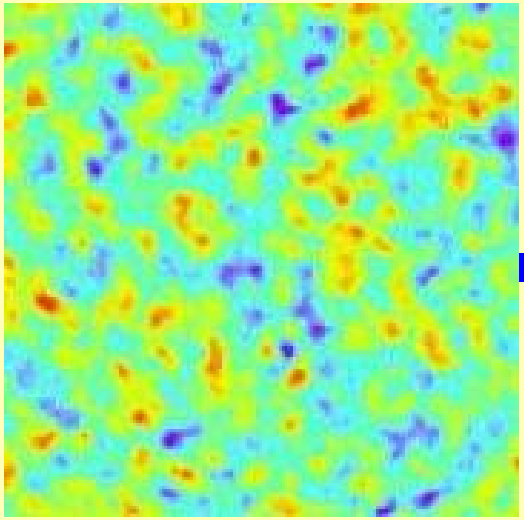
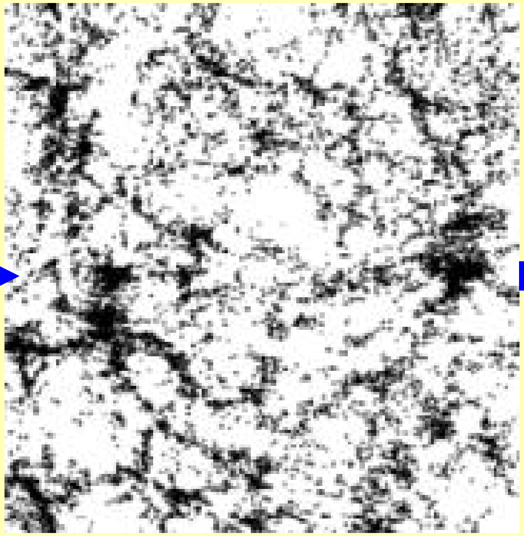
The Early Universe





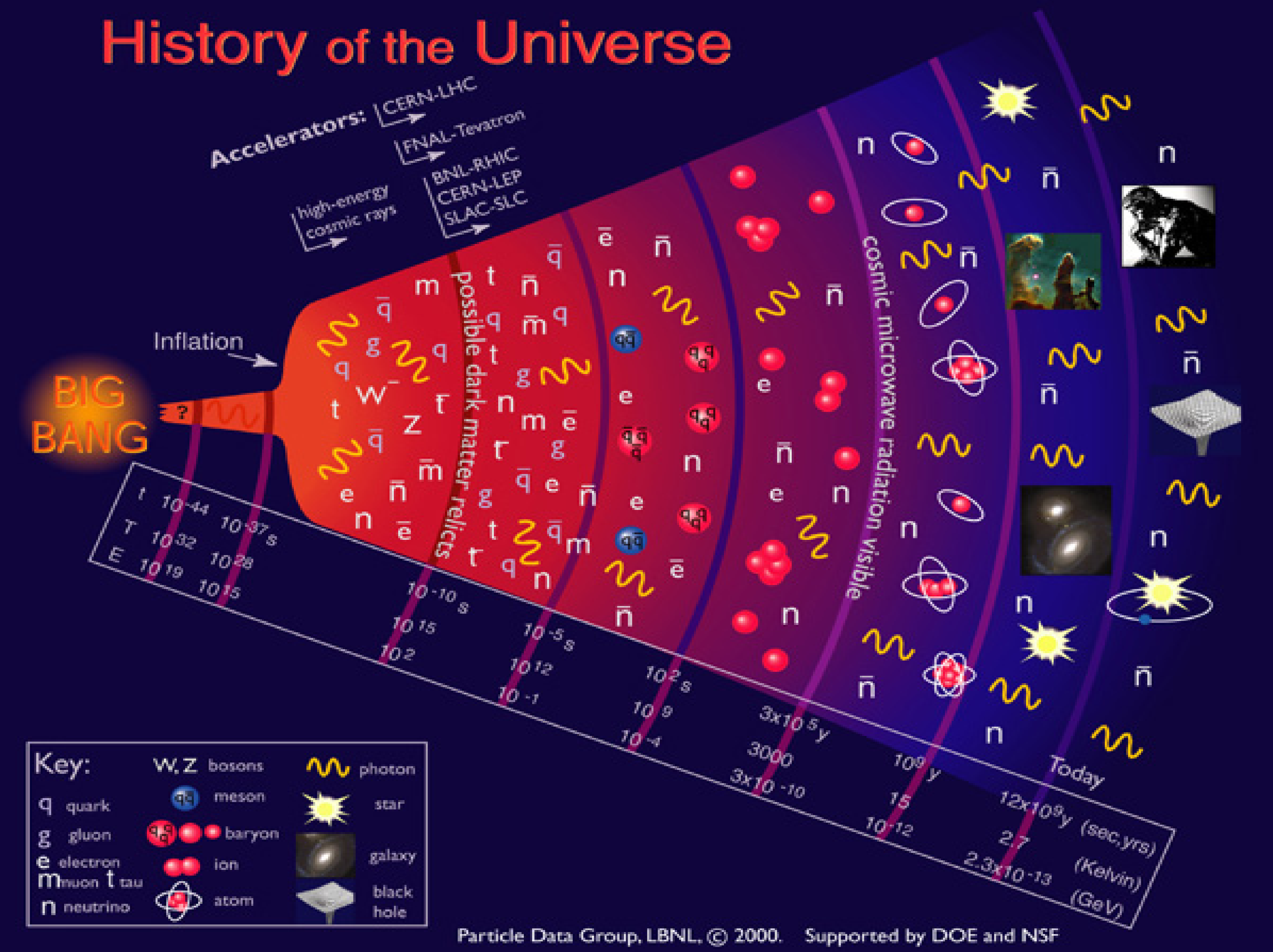
John Peacock

ESA Cosmic Vision

Paris, Sept 2004

The history of modern cosmology

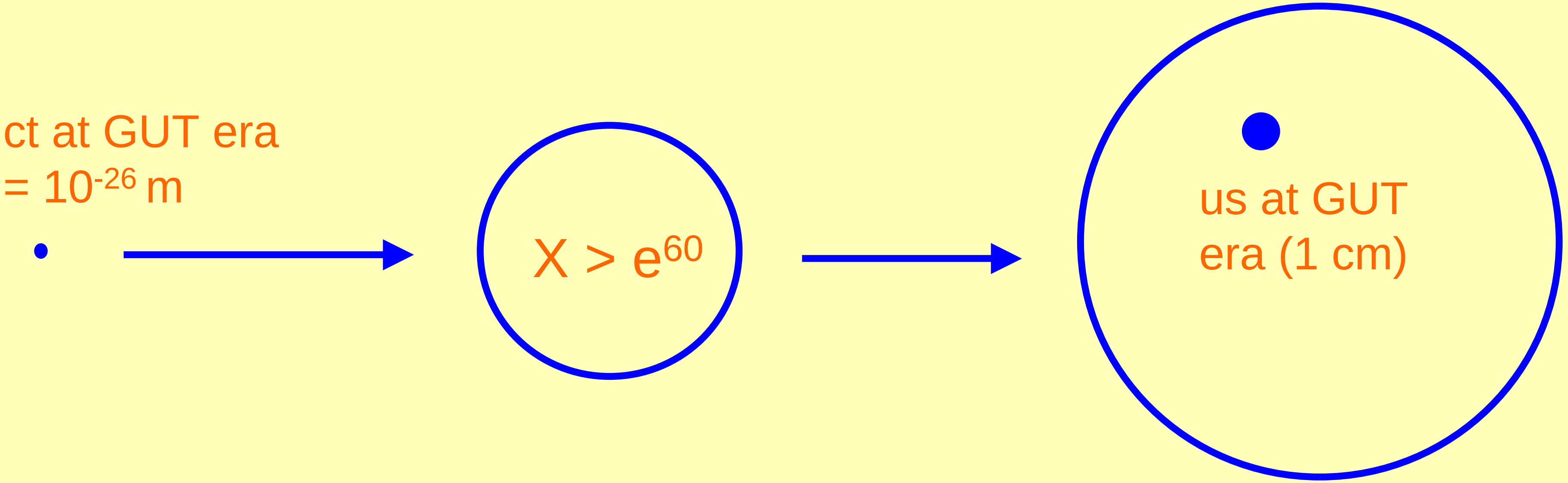
- 1917 Static via cosmological constant? (Einstein)
- 1917 Expansion (Slipher)
- 1952 “Big Bang” criticism (Hoyle)
- 1965 Microwave Background (Penzias/Wilson)
- 1970s Primordial Nucleosynthesis: 25% He
  - Hot Big Bang is observed to $T = 10^{10}$ K
- 1980 Inflation
- 1990s ‘Standard model’ dominated by vacuum energy and cold dark matter
- 2020 ???


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

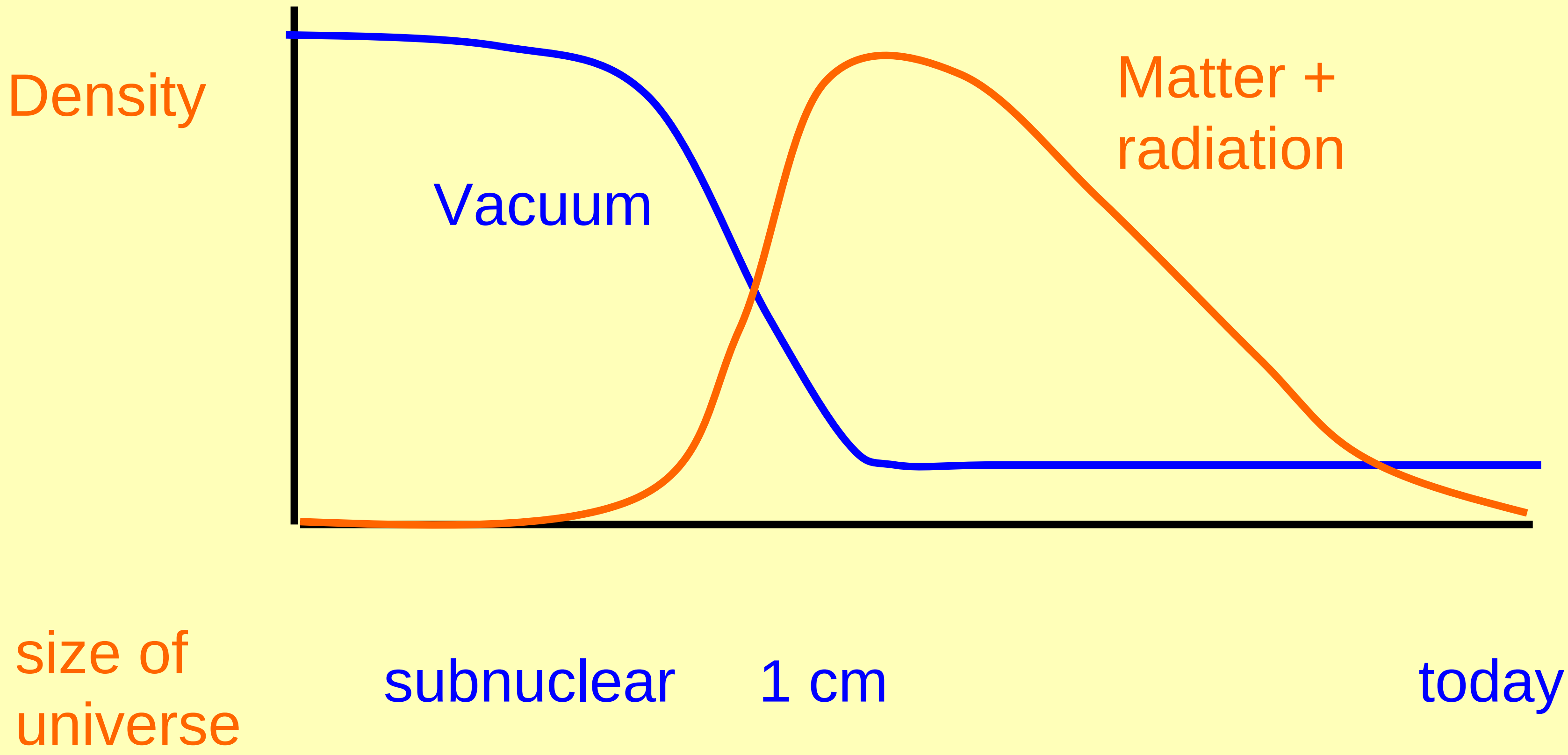
Evading the singularity

- Quantum gravity limit:
  - GR invalid before $t = 10^{-43}$ s ($E = 10^{19}$ GeV)

