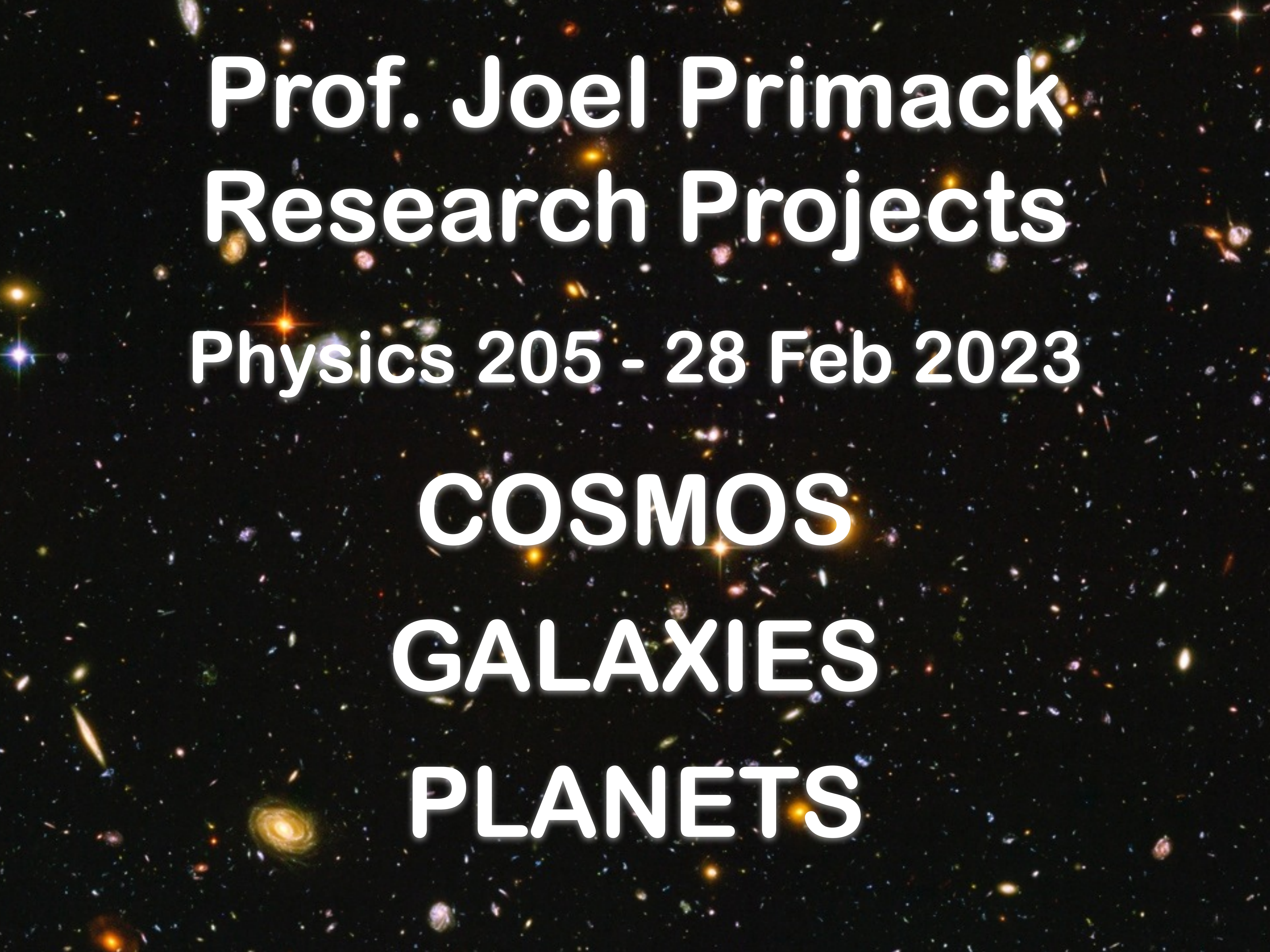


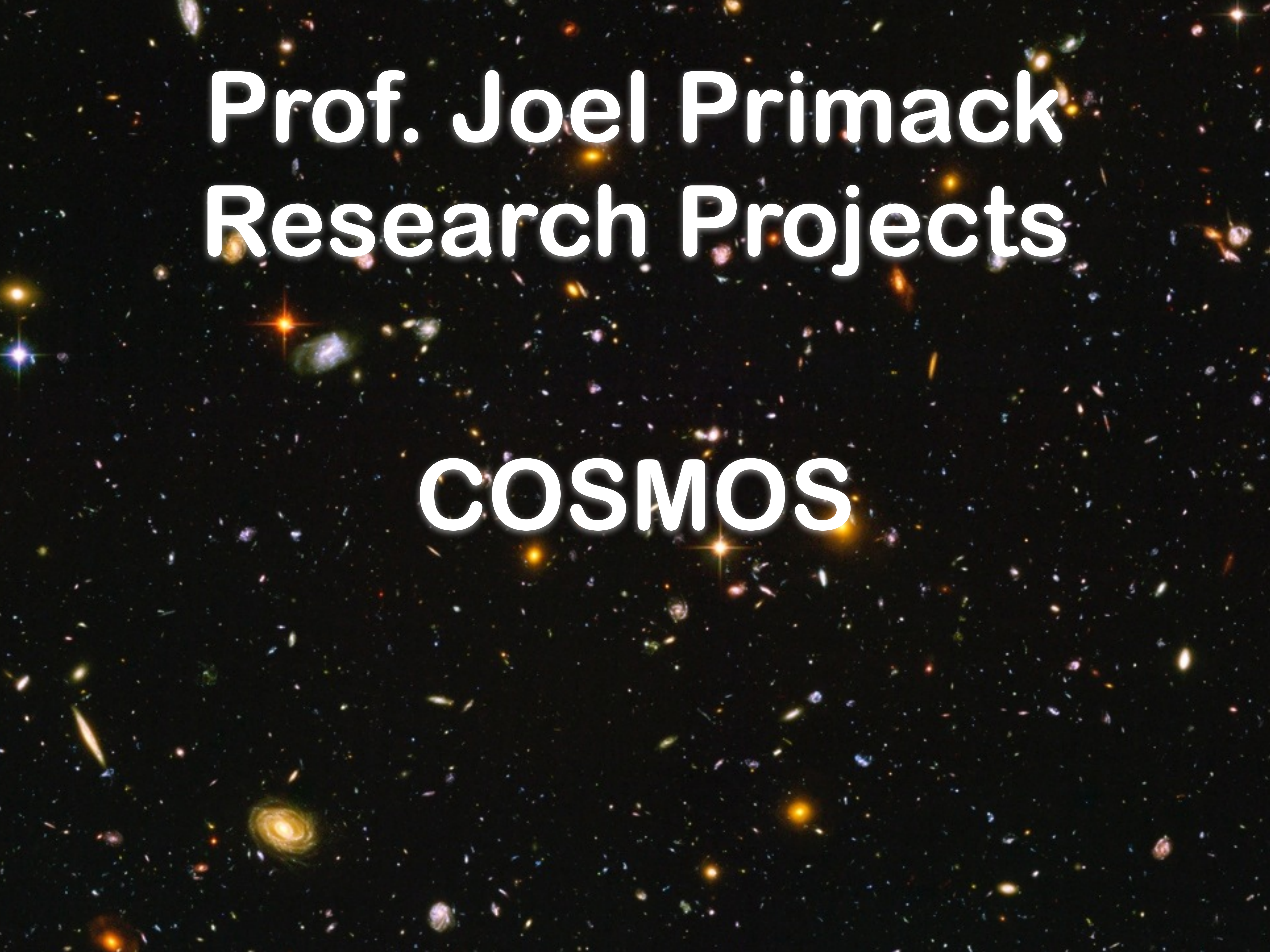
Prof. Joel Primack Research Projects

Physics 205 - 28 Feb 2023

COSMOS

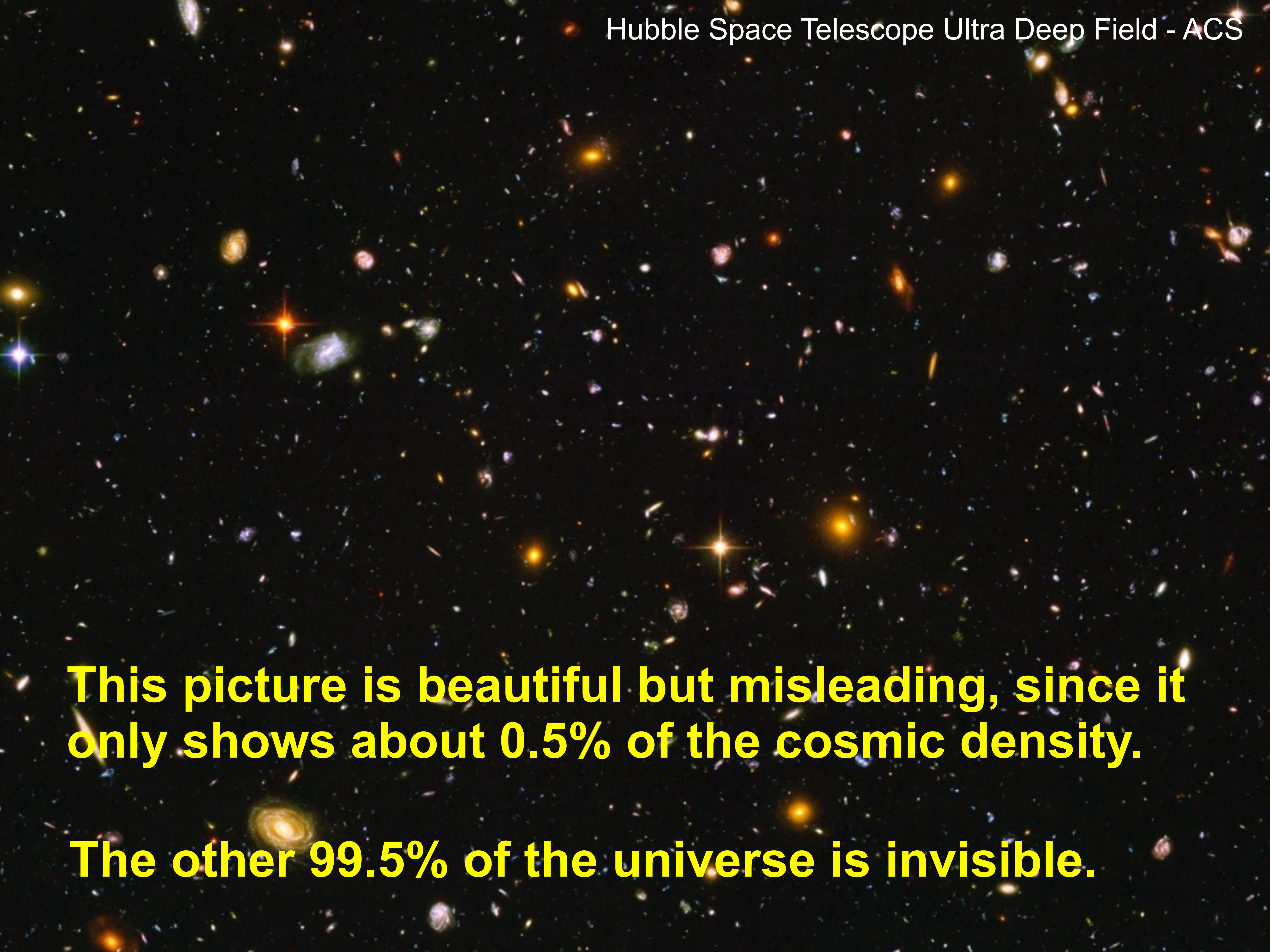
GALAXIES

PLANETS



Prof. Joel Primack Research Projects

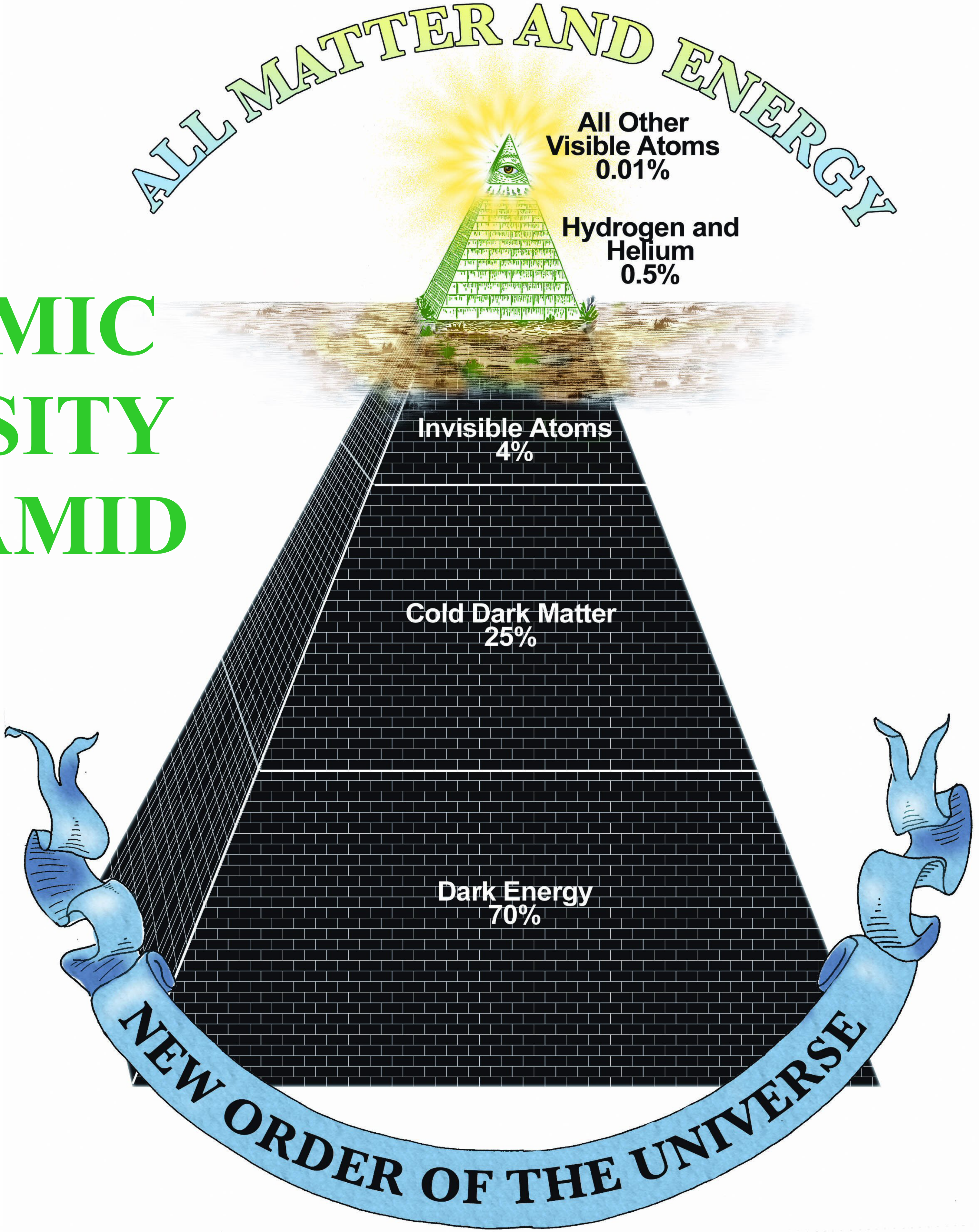
COSMOS



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.

