University of California AstroComputing Institute, Supercomputer Simulations, Using GPUs for Visualization

Joel Primack

University of California, Santa Cruz

Topics

- New University of California AstroComputing Institute linking all 9 academic campuses + 3 national labs − the largest and most powerful computational astrophysics faculty in the world − with education and public outreach

- The "**Bolshoi**" cosmological simulation, based on WMAP5 ΛCDM cosmology. Bolshoi has about an order of magnitude better mass and force resolution than the Millennium Run, and it will be the basis for a new generation of semi-analytic galaxy evolution models.

- Using graphics processor units (GPUs) and the ***Sunrise*** code to convert hydrodynamic galaxy formation simulations to galaxy images in all wavebands including absorption and re-emission by dust.

New UCSC Institute funded by UC Multicampus Research Programs and Initiatives

HIPACC: HIGH PERFORMANCE ASTRO-COMPUTING CENTER

The UC campuses and DOE laboratories are home to what is easily the largest and most powerful computational astrophysics faculty in the world, when astro-simulations are just now reaching their full power to explain and interpret the universe. The goal of HIPACC is to bring together UC computational astrophysicists, computer scientists and engineers, and the builders and users of UC telescopes to A) utilize the next generation of supercomputers, hosting $>10^5$ processors, to understand astrophysical processes through simulation, and B) analyze the petabytes (soon to be exabytes) of data that will flow from new telescopes and supercomputers. It will lay the groundwork for creating one or more major science institutes for projects such as the Thirty Meter Telescope.

HIPACC will organize and fund two major conferences each year, one each in N and S CA, and an annual international summer school. It will also fund travel and lodging for collaborations between UC campus and lab groups, and support publicity and fund raising for UC astro-computing.

Executive committee: Director (Joel Primack), Associate Director, N CA and S CA representatives (to be chosen)

Council: Representatives from UCB, UCD, UCI, UCLA, UCM, UCR, UCSB, UCSC, UCSD, LANL LBNL, LLNL

Staff: Administrator, and staff for Proposal preparation, Publicity, and Education and Outreach (web, print, broadcast, schools, and science museums/planetariums)

UC AstroComputing Institute Goals

To empower computational astrophysicists, physicists, earth and planetary scientists, applied mathematicians, and computer scientists, computer engineers, and the builders and users of the new generation of telescopes to

- utilize the next generation of supercomputers, hosting hundreds of thousands or millions of processors, to understand astrophysical processes through simulation, and

- analyze the petabytes (soon to be exabytes) of data that will flow from new telescopes and supercomputers

New UC AstroComputing Institute

Linking all 9 UC academic campuses + 3 national labs (LANL, LBNL, LLNL), the largest and most powerful computational astrophysics faculty in the world – at a key moment when astro-simulations are just now reaching their full power to explain and interpret the universe

- Annual international AstroComputing summer school
- Two conferences annually, in N and S California
- Grants to facilitate collaborations among UC campuses and between campus and lab astrophysicists and computational scientists
- Staff for computational support, fund raising, publicity, education, and public outreach
- Support at approximately $350K/year for five years from UCOP/Vice President for Research

New UC AstroComputing Institute

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- Annual international AstroComputing summer school
- Two conferences annually, in N and S California
- We will **welcome collaboration** on the annual school and conferences from other California AstroComputing centers including Caltech and Stanford
- NASA Advanced Supercomputing (NAS) at NASA Ames is also welcome to participate, including via UCSC University Affiliated Research Center (UARC) and Silicon Valley Center in development

UC AstroComputing Institute Leadership

Executive Committee

Director: Joel Primack   Deputy Director: TBA

Coordinators from N and S California: TBA

Council	Co-I on HIPACC MRPI Proposal
• UC Berkeley	Christopher McKee
• UC Davis	
• UC Irvine	James Bullock
• UC Los Angeles	Steve Furlanetto
• UC Merced	Michael Sprague
• UC Riverside	Gillian Wilson
• UC San Diego	Michael Norman
• UC Santa Barbara	S. Peng Oh
• UC Santa Cruz	Sandra Faber
• Los Alamos NL	Salman Habib
• Lawrence Berkeley NL	Peter Nugent
• Lawrence Livermore NL	Peter Anninos

UC AstroComputing 2010 Summer School

Tentative plan: focus on galaxy formation simulations, three weeks long (July 26 - August 13), for approximately 60-80 students (with subsidies for ≤20 from Univ of California)

- Director: Anatoly Klypin (New Mexico State University)
- Lectures on key simulation codes: GADGET (Cox?), Gasoline (Governato?), Enzo (Norman/Abel?), ART (Klypin), RAMSES (Tessier), Sunrise (Jonsson)
- Afternoons for projects supervised by lecturers
- Recent international schools on astrocomputing:

Astrophysicalishes Institute Potsdam 2006 - Dir: A. Klypin
Inst for Advanced Study Princeton 2009 - Dirs: S. Tremaine
J. Stone

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Locating this at UCSC will allow synergy with ISIMA, first International Summer Institute for Modeling in Astrophysics July 5 - Aug 13 on Transport Processes in Astrophysics

The topic of the first ISIMA is **"Transport Processes in Astrophysics",** with particular interest in hydrodynamical and magneto-hydrodynamical processes (waves, turbulence) and radiative transfer. It will be held at **UCSC July 3 - August 13, 2010.**
See http://isima.ucsc.edu for more info.

ISIMA will host up to **15 established faculty and 15 post-doctoral researchers (senior participants) and 15 graduate students** for the 6-weeks duration of the program. The overall philosophy of ISIMA is to think "outside the box", by bringing together scientists and students from a broad range of backgrounds not only in astrophysics but in other related fields as well, and create an intense multi-disciplinary environment for innovative research. Financial participation to the program in the form of a studentship will be provided for all selected participating students, and in the form of per diem + travel expenses for all other long-term participants. Students will be provided with accommodation on campus. Help will be available to senior participants in finding accommodation, either in town or on campus.

Director: Pascale Garaud. SOC: Nic Brummell, Pascale Garaud (UCSC Applied Mathematics and Statistics), Mark Krumholz (UCSC Astrophysics), Pat Diamond (UCSD Physics), Michel Rieutord (Toulouse, Astrophysics).

Budget for 2010: approximately $100K

ISIMA

INTERNATIONAL SUMMER INSTITUTE FOR MODELING IN ASTROPHYSICS

- Home
- The Institute
- The current program
- Past programs
- Funding
- Applications
- Information for participants
- Contact

ISIMA 2010: Transport Processes in Astrophysics

UC Santa Cruz, July 5th - August 13th, 2010

The 2010 ISIMA is dedicated to the study of "Transport processes in Astrophysics", and will address topical problems such as radiative transfer, and transport of chemical species, momentum, magnetic fields and energy induced by waves or by hydrodynamical and magnetohydrodynamical turbulence.

- First Annoucement
- SOC
- LOC
- Confirmed participants
- 1st week Workshop program

Student applications for the 2010 ISIMA are due on January 20th, 2010.

http://isima.ucsc.edu

Scientific Organising Committee

- Nic Brummell, Applied Mathematics and Statistics, UC Santa Cruz
- Pat Diamond, Physics, UC San Diego
- Pascale Garaud, Applied Mathematics and Statistics, UC Santa Cruz
- Mark Krumholz, Astronomy and Astrophysics, UC Santa Cruz
- Michel Rieutord, Astrophysics, Toulouse, France.

Web-page maintained by isima@ucsc.edu. Last updated Oct. 1, 2009.

Web-site hosted by the University of California at Santa Cruz.

UC SANTA CRUZ

"Transport Processes in Astrophysics"

Confirmed participants

Local Participants (UC Santa Cruz)

Name	Position	Department	Tentative dates
Clement Baruteau	Postdoc	A&A	Weeks 1-6
Nic Brummell	Professor	AMS	Weeks 1-6
Jonathan Fortney	Asst. Professor	A&A	To be confirmed
Pascale Garaud	Asst. Professor	AMS	Weeks 1-6
Gary Glatzmaier	Professor	Earth & Planetary Sciences	Weeks 1,2,3,5,6
Don Korycansky		Earth & Planetary Sciences	Weeks 1-6
Mark Krumholz	Asst. Professor	A&A	Weeks 1-6
Piero Madau	Professor	A&A	Weeks 1-3
Francis Nimmo	Assoc. Professor	Earth & Planetary Sciences	Weeks 1-6
Joel Primack	Professor	A&A	Weeks 1-6
Enrico Ramirez-Ruiz	Asst. Professor	A&A	To be confirmed
Toby Wood	Postdoc	AMS	Weeks 1-6

Visiting Participants

Name	Position	Department/University	Tentative Dates
Patrick Diamond	Professor	Physics, UC San Diego	Weeks 1-4
Douglas Gough	Professor	IoA, DAMTP, Univ. Cambridge	Weeks 1-3
Michel Rieutord	Professor	Astrophysics, Toulouse	Weeks 1-5
Steve Balbus	Professor	ENS, Paris	2 weeks TBA
Jim Stone	Professor	Princeton	2 weeks TBA
Subhanjoy Mohanty	Lecturer	Imperial College London	Weeks 1-6
Stephan Stellmach	Super-Postdoc	U. Muenster	2 weeks TBA
Andrew Youdin	Postdoc	CITA	Weeks 1-4

AstroComputing Public Outreach

Work with NASA's Advance Supercomputing (NAS) staff and with leading digital planetariums (co-Is from Adler, Morrison) to make visible the 99.5% of the universe that's made of invisible atoms, dark matter, and dark energy

- prepare visualizations for digital dome shows and 3D shows, including supporting educational materials, and help to train planetarium staff
- determine how best to show simultaneously the multiple comonents of the universe (stars, gas, dark matter, and dark energy) to various audiences, with the help of professional educators and evaluators

(Initial proposal just rejected by NASA - we'll try again)

AstroComputing Education

Work with schools such as Pacific Collegiate School, Watsonville High School, and UCSC Education and Computer Science Departments to

- develop new curricular materials to teach modern cosmology and astrobiology at the middle school and high school levels, both as science and as "big history"

- use supercomputer visualizations and other animations and computer games to inspire students to understand the universe and how they fit into it

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- develop new curricular materials to teach modern cosmology and astrobiology at the middle school and high school levels, both as science and as "big history" (proposal just rejected by NASA; we'll keep trying...)

- use supercomputer visualizations and other animations and computer games to inspire students to understand the universe and how they fit into it (proposal submitted to NASA by Adler Planetarium)

UC AstroComputing Institute Challenges

Computational and Data Challenges

- Scale codes efficiently to many thousands of cores, implementing automatic load balancing
- Develop protocols for running algorithms on enormous (practically unmovable) new data sets from telescopes and supercomputers

Organizational Challenges

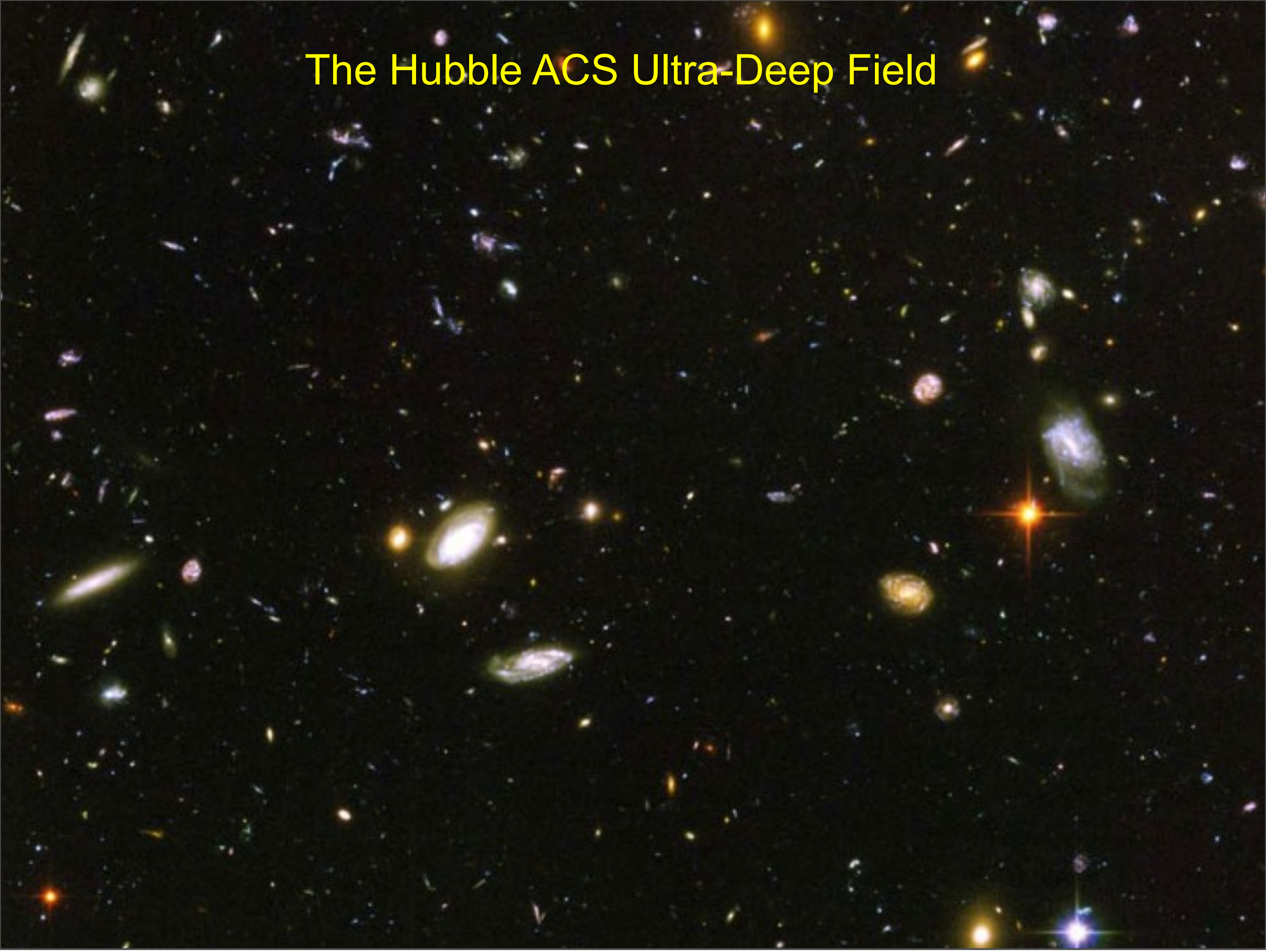
- Create new opportunities for collaboration between astrophysicists and computer scientists and engineers
- Raise funds for staff to work with astrophysicists to create scalable new codes and data technologies, better visualization and data mining techniques, and new approaches to education and outreach

