Observational Cosmology (I)

A tail of a few coincidences…

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$$\rho = 3\,H^2/8\,\pi\,G$$

$$\eta = n_B/n_\gamma$$

$$\rightarrow \Delta T/T = 10^{-5}\ \delta(R=10\ \mathrm{Mpc})$$

$$q_0 = -0.5$$

$$\Omega_m = 0.2$$

Coincidence #1

The Energy of the Universe

$$\rho = 3\, H^2 / 8\, \pi\, G$$

Measurements: energy density vs expansion rate

or

age vs expantion rate

General Relativity (GR) & Cosmology

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1+kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

a(t) = scale factor =1/(1+z) (a_0 = 1)

$R_{\mu\nu} +$ [redacted] $g_{\mu\nu} = -8\pi G\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)$

Einstein's Field Eq.
R = curvature/metric
T = matter content

Hubble Cte (Friedman Eq)
ρ = energy density = $\rho_M + \rho_R$
k = curvature sign
Λ = cosmological cons

$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho}{3} + \frac{k}{a^2} +$ [redacted] $\frac{}{3}$

$$\rho_c \equiv \frac{3\,H_0^2}{8\pi G} \simeq 2\times10^{-29}\;gm\;h^2/cm^3 \simeq 2.78\times10^{11}\;M_\odot\;h^2/Mpc^3$$

$$\Omega_M \equiv \frac{8\pi G\rho_M}{3\,H_0^2} \equiv \frac{\rho_M}{\rho_c}$$

$H^2 = H_0^2\left[\Omega_M\,a^{-3} + \Omega_R\,a^{-4} + \Omega_k\,a^{-2} +\right.$ [redacted] $\left.\right]$

$$\Omega_T \equiv \Omega_M + \Omega_R + \Omega_\Lambda = 1 - \Omega_k$$

$$D_\theta = \frac{2c}{H_0}\left[(1+z)^{-1} - (1+z)^{-3/2}\right]$$

$$D_L = \;=\frac{2c}{H_0}\left[1+z-\sqrt{1+z}\right]$$

Flux= $L/4\pi D_L^2$

$$q = \frac{1}{2}\,\Omega_T - \Omega_\Lambda$$

q = -a''/a'/H^2

Extrapolations

Extrapolations:

Newton's Apple:

3 m Moon ~ $3x10^8$ m

General Relativity:

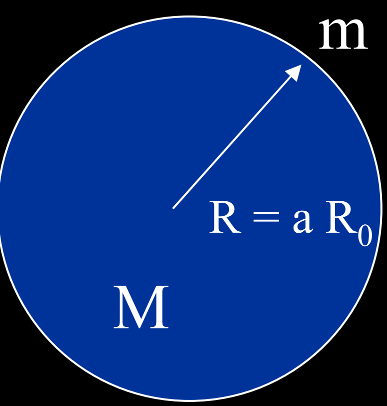
Solar: 1 au ~ $1.5x10^{11}$ m (150 Mkm)
Stars: 1 pc ~ 3 lyr ~ $2x10^5$ au
Galaxy: 10 kpc ~ $2x10^9$ au
Clusters: 10 Mpc ~ $2x10^{12}$ au
Universe: 1 Gpc ~ $2x10^{15}$ au

Homogeneity
↓
Expansion
↓
Hot & dense IC
↓
Nucleosynthesis
↓
Cosmic Background Radiation (atoms)
↓
Large (& small) Scale Structure (LSS): gravity ?

Cosmic Energy 101

Newtonian cosmology

$$E = K + \phi = 1/2\, m\, v^2 - G M m/R = \text{constant!}$$



$$E = 1/2\, m\, H^2 R^2 - 4/3\, \pi\, G\, m\, R^2\, \rho$$

$$M = 4/3\, \pi\, R^3\, \rho$$

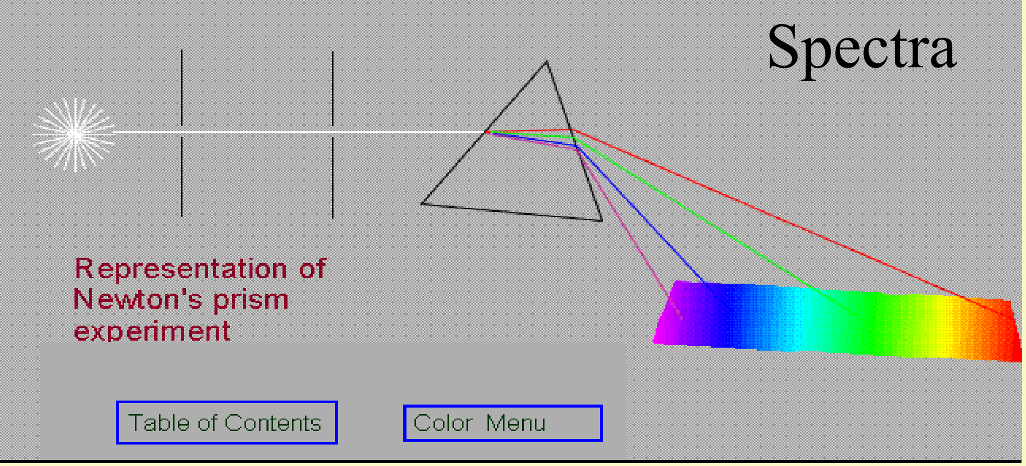
$$\rho = \rho_0\, a^{-3}$$

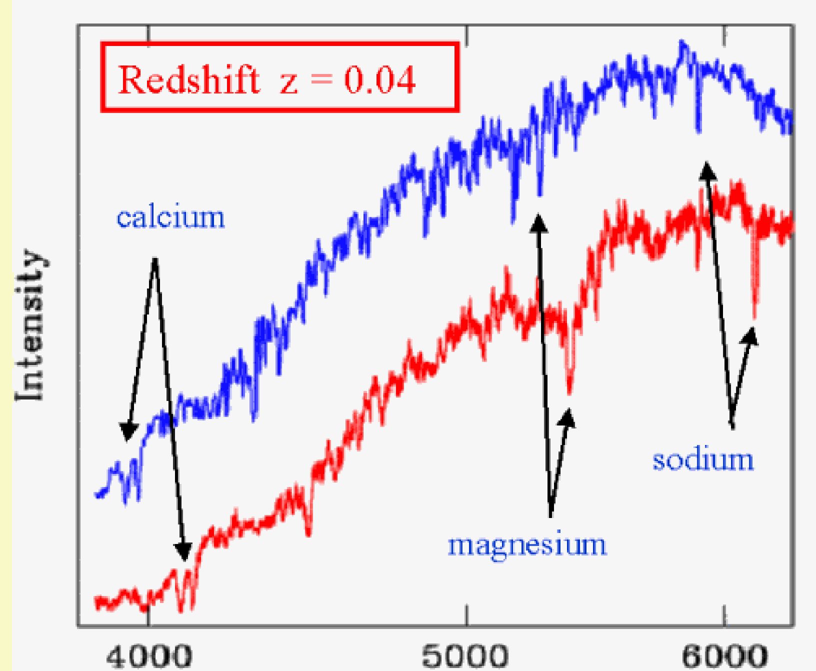
Einstein-deSitter (EdS) Universe: E=0

$\rho = 3 H^2 / 8 \pi G$ critical density $\rho_c \equiv \rho(E=0)$

$\Omega \equiv \rho_0 / \rho_c$ In the general case ($t=t_0$)

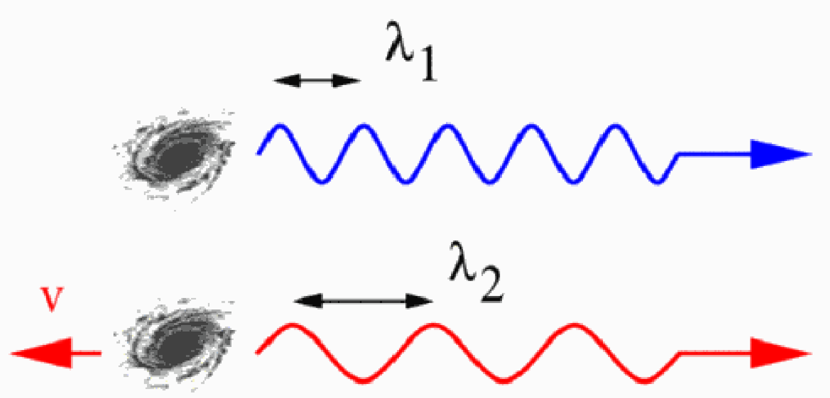
In turns out that Ω_m **=0.2-0.3**, so we do not seem to be in a EdS.
But note how closely related are H^2 and ρ. A coincidence?





