Cosmology

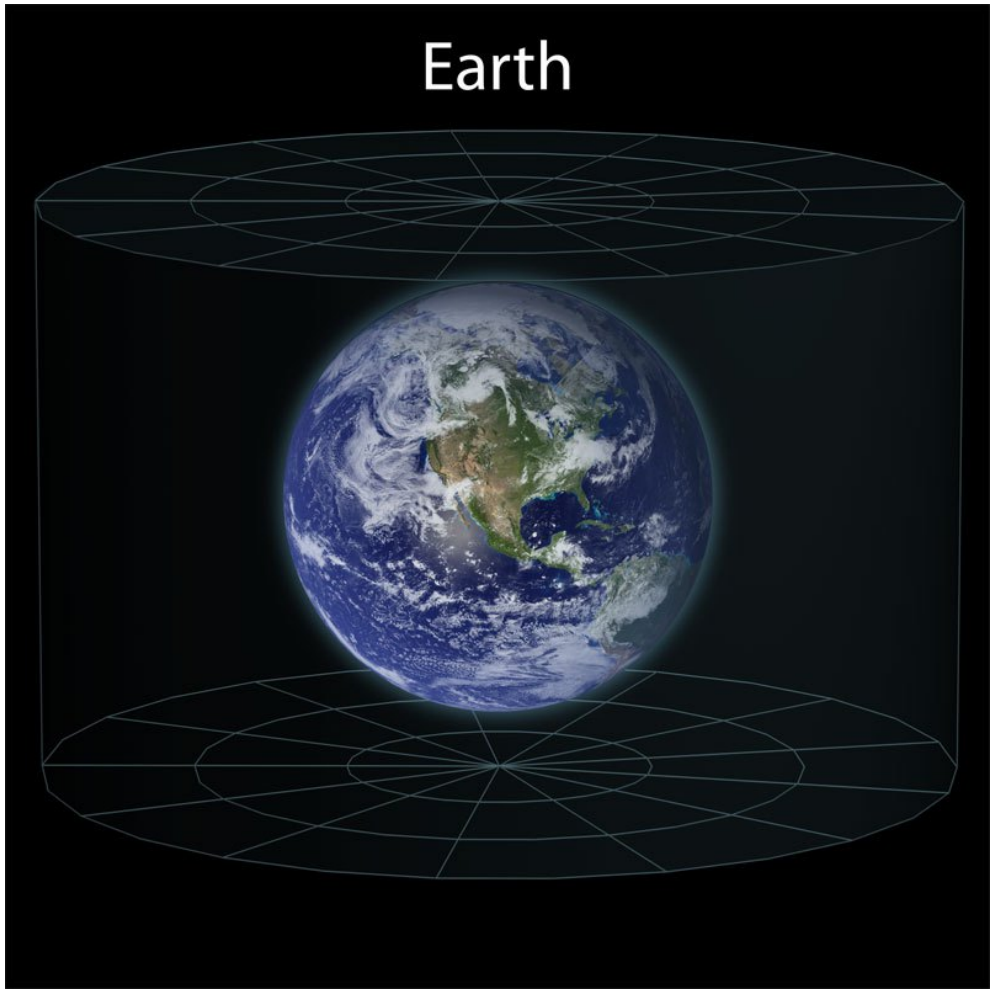
Simulations - Large Scale Structure

Dark Matter - Dark Energy

Eda Gjergo

PhD Physics student @ University of Trieste
INAF Astronomical Observatory of Trieste

Scales of the Universe



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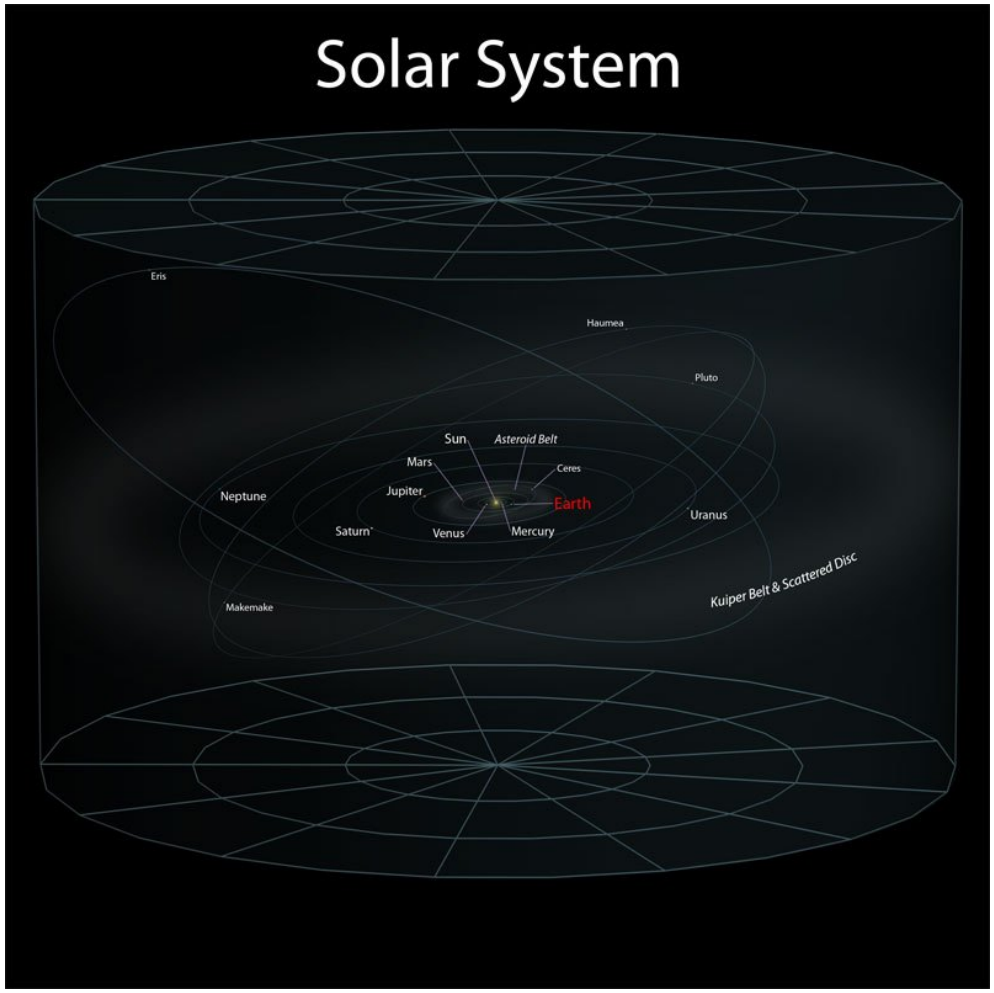
Scales of the Universe



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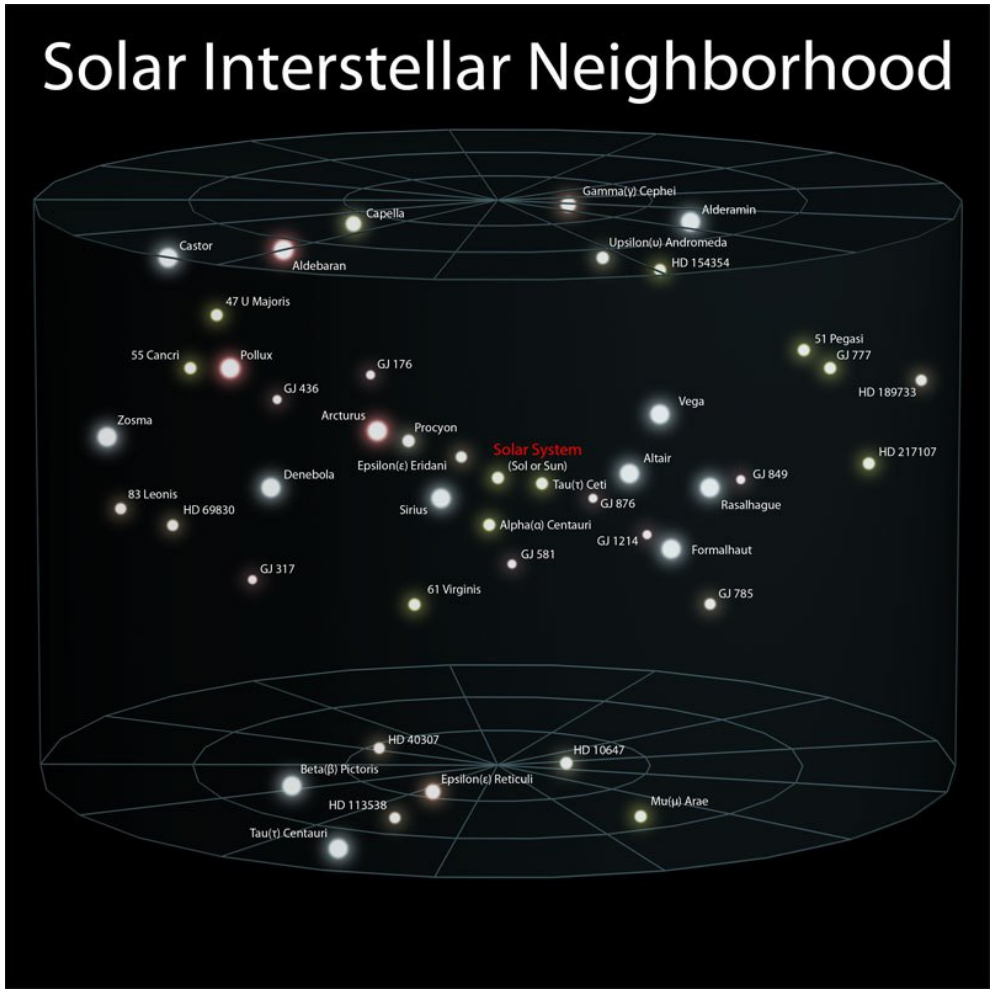
Scales of the Universe



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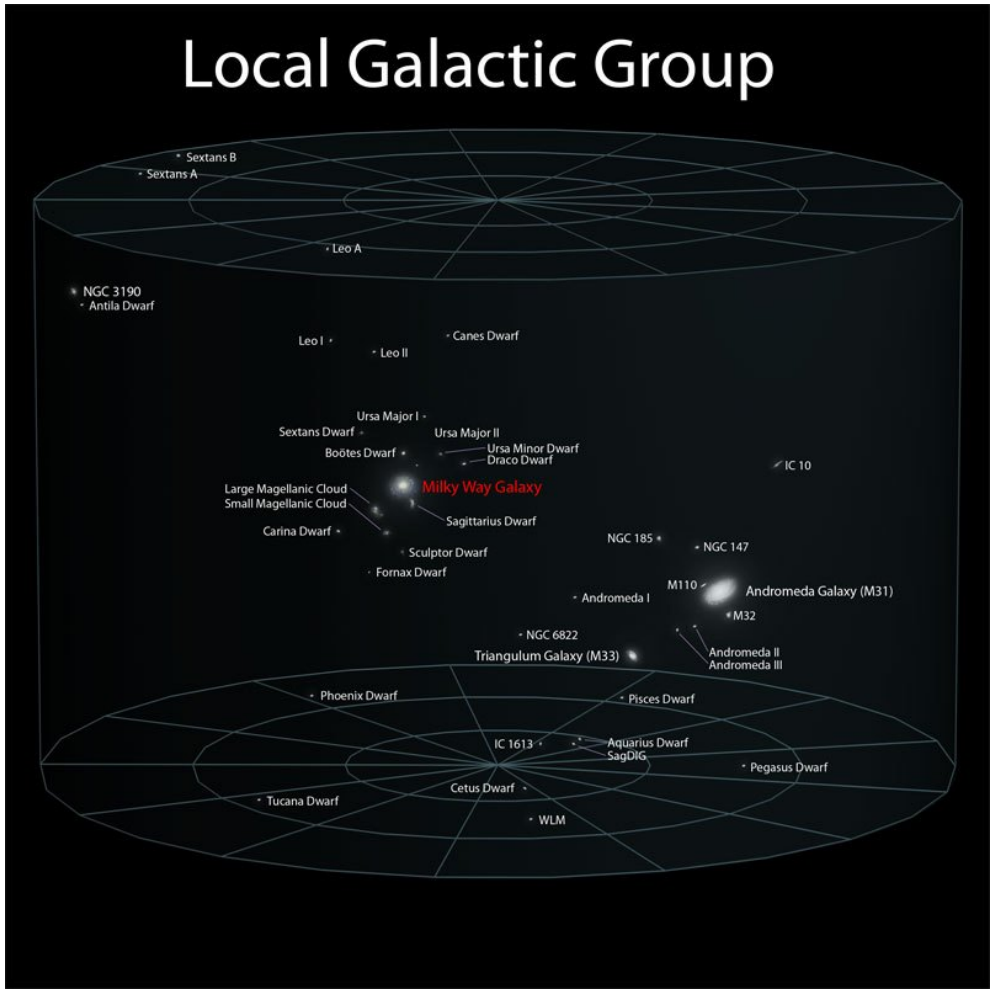

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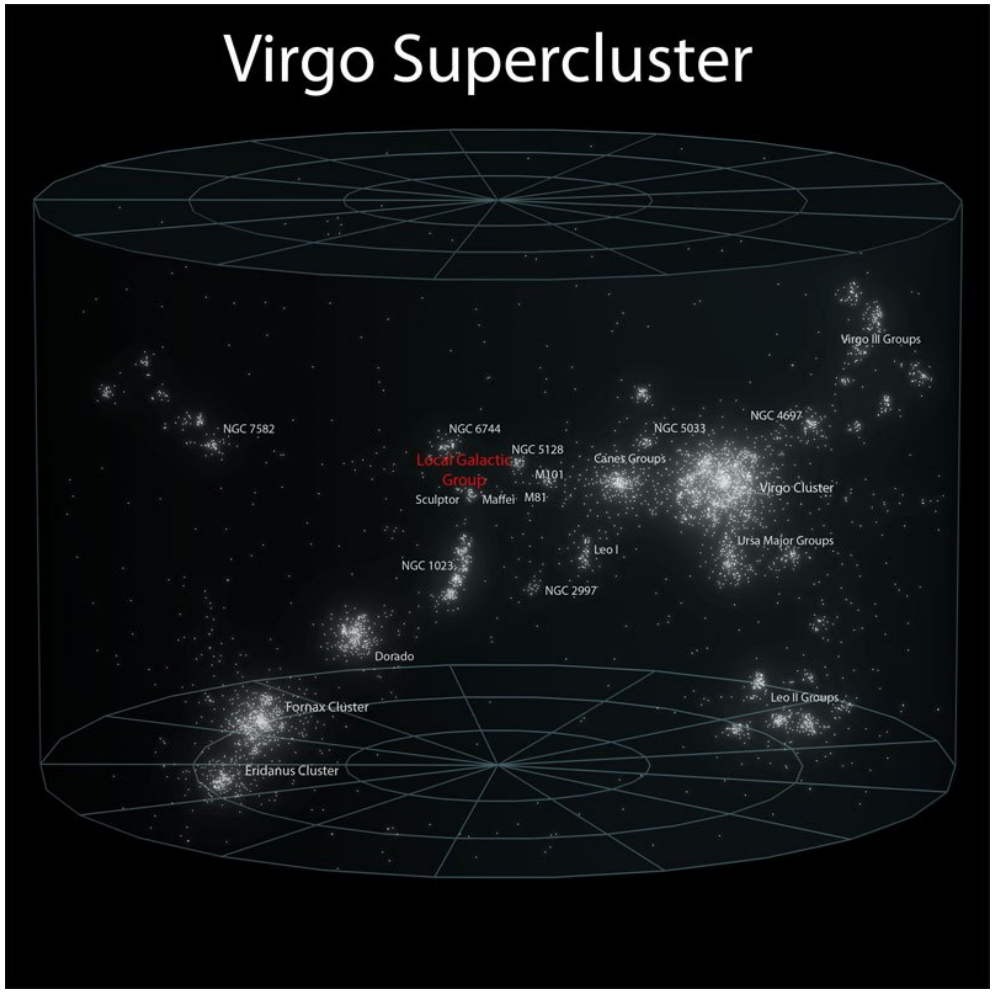

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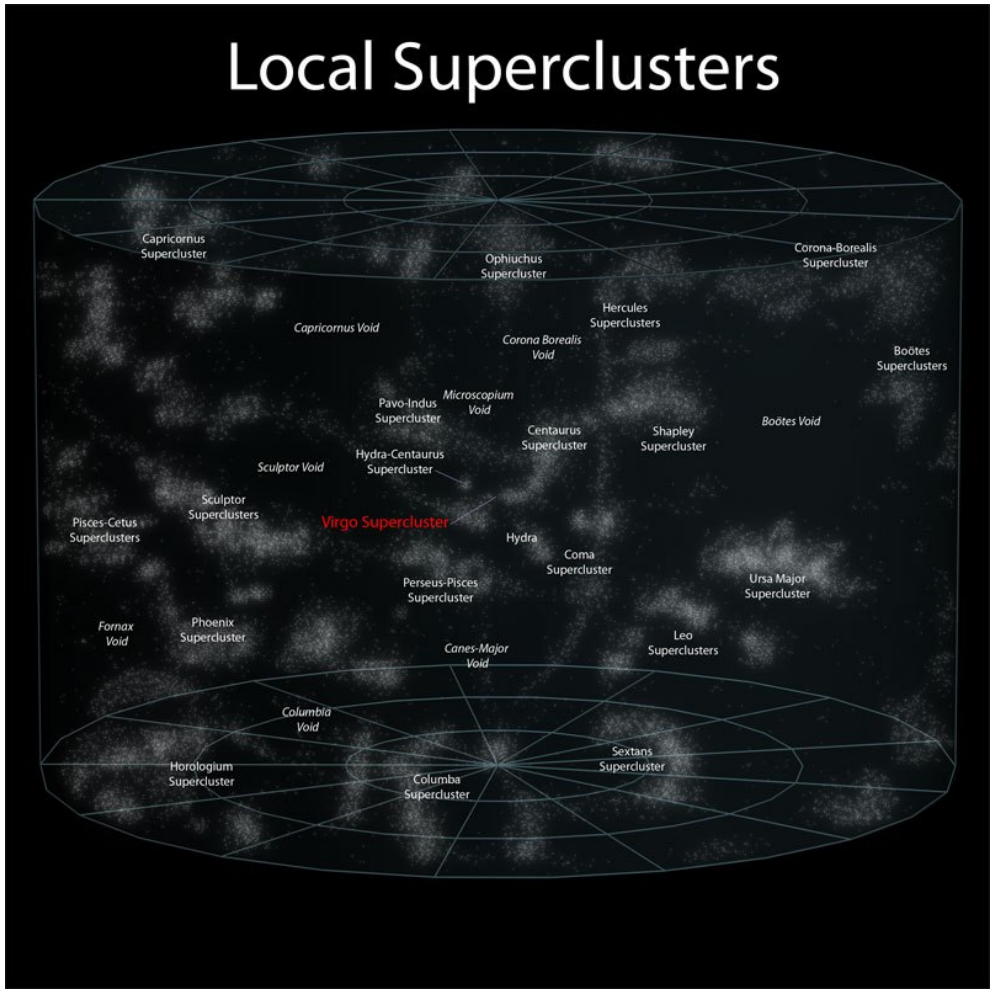
Scales of the Universe



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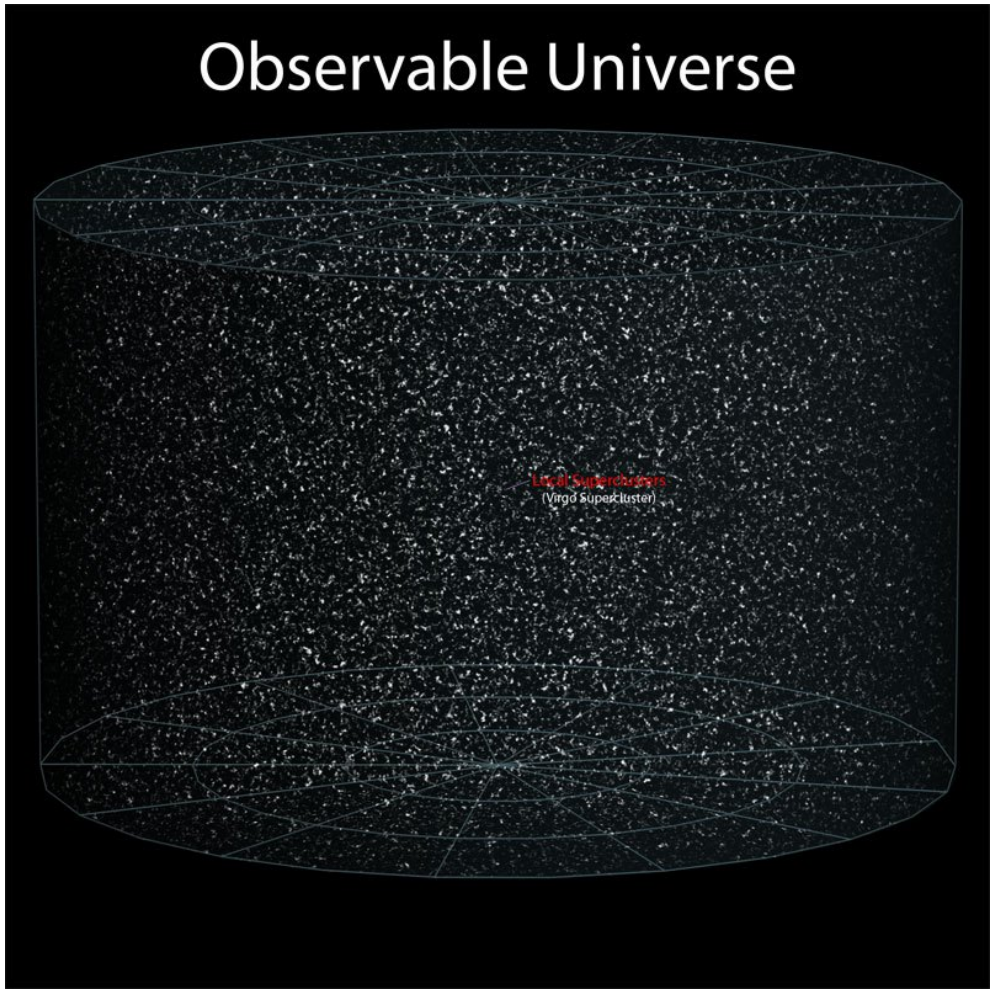
Scales of the Universe



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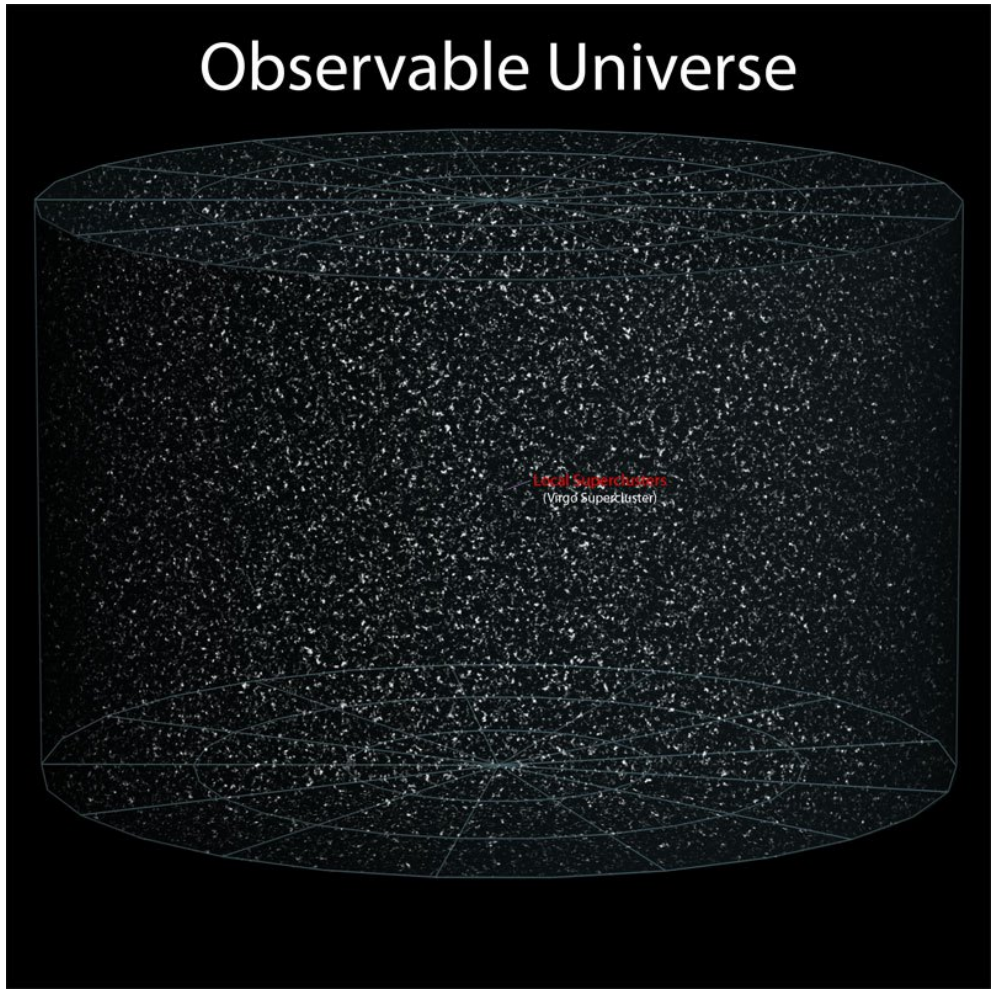
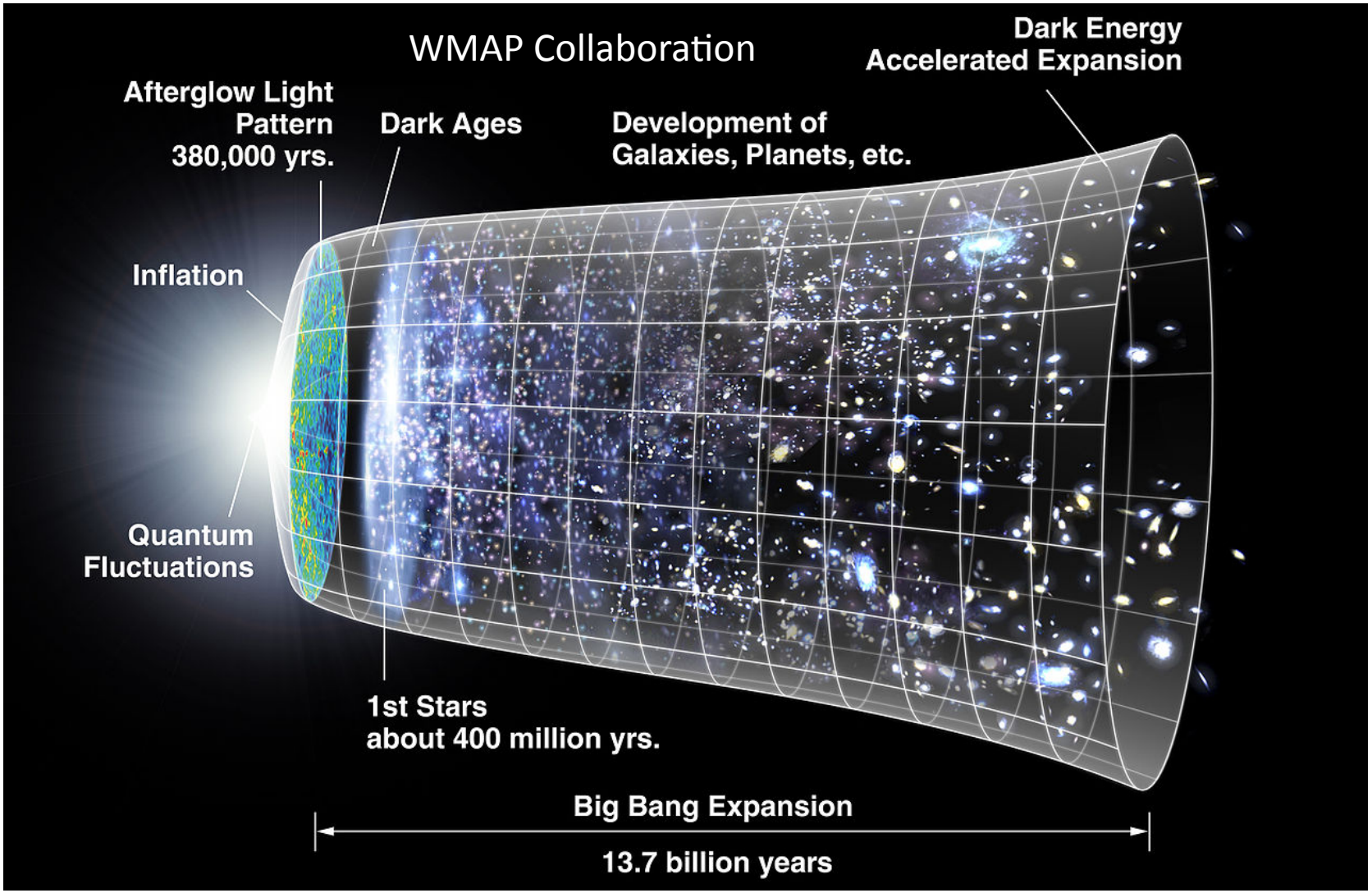
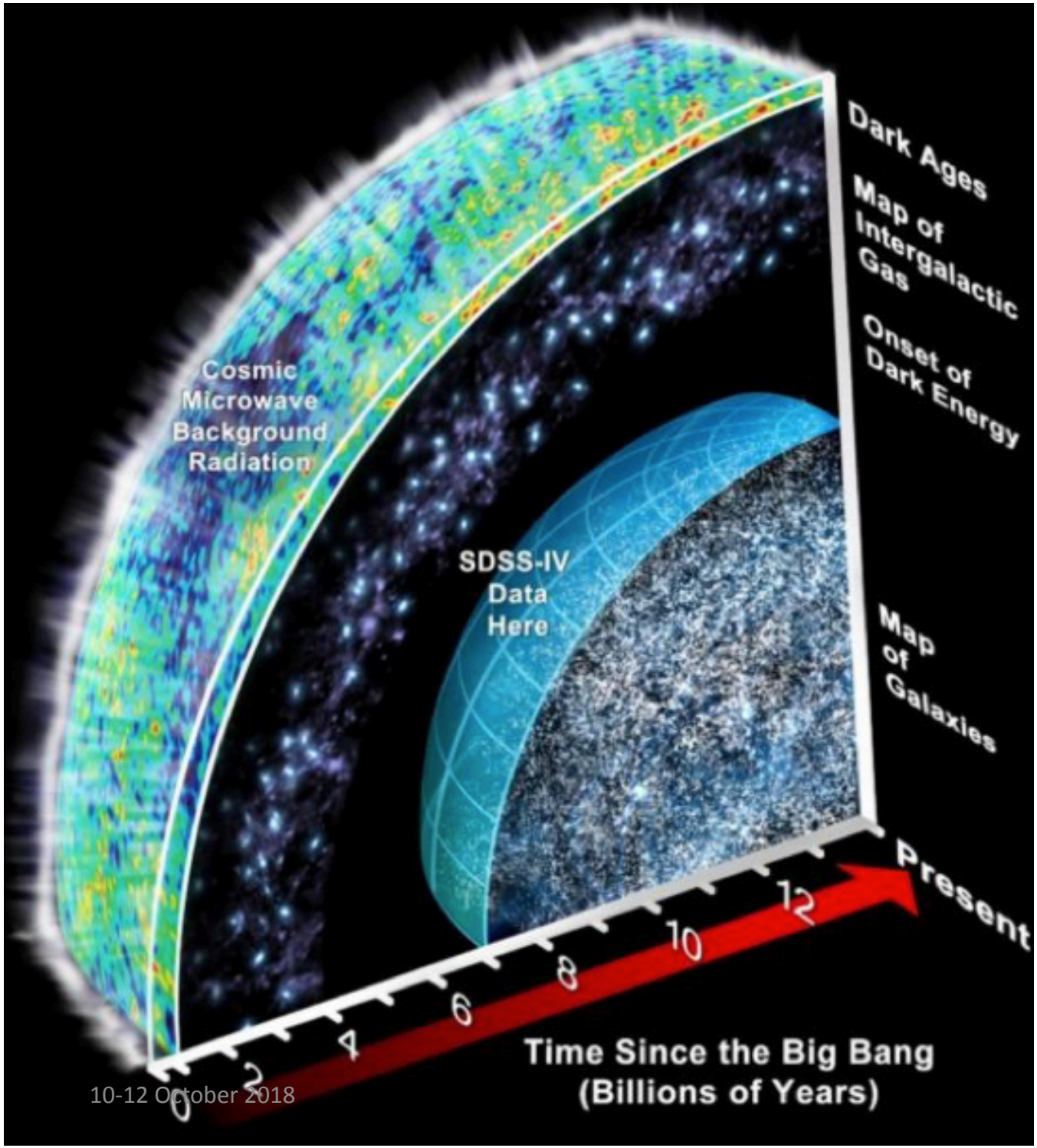
Cosmological Principle



