New views of the Universe

Dragan Huterer
University of Michigan

Illustris simulation

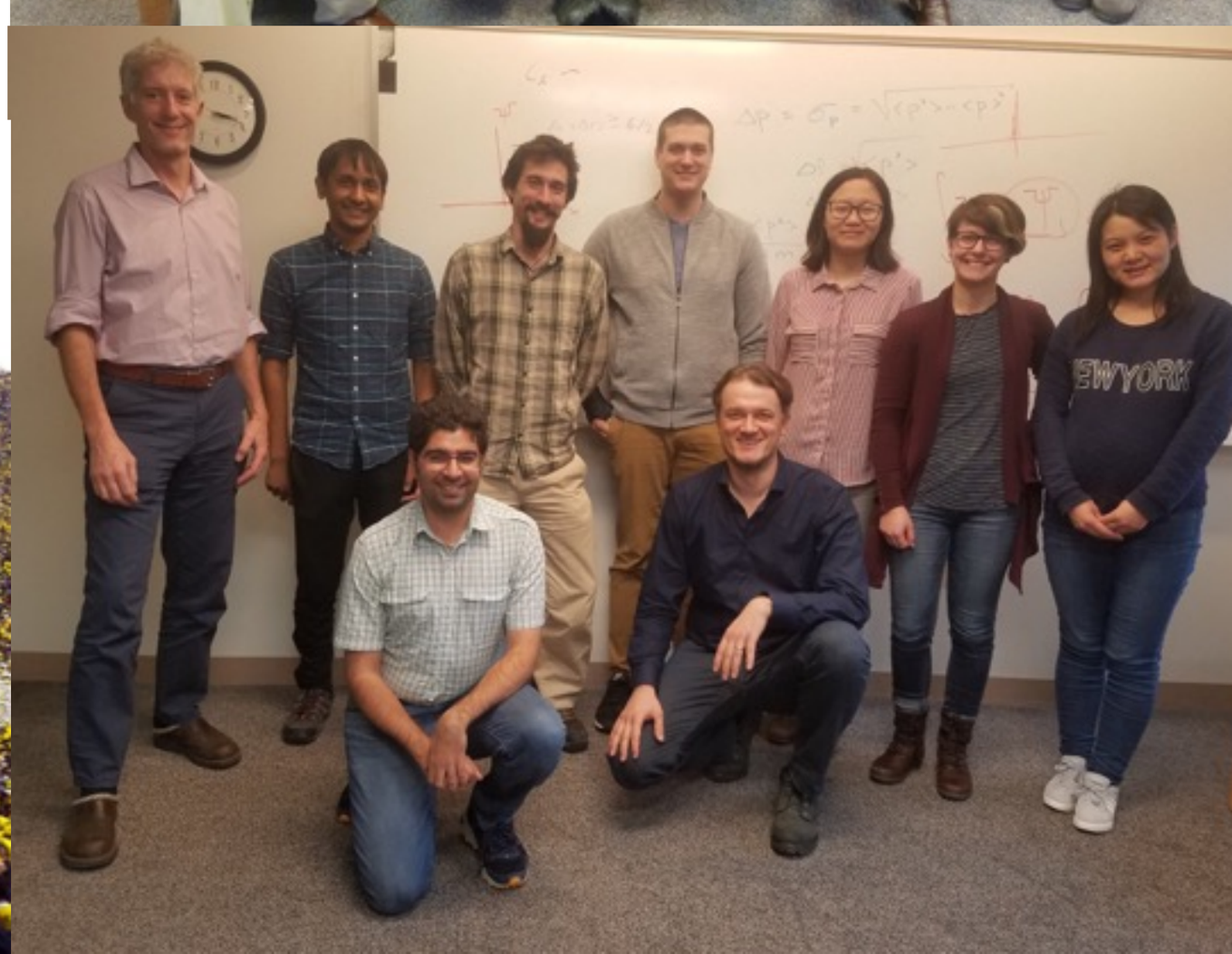
Moj put u svemir

- Odrastao u Sarajevu; Druga Gimnazija - matematika, fizika, kompjuteri
- Pohađao programe u Petnici 1991-e (četiri puta!)
- Proveo ~1 godinu dana planirajući studije u Americi (biblioteka američkog centra u Sarajevu)
- Napustio Sarajevo cargo-avionom u Aprilu 1992, (u Beograd), zatim u Ameriku
- Dodiplomski studiji na MIT-u (1996), doktorat na University of Chicago (2001)
- Profesor na University of Michigan od 2007

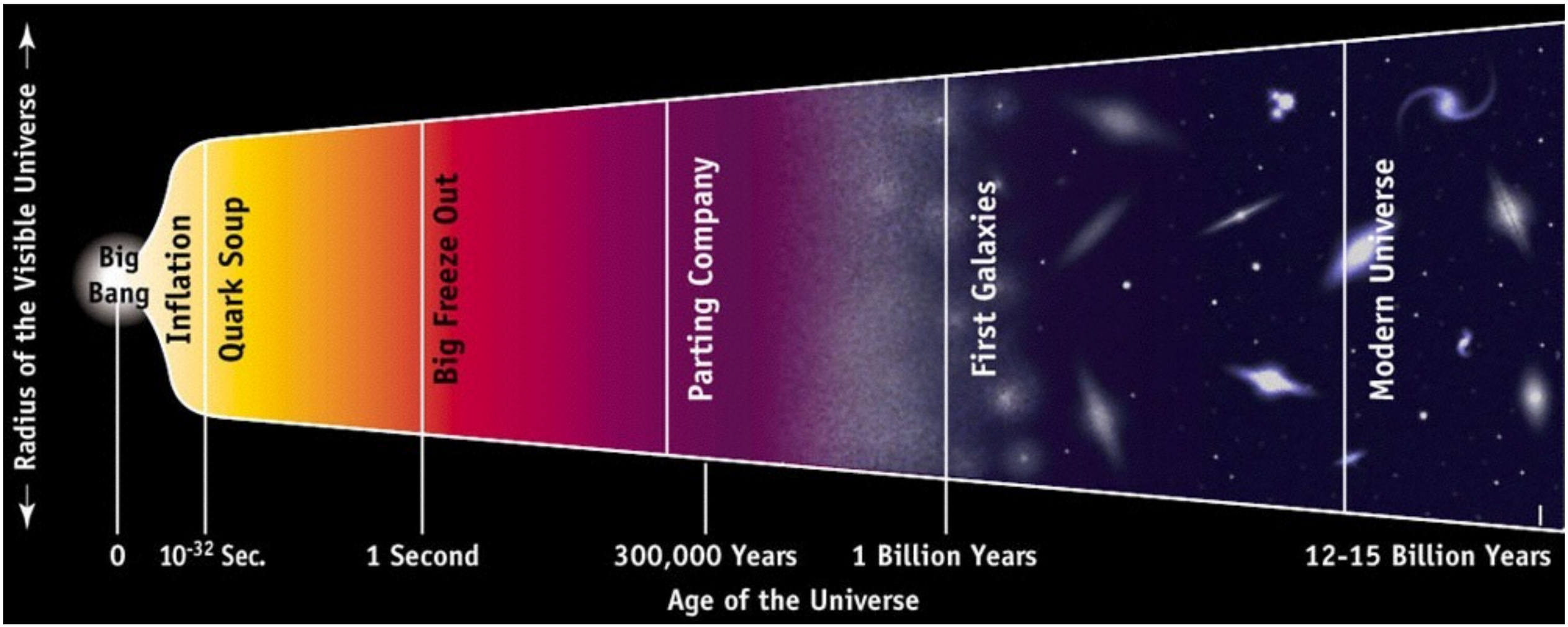
Ann Arbor, Michigan

Michigan Stadium (115,000)