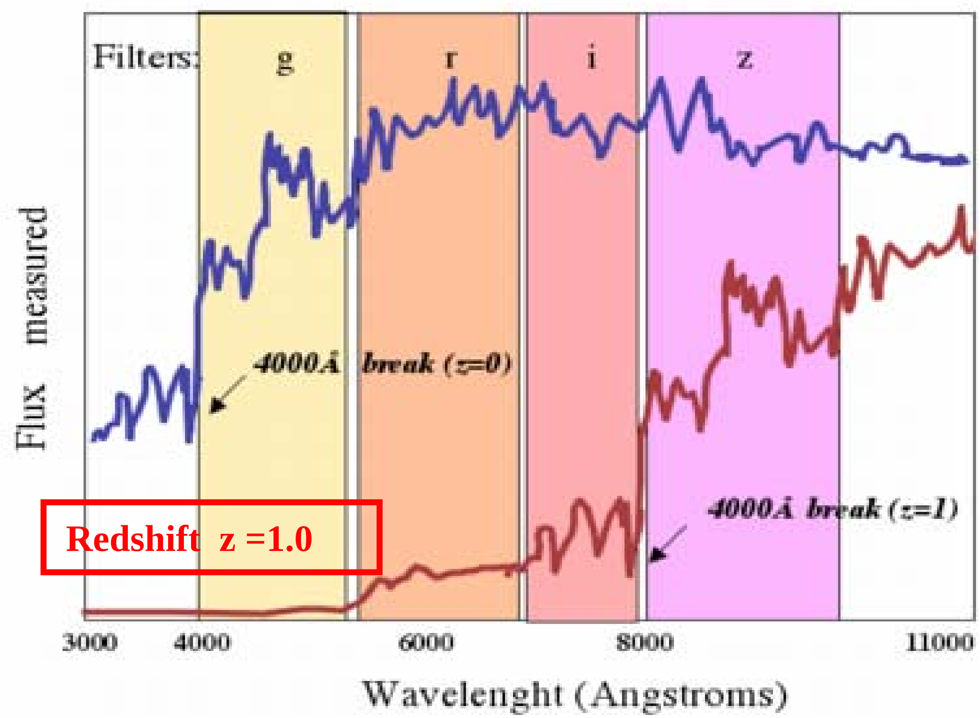
The expanding universe

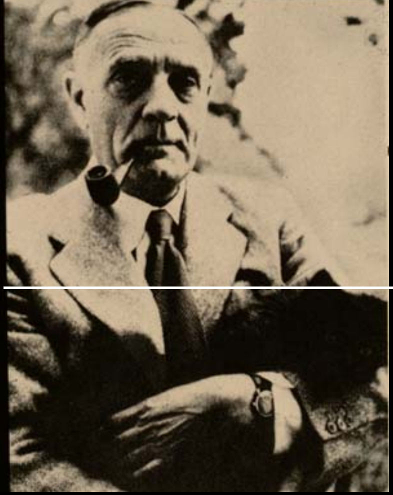
1912 - 1920s: Slipher finds most galaxies are redshifted



$$1 + z = \frac{\lambda_2}{\lambda_1} \simeq 1 + \frac{v}{c}$$

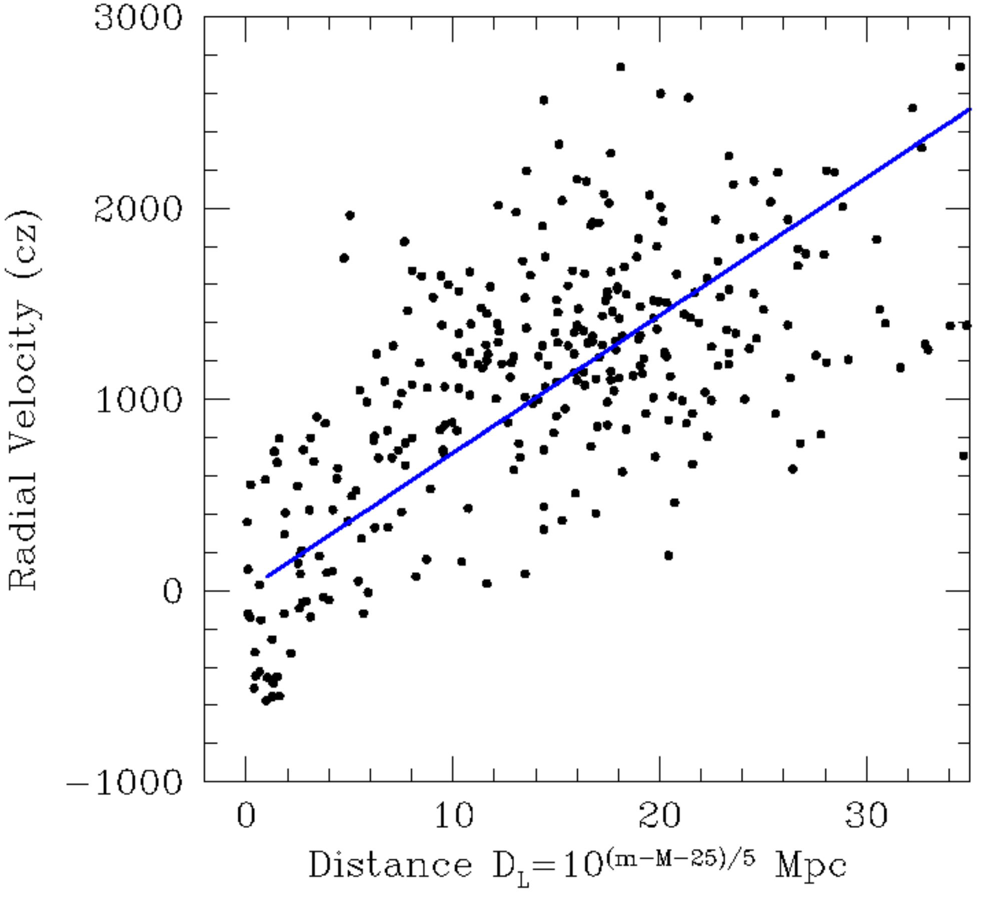
The Dop





Hubble's law: (1929)

$v = cz \approx H\, d$



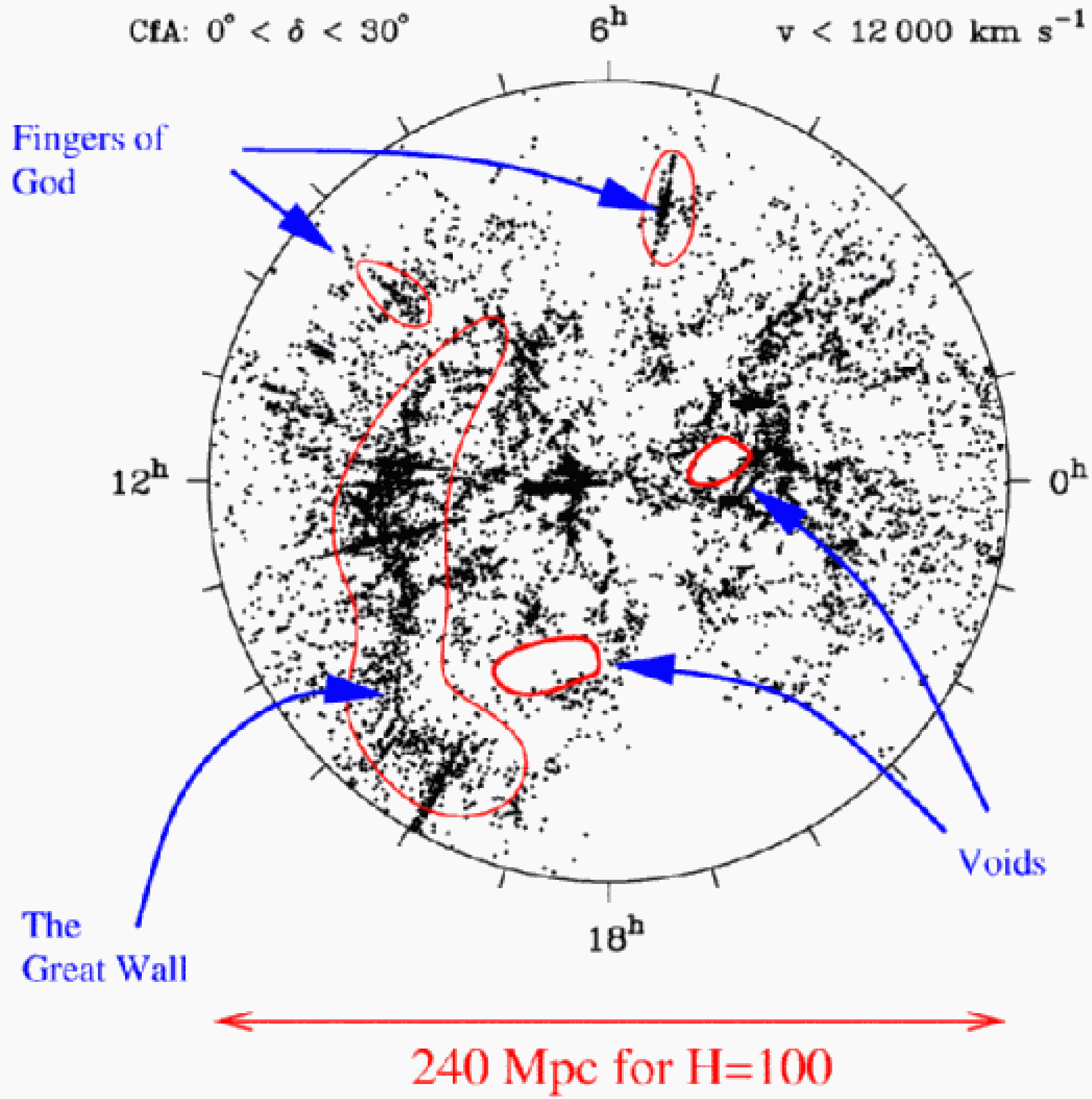
- initial value H_0= 500 Km/h/Mpc
- H_0 = 50 (Sandage/Tammann) ?
- H_0 = 100 (deVaucoulers)?
-H_0 = 72 ± 8 km/s/Mpc (HST)
--> h=0.72 ± 0.08 -> t0 ~ 1 /H_0 ~14 Gyr!

