Title: Peeking in Ancient Holes and Seeking the Holy Grail

Date: Nov 28, 2007 02:00 PM

URL: http://pirsa.org/07110062

Abstract: The Cosmic Microwave Background (CMB) consists of a bath of photons emitted when the universe was 380,000 years old. Carrying the imprint of primordial fluctuations that seeded the formation of structure in the universe, the CMB is one of the most valuable known tools for studying the early universe. In our modern, post WMAP era, the utility of studying temperature anisotropies in the CMB is clear and much of the work has been done. I will describe two exciting new directions in which the field is currently heading: small-scale secondary CMB anisotropy and CMB polarization anisotropy. In this context, I will briefly discuss preliminary results from our small-scale secondary anisotropy experiment, the Sunyaev-Zel\'dovich Array (SZA), and will describe our two upcoming CMB polarization experiments, the Q U Imaging ExperimenT (QUIET) and the E B EXperiment (EBEX).

The Columbia CMB Group

roup Leader: Amber Miller

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Ross Williamson

raduate Students: Stephen Muchovej (NSF Graduate Fellow)
Tony Mroczkowski
Britt Reichborn-Kjennerud (NASA GSRP fellow)
Laura Newburgh
Robert Dumoulin
Alex Stone

ndergraduates: David Tam
Mike Bottom
Yun Liu (Rabi Scholar)
Ethan Dyer
Vedant Misra (Rabi Scholar)
Allison Krupp
Everett Lin

ommunity Members: Paul Duffel
Seth Hilbrand

Outline

•Brief overview current state of the art CMB temperature anisotropy data

•The Sunyaev-Zel'dovich Effect (SZE) and the SZA

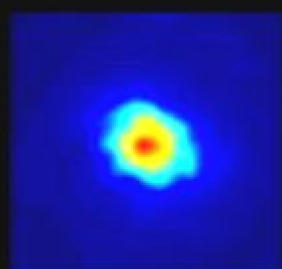
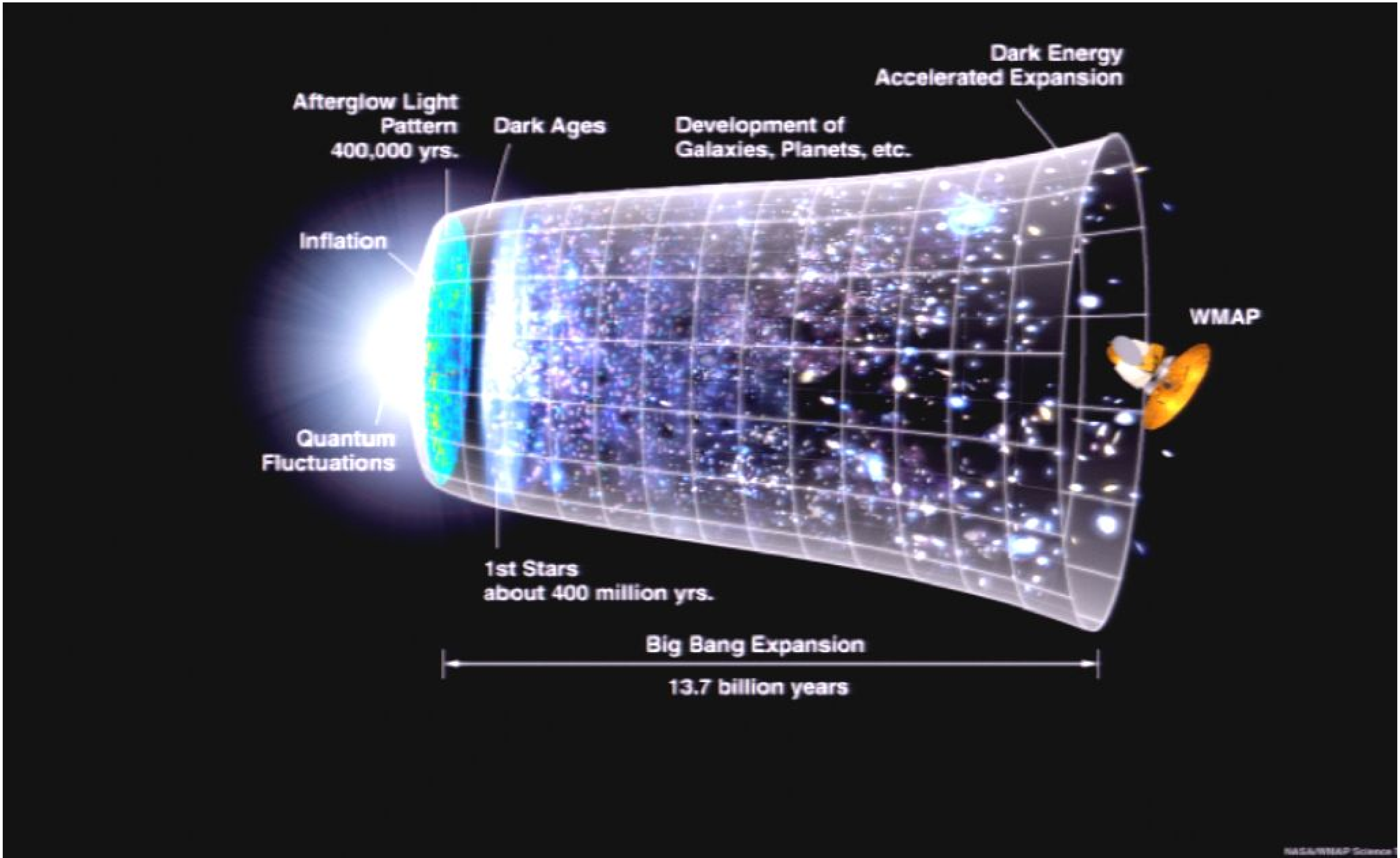


Photo: Leitch

• A few words about CMB polarization and our QUIET and EBEX experiments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Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
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Inflation
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1st Stars
about 400 million yrs.
Big Bang Expansion
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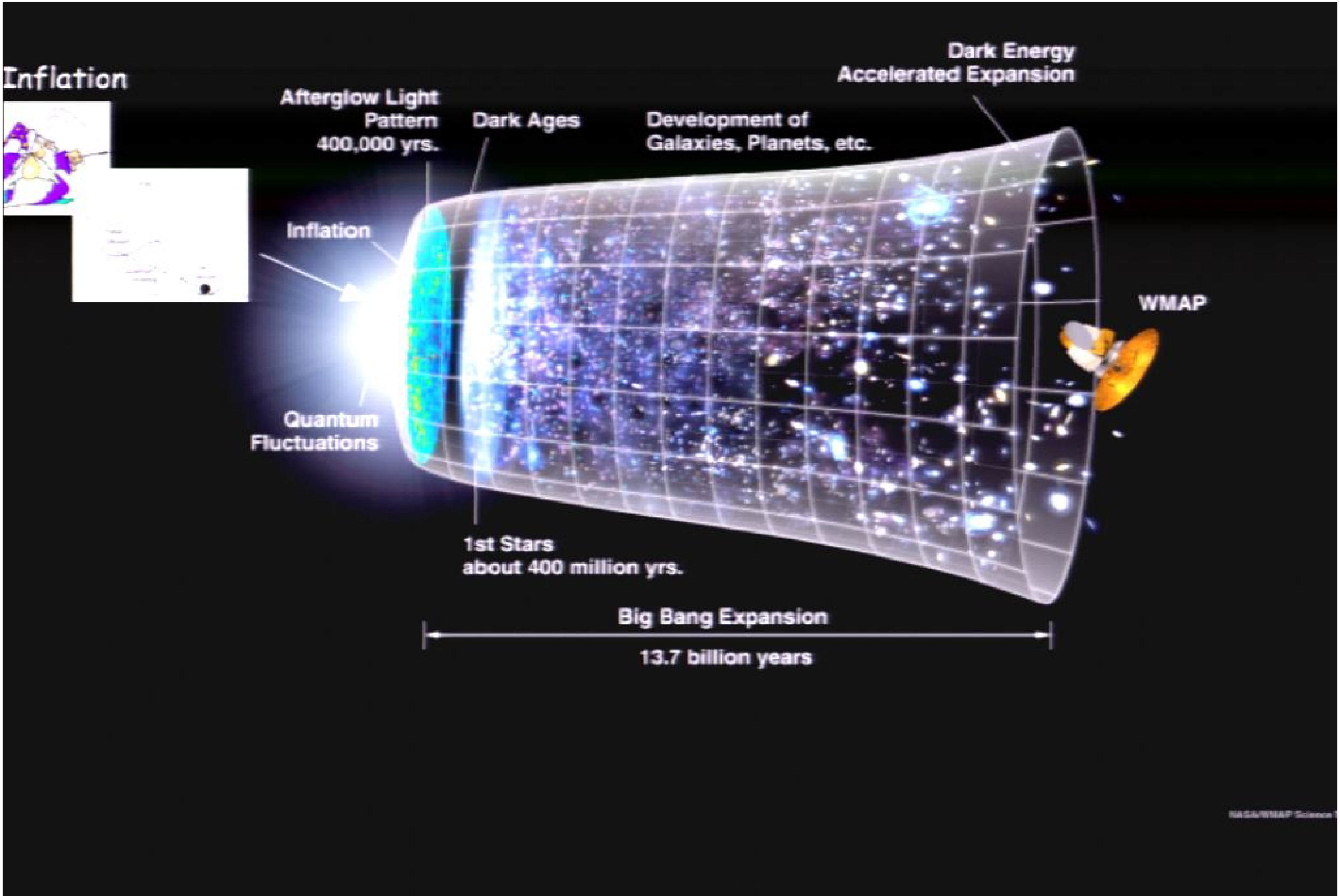
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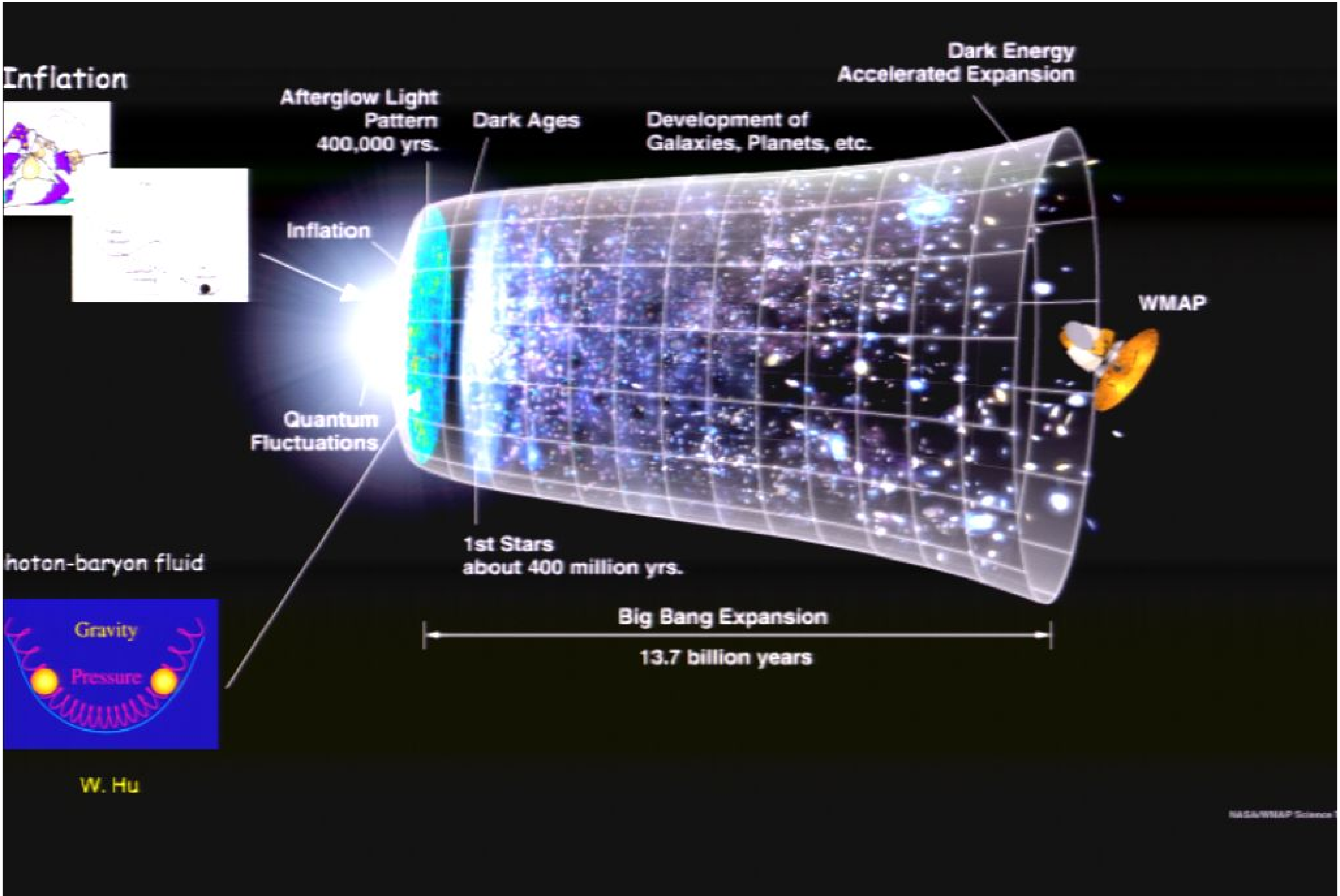
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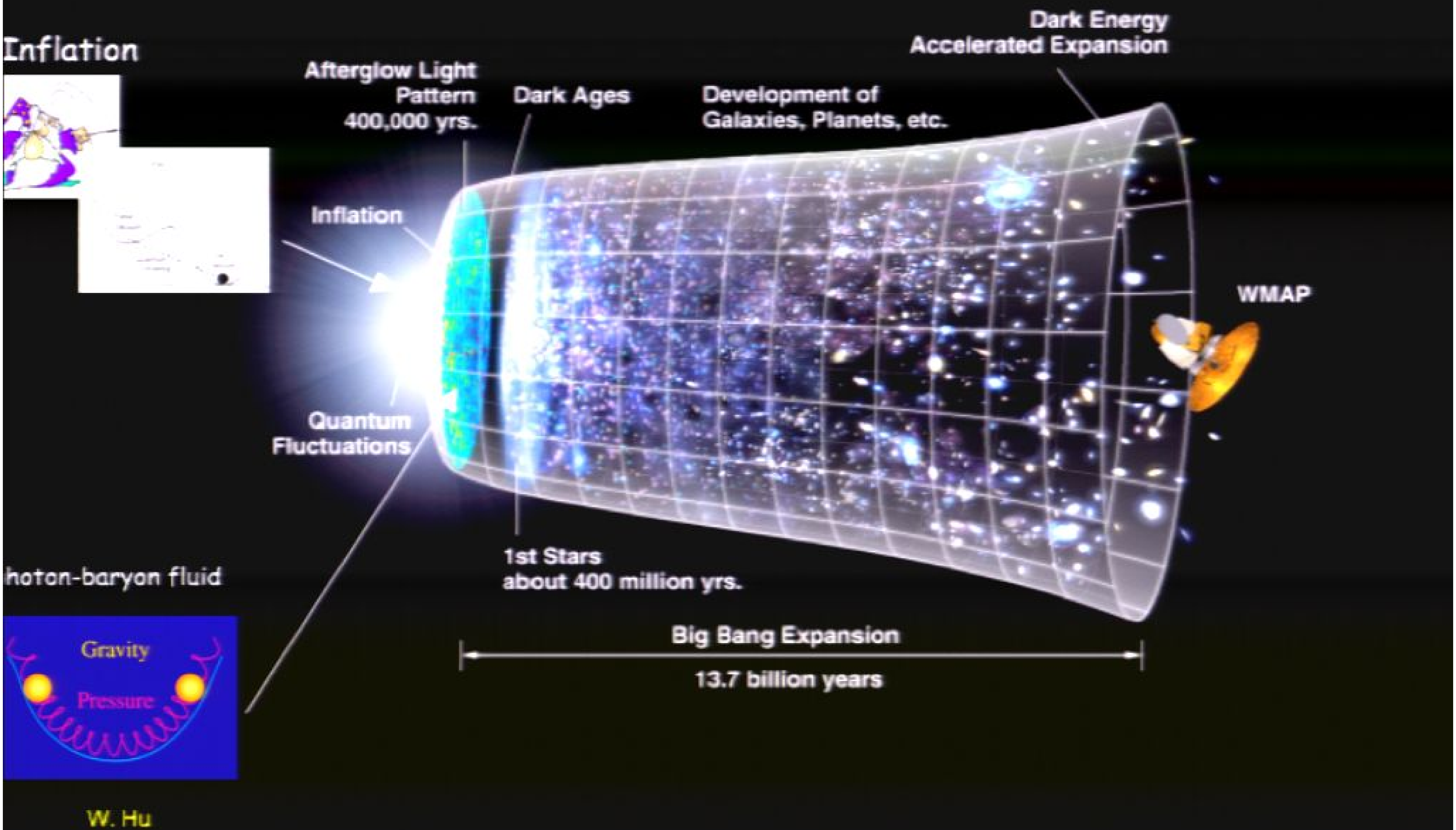
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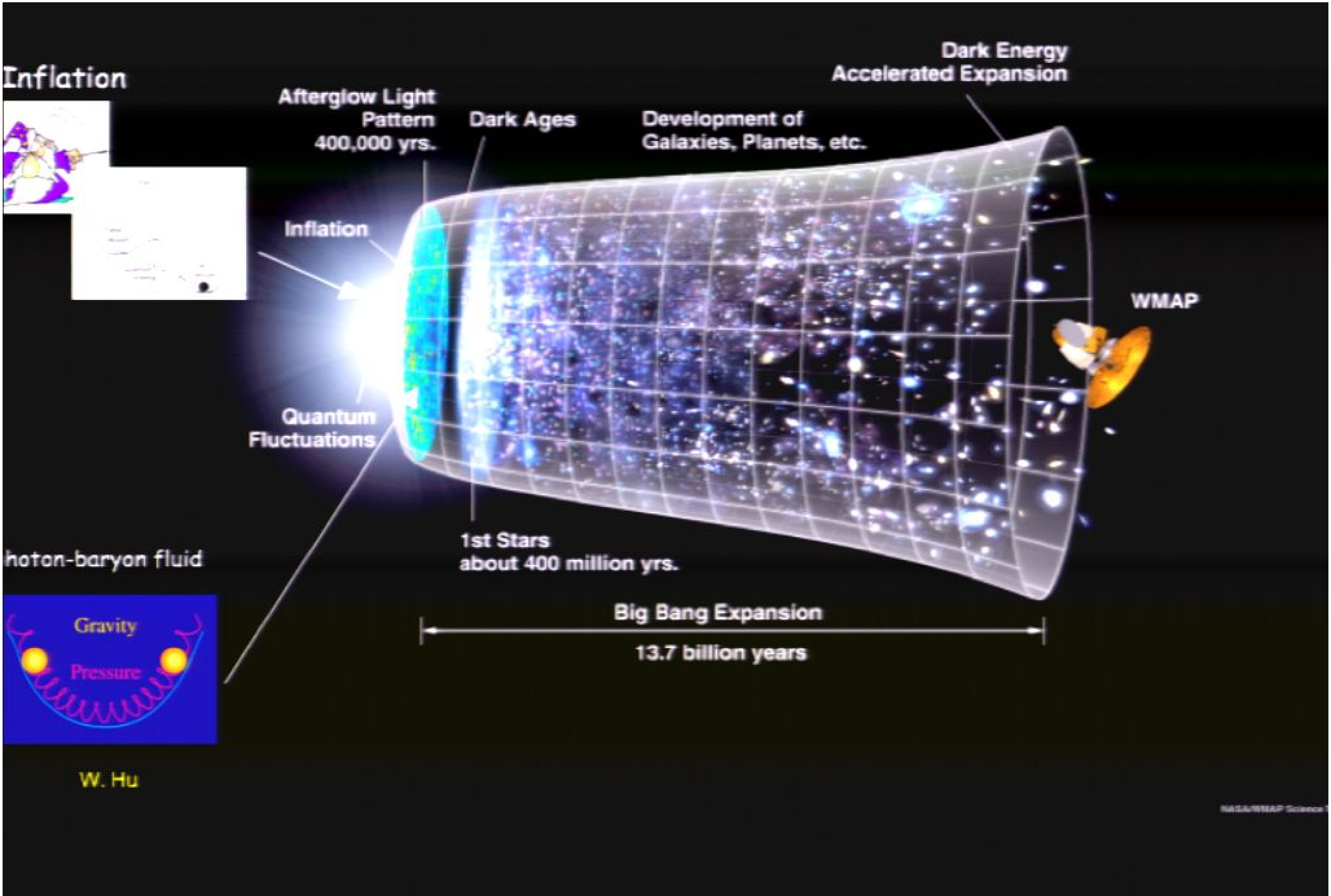
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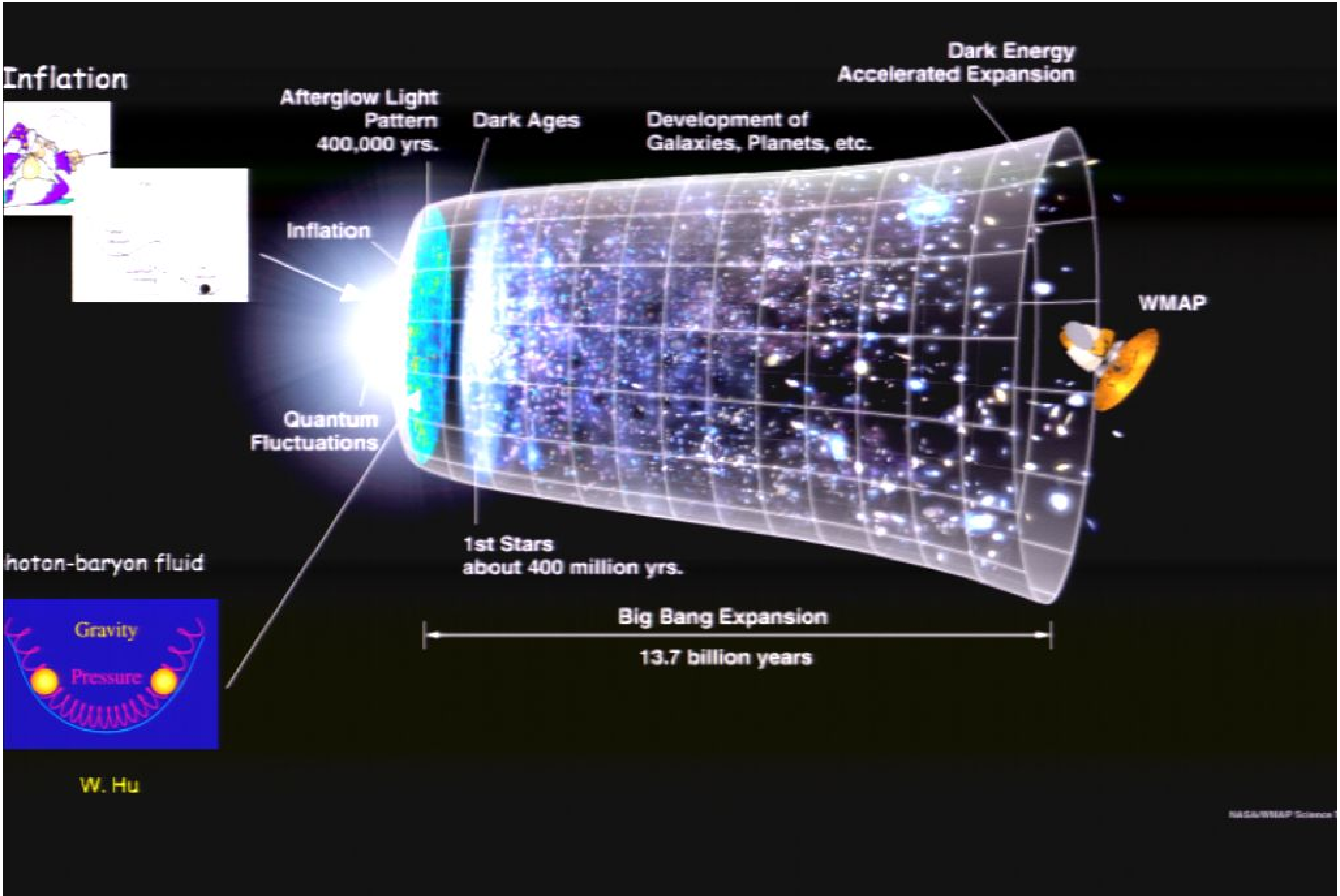
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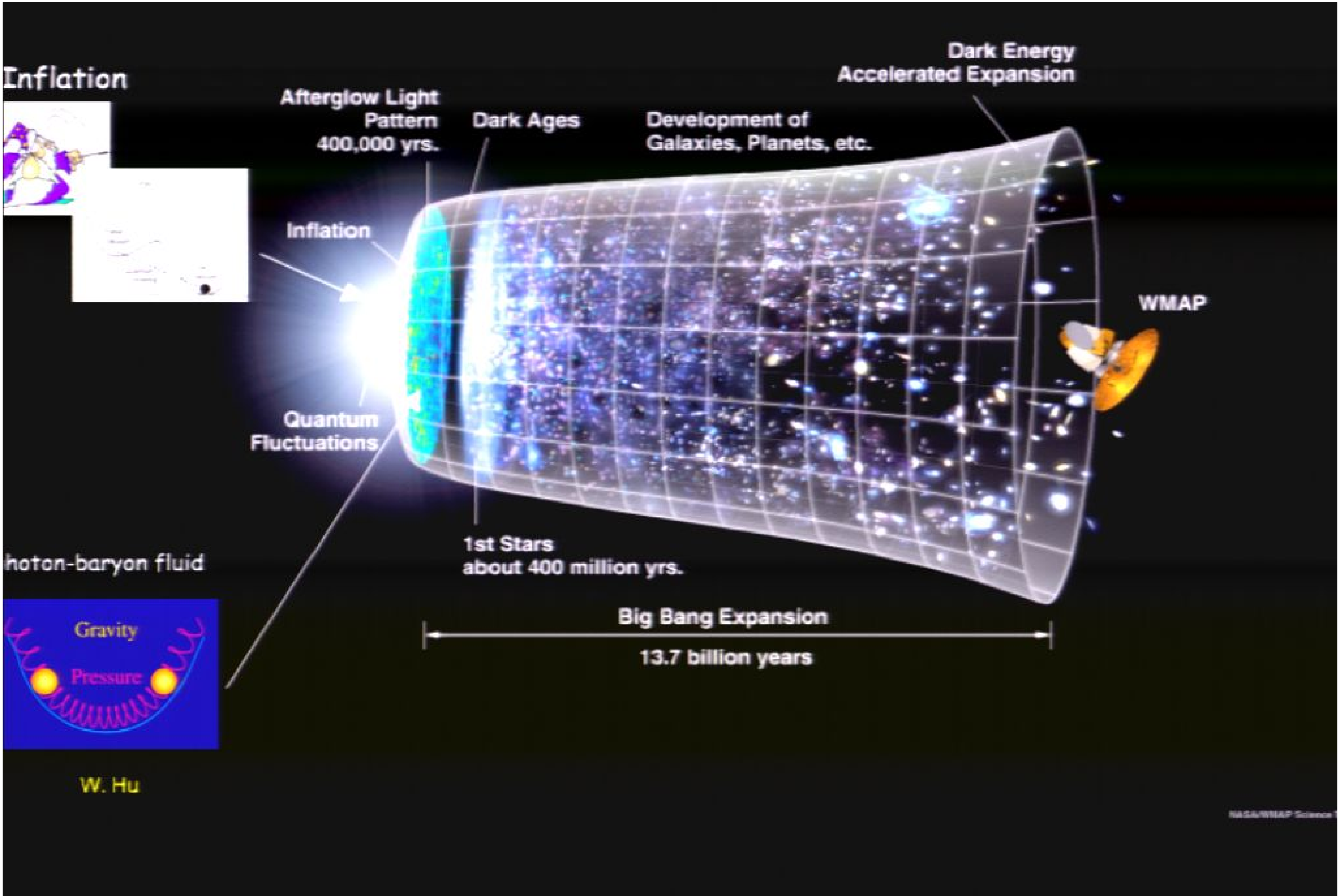
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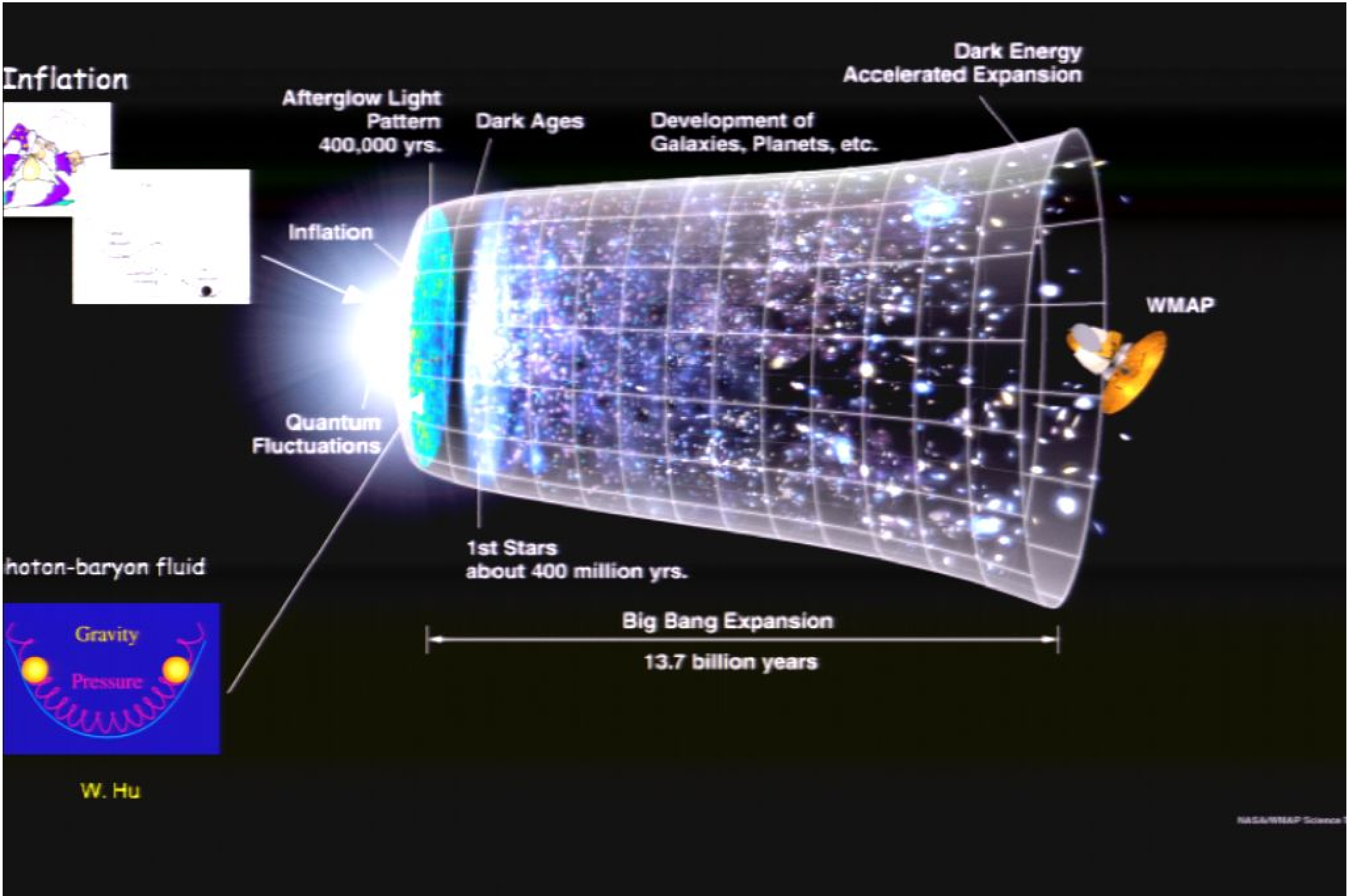
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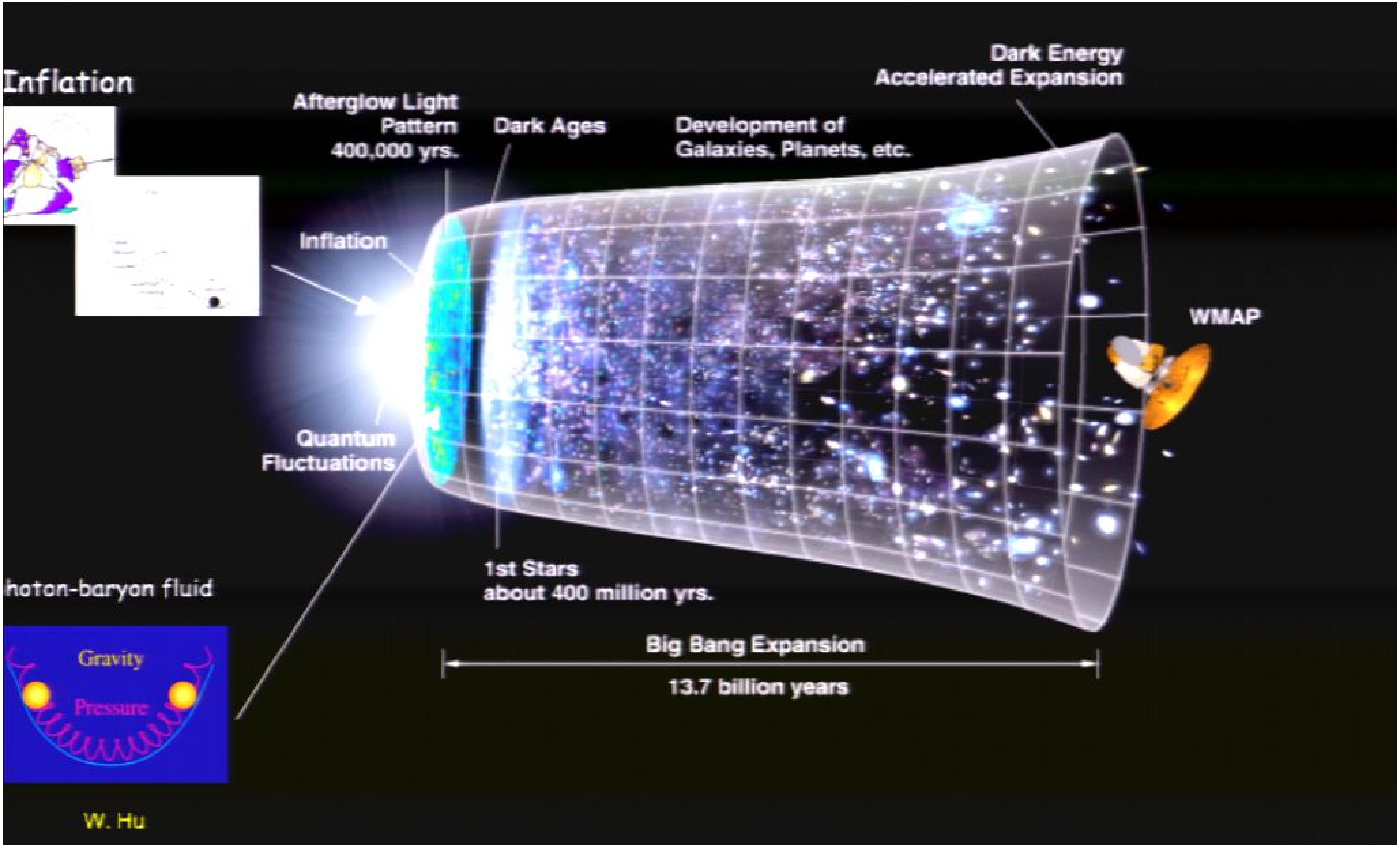
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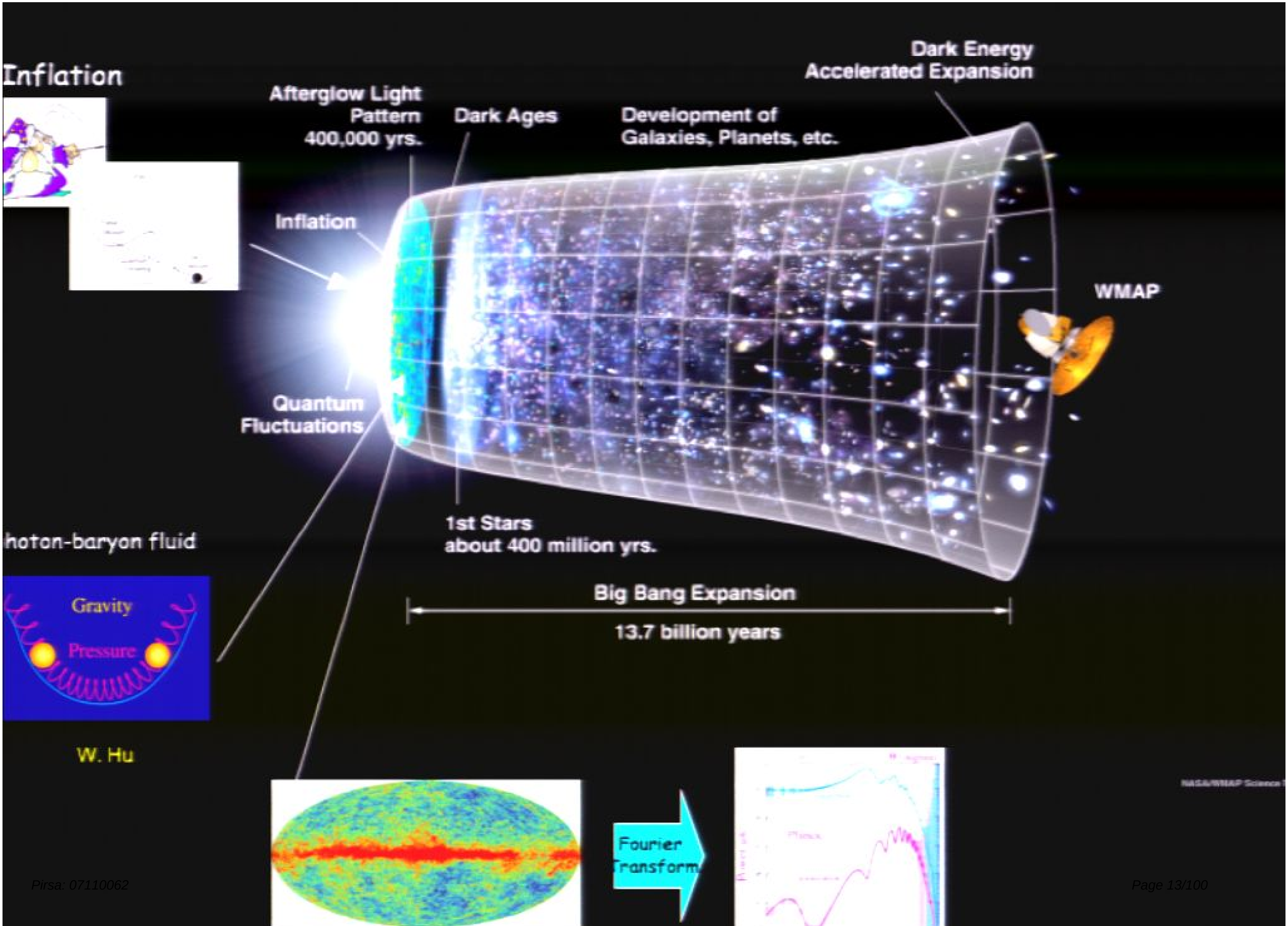