COSMIC DENSITY PYRAMID



ALL MATTER AND ENERGY

All Other Visible Atoms 0.01%

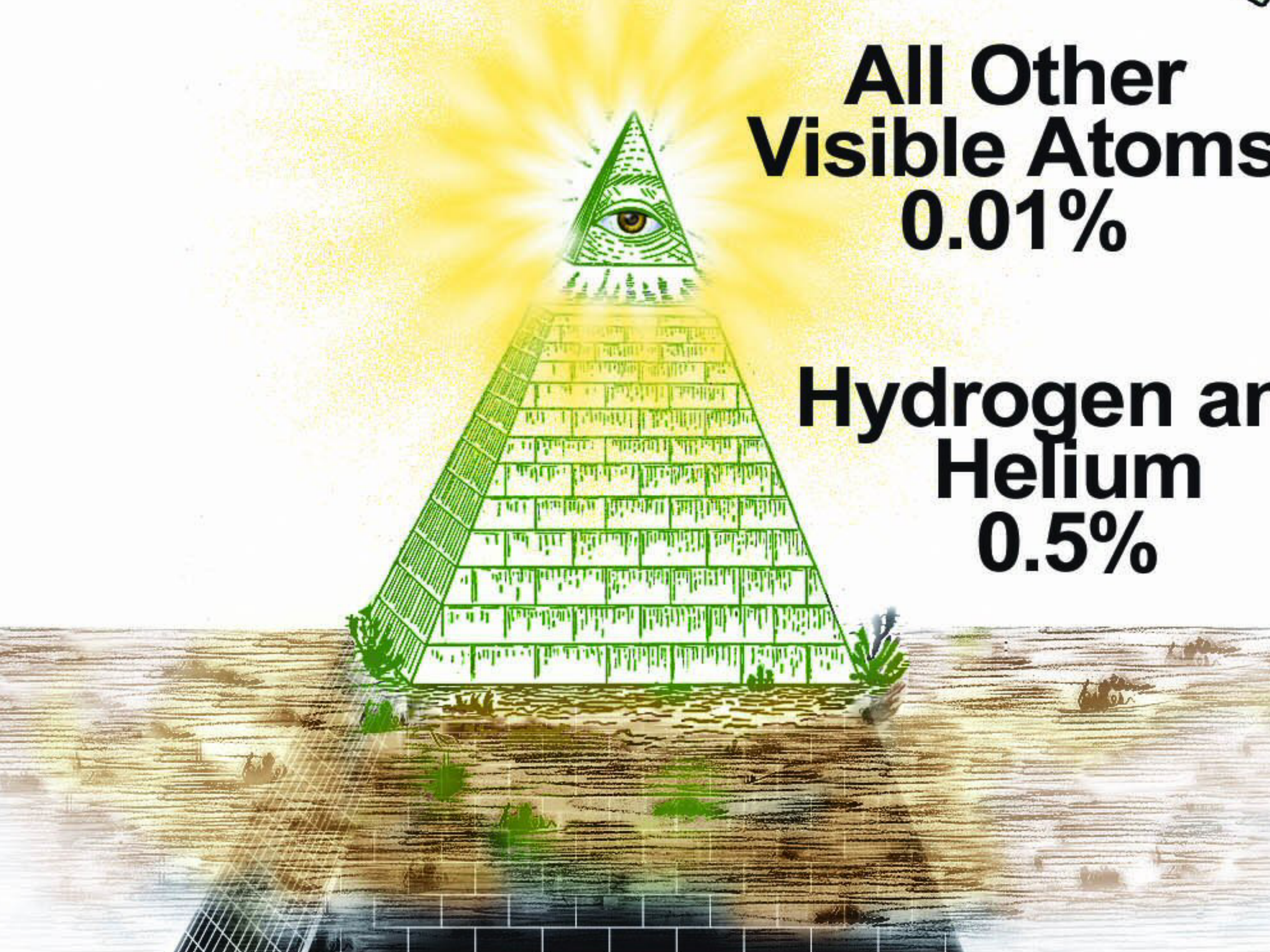
Hydrogen and Helium 0.5%

Invisible Atoms 4%

Cold Dark Matter 25%

Dark Energy 70%

NEW ORDER OF THE UNIVERSE



All Other Visible Atoms 0.01%

Hydrogen an 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

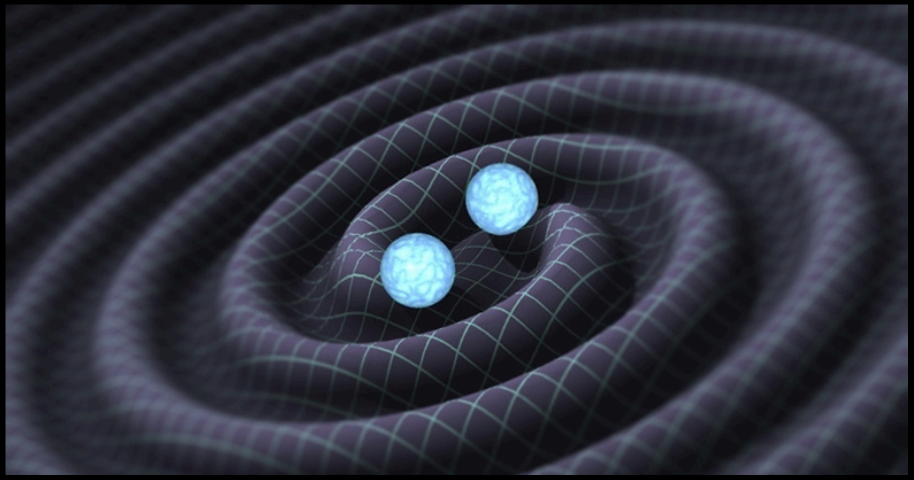
dying low-mass stars

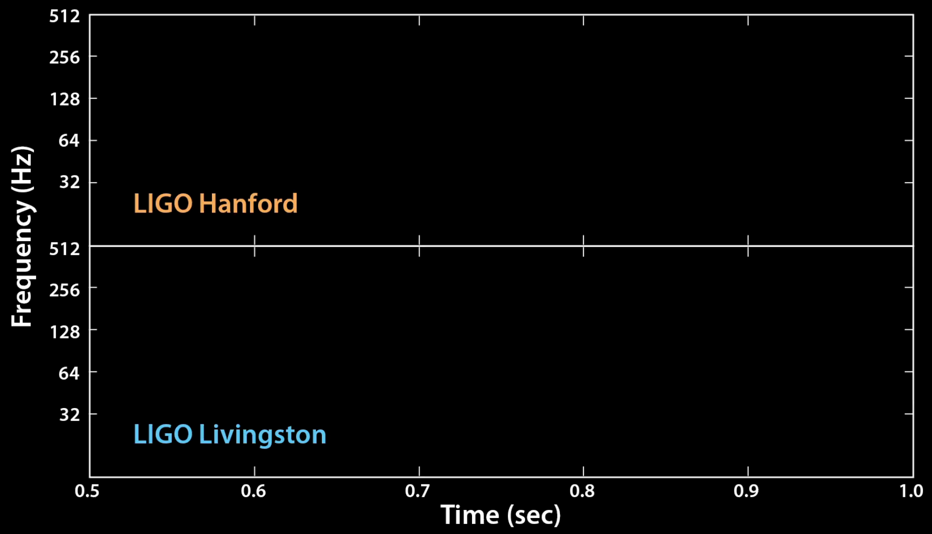
exploding white dwarfs

stardust

stars

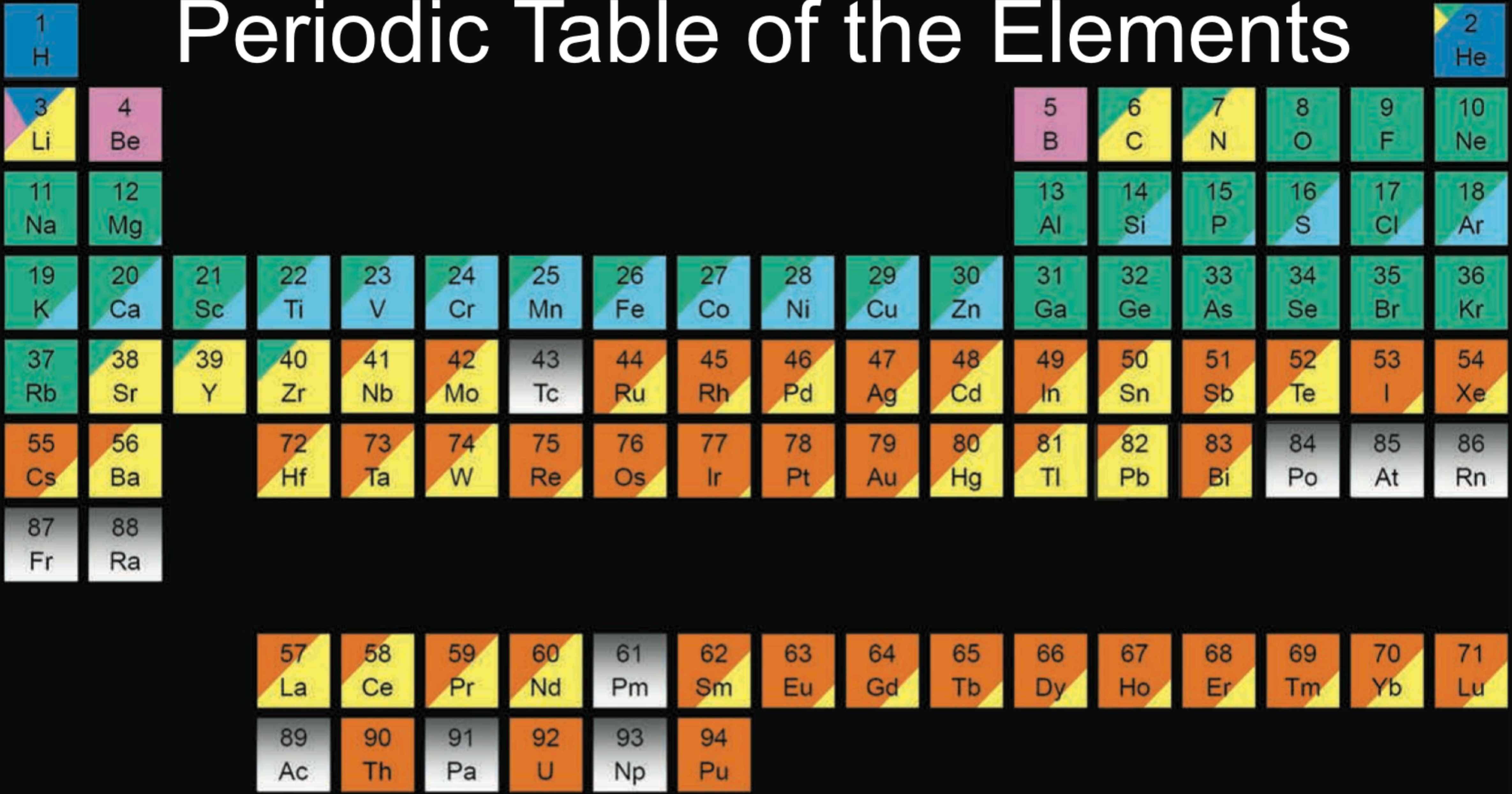
Many stars in the very early universe may have been much more massive than our sun, in binary star systems with other massive stars. When these stars ended their lives as supernovas, they became massive black holes or neutron stars. The Laser Interferometer Gravitational-wave Observatory (LIGO) has now 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



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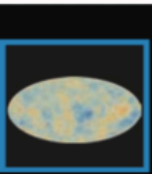
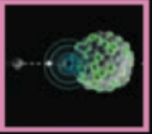
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 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



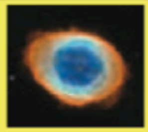
cosmic ray fission



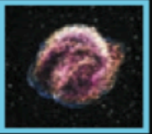
merging neutron stars?

exploding massive stars

dying low-mass stars



exploding white dwarfs

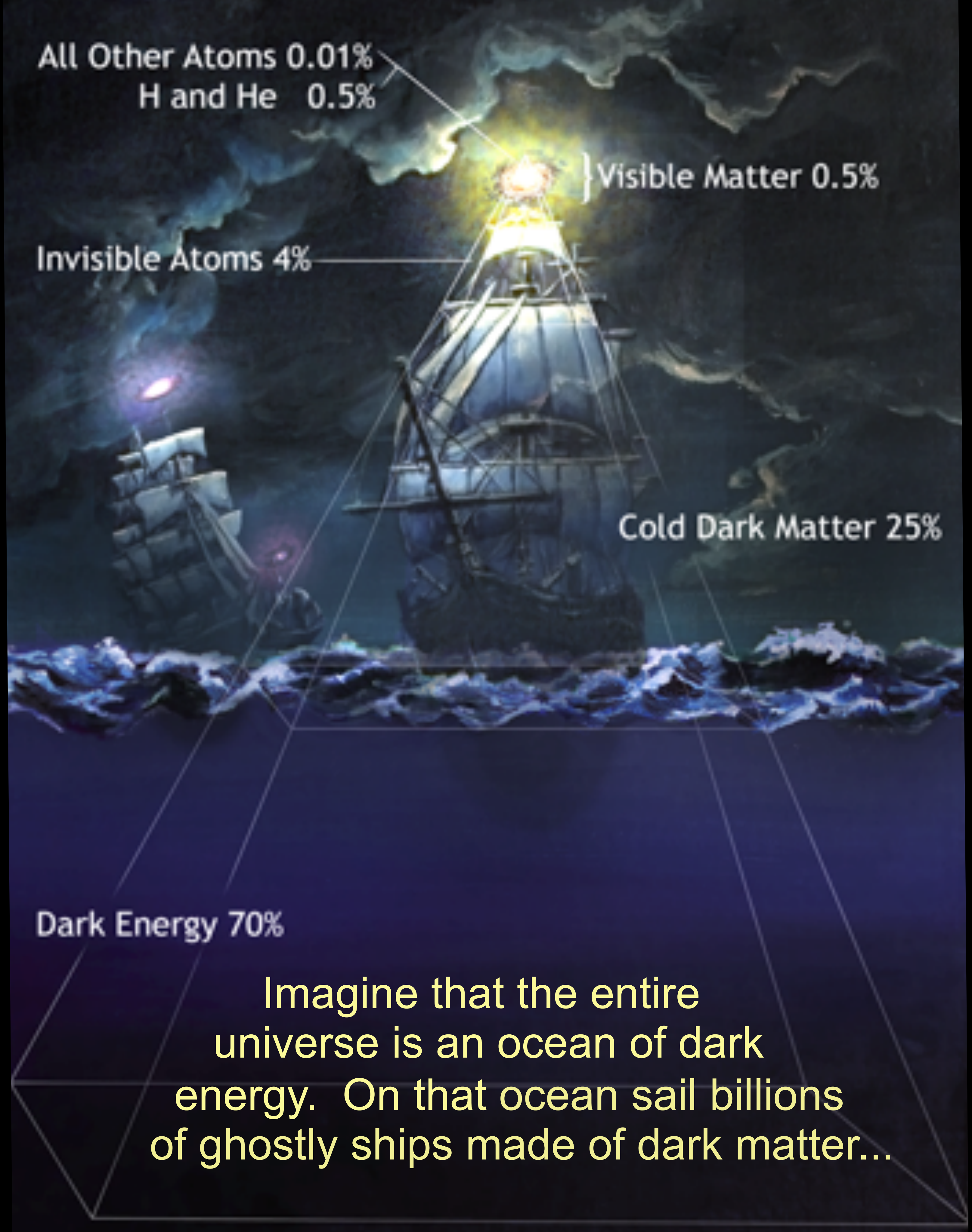


Matter and Energy Content of the Universe

Dark Matter Ships

on a

Dark Energy Ocean

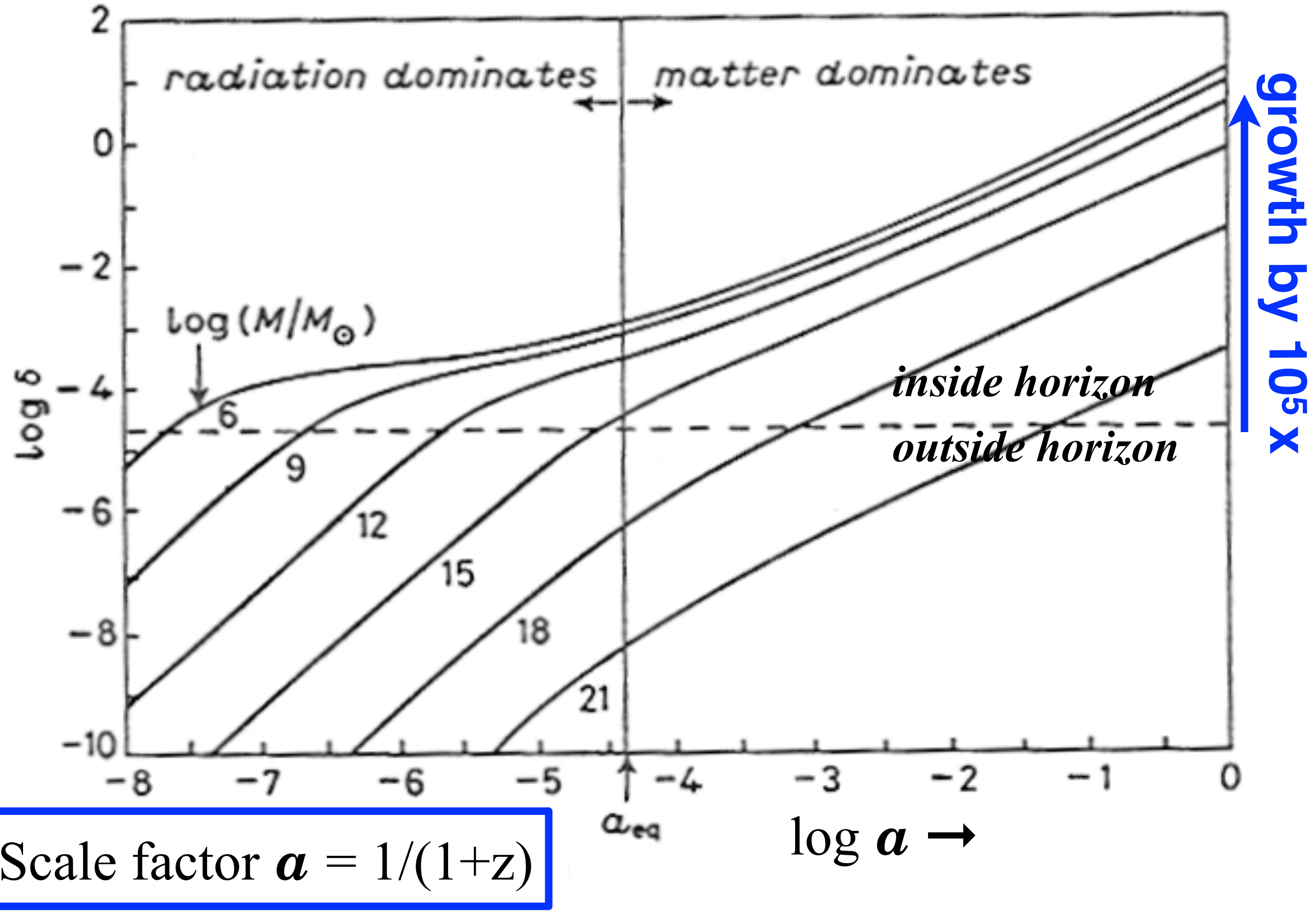


Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

ΛCDM

Double Dark Theory

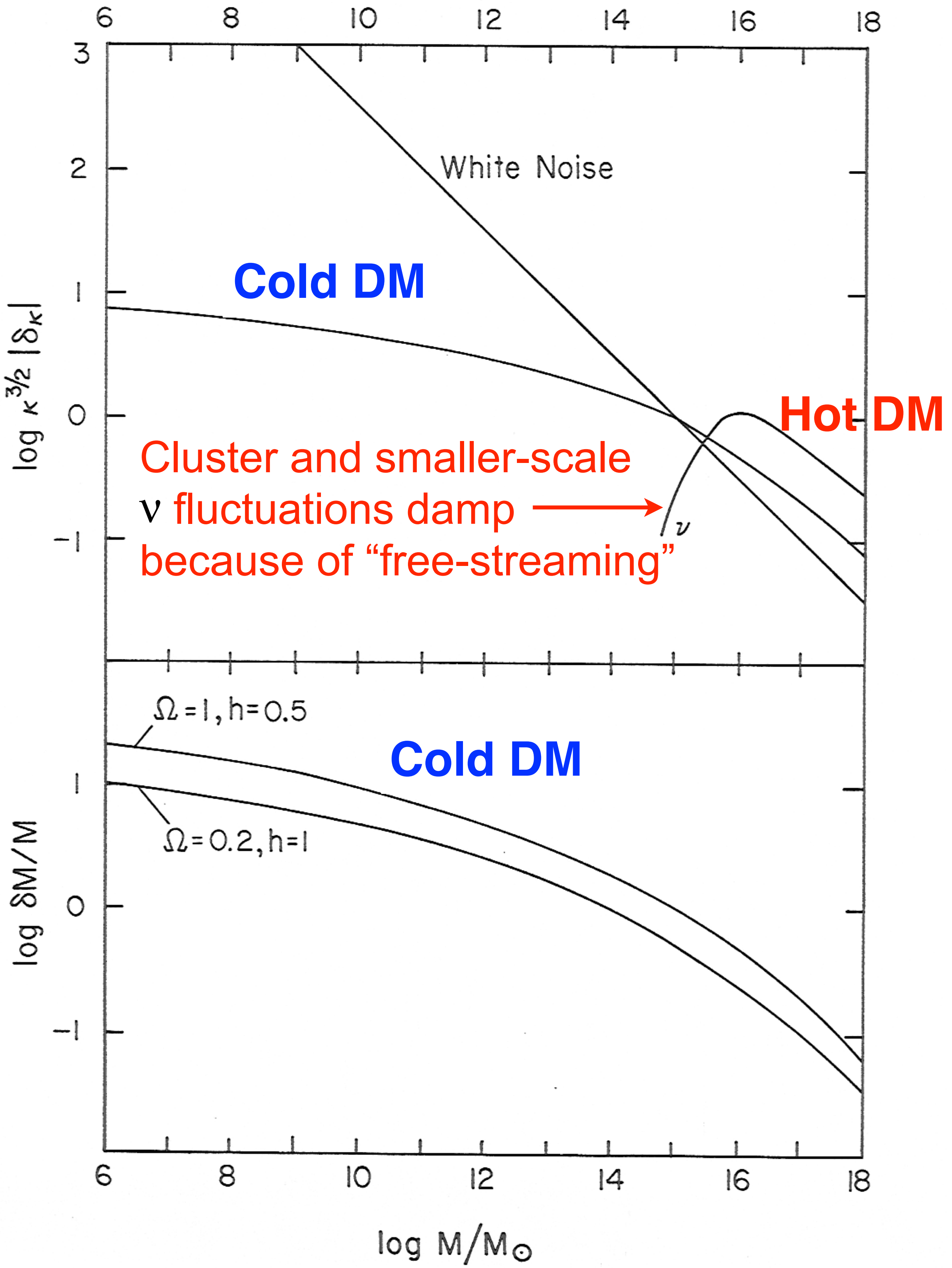
CDM Structure Formation: Linear Theory



Scale factor a = 1/(1+z)