$$\rho_c \equiv \frac{3\ H_0^2}{8\pi G} \simeq 1.88 \times 10^{-29}\ h^2\ gr/cm^3$$
$$\simeq 1.06 \times 10^{4}\ h^2\ eV/cm^3$$
$$\simeq 2.78 \times 10^{11}\ h^2\ M_\odot/Mpc^3$$

Absolute distance callibrations are very difficult

Scatter in distance indicators and in peculiar velocities

Malmquist bias



Redshift surveys (mid-1980s)

Inverting v = cz = Hd gives an approximate distance.

Applied to galaxies on a strip on the sky, gives a 'slice of the universe'

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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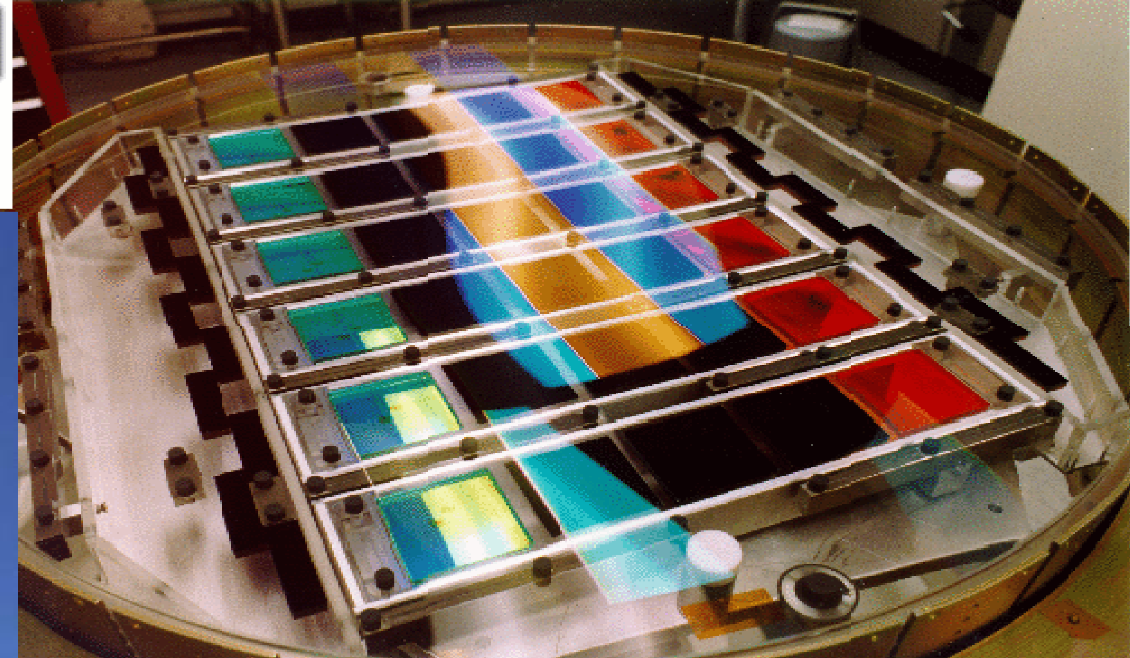
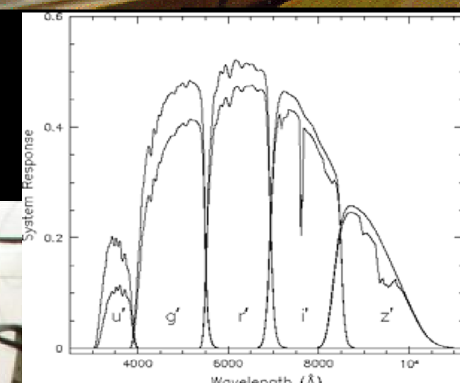
Sloan Digital Sky Survey