- 1980: Inflation
  - Use effective high vacuum density at GUT era ($E = 10^{15}$ GeV, density = 10^{80} kg m^{-3})
  - Vacuum ‘antigravity’ drives exponential expansion

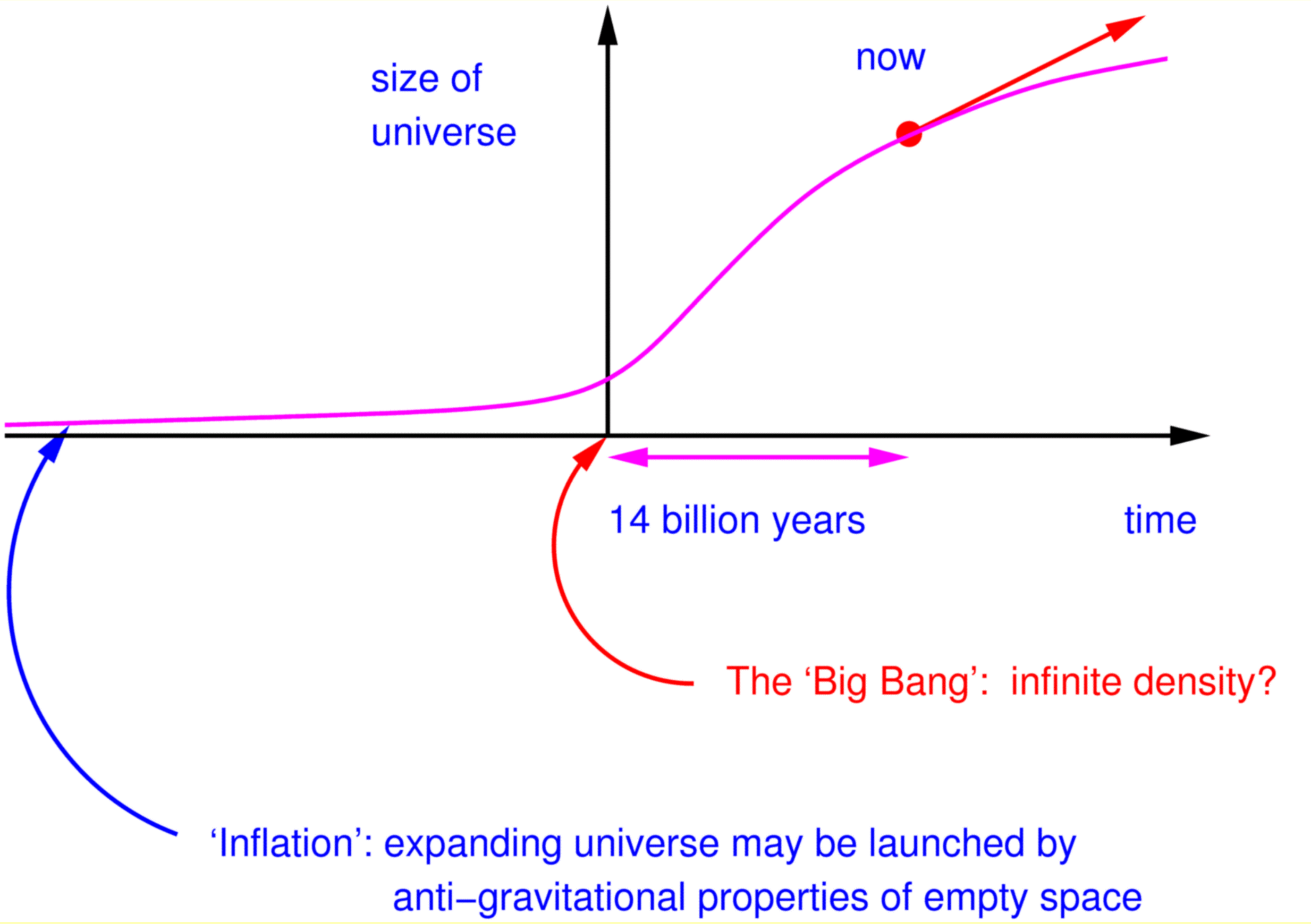


The History of the vacuum?

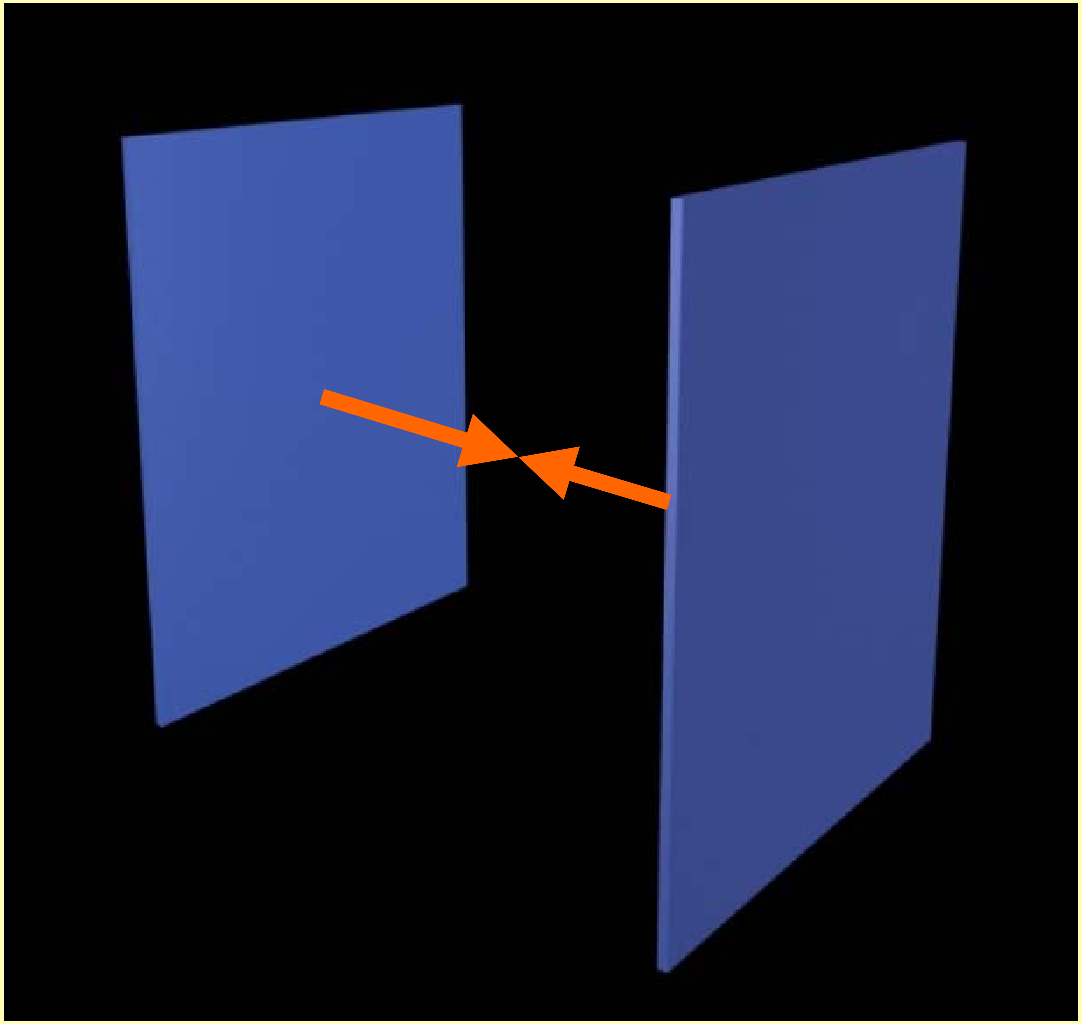


variable vacuum from a new scalar field?

History of the expansion in inflation



Alternative: colliding branes

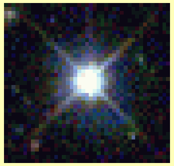


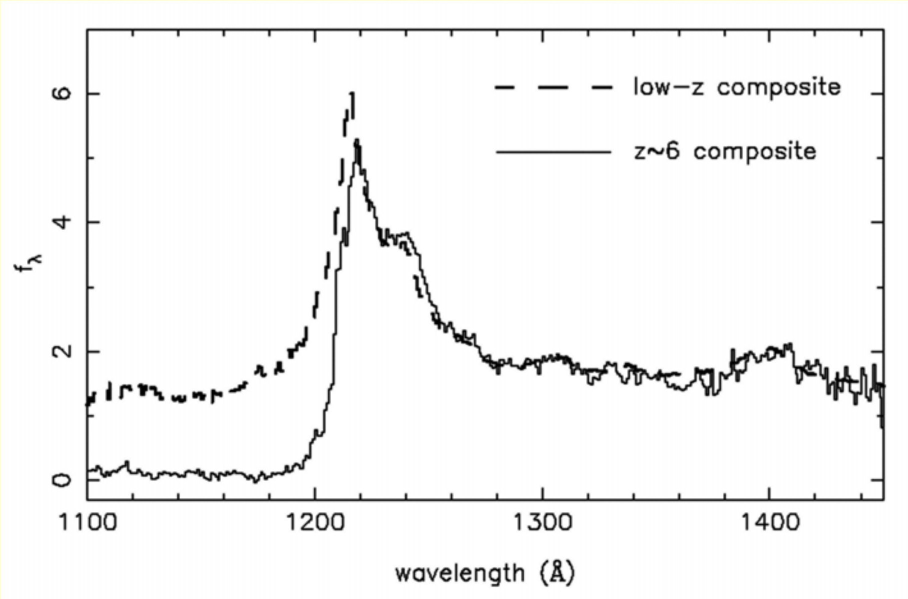
Steinhardt, Turok et al. :

'Ekpyrotic' or cyclic universe motivated by extra dimensions in string theory

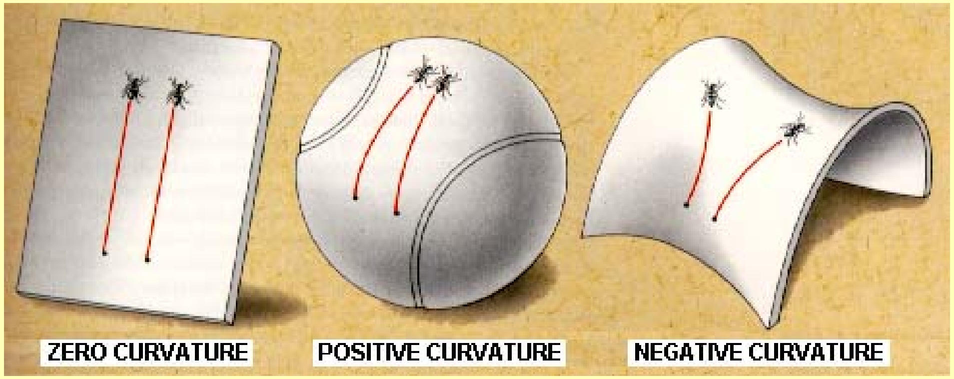
What do we observe?

