YITP: Perspectives in Theoretical Physics

- From Quark-Hadron Sciences to Unification of Theoretical Physics -

Congratulations to the Success & Continuation of the Program!

Have we understood the Universe?

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Golden Age of Cosmology

- Two Nobel Prizes in last 6 years
  - 2006 COBE: John Mather, George Smoot
  - 2011 Acceleration (SNe survey): Saul Perlmutter, Brian P. Schmidt, Adam G. Riess
- Establish the Standard Model of Cosmology
  - Inflation, Big Bang, Cold Dark Matter, Dark Energy
- Flood of observational data
- More to come from new observations/experiments

But, still we understand little about the Universe

Outline

- There was really Big Bang in the early Universe
- Success of Big Bang Cosmology
- What we have understood
- What should be understood
- Summary

Debate: Big Bang vs. Steady State Cosmology

Sir Fred Hoyle

George Gamow

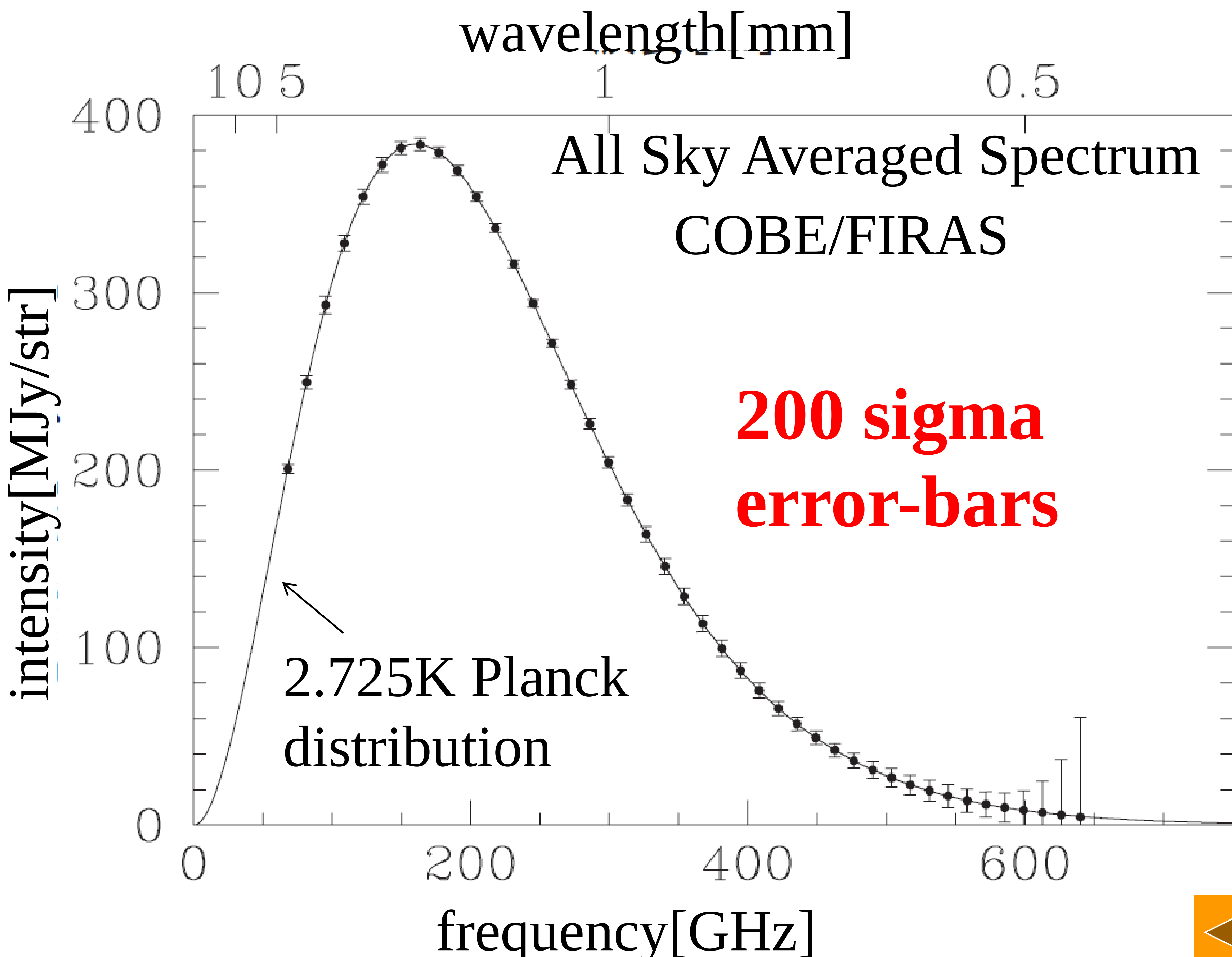
There was really Big Bang in the early Universe

- Evidence: Cosmic Microwave Background Radiation (CMB)
  - Almost complete Planck distribution with 2.725K
  - Very homogenous: inhomogeneity is 10^{-5} level
  - Adiabatic Cooling: $T \propto (1+z)$: z is redshift

John Mather

Arno Allan Penzias

Robert Woodrow Wilson



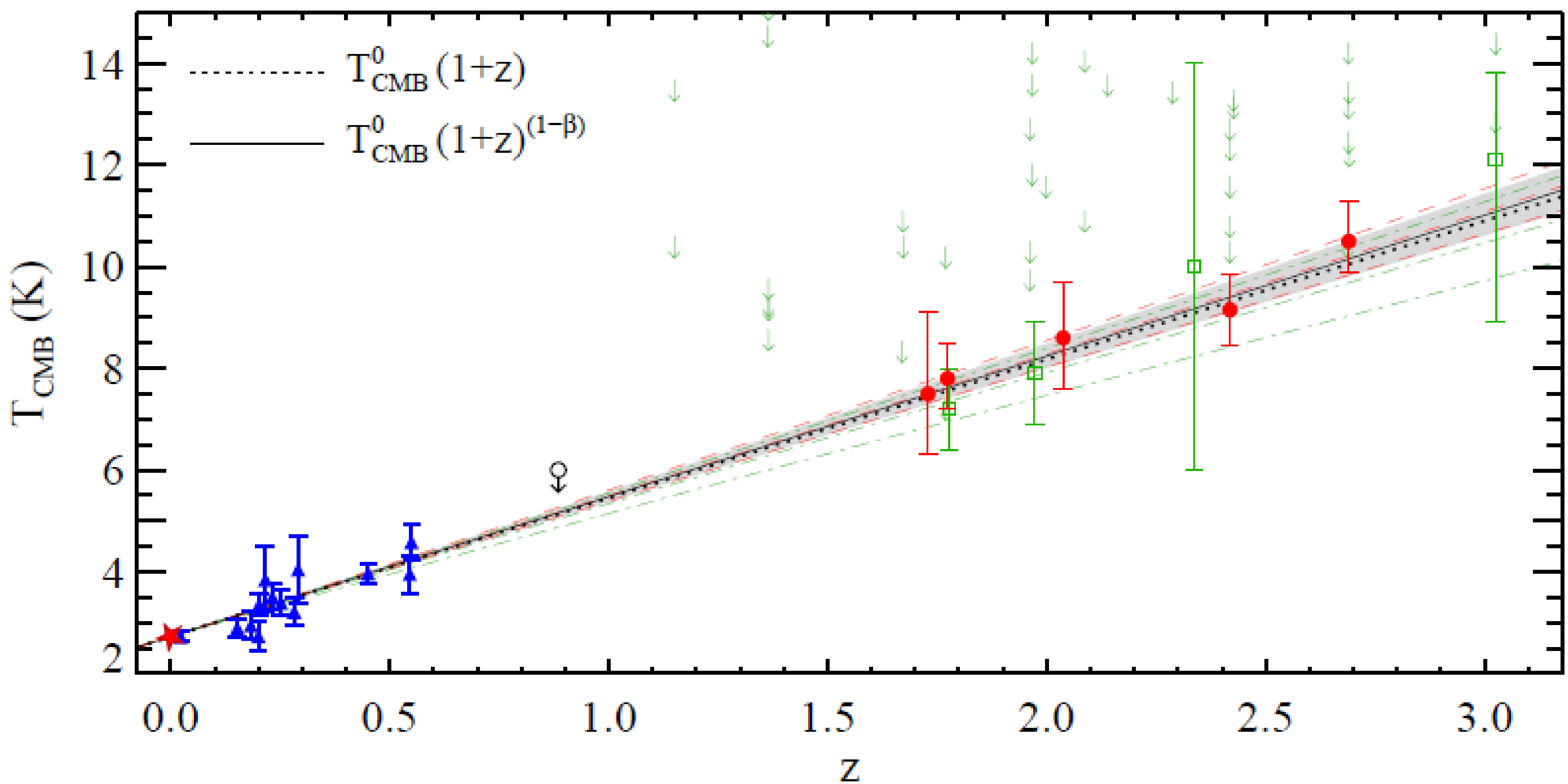
wavelength[mm]
10 5
1
0.5
400
300
200
100
0
All Sky Averaged Spectrum
COBE/FIRAS
200 sigma
error-bars
2.725K Planck
distribution
intensity[MJy/str]
0
200
400
600
frequency[GHz]

Adiabatic: Time Evolution of CMB Temperature

Measurements of T_{CMB} at high redshift from carbon monoxide excitation

Noterdaeme et al., A&Ap 2011

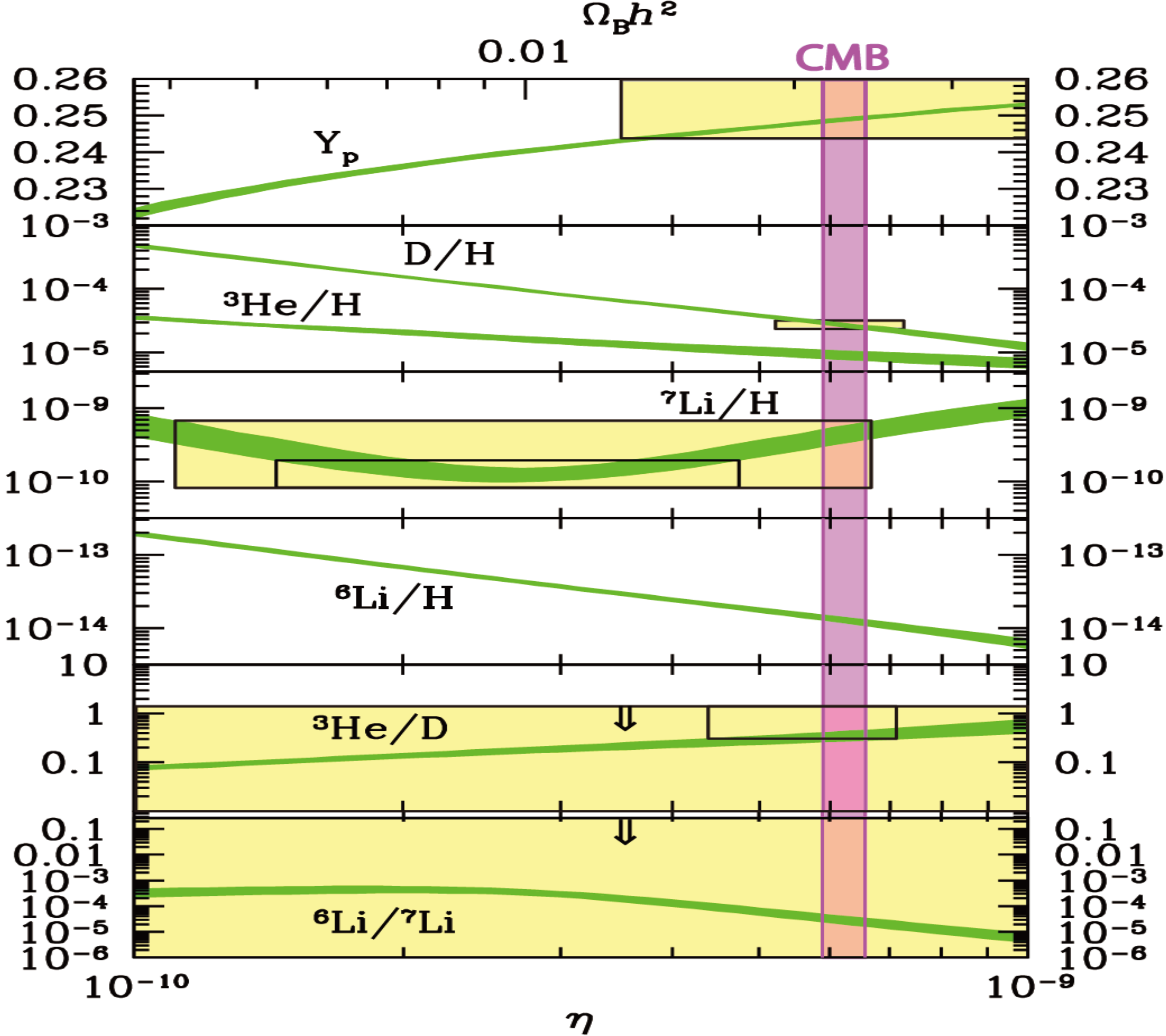
P. Noterdaeme et al.: The evolution of the Cosmic Microwave Background Temperature



$$T_{CMB}(z) = (2.725 \pm 0.002) \times (1+z)^{1-\beta}\ \mathrm{K}: \beta = -0.007 \pm 0.027$$

Success of Big Bang Cosmology

- Existence of CMB
- Primordial Big Bang Nucleosynthesis (BBN)
  - Good agreement between theory and observations of Light Elements, i.e., Helium, Deuterium, Lithium
  - Obtain baryon abundance



$\Omega_B h^2$
0.01
CMB
0.26
0.25
0.24
0.23
Y_p
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-13}
^{6}Li/H
10^{-14}
10
1
^{3}He/D
0.1
0.01
10^{-6}
^{6}Li/^{7}Li
10^{-10}
10^{-9}
η

Fraying of Big Bang?

- Too small amount of baryons to explain the matter in the Universe

⇨ **Non-Baryonic Dark Matter**

- 3 Classical Problems
  - Monopole (Moduli) Problem
  - Horizon Problem
  - Flatness Problem

⇨ **Inflation**

Inflation

- Solve three classical problems
- Generate (density) fluctuations
  - Seeds of structure in the Universe
  - Seeds of Temperature fluctuations of CMB
  - Predict almost scale free spectrum

Argument: Who should get the credit of invention of inflation

[30] A. Starobinsky, "A new type of isotropic cosmological models without singularity", Phys. Lett., **B91**, 99-102, (1980);
K. Sato, "First order phase transition of a vacuum and expansion of the Universe", MNRAS, **195**, 467-479, (1981);
A.H. Guth, "The inflationary universe: A possible solution to the horizon and flatness problems", Phys. Rev., **D23**, 347-356, (1980);
A.D. Linde, "A new inflationary scenario: A possible solution to the horizon, flatness, homogeneity, isotropy and primordial monopole problems", Phys. Lett., **B108**, 389-393, (1981);
A. Albrecht and P.J. Steinhardt, "Cosmology for Grand Unified Theories with radiatively induced symmetry breaking", Phys. Rev. Lett., **48**, 1220-1223, (1982),

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Starobinsky


Sato


Guth

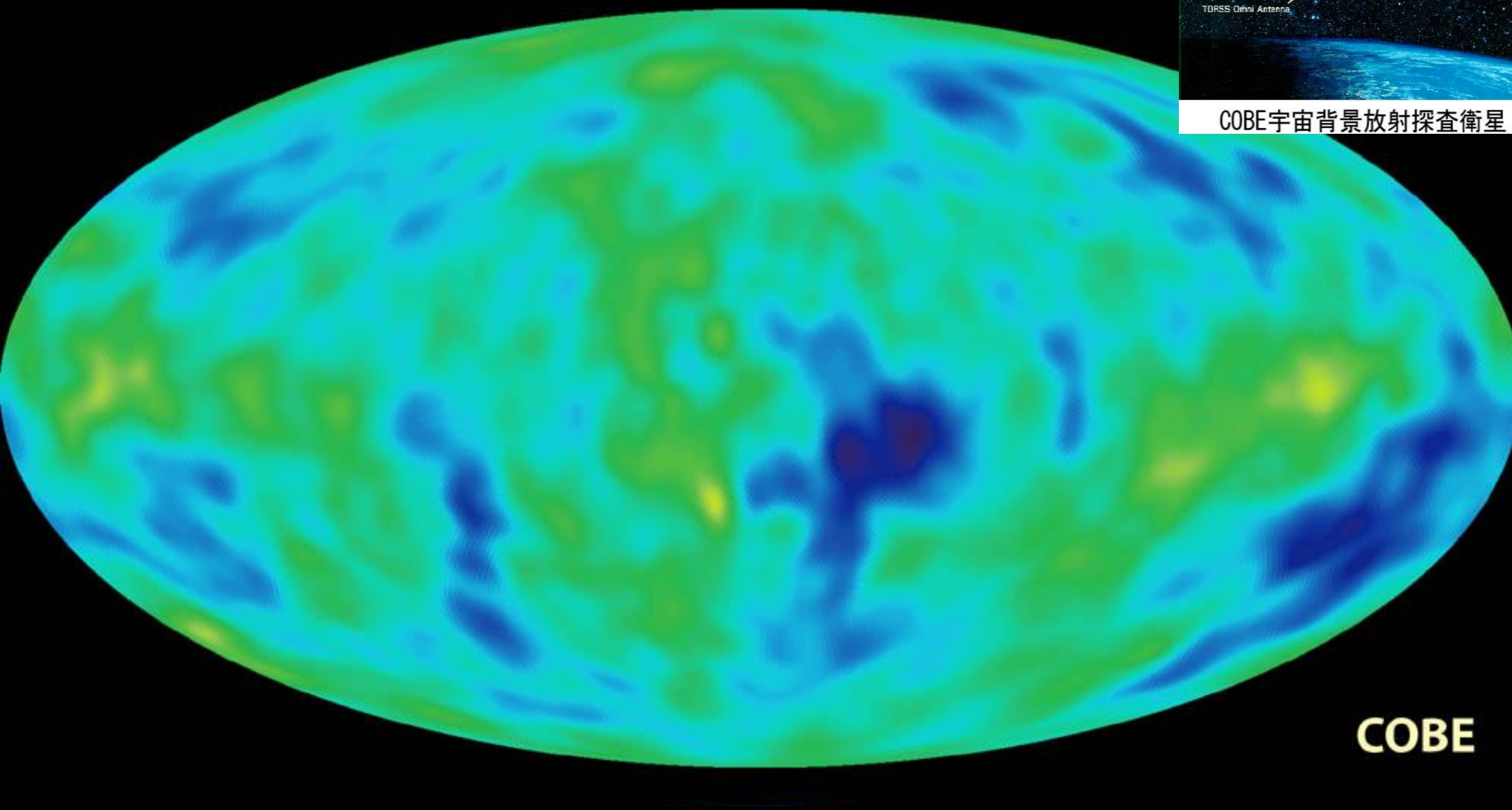

Linde

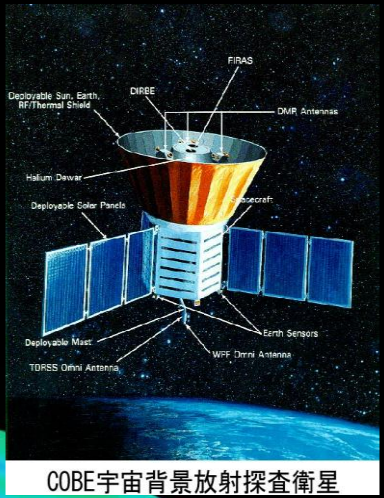

Albrecht

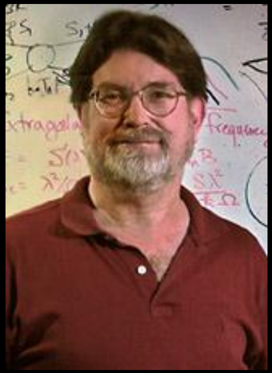

Steinhardt

COBE Satellite measure temperature Anisotropies

Almost Scale Free







George Smoot

Inflation

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  - Seeds of structure in the Universe
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Observations: almost scale free

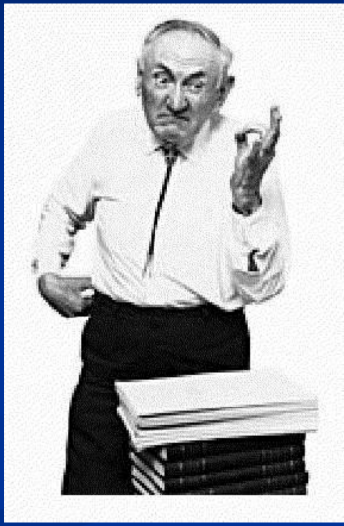
Cosmologists finally have

<u>Standard Model of Cosmology</u>

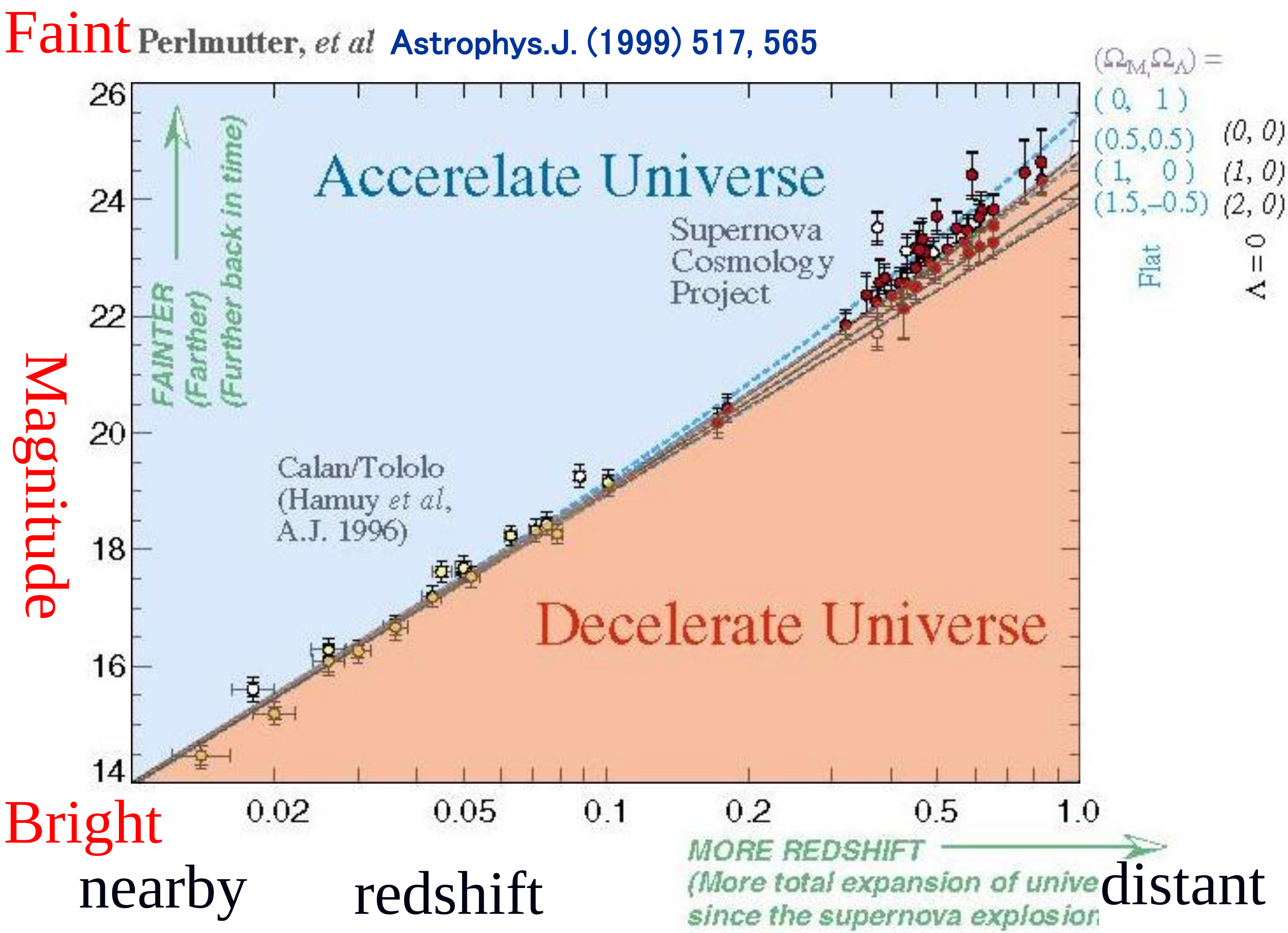
Big Bang + Inflation

Additional Ingredients to the Standard Model of Cosmology

- Dark Matter
  - In 1930's, Zwicky found it from the peculiar motion of member galaxies of a cluster of galaxies
  - Majority of matter in the universe is Dark
  - Non-Baryonic: From Big Bang Nucleosynthesis, and CMB temperature fluctuations



- Dark Energy
  - discovered in 1998, by Supernovae Survey


Faint
Perlmutter, et al Astrophys.J. (1999) 517, 565
Magnitude
Bright
nearby
redshift
distant
Accerelate Universe
Decelerate Universe
Supernova Cosmology Project
Calan/Tololo (Hamuy et al, A.J. 1996)
FAINTER (Farther) (Further back in time)
MORE REDSHIFT (More total expansion of unive since the supernova explosion
$(\Omega_M, \Omega_\Lambda)$ =
(0, 1)
(0.5,0.5)
(1, 0)
(1.5,–0.5)
(0, 0)
(1, 0)
(2, 0)
Flat
$\Lambda = 0$
26
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0

Nobel Prize in Physics 2011

Saul Perlmutter Brian P. Schmidt Adam G. Riess

What we have understood

- Contents of the Universe (cosmological parameters)