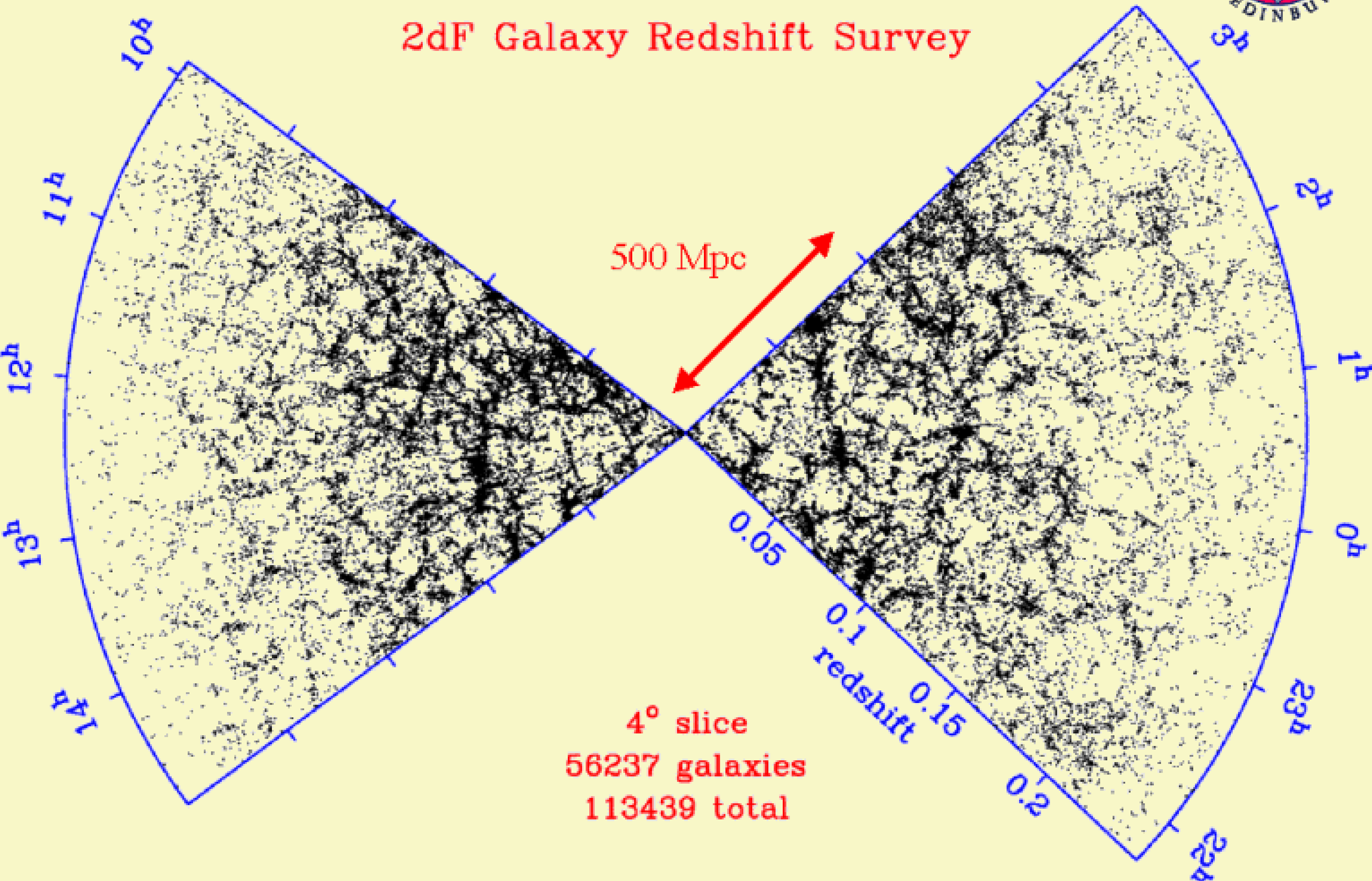


5x6 x 2048 x 2048 = 5 color

24 x 400 x 2048 astrometry /focus



The state of the art in galaxy clustering



Luminosity Function

The 2dFGRS Survey

In the range

$-16.5 > M_{bJ} > -22$ is Schechter function

$$\Phi(L) = dN/dL/dV$$

$$\Phi(L) = \phi^* (L/L^*)^{\alpha} \exp(-L/L^*)\, dL/L^*$$

with

$M^*_{bJ} = -19.66 \pm 0.07$

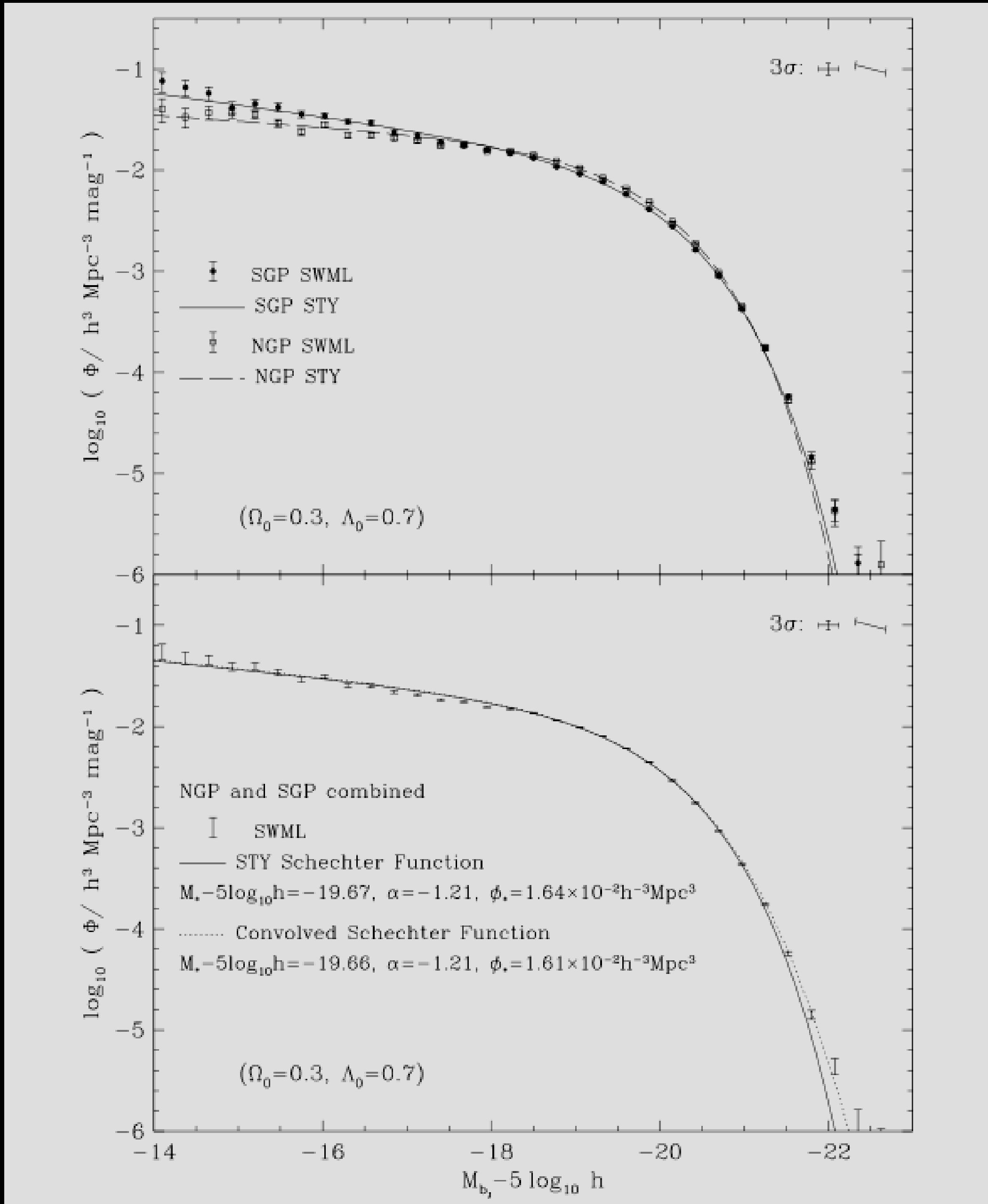
$\alpha = -1.21 \pm 0.03$

$\phi^* = (1.61 \pm 0.08)\, 10^{-2}\, h^3 Mpc^{-3}$

$\rho_L = (1.82 \pm 0.17) 10^{8} h L_{solar} Mpc^{-3}$

Problems:

- Callibration/mergers/LSB
- faint end
- Colour/Luminosity evolution
- K-correctio



$\rho_L = (1.82 \pm 0.17)\ 10^8\ h\ L_{solar}\ Mpc^{-3}$

$$\rho_c \equiv \frac{3\ H_0^2}{8\pi G} \simeq 1.88 \times 10^{-29}\ h^2\ gr/cm^3 \simeq 1.06 \times 10^4\ h^2\ eV/cm^3 \simeq 2.78 \times 10^{11}\ h^2\ M_\odot/Mpc^3$$

For a typical galaxy

$(M/L)^* \sim 15\ (M/L)_{solar}$

–> $\Omega_* \approx 0.01$

Rotational curves in spiral galaxies

+ virial theorem in Elliptical galaxies

(+ baryon fraction in clusters):

$M/L \sim 10\text{-}30\ (M/L)^*$

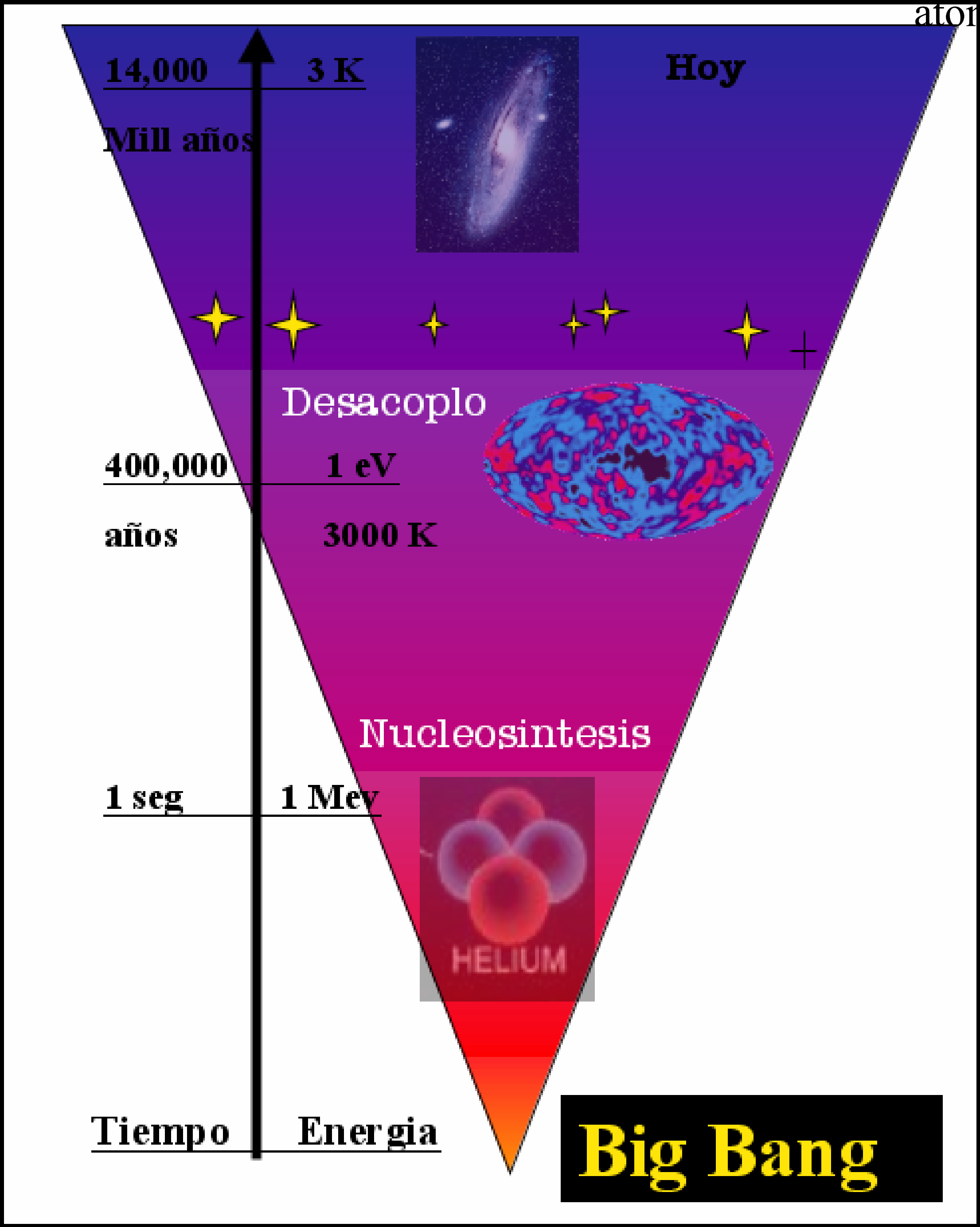
□–> $\Omega_m \approx 0.1\text{-}0.3$ not far from unity