- Expanding universe scale factor R(t)
- Hubble: v = H D (h = H / 100 km s^{-1} Mpc^{-1})
- Redshift: $1 + z = R_{now} / R_{then}$
- most distant quasars z = 6.4





- microwave background z = 1100
- Ω = density / critical for flat

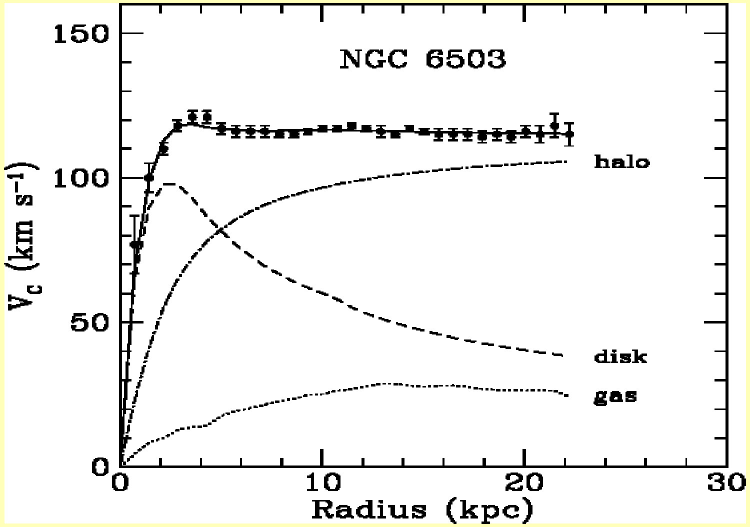


- $\Omega_m = \Omega_{baryons} + \Omega_{dark}$ (= 0.25 ± 15%)
- Inflation $\Rightarrow$ flat $\Rightarrow$ $\Omega_m + \Omega_{vacuum} = 1$

Relics of early / initial phases?

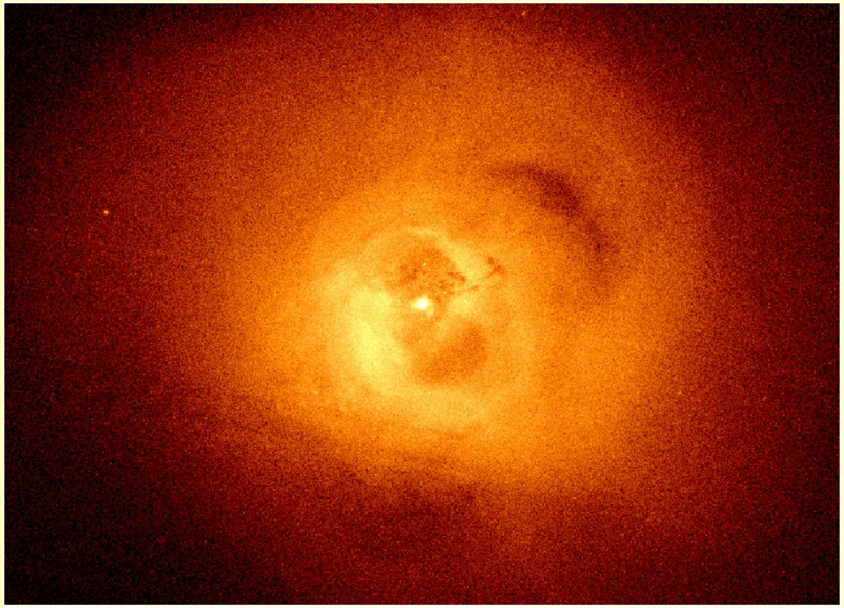
- Baryon asymmetry
- Dark Matter
- Vacuum energy
- Cosmic structure
  - CMB
  - Large-scale clustering
  - Galaxy Formation

Dark Matter



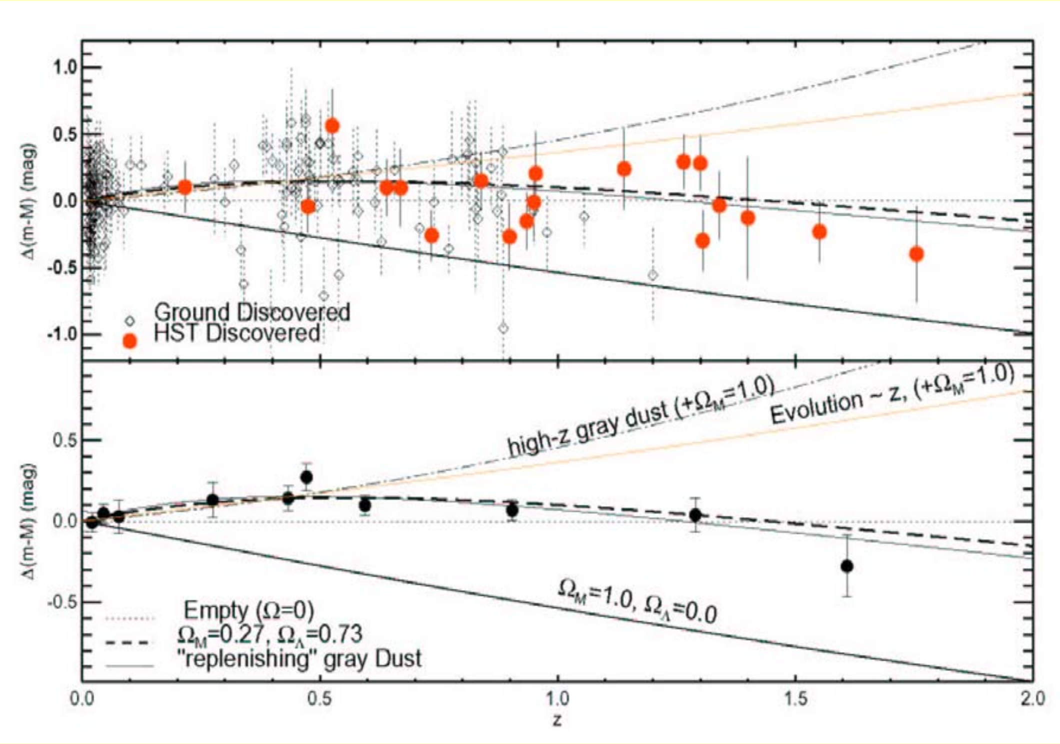
- Seen in spiral rotation curves
- In clusters, gravitational lensing gives total mass and X-rays from IGM gives baryon mass

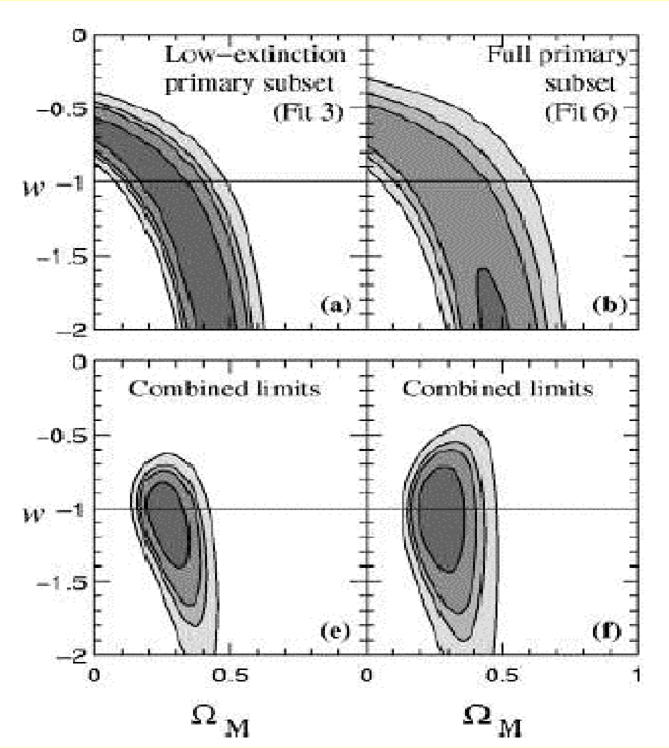
- $M_{total} / M_{baryons}$ ' 10



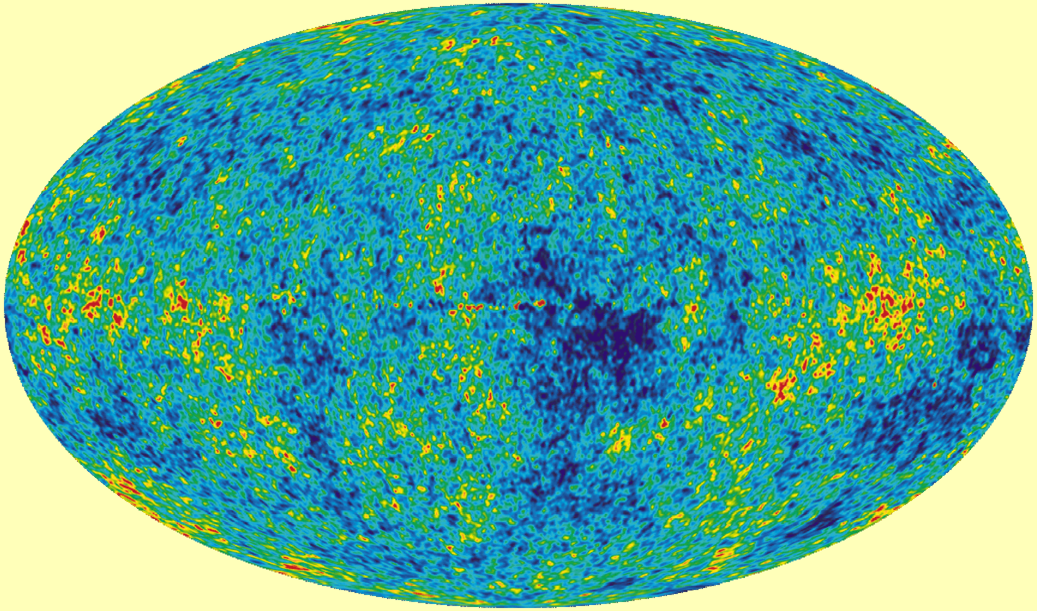
Vacuum energy

- Λ: antigravity from negative pressure ($P = -\rho c^2$): seen with Supernovae $\Rightarrow$ Ω_m ' 0.3 Ω_v ' 0.7 if flat
$$\nabla^2\Phi = 4\pi G(\rho + 3P/c^2)$$
- 'Dark Energy': generalize to $P = w \rho c^2$: degeneracy between w & Ω_m. w = -1 ± 15% with CMB/LSS

