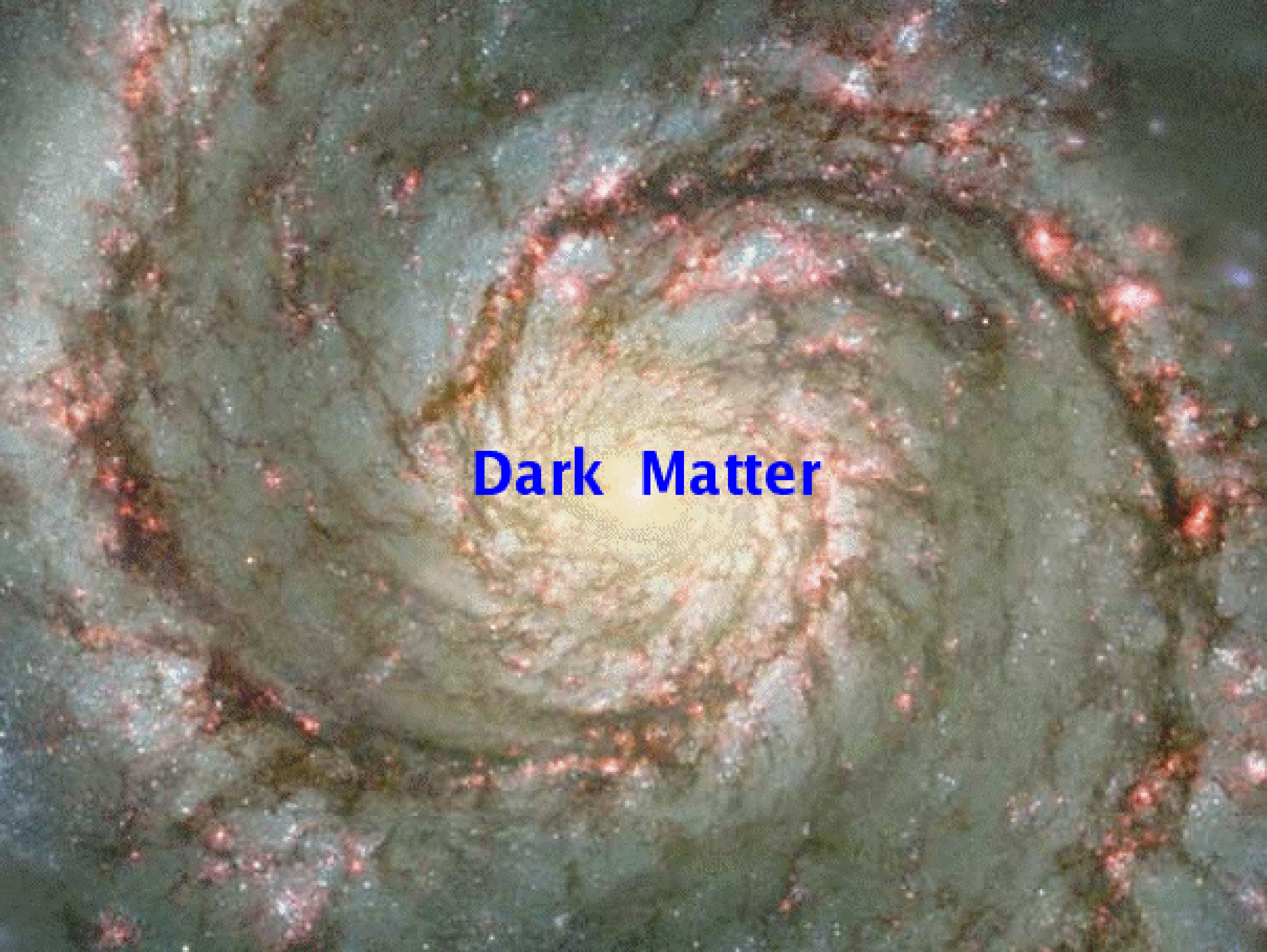
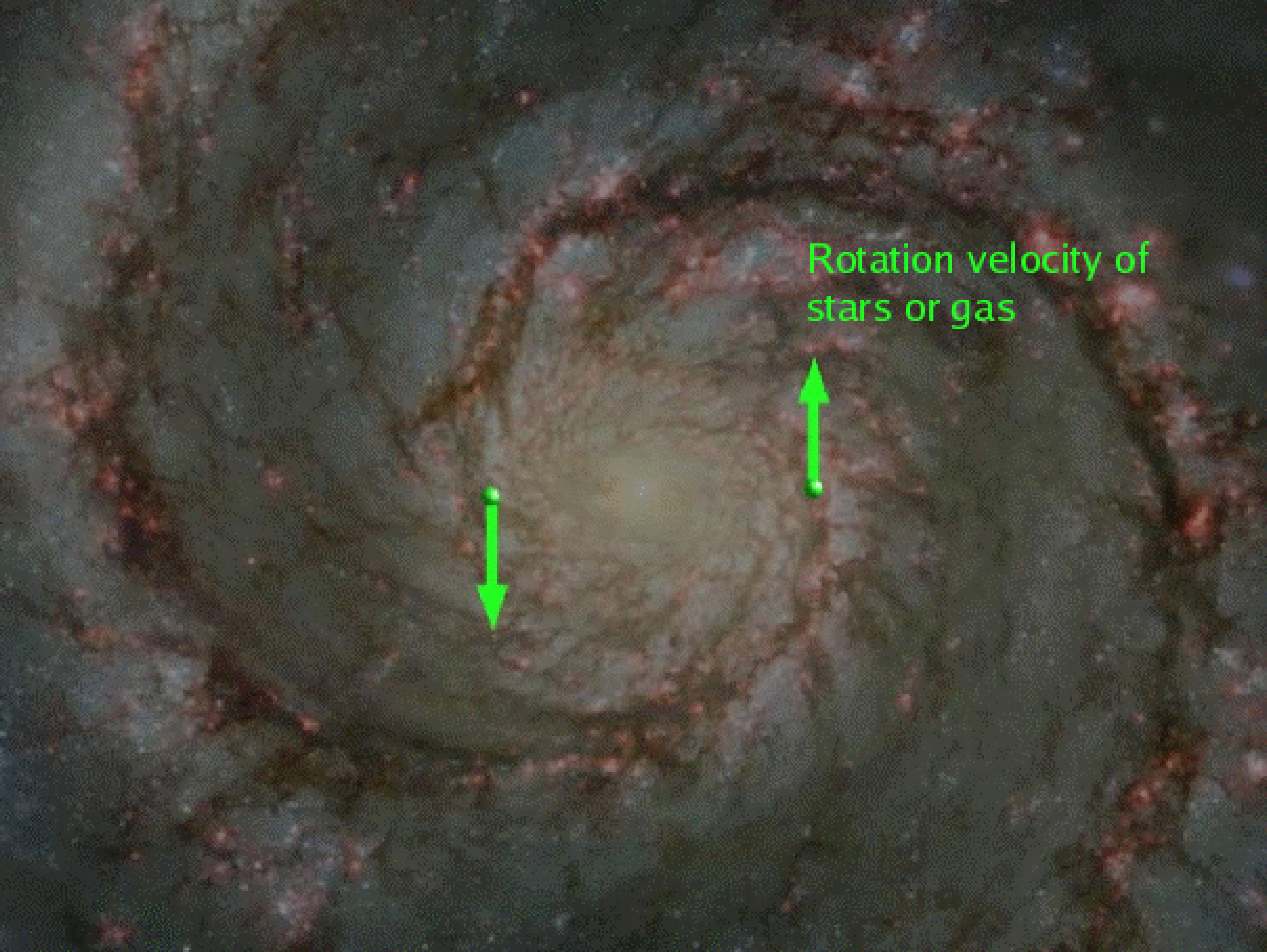
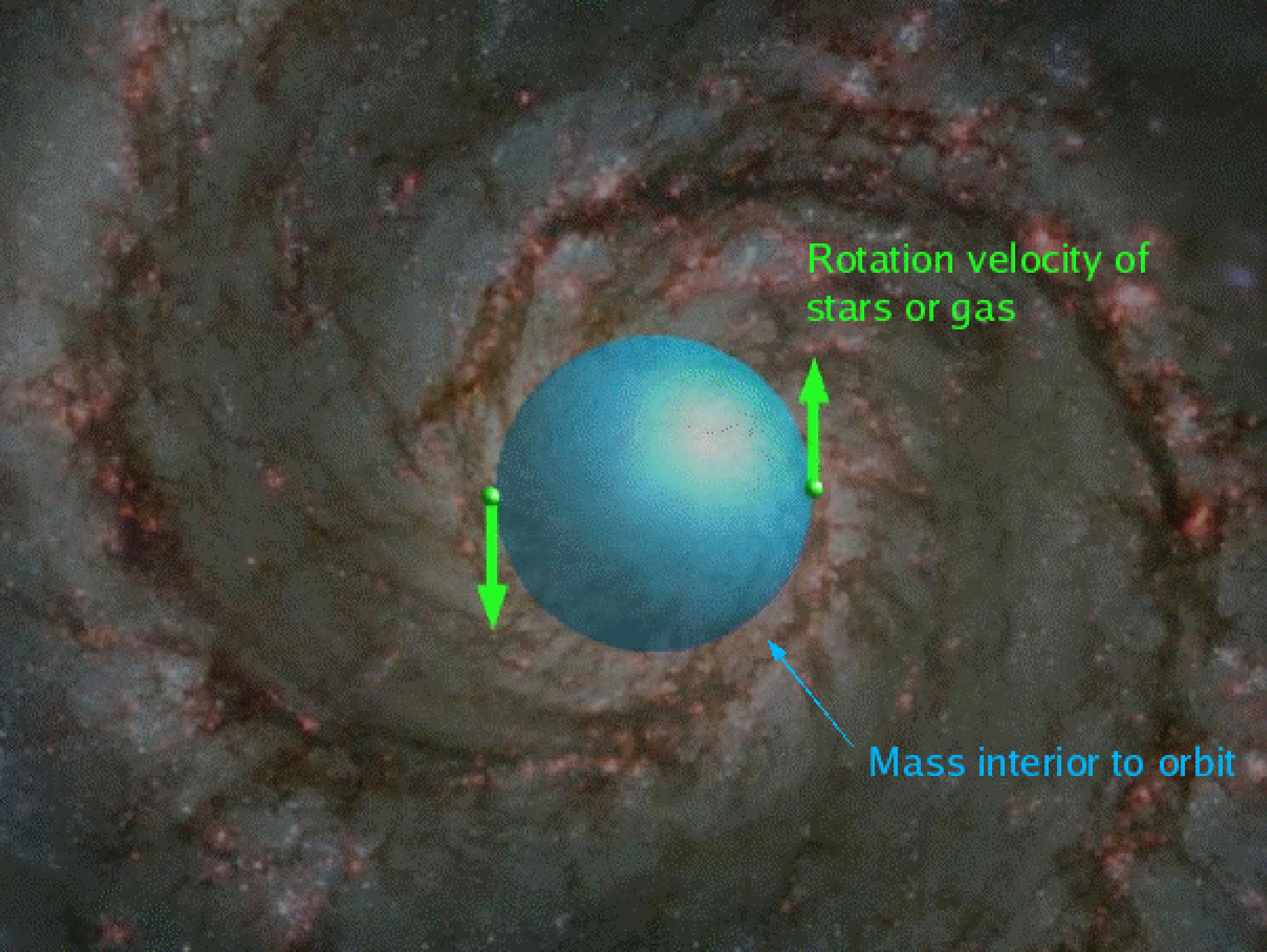
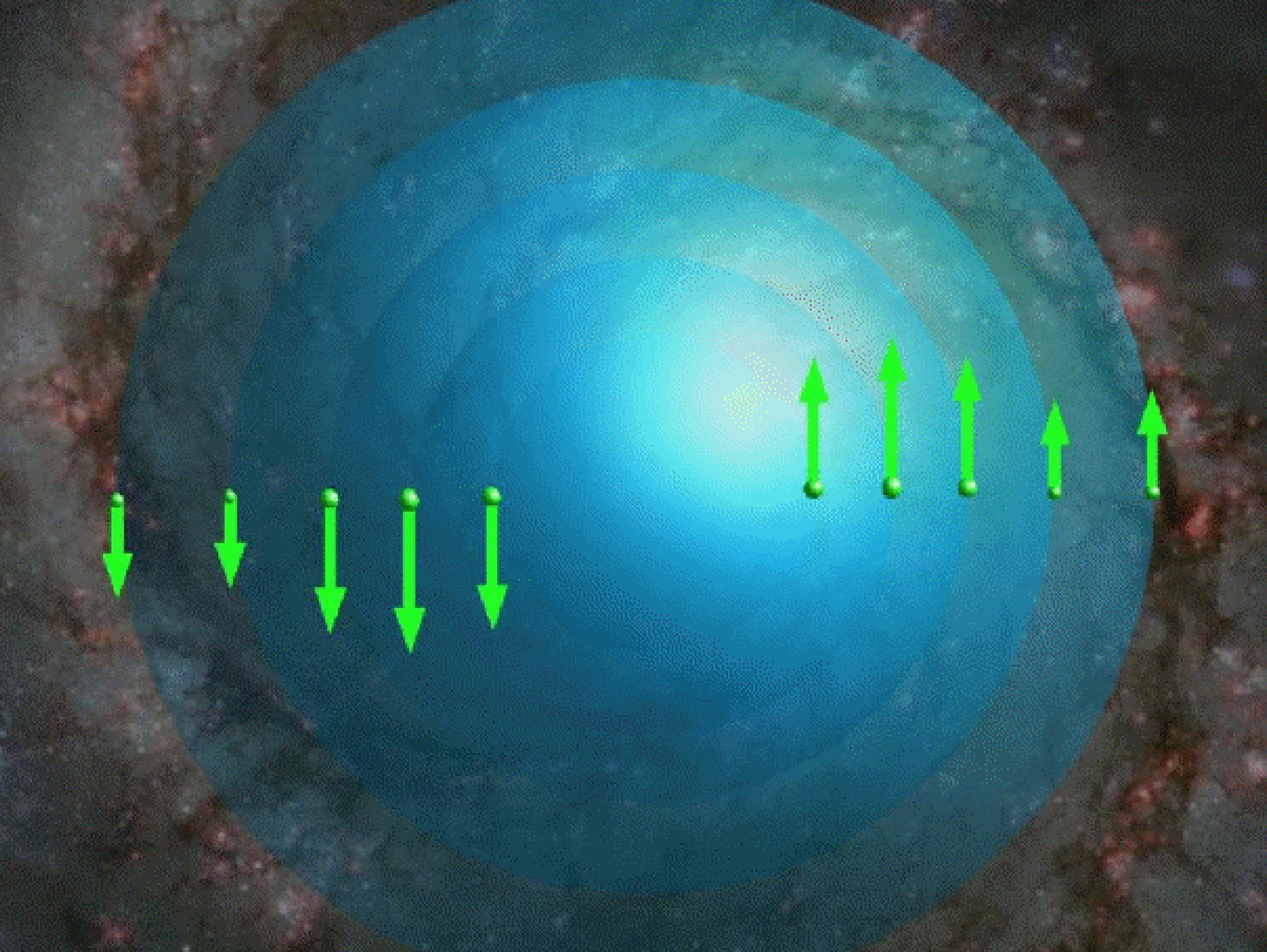
Dark Matter