Coincidence #2 :

The Entropy of the Universe

$$\rightarrow \eta = n_B/n_\gamma$$

Measurements: Primordial Abundances vs baryon density & CMB T_0
(Also confirmed by CMB and matter acoustic oscilations)


ator
14,000
3 K
Hoy
Mill años
Desacoplo
400,000
1 eV
años
3000 K
Nucleosintesis
1 seg
1 Mev
HELIUM
Tiempo
Energia
Big Bang

Nucleosynthesis

- The early universe contained only hydrogen and helium. Because of the expansion of space and its cooling effect, nucleosynthesis only occurred between 3 to 4 minutes after the big bang (A.B.B.) and essentially stopped after helium.

matter $\rho_m \sim a^{-3}$

radiation $\rho_\gamma \sim a^{-4}$

$n = 20.3\ T^3$ photons/cm^3 today 550

$E_\gamma = h\nu = 2.7\ k_B T$ ($k_B \sim 10^{-4}$ eV/K) today $7\ 10^{-4}$ eV

$H^2 = 8\ \pi\ G/3\ \rho_\gamma\ a^{-4}$ -> $a(t) \sim t^{1/2}$

$T = 10^{10}$ K $t^{-1/2}$ -> $E_\gamma = 2$ MeV $t^{-1/2}$

@ t = 1 sec -> $E_\gamma > m_e = 0.5$ MeV ->

electron-positron pairs:

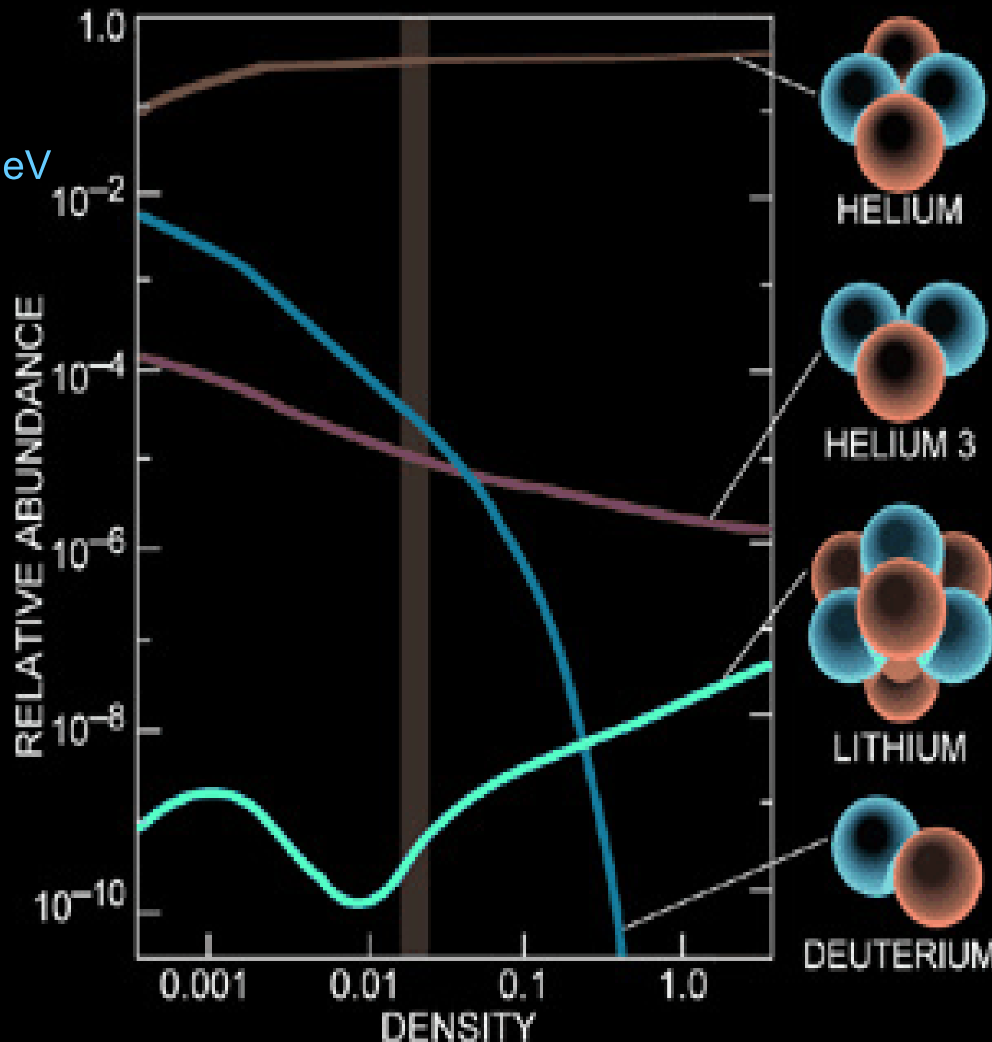
$$p + e^- \rightleftharpoons n + \nu$$

$$p + \nu \rightleftharpoons n + e^+$$

-> $n_n/n_p = \exp(-[m_n - m_p]/k_B T)$

$m_n - m_p \sim 1.3$ MeV @ freeze out 1/5

-> $\eta = 5\ \text{x}10^{-10}$



$\Omega_* \approx 0.01$ -> counting baryons —> $\Omega_B \approx 0.02\text{-}0.04$

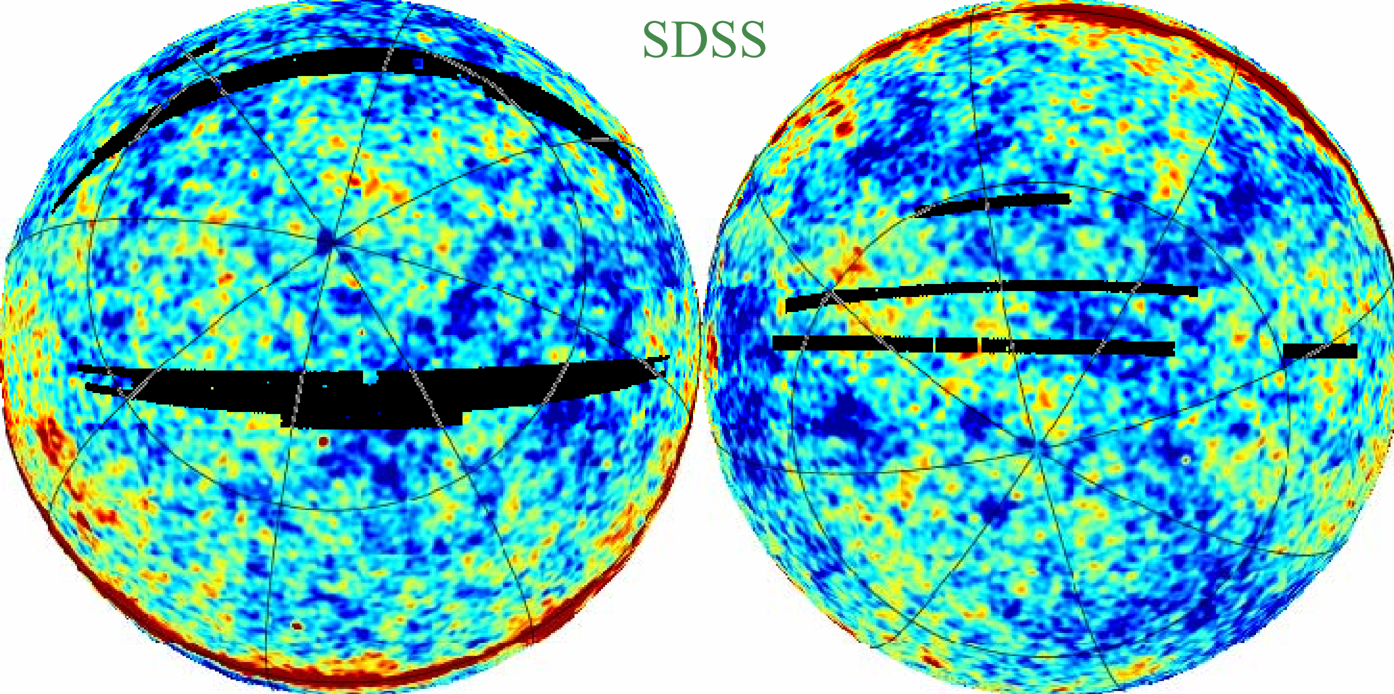
BBN+CMB-> $\eta = 5 \times 10^{-10}$ -> $\Omega_B \approx 0.03\text{-}0.05$

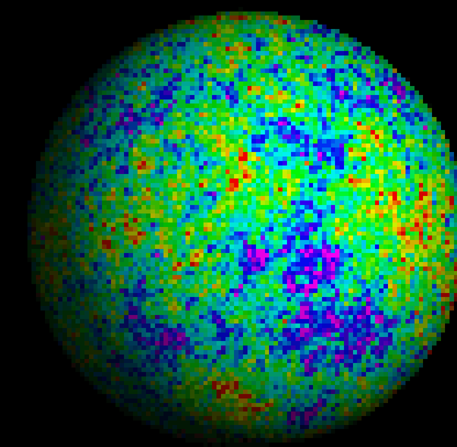
Coincidence #3 :