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



Cluster and smaller-scale
ν fluctuations damp →
because of "free-streaming"

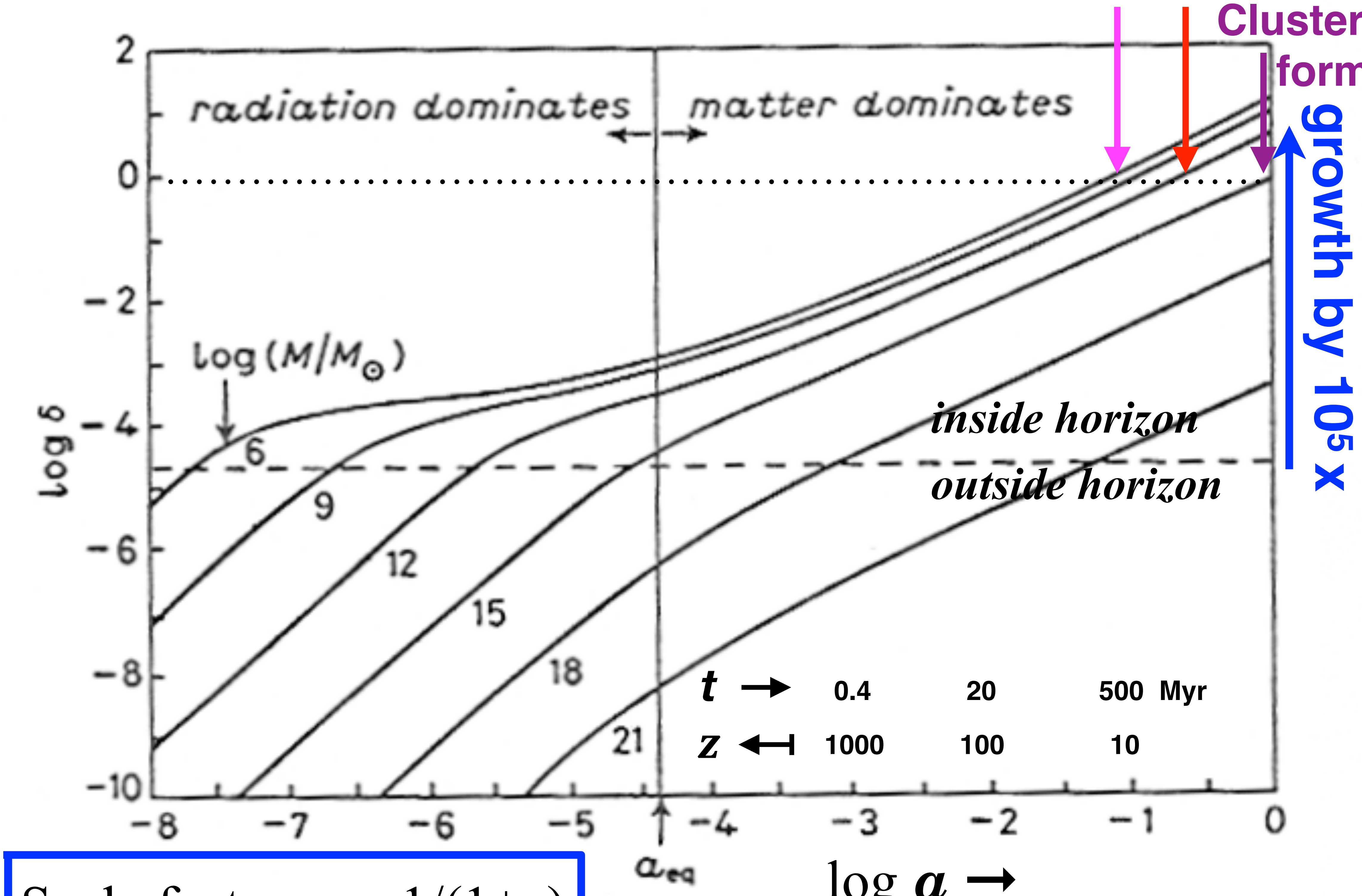
Blumenthal, Faber, Primack, & Rees 1984

CDM Structure Formation

Dwarf galaxies start forming

Milky Way mass galaxies start forming

Clusters start forming

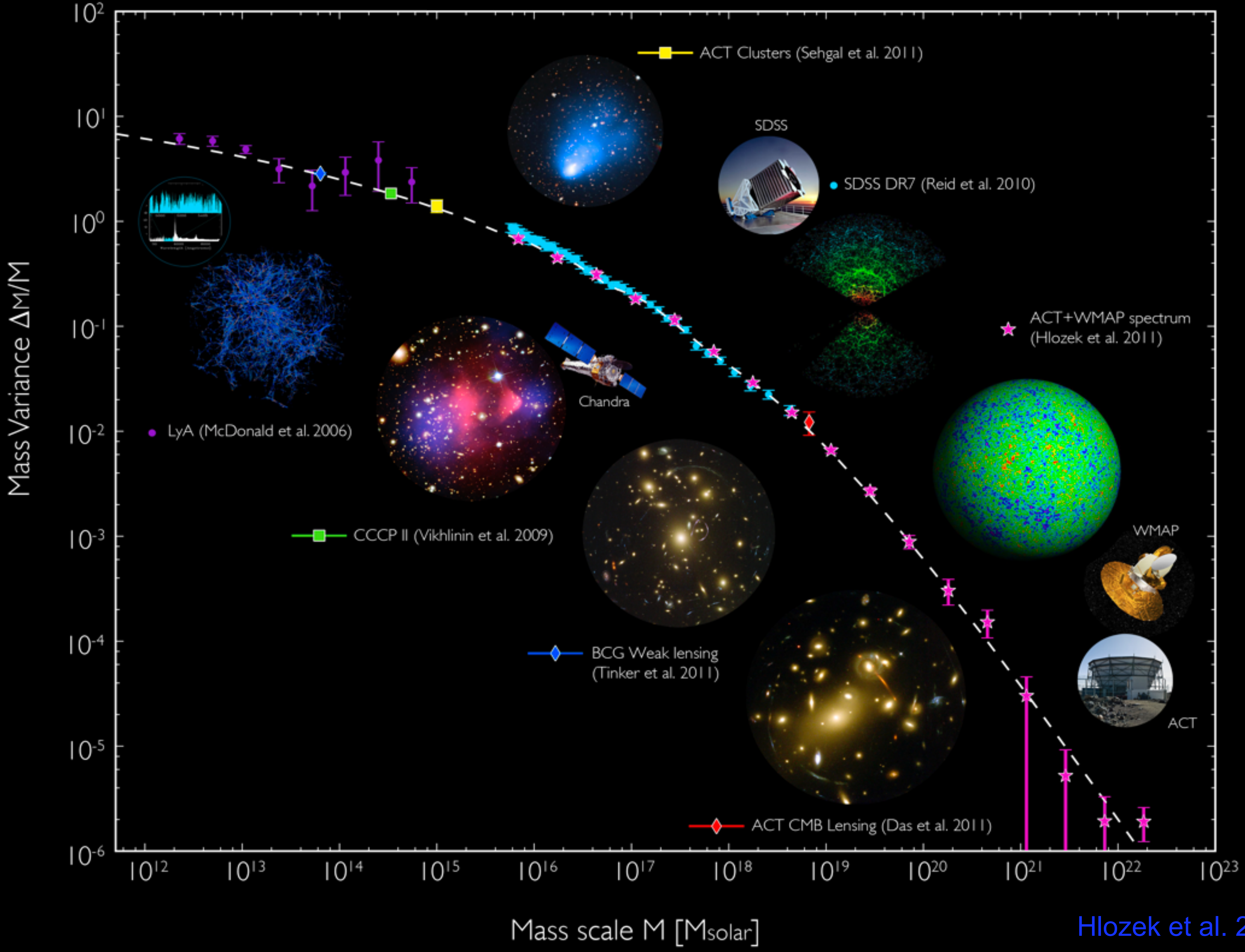


t → 0.4 20 500 Myr

z ↤ 1000 100 10

Scale factor ***a*** = 1/(1+z)

Matter Distribution Agrees with Double Dark Theory!

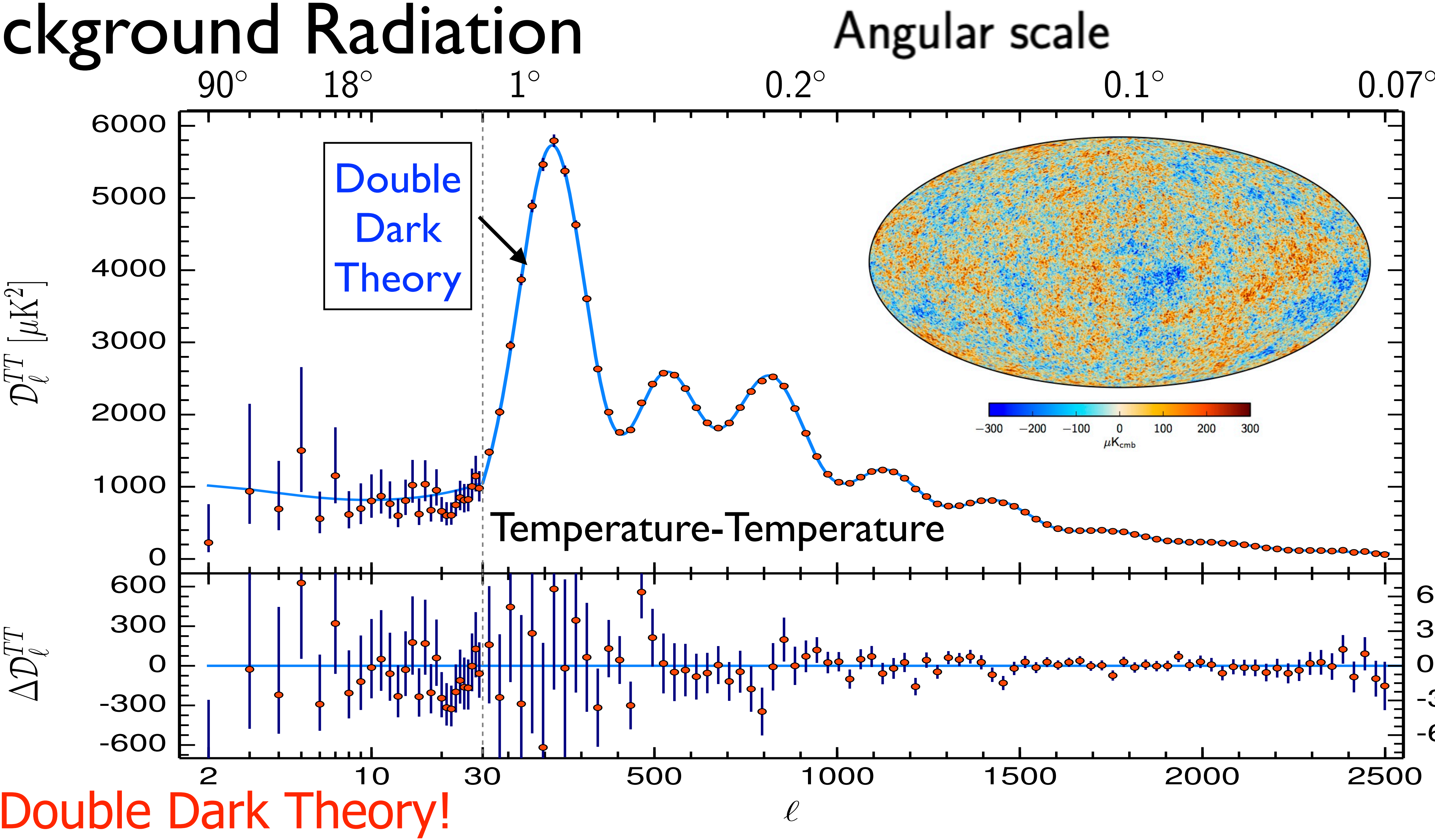


Hlozek et al. 2012

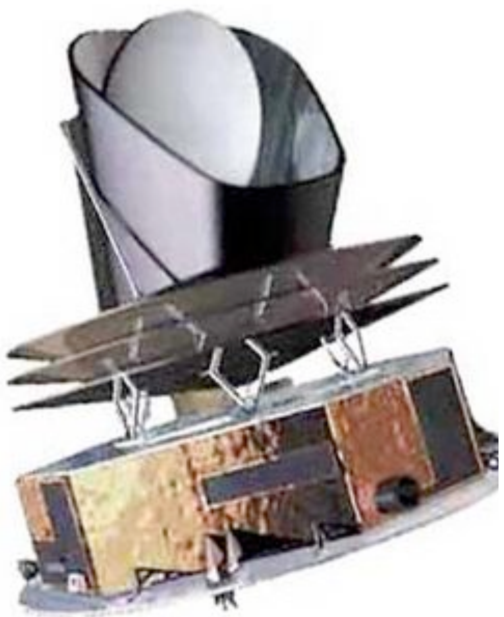
Cosmic Background Radiation

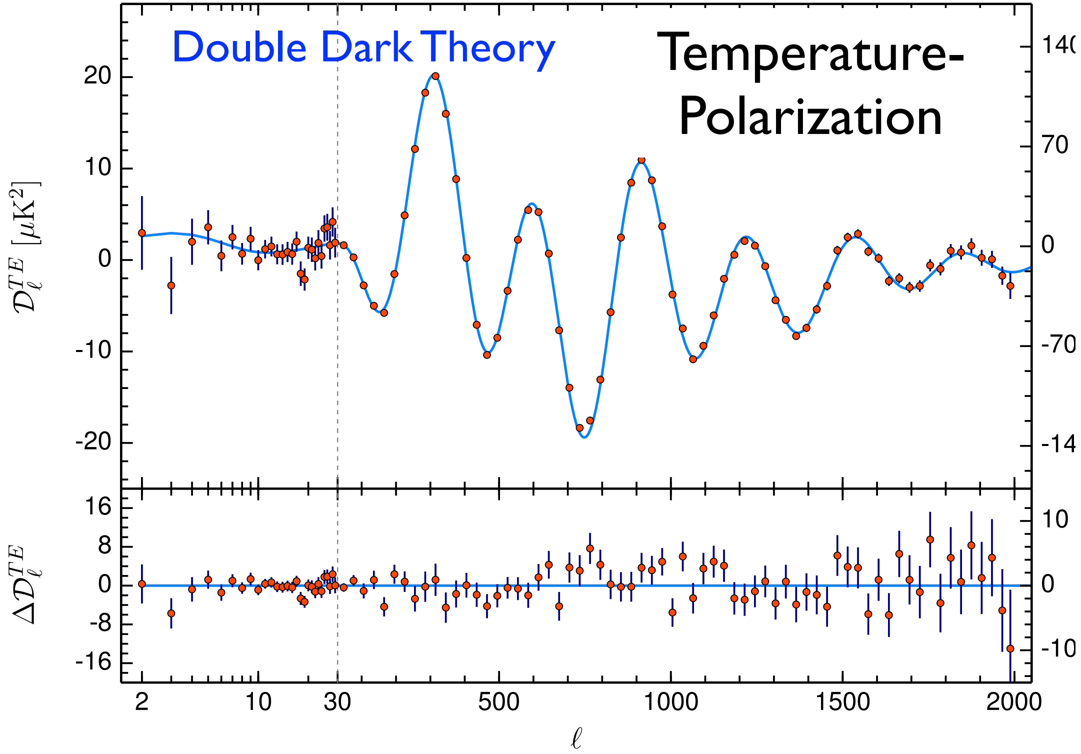
European Space Agency PLANCK Satellite Data

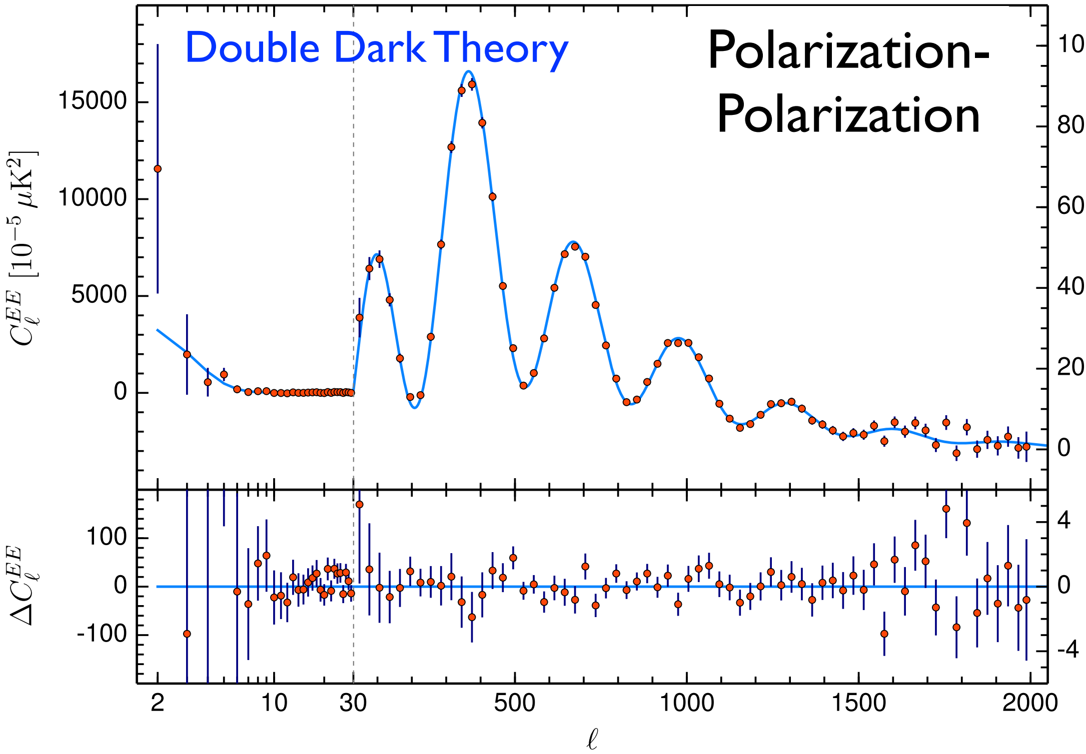
Released September 24, 2019



Agrees with Double Dark Theory!