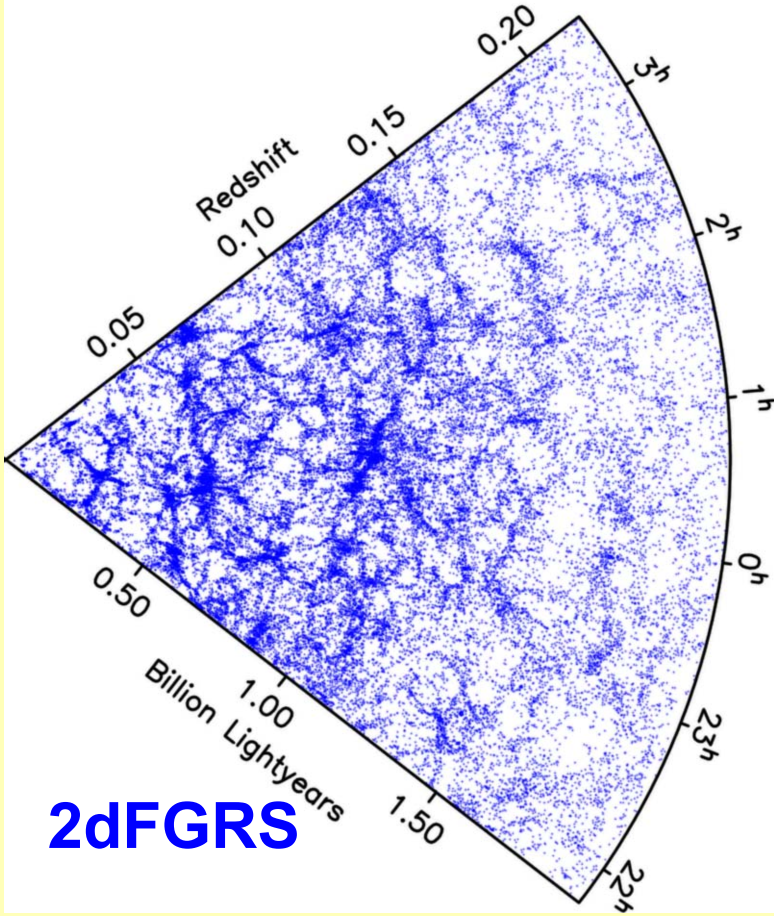




Cosmic structure



WMAP



2dFGRS

- In combination, standard model for cosmology:
  - Flat: $\Omega_m + \Omega_v = 1 \pm 0.02$
  - $\Omega_m = 0.25 \pm 15\%$; $h = 0.73 \pm 5\%$

Weighing the universe with horizons

Growth of structure is affected by pressure on small scales

$\Rightarrow$ **Horizon scale $c_{sound}\, t$ / $c\, t$ = D_H leaves imprint in late-time structure**

Three key eras:

(1) Matter-radiation equality (z=23,900 $\Omega_m\, h^2$): $D_H = 16\, (\Omega_m\, h^2)^{-1}$ Mpc

(2) Last scattering (z=1100): $D_H = 184\, (\Omega_m\, h^2)^{-1/2}$ Mpc

(3) Today (z=0): $D_H = 6000\, \Omega_m^{-0.4}\, h^{-1}$ Mpc

- **100-Mpc 'break' in LSS from (1)**
- **1-degree scale on CMB sky from (2) / (3)**

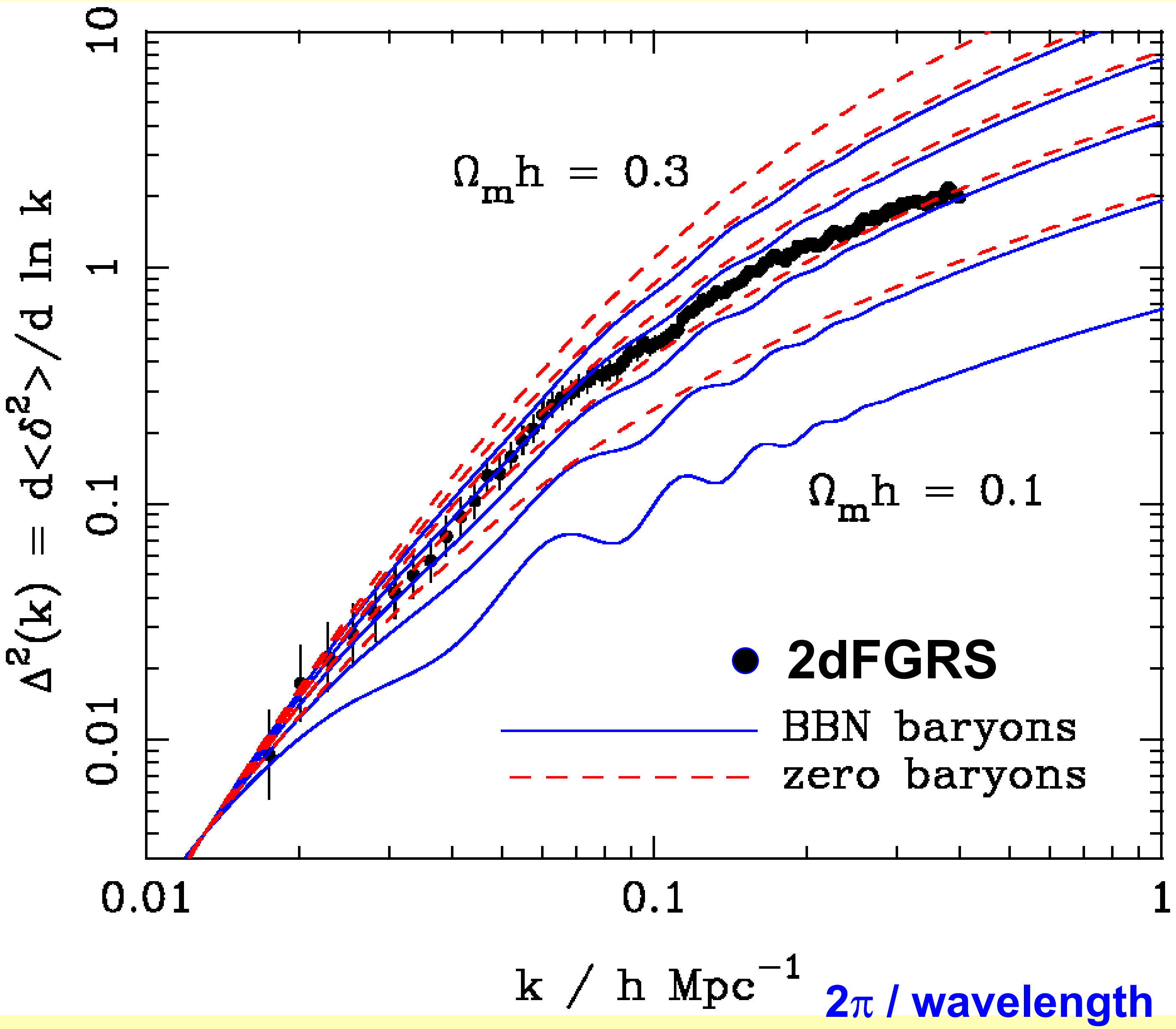
Galaxy power spectrum

Dimensionless power:

d (fractional variance in density) / d ln k

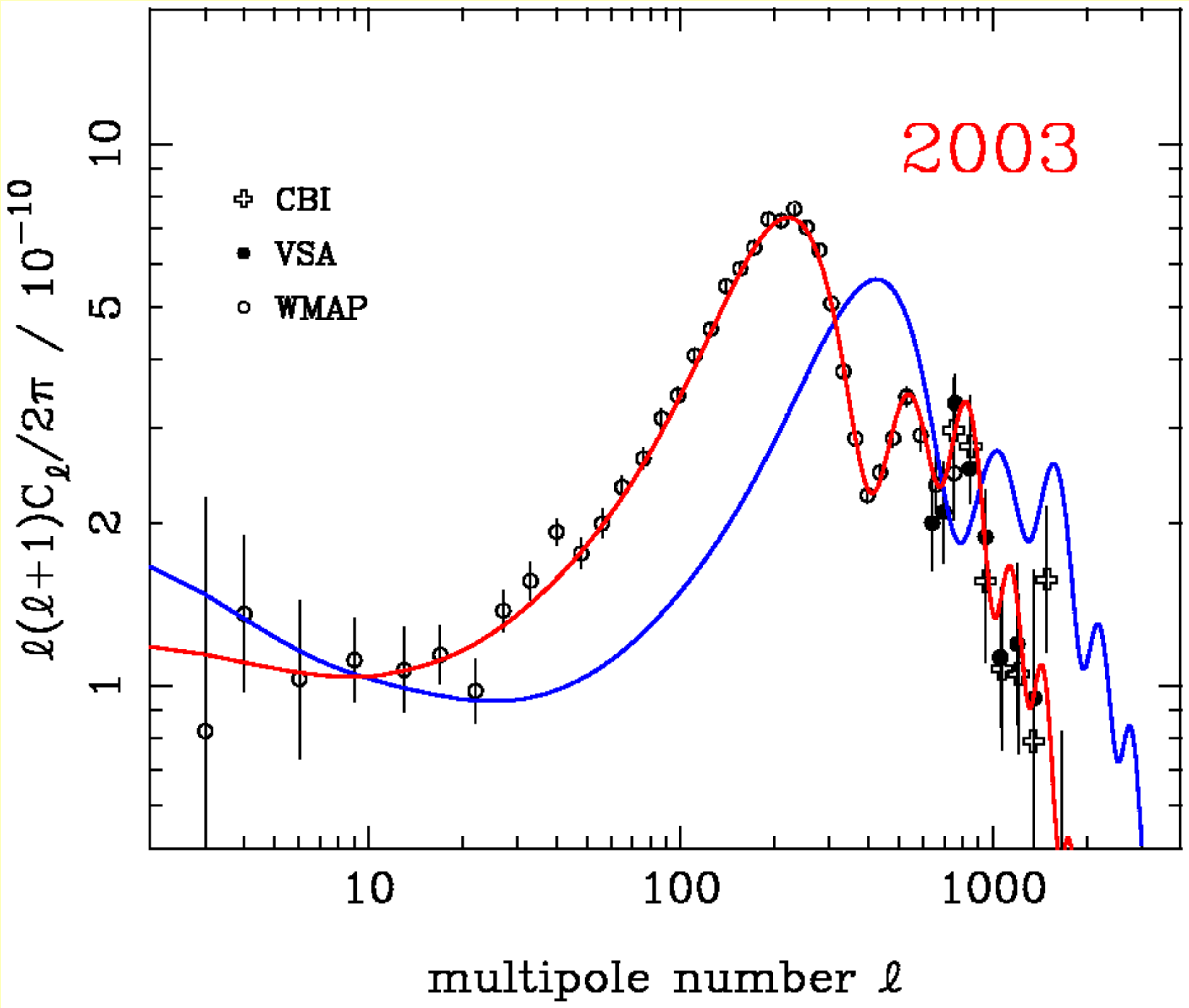
Note no large oscillations: pure baryon universe disfavoured

Percival et al. MNRAS 327, 1279 (2001)



CMB power spectrum

variance in T



Flat $\Omega_m = 0.3$ (vacuum dominated)

Open $\Omega_m = 0.3$ (no vacuum)