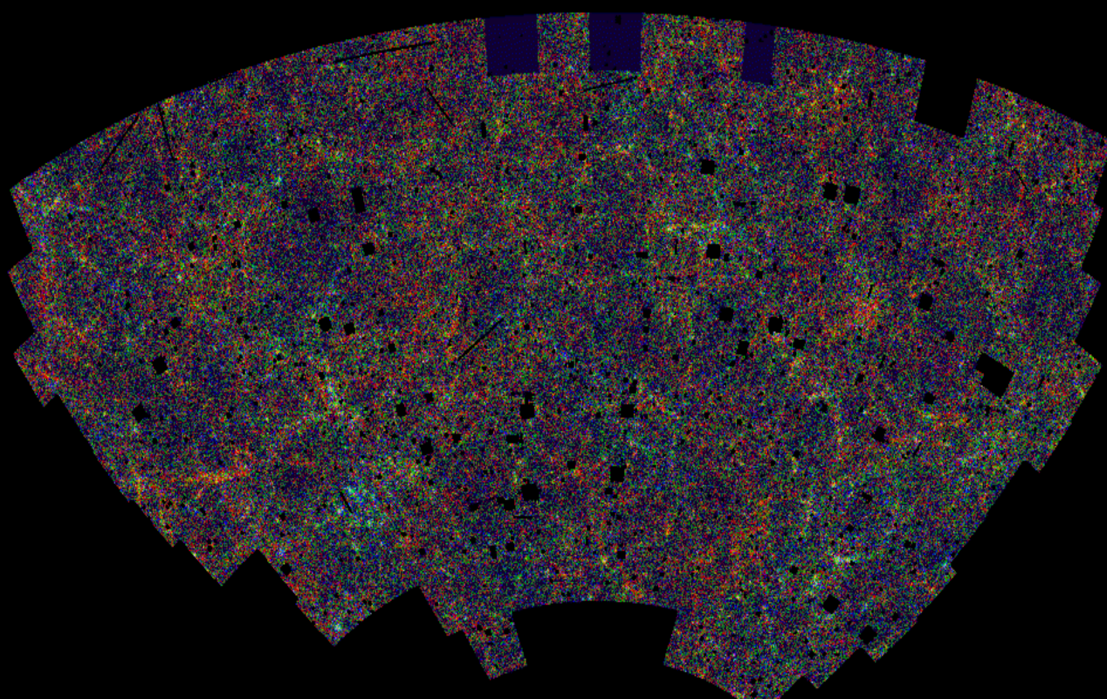
Amplitude of fluctuations in the Universe

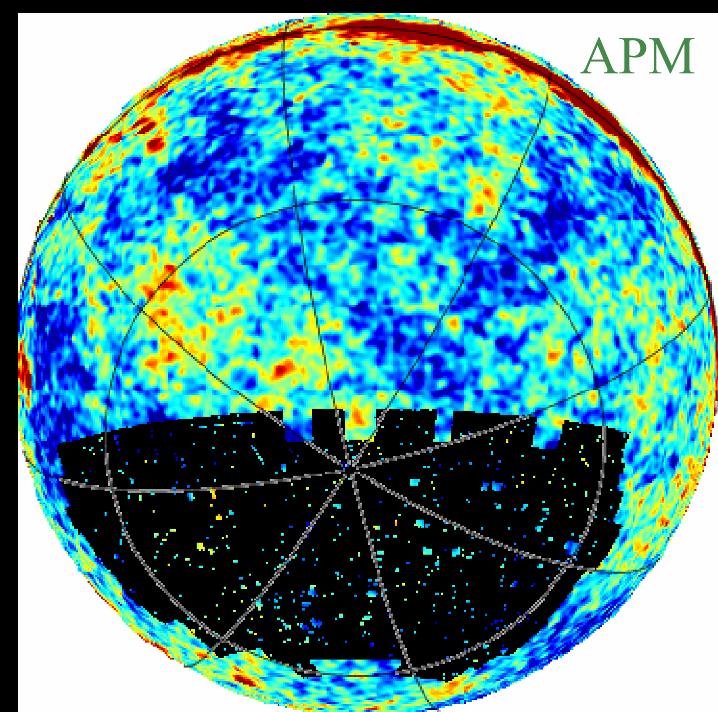
$$\rightarrow \Delta T/T = 10^{-5}\ \delta_{(R=10\ \mathrm{Mpc})}$$

Measurements: Temperature fluctuations vs galaxy fluctuations


SDSS





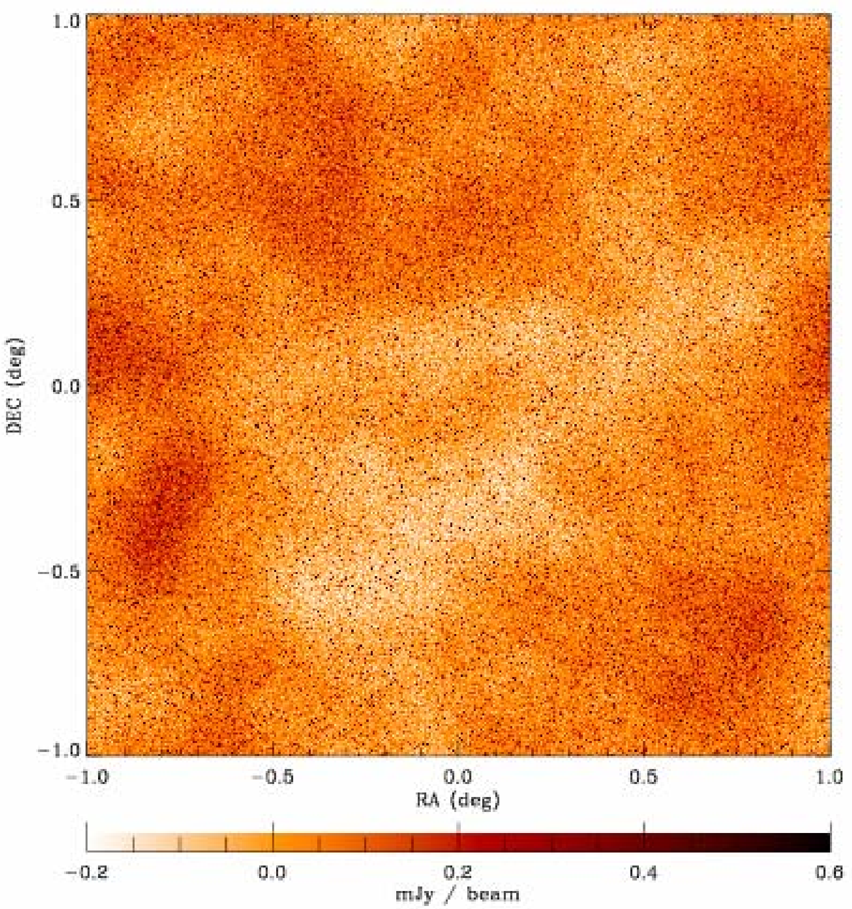

APM

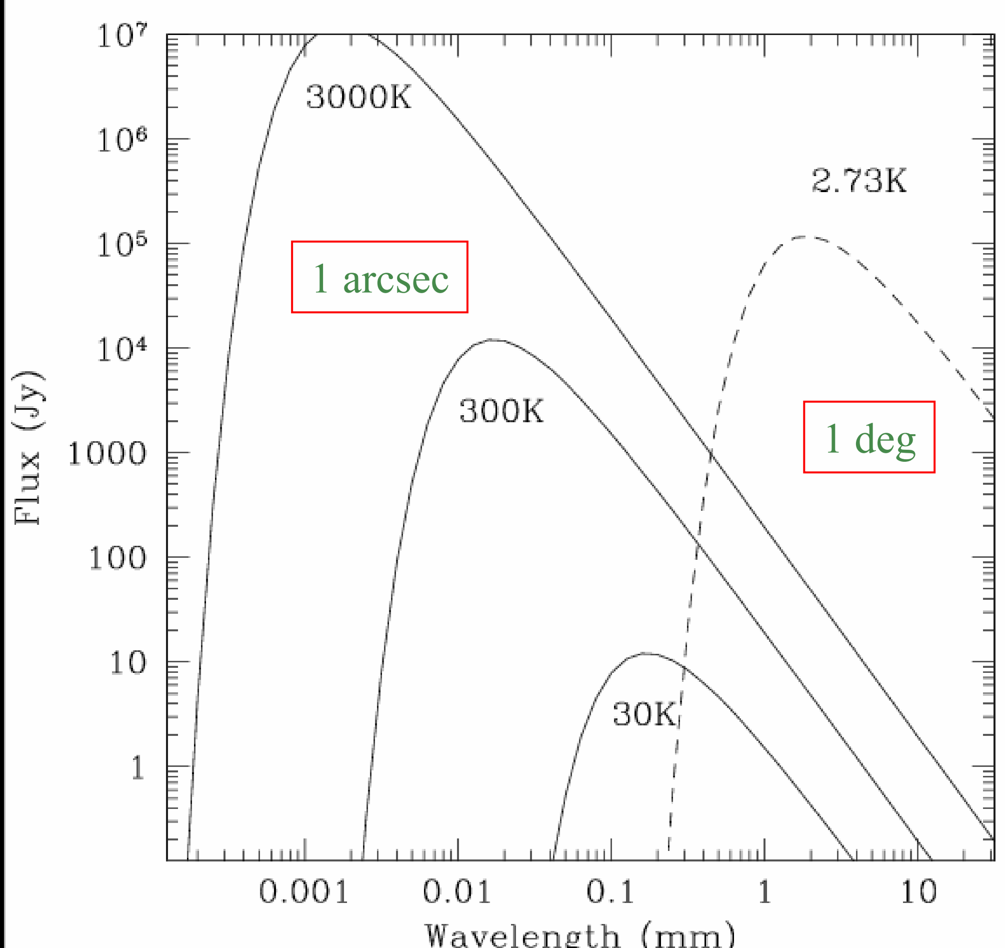
On scales larger than few arcminutes, the millimeter sky is dominated by CMB temperature fluctuations. In fact the sky is not dark, but quite bright!