Homogeneous and isotropic

Evolution History of the Universe

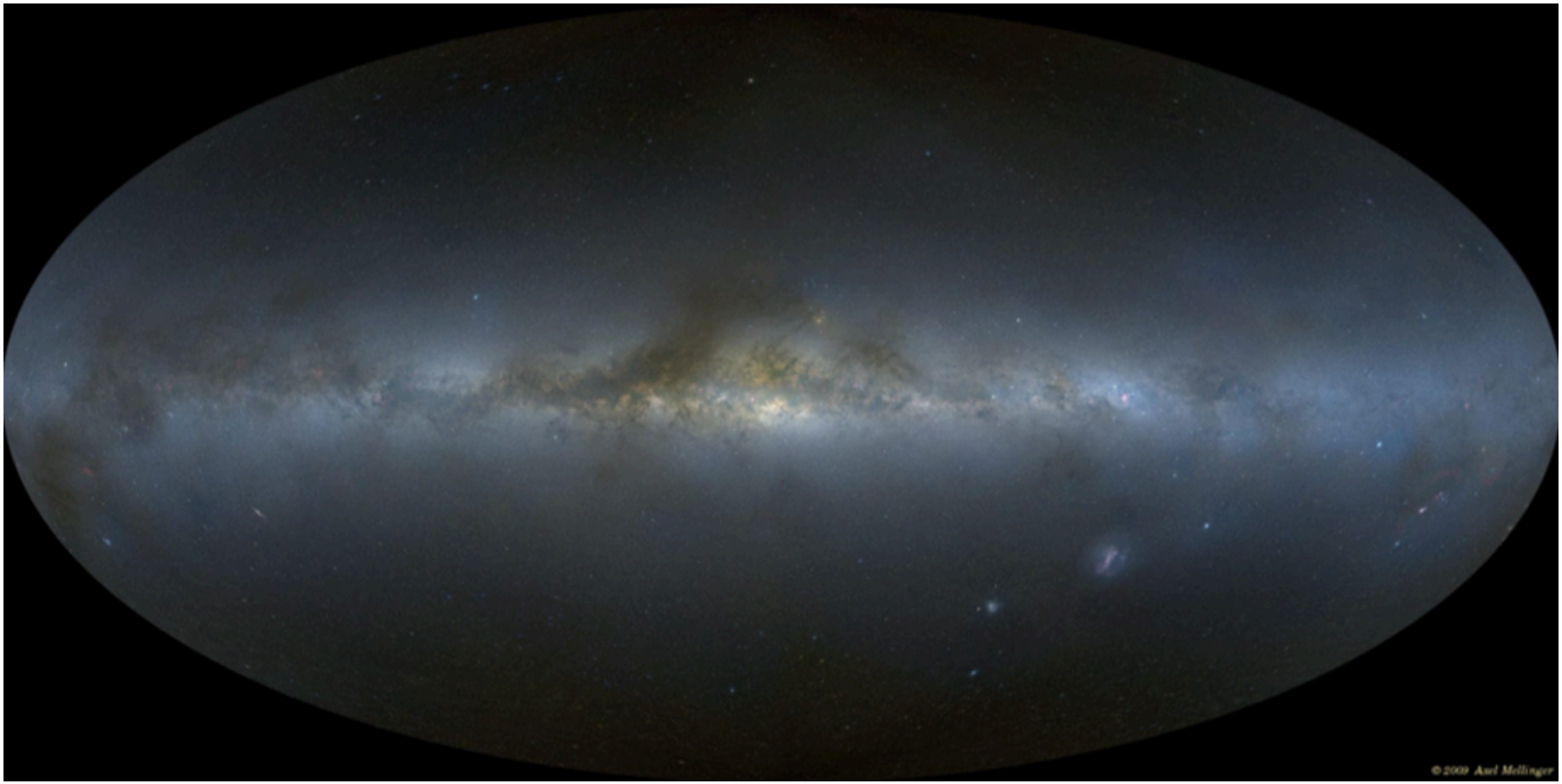




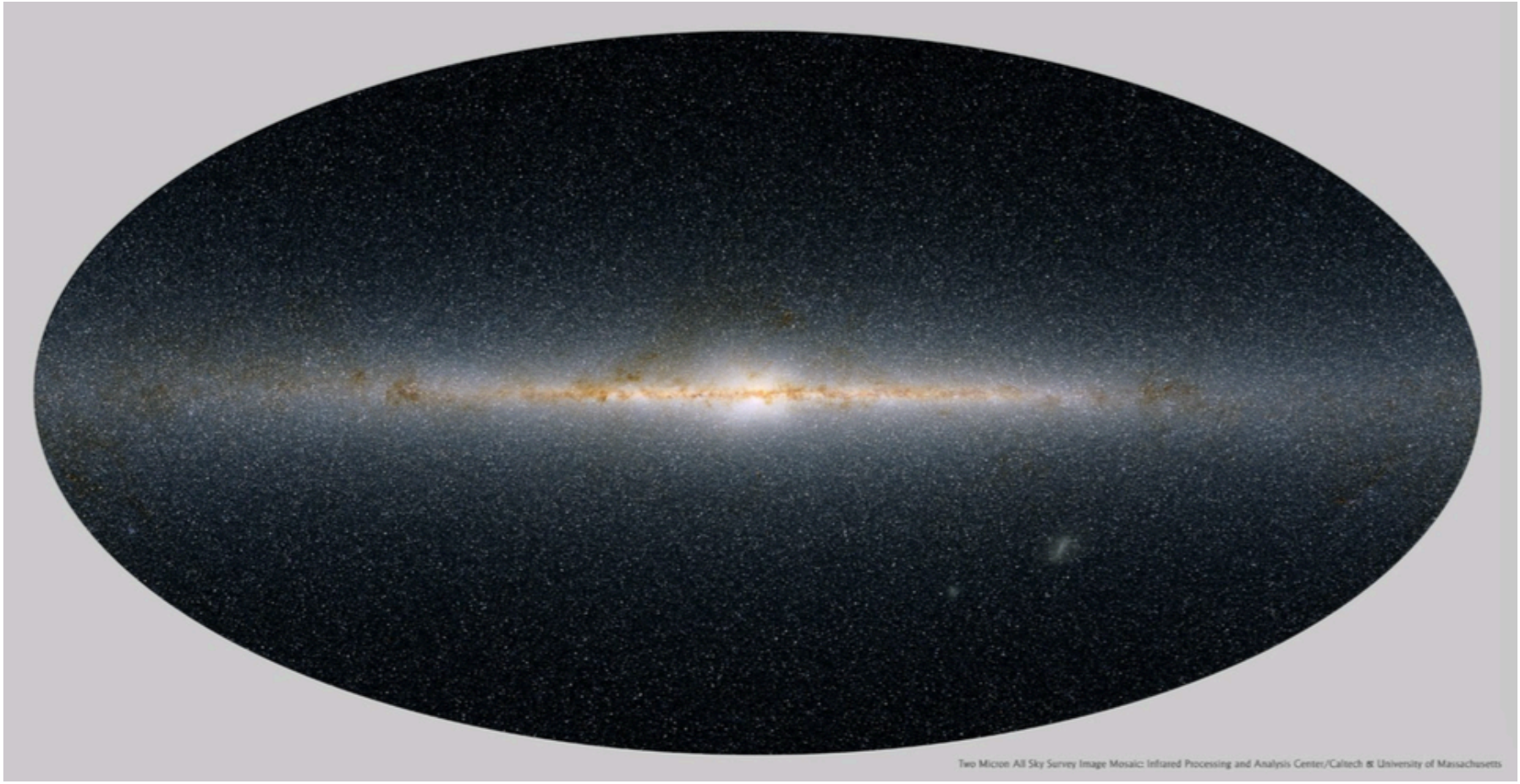
SDSS IV data release

https://www.youtube.com/watch?v=lz9Dqq0FpKk

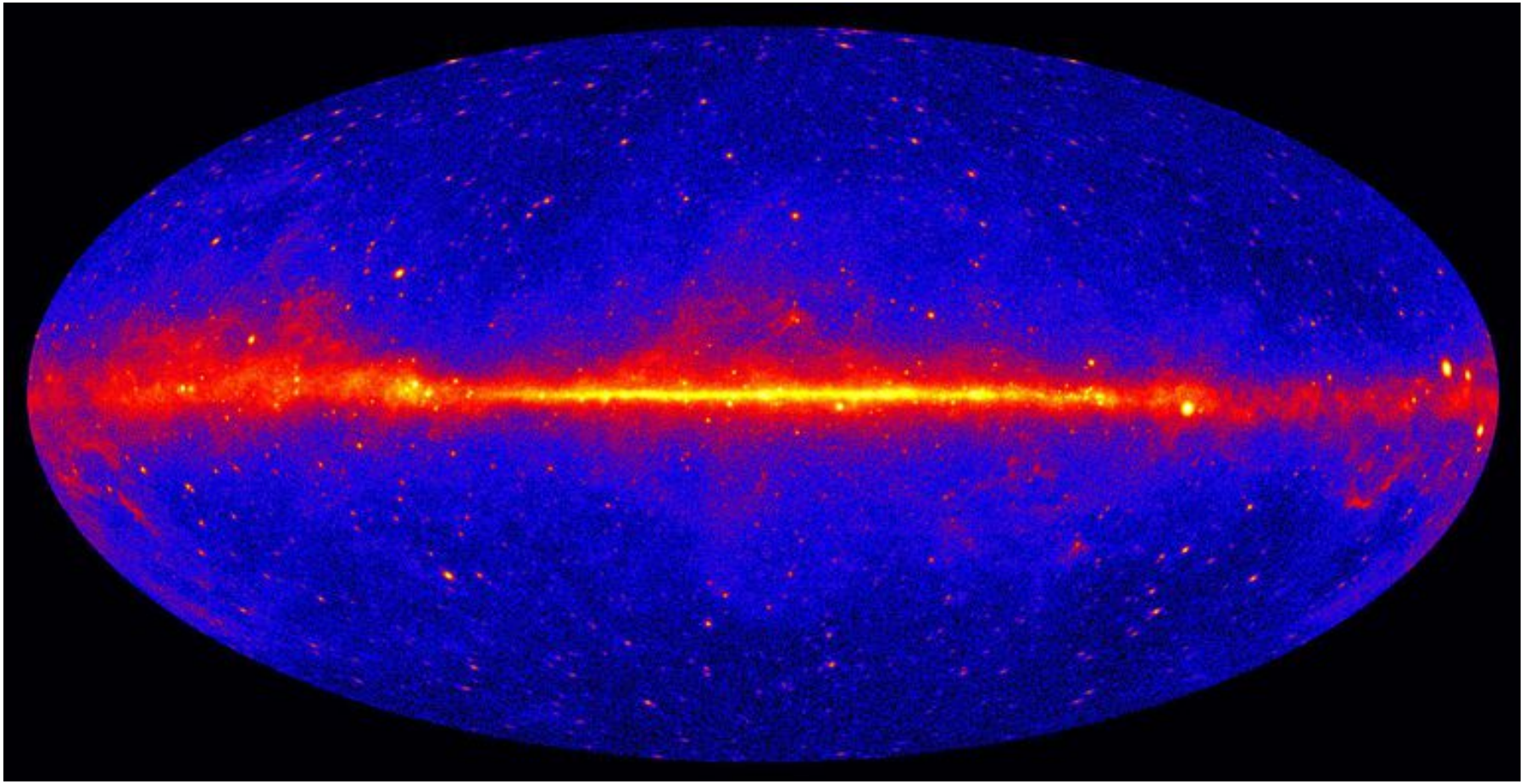
Optical Universe



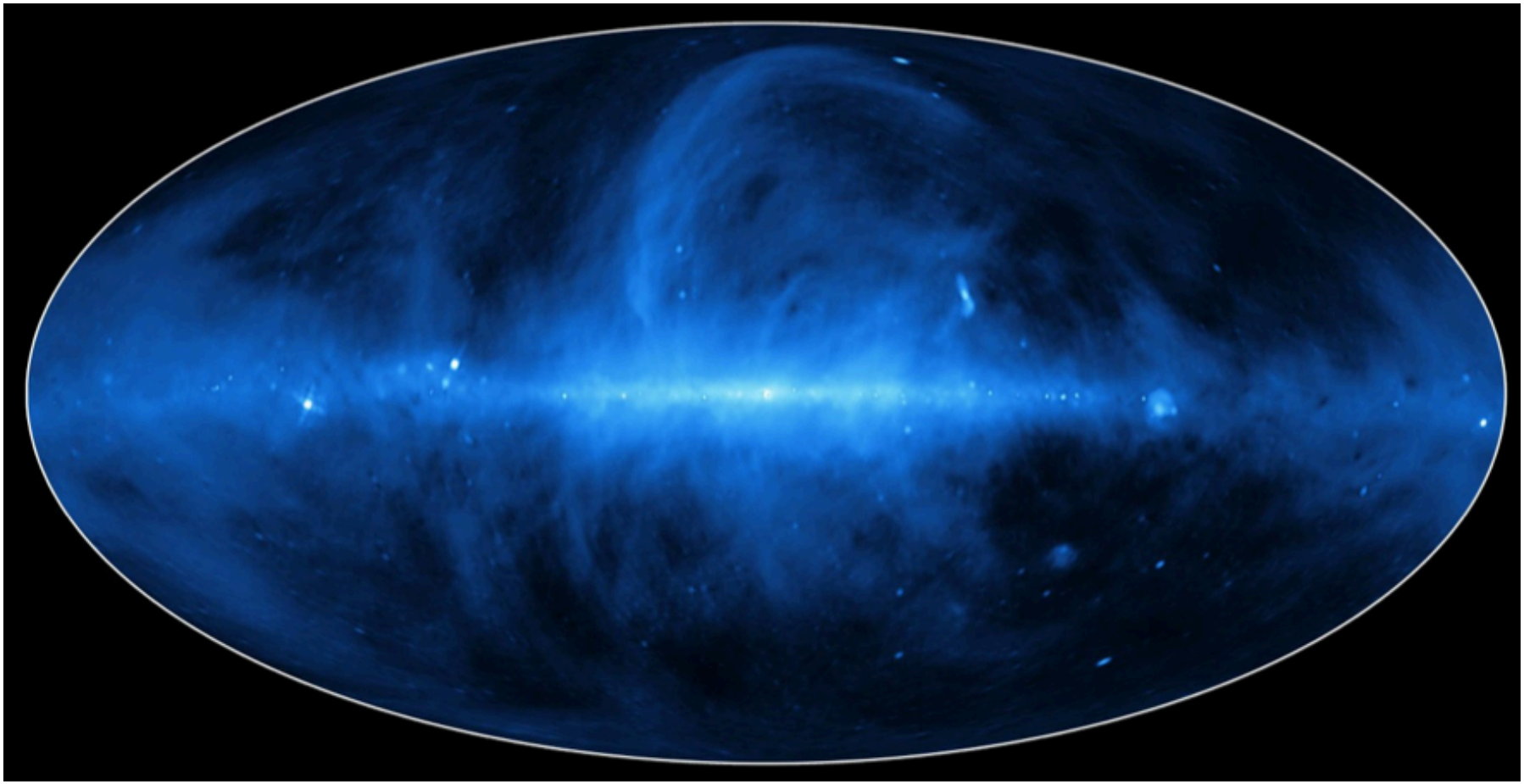
Infrared Universe



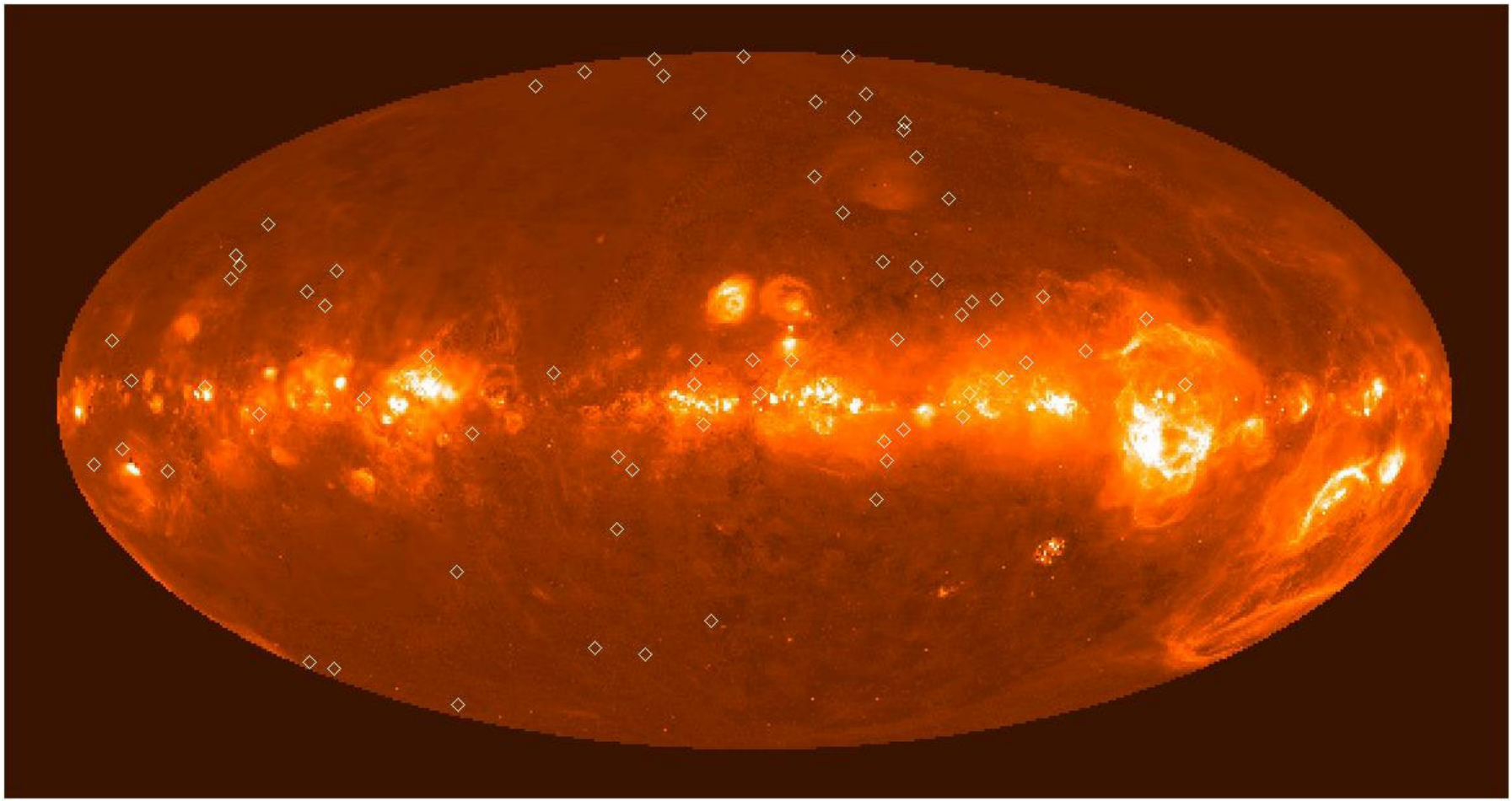
Gamma Ray Universe



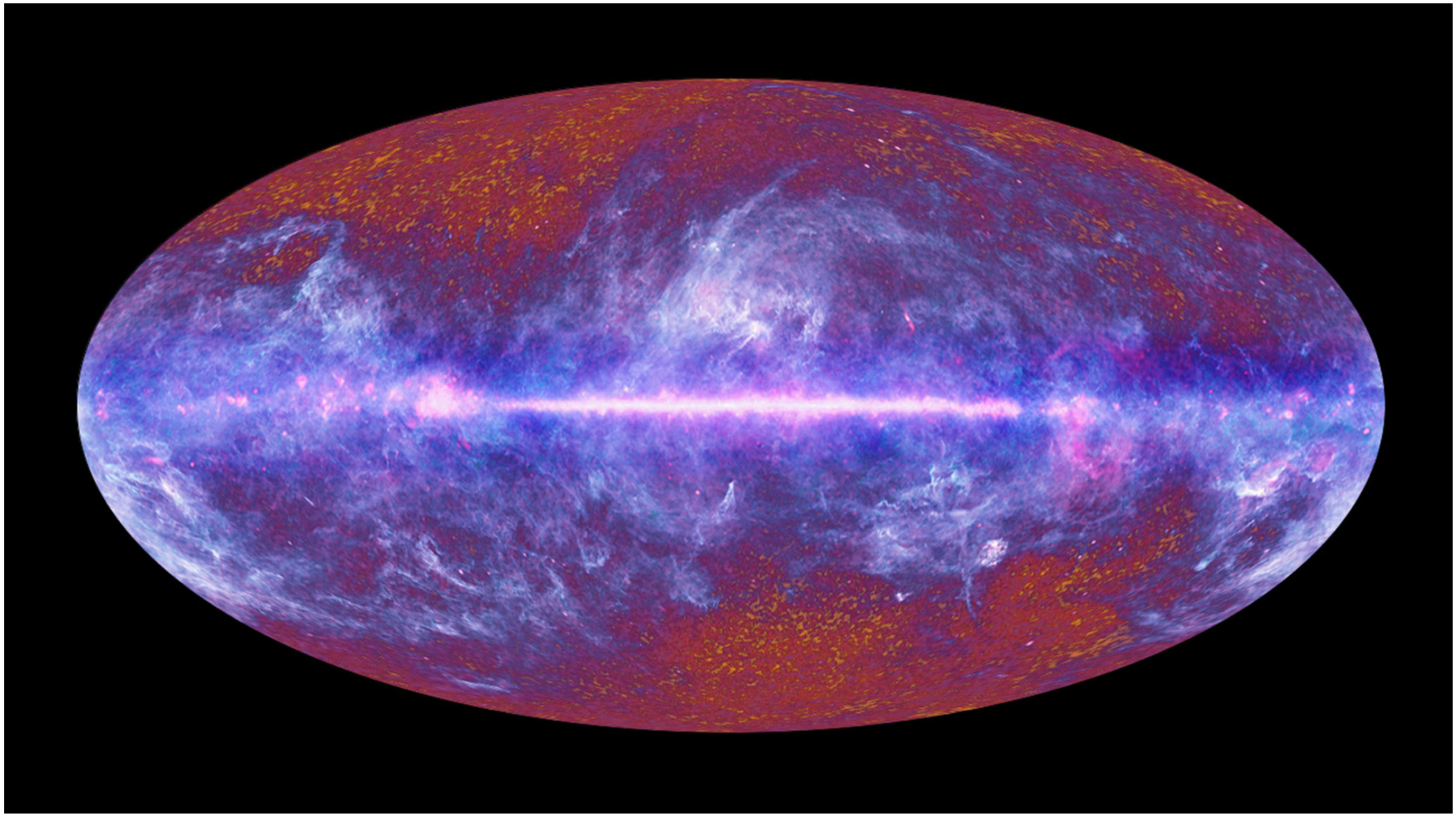
Radio Universe



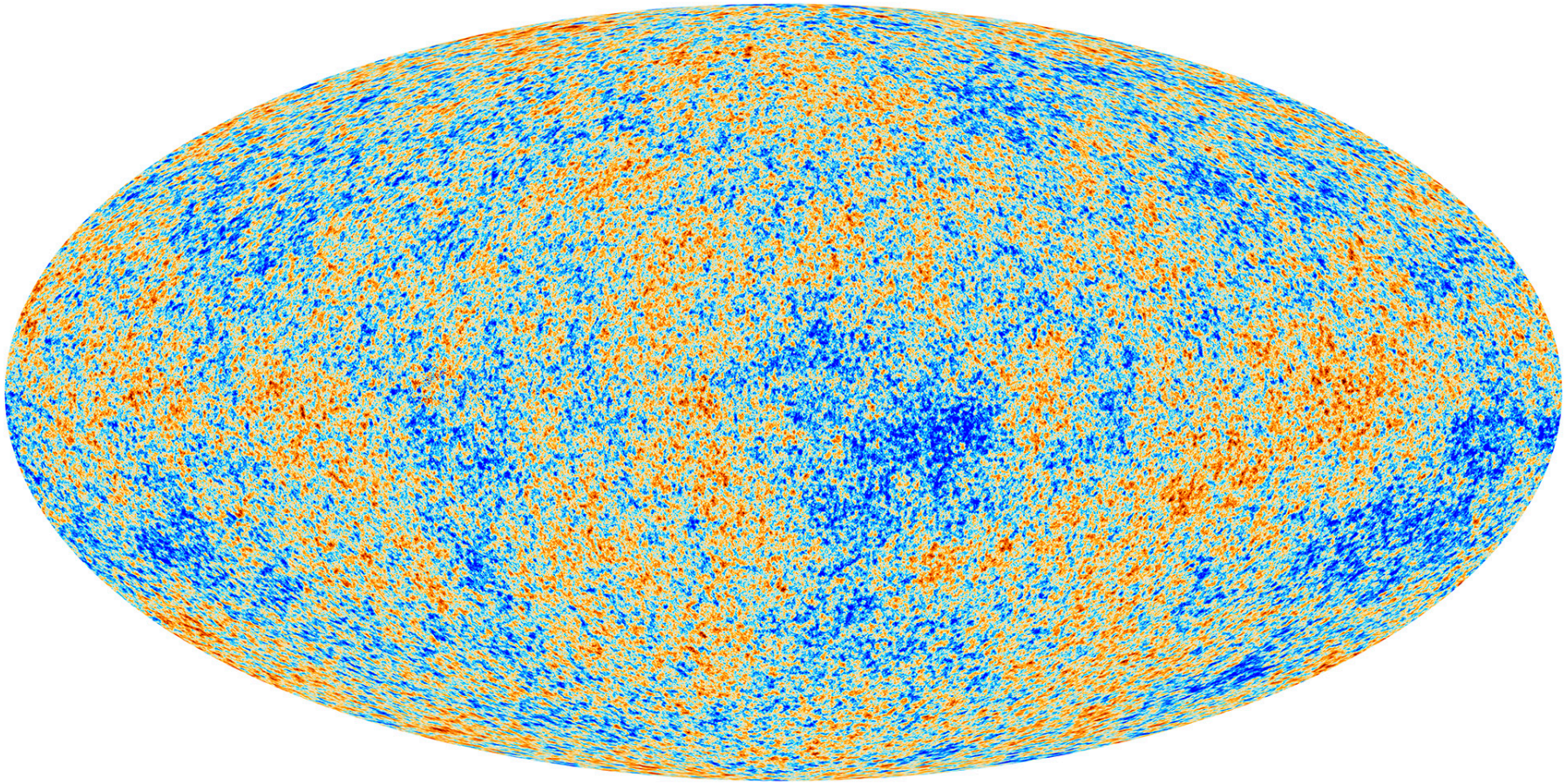
X-ray Universe



CMB Universe



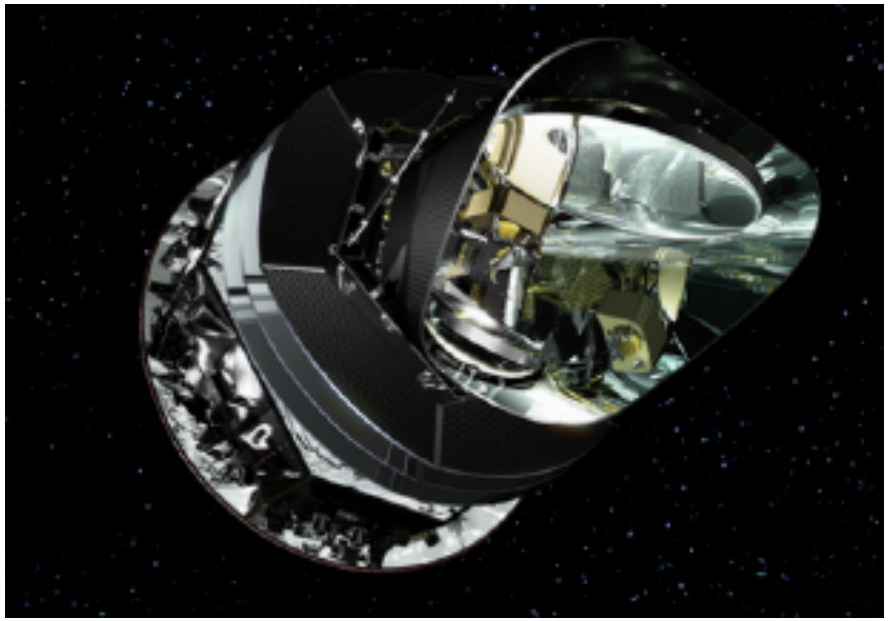
Clean CMB Universe



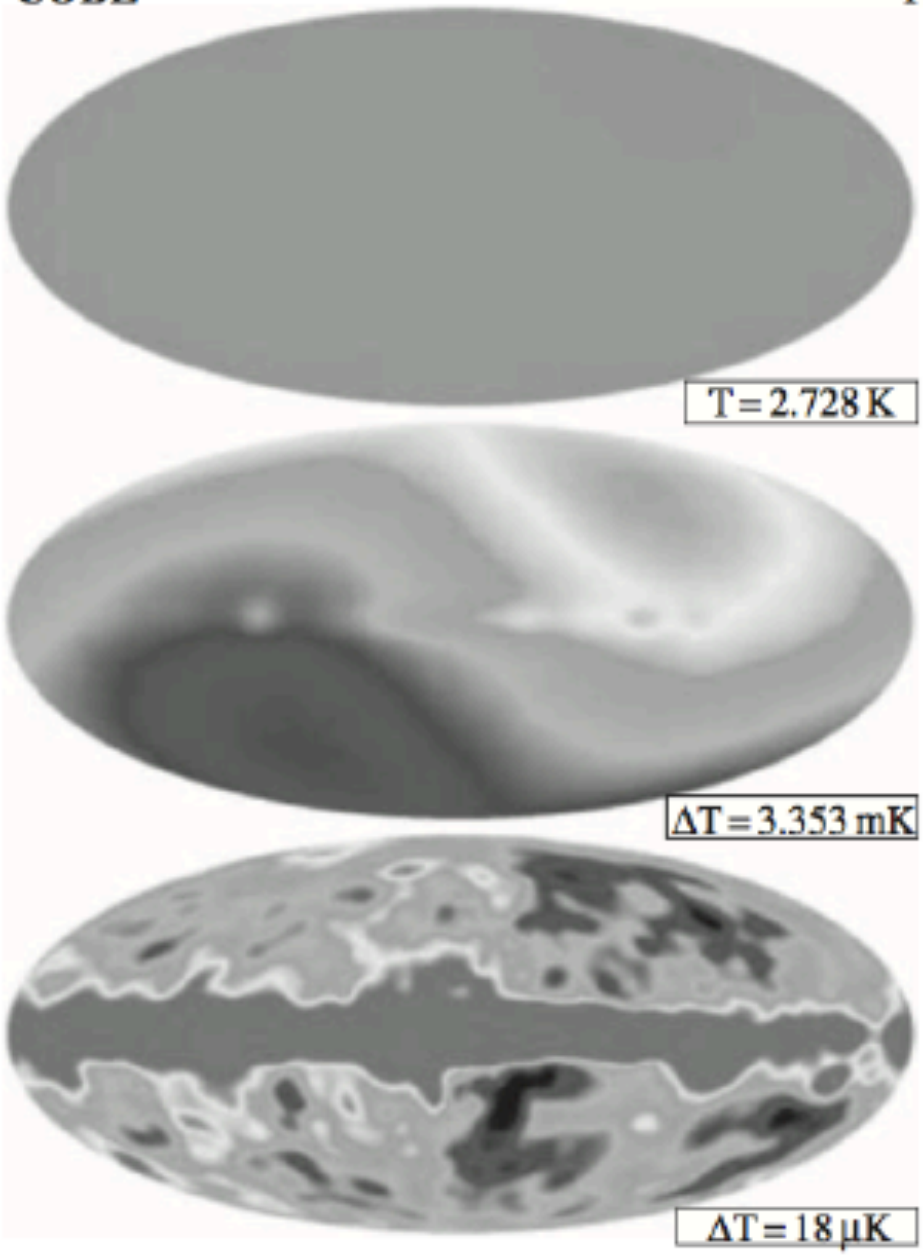
First CMB Detection

Penzias & Wilson 1965

Planck Satellite (2009)



