

**Prof. Joel Primack  
Research Projects**

**Physics 205 - 23Feb2021**

**COSMOS**

**GALAXIES**

**PLANETS**



**Prof. Joel Primack  
Research Projects**

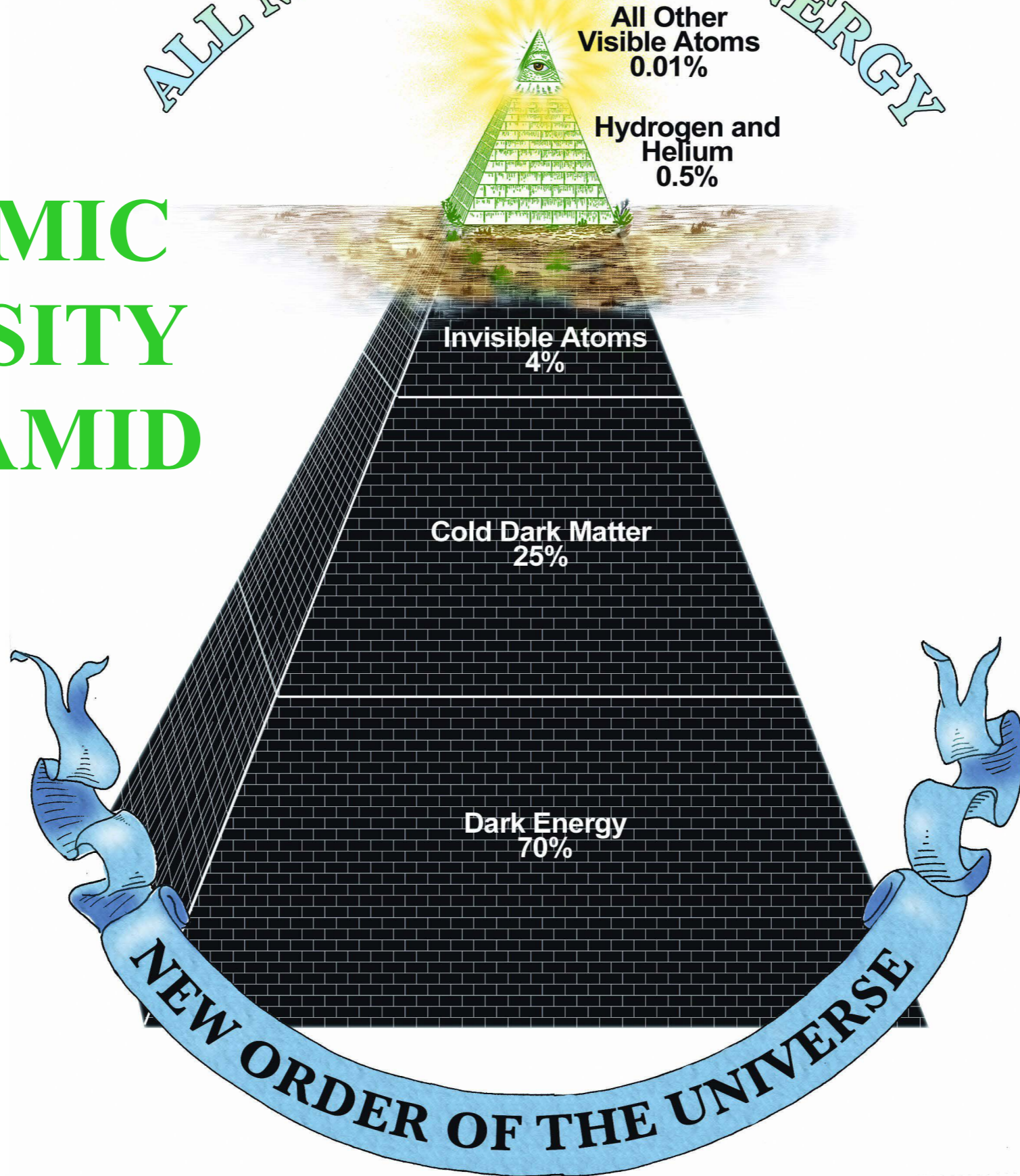
**COSMOS**

**This picture is beautiful but misleading, since it only shows about 0.5% of the cosmic density.**

**The other 99.5% of the universe is invisible.**

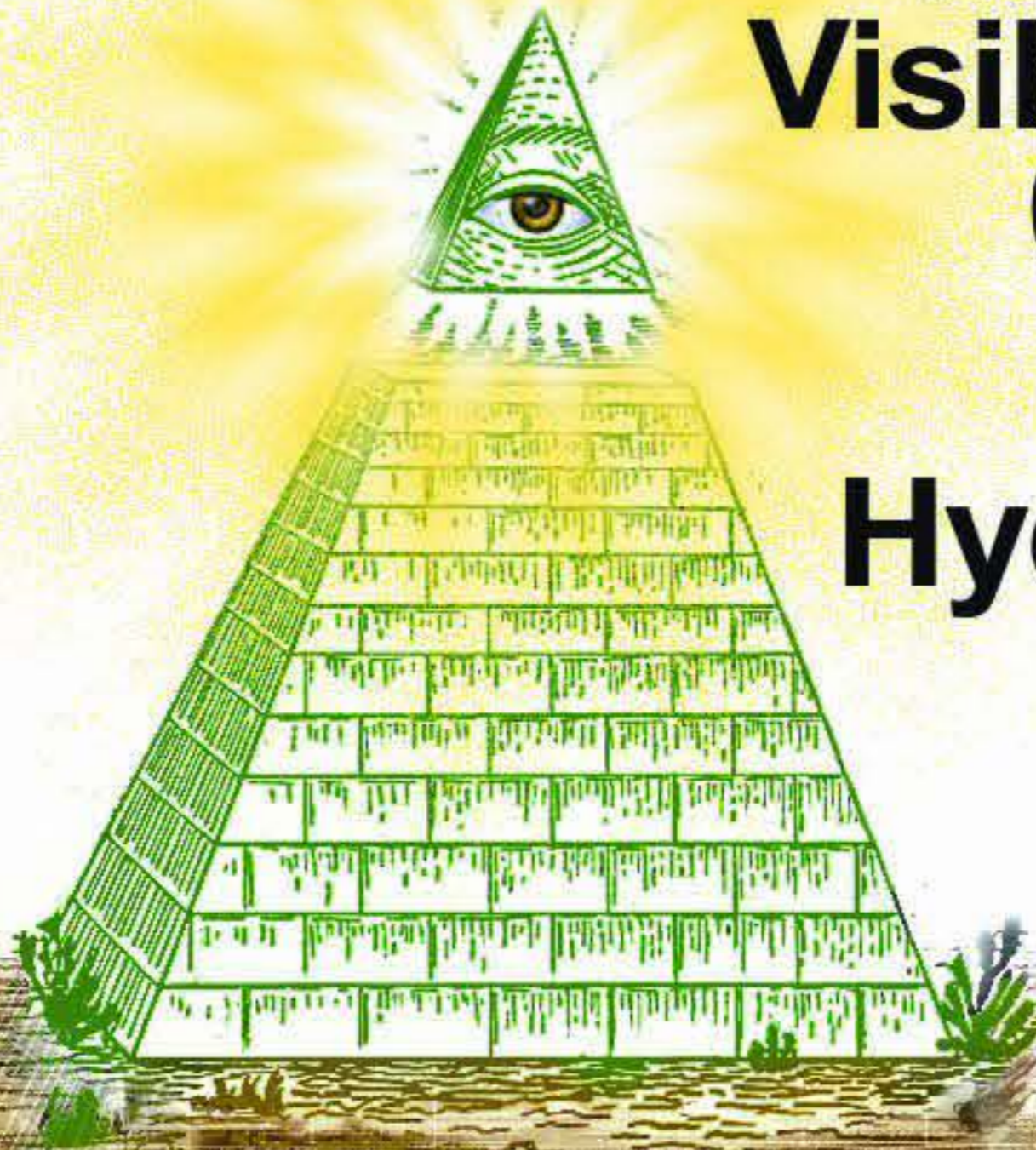
ALL MATTER AND ENERGY

# COSMIC DENSITY PYRAMID



**All Other  
Visible Atoms  
0.01%**

**Hydrogen and  
Helium  
0.5%**



# Periodic Table of the Elements

1 H																	2 He									
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne									
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar									
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr									
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe									
55 Cs	56 Ba											72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																									
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu										
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu																			

short-lived radioactive isotopes; nothing left from stars

Big Bang fusion



cosmic ray fission



merging neutron stars?



exploding massive stars



dying low-mass stars



exploding white dwarfs



VISIBLE MATTER

ALL OTHER  
VISIBLE ATOMS

stardust

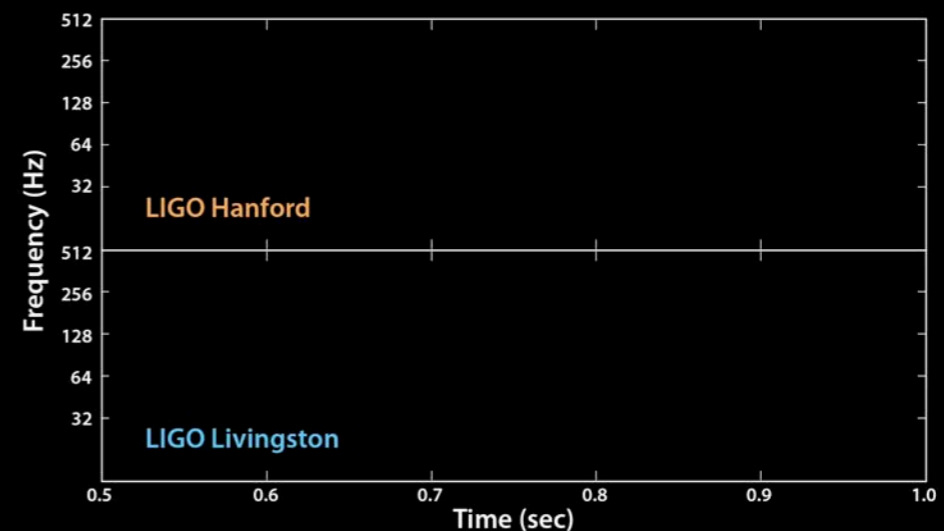
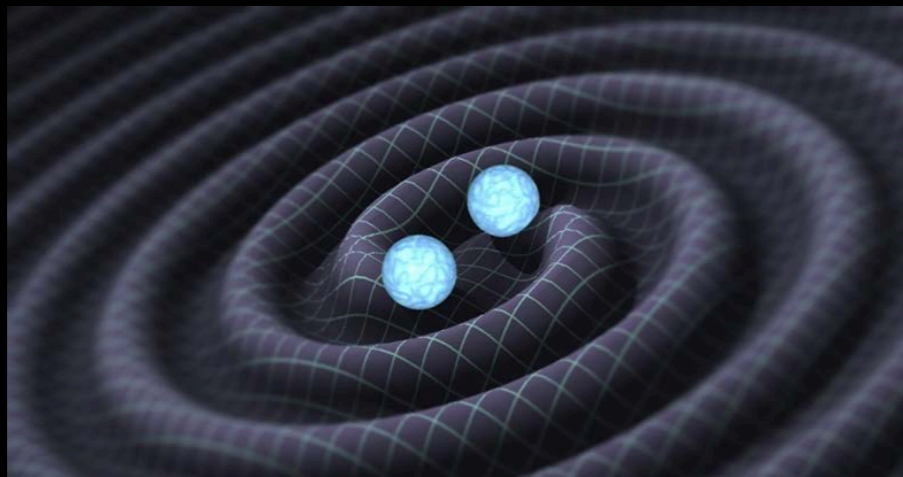
HYDROGEN  
AND HELIUM

stars

NOVUS ORDO SECLORUM



Many stars in the very early universe may have been much more massive than our sun, in binary star systems with other massive stars. When these stars ended their lives as supernovas, they became massive black holes or neutron stars. The Laser Interferometer Gravitational-wave Observatory (LIGO) has now detected  $> 50$  mergers of massive black holes. This confirmed key predictions of Einstein's general relativity for the first time.



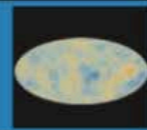
In August 2017 LIGO and VIRGO announced the discovery of gravity waves from merging neutron stars. Data from telescopes shows that such events probably generate most of the heavy elements like europium, gold, thorium, and uranium.

# Periodic Table of the Elements

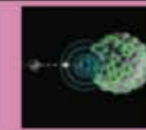
1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu											

short-lived radioactive isotopes; nothing left from stars

Big Bang fusion



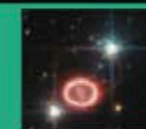
cosmic ray fission



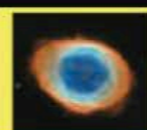
merging neutron stars?



exploding massive stars



dying low-mass stars



exploding white dwarfs





All Other Atoms 0.01%  
H and He 0.5%

Visible Matter 0.5%

Invisible Atoms 4%

Cold Dark Matter 25%

Dark Energy 70%

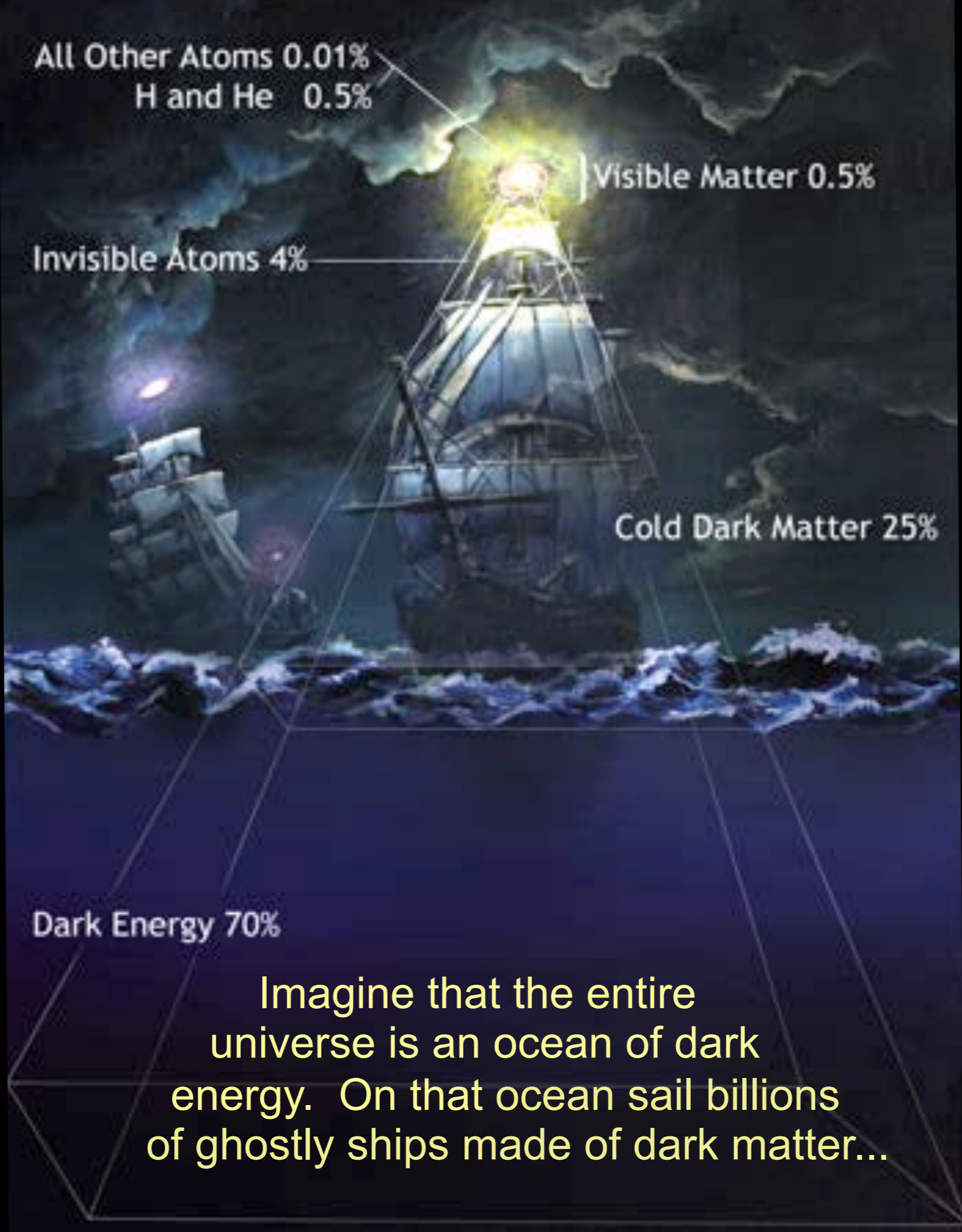
Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Matter and Energy Content of the Universe