Principal Questions

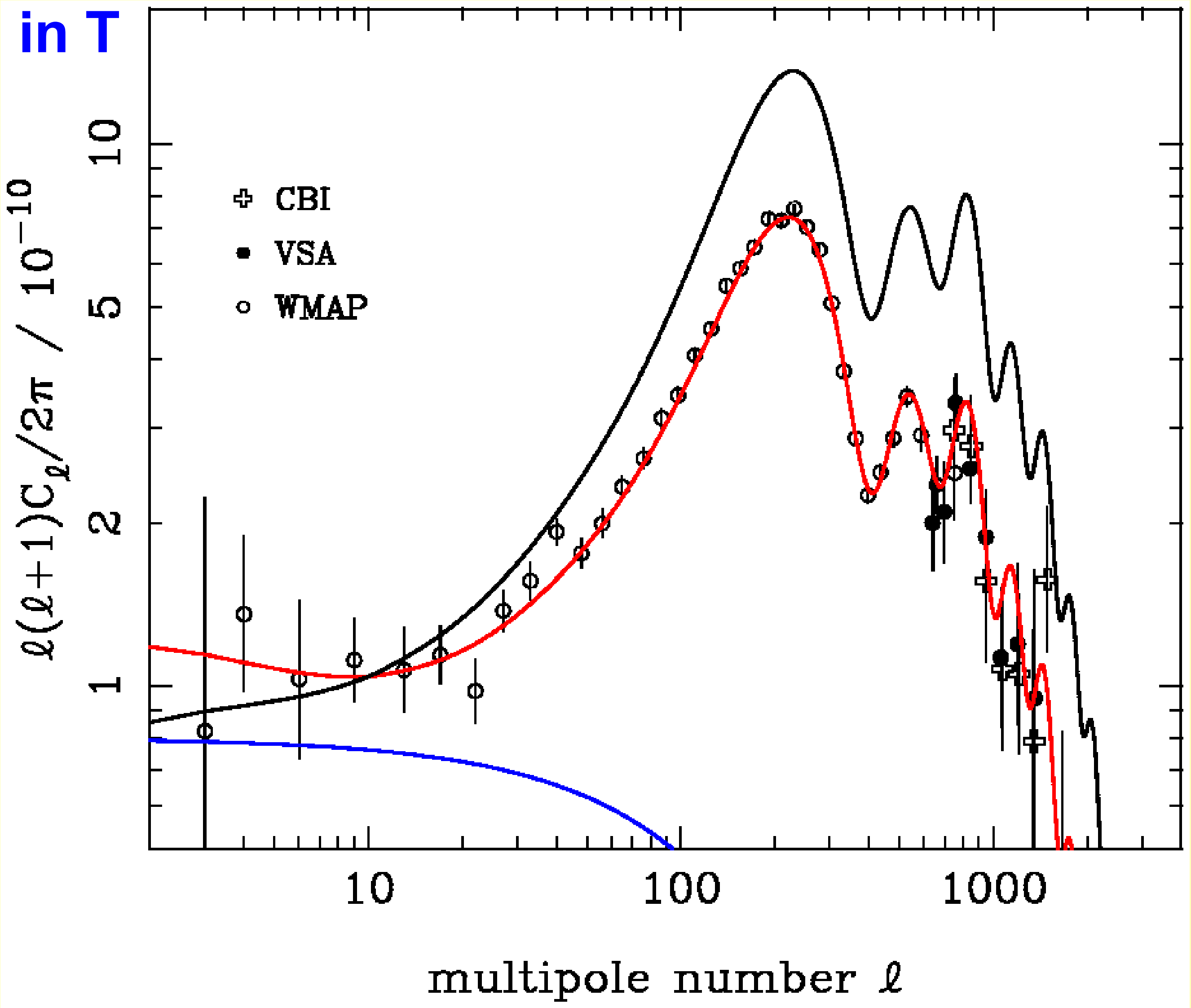
- Dark Matter – is it a WIMP?
  - Detect in accelerators (new) underground (relics)
  - Or via free-streaming scale in LSS for non-standard mass
- Vacuum – is it Λ or dynamical?
  - measure $w = P / \rho c^2$ and evolution with z
- Is there evidence for inflation (or an alternative such as extra dimensions) ?
- Can we connect initial conditions to galaxy formation?
  - Combine large-scale structure & CMB

Tools

- SNe: use sqrt(n)   [but need type and extinction]
- CMB
  - Temperature maps
  - Polarization
- Structure formation
  - Large-scale clustering and evolution
  - Observing formation of galaxies
- Gravitational lensing
  - See DM directly and relation to light

CMB: signatures of inflation

variance in T



(1) Tilt:

Degenerate with matter content

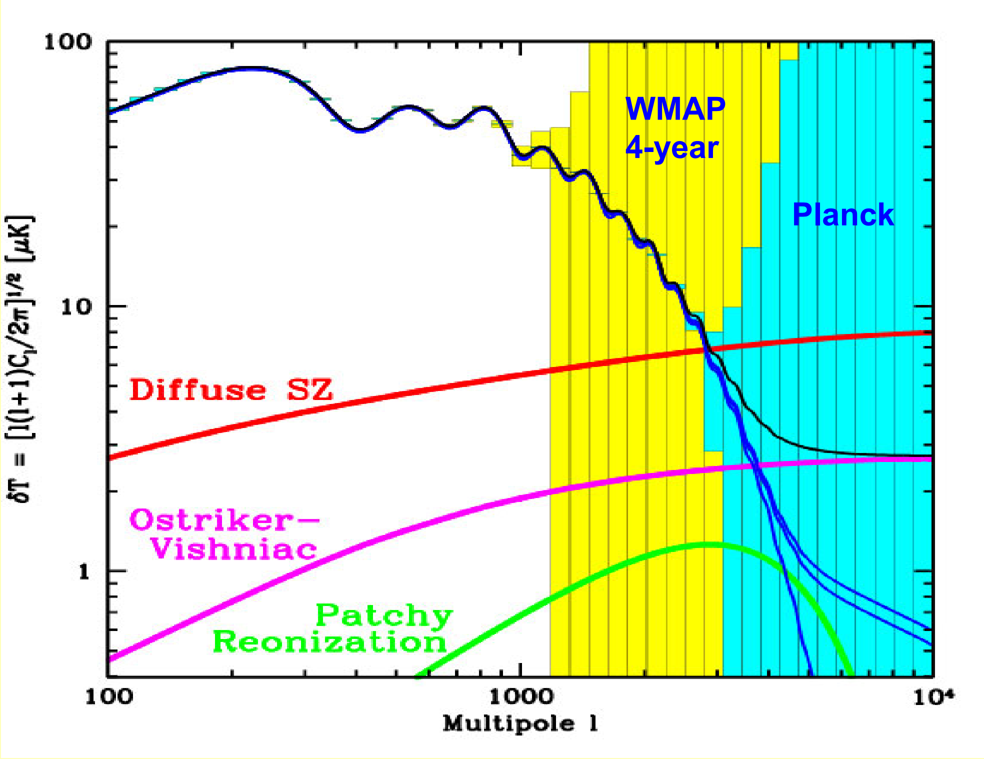
spectrum / k^{n-1}
now: n = 0.98 ± 0.02
target: Δn = 0.01

(2) Tensors:

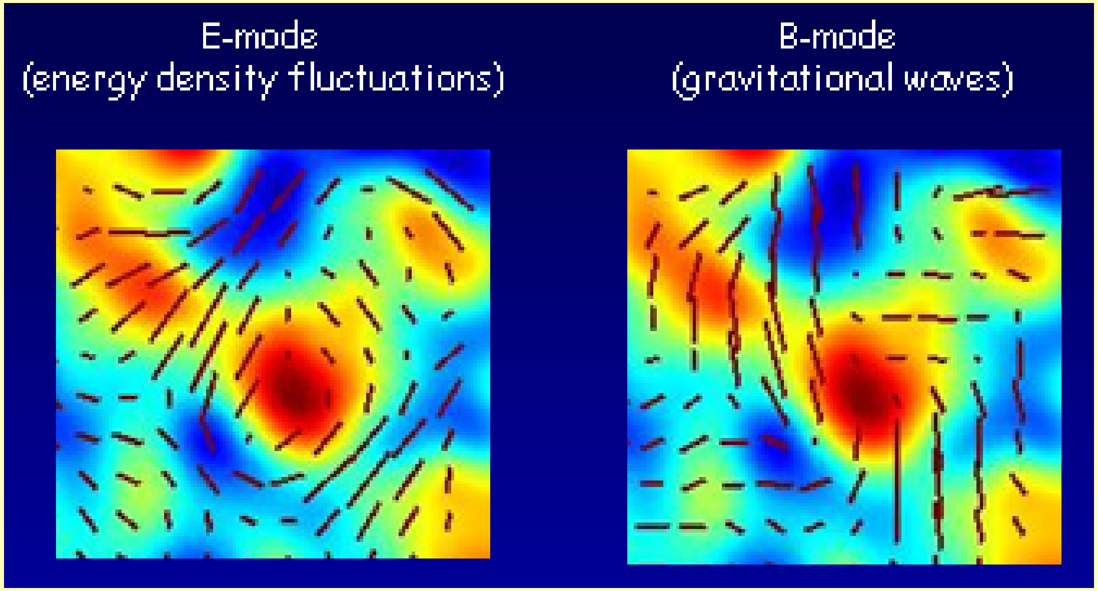
Primordial gravity waves. Large scales only

now: r = T/S < 0.5
target: r = 10^{-3}

CMB Outlook



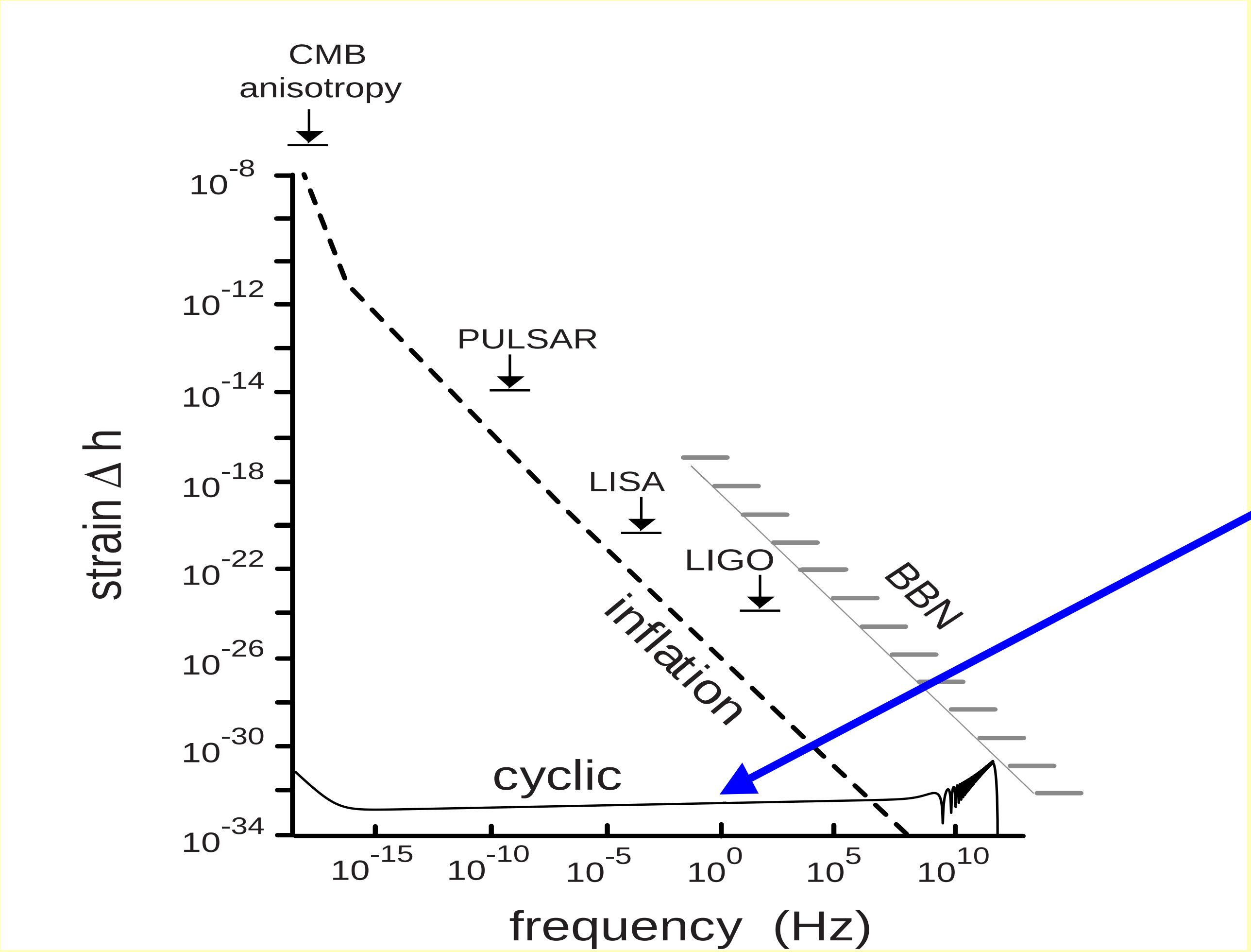
Planck will measure T fluctuations perfectly to multipole ~3000, where nonlinear foregrounds enter