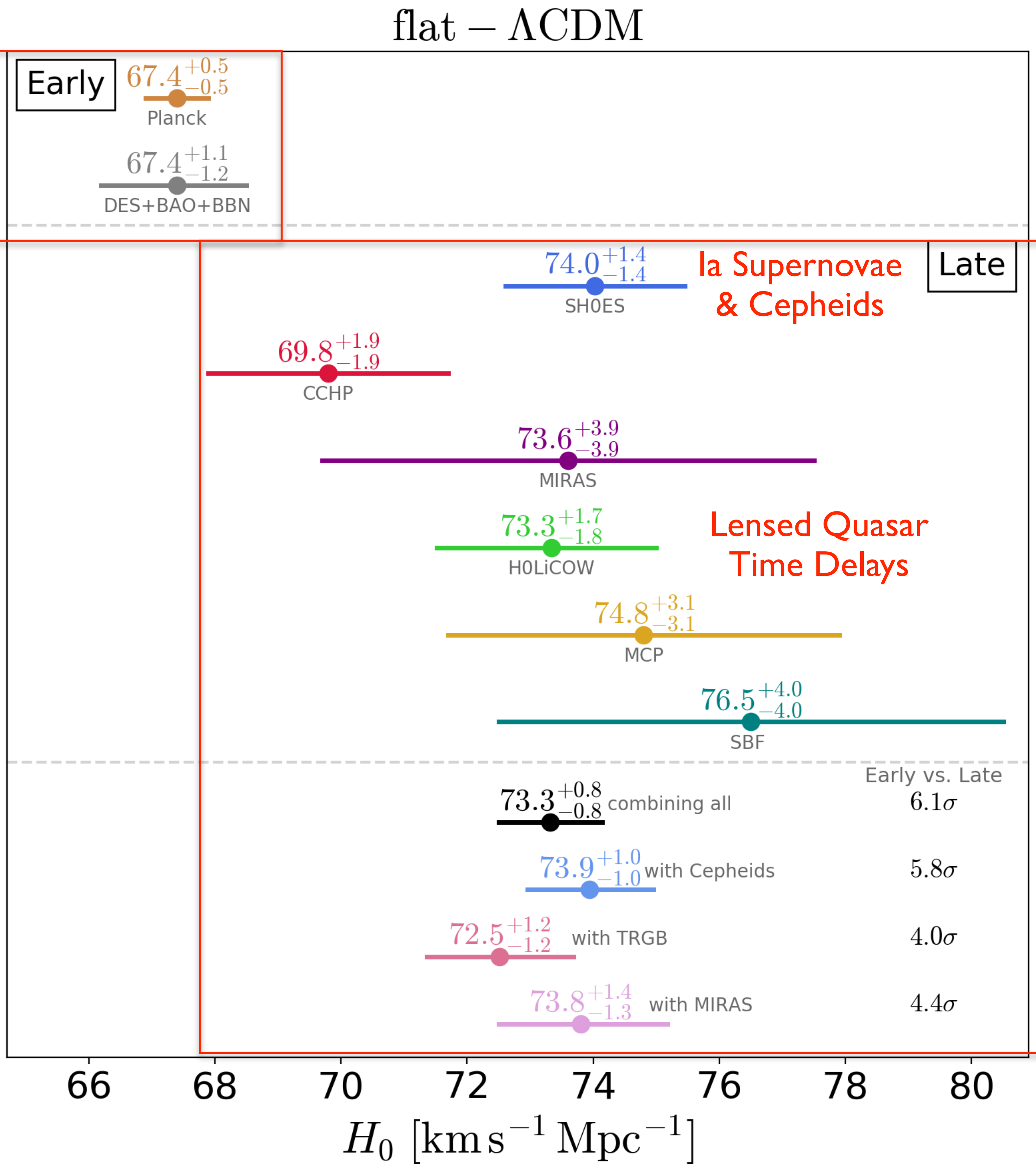






The Hubble parameter H_0 is the expansion rate of the universe today.

A possibly serious difficulty for ΛCDM is the **Hubble parameter tension:**



Cosmic Background Radiation plus ΛCDM gives $H_0 = 67.4 \pm 0.4$

Ia Supernovae & Cepheids

Lensed Quasar Time Delays

Several kinds of nearby observations give $H_0 = 73.3 \pm 0.8$

Verde Treu Riess 2019

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

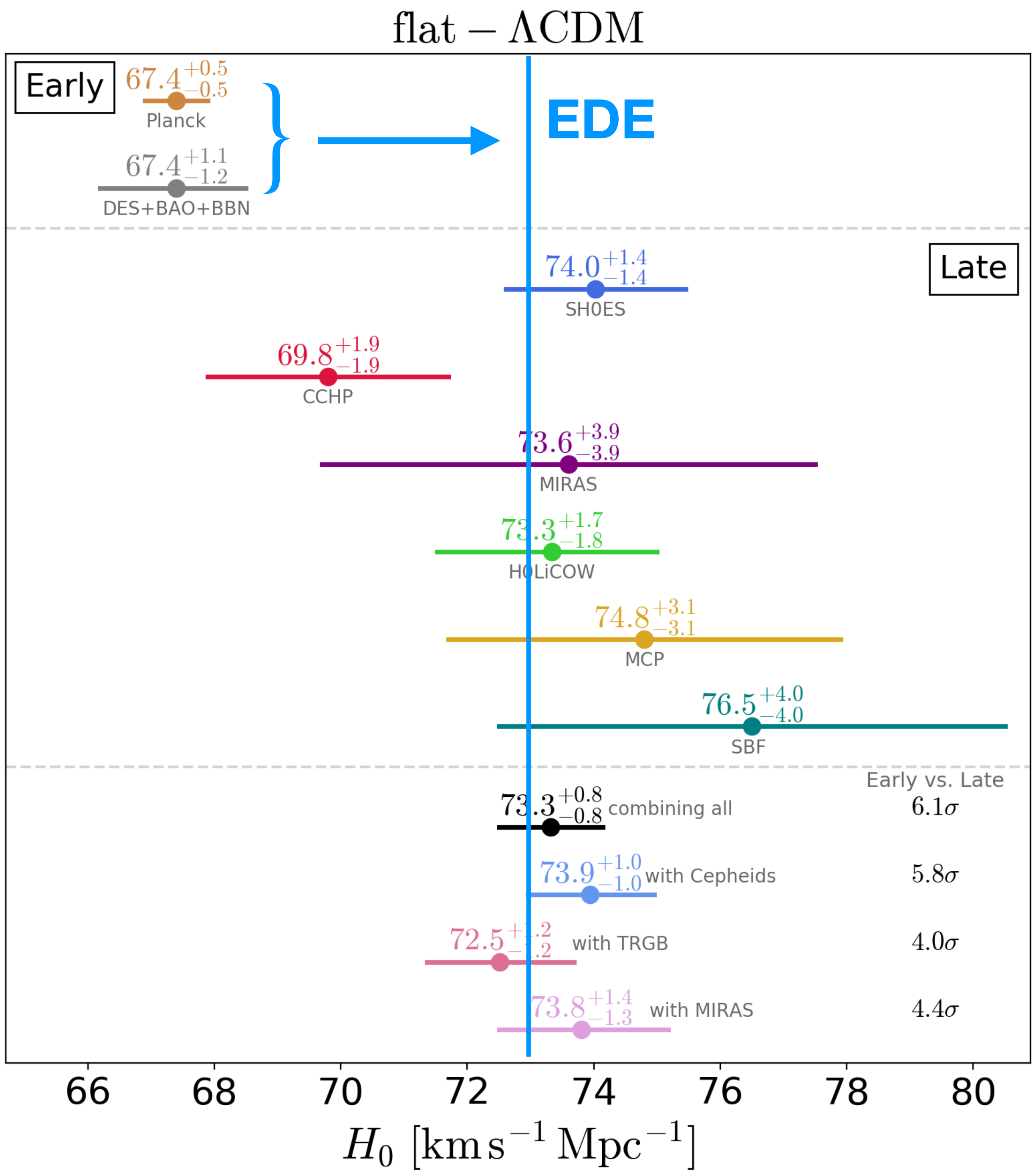
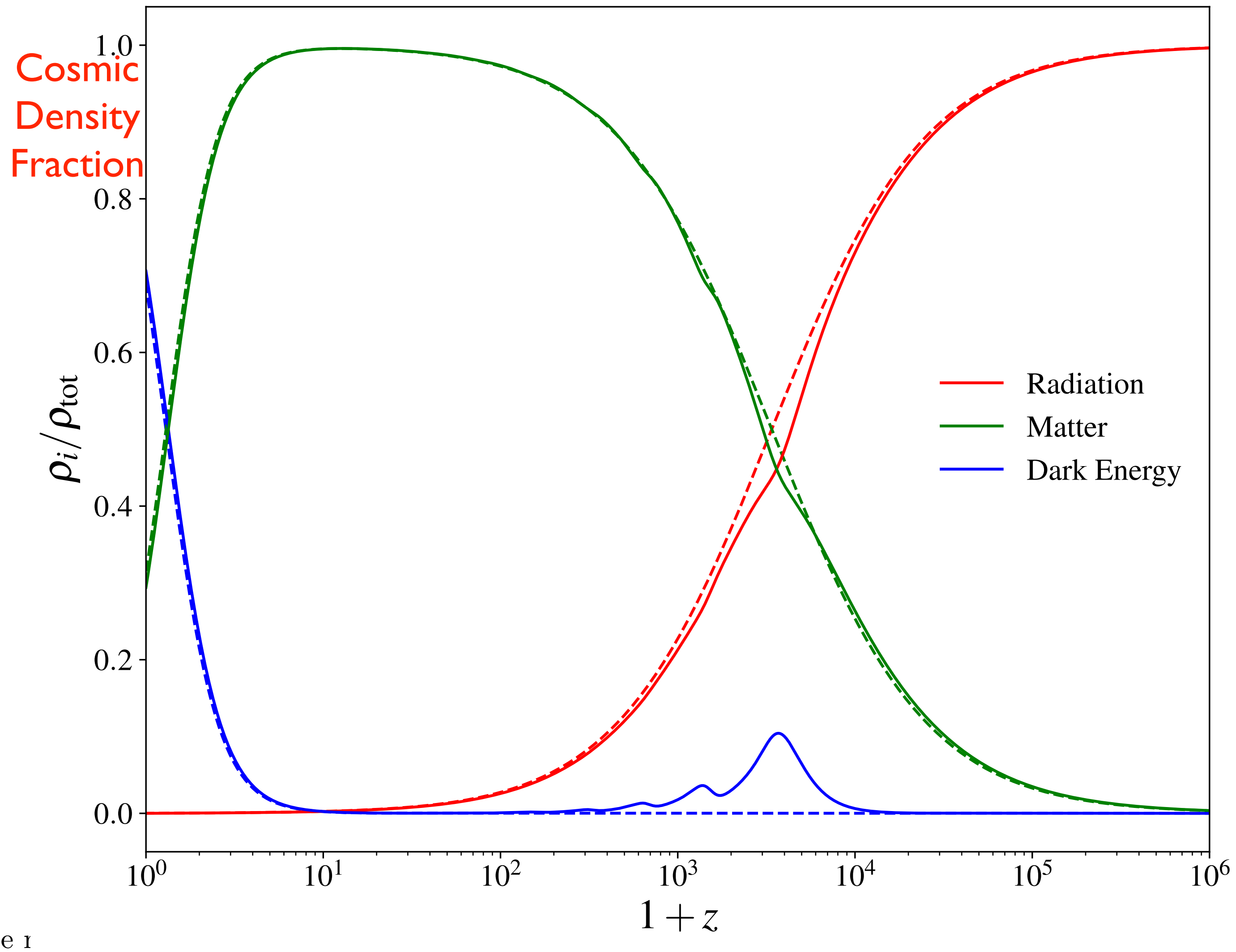


Figure 1. Compilation of Hubble Constant predictions and measurements taken from the r cent literature and presented or discussed at the meeting. Two independent predictions based on early-Universe data (Planck Collaboration et al. 2018; Abbott et al. 2018) are shown at the top left (more utilizing other 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 σ, less than 6 σ, while robust to exclusion of any one method, team or source. Figure courtesy of Vivien Bonvin.

Verde, Treu, Riess 2019

A brief episode of Early Dark Energy about ~ 35,000 years after the Big Bang modifies the ΛCDM extrapolation of H_0 and avoids the Hubble tension.



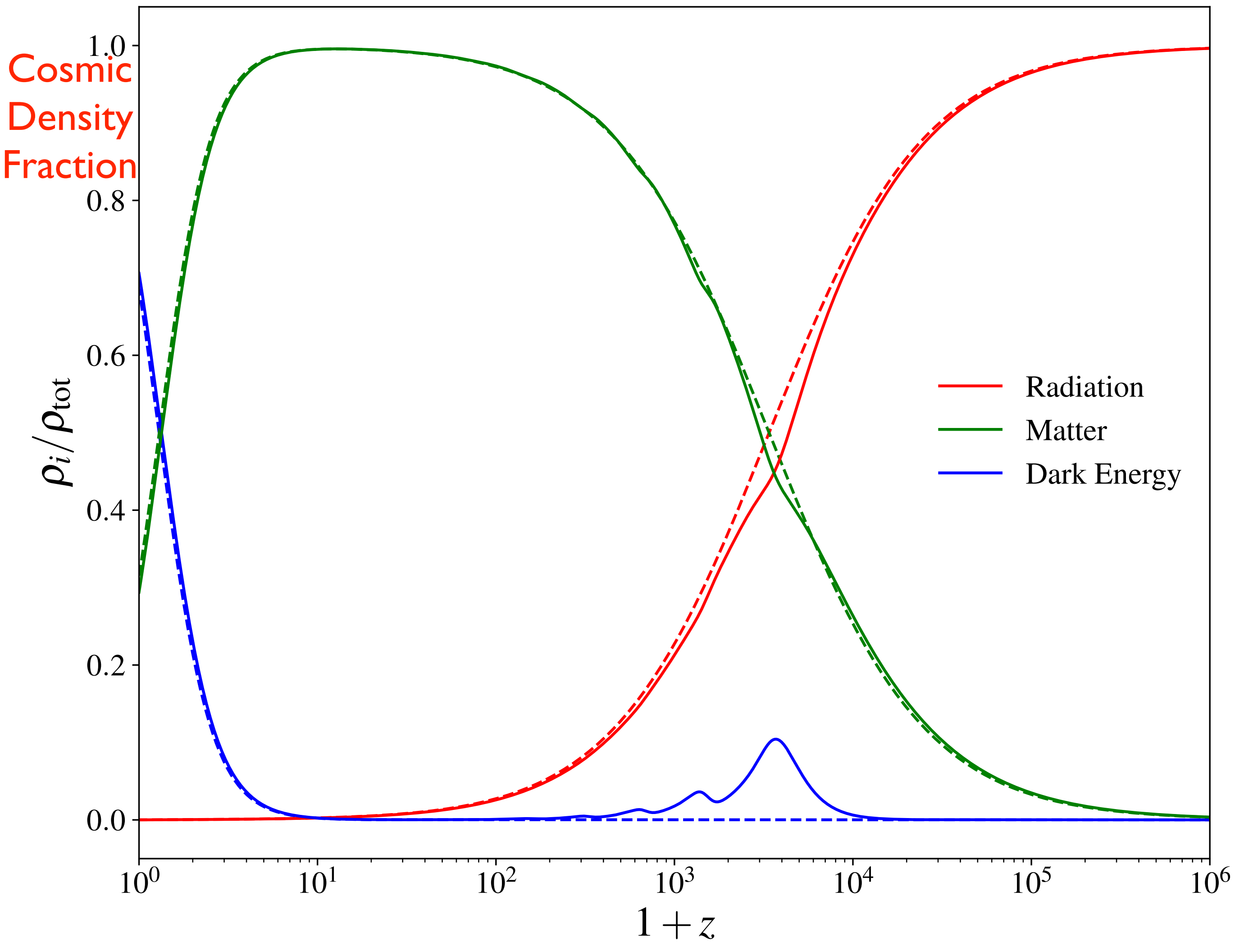
Cosmic Density Fraction

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

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

A brief episode of Early Dark Energy about ~ 35,000 years after the Big Bang modifies the ΛCDM extrapolation of H_0 and avoids the Hubble tension.