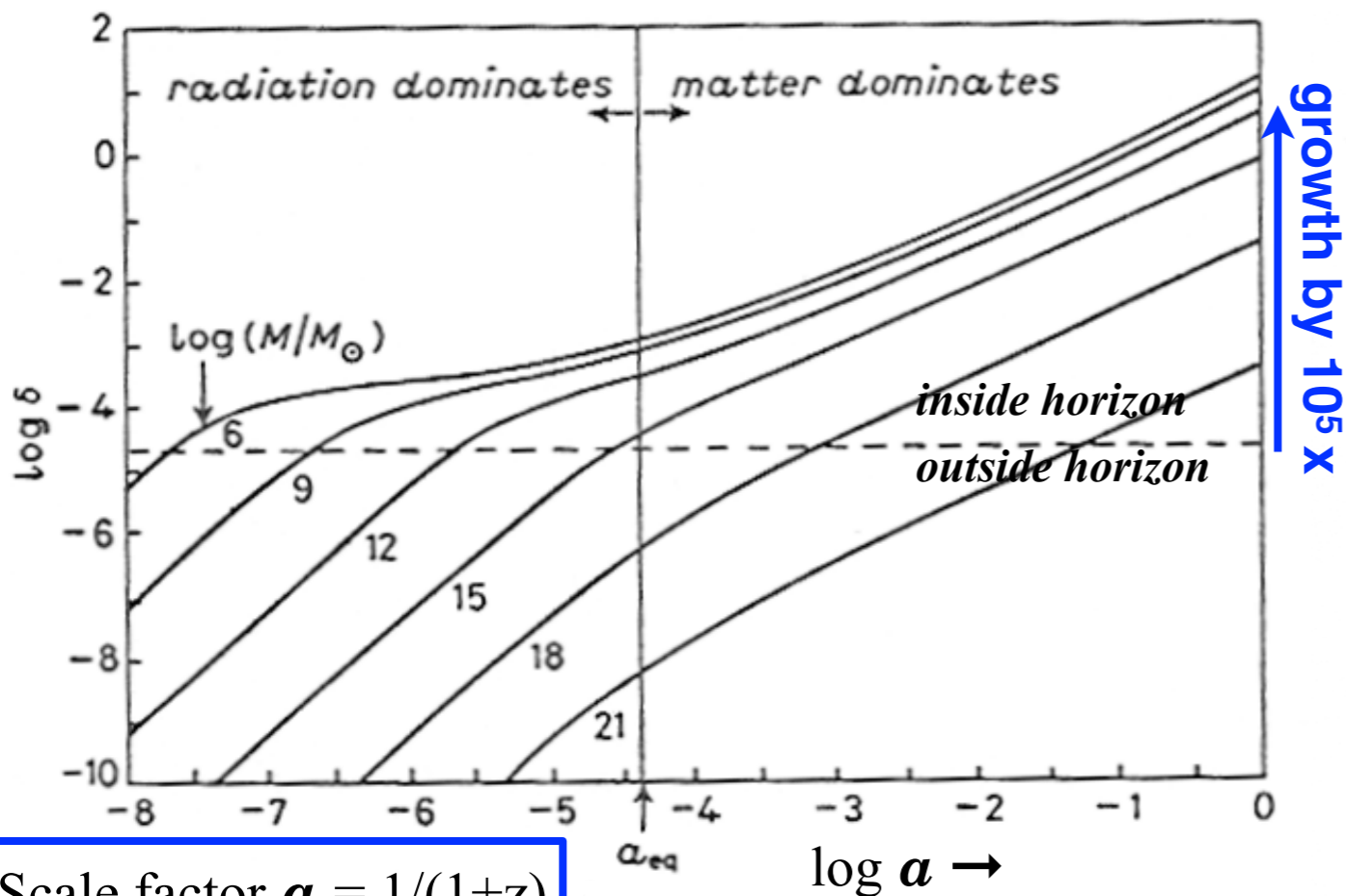
$\Lambda$ CDM

Double Dark Theory

Dark Matter Ships on a Dark Energy Ocean

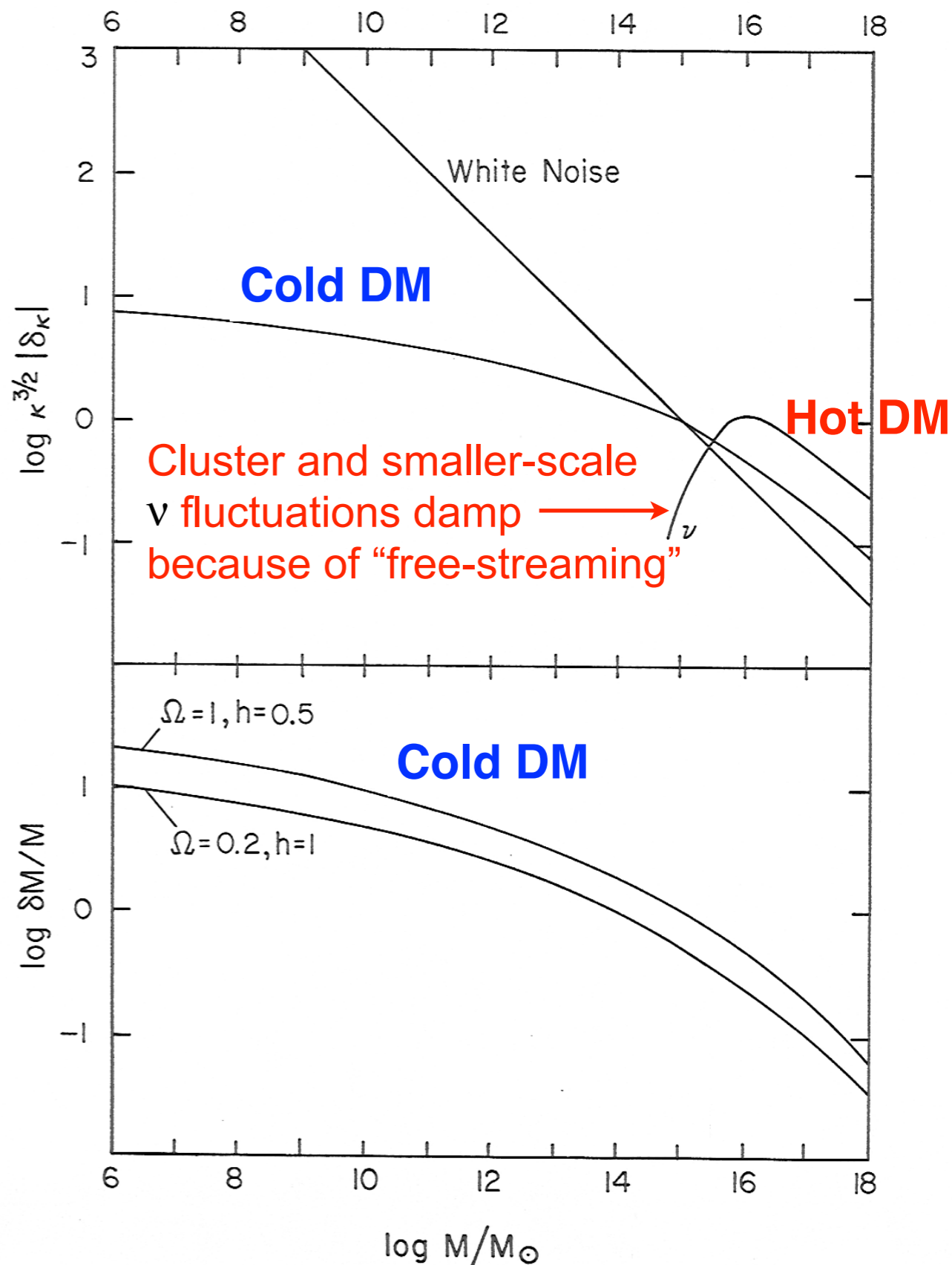


# CDM Structure Formation: Linear Theory



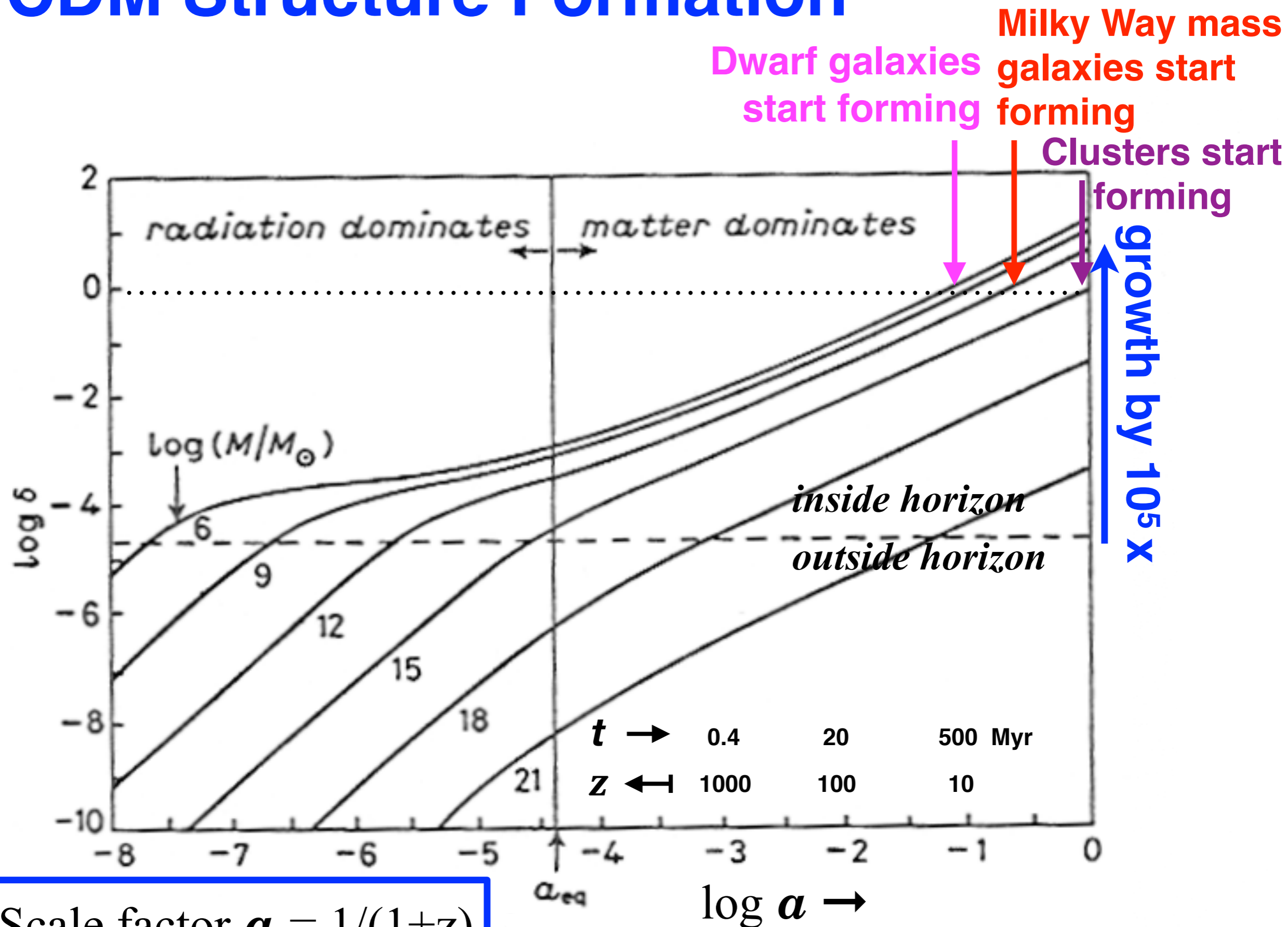
CDM fluctuations that enter the horizon during the radiation dominated era, with masses less than about  $10^{15} M_\odot$ , grow only  $\propto \log a$ , because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow  $\propto a$ . This explains the characteristic shape of the CDM fluctuation spectrum, with  $\delta(k) \propto k^{-n/2-2} \log k$  and  $\delta_{\text{primordial}} = k^n$