Huterer group



Three key questions in cosmology

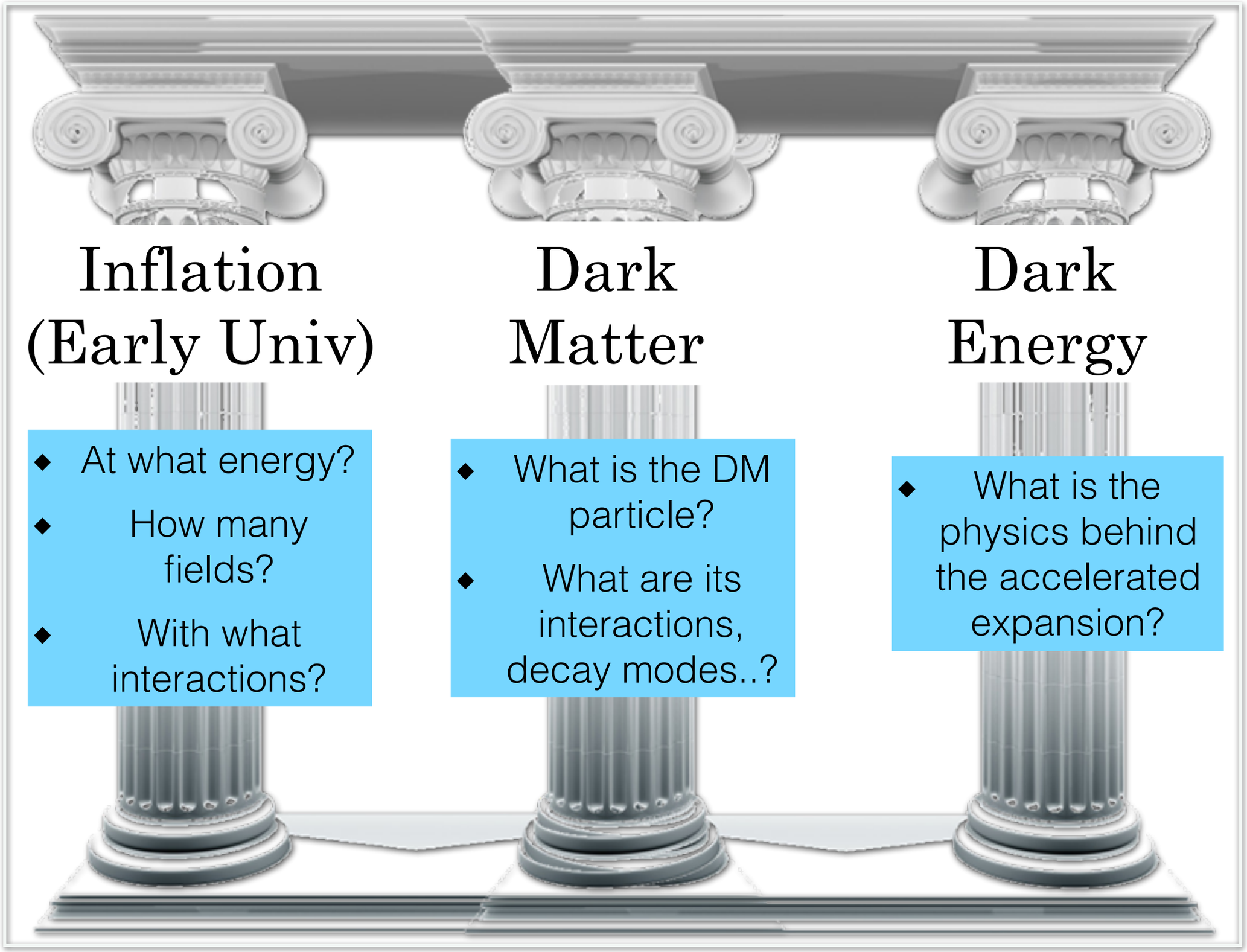


Inflation

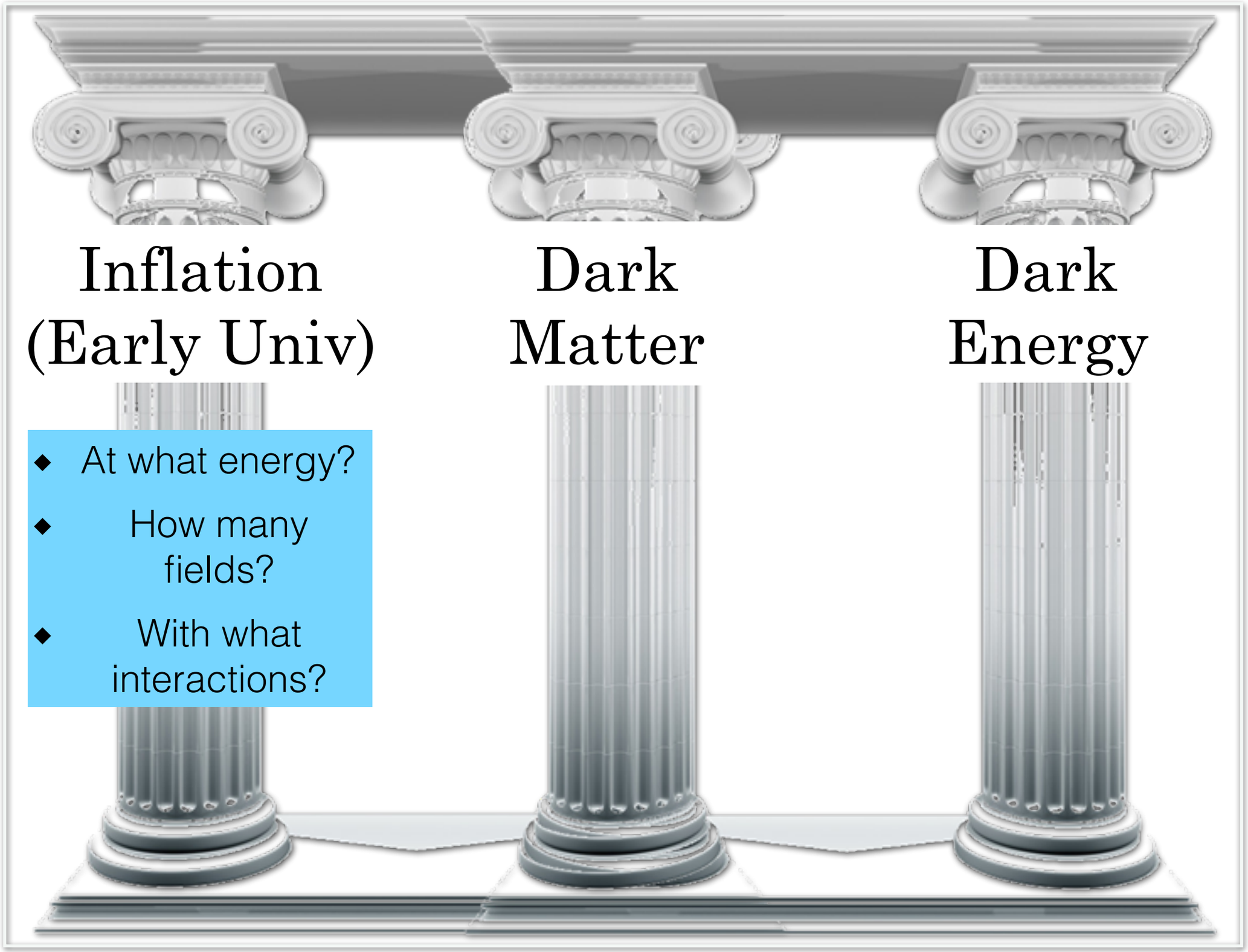
Dark Matter

Dark Energy

Three big questions in cosmology

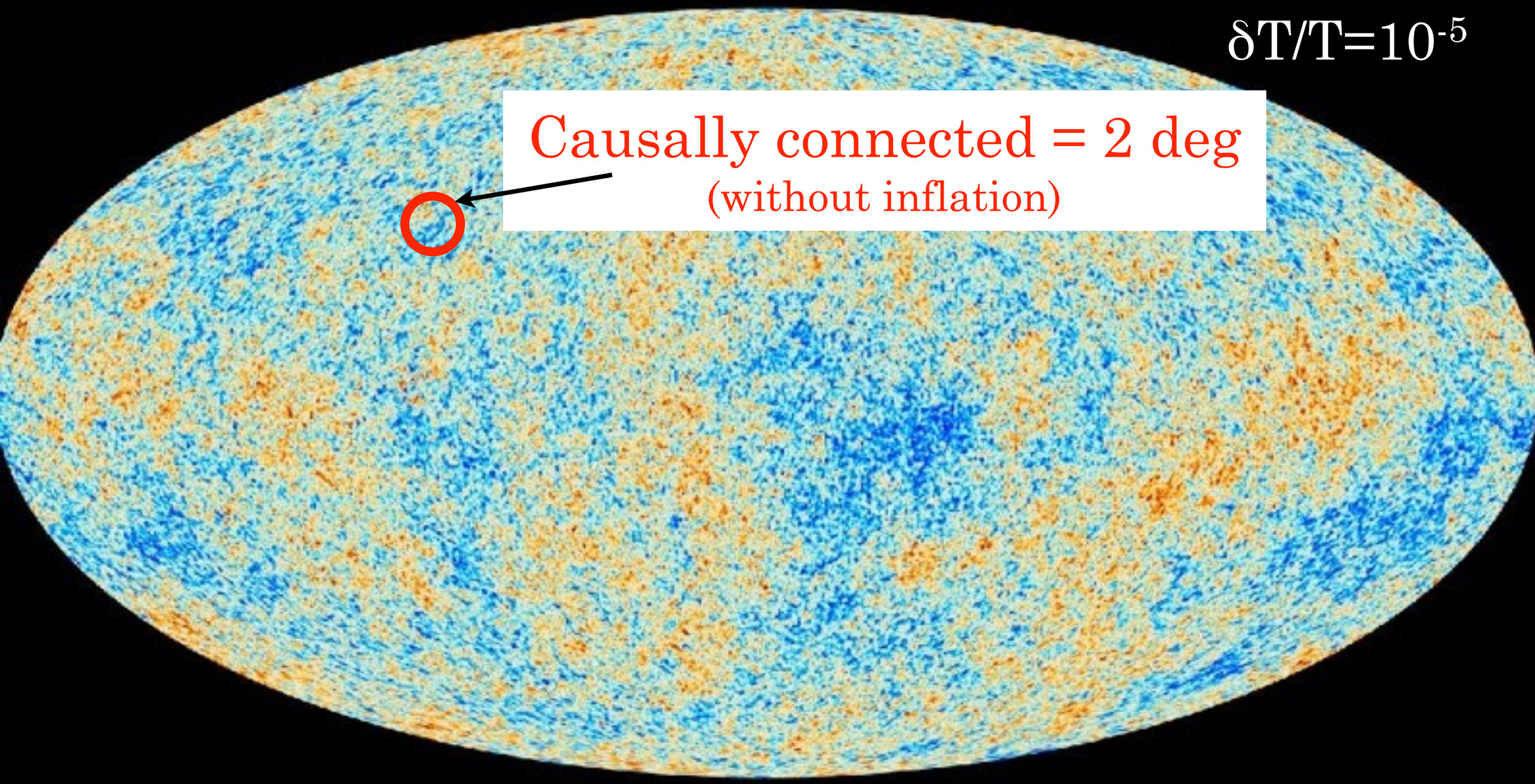


Three big questions in cosmology



Horizon problem

T=2.725K
$\delta T/T=10^{-5}$



CMB temperature is uniform to 1 part in 100,000
over ~10,000 independent patches - why?? Answer: inflation

Extremely successful theory of post-BB universe:

Inflation!

Alan Guth (1981)

Alan Guth

Guth's office at MIT

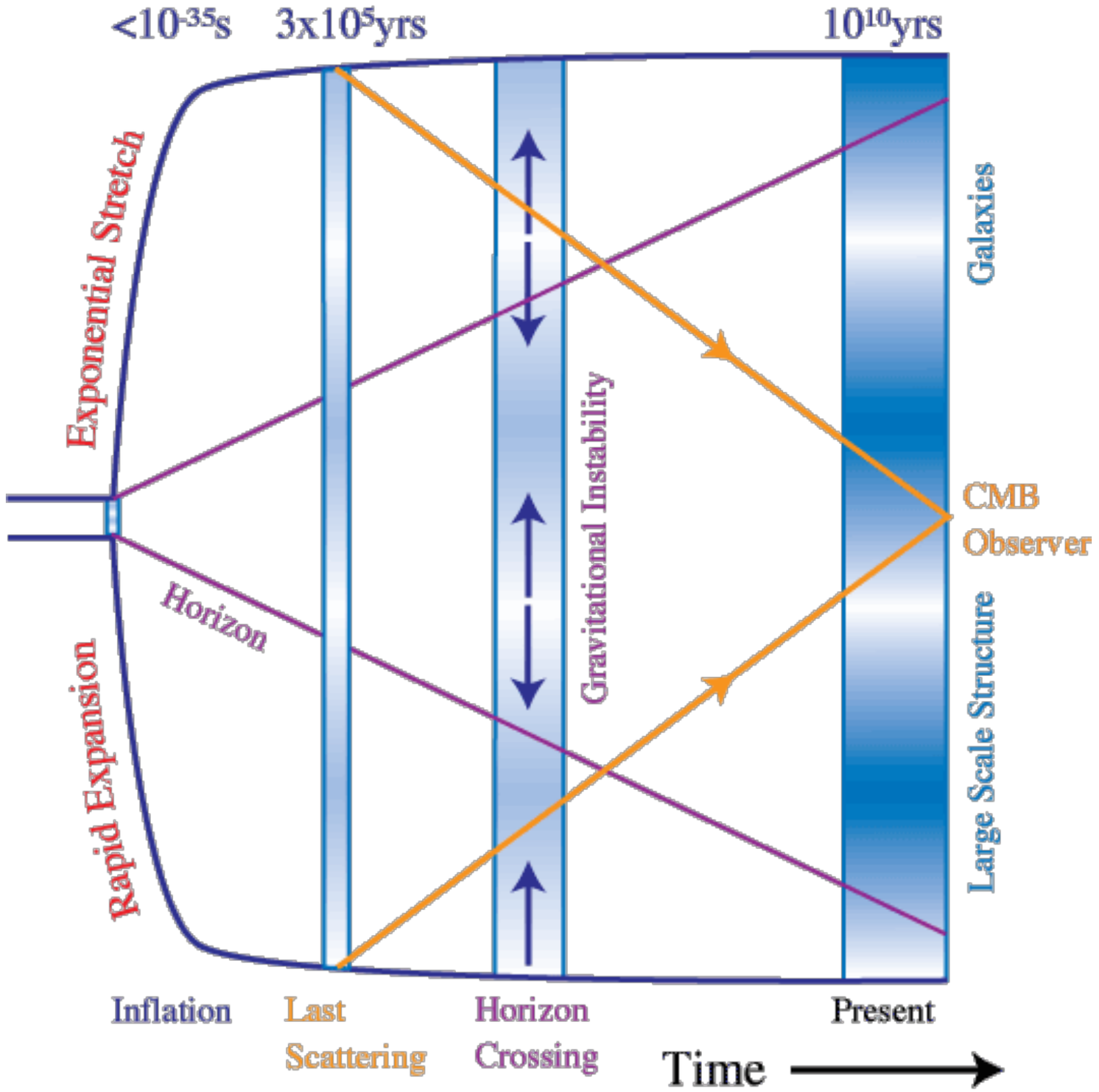
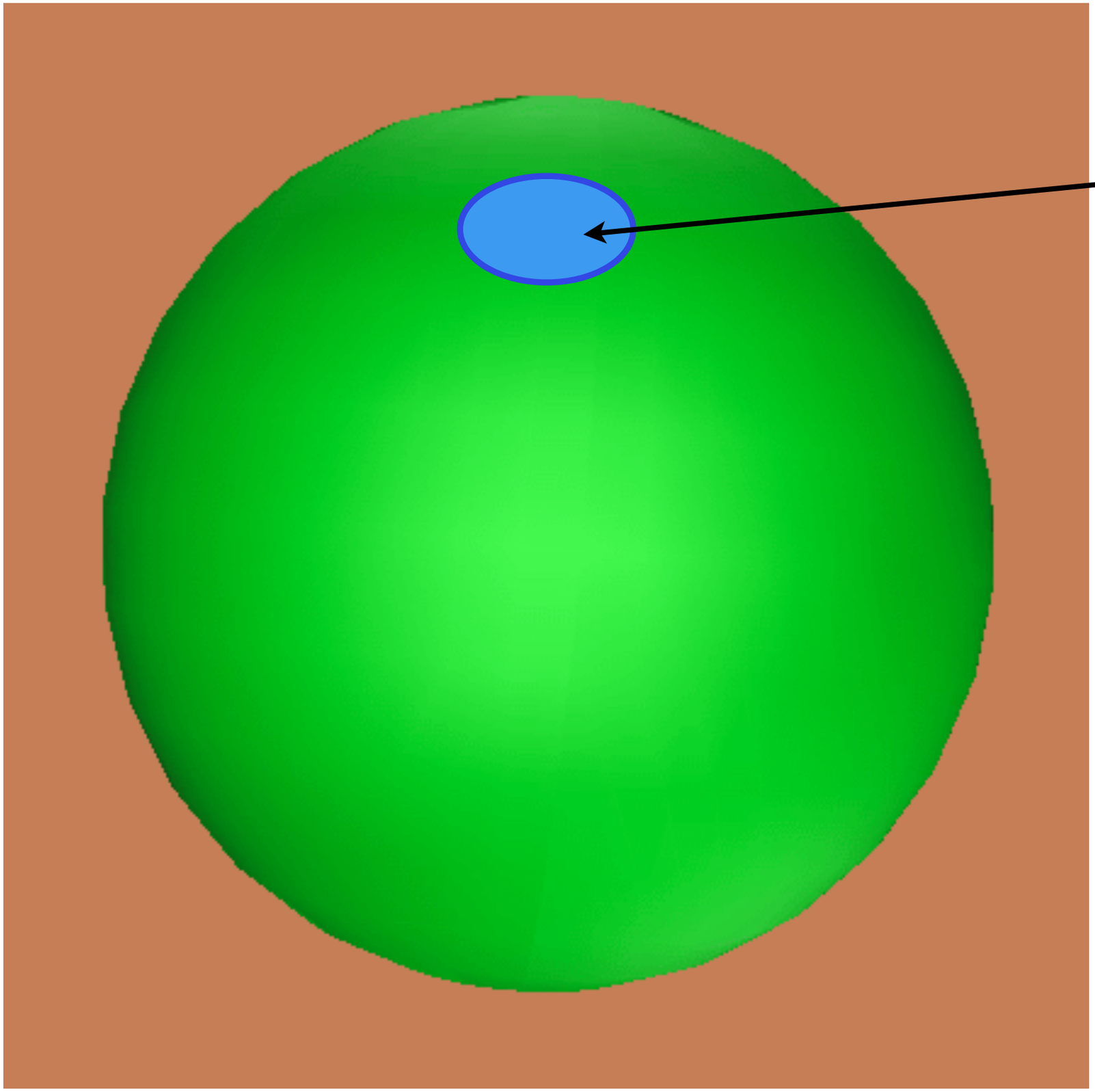


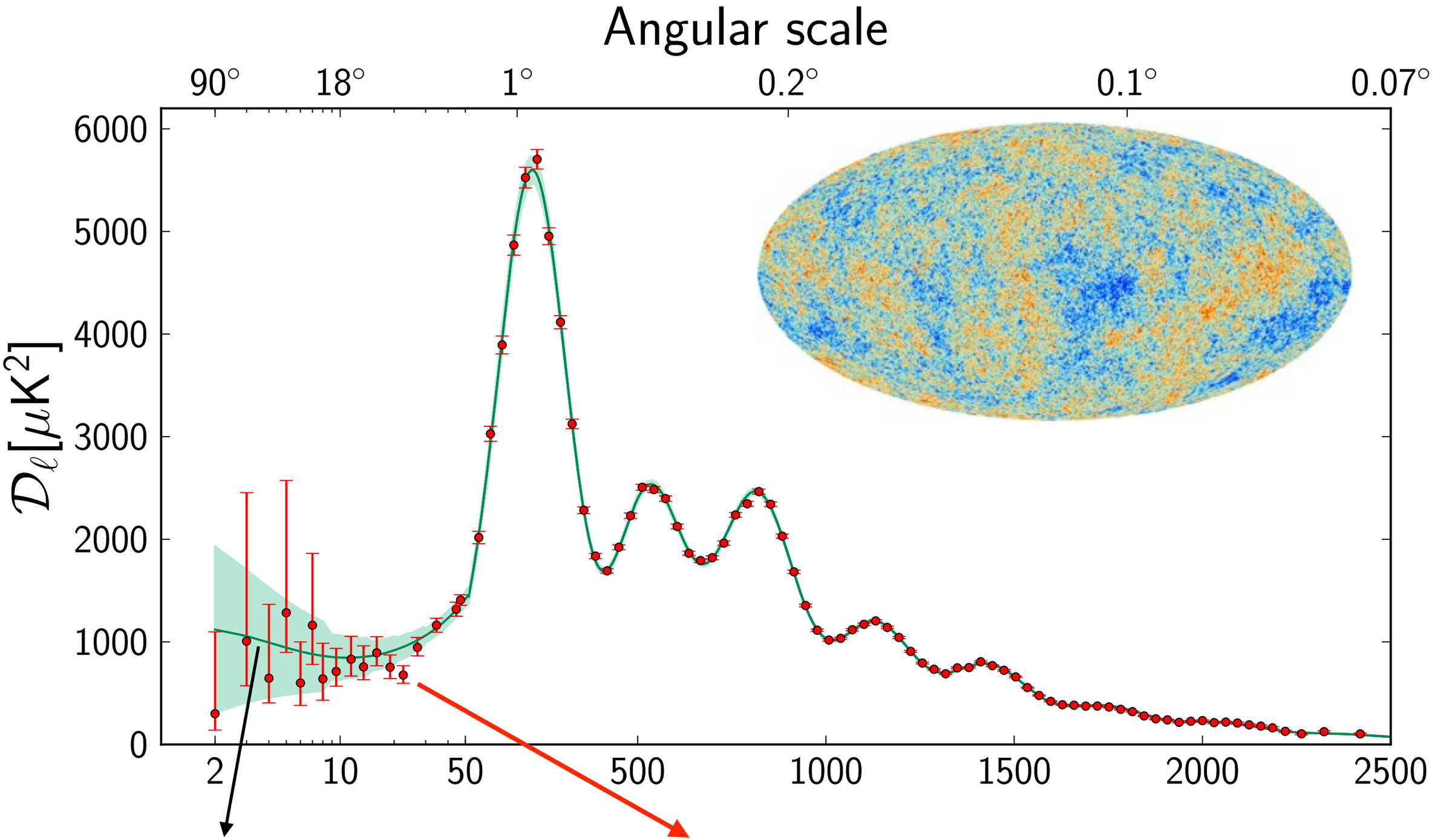
Figure credit Wayne Hu

Inflation “flattens” curved space ⇔
verified by CMB observations!