  Dark energy density Ω_Λ, Matter density Ω_M , Curvature Ω_K, Hubble parameter H_0 (h), Baryon density Ω_B : $\Omega_K = 1 - \Omega_\Lambda - \Omega_M$
  - Temperature Fluctuations of CMB
    - COBE/WMAP
    - Precise measurement of Matter, Baryon and Curvature (but they are degenerate, need additional probe)
  - Supernovae Survey
    - Measurement of dark energy
  - Gravitational lensing
    - Strong lensing: Proof of dark matter
    - Weak lensing: Tracer of large scale structure

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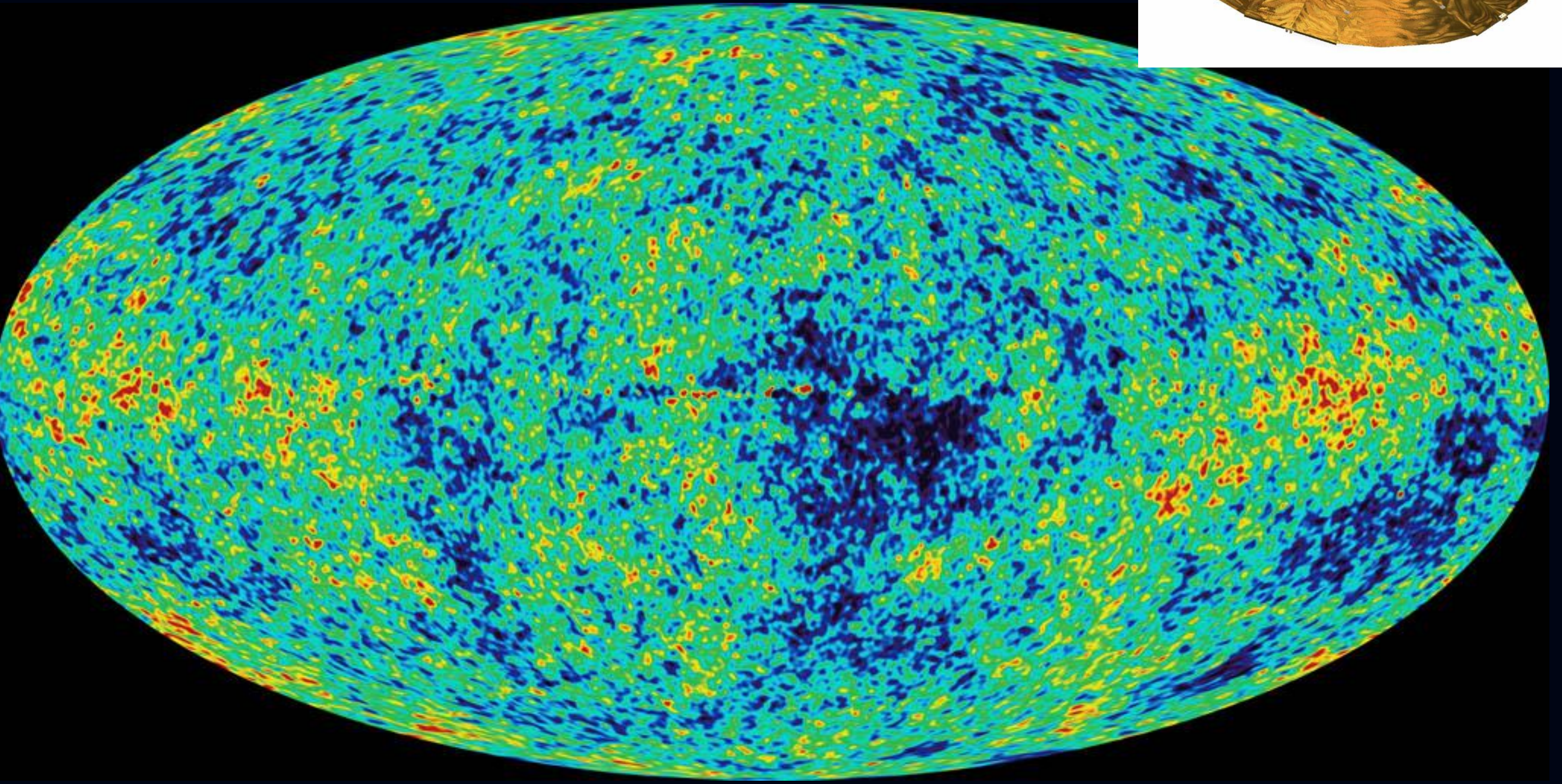
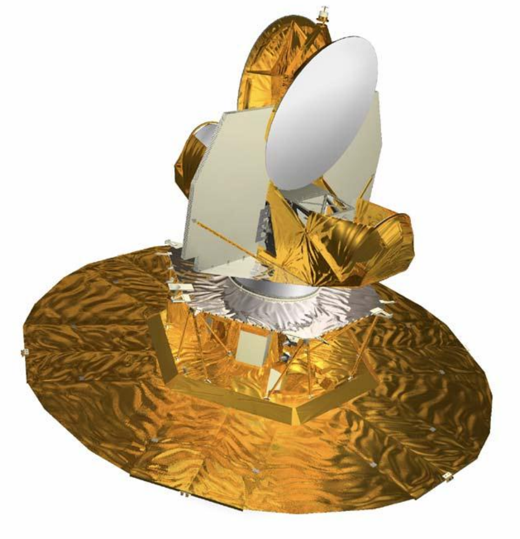
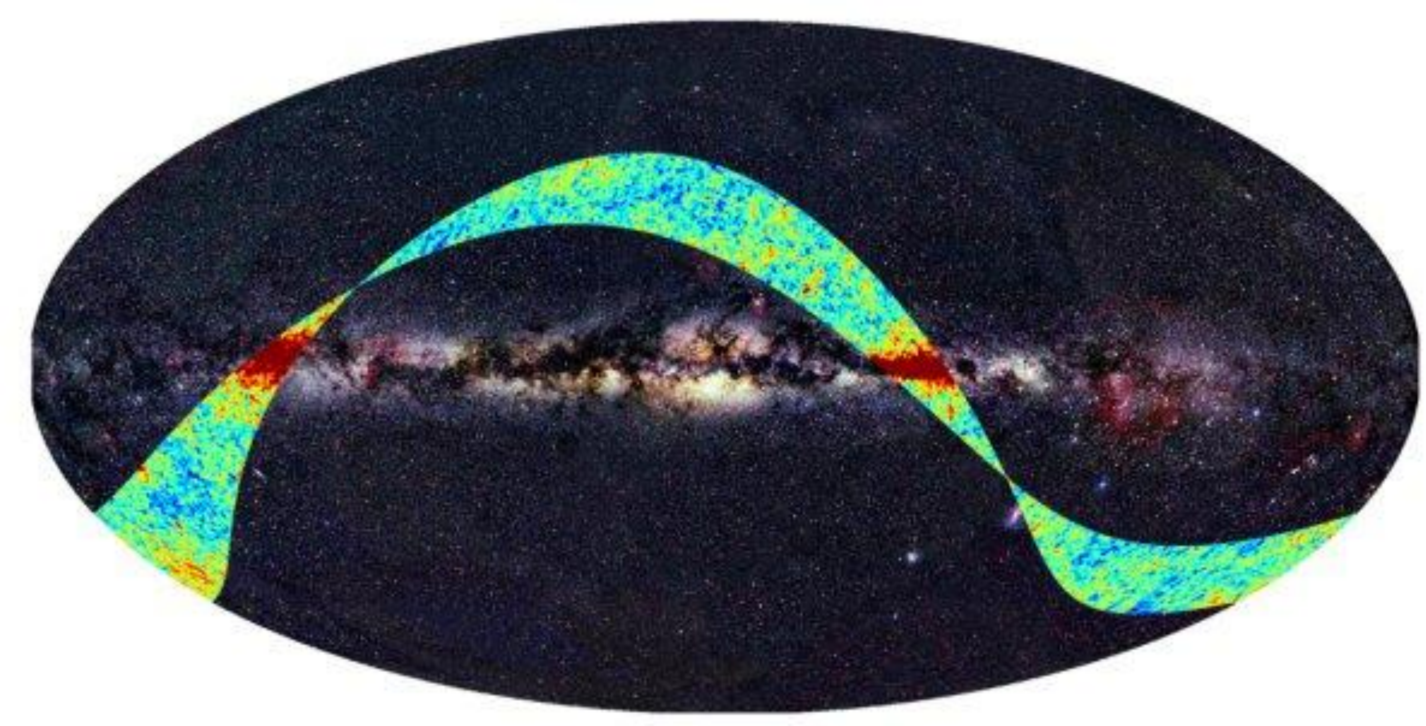
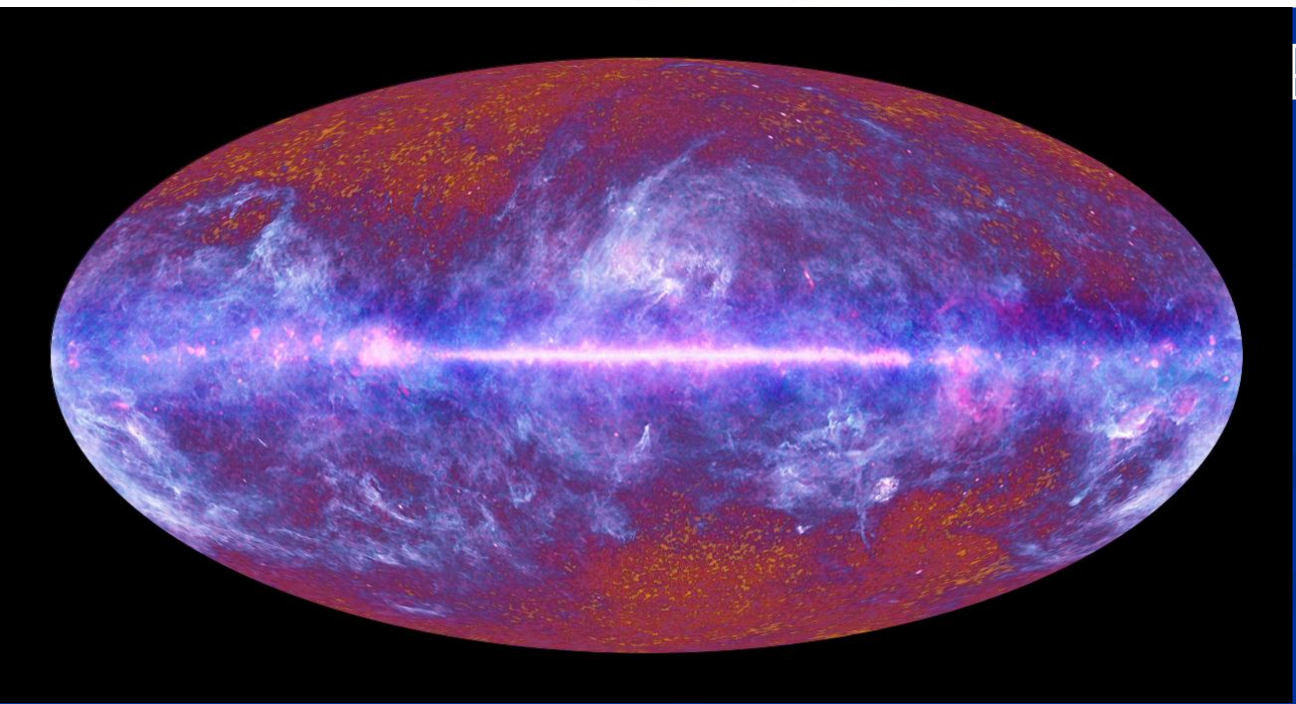
WMAP

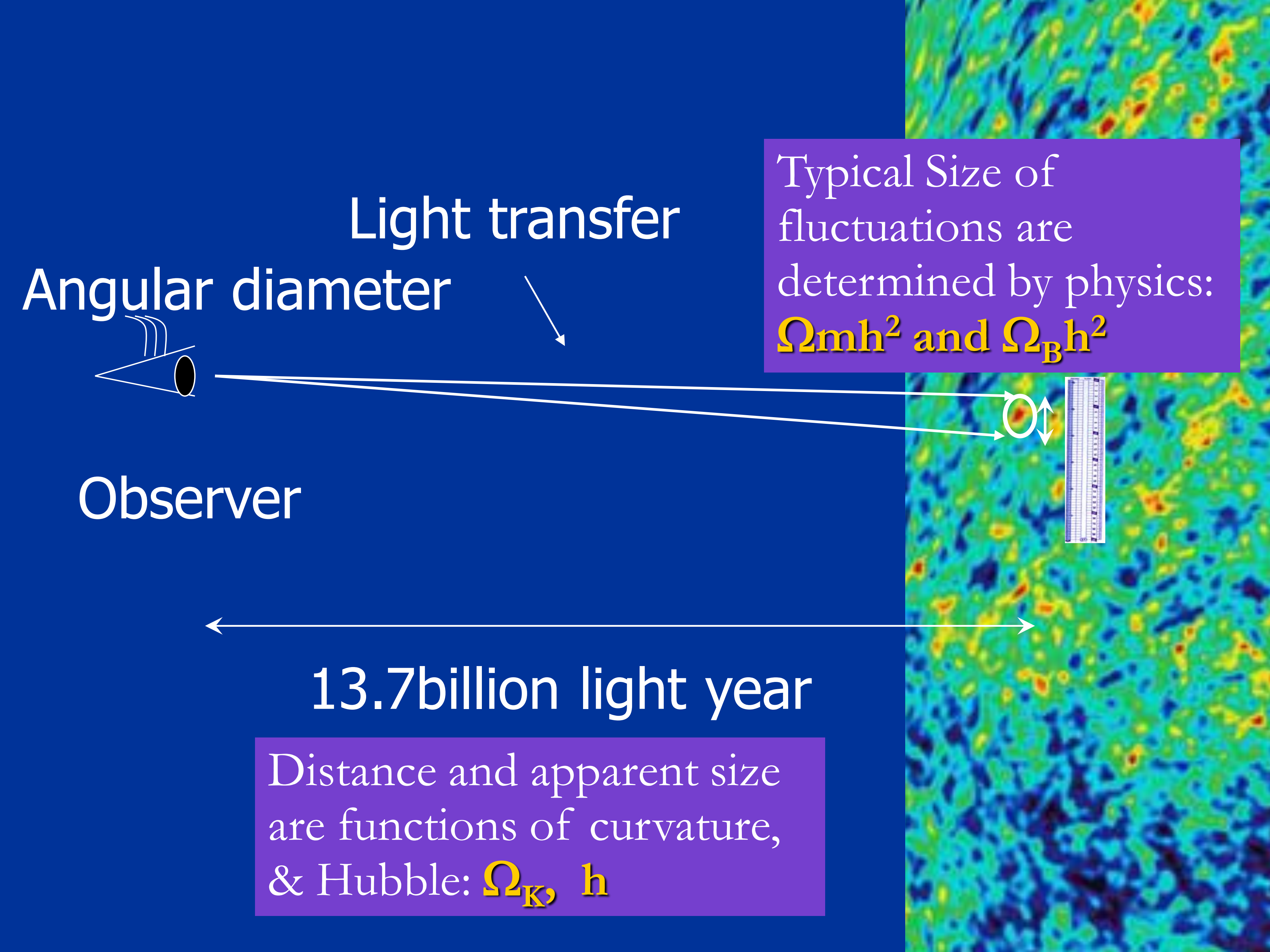


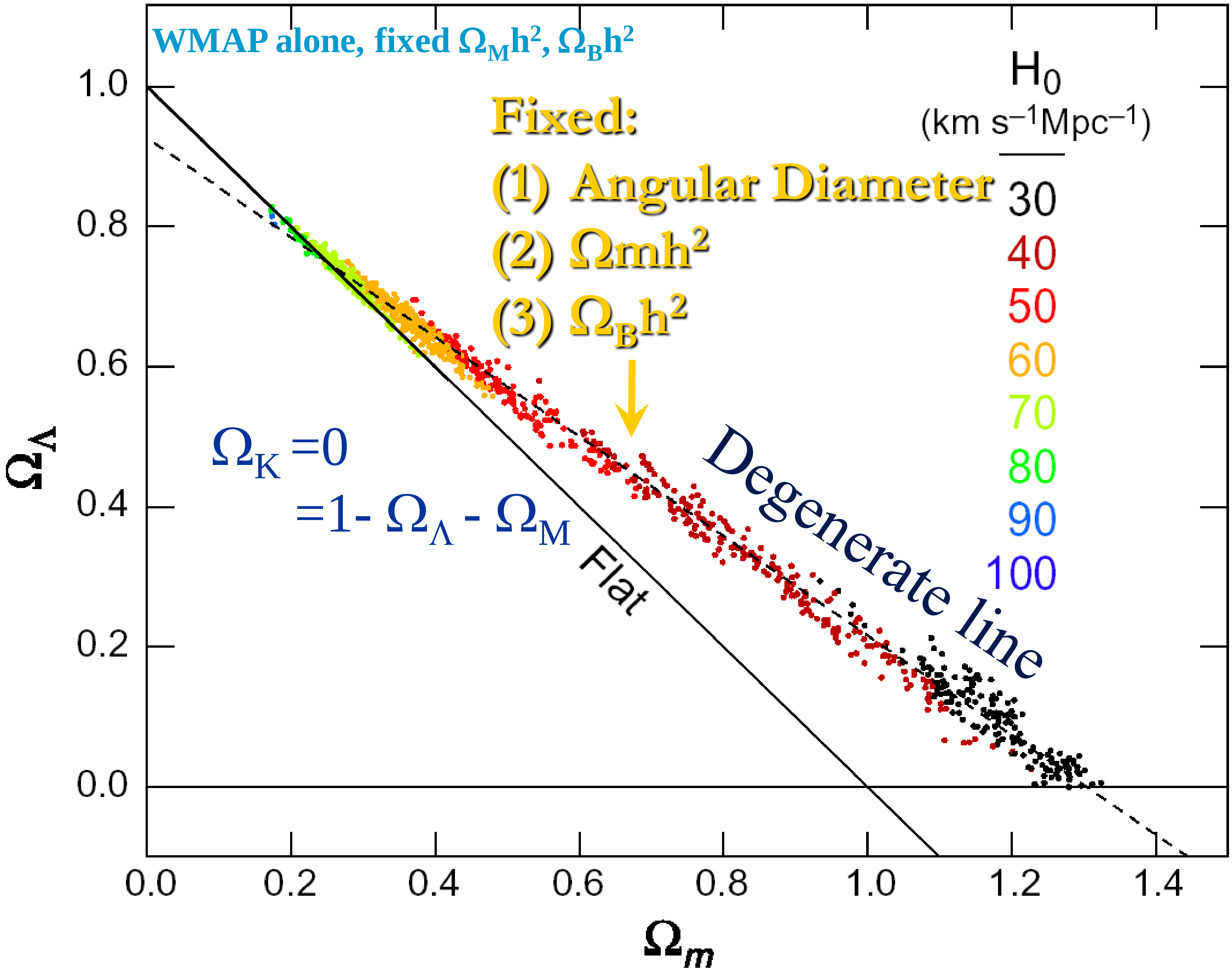


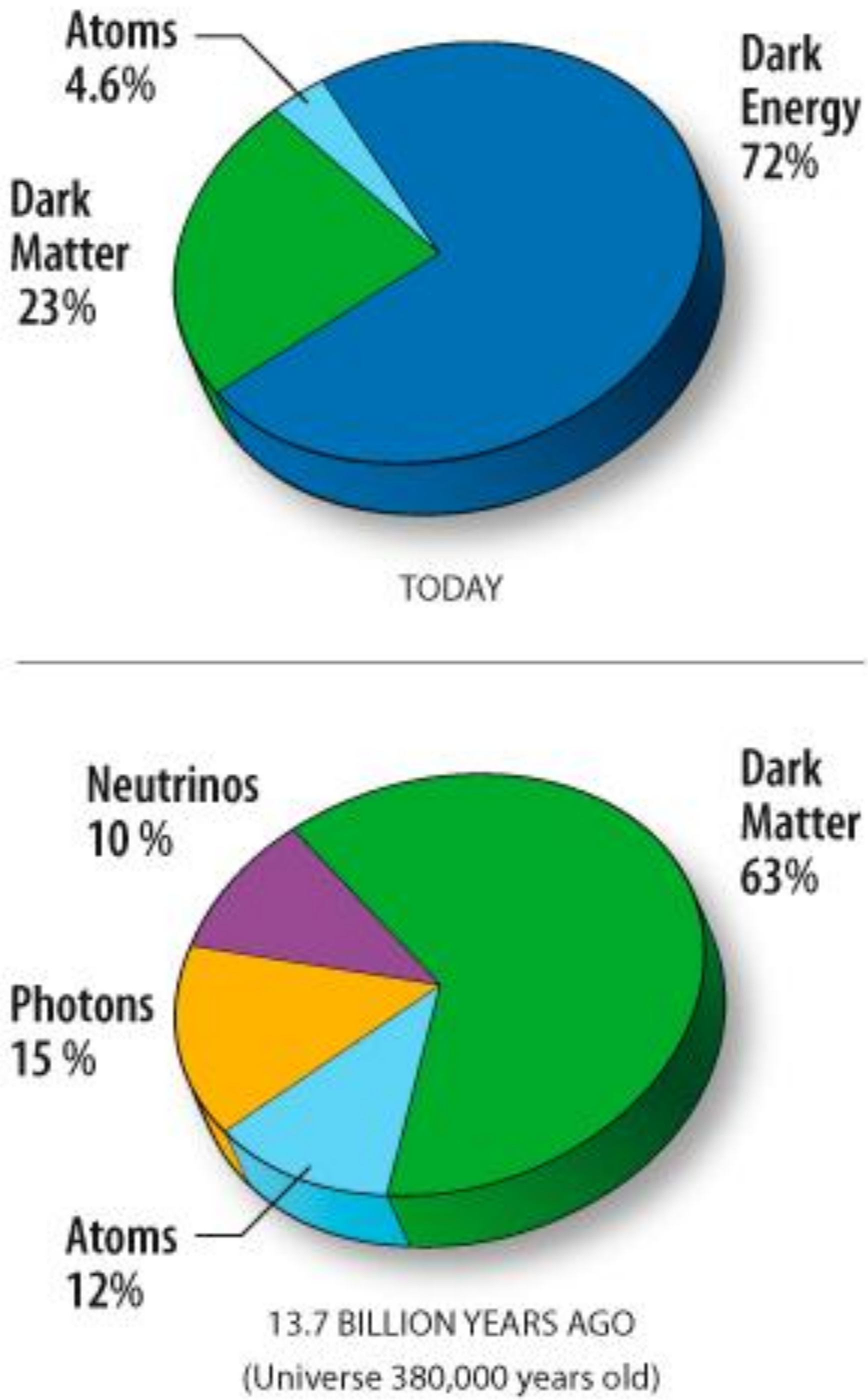


Planck is coming!




Light transfer
Angular diameter
Observer
13.7billion light year
Typical Size of fluctuations are determined by physics: $\Omega m h^2$ and $\Omega_B h^2$
Distance and apparent size are functions of curvature, & Hubble: Ω_K, h


WMAP alone, fixed $\Omega_M h^2$, $\Omega_B h^2$
Fixed:
(1) Angular Diameter
(2) $\Omega m h^2$
(3) $\Omega_B h^2$
H_0
(km s^{-1} Mpc^{-1})
30
40
50
60
70
80
90
100
$\Omega_K = 0$
$= 1 - \Omega_\Lambda - \Omega_M$
Flat
Degenerate line
Ω_Λ
Ω_m
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4



Either Assume: Flat space

$\Omega_\Lambda = 1 - \Omega_M$

Or

Combine with SNe etc.