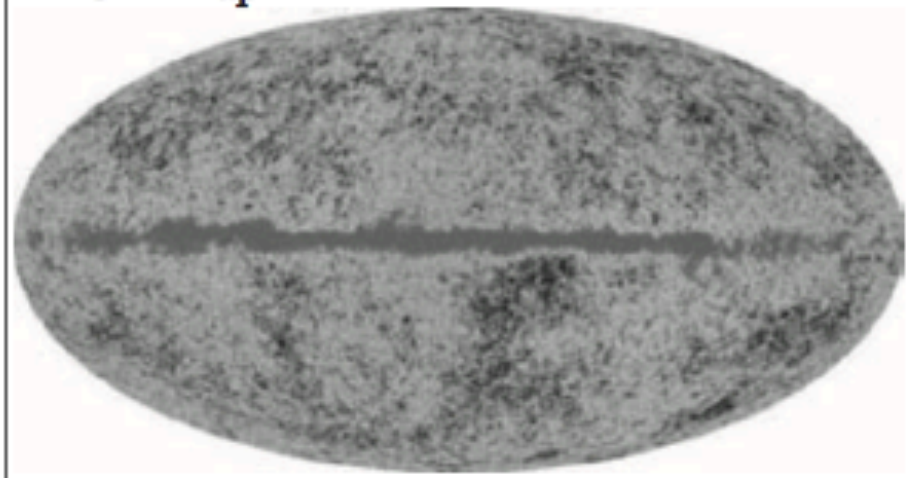
COBE DMR 53 GHz Maps



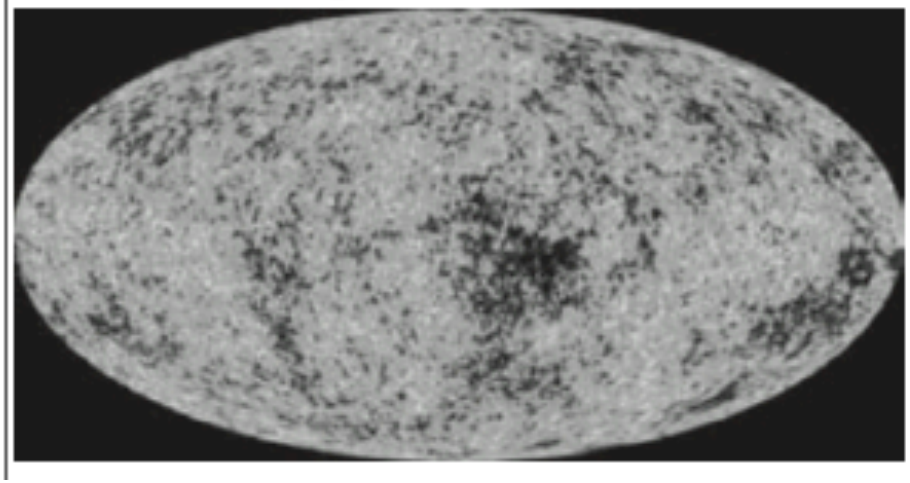
WMAP

Linear scale from –200→200 μK

41 GHz map

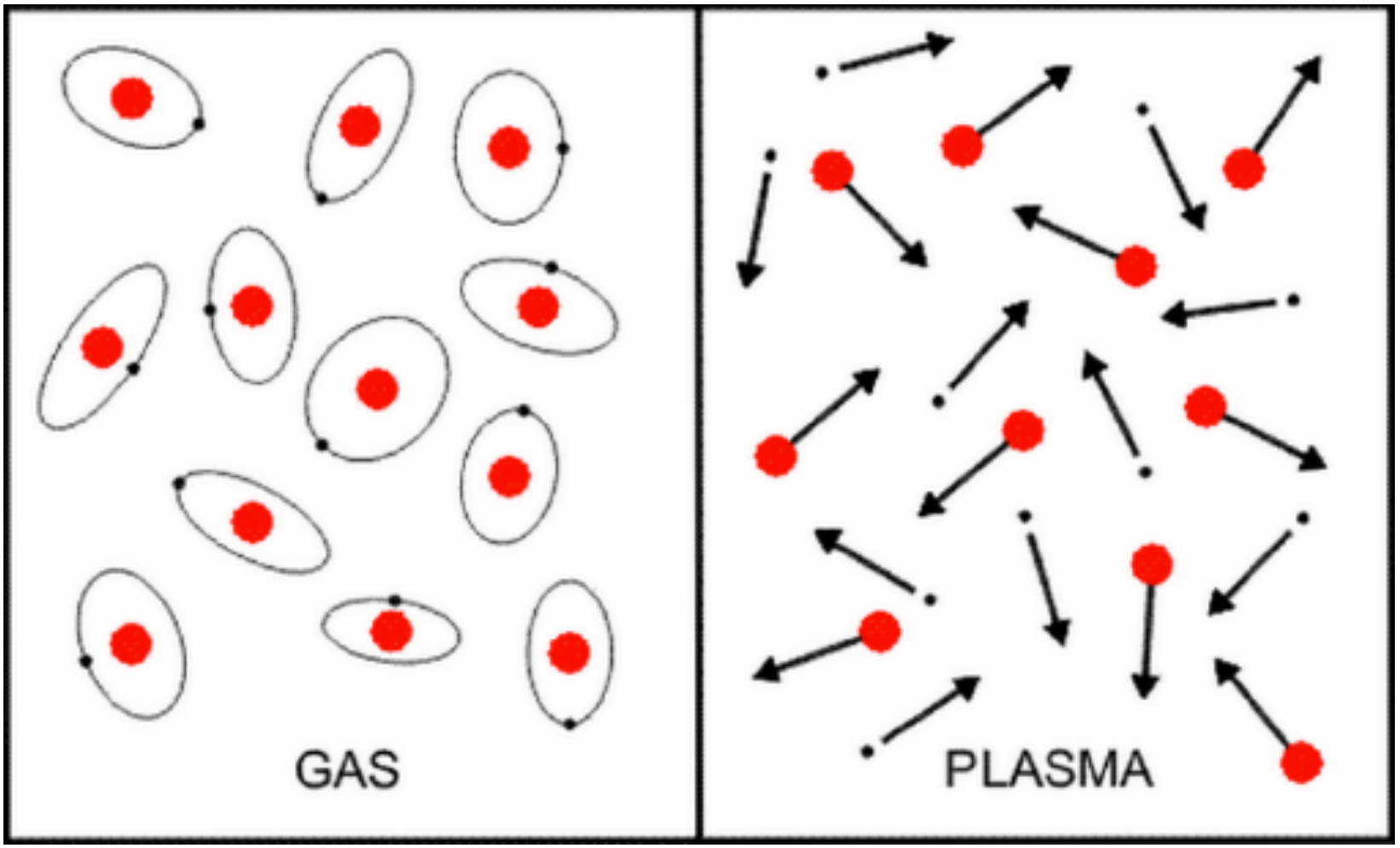


Combination map



Recombination

Temperature goes as a^{-1} as the Universe expands.

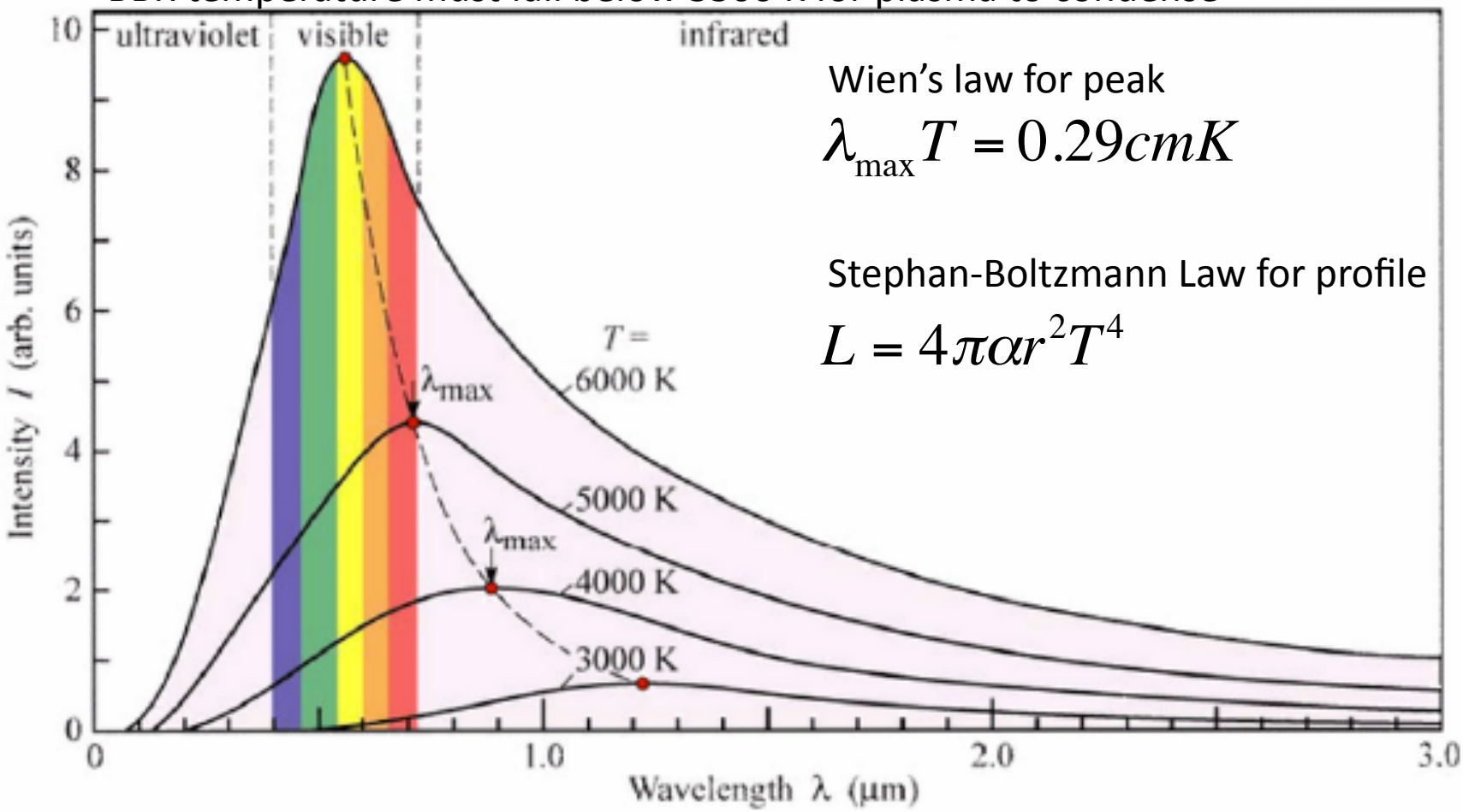


Universe after Recombination

Early Universe

Black Body Radiation

BBR temperature must fall below 3300 K for plasma to condense



Wien's law for peak

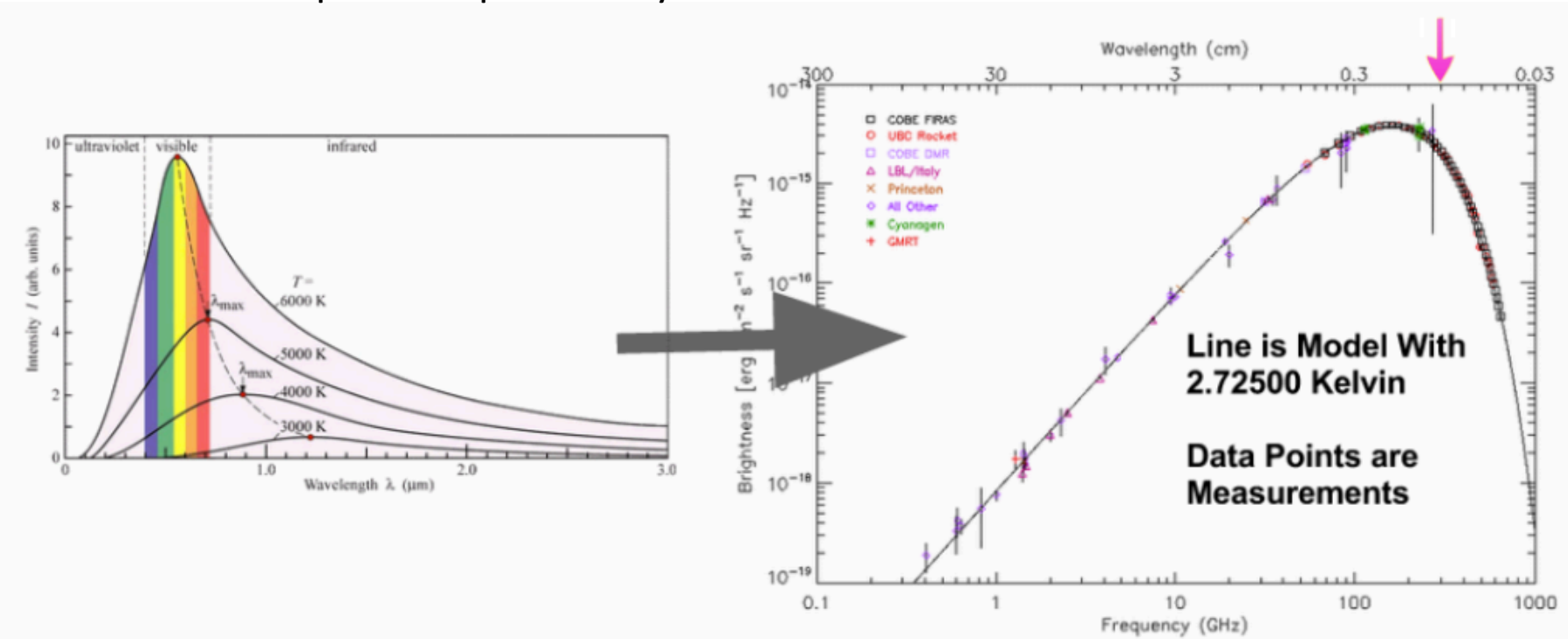
$$\lambda_{\max} T = 0.29 cmK$$

Stephan-Boltzmann Law for profile

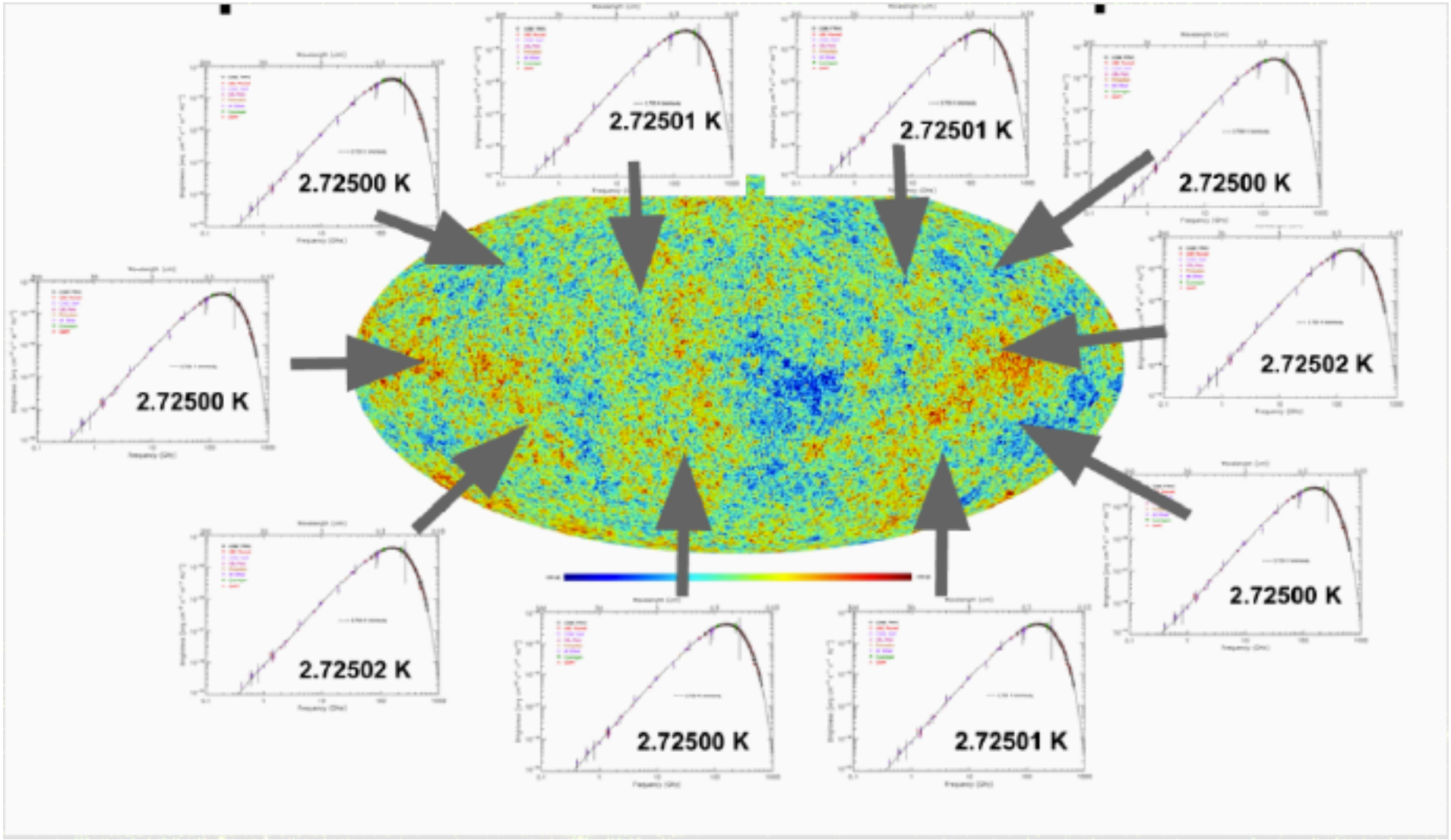
$$L = 4\pi\alpha r^2 T^4$$

Recombination radiation today

Radiation stretched by a factor of 1100 due to the expansion of the universe
The BBR temperature peak today has stretched to 3K



Planck measured the Universe's temperature at every point. Fluctuations are small!



CMB ANISOTROPIES

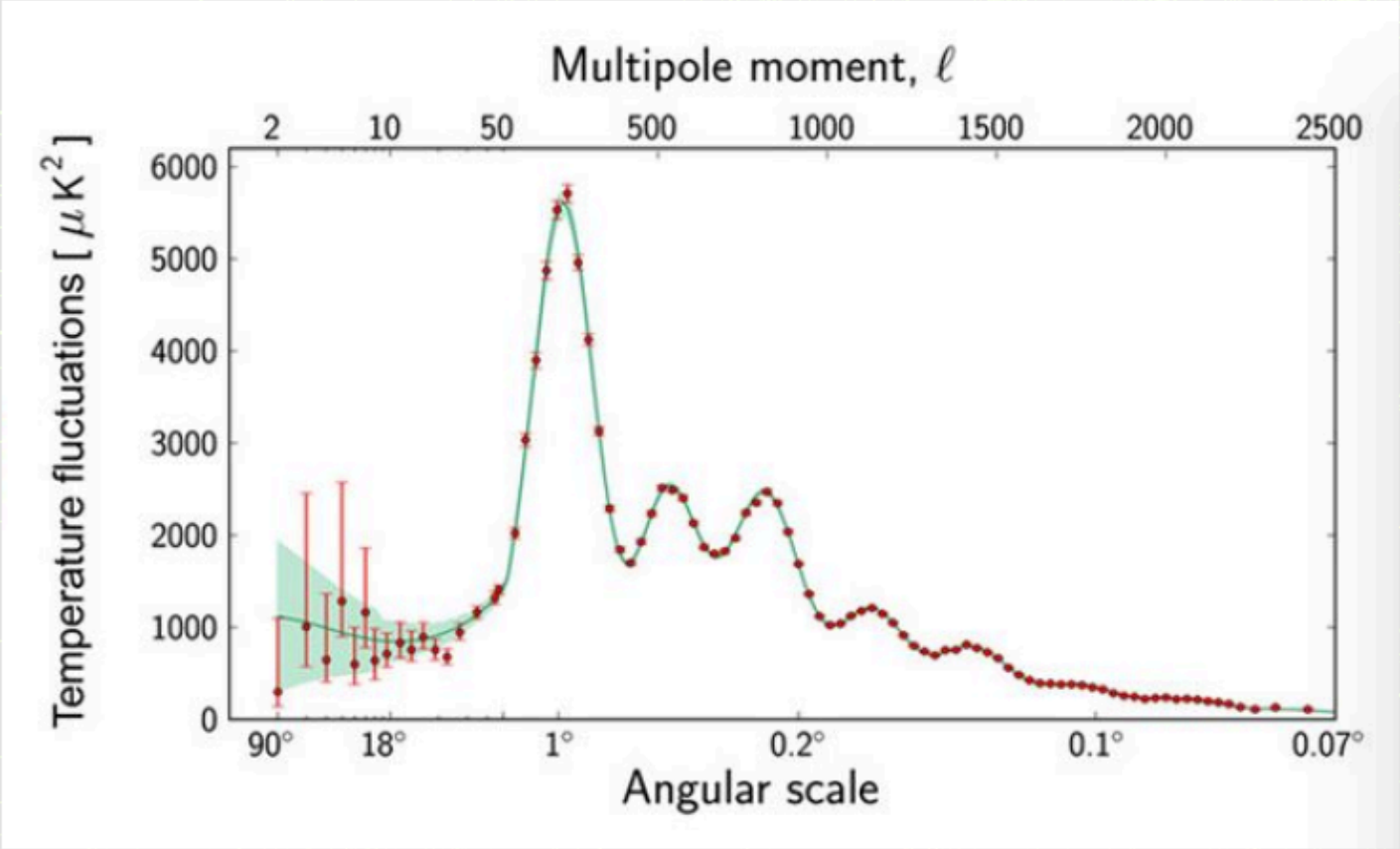


FIGURE: The acoustic peaks in the Cosmic Microwave Background (CMB) anisotropies depend strongly on total matter.

Ultimate proof there is indeed non-visible matter in the universe.

Objectives of Cosmology

All questions boil down to:

- How has and will the Universe evolve?
- What is the Universe made of?

The Friedmann Equation addresses both:

$$H^2 =$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\sum_i \rho_i \qquad (1)$$

$$= \frac{8\pi G}{3c^2}\left(\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda\right)$$

Expansion history

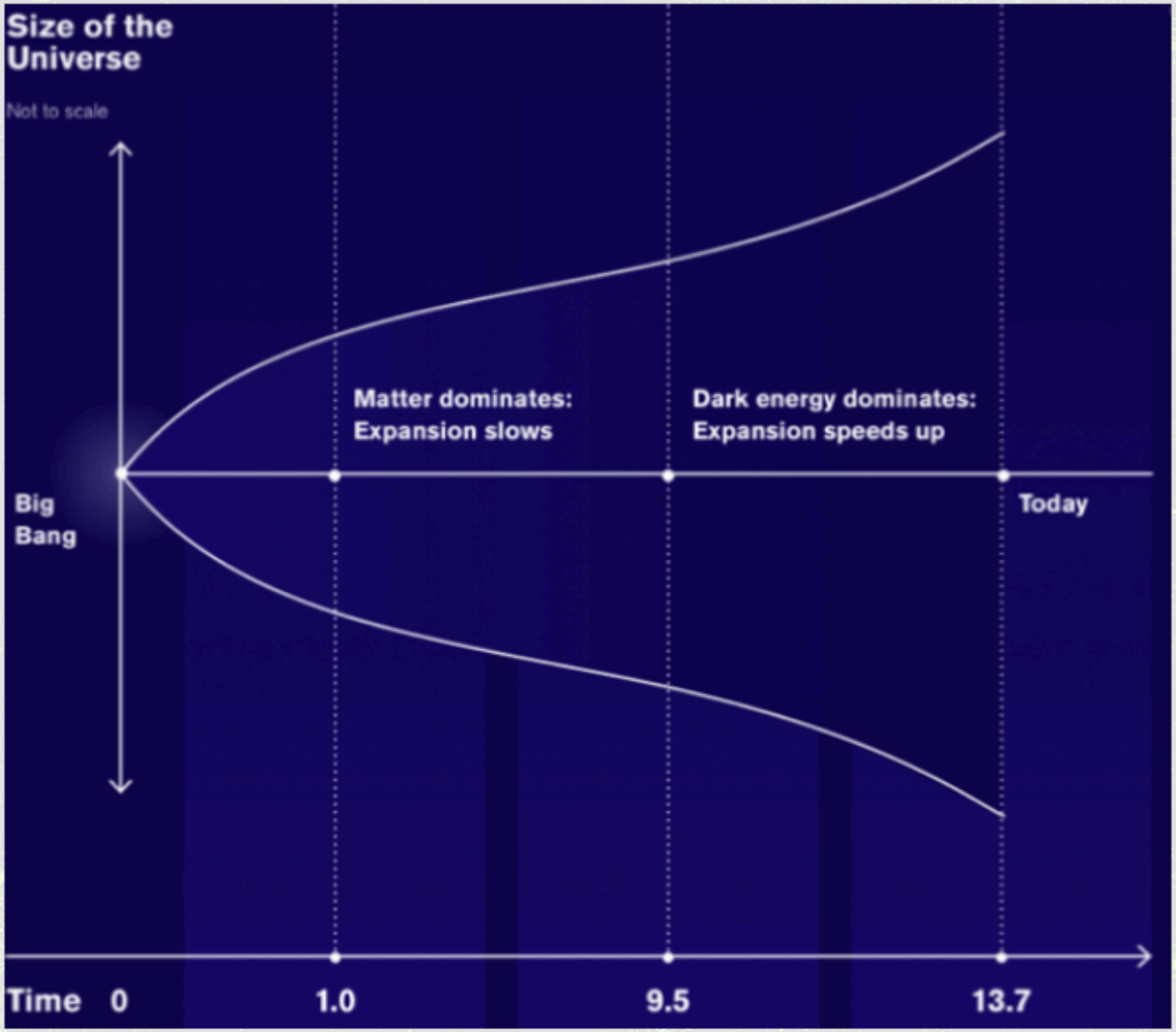


Figure: The y-axis is the scale factor from the Friedmann equation. The evolution of the Universe is entirely governed by its components. (© DESC)

Components of the Universe

Let's assume that General Relativity is correct, then these are the abundances of the Universe's content:

