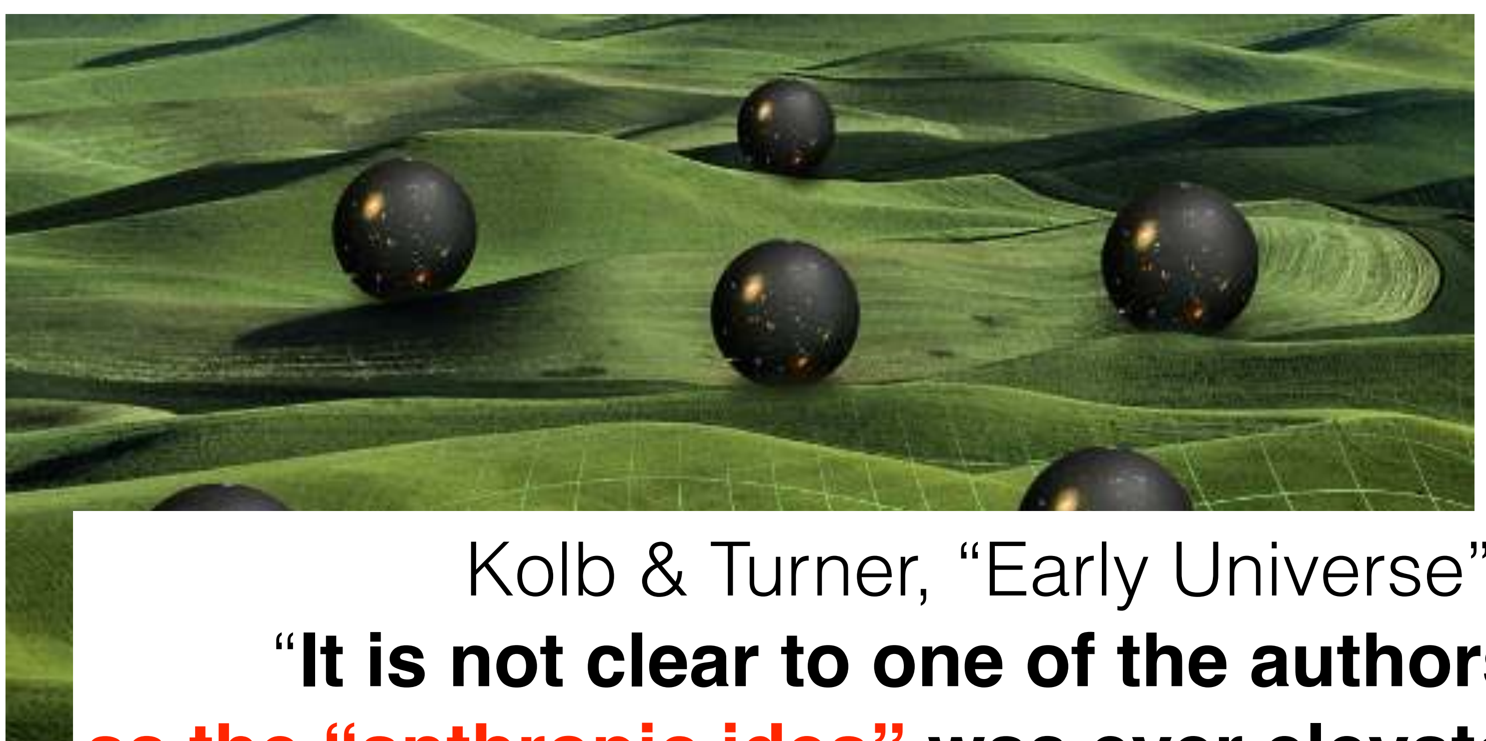
String landscape?



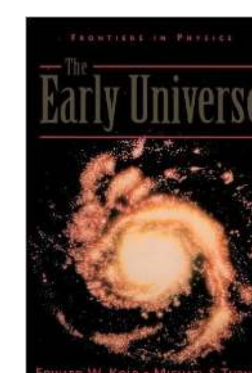
Among the $\sim 10^{500}$ minima,

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:

$$(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ \mathrm{eV}^2$$

$$(\Delta m^2)_{atm} \simeq 3\times10^{-3}\ \mathrm{eV}^2$$

$\sum m_i = 0.06$ eV* (normal)

vs.