Cosmic Density Fraction



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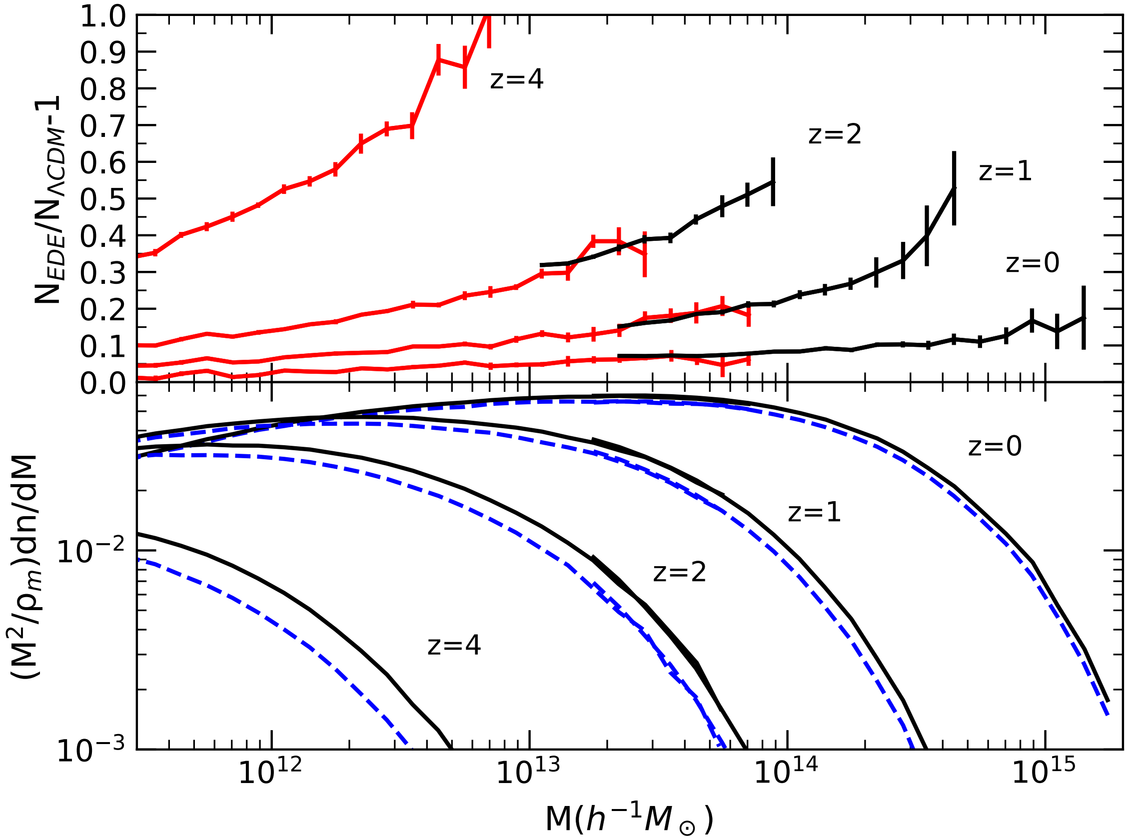
Klypin, Poulin, Prada, Primack, et al. 2021



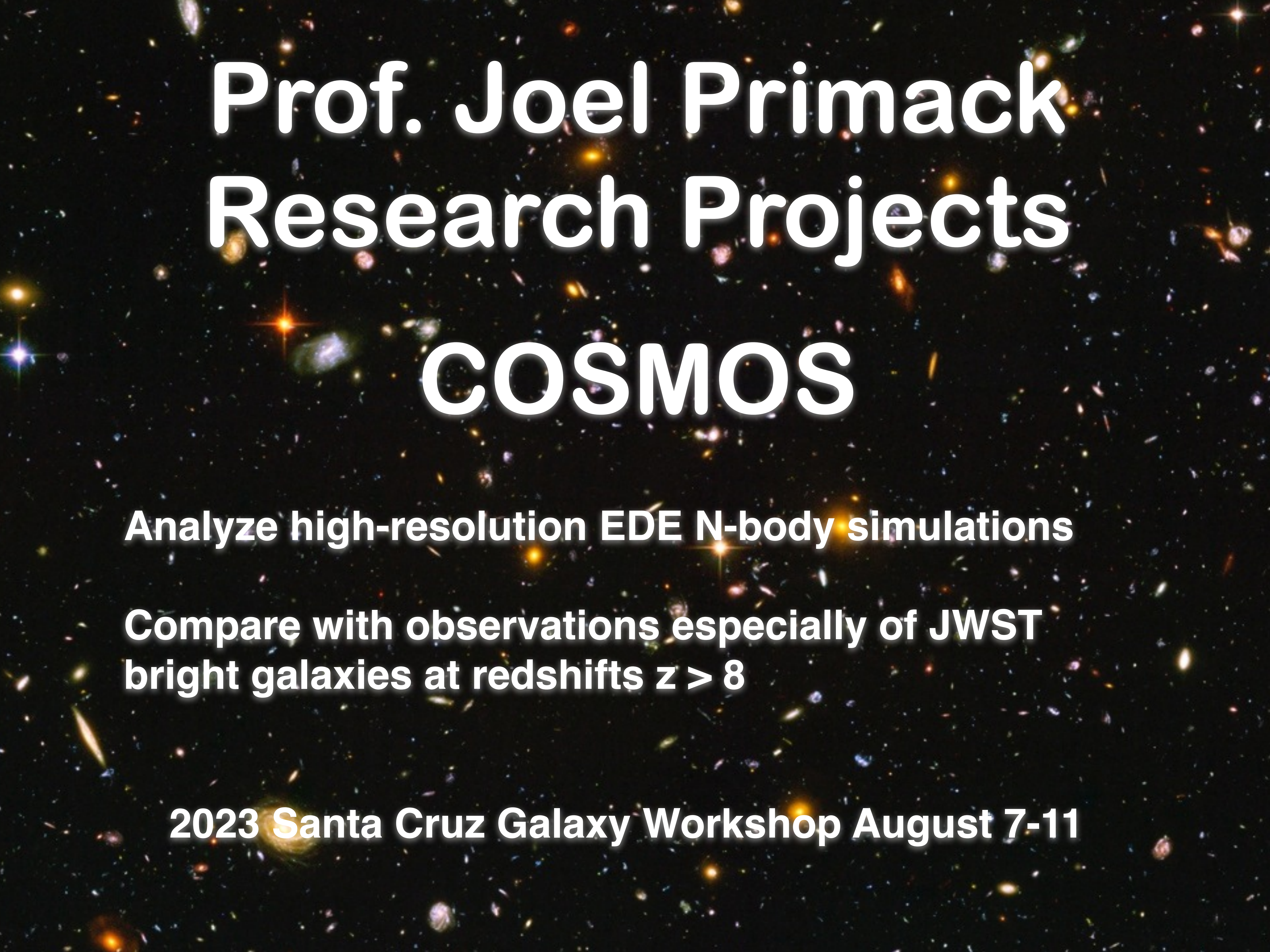
EDE: 50% more clusters at z ~ 1, 2x more galaxies at z ~ 4

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 ΛCDM simulations. The smaller box and better resolution simulations $\mathrm{EDE}_{0.5}$ and $\Lambda\mathrm{CDM}_{0.5}$ are used for masses below $M \lesssim 10^{14}h^{-1}$Mpc. They are shown as red curves in the top panel. Larger box and lower resolution simulations EDE_{2A} and $\Lambda\mathrm{CDM}_{2A}$ (black curves in the top panel) are used for massive halos with $M \gtrsim 2\times10^{13}h^{-1}$Mpc. At $z = 0$ halo abundances are very similar for the models: EDE predicts ~ 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. 2021**

Work in progress

EDE: 6x more massive galaxies at z ~ 10,
15x more massive galaxies at z ~ 15

Is JWST seeing these high-redshift galaxies?



Prof. Joel Primack Research Projects

COSMOS

Analyze high-resolution EDE N-body simulations

Compare with observations especially of JWST bright galaxies at redshifts $z > 8$