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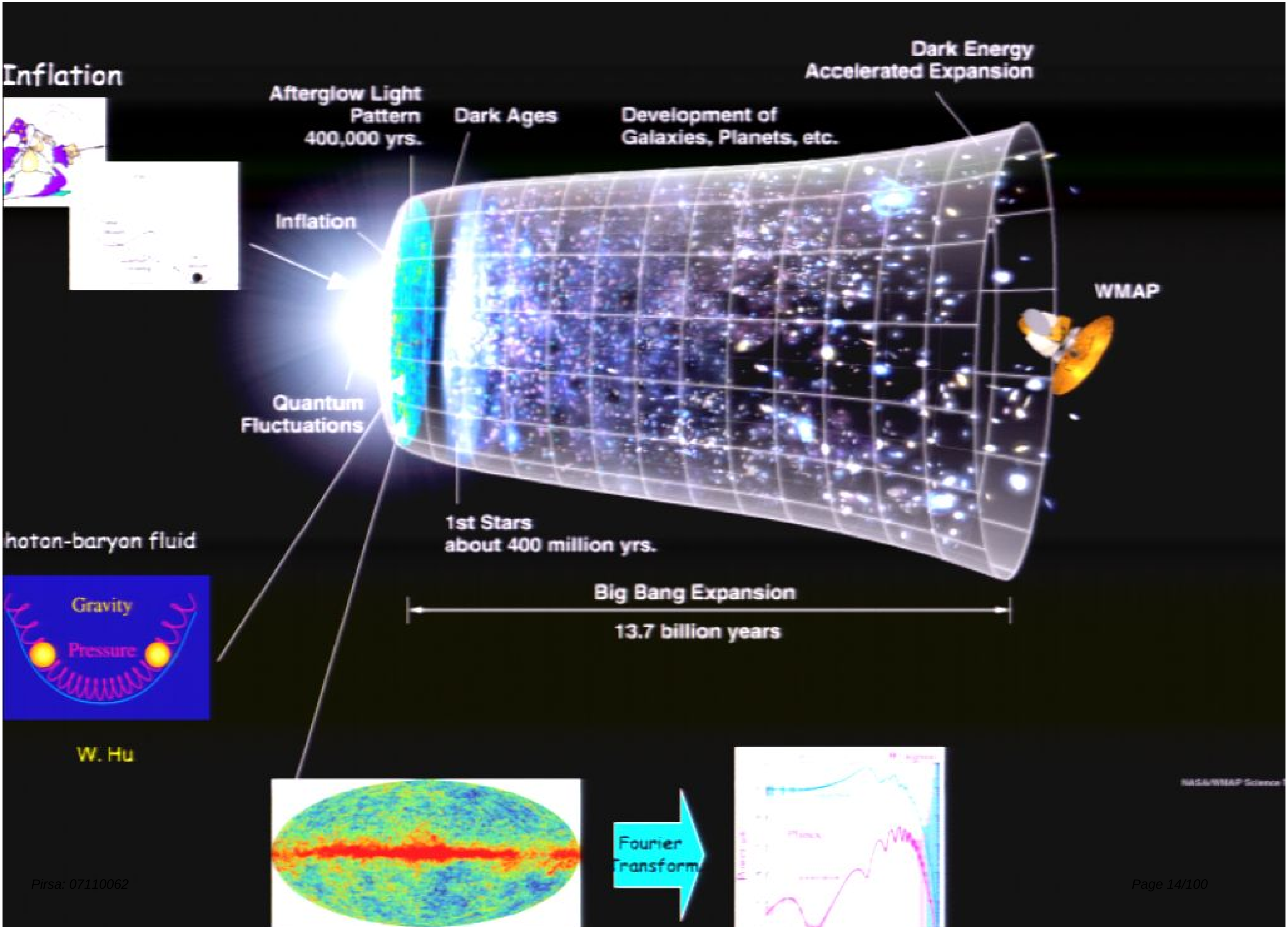
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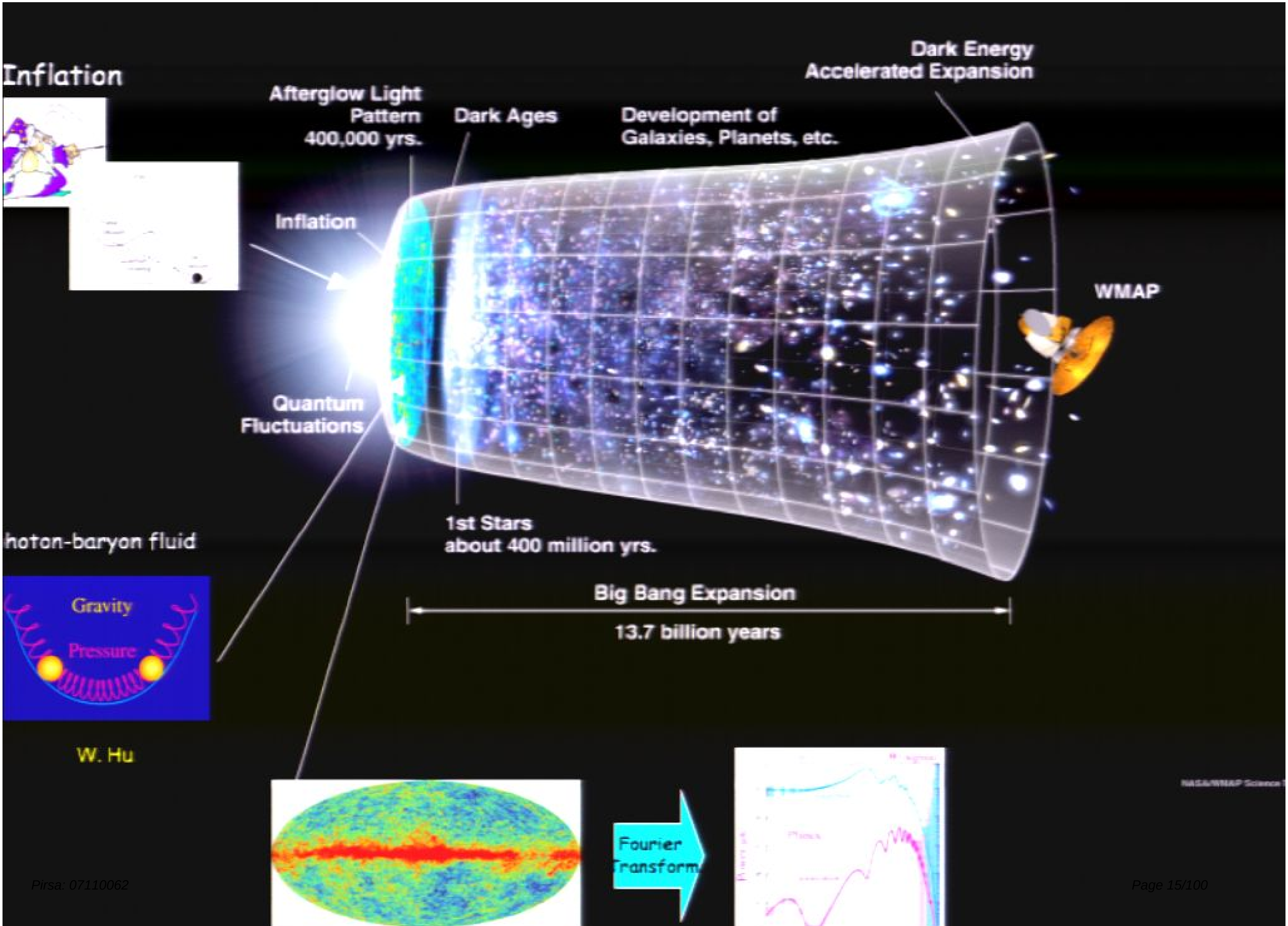
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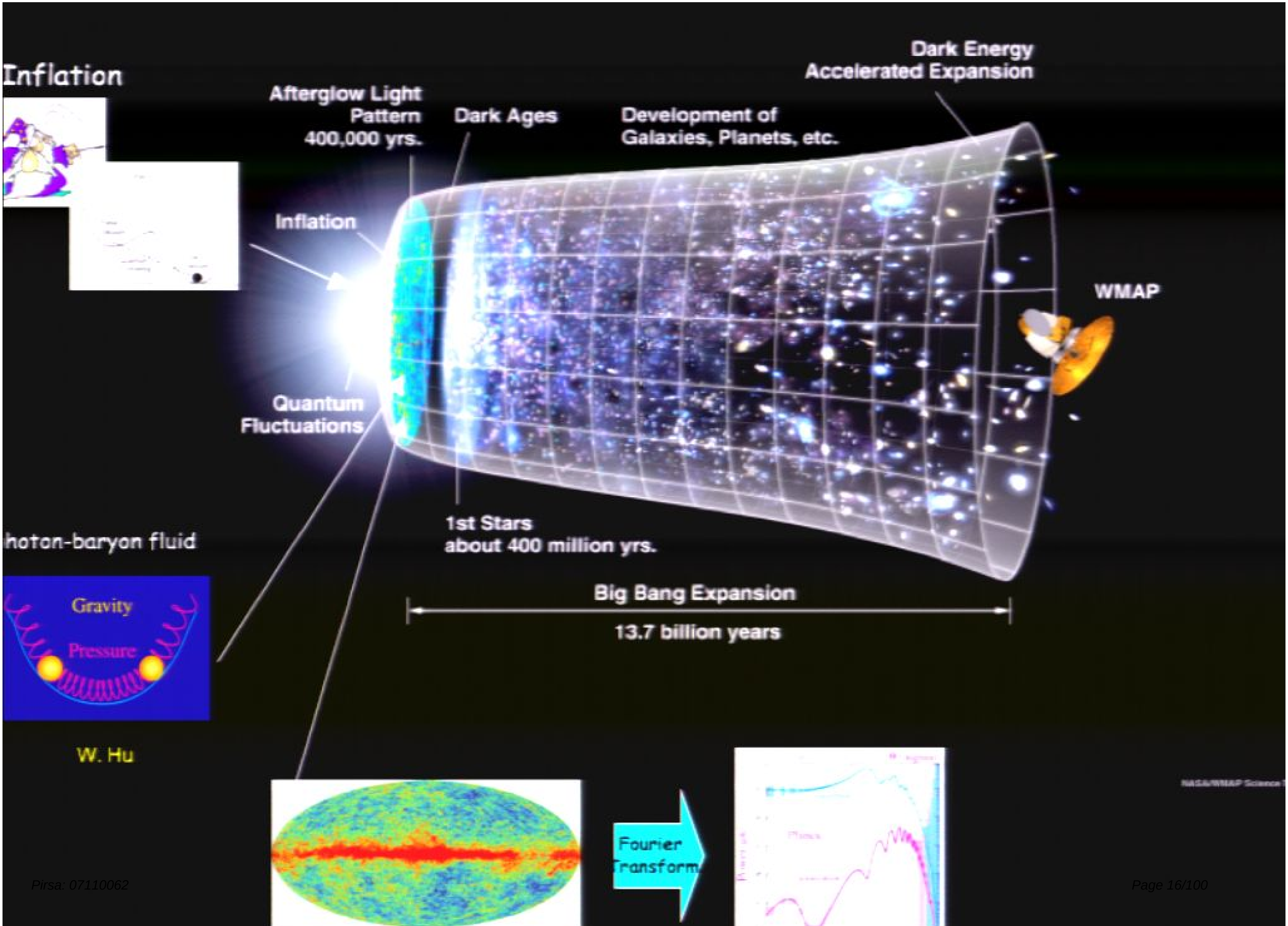
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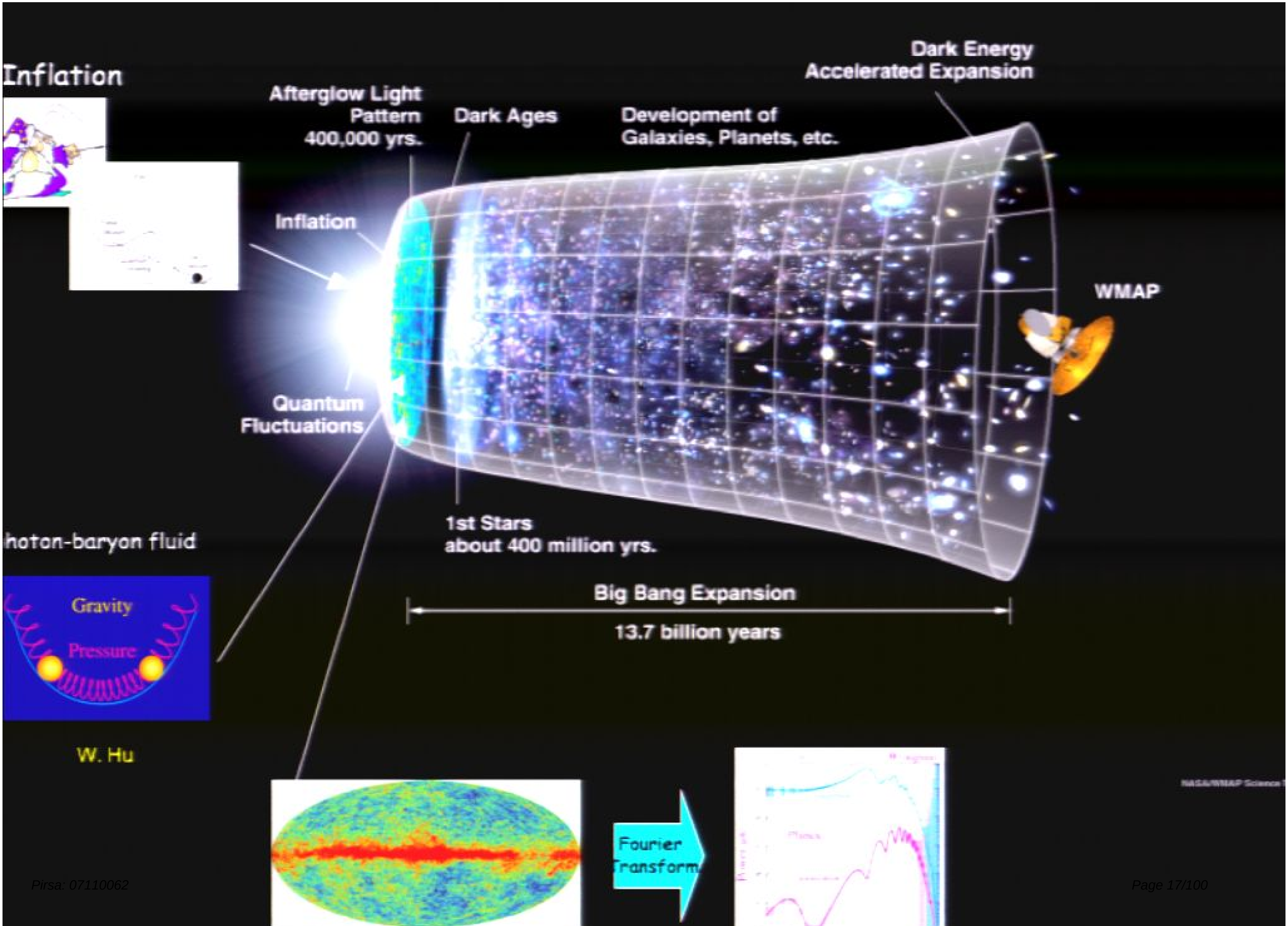

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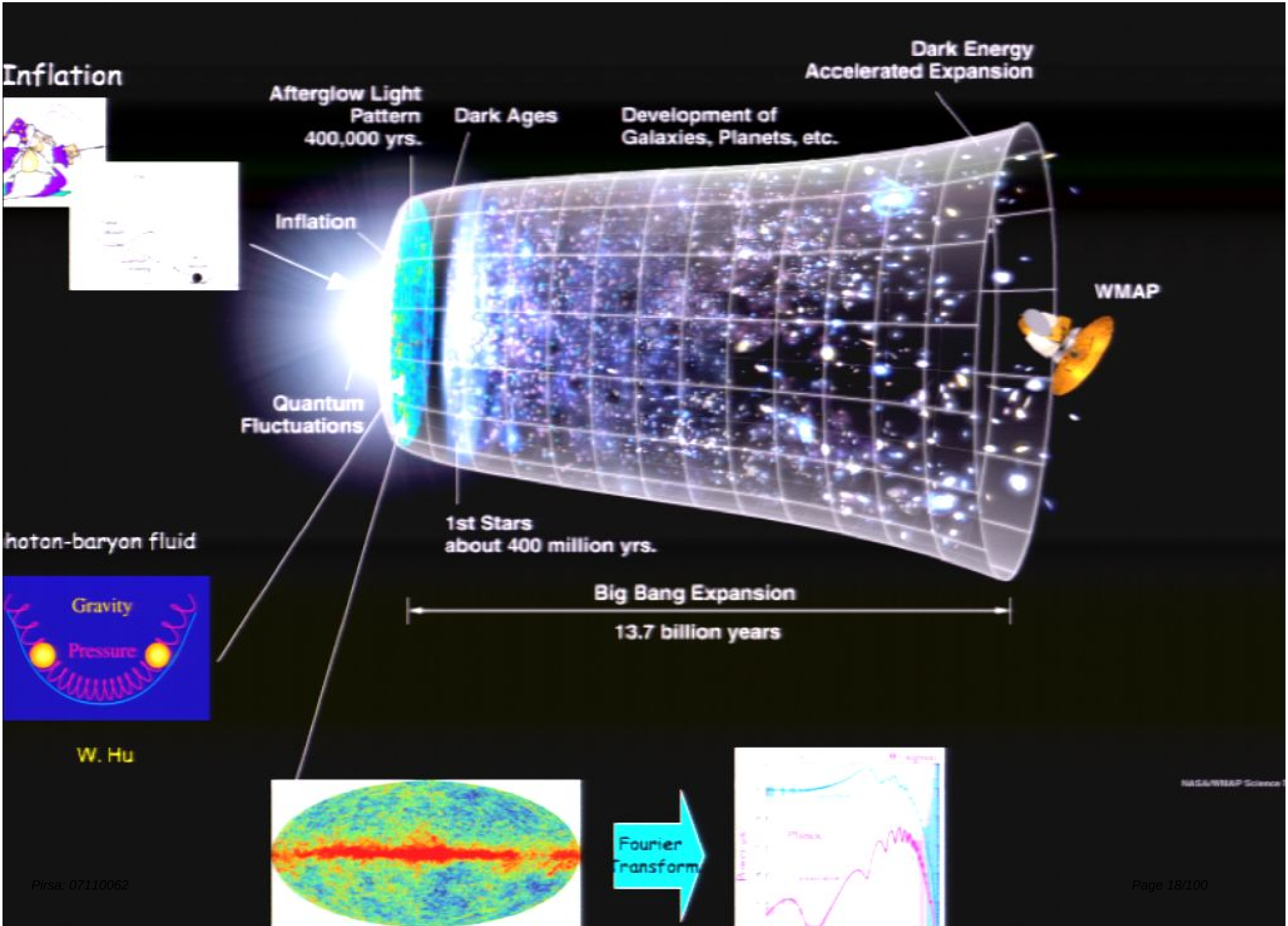
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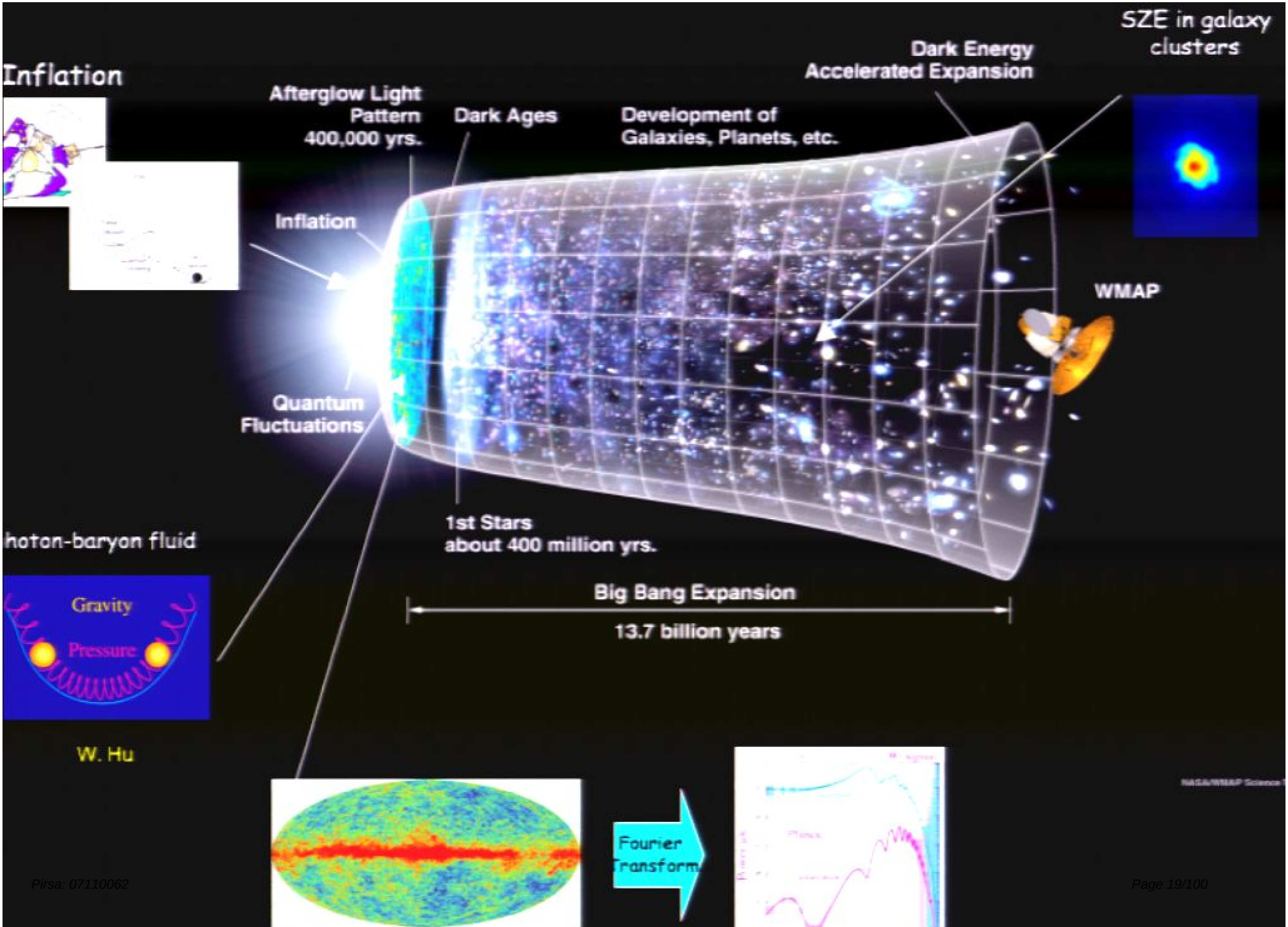
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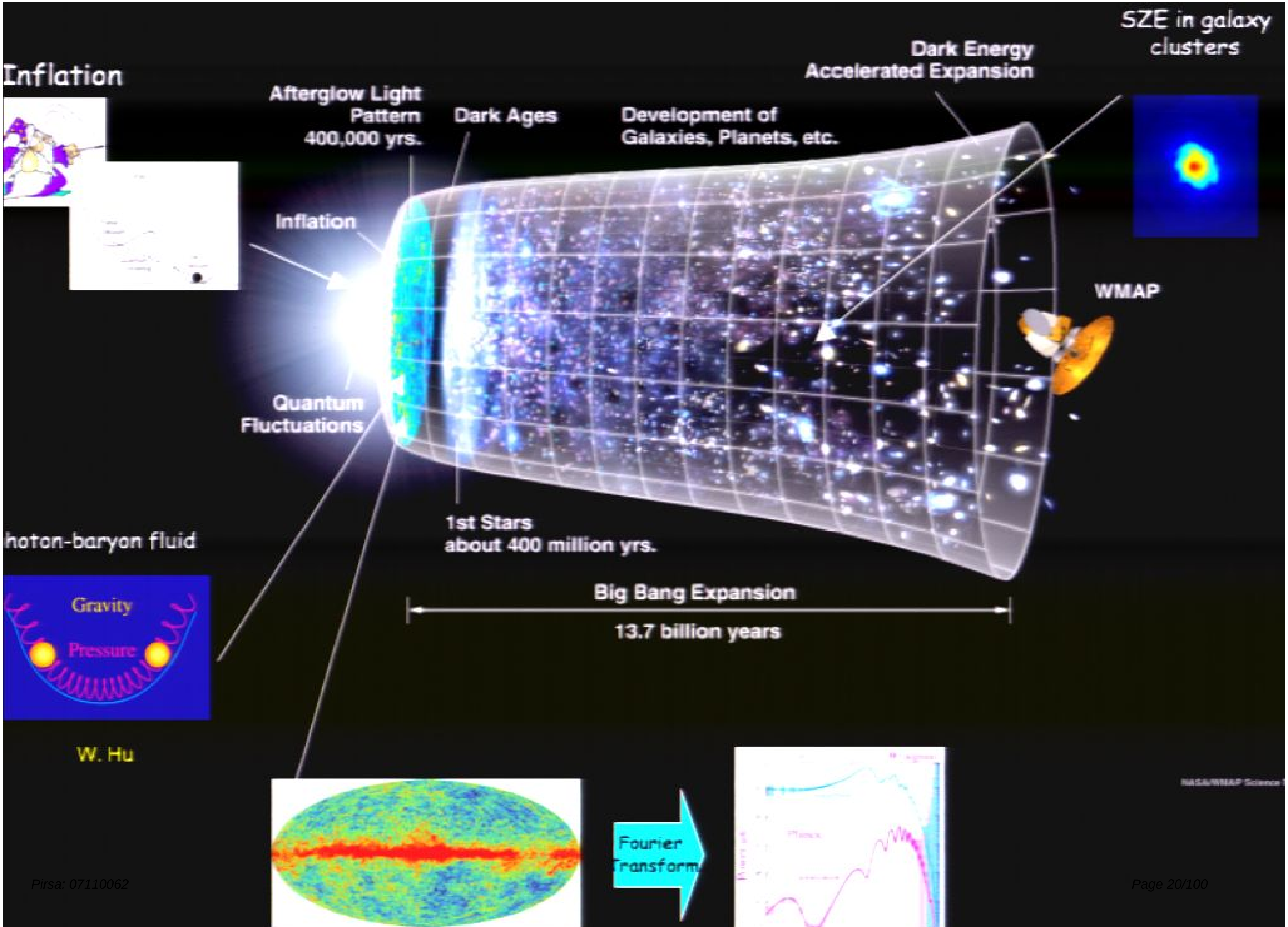
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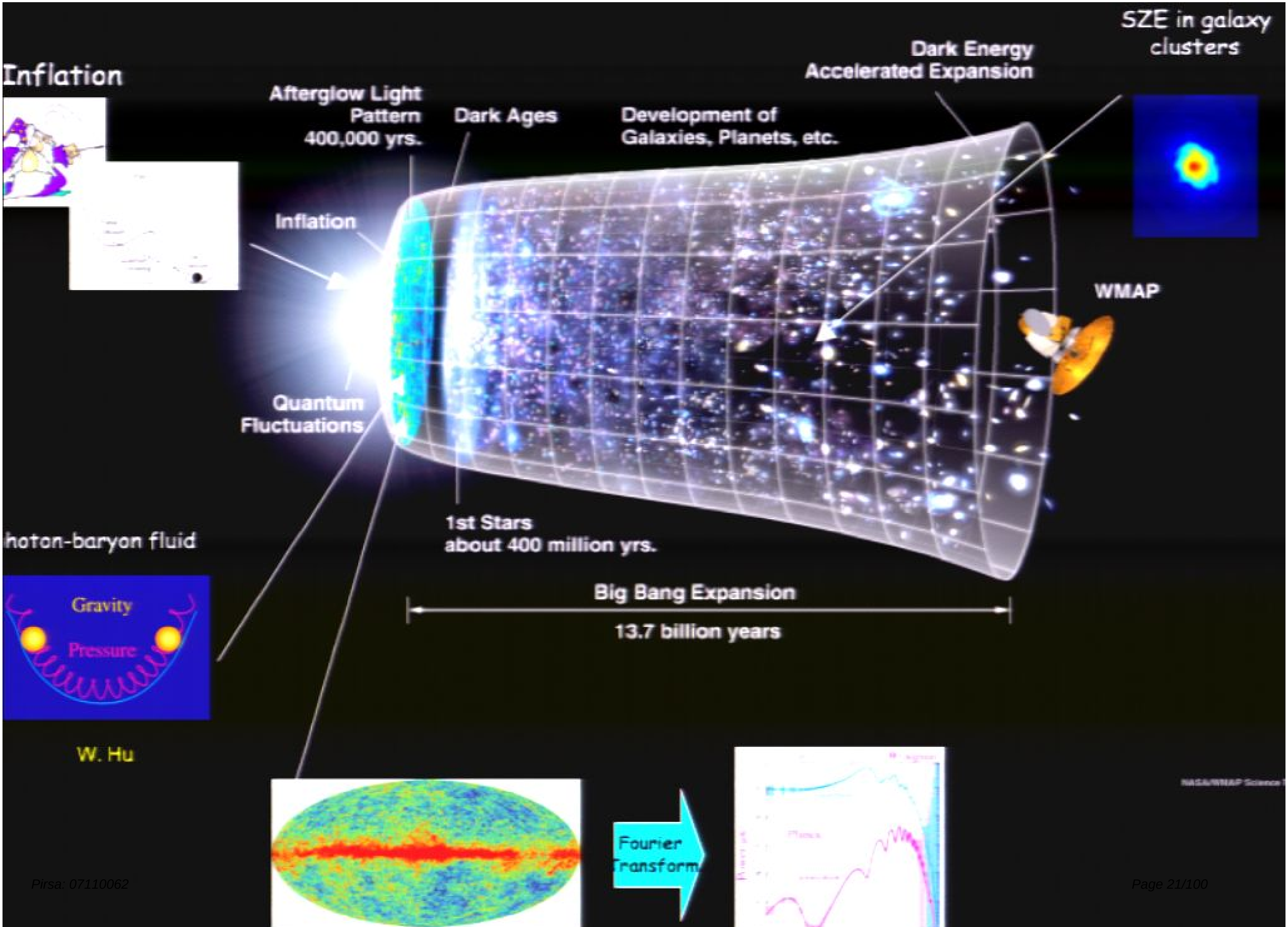
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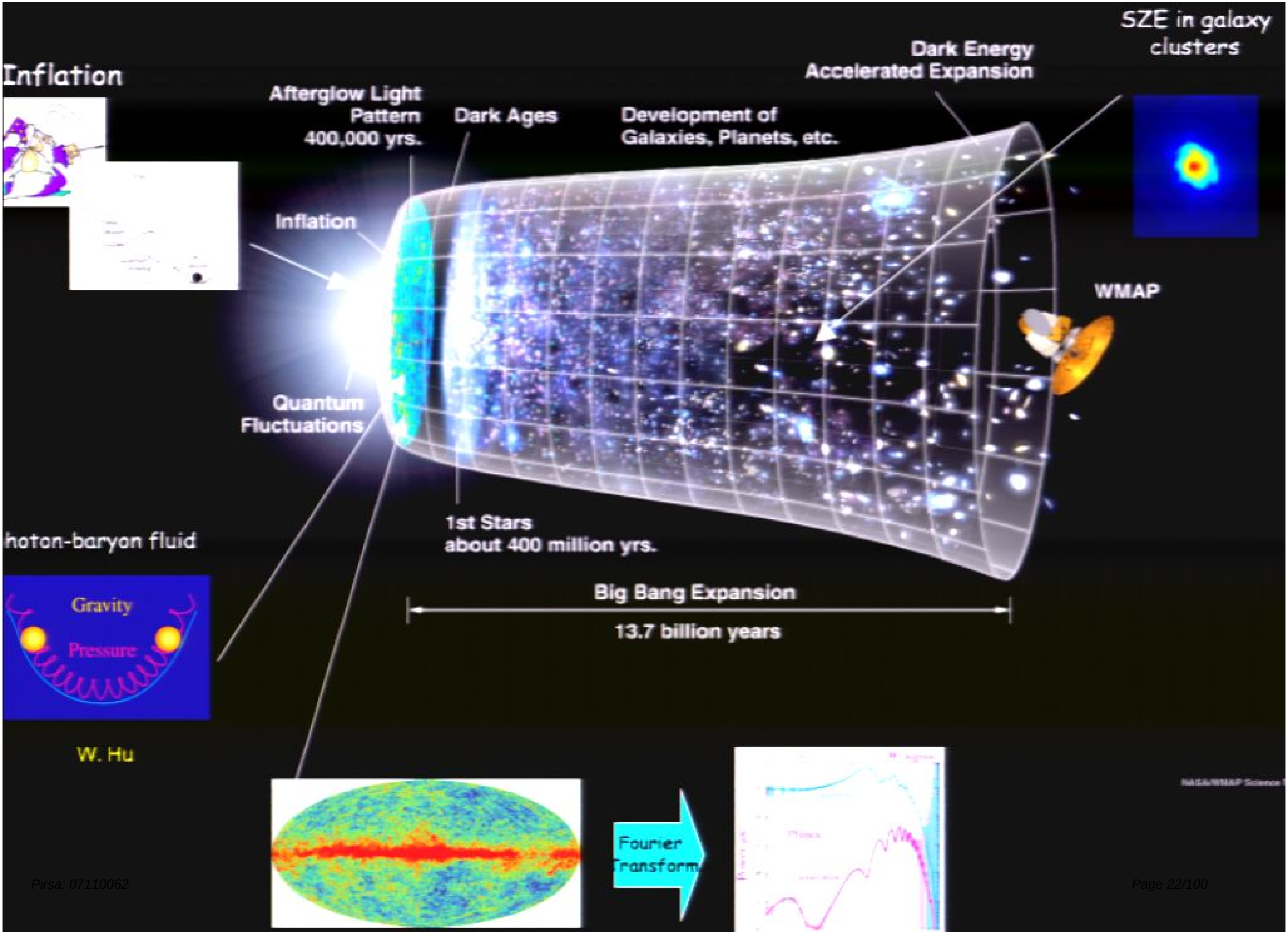