$\sum m_i = 0.11$ eV* (inverted)

*(assuming $m_3=0$)

2. Higgs Boson mass (before LHC 2012):

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

(assuming Standard Model Higgs)

Ongoing or upcoming DE experiments:

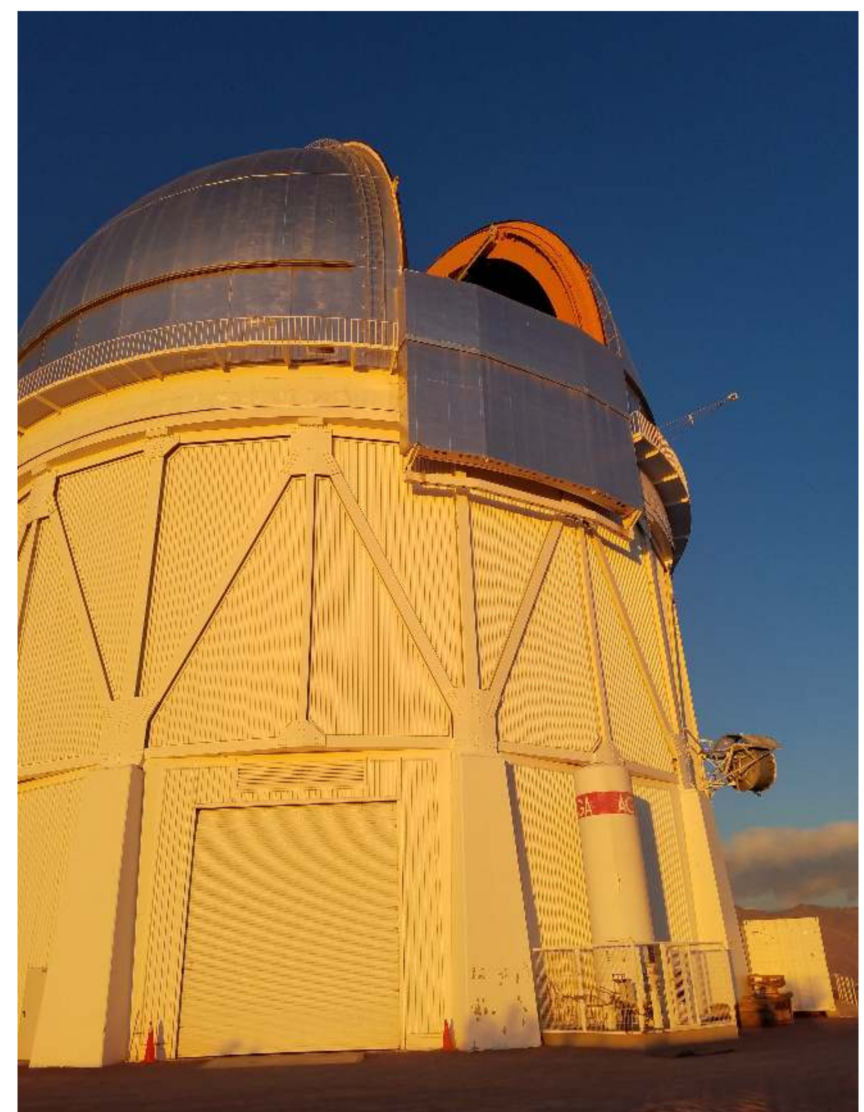
- **Ground photometric:**
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES)
  - Hyper Supreme Cam (HSC)
  - Large Synoptic Survey Telescope (LSST)
- **Ground spectroscopic:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Prime Focus Spectrograph (PFS)
  - Dark Energy Spectroscopic Instrument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