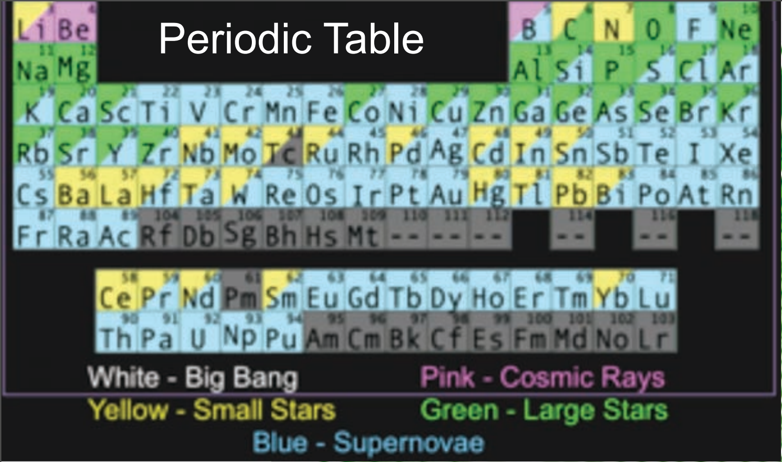
UC AstroComputing Institute Future Goal

To grow into (part of) an astronomical science institute for the next generation of world-class California-led telescopes: the Thirty Meter Telescope (TMT) and the Large Synoptic Survey Telescope (LSST)

- help plan observations and design instruments
- staff to help scientists utilize the next generation of supercomputers, hosting hundreds of thousands or millions of processors, to understand astrophysical processes through simulation, and
- a center to host the petabytes (soon to be exabytes) of data that will flow from the new telescopes and supercomputers