Primack & Blumenthal 1983,  
Primack Varenna Lectures 1984



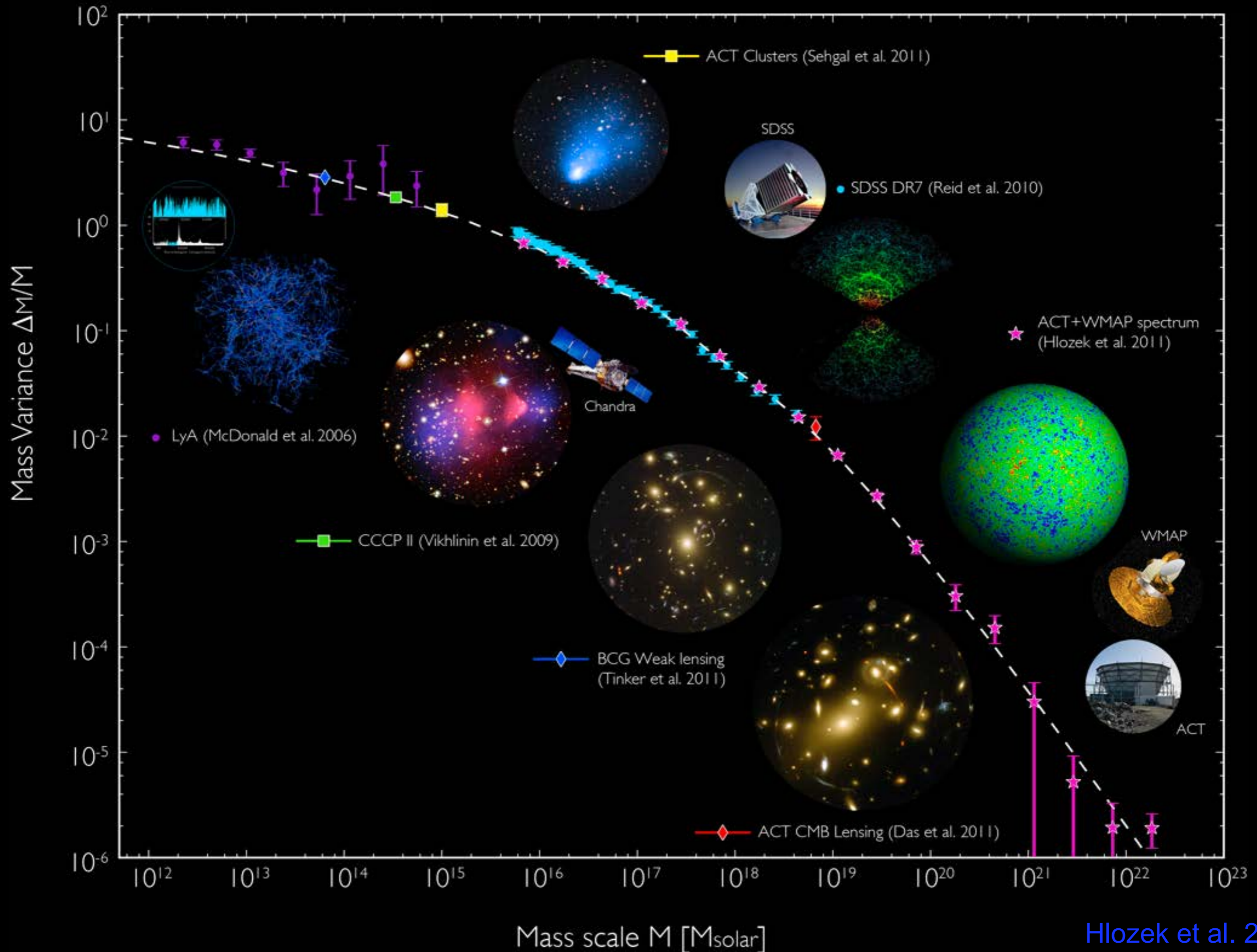
Blumenthal, Faber, Primack, & Rees 1984

# CDM Structure Formation



Scale factor  $\mathbf{a} = 1/(1+z)$

# Matter Distribution Agrees with Double Dark Theory!

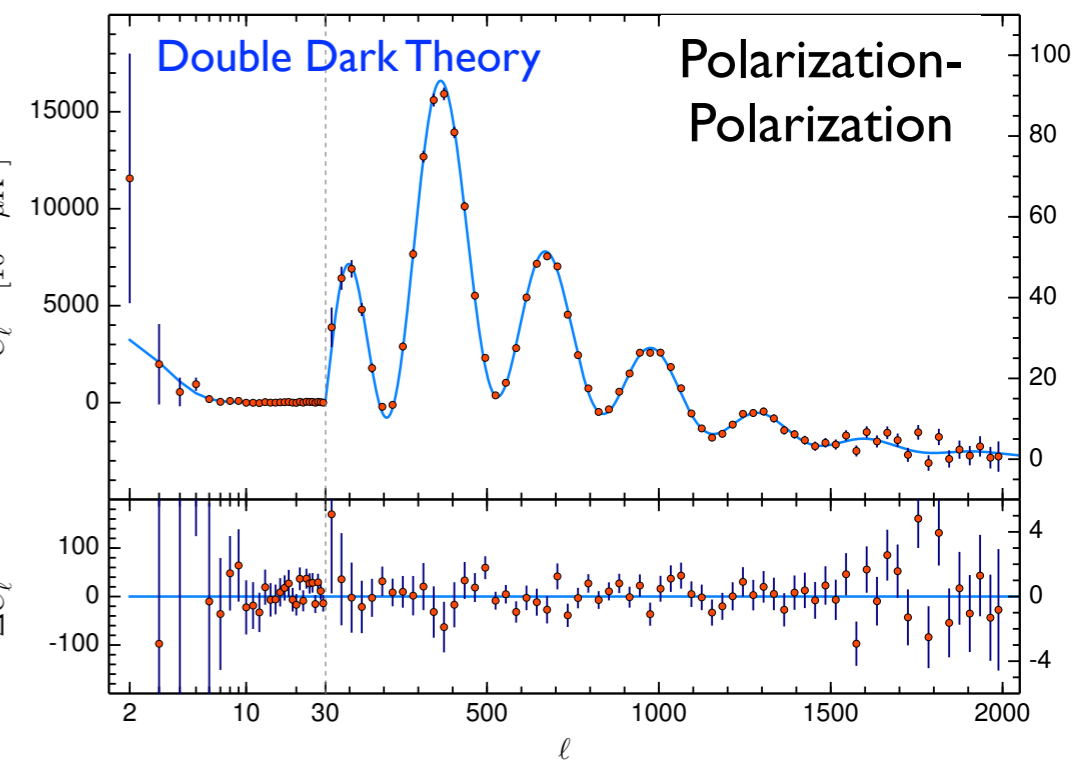
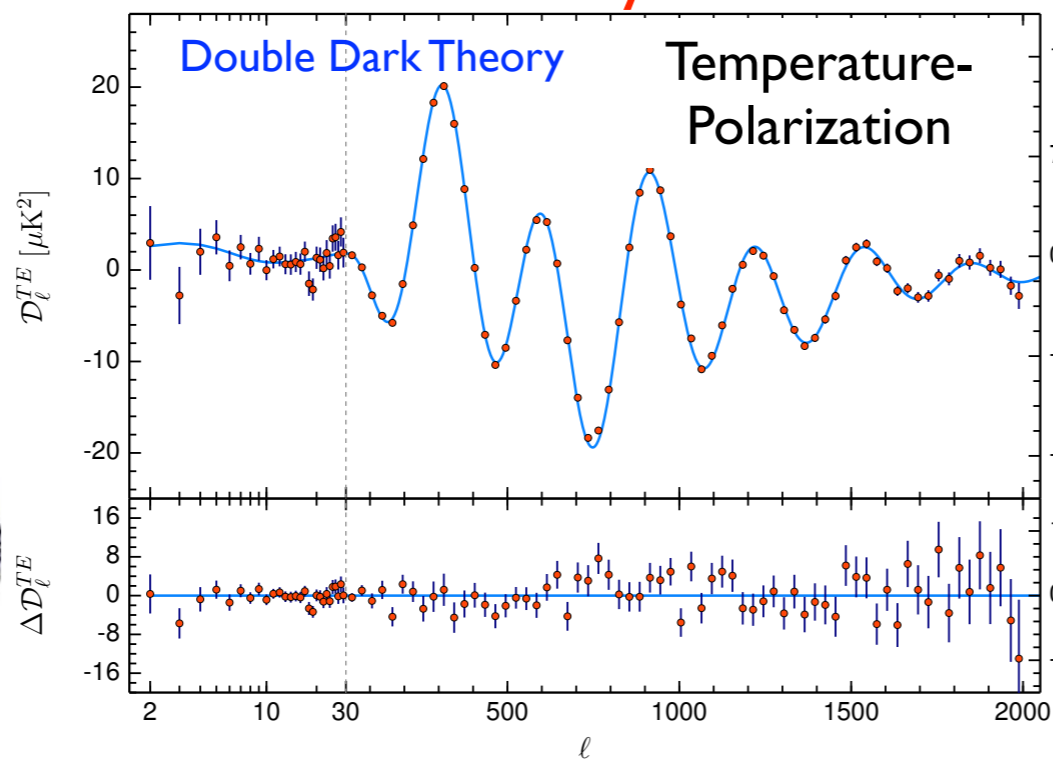
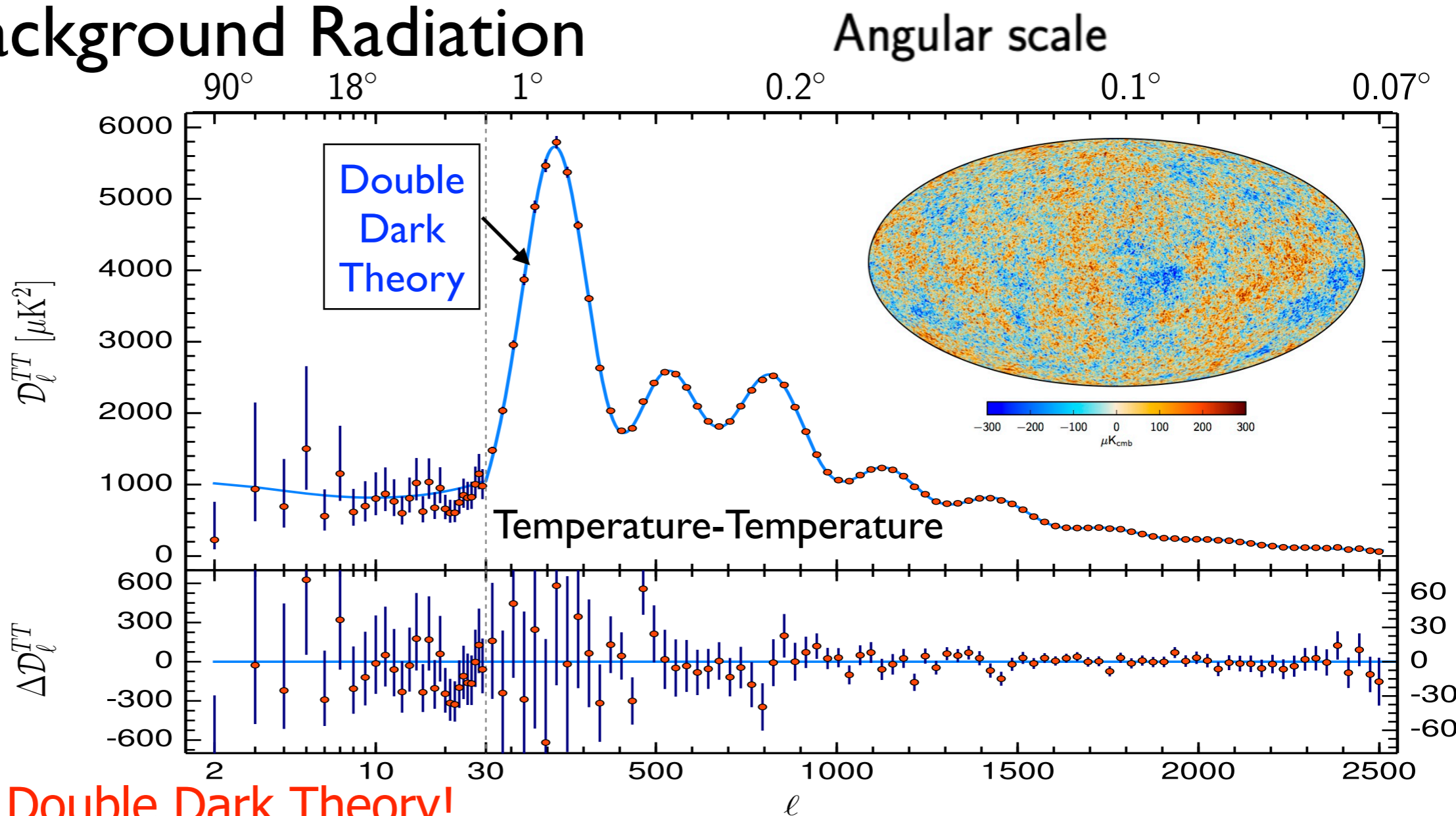
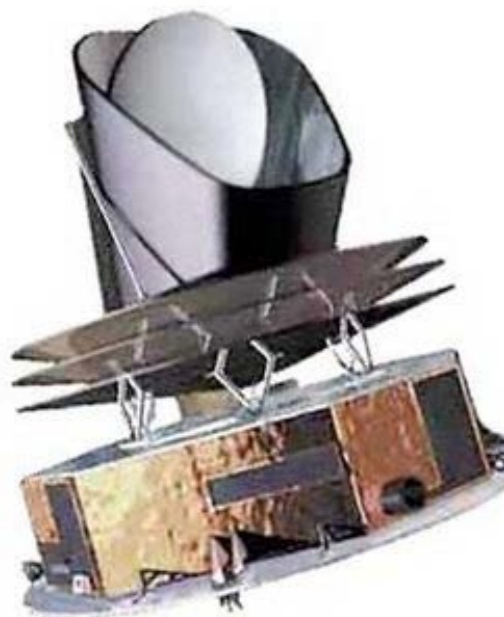


# Cosmic Background Radiation

European  
Space  
Agency  
PLANCK  
Satellite  
Data

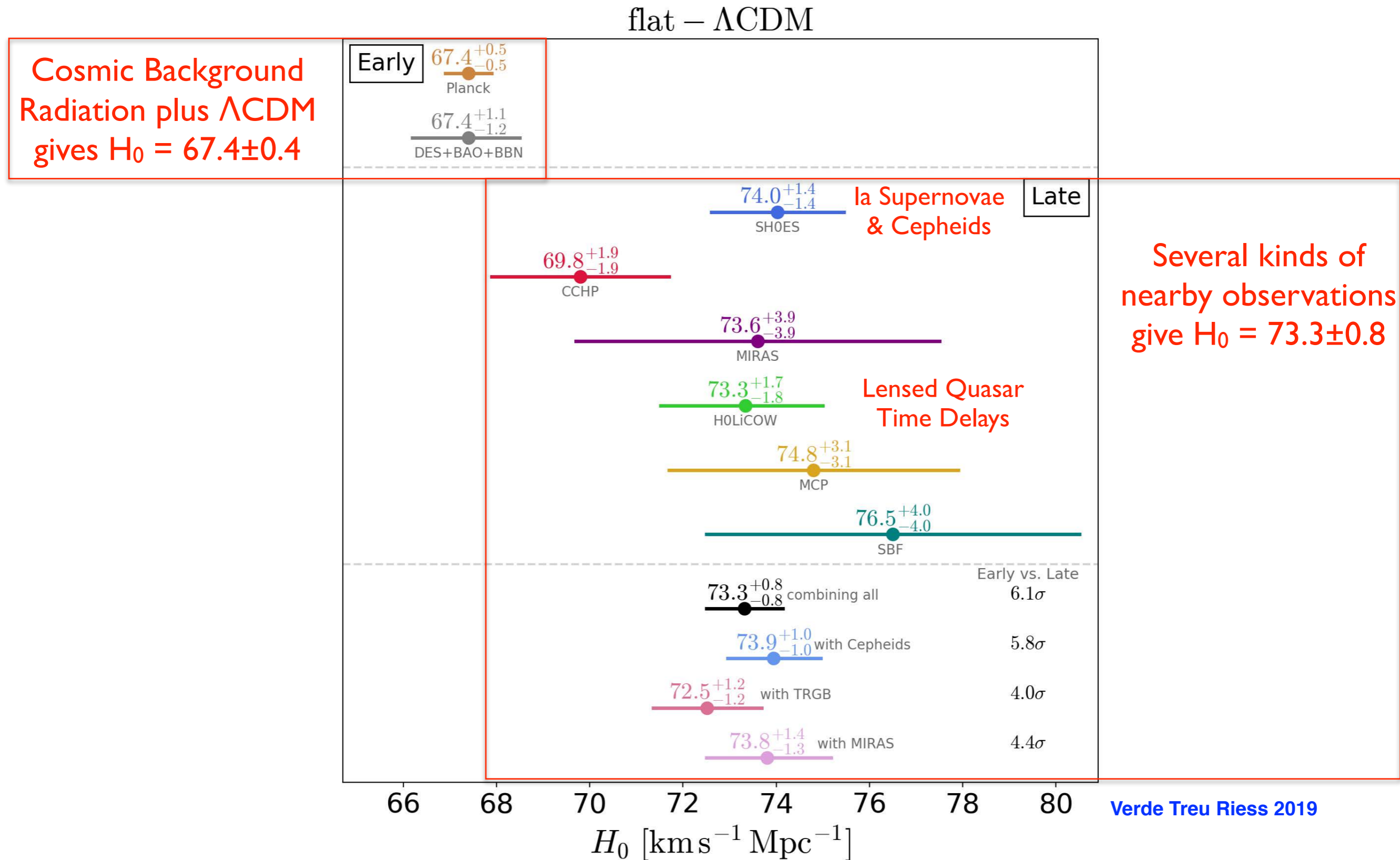
Released  
September 24,  
2019

Agrees with Double Dark Theory!