Dark Energy Survey

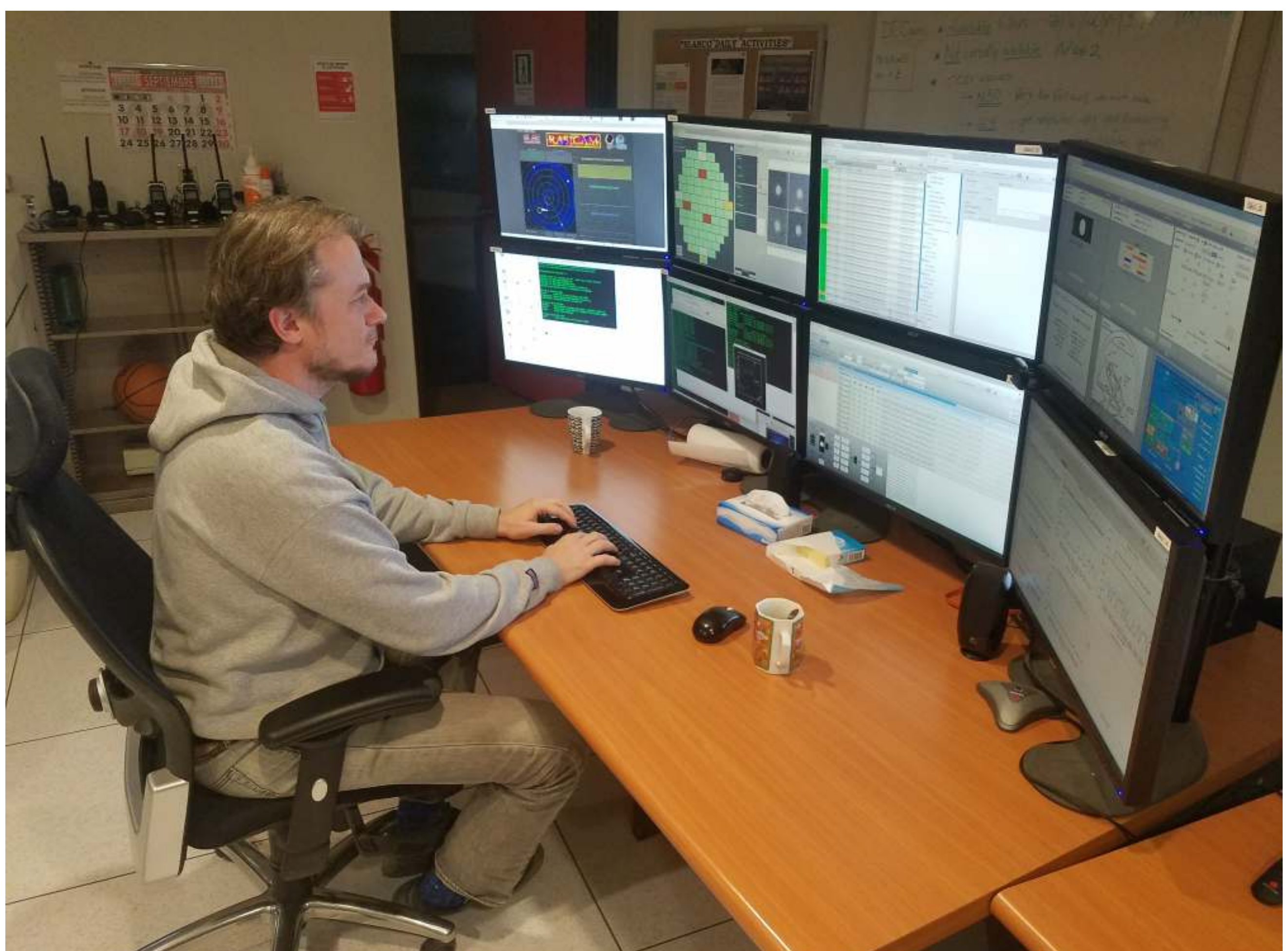
- New camera on 4m telescope in Chile
- Observations 2013-2019
- ~700 scientists worldwide
- Analyses in progress (first major results Aug 2017)

Dark Energy Survey (DES)