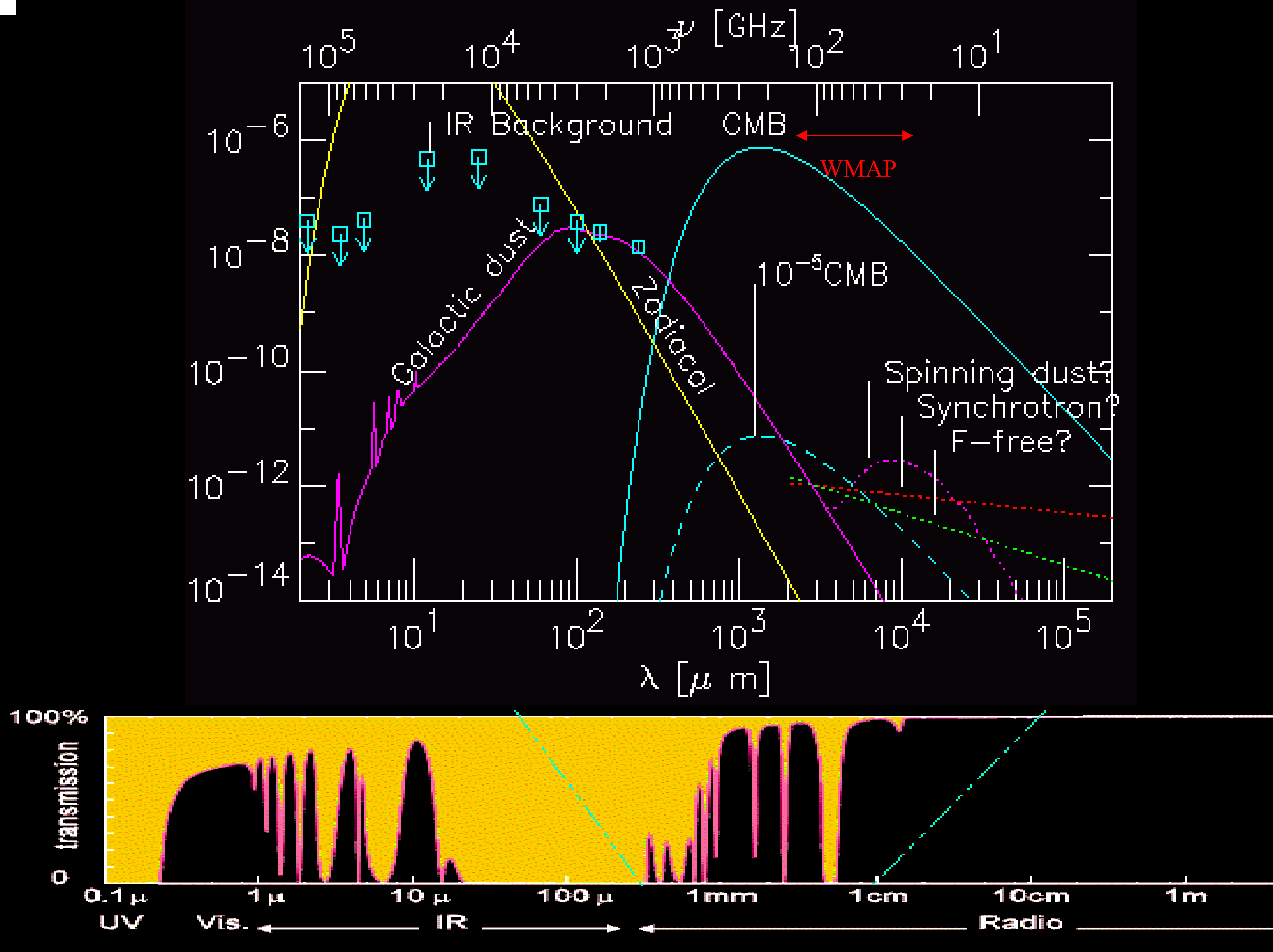
A significant fraction of these CMB photons encode a wealth of information about its interaction with the local matter distribution (eg lensing, SZ, ISW or RS effects).

On smaller scales, the millimeter sky is dominated by high redshift star forming galaxies. This provides a complementary tool to optical/IR view of the universe:

Alfredo Montana, Msc. Thesis @ INAOE







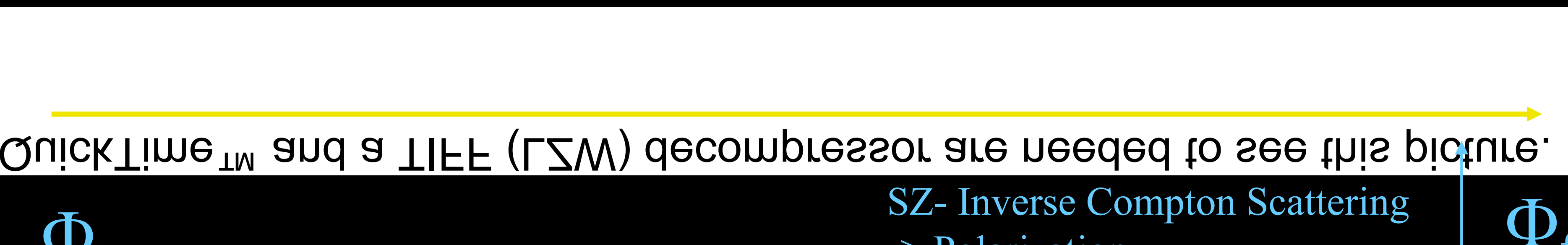
ν [GHz]
10^5 10^4 10^3 10^2 10^1
10^−6 10^−8 10^−10 10^−12 10^−14
IR Background
CMB
WMAP
Galactic dust
Zodiacal
10^−5CMB
Spinning dust?
Synchrotron?
F−free?
10^1 10^2 10^3 10^4 10^5
λ [μ m]
100%
transmission
0
0.1 μ
1 μ
10 μ
100 μ
1mm
1cm
10cm
1m
UV
Vis.
IR
Radio

PRIMARY & SECONDARY CMB ANISOTROPIES

Sachs-Wolfe (ApJ, 1967)

$$\Delta T/T(n) = [\ 1/4\ \delta\gamma\ (n)\ +\ v.n\ +\ \Phi\ (n)\ ]_i^f$$

Temp. F. = Photon-baryon fluid AP + Doppler + N.Potential (SW)