The Hubble ACS Ultra-Deep Field

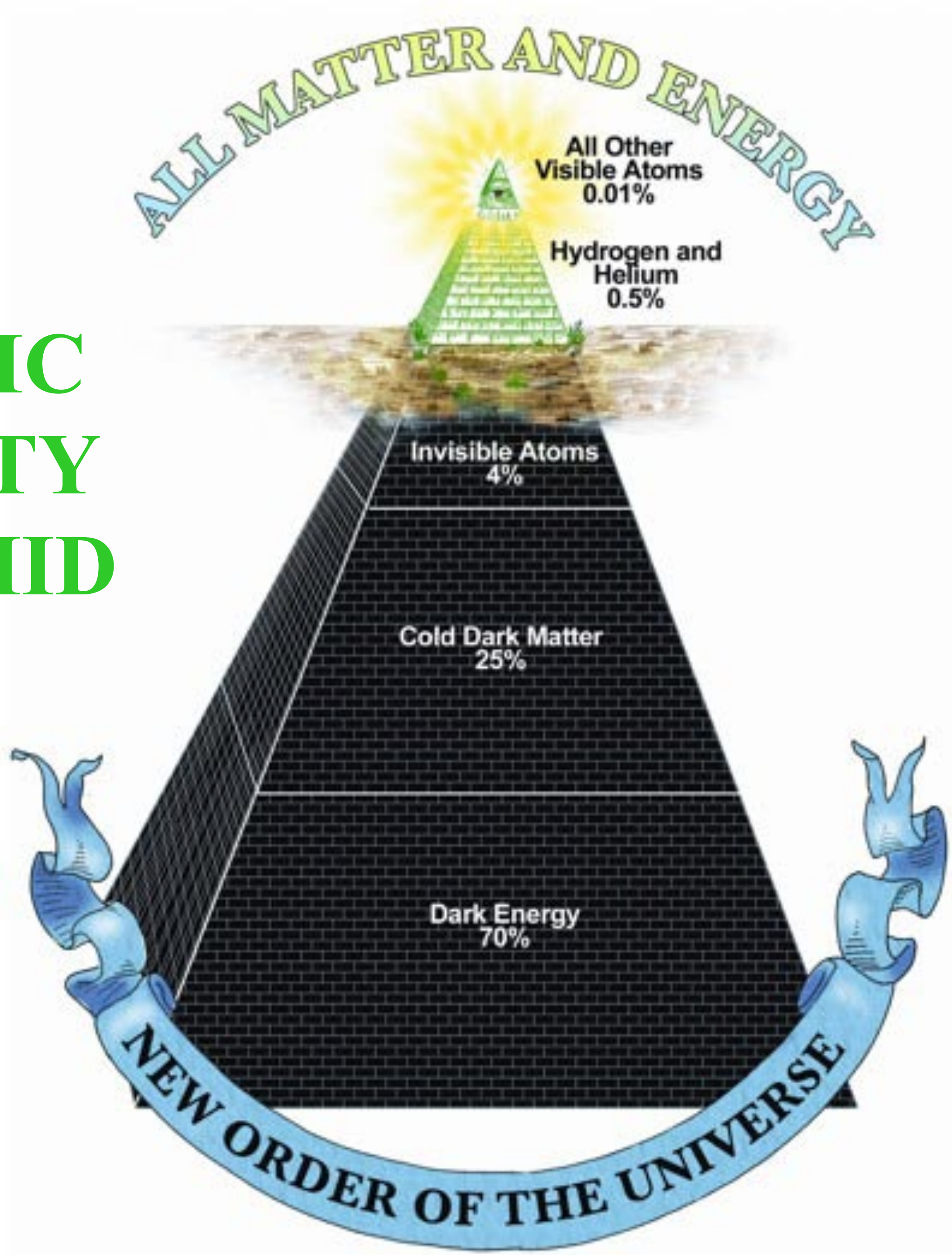


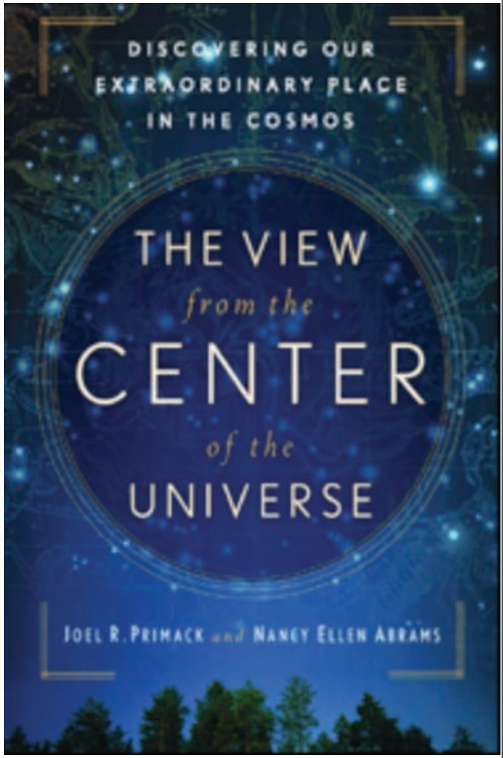


stardust

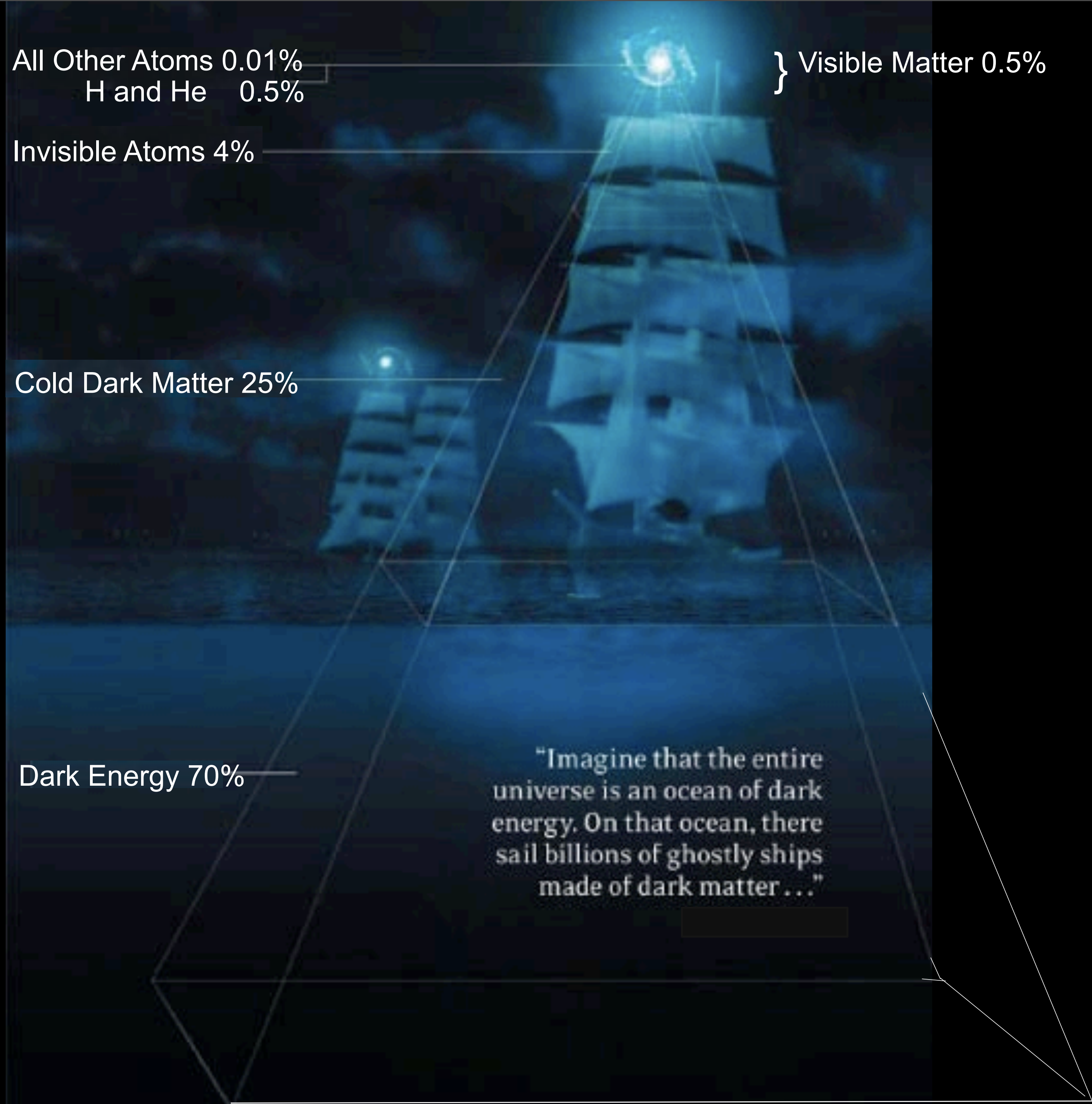
stars

COSMIC DENSITY PYRAMID



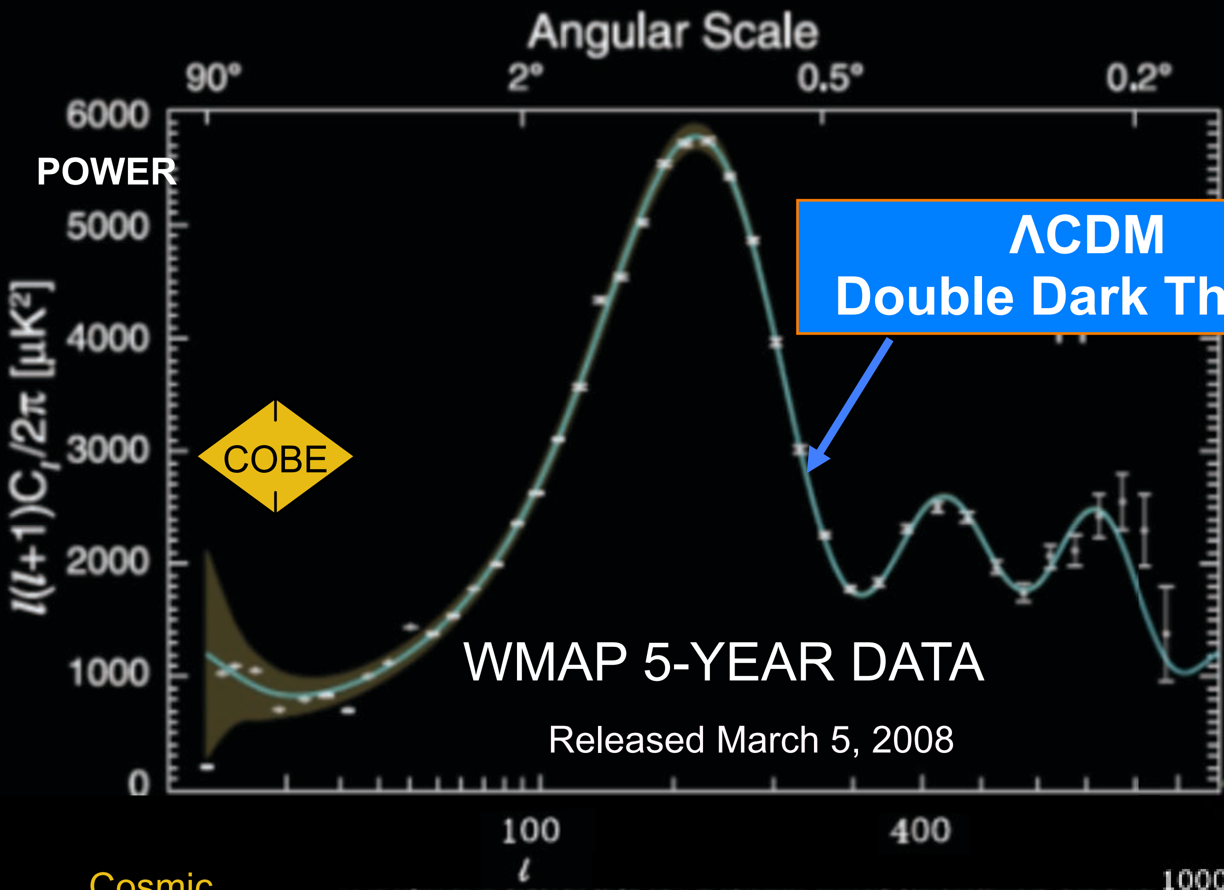


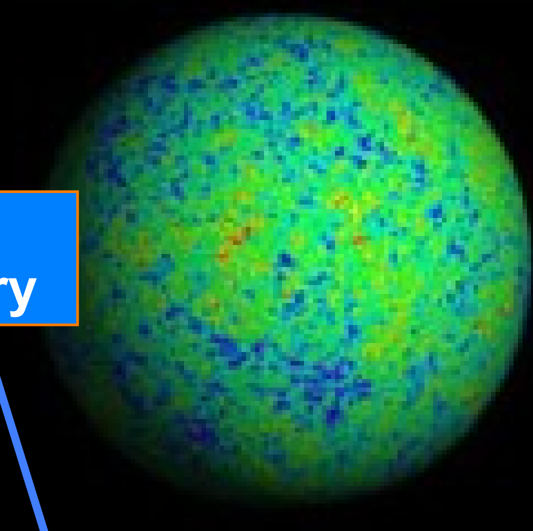
http://ViewfromtheCenter.com

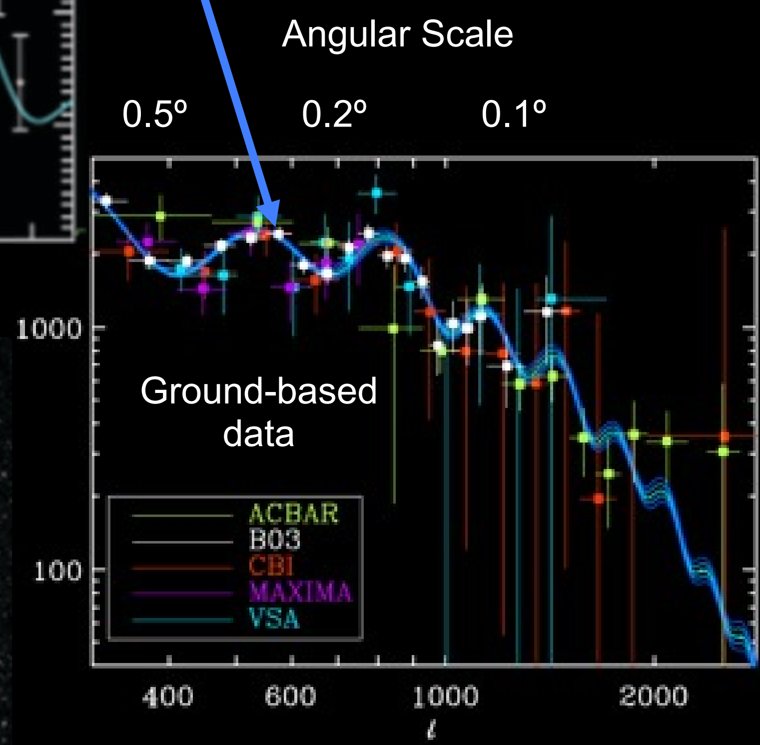


All Other Atoms 0.01%
H and He 0.5%
} Visible Matter 0.5%
Invisible Atoms 4%
Cold Dark Matter 25%
Dark Energy 70%
"Imagine that the entire universe is an ocean of dark energy. On that ocean, there sail billions of ghostly ships made of dark matter . . ."

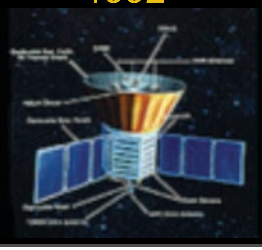
Big Bang Data Agrees with Double Dark Theory!

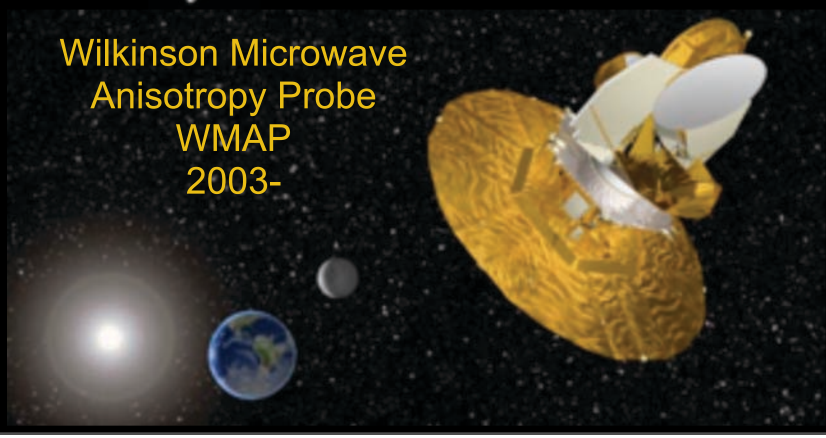






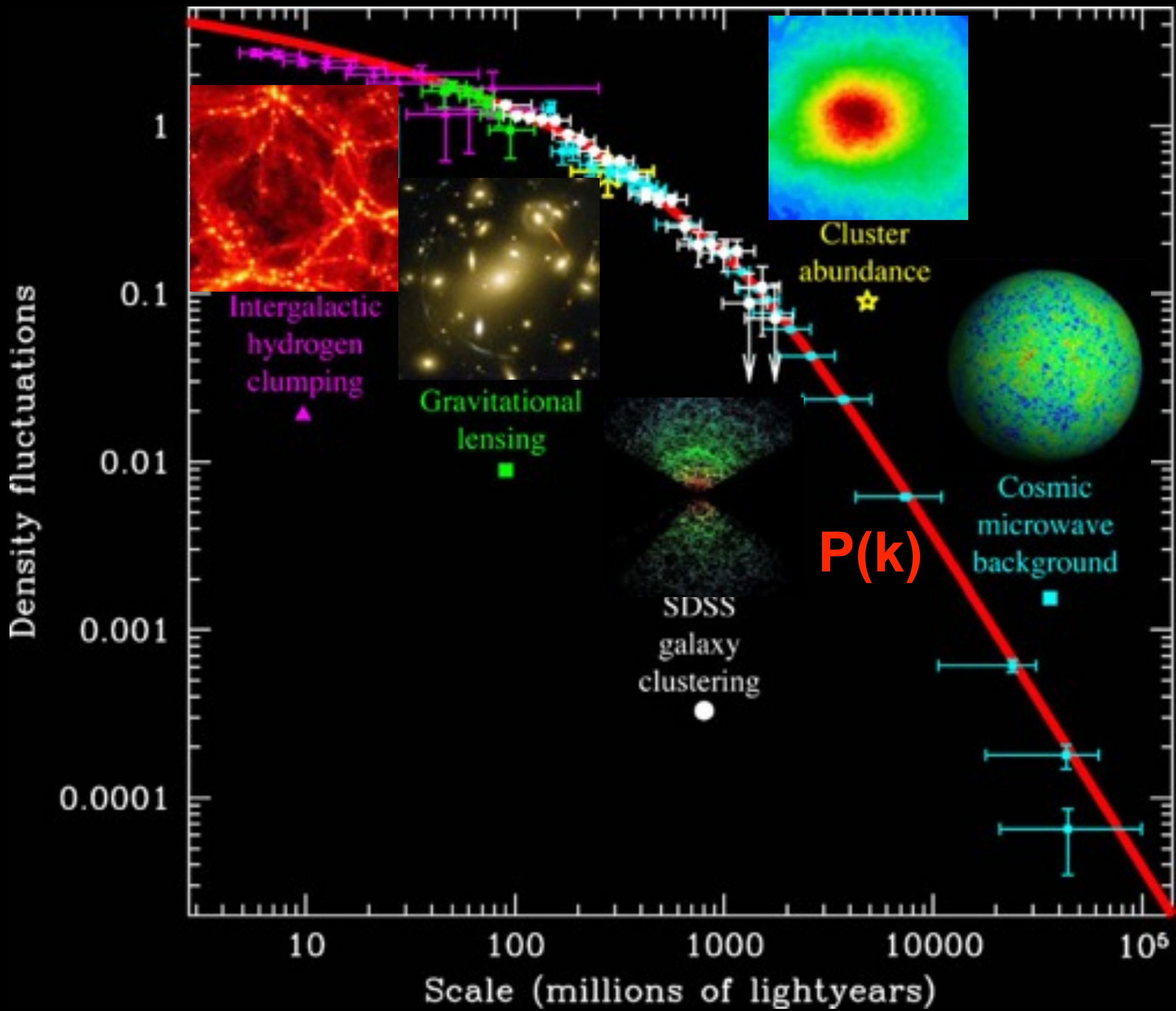
Cosmic Background Explorer COBE 1992





Distribution of Matter

Also Agrees with Double Dark Theory!



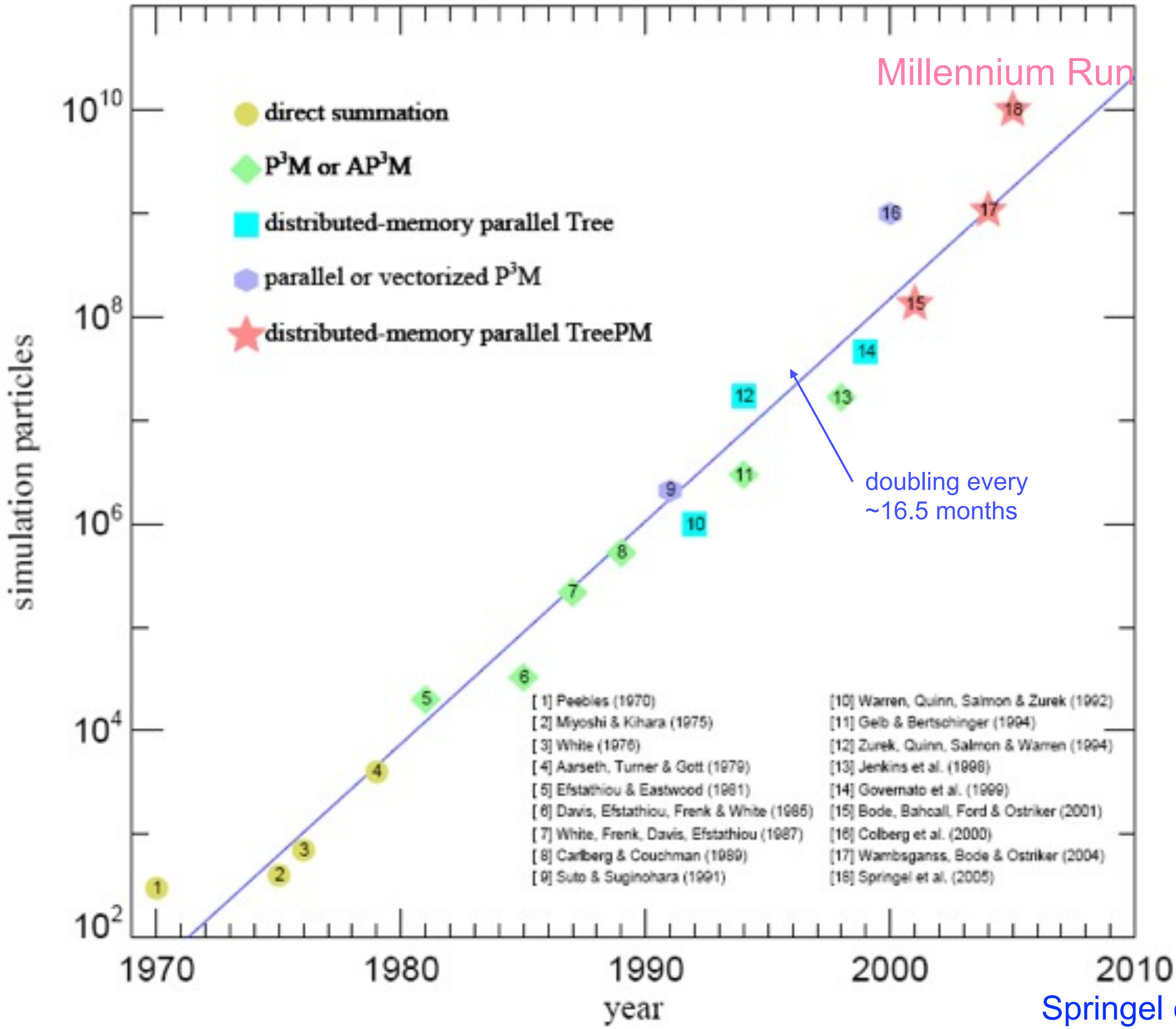
Max Tegmark

Because the ΛCDM **Dark Energy + Cold Dark Matter** (**"Double Dark"**) theory of structure formation is now so well confirmed by observations, we can now use the predictions of this theory for the formation of dark matter structure in the universe to improve our understanding of the visible objects that we can study with telescopes: galaxies, clusters, and large-scale structure.