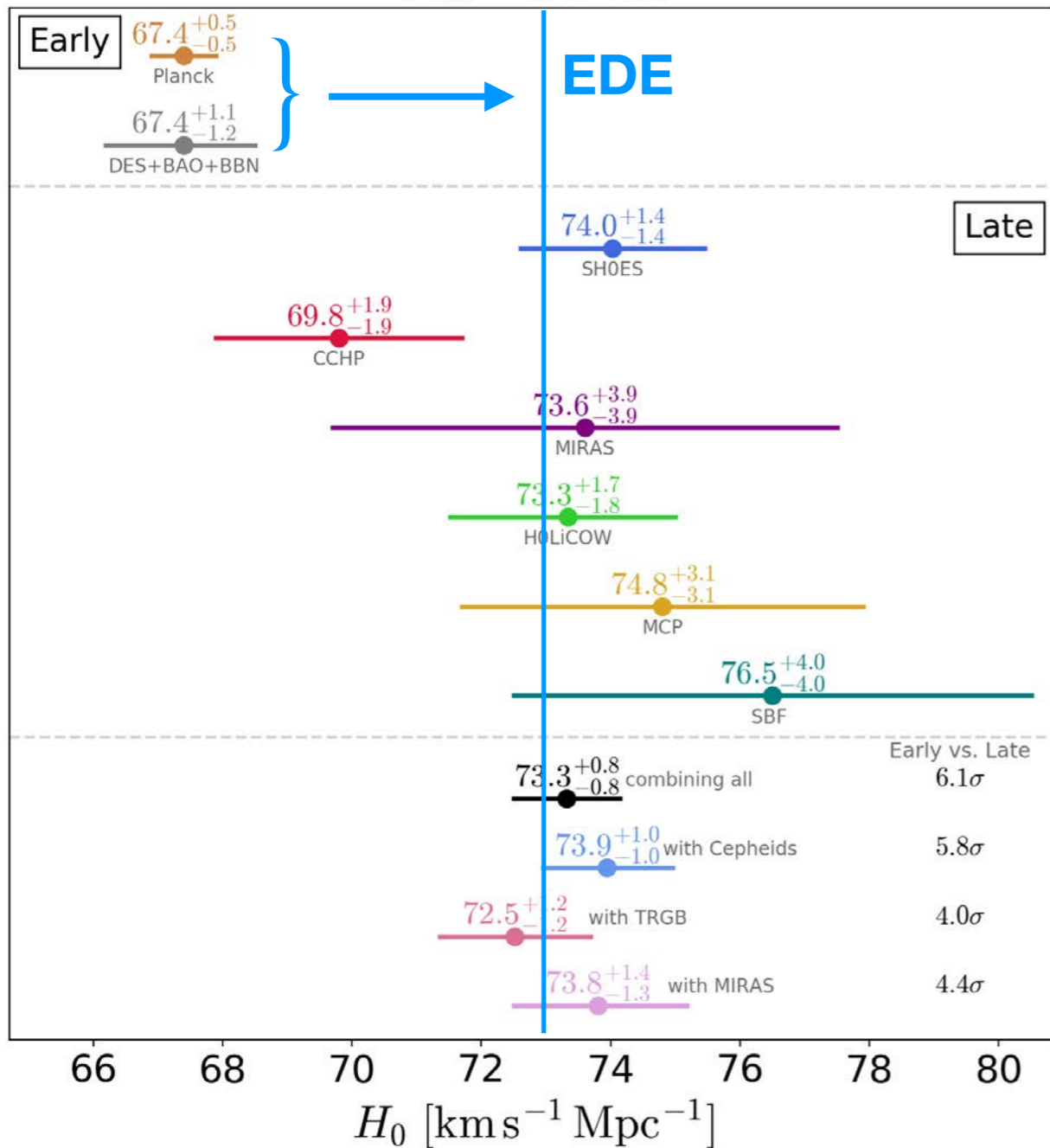
The Hubble parameter  $H_0$  is the expansion rate of the universe today.

A possibly serious difficulty for  $\Lambda$ CDM is the **Hubble parameter tension**:

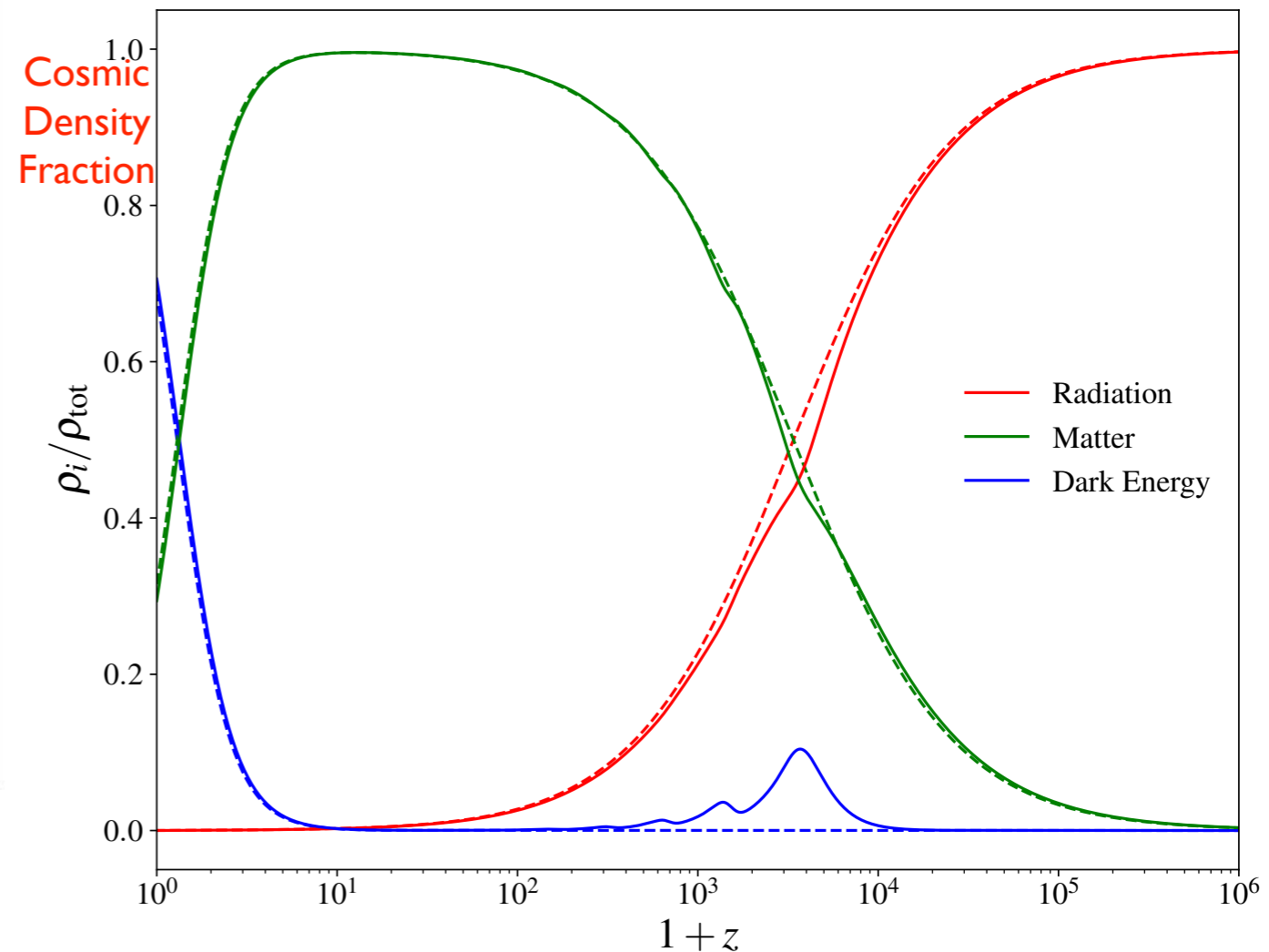


“Early Dark Energy,” a brief period of  $\sim 5\%$  extra dark energy at  $z \sim 4000$ , could resolve this

# flat – $\Lambda$ CDM



A brief episode of **Early Dark Energy** about  $\sim 35,000$  years after the Big Bang modifies the  $\Lambda$ CDM extrapolation of  $H_0$  and avoids the Hubble tension.



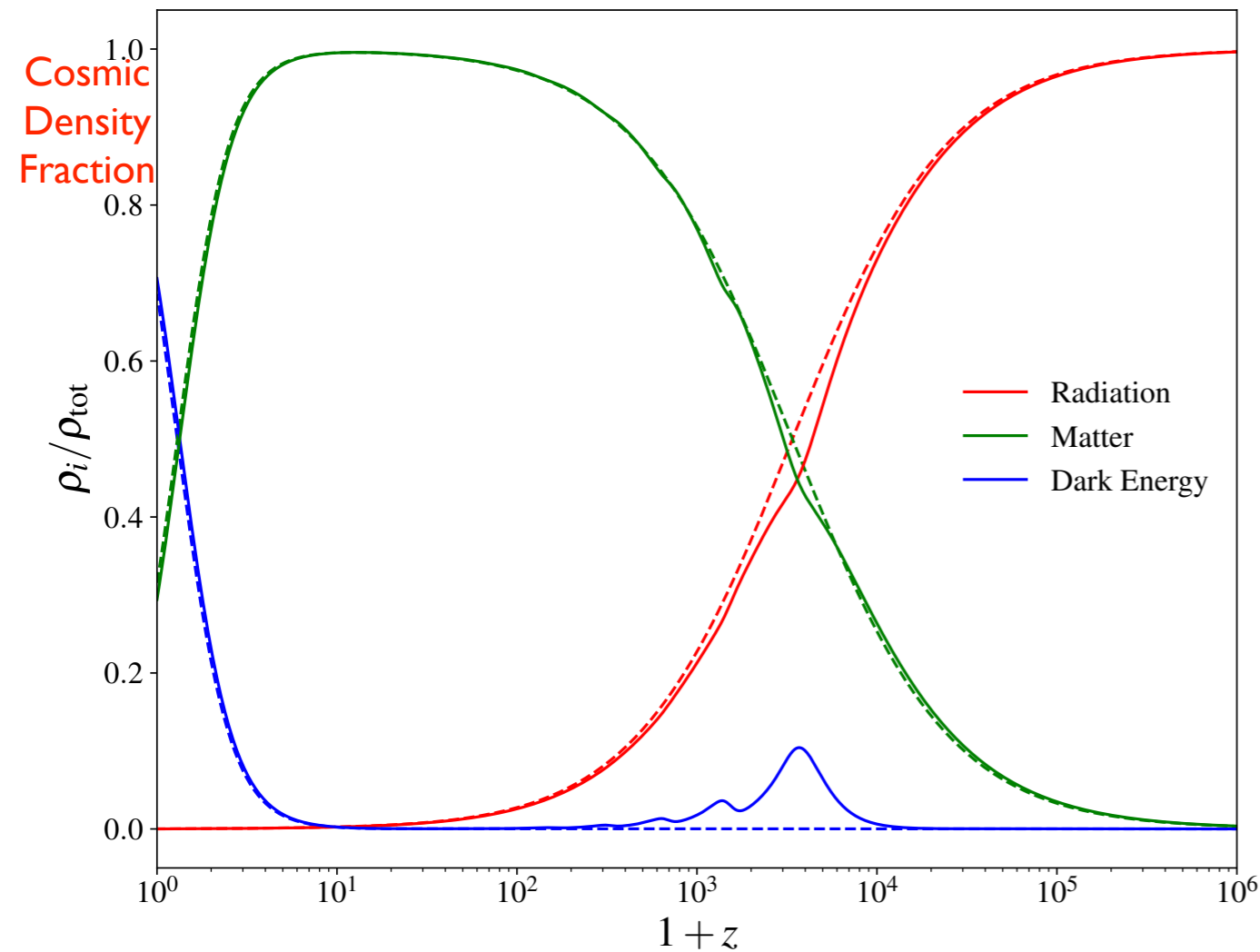
**Figure 1.** Compilation of Hubble Constant predictions and measurements taken from the recent literature and presented or discussed at the meeting. Two independent predictions based on early-Universe data (Planck Collaboration et al. 2018; Abbott et al. 2018) are shown at the top left (more utilizing other CMB experiments have been presented with similar findings), while the middle panel shows late Universe measurements. The bottom panel shows combinations of the late-Universe measurements and lists the tension with the early-Universe predictions. We stress that the three variants of the local distance ladder method (SHOES=Cepheids; CCHP=TRGB; MIRAS) share some Ia calibrators and cannot be considered as statistically independent. Likewise the SBF method is calibrated based on Cepheids or TRGB and thus it cannot be considered as fully independent of the local distance ladder method. Thus the “combining all” value should be taken for illustration only, since its derivation neglects covariance between the data. The three combinations based on Cepheids, TRGB, Miras are based on statistically independent datasets and therefore the significance of their discrepancy with the early universe prediction is correct - even though of course separating the probes gives up some precision. A fair summary is that the difference is more than  $4\sigma$ , less than  $6\sigma$ , while robust to exclusion of any one method, team or source. Figure courtesy of Vivien Bonvin.

Verde, Treu, Riess 2019

Solid curves represent our  $\Lambda$ CDM+EDE model, and dashed curves are standard  $\Lambda$ CDM with the Planck parameters. Our N-body simulations show that structure forms earlier than in standard  $\Lambda$ CDM, but the present-day universe is very similar.

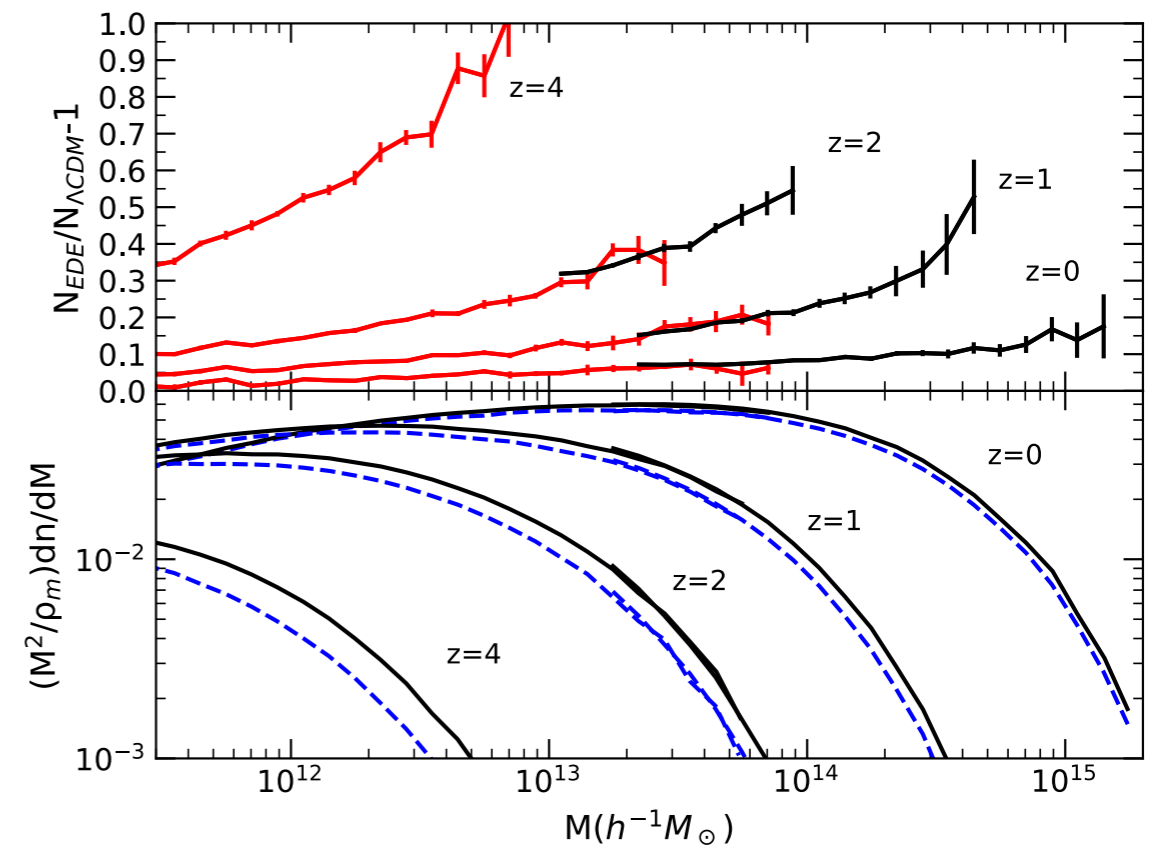
Klypin, Poulin, Prada, Primack, et al. 2020

A brief episode of **Early Dark Energy** about  $\sim 35,000$  years after the Big Bang modifies the  $\Lambda$ CDM extrapolation of  $H_0$  and avoids the Hubble tension.