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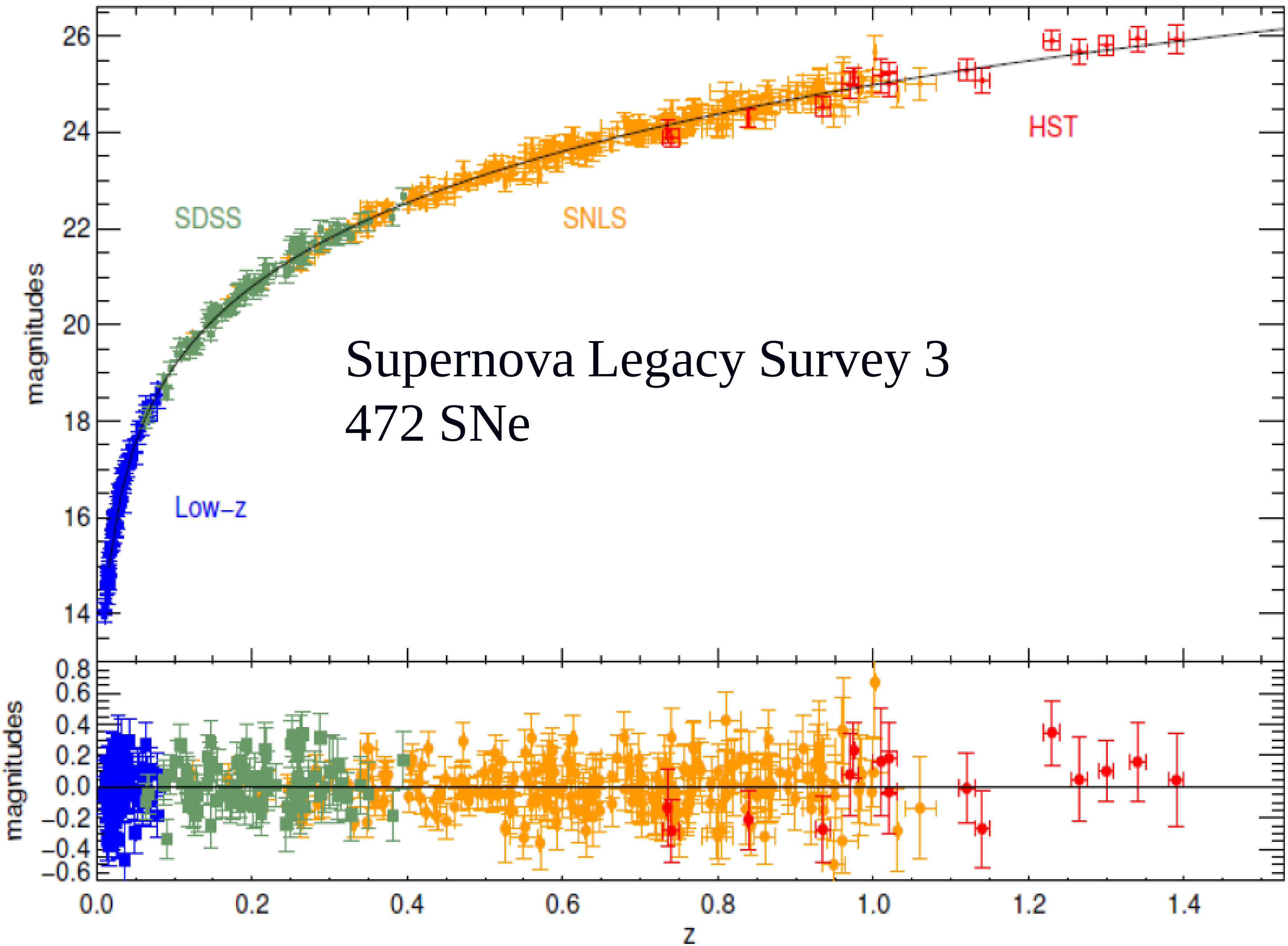
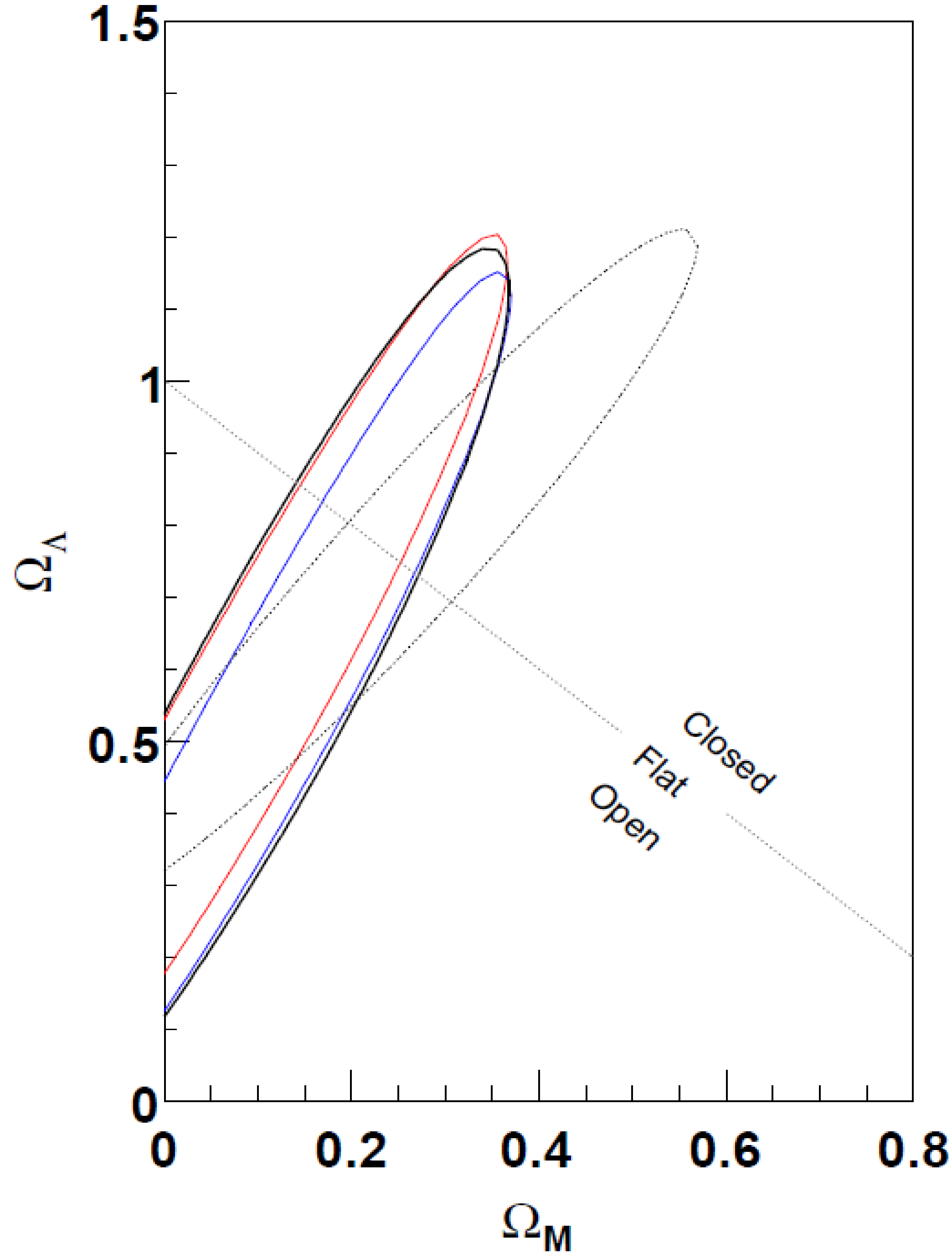
Supernova Legacy Survey 3
472 SNe





1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
Ω_Λ
Ω_M
Closed
Flat
Open

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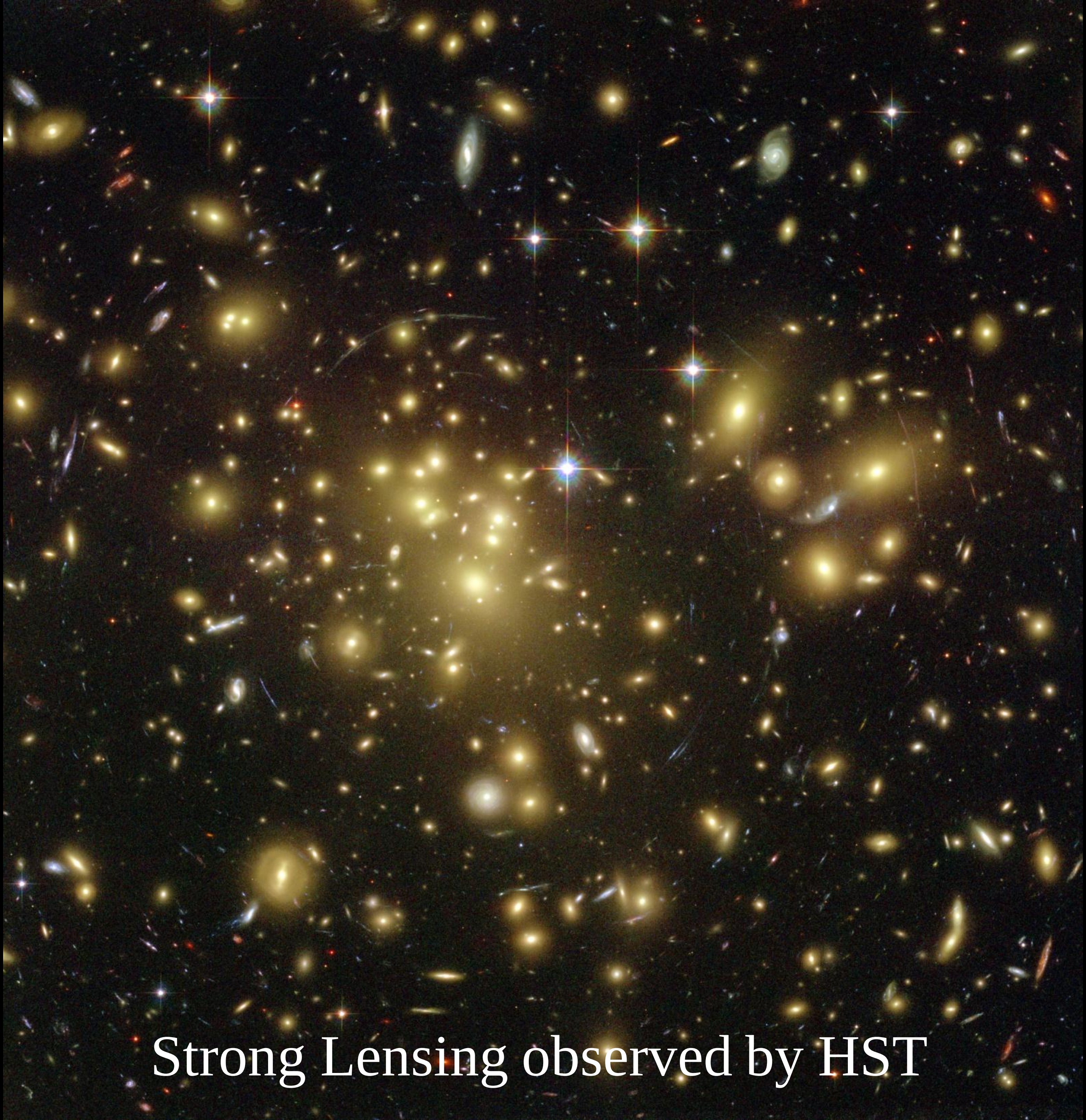
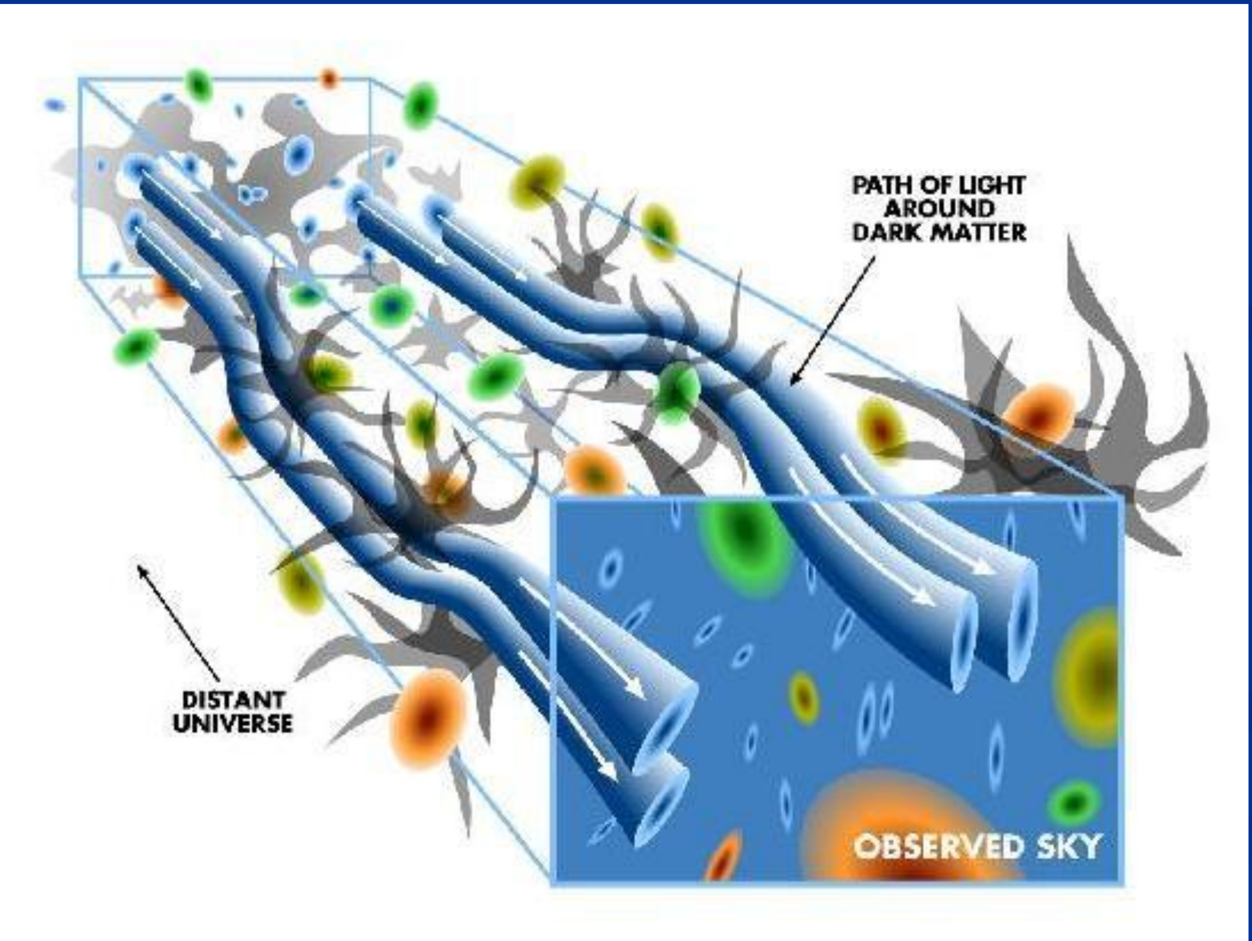
Strong Lensing



Strong Lensing observed by HST

Weak gravitational lensing

Measure the cosmic shear field



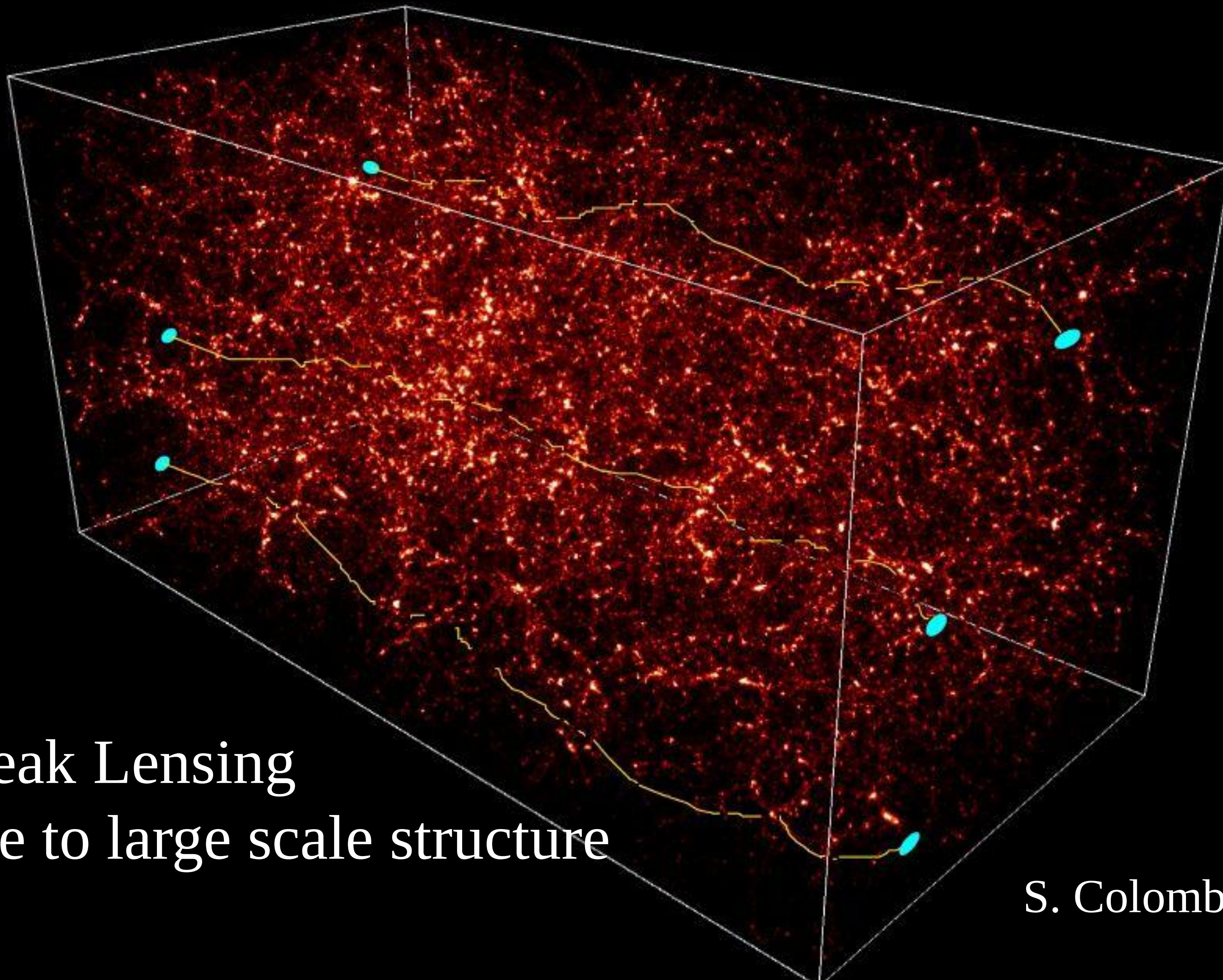
Witteman et al.

Nature 405, 143 (00)

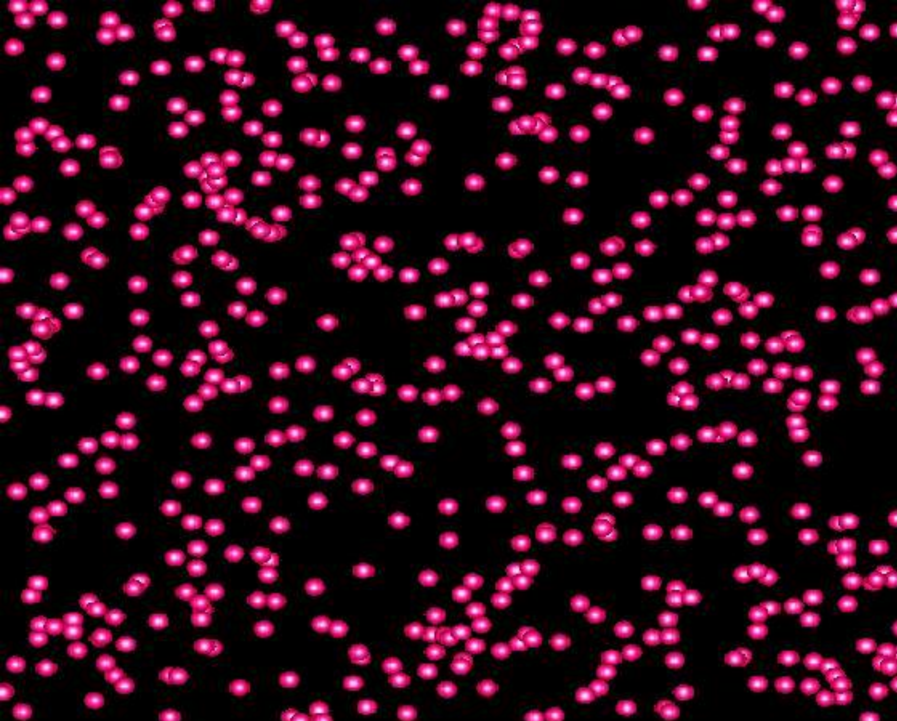
$$\left\langle \gamma^2 \right\rangle \sim \Omega_M^{1.2} P(k)$$

$$\sim \Omega_M^{1.2} \sigma_8^2$$

Weak Lensing
due to large scale structure

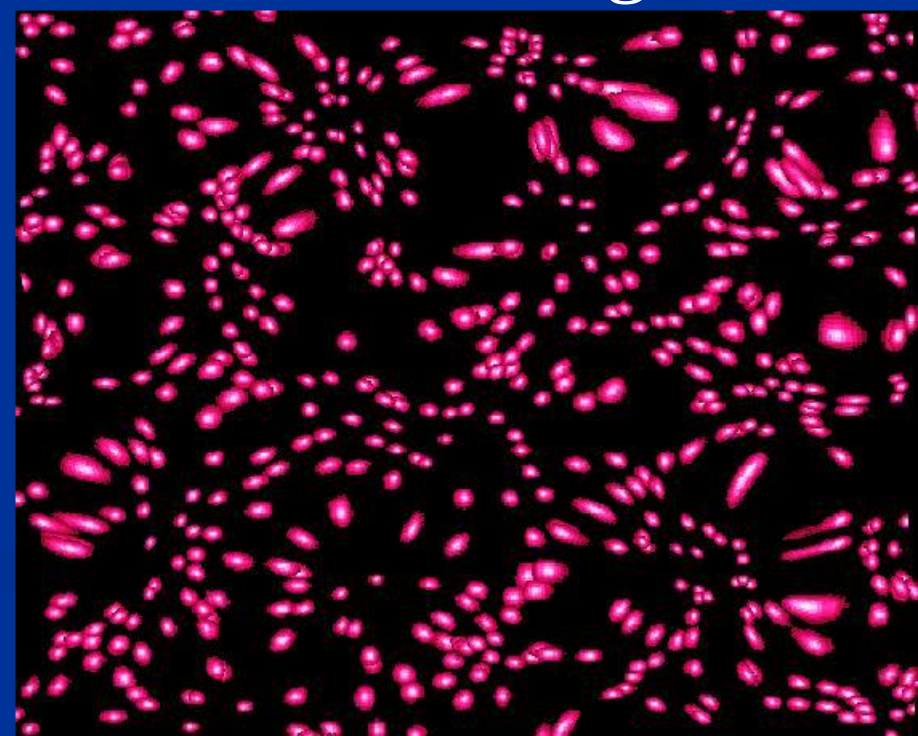


S. Colombi



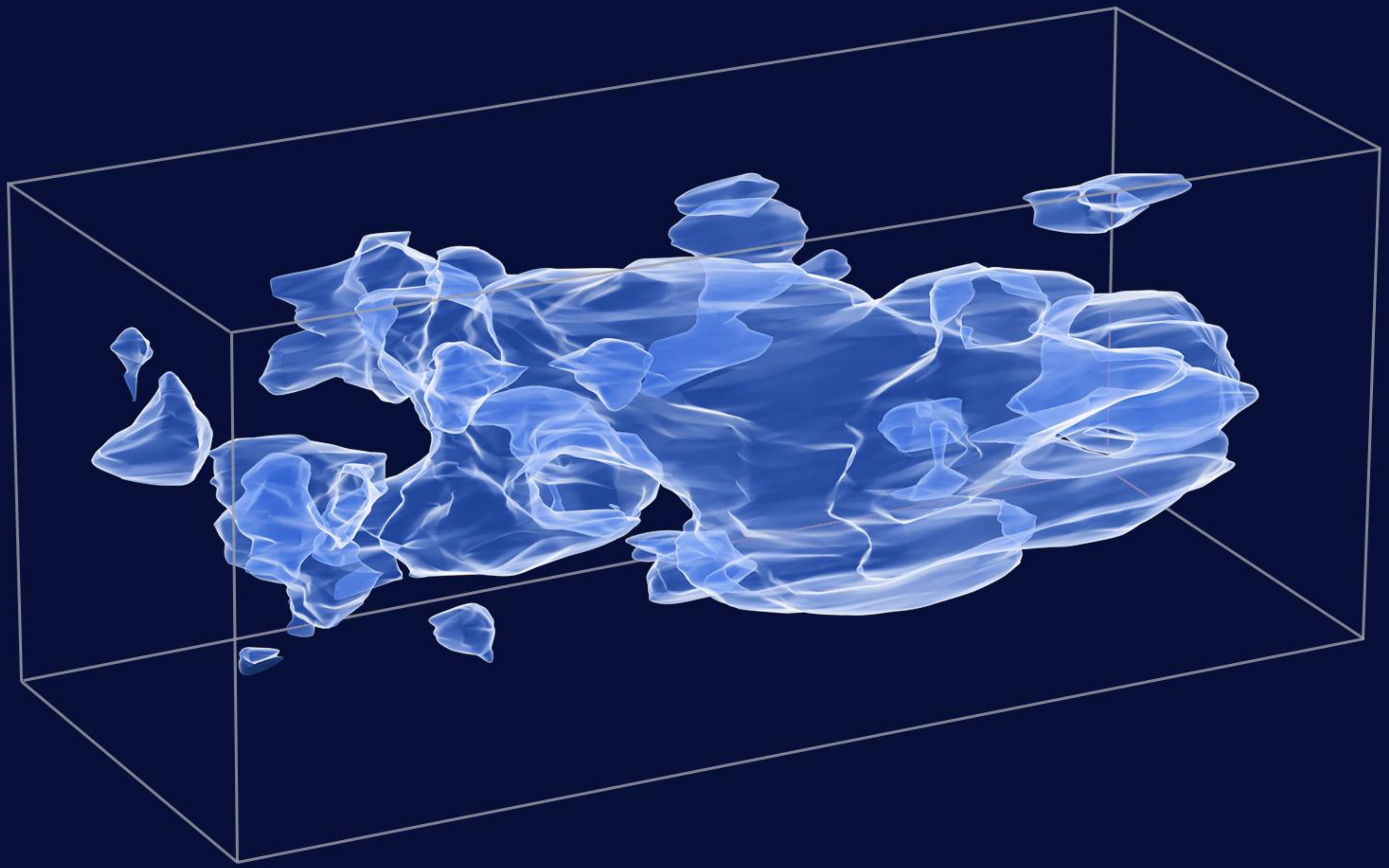
Original

Weak lensing



Jason Rhoads @ Caltech

Weak lensing observed by HST



3 dimensional shape of dark matter distribution obtained by weak lengin (COSMOS: HST, Subaru etc)

What we have understood (cont.)