Our observable universe

Inflation fits data fabulously well

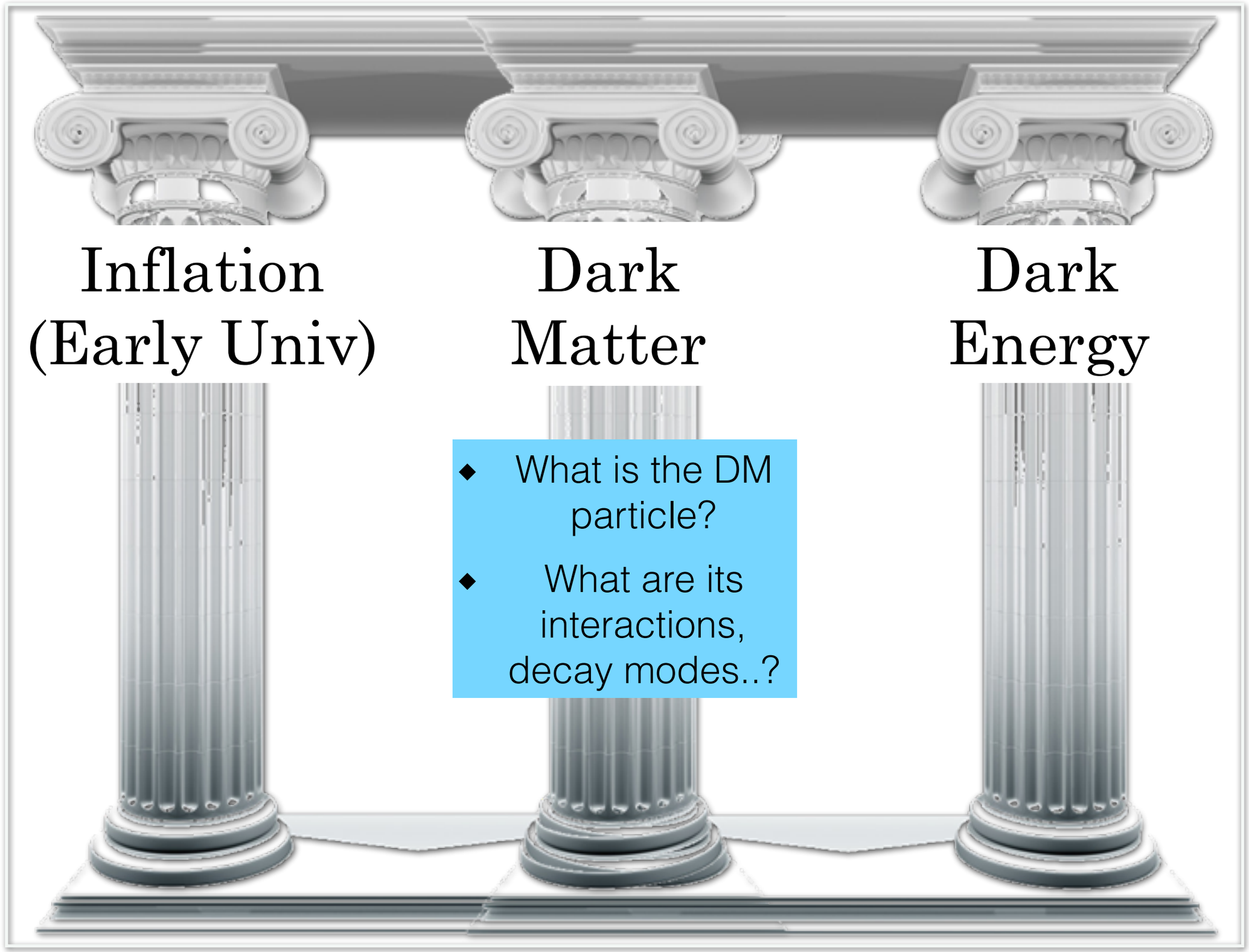


Solid line:
inflation theory

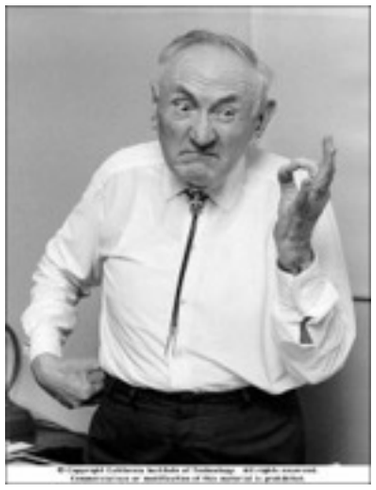
Points with error bars:
Planck measurements