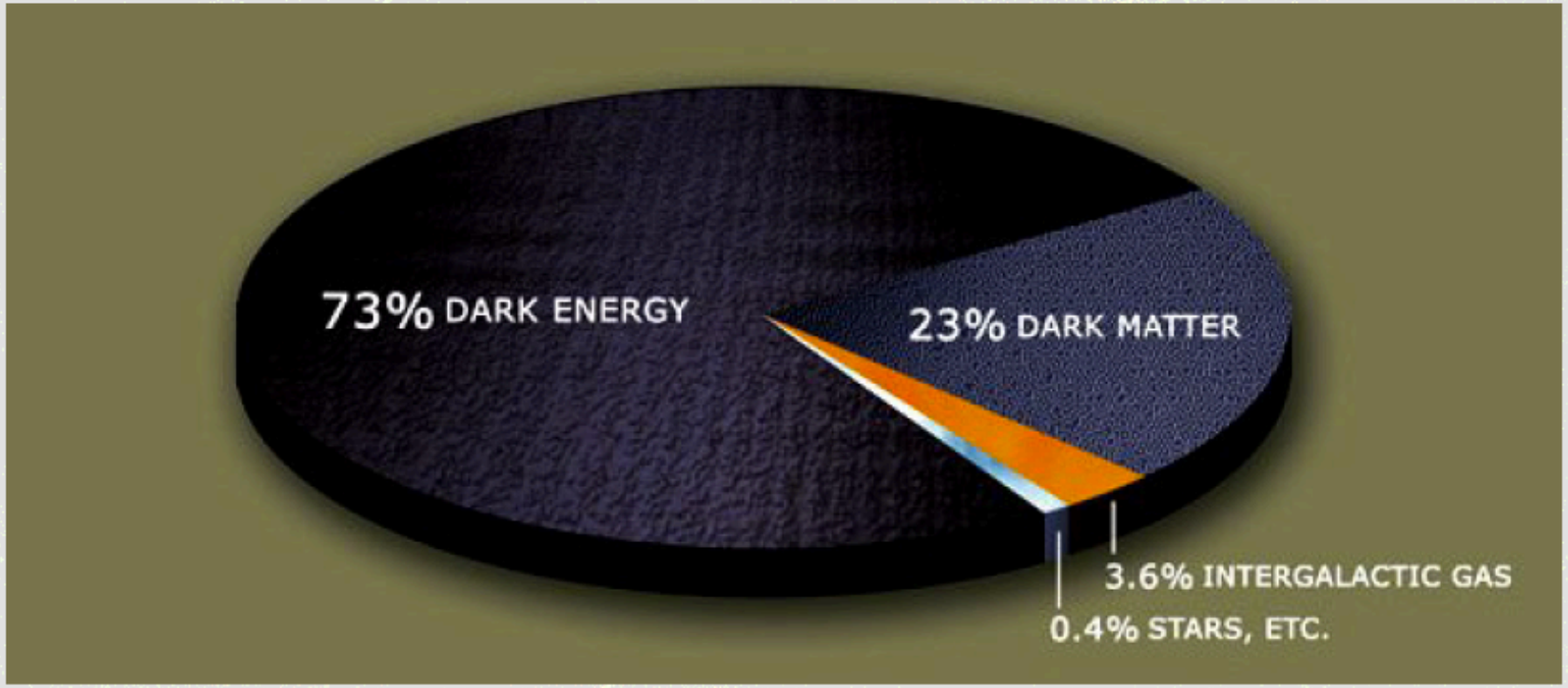
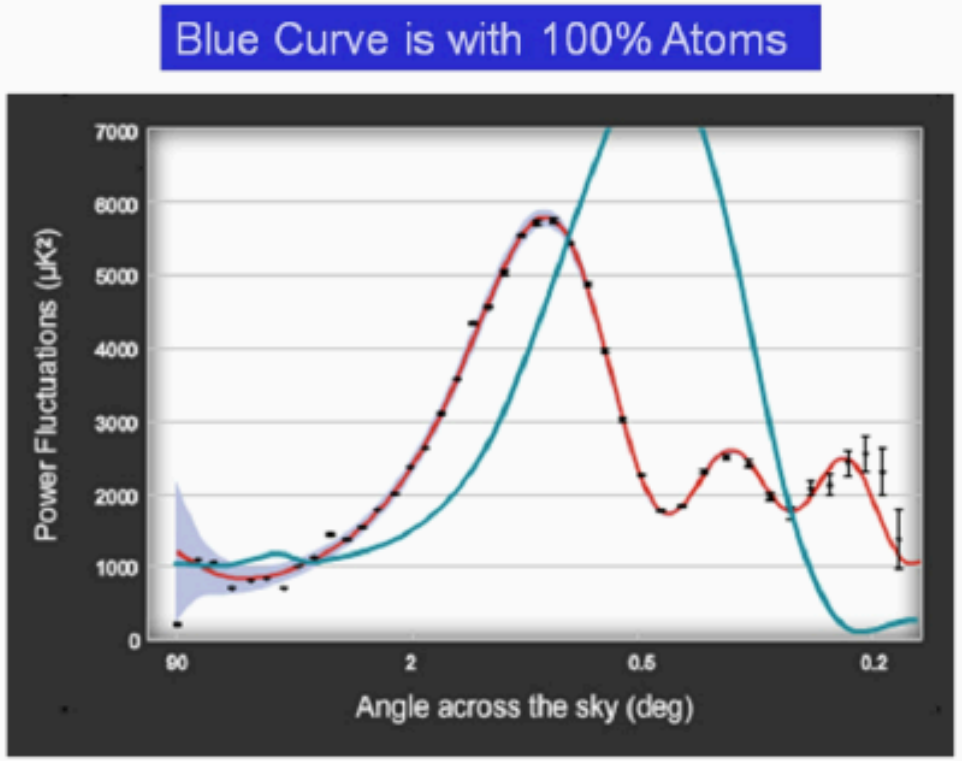


Figure: © Planck Collaboration

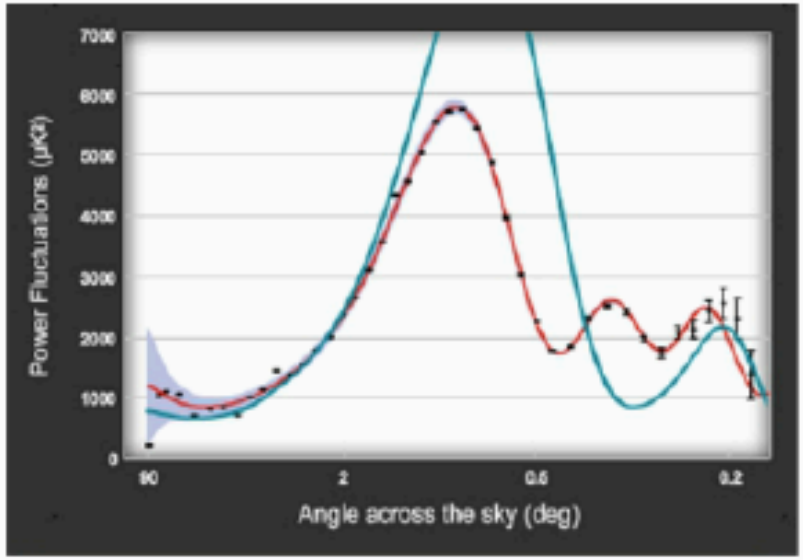
CMB cannot be understood without appropriate component percentages



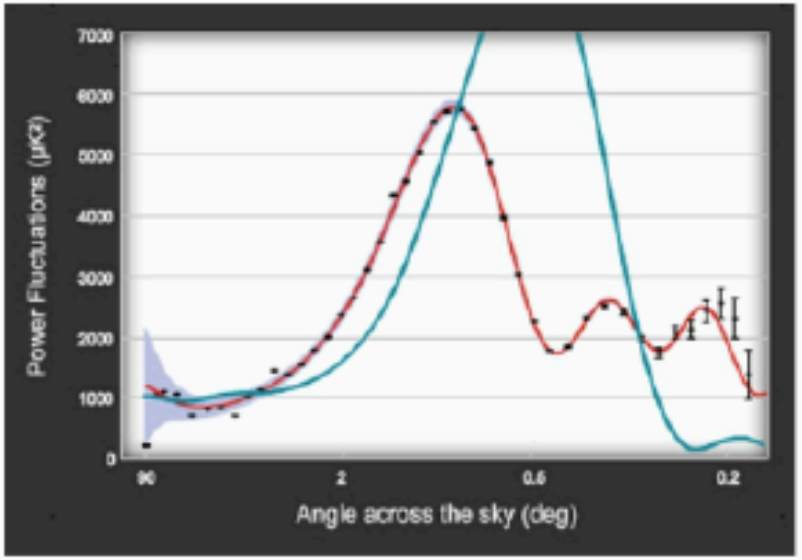
http://map.gsfc.nasa.gov/resources/camb_tool/index.html

http://map.gsfc.nasa.gov/resources/camb_tool/cmb_plot.swf

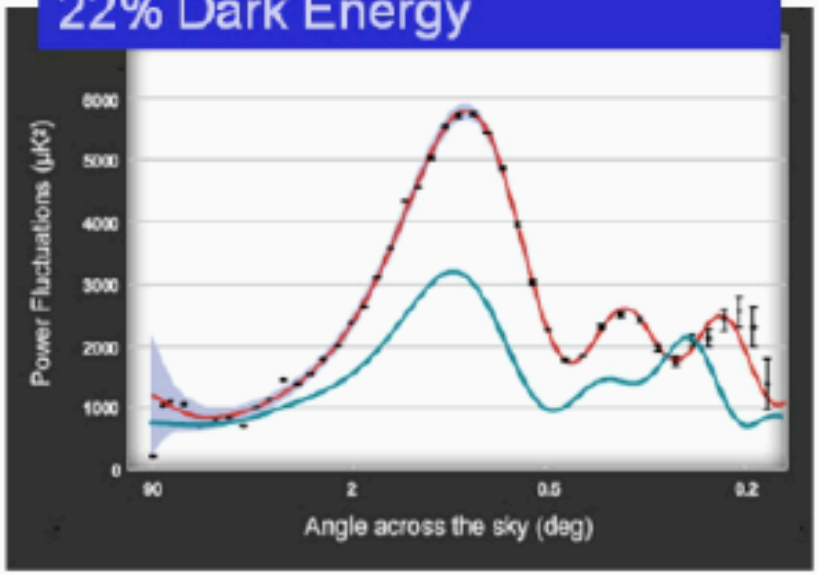
74% Dark Matter, 22% Atoms, 4% Dark Energy



74% Atoms, 22% Dark Energy, 4% Dark Matter



74% Dark Matter, 4% Atoms, 22% Dark Energy



74% Dark Energy, 22% Dark Matter, 4% Atoms

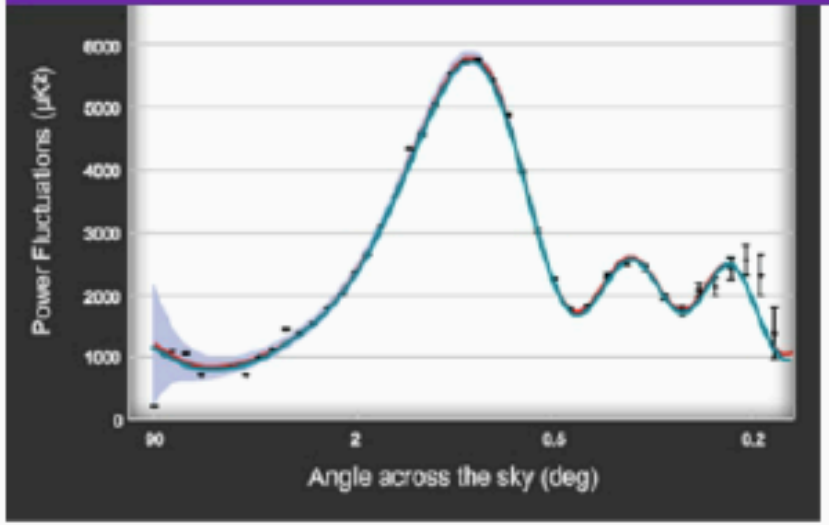


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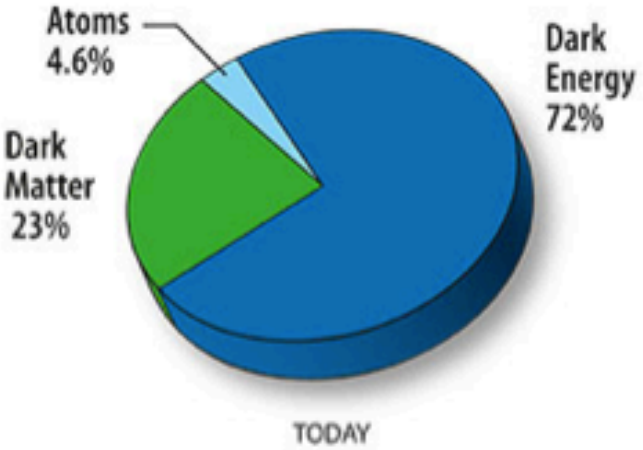
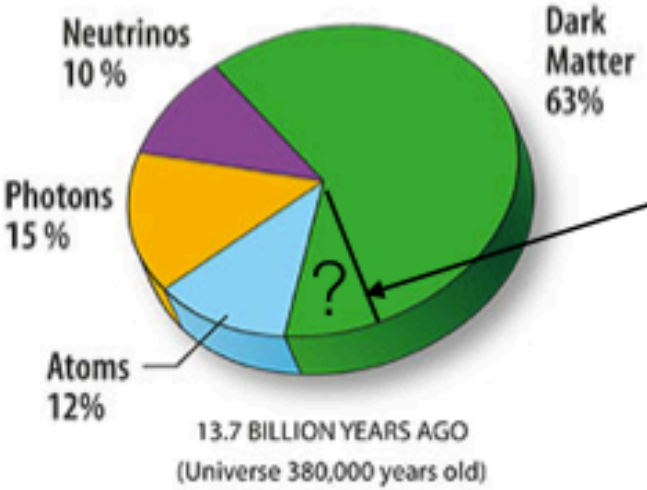
Figure: © Planck Collaboration



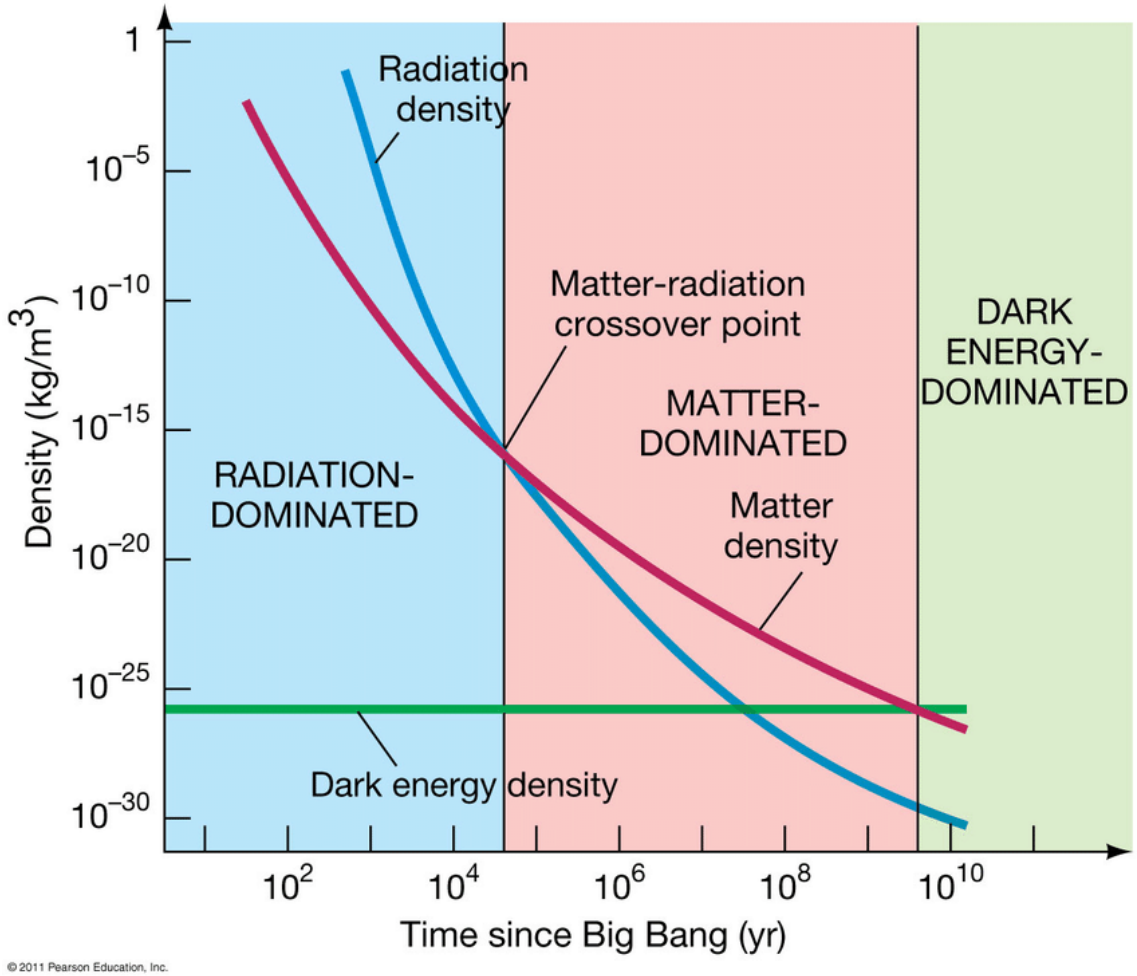


Lloyd Knox
UC Davis

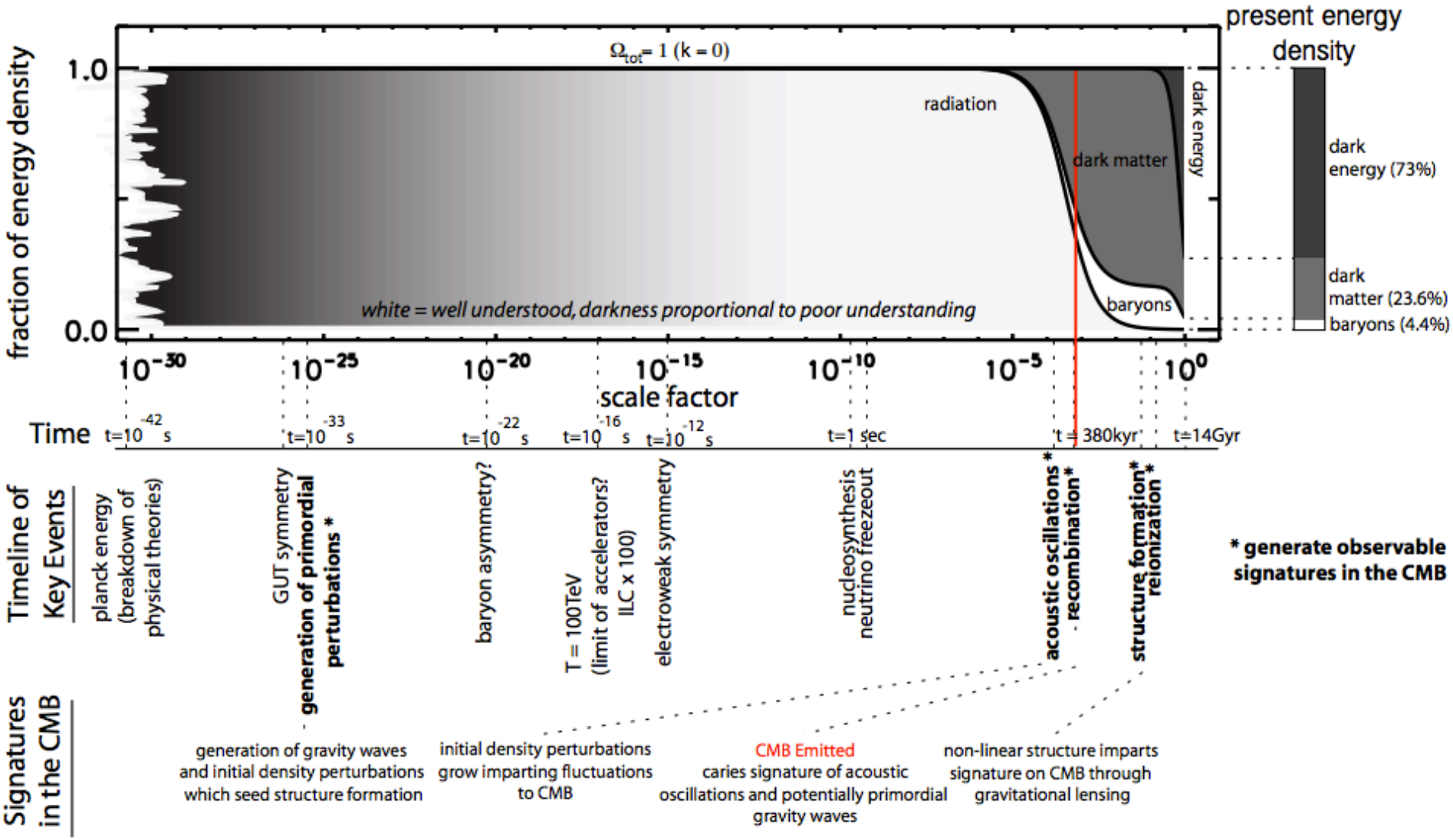
with K. Aylor, M. Joy, **M. Millea**, S. Raghunathan, K. Wu, and F.-Y. Cyr-Racine

An additional dark component important at early times?

Cosmic Evolution in terms of Dominating Density



Composition of and Key Events During the Evolution of the Universe



First issue: Dark Matter

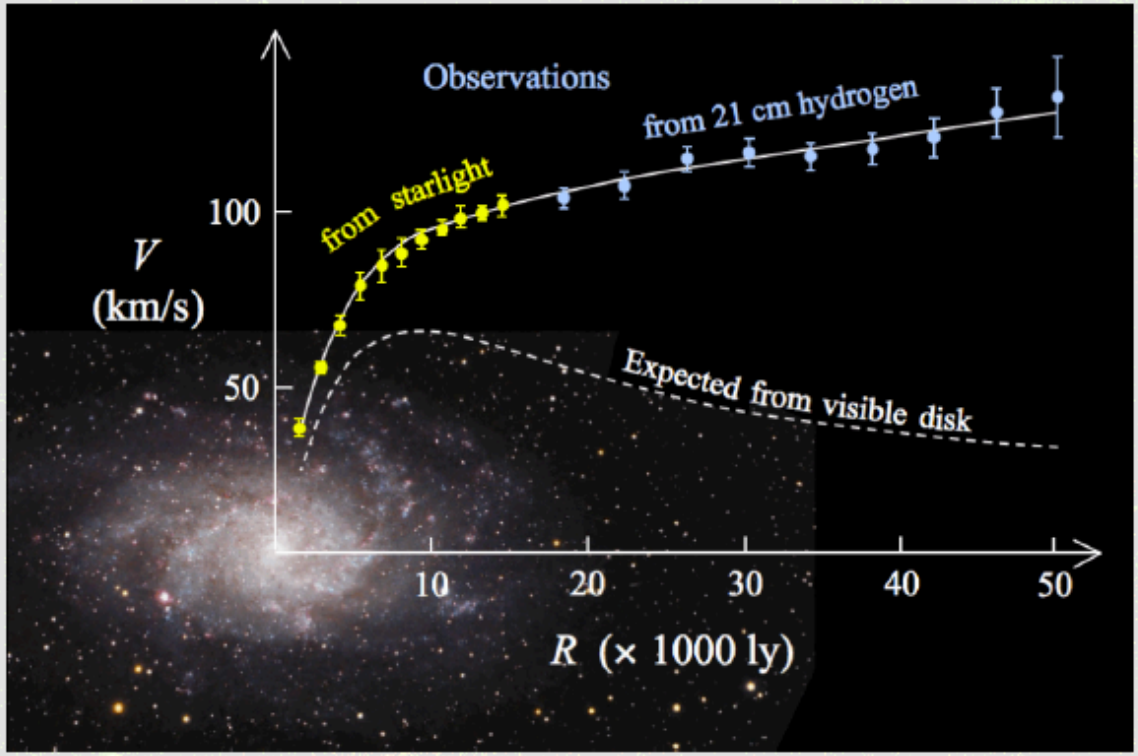


Figure: Galaxy Rotation Problem (in fig. M33): mass inferred from total brightness is much smaller than that inferred from the stars' velocity.

Same behaviour observed in clusters.
But is it missing matter?

Galaxy Rotation Problem

Bullet cluster

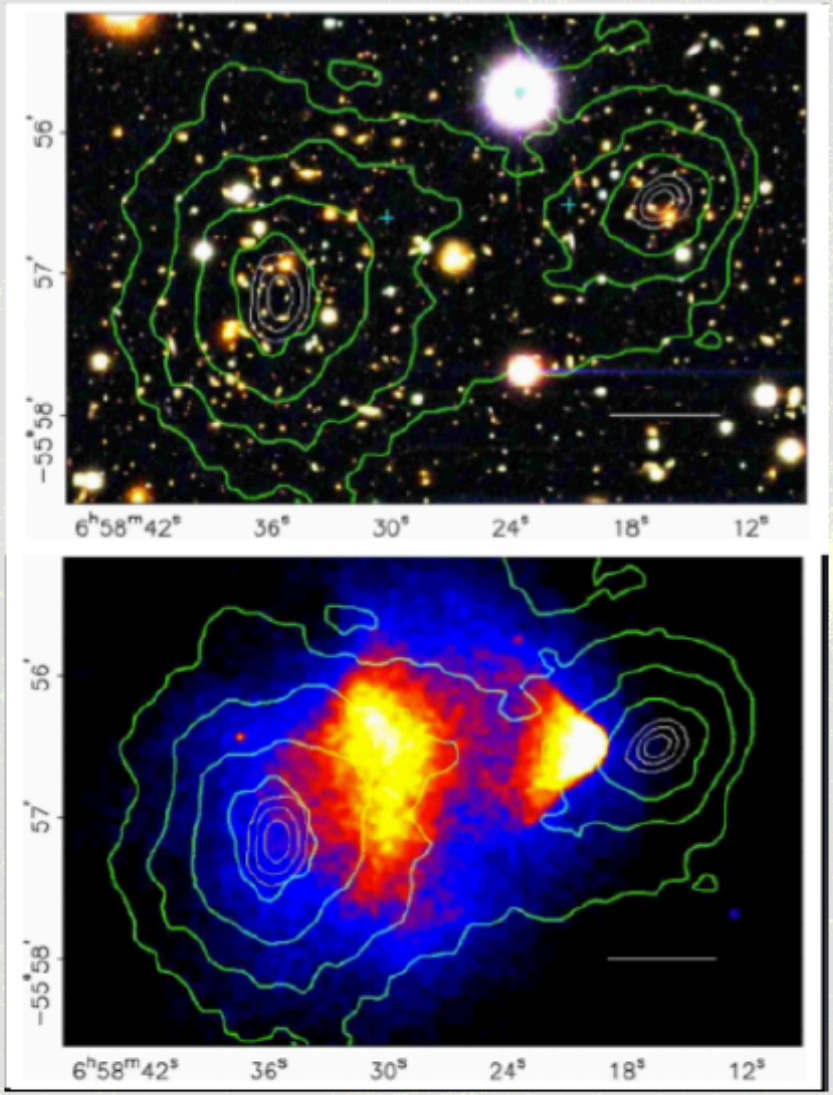
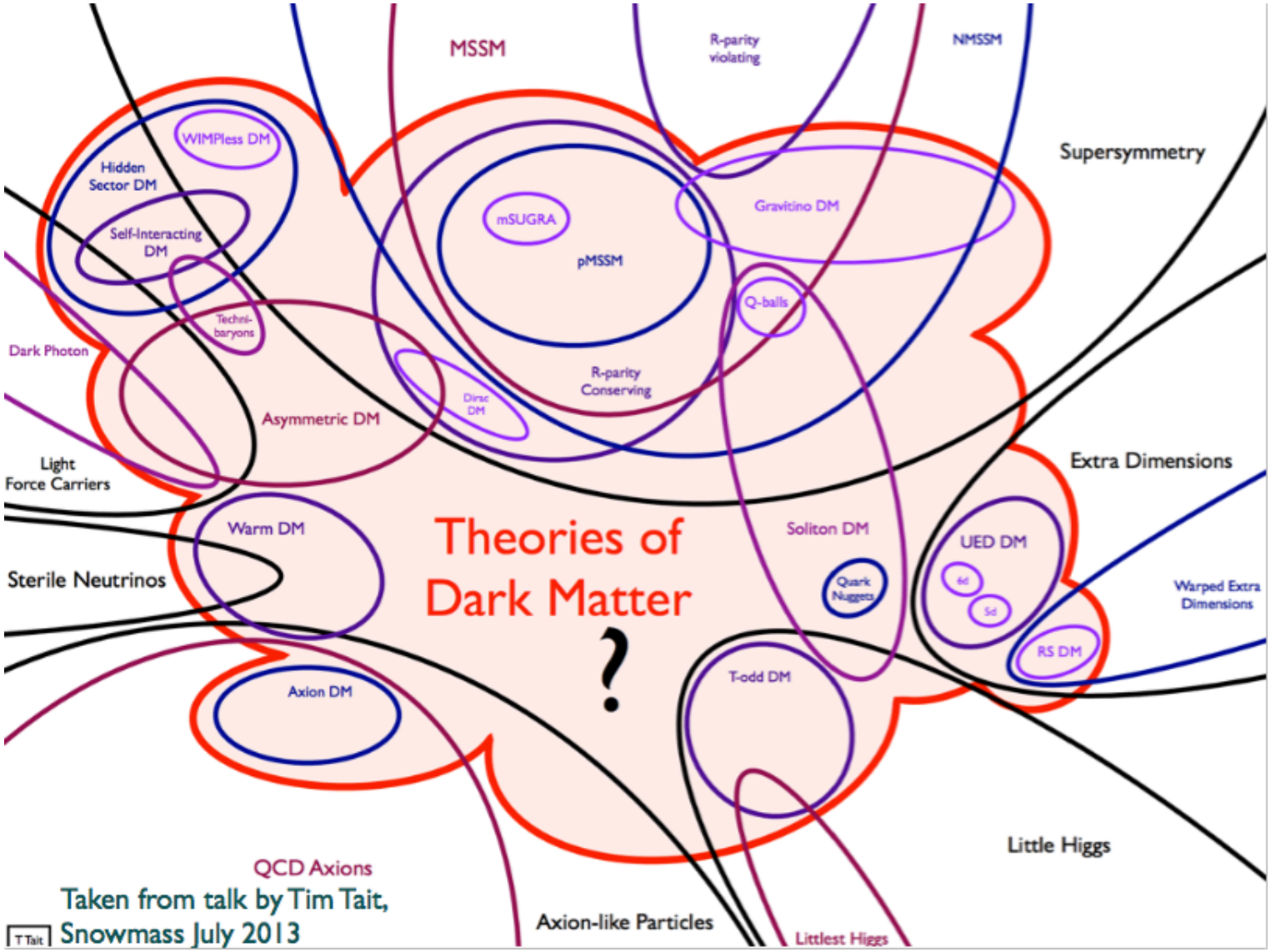


Figure: Clowe et al. (2006). Hot plasma distribution measured by CHANDRA in X-rays. Mass distribution contours from weak gravitational lensing.

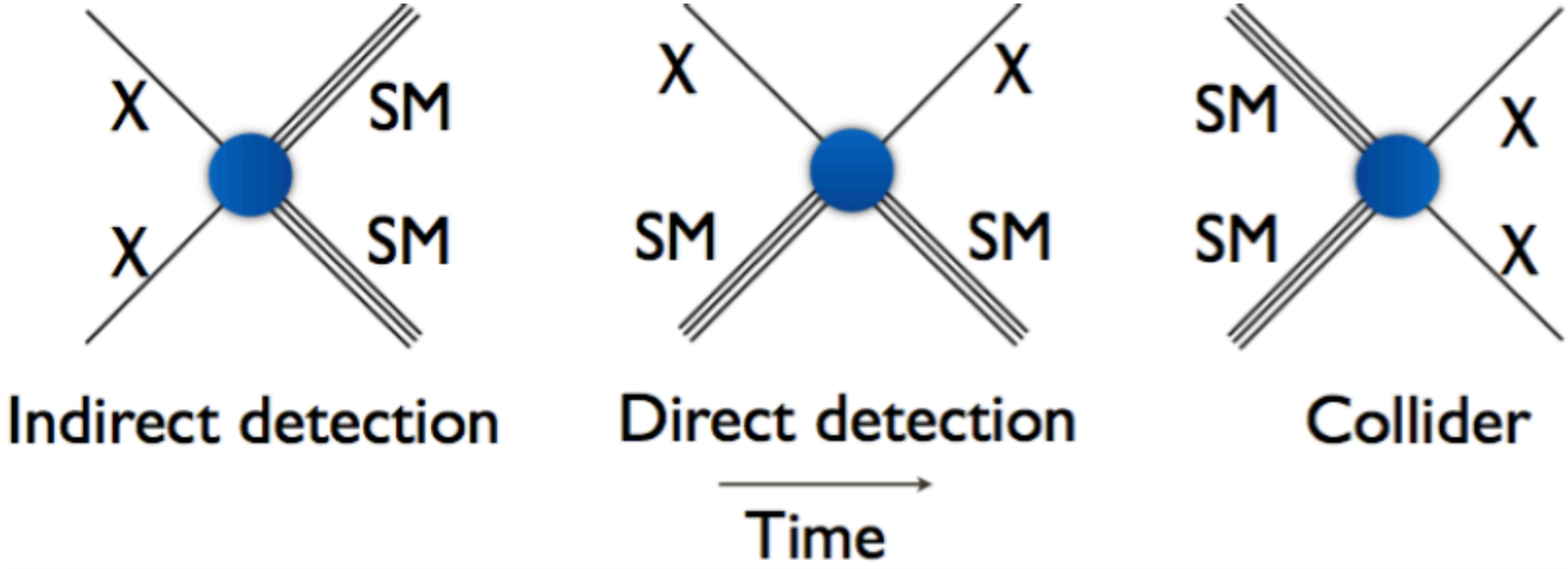
Properties of Dark Matter

- **Stable**: present from early epochs until today.
- **Collisionless**: electromagnetically neutral. If EM interactions occur, they must be very weak.
- **Cold**: non-relativistic, since early epochs.