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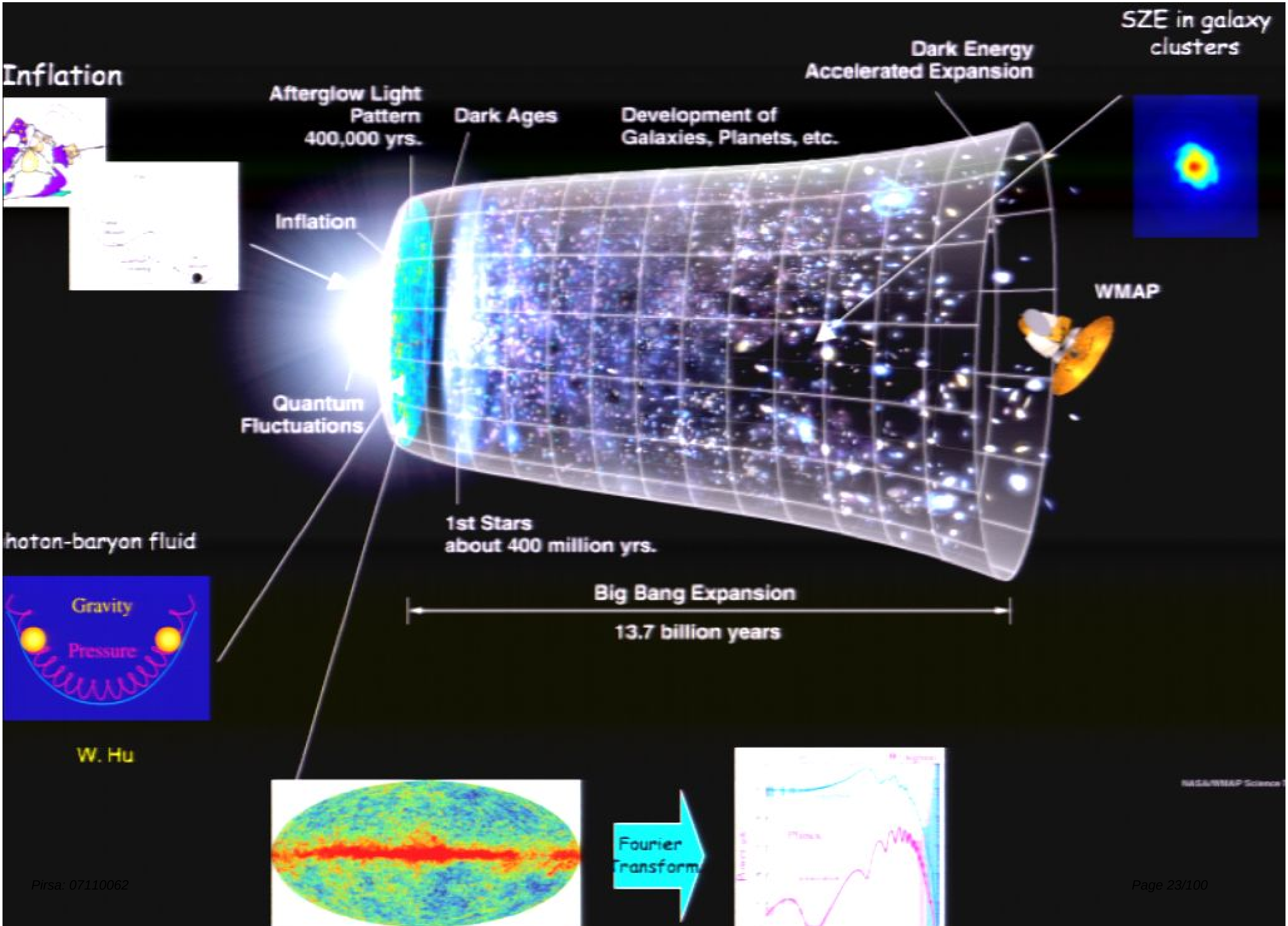
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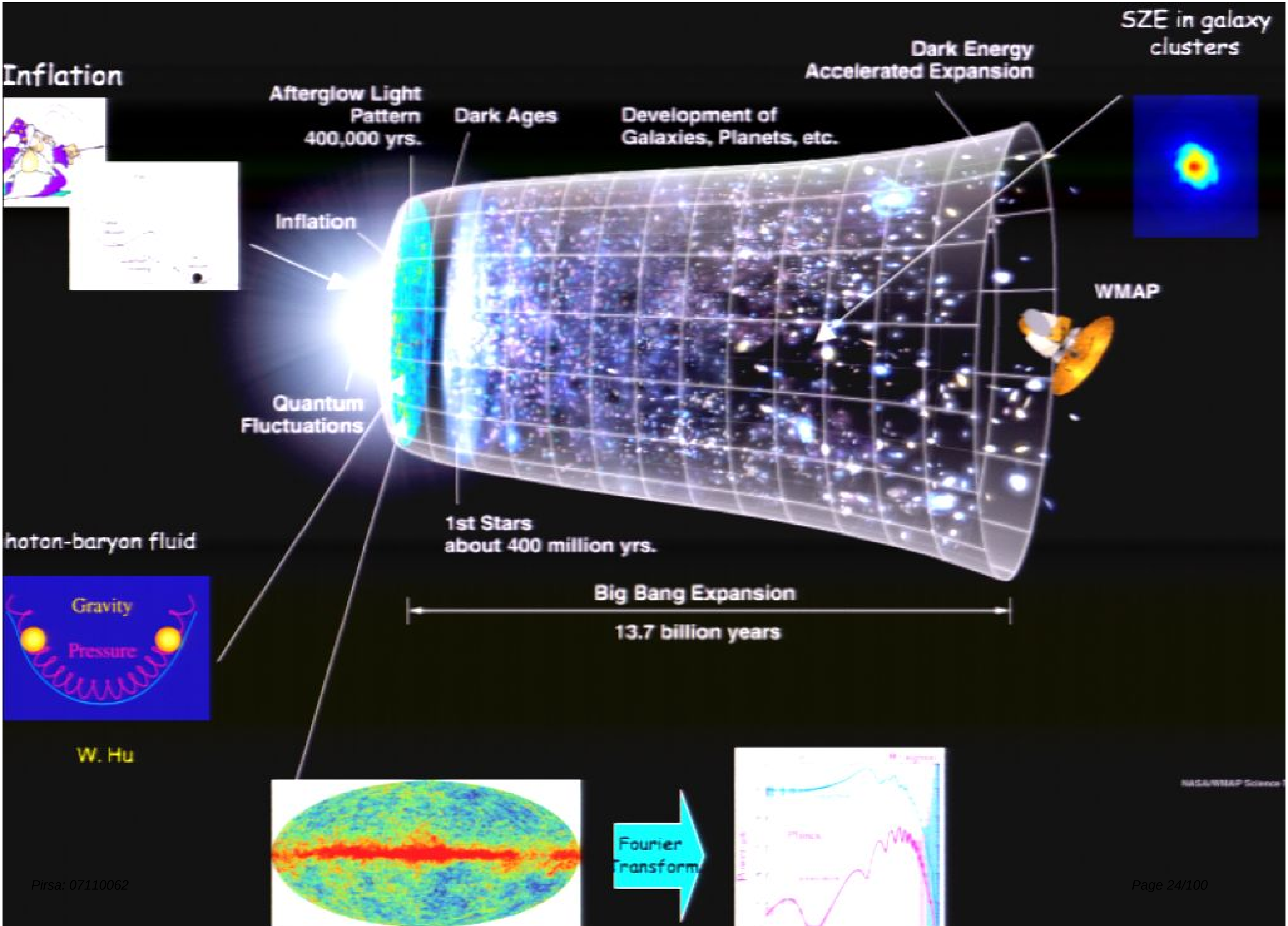
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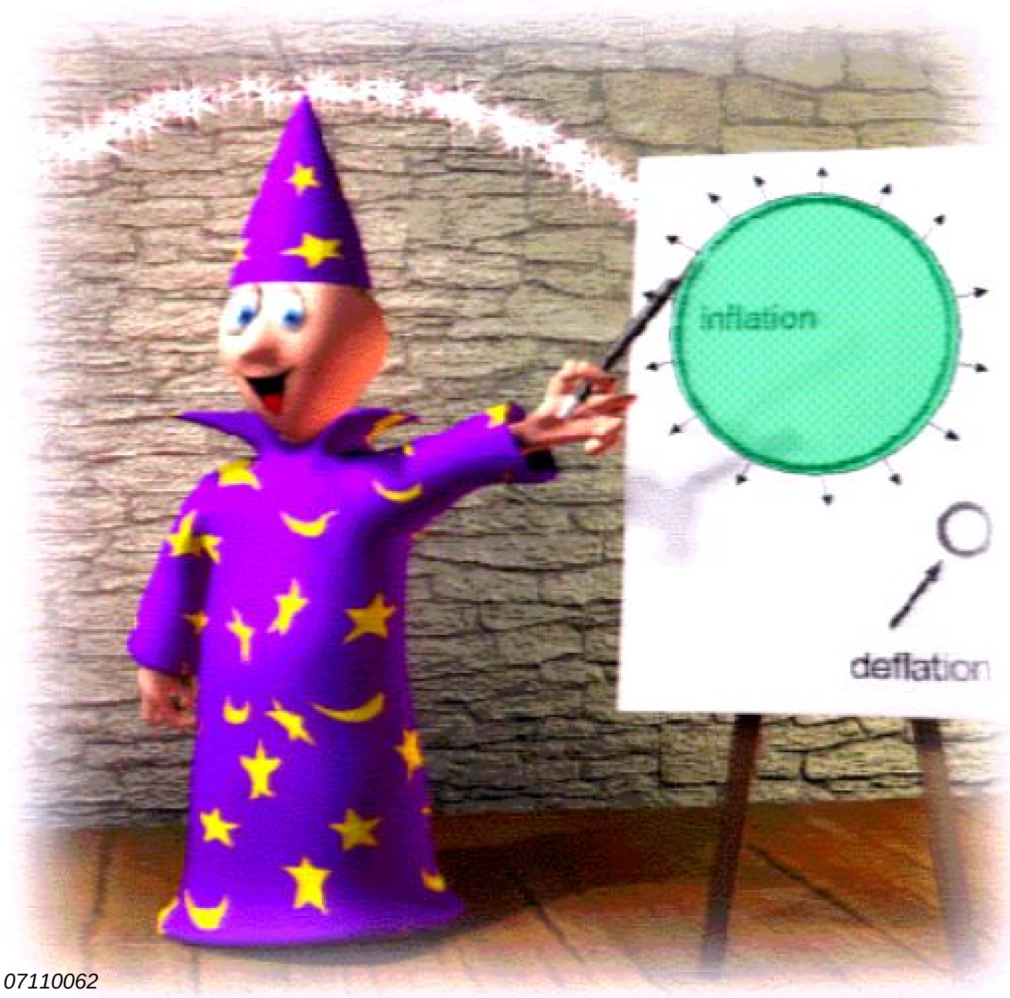
Inflation

Universe << 1 sec old



- Quantum fluctuations in the primordial density field are stretched to cosmic scales by inflation (period of rapid expansion).
- These fluctuations in the energy density lead to fluctuations in the local gravitational potential.
- Potential wells are created in regions of high density. Potential hills are created in regions of lower density

Genesis of Fundamental Particles (Age < 3 minutes, T~10^9 K)

Following Inflation, the Universe continues to expand (much more slowly) and cool

A series of phase transitions take place, fundamental symmetries are broken, particle species are differentiated

- baryogenesis (hadrons,mesons freeze out) ~10^{-15} sec
- leptogenesis (leptons freeze out) ~1 sec
- nucleosynthesis (H, He, trace amounts heavier elements formed) ~2-3 minutes

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photon-baryon fluid (Age < 380,000 yrs, T > 3000 K)

- Electrons are bound to baryons by electromagnetic interactions
- Photons coupled to free electrons by Thomson scattering
- The baryons drag the photons into dark matter potential wells
- As the fluid is compressed in the potential wells, the radiation pressure builds up and eventually it wins.
- The fluid oscillates sinusoidally in the potential wells (acoustic oscillations)

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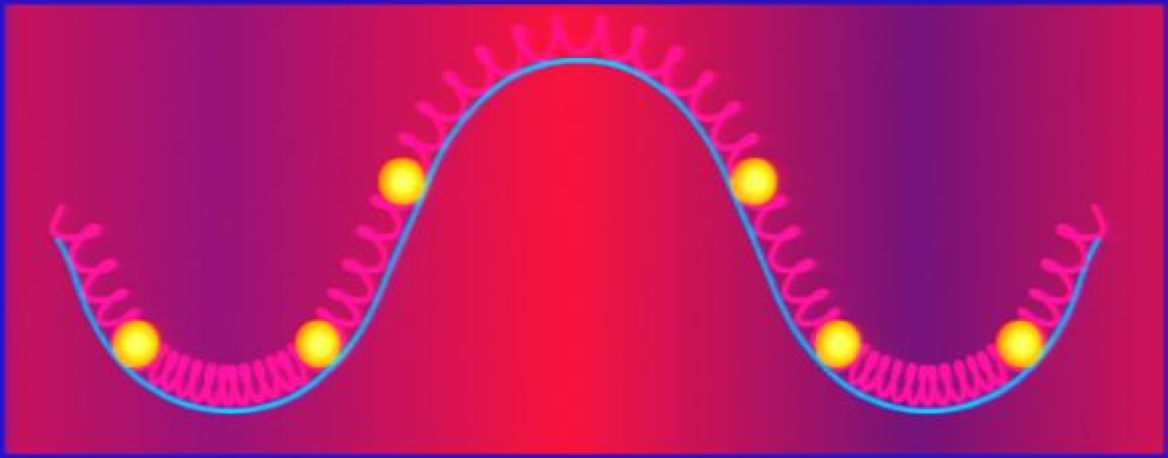

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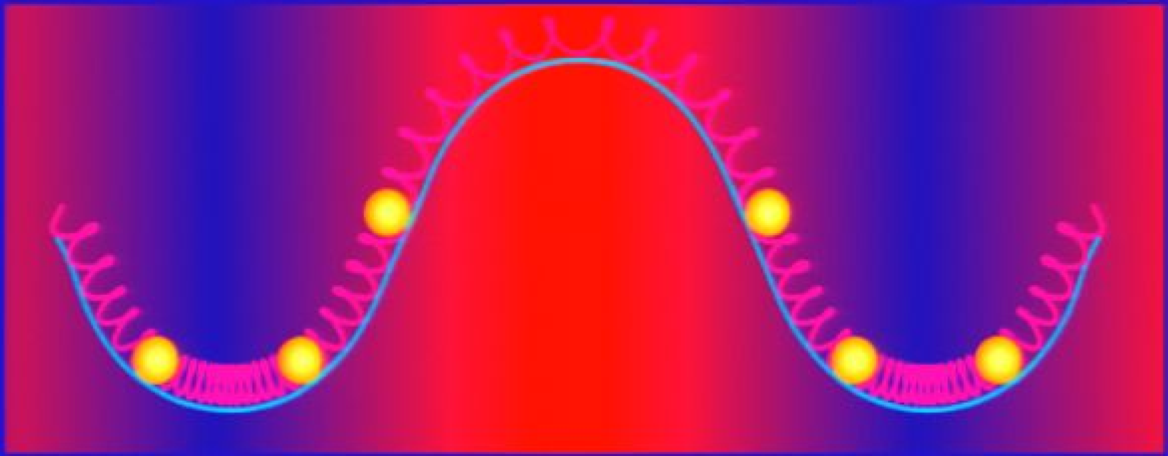

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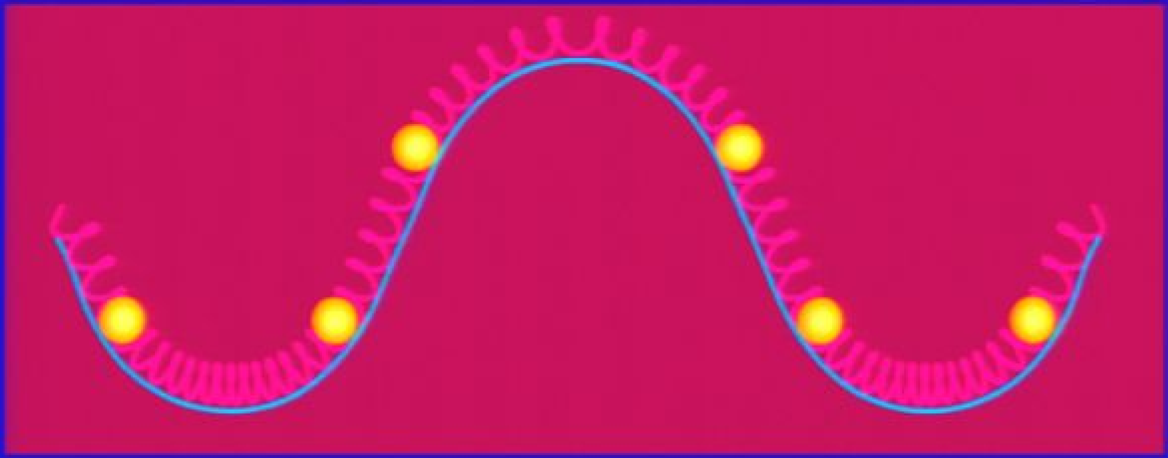

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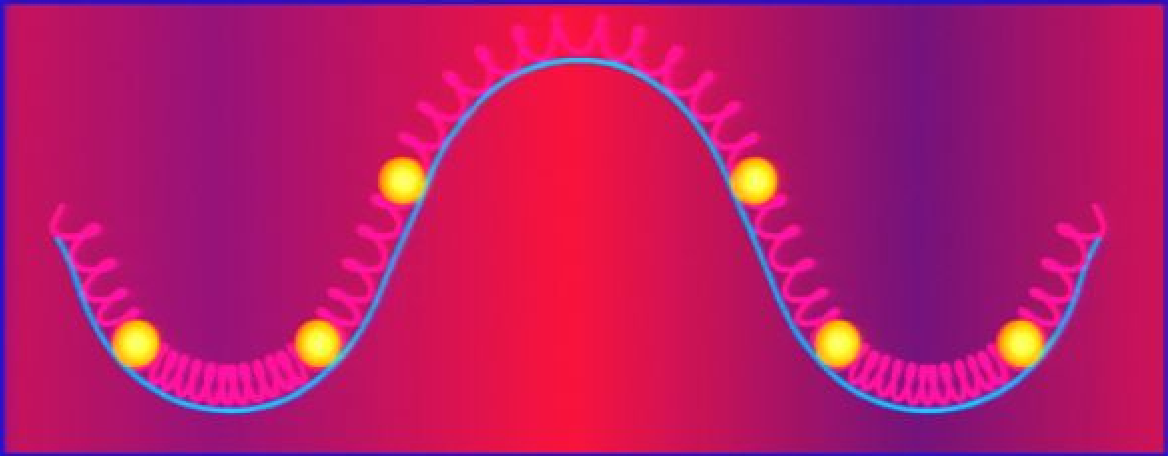

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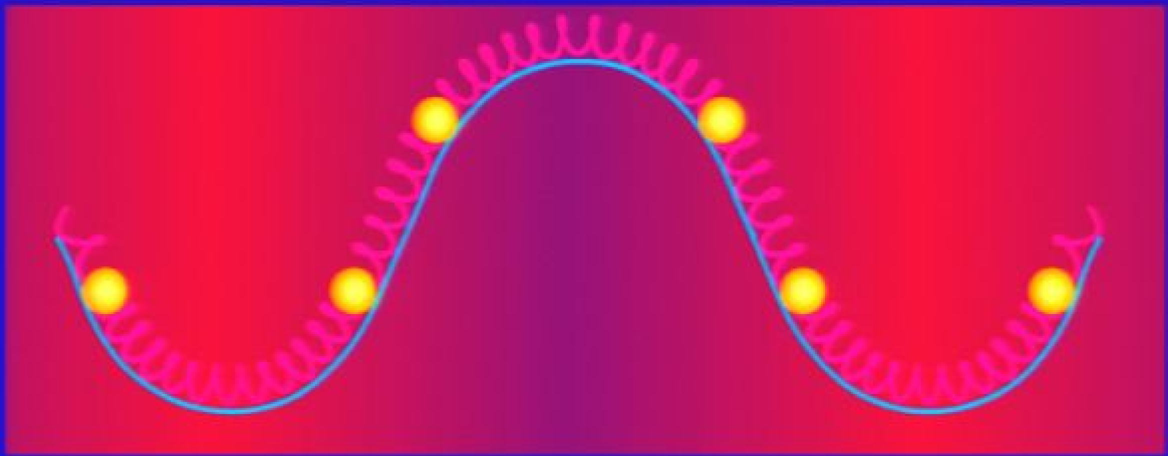

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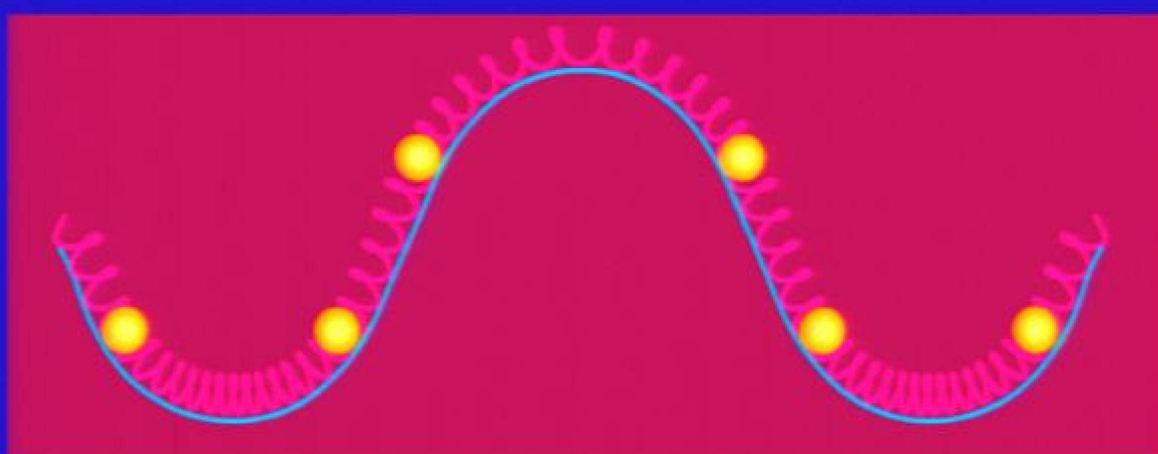

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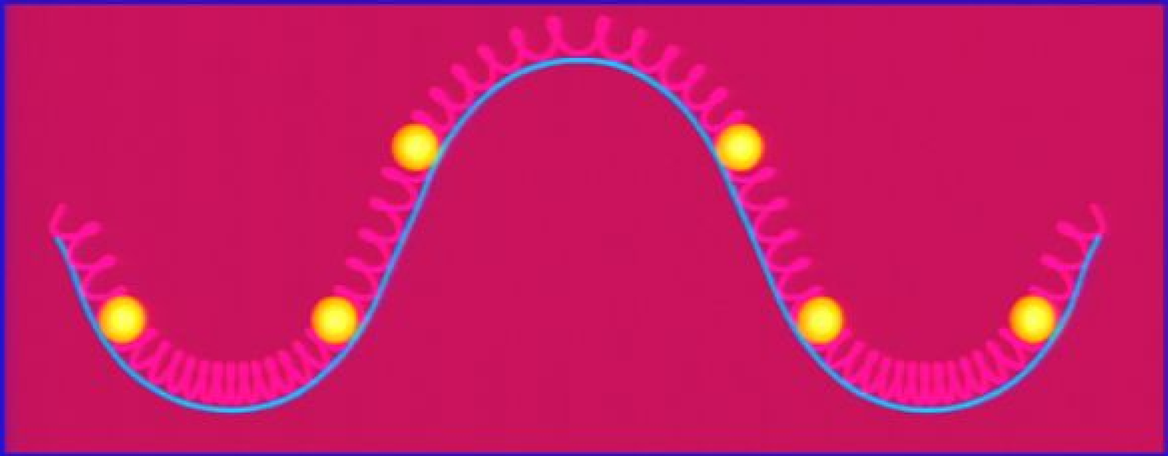

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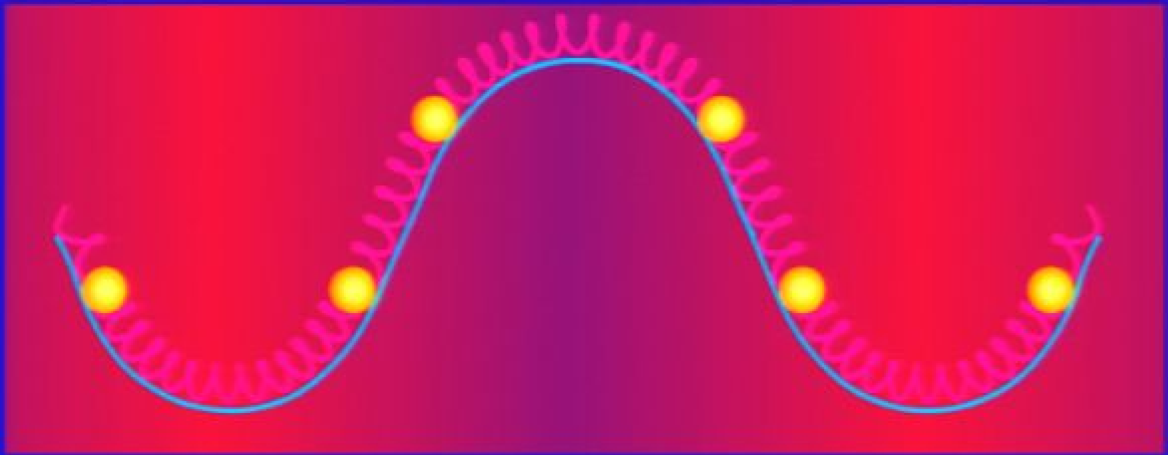
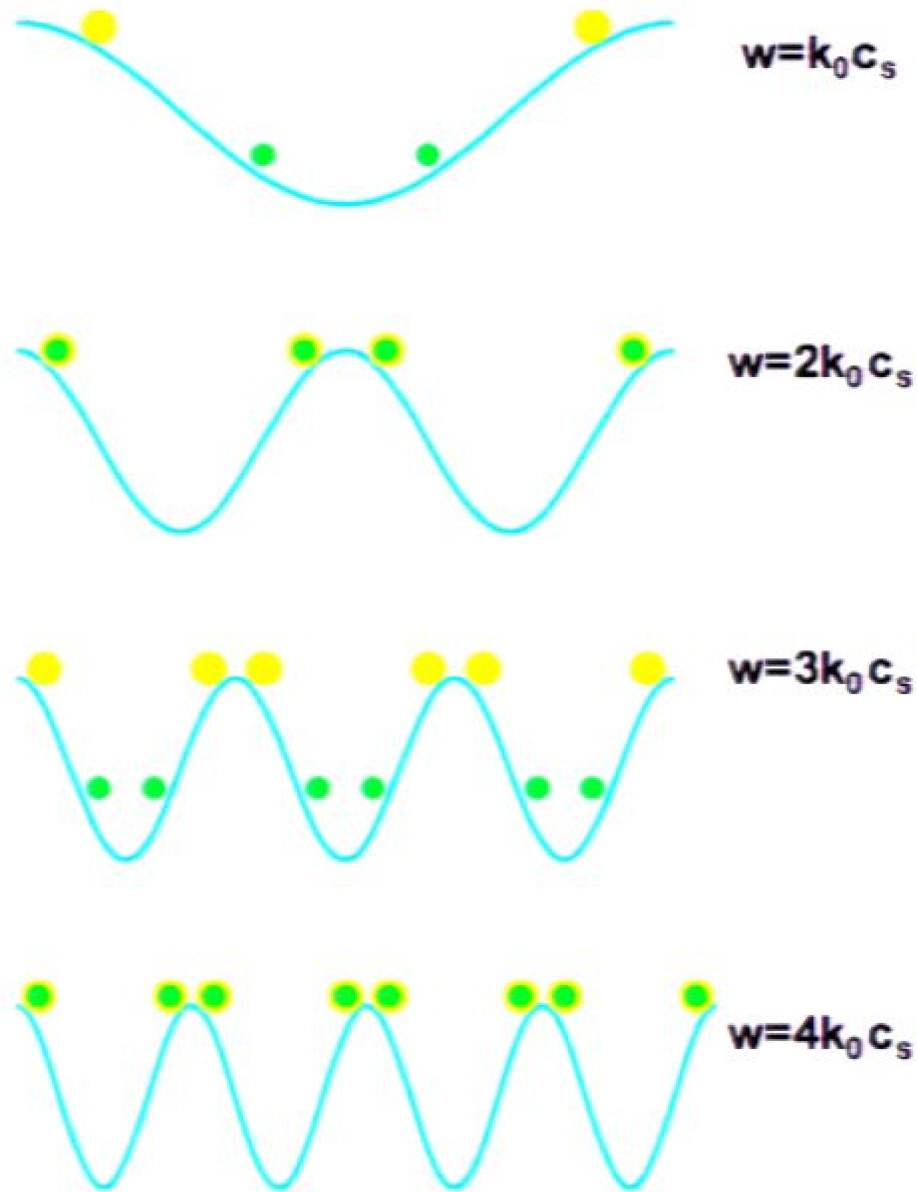


Wayne Hu

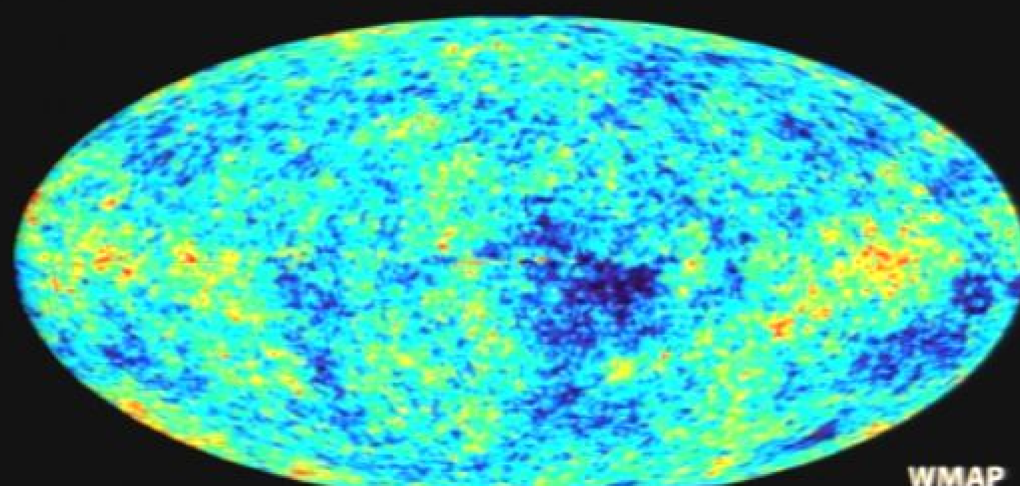
Special modes



- Potential fluctuations are laid down on *all* scales
- We Fourier decompose the potential fluctuations in space into plane waves of different wavelengths (distinct modes)
- All modes with a given wavenumber are in phase (oscillations are coherent)
- Modes with wavenumbers related by integral multiples have related oscillation frequencies.