Green region:
theory error

Three big questions in cosmology



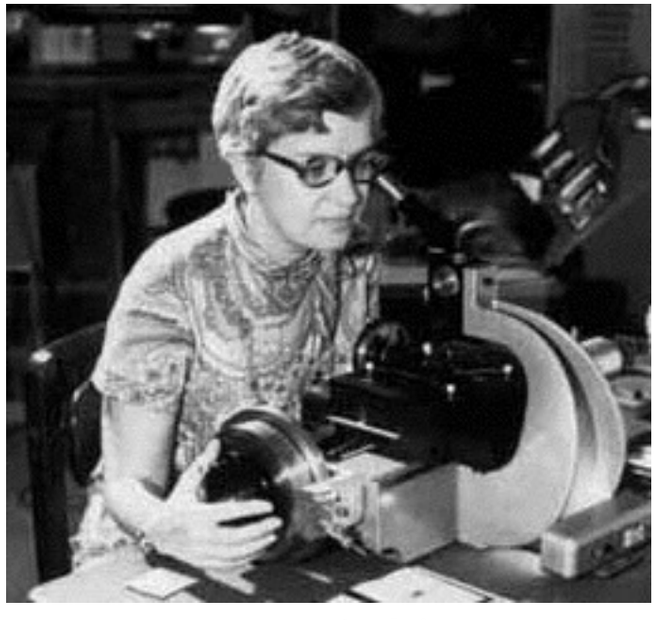
Dark Matter



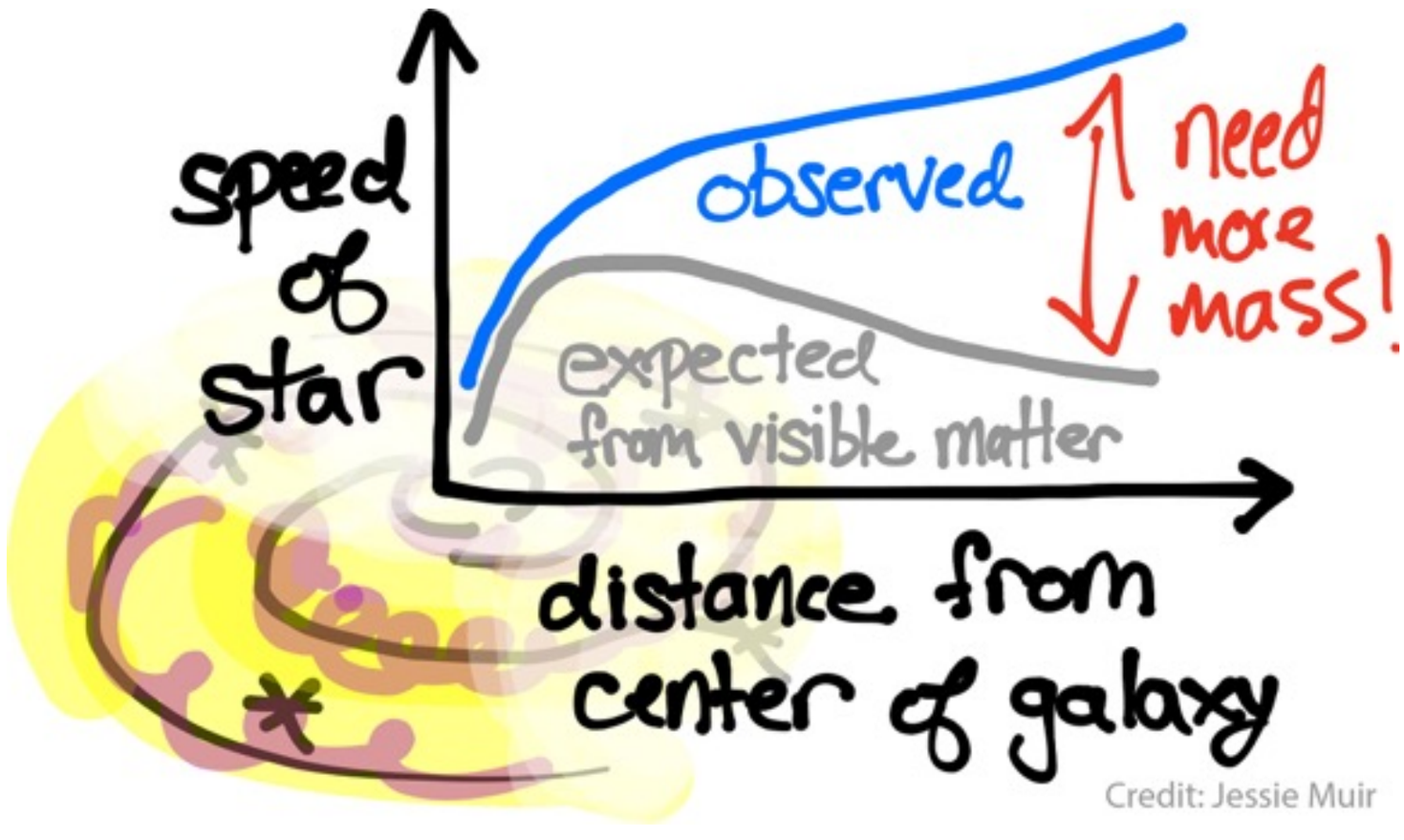
Fritz Zwicky
"Dunkle Materie",1933

Coma cluster
of galaxies

Illustration:
Jessie Muir

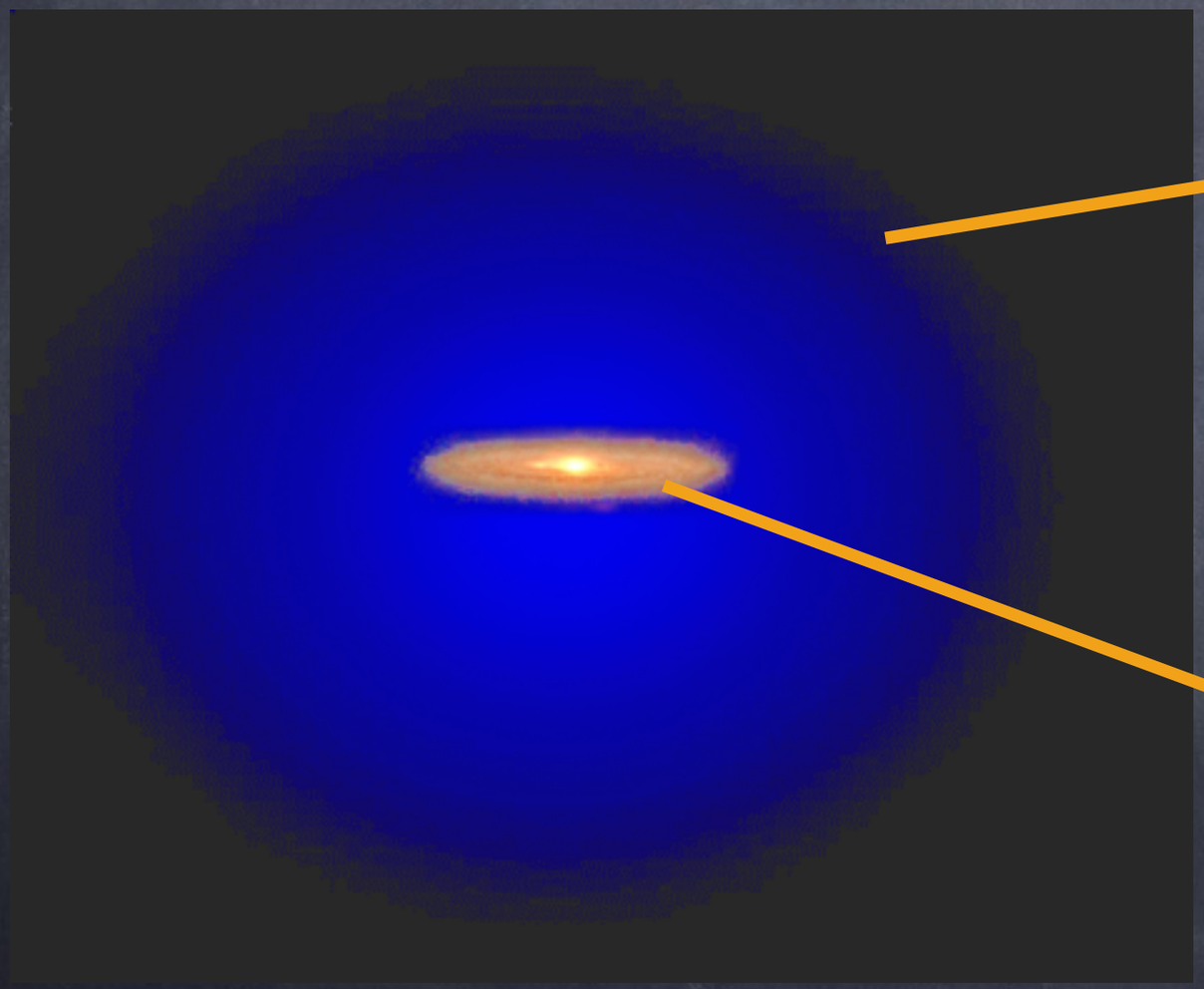


Vera Rubin
flat rotation curves, 1970s



Dark Matter is in "halos" around galaxies

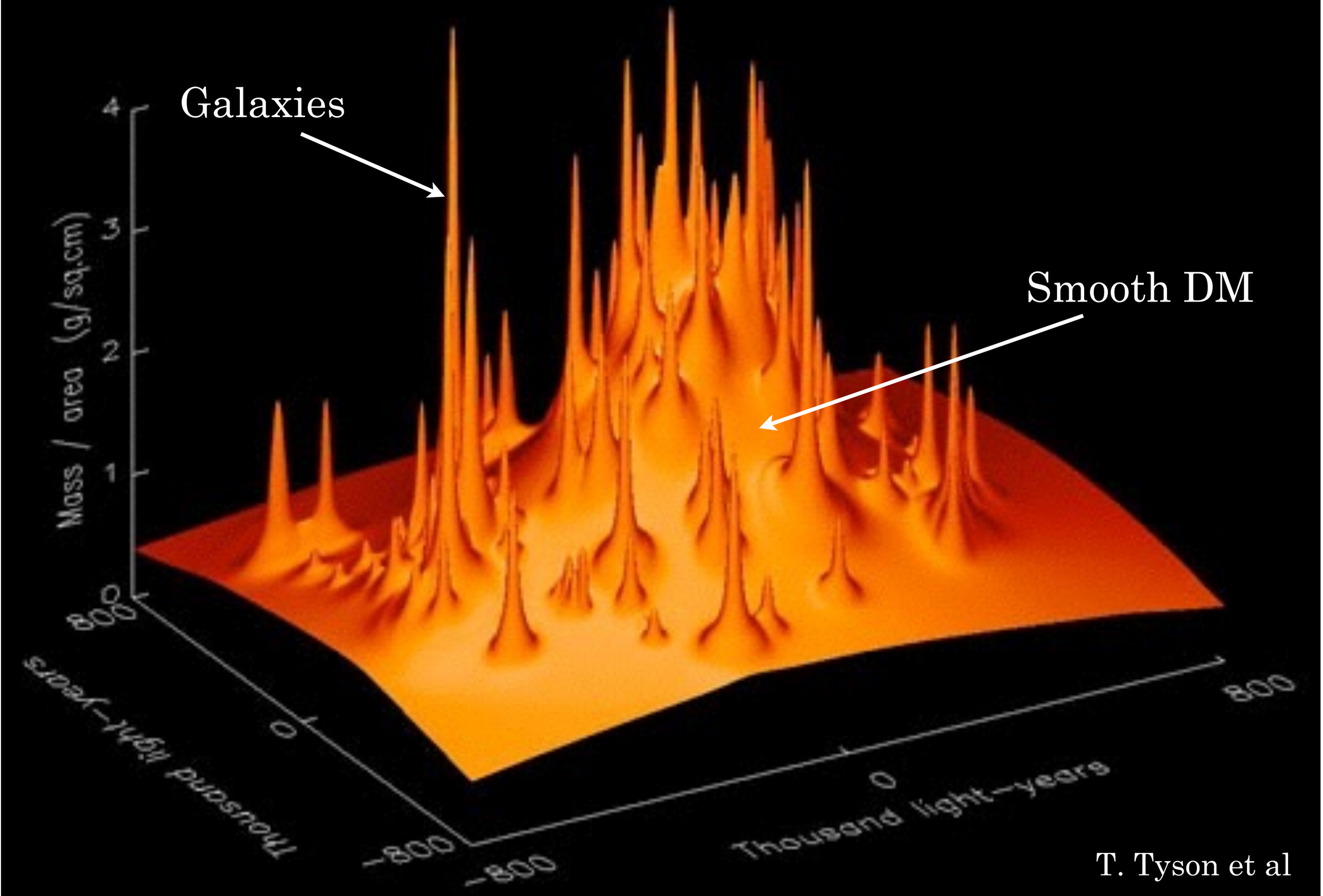
(and also around clusters)



(invisible)
Dark Matter halo

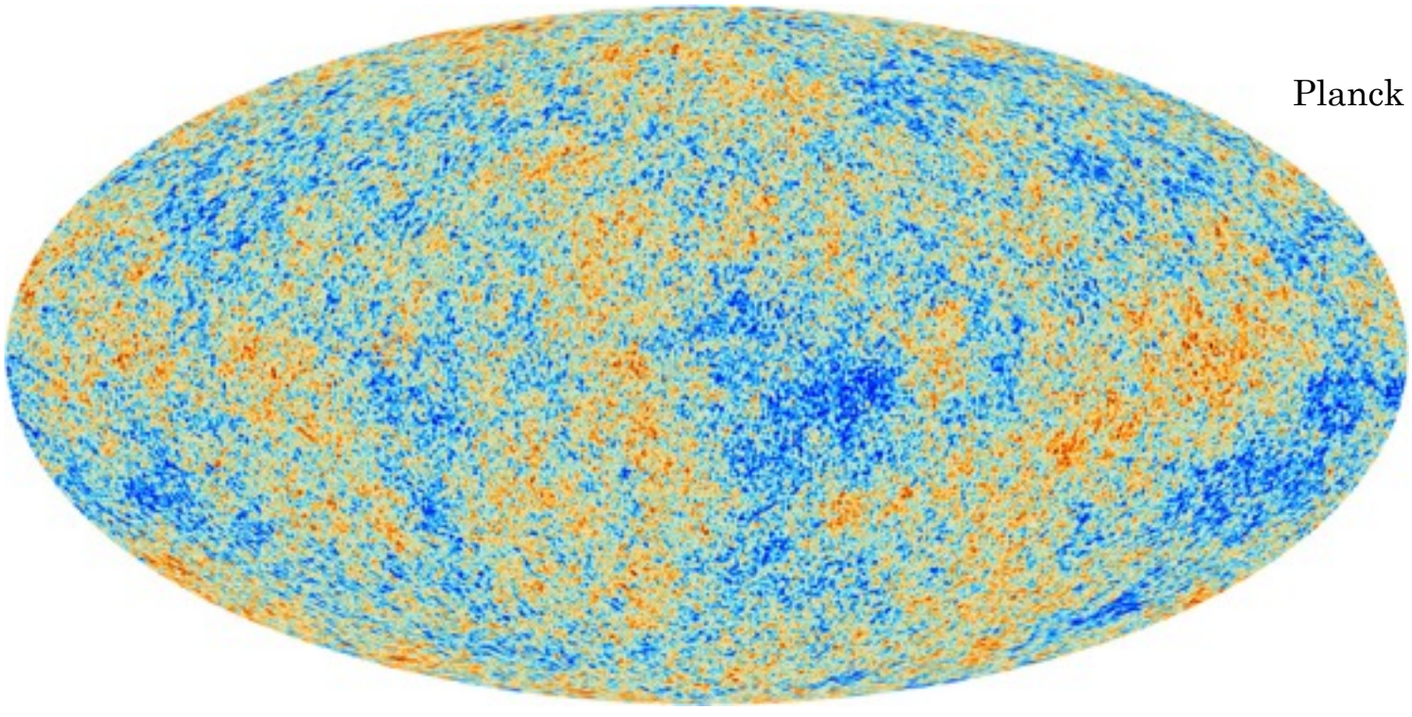
(visible) light
from galaxy

DM “imaged” using gravitational lensing



T. Tyson et al

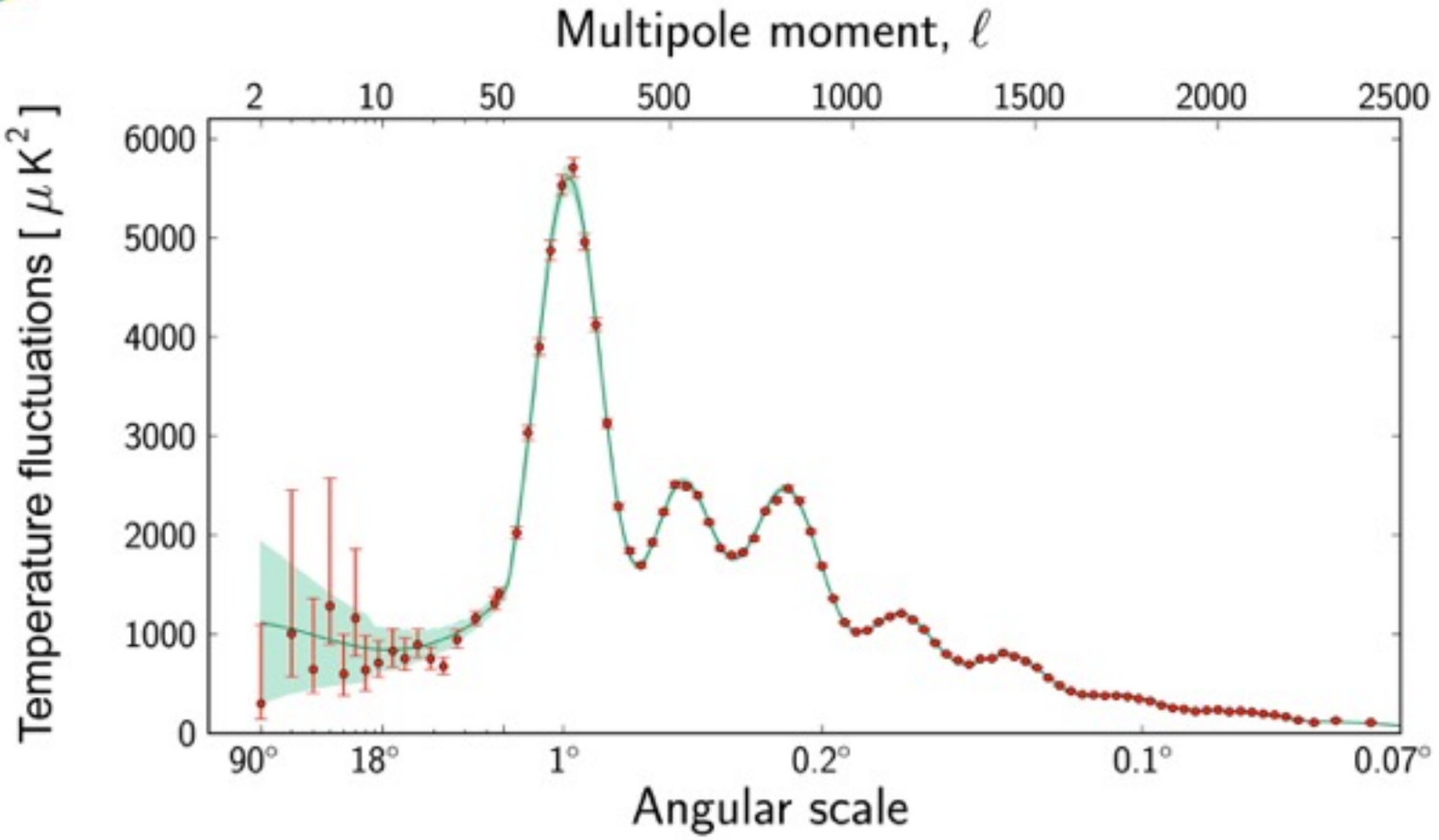
Modern evidence for Dark Matter



Planck full-sky map

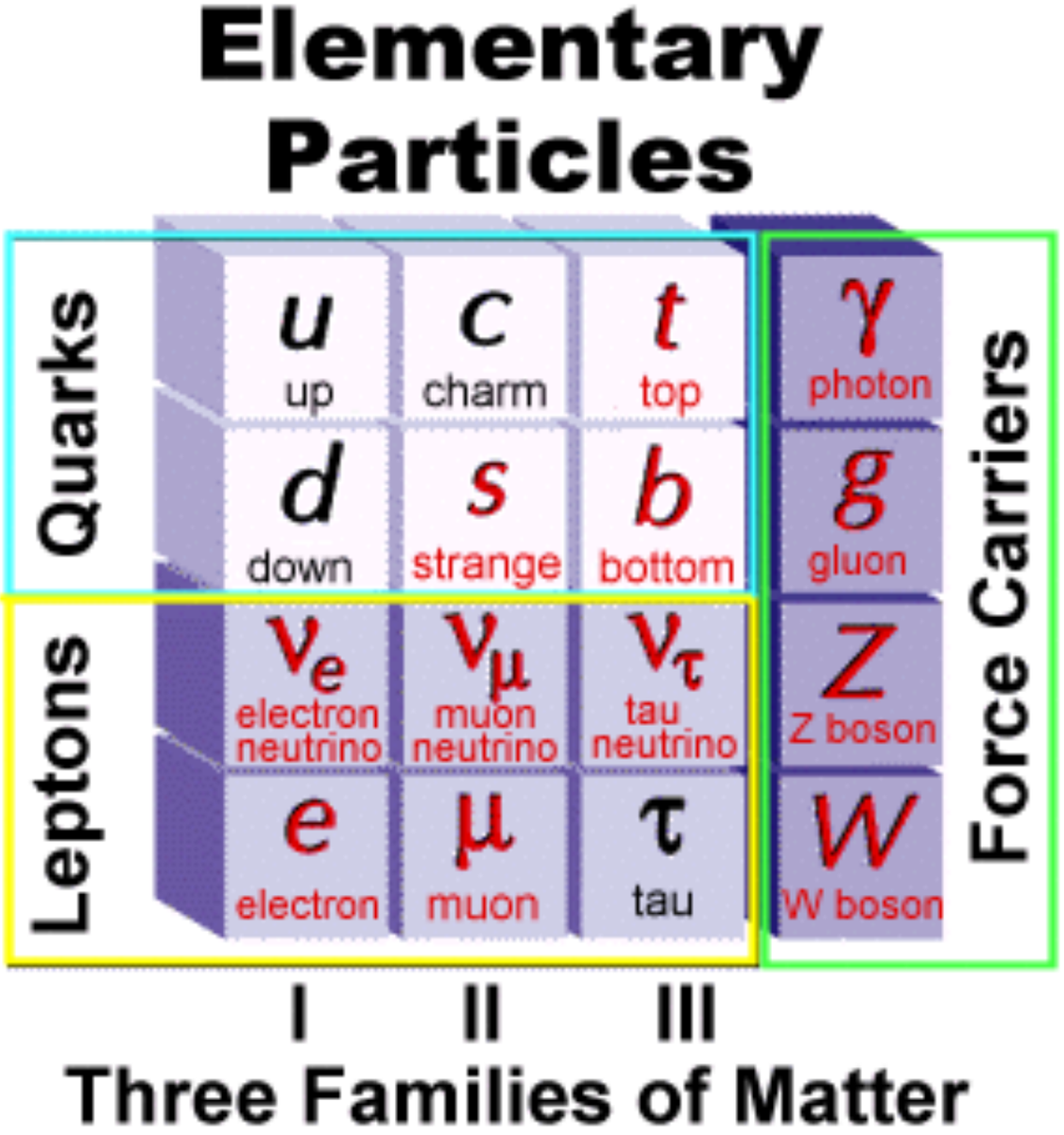
$$\Omega_{\text{dark matter}} h^2 = 0.1193 \pm 0.0014$$

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

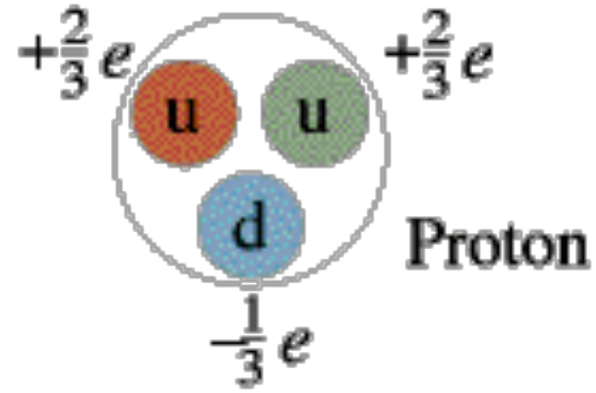


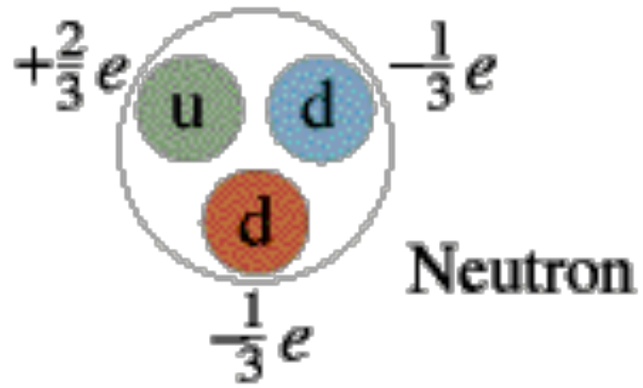
Planck 2015

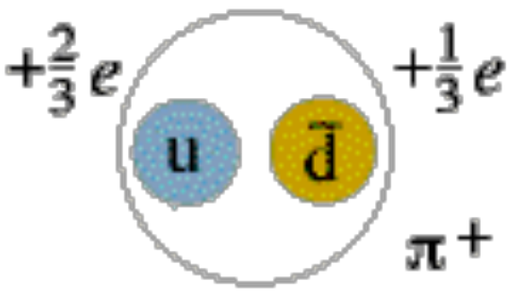
DM **cannot** be one of these!