2023 Santa Cruz Galaxy Workshop August 7-11

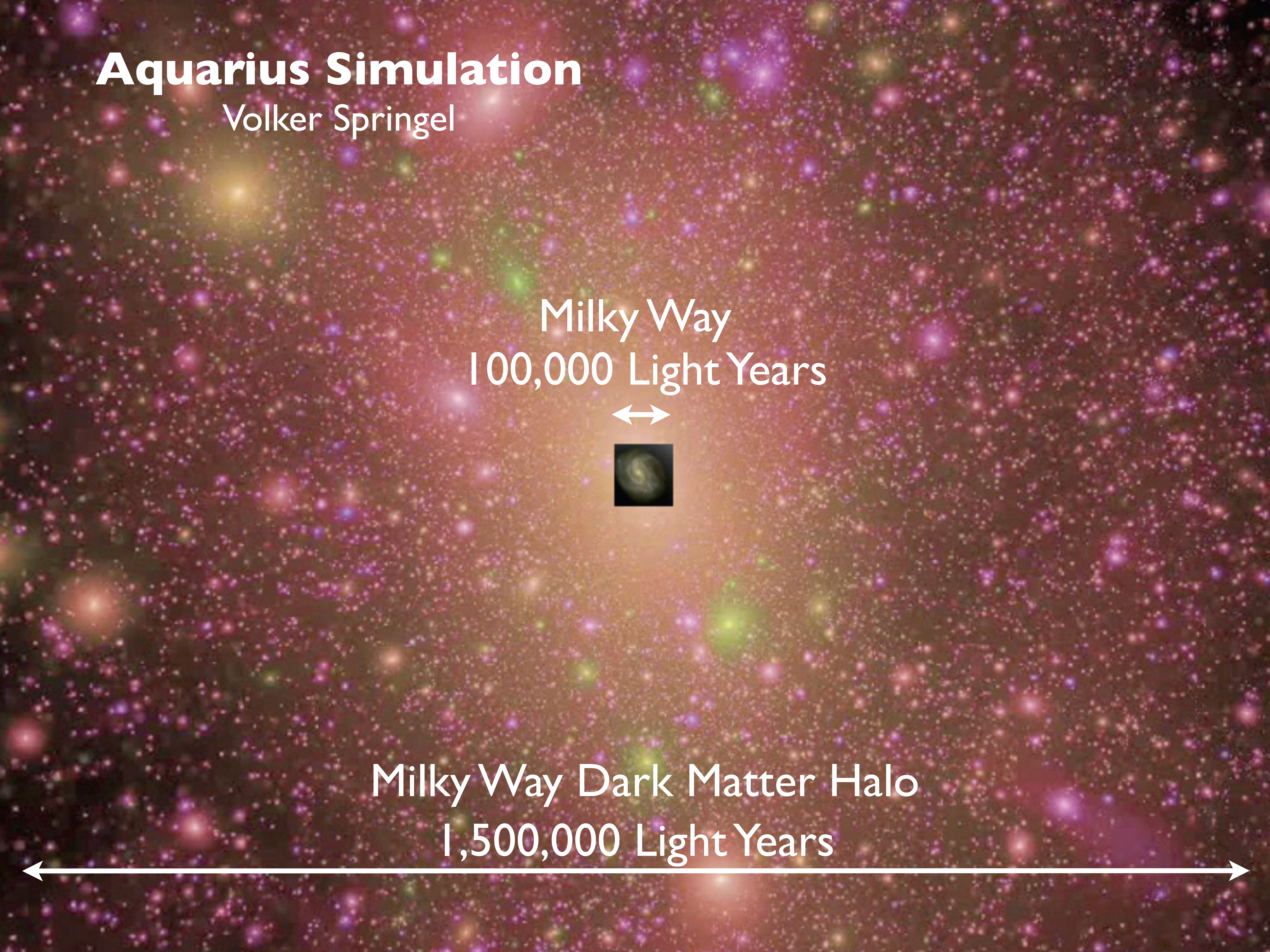
Prof. Joel Primack Research Projects

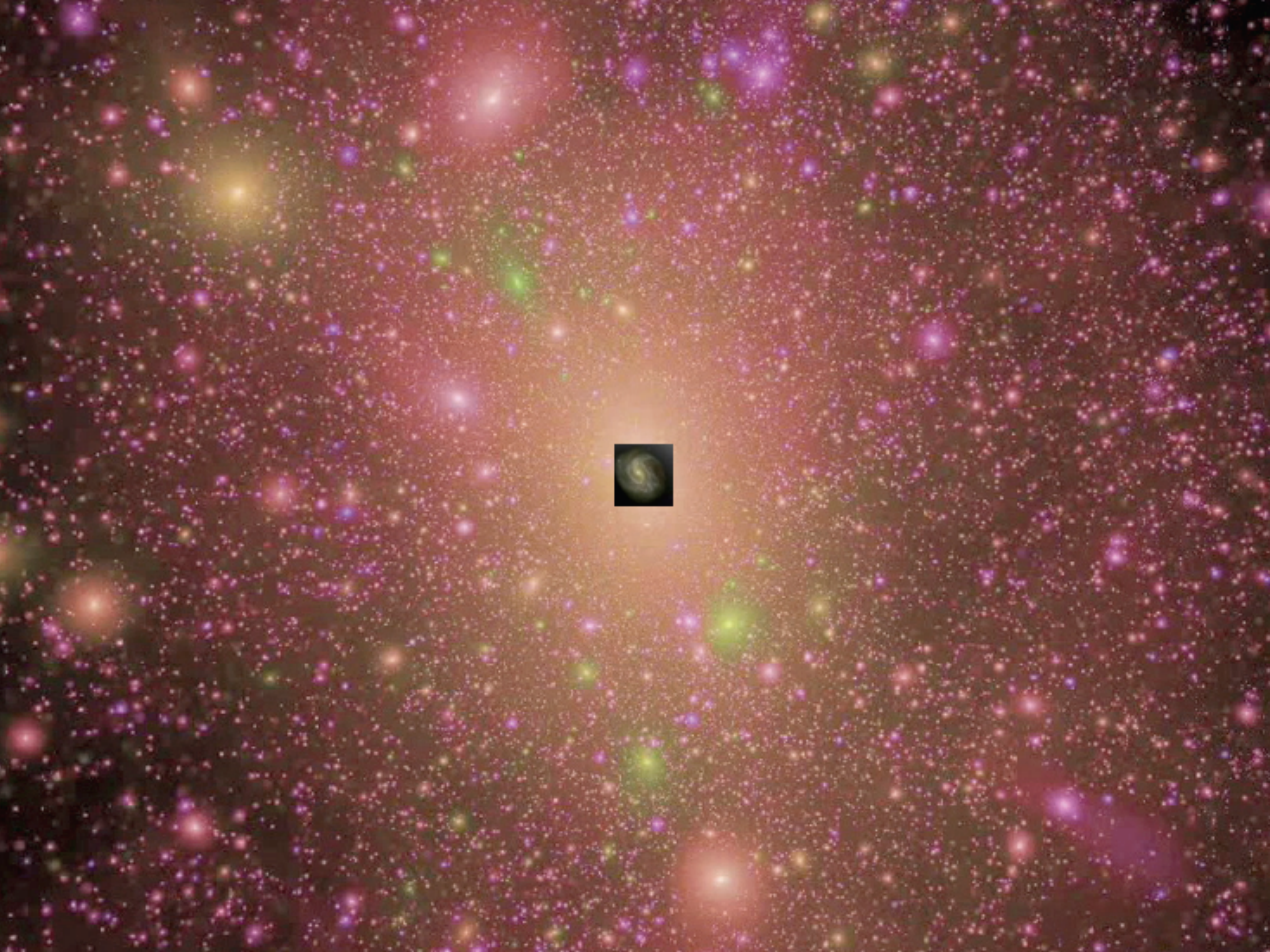
COSMOS

GALAXIES

Aquarius Simulation

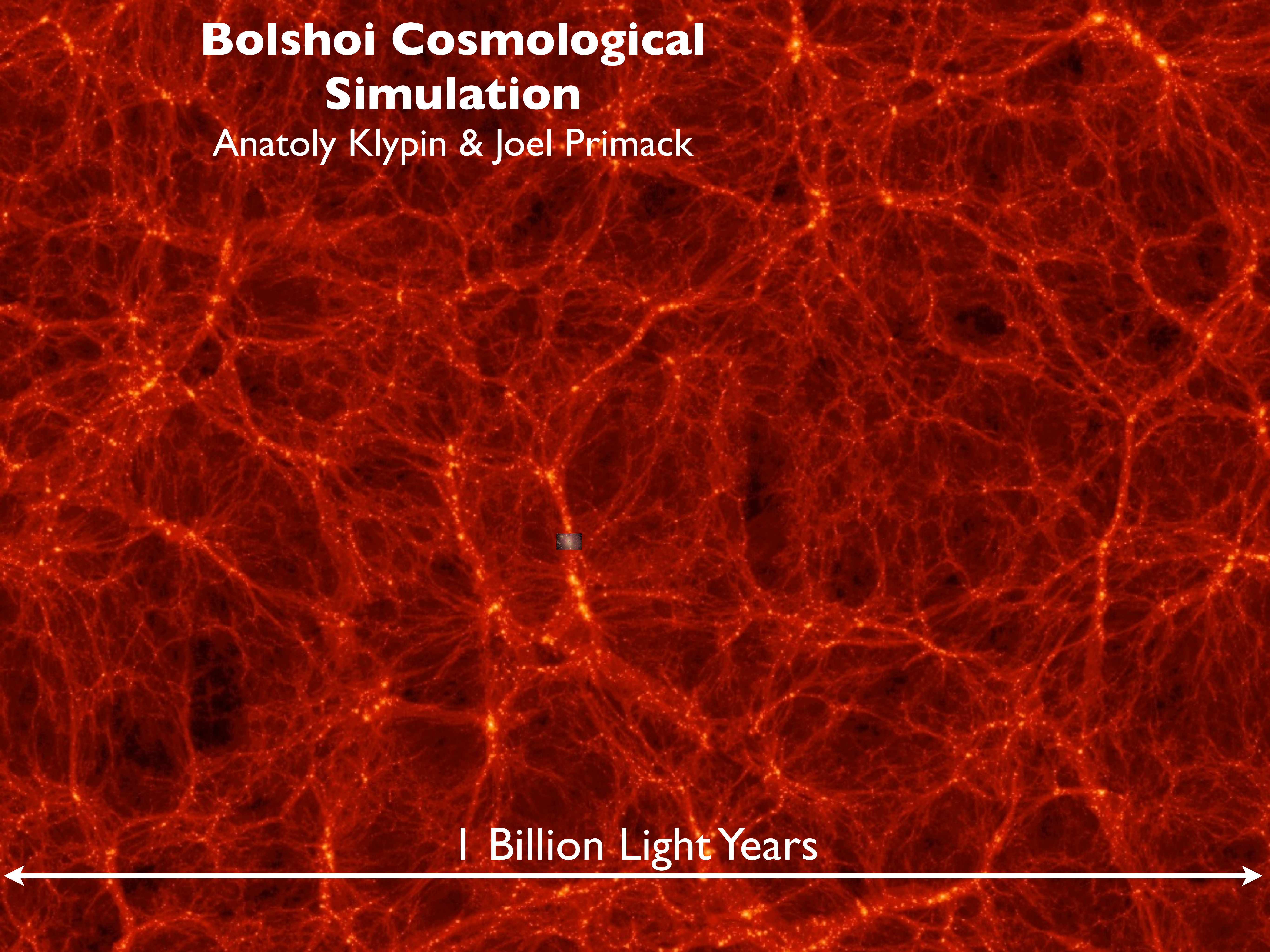
Volker Springel

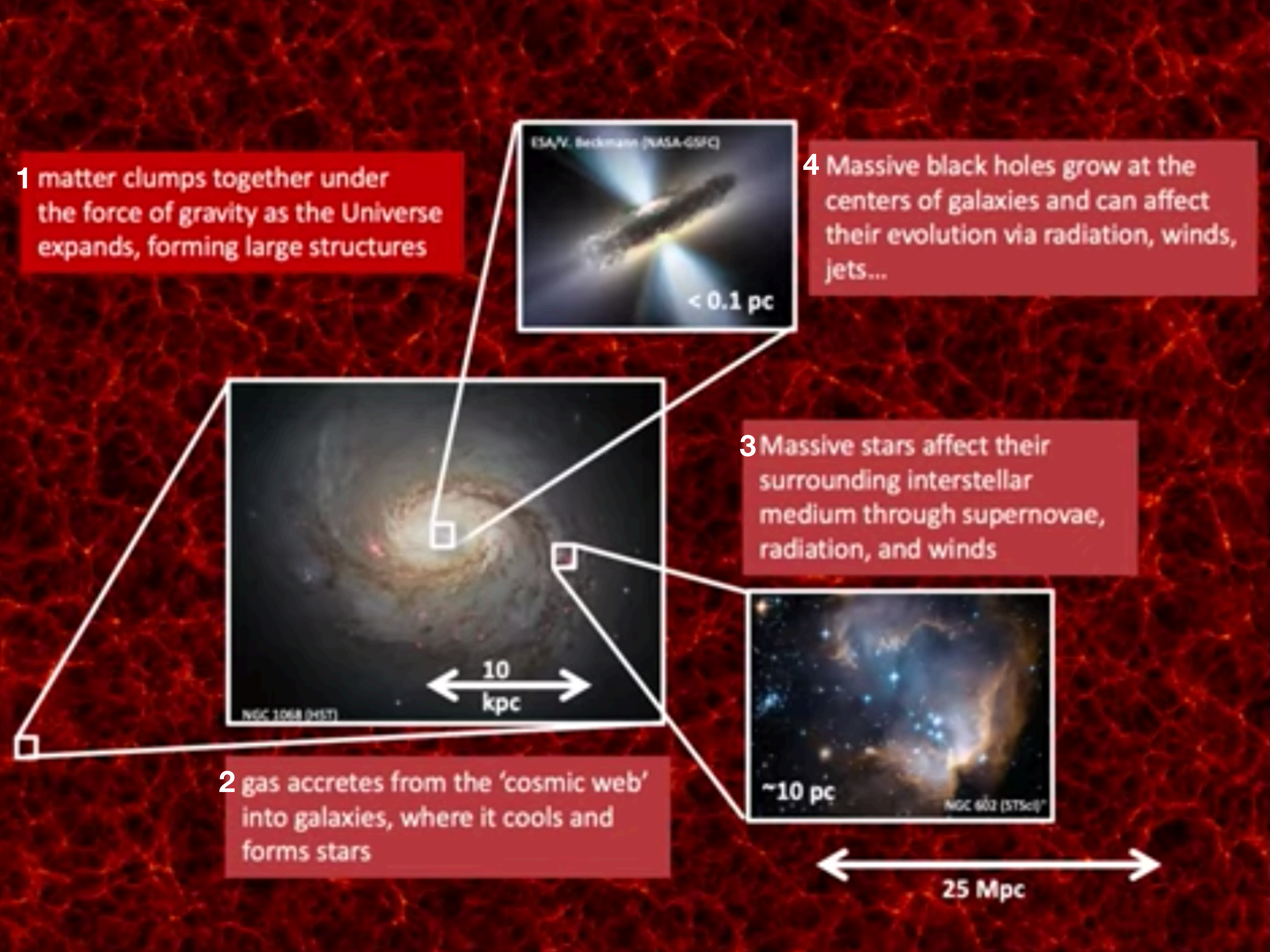




Bolshoi Cosmological Simulation

Anatoly Klypin & Joel Primack





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

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

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

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

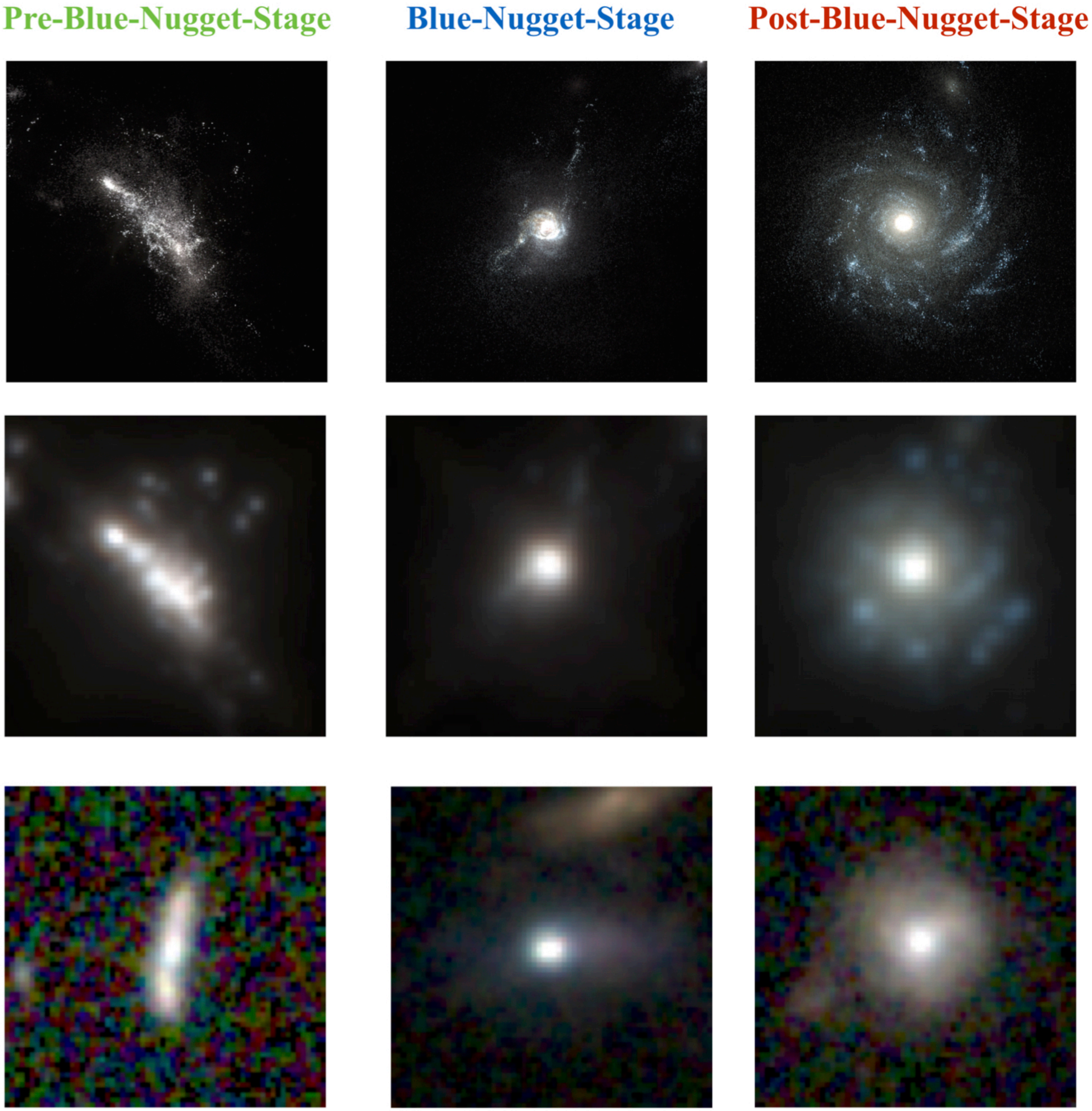
Almost all the stars today are in large galaxies like our Milky Way. Nearby large galaxies are disk galaxies like our galaxy or big balls of stars called elliptical galaxies. But most galaxies in the early universe didn't look anything like our Milky Way. Many of them are pickle-shaped and clumpy.

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.

“Face Recognition for Galaxies”

Huertas-Company, Primack, et al. 2018, 2020, 2021 using Machine Learning

Pre-BN **BN** **Post-BN**

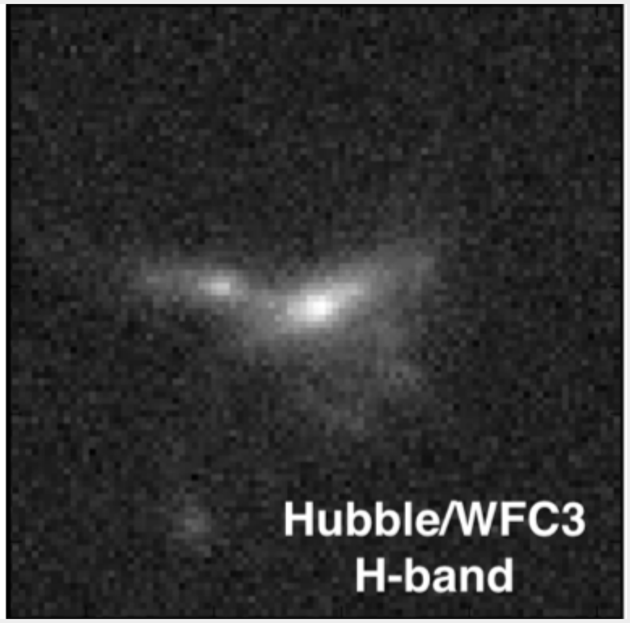


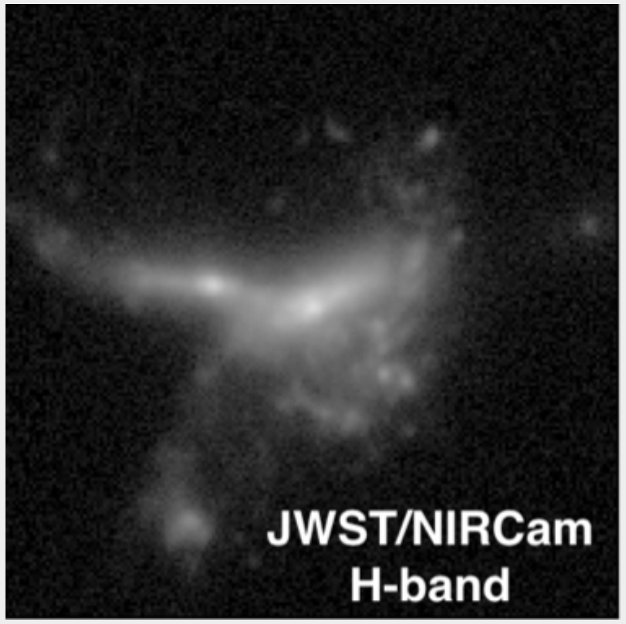
VELA High-Res Sunrise Images

VELA HST-Res Sunrise Images

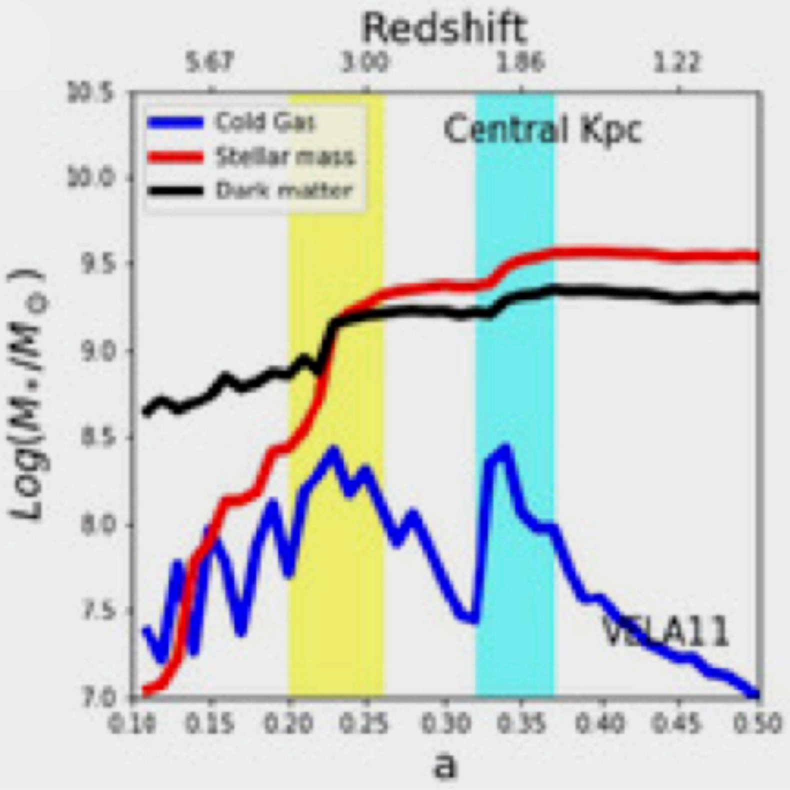
CANDELS HST Images

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

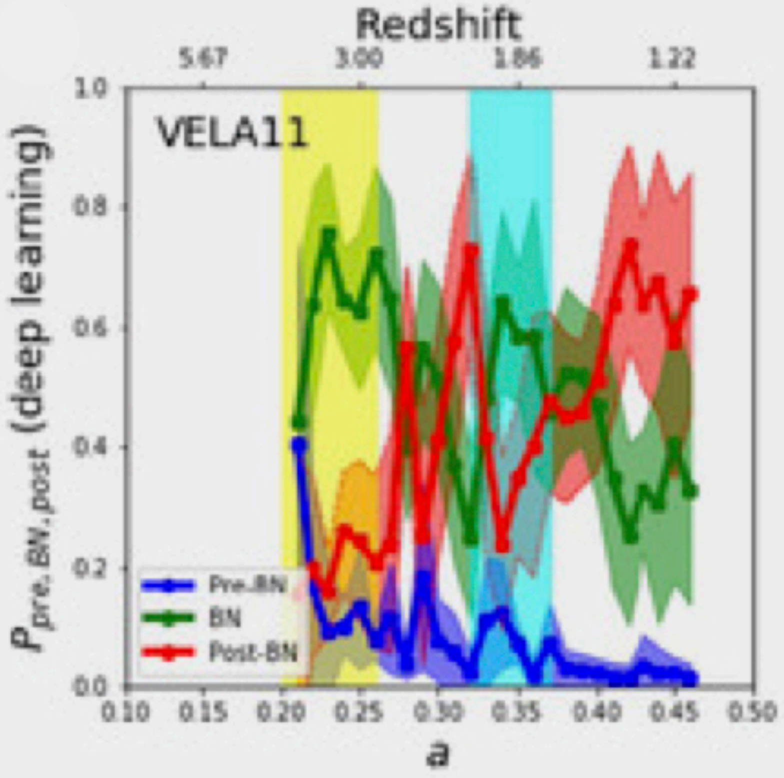




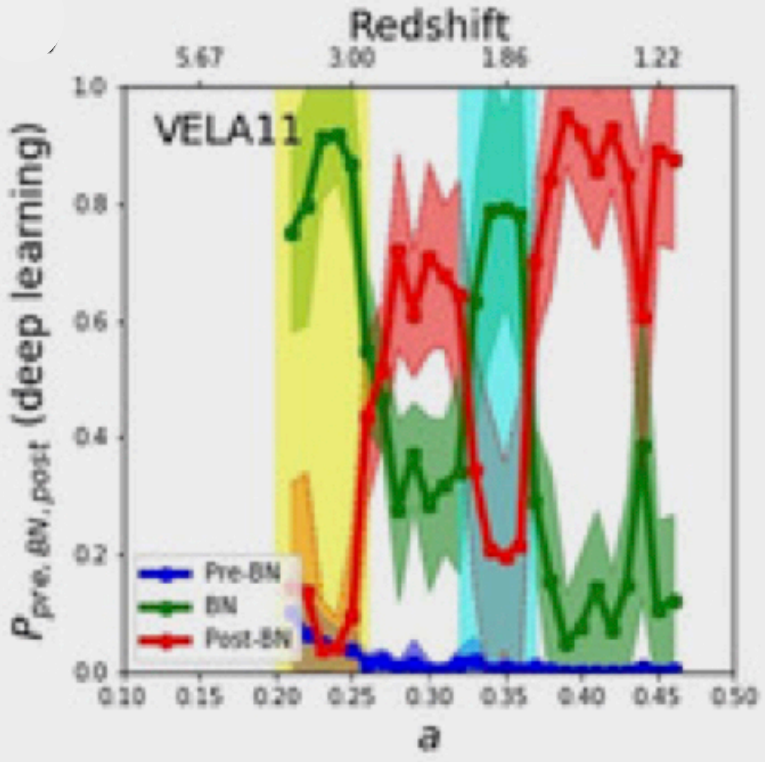
Simulation Metadata



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



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



Deep learning does much better with JWST images

HST = Hubble Space Telescope
JWST = James Web Space Telescope

Convolutional Neural Net (Deep Learning)

High-Redshift Galaxy Giant Clumps: HST vs. JWST

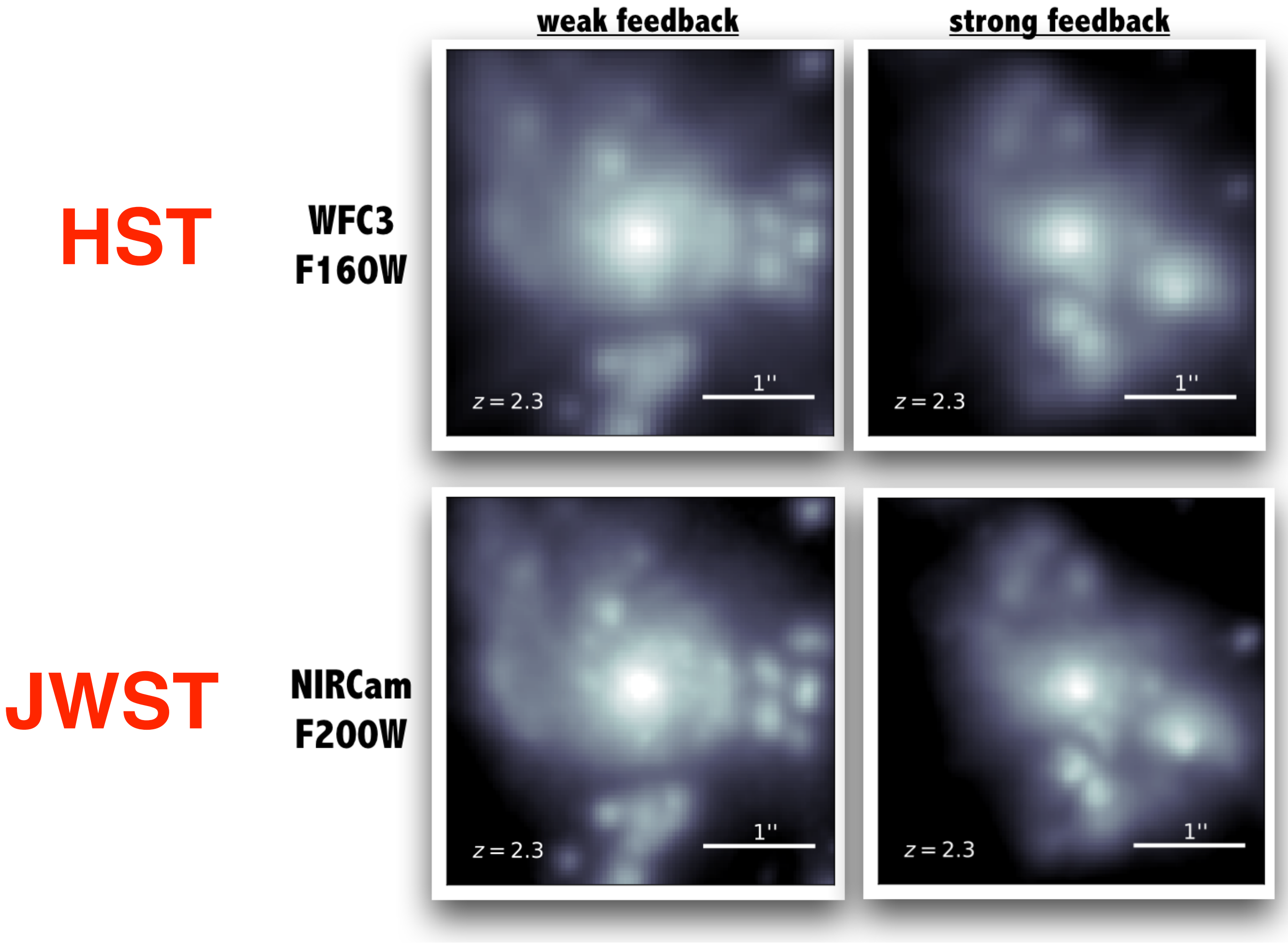
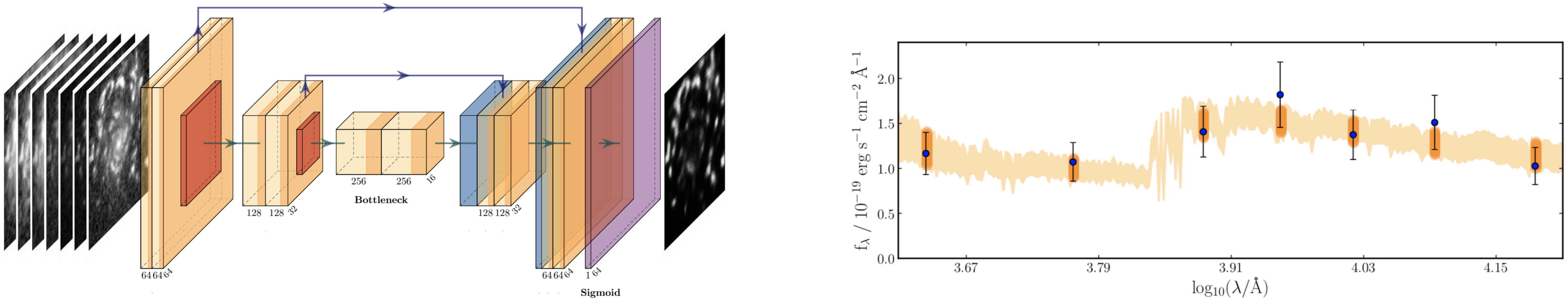