Detection of tensors will require detailed measurements of CMB polarization

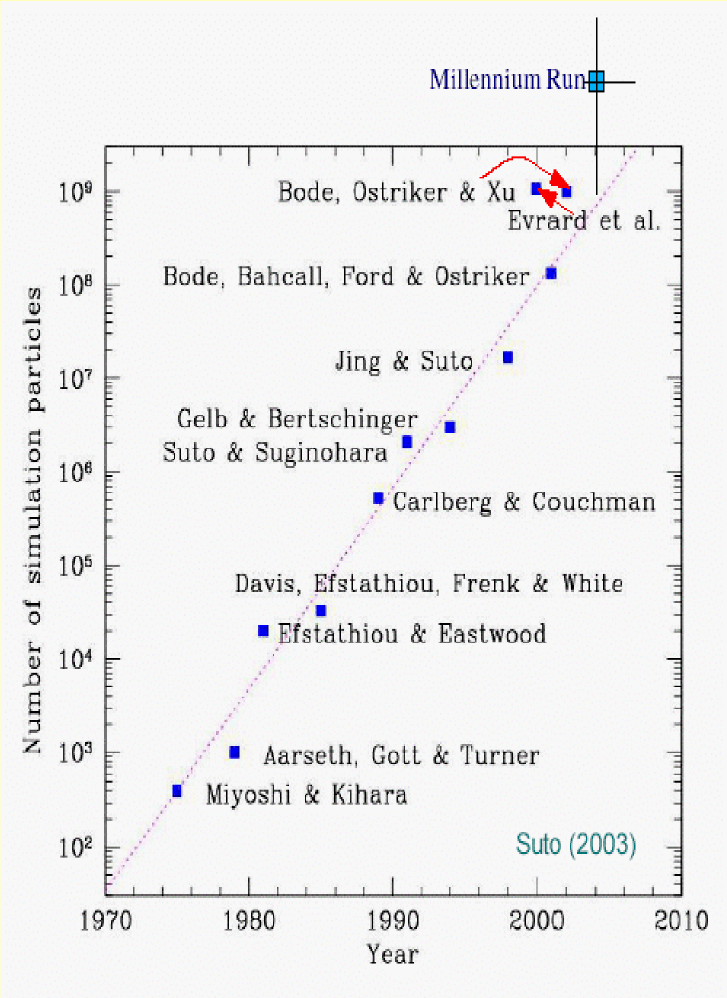
→ Puget

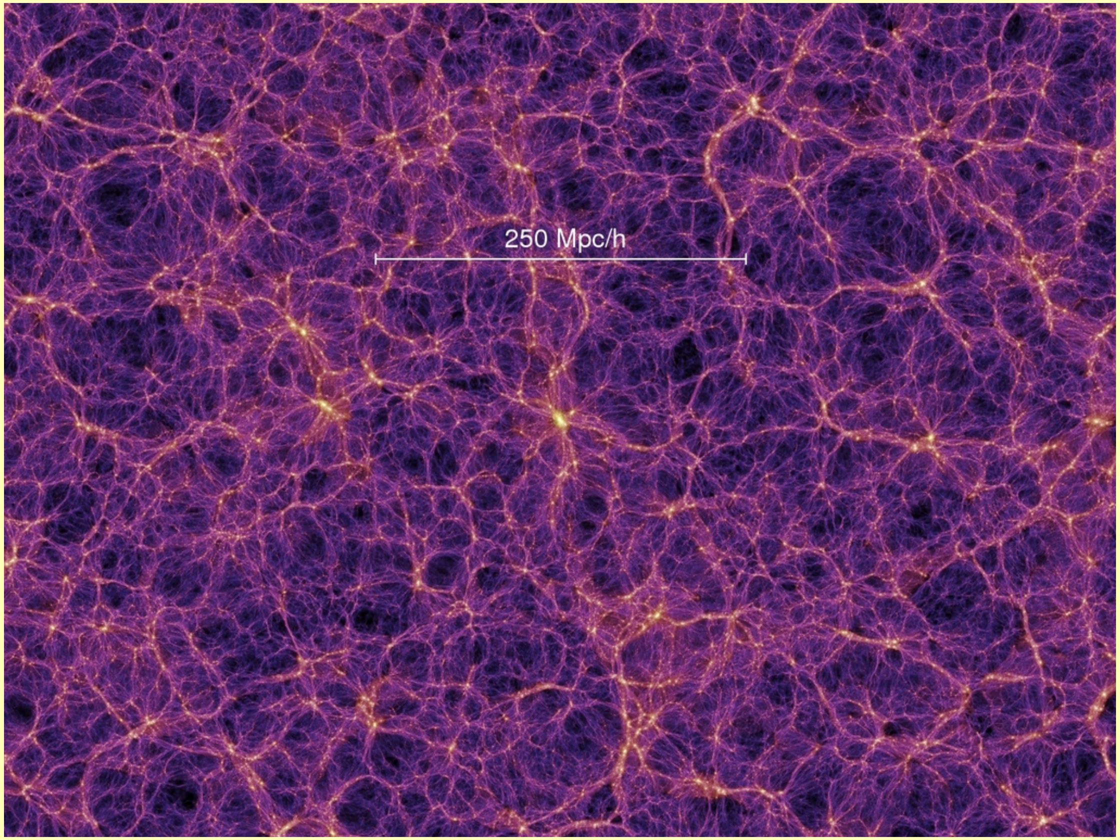
– or direct detection of gravity-wave background?