Examples:

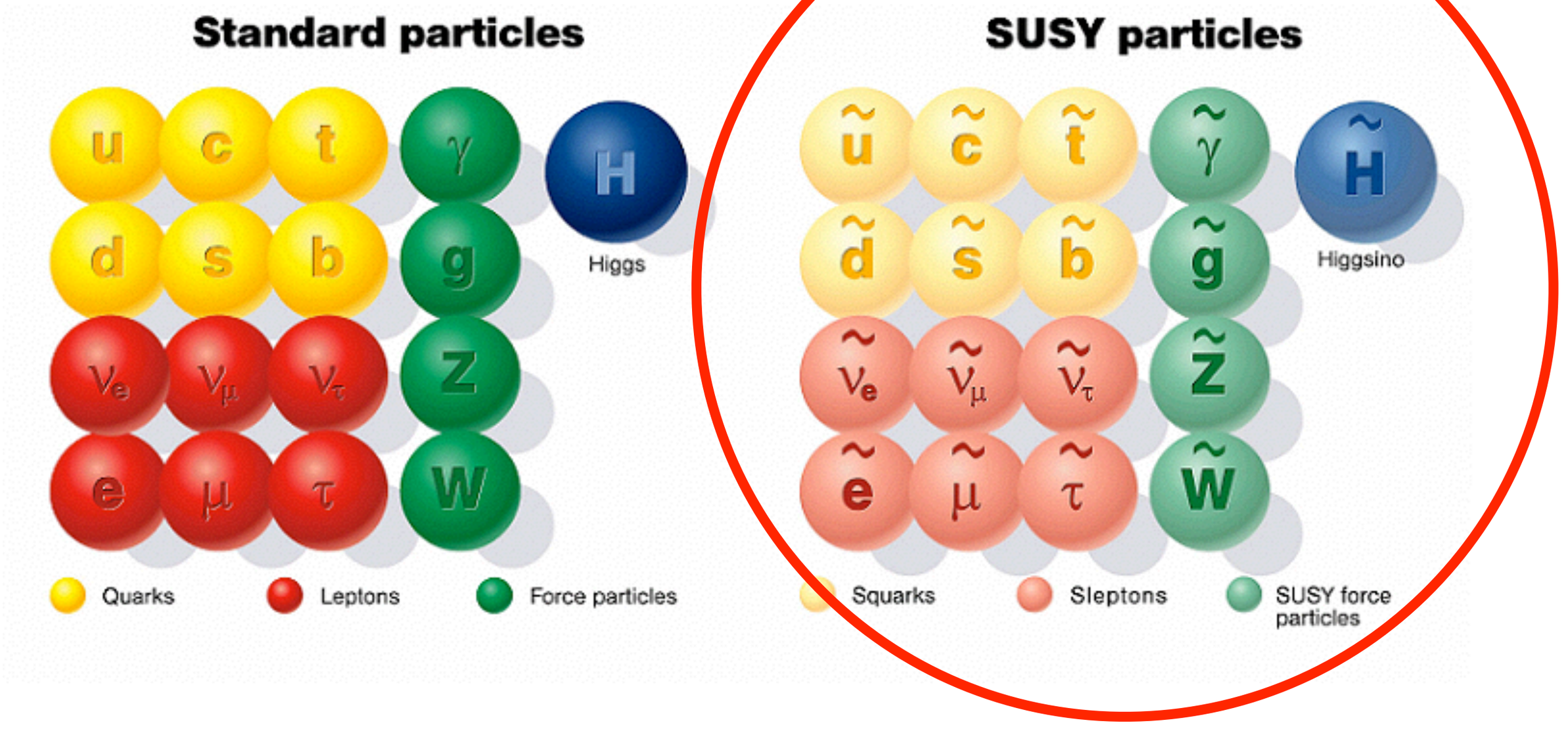






- Hadrons: particle made of quarks
  - baryons: 3 quarks
  - mesons: 2 quarks
- Leptons and force carries are not made of quarks

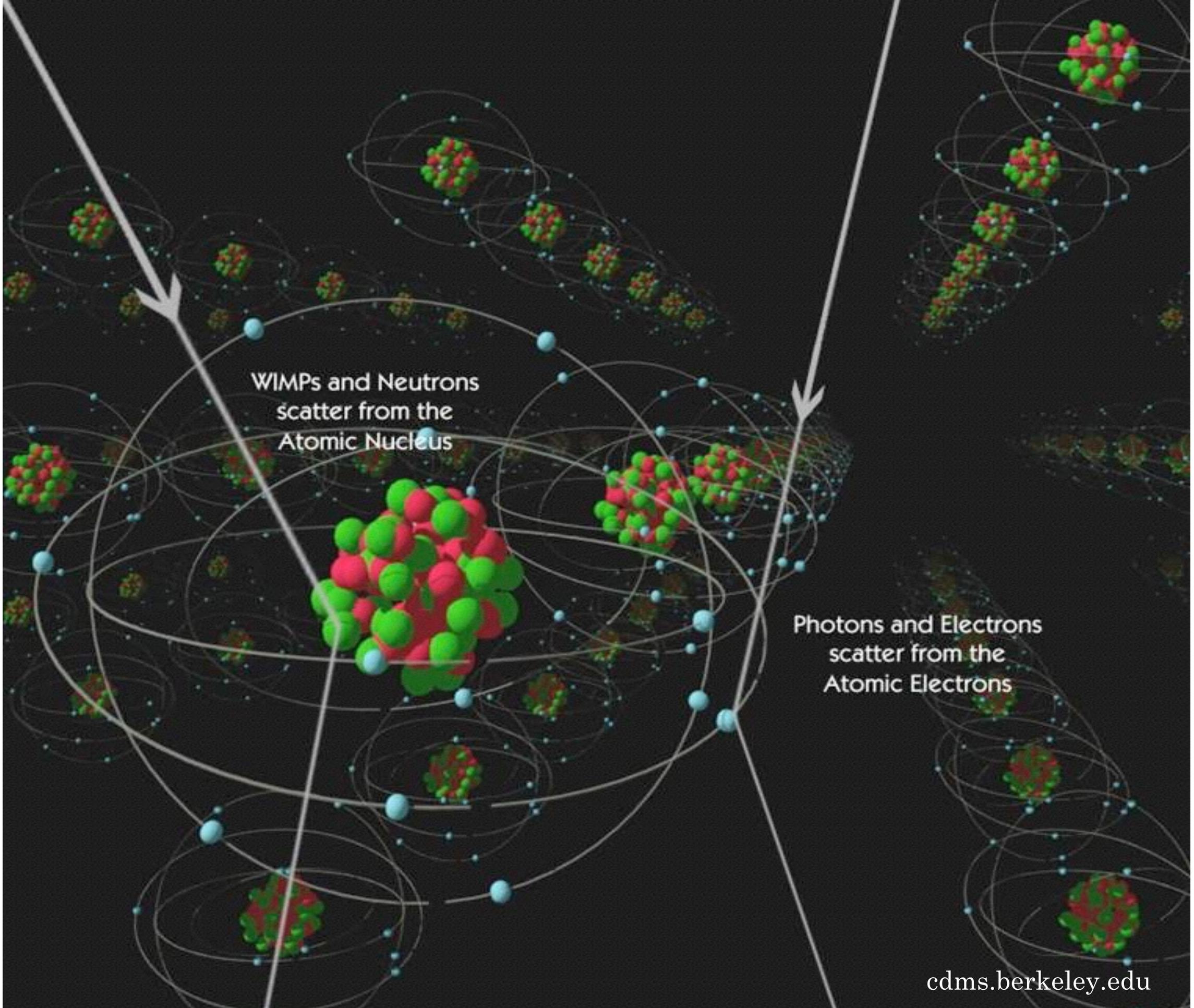
DM *could* be one of these supersymmetric particles
(there are other possibilities too...)



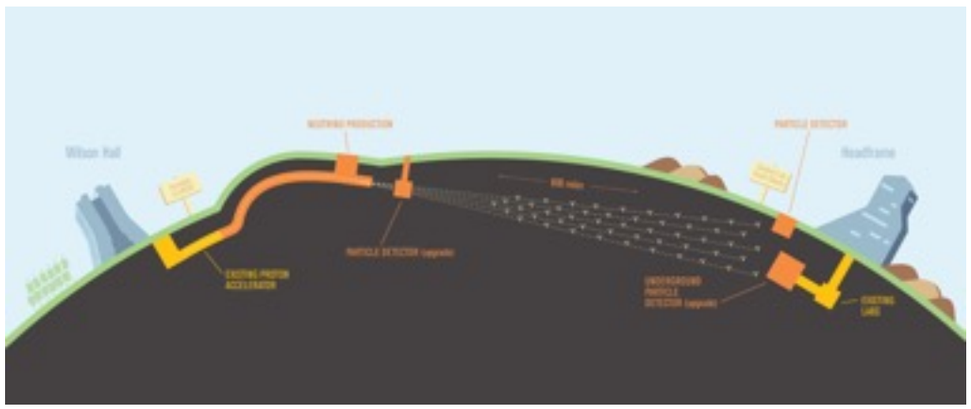
Direct and Indirect Searches for Dark Matter:

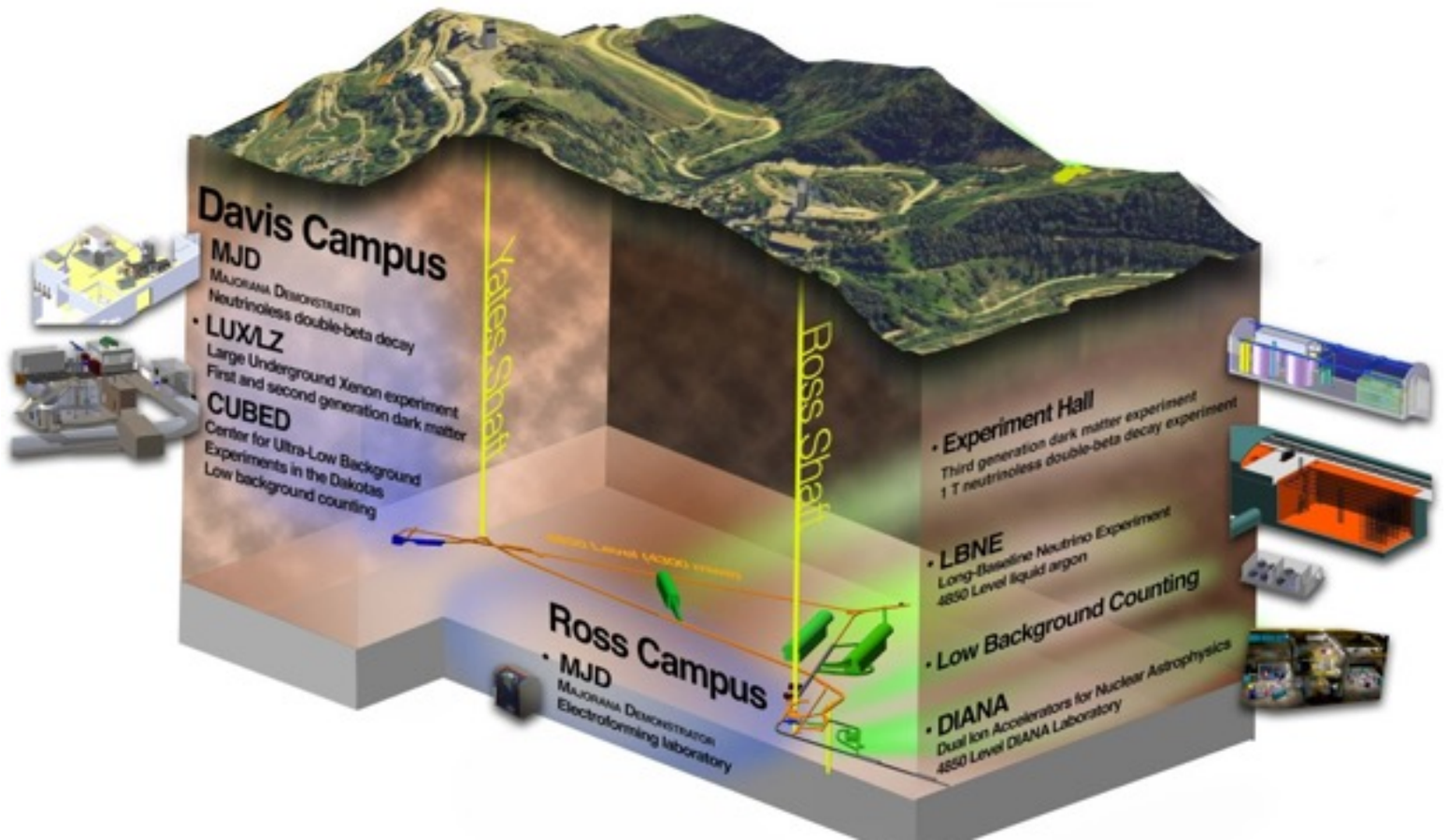
Direct detection - wait for WIMP to scatter off of nuclei in underground detectors