Astronomical observations represent snapshots of moments in time.

It is the role of astrophysical theory to produce movies that link these snapshots together into a coherent physical theory.

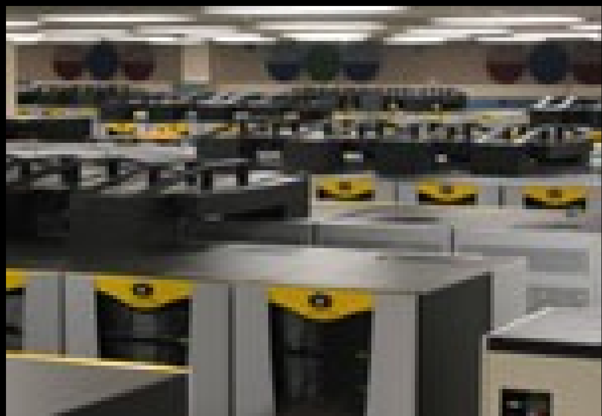
Particle number in cosmological N-body simulations vs. pub date



Springel et al. 2006

Cosmological Simulations on

COLUMBIA PLEIADES



NASA
Ames
Research
Center

P. I.:

Joel Primack
University of California, Santa Cruz

Co-Investigators:

Anatoly Klypin
New Mexico State University

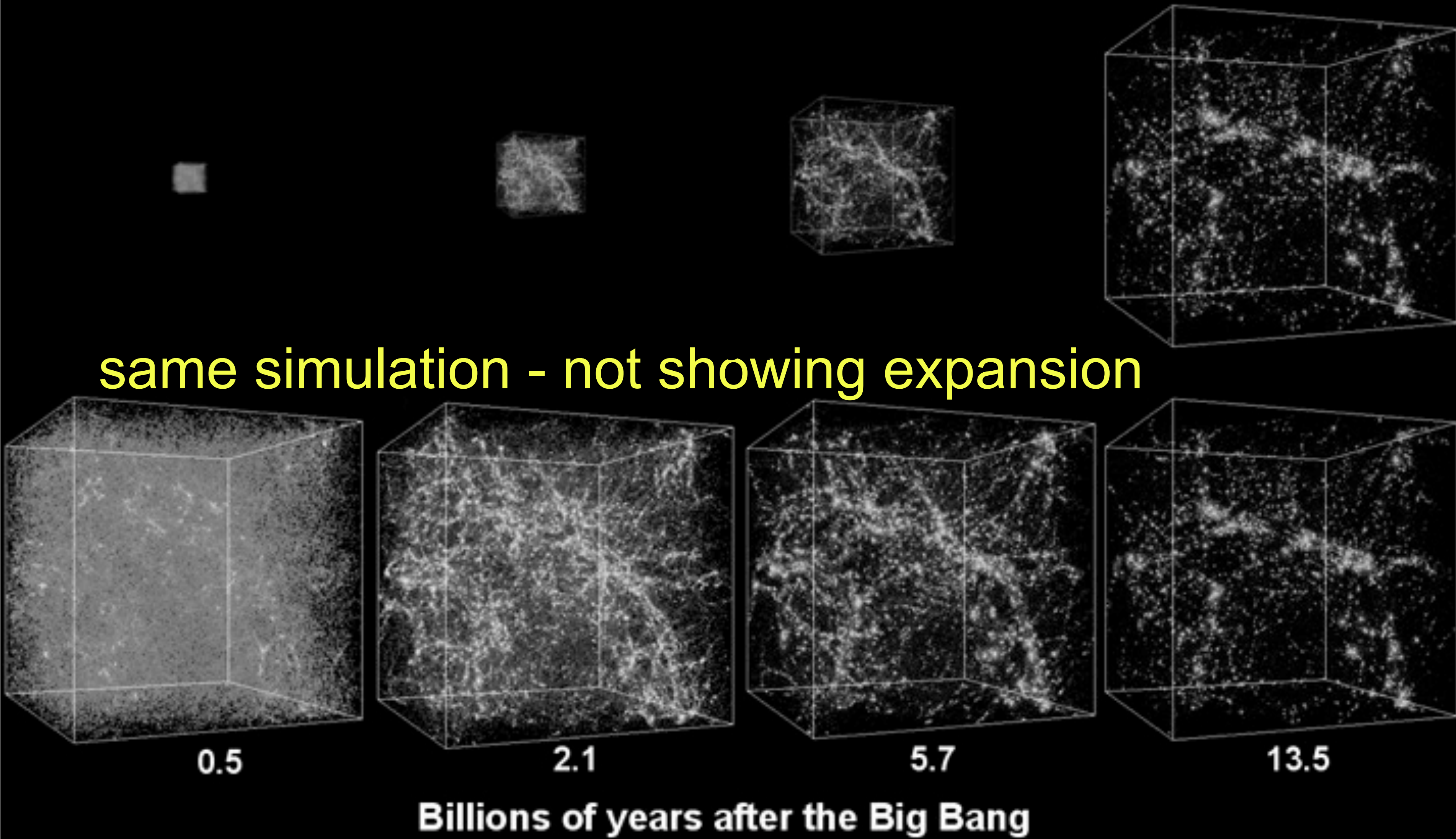
Andrey Kravtsov
University of Chicago

Patrik Jonsson
Harvard University - Smithsonian CfA

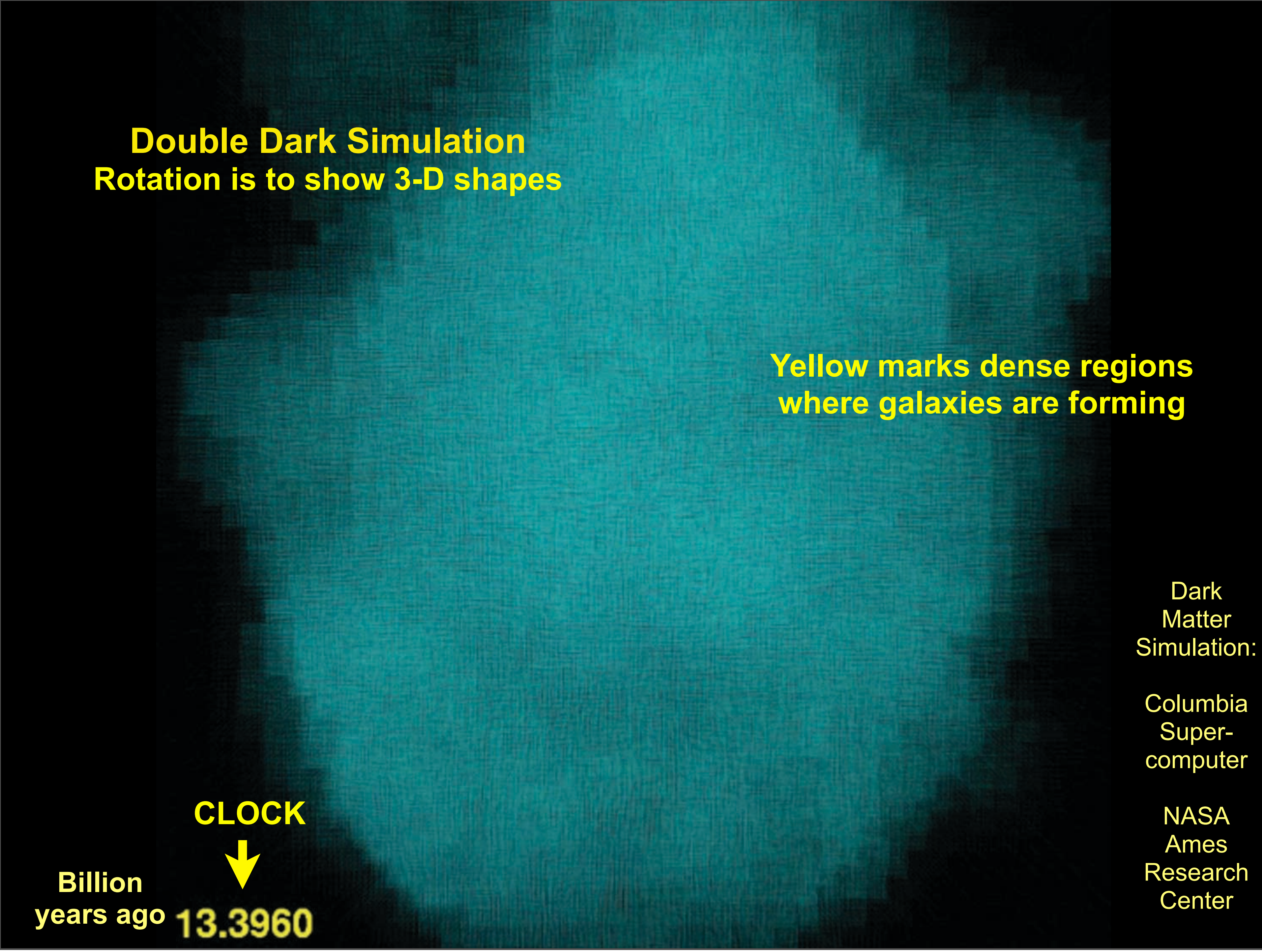
"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