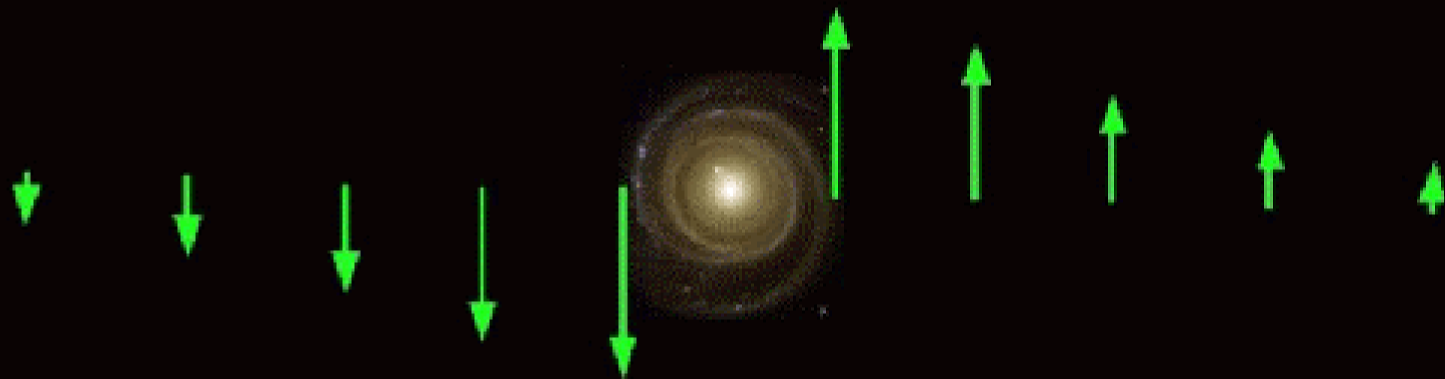

Dark Matter


Rotation velocity of
stars or gas

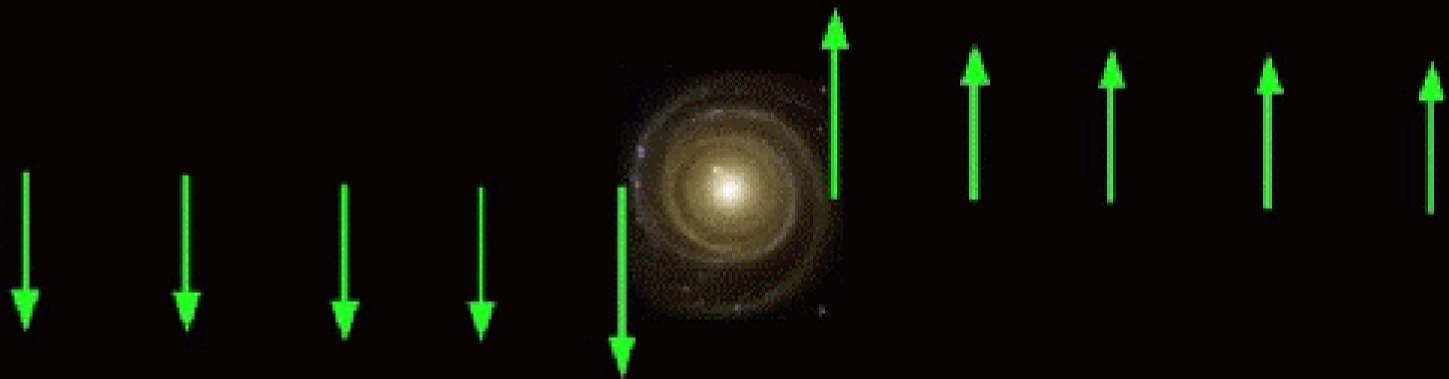

Rotation velocity of
stars or gas
Mass interior to orbit



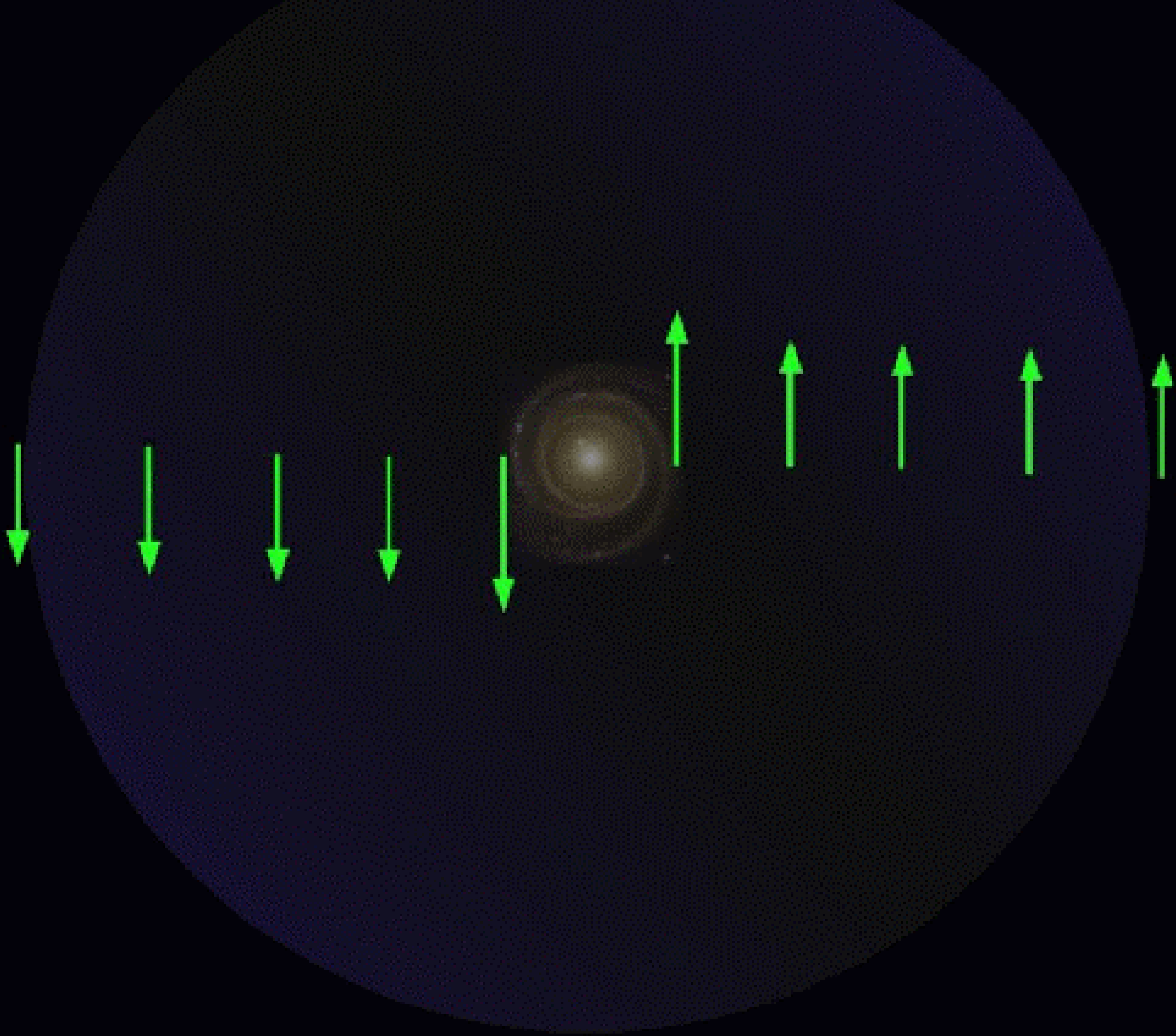
What we expected to see

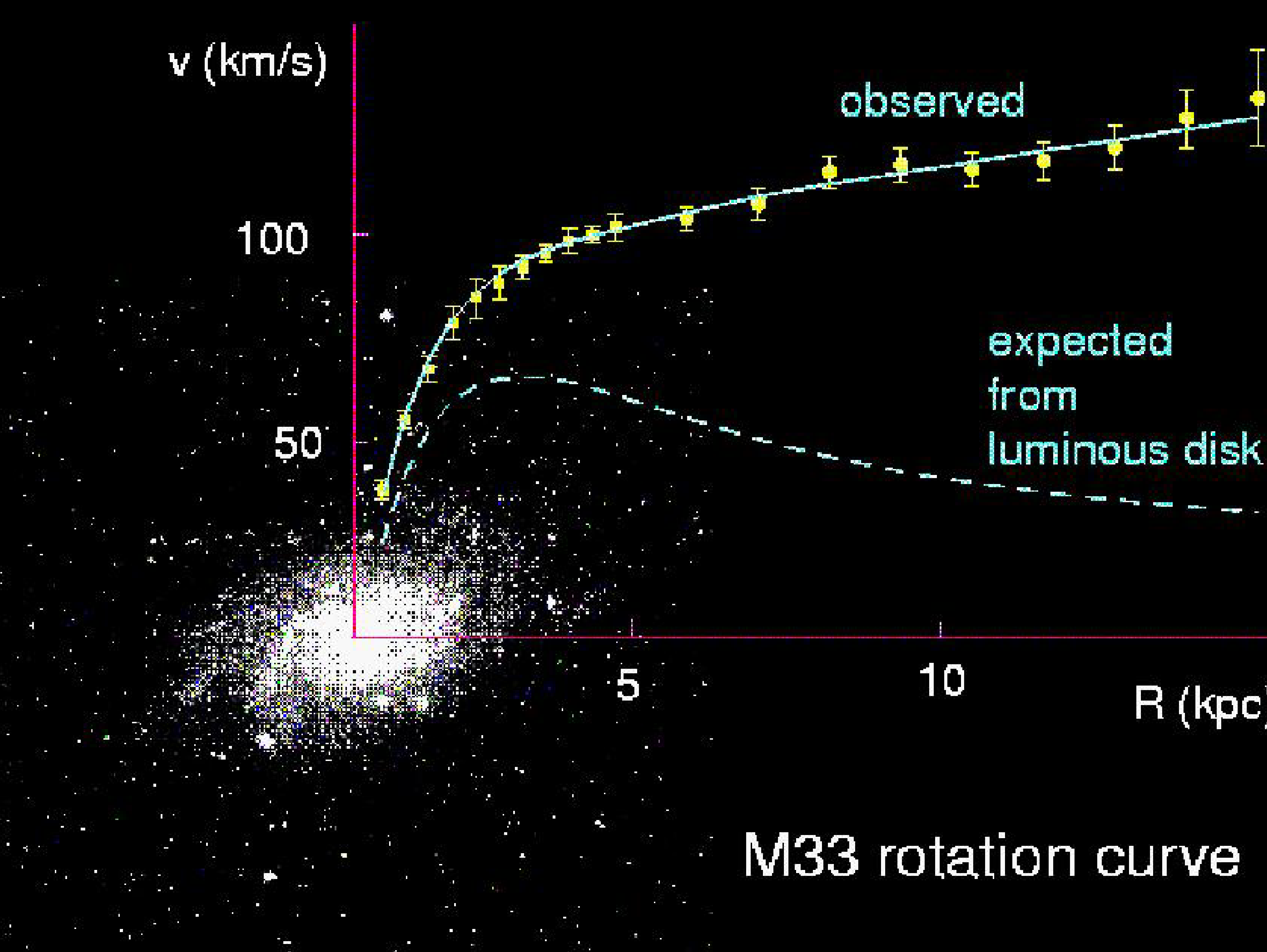


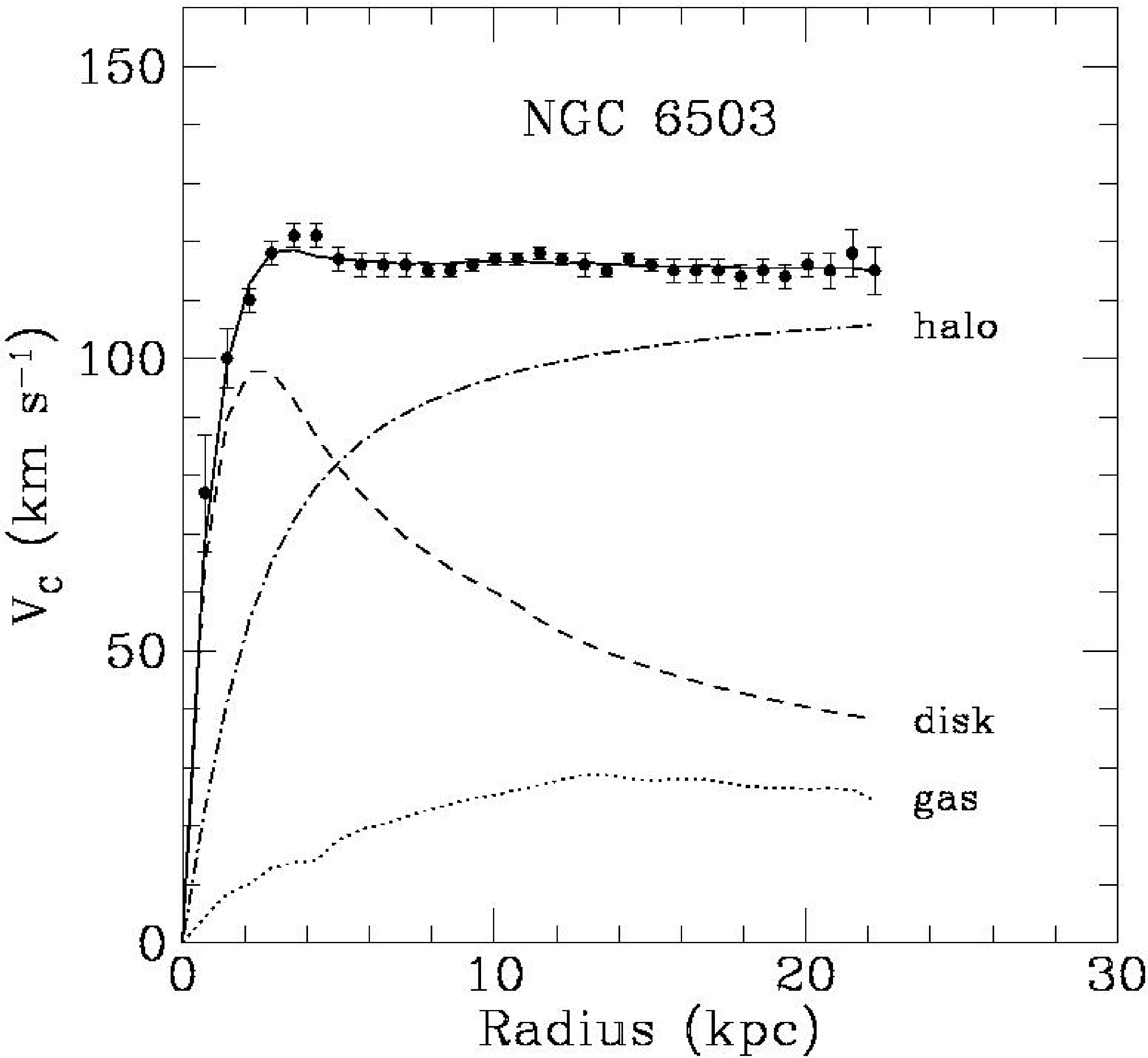
What we actually saw



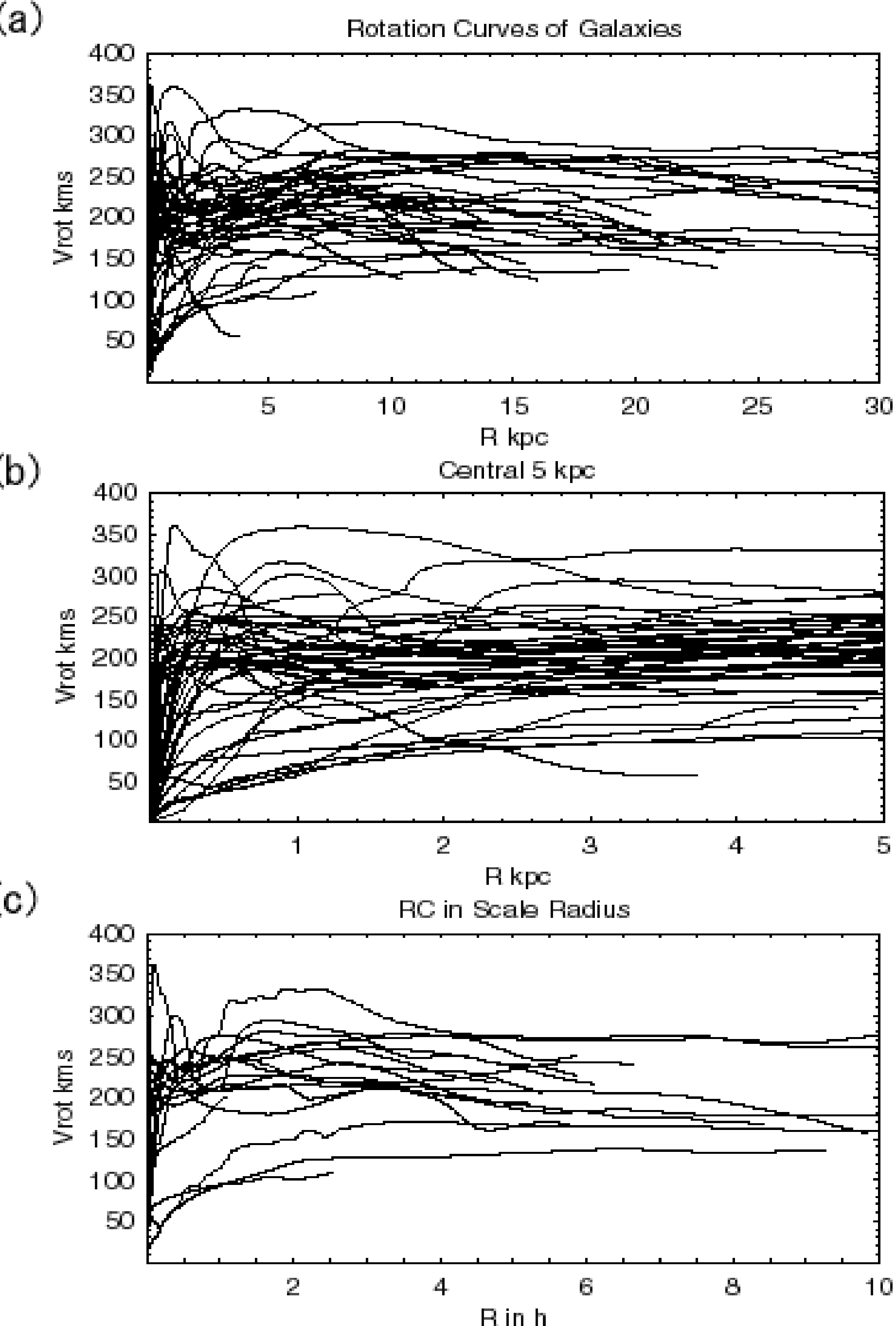
Galaxies have dark halos




v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve



NGC 6503
halo
disk
gas
Radius (kpc)
V_c (km s^{-1})
0
10
20
30
0
50
100
150

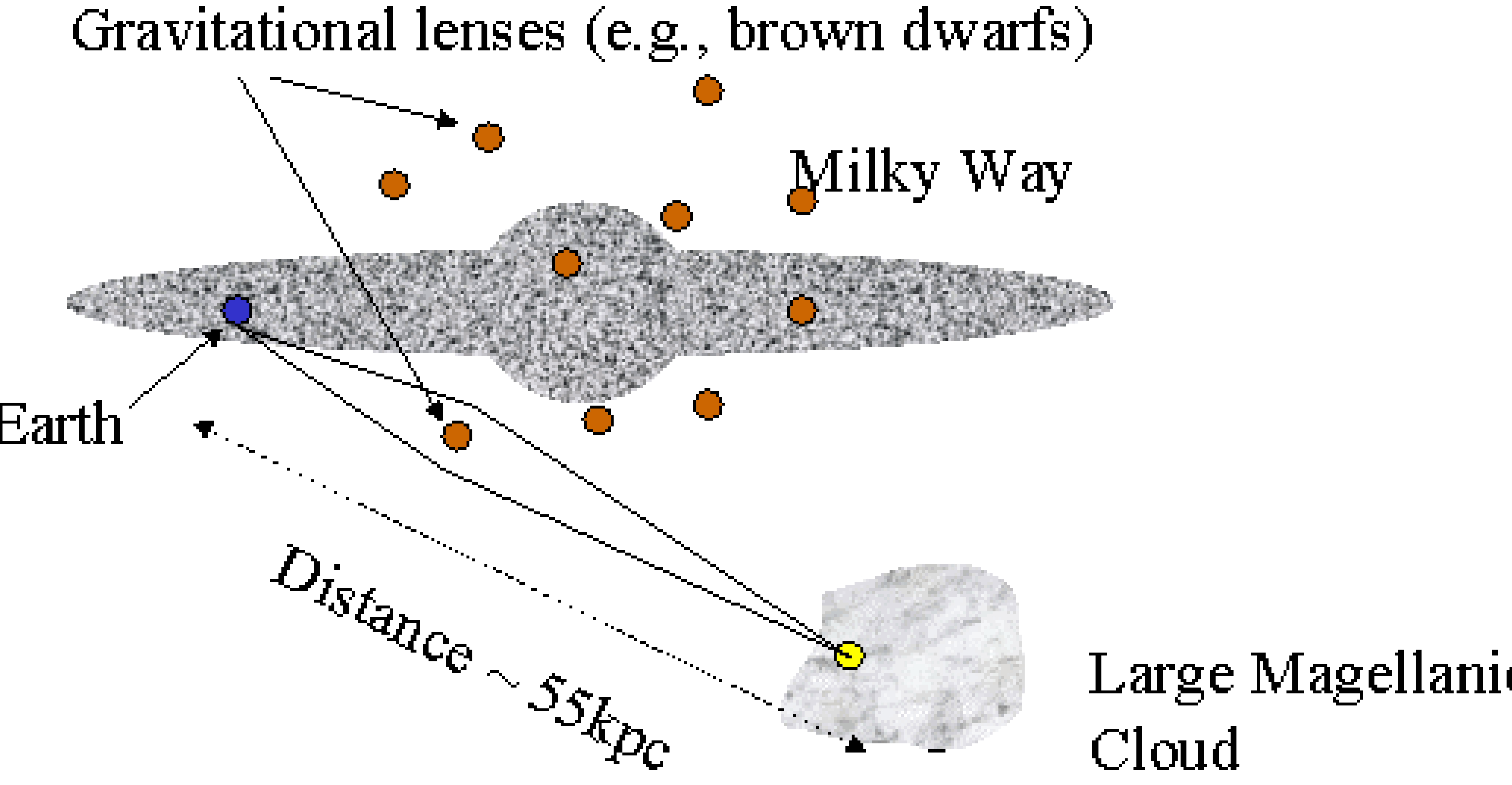


Rotation curves of galaxies

$$\Omega_{dark} \approx 10\,\Omega_{visible}$$

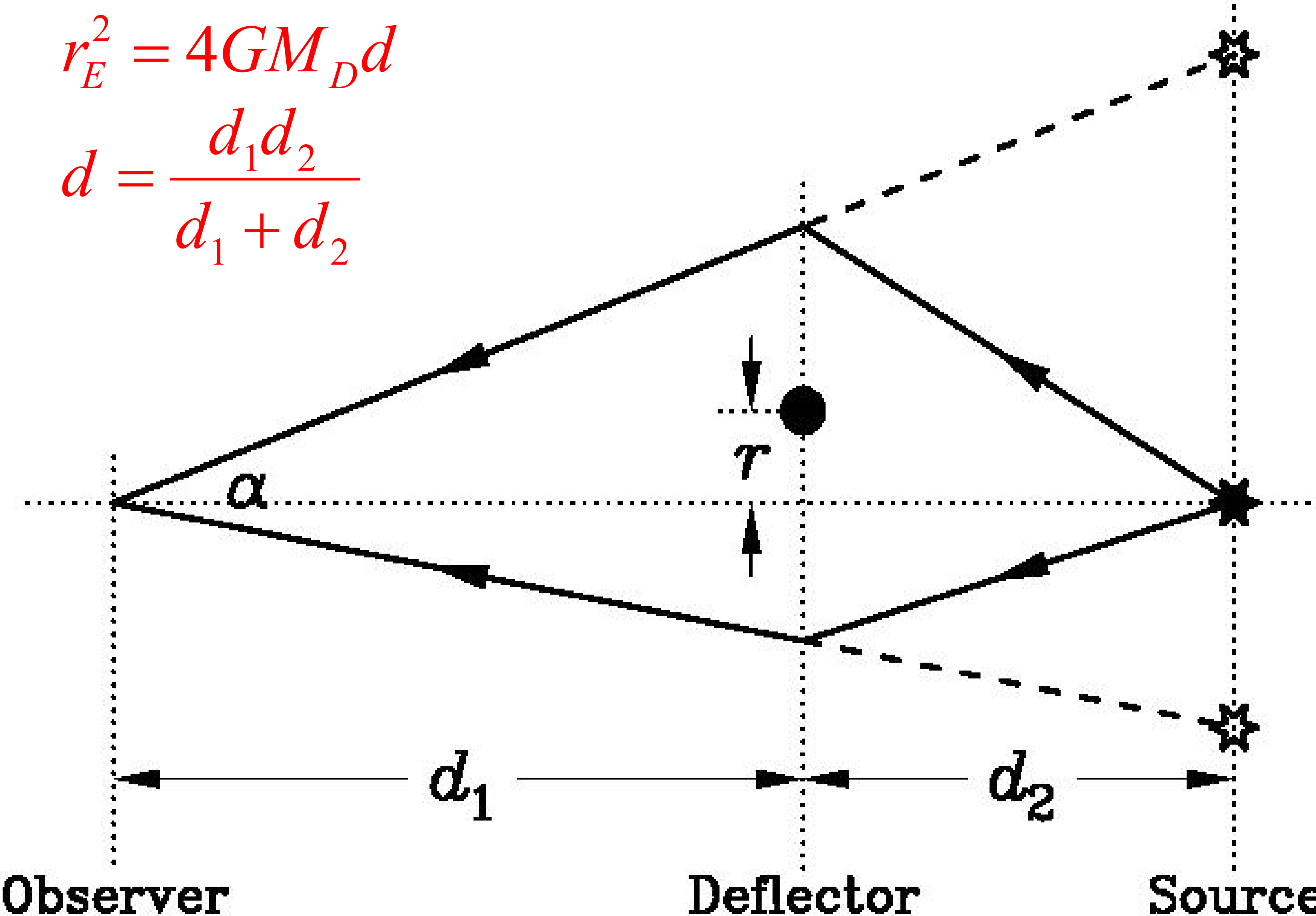
Microlensing

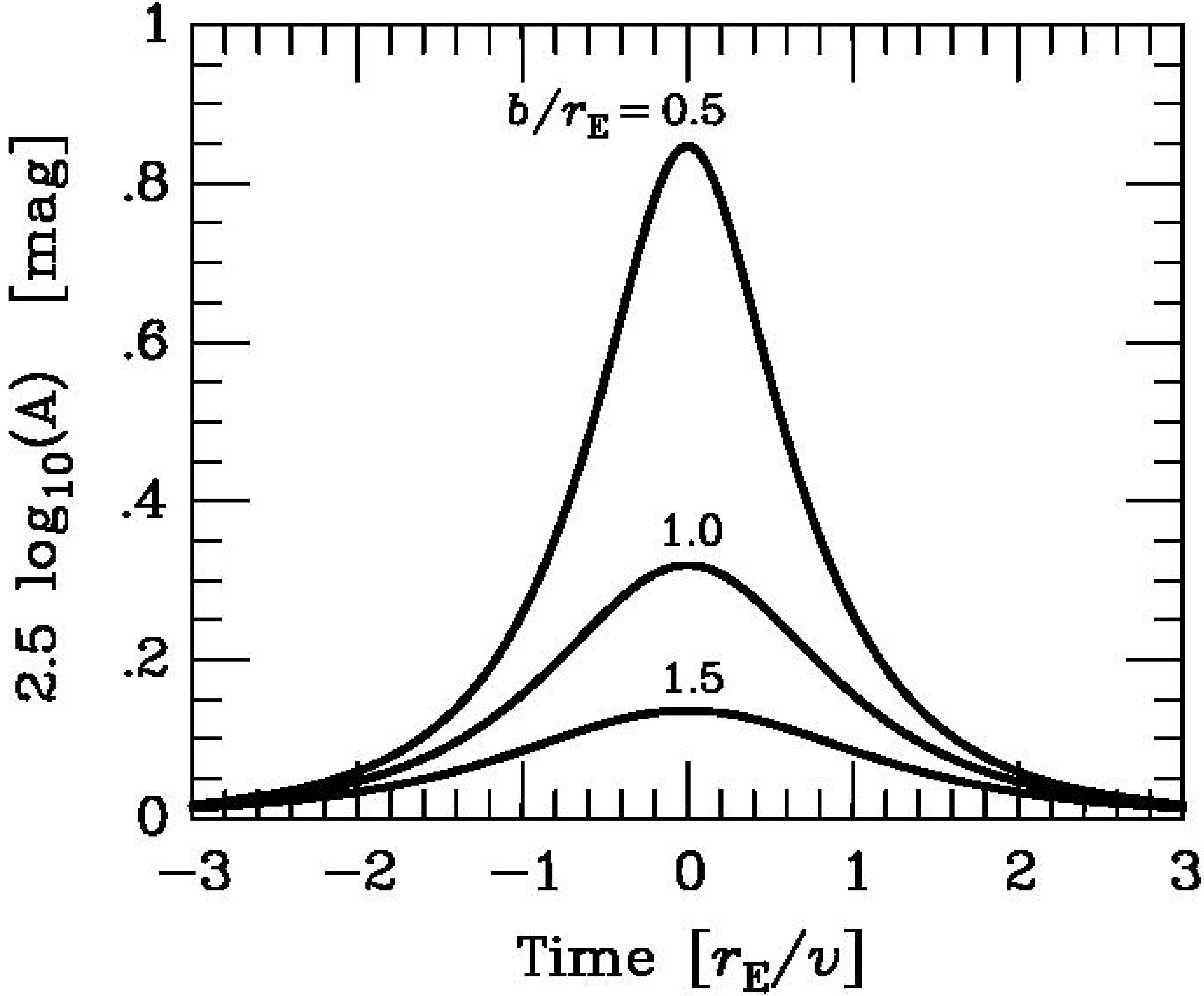
Microlensing



$$r_E^2 = 4GM_D d$$

$$d = \frac{d_1 d_2}{d_1 + d_2}$$





$b/r_E = 0.5$
1.0
1.5
1
.8
.6
.4
.2
0
−3
−2
−1
0
1
2
3
2.5 log10(A) [mag]
Time [r_E/v]

$$A = \frac{2+u^2}{u\sqrt{4+u^2}} \qquad u = \frac{r}{r_E}$$ amplification

$$\overline{\Delta t} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v}$$ average duration

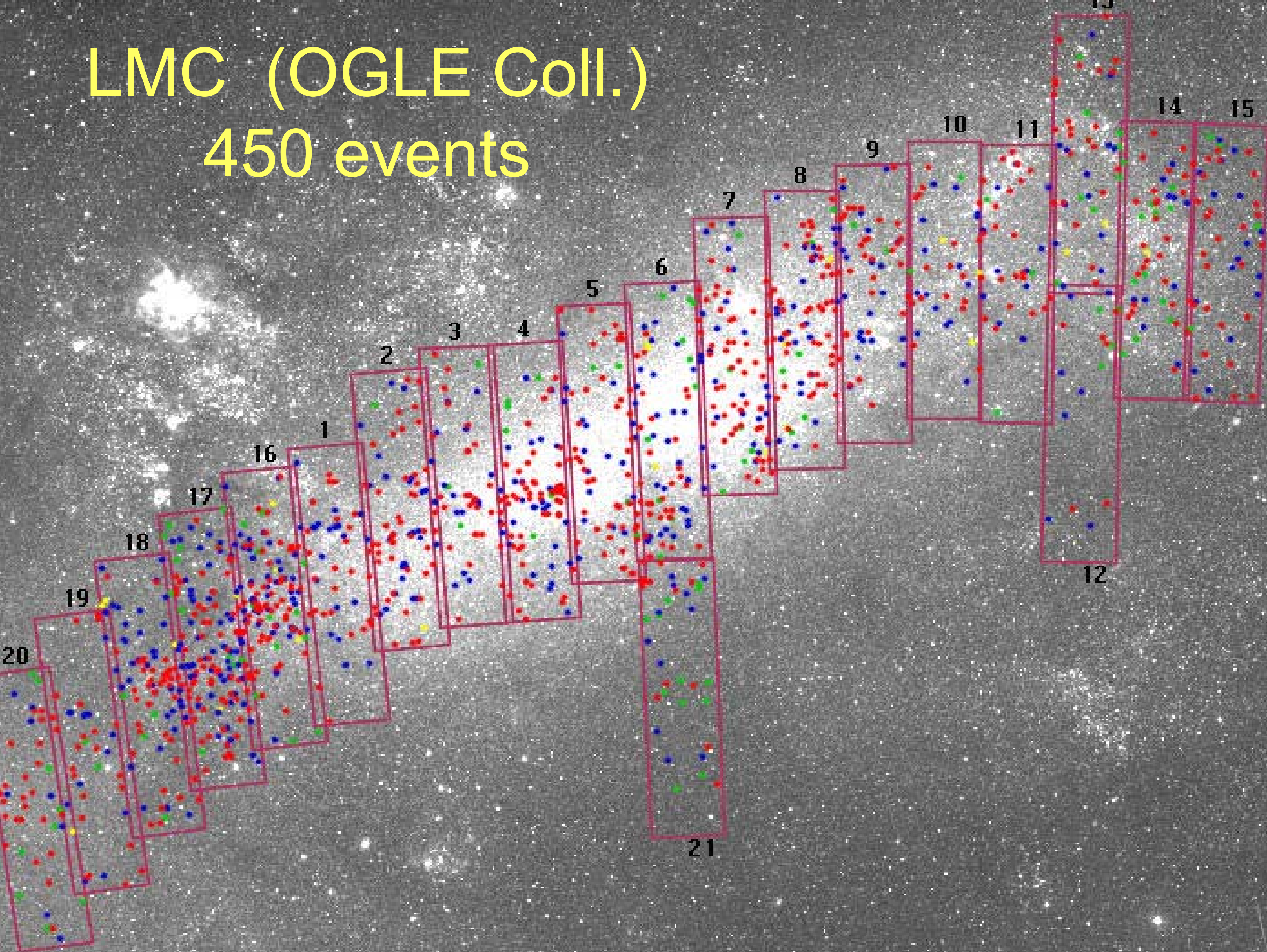
$$M_D = 1\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 3 \text{ months}$$

$$M_D = 0.1\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 1 \text{ month}$$

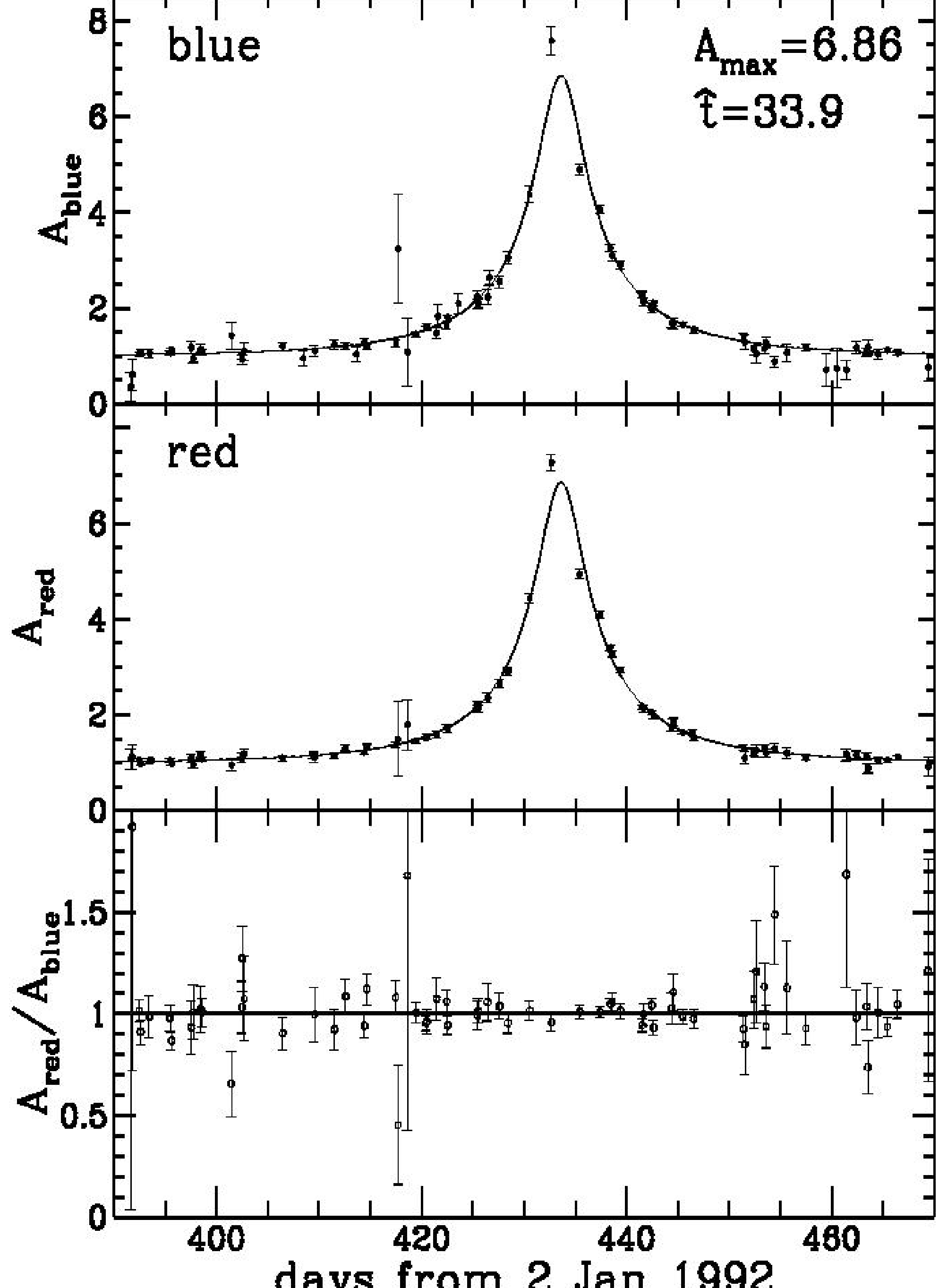
$$M_D = 10^{-2}\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 9 \text{ days}$$

$$M_D = 10^{-4}\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 1 \text{ day}$$

$$M_D = 10^{-6}\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 2 \text{ hours}$$



LMC (OGLE Coll.)
450 events
1
2
3
4
5
6
7
8
9
10
11
12
14
15
16
17
18
19
20
21



symmetric

$$A_{\mathbf{max}} = 7.20 \pm 0.09$$

achromatic

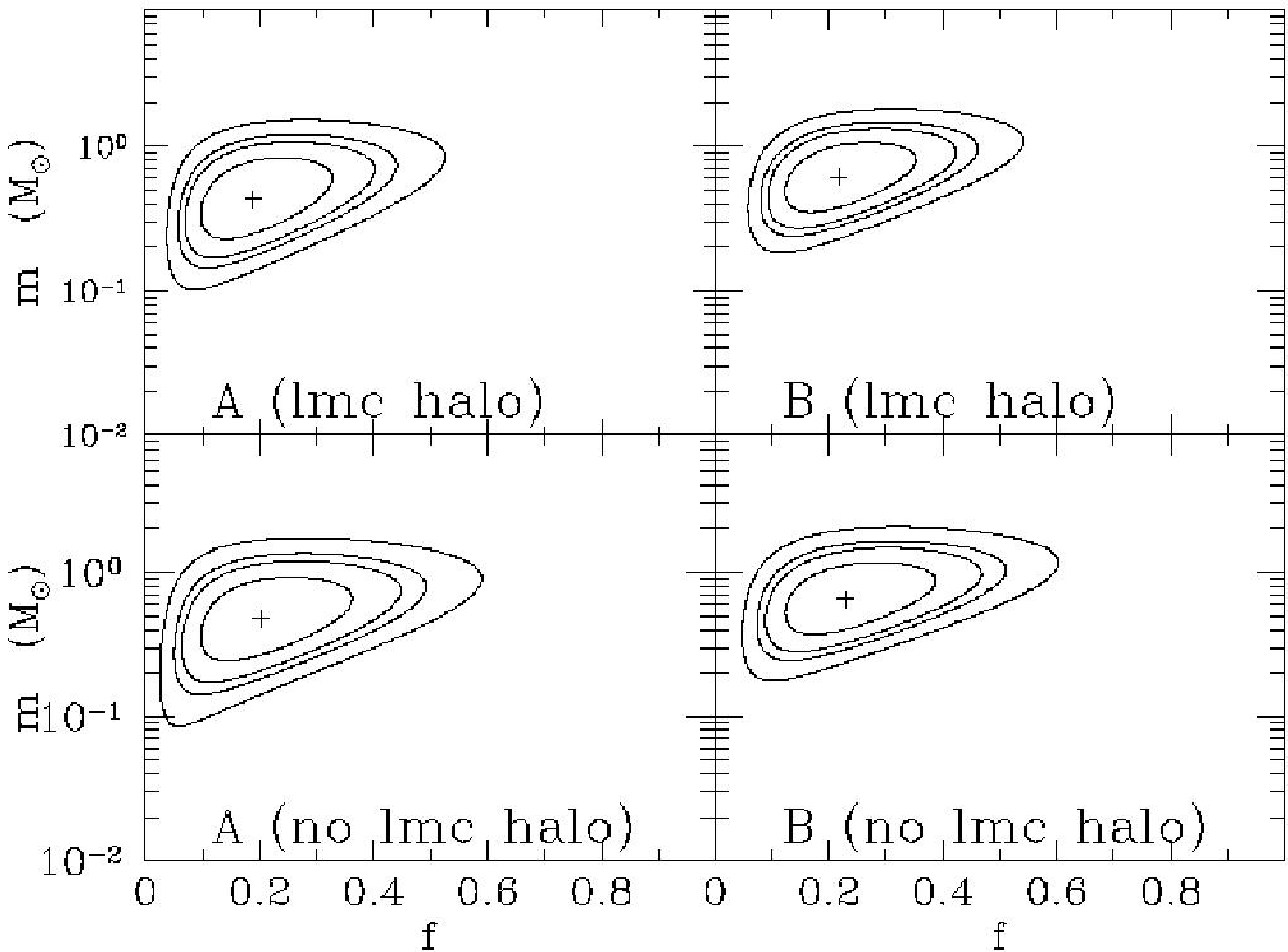
$$\frac{A_{red}}{A_{blue}} = 1.00 \pm 0.05$$

unique

$$t = 34.8 \pm 0.2 \text{ days}$$

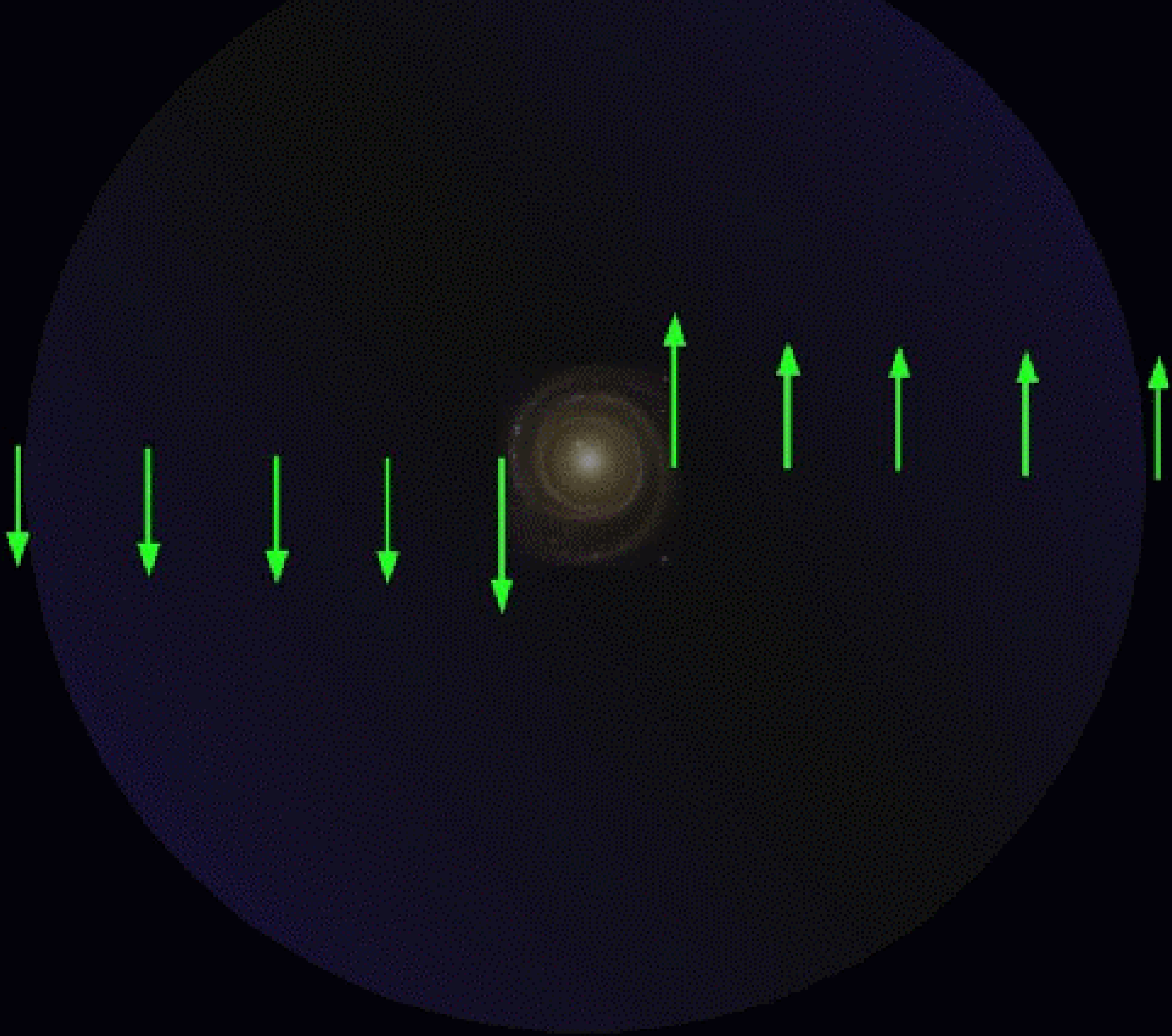
$$\Rightarrow \quad M_D \approx 0.1 M_\Theta$$

MACHO Coll. (2000)