What is Dark Matter?



How could we observe Dark Matter?



Direct Dark Matter Experiments

Example: LUX (Large Underground Xenon experiment)

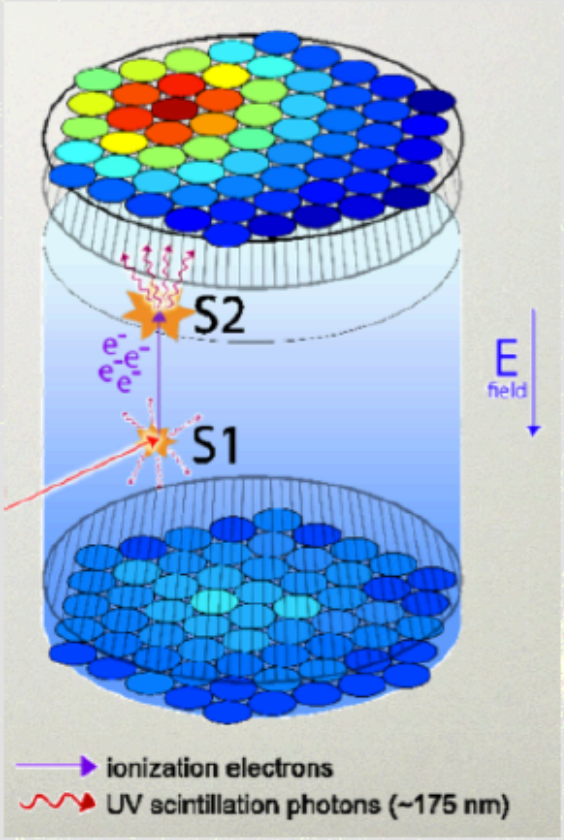
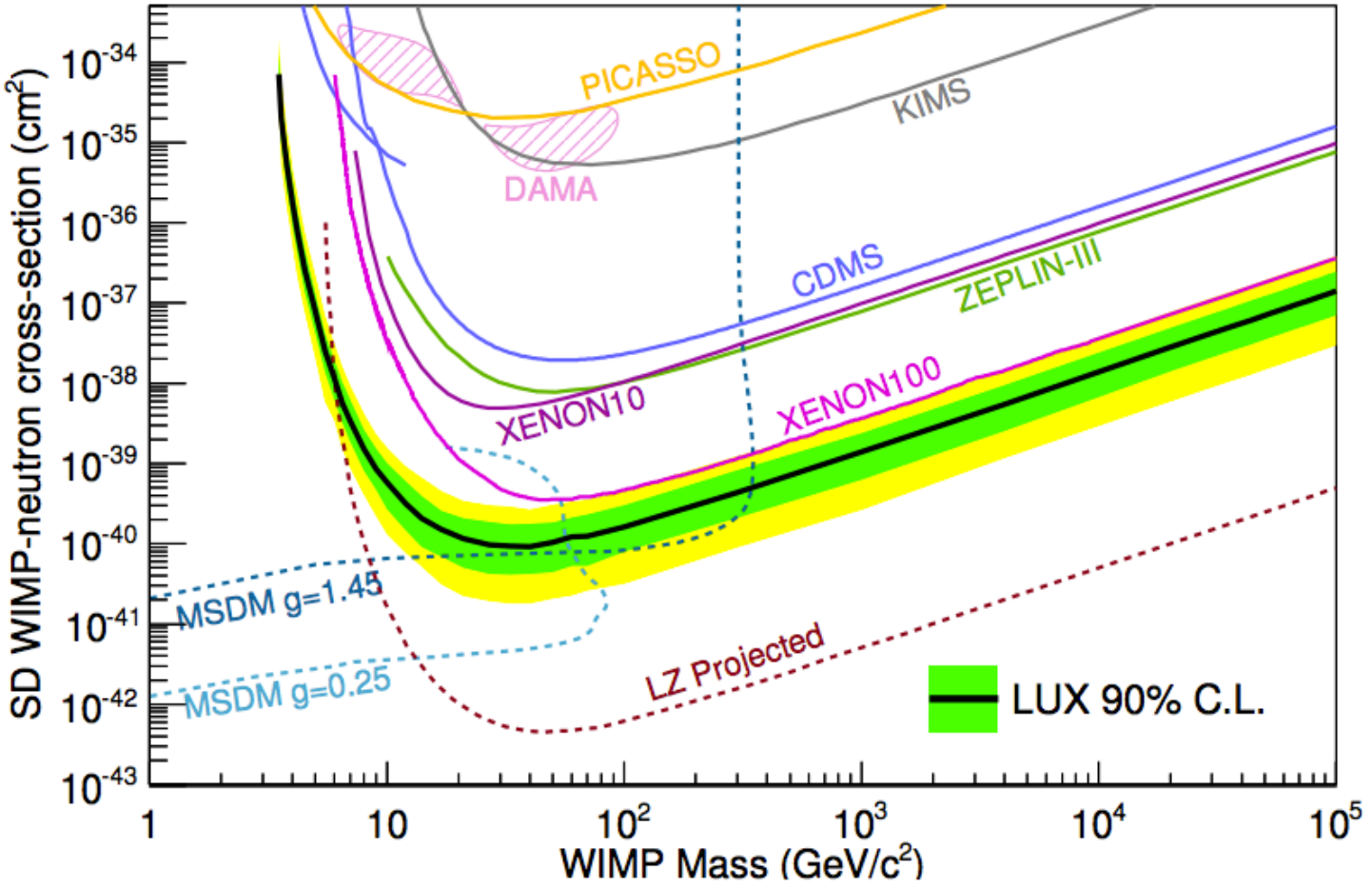


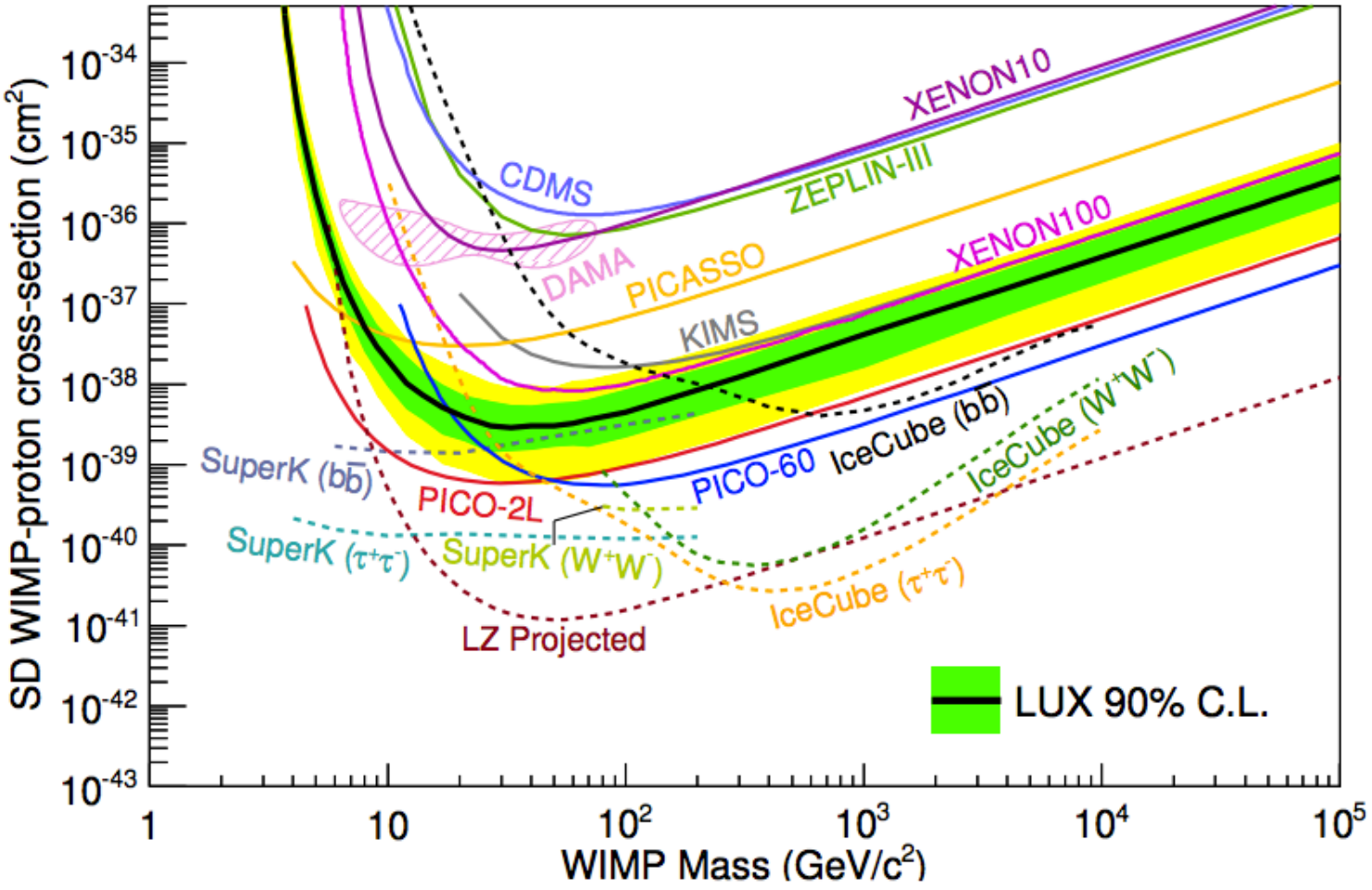
Figure: LUX diagram.
Fine-tuned to detect Weakly Interacting Massive Particles (WIMPs)

- Dual-phase time-projection chamber, liquid-noble DM experiment.
- Photomultiplier sensors on top and bottom.
- buried 1.5 km underground (10^7 reduction in cosmic muon rate). $\approx 125,000 cm^3$
- Supposed WIMP collides with nucleus S1, which scintillates. Electrons are drifted by the applied field to the surface, where liquid Xenon resides. Second scintillation occurs. Time-delay measured between first and second scintillation.
- multiple scatter detection possible

WIMP-neutron cross-section



WIMP-proton cross-section



Complete picture

For WIMPs...

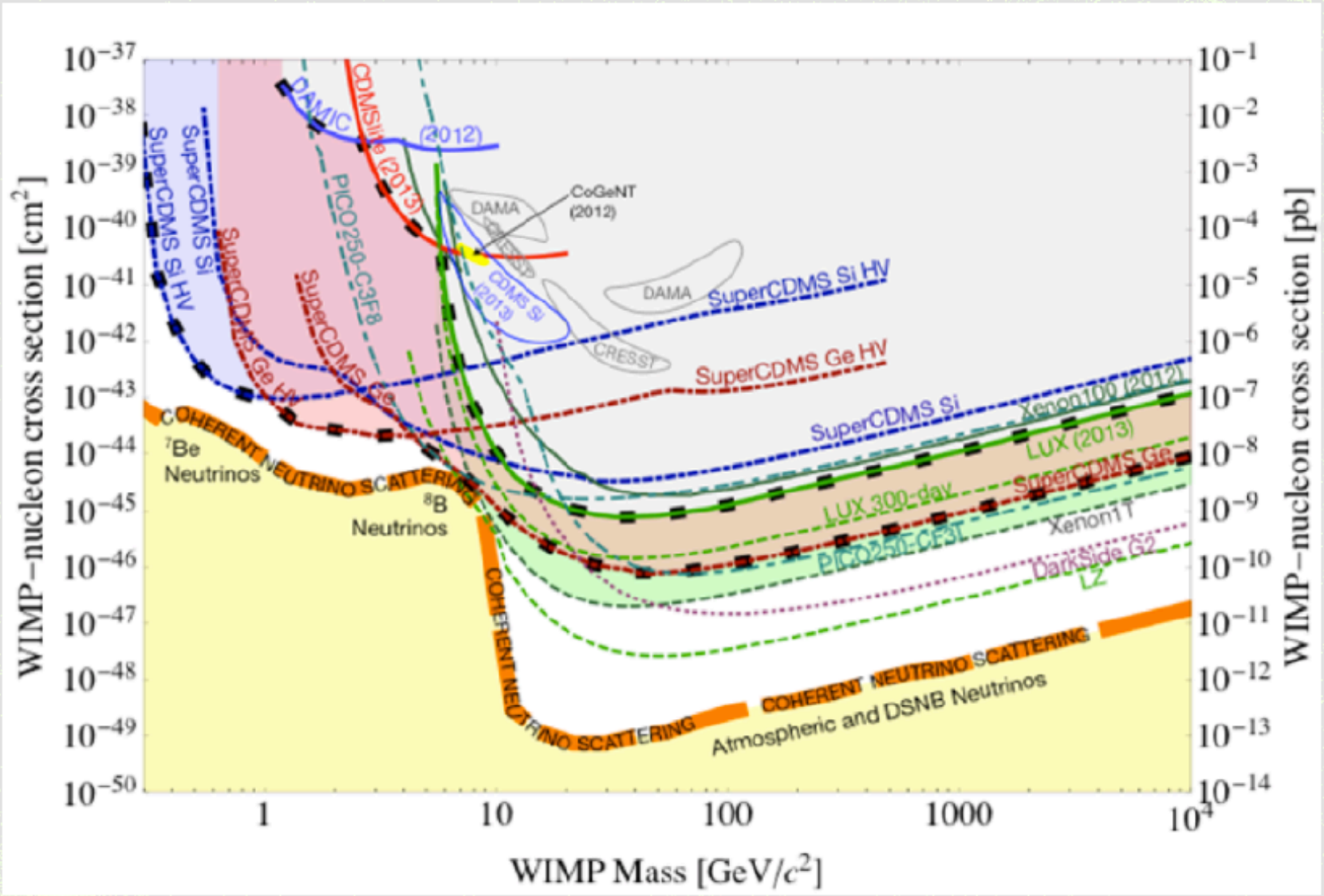
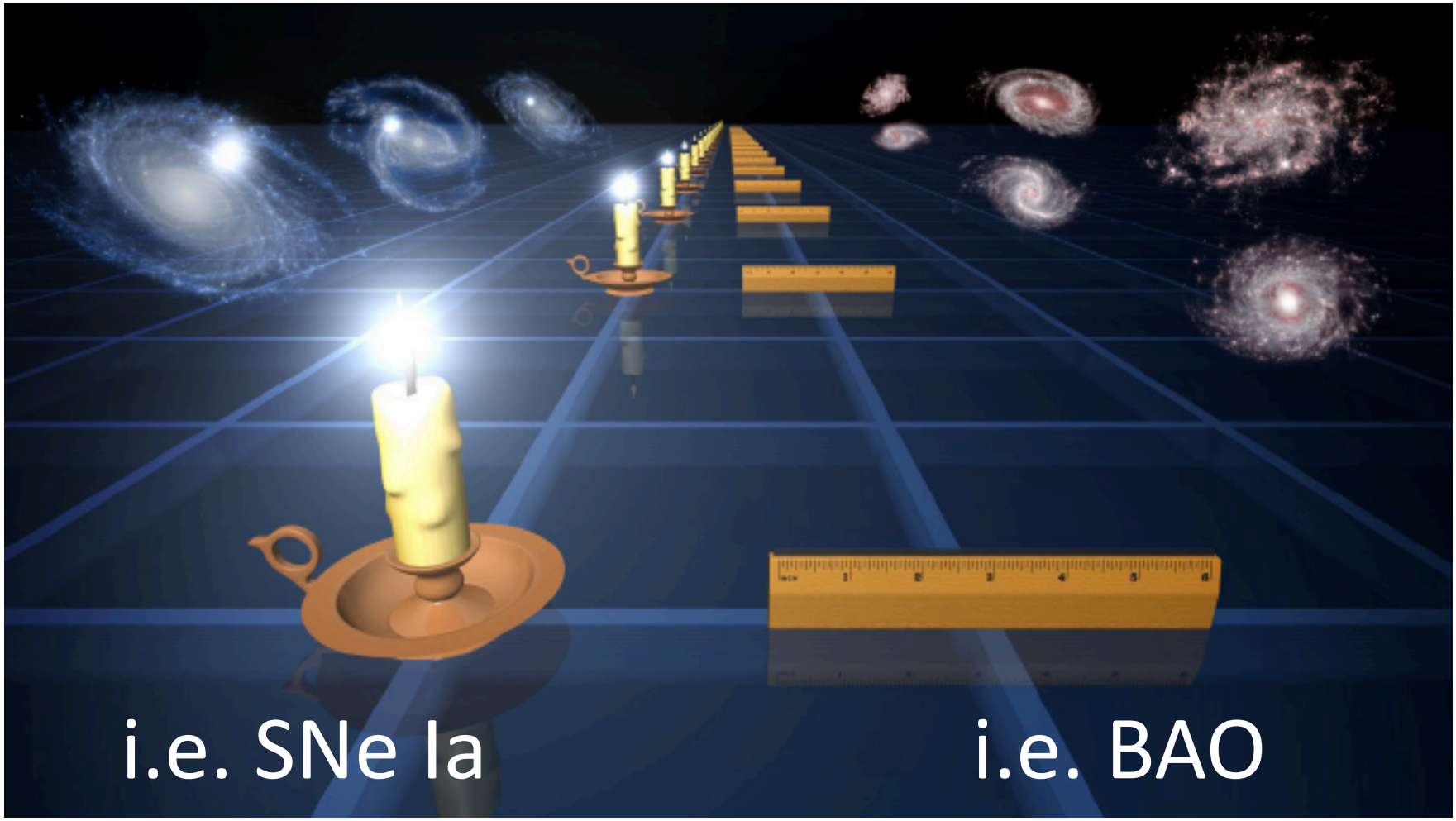
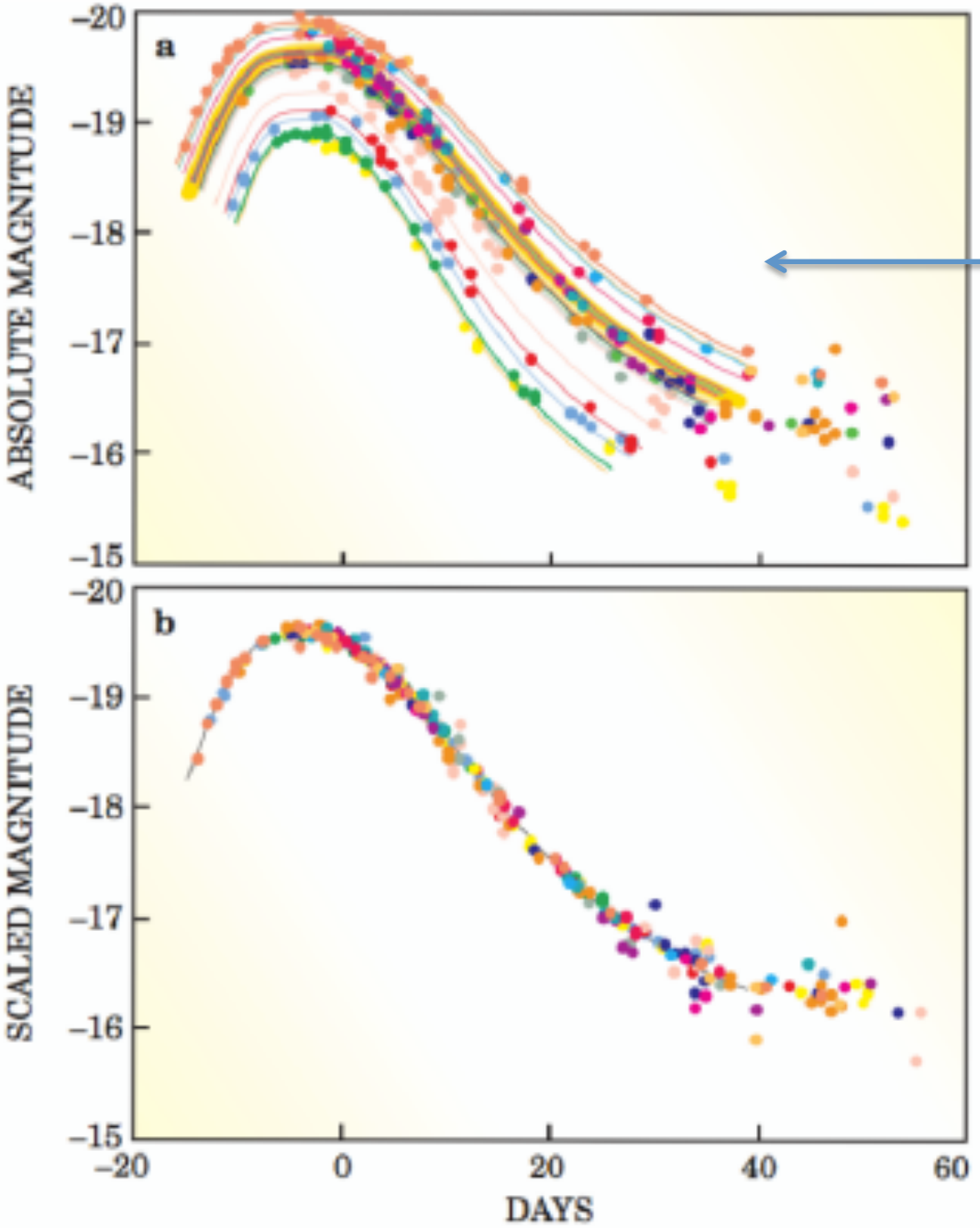


Figure: Berkeley Workshop on Dark Matter Detection, June 2015. Smaller WIMP masses

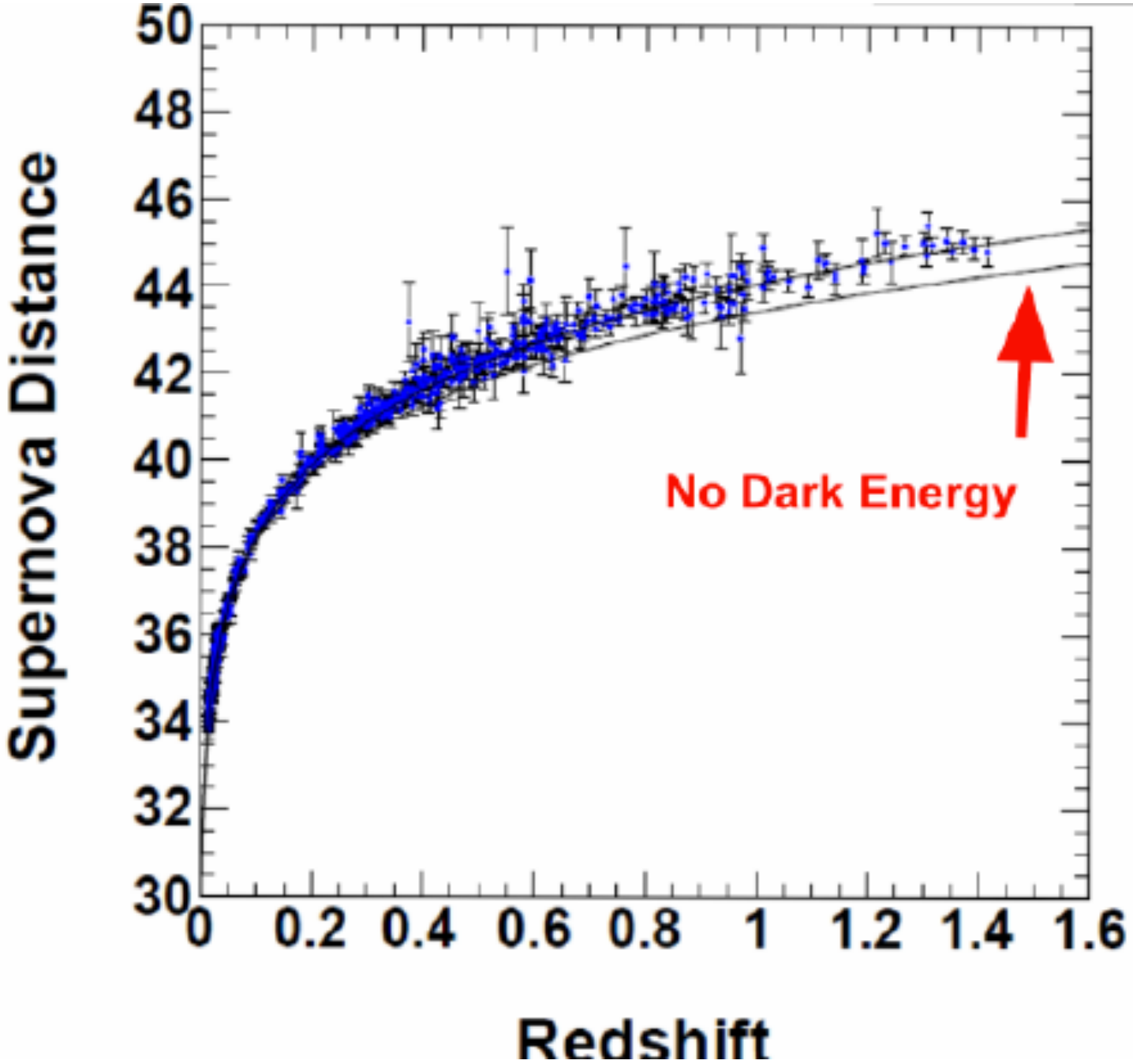
Standard candles & Standard rulers





Light curves

Standardization of SN Ia
Kim et al. (1997)



Supernova distance
Is the
distance modulus
m – M

Redshift is related
To the scale factor
by

$$a = \frac{1}{1+z}$$

i.e.
Gjergo et al. (2013)

Dark Energy

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\sum_i \rho_i = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda a^{-3(1+w)}\right]$$

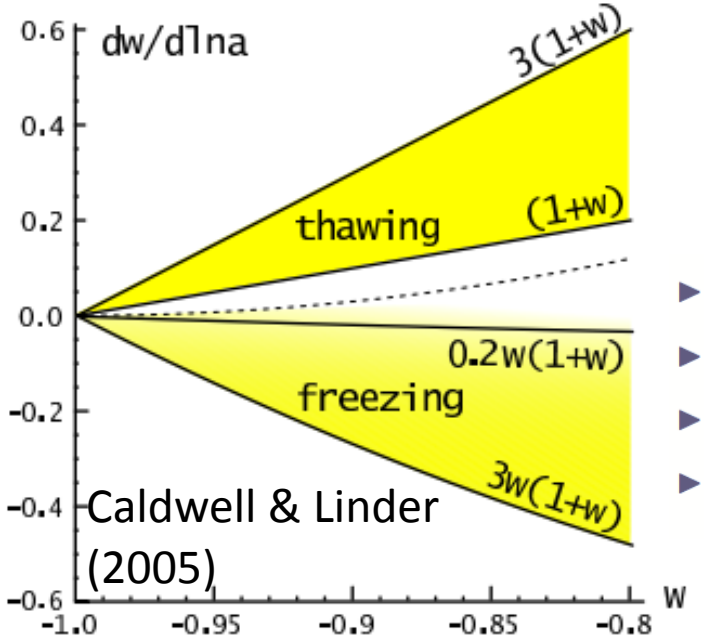
Quintessence

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\left(\sum_i \rho_i + \frac{1}{2c^2}\dot{\phi}^2 + V(\phi)\right)$$

Modified Gravity

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{1}{6}f - \frac{\ddot{a}}{a}f_R + \frac{\dot{a}}{a}\dot{f}_R = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4}\right]$$

$$S = \int d^4x\sqrt{-g}\left[\frac{R + f(R)}{2\kappa^2} + \mathcal{L}_m\right]$$



Caldwell & Linder (2005)

- $V = M^{4-n}\phi^n$ - Thawing behavior
- $V = M^{4+n}\phi^{-n}$ - Freezing behavior
- $V = M^4 cos^2(\phi/2f)$ - Axion-like
- Many others

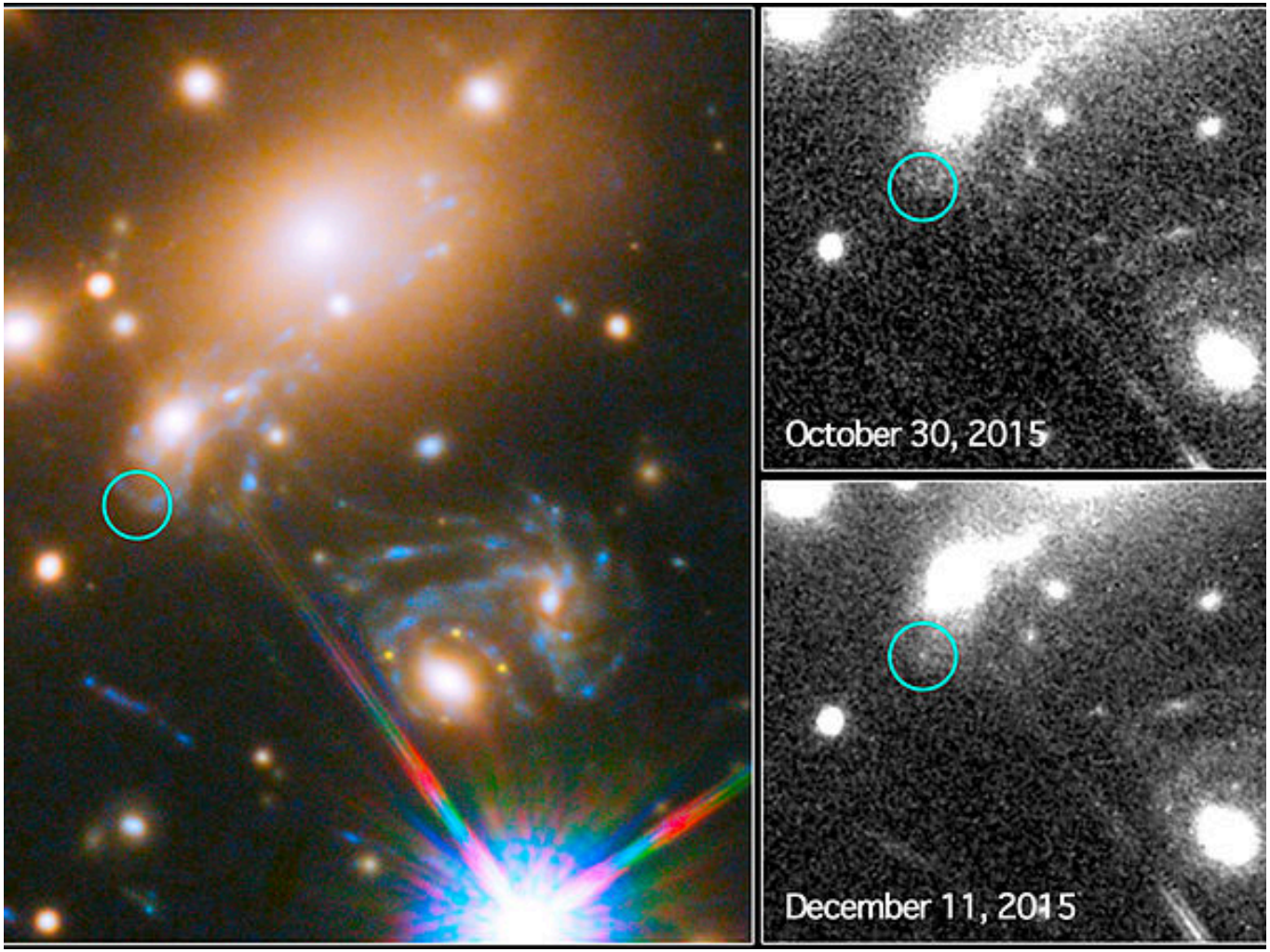
Cosmological Late Time Probes

Probe	Physical Observable
Weak lensing (imaging)	Coherent distortions in galaxy shapes
Large Scale Structure (Spectroscopic)	Power Spectrum of Galaxy Distribution
Galaxy Clusters (Imaging + SZ/X-ray)	Abundance of Massive Clusters
Type Ia supernovae (Imaging + Spectra)	Fluxes of Standard Candles
Strong lensing (Imaging + Spectra)	Time Delays