Cerro Tololo, Chile

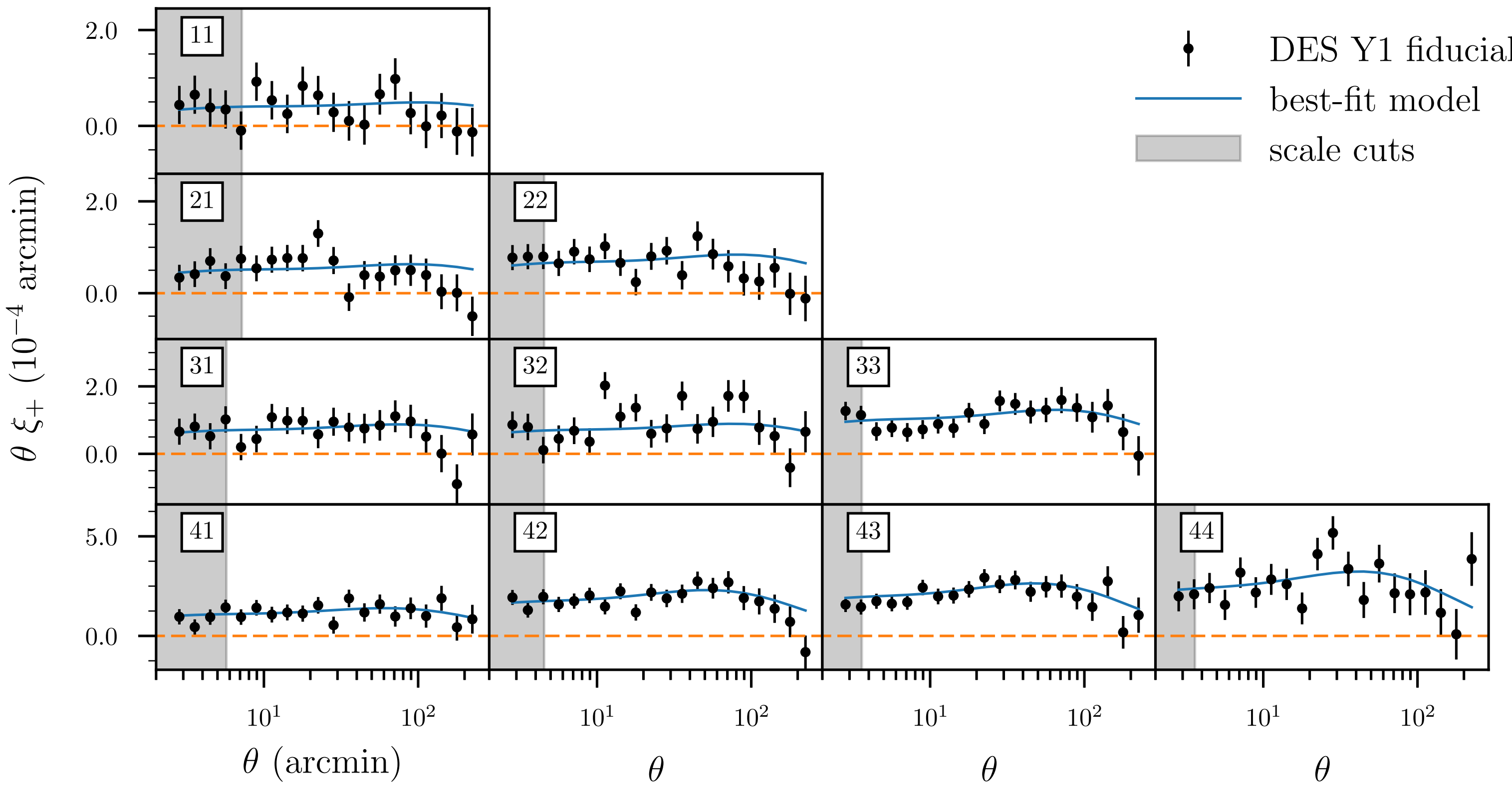


Blanco Telescope

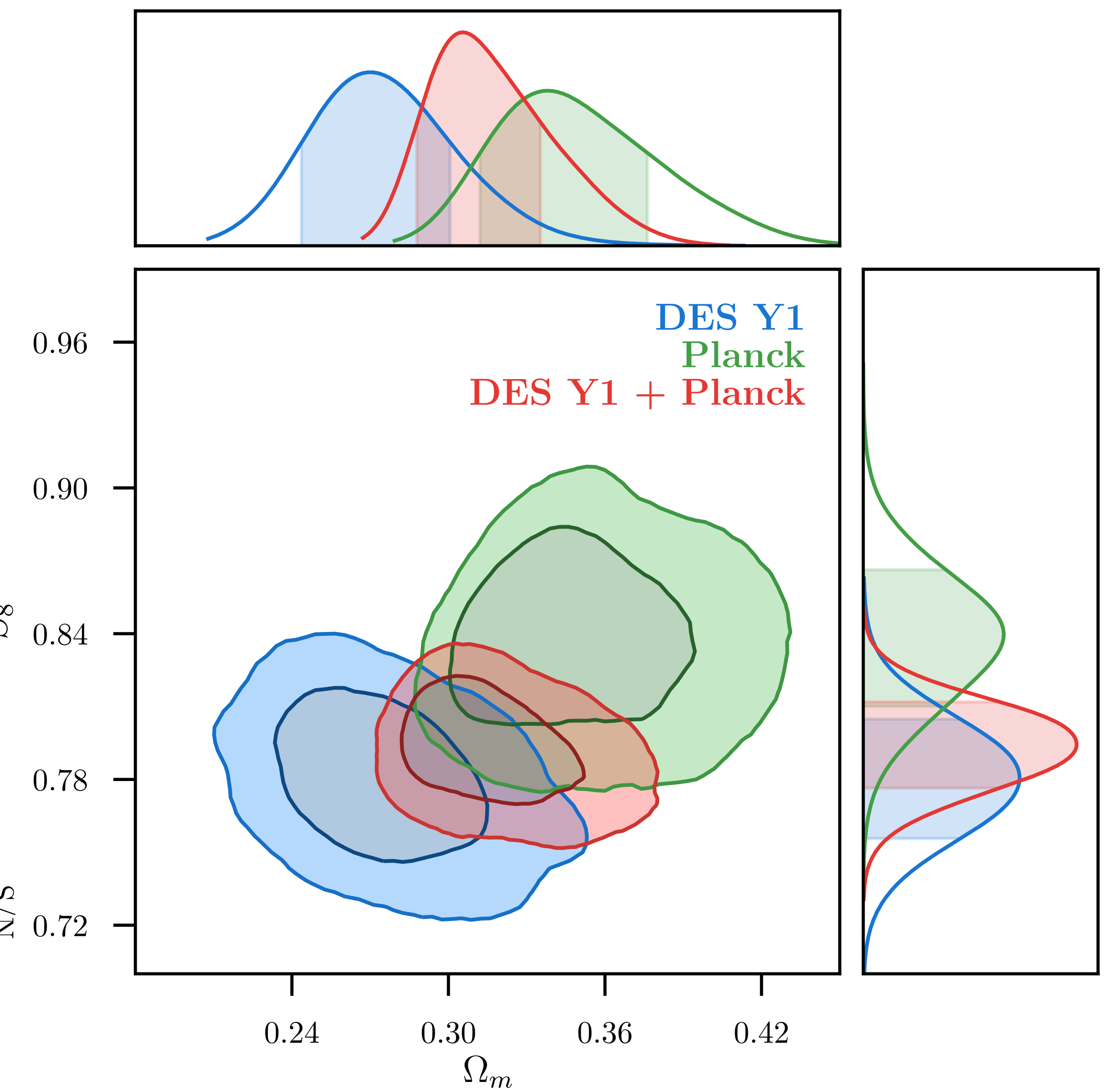


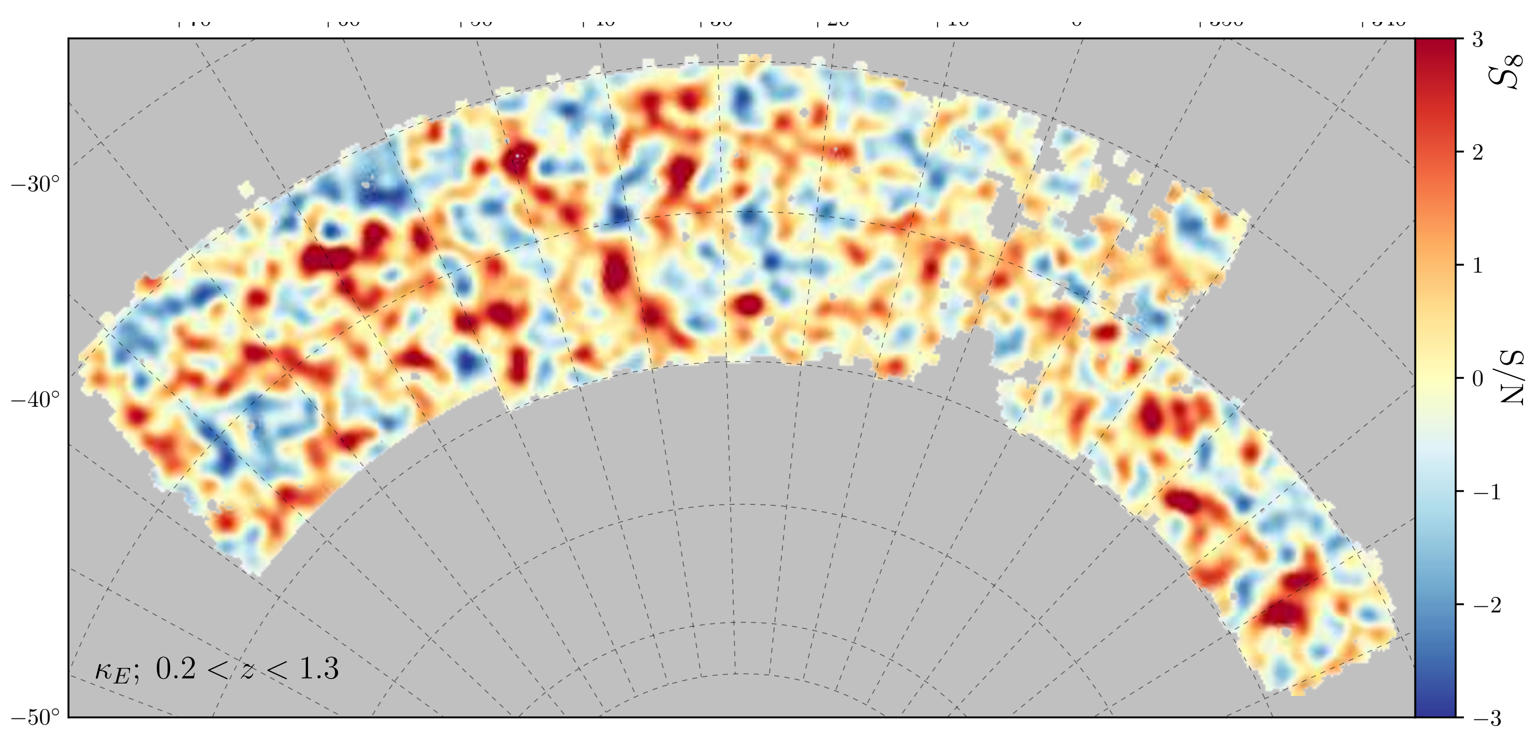
DES Year-1 results (August 2017)