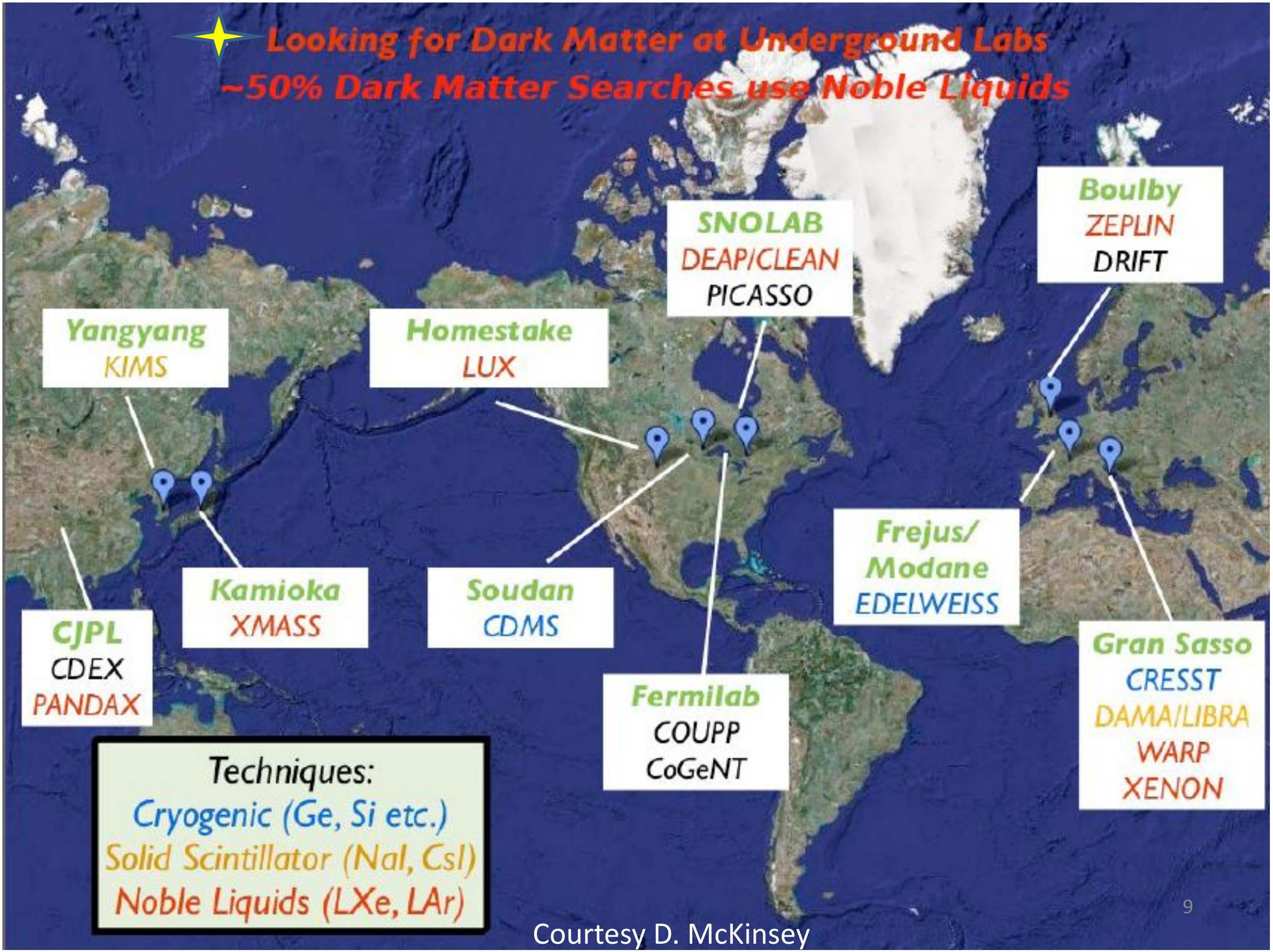
Indirect detection: detect products - "normal" particles - of WIMP annihilation in the center of Galaxy (or other galaxies)


WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons
cdms.berkeley.edu

Sanford Underground Research Facility (SD)

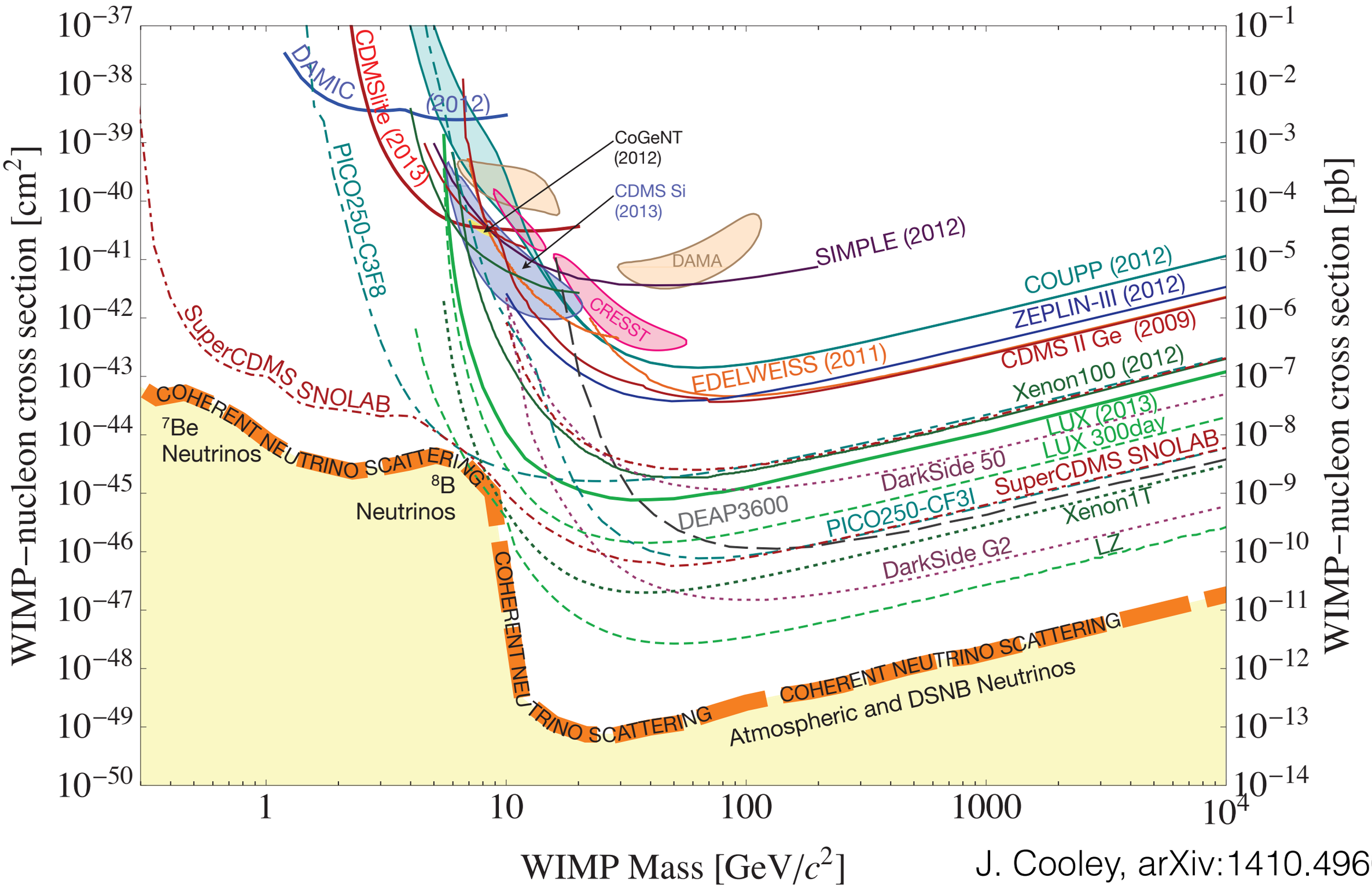






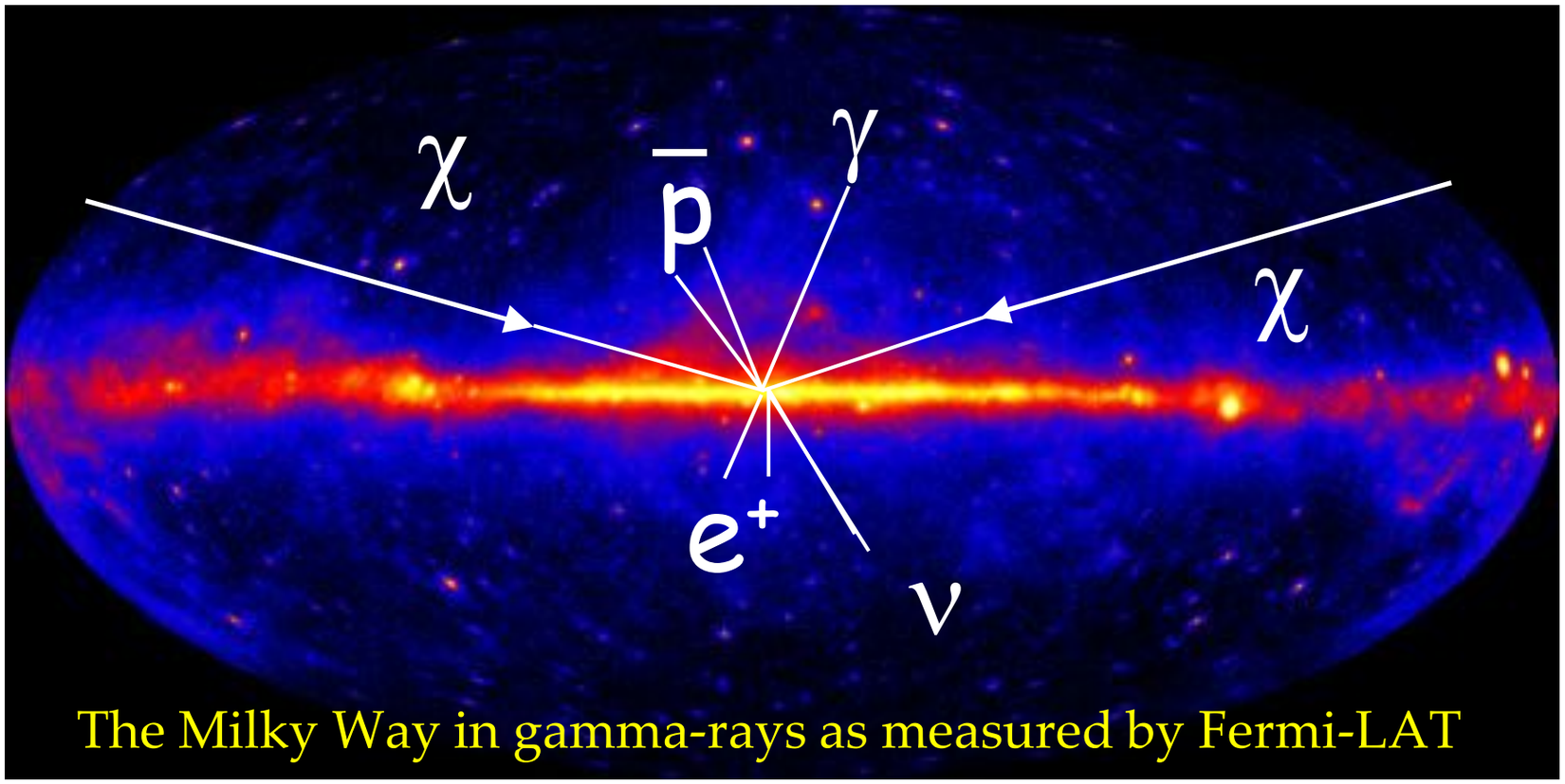
Courtesy D. McKinsey

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

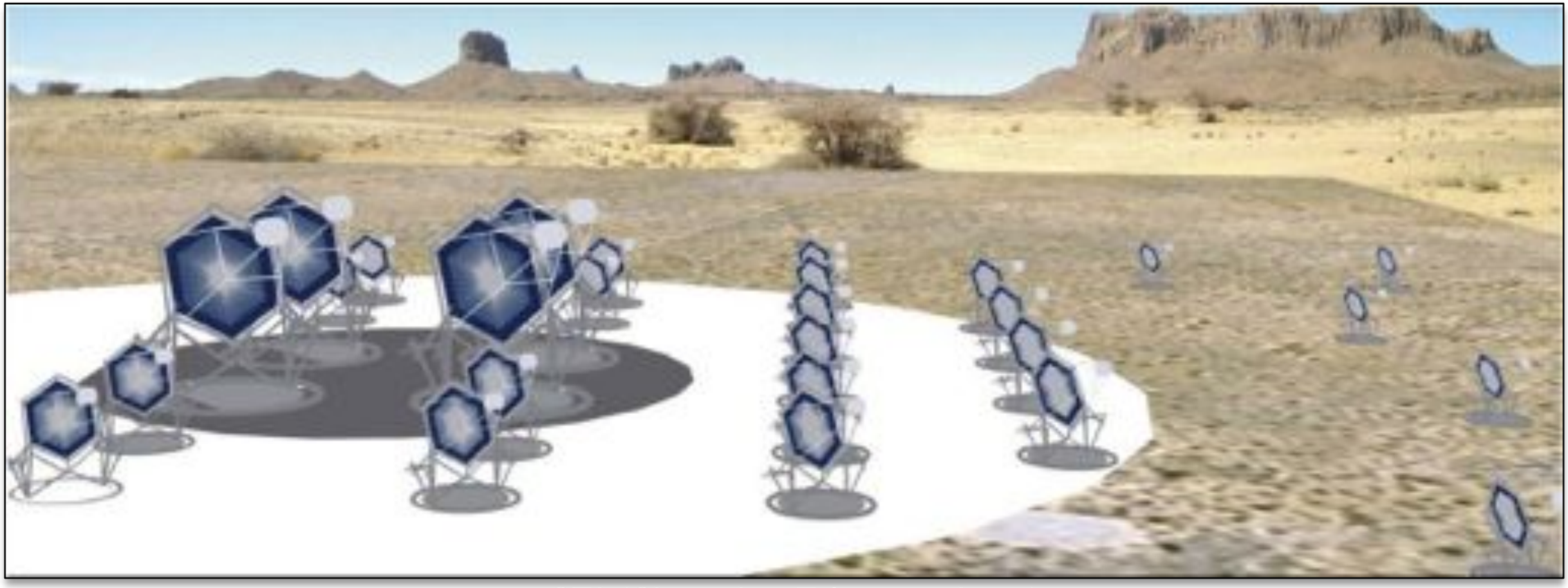
Exciting and fast-developing field, but will be **hard to have a convincing detection of DM just from indirect detection**

Indirect detection through γ-rays from DM annihilation

Fermi-LAT (Fermi Large Area Telescope)