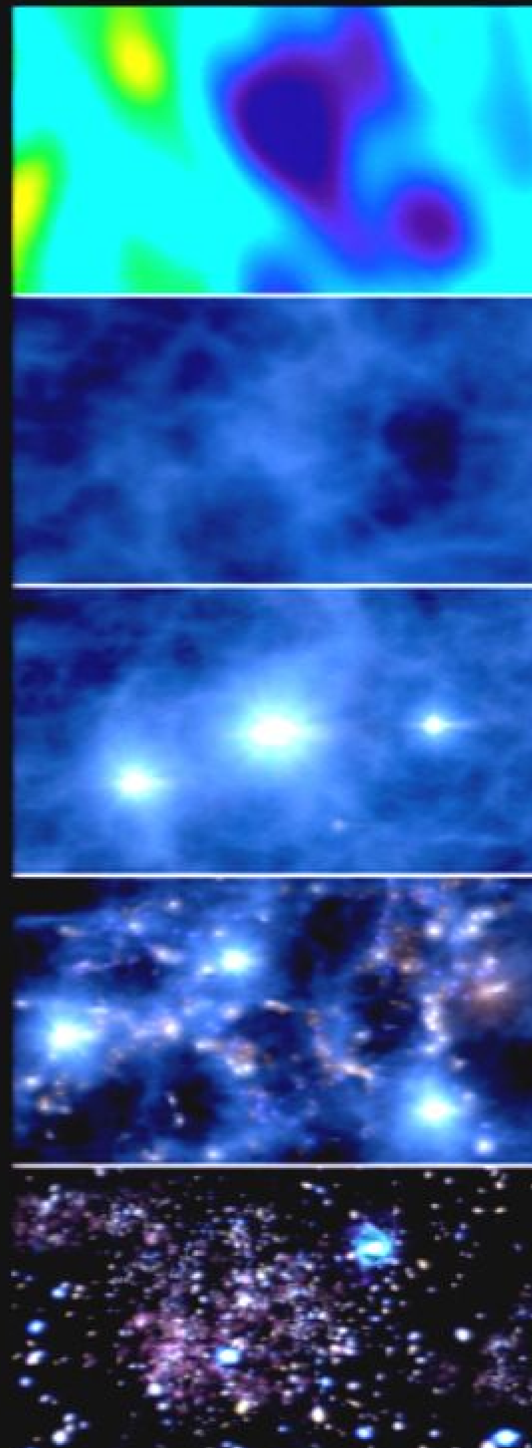
The Surface of Last Scattering

- The universe cools enough to allow the formation of neutral hydrogen
- The mean free path for Compton scattering decreases
- The photons free-stream (decoupling)
- Oscillations stop
- Modes caught at the extrema of their oscillations show enhanced emperature fluctuations
- Fluctuations are temporally coherent but spatially incoherent



After Decoupling, Matter and Radiation have very different behavior

Matter…



a) Initial Density Fluctuations universe is isotropic to 1 part in 10^5

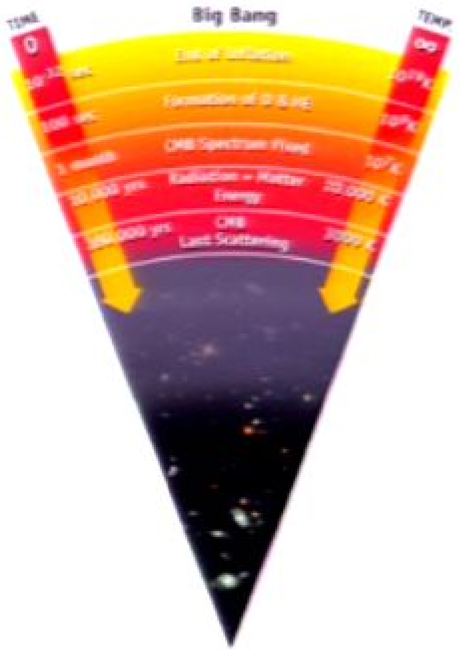
b) Matter begins to condense as gravity pulls matter from regions of lower density onto regions of higher density (no longer supported by photon pressure)

c) The first stars form (200 million years after the Big Bang). Gas has condensed and heated up to temperatures high enough to initiate nuclear fusion, the engine of the stars.

d) More stars turn on. Galaxy chains forms along those filaments first seen in (b).

e) Modern era - lots of collapsed structure (stars, galaxies, etc.), highly anisotropic universe

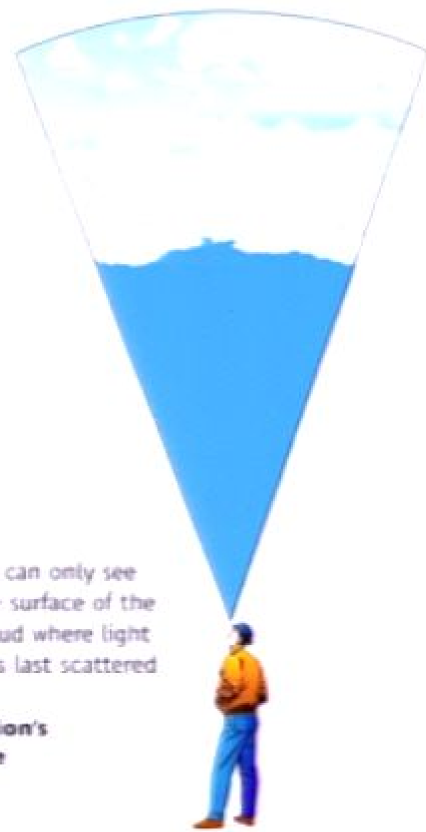
Radiation…



PRESENT
13.7 Billion Years
after the Big Bang

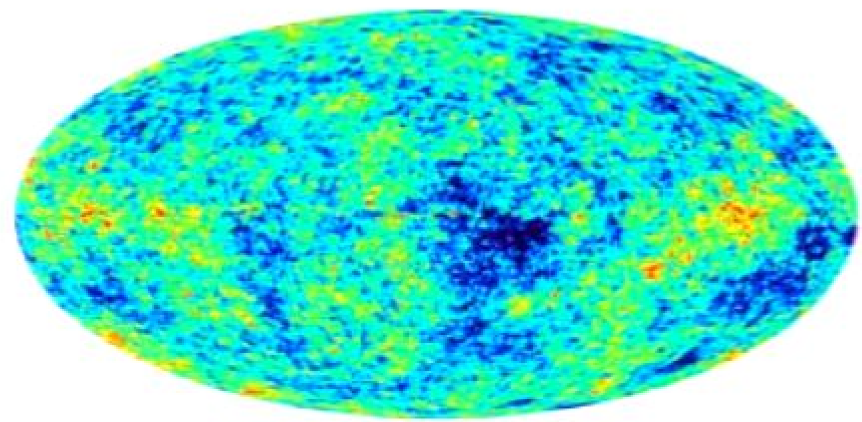
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

We can only see the surface of the cloud where light was last scattered



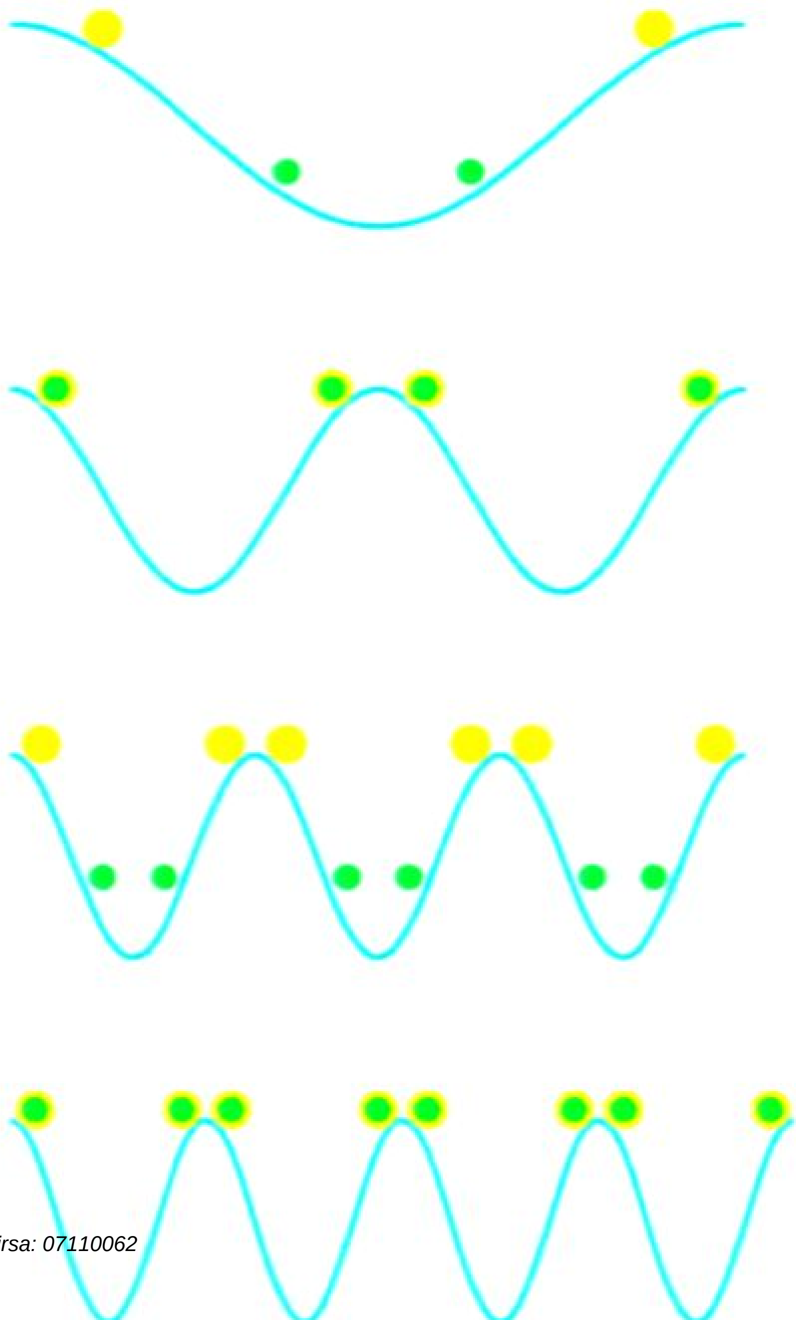
After Last Scattering, photons escape and free-stream (interacting very little with anything for the rest of the history of the universe

Small variations in density lead to variations in blackbody temperature of emitted radiation - detected by us as temperature variations (anisotropy) in the CMB



Maps of the CMB are effectively a snapshot of the surface of last scattering (baby picture of the universe)

map.gsfc.nasa.gov/m_uni/ uni_101bbtest3.html

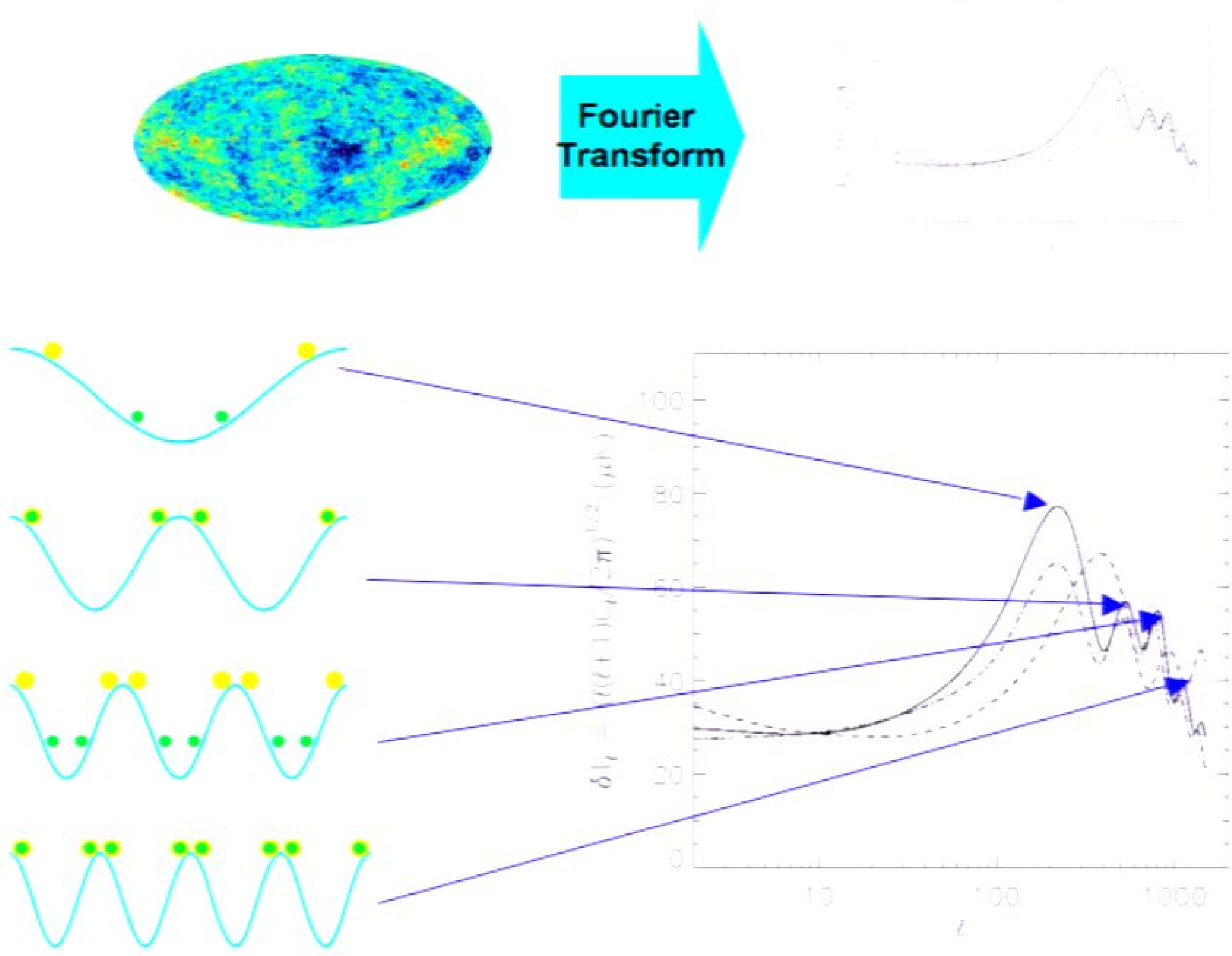


Decoupling Sets our "Special Modes"

➢Oscillations on all scales start at the same time

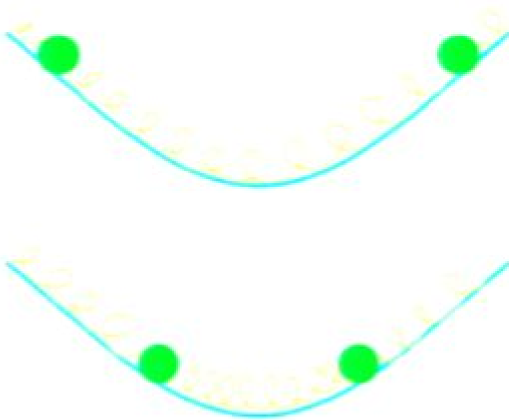
➢At decoupling, there will be a certain set of modes that will have had time to collapse and expand an integral number of times

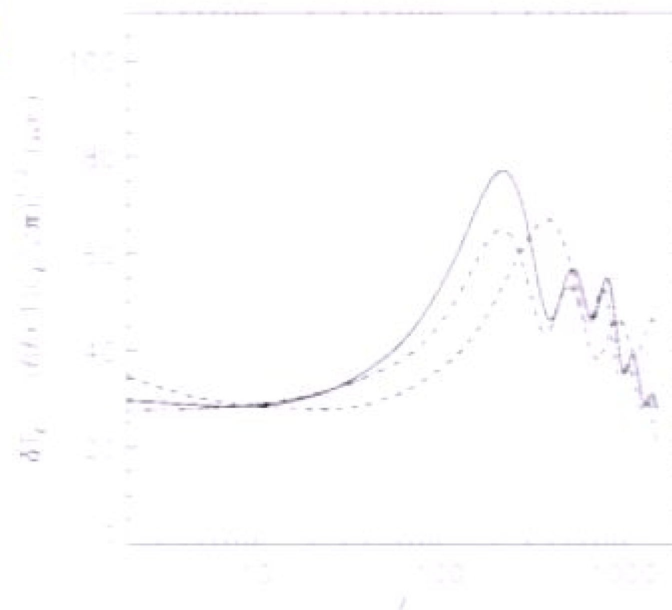
➢Since the oscillations stop at decoupling, these modes will be caught at extrema (Most fluctuation power in these modes)



These modes are seen in the CMB power spectrum as peaks "acoustic peaks" (compression maxima) and troughs (rarefaction maxima)

The first "Doppler Peak"





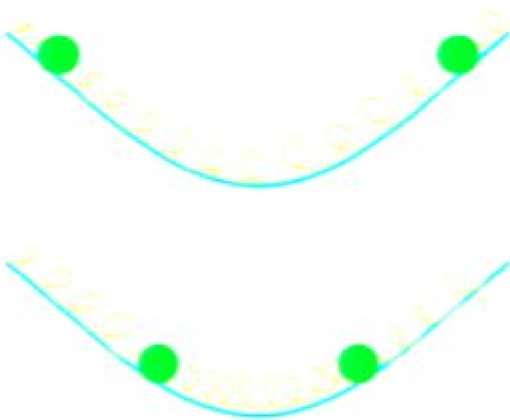
> It takes longer for the fluid to collapse in large potential wells than smaller ones

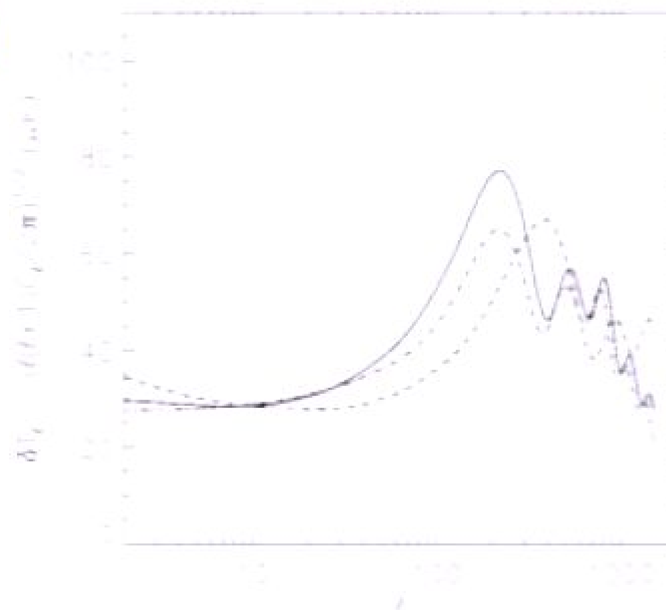
> The distance that the fluid can collapse in the time between when the oscillations start and decoupling sets the size of the largest potential well that can collapse (sound horizon)

> The oscillations in photon baryon fluid are *acoustic* in the sense that they result from compressions and expansions of a fluid

> The oscillation frequency is set by the speed of sound in the fluid ($w=kc_s$)

The first "Doppler Peak"





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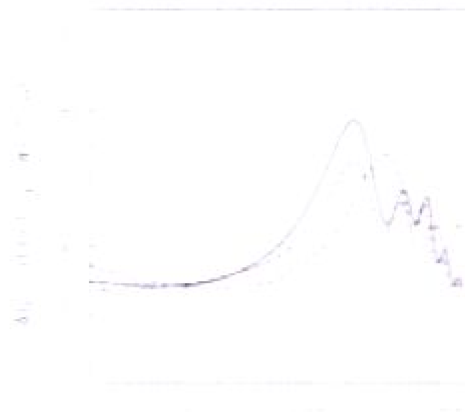
We don't listen to the CMB...

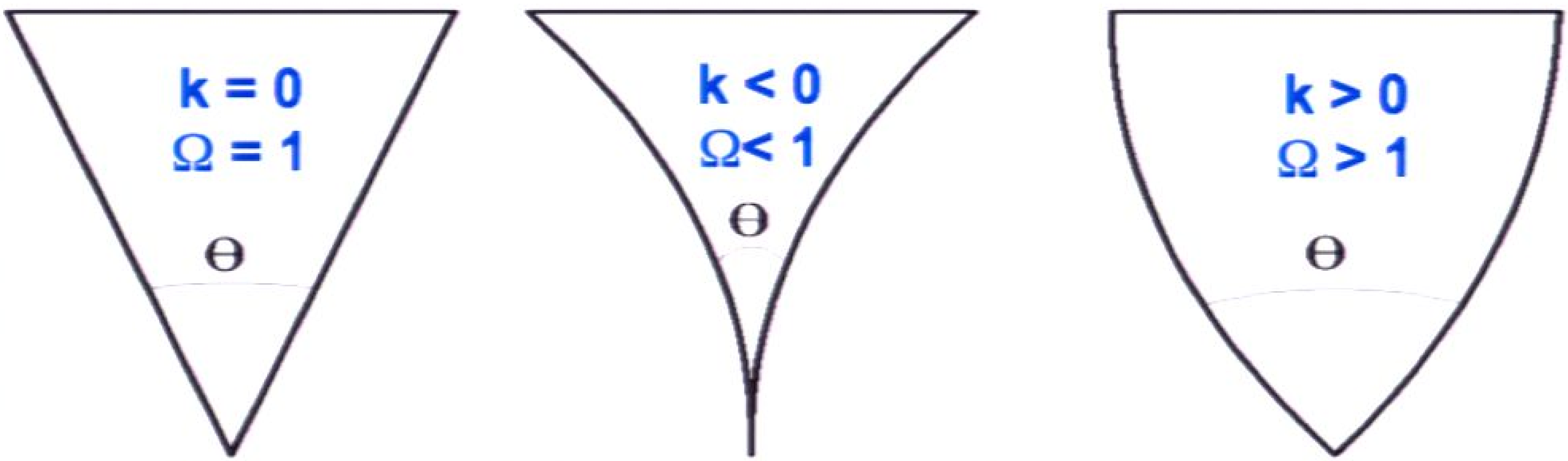
The First Doppler Peak



The scale of the sound horizon in the photon-baryon fluid before decoupling sets the maximum size of a causally connected region

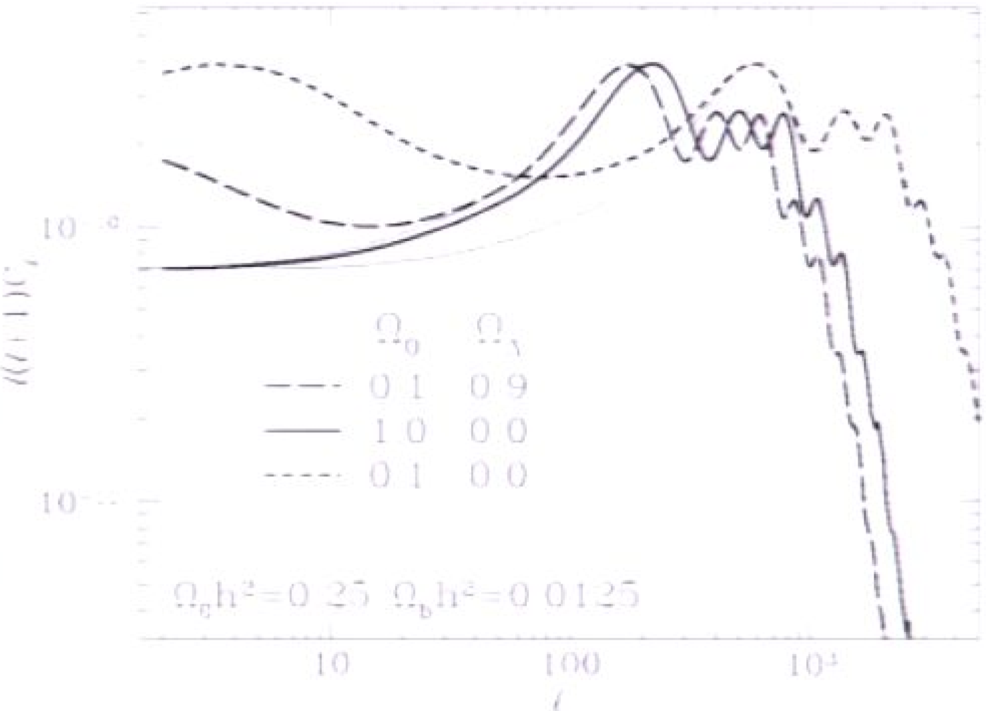
The physical size of the sound horizon depends very weakly on cosmological parameters so it can be used as a standard ruler

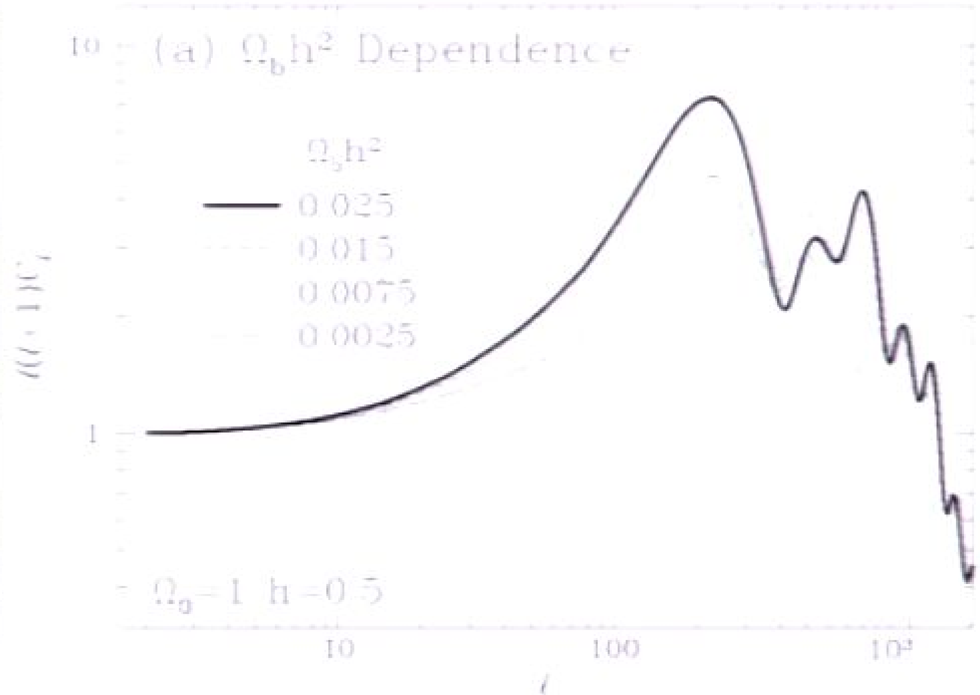
The measured angular scale at which the peak is detected sheds light on the background geometry



flat Negatively curved Positively curved

The shape of the angular spectrum depends on cosmological parameters



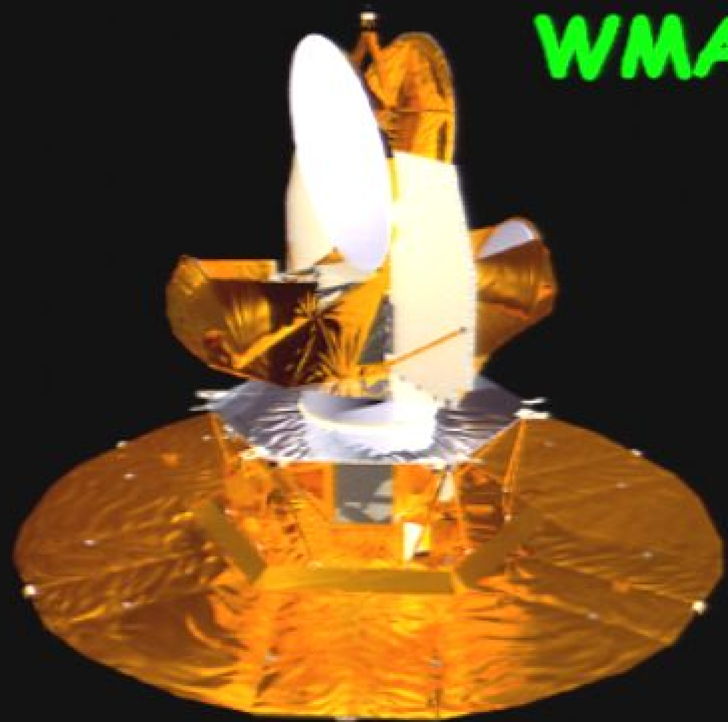


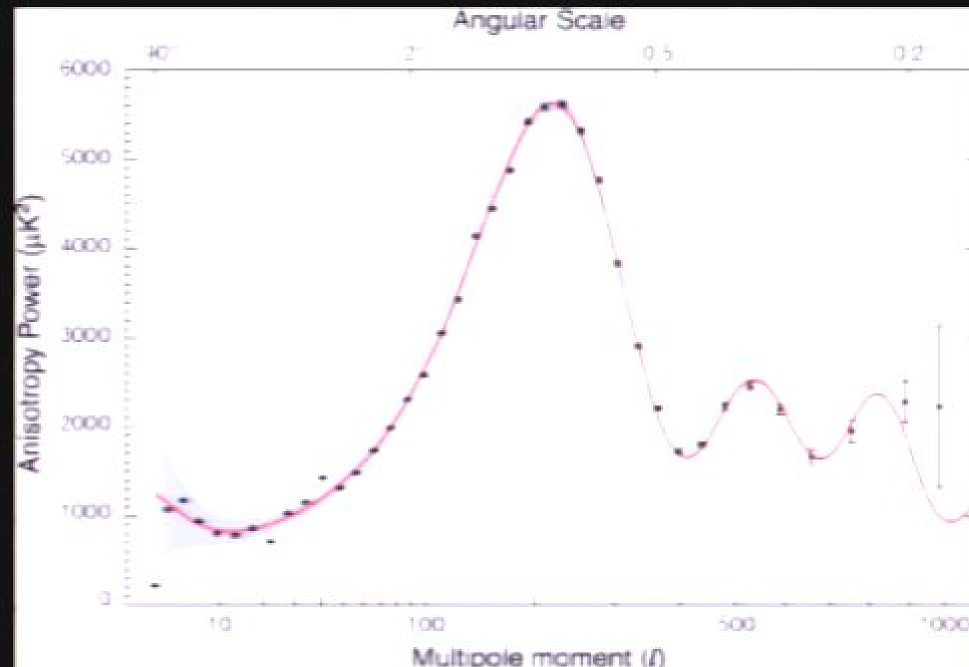
Geometry sets the position in *l*-space of the peaks

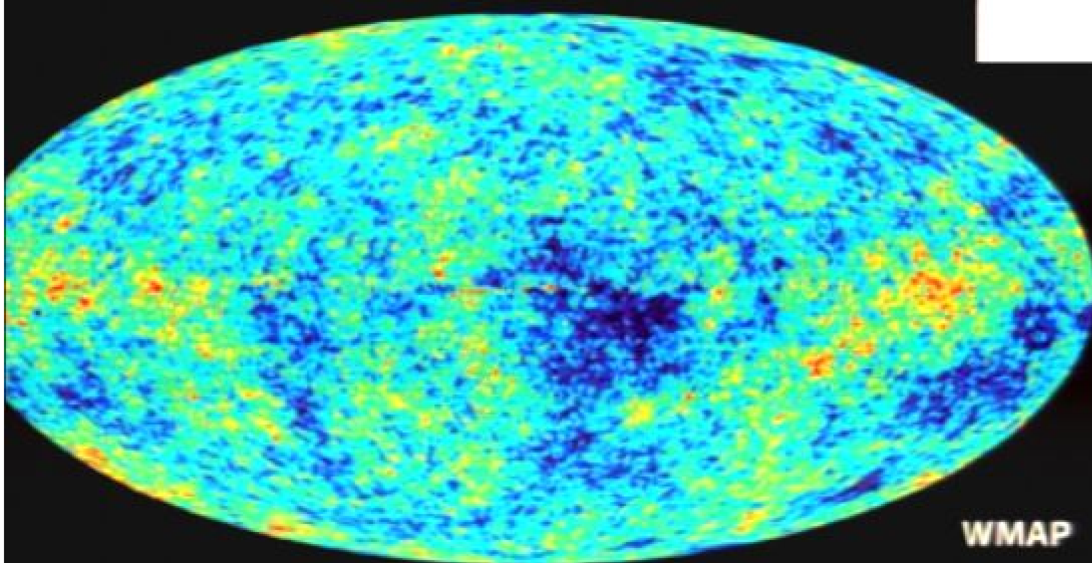
$\Omega_b h^2$ sets the relative height of the peaks

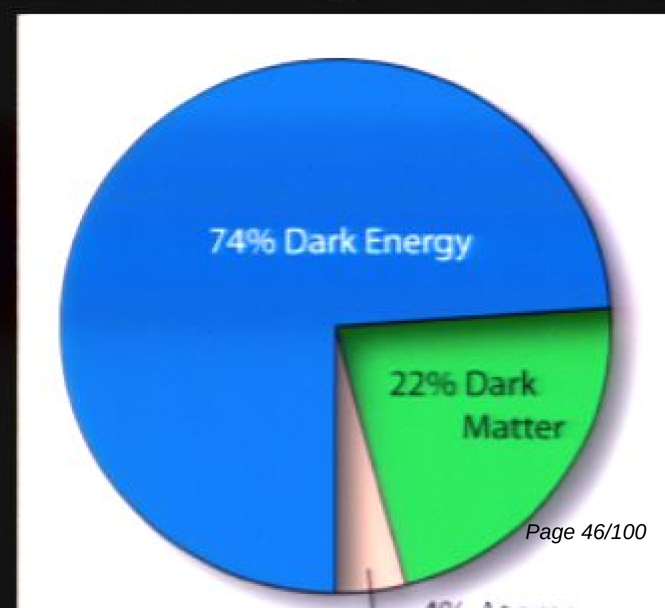
Figures from: Hu and White 1996

WMAP Results (2006)





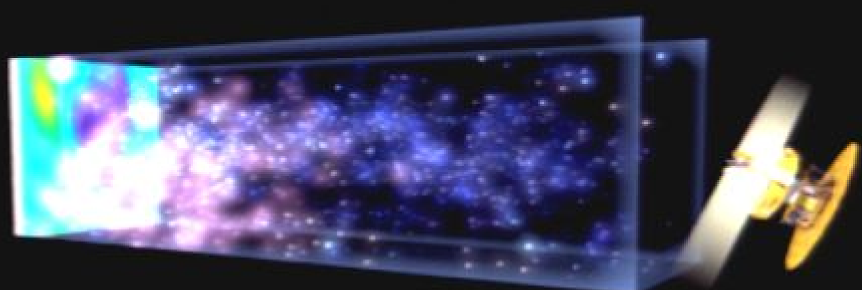




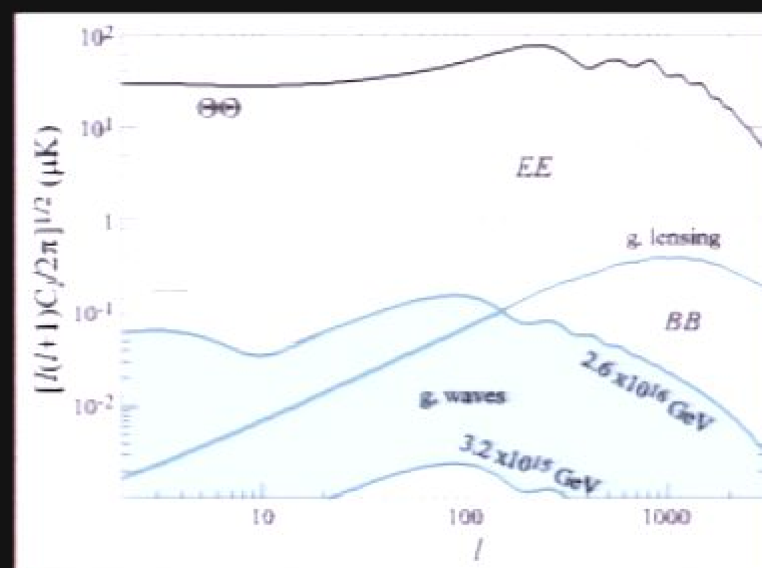
Where are we going?