models with extra dimensions predict high-frequency GW only

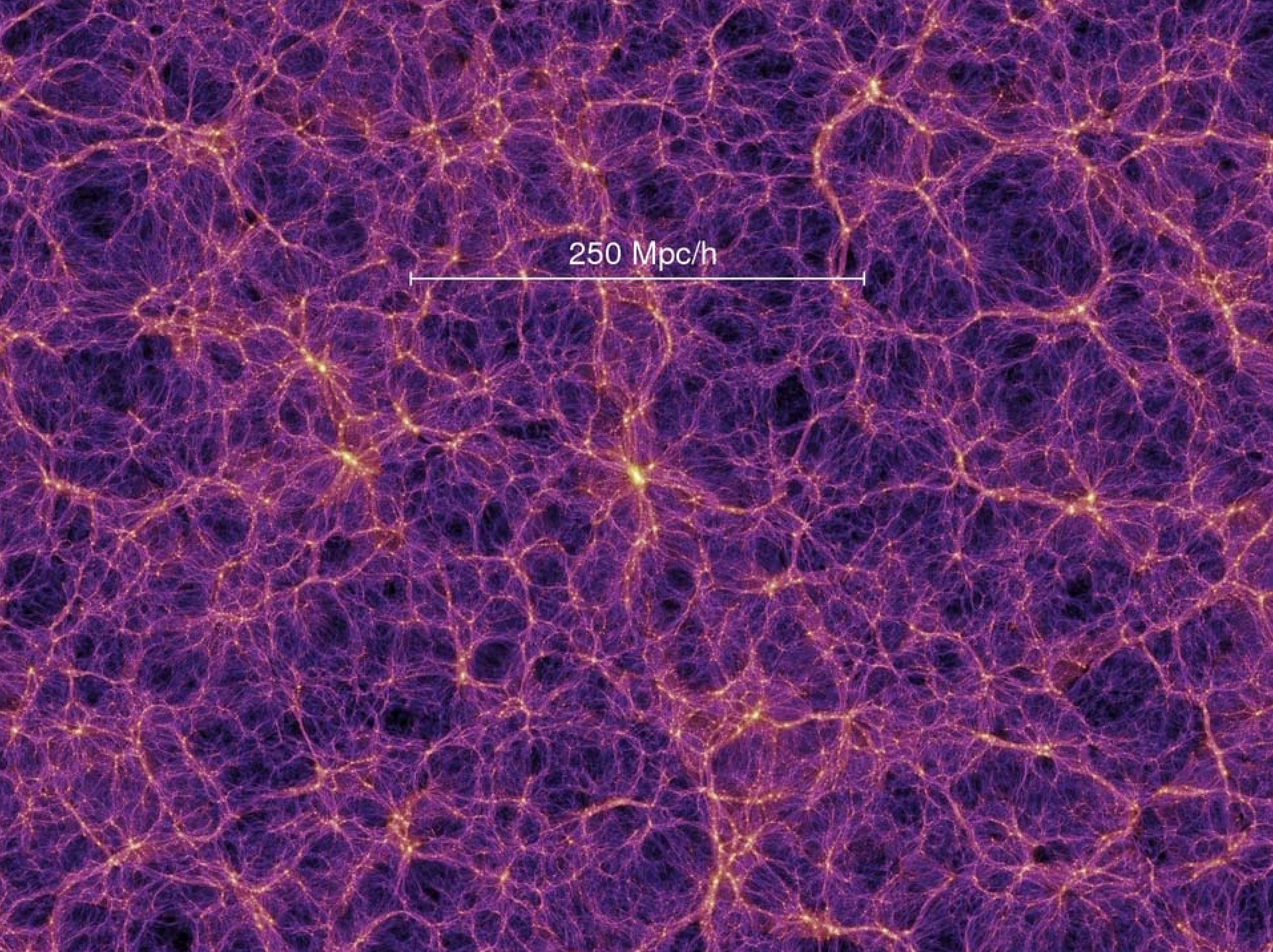
Numerical structure formation

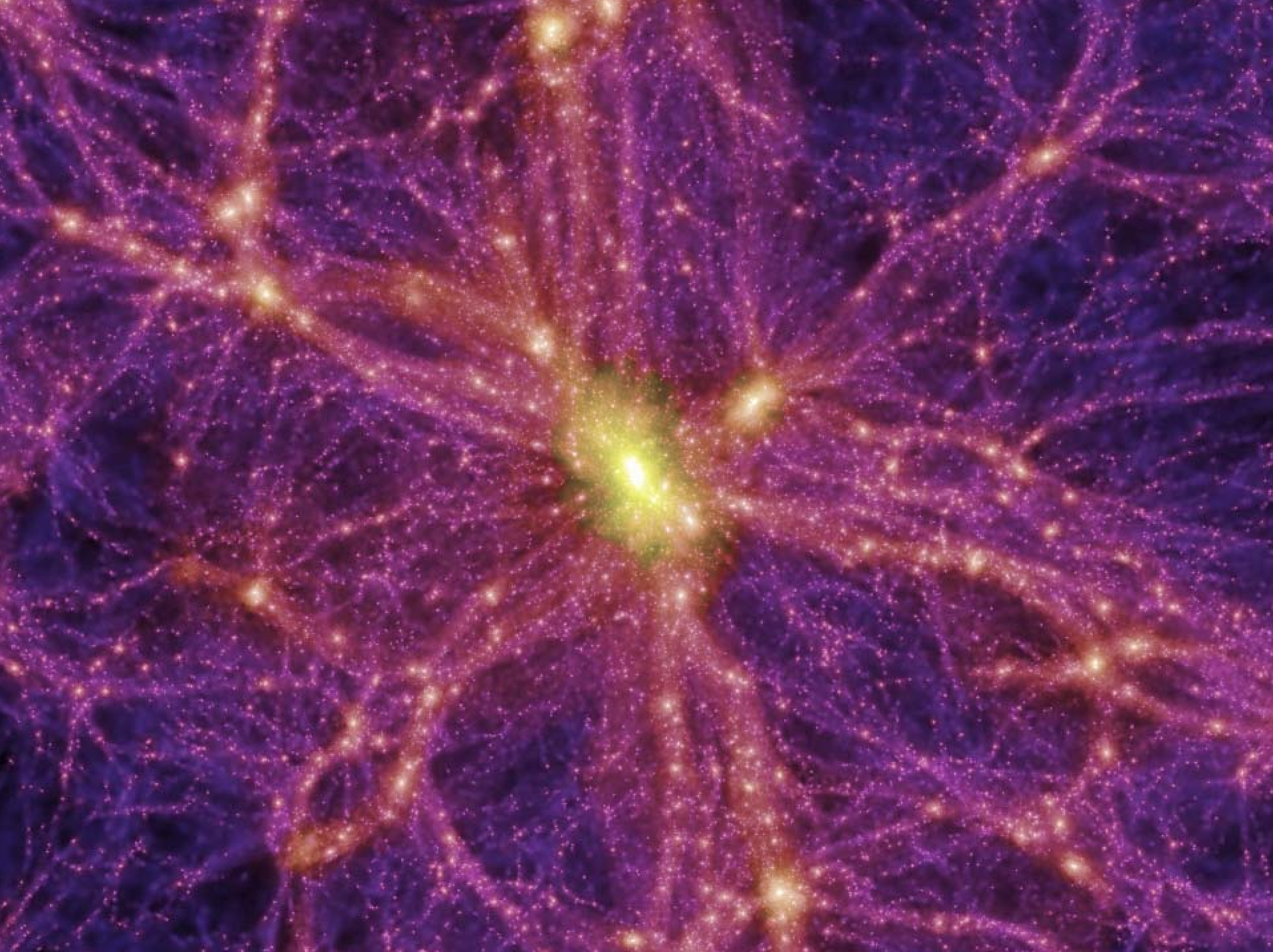




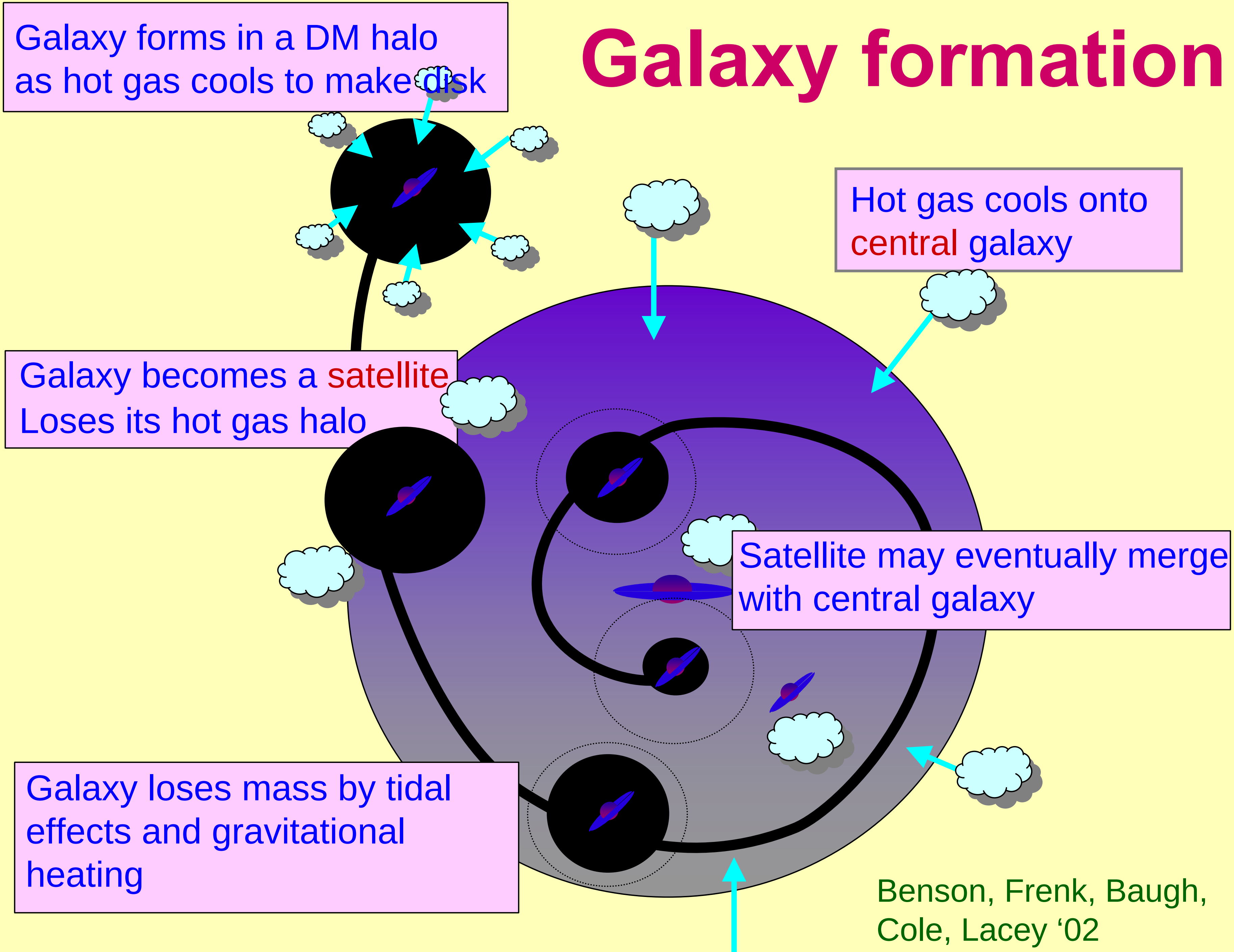
European leadership: 10^{10} particles from Virgo Consortium's 'Millennium Run'