- Mapping the universe by galaxy survey
  - 2dF/SDSS
  - Baryon Acoustic Oscillation
- The most distant galaxy and reionization
  - Ly-alpha emitter by Subaru: z=6.9
  - Gamma ray burst: z=8.2
  - HST/Wide Field Camera 3: z~8-8.5
  - Reionization was completed by z~6 (SDSS-QSO)
  - WMAP polarization: reionziation at z~10

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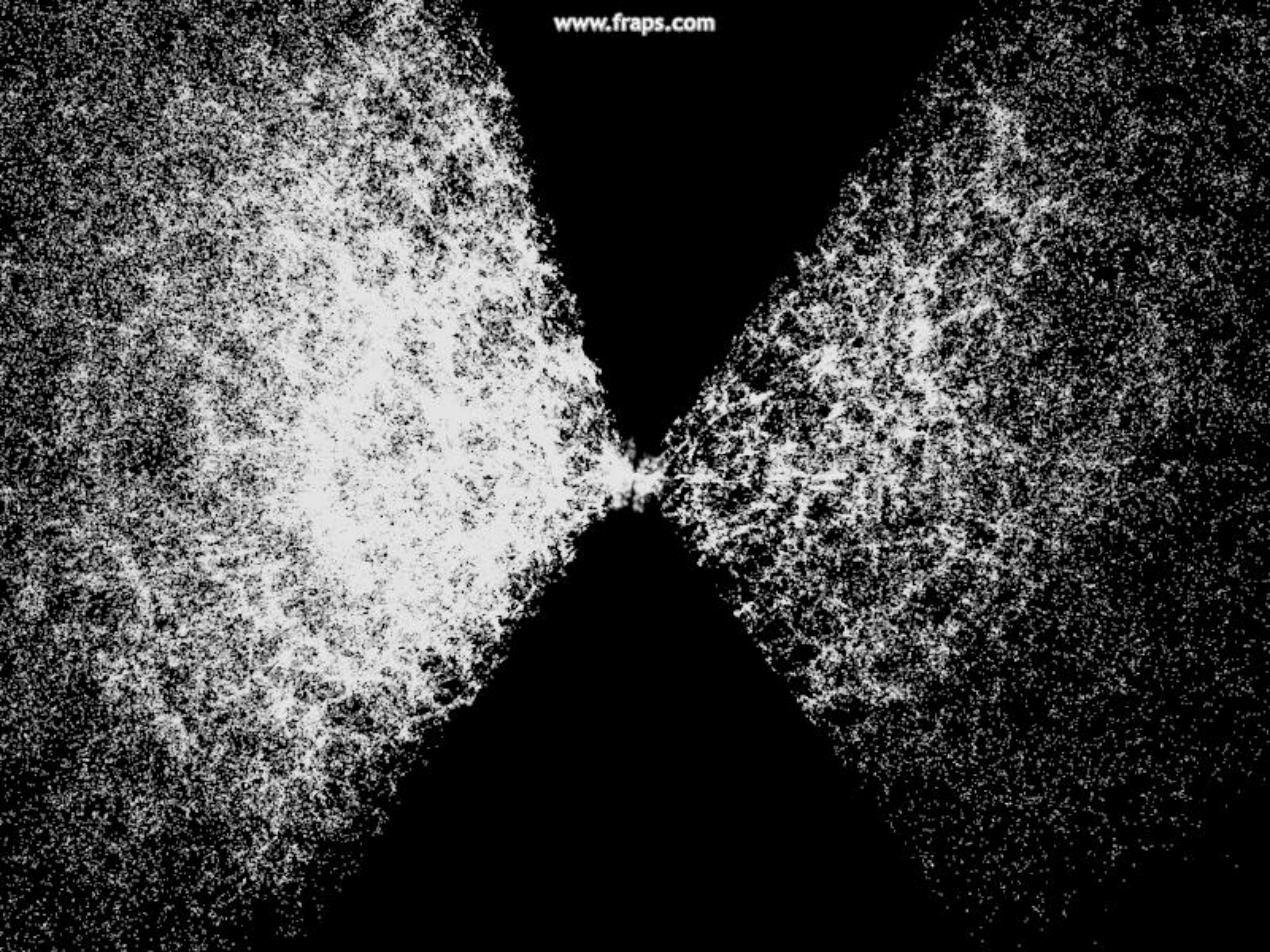
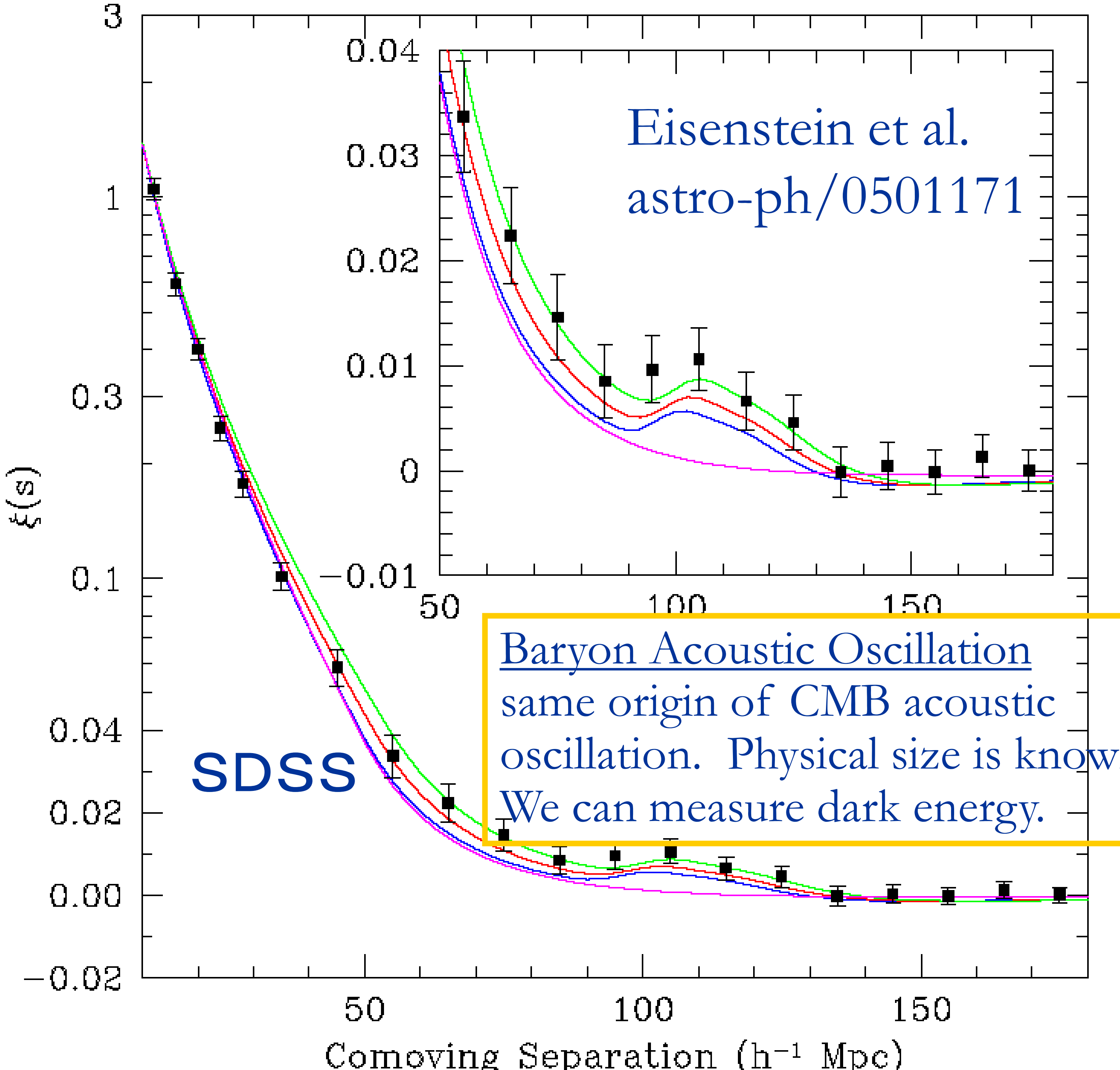
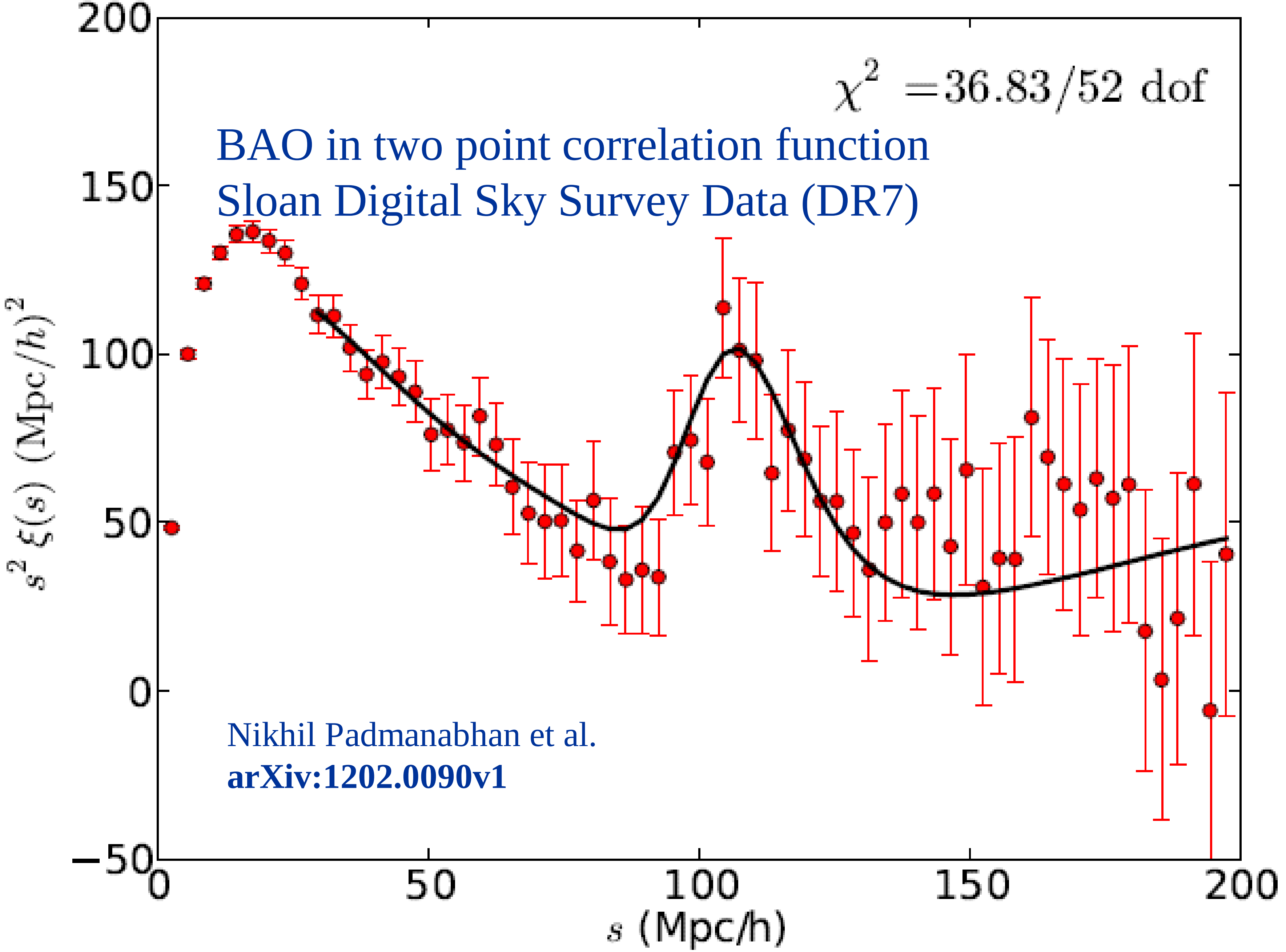


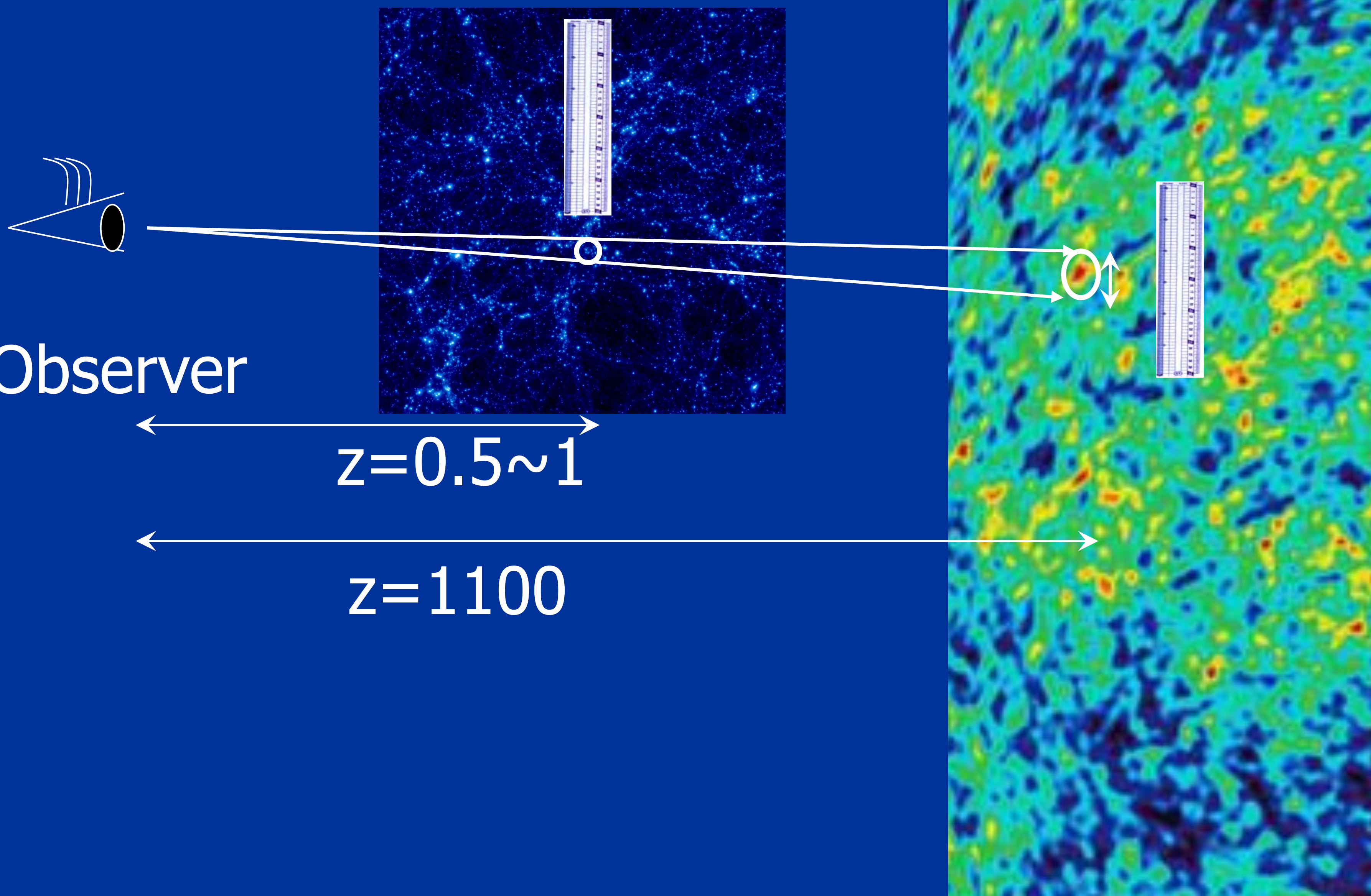


Baryon Acoustic Oscillation
same origin of CMB acoustic oscillation. Physical size is known.
We can measure dark energy.



$\chi^2 = 36.83/52$ dof
BAO in two point correlation function
Sloan Digital Sky Survey Data (DR7)
Nikhil Padmanabhan et al.
arXiv:1202.0090v1
$s^2\xi(s)\ (\mathrm{Mpc}/h)^2$
s (Mpc/h)
200
150
100
50
0
−50
0
50
100
150
200

BAO is a new ruler in the universe at the epoch of dark energy domination



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  - HST/Wide Field Camera 3: z=8.55
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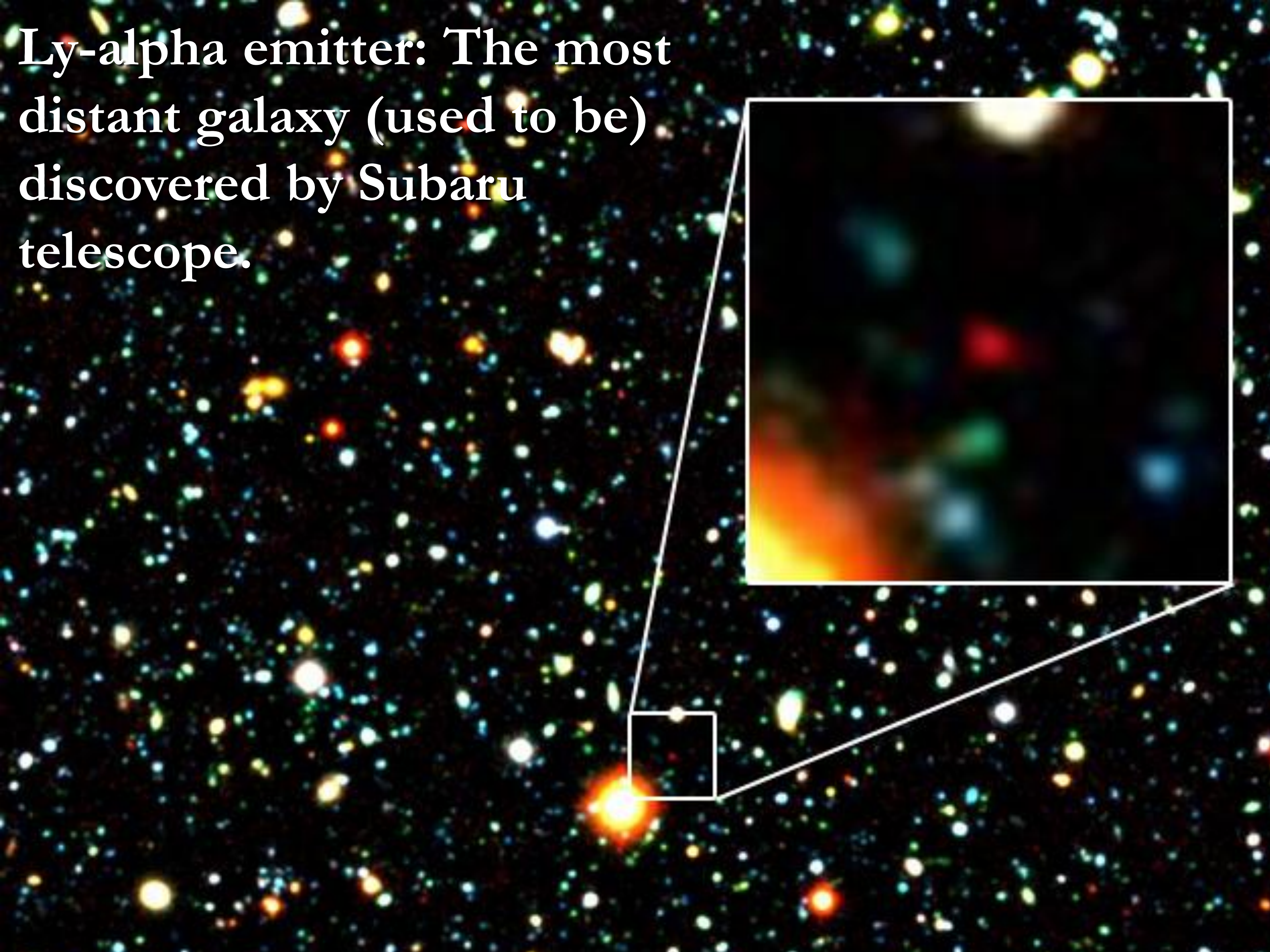
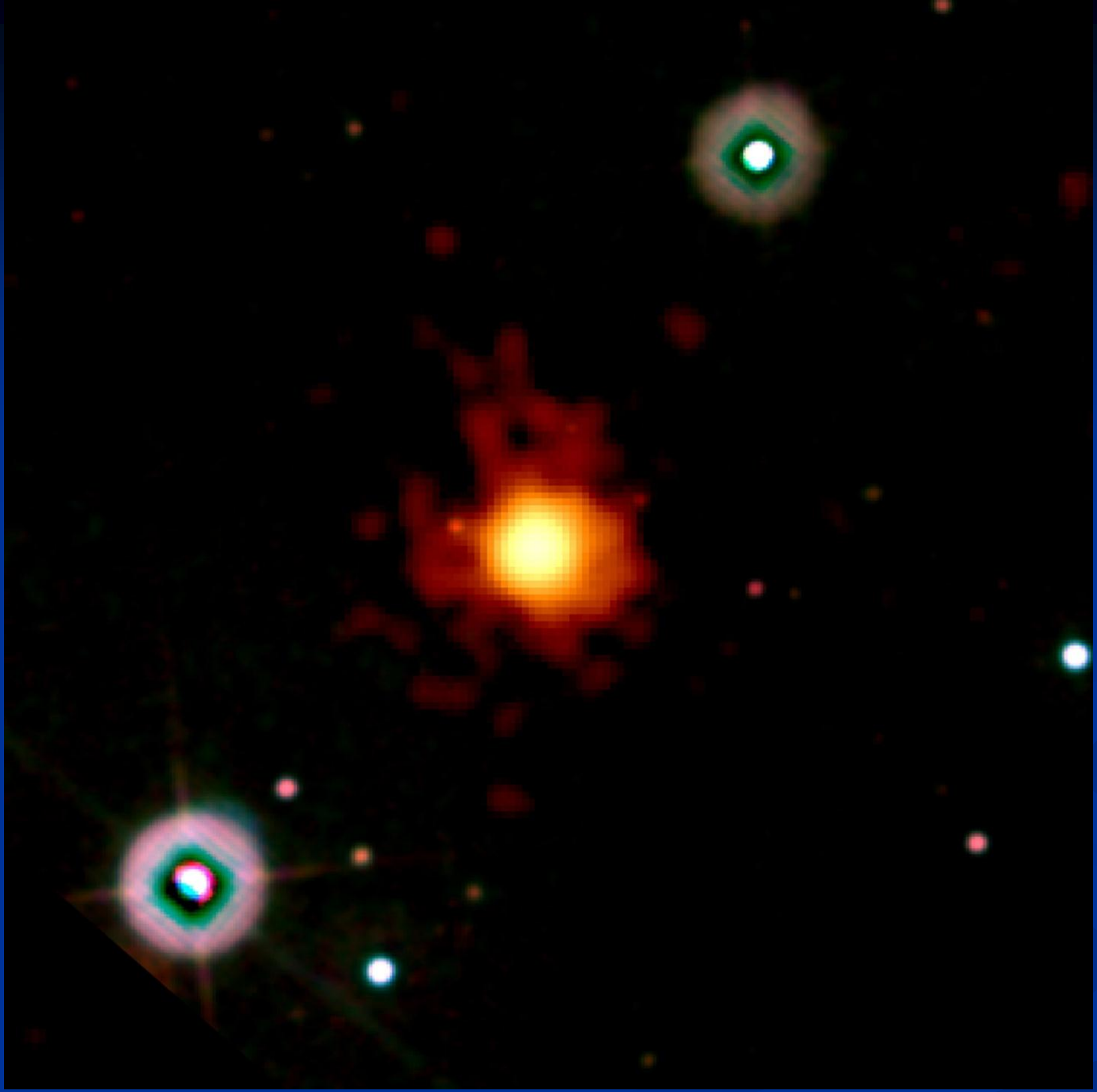
Ly-alpha emitter: The most distant galaxy (used to be) discovered by Subaru telescope.





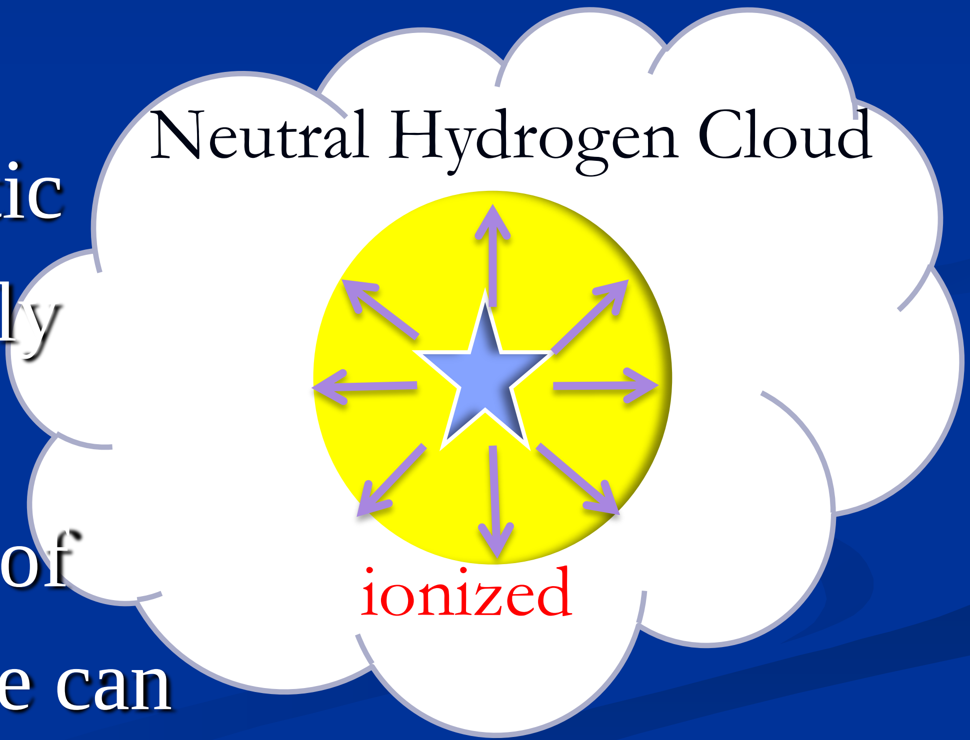
GRB 090423 taken by Swift's Ultraviolet/Optical (blue, green) and X-Ray (orange, red) telescopes.