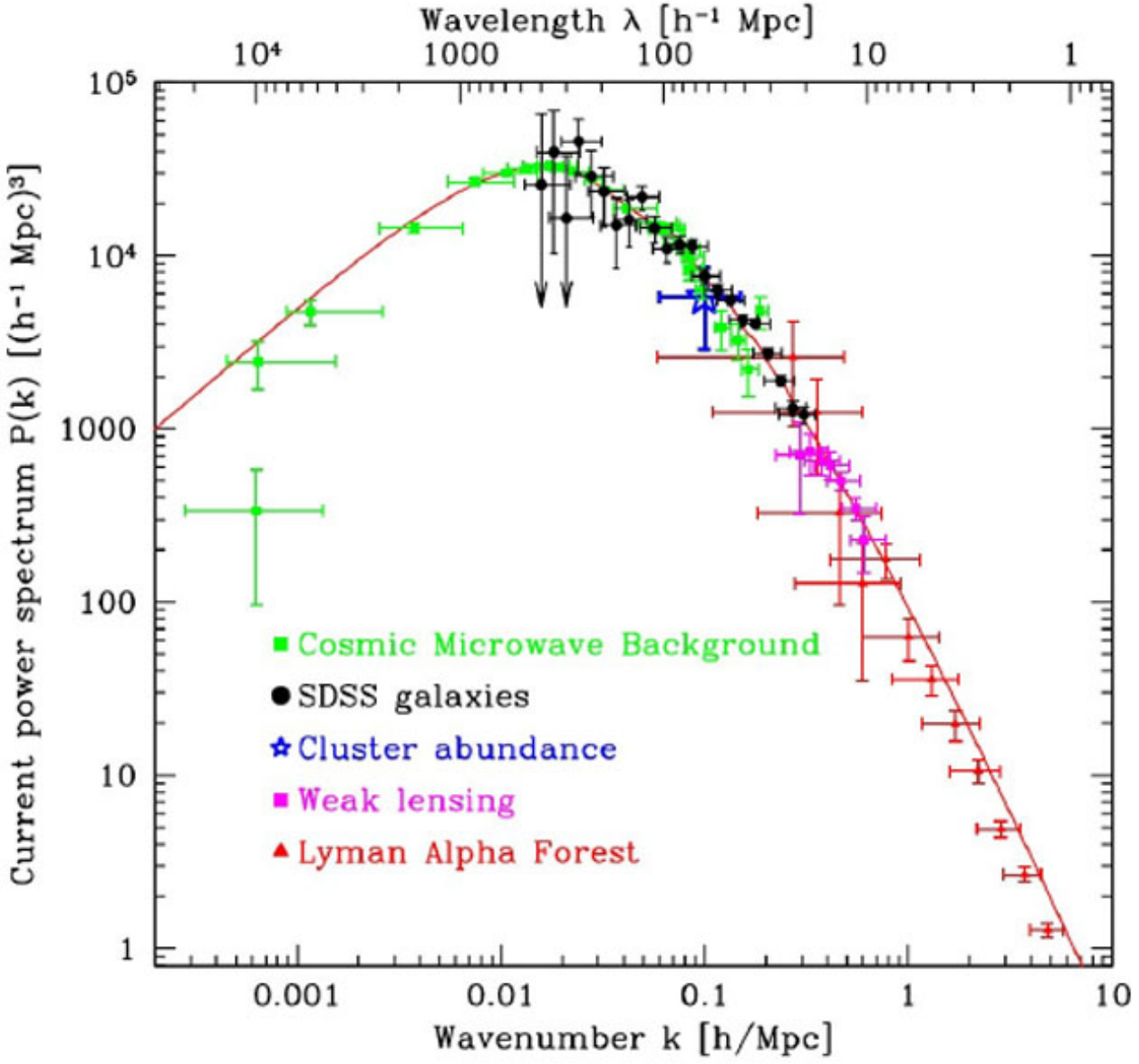
Strong Lensing

- SN Refsdal

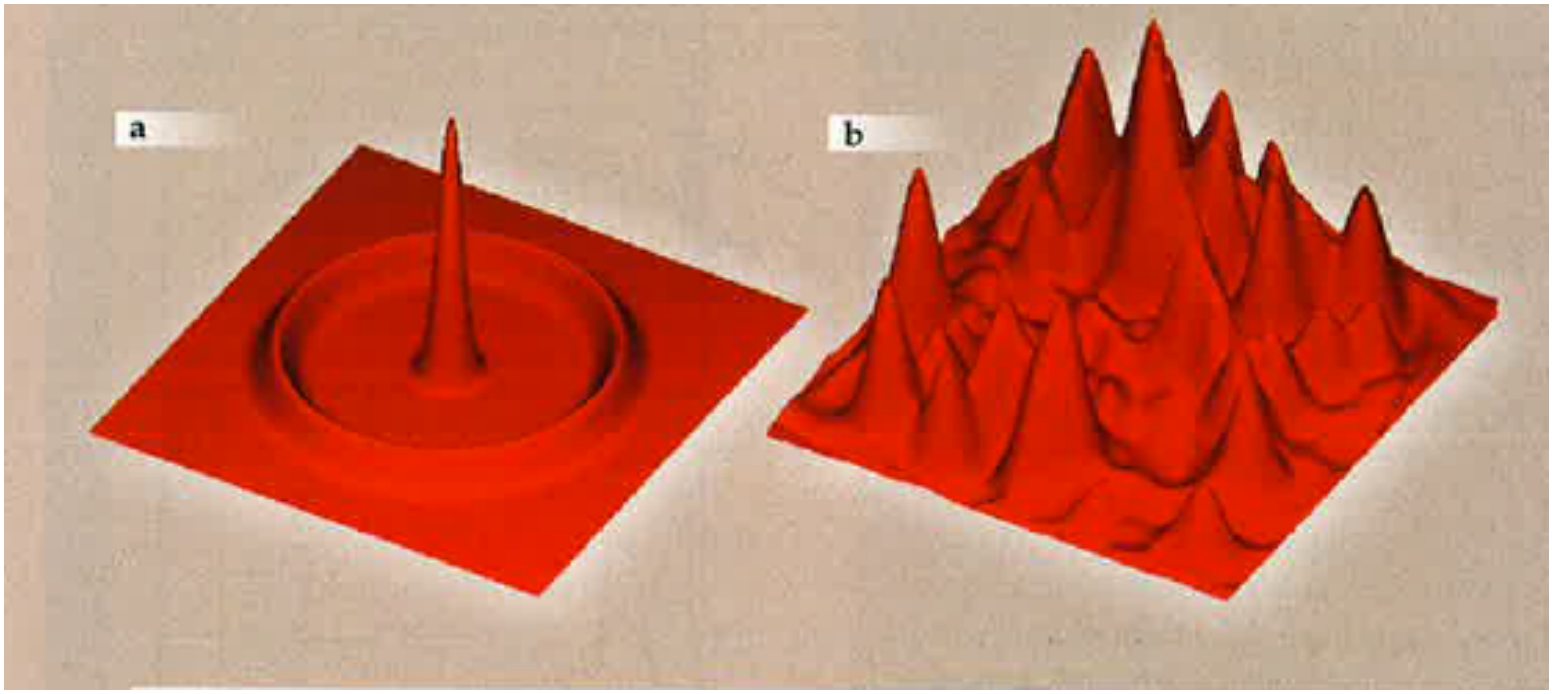
https://www.youtube.com/watch?v=UUMlYBeU4yE



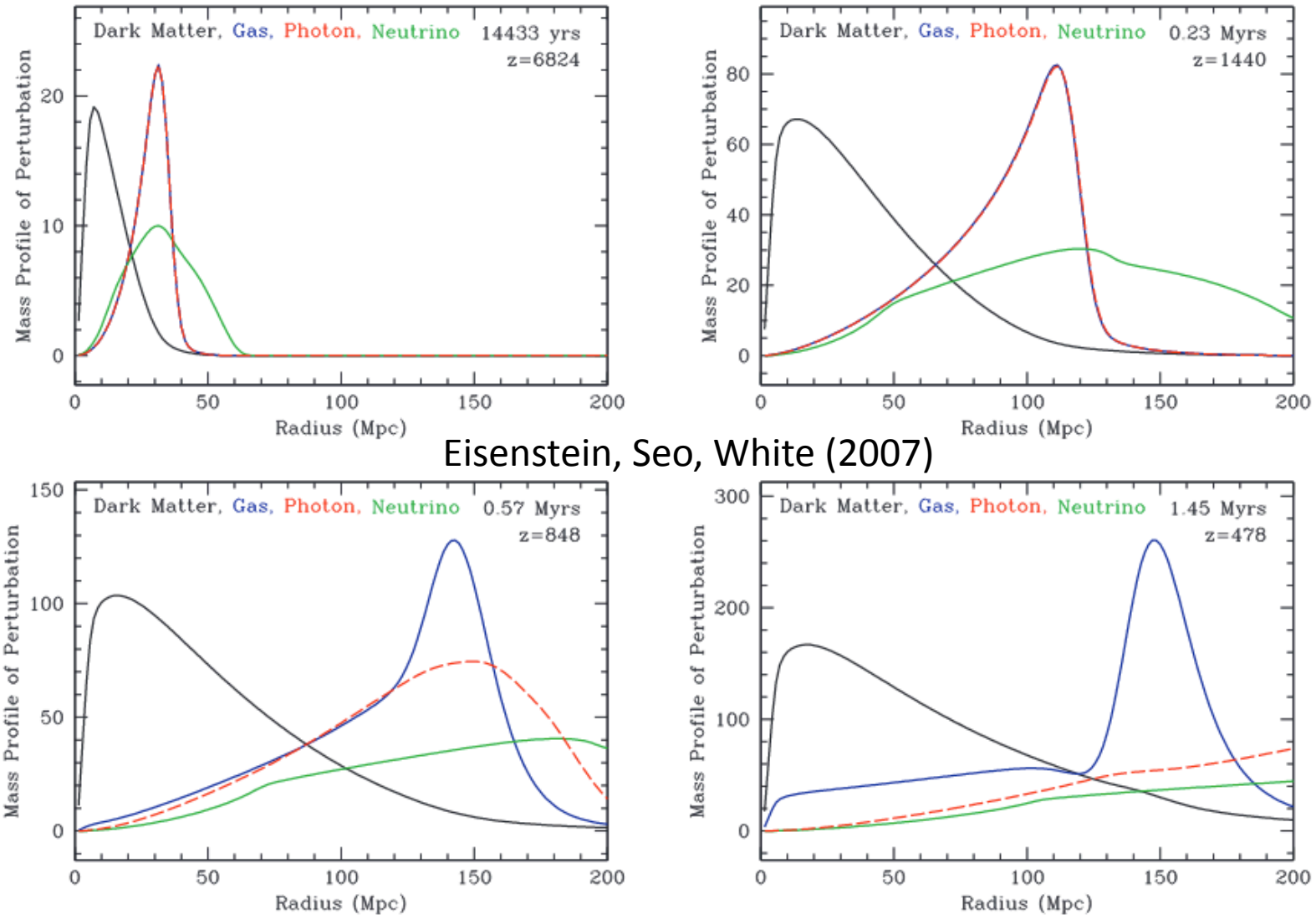
Cluster Power Spectrum



Baryon Acoustic Oscillations from Eisenstein & Bennet, Physics Today, 2008



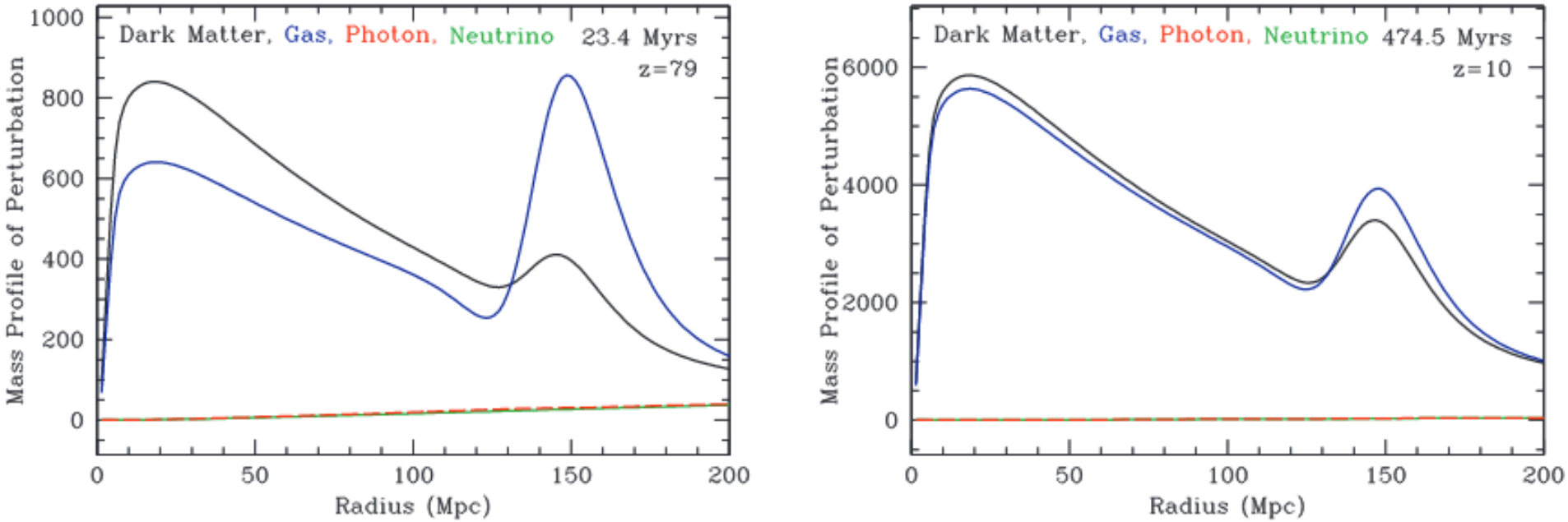
Baryon Acoustic Oscillations



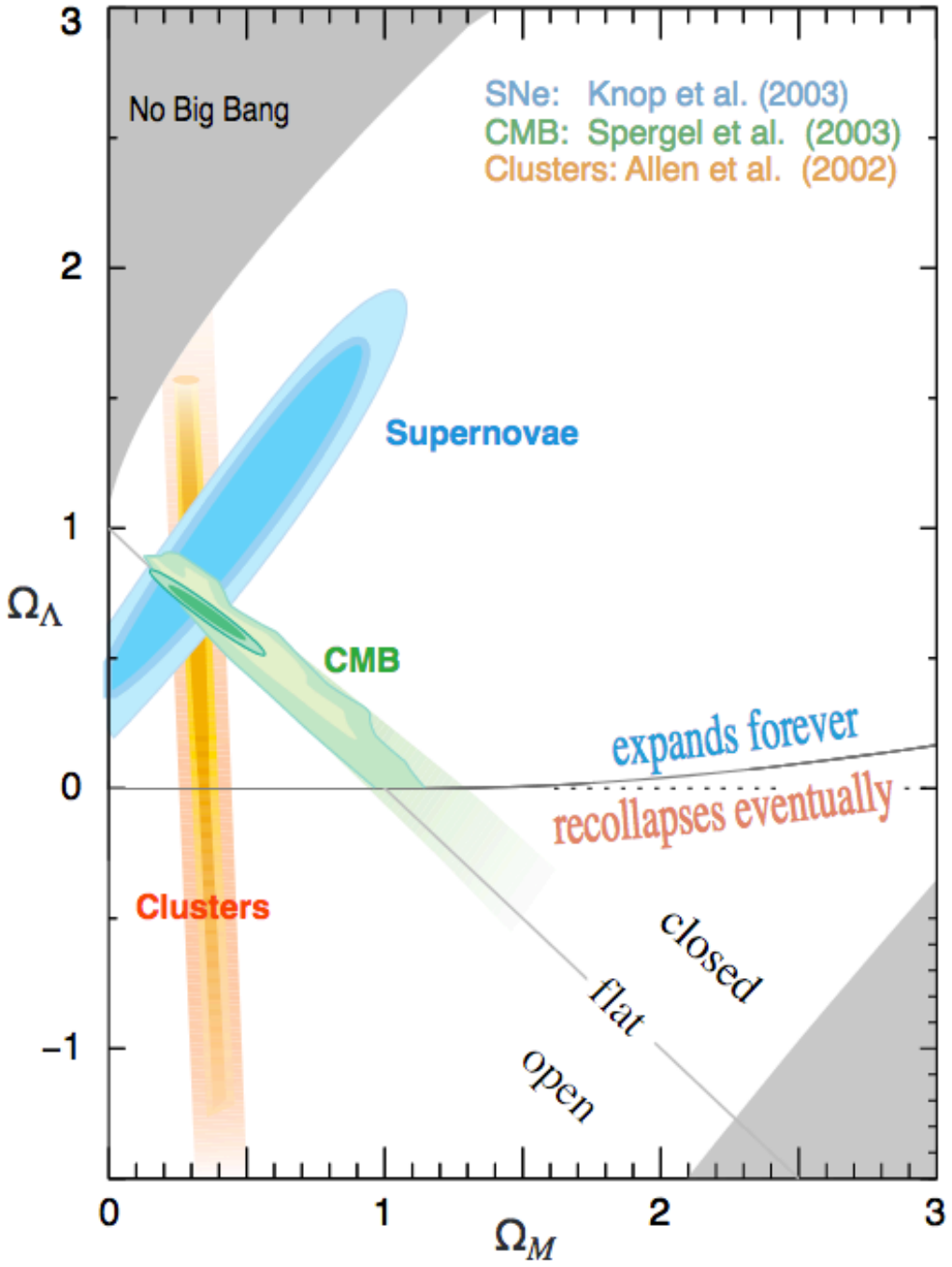
Eisenstein, Seo, White (2007)

Baryon Acoustic Oscillations

Eisenstein, Seo, White (2007)

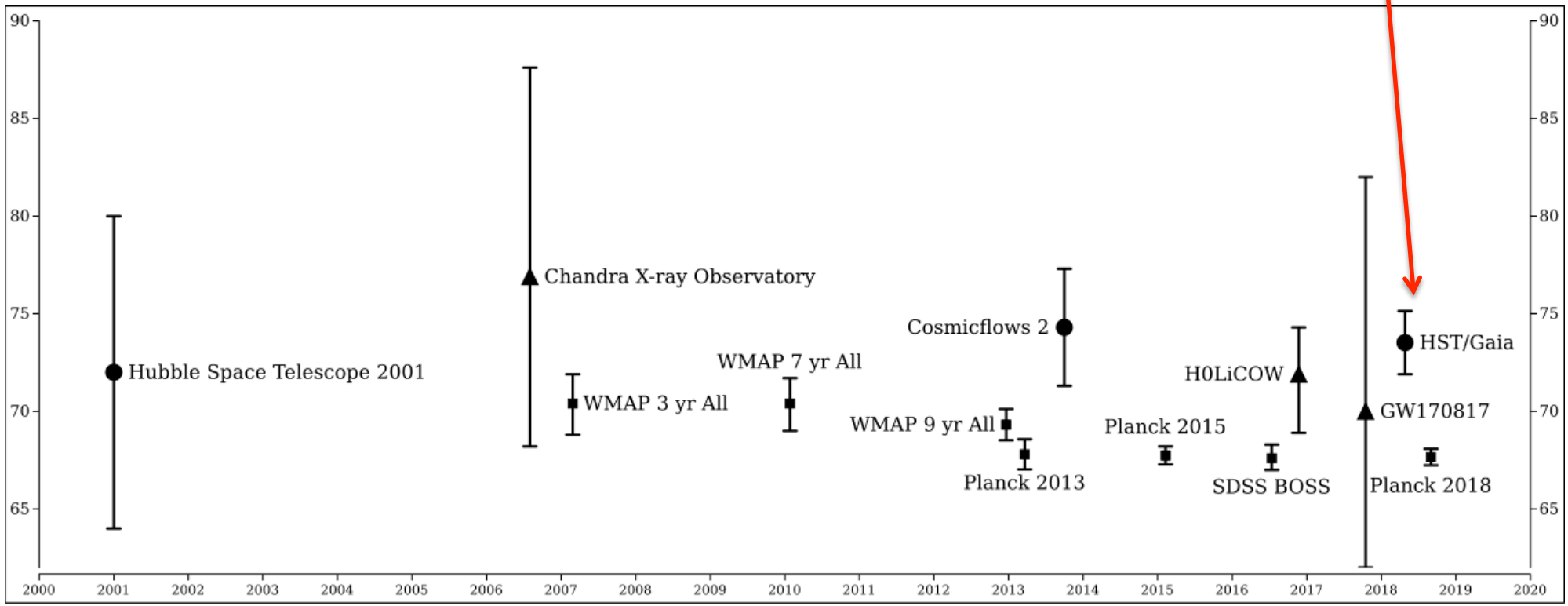


Cosmic Concordance



H_0 through the years

3.6 σ tension between HST/Gaia & Planck



Cosmological Parameters (Tegmark+04)

Parameter	Meaning	Status	Use	Definition
τ	Reionization optical depth	Not optional		
ω_b	Baryon density	Not optional	MCMC	$\omega_b = \Omega_b h^2 = \rho_b/(1.88 \times 10^{-26}\mathrm{kg/m^3})$
ω_d	Dark matter density	Not optional	MCMC	$\omega_d = \Omega_d h^2 = \rho_d/(1.88 \times 10^{-26}\mathrm{kg/m^3})$
f_ν	Dark matter neutrino fraction	Well motivated	MCMC	$f_\nu = \rho_\nu/\rho_d$
Ω_Λ	Dark energy density	Not optional	MCMC	
w	Dark energy equation of state	Worth testing	MCMC	p_Λ/ρ_Λ (approximated as constant)
Ω_k	Spatial curvature	Worth testing		
A_s	Scalar fluctuation amplitude	Not optional		Primordial scalar power at $k = 0.05$/Mpc
n_s	Scalar spectral index	Well motivated	MCMC	Primordial spectral index at $k = 0.05$/Mpc
α	Running of spectral index	Worth testing	MCMC	$\alpha = d\ln n_s/d\ln k$ (approximated as constant)
r	Tensor-to-scalar ratio	Well motivated	MCMC	Tensor-to-scalar power ratio at $k = 0.05$/Mpc
n_t	Tensor spectral index	Well motivated	MCMC	
b	Galaxy bias factor	Not optional	MCMC	$b = [P_{\mathrm{galaxy}}(k)/P(k)]^{1/2}$ (assumed constant for $k < 0.2h$/Mpc)
z_{ion}	Reionization redshift (abrupt)			$z_{\mathrm{ion}} \approx 92(0.03h\tau/\omega_b)^{2/3}\Omega_m^{1/3}$ (assuming abrupt reionization; [37])
ω_{m}	Physical matter density		Fits	$\omega_{\mathrm{m}} = \omega_b + \omega_d = \Omega_m h^2$
Ω_m	Matter density/critical density			$\Omega_m = 1 - \Omega_\Lambda - \Omega_k$
Ω_{tot}	Total density/critical density			$\Omega_{\mathrm{tot}} = \Omega_m + \Omega_\Lambda = 1 - \Omega_k$
A_t	Tensor fluctuation amplitude			$A_t = rA_s$
M_ν	Sum of neutrino masses			$M_\nu \approx (94.4\,\mathrm{eV}) \times \omega_d f_\nu$ [38]
h	Hubble parameter			$h = \sqrt{(\omega_d + \omega_b)/(1 - \Omega_k - \Omega_\Lambda)}$
β	Redshift distortion parameter			$\beta \approx [\Omega_m^{4/7} + (1 + \Omega_m/2)(\Omega_\Lambda/70)]/b$ [39, 40]
t_0	Age of Universe			$t_0 \approx (9.785\ \mathrm{Gyr}) \times h^{-1} \int_0^1 [(\Omega_\Lambda a^{-(1+3w)} + \Omega_k + \Omega_m/a)]^{-1/2} da$ [38]
σ_8	Galaxy fluctuation amplitude			$\sigma_8 = \{4\pi \int_0^\infty [\frac{3}{x^3}(\sin x - x\cos x)]^2 P(k) \frac{k^2 dk}{(2\pi)^3}\}^{1/2}$, $x \equiv k \times 8h^{-1}$Mpc
Z	CMB peak suppression factor		MCMC	$Z = e^{-2\tau}$
A_p	Amplitude on CMB peak scales		MCMC	$A_p = A_s e^{-2\tau}$
Θ_s	Acoustic peak scale (degrees)		MCMC	$\Theta_s(\Omega_k, \Omega_\Lambda, w, \omega_d, \omega_b)$ given by [25]
H_2	2nd to 1st CMB peak ratio		Fits	$H_2 = (0.925\omega_{\mathrm{m}}^{0.18} 2.4^{n_s-1})/[1 + (\omega_b/0.0164)^{12\omega_{\mathrm{m}}^{0.52}})]^{0.2}$ [25]
H_3	3rd to 1st CMB peak ratio		Fits	$H_3 = 2.17[1 + (\omega_b/0.044)^2]^{-1}\omega_{\mathrm{m}}^{0.59} 3.6^{n_s-1}/[1 + 1.63(1 - \omega_b/0.071)\omega_{\mathrm{m}}]$
A_*	Amplitude at pivot point		Fits	$A_* = 0.82^{n_s-1} A_p$

Preliminary results

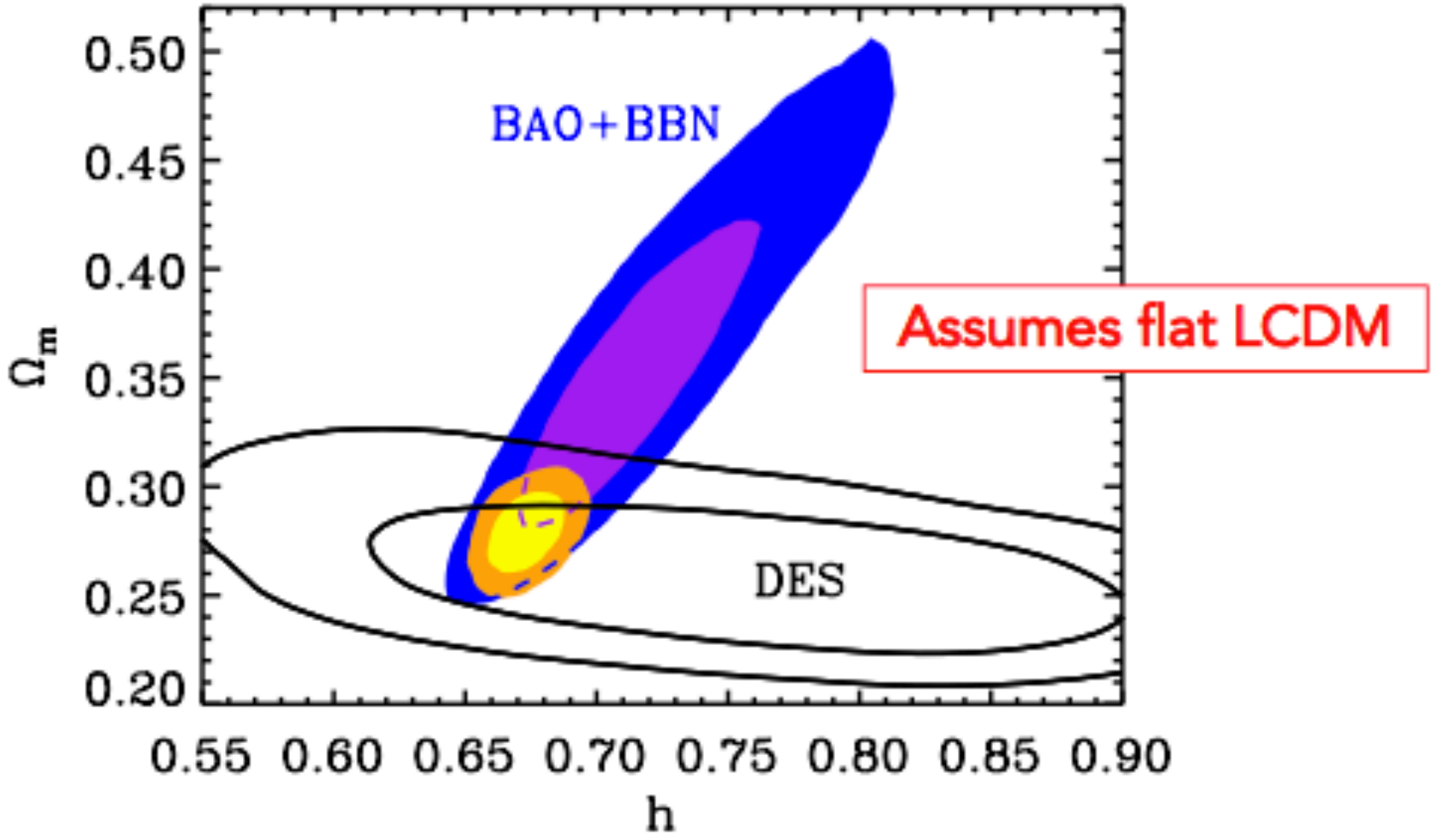
- From the workshop
  The Future of H_0: Crisis or Concordance? – Chicago, IL

Lloyd talk

- Does not seem like it's systematics in the distance ladder. The astronomers seem to be making a strong case for H0 of around 73 or 74.

- It's not cosmology at z < 1100: only way to get sound horizon down (to agree with Cepheids+SNe+BAO inference of sound horizon) is to change physics while there is a plasma to support propagation of sound waves.