Solid curves represent our  $\Lambda$ CDM+EDE model, and dashed curves are standard  $\Lambda$ CDM with the Planck parameters. Our N-body simulations show that structure forms earlier than in standard  $\Lambda$ CDM, but the present-day universe is very similar.

Klypin, Poulin, Prada, Primack, et al. 2020



**EDE: 50% more cluster at  $z \sim 1$ , 2x more massive galaxies at  $z \sim 4$**

**Figure 10.** Halo mass function at redshifts  $z = 0 - 4$ . Full curves in the bottom panel are for the EDE simulations and dashed curves are for the  $\Lambda$ CDM simulations. The smaller box and better resolution simulations EDE<sub>0.5</sub> and  $\Lambda$ CDM<sub>0.5</sub> are used for masses below  $M \lesssim 10^{14} h^{-1} \text{Mpc}$ . They are shown as red curves in the top panel. Larger box and lower resolution simulations EDE<sub>2A</sub> and  $\Lambda$ CDM<sub>2A</sub> (black curves in the top panel) are used for massive halos with  $M \gtrsim 2 \times 10^{13} h^{-1} \text{Mpc}$ . At  $z = 0$  halo abundances are very similar for the models: EDE predicts  $\sim 10\%$  more of the most massive clusters  $M \approx 10^{15} h^{-1} M_\odot$  and 1%-2% more of galaxy-size halos with  $M \approx 10^{12-13} h^{-1} M_\odot$ . The differences in abundances increase substantially with the redshift. [Klypin, Poulin, Prada, Primack, et al. 2020](#)

## Research Projects:

Run and analyze high-resolution EDE N-body simulations

Fill high-res simulations with galaxies and clusters

Compare with observations



The background of the slide is a rich field of galaxies, including spiral, elliptical, and irregular shapes in various colors like yellow, blue, and purple, set against a dark, star-filled space.

# Prof. Joel Primack Research Projects

**COSMOS**

**GALAXIES**

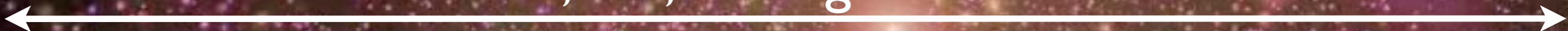
# Aquarius Simulation

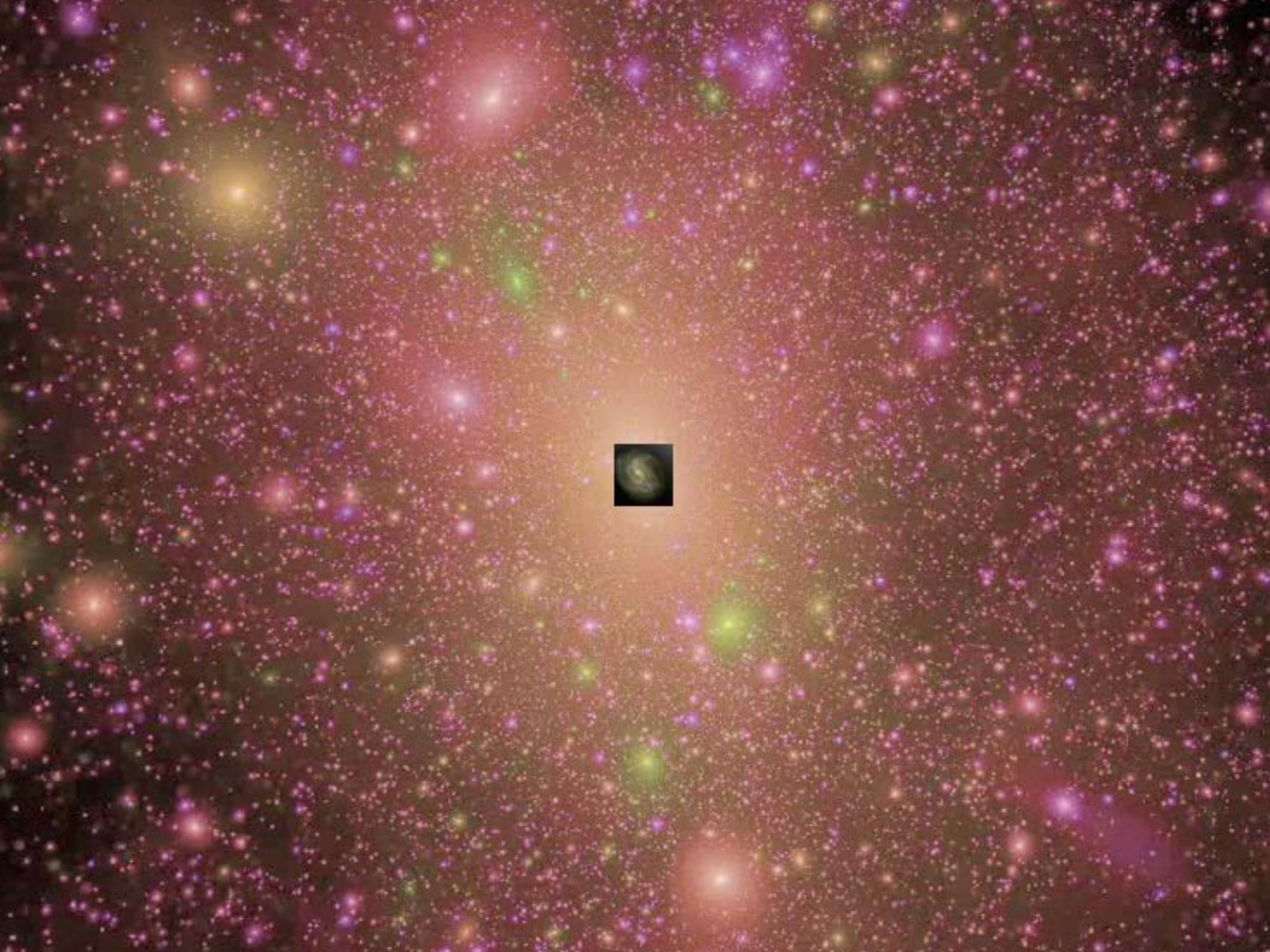
Volker Springel

Milky Way  
100,000 Light Years



Milky Way Dark Matter Halo  
1,500,000 Light Years





# **Bolshoi Cosmological Simulation**

Anatoly Klypin & Joel Primack



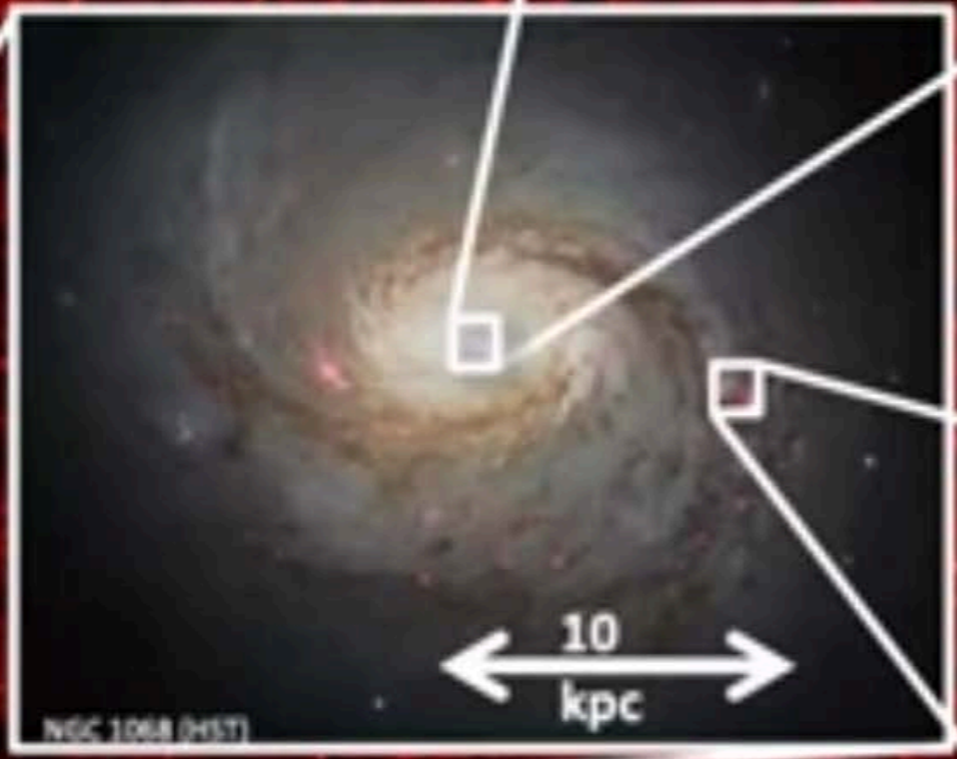
1 Billion Light Years



1 matter clumps together under the force of gravity as the Universe expands, forming large structures



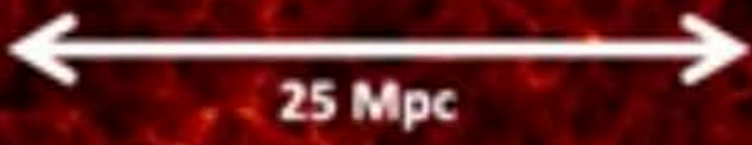
4 Massive black holes grow at the centers of galaxies and can affect their evolution via radiation, winds, jets...



3 Massive stars affect their surrounding interstellar medium through supernovae, radiation, and winds



2 gas accretes from the 'cosmic web' into galaxies, where it cools and forms stars



Almost all the stars today are in large galaxies like our Milky Way. Nearby large galaxies are disk galaxies like our galaxy or big balls of stars called elliptical galaxies. But most galaxies in the early universe didn't look anything like our Milky Way. Many of them are pickle-shaped and clumpy.



We are just now figuring out how galaxies form and evolve with the help of big ground-based telescopes, and Hubble and other space telescopes that let us see radiation that doesn't penetrate the atmosphere.



Keck  
Observatory



Hubble  
Space  
Telescope

# “Face Recognition for Galaxies”

## Deep Learning Identifies High-z Galaxies in a Central Blue Nugget Phase in a Characteristic Mass Range

Marc Huertas-Company, Joel Primack, Avishai Dekel, David Koo, Sharon Lapiner, Daniel Ceverino, Raymond Simons, Greg Snyder, et al. [ApJ 2018](#)

Cosmological zoom-in simulations model how individual galaxies evolve through the interaction of atomic matter, dark matter, and dark energy

Our VELA galaxy simulations agree with HST CANDELS observations that most galaxies start prolate, becoming spheroids or disks after compaction events

A deep learning code was trained with VELA galaxy images plus metadata describing whether they are pre-compaction, compaction, or post-compaction

The trained deep learning code was able to identify the compaction and post-compaction phases in CANDELized images

The trained deep learning code was also able to identify these phases in real HST CANDELS observations, finding that compaction occurred for stellar mass  $10^{9.5-10.3} M_{\text{sun}}$ , as in the simulations

[James Webb Space Telescope will allow us to do even better](#)

# “Face Recognition for Galaxies”

Huertas-Company,  
Primack, et al. ApJ 2018

**Pre-BN**

**BN**

**Post-BN**

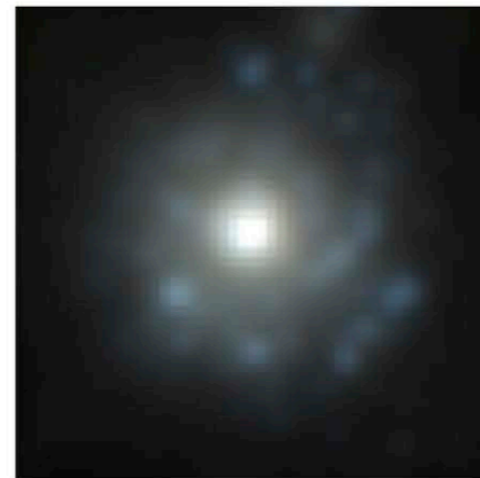
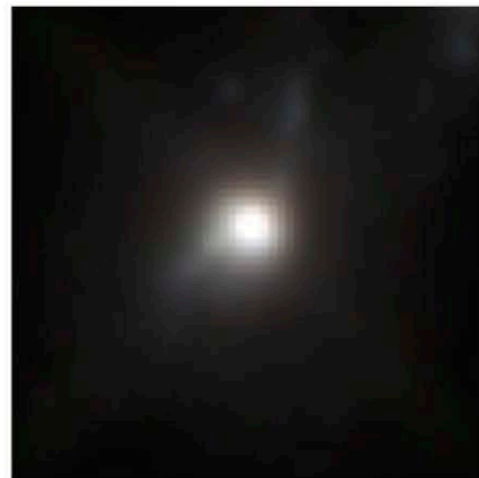
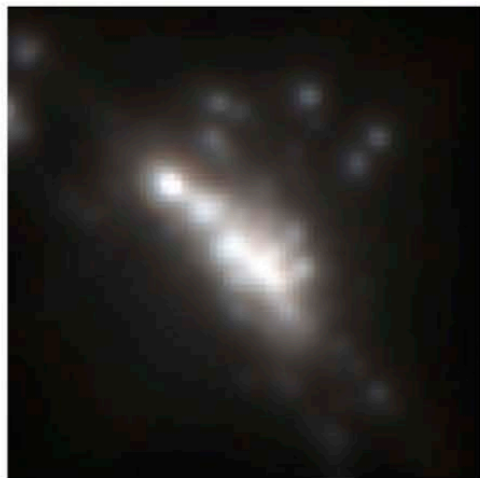
Pre-Blue-Nugget-Stage

Blue-Nugget-Stage

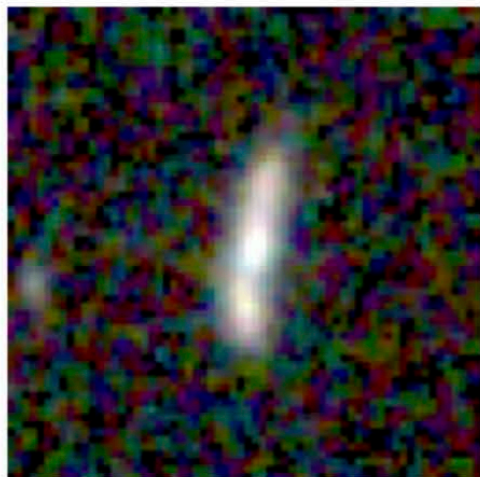
Post-Blue-Nugget-Stage



**VELA High-Res  
Sunrise Images**



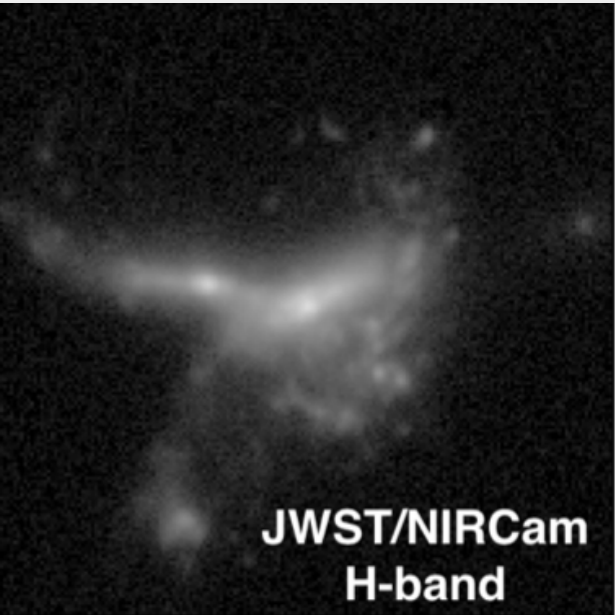
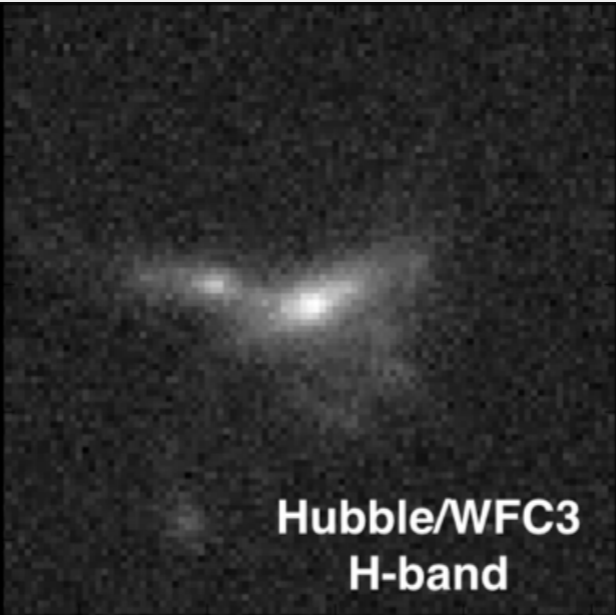
**VELA HST-Res  
Sunrise Images**