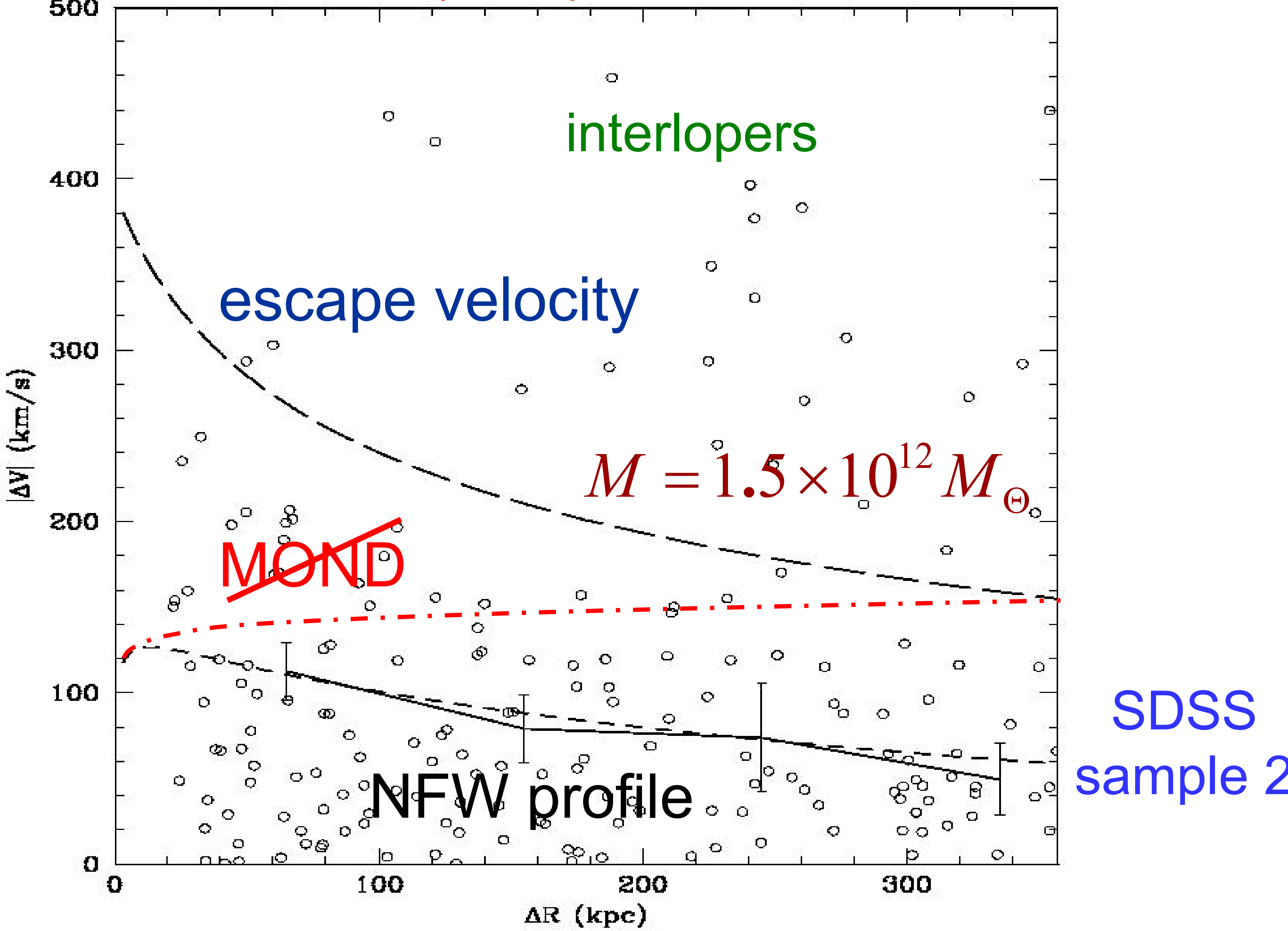


The edges of Dark Matter Haloes

Galaxies have dark halos

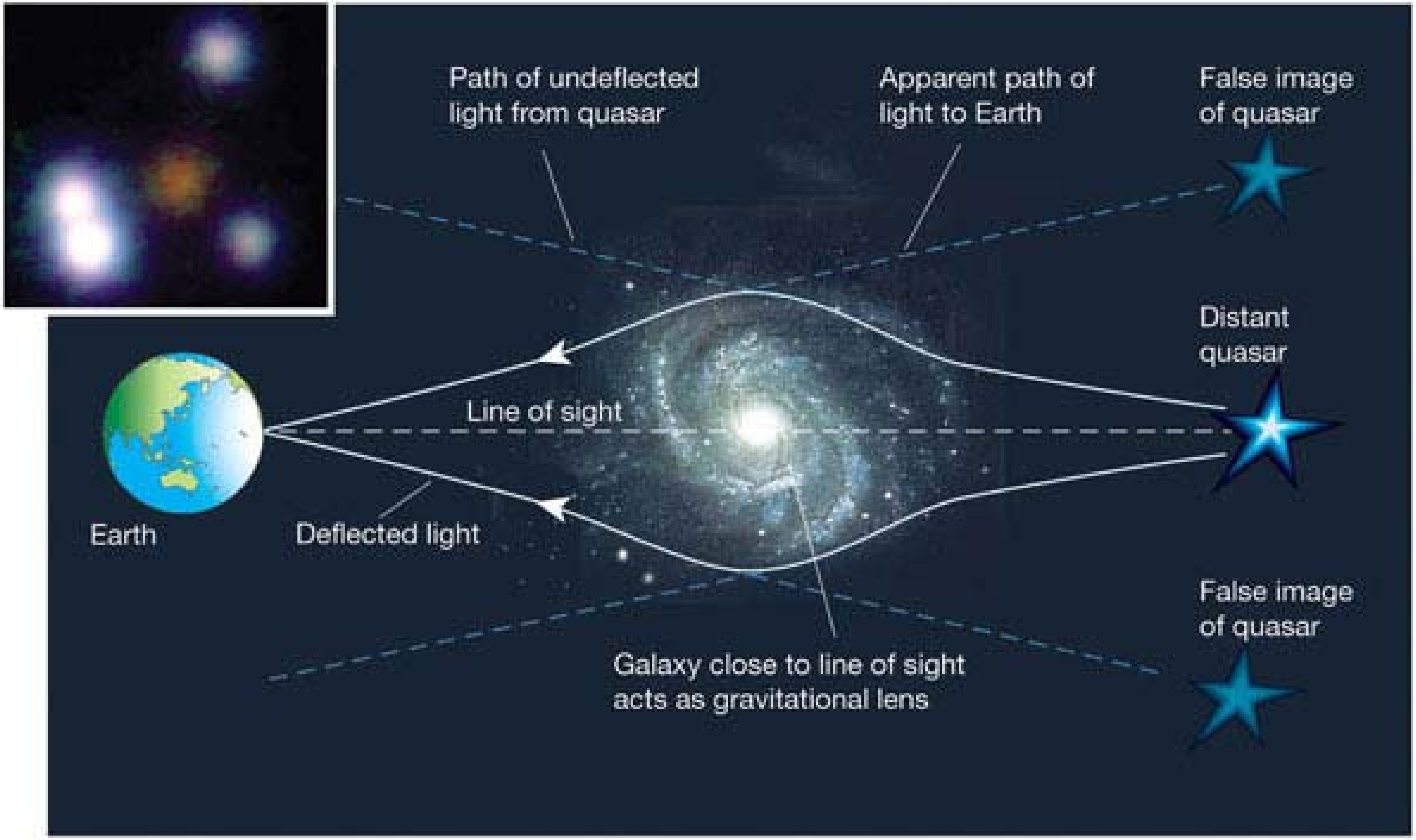


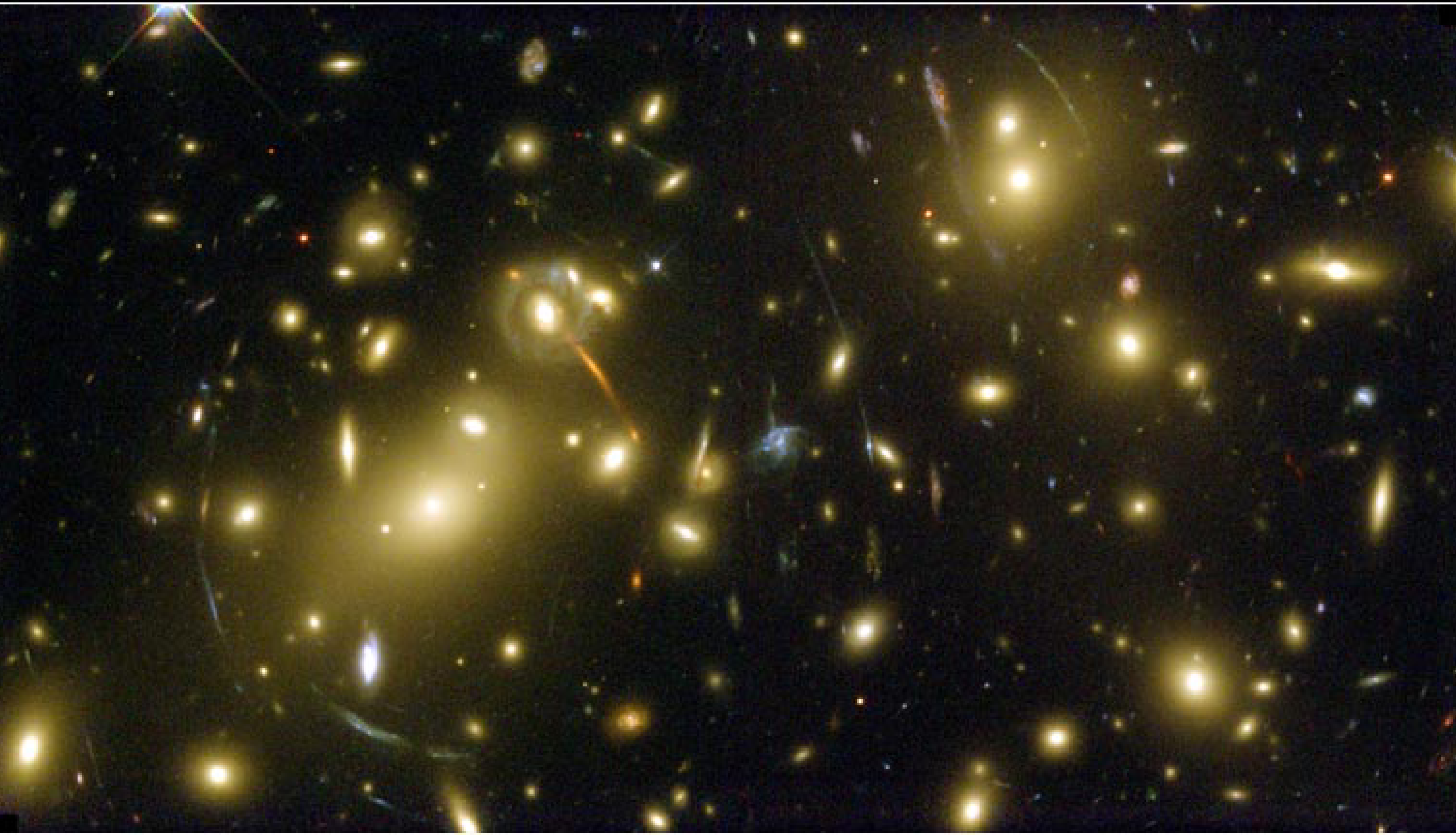
Prada et al. (2003)



Evidence on Larger Scales

Gravitational Lensing

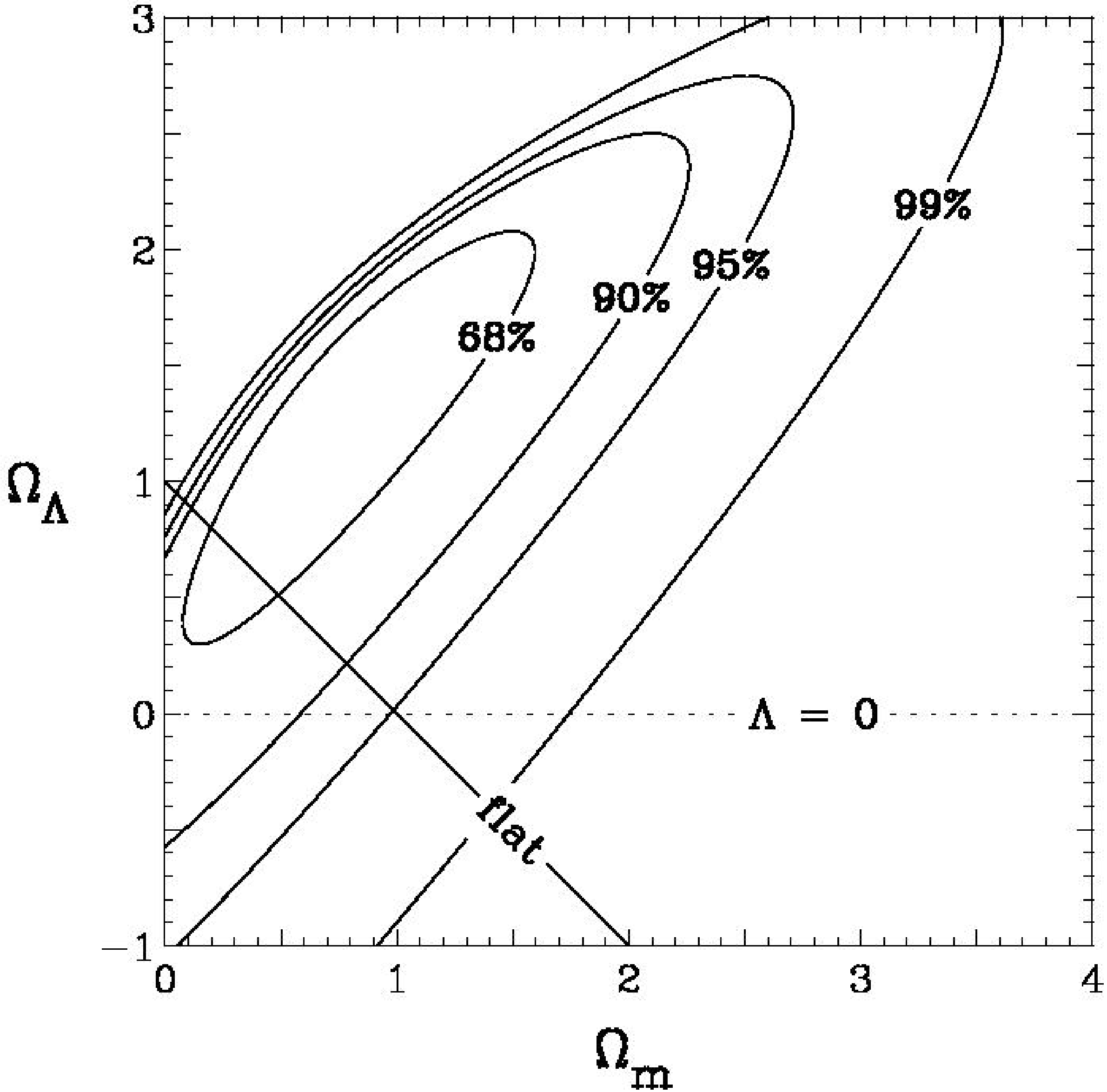




alaxy Cluster Abell 2218 **HST • WFPC**

ASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

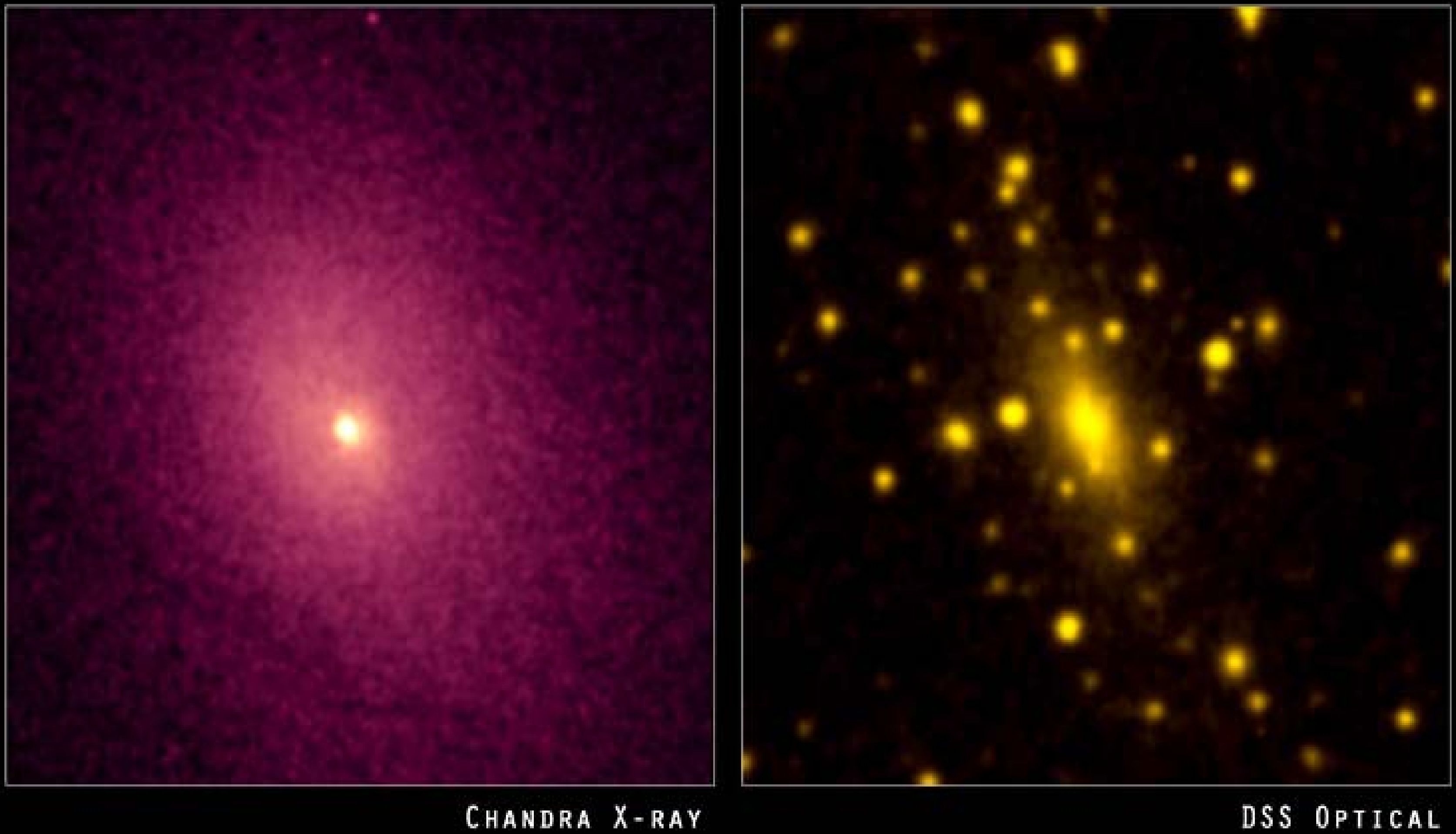
Gravitational Lensing



1,000 systems

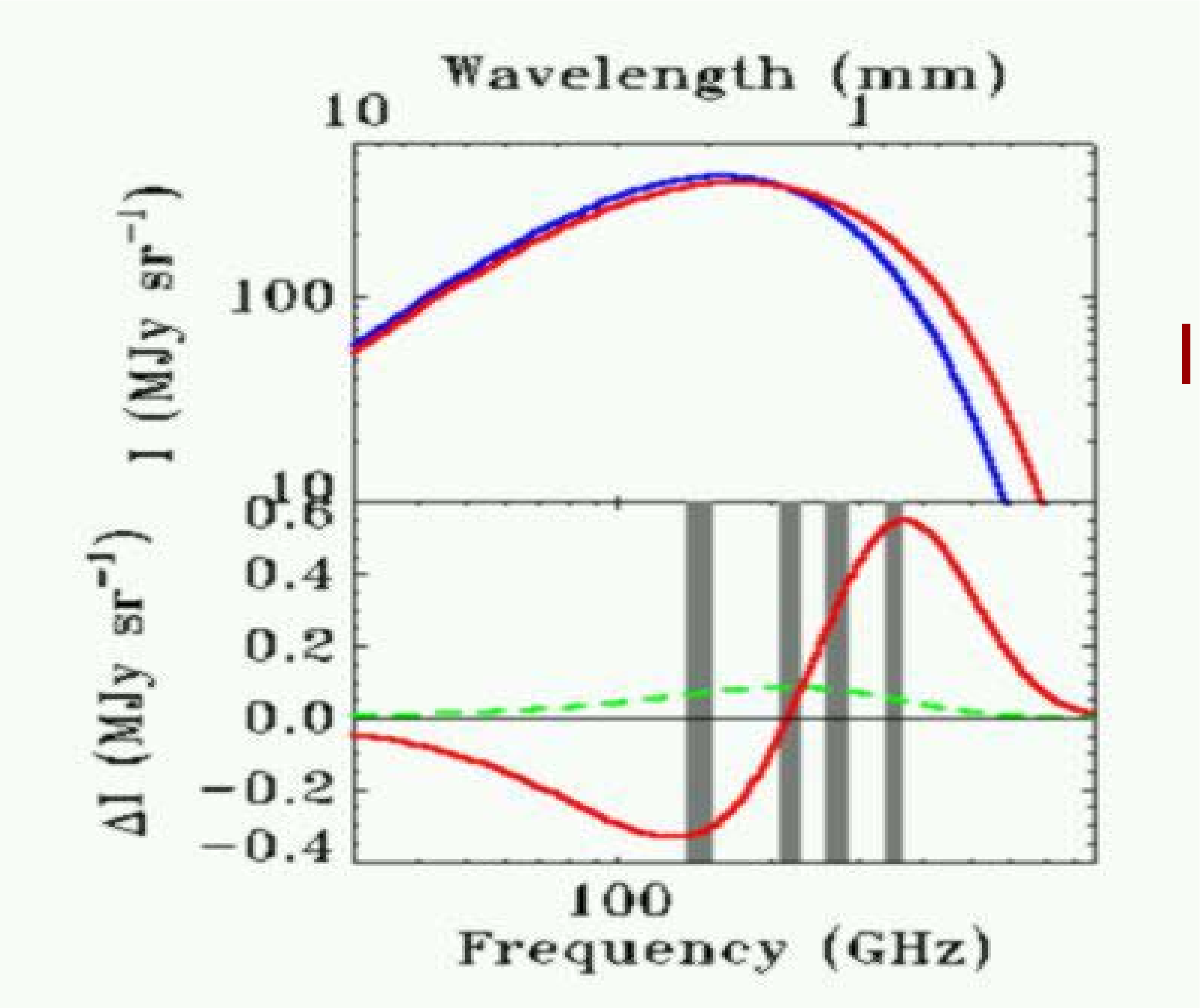
MERLIN
CLASS
CASTLeS

Clusters of galaxies



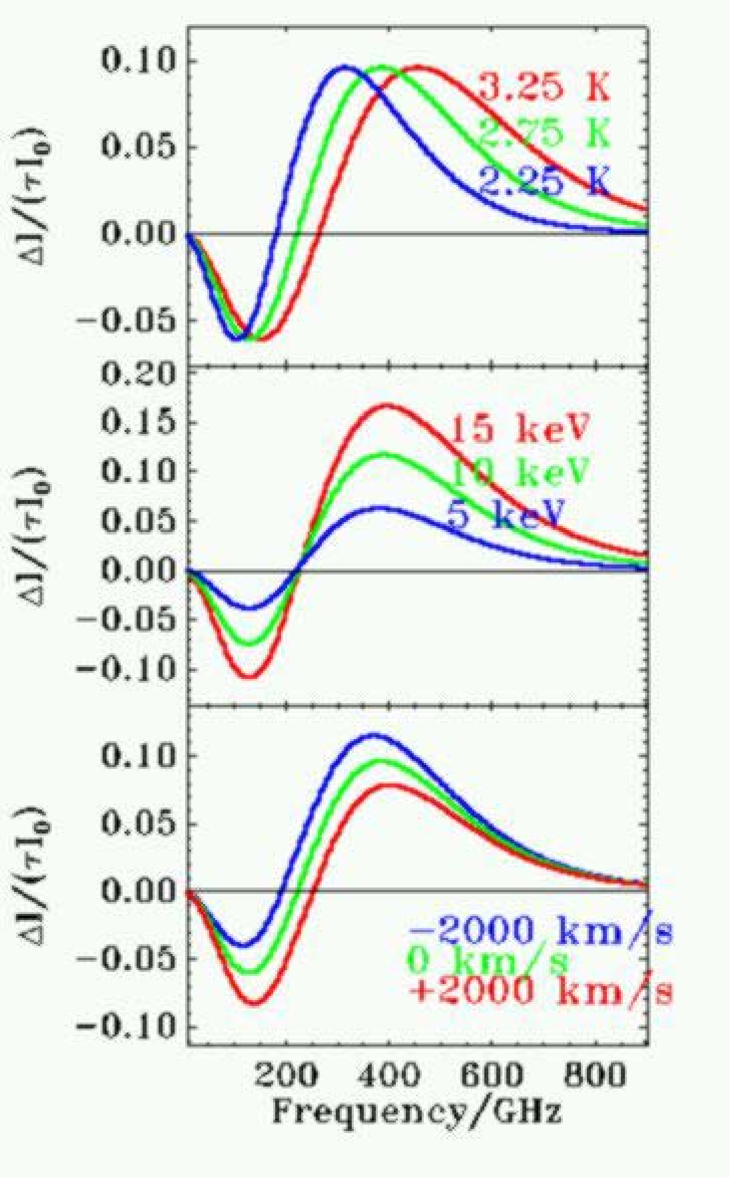
$$f_B h^{3/2} = 0.08 \pm 0.03 \quad \Rightarrow \quad \frac{\Omega_B}{\Omega_M} \approx 0.15 \quad \text{for} \quad h = 0.7$$

Sunyaev-Zel'dovich Effect



ICS

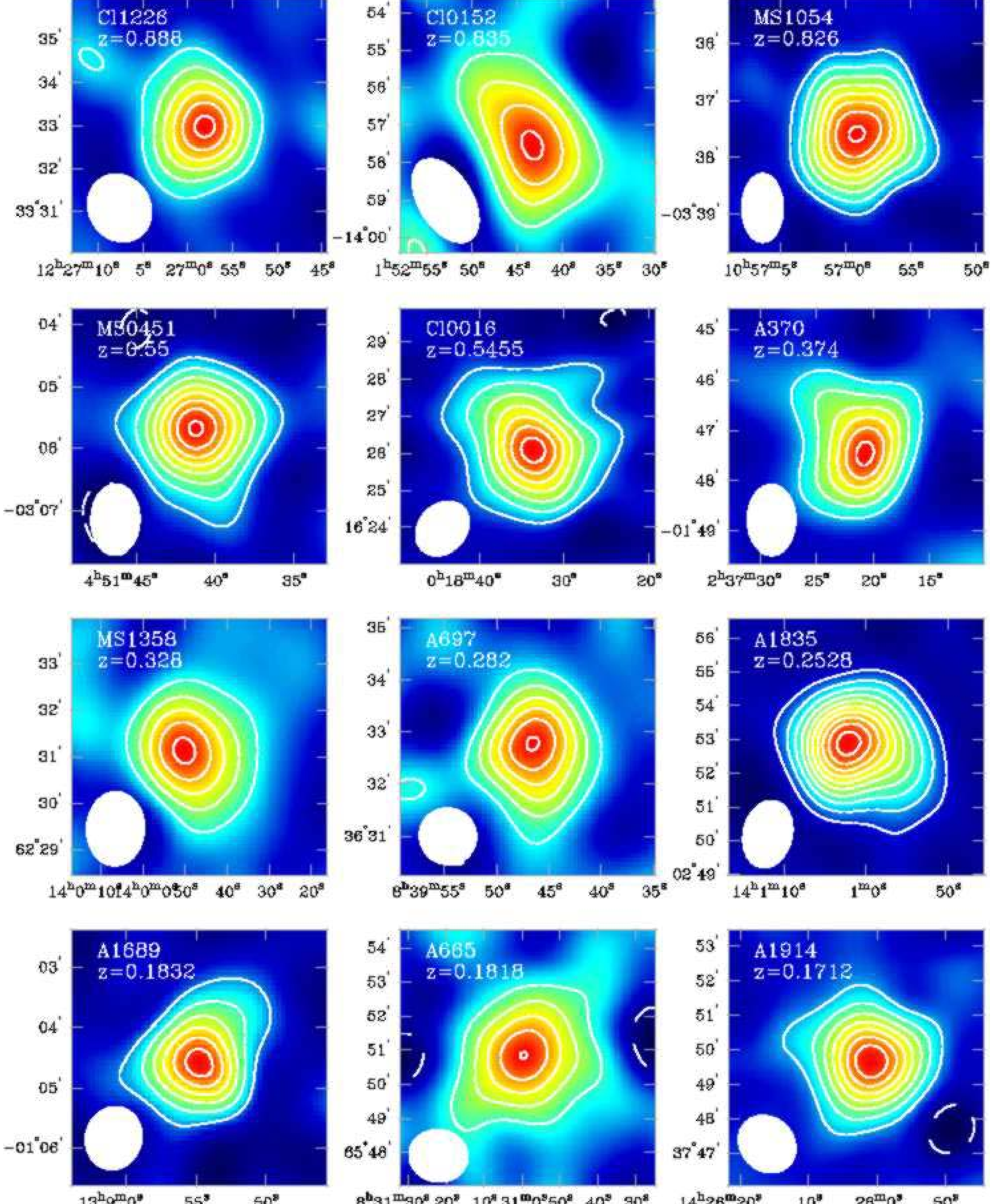
Sunyaev-Zel'dovich Effect



CMB

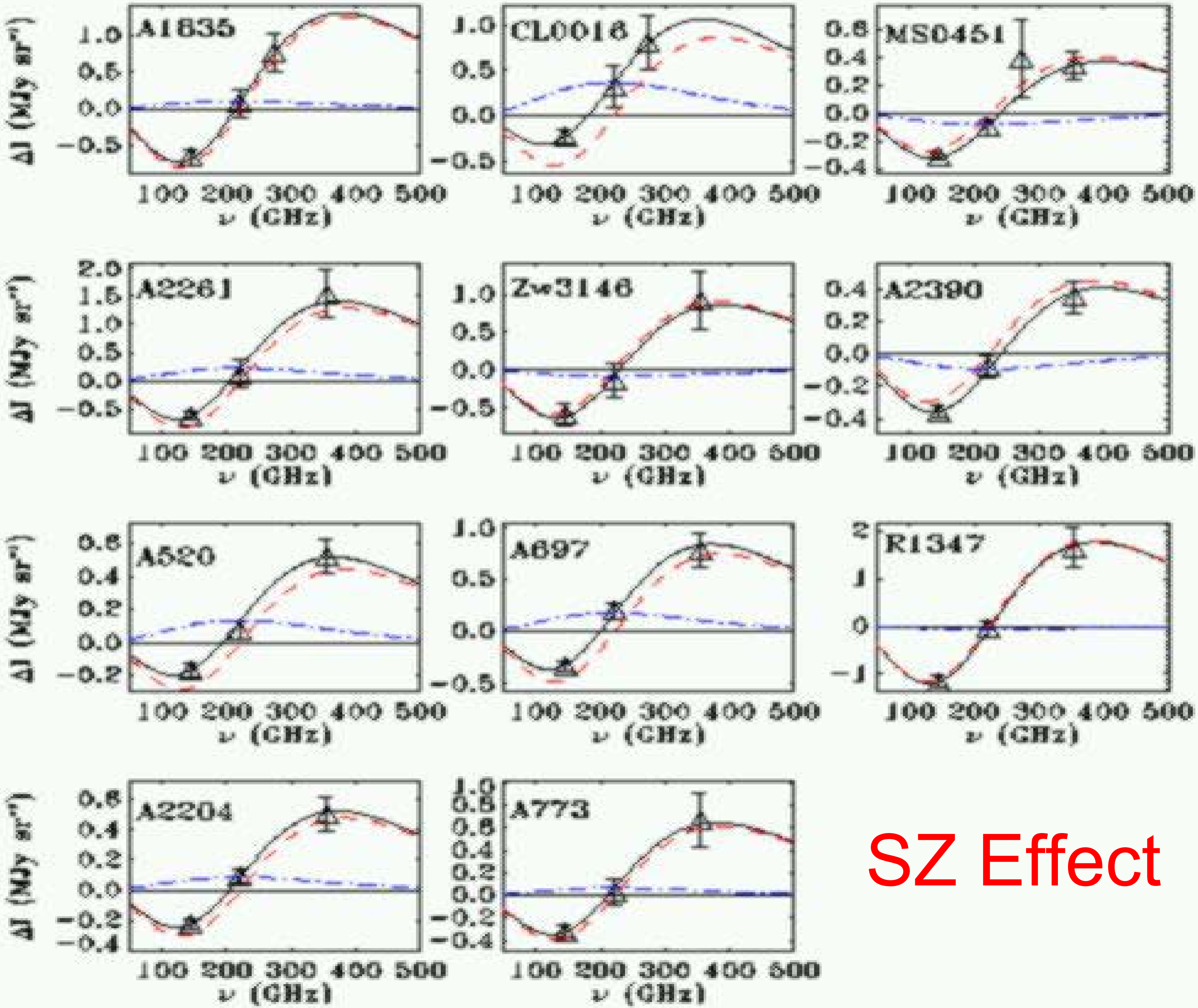
cluster

peculiar velocities



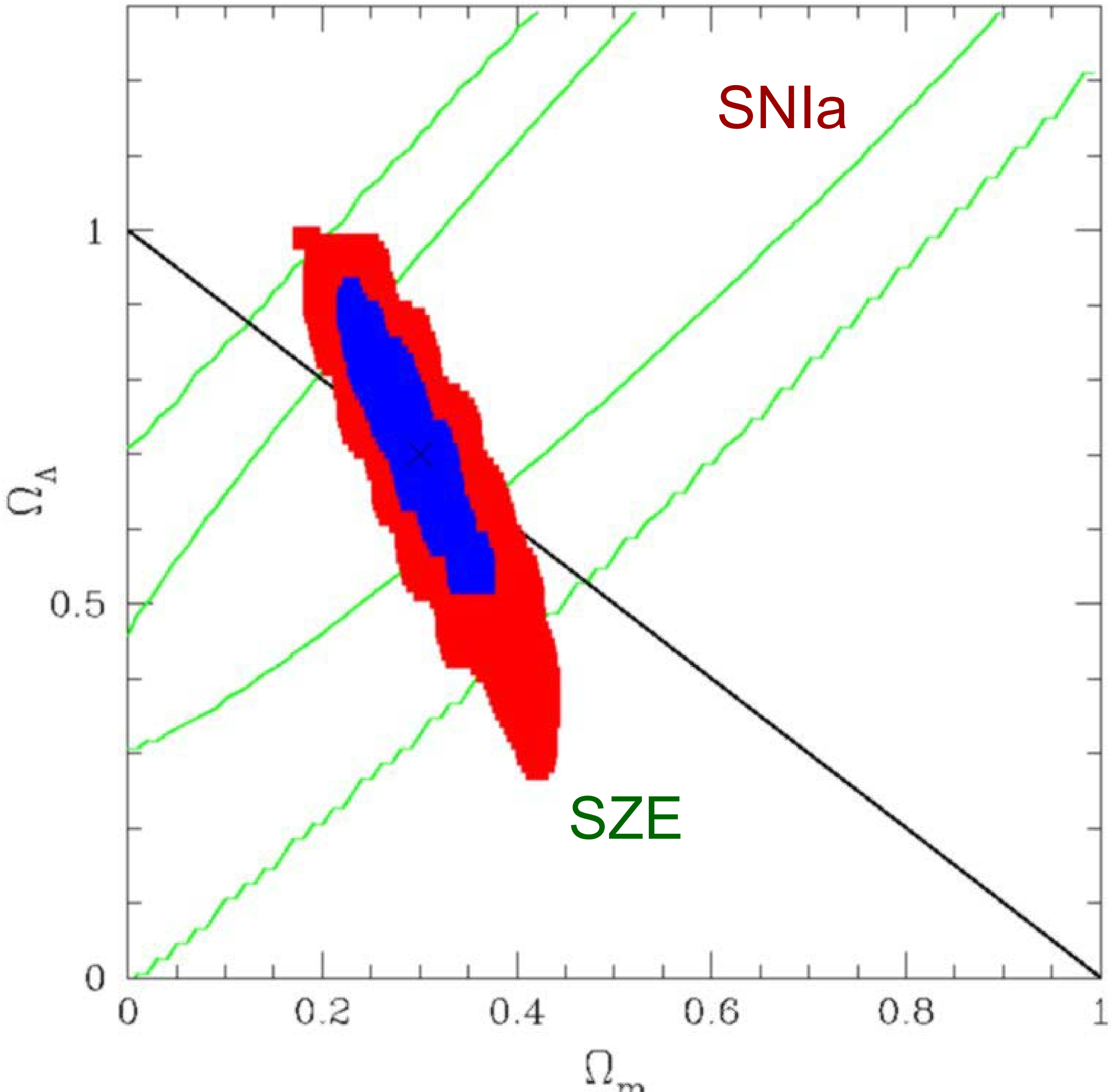
Cl1226
z=0.888
Cl0152
z=0.835
MS1054
z=0.826
MS0451
z=0.55
Cl0016
z=0.5455
A370
z=0.374
MS1358
z=0.328
A697
z=0.282
A1835
z=0.2528
A1689
z=0.1832
A665
z=0.1818
A1914
z=0.1712