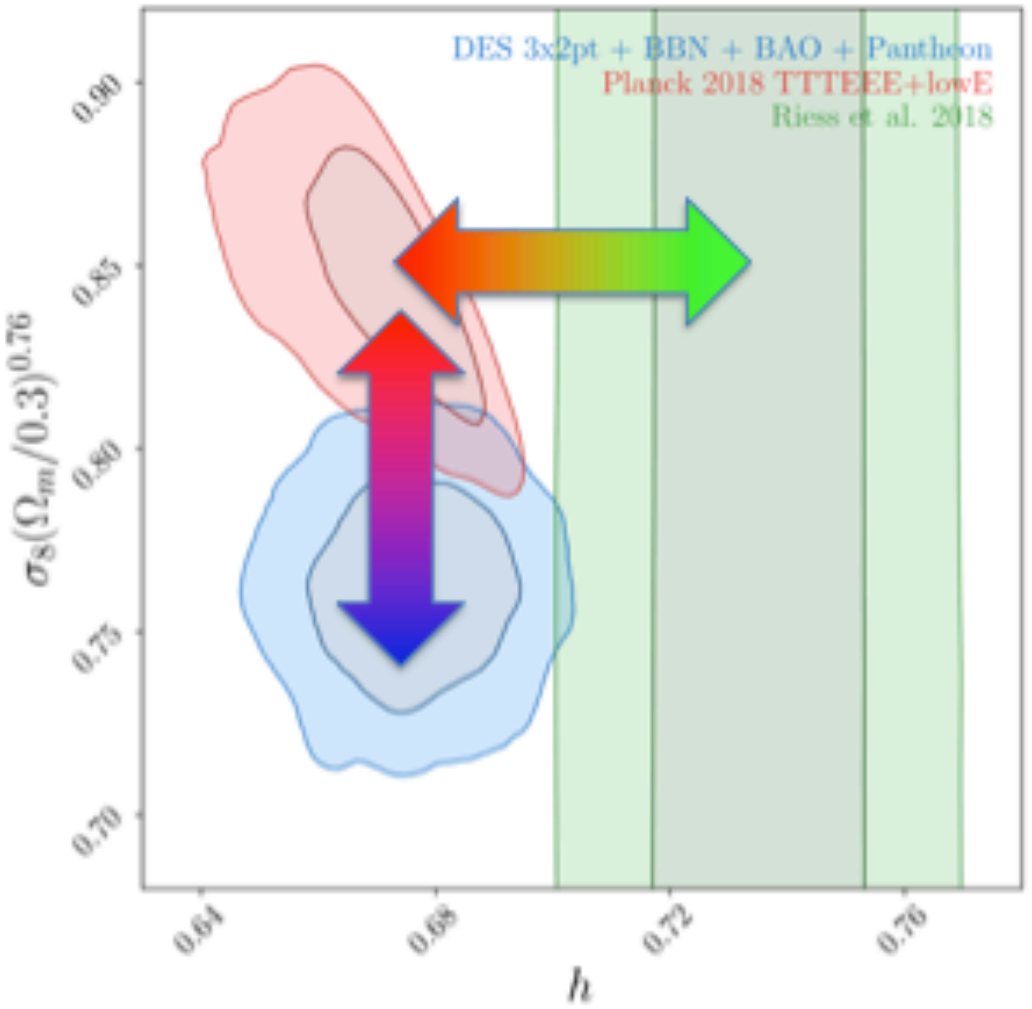
$$H_0 = 67.4^{+1.1}_{-1.2}\ \text{km/s/Mpc}$$



Rozo talk

Dark Energy Survey Year 1 Results: 1711.00403

These Tensions Are Not Related!

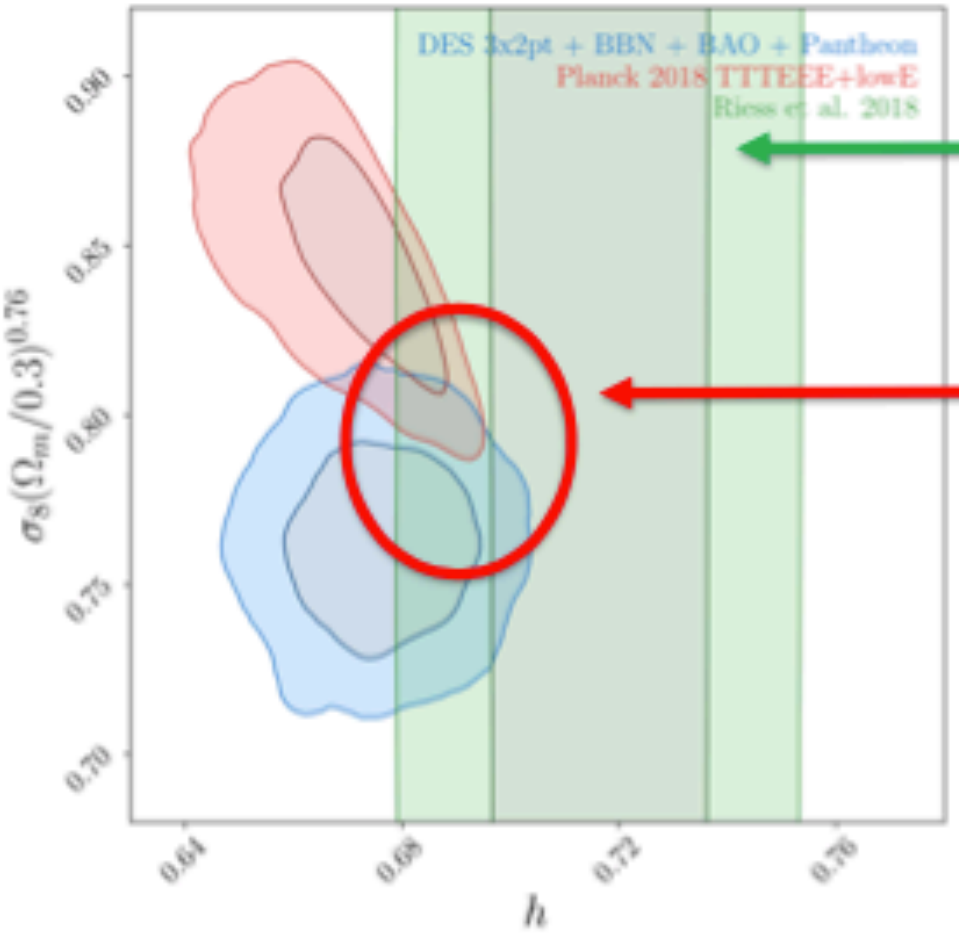


Rozo talk

Preliminary

Park and Rozo, in prep.

If I Were a Betting Man…



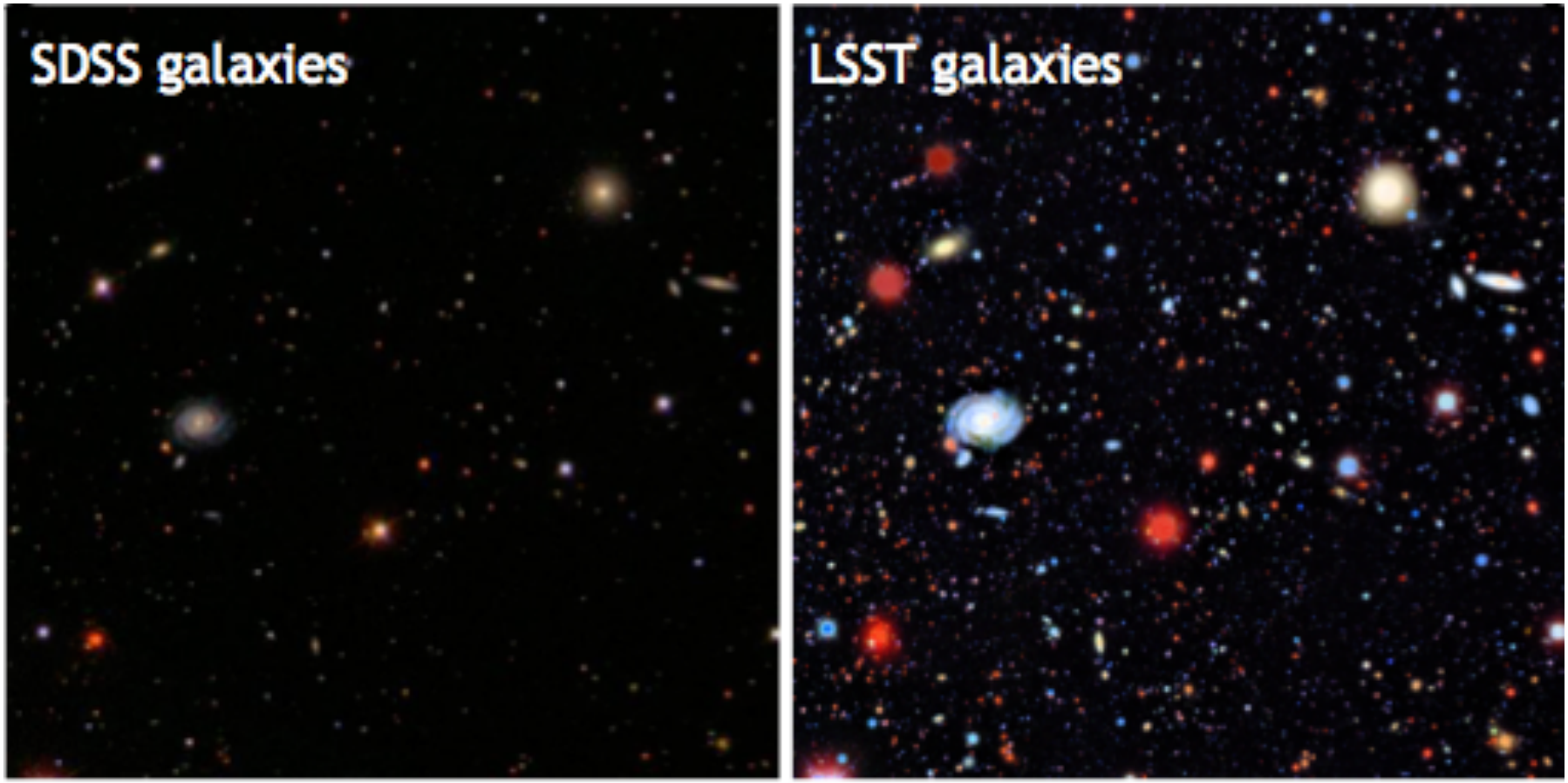
- Distance ladder with maser+LMC only.
- This region looks pretty good!
- Alternative is breaking LCDM in two different places!

Preliminary

Rozo talk

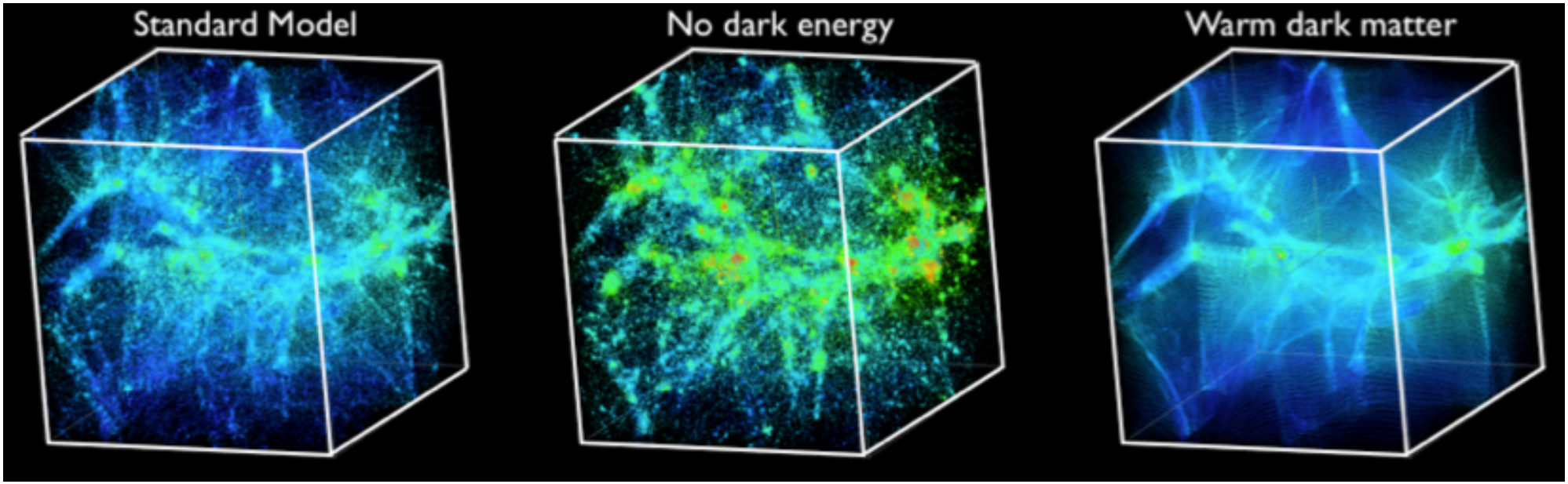
Park and Rozo, in prep.

LSST



Credit: Katrin Heitmann, Argonne National Lab

Usefulness of numerical simulations

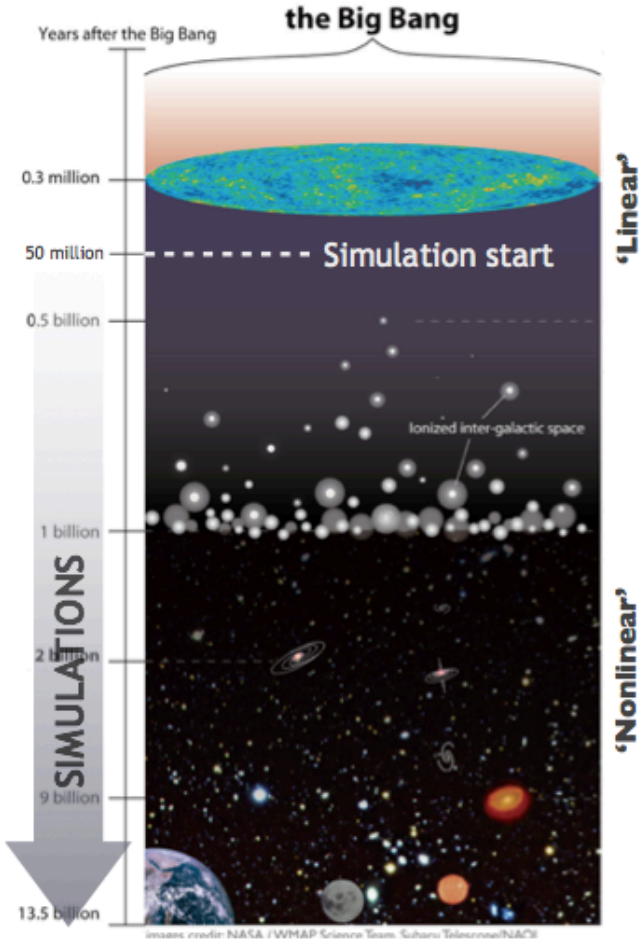


Millennium Simulation (Springel+05)

Simulations including Baryon Physics

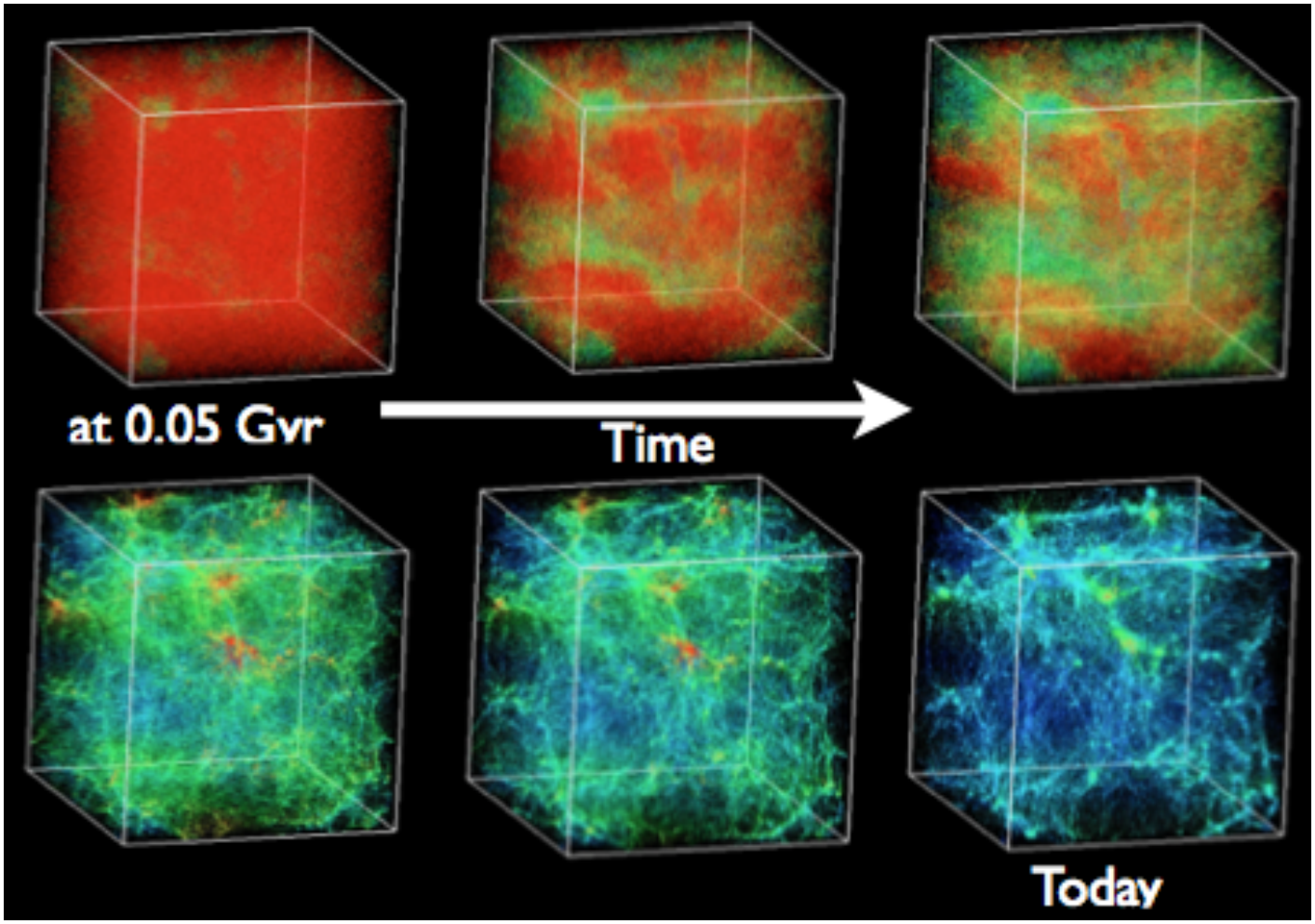
Cosmological Simulations

- **Solid understanding of structure formation; success underpins most cosmic discovery**
  - Initial conditions determined by primordial fluctuations, measured from the cosmic microwave background
  - Initial perturbations amplified by gravitational instability in a dark matter-dominated Universe
  - Relevant theory is gravity, field theory, and atomic physics ('first principles')
- **Early Universe:** Linear perturbation theory very successful (CMB)
- **Latter half of the history of the Universe:** Nonlinear domain of structure formation, impossible to treat without large-scale computing

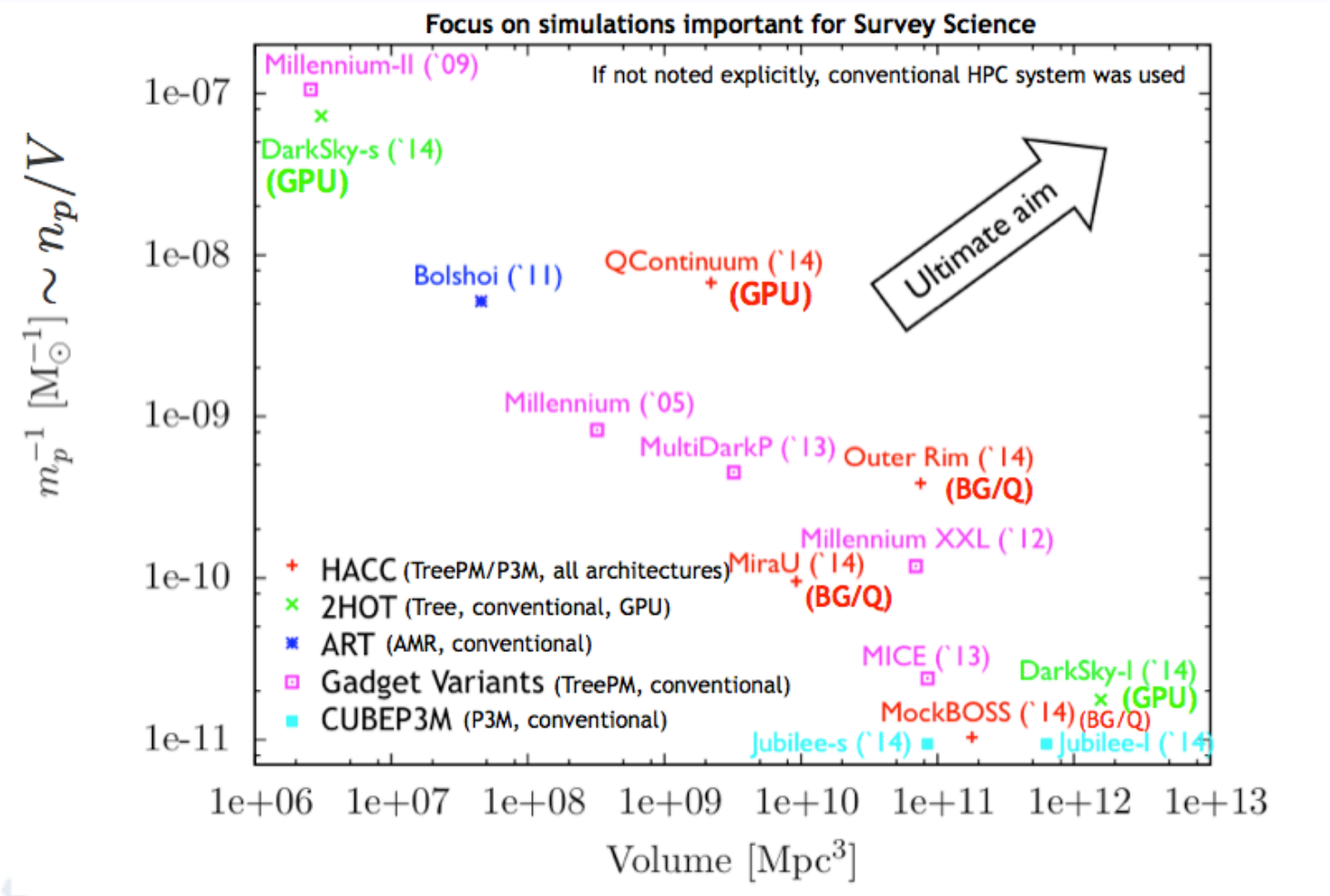


Credit: LSST DESchool

Time evolution of simulations



Current state of the art simulations



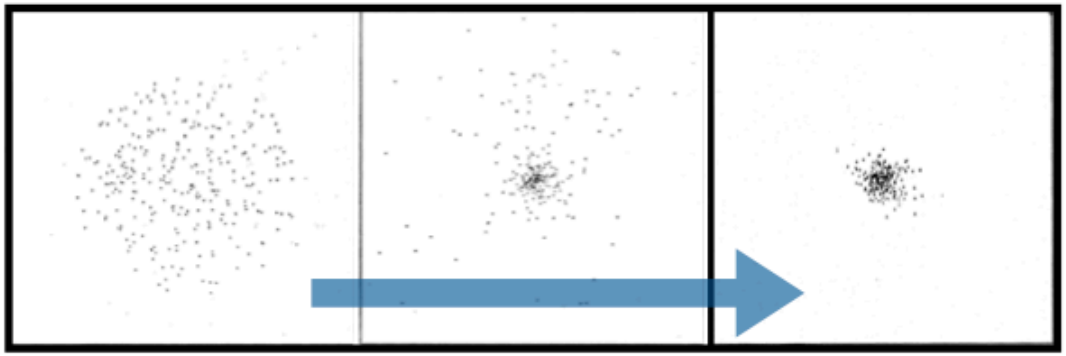
First cosmological simulation

ASTRONOMICAL JOURNAL VOLUME 75, NUMBER 1 FEBRUARY 1970

Structure of the Coma Cluster of Galaxies*

P. J. E. Peebles†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 7 October 1969)

In some cosmologies, a cluster of galaxies is imagined to be a gravitationally bound system which, in analogy with the formation of the Galaxy, originated as a collapsing protocluster. It is shown that a numerical model based on this picture is consistent with the observed features of the Coma Cluster of galaxies. The cluster mass derived from this model agrees with previous values; however, an analysis of the observational uncertainty within the framework of the model shows that the derived mass could be consistent with the estimated total mass provided by the galaxies in the cluster.



His Acknowledgement: The lengthy numerical computations were made possible through the generous hospitality of the Los Alamos Scientific Laboratory.

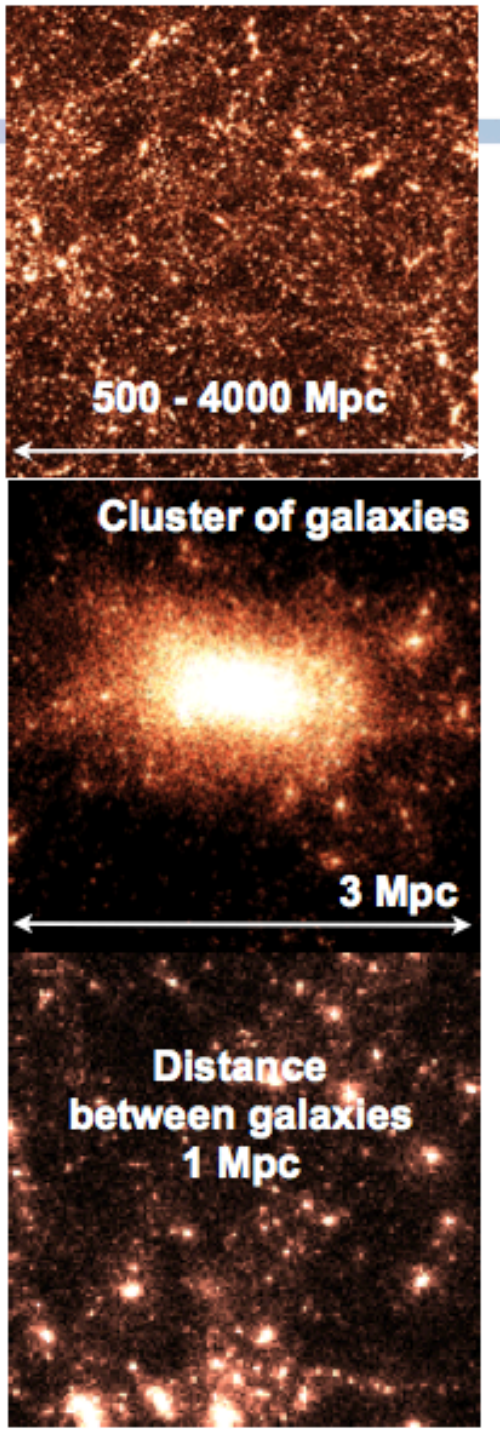
- Suite of 300 particle simulations
- Run on a CDC 3600, ~1Mflops*, 32KB+ memory at Los Alamos
- Is 9 orders of magnitude in improvement in both performance and memory enough for precision cosmology?