HST/Wide Field Camera 3: z~8-8.5 galaxies

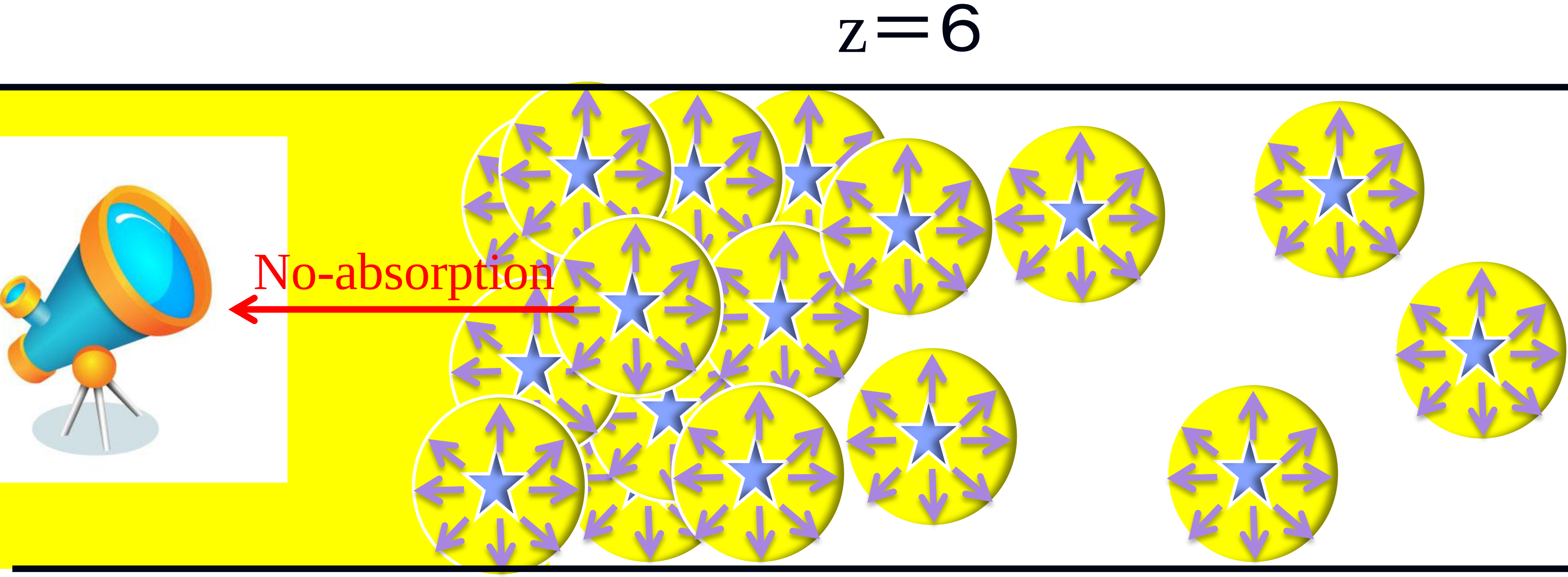

z=8.5549 galaxy found by VLT
600Million yrs. after big bang

Reionization: when first stars shine?

- Before the first star: **Dark Ages**
- First stars or AGNs (active galactic nuclei) emitted UV lights and ionized neutral Hydrogen
- Eventually intergalactic clouds were completely ionized
- Go back to the epoch of first star formation, we can find neutral hydorgen



Yellow : ionized regions
White : neutral regions



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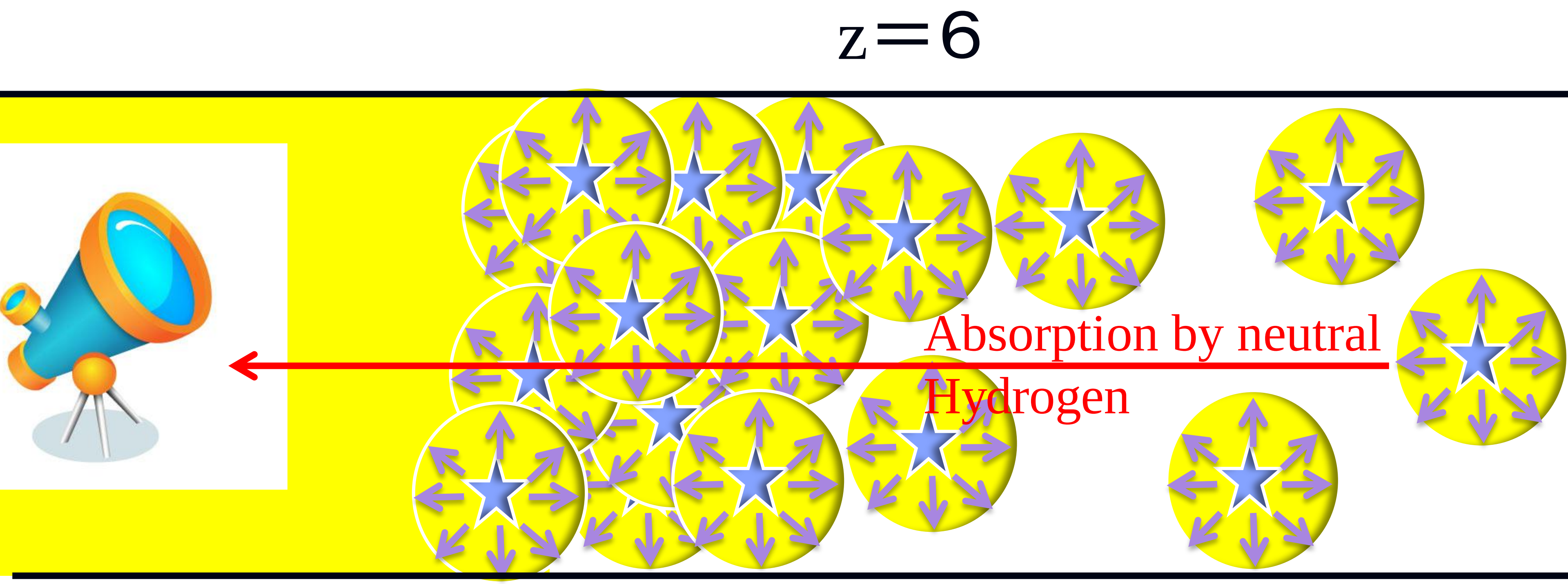
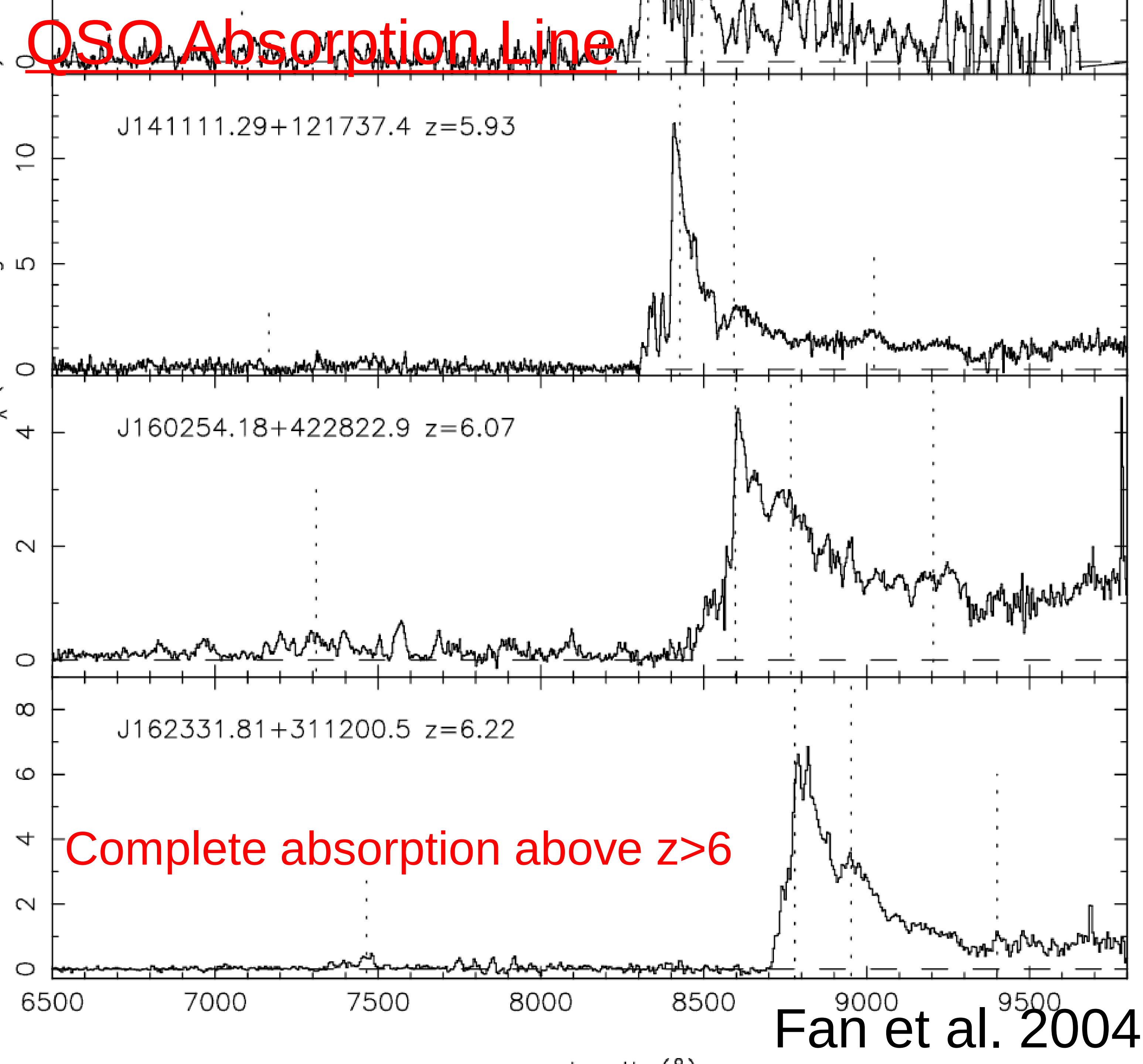


Reionization completed by z=6

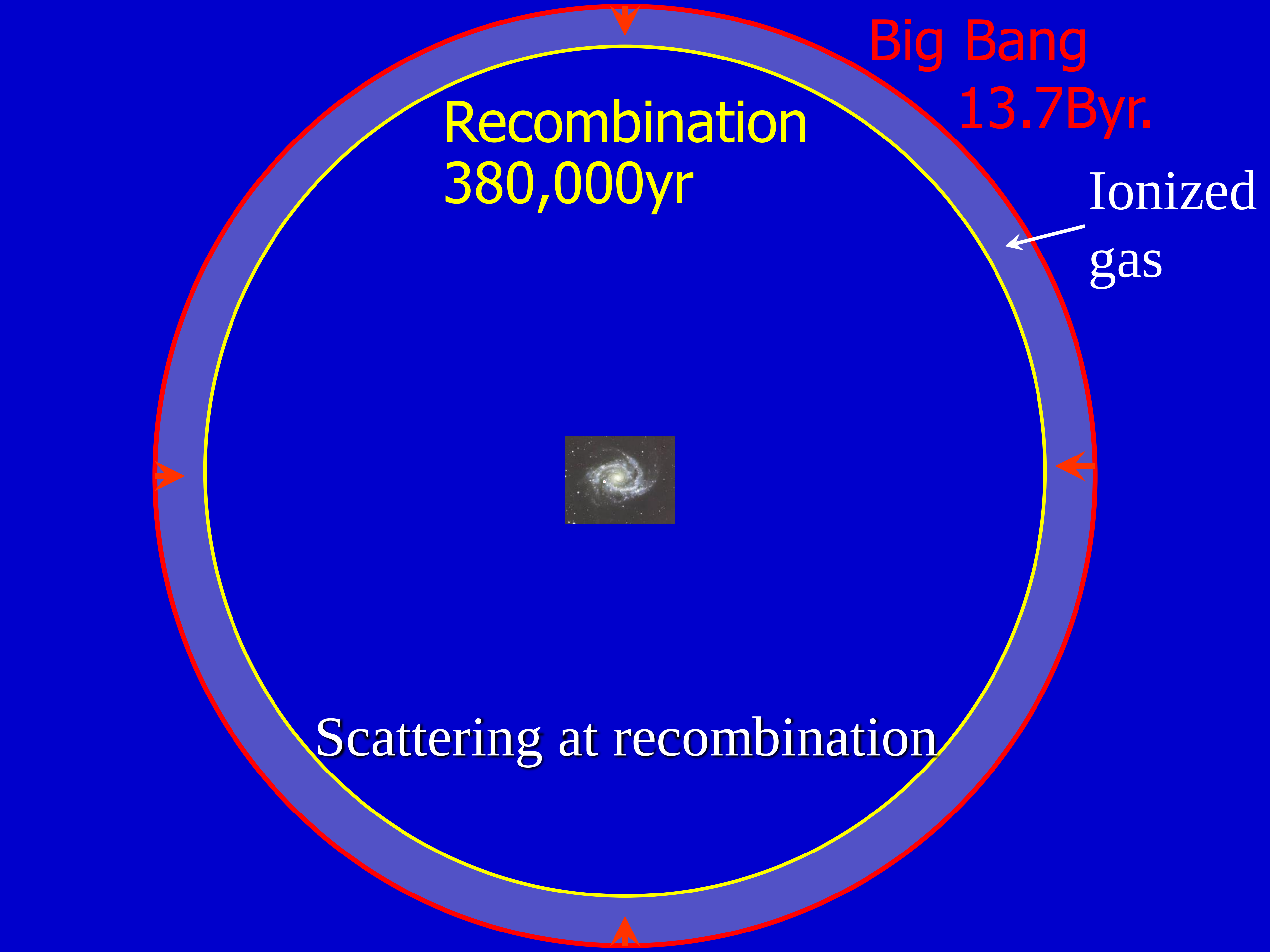
QSO Absorption Line

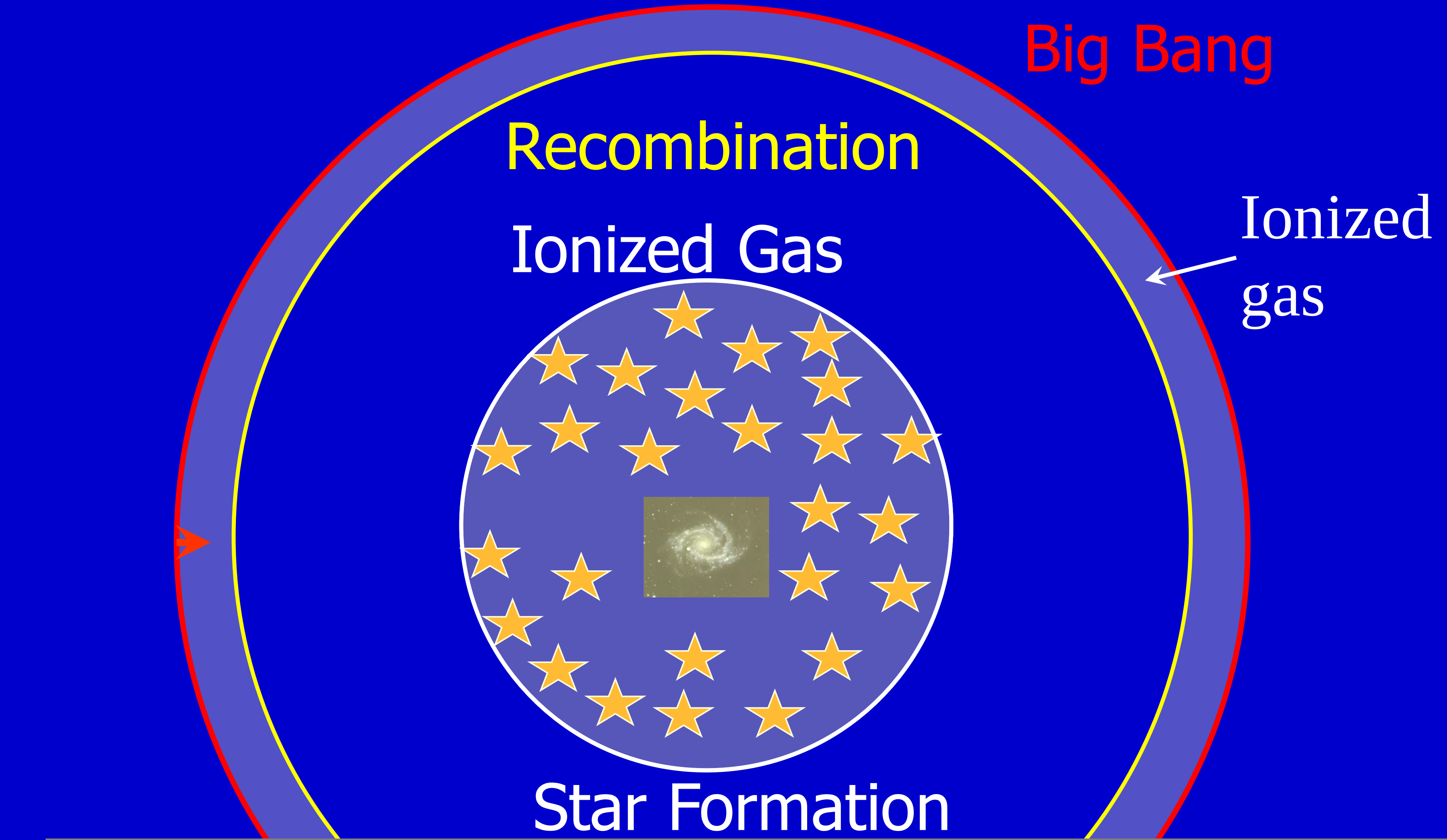


Complete absorption above z>6

Fan et al. 2004

CMB photons were also scattered off by electrons of ionized medium


Big Bang
13.7Byr.
Recombination
380,000yr
Ionized
gas
Scattering at recombination



Some photons last scattered at the late epoch

- **Temperature Fluctuations were damped away**
- **Polarizations were generated due to scattering**

Reionization from WMAP

- Thomson Optical depth =0.84,
  - Damping of temperature anisotropies
  - Polarization
- Reionization epoch: z=10.8 if complete reionization 430Million yrs. after Big Bang
- But, it is not clear when it starts to reionize

Summary: Standard Cosmology

- We understand the contents of the universe:

  However…

  - no idea about dark energy
  - no evidence of dark matter particles
  - Yet most of baryons are unseen

- We start to see the end of dark ages

  However…

  - We don’t know how and when it starts
  - We don’t know how long it stays

Summary: Standard Cosmology

- We are almost certain the existence of Inflation
  However…
  - no idea about the exact mechanism of Inflation
  - no direct proof of Inflation yet (Nobel Prize!?)
  - We don’t know how and when Inflation ended

What should be understood

1. Existence of Inflation
2. Mechanism of Inflation
3. Baryon Number generation: when and how
4. First star formation, end of dark ages
5. What is dark matter
6. What is dark energy

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1. Prove the Existence of Inflation

- Almost Scale Free Fluctuations: Done
- Consistency Relation
  - Relation between Density (scalar) fluctuations and Gravity wave (tensor) mode fluctuations
  - Observationally, measure polarization of CMB, and find parity odd mode (B-mode)

We can Prove Inflation from B-mode Polarization

- Consistency Relation

$$n_T = -2A_T / A_S$$

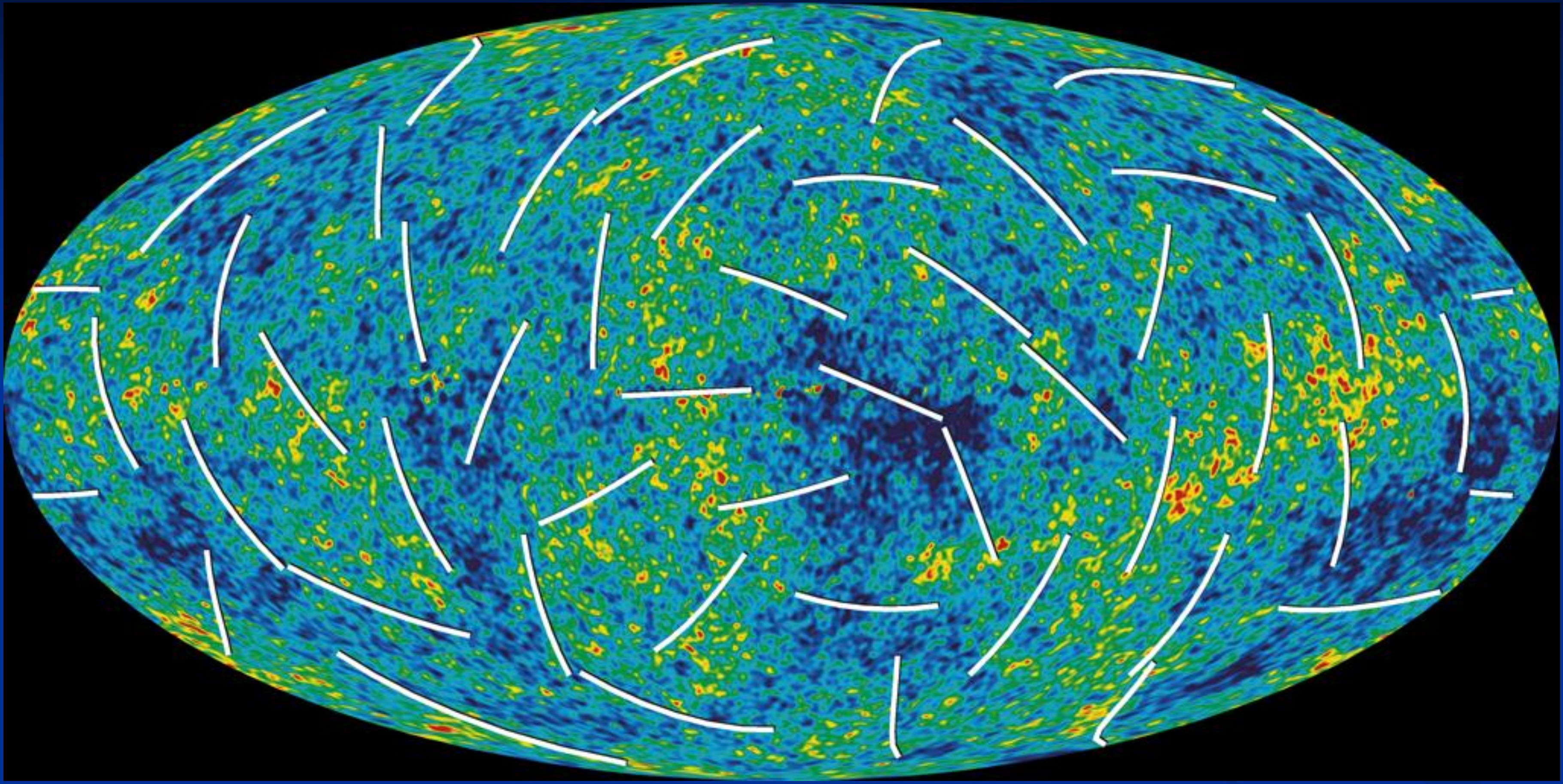
  - n_T: Tensor Power Law Index
  - A_T: Tensor Amplitude
  - A_S: Scalar Amplitude
- If we can find B-mode, we can measure tensor spectrum (n_T & A_T), and test consistency relation

Observations

Very difficult to detect

- Typically amplitude of polarization is factor 10 smaller than temperature fluctuations
- Foreground from the Galaxy

- First Detection of E-mode (parity even) Polarization was from DESI experiments
- Boomerang Experiment (Balloon at Antarctica)
- WMAP made clear detection of E-mode polarization in the all sky map (3yr data)



Polarization for WMAP is Temperature Fluctuations for COBE

anyway, detect (E-mode)!

But only upper bound for B-mode Polarization

Now a big race who is going to detect B-mode first time is open!