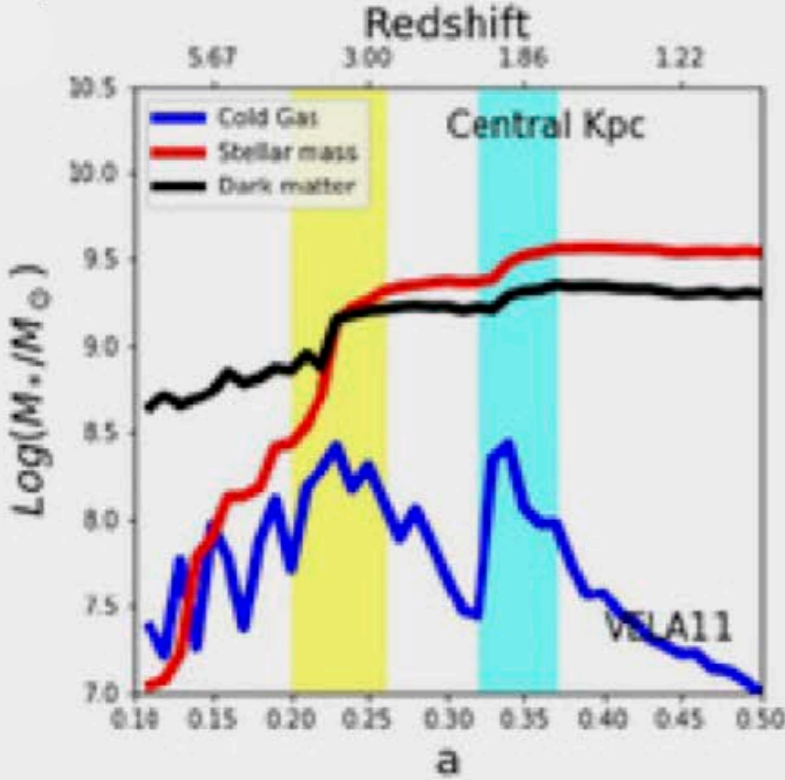
**CANDELS HST  
Images**



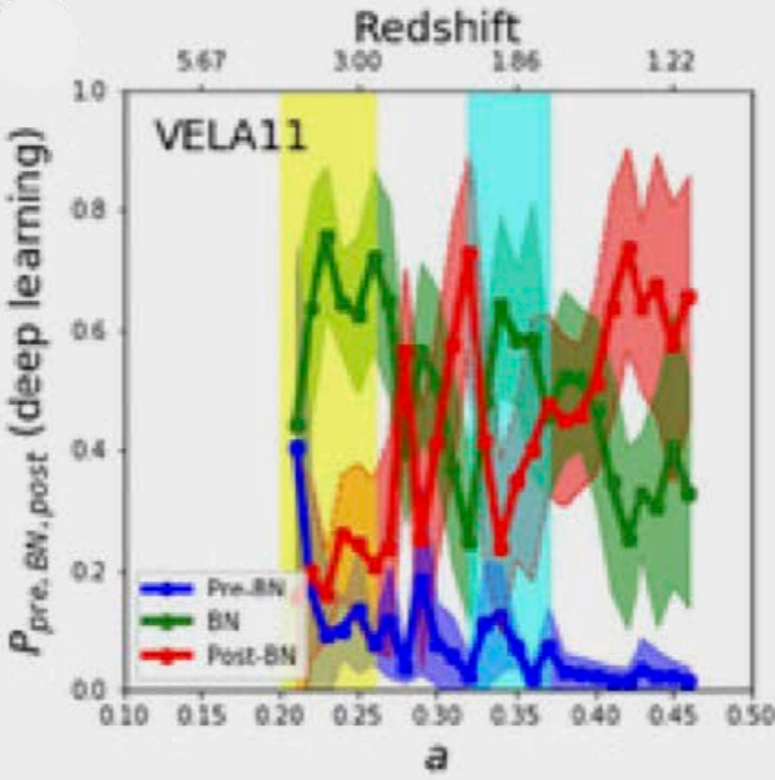
# Convolutional Neural Net (Deep Learning) Galaxy Evolution Phase Determination: HST vs. JWST



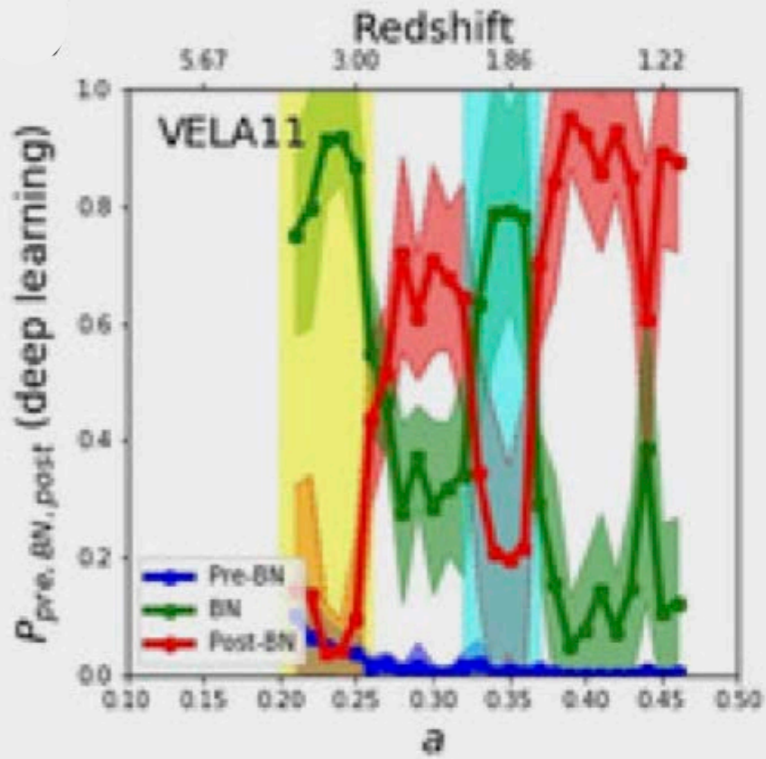
Simulation Metadata



CNN Trained with HST-like  
Images (3 NIR filters)



CNN Trained with JWST-like  
Images (3 NIR filters)



HST = Hubble Space Telescope  
JWST = James Web Space Telescope

Deep learning does much better with JWST images

# Convolutional Neural Net (Deep Learning)

## High-Redshift Galaxy Giant Clumps: HST vs. JWST

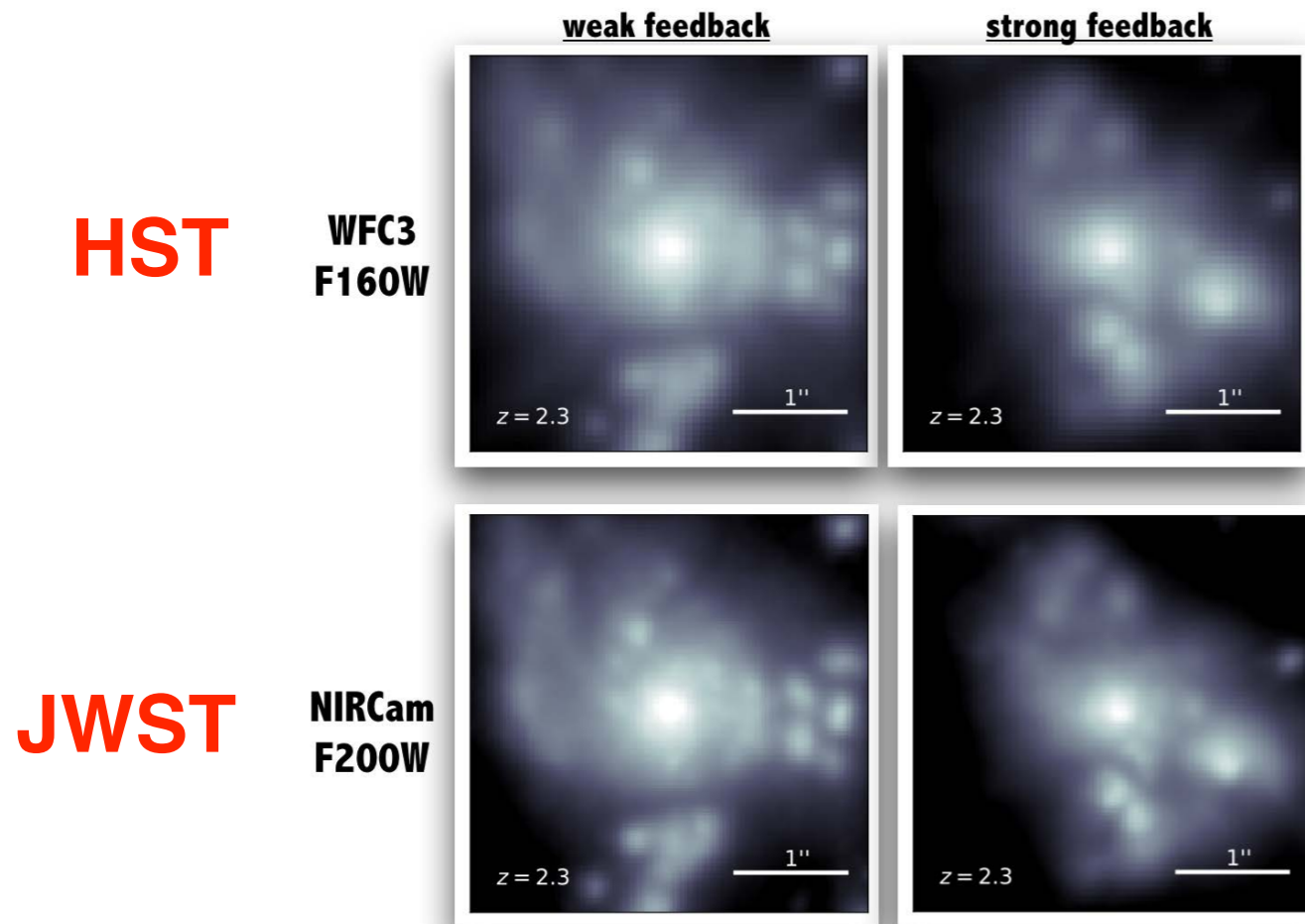
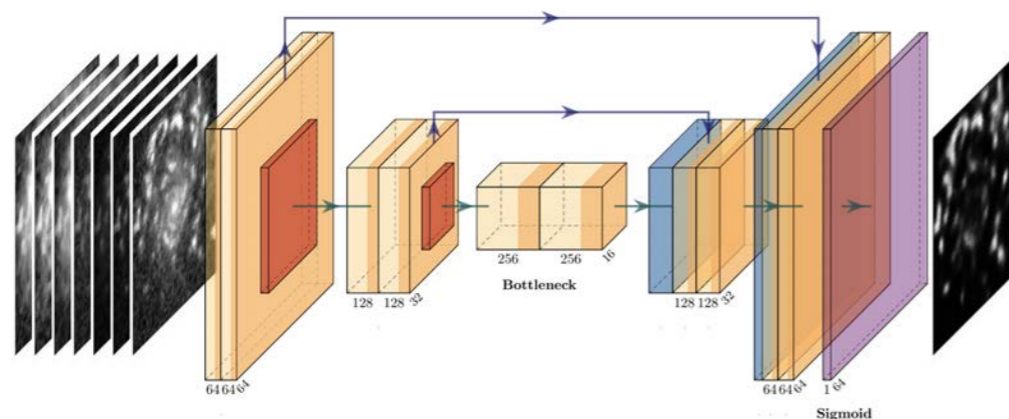
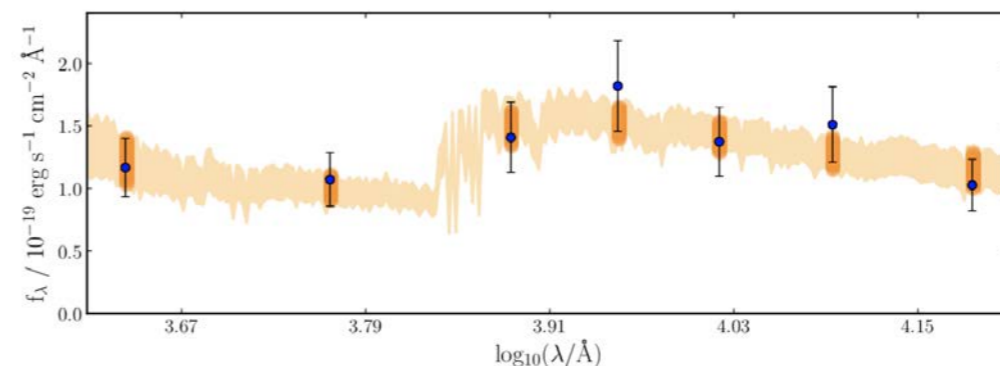


Figure 2: Effect of varying feedback on the frequency and properties of clumps. The figure shows the same VELA galaxy at  $z \sim 2$  simulated with two different feedback strengths (weak: left column, strong: right column). Rows show HST (top) and JWST imaging. More low-mass clumps are observed in a weak feedback regime. The NIRCcam resolution better captures the difference, especially in central regions.