* Today's laptop is ~1000 faster

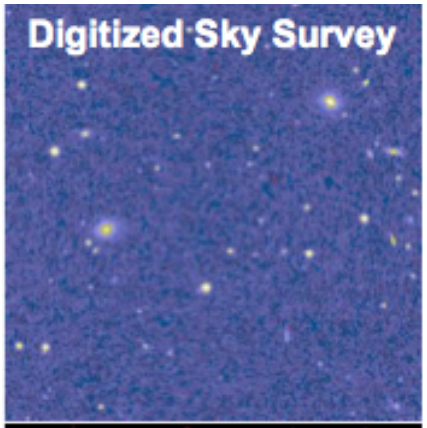
LSST DESC

Simulating Surveys

- **Simulation Volume:** Large survey sizes impose simulation volumes ~(4 Gpc)^3, memory required ~100TB - 1PB
- **Number of Particles:** Mass resolution depends on ultimate object to be resolved, $\sim 10^8 M_\odot - 10^{10} M_\odot$ (subhalos to halos), N~$10^{11} - 10^{12}$
- **Easy to remember:** ~(1000 Mpc)^3 and ~(1000)^3 particles lead to a mass resolution of $\sim 10^{11} M_\odot$
- **Therefore:** ~(10,000)^3 particles in ~(1000 Mpc)^3 leads to $\sim 10^8 M_\odot$, (5Gpc)^3 at this mass resolution would require 125 trillion particles = 5PB per snapshot! (Mira has 0.75PB overall, biggest DOE open machine)
- **Force Resolution:** ~kpc, yields a (global) spatial dynamic range of ~10^6

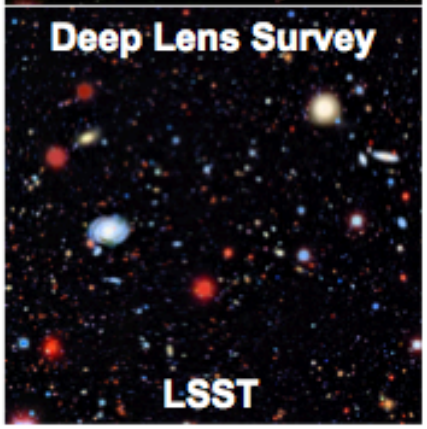


Past



Present

Future

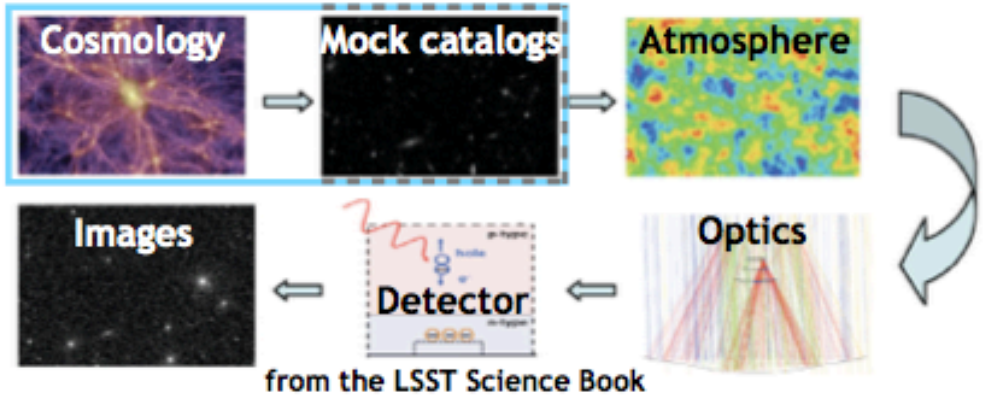


(1) Solving the Inverse Problem

- Exploring fundamental physics
- Fast, very accurate predictions tools (emulators) for physics and observables of interest
- Astrophysical systematics
- Predictions for covariances

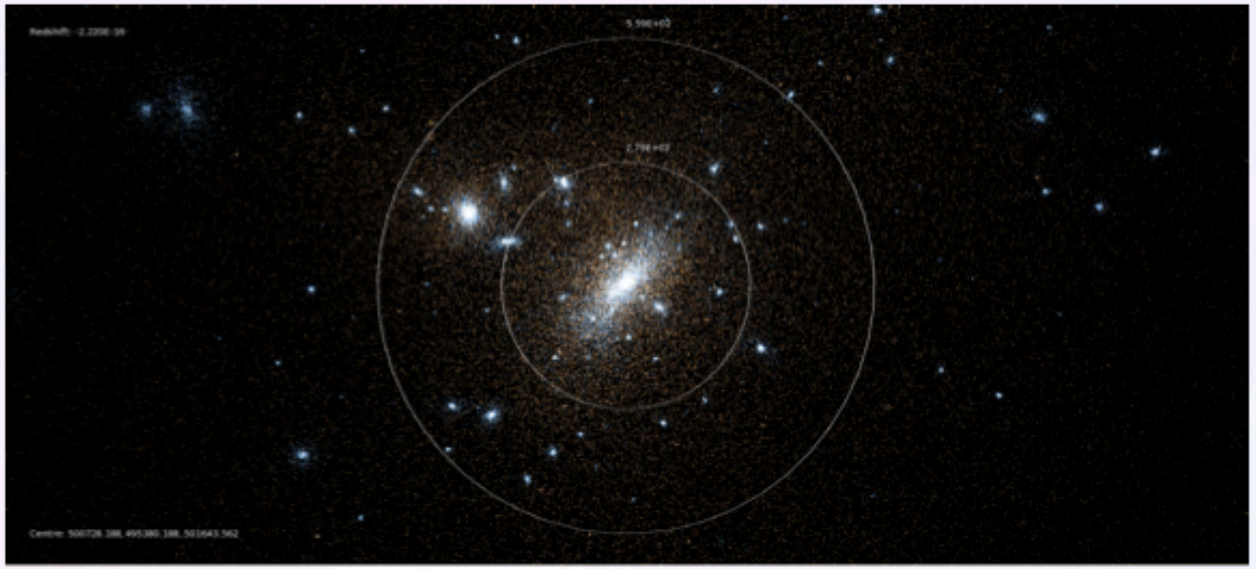
(2) Cosmology simulations and the survey

- First part of end-to-end simulation
- Control of systematics



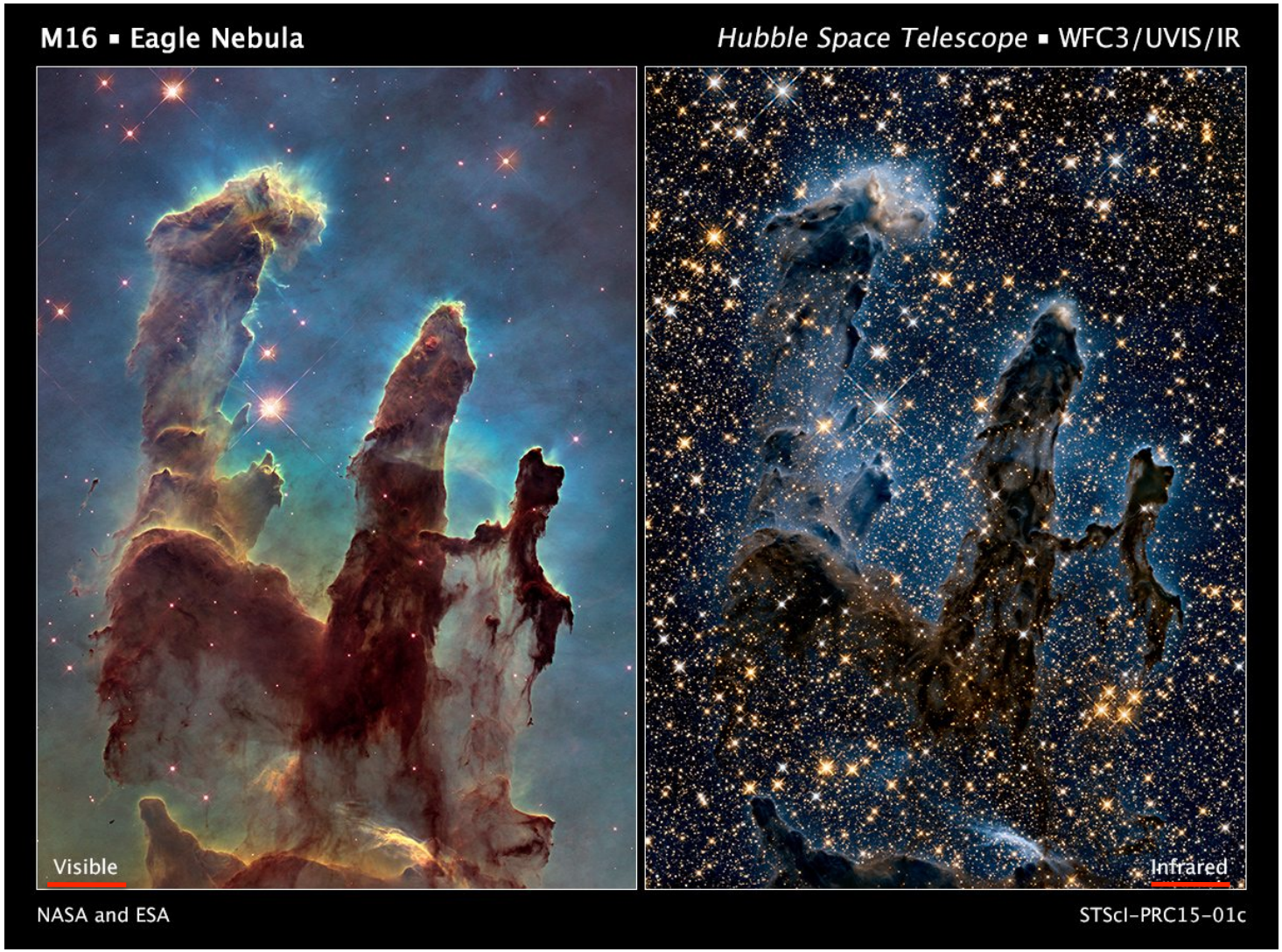
from the LSST Science Book

At the Observatory of Trieste:



- Private GADGET-3 (Ragone-Figueroa+13) with:
  - **gravity** + smoothed particle **hydrodynamics**.
  - **subgrid** physics:
    - radiative cooling.
    - Star formation and stellar feedback.
    - chemical evolution.
    - AGN feedback.
- We investigated 4 test regions producing by $z = 0$ **massive galaxy clusters**:
  - 2 clusters of $\simeq 5 \times 10^{14} M_{\odot}$
  - and 2 clusters of $\simeq 10^{15} M_{\odot}$.
- $M_{\rm gas} = 1.53 \times 10^{8}\, M_{\odot}$.
- $\sim 2 \times 10^{6}$ gas particles.

Cosmic Dust


M16 ▪ Eagle Nebula
Hubble Space Telescope ▪ WFC3/UVIS/IR
Visible
Infrared
NASA and ESA
STScI-PRC15-01c

Why does dust matter?

- Observations of spectral energy distributions (SEDs)

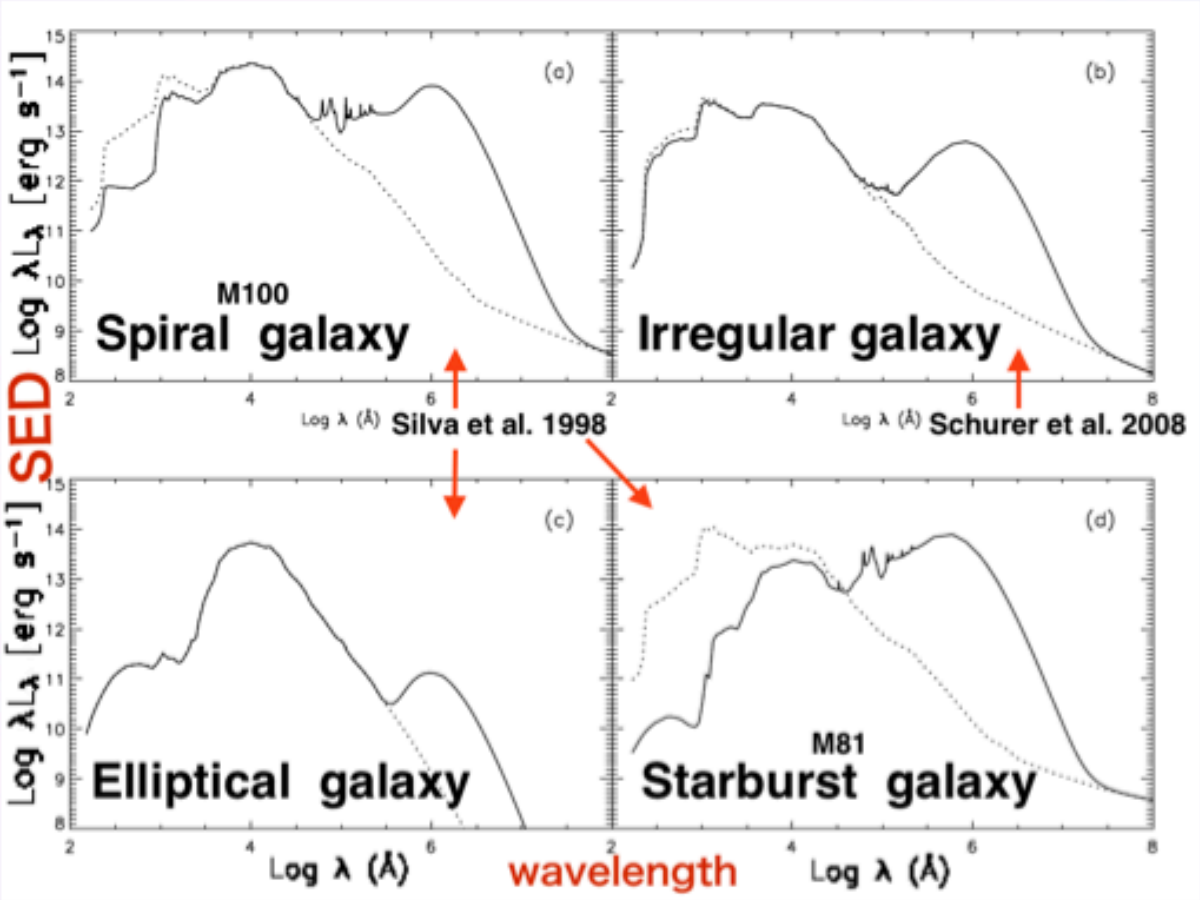
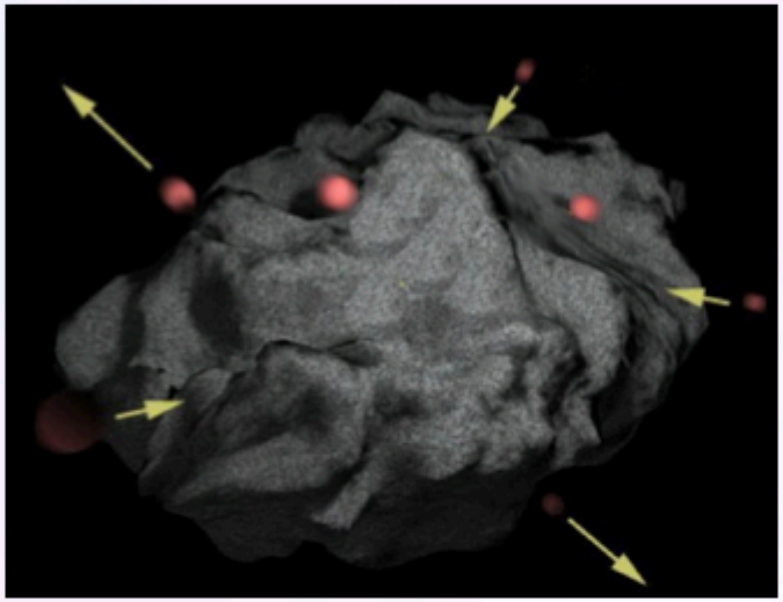


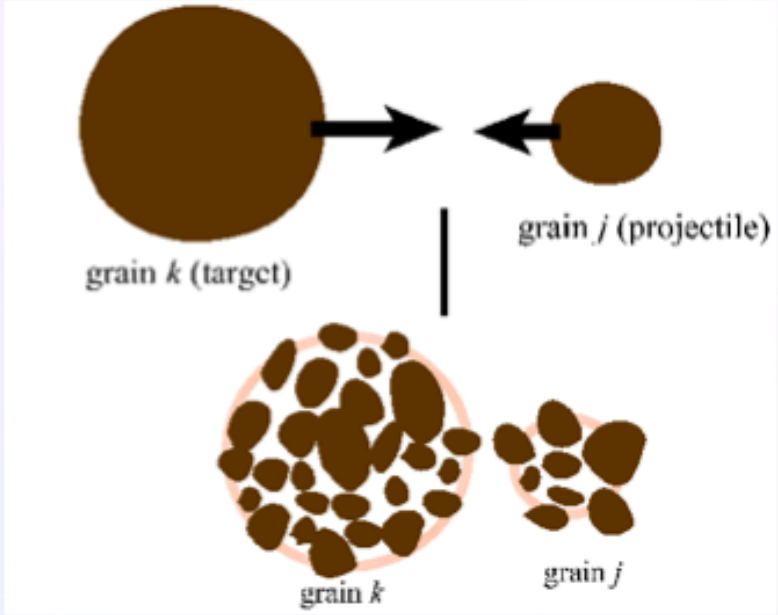
FIGURE: From Schurer A., PhD Thesis, 2009, Graph which shows the effect of dust on the SED of local galaxies. Solid lines: SED after dust reprocessing. Dashed lines: the intrinsic SED.

- H_2 catalysis $\rightarrow$ molecular cloud cooling $\rightarrow$ star formation $\rightarrow$ galaxy evolution $\rightarrow$ dust is important!

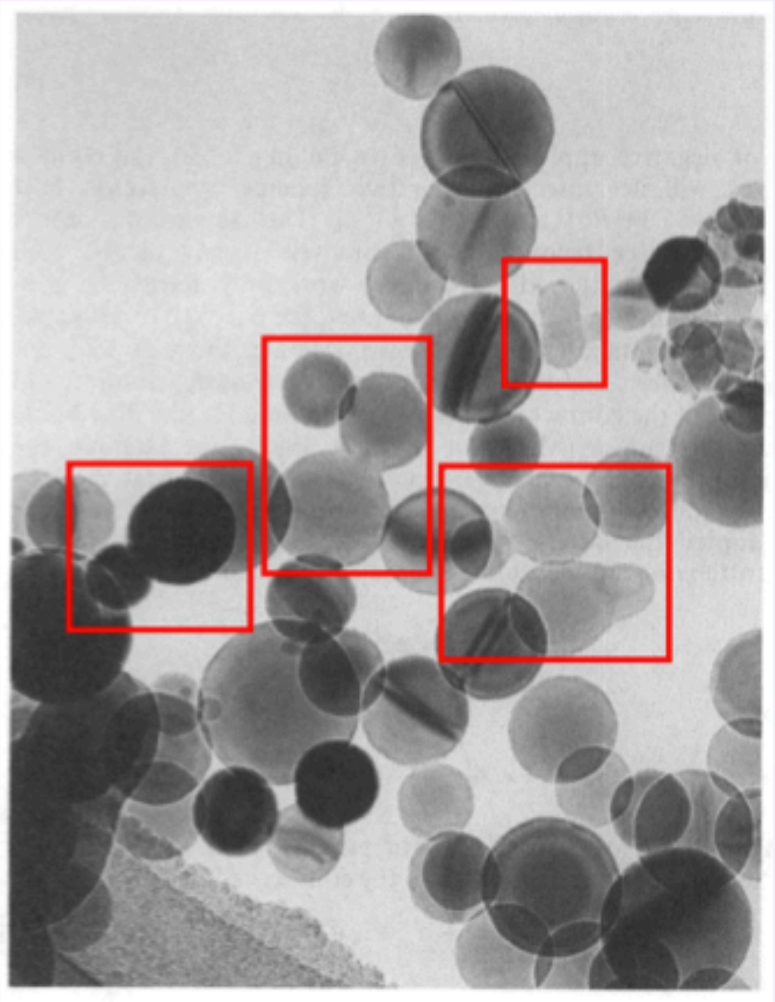
Physical processes on grains



gas-grain interactions (accretion)



grain-grain interactions (shattering)



grain-grain int. (coagulation)

(Iijima+87: Electromicrograph showing coagulated spherical Si particles, fabricated in a laboratory by a gas evaporation method. A typical grain has a diameter of 0.07μm.)

Galaxy Data Comparison

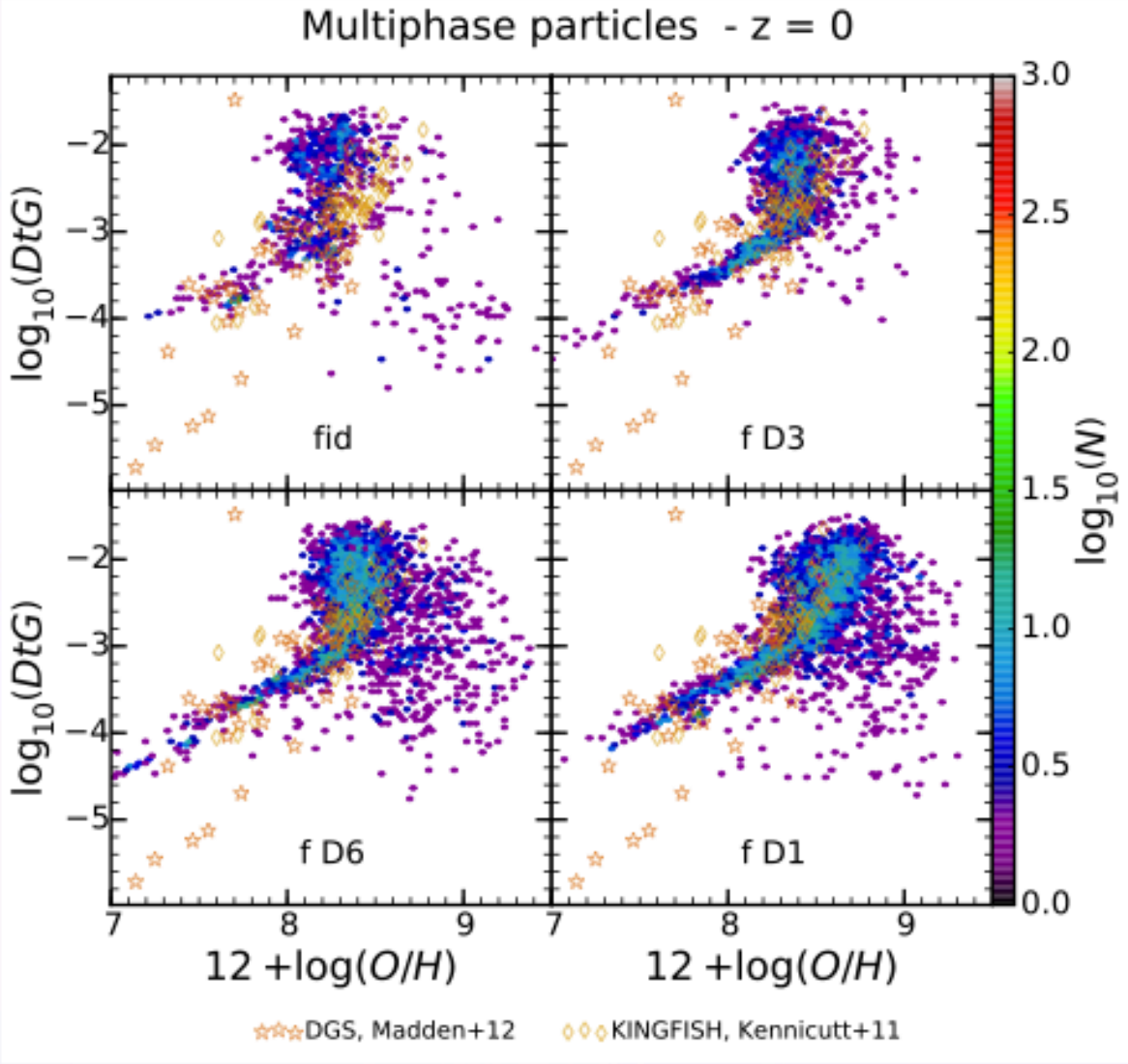


Figure: 2D histogram of the DtG vs Oxygen abundance at $z = 0$ compared with galactic data from Kennicutt+11 (diamonds) and Madden+12 (stars).

Cluster Data Comparison

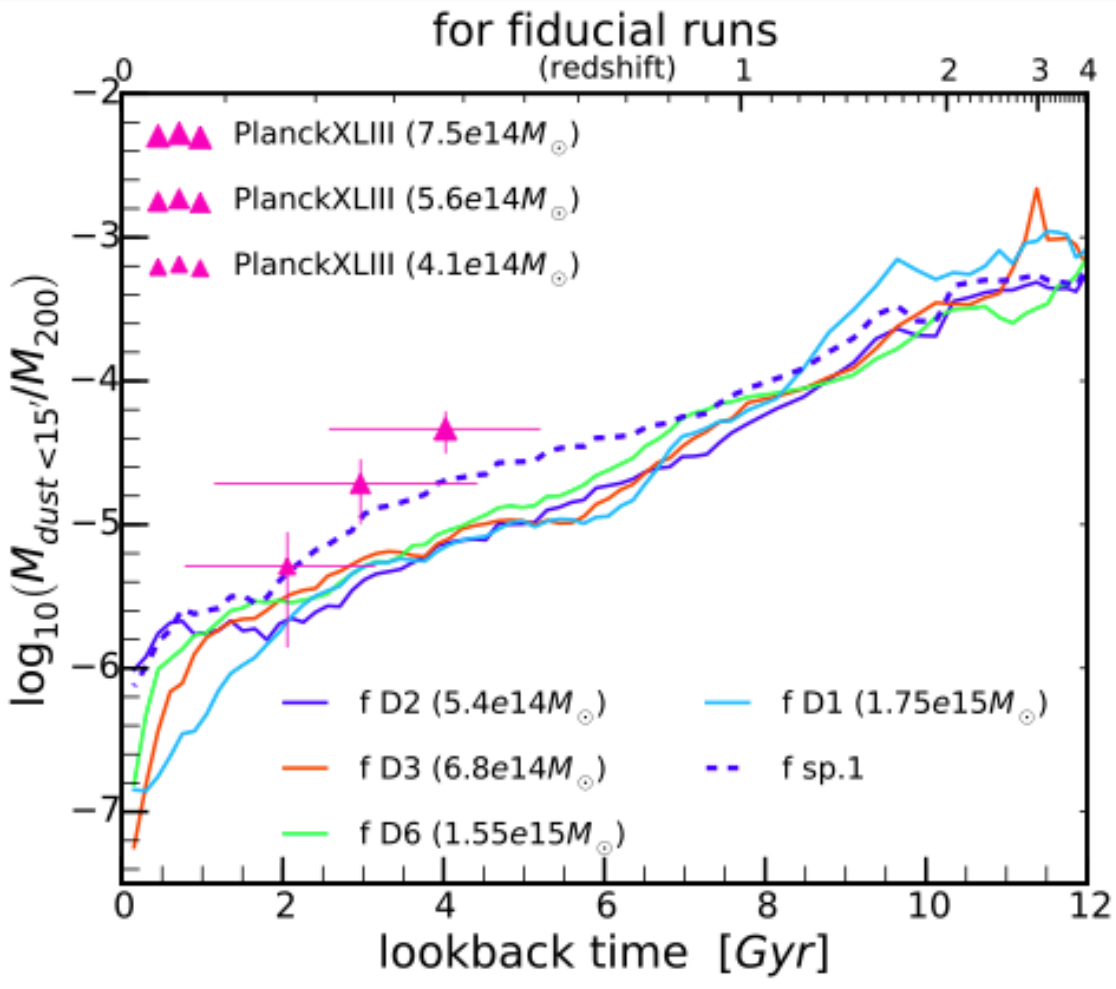


Figure: For the the 4 different zoom-in cluster simulations considered in this work (`fid (D2)`, `f-D3`, `f-D1`, `f-D6`) we show the evolution of the ratio between the dust mass within a 15 arcmin aperture and M_{200}. For the region D2, we show also the run with reduced sputtering, `f-sp.1`.

Summary

- Overview of our current understanding in Cosmology
  - DM/DE difference
  - Evolution History
  - Usefulness of Cosmological Simulations
  - Probes
    - CMB, BAO, Type Ia SNe, LSS, lensing, etc.
- Issues with predictions of Hubble constant with Cepheid local data, DES, and Planck
- New preliminary tension found in σ_8

Institutes offering a Physics PhD in Trieste

- Università degli Studi di Trieste
- SISSA (International School for Advanced Studies)
- ICTP (International Center for Theoretical Physics)
- Trieste facilities:
  - INAF Astronomical Observatory of Trieste
  - Electra
  - IFPU
  - ~60 private and public research centers

References

- 2018 Summer School in Cosmology – Trieste, Italy
- The Future of H_0: Crisis or Concordance? – Chicago, IL
- Dark Matter at the Dawn of Discovery? – Heidelberg, Germany

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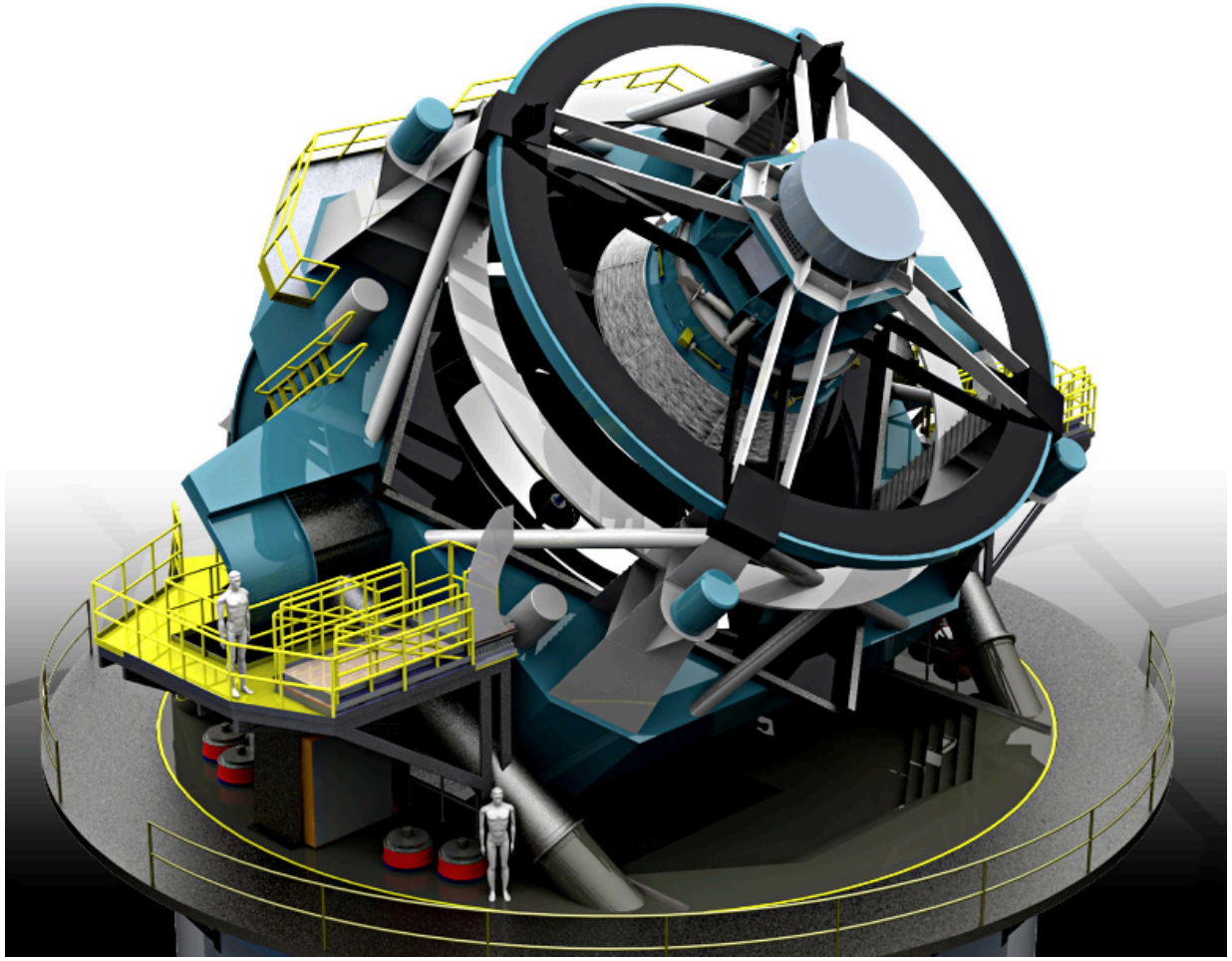


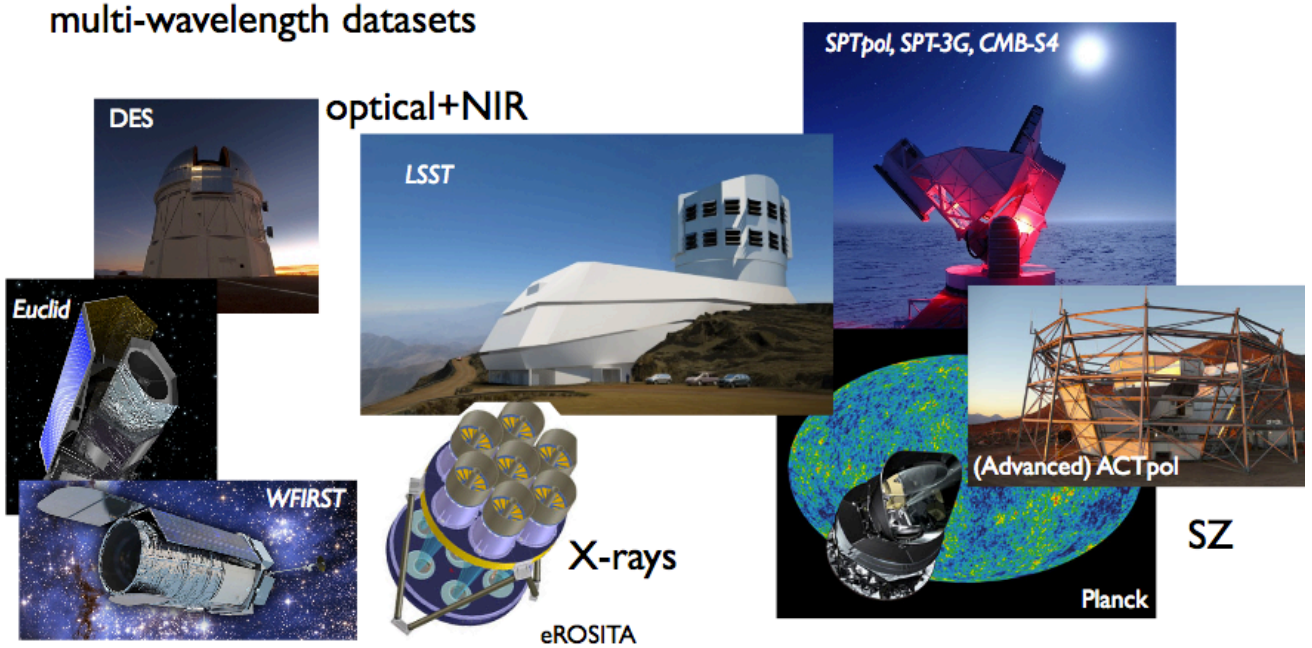
New Era of Large Surveys

Credit: Phil Bull, JPL/Caltech

Cluster Surveys in the 2020s

many surveys in optical, SZ, X-rays on-going, starting, or planned

→ great synergy prospects; 100s of 1000s of clusters

→ key developments: mass calibration + redshift leverage

→ best cosmology constraints will come from the combination from multi-wavelength datasets