dark matter simulation - expanding with the universe

same simulation - not showing expansion



Andrey Kravtsov



Monday, November 30, 2009

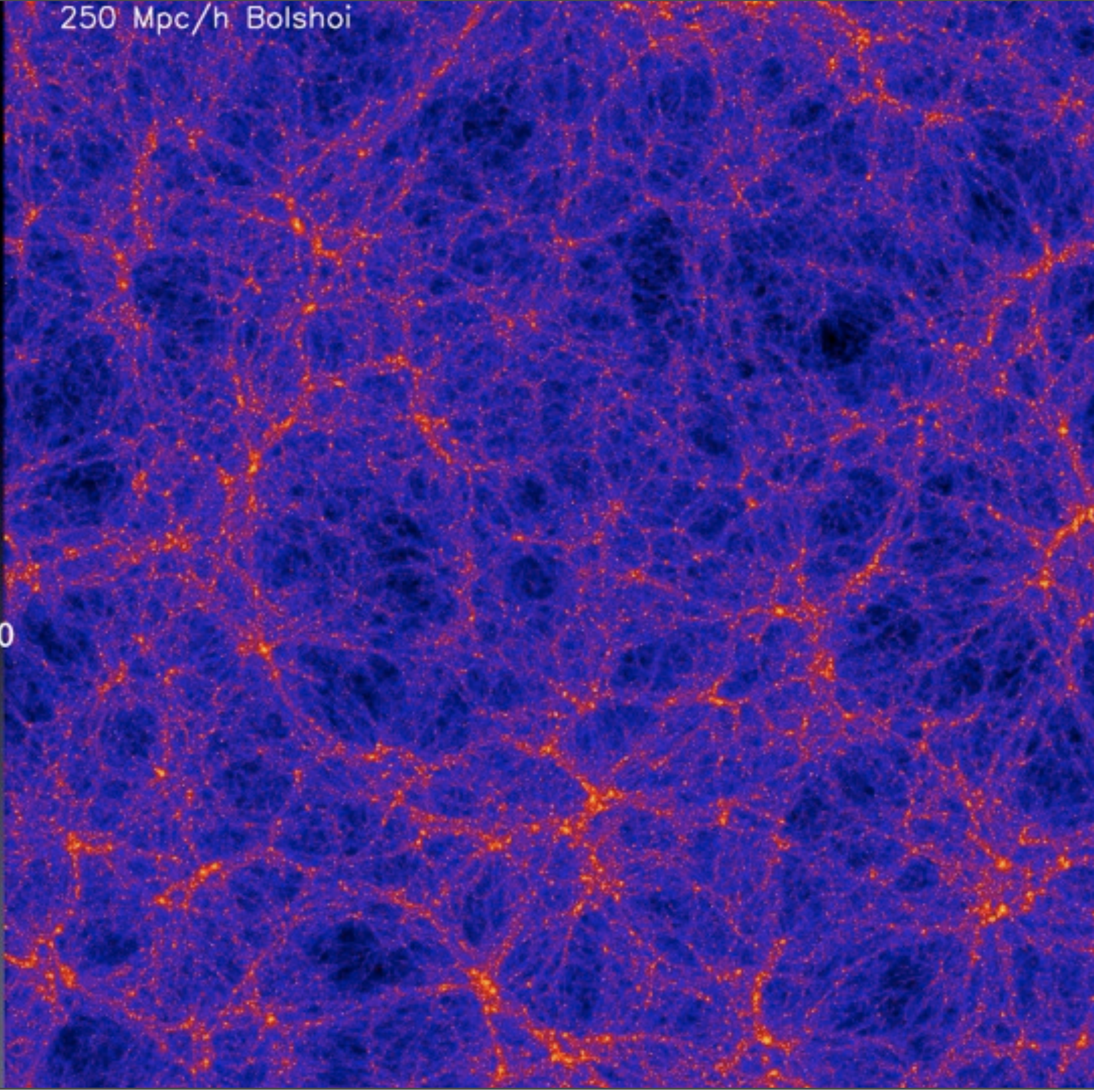
The Bolshoi simulation

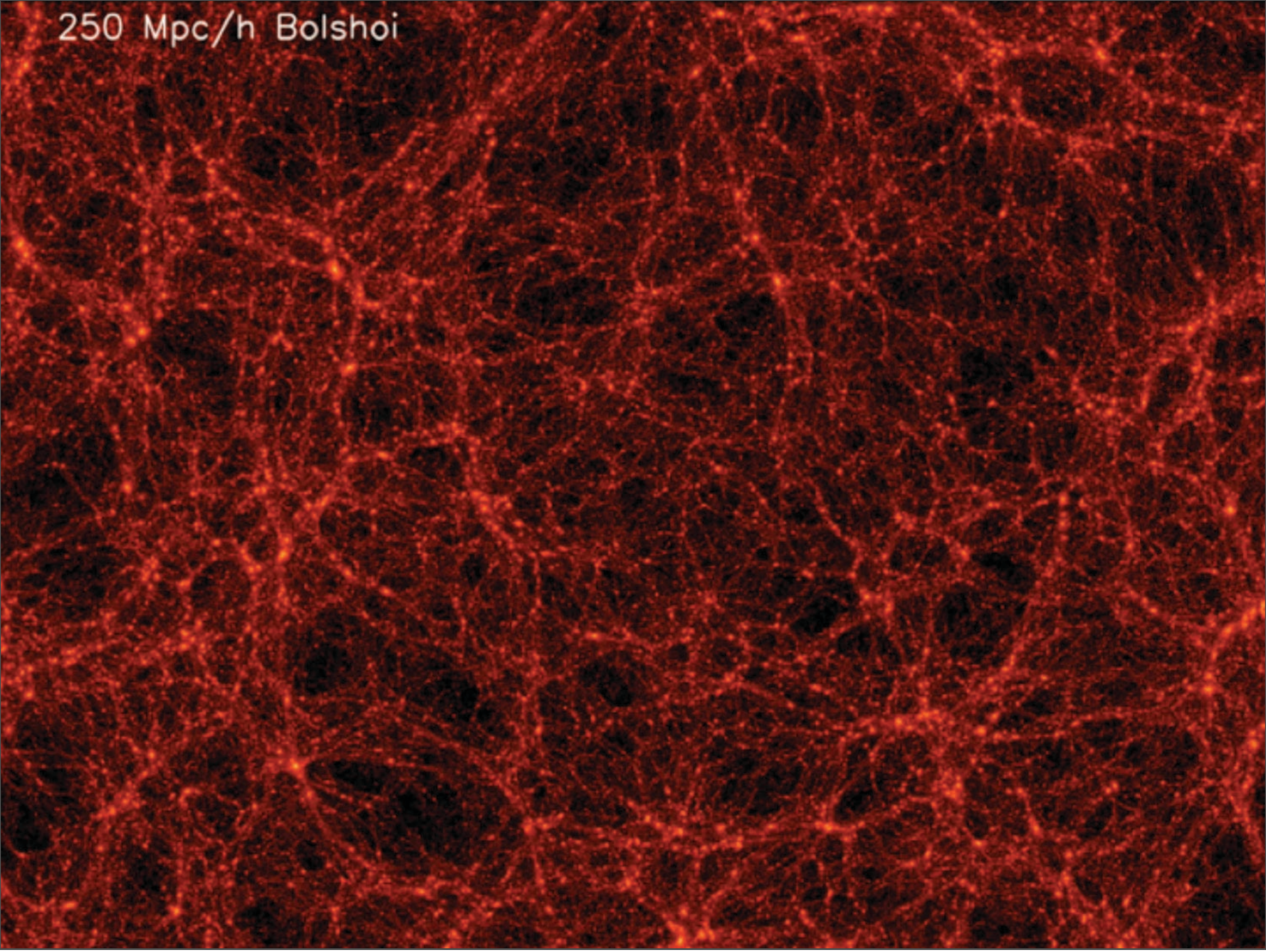
ART code

250Mpc/h Box
LCDM
s8 = 0.83
h = 0.73
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

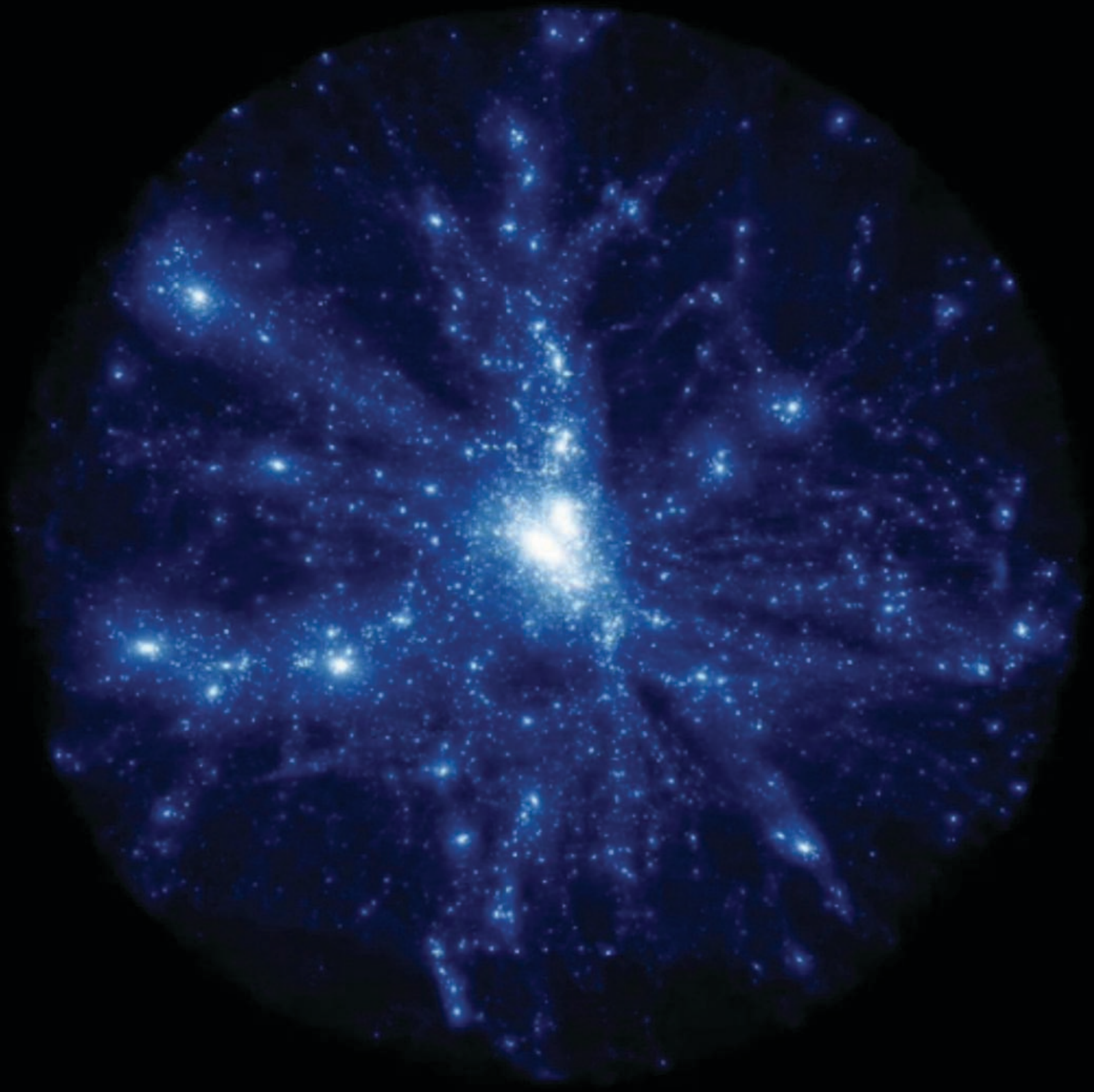
dynamical range 262,000
time-steps = 400,000

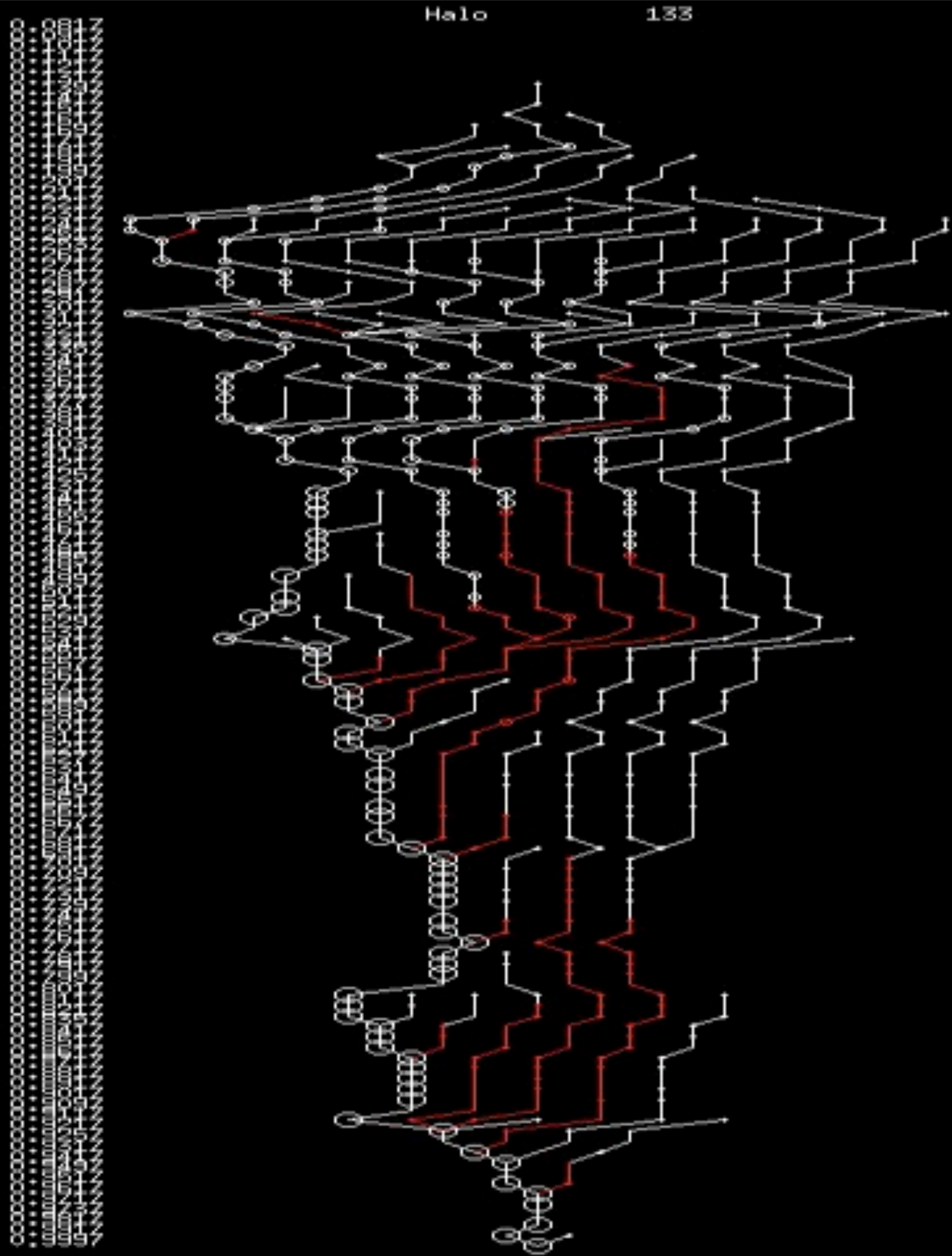
NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time




250 Mpc/h Bolshoi

BOLSHOI SIMULATION FLY-THROUGH





Merger history (tree) of a galaxy mass halo. The y axis is scale factor (time) with time increasing as you go down. The circles are identified halos at that scale factor. White circle are distinct (isolated) halos and red circles are subhalos (most often of the most massive progenitor, which is always the halo on the left). The size of the circle is a relative indication of the size of the virial radius.

Progress Report: All 170 stored timesteps of the Bolshoi simulation have now been analyzed to find halos and subhalos using BDM, and fof/subfind analysis is in progress in collaboration with Risa Wechsler and Mike Busha (KIPAC) and Stefan Gottloeber (AIP). The first Bolshoi merger trees have just been computed.