SZ Effect


A1835
CL0016
MS0451
A2261
Zw3146
A2390
A520
A697
R1347
A2204
A773
ΔI (MJy sr⁻¹)
ν (GHz)
100 200 300 400 500

SZ Effect

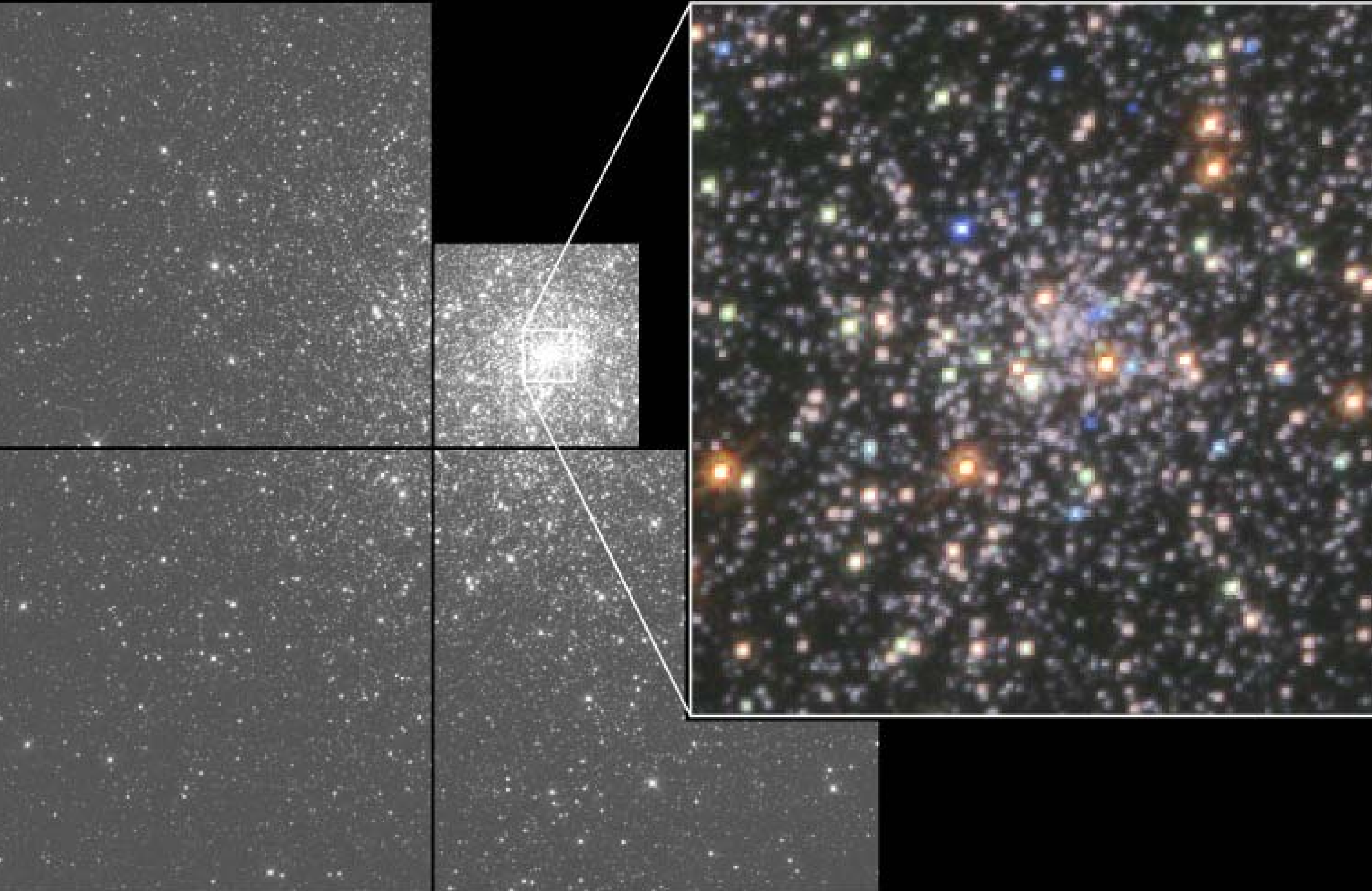
Sunyaev-Zel'dovich Effect



15,000
clusters

Planck
ATCA

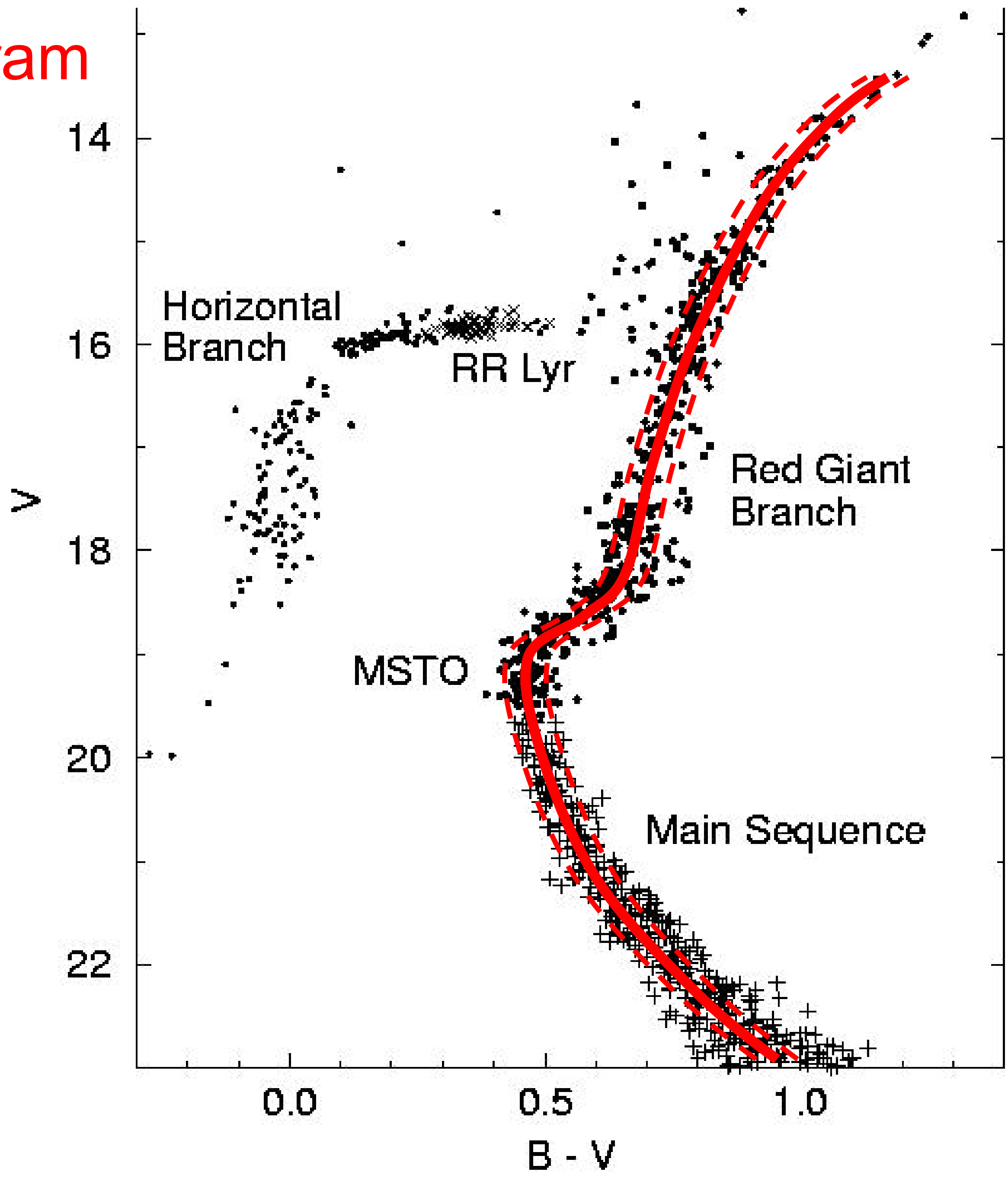
Further Cosmological Evidence: Age Universe



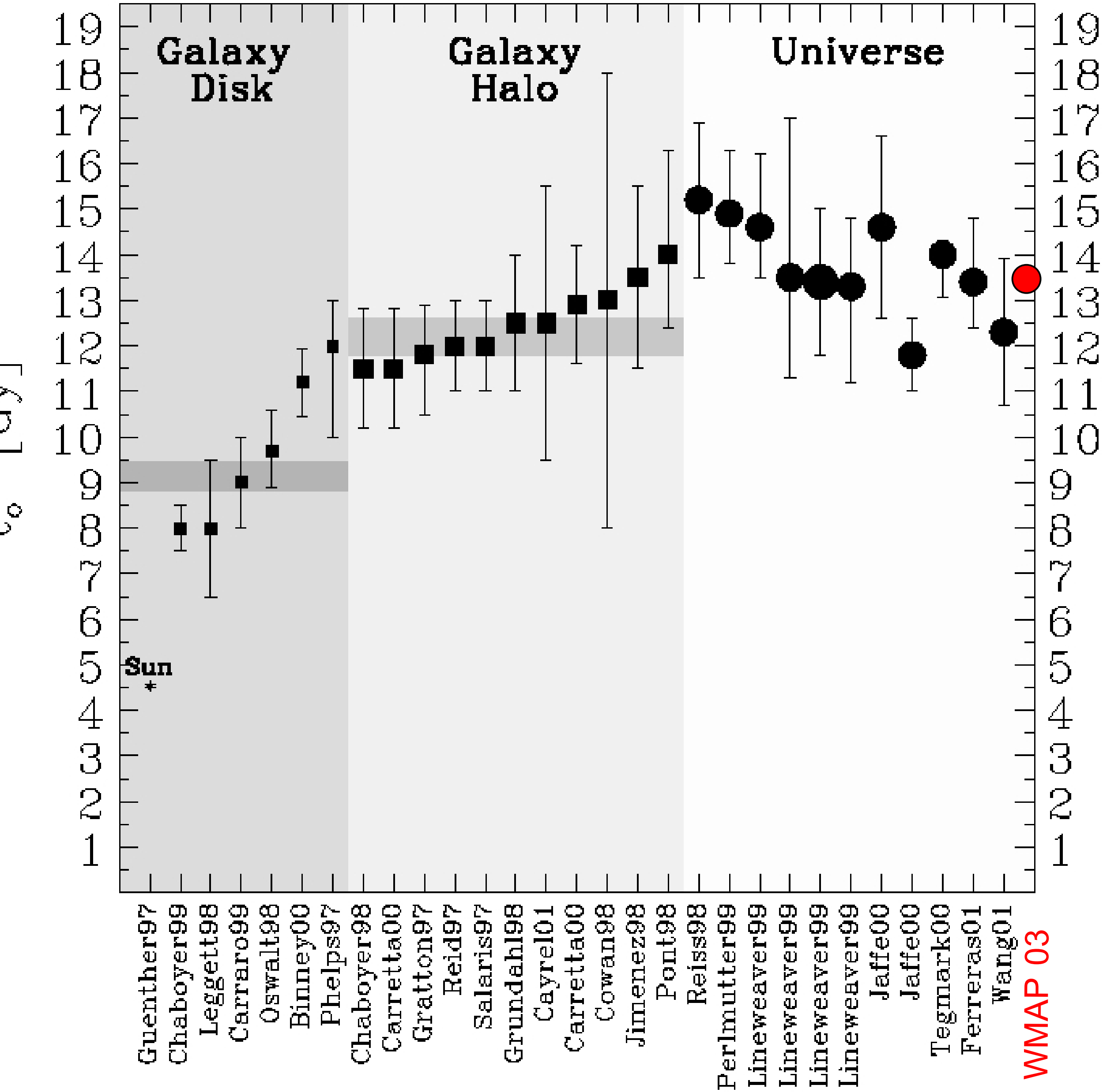
Globular Cluster M15 HST • WFPC

RC95-06 • ST ScI OPO • November 1995 • P. Guhathakurta (UC Santa Cruz), NASA

HR-diagram



Horizontal Branch
RR Lyr
Red Giant Branch
MSTO
Main Sequence
V
14
16
18
20
22
0.0
0.5
1.0
B - V

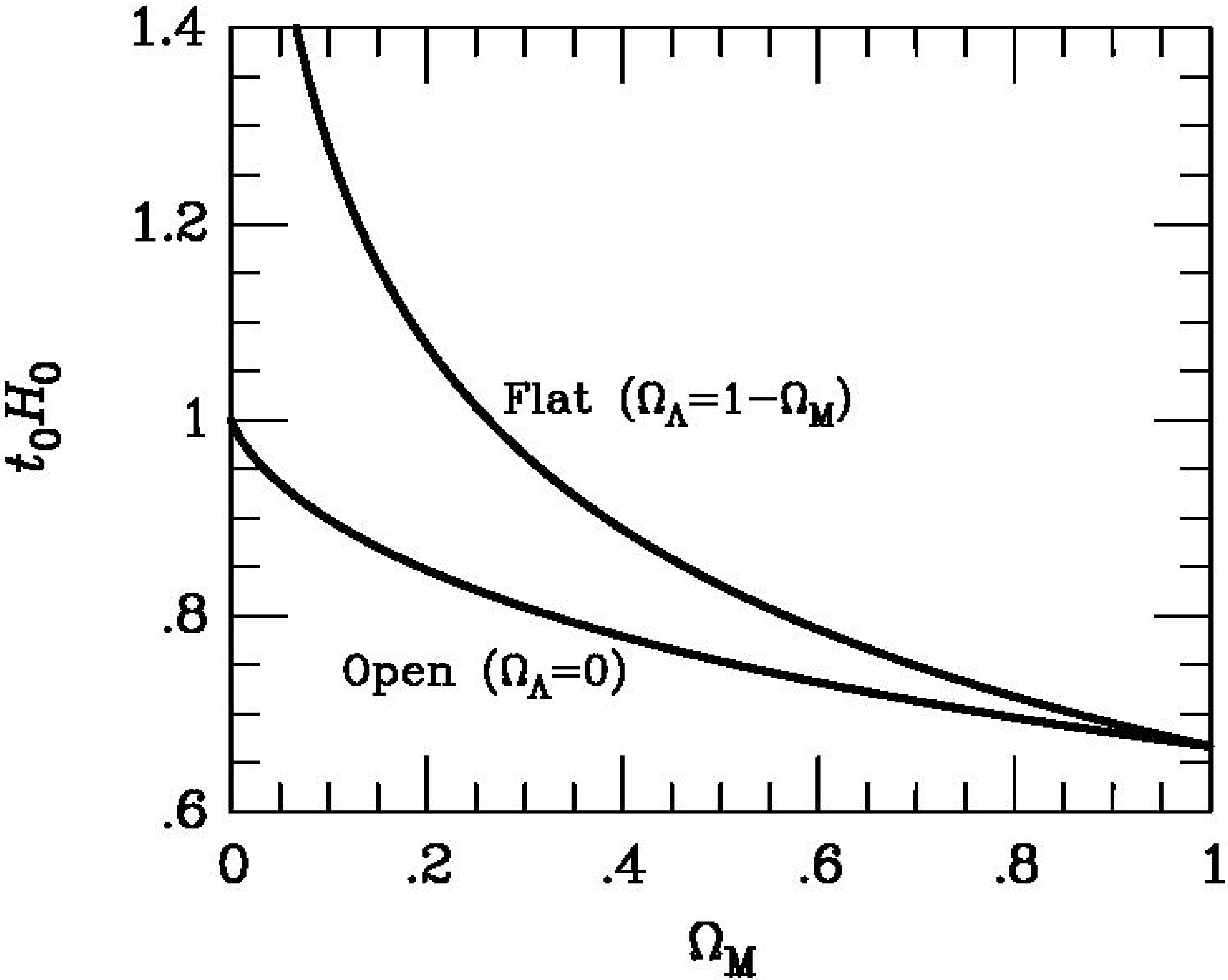


AGE OF UNIVERSE

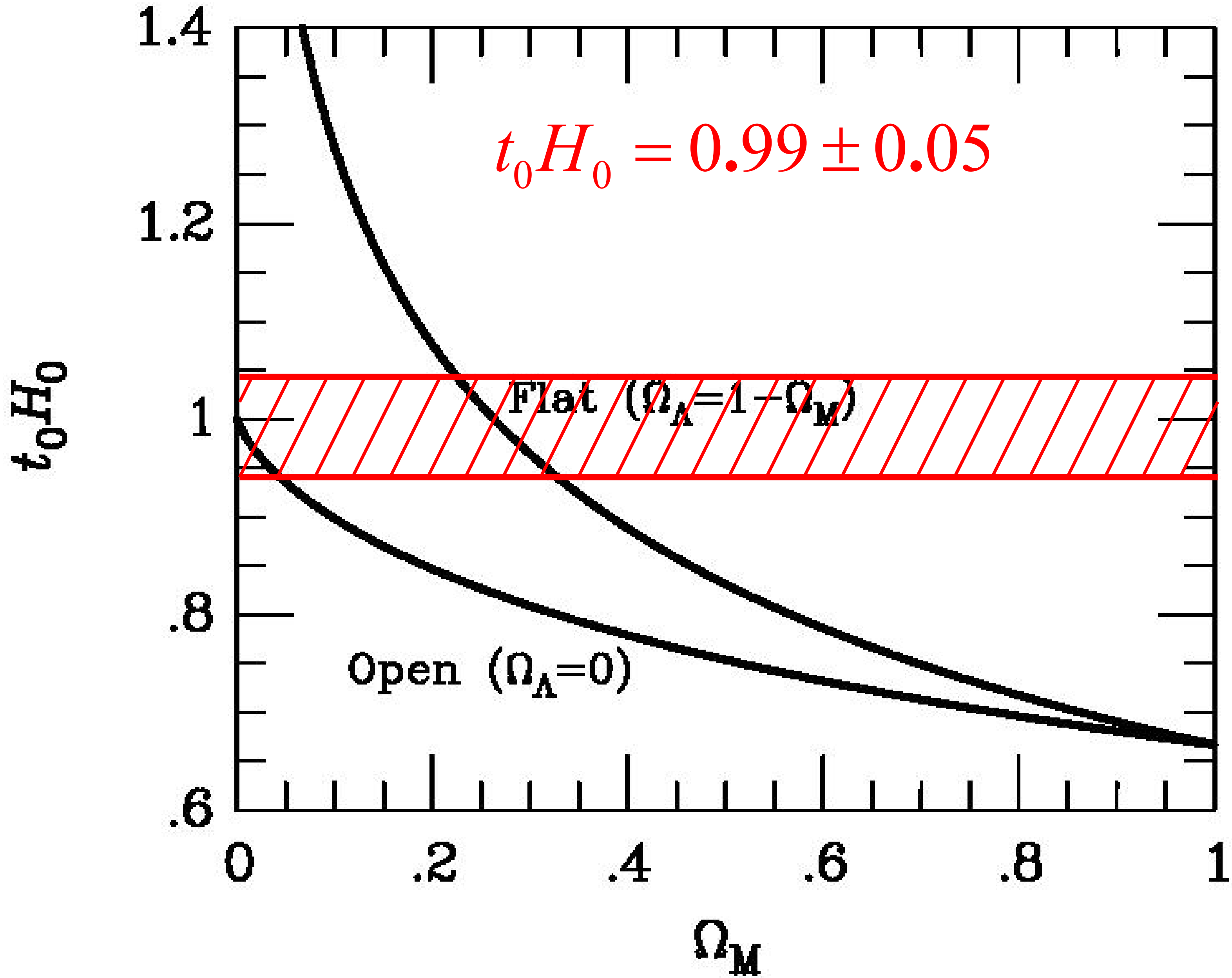
WMAP (2003)

$$t_0 = 13.6 \pm 0.2$$

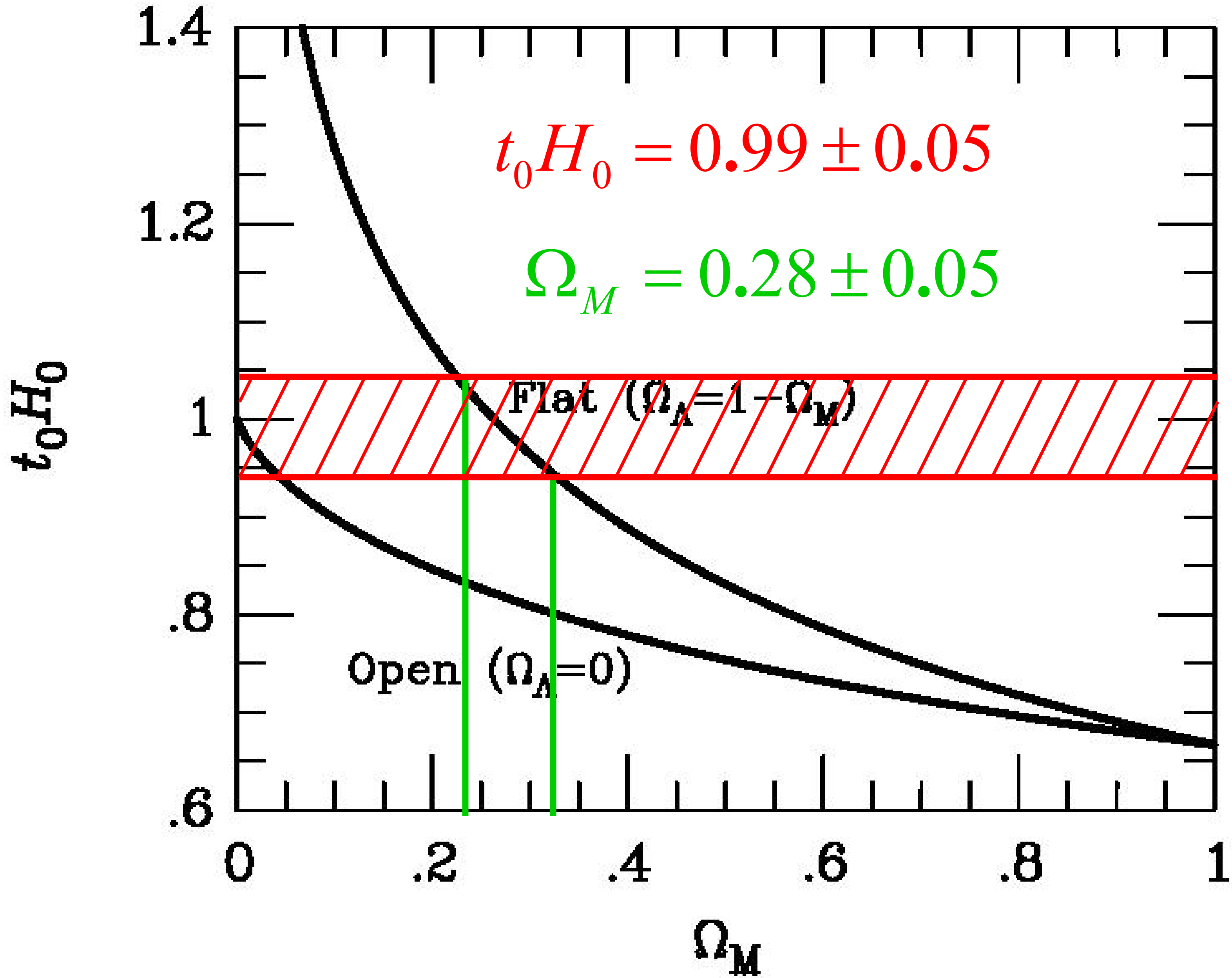
Gyr



1.4
1.2
1
.8
.6
0
.2
.4
.6
.8
1
$t_0 H_0$
Ω_M
Flat (Ω_Λ=1−Ω_M)
Open (Ω_Λ=0)



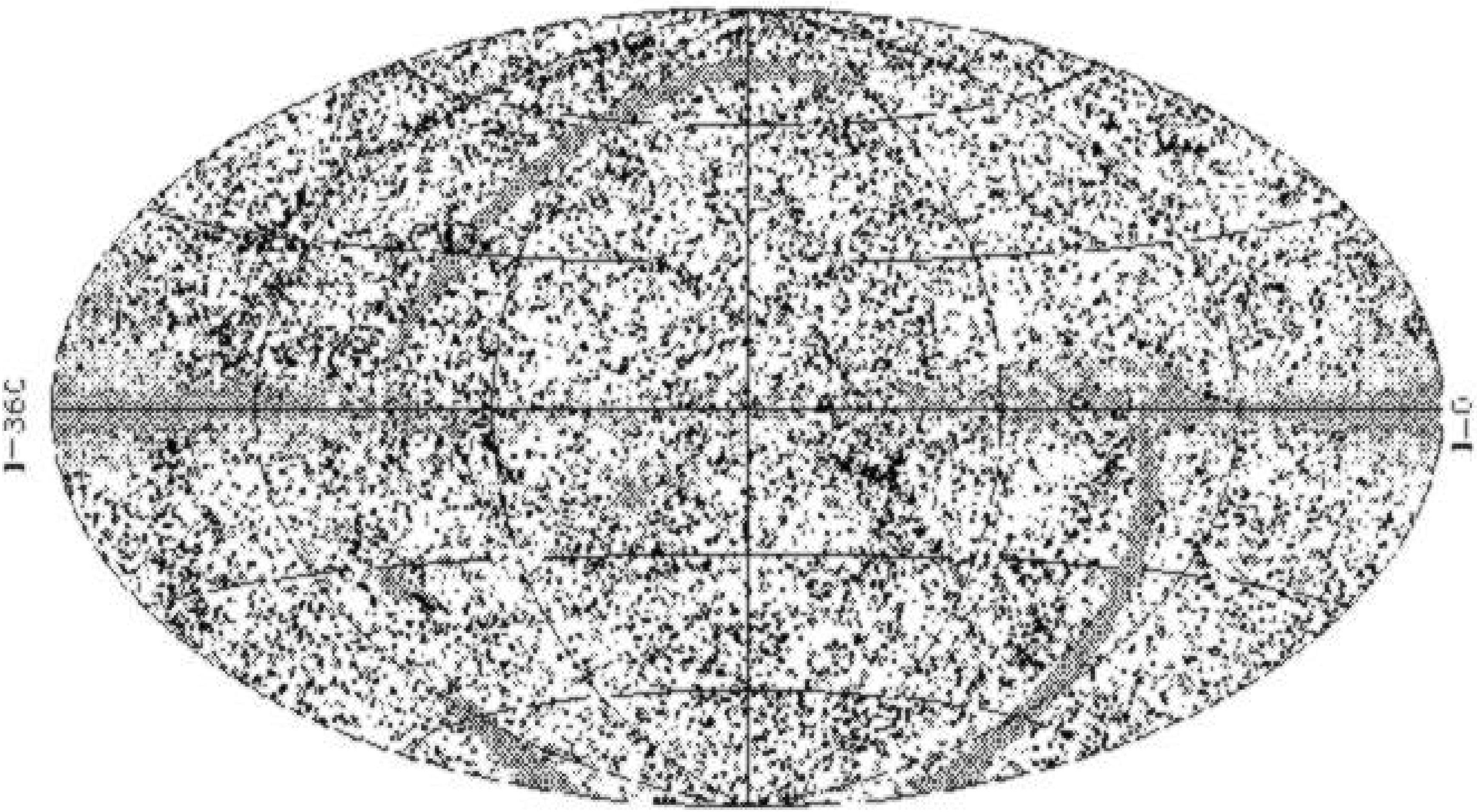
$t_0 H_0 = 0.99 \pm 0.05$
Flat ($\Omega_\Lambda = 1 - \Omega_M$)
Open ($\Omega_\Lambda = 0$)
$t_0 H_0$
Ω_M
1.4
1.2
1
.8
.6
0
.2
.4
.6
.8
1



$t_0 H_0 = 0.99 \pm 0.05$
$\Omega_M = 0.28 \pm 0.05$
Flat ($\Omega_\Lambda = 1 - \Omega_M$)
Open ($\Omega_\Lambda = 0$)
$t_0 H_0$
Ω_M
1.4
1.2
1
.8
.6
0
.2
.4
.6
.8
1