- SPTPol
- ACTPol
- PolarBear

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2. Mechanism of Inflation

- Detection of non-Gaussianity
- Direct Detection of Gravity wave from Inflation
  - Traces of end of inflation to big bang (reheating)
  - Traces of history of big bang

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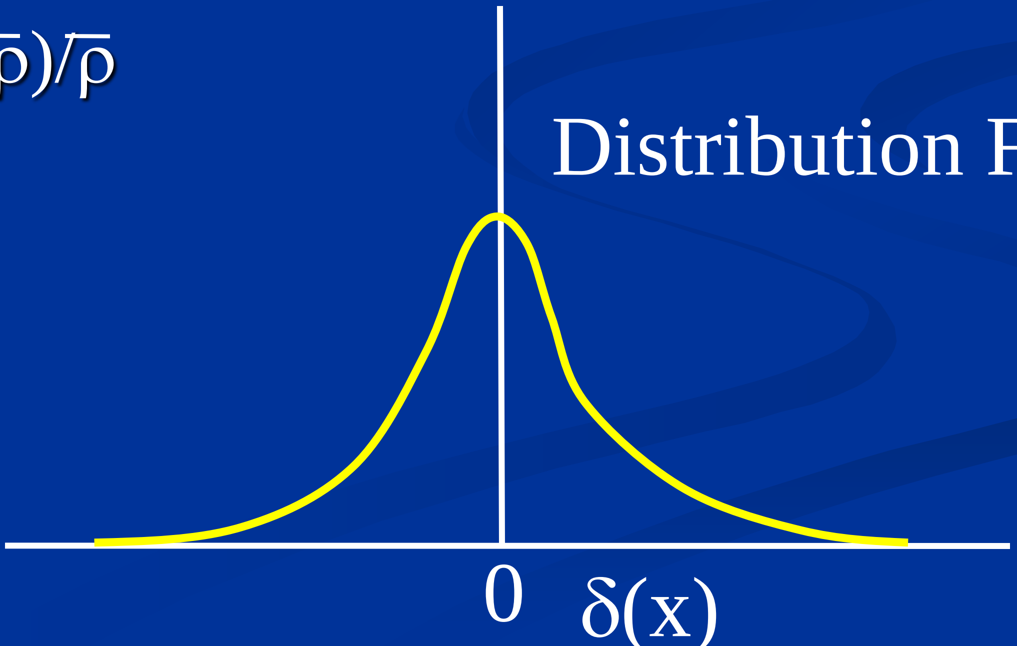
Recent Hot Topics: Non-Gaussianity

- Fluctuations generated during the inflation epoch
  - Quantum Origin
  - Gaussian as a first approximation

$\delta(x) \equiv (\rho(x) - \bar{\rho})/\bar{\rho}$



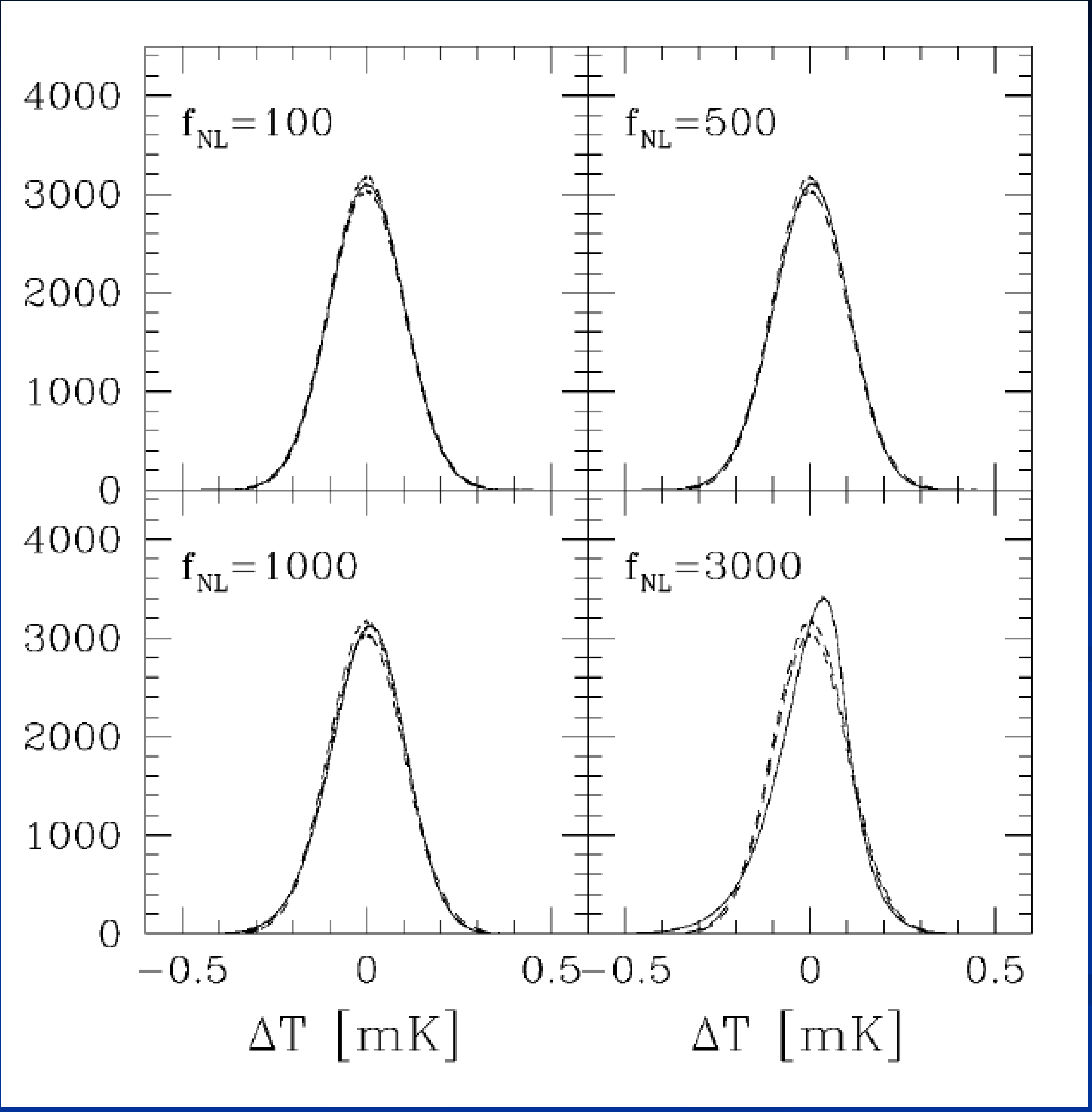
Non Gaussianity from Second Order Perturbations of the inflationary induced fluctuations

- $\Phi = \Phi_{Linear} + f_{NL}(\Phi_{Linear})^2$

  $\Phi_{Linear} = O(10^{-5})$, non-Gaussianity is tiny!

  Amplitude f_{NL} depends on inflation model

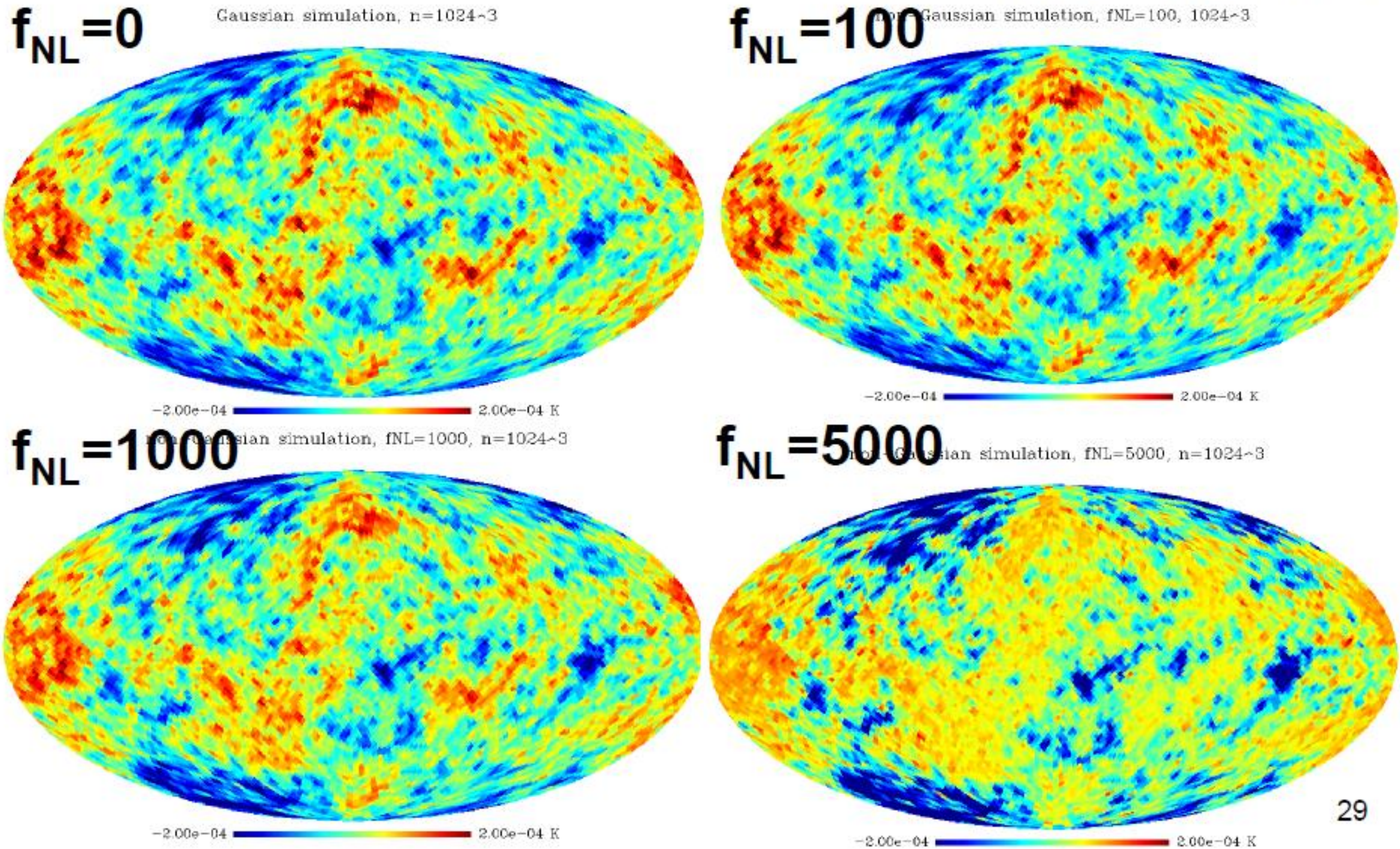
  [quadratic potential provides $f_{NL} = O(10^{-2})$]



4000
3000
2000
1000
0
$f_{NL}=100$
$f_{NL}=500$
$f_{NL}=1000$
$f_{NL}=3000$
−0.5
0
0.5
ΔT [mK]

Positive f_{NL} = More Cold Spots

Simulated temperature maps from $\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$



Very Tiny Effect:
Fancy analysis (Bispectrum etc) starts to reveal non-Gaussianity?

First "Detection" in WMAP CMB map

$+27 < f_{NL}(\text{local}) < +147$ (95% CL; **lmax=750**)
(Yadav & Wandelt, arXiv:0712.1148)

$$f_{NL}^{\text{local}} = 32 \pm 21 \text{ (68\% CL)}.$$

Komatsu et al. WMAP 7 yr.

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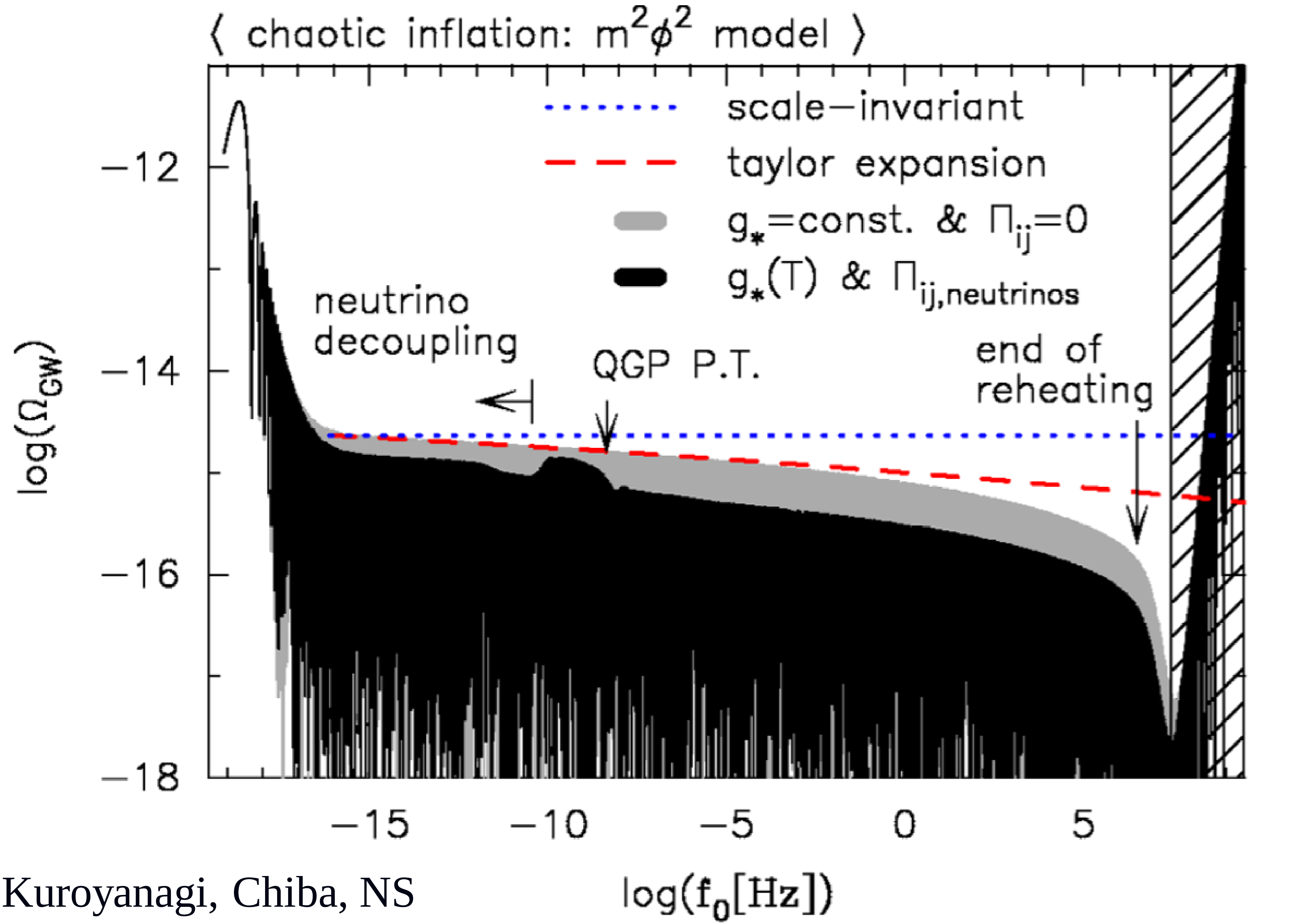

Kuroyanagi, Chiba, NS

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3. Baryon Number generation: when and how

- Leave this question to particle physicists

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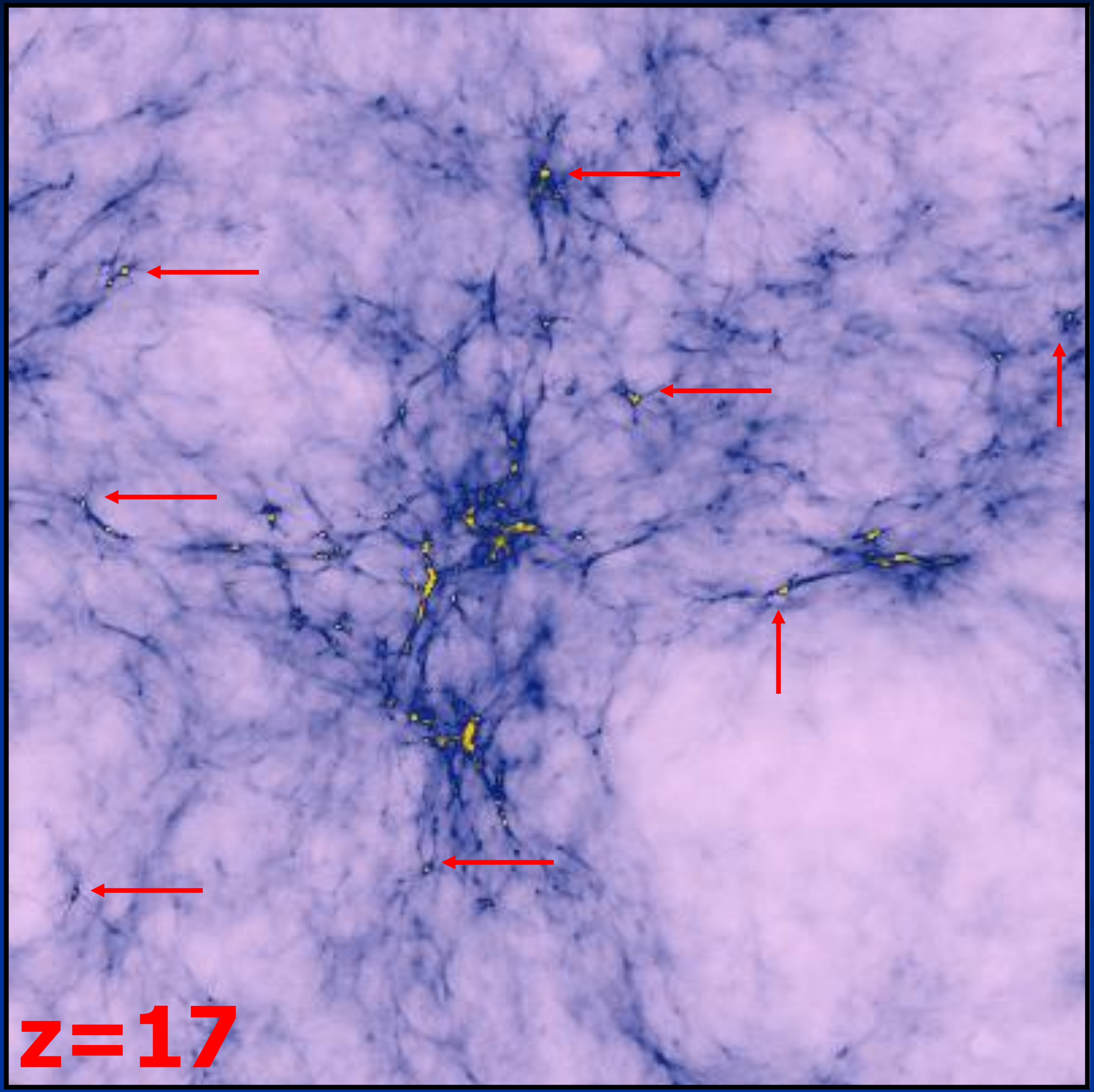
4. First star formation, end of dark ages

- 21cm radio emission from neutral hydrogens
  - EDGES, LOFAR, MWA, PAPER
  - SKA will be the one
- CMB polarization

First Epoch of Structure Formation

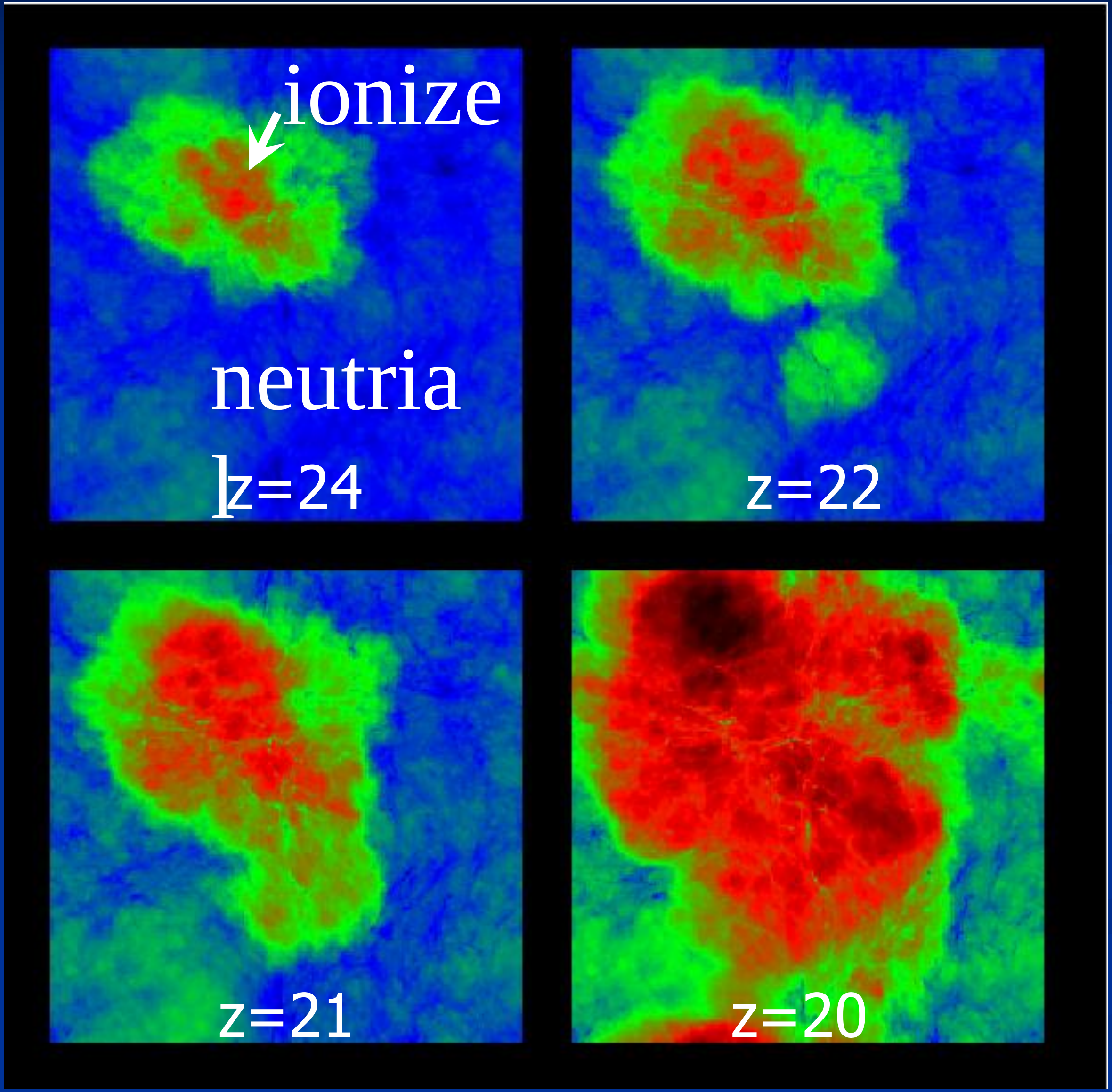


1 Mpc

Yoshida et al. (2003

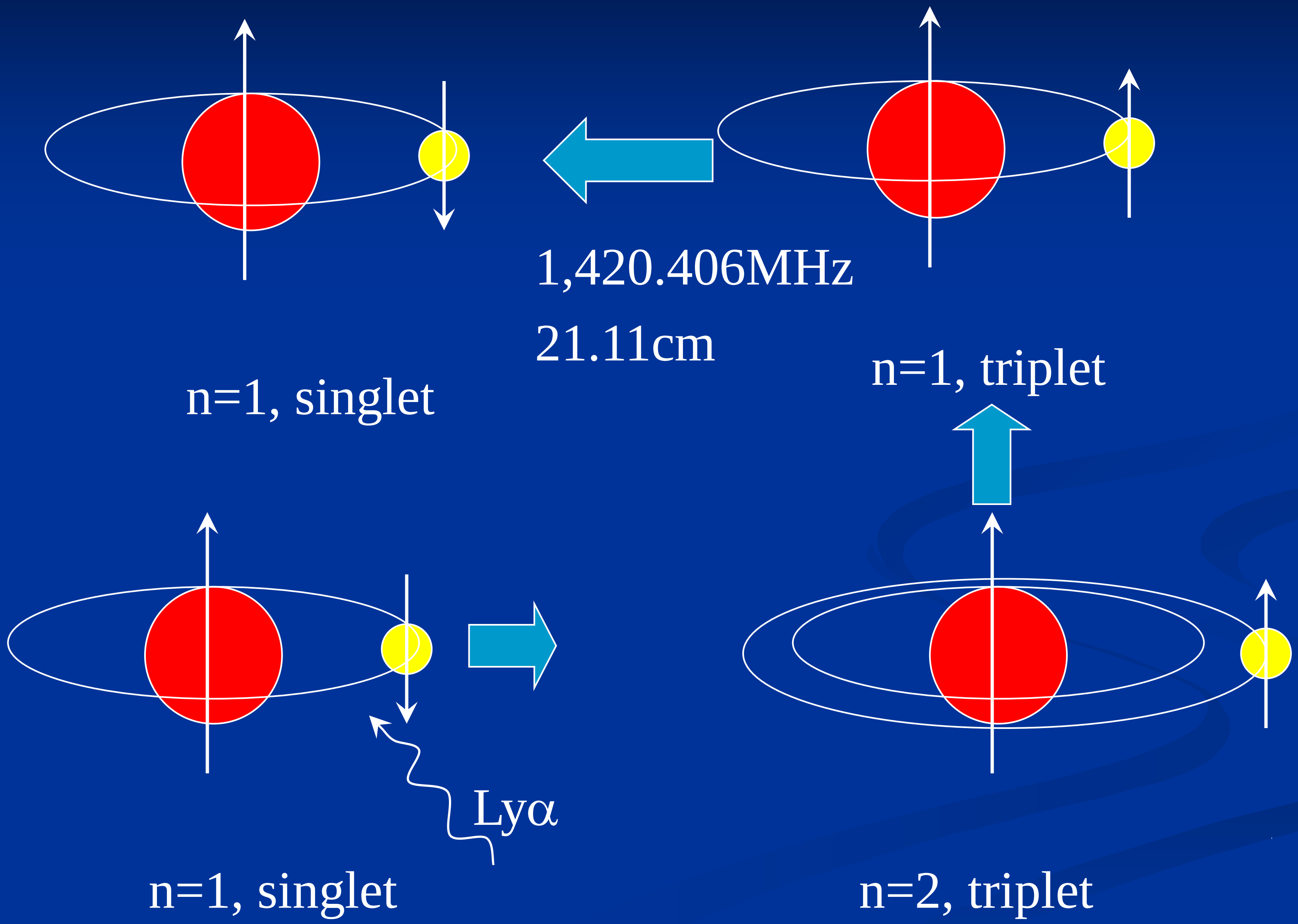
First HII Region and Reionization of the Universe

Sokasian, Yoshida, Abel, Hernquist (2003)