(a)



(b)

Figure 4: Example of (a) clump detection with ML and (b) SED fitting for optical detected clumps in CANDELS. A similar approach will be followed in this program, extending the analysis of clump properties to  $z > 3$ . **(Figures from my JWST proposal.)**

# Vera Rubin Observatory

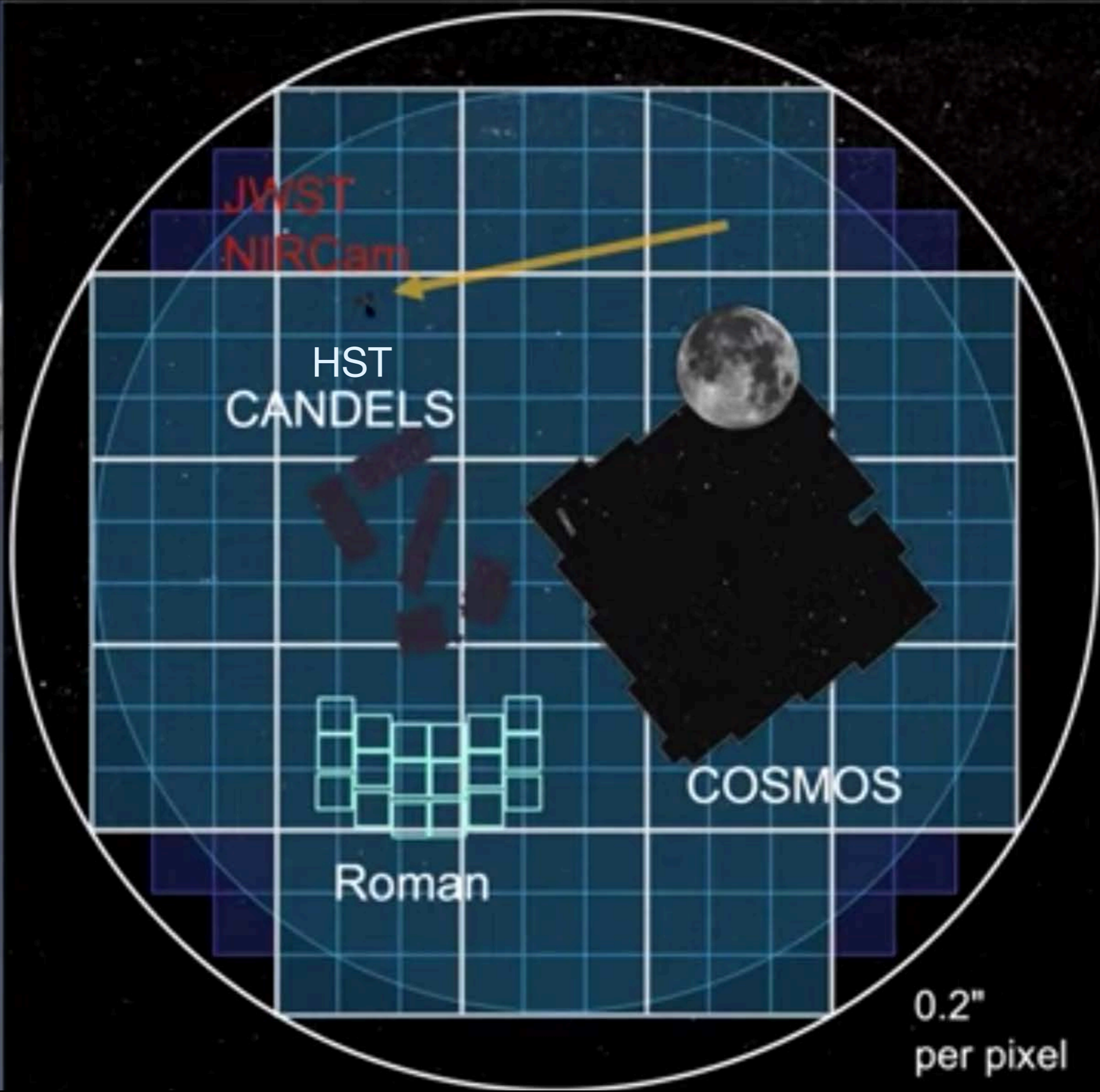


New observatories will have great new capabilities:

JWST - higher res, more light,  $> \lambda$

Roman (WFIRST) - 100x HST area

Rubin (LSST) - all S sky transients, co-added depth



0.2''  
per pixel


# **GALAXIES Research Projects:**

**Run and analyze more high-resolution galaxy simulations**

**Convert them into realistic images, including galaxy substructures**

**Use improved Semi-Analytic Models to predict galaxy populations**

**Compare with images from HST, JWST, Roman Space Telescope and ground-based telescopes including Subaru HSC and Rubin**



# Prof. Joel Primack Research Projects

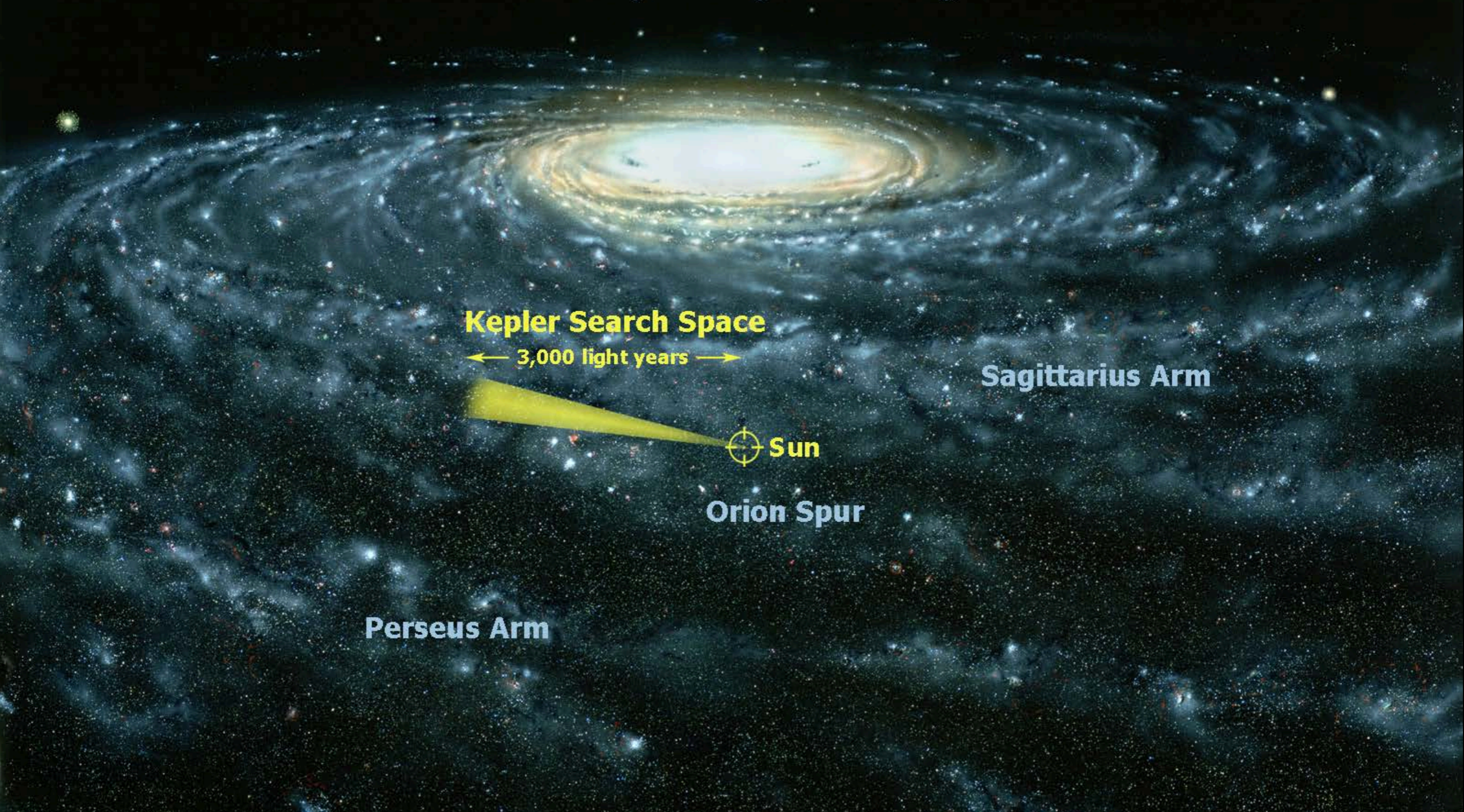
COSMOS

GALAXIES

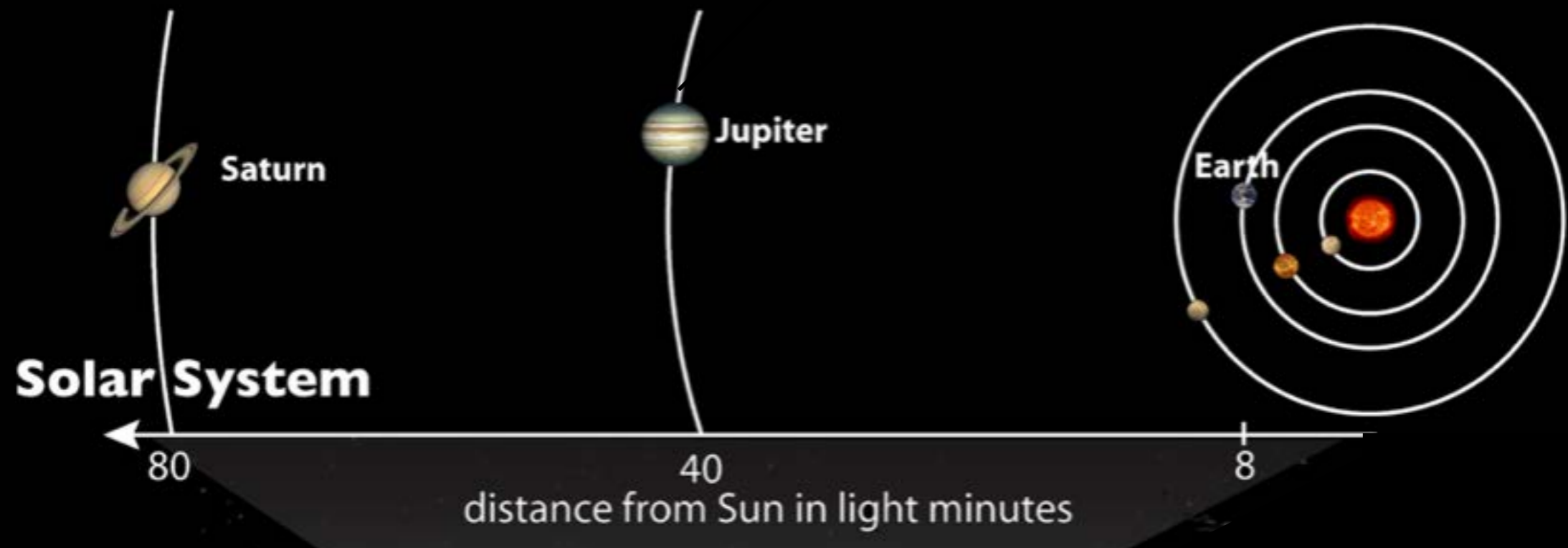
PLANETS

We have now discovered about 4000 planetary systems, mainly using star radial velocities from ground-based telescopes and planet-star transits observed by NASA's satellites Kepler and TESS.

# Milky Way Galaxy



We used to think that our system is typical, with rocky planets near our star and gas giants farther away.



There may be **galactic habitable zones** — not too close to galaxy centers where there are frequent supernovae, nor too far where metals (elements beyond He) may be too rare to form rocky planets.

Of the ~ 4000 planetary systems astronomers have discovered, there are very few like ours, with all the planets widely spaced in nearly circular orbits. Most planetary systems are much smaller.

The most common type of planet seems to be 2 to 6 times Earth's mass, a "**super-Earth**". No such planet exists in our Solar System.

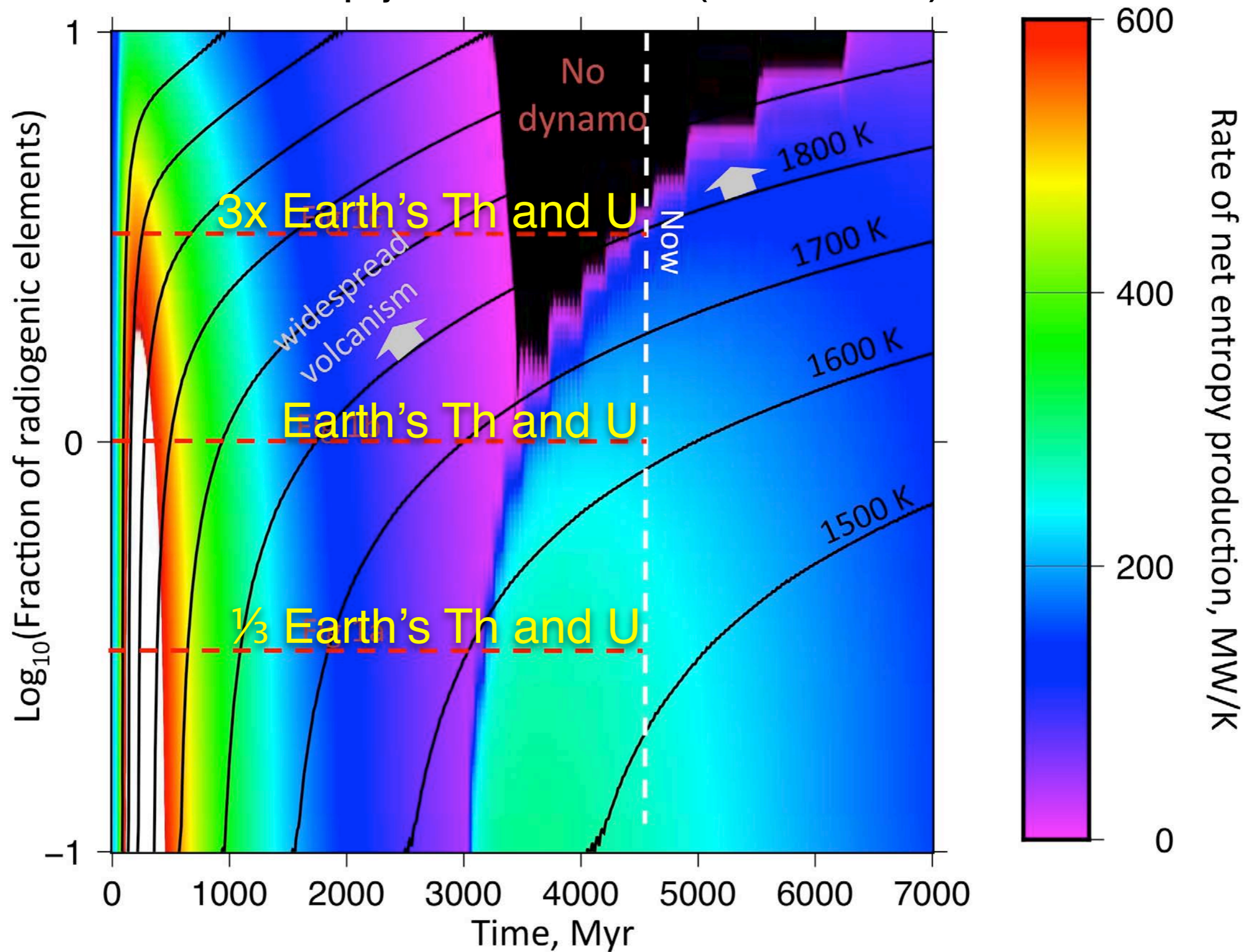
Some planets are in the **habitable zone around their stars** in which water would be in liquid form, but most of these planets are probably not hospitable to advanced forms of life. For one thing, they might not have an optimal abundance of the long-lived radioactive elements thorium and uranium to power a magnetic dynamo and plate tectonics. Too much Th and U would result in a lava world with frequent flood volcanism, which caused the greatest mass extinction events on Earth. **Our living Earth may be a rare "Goldilocks" planet** with just the right amount of Th and U.