Large Scale Structure

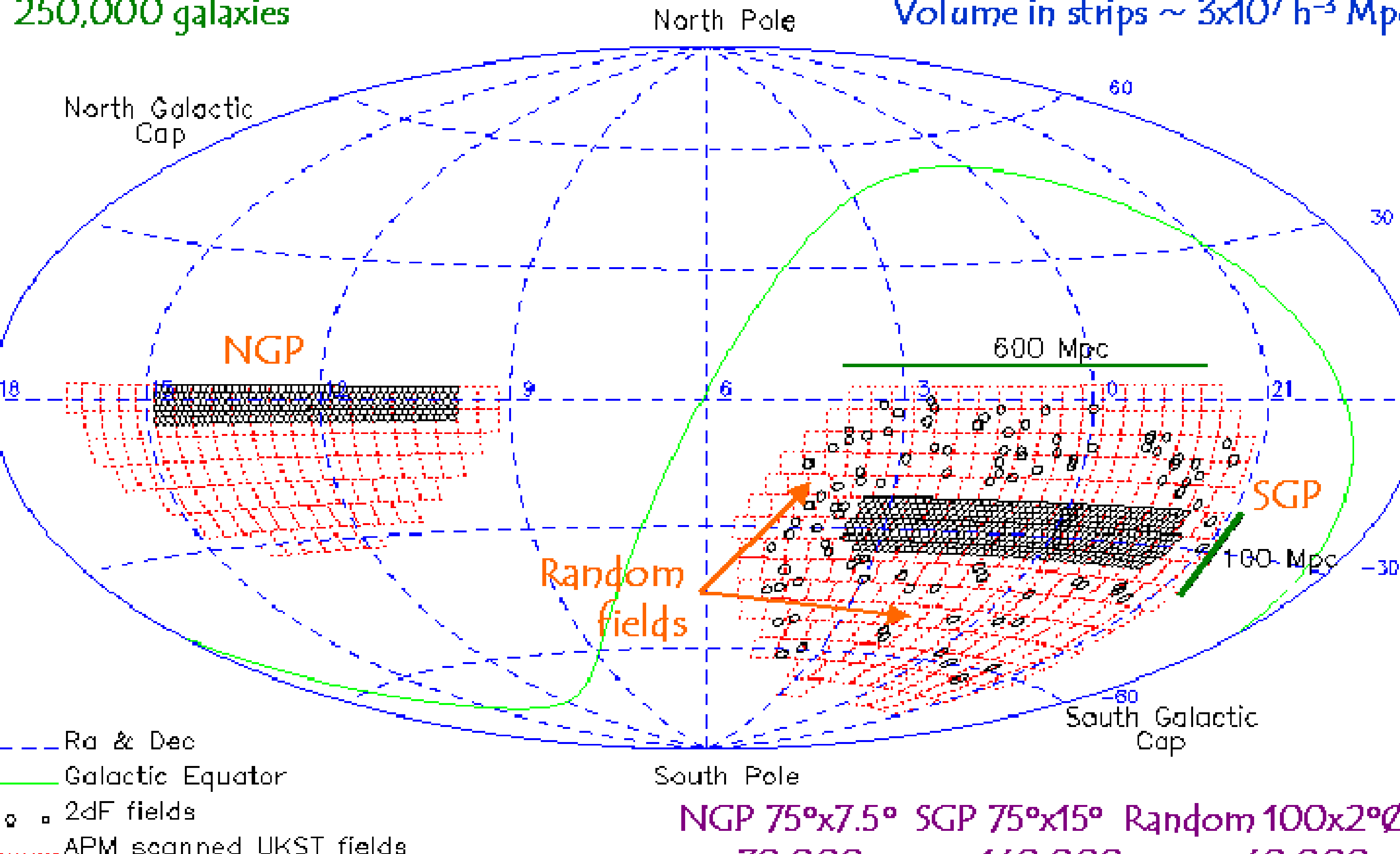
IRAS Point Source z Catalog



2dFGRS survey design

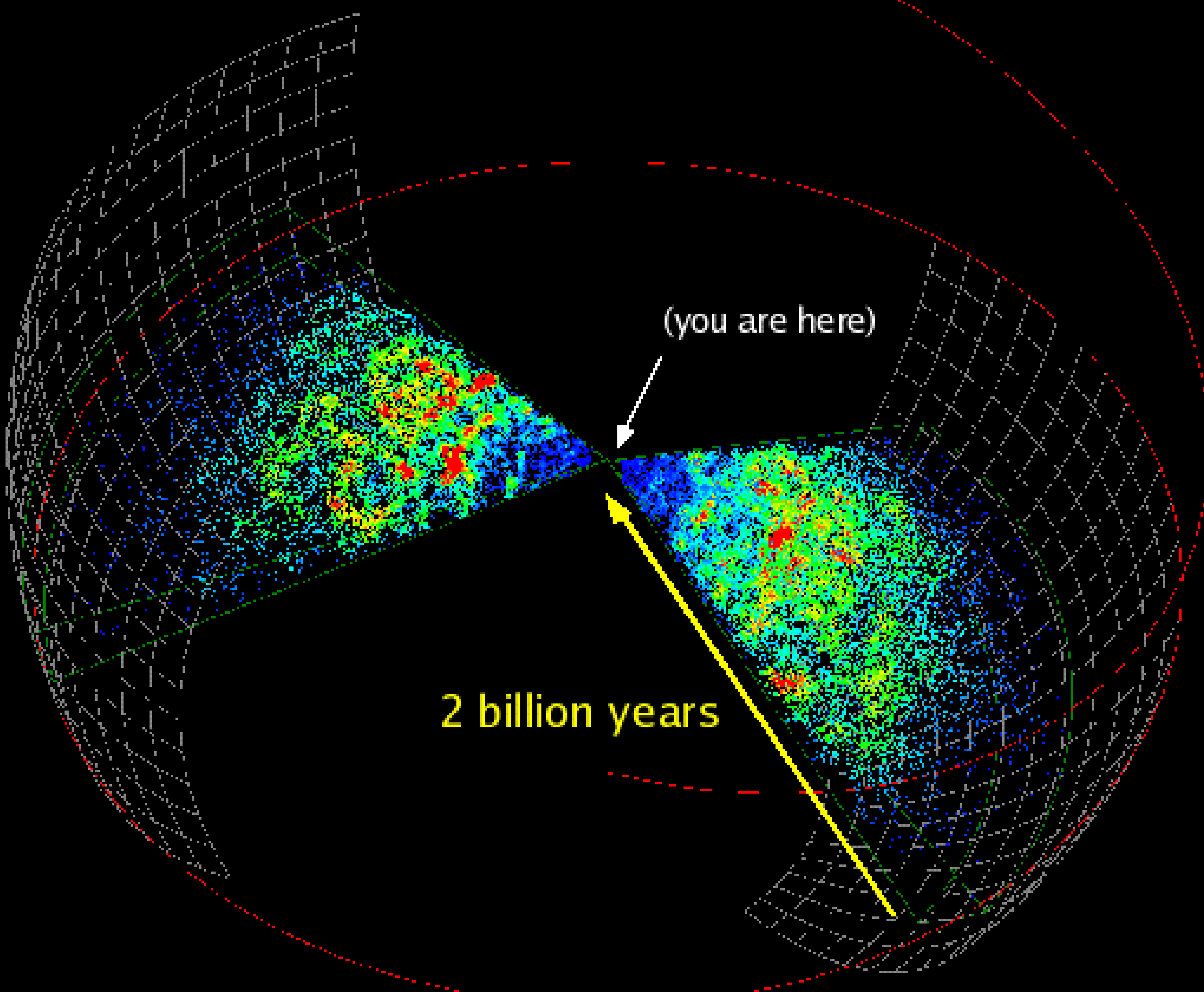
~2000 sq.deg. to b_J=19.45
250,000 galaxies

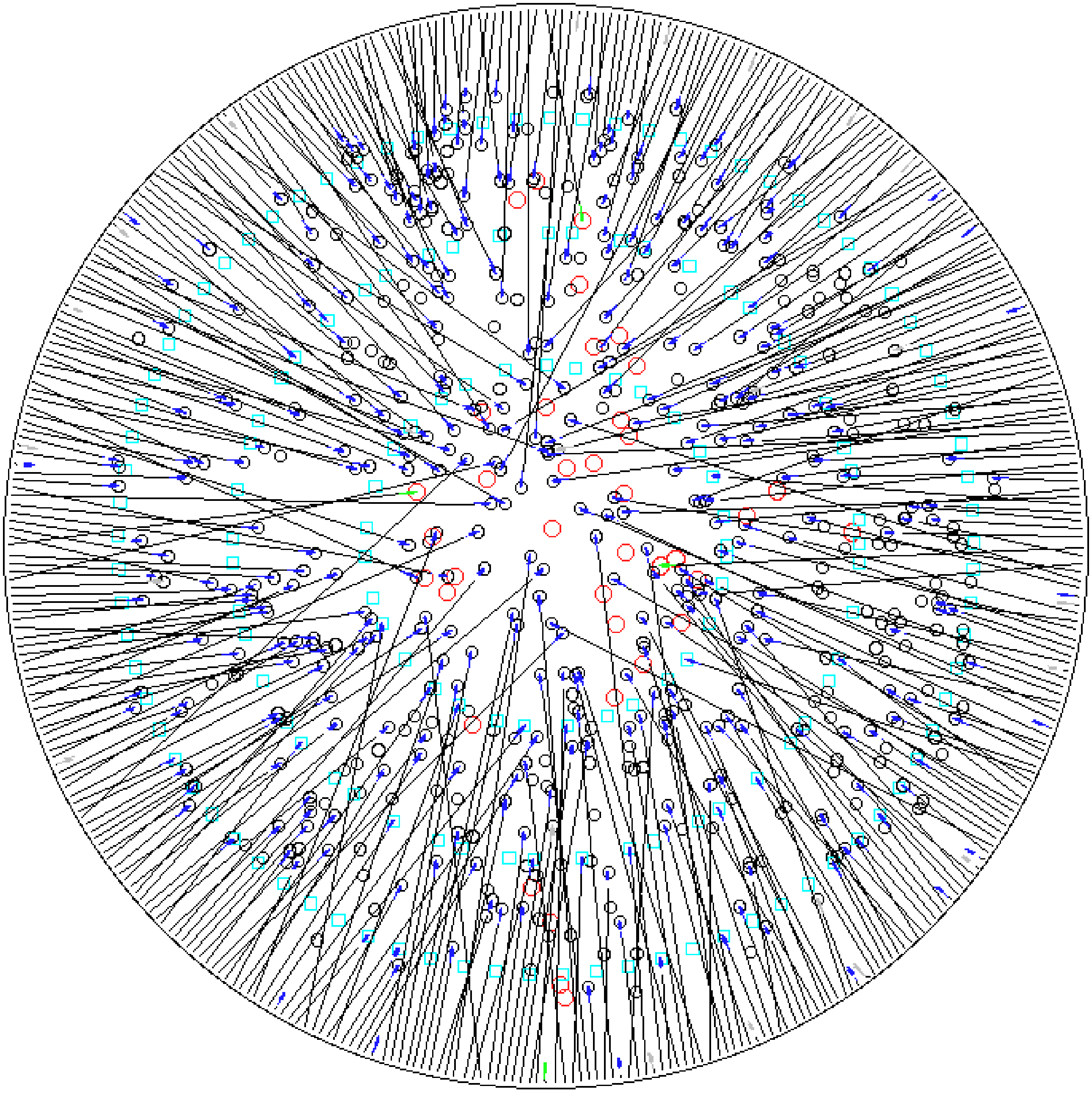
Strips+random fields ~ $1\times10^{8}\ h^{-3}$ Mp
Volume in strips ~ $3\times10^{7}\ h^{-3}$ Mp



NGP 75°x7.5° SGP 75°x15° Random 100x2°Ø
~70,000 ~140,000 ~40,000

The 2dF Galaxy Survey



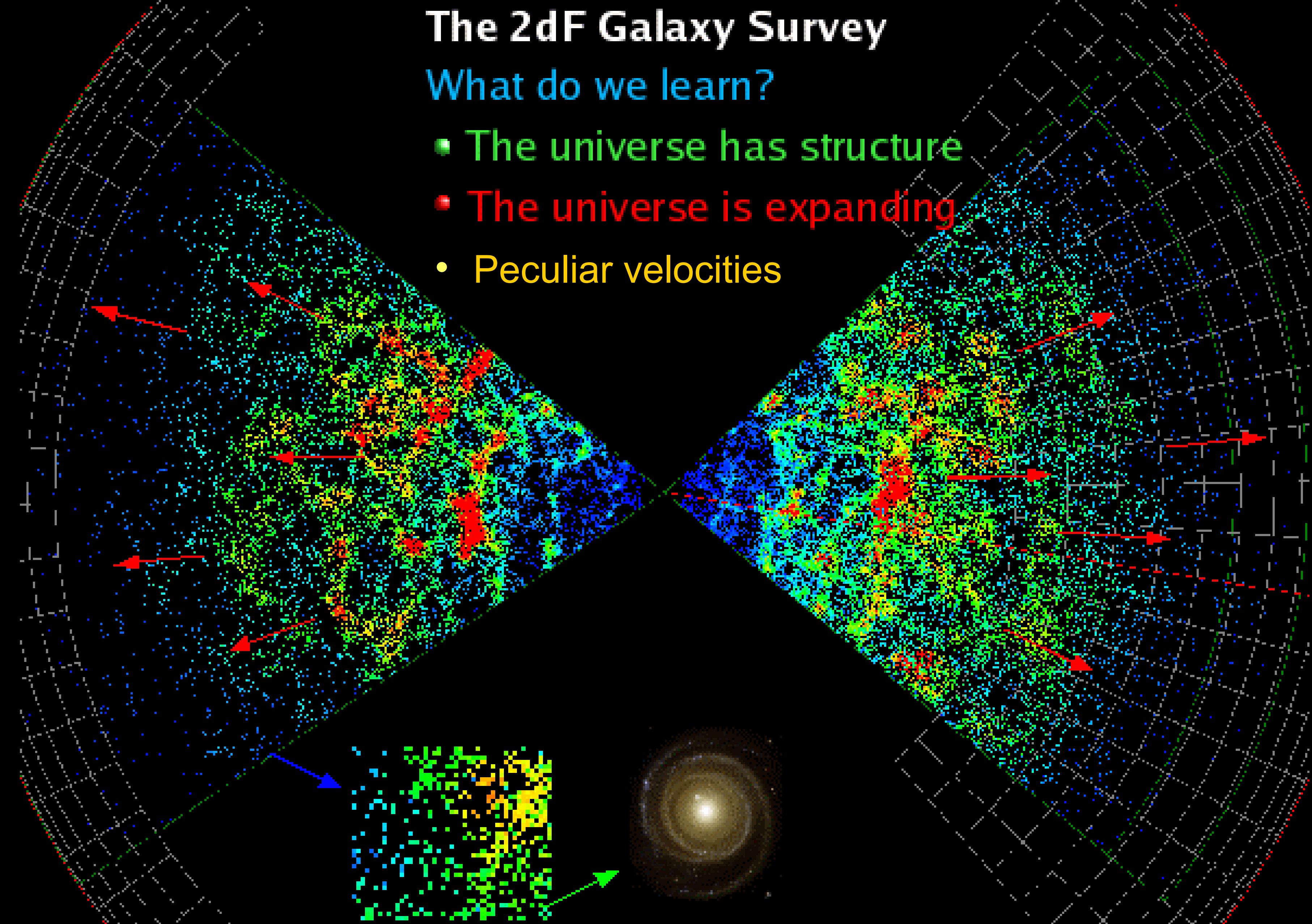


Multifiber:
200 redshifts
per hour

The 2dF Galaxy Survey

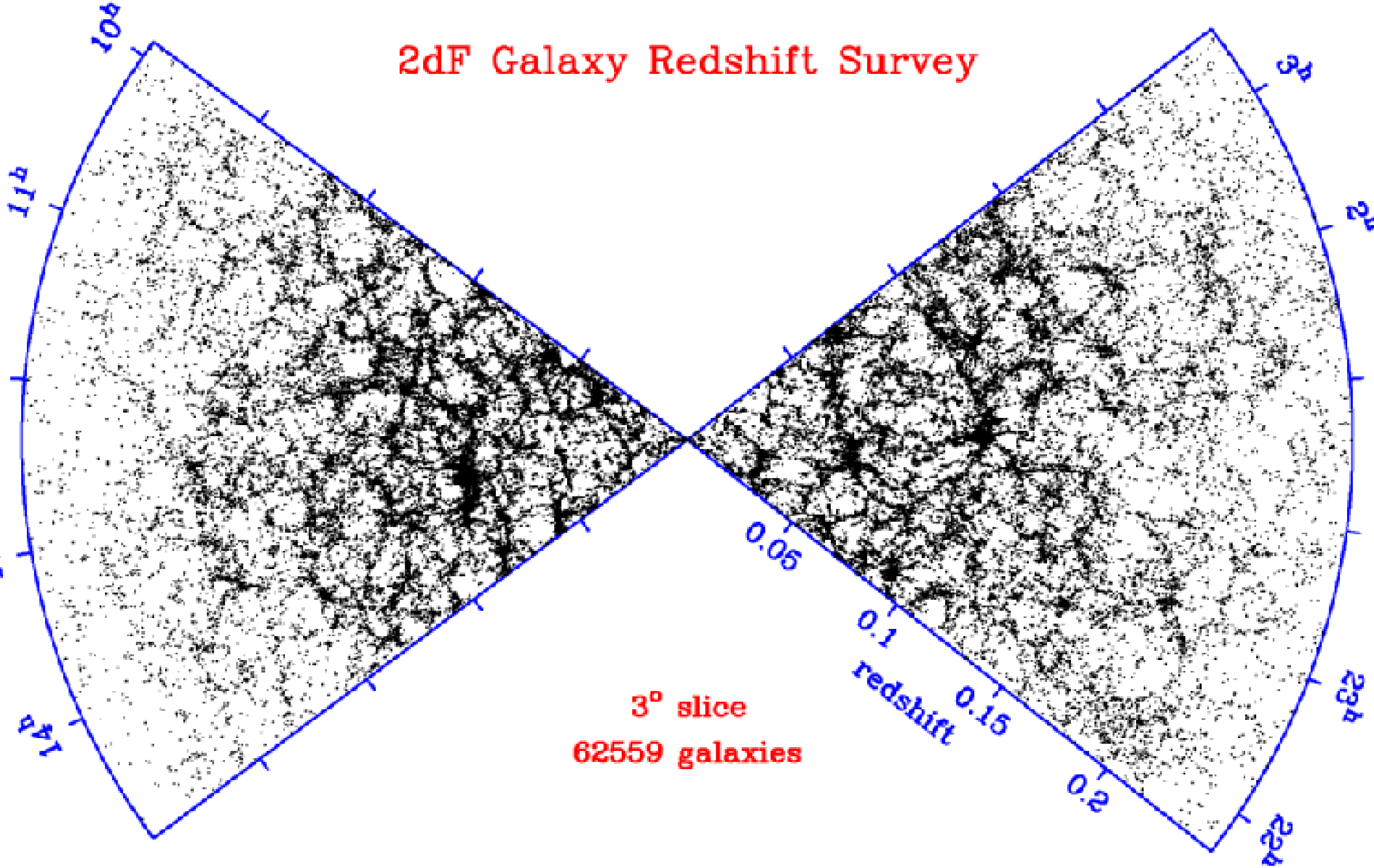
What do we learn?

- The universe has structure
- The universe is expanding
- Peculiar velocities

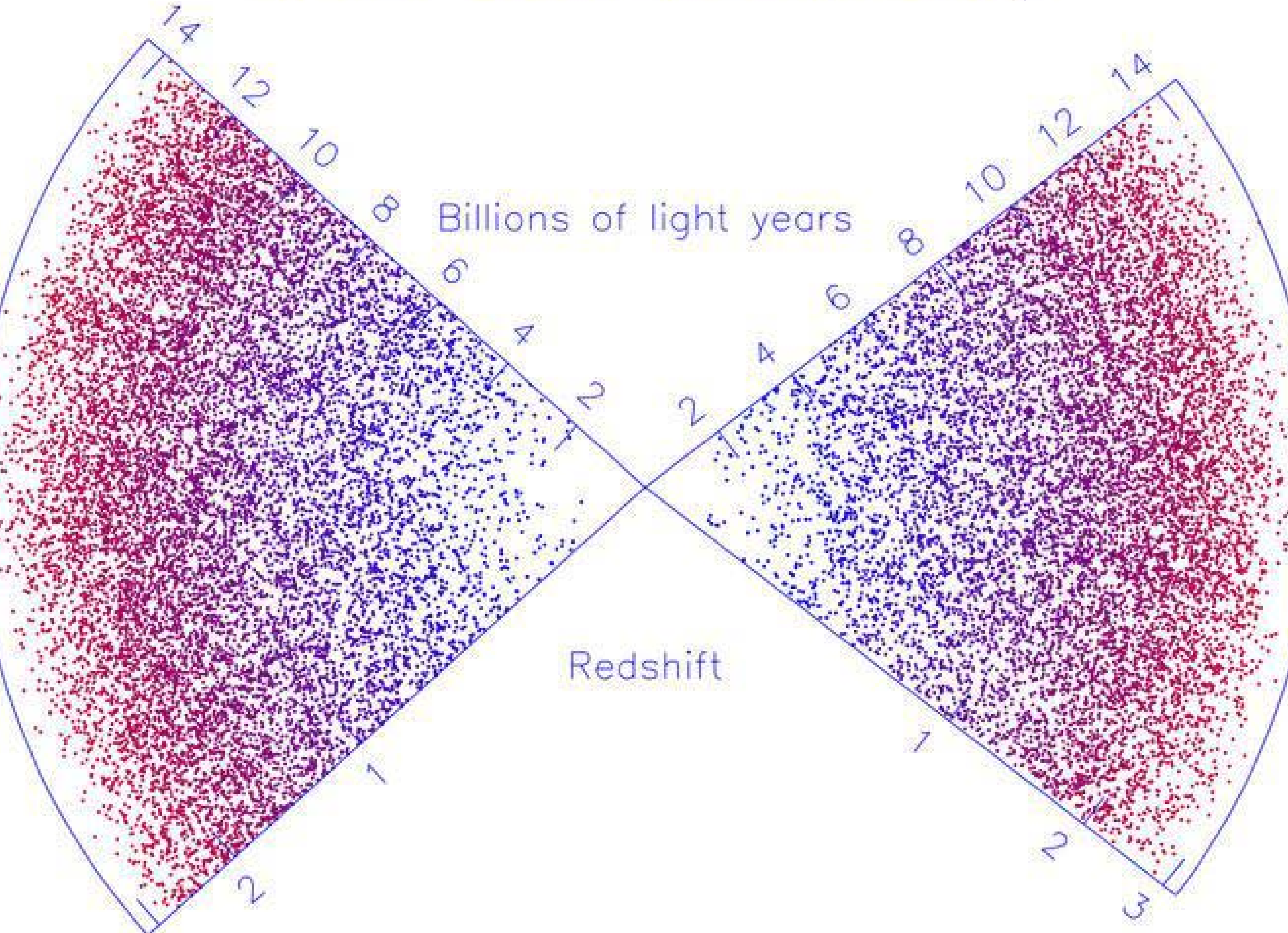


Each dot is (more than one) galaxy:

Cone diagram: 3-degree slice



The 2dF Quasar Redshift Survey



Matter Power Spectrum

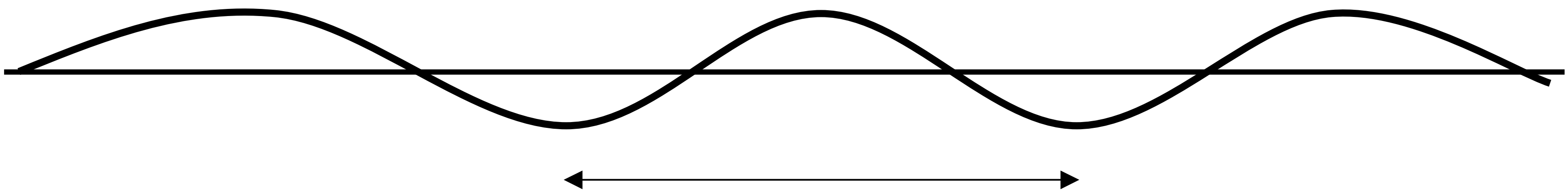
$$\delta(\vec{x},a) = \frac{\rho(\vec{x},a) - \rho(a)}{\rho(a)}$$ density contrast

$$\rho(a) = \rho_0\, a^3$$ average density

$$\delta(x,a) = \int d^3k\, \delta_{\mathrm{k}}(a)\, e^{ikx}$$

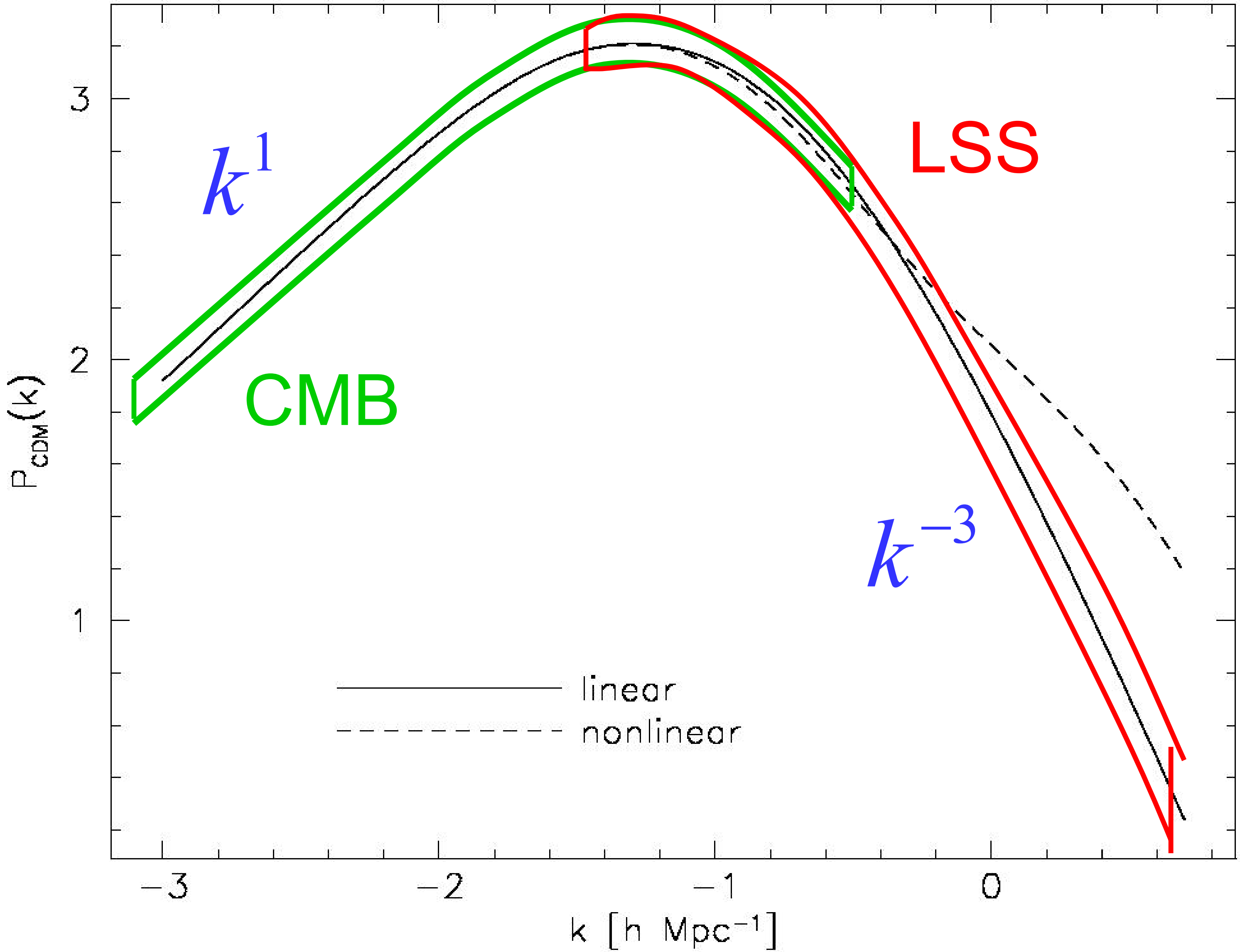
$$\mathrm{P(k)} \equiv \left\langle \left|\delta_{\mathrm{k}}\right|^2 \right\rangle \approx A\, k^n$$ Power Spectrum

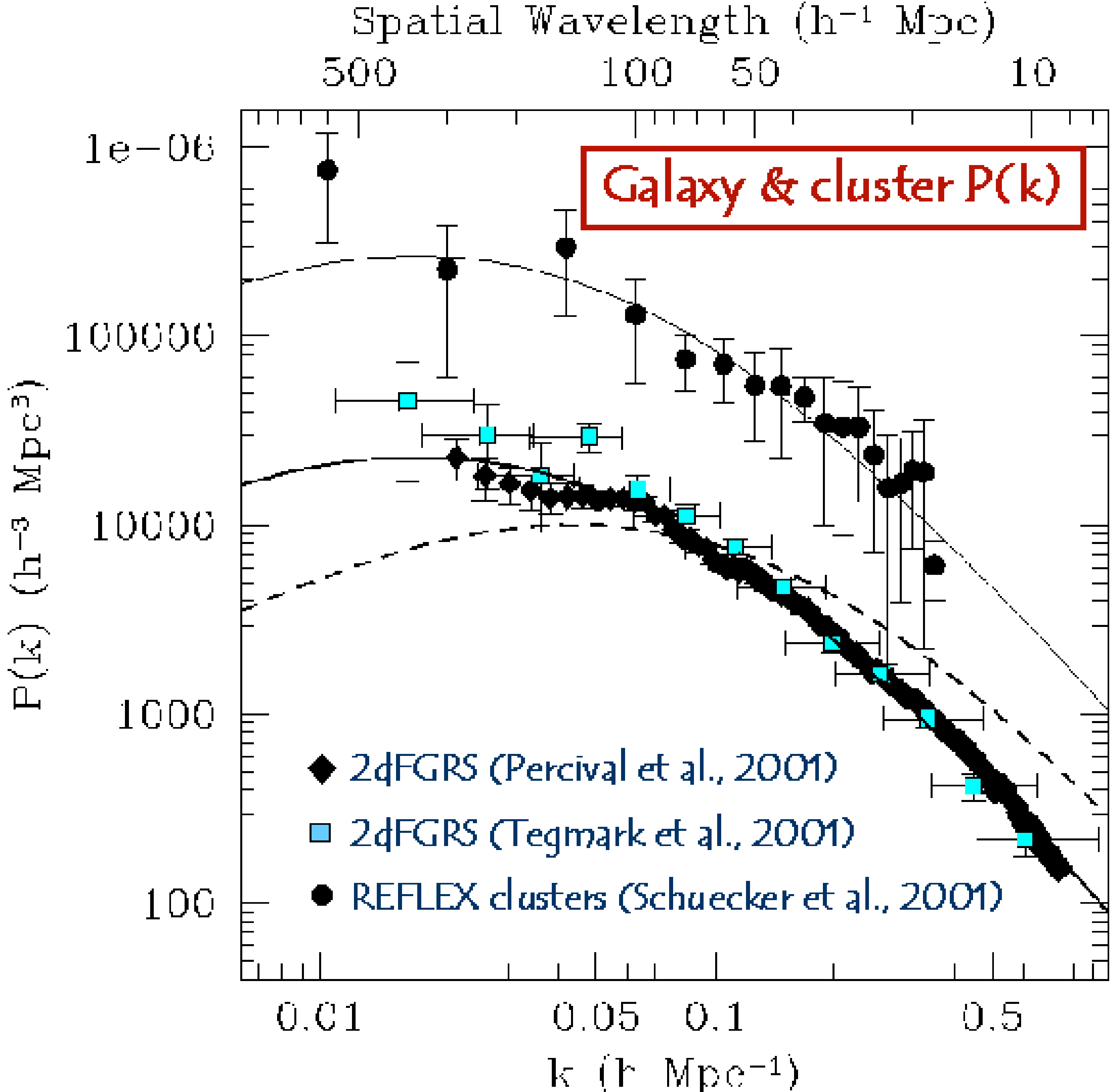
$$\delta_k(a)$$



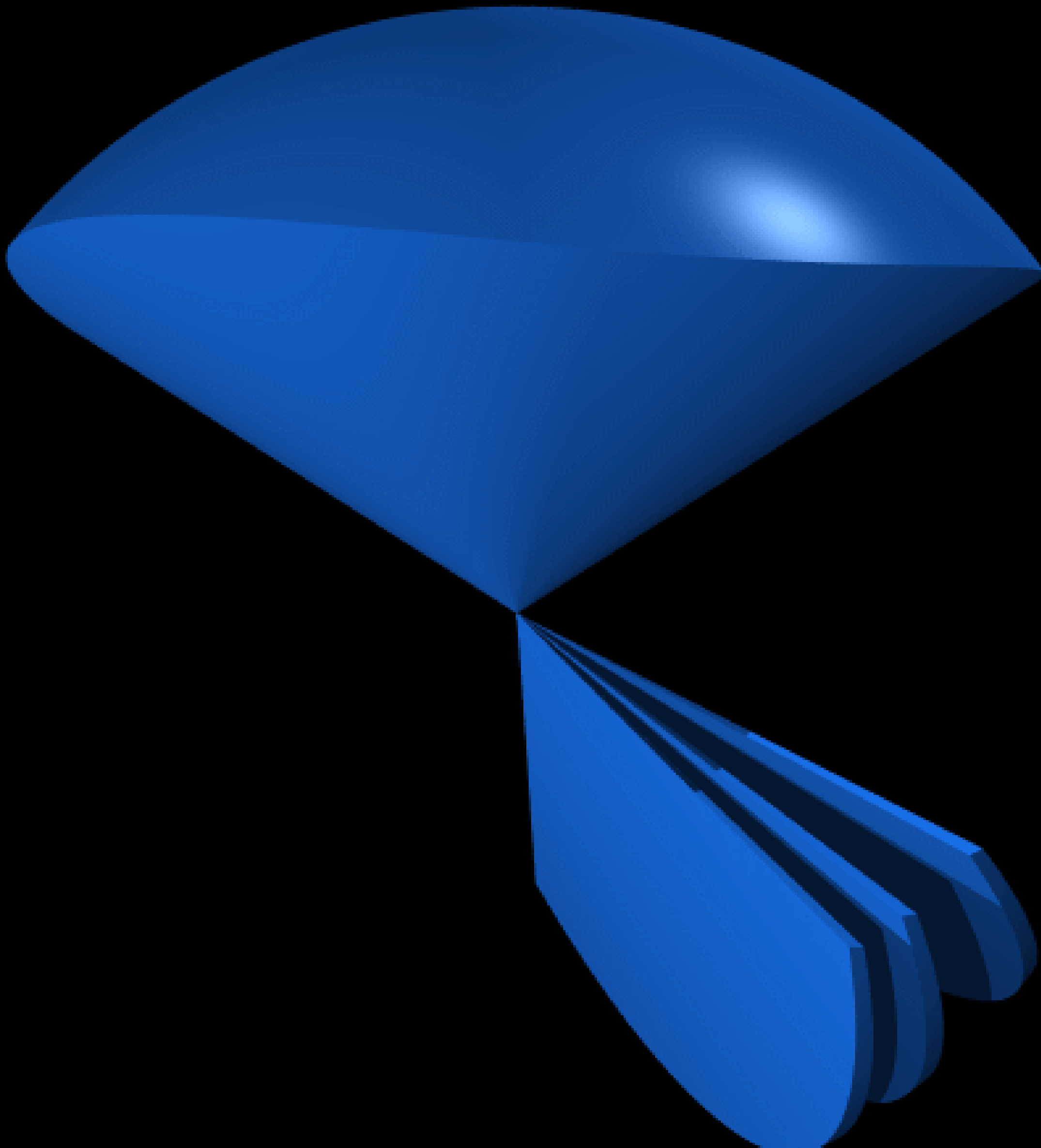
$$\lambda = \frac{2\pi}{k}$$

$$P(k) \equiv \left\langle \left|\delta_k\right|^2 \right\rangle \approx A\,k^n$$