These will be inputs to a new generation of Semi-Analytic Models (SAMs) of galaxy formation and evolution:

Munich-type SAM - Darren Croton (Swinburne)
Santa Cruz-type SAM - Rachel Somerville (STScI)
Durham-type SAM - Andrew Benson (Caltech) &
Lauren Porter (UCSC/Primack)

Our cosmological simulations and analyses are allowing us to model the local universe and study the evolution and structure of dark matter halos, and produce detailed models of halo and galaxy evolution. Our work is being used to interpret the results from the largest galaxy surveys: SDSS, the Sloan Digital Sky Survey of the nearby universe, and DEEP, the Deep Extragalactic Evolutionary Probe of galaxies during their period of assembly (the largest project of the Keck Observatory, with crucial satellite data from *HST, Spitzer, GALEX, and Chandra*). And also data from even higher redshifts.

Simulations of Dust in Interacting Galaxies

Patrik Jonsson

UCSC / Harvard

HST image of “The Antennae”

Dust in galaxies is important

- Absorbs about 40% of the local bolometric luminosity
- Makes brightness of spirals inclination-dependent
- Completely hides the most spectacular bursts of star formation
- Makes high-redshift star formation very uncertain

Dust in galaxies is complicated

- The mixed geometry of stars and dust makes dust effects geometry-dependent and nontrivial to deduce
- Needs full radiative transfer model to calculate realistically

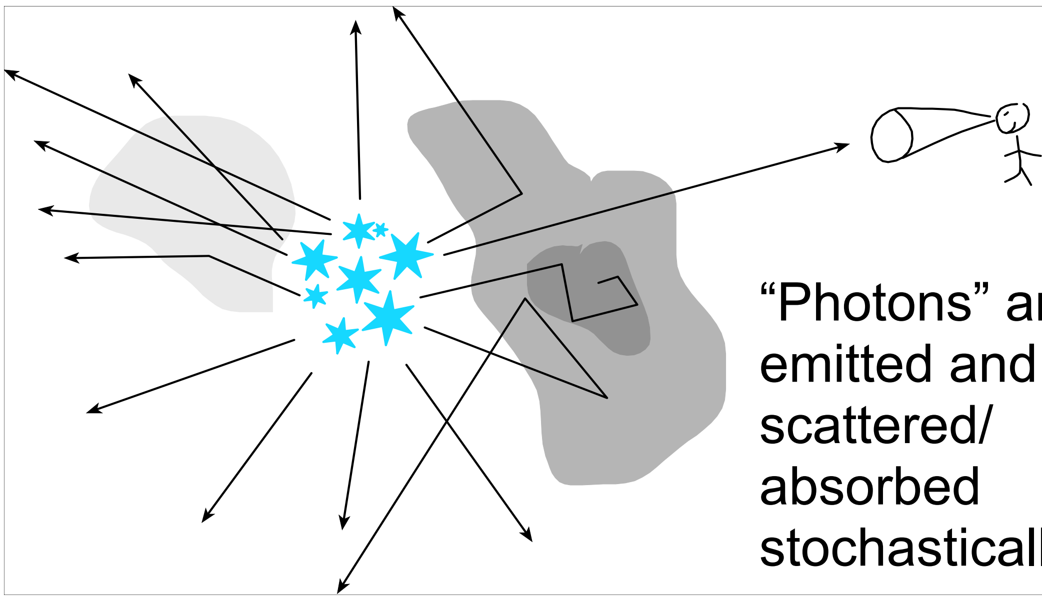
Previous efforts have used 2 strategies

- Assume a simple, schematic geometry like exponential disks, or
- Simulate star-forming regions in some detail, assuming the galaxy is made up of such independent regions
- Have not used information from hydrodynamic simulations

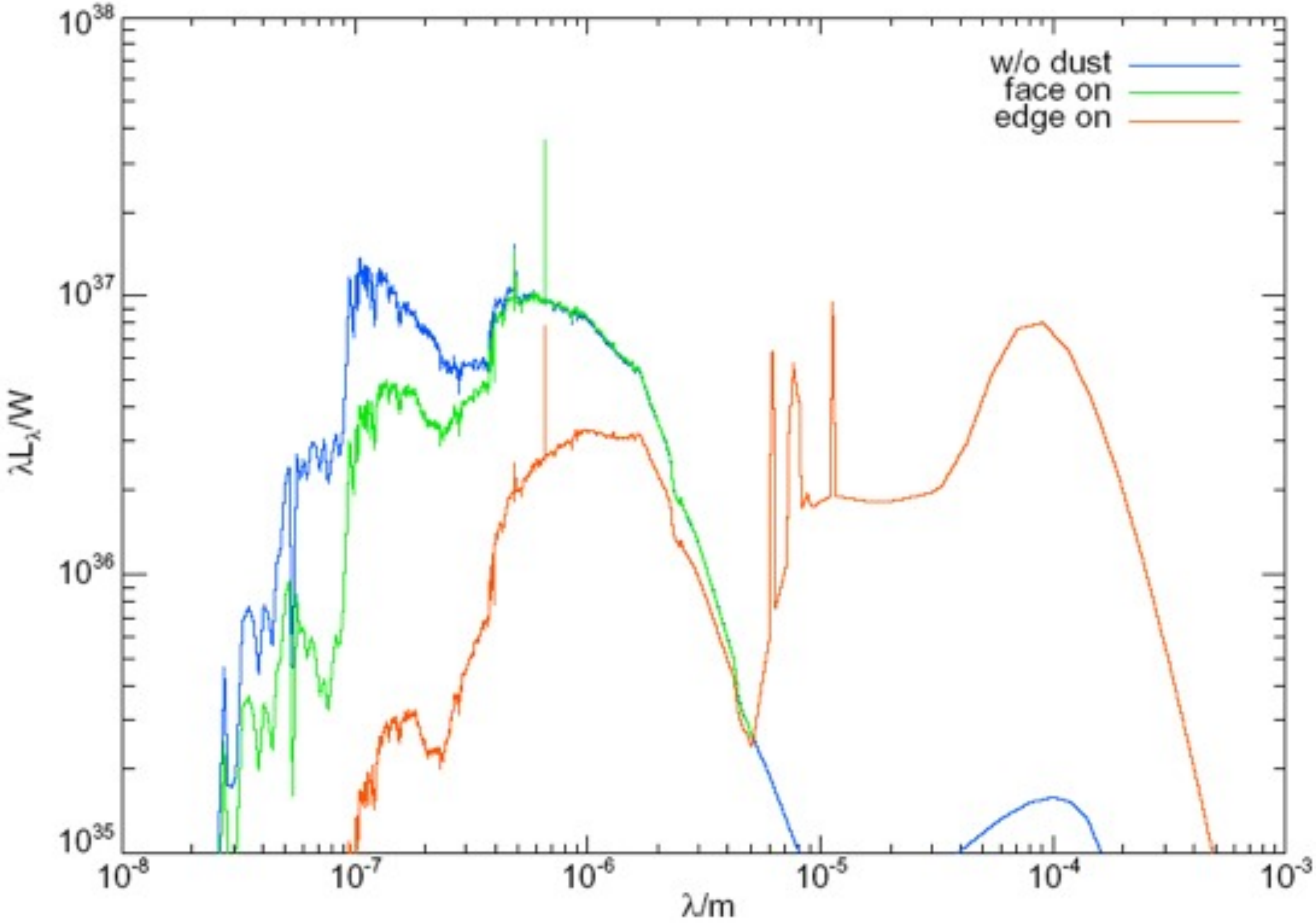
Our Approach

For every simulation snapshot:

- SED calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- "Polychromatic" rays save CPU time