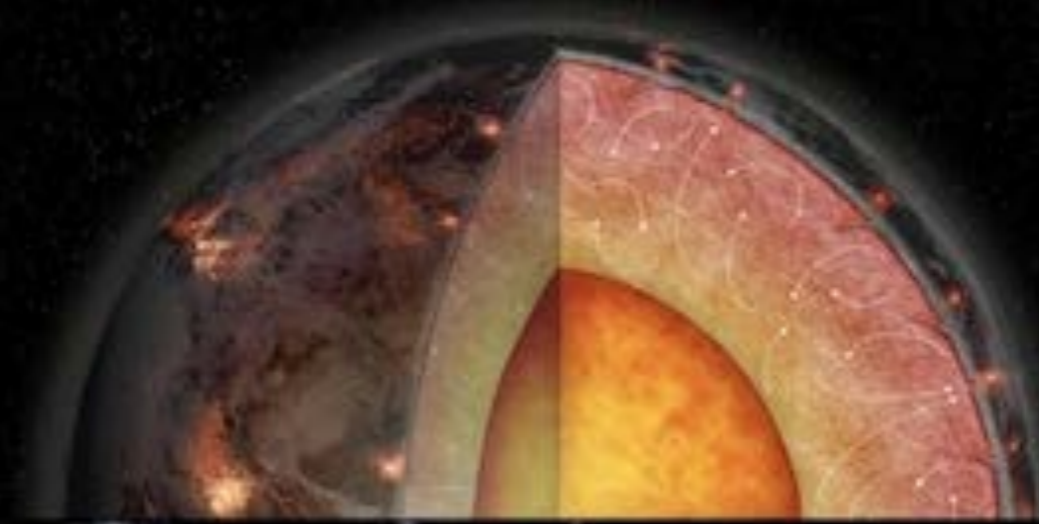
# Radiogenic Heating and its Influence on Rocky Planet Dynamos and Habitability

Francis Nimmo, Joel Primack, S. M. Faber, Enrico Ramirez-Ruiz, and Mohammadtaher Safarzadeh

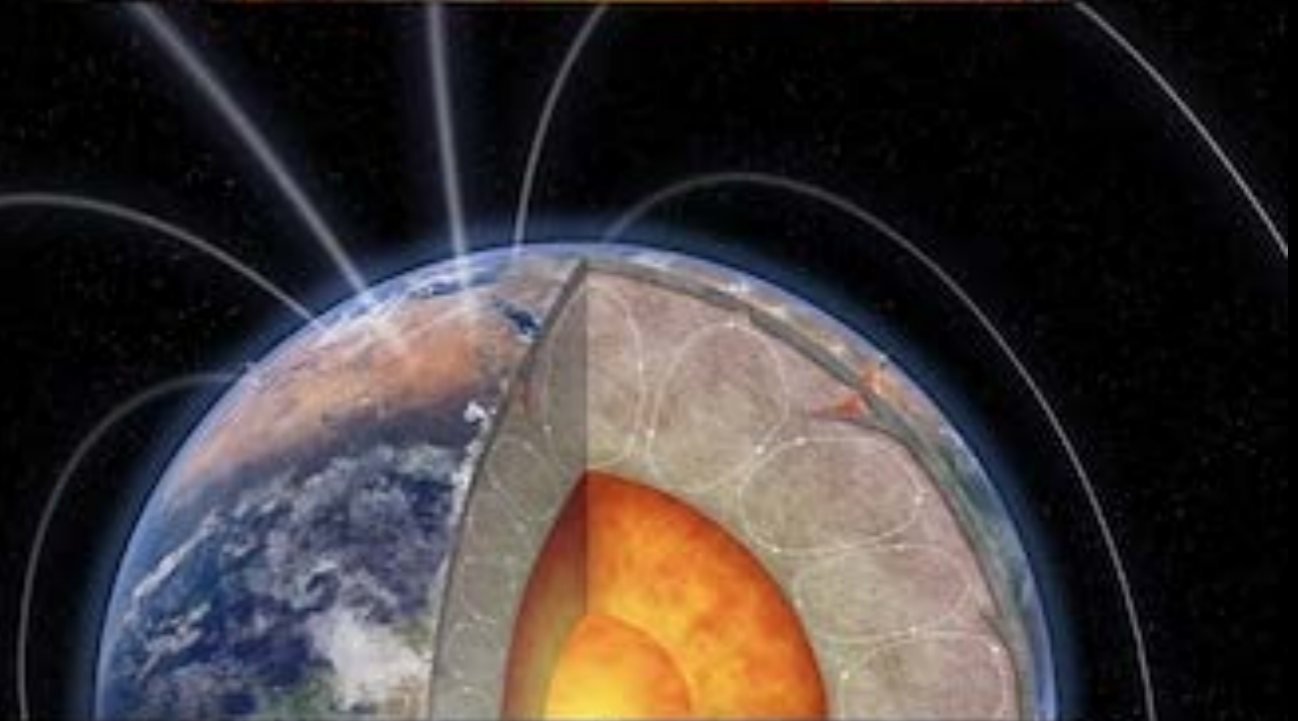
Astrophysical Journal Letters (November 2020)



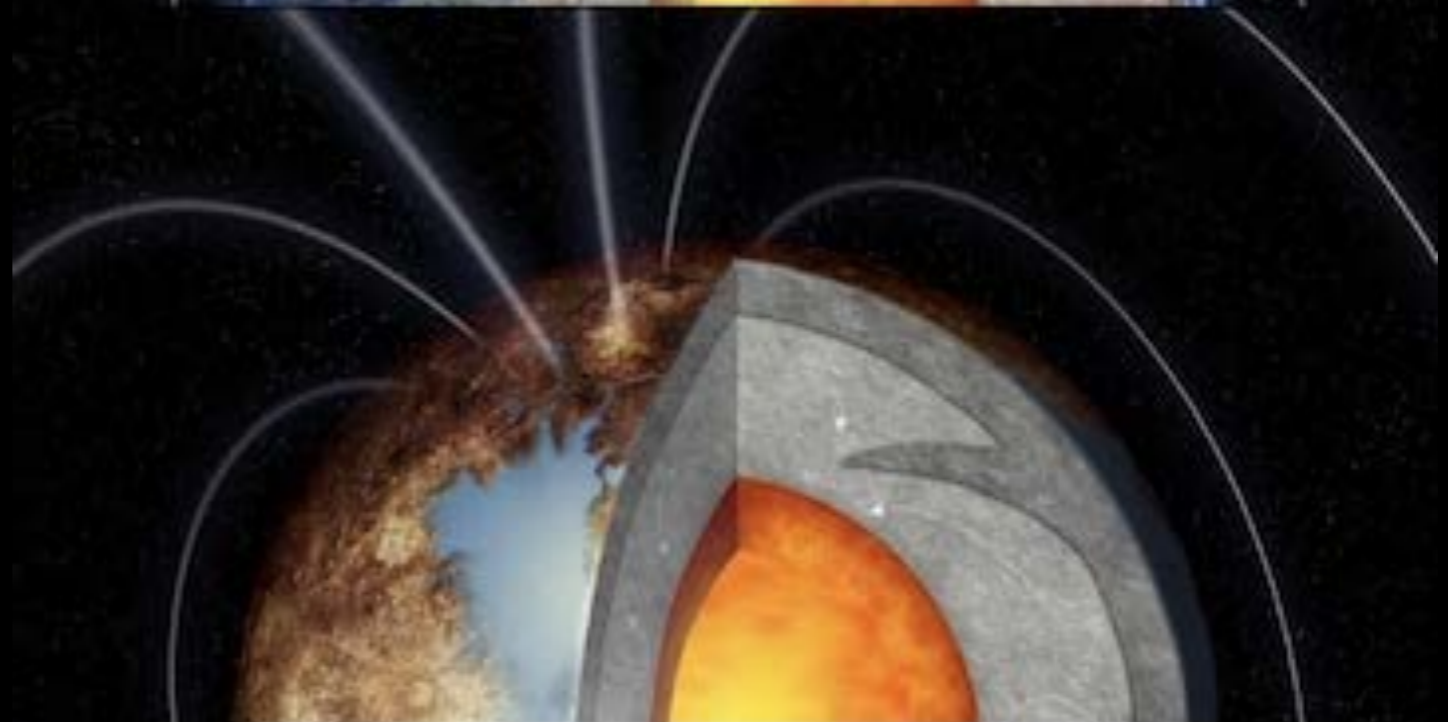
**3x Earth's Th and U**  
No magnetic dynamo &  
frequent flood volcanism



**Earth's Th and U**  
Magnetic dynamo &  
plate tectonics



**1/3 Earth's Th and U**  
Magnetic dynamo  
but no plate tectonics



# Periodic Table of the Elements

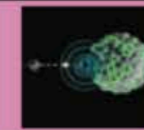
1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu											

short-lived radioactive isotopes; nothing left from stars

Big Bang fusion



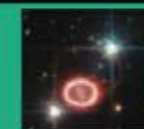
cosmic ray fission



merging neutron stars?



exploding massive stars



dying low-mass stars



exploding white dwarfs

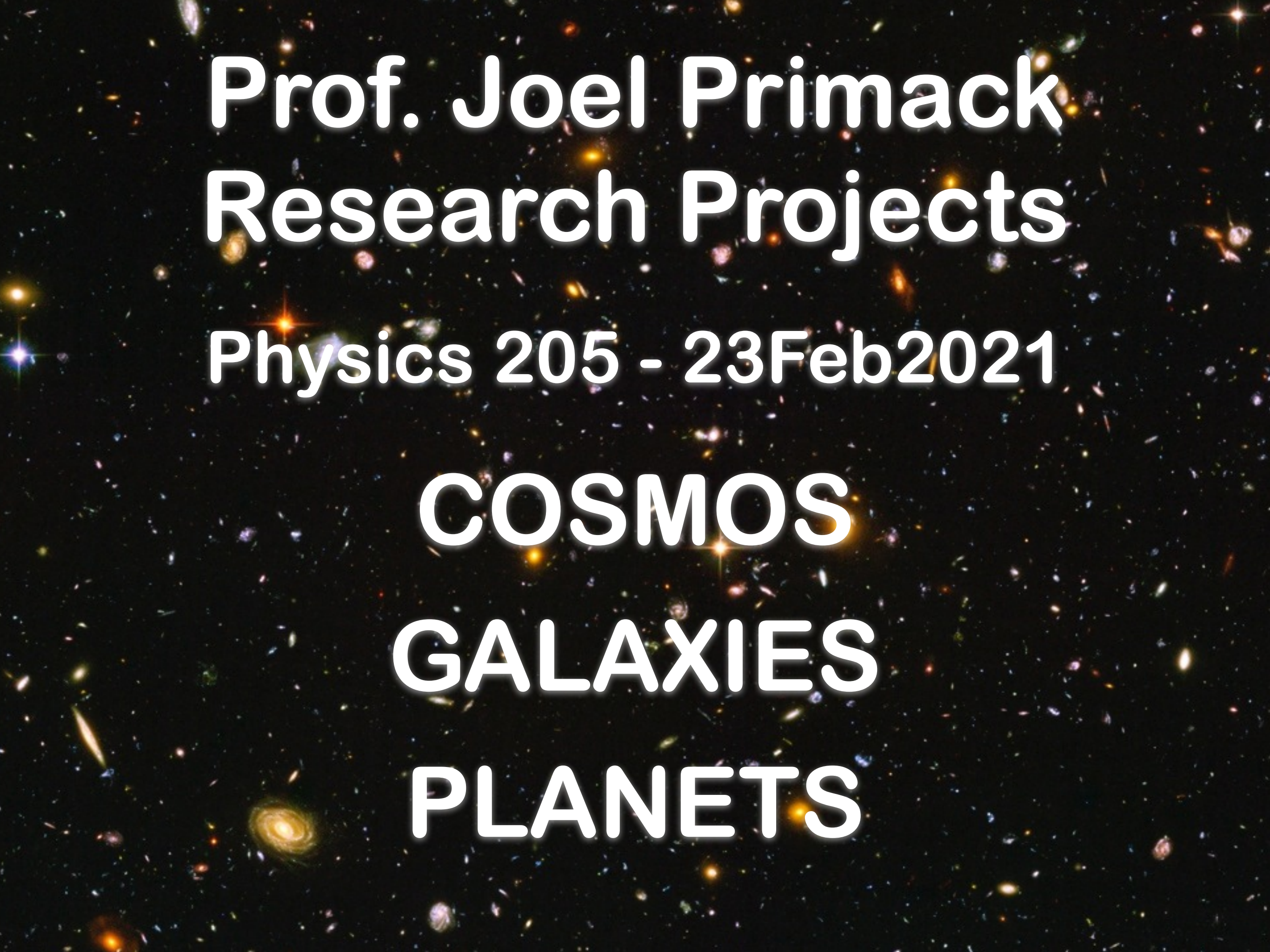


# PLANETS Research Projects:

Predict radioactive heating habitability of rocky exoplanets using their star's Europium abundance

Run 2D and 3D simulations of rocky planets, to verify and improve on our 1D modeling

Examine other long-term constraints on habitability of rocky planets: changes in orbits, obliquity, effects of supernovas ...



**Prof. Joel Primack  
Research Projects**

**Physics 205 - 23Feb2021**

**COSMOS**

**GALAXIES**

**PLANETS**

# Some Concluding Thoughts

## **Without Dark Matter We Wouldn't Exist**

With only the ordinary matter, the universe would be a low-density featureless soup

Dark matter started to form structures very early

Galaxies formed within bound “halos” of dark matter

Stars formed within galaxies, and stars made elements beyond hydrogen and helium: carbon, oxygen, ...

Rocky planets formed from these heavier elements

Life began and evolved on one such planet

***Dark matter is our ancestor and our friend!***

## **Science Is Much Stranger Than Fiction**

Before the discovery that most of the density of the universe is invisible, no one imagined this

***What else remains to be discovered?***

## Joel Primack RECENT PhD STUDENTS

**Rachel Somerville** (PhD 1997) Jerusalem (postdoc) – Cambridge (postdoc) – Michigan (Asst. Prof.) – MPI Astronomy Heidelberg (Professor) – STScI/Johns Hopkins – Rutgers (Professor)

**Michael Gross** (PhD 1997) Goddard (postdoc) – UCSC (staff) – NASA Ames (staff)

**James Bullock** (PhD 1999) Ohio State – Harvard ([Hubble Fellow](#)) – UC Irvine (Professor, Dean)

**Ari Maller** (PhD 1999) Jerusalem – U Mass Amherst (postdoc) – CityTech CUNY (Assoc. Prof.)

**Risa Wechsler** (PhD 2001) Michigan – Chicago ([Hubble Fellow](#)) – Stanford U (Prof., KIPAC Dir.)

**T. J. Cox** (PhD 2004) – Harvard (postdoc, Keck Fellow) – Carnegie Observatories (postdoc) – Data Scientist at Voxer, San Francisco – Data Scientist at Apple, Cupertino

**Patrik Jonsson** (PhD 2004) UCSC (postdoc) – Harvard CfA (staff) – SpaceX Senior Programmer

**Brandon Allgood** (PhD 2005) – Numerate, Inc. (co-founder)

**Matt Covington** (PhD 2008) – analytic understanding of galaxy mergers, semi-analytic models of galaxy formation – U Minn (postdoc) – U Arkansas (Assoc. Prof. of Geology)

**Greg Novak** (PhD 2008) – running and comparing galaxy merger simulations with observations – Princeton (postdoc) – Inst Astrophysique de Paris (postdoc) – Data Scientist at Stitch Fix

**Christy Pierce** (PhD 2009) – AGN in galaxy mergers – Georgia Tech (postdoc) – teaching

**Rudy Gilmore** (PhD 2009) – WIMP properties and annihilation; extragalactic background light and gamma ray absorption – SISSA, Trieste, Italy (postdoc) – Data Scientist at TrueCar, L.A.

**Alberto Dominguez** (PhD 2011) – UCR (postdoc), Clemson (postdoc), Madrid (postdoc)

**Lauren Porter** (PhD 2013) – semi-analytic predictions vs. observations – Data Sci at Facebook

**Chris Moody** – analysis of high-resolution galaxy simulations: galaxy morphology transformations (PhD 2014) – Data Scientist at Square – Chief Data Scientist at Stitch Fix, San Francisco

**Christoph Lee** (PhD 2019) – galaxy simulations vs. observations with AI – Data Sci at Outschool

**David Reiman** (PhD 2020) – astrophysics deep learning applications – AI Scientist at DeepMind

## Joel Primack CURRENT PhD STUDENTS

**Viraj Pandya** – semi-analytic models compared with observations (with Rachel Somerville)

**Clayton Strawn** – circumgalactic medium: simulations vs. observations

**James Kakos** – combining spectroscopic & photometric redshifts with SORT