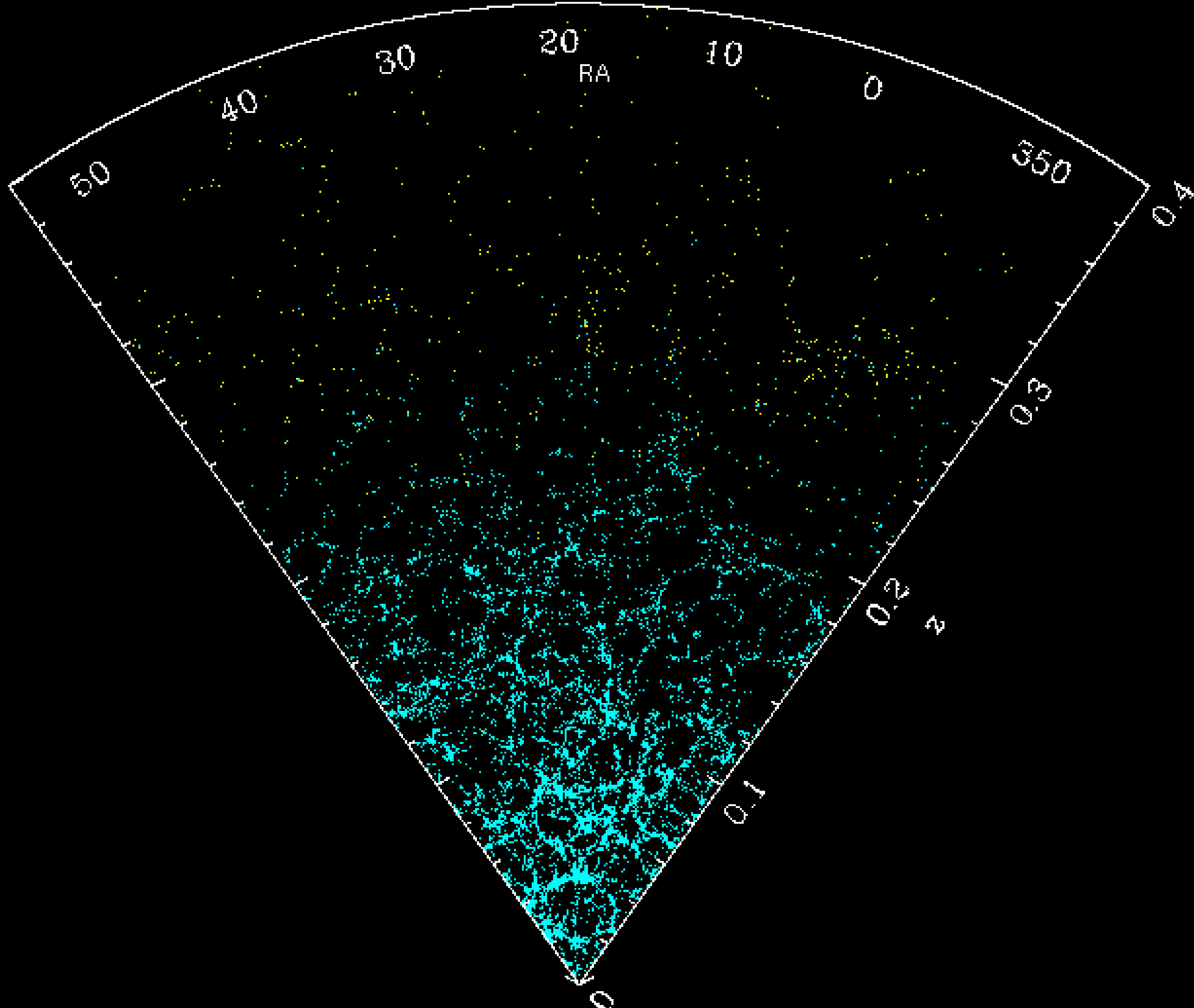




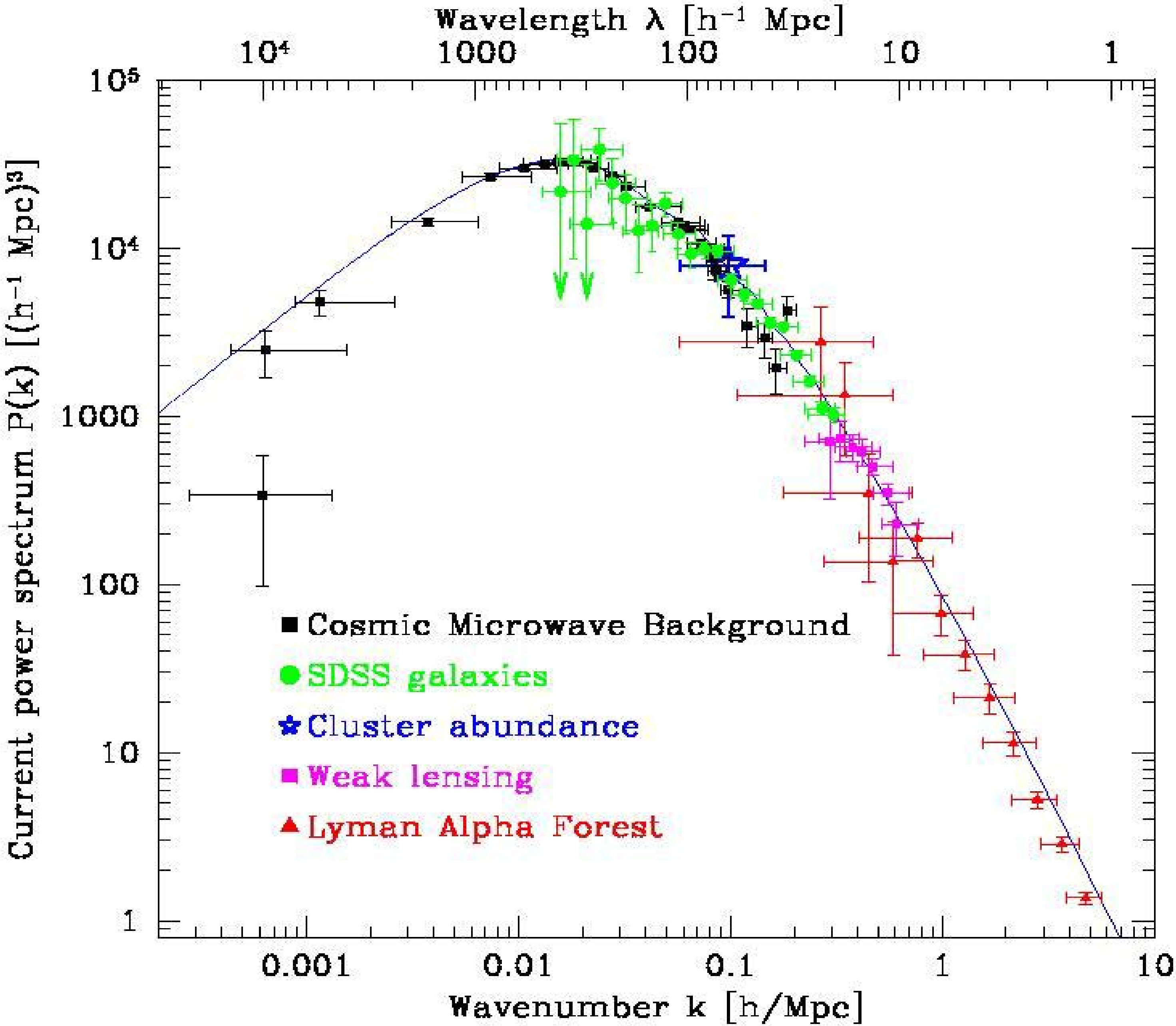
Spatial Wavelength (h⁻¹ Mpc)
500
100
50
10
Galaxy & cluster P(k)
1e-06
100000
10000
1000
100
P(k) (h⁻³ Mpc³)
2dFGRS (Percival et al., 2001)
2dFGRS (Tegmark et al., 2001)
REFLEX clusters (Schuecker et al., 2001)
0.01
0.05
0.1
0.5
k (h Mpc⁻¹)



SDSS

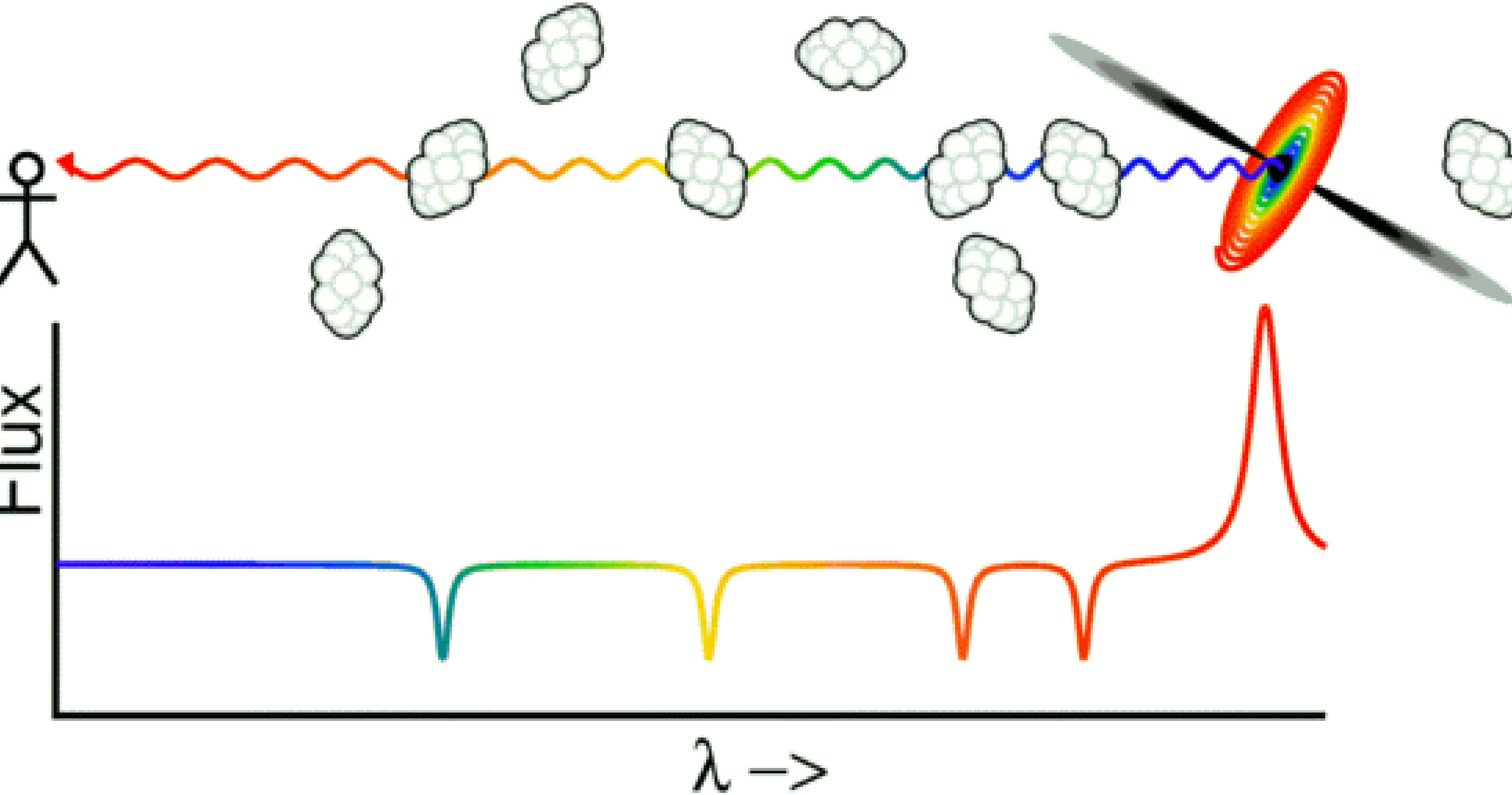


50
40
30
20
RA
10
0
350
0.4
0.3
0.2
z
0.1
0

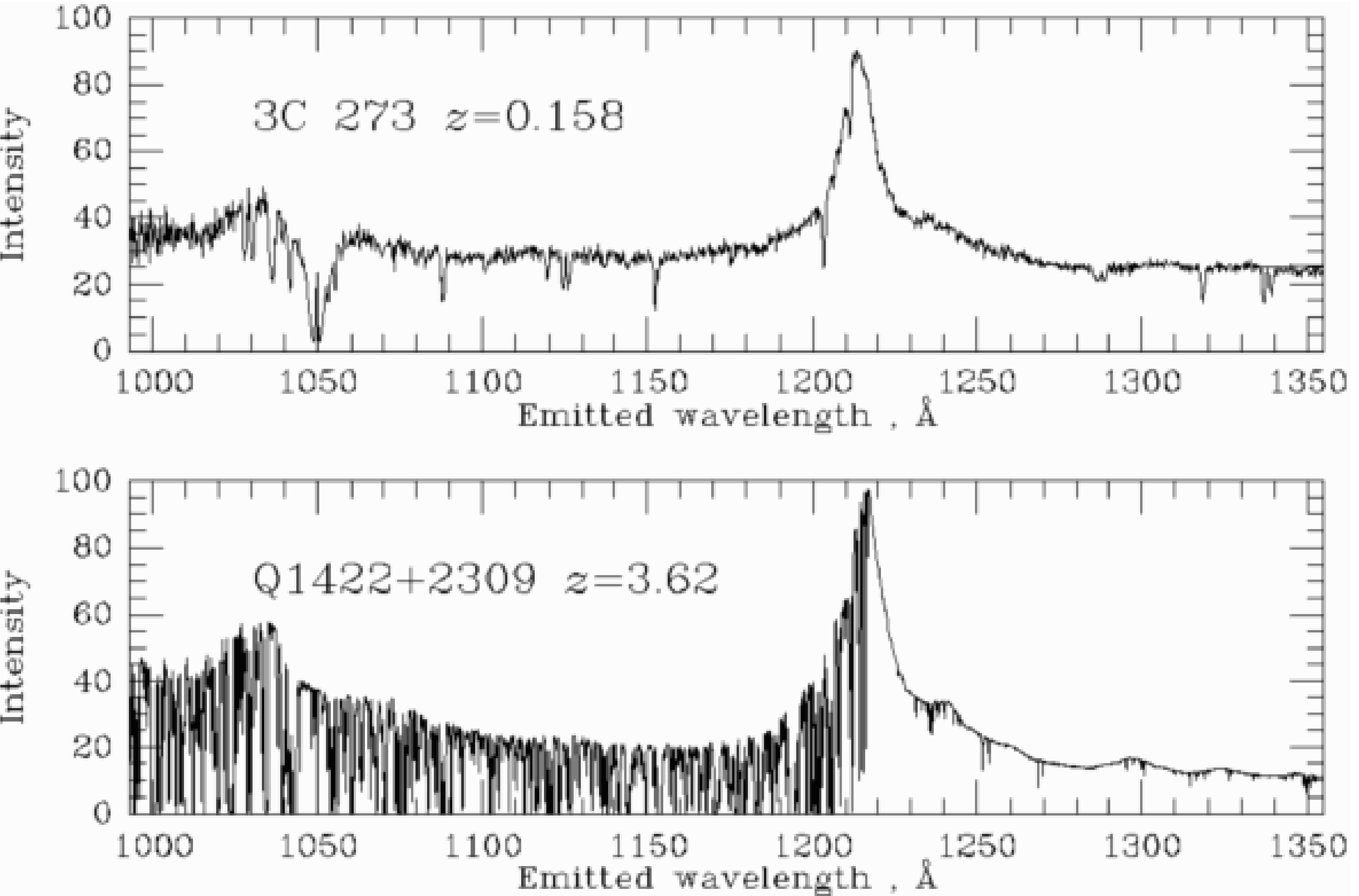


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
10⁵
10⁴
1000
100
10
1
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]

Lyman-α Forest

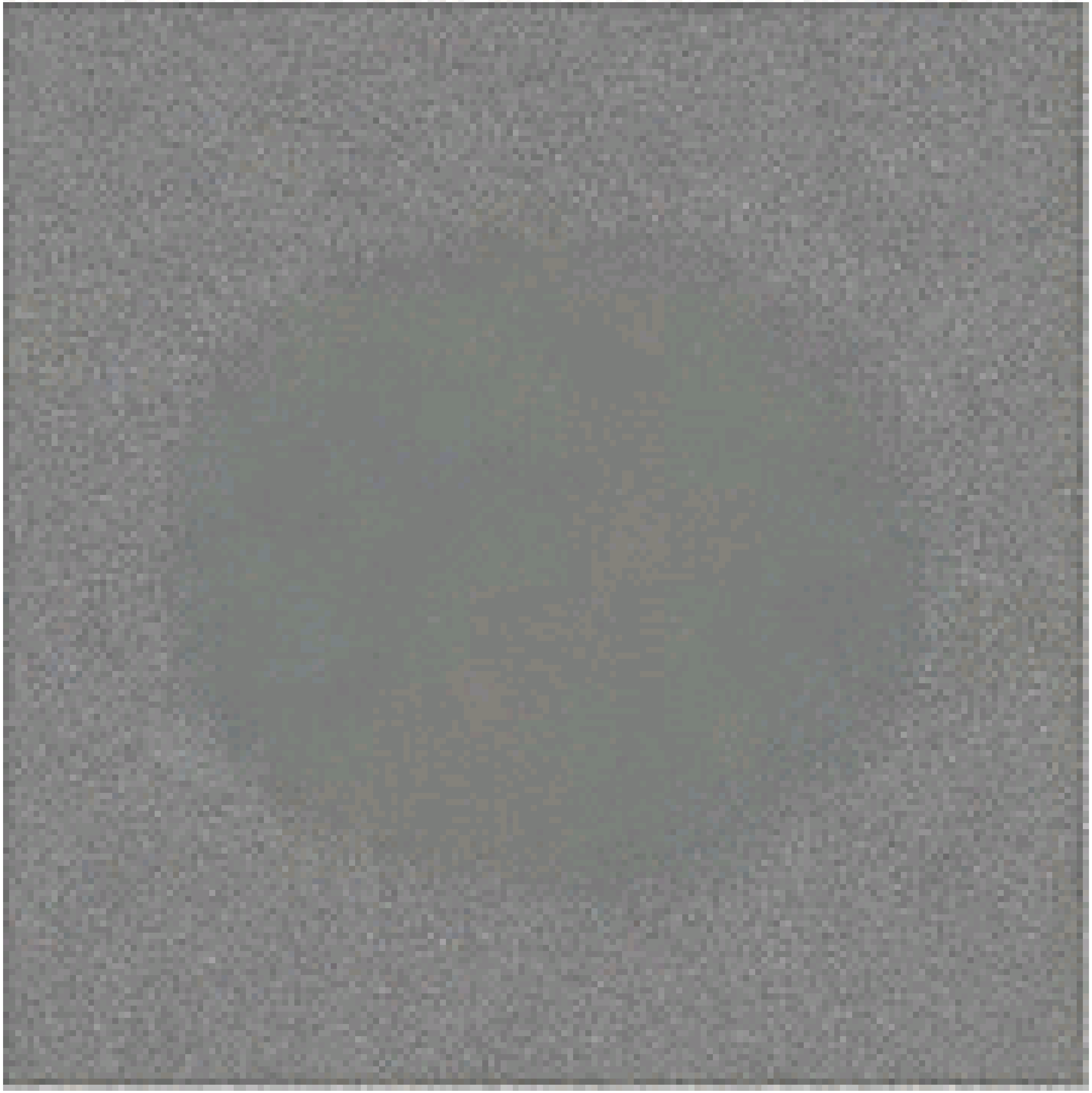


Lyman-α Forest



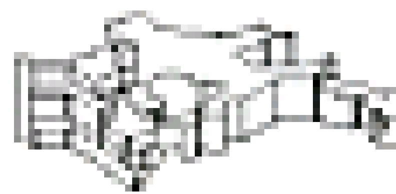
Numerical Simulations

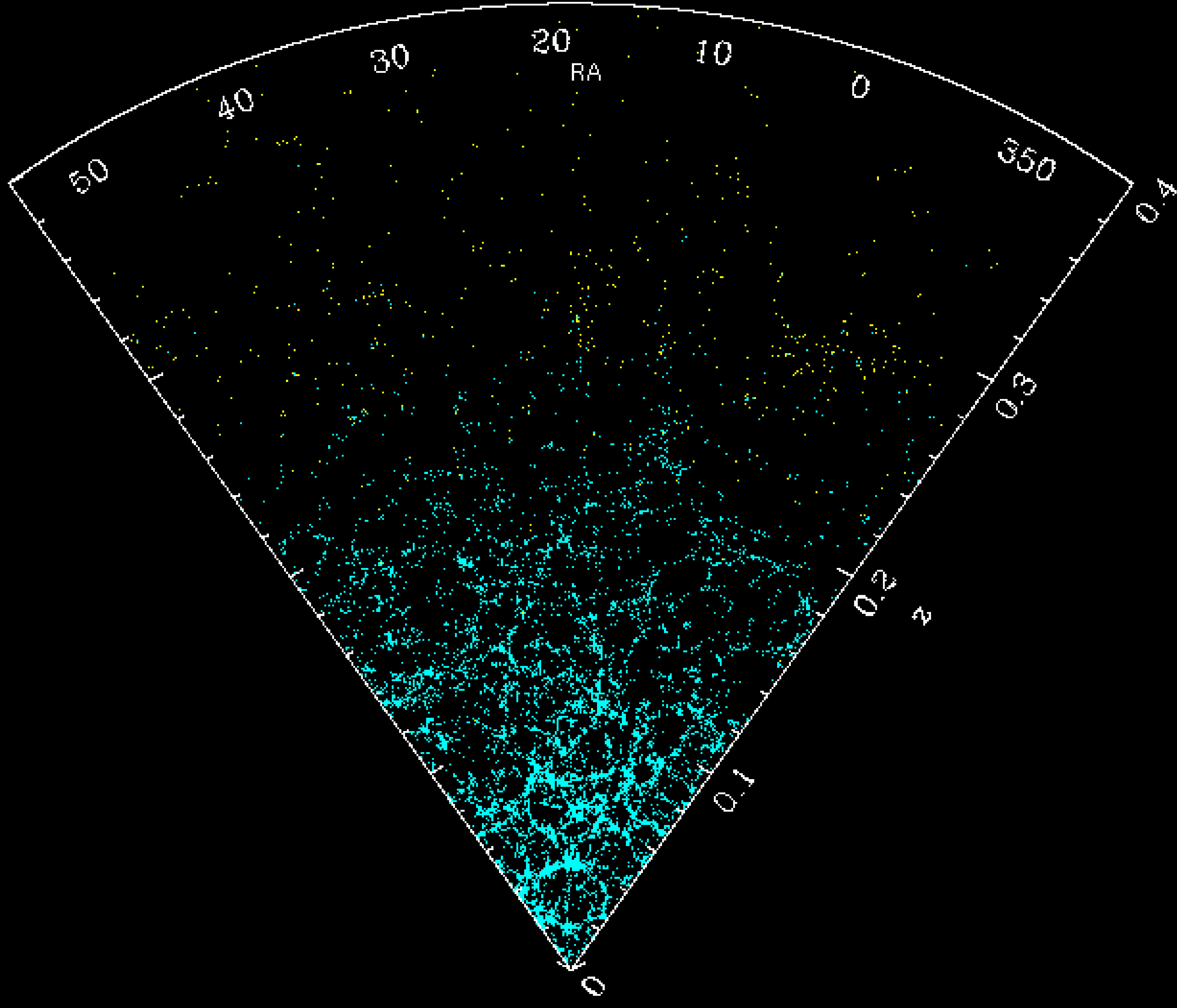
(beyond pert. Theory)



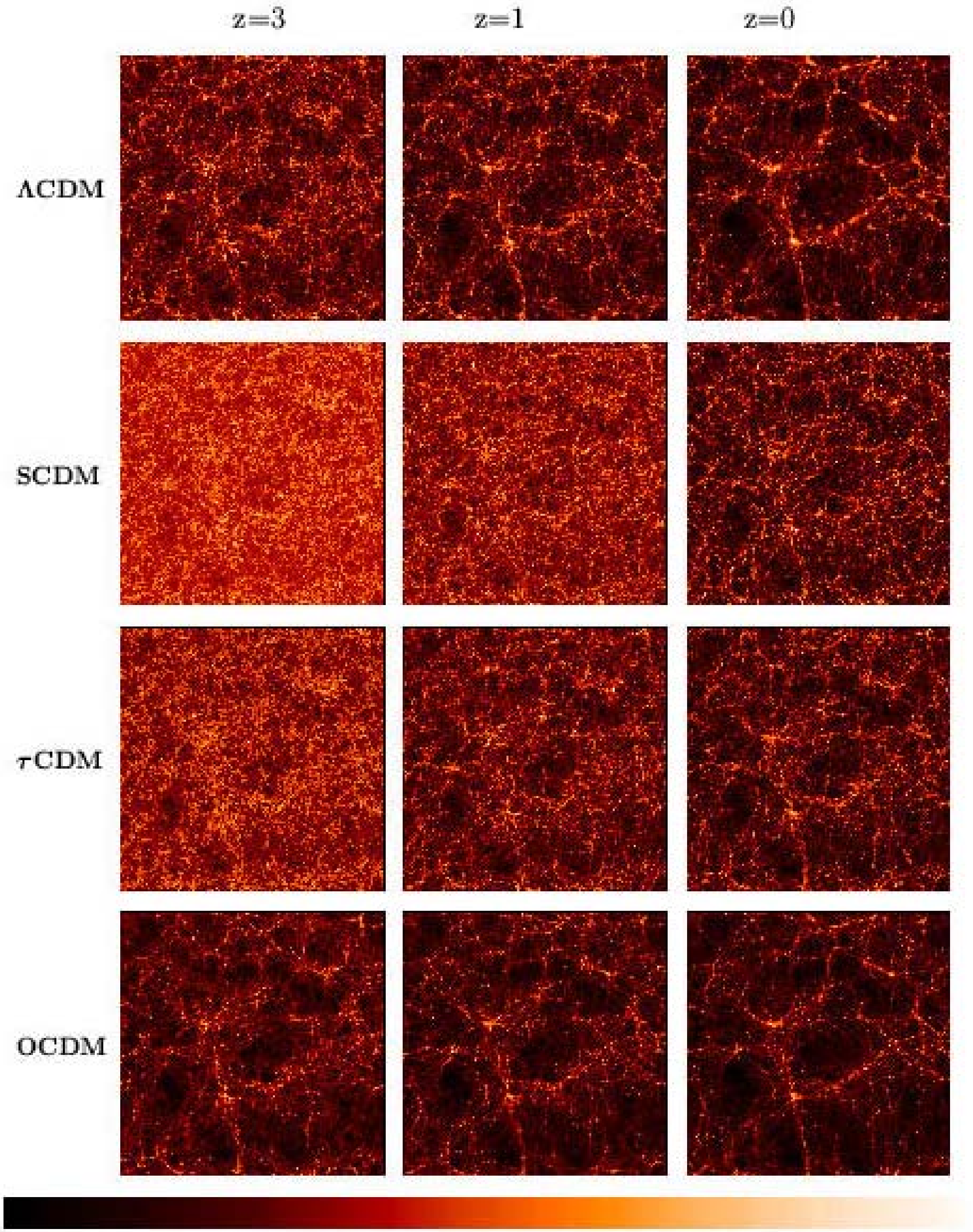
CR

z=20.0





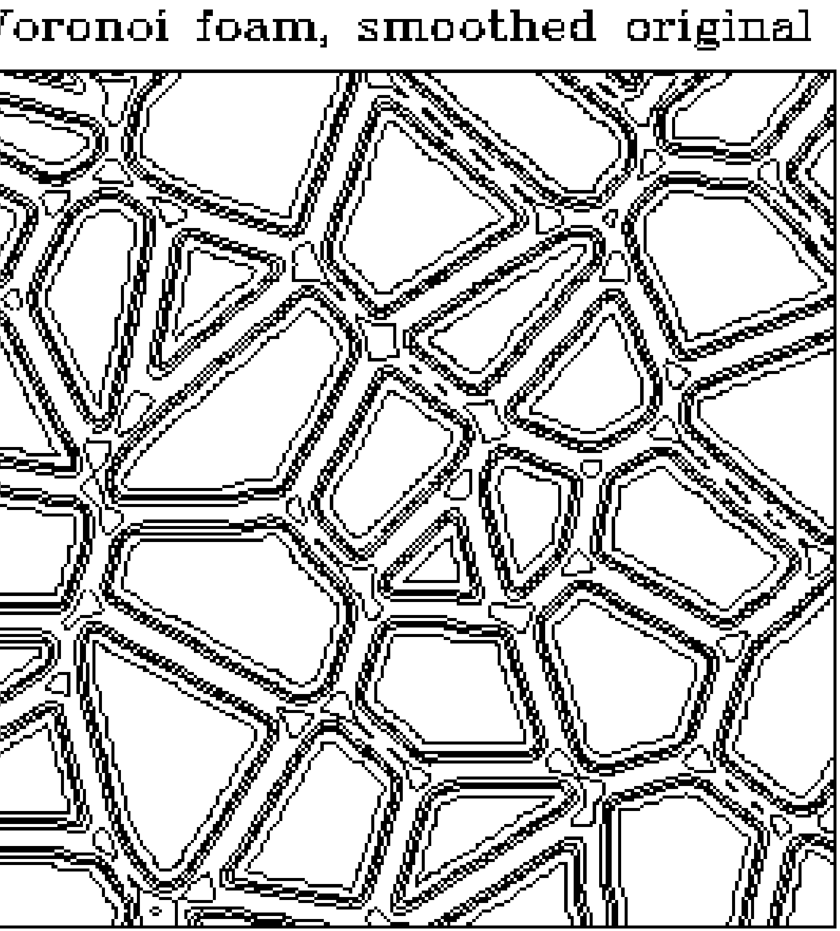
RA
50
40
30
20
10
0
350
z
0
0.1
0.2
0.3
0.4