1350 sq. deg., 35 million galaxies, "double pipeline" for everything



Abbott et al, arXiv:1708.01530





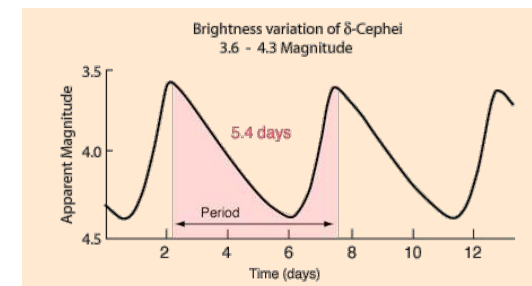
Year-3 data coming out "any month now", 3x area (close to 5000 sqdeg), 200-300 million galaxies, leading galaxy survey

Breaking news:

Hubble tension!

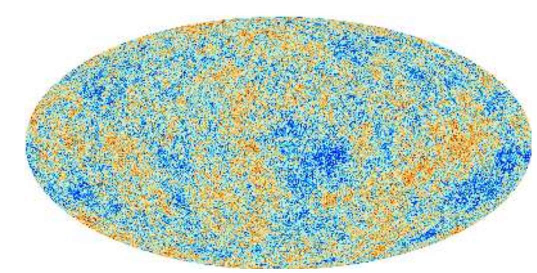
Type Ia supernovae + Cepheid distances give