The Sunyaev-Zel'dovich Effect (SZE) and small-scale CMB temperature anisotropy

- use the CMB to light up younger structure



CMB Polarization Anisotropy



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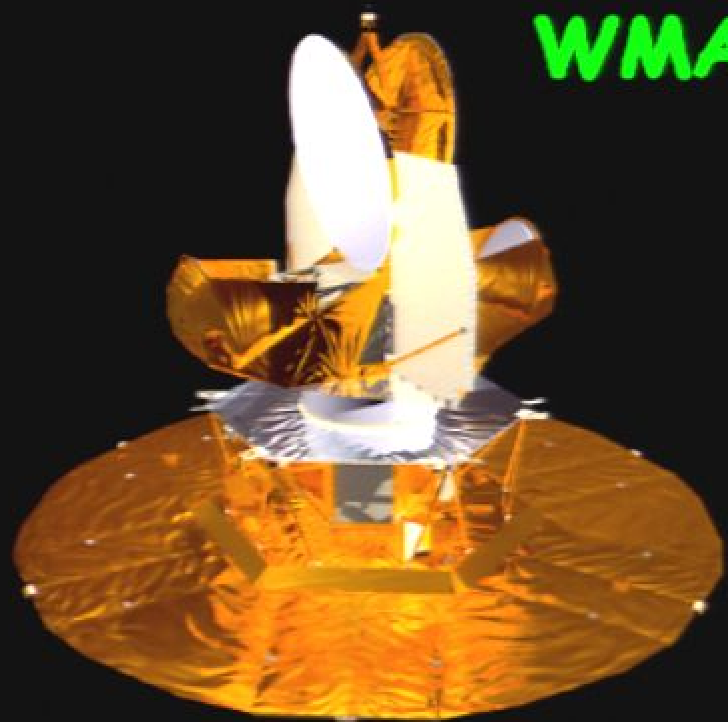

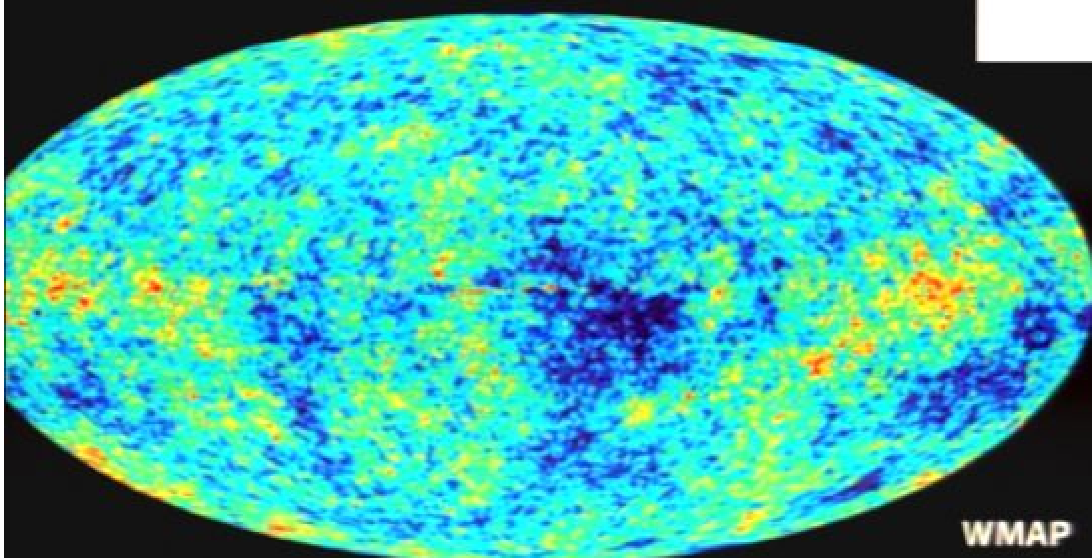

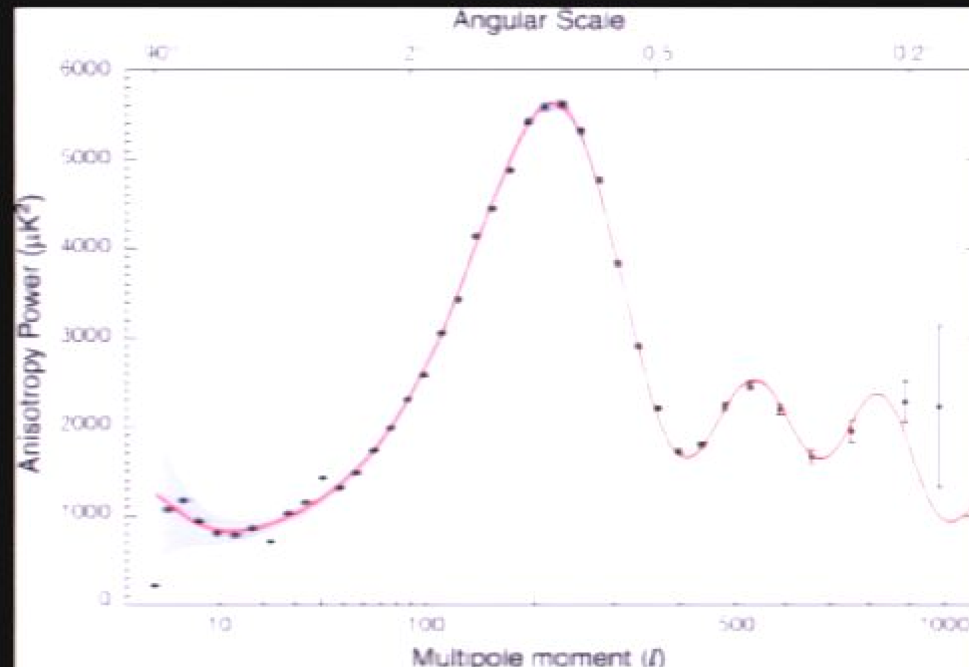

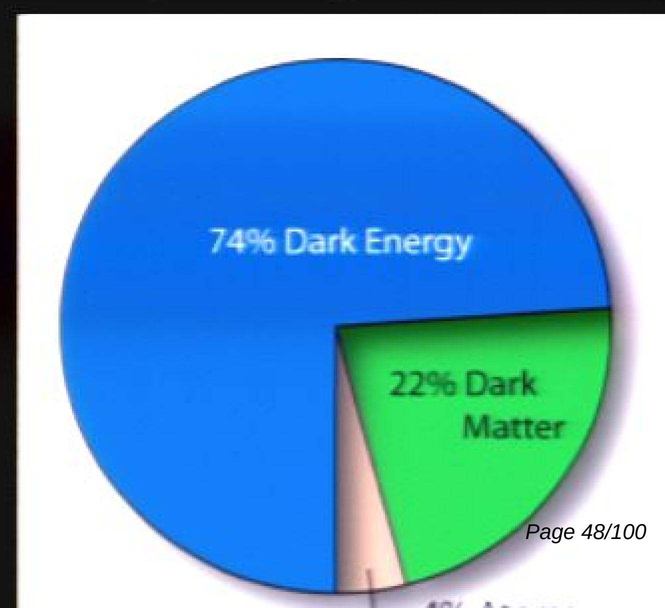

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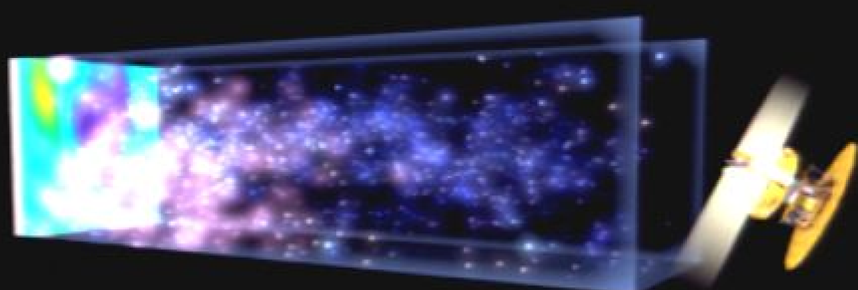
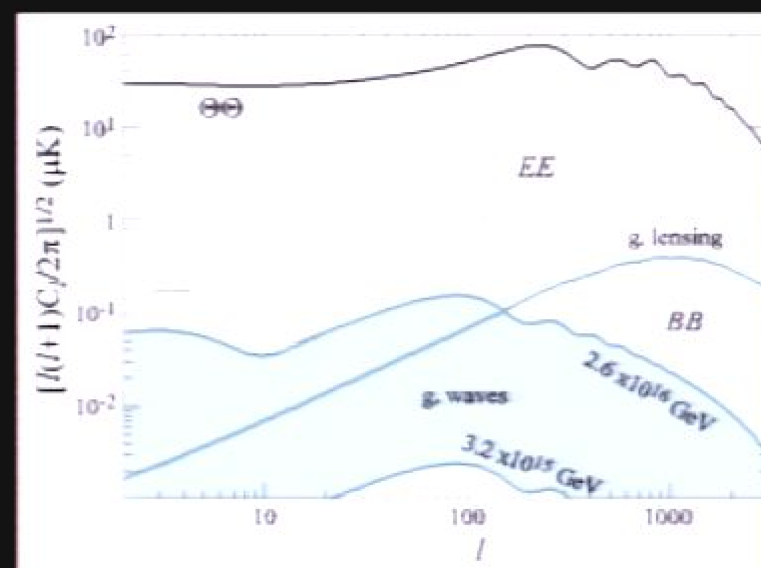
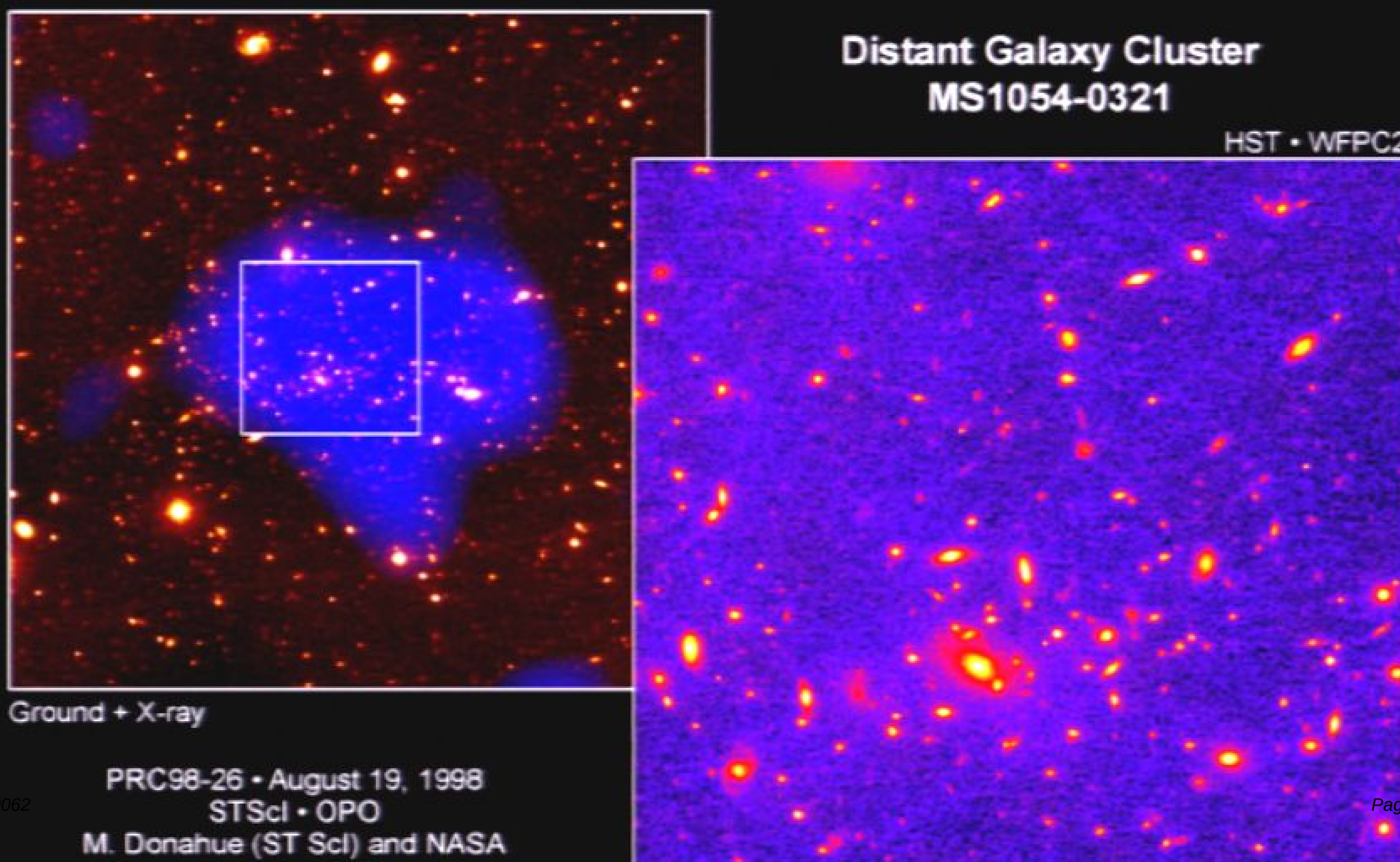


CMB Polarization Anisotropy



Clusters of Galaxies

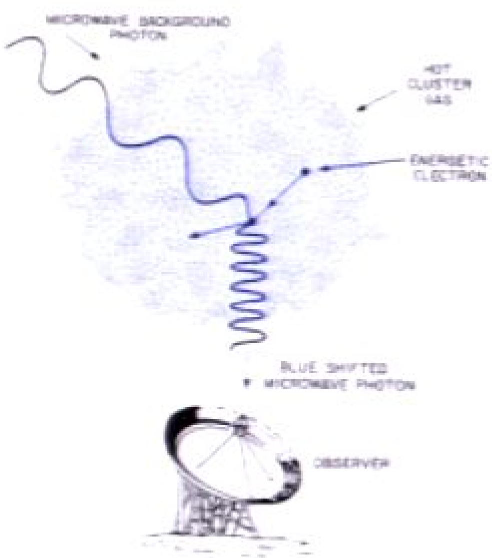
Largest collapsed objects in the universe - from volumes of ~1000 Mpc^3
Composition of cluster is thought to be fair sample of composition of universe as a whole
Baryonic matter in clusters is ~90% gas



The Sunyaev-Zel'dovich Effect (SZE)

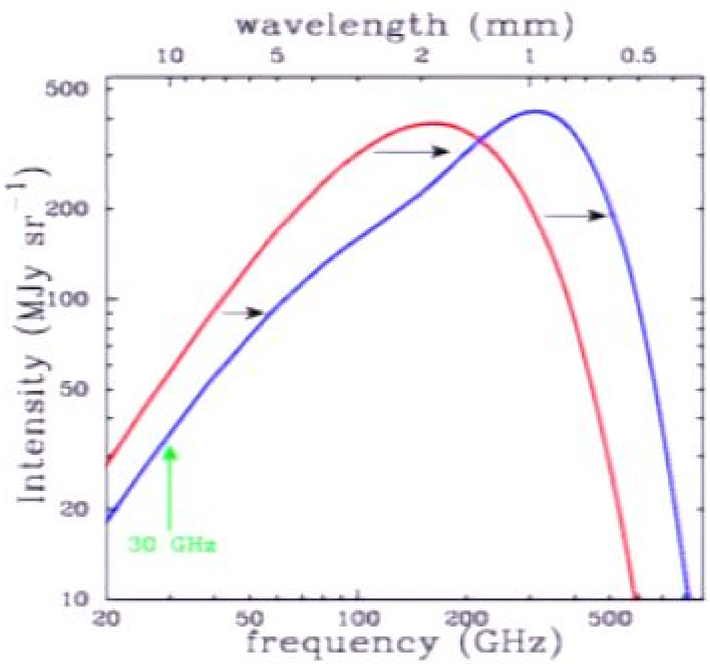
Produces a distortion in the CMB blackbody spectrum - depends on cluster physics

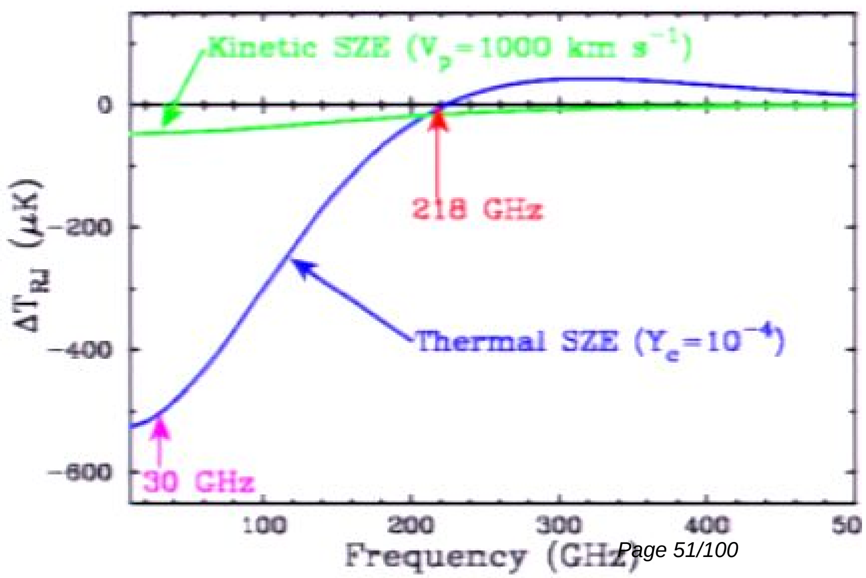
(very nearly redshift-independent)



Adapted from L. Van Speybroeck

$$\left.\frac{\Delta T_{CMB}}{T_{CMB}}\right|_{RJ} = -2\int \frac{k_B T_e}{m_e c^2} n_e \sigma_T dl = -2y$$

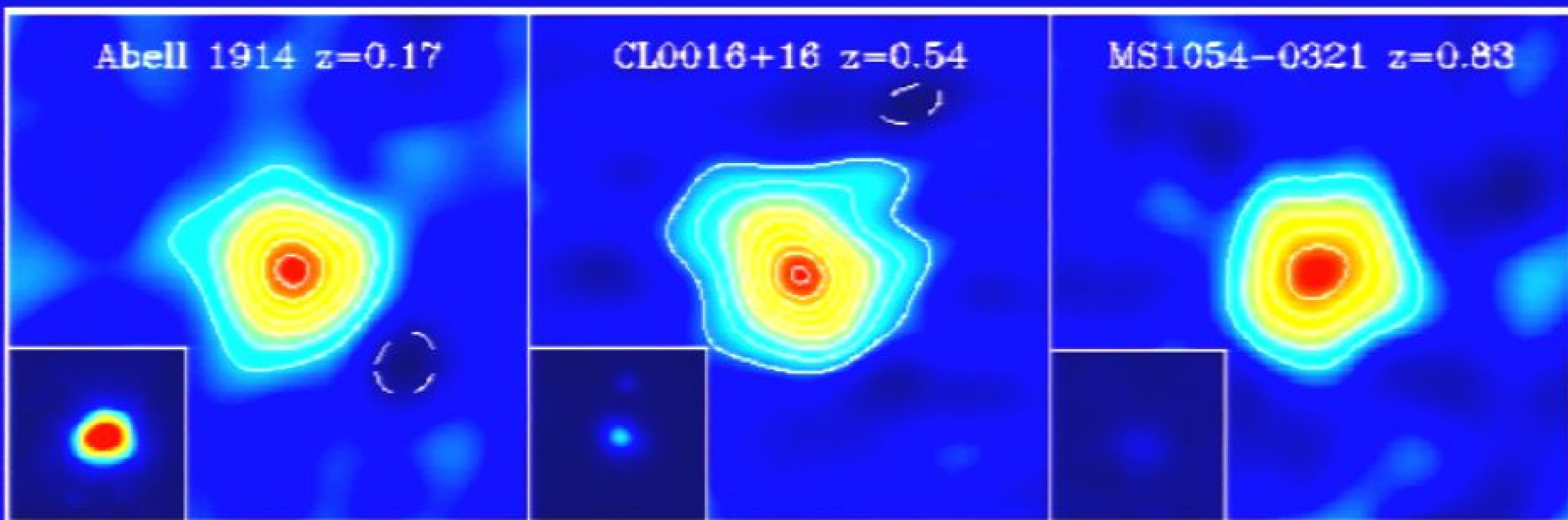




Plots courtesy of Reese

SZE Surveys - Exploit SZE redshift independence

Can Probe of Structure Formation and provide mass-limited cluster sample



Carlstrom and Mohr

SZE contours every 75μK. Same range of X-ray surface brightness in all three insets.

$$\text{SZE Flux}: S \propto \frac{1}{d_A(z)^2}\int n_e T_e dV$$

The Sunyaev-Zel'dovich Array (SZA)

hicago: John Carlstrom, Clem ryke, John Cartwright, Marcus unyan Ryan Hennessy, Chris reer, Michael Loh, Matthew harp

olumbia: Amber Miller, Stephen uchovej, Tony Mroczkowski, avid Tam, Ben Hooberman, Dan larlow, Jhumki Basu (with enaissance Charter School tudents)

altech: David Woody, David lawkins, James Lamb

IASA/MSFC: Marshal Joy, eorgia Richards

PL: Erik Leitch

Photo: Lei

SZA Essentials

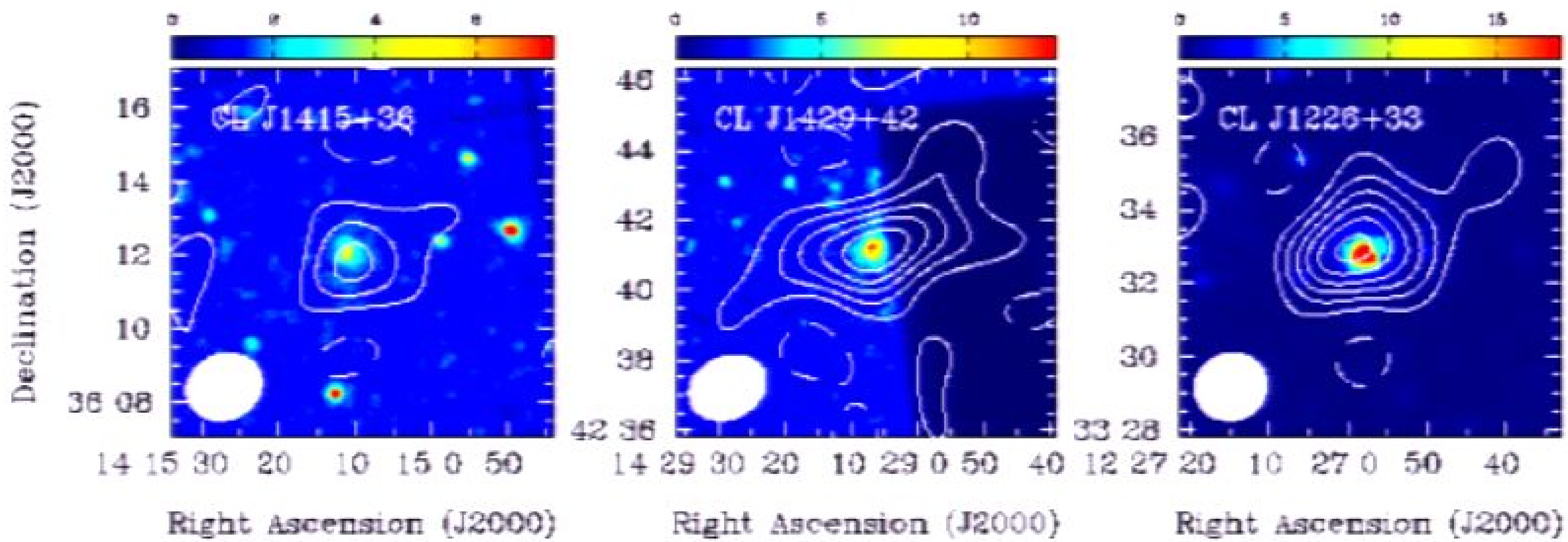
- Eight 3.5 m diameter telescopes (30 μm RMS surface, 1" pointing)
- Close-packed configuration for high surface brightness (1.2 diameter spacings)
- 30 GHz Receivers (cluster survey)
- 90 GHz Receivers (detailed cluster observations)
- Broadband 8 GHz digital correlator (dense sampling in the Fourier plane)

- Currently taking science data

- SZA to be integrated with
)VRO and BIMA telescopes
CARMA) will allow detailed
naging to ~5"

Receiver Construction and Testing - Columbia

Three High z clusters observed with SZA



1.5 σ contours

Cl1415 is highest redshift cluster yet seen in SZE (and one of lowest mass)
SZA is sensitive to angular scales out to ~4′ (outer regions of cluster)

Calculated masses and temperatures agree with X-ray determined values

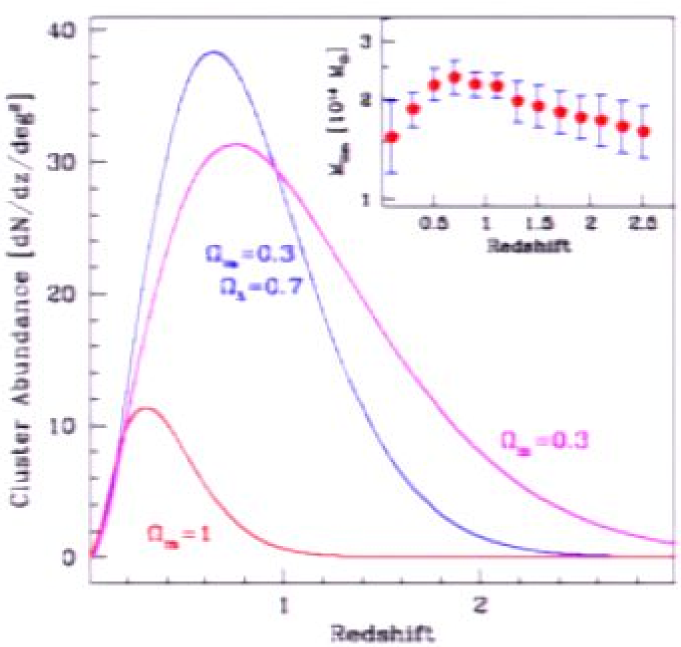
Demonstrates ability of SZA to probe cluster physics (even in survey configuration)

Bodes well for cluster survey underway

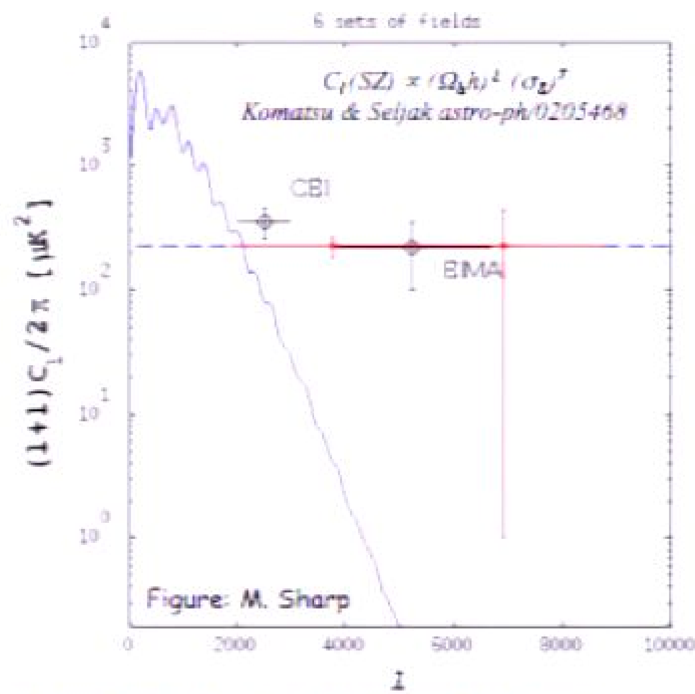
Muchovej et al. 2006

Survey Science

- Cluster Abundance dN/dz
- Measure σ_8 (rms linear fluctuations in the mass distribution on scales of 8 Mpc) - normalizes the amplitude of matter perturbations in the universe (present time)
- Tests of Non-Gaussianity



Mohr 2001

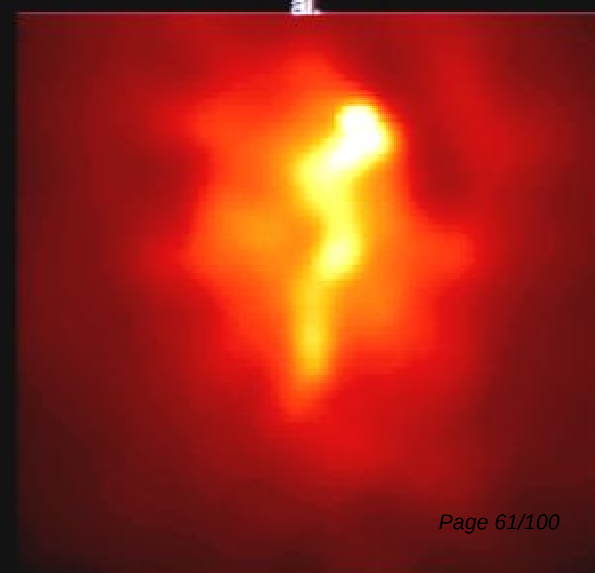


Predicted errors for 1/6 of data already taken
(simulation, with realistic noise and array parameters - not real data)

Pointed Cluster Observations

- SZE + X-ray + optical + cluster simulations comparison of individual objects ➔ study how various effects impact cosmological parameter determination
  - scatter in observables due to projection effects, ellipticity
  - uncertainty in gas density profile, cluster structure
  - cluster evolution
  - cooling cores, cold fronts, shock fronts, evacuated cavities
  - merger history, current dynamical state, relationship of intra-cluster gas to stellar population
- Study proto-cluster candidates

Abell 2597: NASA/CXC/Ohio U/B.McNamara et al.