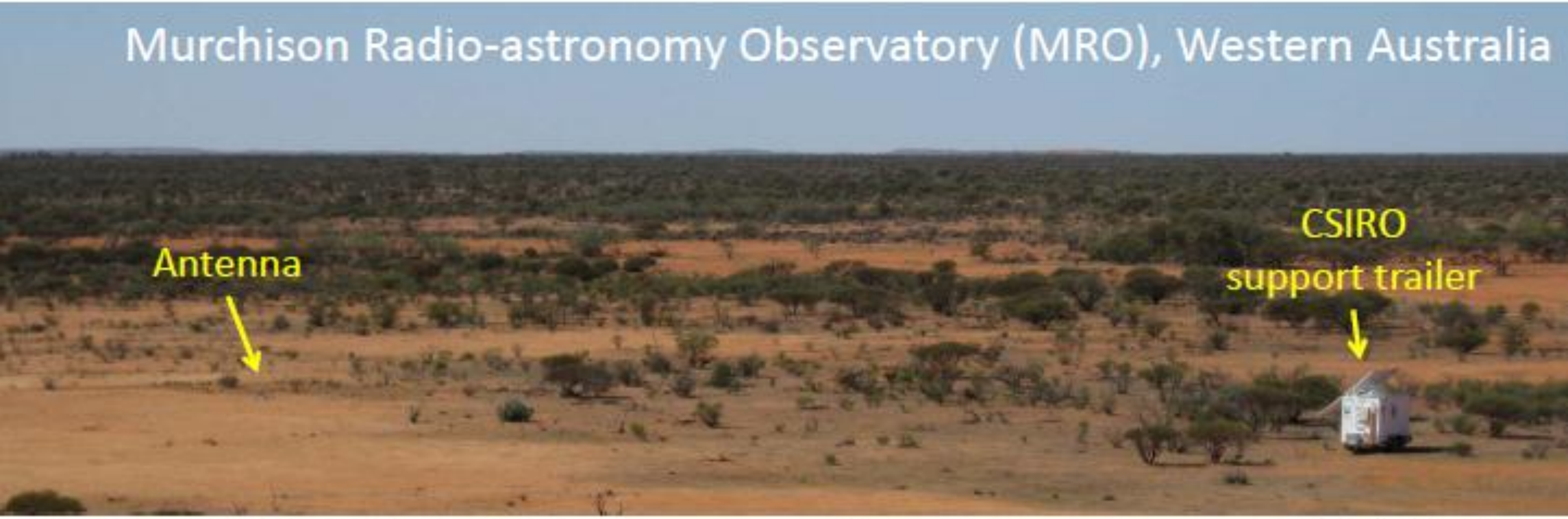


UV light from massive Start reionize IGM

21cm radio emission as a probe of neutral hydrogen



EDGES – Experiment to Detect the Global EoR Signature



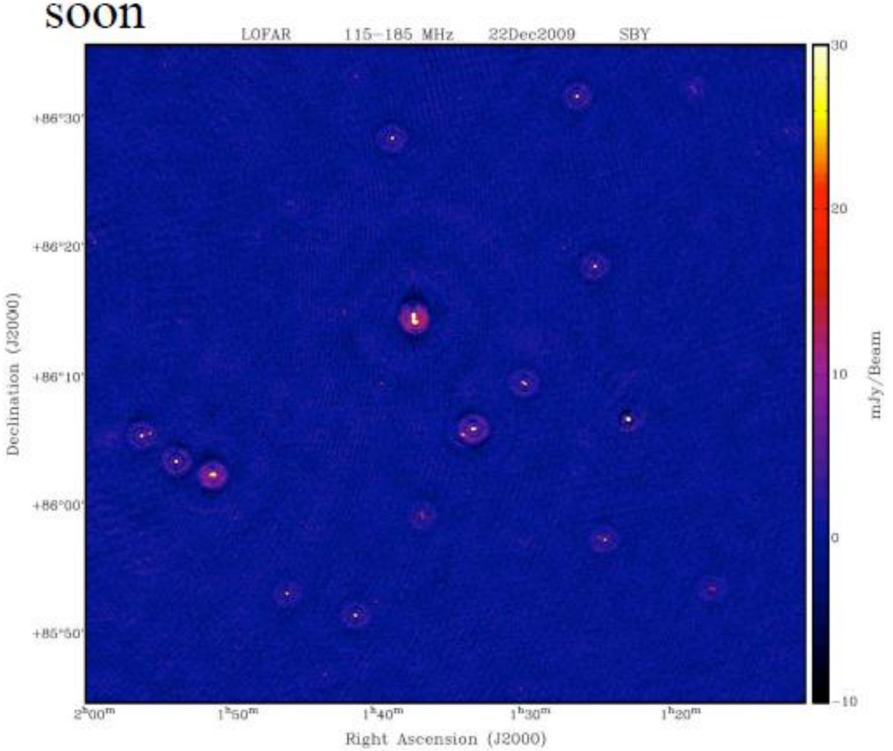


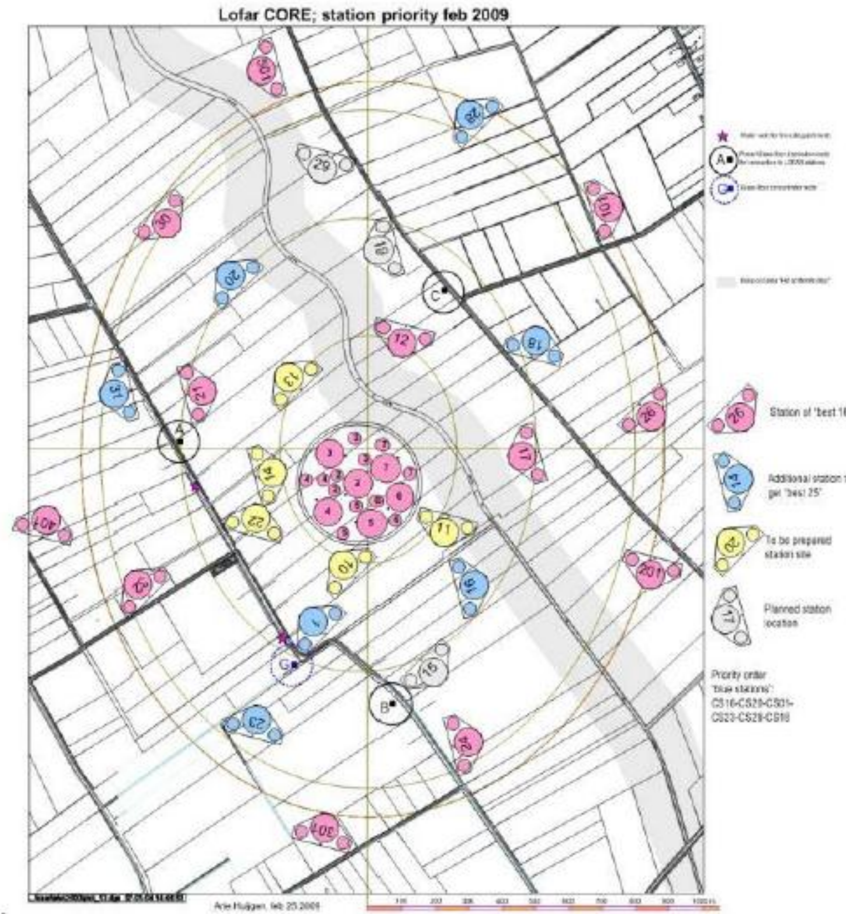

A lower limit of $\Delta z > 0.06$ for the duration of the reionization epoch

J.D. Bowman & A.E.E. Rogers, Nature 2010

LOFAR

- 15 Core Stations (where the HBA are split into 2 substations of each 24 tiles)
- 5 Remote stations
- 3 German stations
- Most of the array should be operational by 2010H2
- Million source shallow survey starting soon

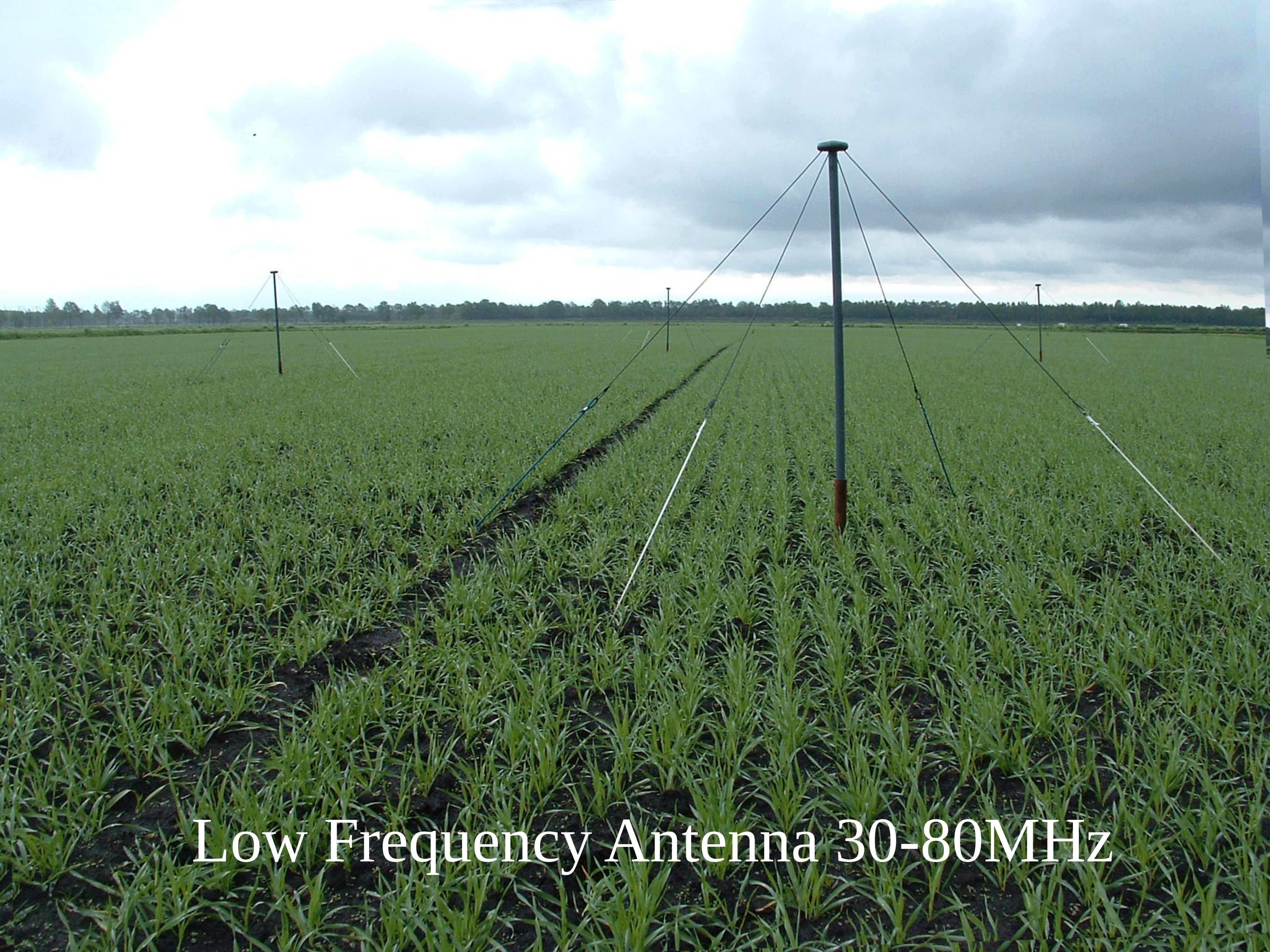


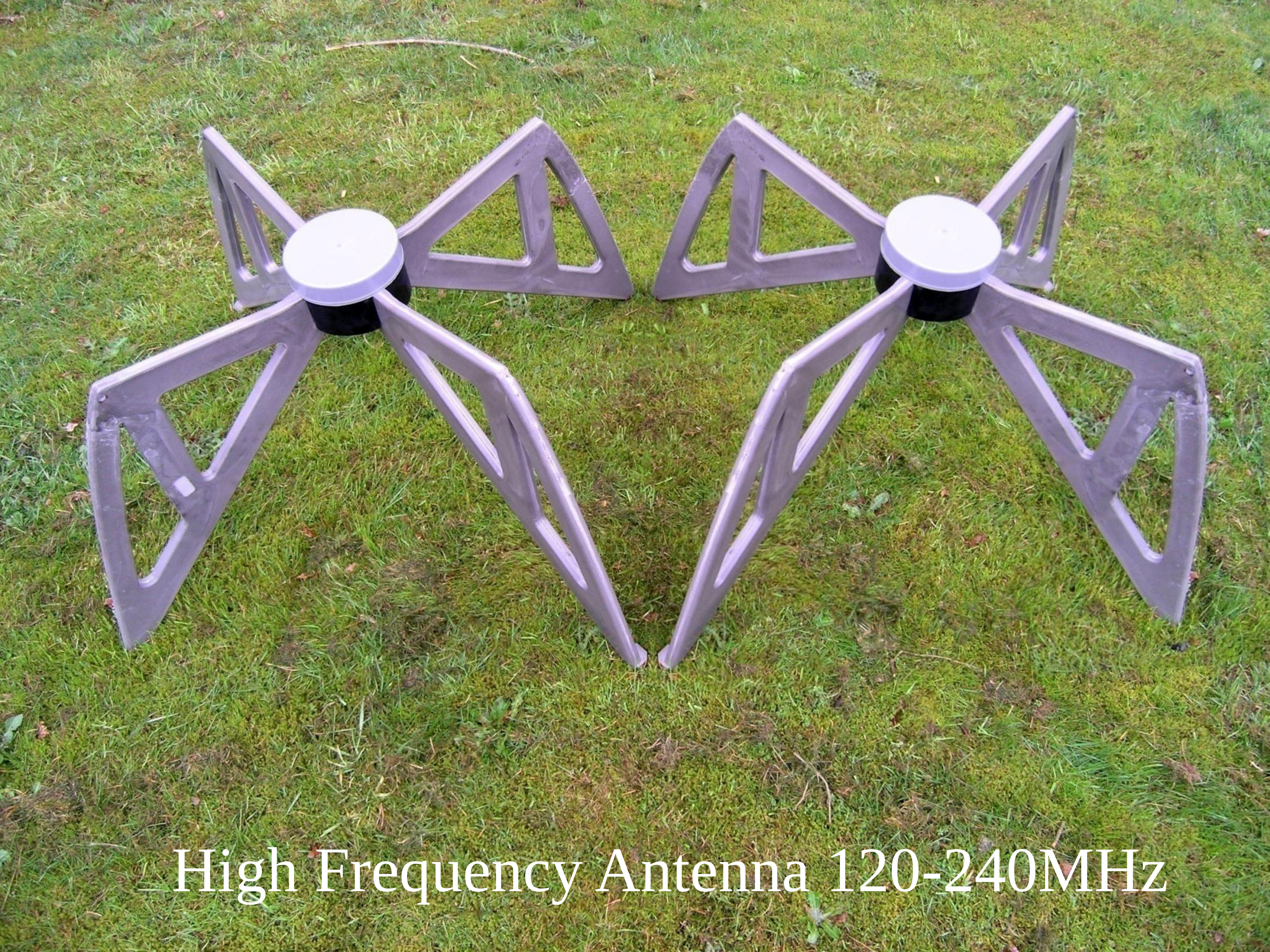


Survey image: 10" PSF, 1 mJy noise, 120-170 MHz, not deconvolved

Ger du Bruyn


LOFAR


Low Frequency Antenna 30-80MHz



High Frequency Antenna 120-240MHz

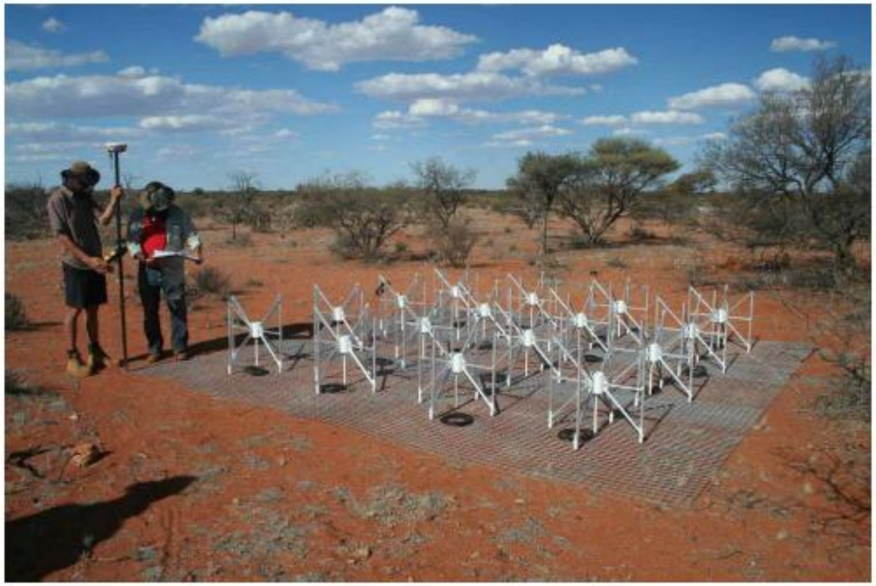
PAPER in South Africa: PSA-32

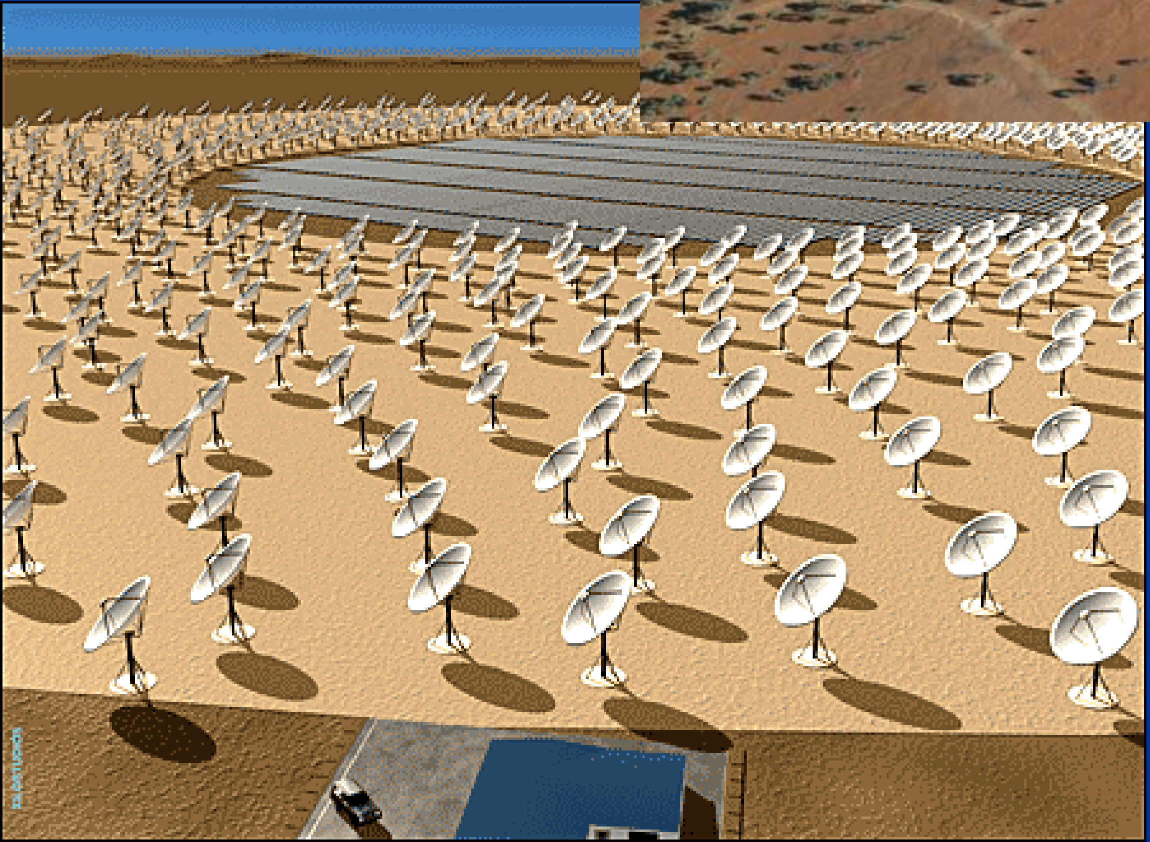
Murchison Widefield Array (MWA)

Table 1. MWA Specifications

Frequency range	80-300 MHz
Number of receptors	8192 dual polarization dipoles
Number of antenna tiles	512
Number of baselines	130,816
Collecting area	~8000 m^2 (at 200 MHz)
Field of View	~15°-50° (1000 deg^2 at 200 MHz)
Configuration	Core array ~1.5 km diameter (97% of area) + extended array ~3 km diameter (3% of area)
Bandwidth	220 MHz (Sampled); 30.72 MHz (Processed)
Spectral channels	1024 (30 kHz spectral resolution)
Temporal resolution	0.5 sec uncalibrated, 8 sec calibrated
Polarization	Full Stokes
Continuum point source sensitivity	20mJy in 1 sec (at 200 MHz full bandwidth); 0.34mJy in 1 hr
Array voltage-beams	32, single polarization

Science: 21 cm cosmology, heliosphere, transients, and Galactic physics





Square Kilometer Array
SKA

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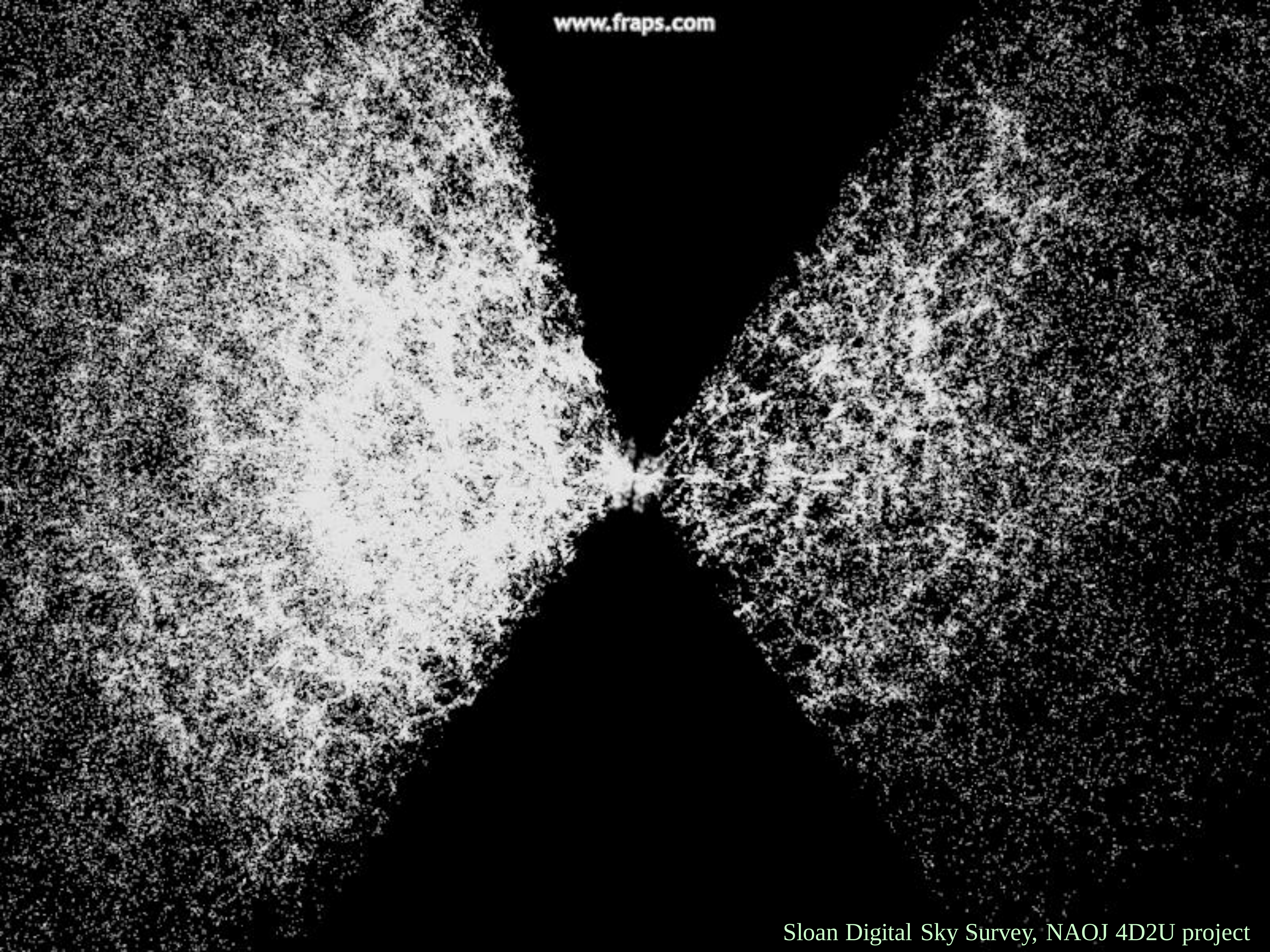
5. What is Dark Matter

- If it is a elementary particle
  - Direct detection from underground experiments
  - Create it at LHC
- Understand its nature from large scale structure formation