Figure 2: Effect of varying feedback on the frequency and properties of clumps. The figure shows the same VELA galaxy at $z \sim 2$ simulated with two different feedback strengths (weak: left column, strong: right column). Rows show HST (top) and JWST imaging. More low-mass clumps are observed in a weak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

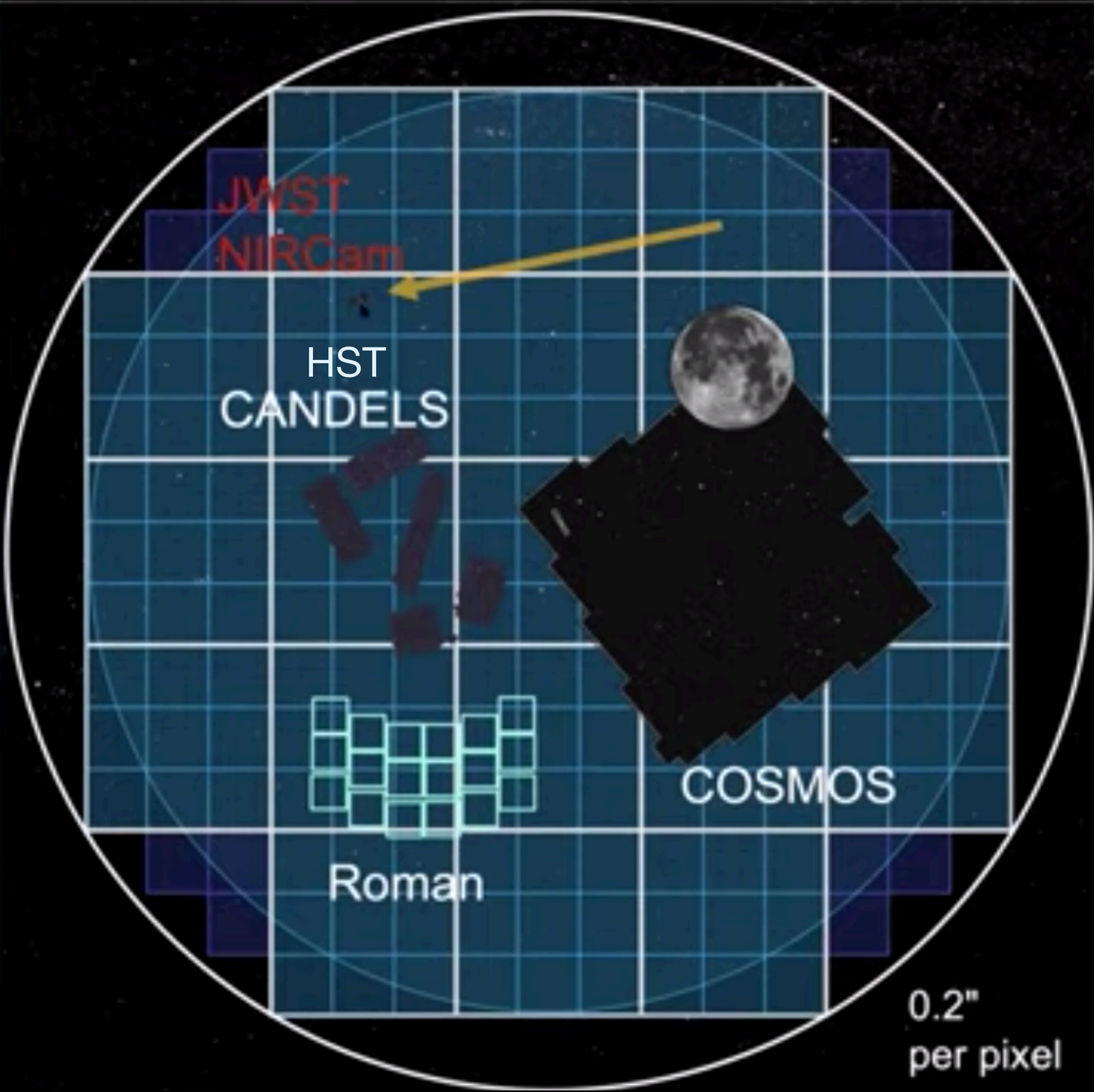
Vera Rubin Observatory

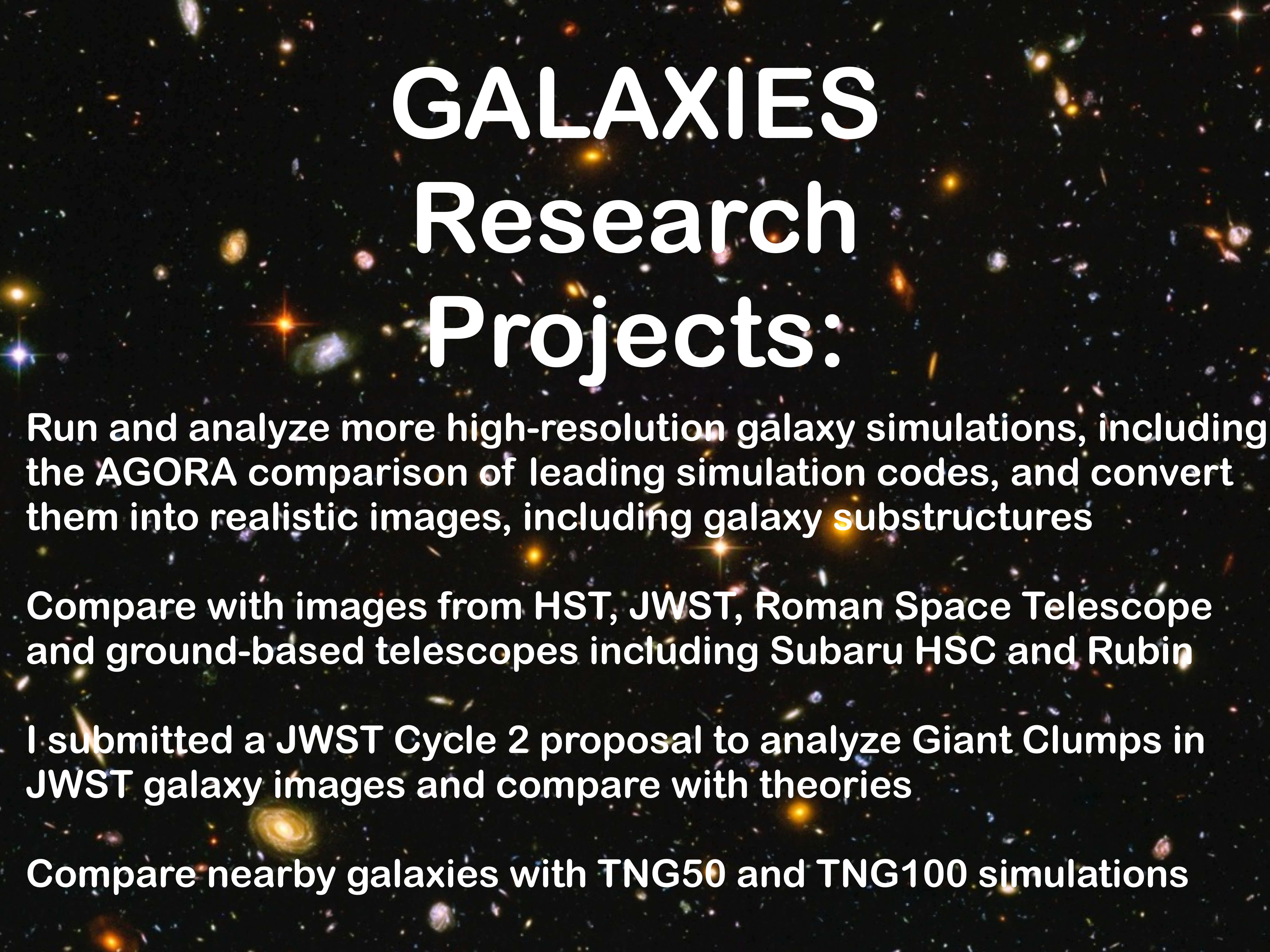
New observatories will have great new capabilities:

JWST - higher res, more light, > λ

Roman (WFIRST) - 100x HST area

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





GALAXIES Research Projects:

Run and analyze more high-resolution galaxy simulations, including the AGORA comparison of leading simulation codes, and convert them into realistic images, including galaxy substructures

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

I submitted a JWST Cycle 2 proposal to analyze Giant Clumps in JWST galaxy images and compare with theories

Compare nearby galaxies with TNG50 and TNG100 simulations

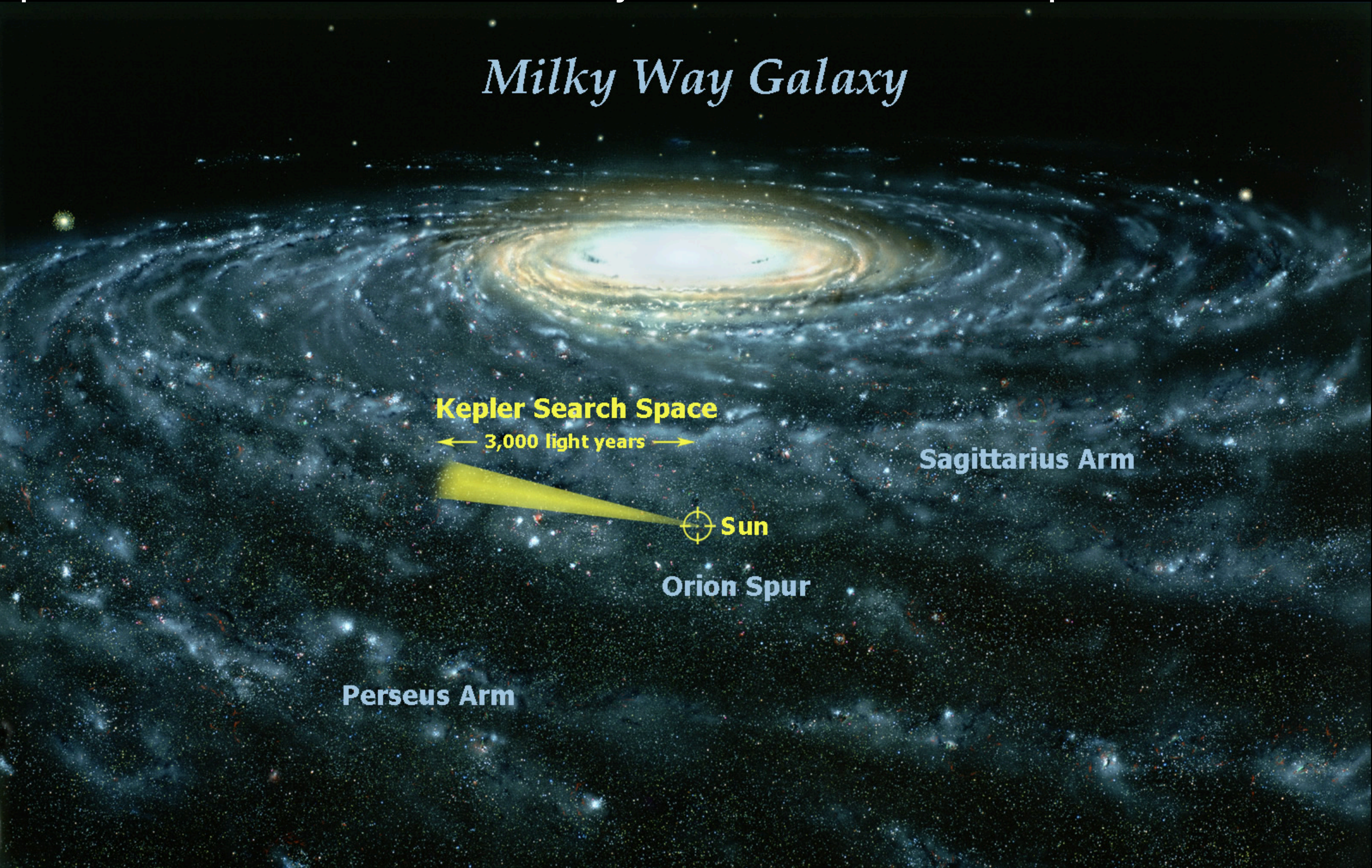
Prof. Joel Primack Research Projects

COSMOS

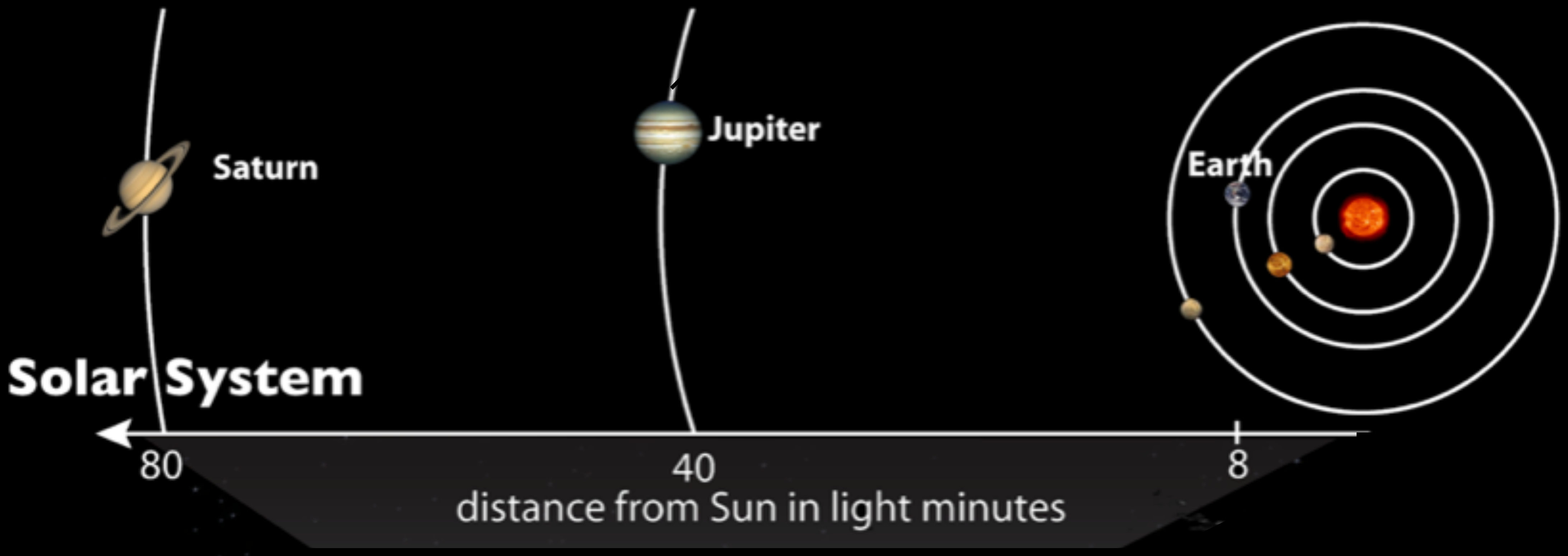
GALAXIES

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.



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.

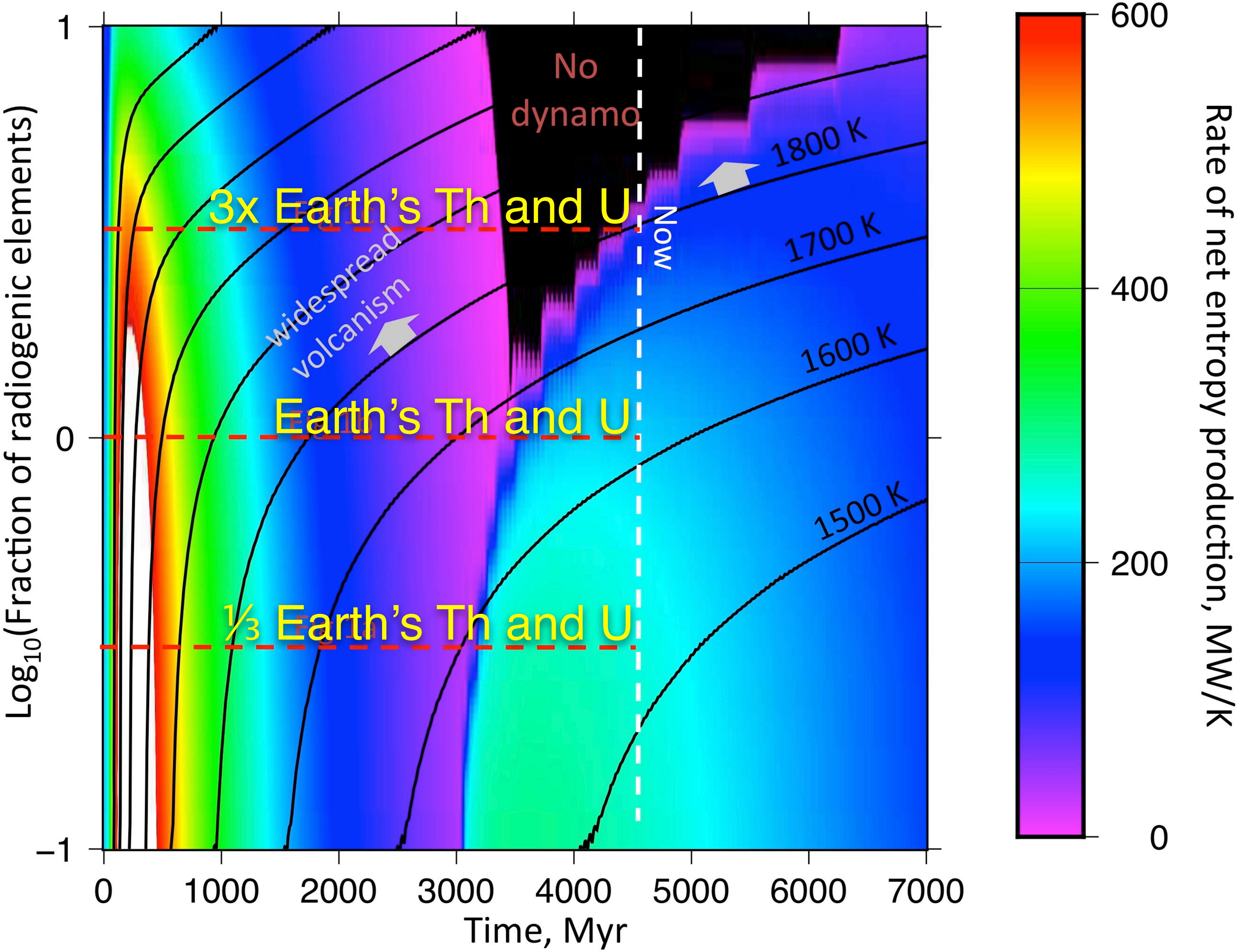
The most common type of planet seems to be 2 to 6 times Earth's mass, a "**super-Earth**". No such planet exists in our Solar System.