Improved Model for Reconstructing Cluster Physical Parameters
(SZ + X-ray luminosity data - no spectroscopic temperature profiles)

Need a model for fitting SZ data that allows for a joint fit with x-ray data but does not insist that the SZ profile (a measure of the cluster pressure profile) and the x-ray profile (a measure of the cluster gas density) are identical

We fit SZ data to generalized NFW profile (Nagai et al. 2007), shown to be a good fit to SZ profiles using simulations

We use a modified β model with two extra degrees of freedom (Vikhlinin et al. 2006) to fit x-ray cluster density profiles

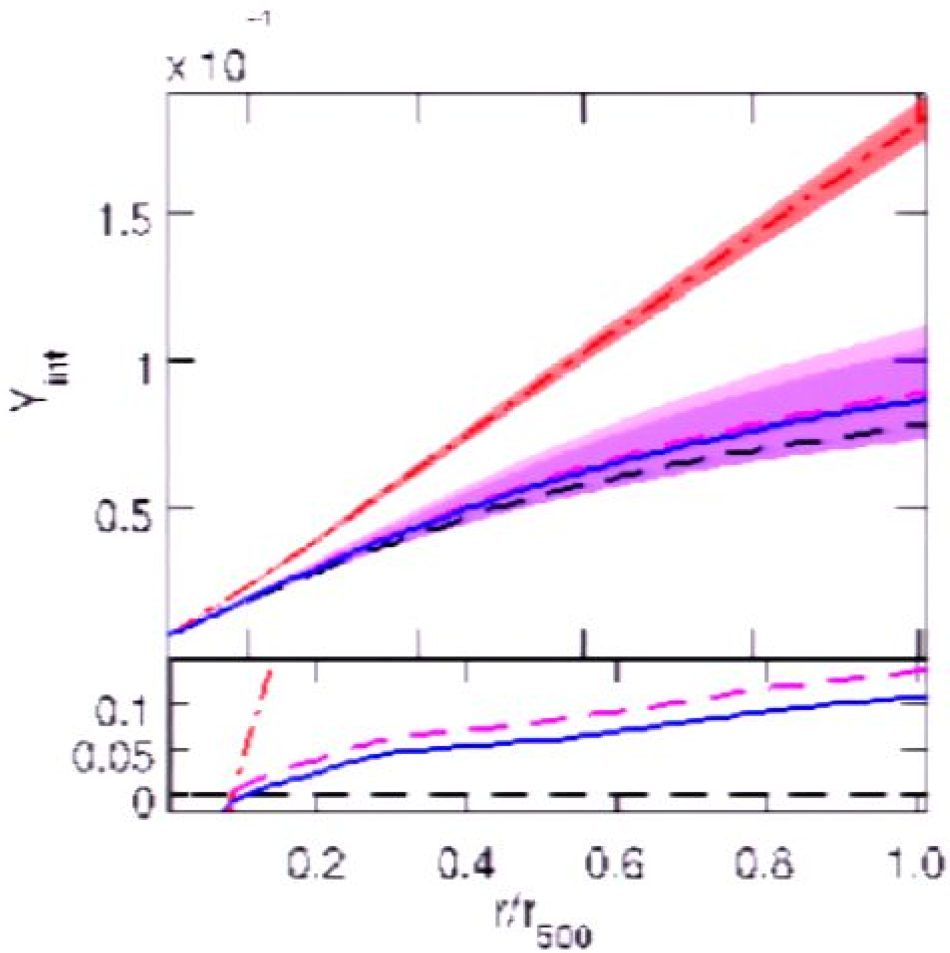
The two profiles are linked using the ideal gas law (solve for cluster temperature - we do not use x-ray spectroscopic temperatures)

We find that we can recover the integrated SZ decrement much more reliably with this new model --> better cluster gas masses, total cluster masses, Hubble constant (if x-ray spectroscopic temperatures added), etc.

Temperature recovery (SZ + x-ray luminosity data) also very promising for high redshift cluster observations

Mroczkowski et al. 2007 in prep.

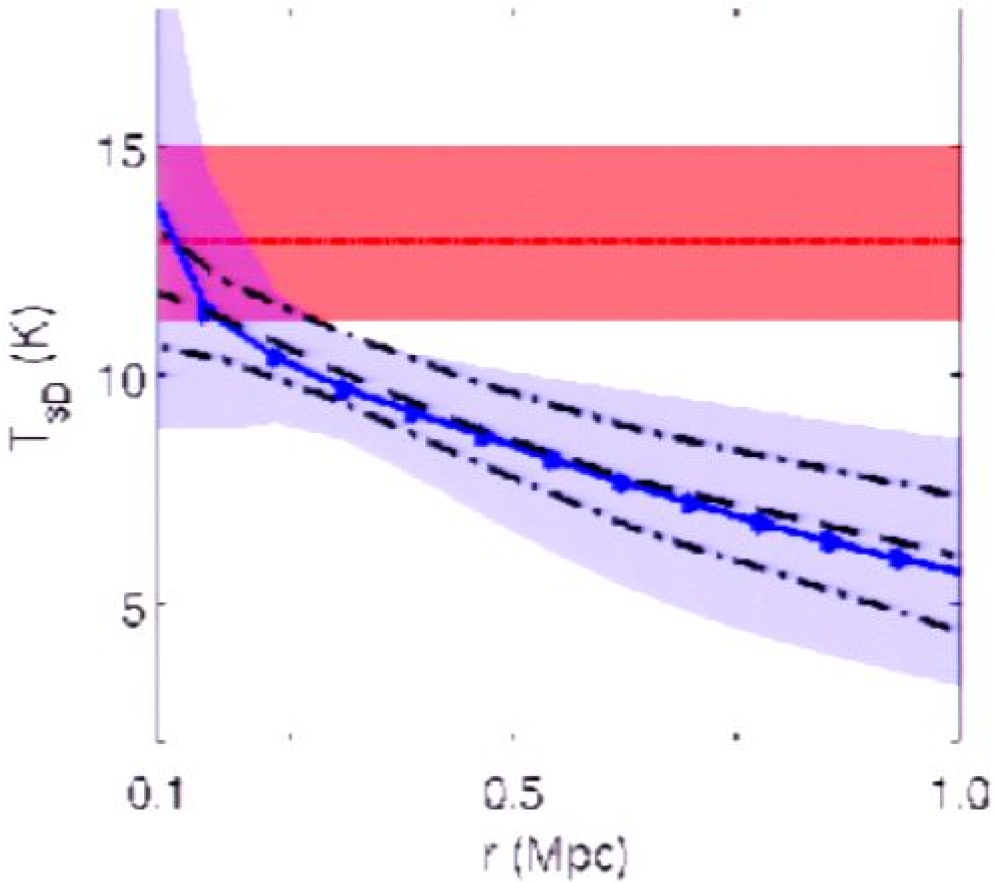
Improved Model for Reconstructing Cluster Physical Parameters
(SZ + X-ray luminosity data - no spectroscopic temperature profiles)



Mroczkowski et al. 2007 in prep.

- We fit mock SZA 30 GHz observations for several mock clusters in several projections (Nagai)
- On left is a relaxed, 8 keV simulated cluster
- The Ysz from the simulation is the black, dashed line.
- Overlapping blue and pink regions are joint (SZA+X-ray) and the SZA-only fits (68% confidence) to the cluster observation.
- The figure shows the isothermal beta model (jointly fit with a mock Chandra X-ray observation) in red.

Testing Temperature Recovery with a Well-Studied Cluster (CL1226+3332)

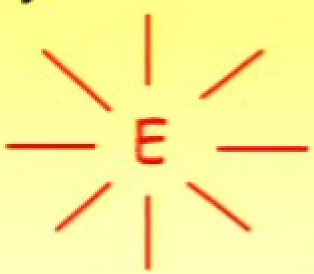


- The blue region shows the derived, joint temperature (1-sigma confidence) of the N07 + simplified Vikhlinin density model fit.
- The red region (1-sigma confidence) is the isothermal beta model's temperature.
- We compare the derived 3D temperature to a detailed, joint *Chandra+XMM* X-ray study (black dashed lines) of this cluster (B. Maughan, C. Jones, L.R. Jones, and L. Van Speybroeck 2007; personal communications with B. Maughan)

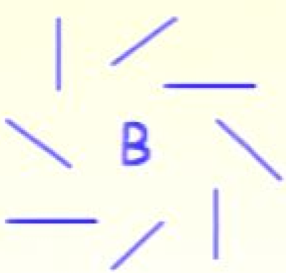
Mroczkowski et al. 2007 in prep.

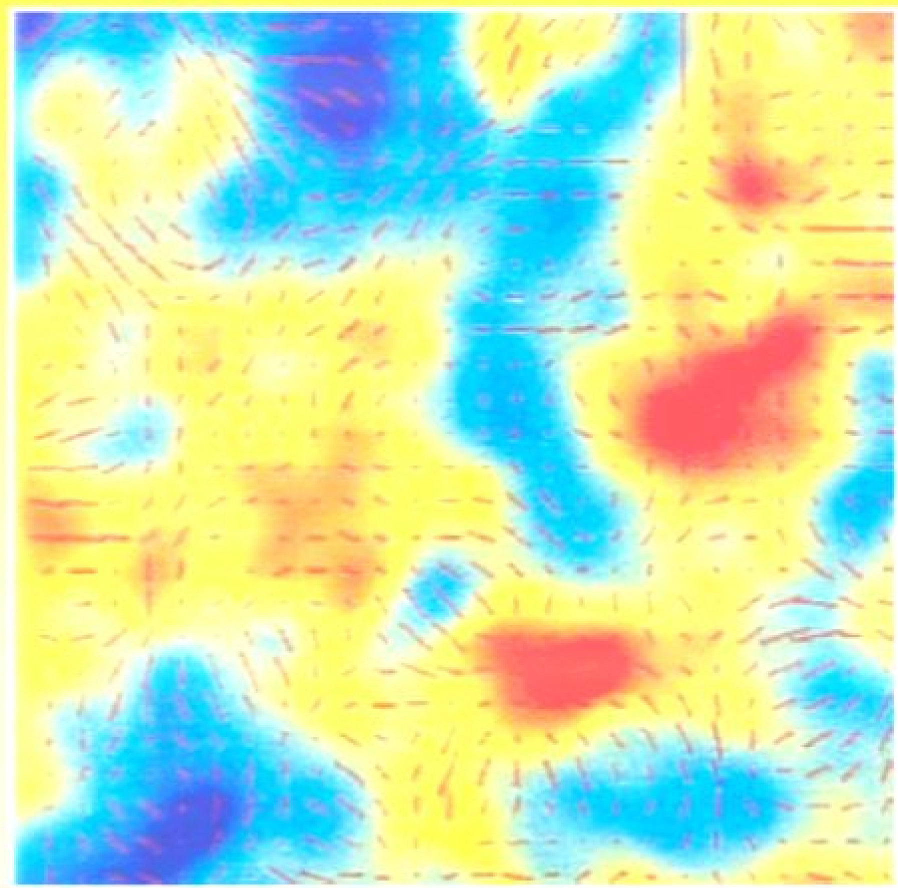
CMB Polarization

- Scalar Modes – generated by lensity perturbations (E-mode olarization)



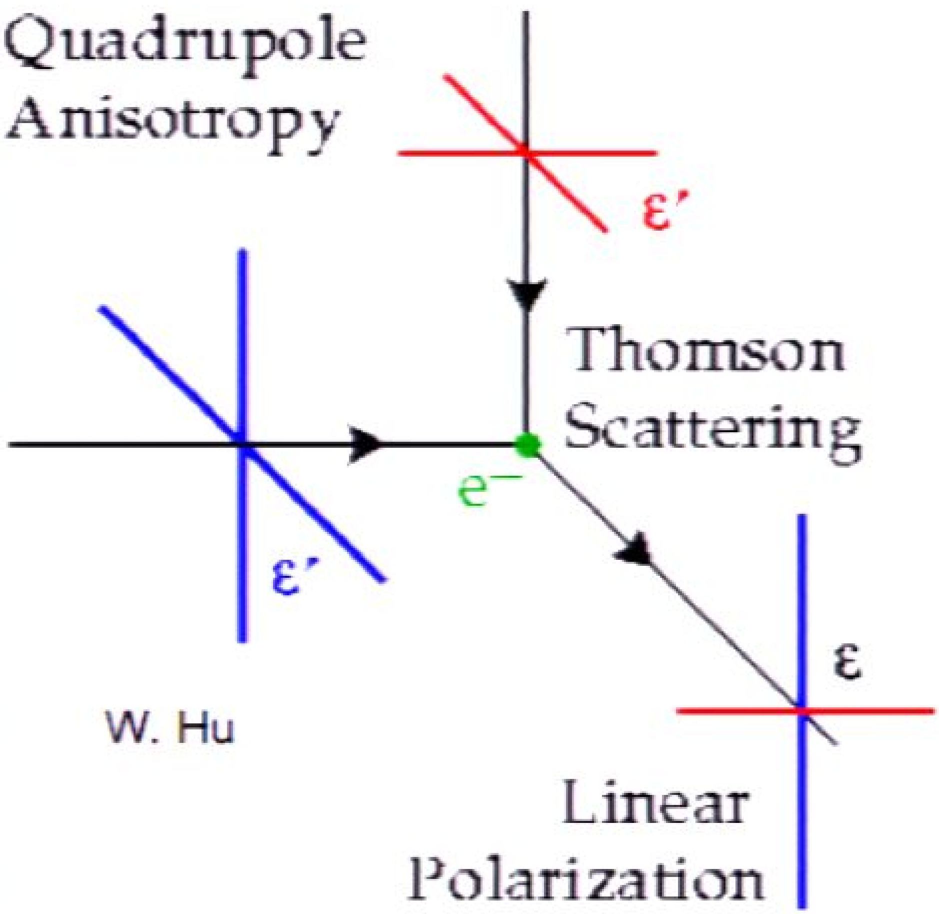
- Tensor Modes – generated by ravitational Waves (B-mode olarization)





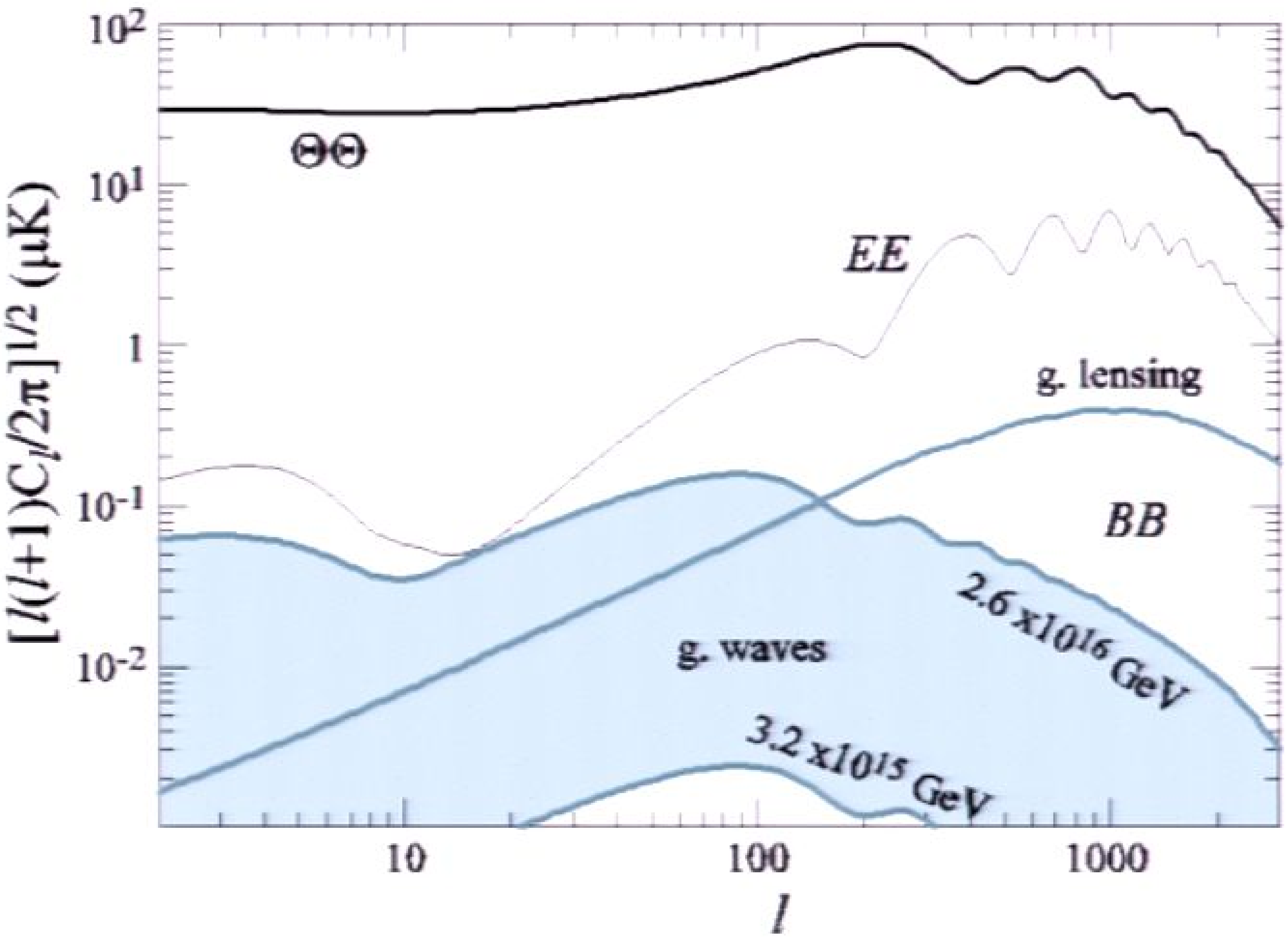
From Seljak and Zaldarriaga

CMB Polarization from Quadrupole Anisotropies



- Isotropic radiation scatters into unpolarized radiation
- Quadrupole anisotropies scatter into linear polarization
- Density inhomogeneities create curl-free polarization (E-modes)
- Gravitational Waves generate both divergence-free and curl-free polarization (E-modes and B-modes)

CMB Polarization Angular Power Spectra (theoretical curves)



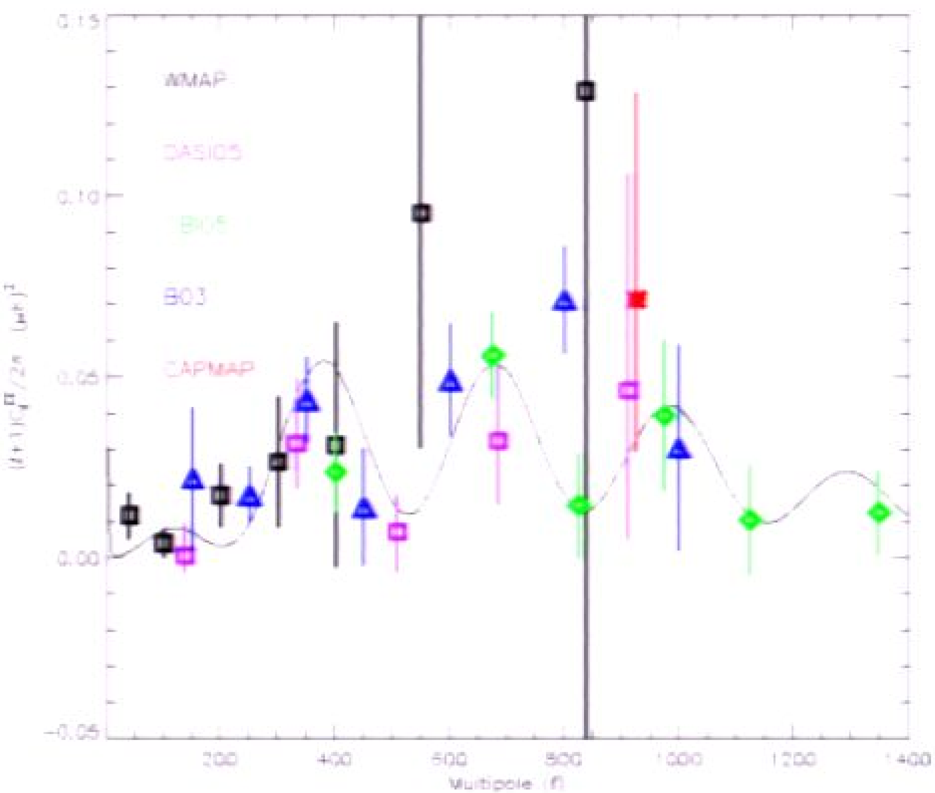
- Quadrupole anisotropy is generated on diffusion scale
- Primary peak coincides with the beginning of the damping tail (l~1000)
- Peak at low l reflects the horizon scale when universe was reionized by light from first stars (l<10)

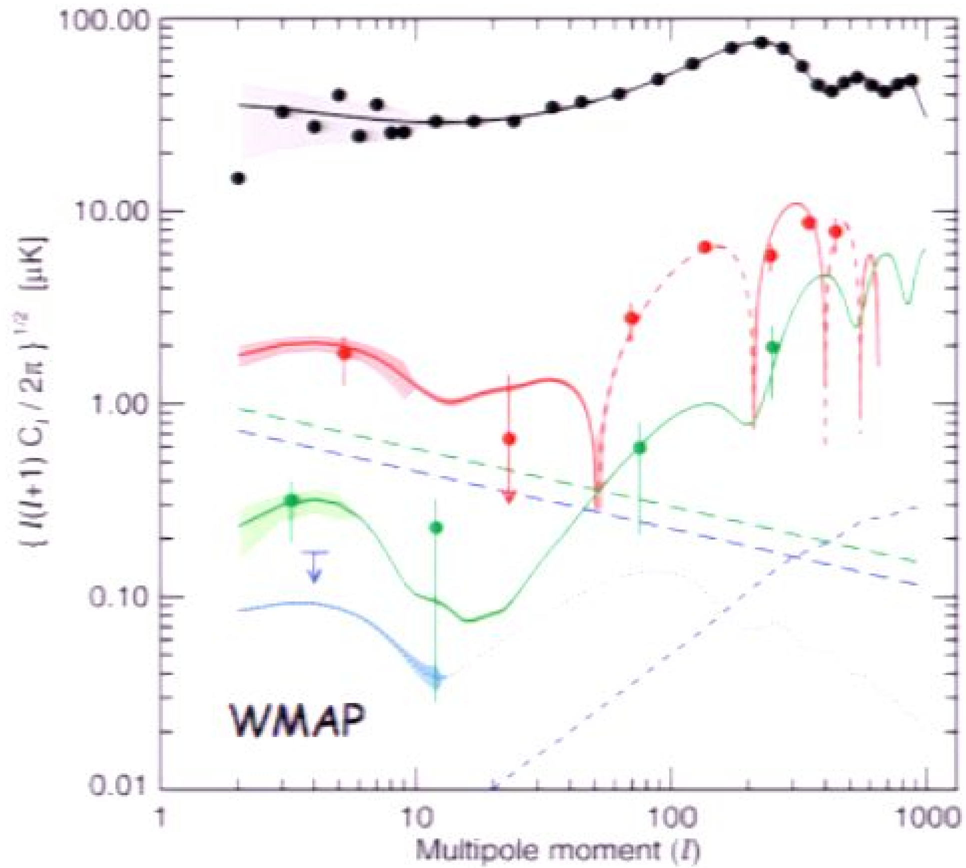
Hu, Hedman, and Zaldarriaga, 2003

Why Measure E-mode Polarization?

- Generated only by scattering (most direct probe of physics at ecombination)
- Probe epoch of reionization by first stars
- Serves as a consistency check on interpretation of temperature nisotropy as signature of gravitational instability model
- Remove degeneracies in cosmological parameters inferred from rimary anisotropies and enhance precision with which cosmological arameters are measured

State of the Art E-Mode Polarization





Curves generated from best-fit to Temperature anisotropy data

Page et al. 2006

CMB B-Mode Polarization

Generated by perturbations in the spacetime metric - gravitational waves

photons propagating in perturbed spacetime are redshifted or lueshifted depending on their propagation direction relative to the ravitational wave's propagation direction, polarization, and frequency

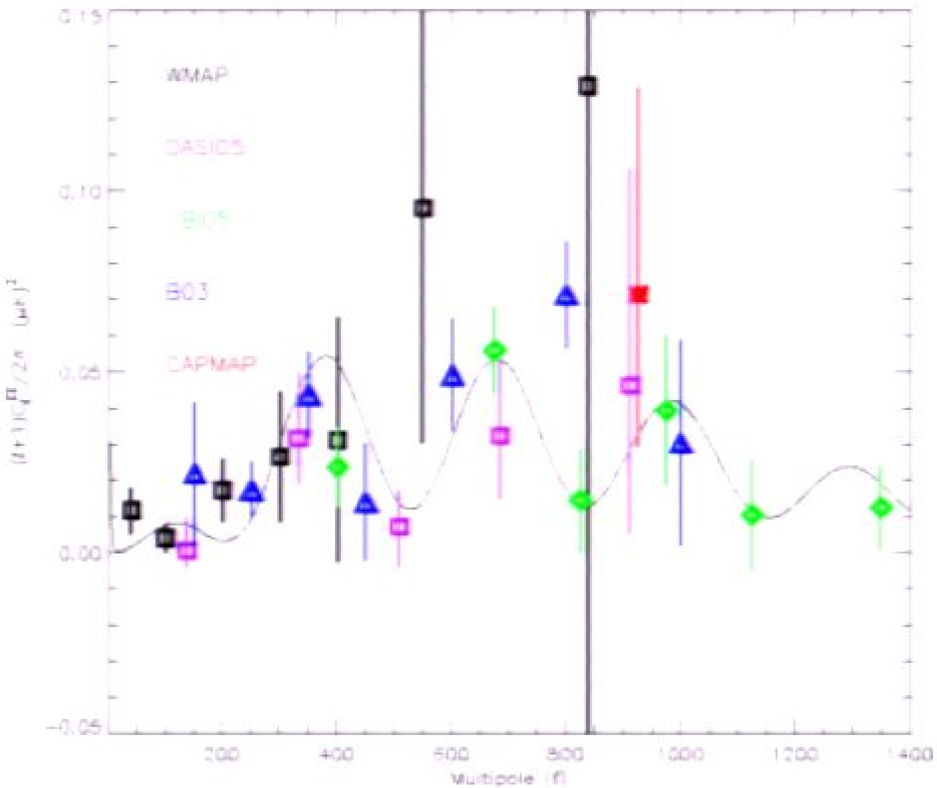
Induced frequency shifts are equivalent to shifts in the temperature of he CMB blackbody spectrum (too small to see in ΔT)

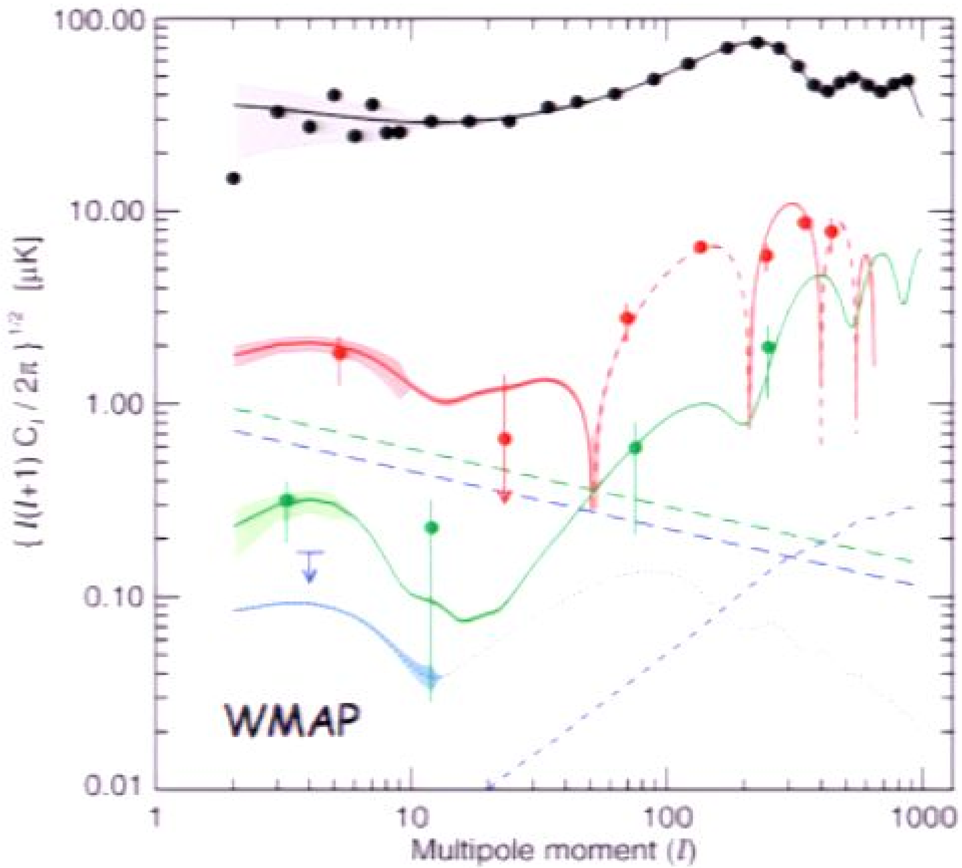
Thomson scattering converts these temperature anisotropies to olarization anisotropies which have a unique "curl" signature so are eparable from E-mode polarization even though their amplitude is very mall

The square of the dimensionless amplitude of these gravitational waves is he density of the universe during inflation (in Planck units) - so a direct ay to measure the cosmic density during inflation

Not only interesting for cosmology, but provides physics on scales MUCH igher than those on which laboratory measurements are possible

State of the Art E-Mode Polarization





Curves generated from best-fit to Temperature anisotropy data

Page et al. 2006

CMB B-Mode Polarization

Generated by perturbations in the spacetime metric - gravitational waves

photons propagating in perturbed spacetime are redshifted or lueshifted depending on their propagation direction relative to the ravitational wave's propagation direction, polarization, and frequency

Induced frequency shifts are equivalent to shifts in the temperature of he CMB blackbody spectrum (too small to see in ΔT)

Thomson scattering converts these temperature anisotropies to olarization anisotropies which have a unique "curl" signature so are eparable from E-mode polarization even though their amplitude is very mall

The square of the dimensionless amplitude of these gravitational waves is he density of the universe during inflation (in Planck units) - so a direct ay to measure the cosmic density during inflation

Not only interesting for cosmology, but provides physics on scales MUCH igher than those on which laboratory measurements are possible

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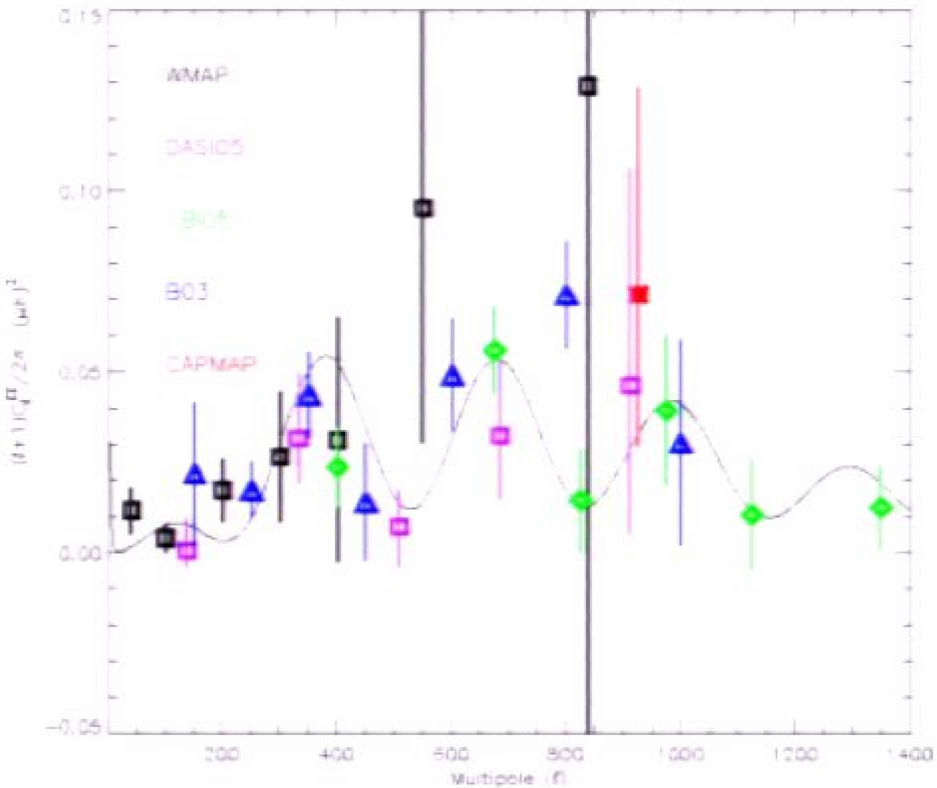