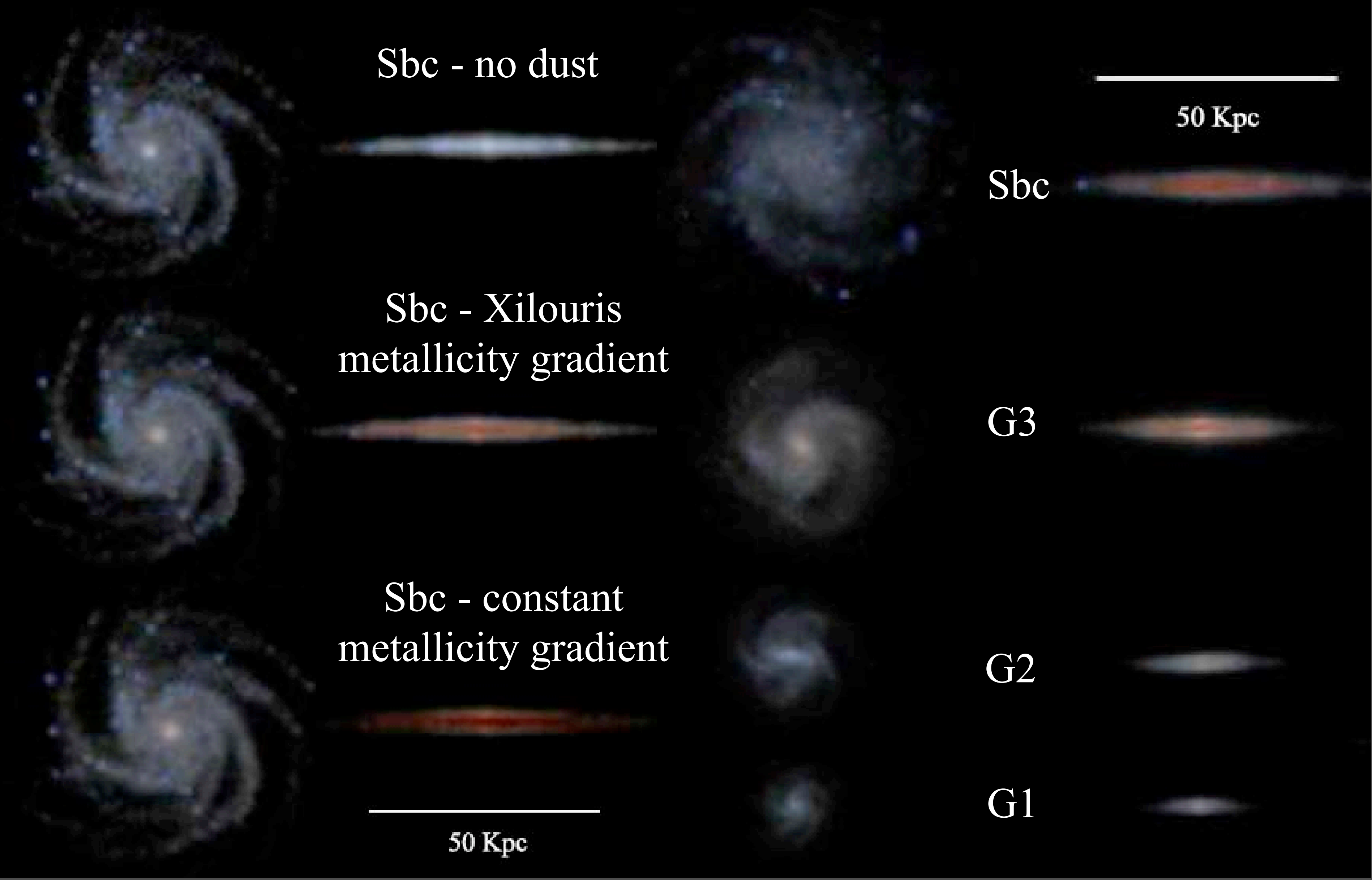
Spectral Energy Distribution

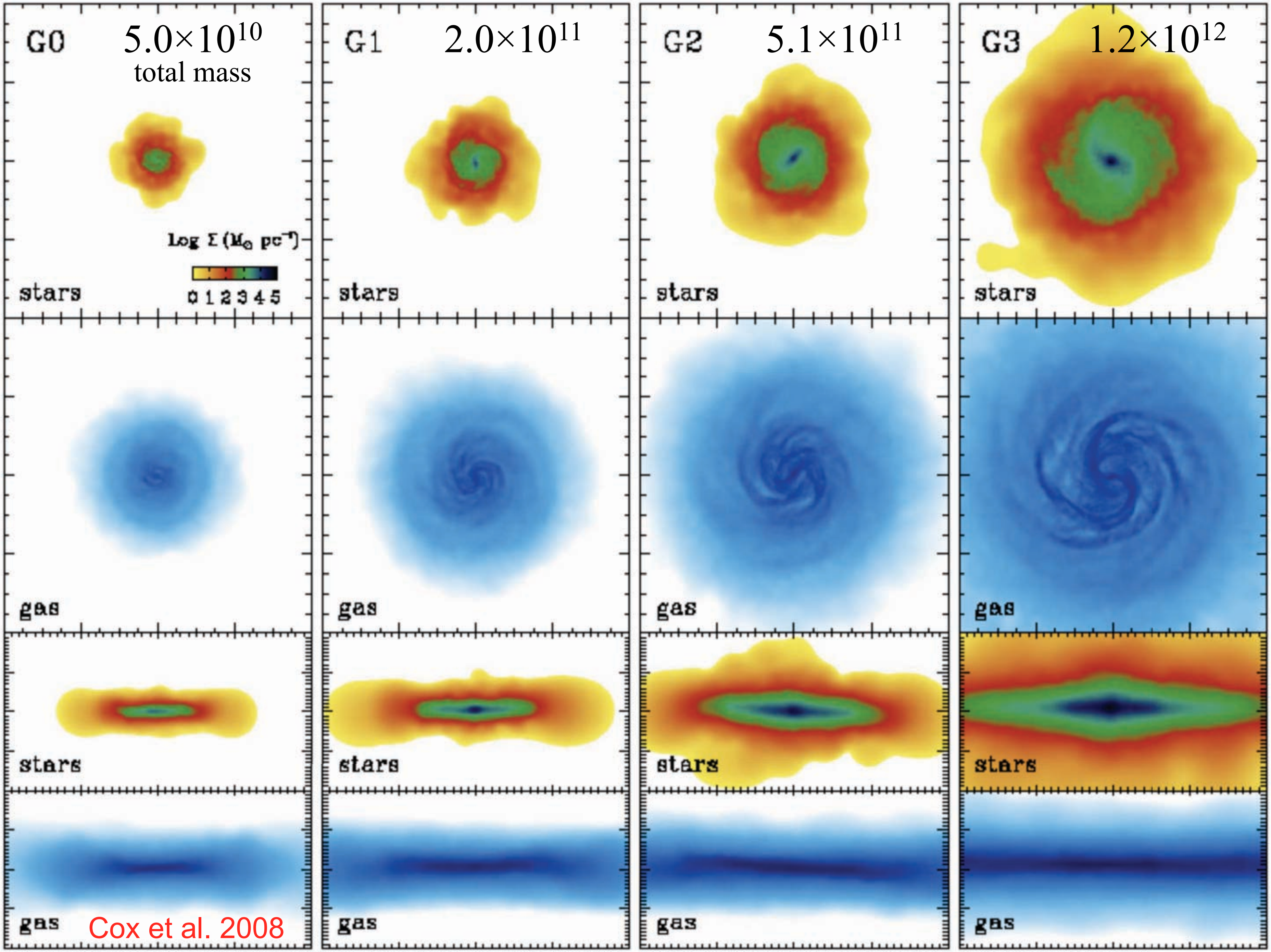


Dust Attenuation in Hydrodynamic Simulations of Spiral Galaxies

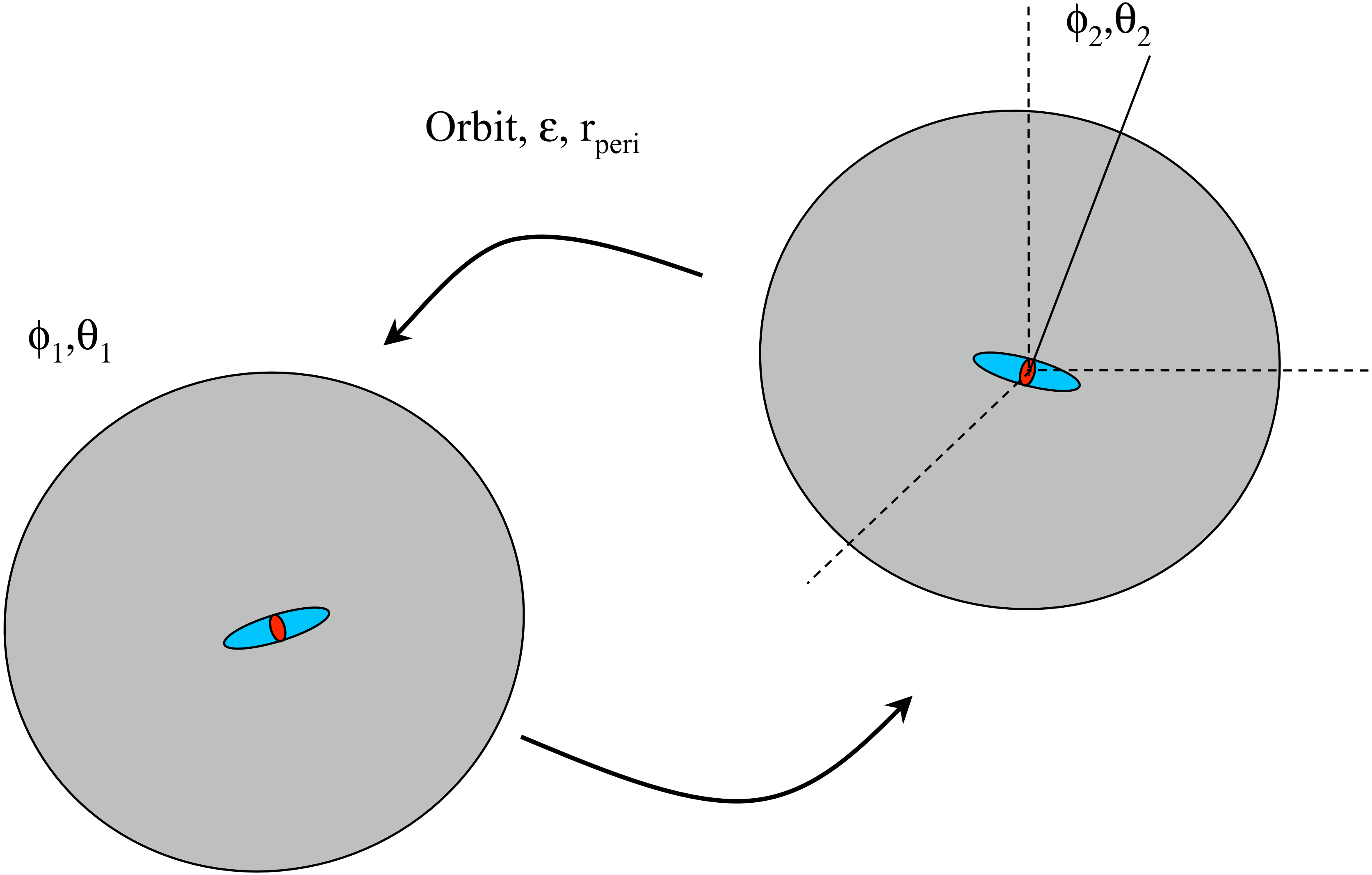
Rocha, Jonsson, Primack, & Cox 2008 MN

Right hand side:
Xilouris et al. 1999
metallicity gradient

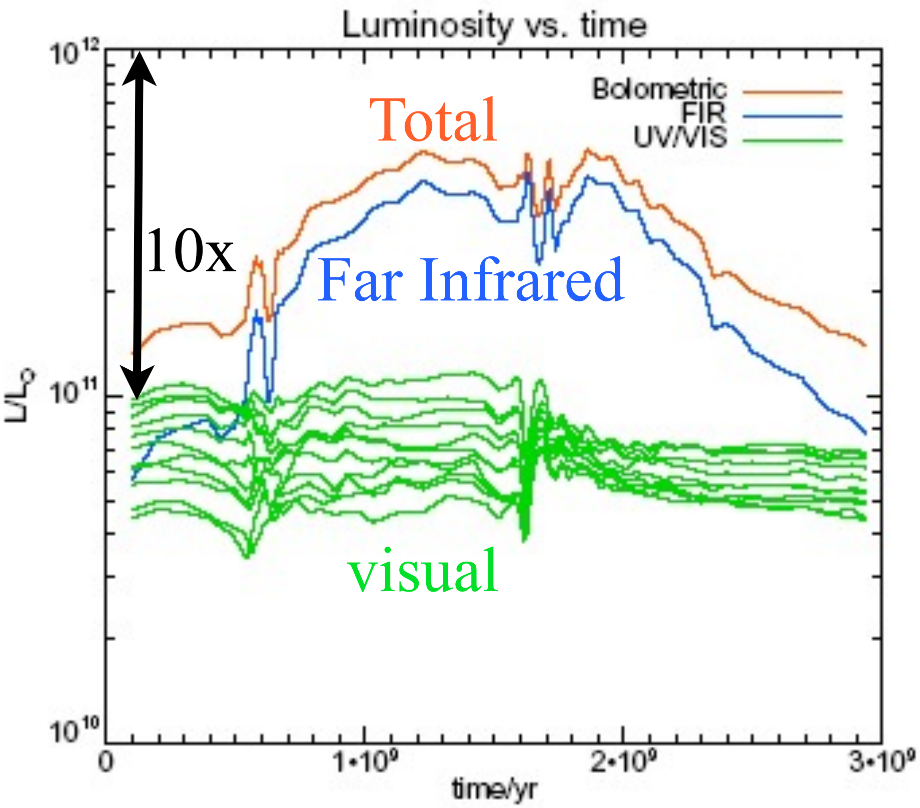



G0
5.0×10^10
total mass
G1
2.0×10^11
G2
5.1×10^11
G3
1.2×10^12
Log Σ (M☉ pc⁻²)
0 1 2 3 4 5
stars
gas
Cox et al. 2008

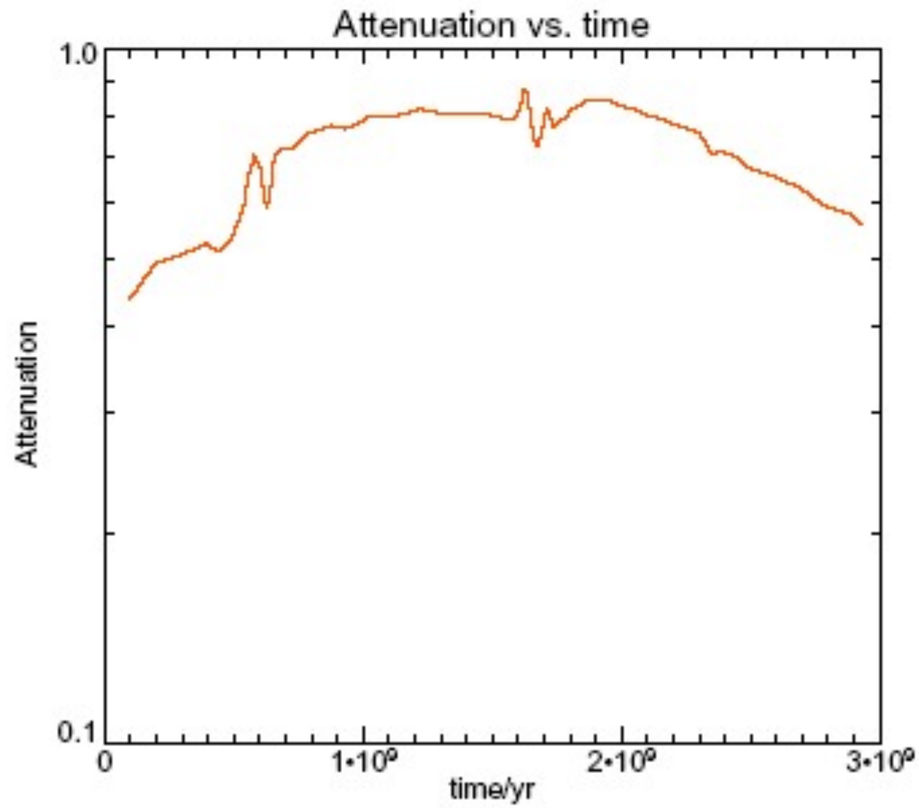
So Let's Merge Two Disks



Luminosity vs. Time

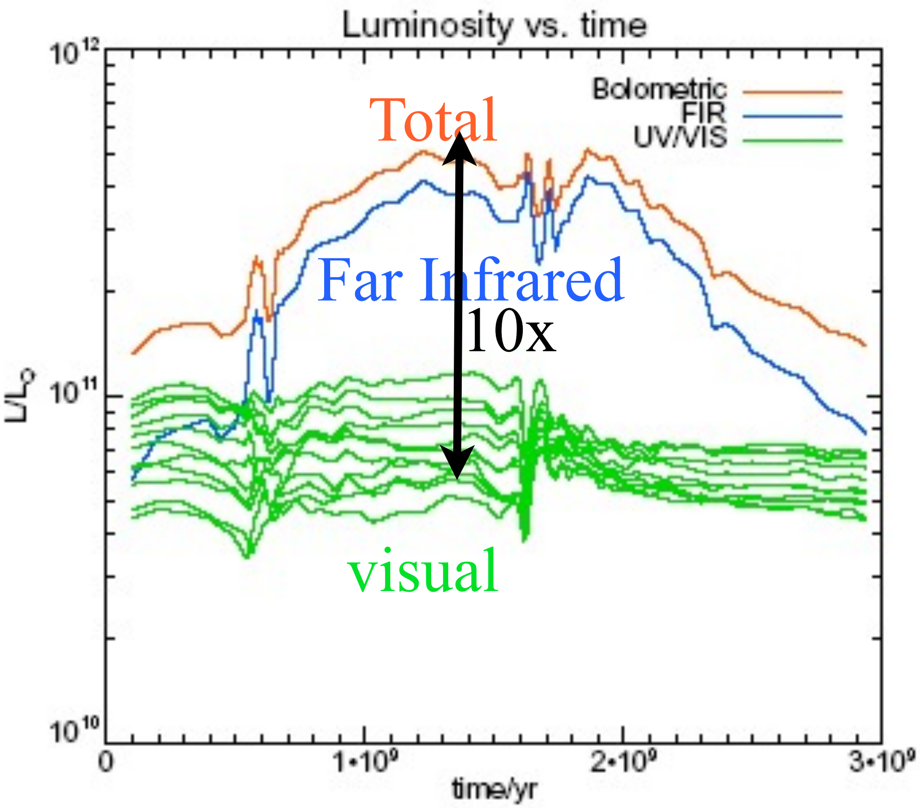


Attenuation vs. Time

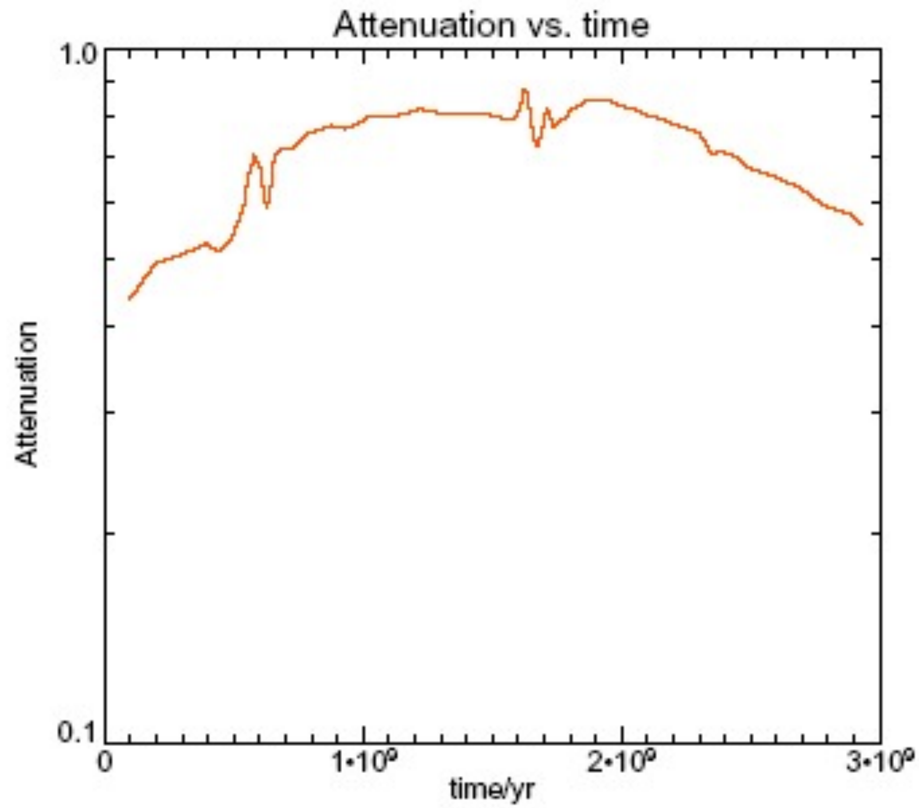


Visual luminosity is practically constant over time, even though the bolometric luminosity increases ~10x during the merger, because attenuation increases with luminosity.