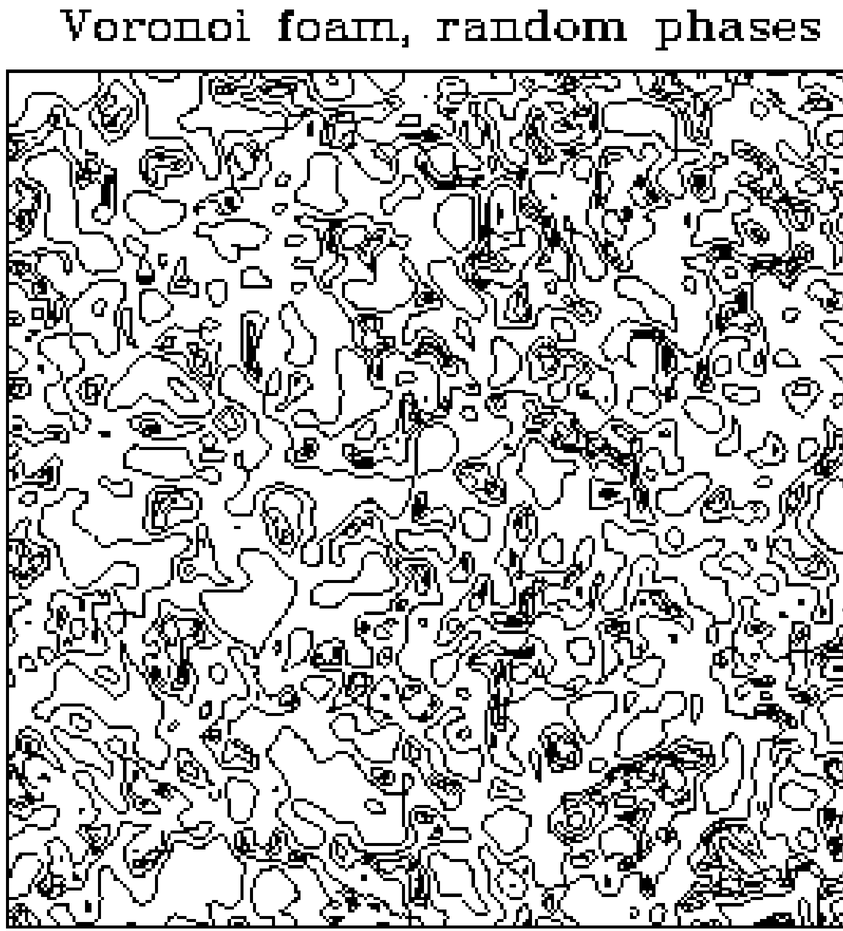


The VIRGO Collaboration 1996

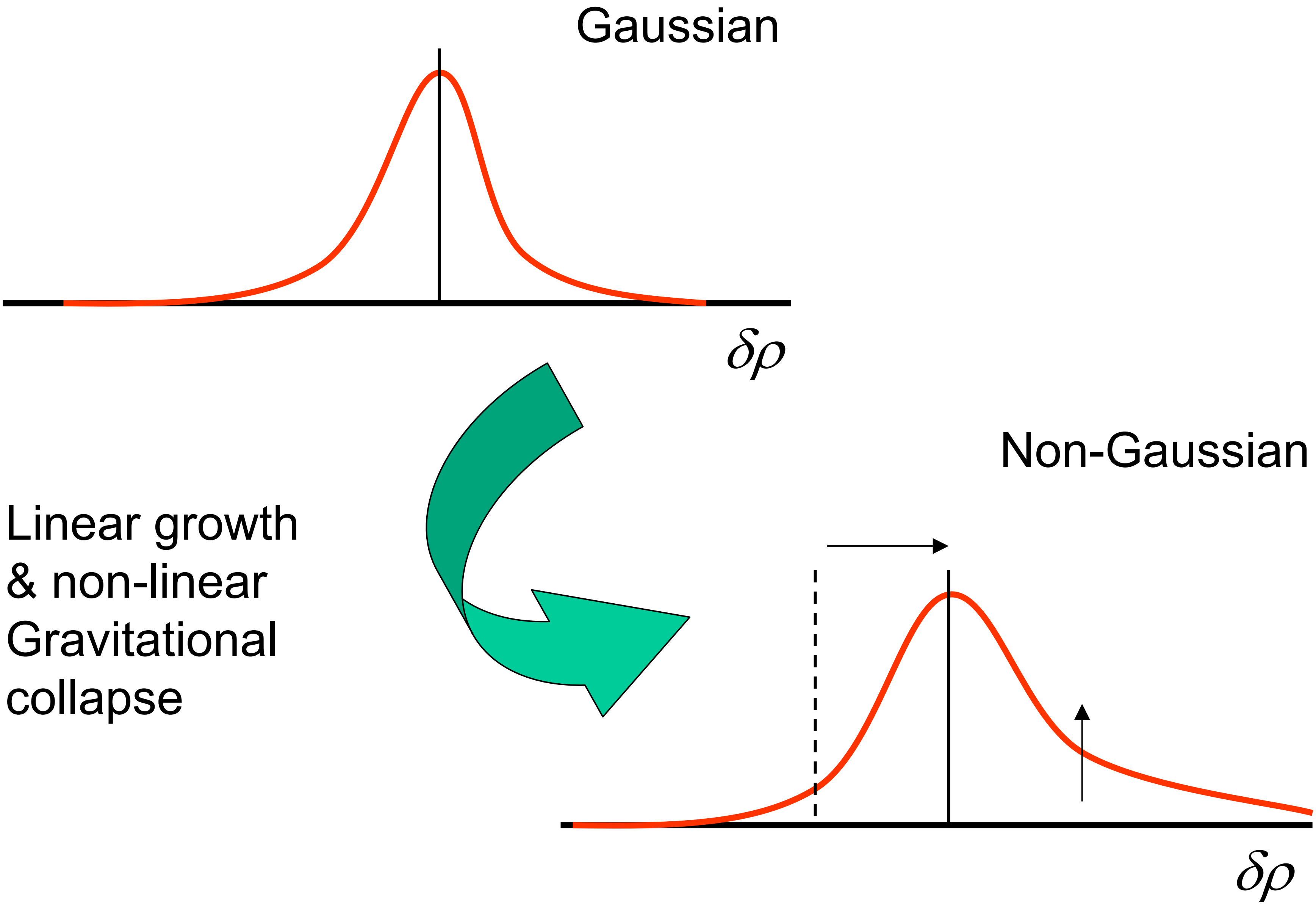
Large Scale Structure Simulations (1996)

Non Gaussianities

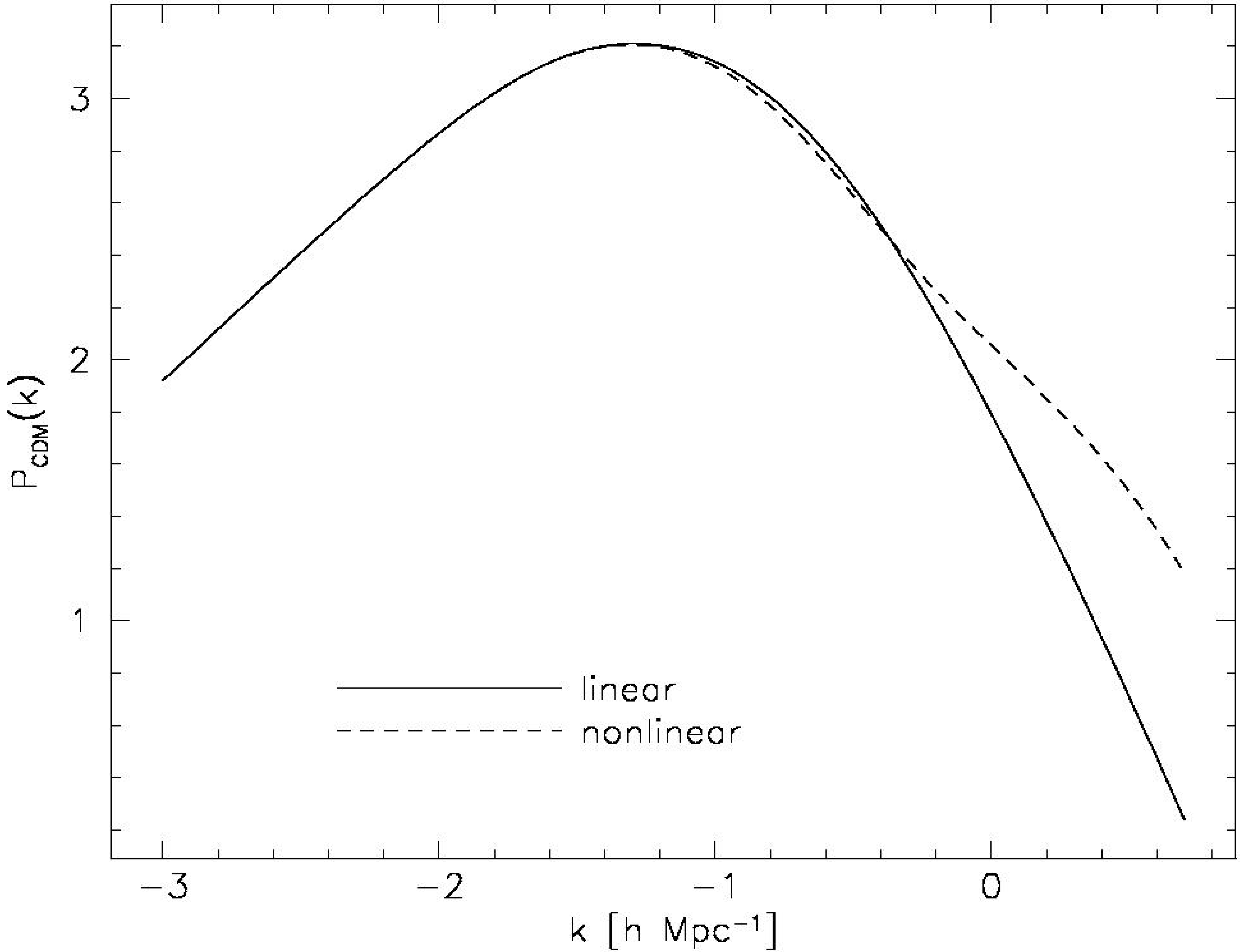


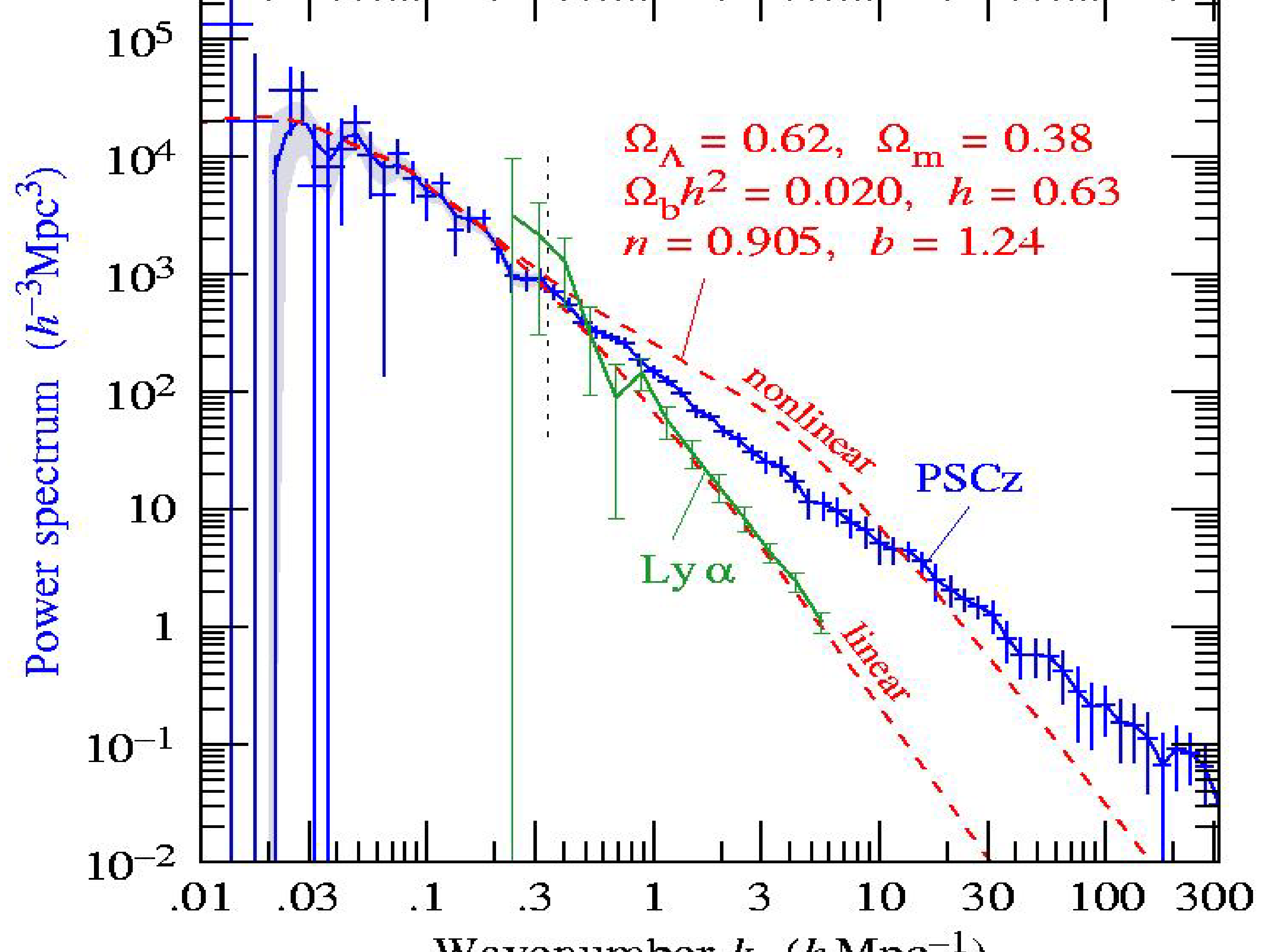


Same Power Spectrum P(k)

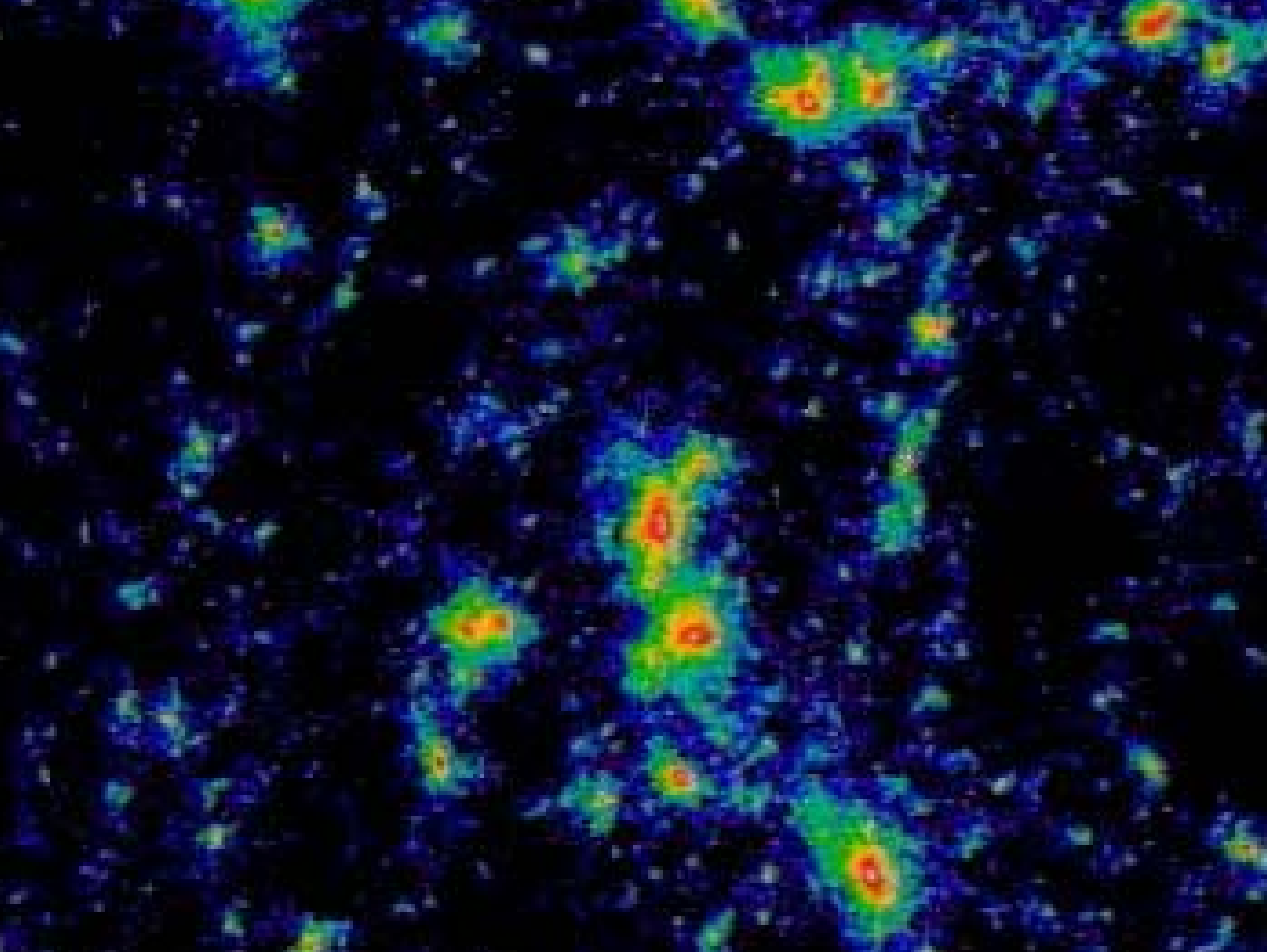

Gaussian
δρ
Linear growth
& non-linear
Gravitational
collapse
Non-Gaussian
δρ

Non linear P(k)



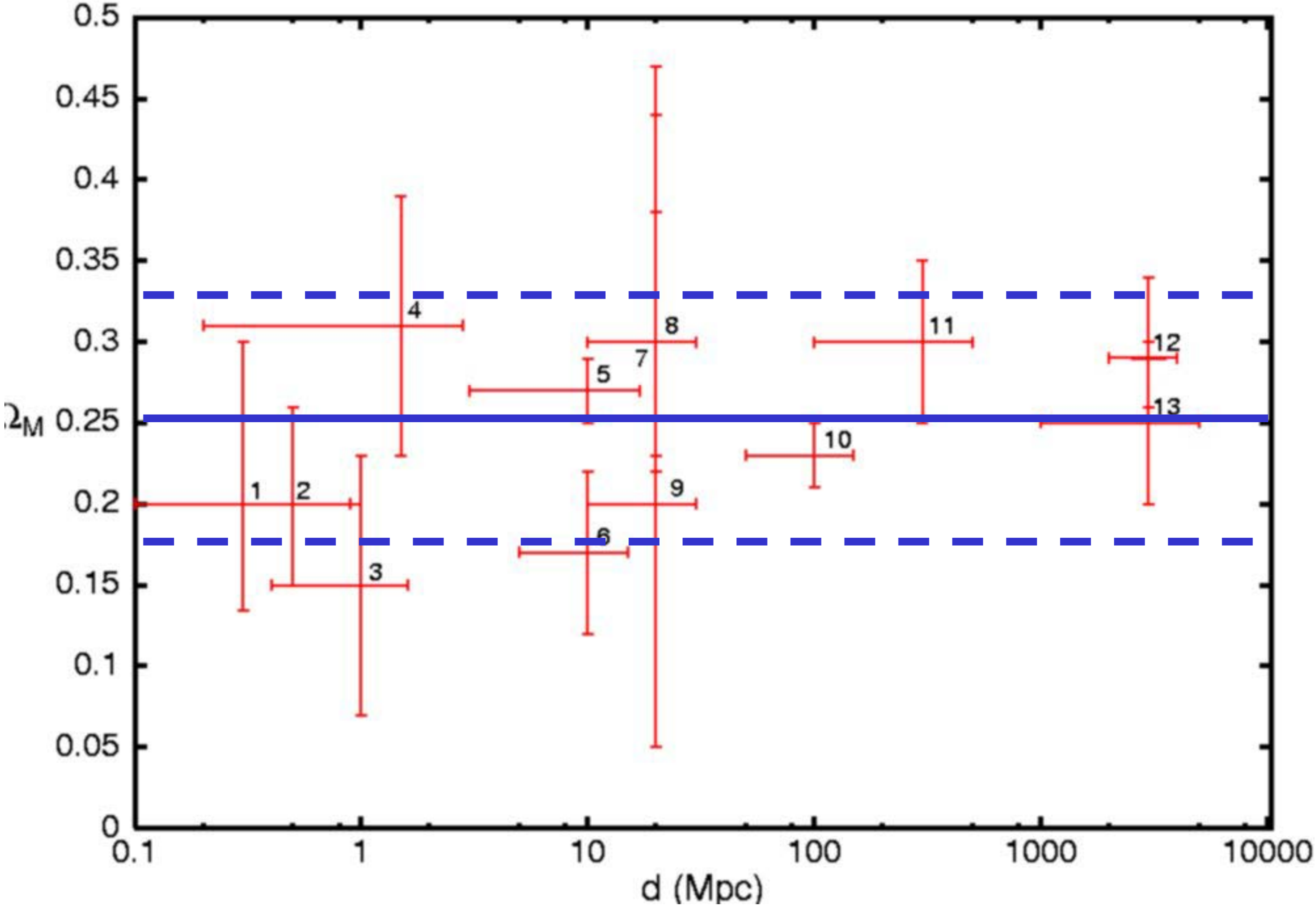


$\Omega_\Lambda = 0.62, \Omega_m = 0.38$
$\Omega_b h^2 = 0.020, h = 0.63$
$n = 0.905, b = 1.24$
nonlinear
linear
PSCz
Ly α
Power spectrum (h^{-3}Mpc^3)
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
.01
.03
.1
.3
1
3
10
30
100
300



Summary of Dark Matter Content

$$\Omega_M = 0.26 \pm 0.08$$



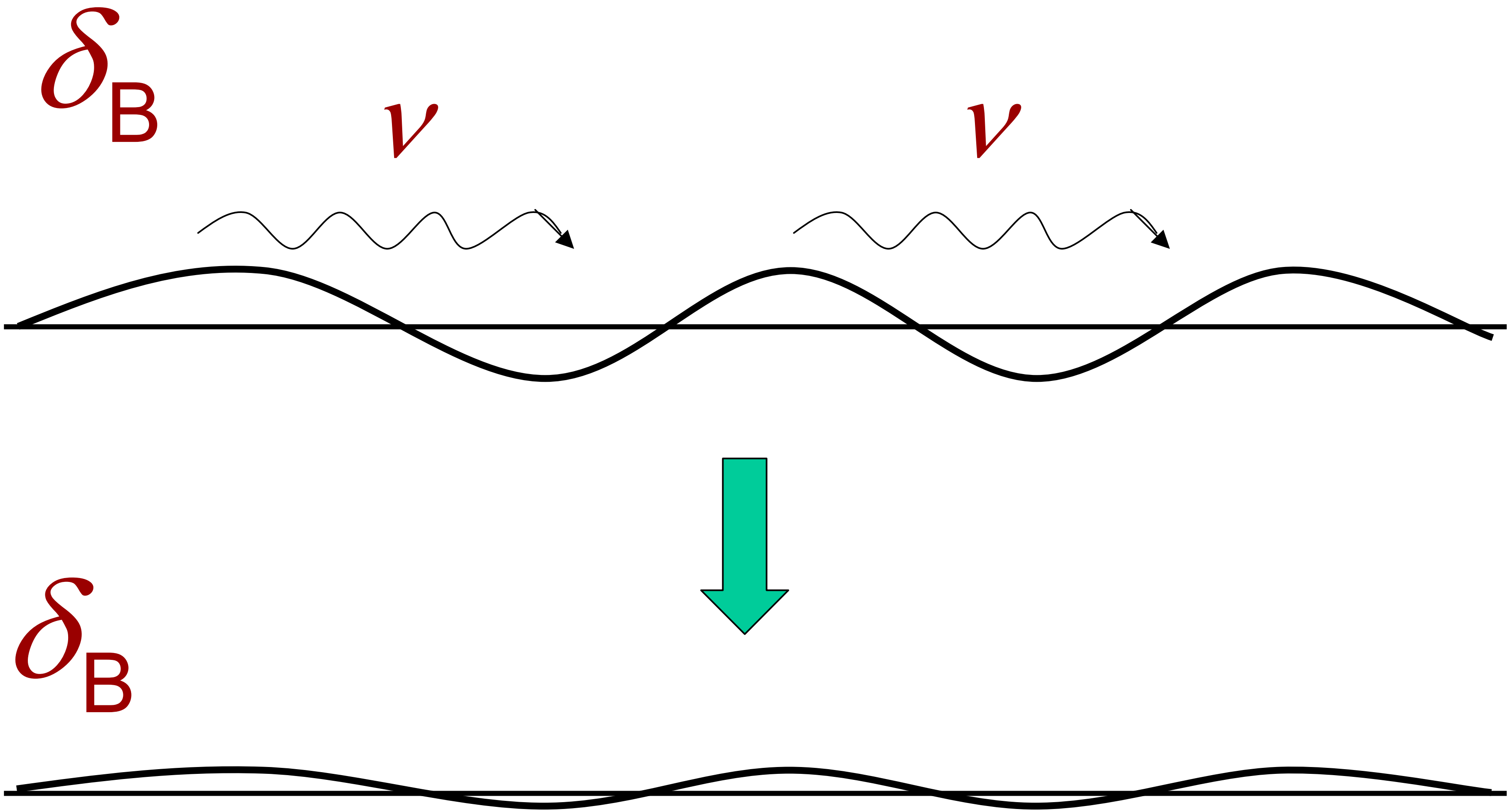
1 peculiar velocities; 2 weak lensing; 3 shear correlations; 4 local group; 5 baryon mass fraction; 6 cluster mass function; 7 virgocentric flow; 8 mean relative velocities; 9 redshift space distorsions; 10 mass power spectrum; 11 ISW effect; 12 angular diameter distance SNe; 13 cluster baryon fraction

What is the dark matter?

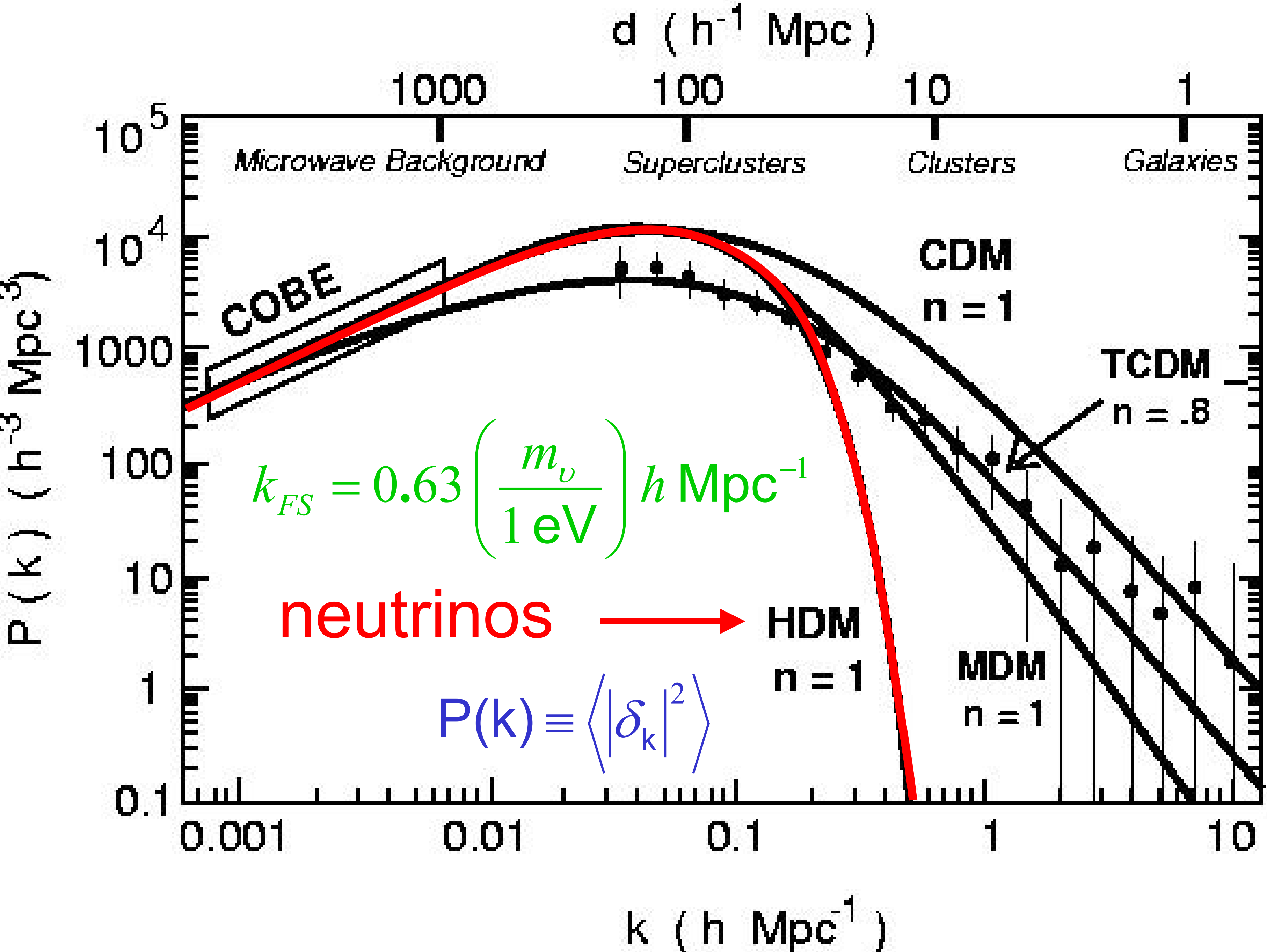
- Planets?
- Failed stars, aka “brown dwarfs”?
- Black holes?
- Relic particles from the Big Bang?
  - neutrinos
  - axions
  - neutralinos

**Lots of good ideas,
but nobody knows for sure...**

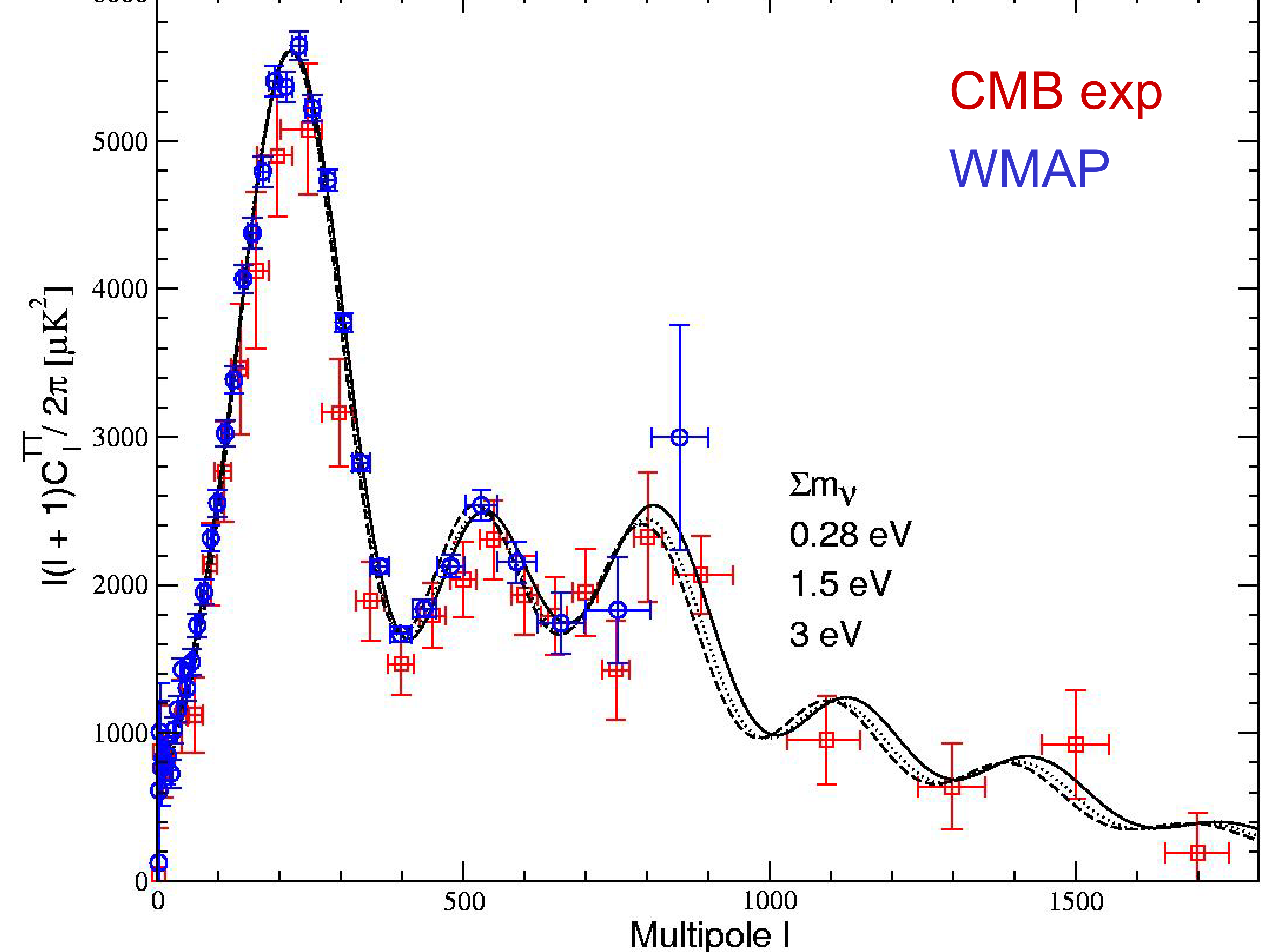
Are Neutrinos The Dark Matter?