VIRGO


250 Mpc/h

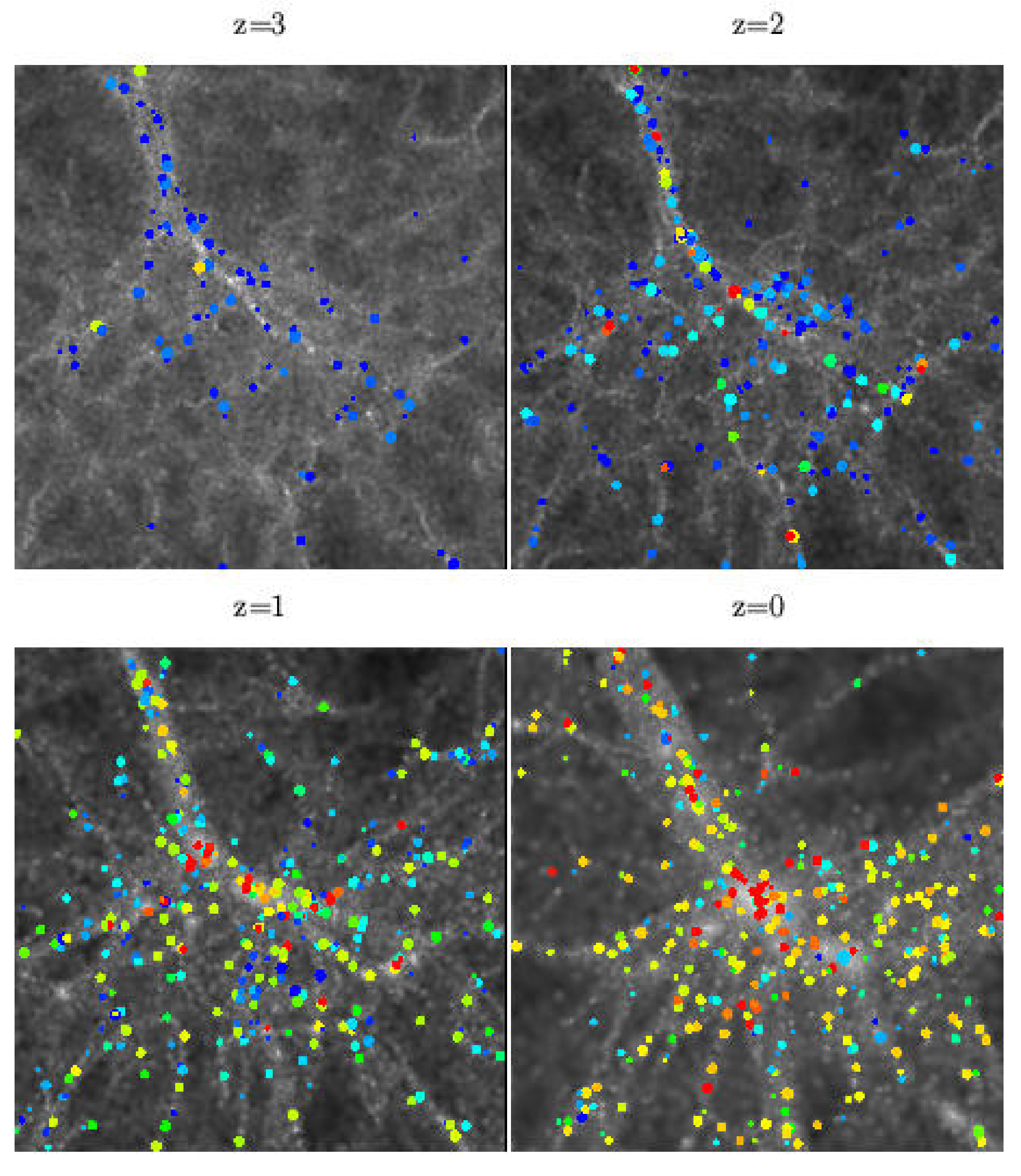


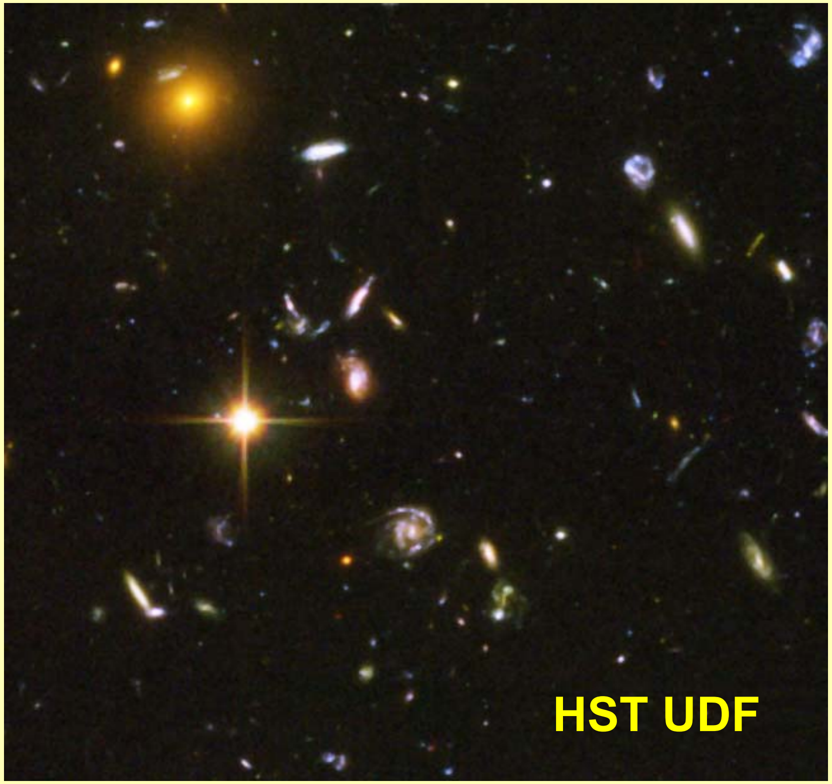
Galaxy formation



Benson, Frenk, Baugh, Cole, Lacey '02

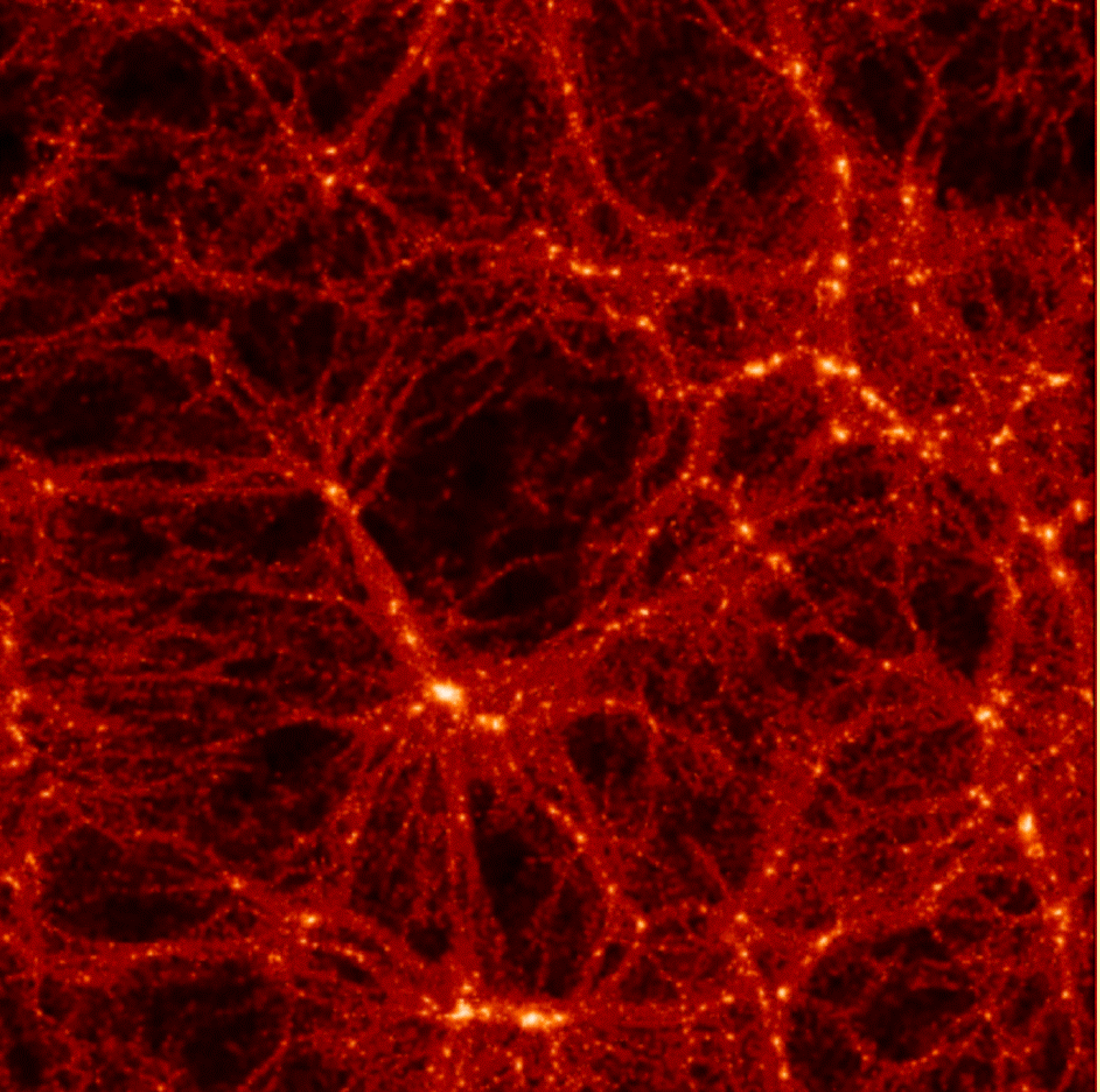
Testing the models





Must observe key ingredient of merging-driven star formation

→ **Griffin**



More directly:

observe the predicted evolution of DM clustering

(comoving view)

redshift z=3

(1/4 present size)

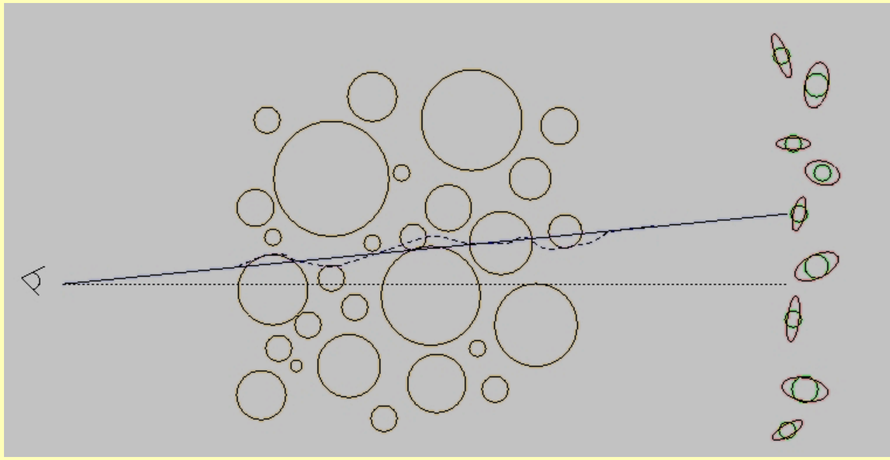
redshift z=1

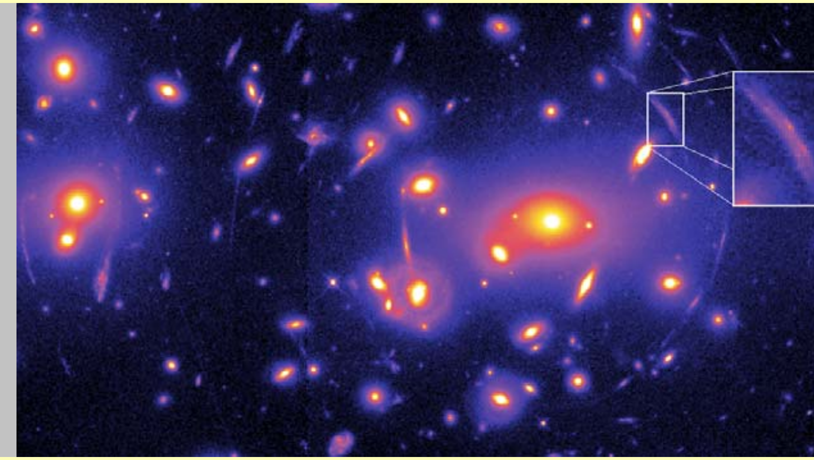
(1/2 present size)

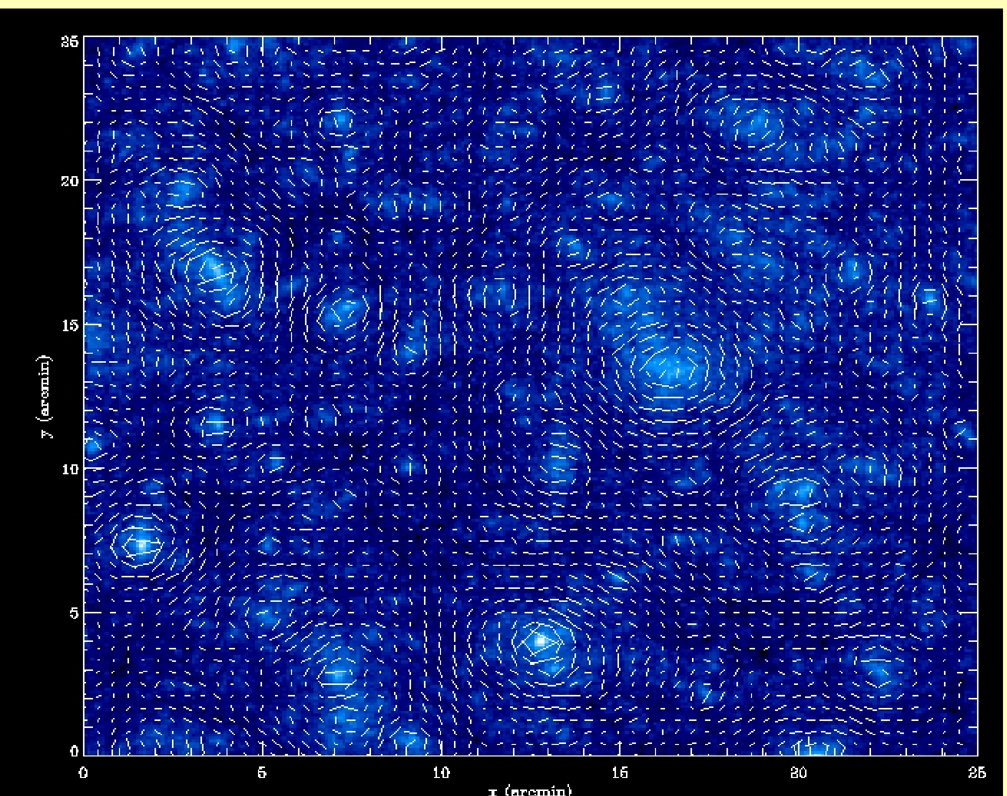
Redshift z=0

(today)

Gravitational lensing







Large-area surveys of weak shear can measure the dark matter with similar precision to the CMB. CMB + lensing will be a key tool

Outlook for cosmology in 2020

- What can we hope for?
  - Direct detection of SUSY WIMP DM
  - Detection of tilt & tensors, or limits $|n - 1| < 0.005$, $r < 10^{-5}$
  - Proof that dark energy is not Λ, or $|w + 1| < 0.05$
  - Understand star formation in galaxies and its evolution

Every prospect of answers to main current questions in cosmology – and starting new fields.

But the field is moving fast: need for timely action