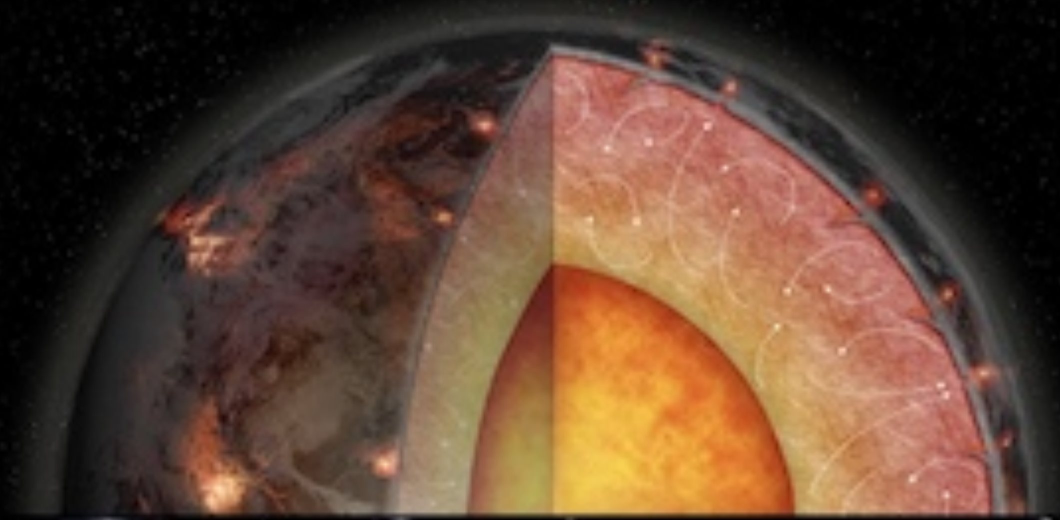
Some planets are in the **habitable zone around their stars** in which water would be in liquid form, but most of these planets are probably not hospitable to advanced forms of life. For one thing, they might not have an optimal abundance of the long-lived radioactive elements thorium and uranium to power a magnetic dynamo and plate tectonics. Too much Th and U would result in a lava world with frequent flood vulcanism, 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

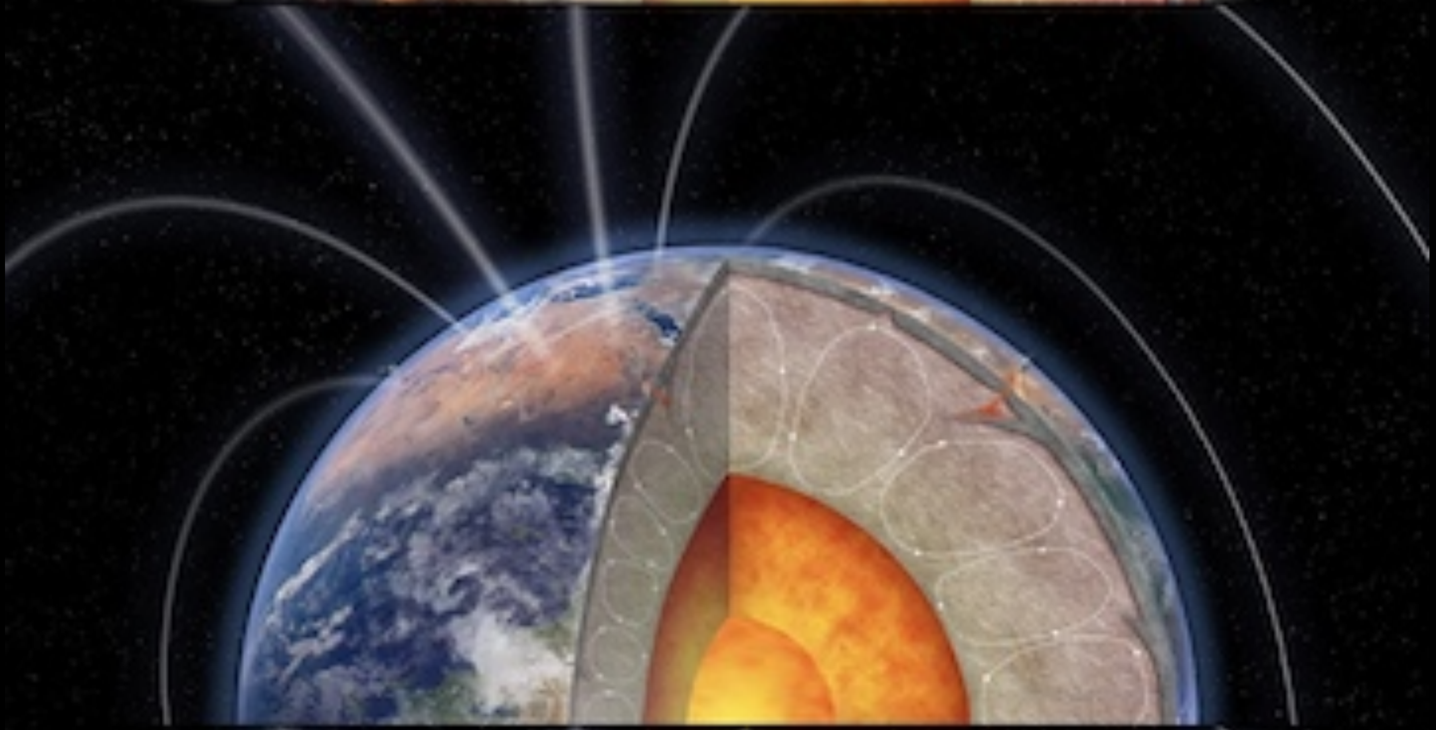
Francis Nimmo, Joel Primack, S. M. Faber, Enrico Ramirez-Ruiz, and Mohammadtaher Safarzadeh

Astrophysical Journal Letters (November 2020)

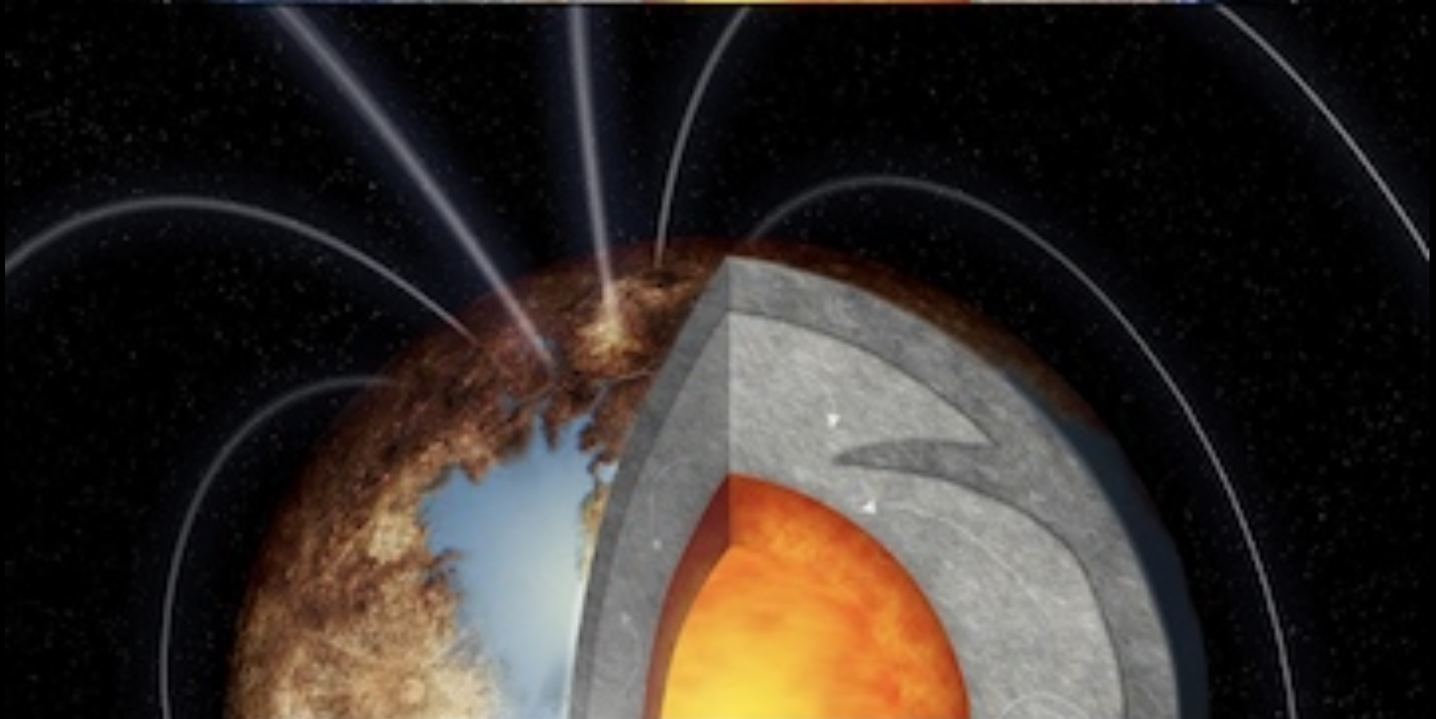




3x Earth’s Th and U
No magnetic dynamo &
frequent flood vulcanism

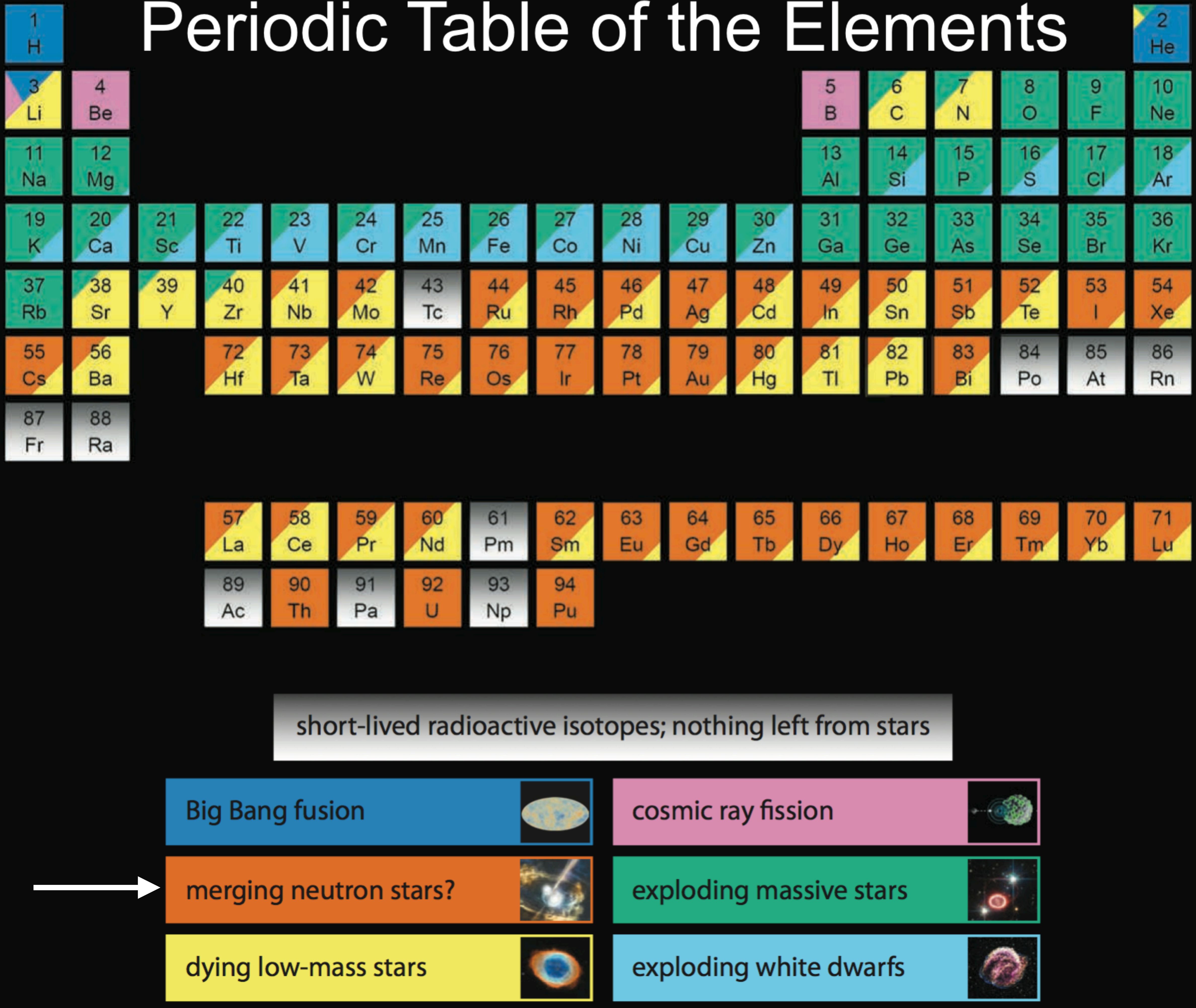


Earth’s Th and U
Magnetic dynamo &
plate tectonics



⅓ 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

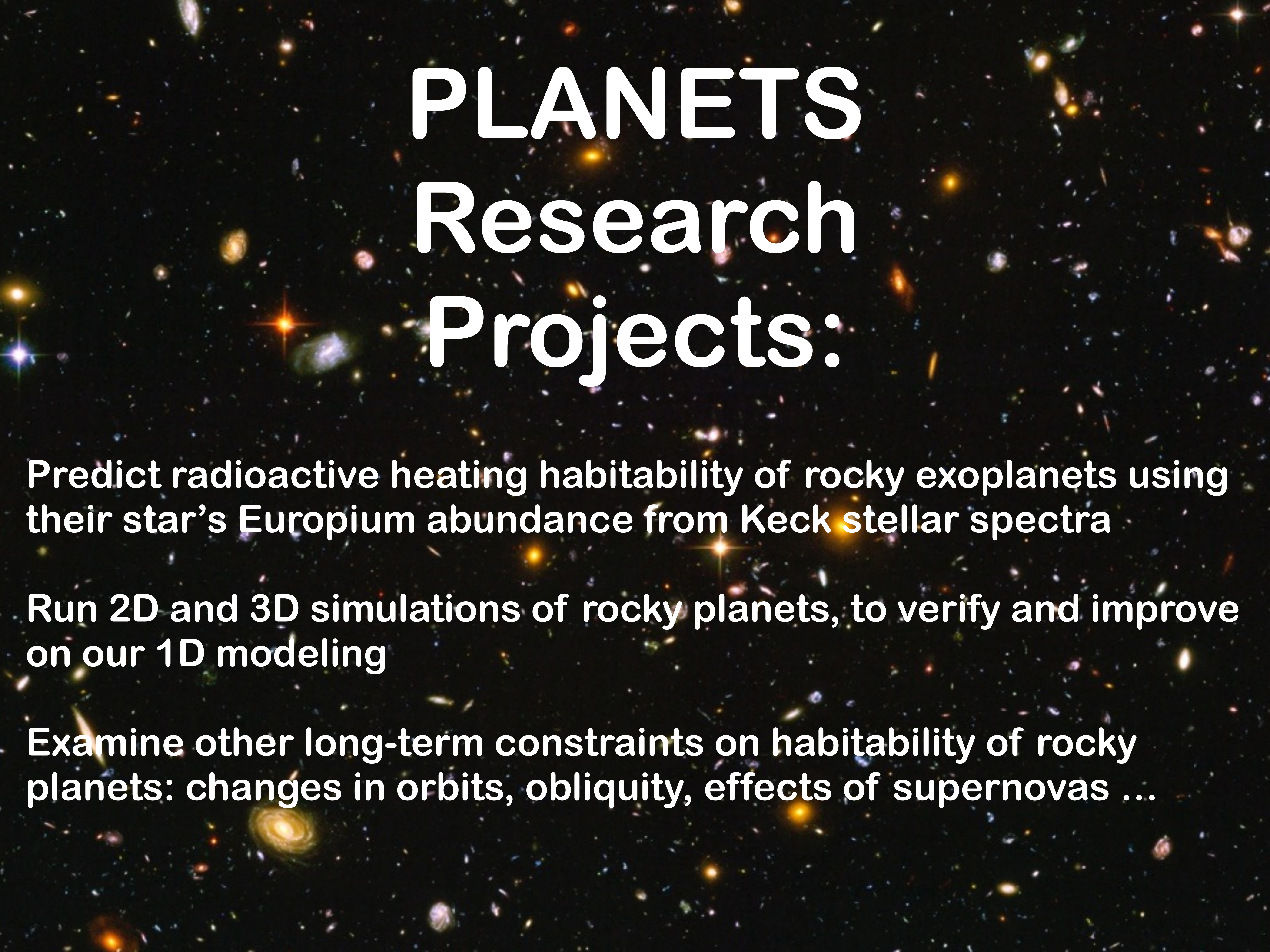
cosmic ray fission

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 from Keck stellar spectra

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 - 22Feb202

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

Clayton Strawn — circumgalacticlactic medium: simulations vs. observations
James Kakos — combining spectroscopic & photometric redshifts with SORT, compare galaxy properties distributions with theory