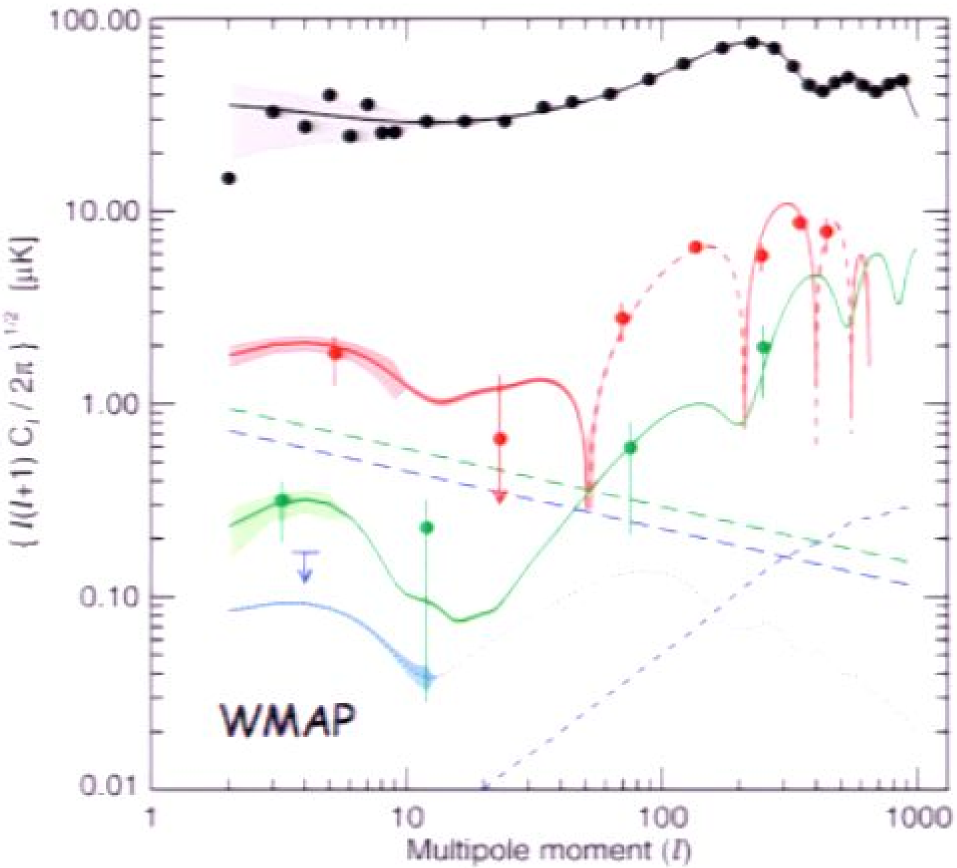

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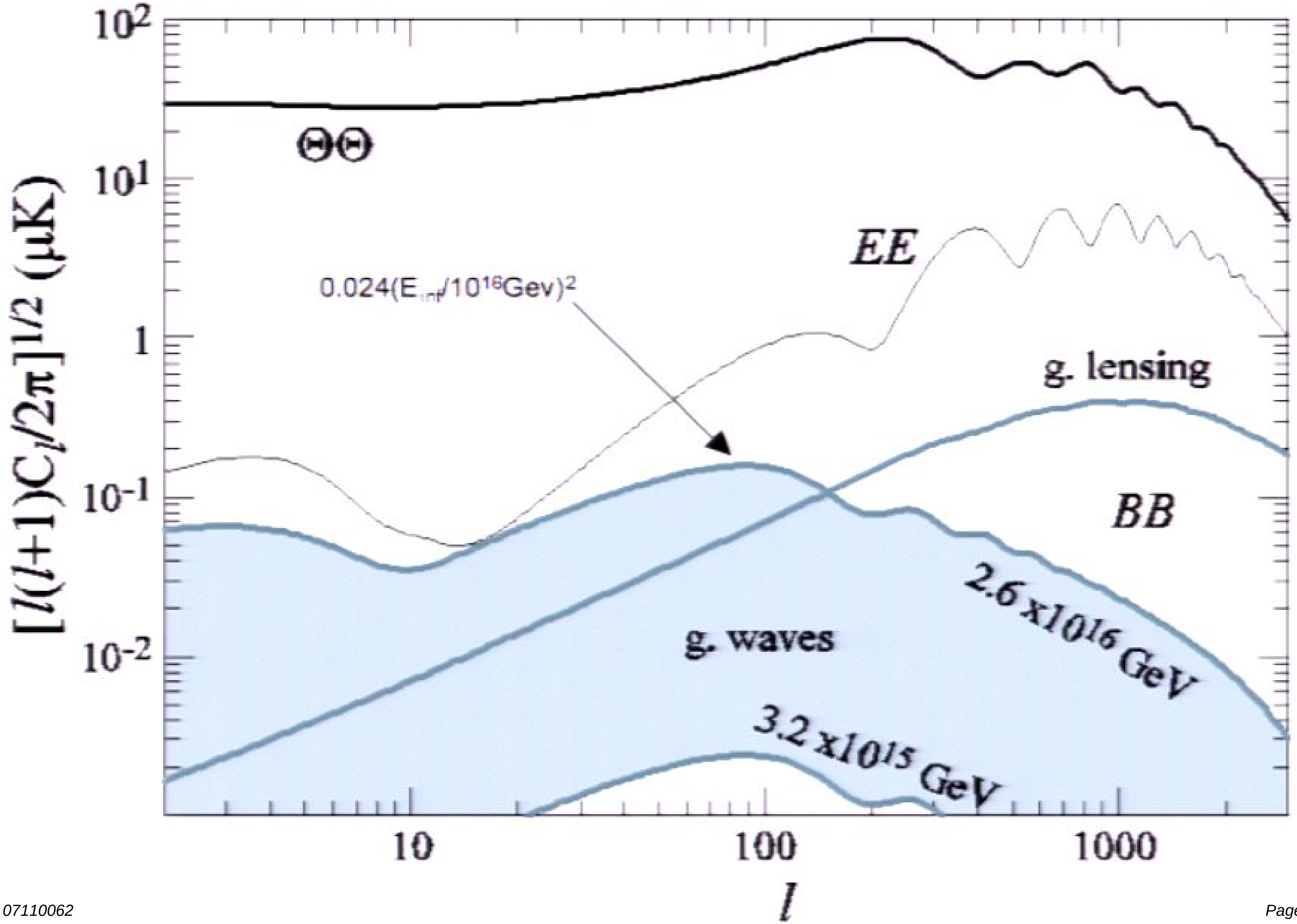
CMB Polarization Angular Power Spectra (theoretical curves)



Hu, Hedman, and Zaldarriaga, 2003

State of the Art B-mode Polarization

CMB Polarization

Columbia - two experiments with same science goals, completely different technical approach (subject to different foregrounds, different systematic errors), lots of complementary work and exchange of ideas

<u>QUIET - Q U Imaging Experiment</u>

Coherent Polarimeters
all frequency and polarization separation takes place in module, simple optics, simple cryogenics
Low frequency (40, 90 GHz)
Ground-based

<u>EBEX - E B Experiment</u>

Bolometers
most sensitive CMB detectors

High frequency (150, 250, 420 GHz)
Balloon-Borne

EBEx - E and B EXperiment

Brown
- Greg Tucker
- John Macaluso
- Jerry Vinokurov
- Andrei Korotkov

Caltech
- Tomotake Matsumura

Cardiff
- Peter Ade
- Enzo Pascale

Columbia University
- Amber Miller
- Will Grainger
- Britt Reichborn-Kjennerud

APC, Paris
- Radek Stompor

Harvard
- Matias Zaldarriaga

Imperial College London
- Andrew Jaffe

IAS
- Nicolas Ponthieu

SISSA/ISAS
- Carlo Baccigalupi
- Sam Leach
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McGill
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Oxford
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UC Berkeley, LBNL
- Adrian Lee
- Xiaofan Meng

UC San Diego
- Tom Renbarger

U. of Minnesota
- Shaul Hanany
- Asad Aboobaker
- Clayton Hogen-Chin
- Hannes Hubmayr
- Terry Jones
- Jeff Klein
- Michael Milligan
- Kyle Zilic
- Dan Polsgrove
- Ilan Sagiv

Weizmann Institute of Science
- Lorne Levinson

Science--CMB Polarization

- Detect the primordial B-mode signal if its strength is 1/5th the current upper limit (r=T/S=0.1) or reduce the upper limit by a factor of 15.

- Measure the E-mode polarization to unprecedented precision, improving our constraints on cosmological parameters.

- Detect the lensing of the CMB; if the amplitude of the signal is as expected, EBEX will constrain the lensing amplitude within 4%.

- Characterize foregrounds in our frequency bands (150, 250, 420 GHz)

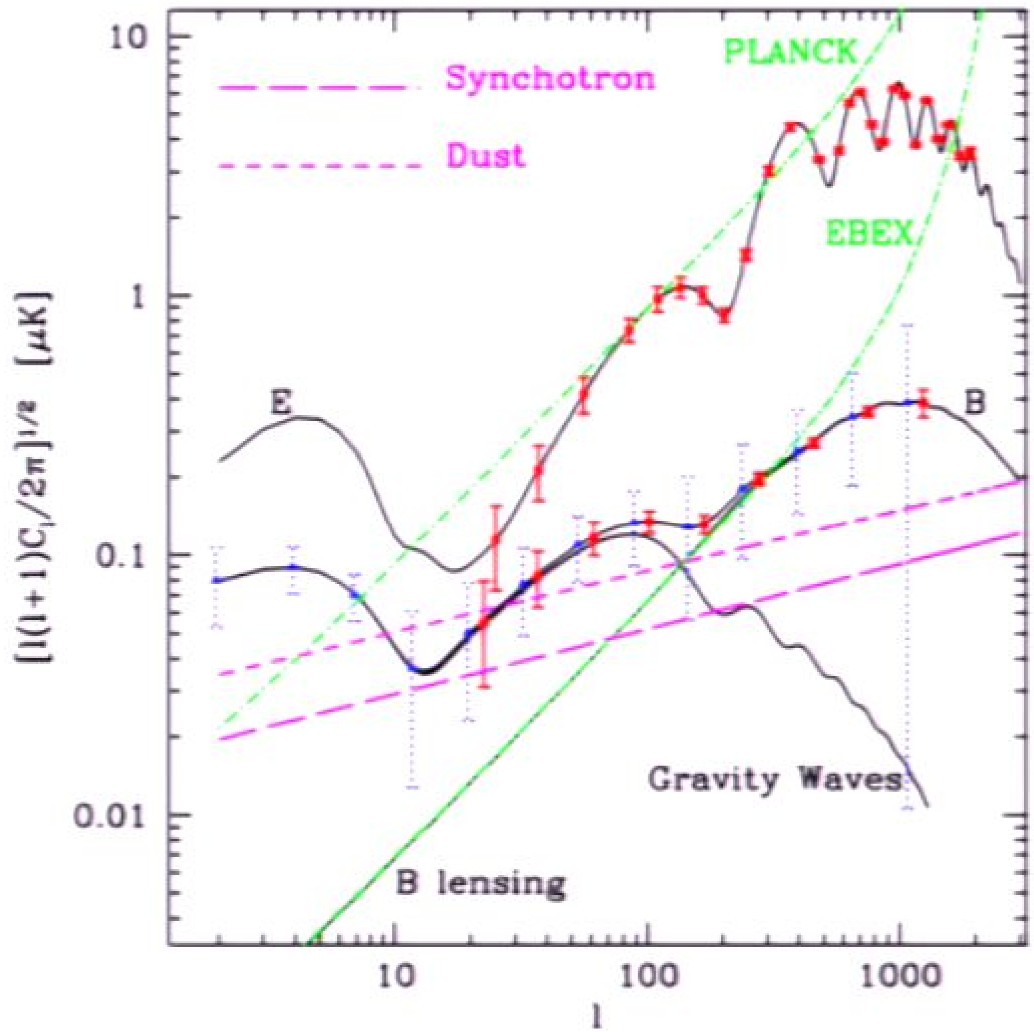


Figure Courtesy of Matis Zaldarriaga

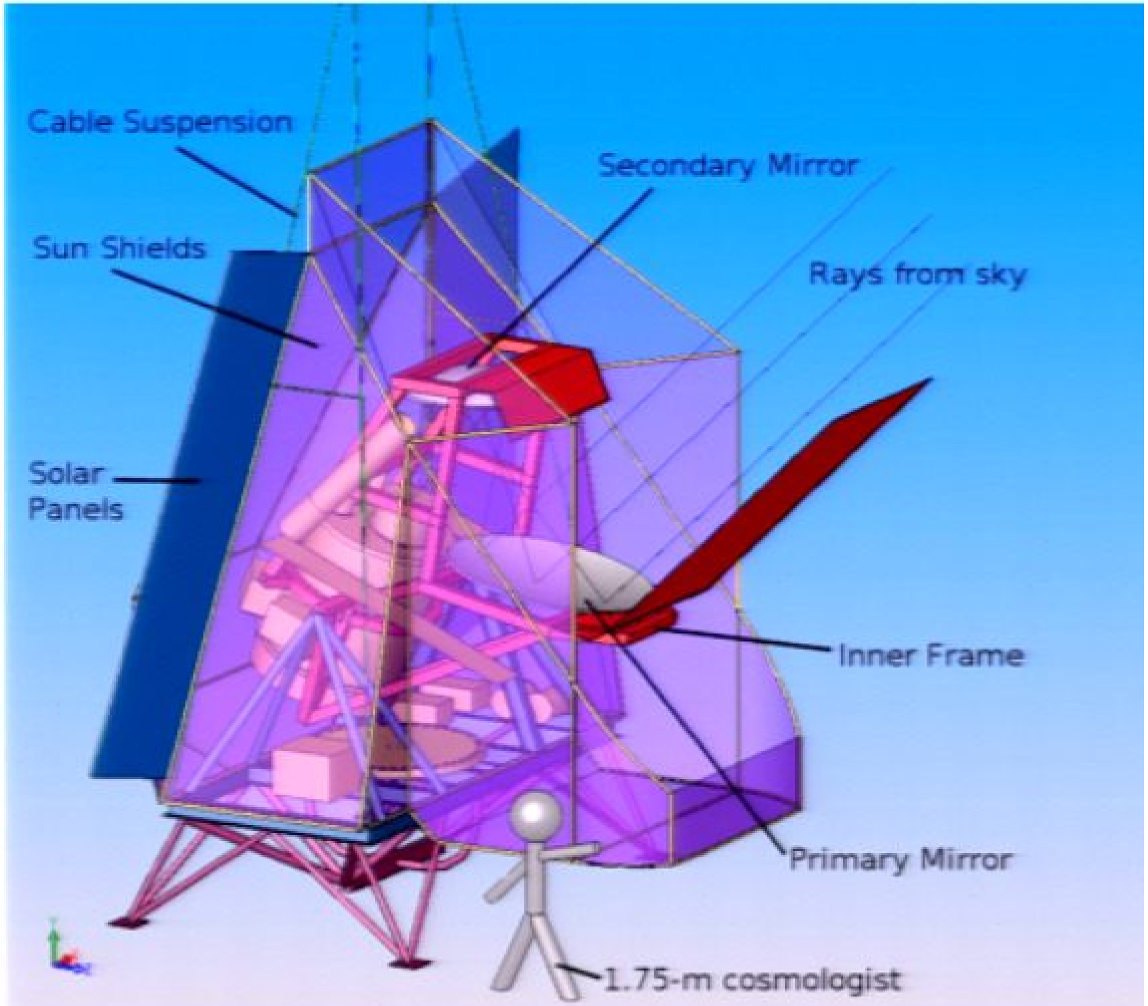
Red=1s detection: EBEX after 14-day flight

Blue= 1s detection: PLANK after 1 year

Solid=Theoretical LCDM with r=T/S=0.1

Overview

- Long duration balloon borne
- Long Duration (10-14 day science flight in Antarctica planned for December 2009), Engineering flight upcoming summer 2008
- Up to 1476 bolometric TES
- 3 Frequency bands: 150, 250, 420 GHz
- Resolution: 8' at all frequencies
- Polarimetry with half wave plate
- BLAST (+BOOM,MAXIMA) balloon technologies



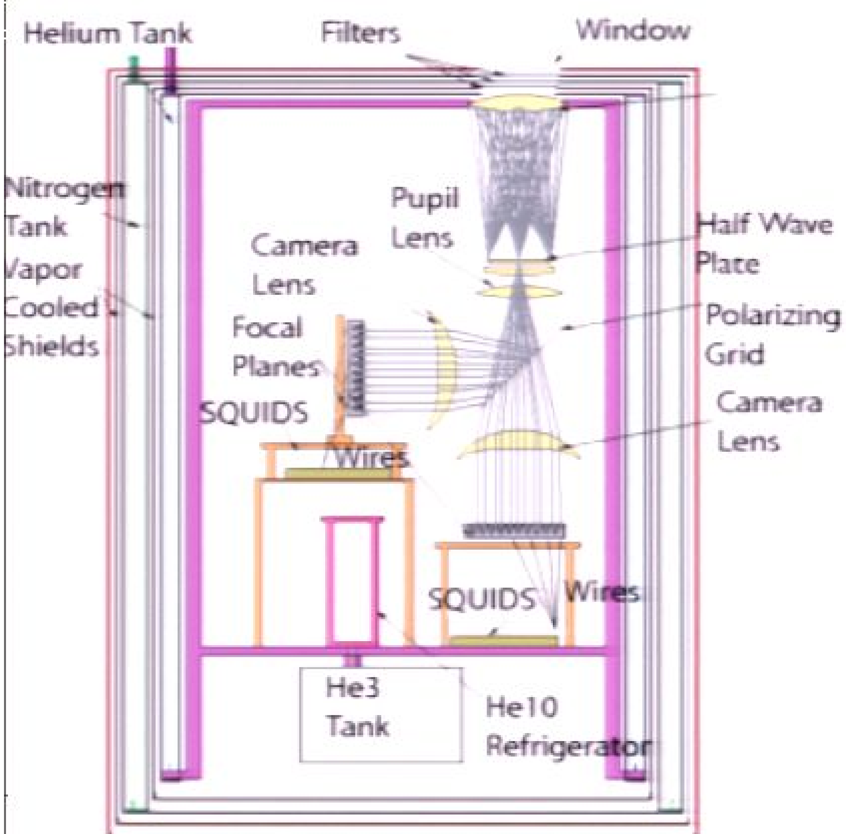
Gondola

- Gondola consists of
  - outer frame including GPS antennas, magnetometer and baffle mount and NSBF equipment attached from below
  - inner frame which holds optics, cryostat, some pointing sensors

Gondola at the Columbia Nevis facility being integrated with pointing sensors, motors, dummy cryostat and optics masses, etc.

Cold Optics

- Polarization is modulated by half wave plate
- Wire grid polarizer splits light into orthogonal polarizations and directs it to two focal planes

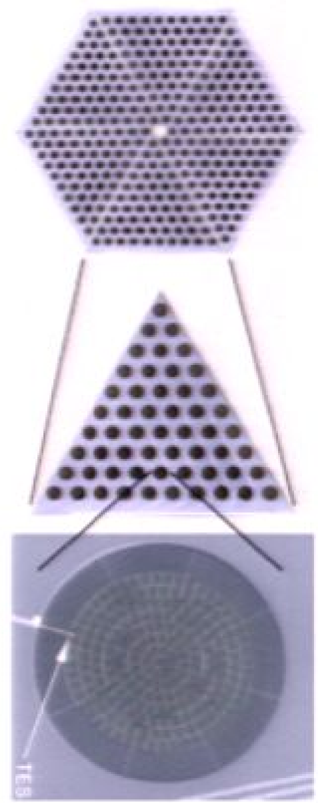


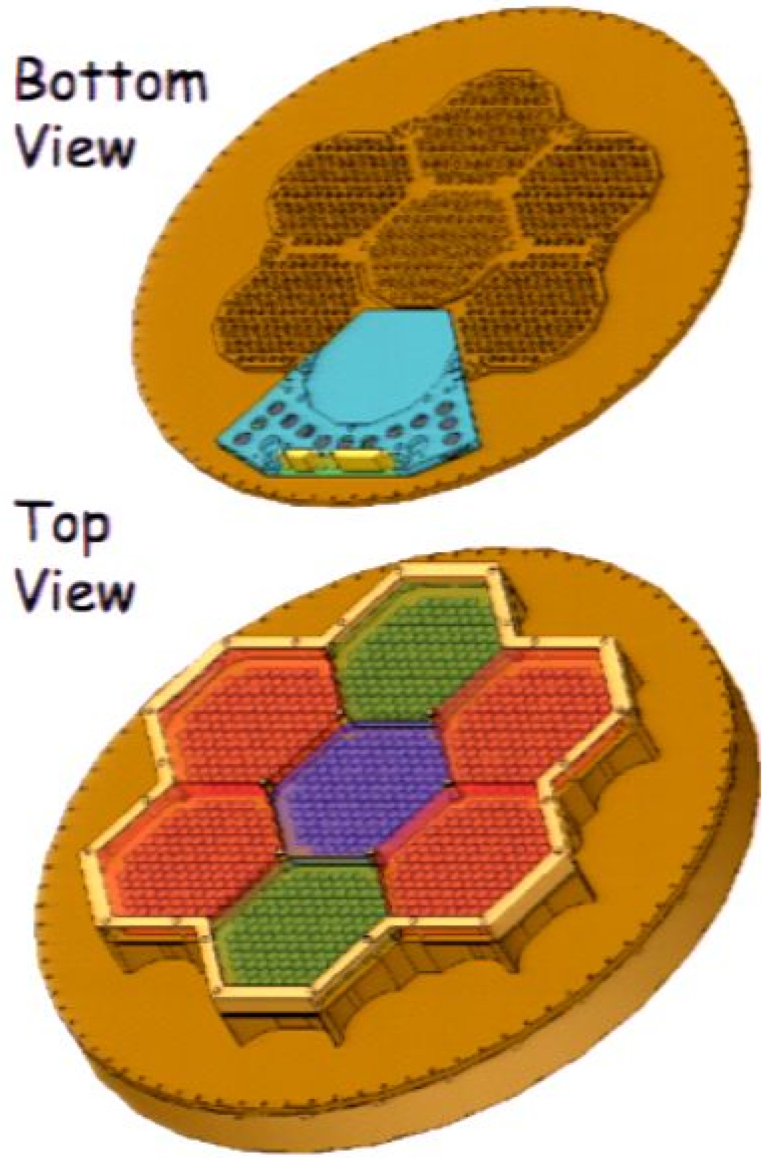
Schematic of the Cold Optics

Figure Courtesy of Kyle Zilic

Focal Plane

- Filters which break radiation into component frequencies
- An array of horns which feed the bolometric detectors
- Electronics behind the focal plane contain the electronics boards
- Detectors are Transition Edge sensitive (TES) bolometers (>1000 detectors total)
- AC bias each detector with unique kHz frequency
- Multiplex readout of 12-16 channels (essential to limit power consumption and heat generation--also limits # of wires into cryostat)
- 1 SQUID reads out the signal from each group of bolometers





TES Bolometers: Adrian Lee

Figures Courtesy of Clayton Hogen-Chin

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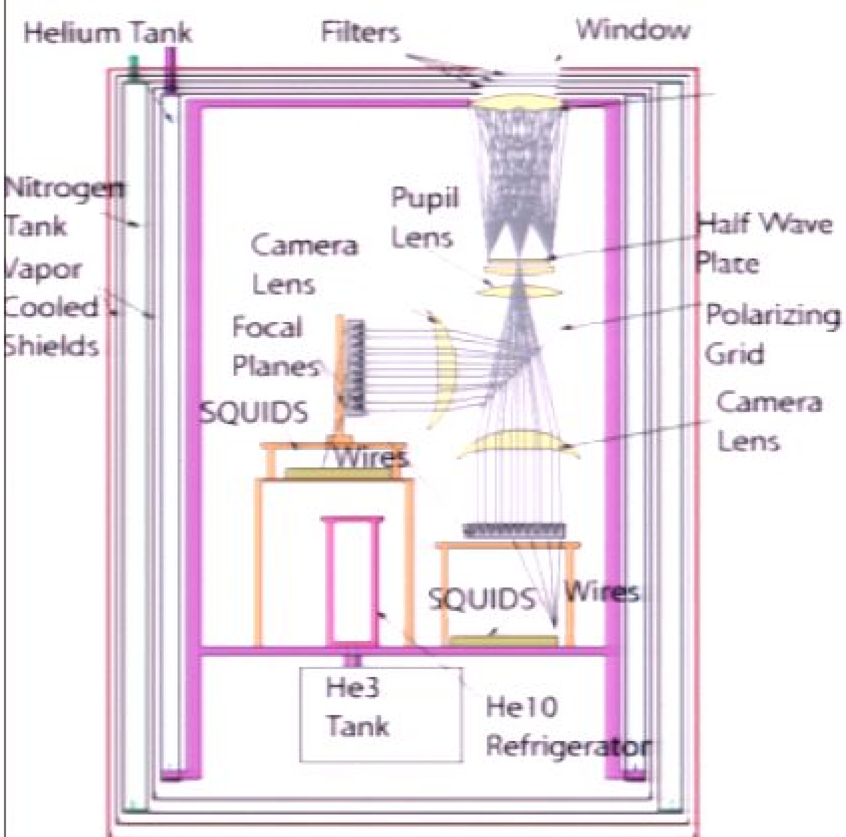

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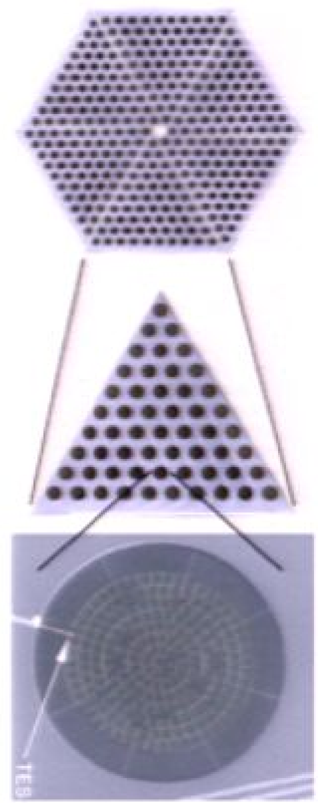

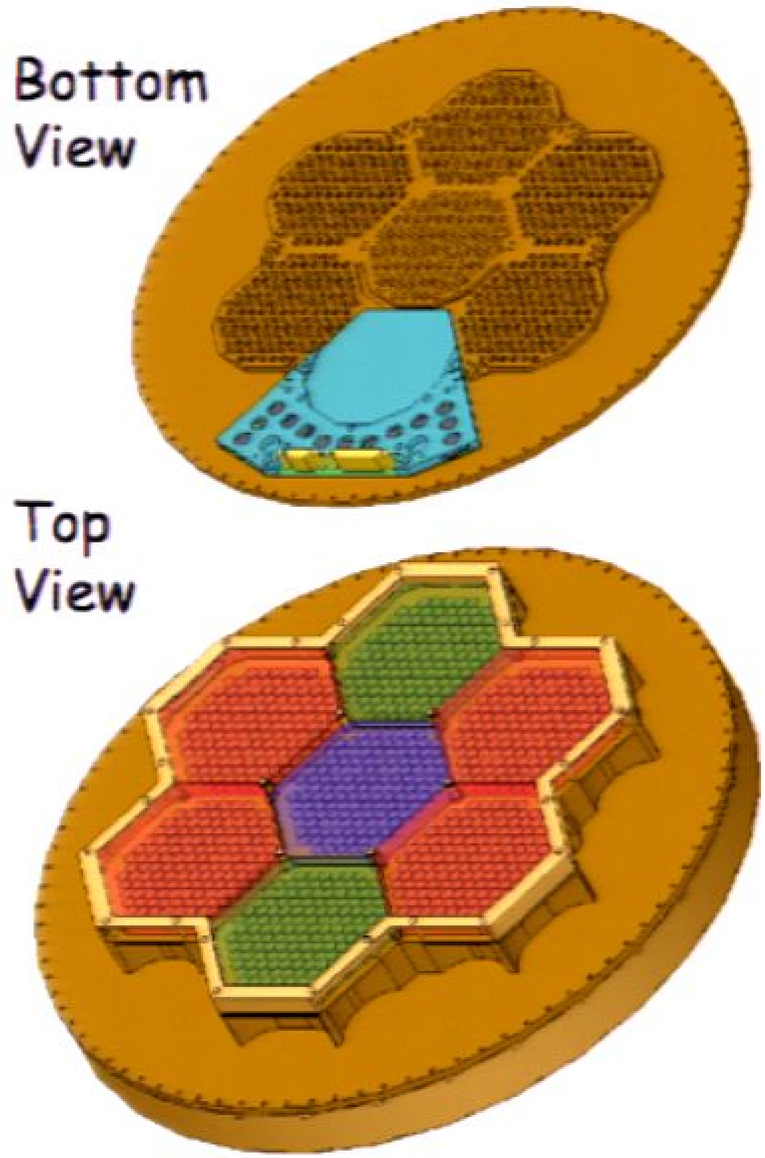

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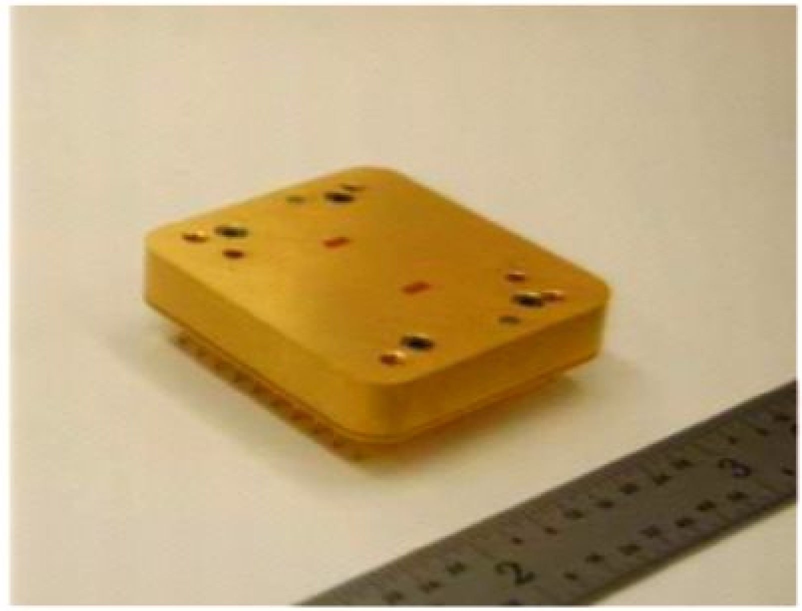
QU Imaging ExperimenT (QUIET)

The Collaboration

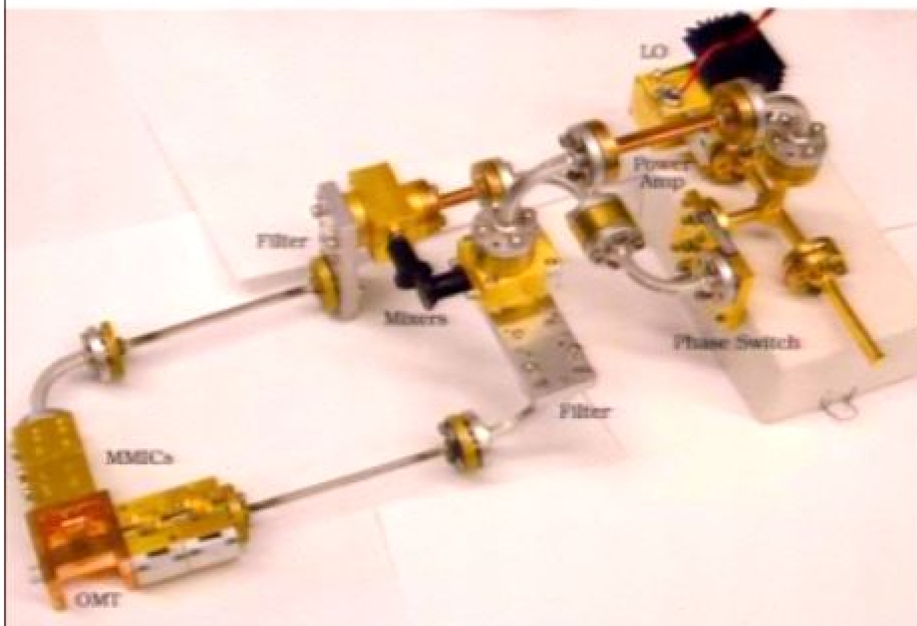
- Columbia
- Chicago
- Caltech
- JPL
- Miami
- Princeton
- NASA Goddard
- Harvard
- Stanford
- Oxford
- MPI-Bonn
- Manchester

Breakthrough in MMIC Packaging makes QUIET possible

QUIET Polarimeter IC



CAPMAP 90 GHz Polarimeter



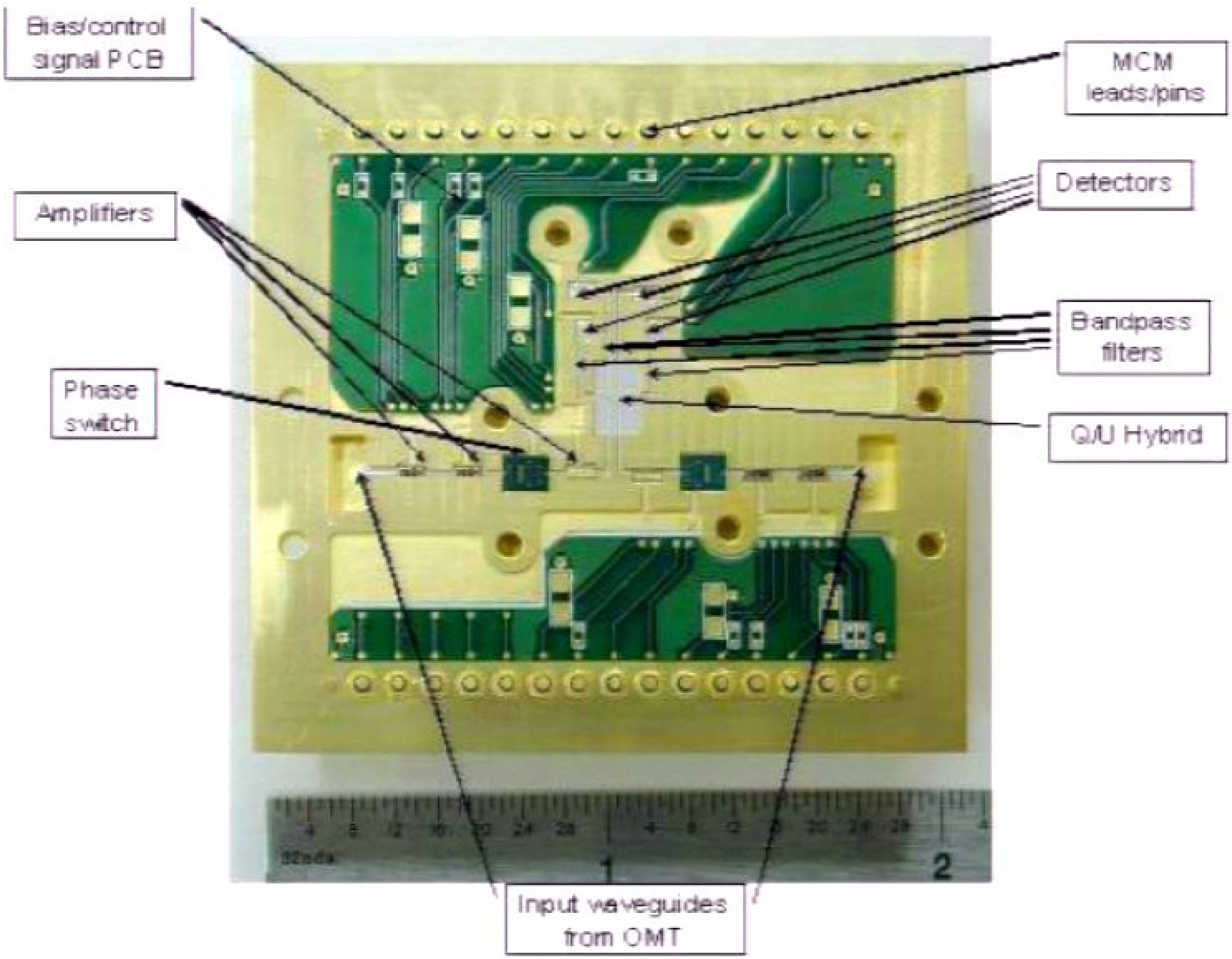
X-Y Polarizer

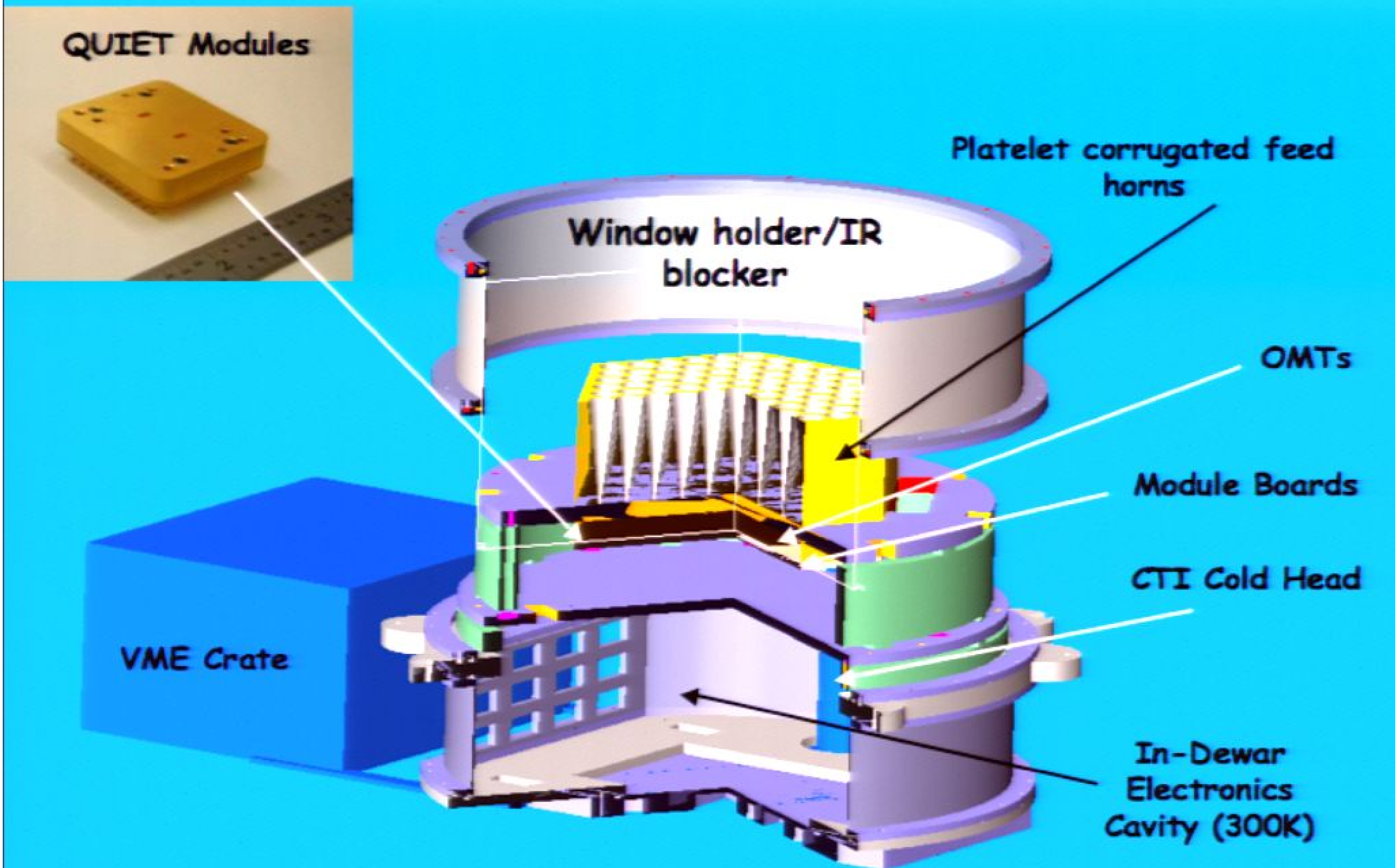
· $40K and 50 physicist-hours for checking, haracterizing, etc