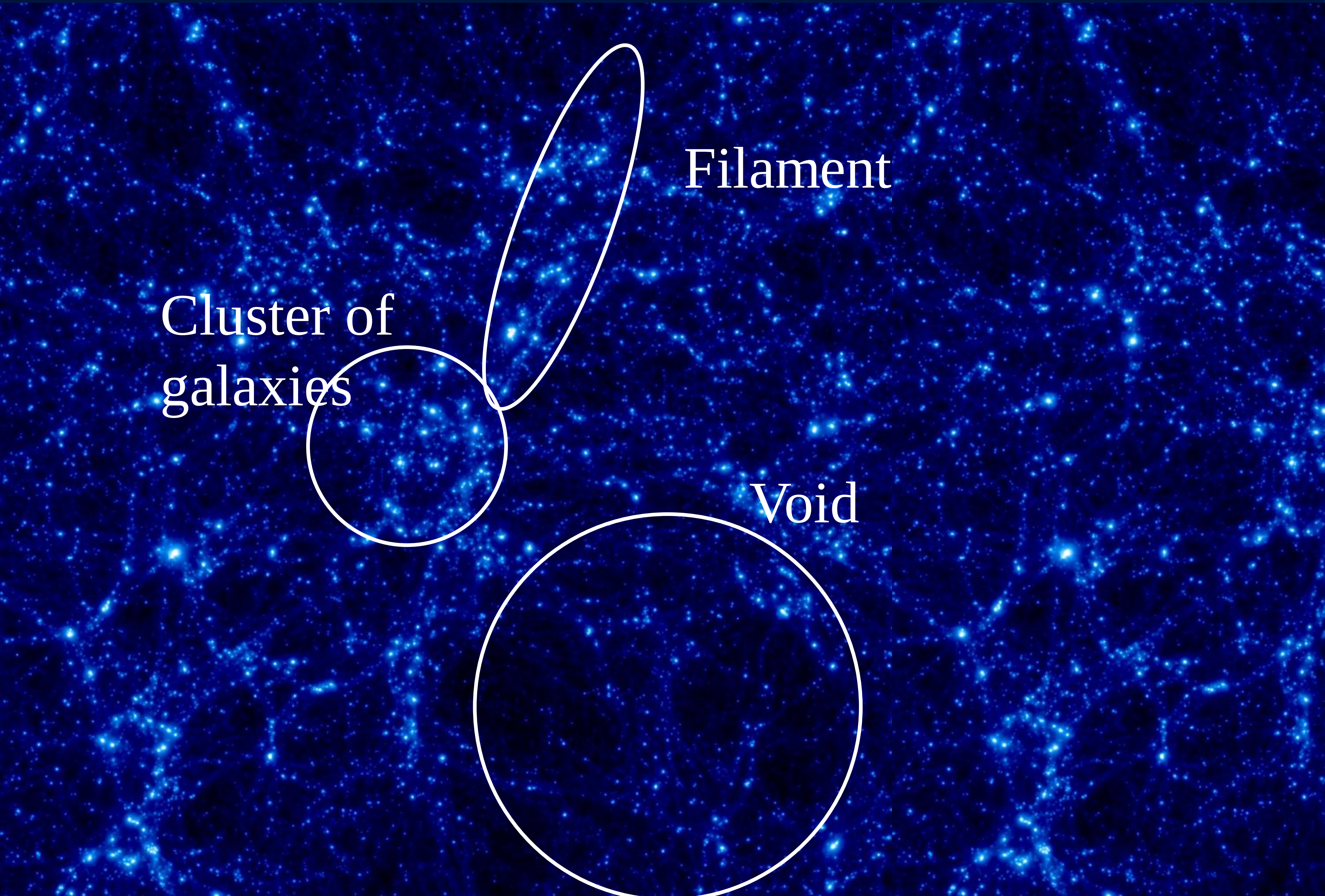
Sloan Digital Sky Survey, NAOJ 4D2U project

N-Body Simulation:
Calculate Gravity between dark matter particles

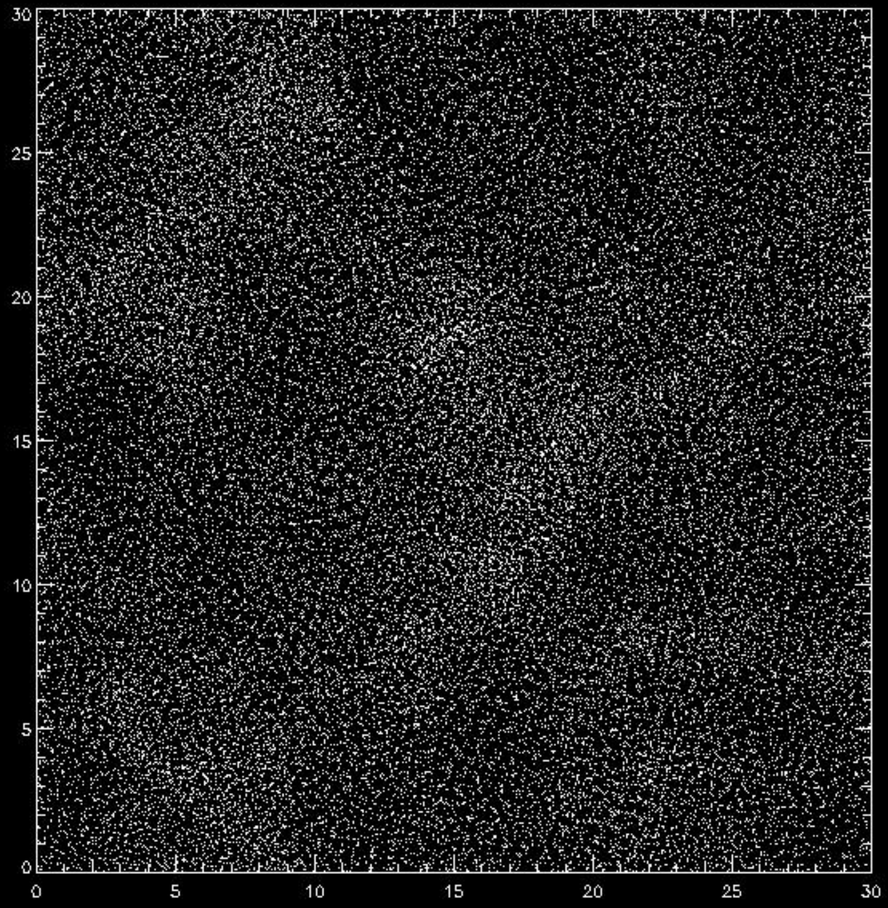
1 billion light yr.

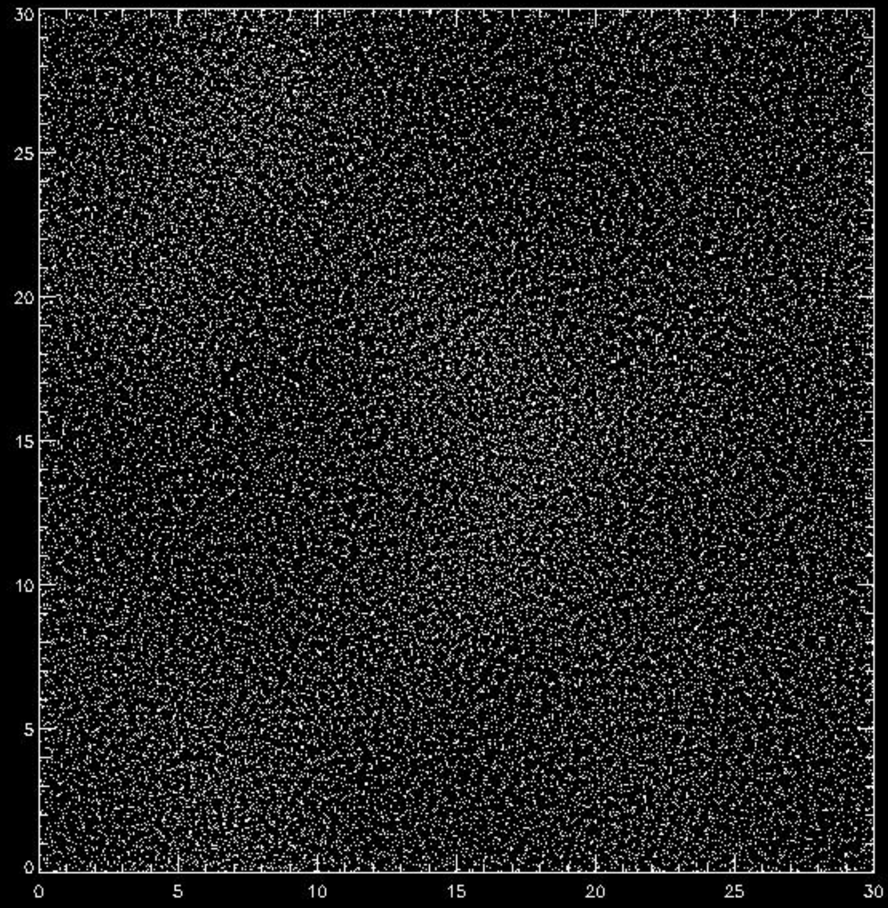
Naoki Yoshida

Large Scale Structure



Dark Matter Should be Cold (low kinetic energy)

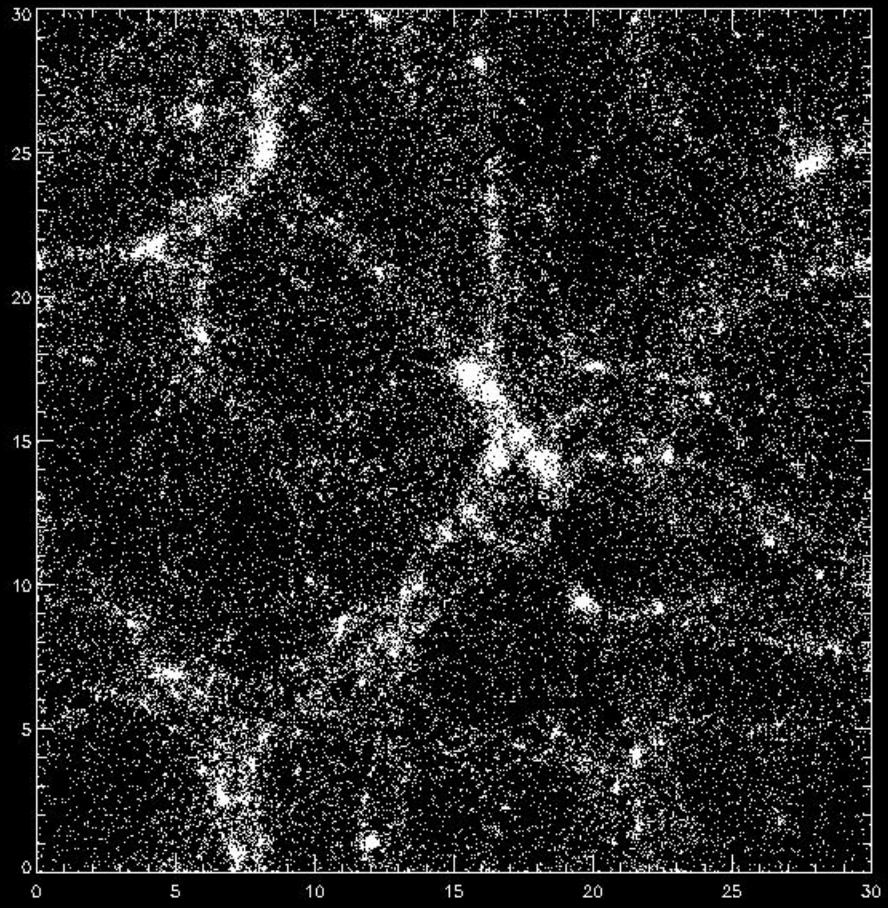


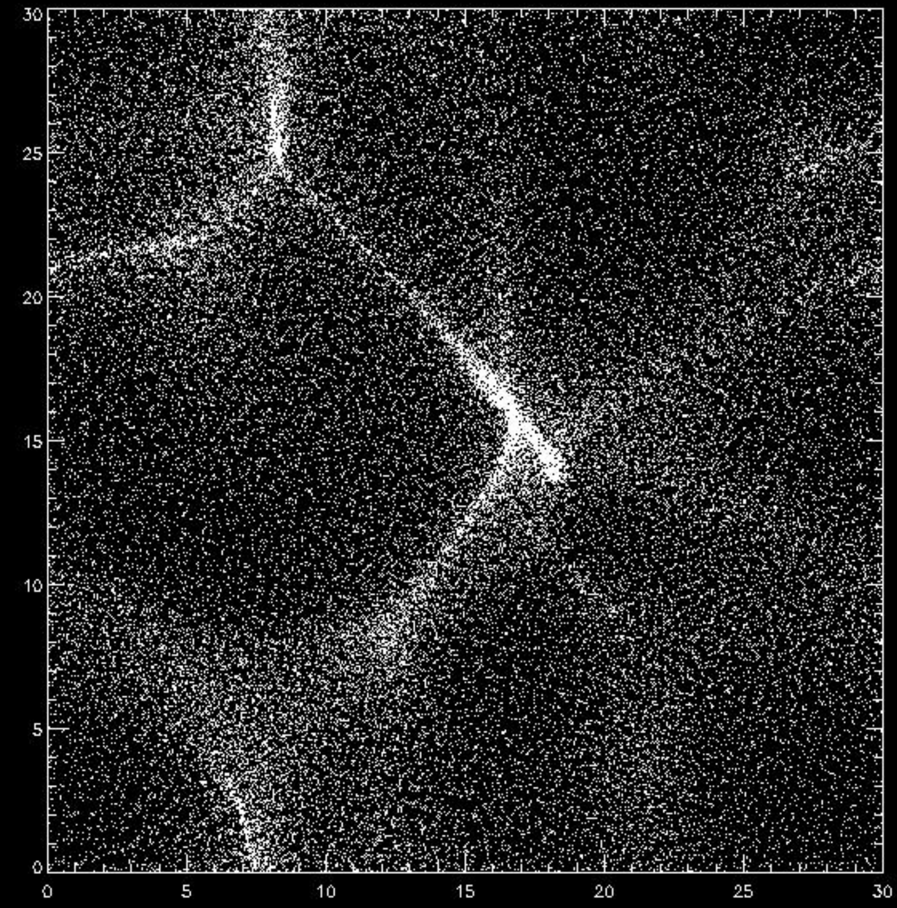


Cold Dark Matter

Neutrino as Dark Matter (Hot Dark Matter)

Numerical Simulation, at z=10

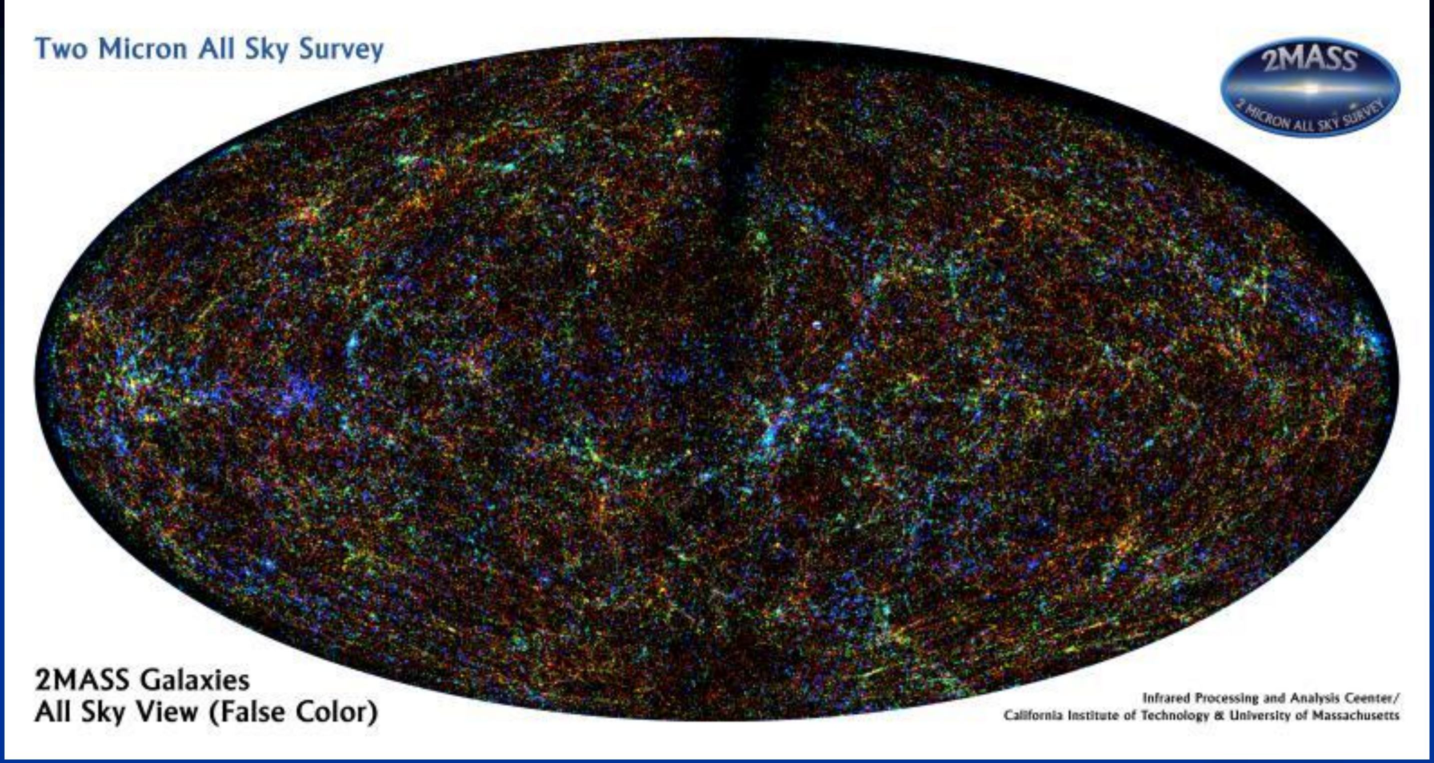


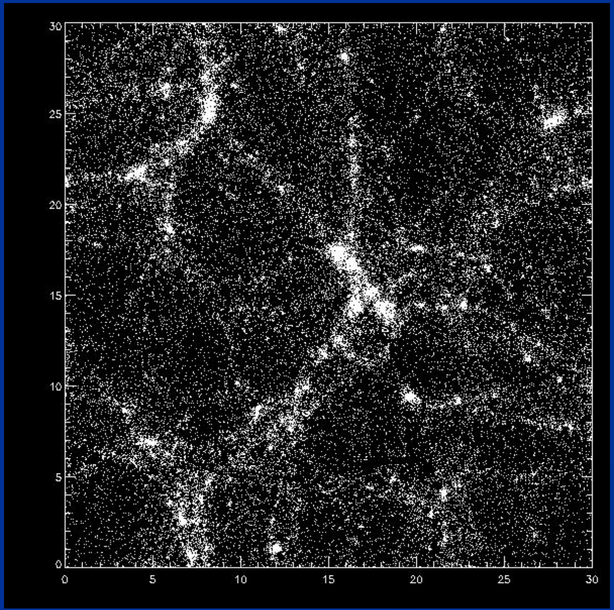


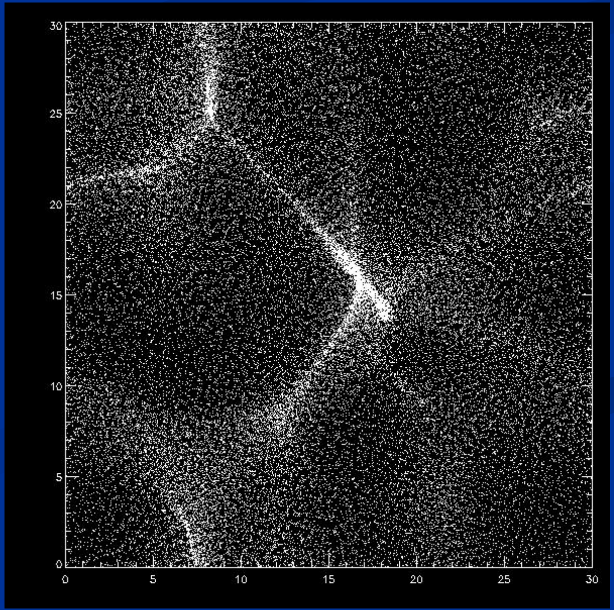
Cold Dark Matter

Neutrino as Dark Matter (Hot Dark Matter)

Numerical Simulation, at present


Two Micron All Sky Survey
2MASS
2 MICRON ALL SKY SURVEY
2MASS Galaxies
All Sky View (False Color)
Infrared Processing and Analysis Center/
California Institute of Technology & University of Massachusetts


0
5
10
15
20
25
30


0
5
10
15
20
25
30

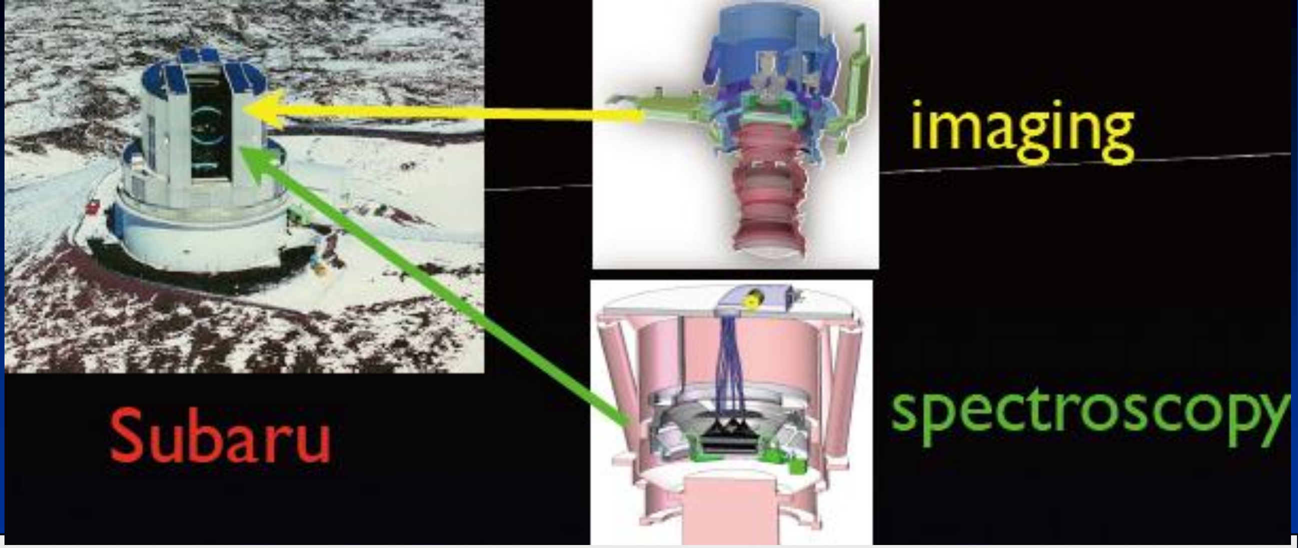
6. What is dark energy

- Measure time variation of accretion of the Universe
  - Baryon Acoustic Oscillation

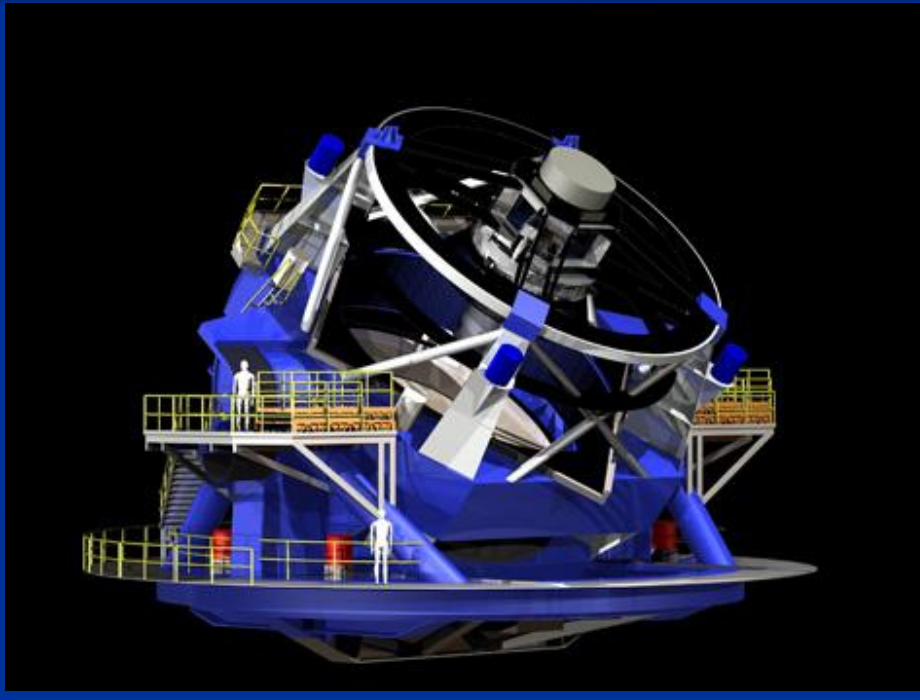
    physically known size: use as a ruler
  - Tomography of Gravitational lensing

    Time evolution of density fluctuations
  - Observe Many emission lines in 10 years of separation

    direct observation of expansion



Wide Field Camera + Multi-Fiber Spectrograph
Subaru Measurement of Images and Redshifts (SuMIRe)



LSST
Specially Designed 8.4m Telescope: Ultra-Wide field

Thirty Meter Telescope (TMT)

Summary

What we have understood

- Contents of the Universe (cosmological parameters)

  Dark energy density Ω_Λ, Matter density Ω_M , Curvature Ω_K, Hubble parameter H_0 (h), Baryon density Ω_B : $\Omega_K = 1 - \Omega_\Lambda - \Omega_M$
  - Temperature Fluctuations of CMB
    - COBE/WMAP
    - Precise measurement of Matter, Baryon and Curvature (but they are degenerate, need additional probe)
  - Supernovae Survey
    - Measurement of dark energy
  - Gravitational lensing
    - Strong lensing: Proof of dark matter
    - Weak lensing: Tracer of large scale structure

What we have understood (cont.)

- Mapping the universe by galaxy survey
  - 2dF/SDSS
  - Baryon Acoustic Oscillation
- The most distant galaxy and reionization
  - Ly-alpha emitter by Subaru: z=6.9
  - Gamma ray burst: z=8.2
  - HST/Wide Field Camera 3: z~8-8.5
  - Reionization was completed by z~6 (SDSS-QSO)
  - WMAP polarization: reionziation at z~10

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It is still long way to go to understand the Universe
But observationally, a lot to come, stay tune!