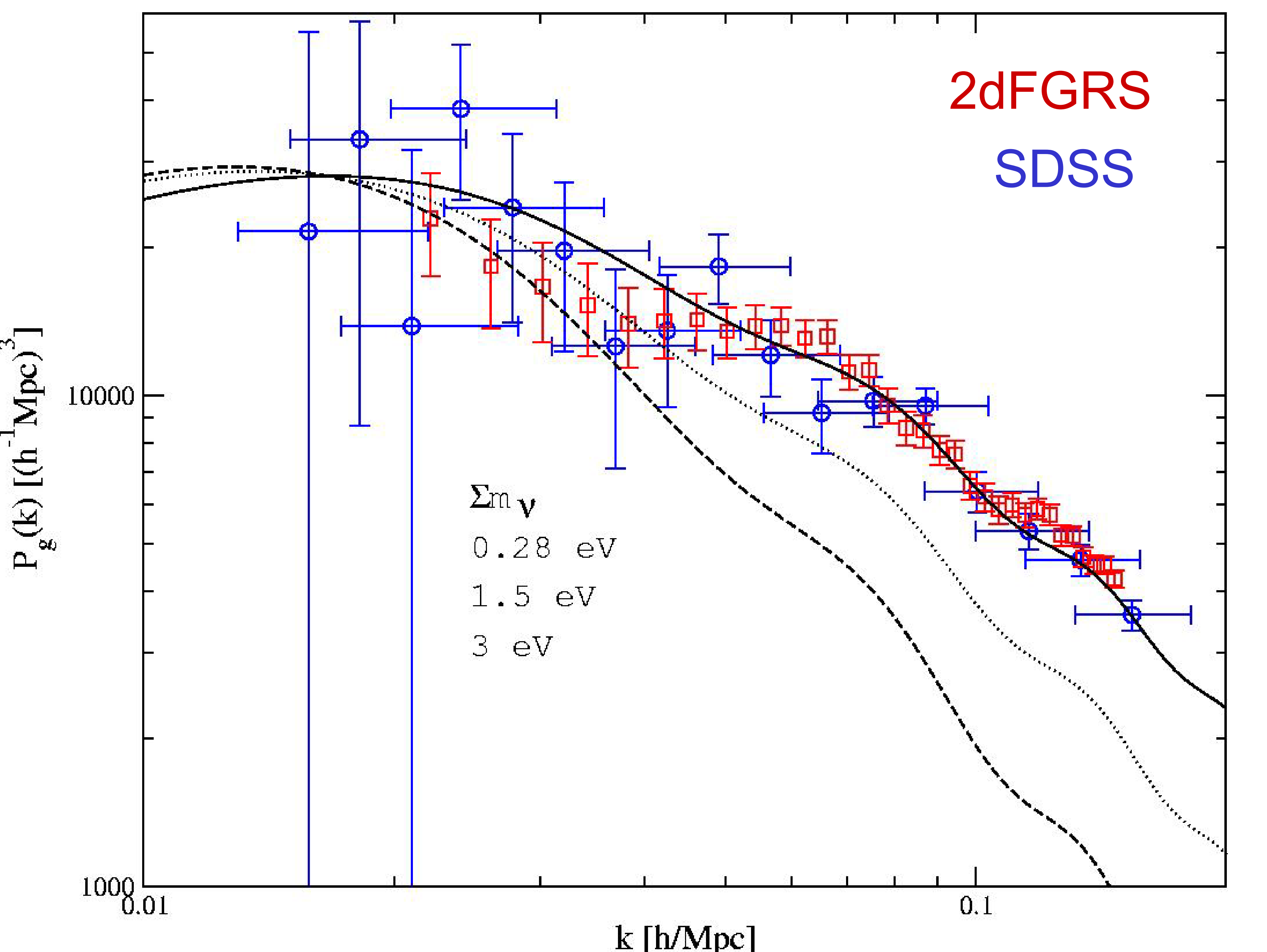
δ_B
ν
ν
δ_B

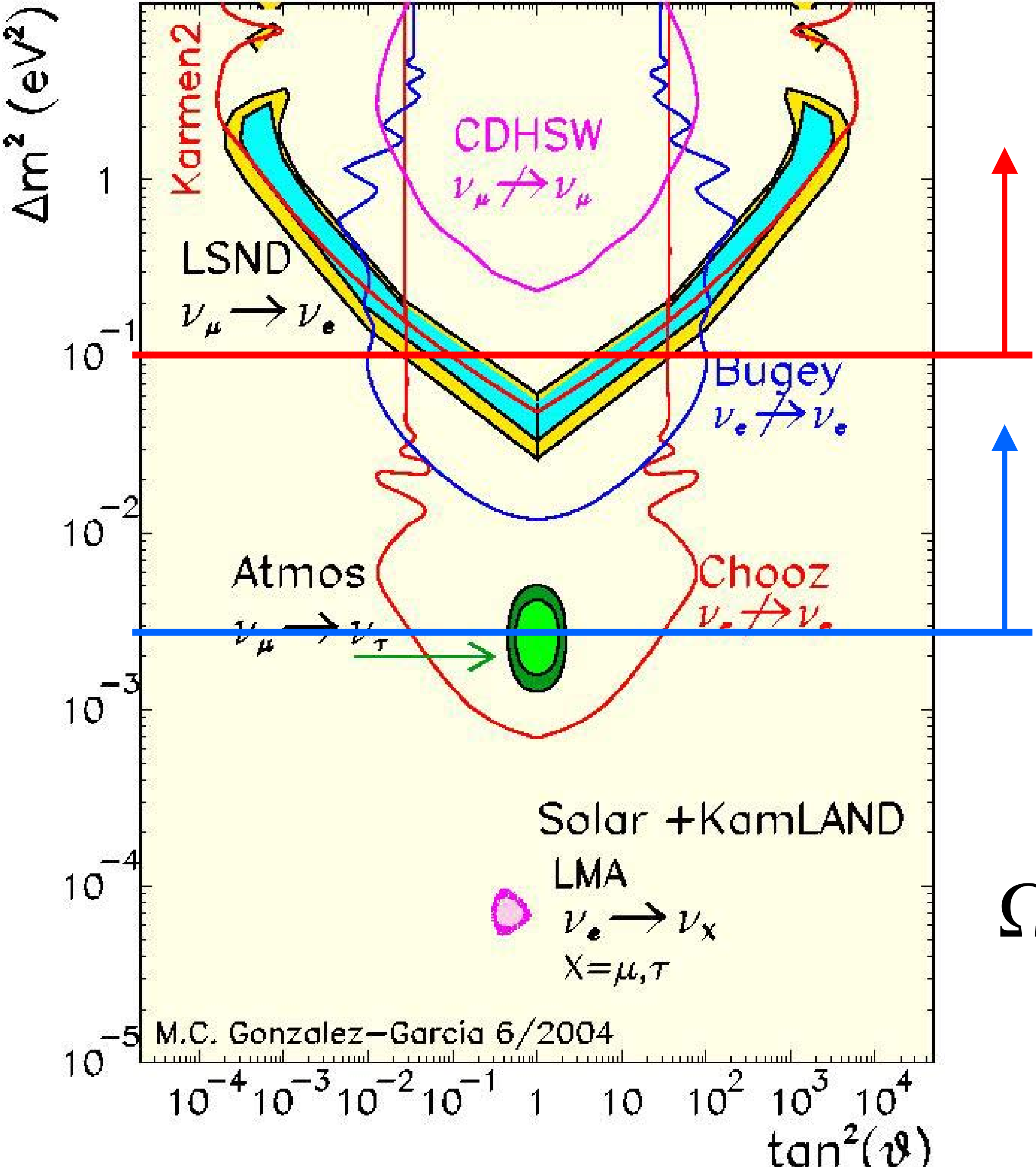


d (h-1 Mpc)
1000
100
10
1
Microwave Background
Superclusters
Clusters
Galaxies
COBE
CDM
n = 1
TCDM
n = .8
HDM
n = 1
MDM
n = 1
neutrinos
$k_{FS} = 0.63\left(\frac{m_\upsilon}{1\,\mathrm{eV}}\right) h\,\mathrm{Mpc}^{-1}$
$P(k) \equiv \left\langle \left|\delta_k\right|^2 \right\rangle$
P (k) (h-3 Mpc3)
10^5
10^4
1000
100
10
1
0.1
0.001
0.01
0.1
1
10
k (h Mpc-1)



CMB exp
WMAP
Σm_ν
0.28 eV
1.5 eV
3 eV
l(l + 1)C_l^TT / 2π [μK^2]
Multipole l
0
1000
2000
3000
4000
5000
0
500
1000
1500


2dFGRS
SDSS
Σm ν
0.28 eV
1.5 eV
3 eV
10000
1000
0.01
0.1
k [h/Mpc]
P g (k) [(h -1 Mpc) 3]



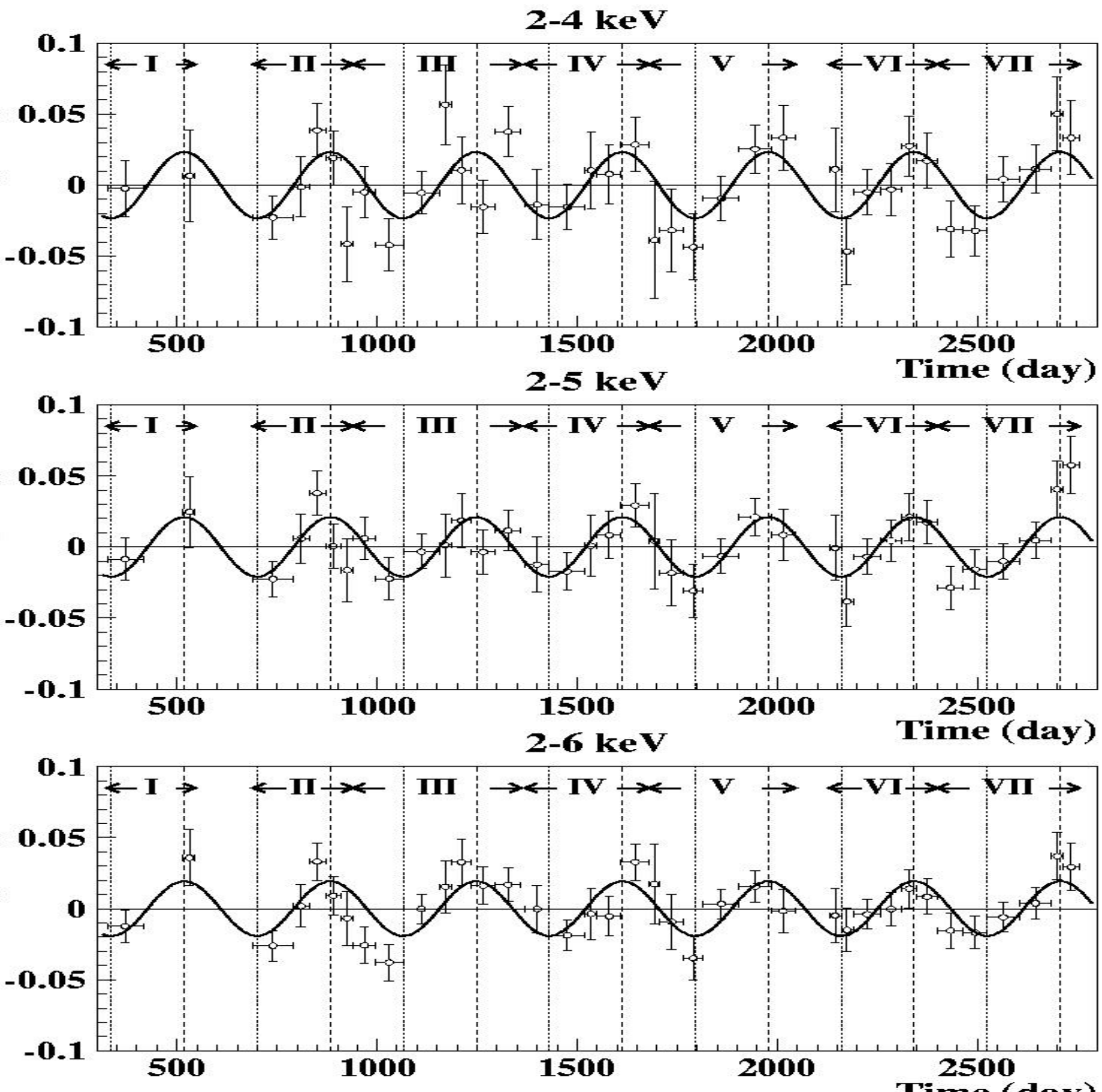
Cosmologically Excluded (WMAP/SDSS)

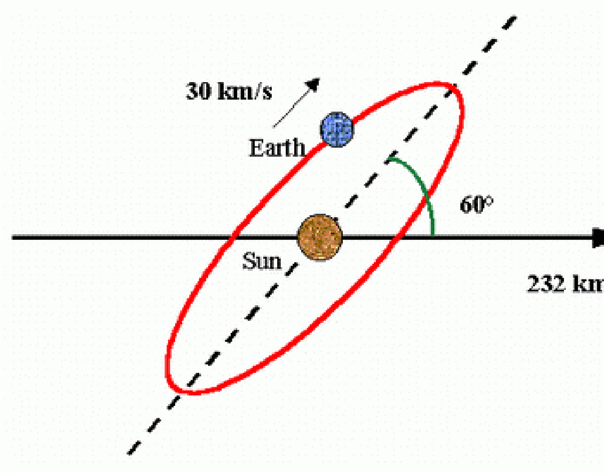
Cosmologically Detectable (Planck)

$$\Omega_\upsilon = \frac{\sum m_\upsilon \, h^{-2}}{93.2\ \text{eV}}$$

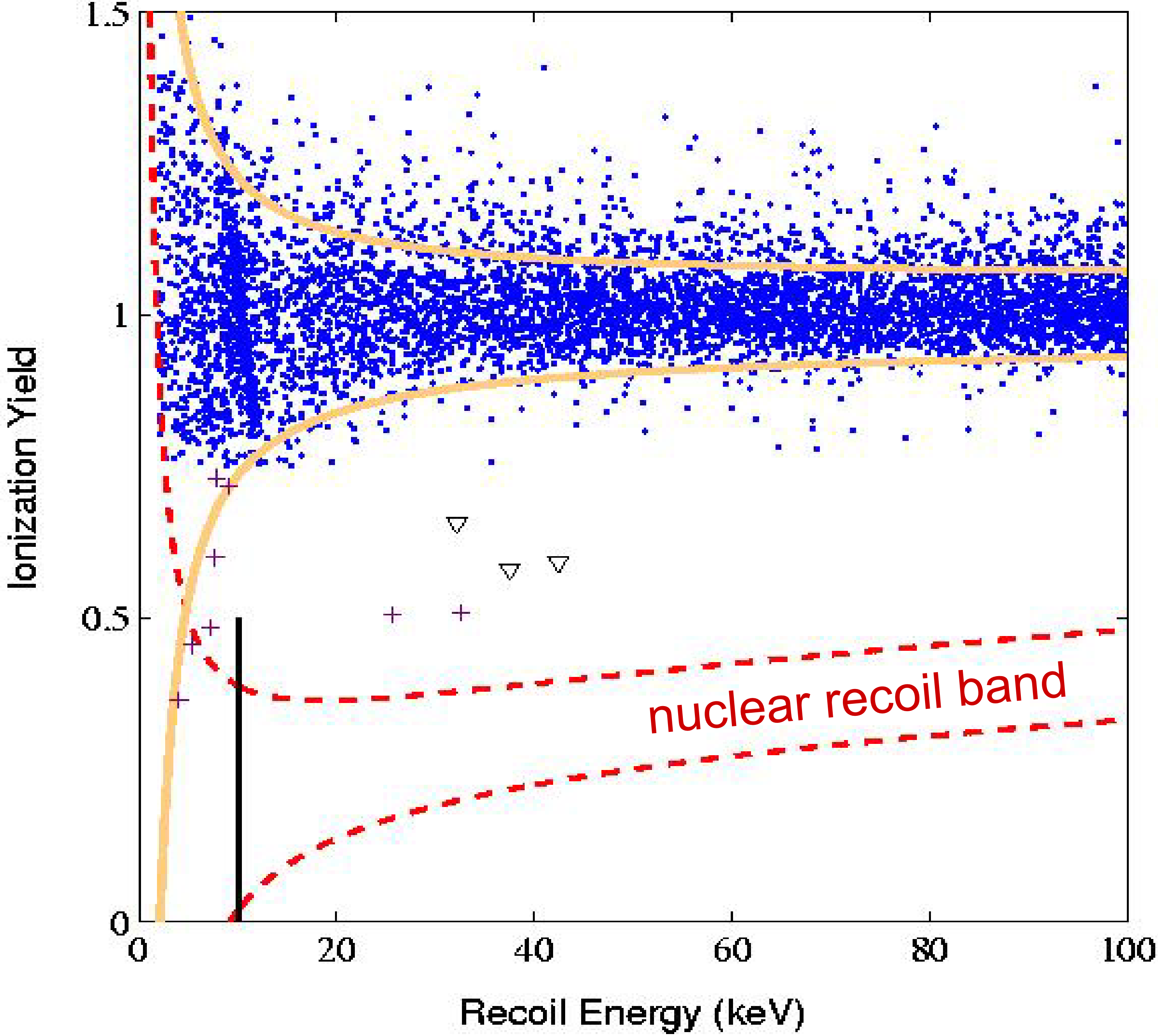
Direct Search for Dark Matter Particles

DAMA 7 year data (2003)

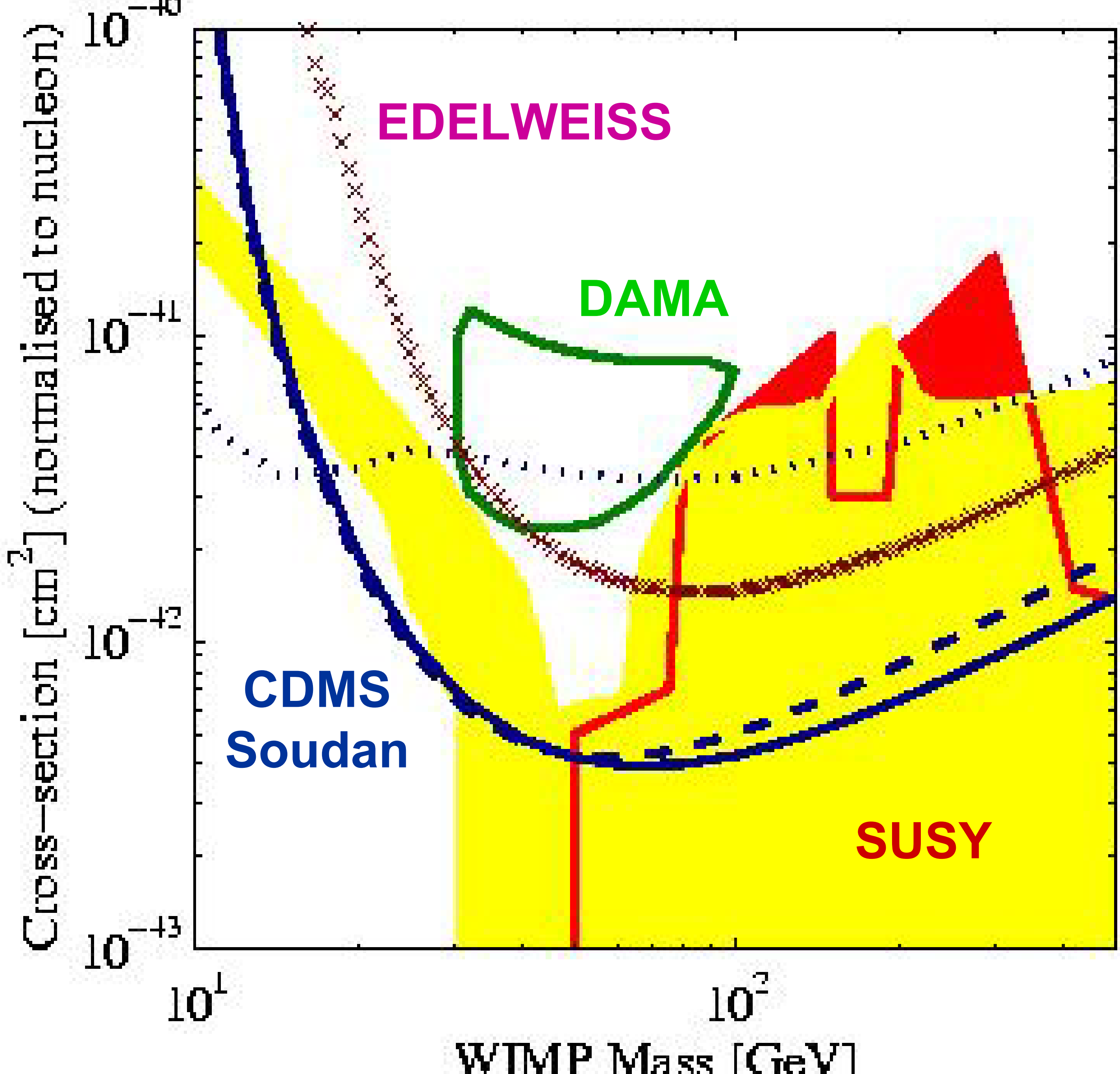




4% modulation due to Earth's motion through DM halo ("ether"?)



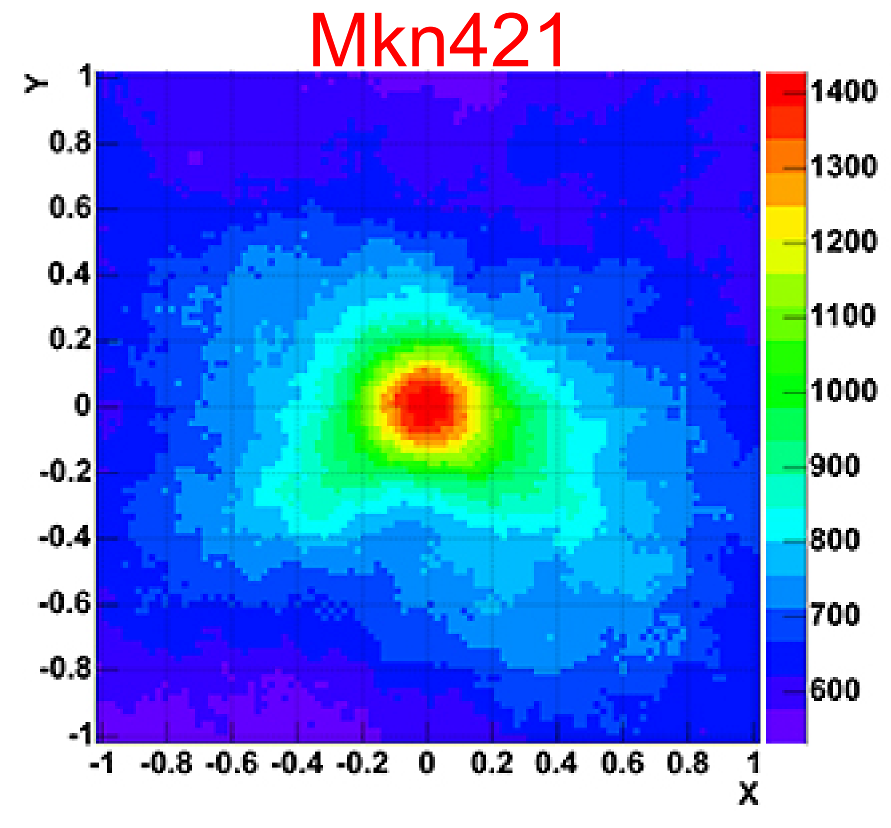
CDMS Soudan (2004)



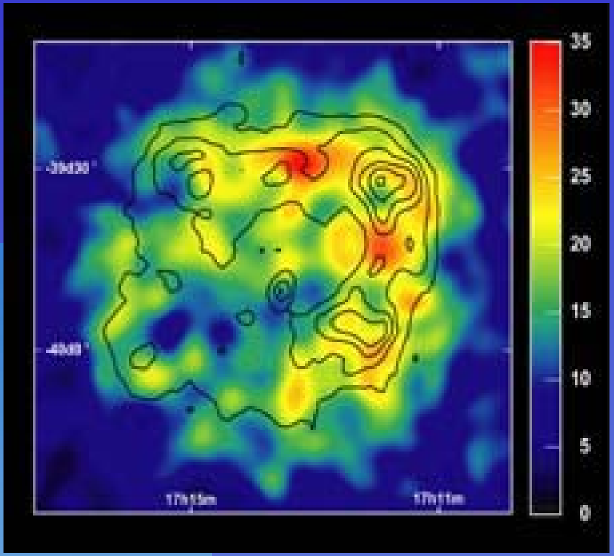
CDMS
Soudan
(2004)

Indirect Search for Dark Matter Particles

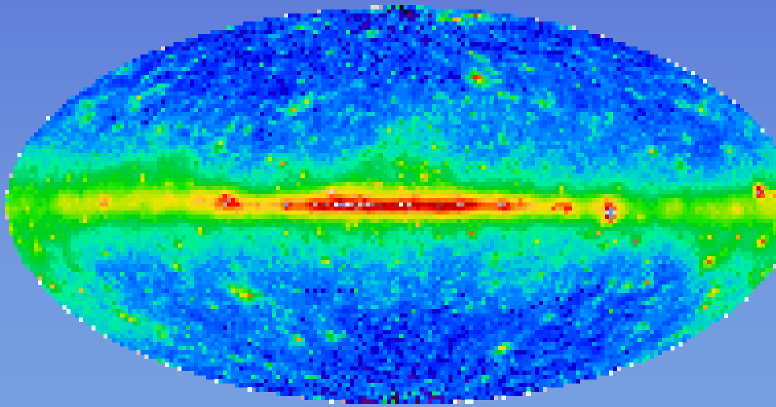
MAGIC


Mkn421
Y
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
X
1400
1300
1200
1100
1000
900
800
700
600

HESS

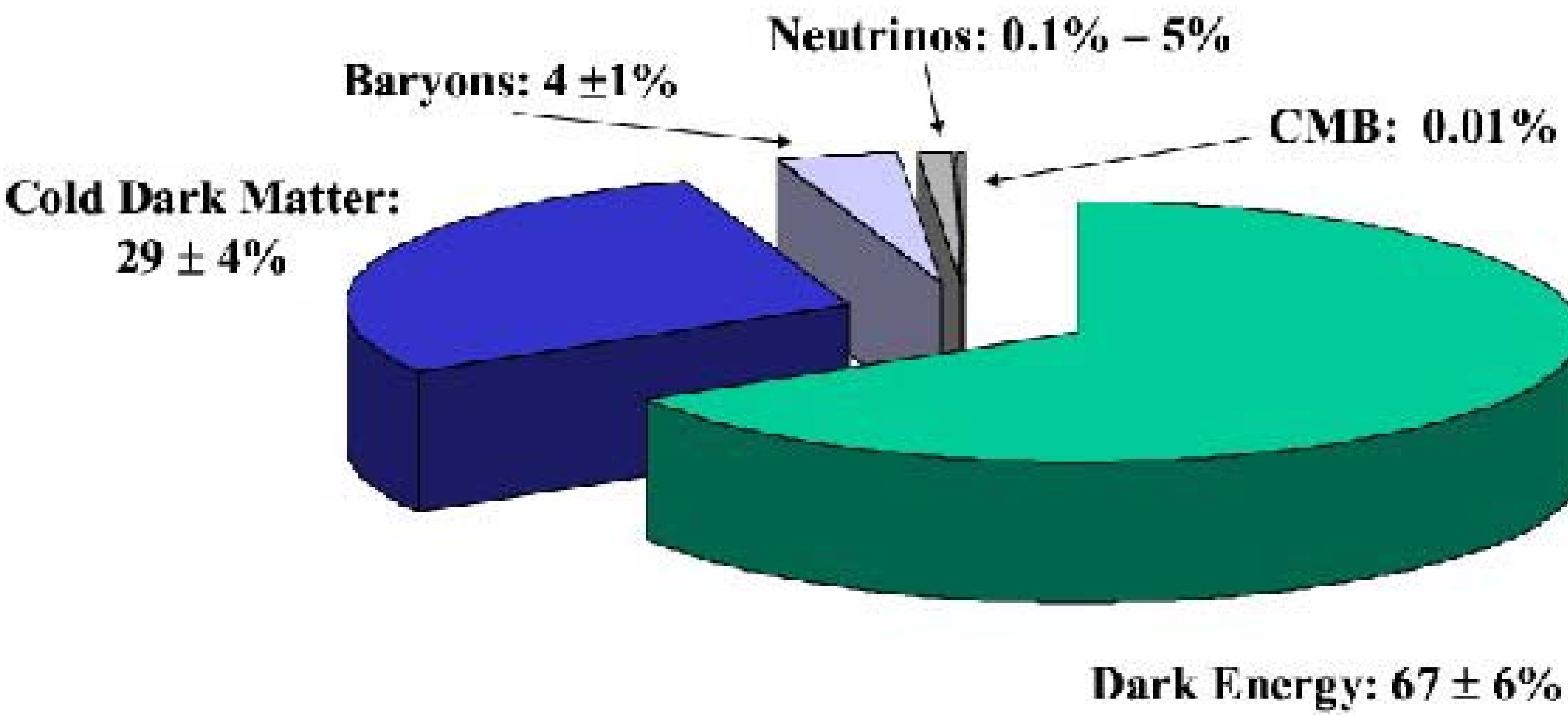


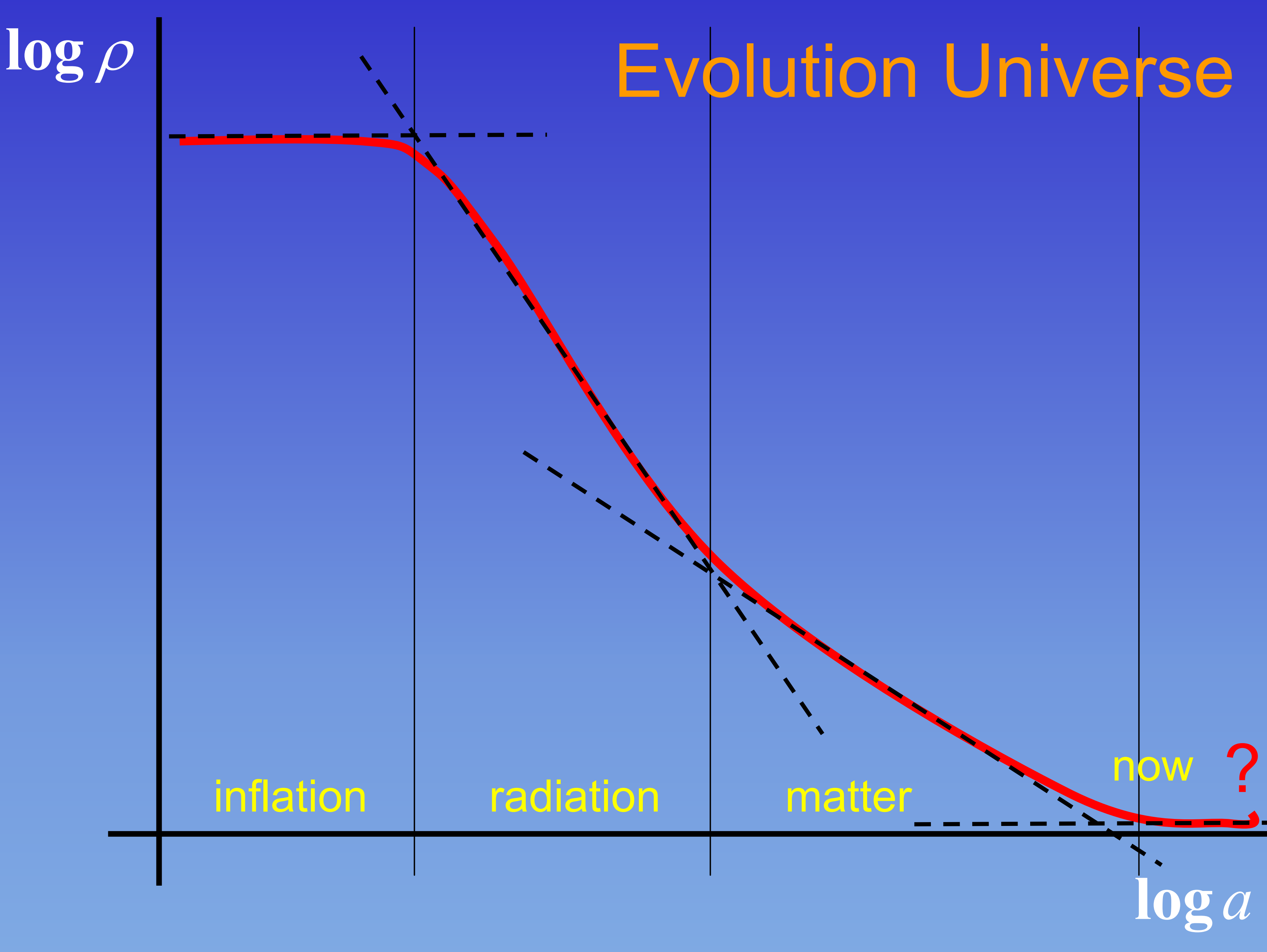
GLAST



Summary

Matter and Energy in the Universe: A Strange Recipe





log ρ
Evolution Universe
inflation
radiation
matter
now
?
log a

Cosmic coincidence?