<u>~ $500 and automated assembly and test, completely scalable</u>

Slide: Todd Gaier

Q-band QUIET module

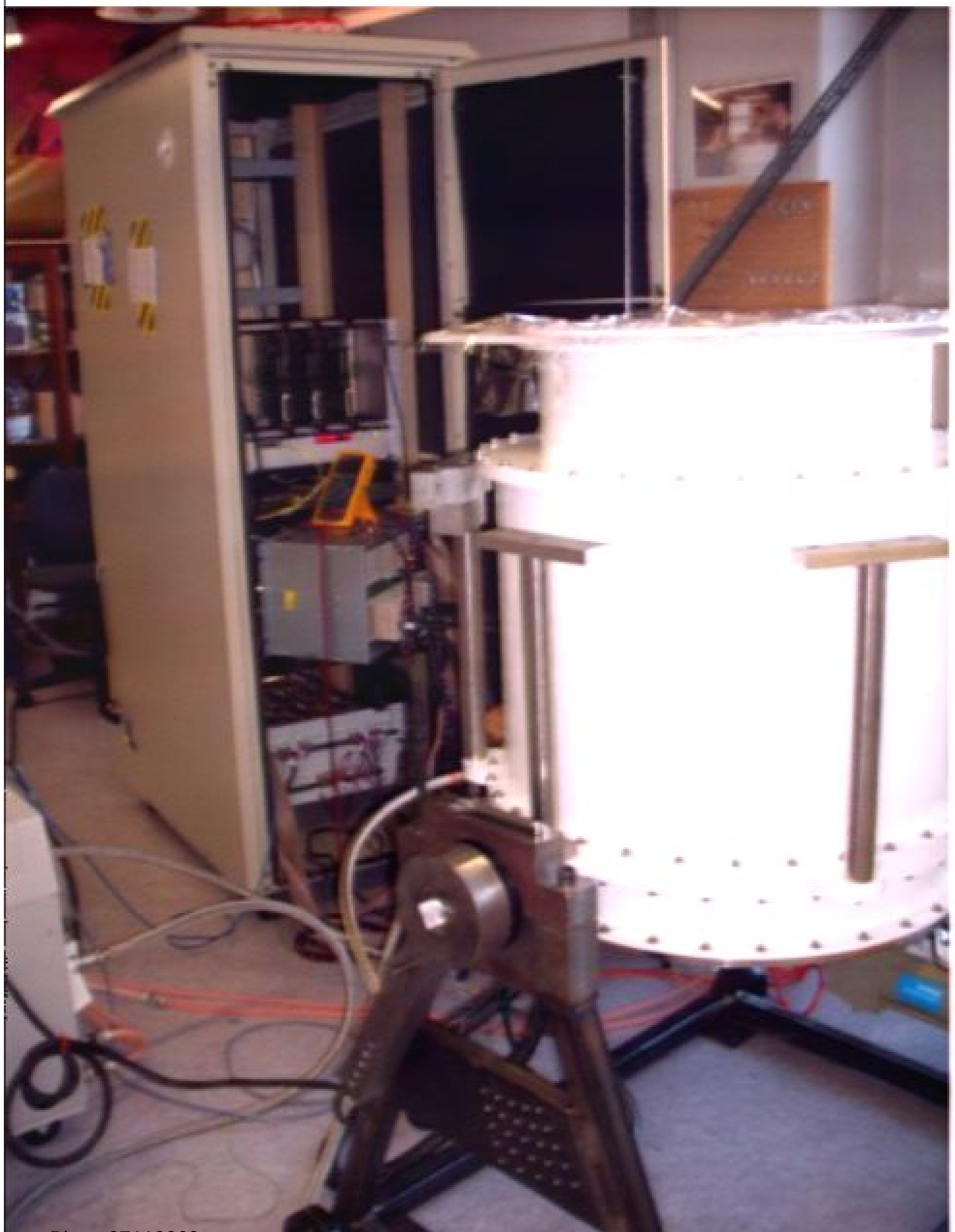


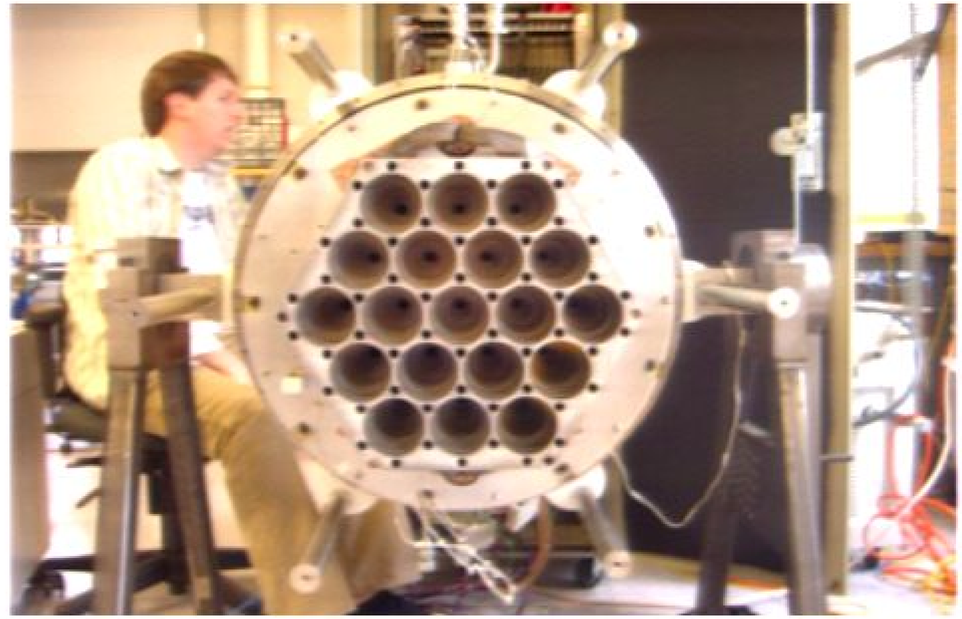


Drawings: Laura Newburgh

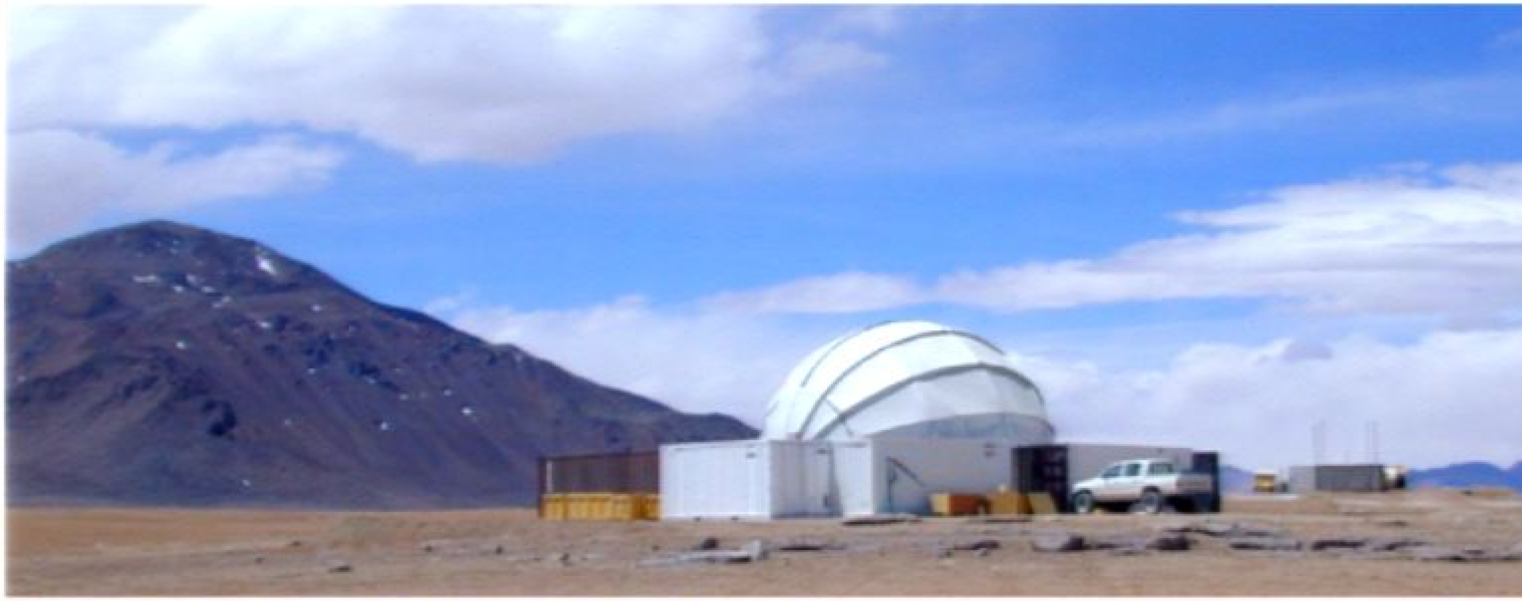
Columbia University

QUIET Components





HILE: the Atacama Plateau (operational support from SAINT)



Large Scale QUIET (Existing CBI Platform)

Small Scale QUIET (7 meter Bell Labs telescope to move to Chile)

Ground-screen: Oxford

- 5000 meter (~16,000 ft.) elevation
- atmospheric transmission 0.988
- 1.38 mm PWV
- At the current CBI site, Near the former Toco site (future ACT site), Near the future te for ALMA – site has sufficient space for Lucent 7m telescope
- Logistical support available from San Pedro de Atacama (only 50 minute drive)

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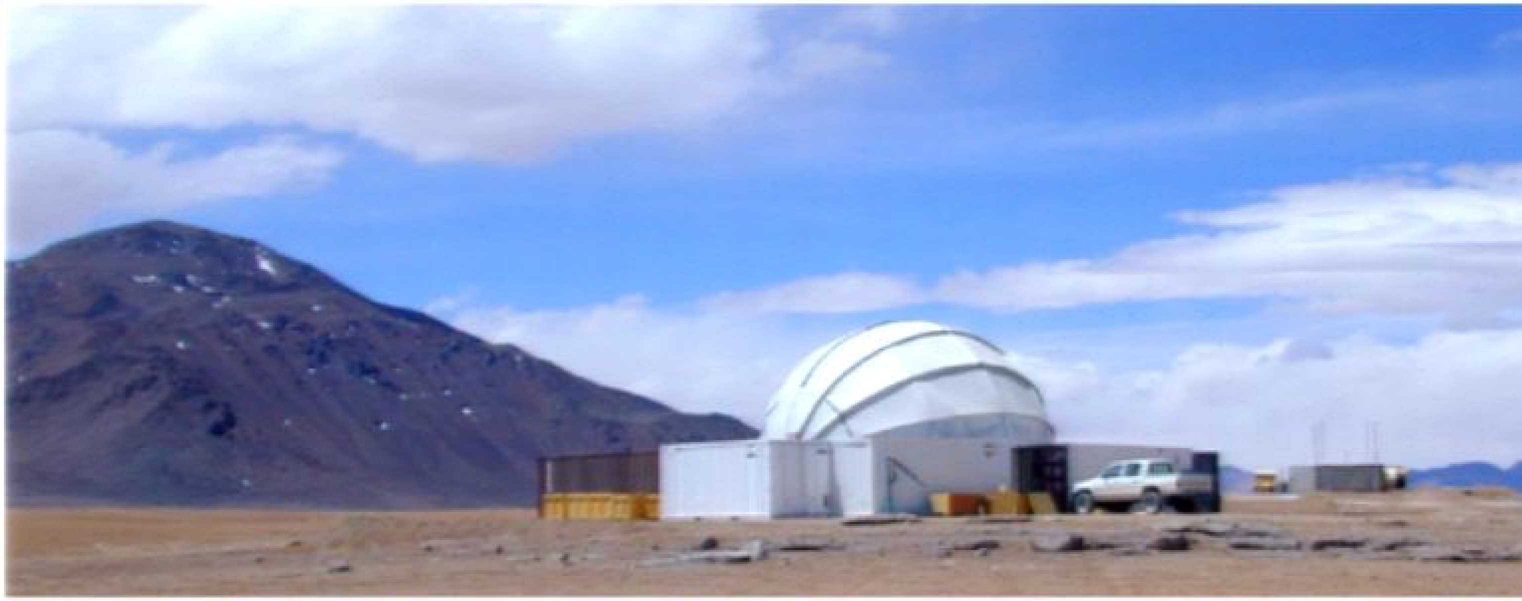

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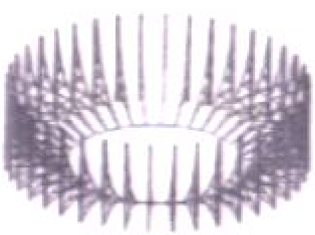

Ground-screen: Oxford

Also...

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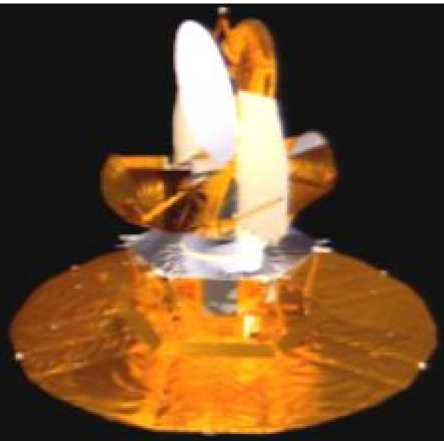
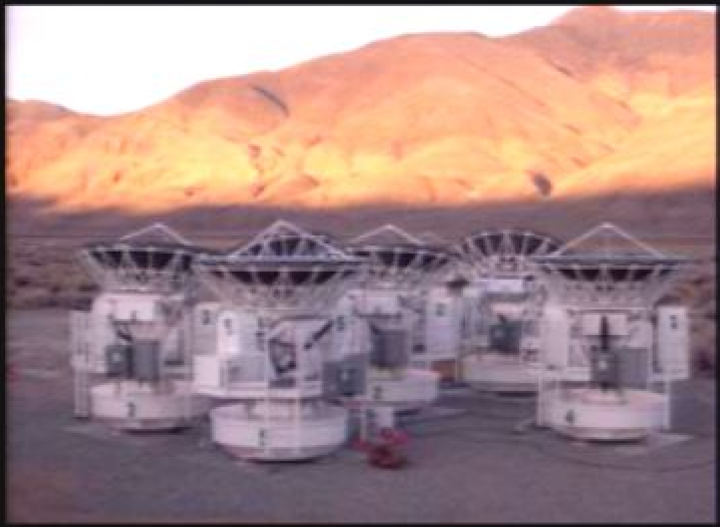
Conclusion



- CMB has come a long way
- CMB has a long way to come
- Lots of exciting things to look forward to in the future
  - Sunyaev-Zel'dovich Effect
    - trace structure formation history
    - learn about cluster physics
  - Polarization anisotropy
    - break degeneracies in measurements of cosmological parameters
    - learn about inflation
  - Also – small-scale temperature anisotropy (not discussed much here but exciting)



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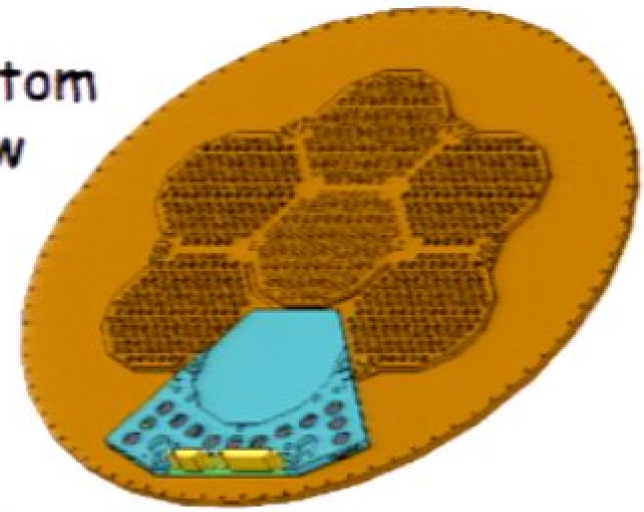
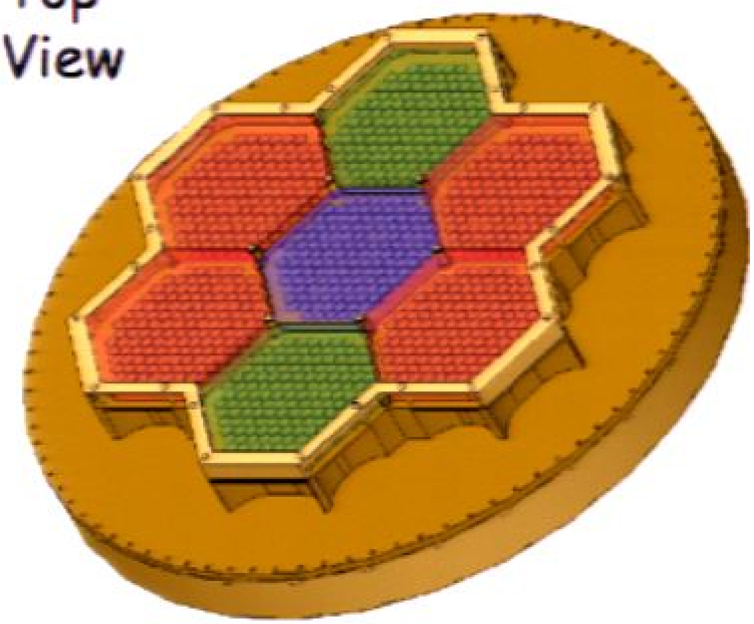
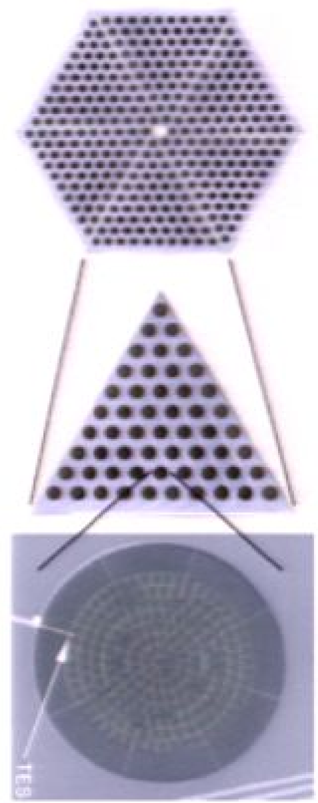
Bottom View



Top View





TES Bolometers: Adrian Lee

Figures Courtesy of Clayton Hogen-Chin

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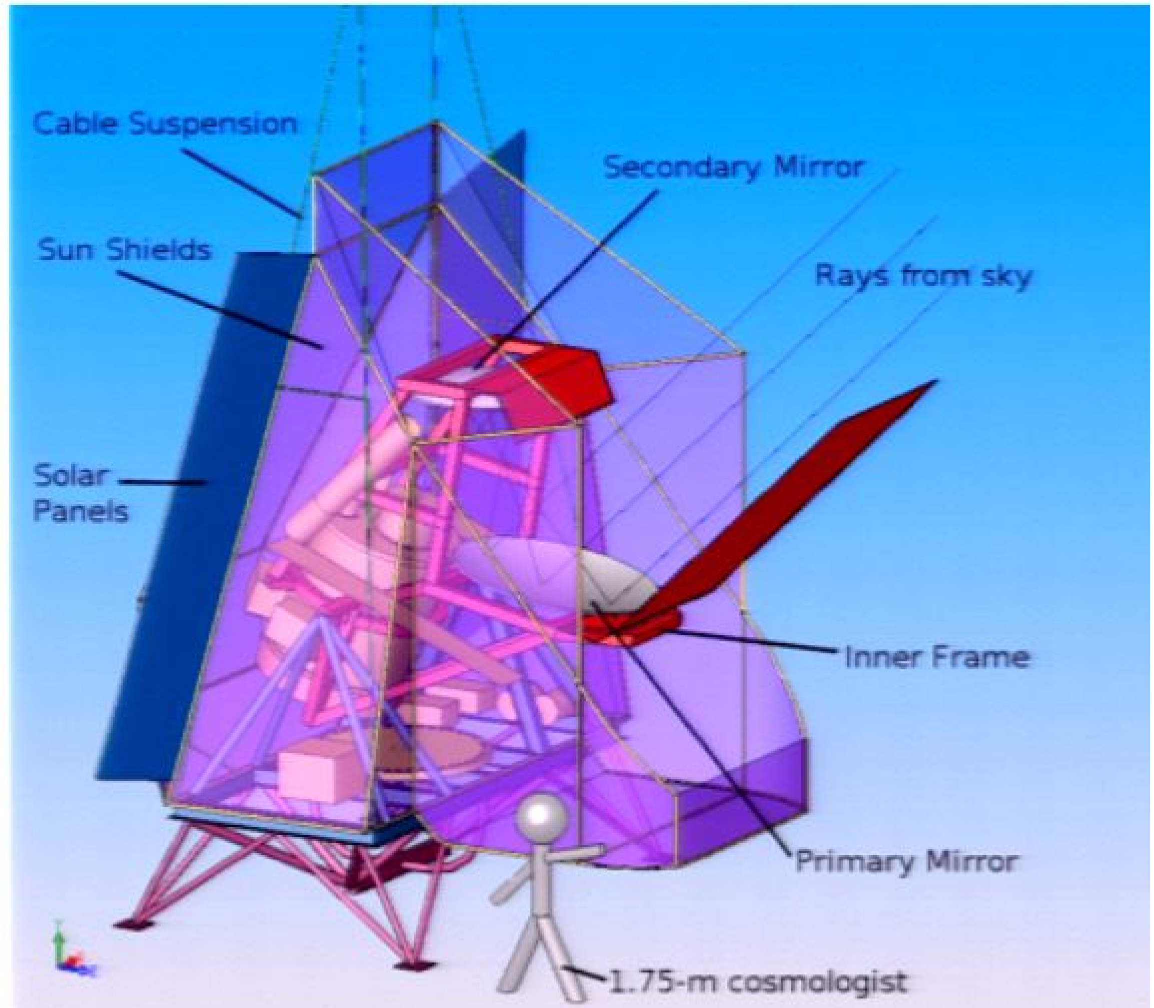

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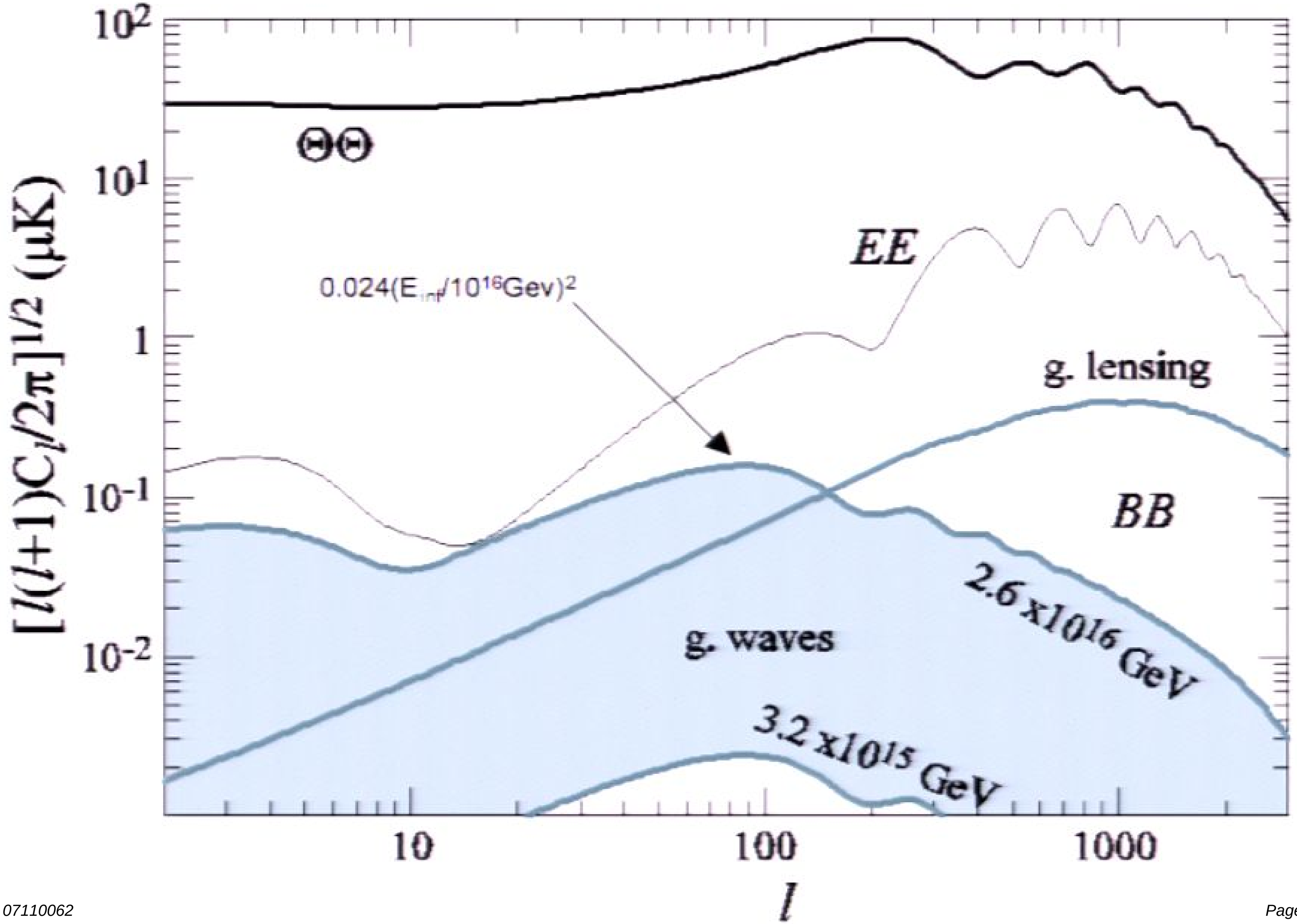
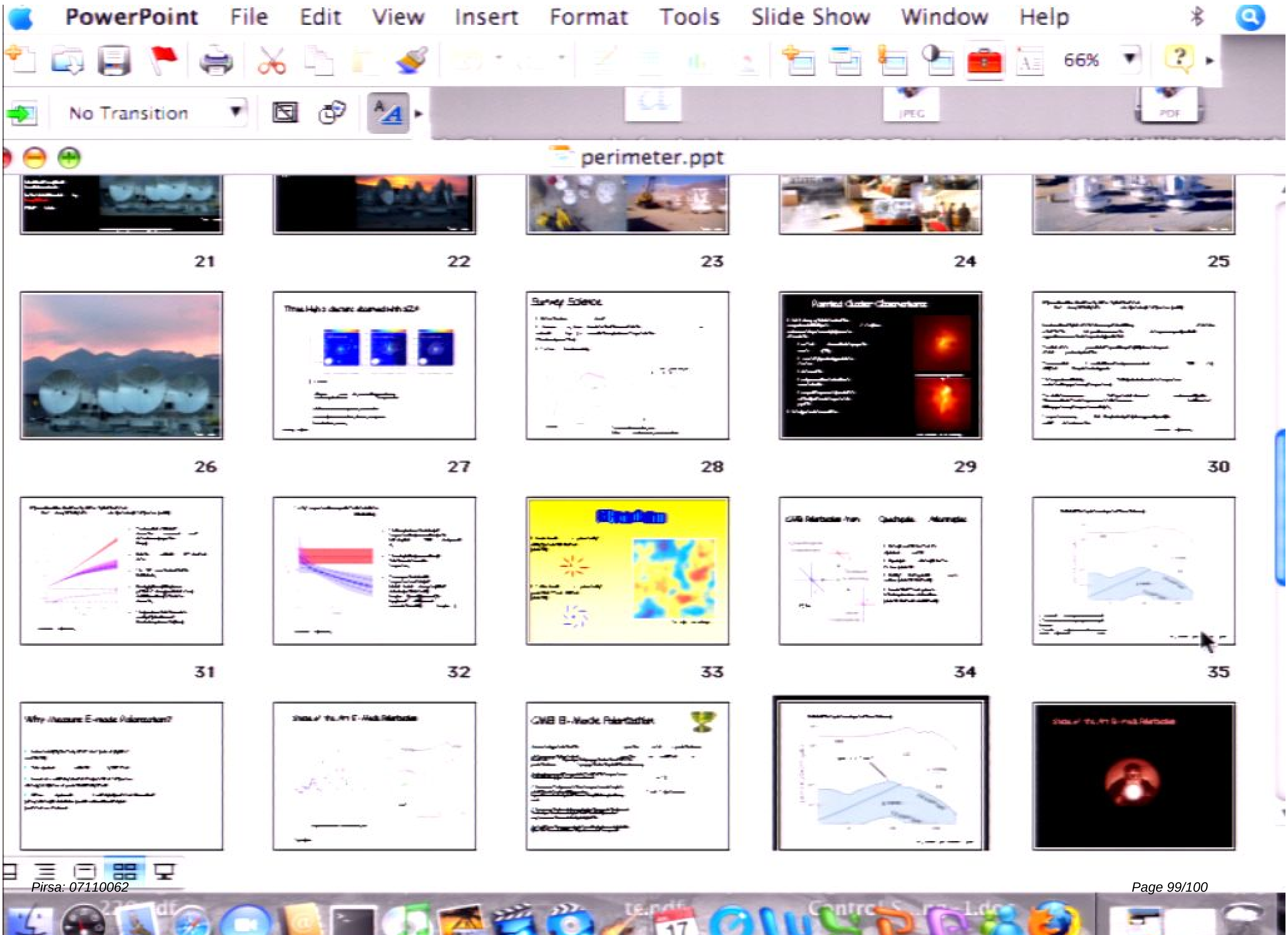
CMB Polarization Angular Power Spectra (theoretical curves)



Hu, Hedman, and Zaldarriaga, 2003


PowerPoint
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Survey Science
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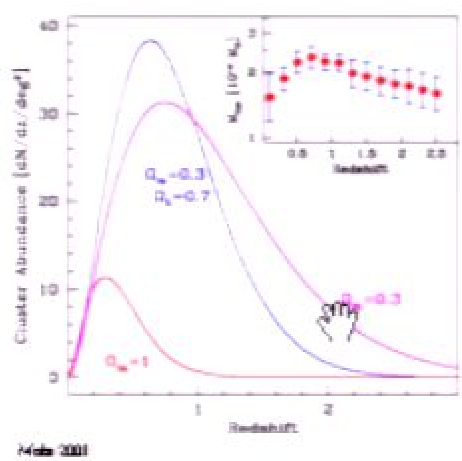
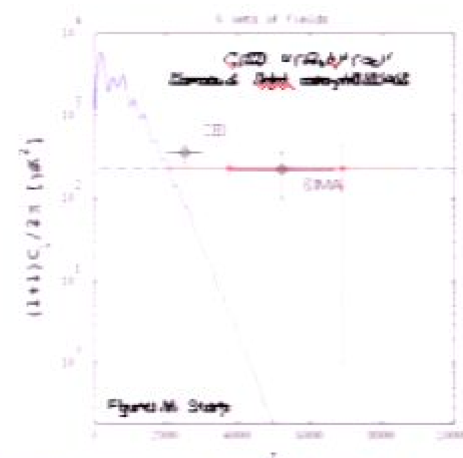
Survey Science

- Cluster Abundance dN/dz
- Measure σ_8 (rms linear fluctuations in the mass distribution on scales of 8 Mpc) - normalizes the amplitude of matter perturbations in the universe (present time)
- Tests of Non-Gaussianity





Predicted errors for 1/6 of data already taken
(simulation with realistic noise and array parameters - not real data)

Click to add notes

Slide 28 of 58