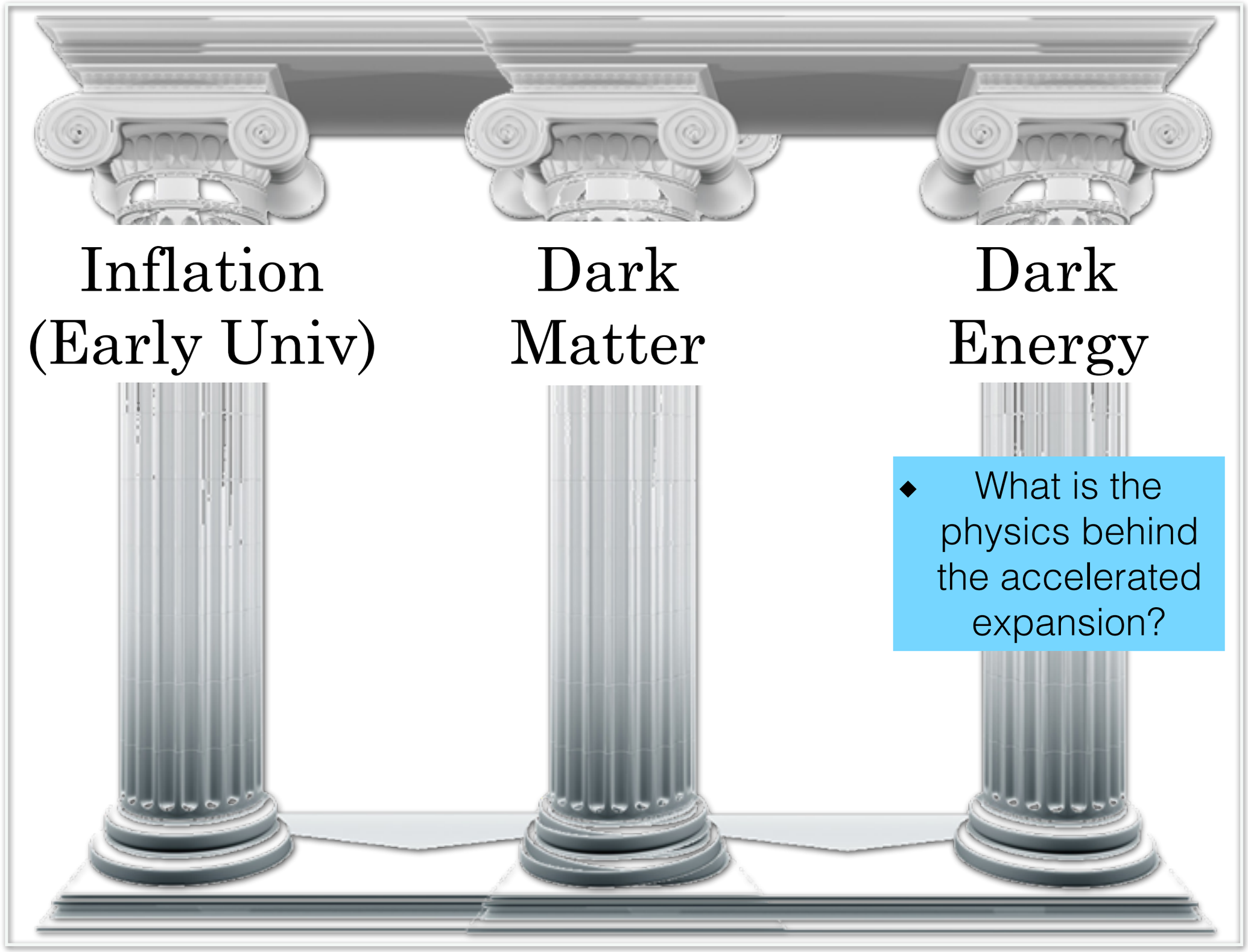
H.E.S.S. & H.E.S.S.-2

VERITAS



CTA (Cherenkov Telescope Array)

Three big questions in cosmology

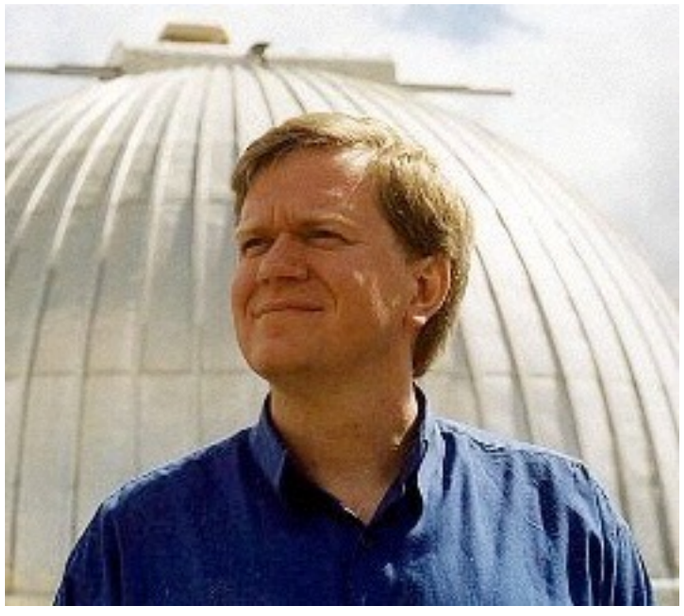


Nobel Prize in Physics 2011

Saul Perlmutter,
Age 52
Lawrence Berkeley Lab

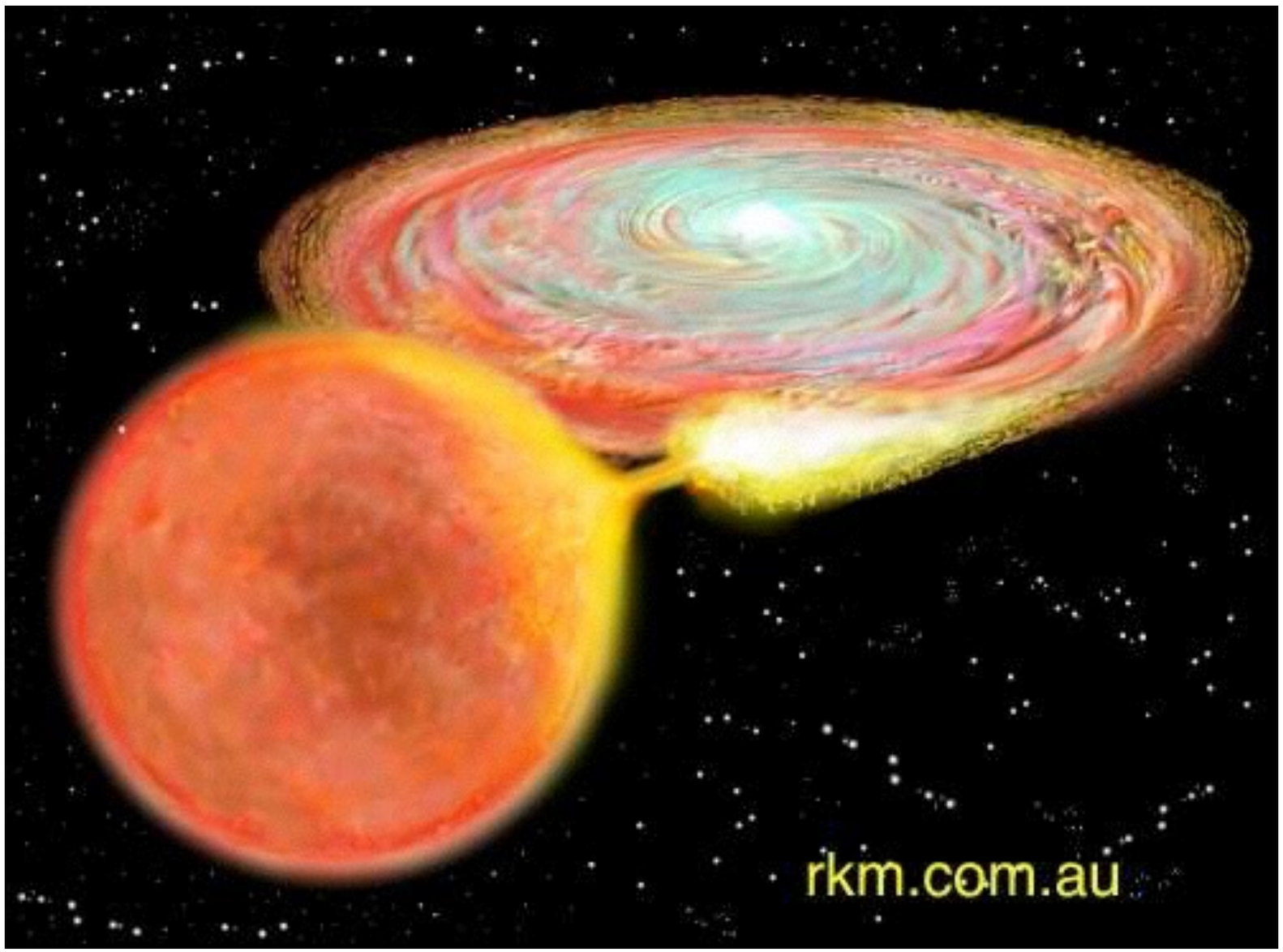
Adam Riess
Age 41
Johns Hopkins University

Brian Schmidt,
Age 44
Australian National University

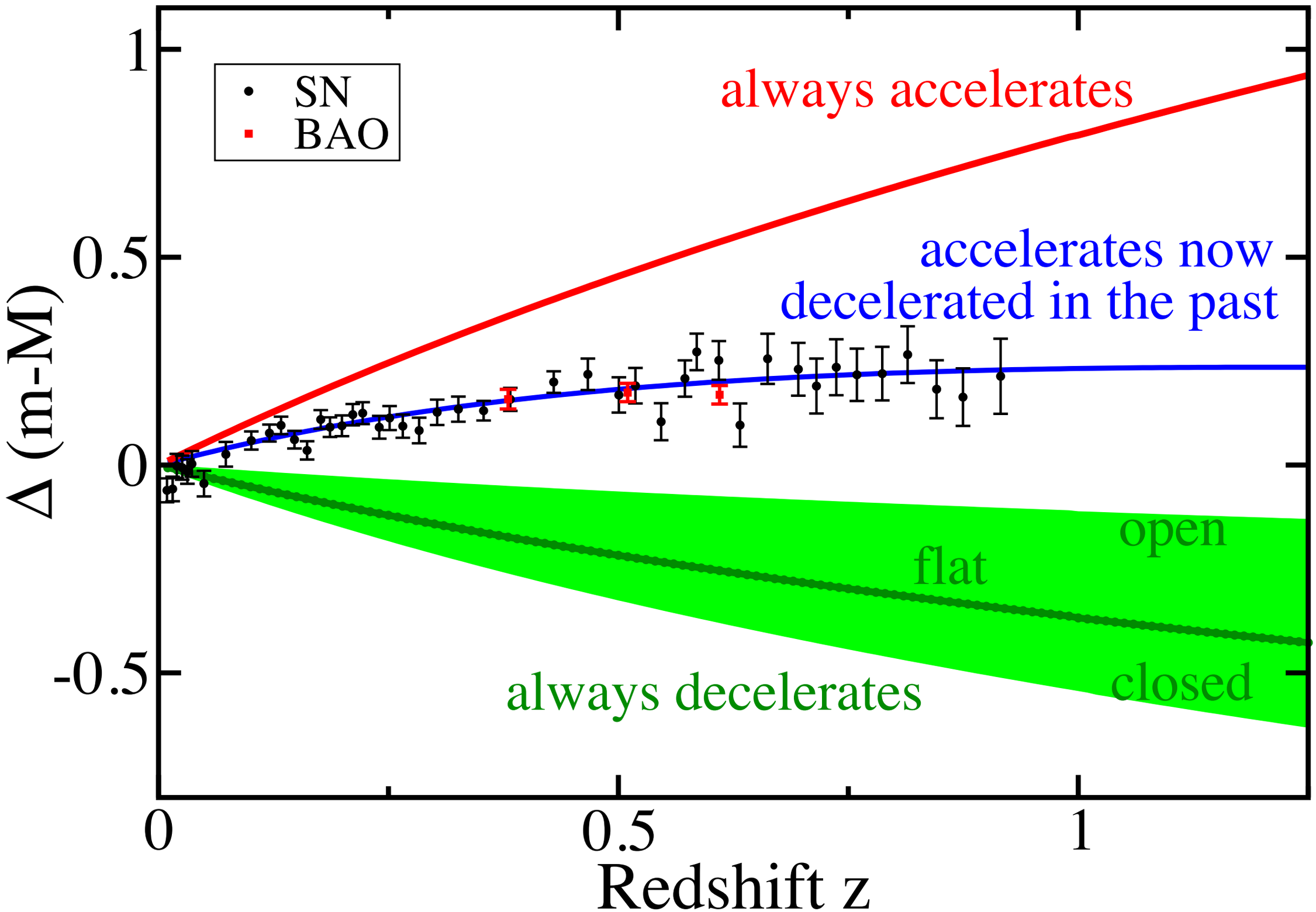


Type Ia Supernovae

A white dwarf accretes matter from a companion.



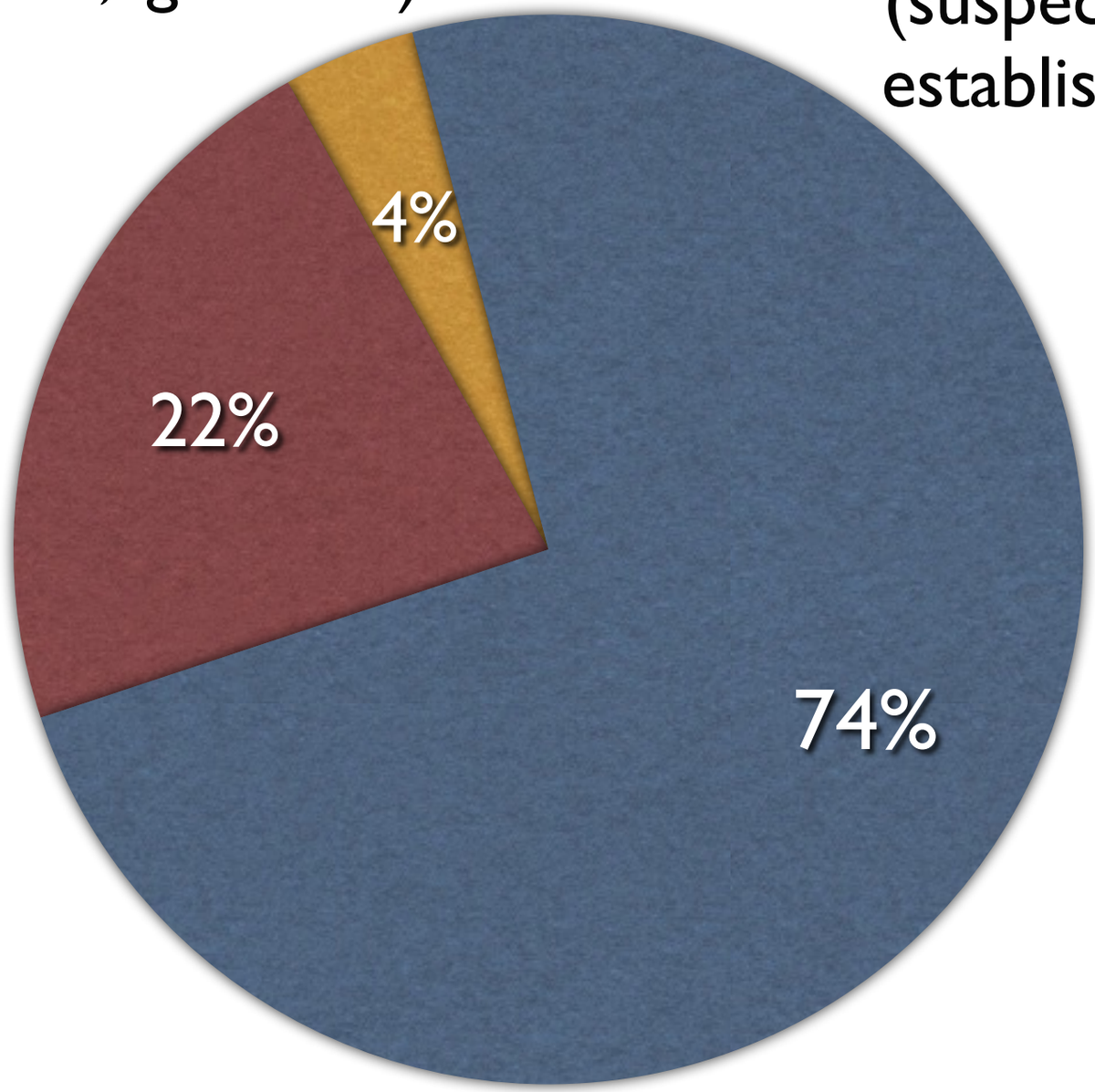
Evidence for Dark energy from type Ia Supernovae