$$H_0 = 74.0 \pm 1.4 \text{ (km/s/Mpc)}$$



Cosmic Microwave Anisotropies give

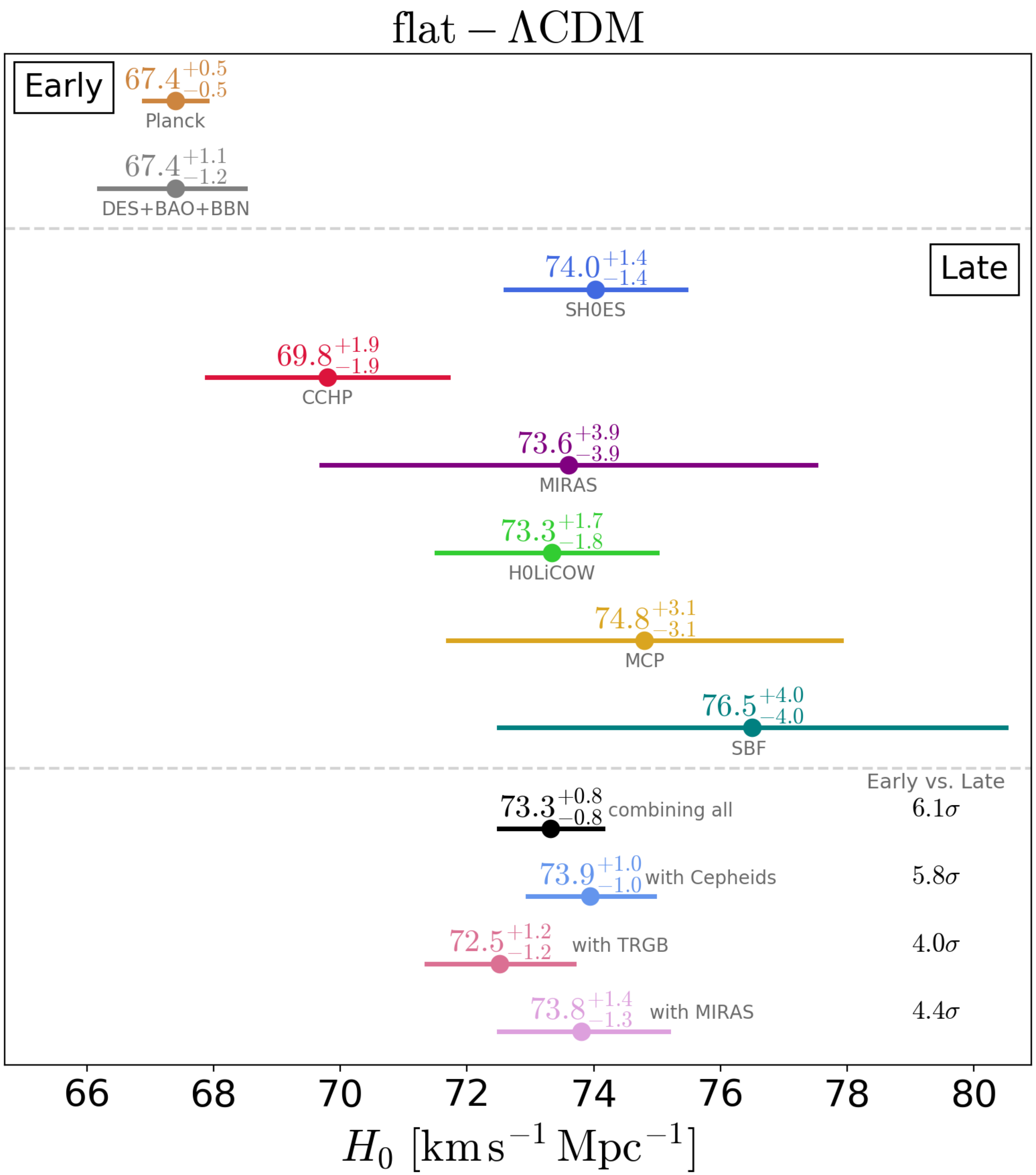
$$H_0 = 67.4 \pm 0.4 \text{ (km/s/Mpc)}$$



These two measurements are discrepant at about five sigma!*

* once strong-lensing constraints are added, which come out high (H_0 ~ 73)

Hubble tension!



Verde, Treu & Riess arXiv:1907.10625

- Currently the most exciting thing in field of cosmology
- Difference between early- and late-universe meas. (?)
- Many hundreds of papers on topic, no compelling solution
- Weird systematics? New properties of DM or DE? ….

Conclusions

- Huge variety of new observations in cosmology, particularly in the large-scale structure
- 3 big questions: dark matter, dark energy, inflation
- Tremendous successes (DM, DE, inflation “proven”), yet challenges (what is the physics behind them?)
- Like particle physicists, we would really like to see some “bumps” in the data - signatures of new physics
- The current Hubble tension may be a signature of such a “bump”