Luminosity vs. Time



Attenuation vs. Time



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Galaxy Merger Simulation

run on the Columbia Supercomputer

This image and the following videos show a merger between two Sbc galaxies, each simulated with 1.7 million particles. The images are realistic color composites of u, r, and z-band images. Galaxy mergers like this one trigger gigantic “starbursts” in which millions of stars form. But dust absorbs about 90% of the light, and reradiates the energy in the far infrared. We calculate this “radiative transfer” using ~10^6 light rays per image. The simulation was run by Greg Novak, and the visualization is by Patrik Jonsson.

Galaxy Merger Simulation

Patrik Jonsson, Greg Novak, Joel Primack

music by Nancy Abrams

Accelerating Dust Temperature Calculations with Graphics Processing Units

Patrik Jonsson, Joel R. Primack

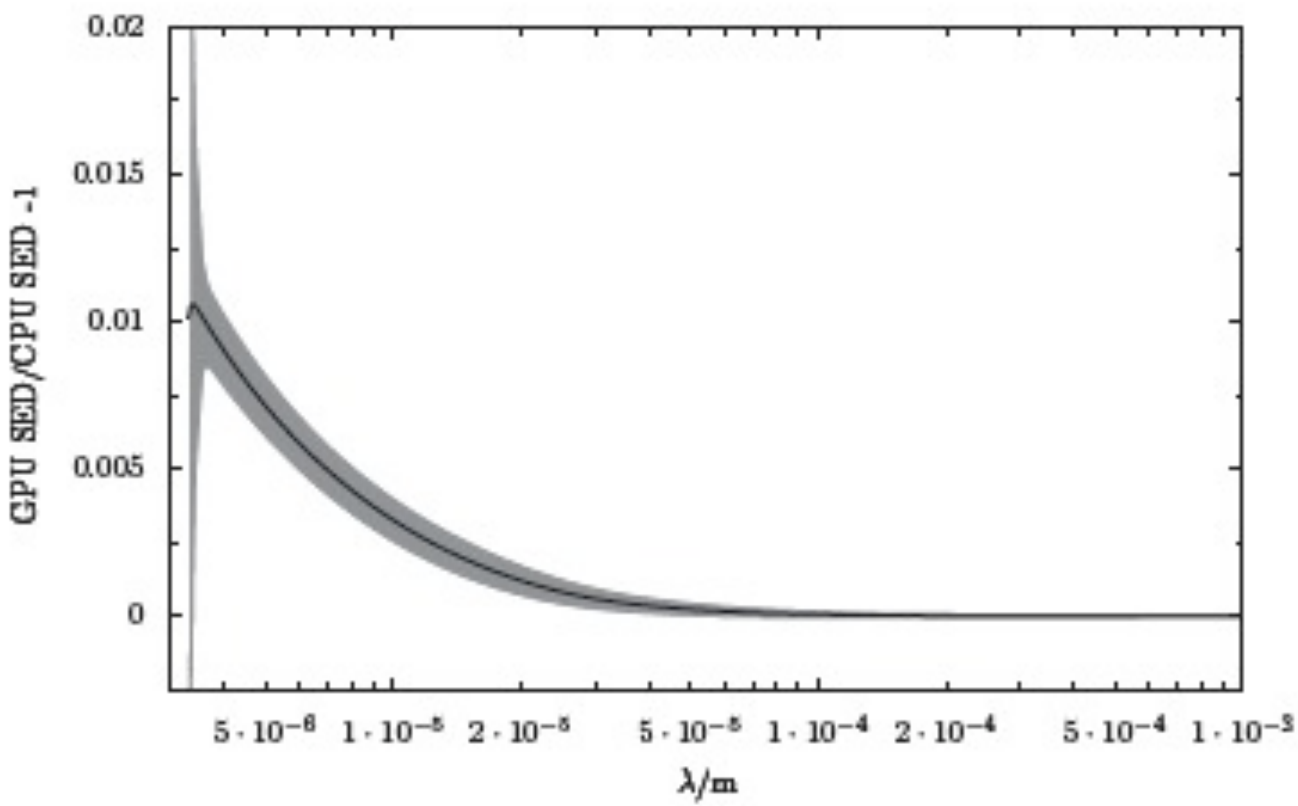
submitted to New Astronomy (arXiv:0907.3768)

When calculating the infrared spectral energy distributions (SEDs) of galaxies in radiation-transfer models, the calculation of dust grain temperatures is generally the most time-consuming part of the calculation. Because of its highly parallel nature, this calculation is perfectly suited for massively parallel general-purpose Graphics Processing Units (GPUs). This paper presents an implementation of the calculation of dust grain equilibrium temperatures on GPUs in the Monte-Carlo radiation transfer code Sunrise, using the CUDA API. The Nvidia Tesla GPU can perform this calculation 55 times faster than the 8 CPU cores, showing great potential for accelerating calculations of galaxy SEDs.

This paper presents an implementation of the dust grain equilibrium temperature and emission SED calculation in CUDA for the Monte-Carlo radiation transfer code sunrise (Jonsson, 2006; Jonsson et al., 2009). The CUDA version obtains a speedup of more than two orders of magnitude compared to a modern CPU core when using an Nvidia Tesla C1060 high-performance computing card with 4GB of memory using CUDA version 2.3, to that performed on an 8-core Intel Xeon E5420 (2.5 GHz) Linux machine with 32 GB RAM.

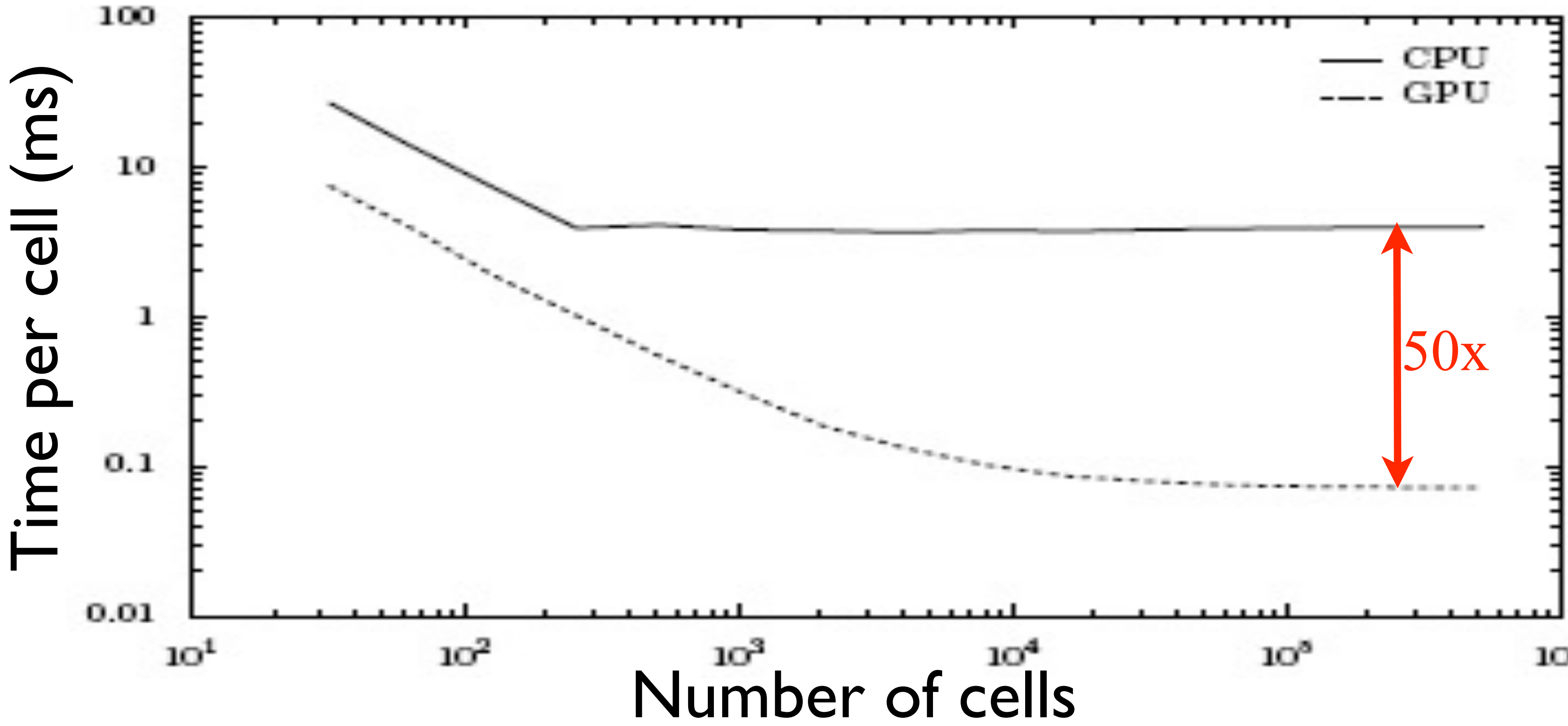
The exact calculation of $L_e(\lambda)$ performed on the GPU is actually competitive with a temperature table interpolation implemented on the CPU, a remarkable fact in itself. Second, the implementation of the calculation of equilibrium temperature emission serves as a useful warm-up for implementing the calculation of grains with fluctuating temperatures, which is even more computationally intensive.

Accuracy of Spectral Energy Distribution Calculation



The dust emission SED calculated by the GPU compared to that calculated on the CPU. The line indicates the mean over all cells of the SED ratio, weighted by the CPU SED. The shaded region indicates the 1σ variance (also SED-weighted) over the cells. The blow-up at short wavelengths occurs because the GPU SED is calculated in single-precision and, for the dust temperatures encountered in the problem, the exponential blackbody cutoff will underflow to zero at short wavelengths. This increase in variance at short wavelengths has no practical signicance as it occurs precisely because the actual emission drops to negligible levels.

GPU is 50x Faster than 8 modern cores



The time required to calculate the dust emission SED of one grid cell, as a function of the total number of cells, for the CPU and GPU. This problem used the graphite cross sections of Laor and Draine (1993), with 81 size bins and 968 wavelengths. For small problem sizes, the GPU time is dominated by kernel launch and data transfer overhead and is essentially independent of number of cells up to > 10^3 cells. For the CPU calculation, a block size of 32 cells was used, so for 256 cells or fewer, there are not enough blocks to load all 8 cores, so the time is then independent of problem size. This is merely an artifact of the block size used.

Comment

It is clear from the performance numbers presented here that the GPU temperature calculation dramatically outperforms the calculation done on an 8-core modern CPU. The theoretical maximum floating point performance of the Tesla unit used here is about 6 times greater than that of the 8 Xeon cores. What is perhaps surprising is that the difference in performance actually is almost an order of magnitude greater than this. While the large performance difference shows that the calculation performed here is perfectly suited for the massively parallel GPU, one part of the explanation is surely that the CUDA code is a low-level calculation purposely written directly to conform to the rules for getting maximum performance out of the GPU, while the CPU C++ code is written at a much higher abstraction level that largely trusts that the compiler can generate effcient code.and that the CPU cache machinery can hide memory latency. The performance comparisons presented here thus say less about the innate performance difference between the two architectures and more about the speedups that are possible when a small part of an existing code is rewritten for maximum performance.

Implications

We have shown that the inherently parallel nature of the dust grain temperature calculation is perfectly suited to the GPU. As grain temperature calculations, not the actual transfer of radiation, are normally the most computationally expensive part of calculating the SED of a galaxy, this holds great promise for accelerating such calculations.

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Thanks for making our supercomputing for cosmology possible!