Makeup of universe today

Baryonic Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)



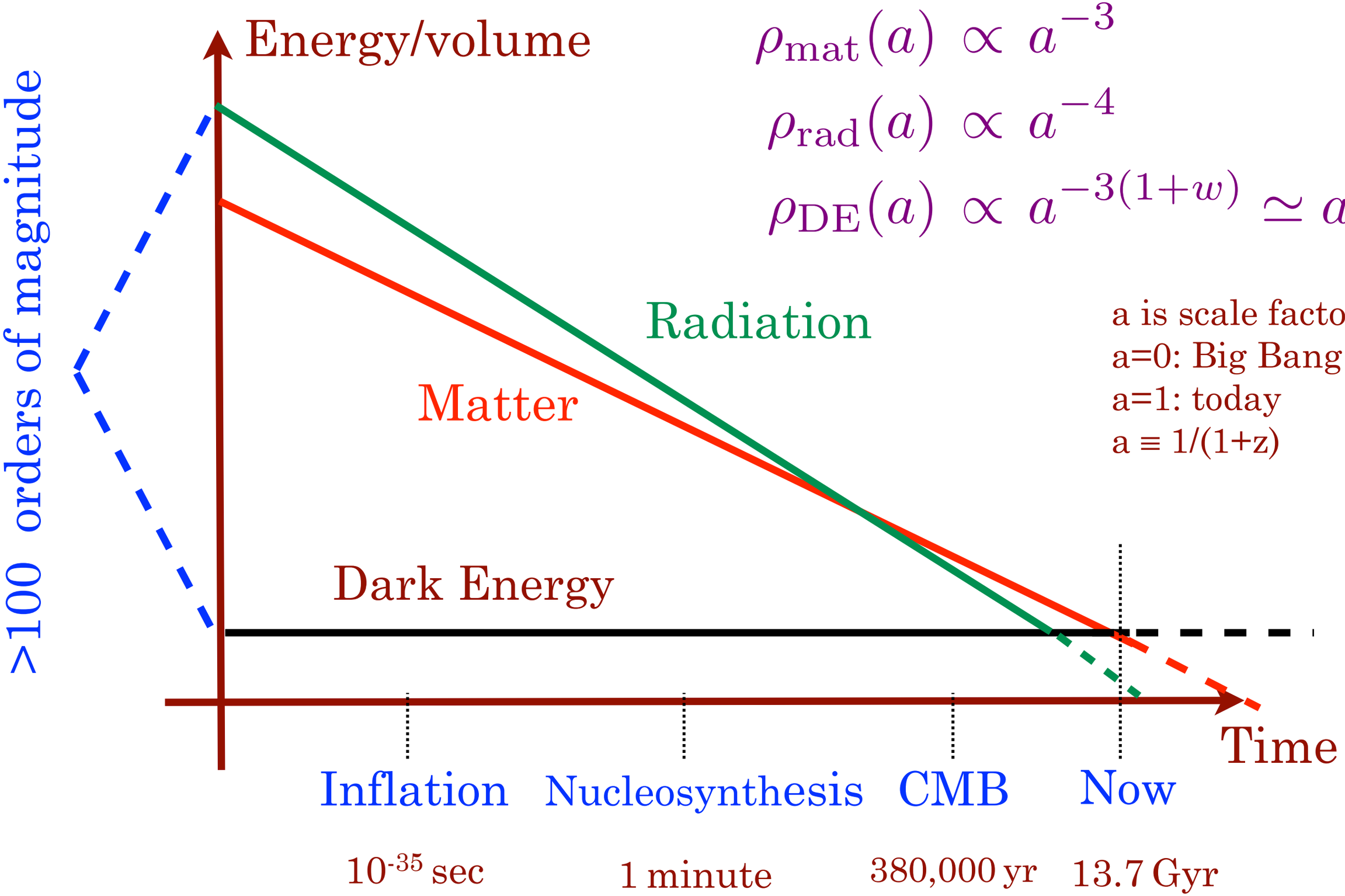
Dark Matter
(suspected since 1930s
established since 1970s)

Also:
radiation (0.01%)

Dark Energy:

Two Grand Mysteries

Fine-tuning problem I: Coincidence problem



$$\rho_{\rm mat}(a) \propto a^{-3}$$

$$\rho_{\rm rad}(a) \propto a^{-4}$$

$$\rho_{\rm DE}(a) \propto a^{-3(1+w)} \simeq a^{0}$$

a is scale factor
a=0: Big Bang
a=1: today
a ≡ 1/(1+z)

Fine Tuning Problem II: "Why so small"?

Vacuum Energy: Quantum Field Theory predicts it to be 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!!

Theoretical explanation for DE: many ideas, no successful ones!

Steven Weinberg:

``Right now, not only for cosmology but for elementary particle theory, this is the bone in our throat"

Frank Wilczek:

``... maybe the most fundamentally mysterious thing in all of basic science"

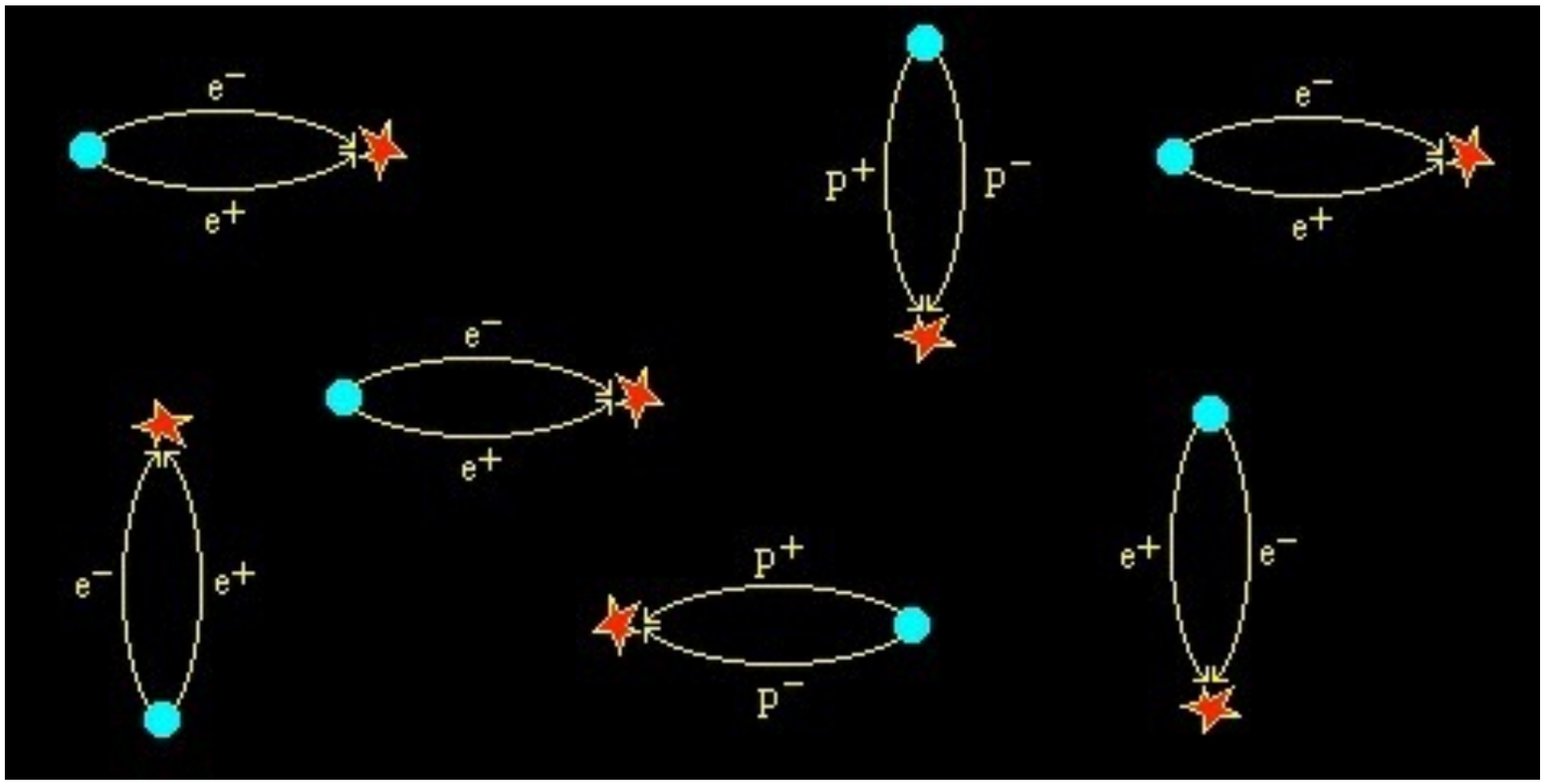
Ed Witten:

``... would be the number 1 on my list of things to figure out"

Michael Turner:

“... the biggest embarrassment in theoretical physics”

Why is DE so small relative to theoretical prediction (and yet not zero)?



Is there a cancellation mechanism that sets vacuum energy to nearly but not precisely zero?

Is there a huge number of universes with

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

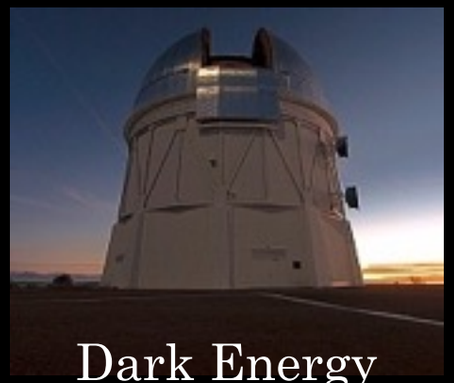
"**It is not clear to one of the authors how a concept as lame as the "anthropic idea" was ever elevated to the status of a principle**"

(Bizarre) Consequences of DE

- Geometry is not destiny any more! Fate of the universe (accelerates forever vs. recollapses etc) depends on the future behavior of DE
- In the accelerating universe, galaxies are leaving our observable patch -> the sky will be empty in 100 billion years
  - Under certain conditions we will have a Big Rip - galaxies, stars, planets, our houses, atoms, and then the fabric of space itself will rip apart!

Ongoing or upcoming DE experiments:

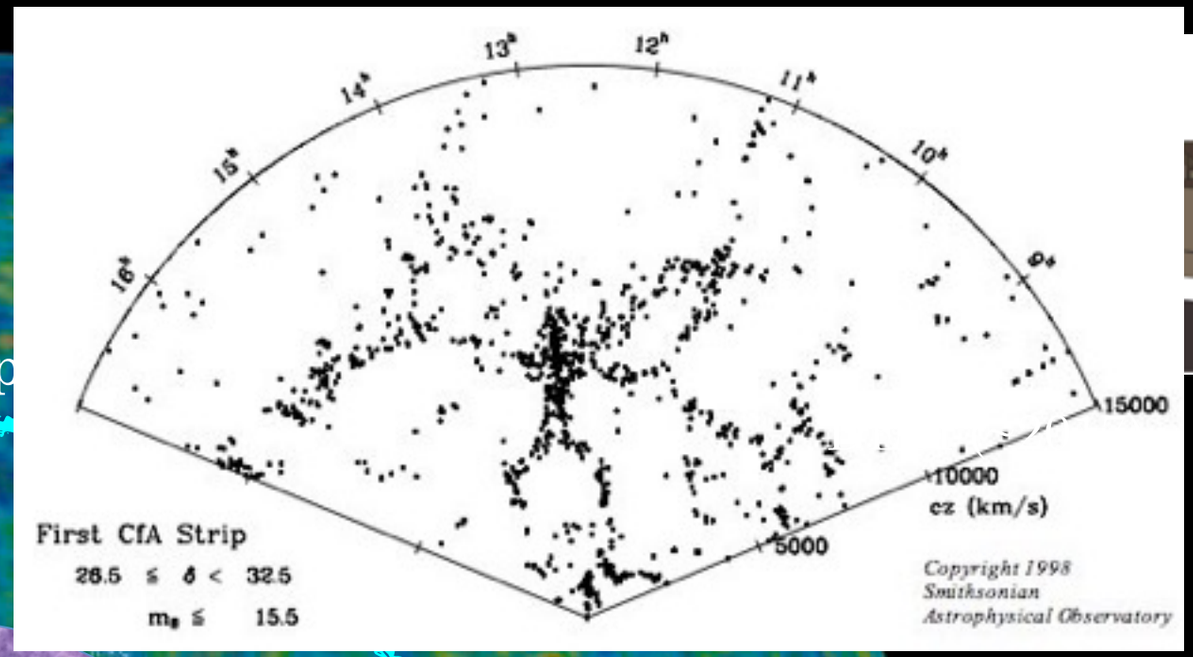
- **Ground photometric:**
  - Dark Energy Survey (DES)
  - Pan-STARRS
  - Hyper Supreme Cam (HSC)
  - Large Synoptic Survey Telescope (LSST)
- **Ground spectroscopic:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Prime Focus Spectrograph (PFS)
  - Dark Energy Spectroscopic Instrument (DESI)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



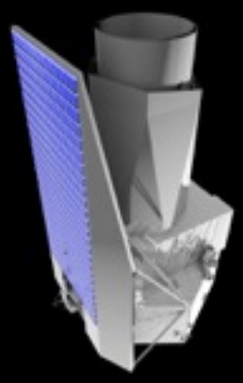
Dark Energy Survey (2012)

▲Harvard-Cfa survey (1980s)

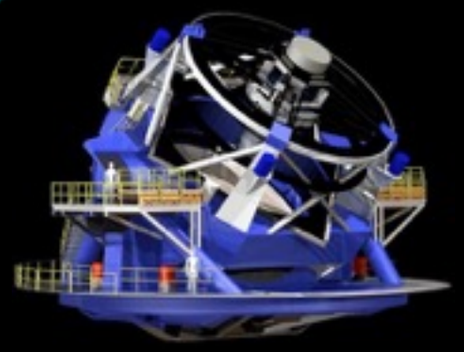
21cm mapp



Euclid and WFIRST (~202X)



LSST (~2018)



Dark Energy Survey

- New camera on 4m telescope in Chile
- Observations 2013-2019
- >400 scientists worldwide
- Analyses in progress (first major papers Aug 2017)

Summary

- Huge variety of various observations in cosmology (since 1992) is revolutionizing our understanding of the universe

- Inflation: period of accelerated expansion ~10^{-35} sec after Big Bang; spectacular agreement with data; more details to discover

- Dark Matter: probably a massive particle (but not a baryon!); still undetected; worldwide search ongoing

- Dark Energy: perhaps the most puzzling problem in physics - why is the expansion of the universe today accelerating?