Φ_i

SZ- Inverse Compton Scattering
-> Polarization

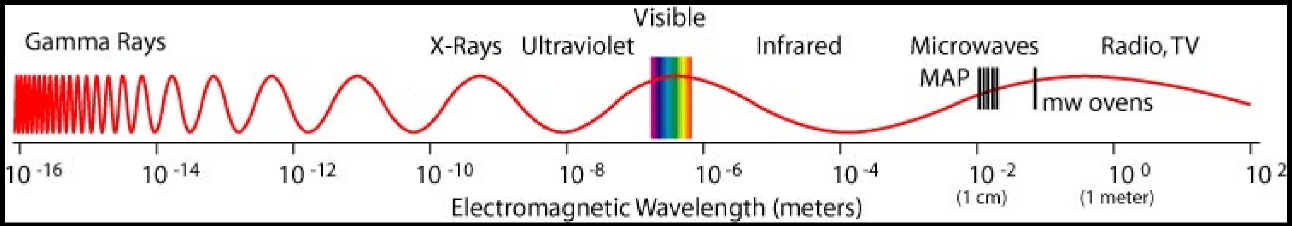
Φ_f

+ Integrated Sachs-Wolfe (ISW) & Rees-Sciama (Nature, 1968) non-linear

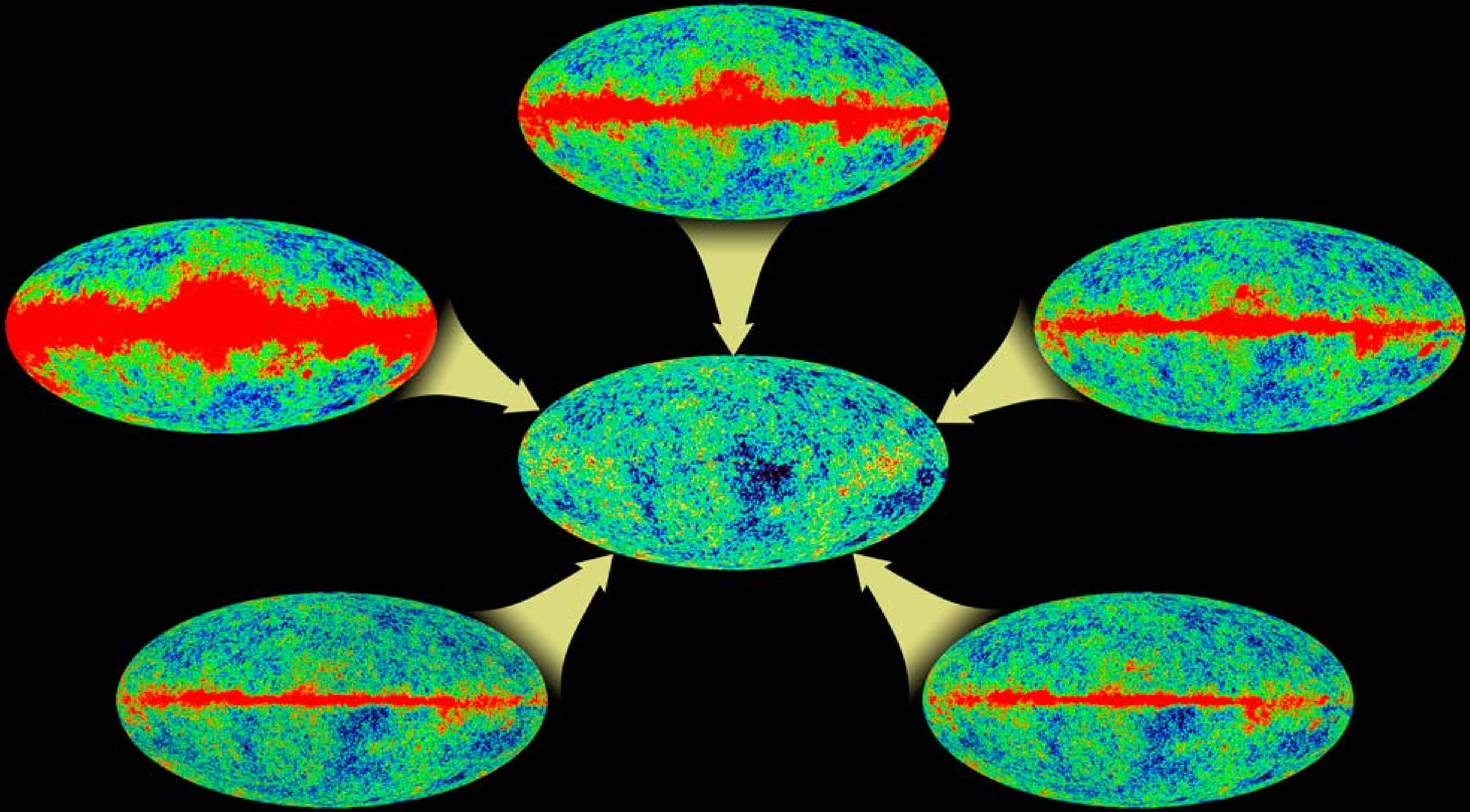
$$+\ 2 \int_i^f d\tau\ \ d\Phi/d\tau\ (n)$$

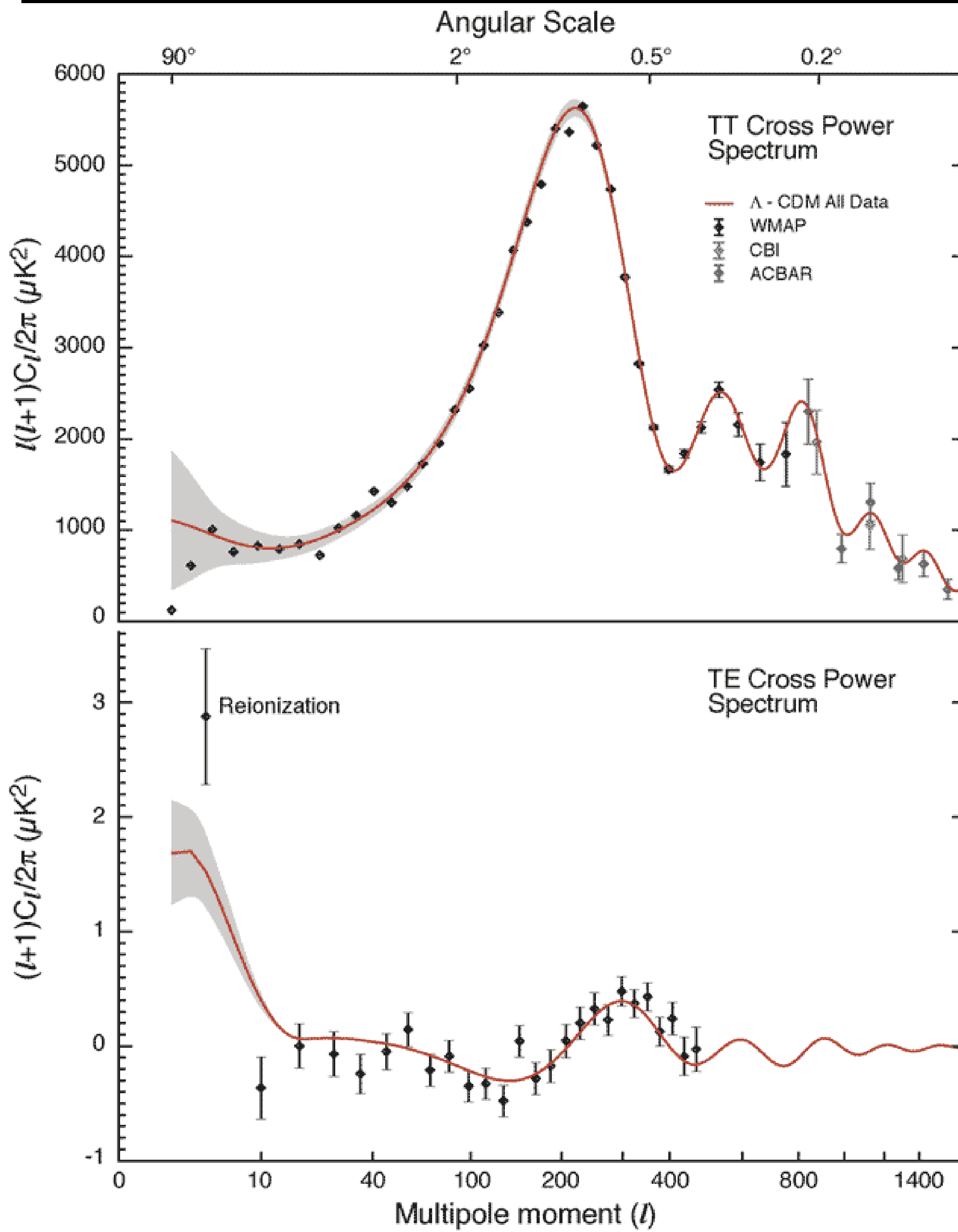
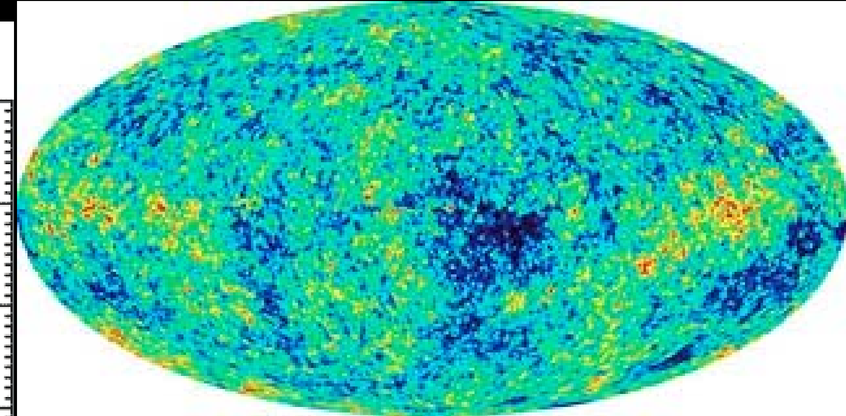
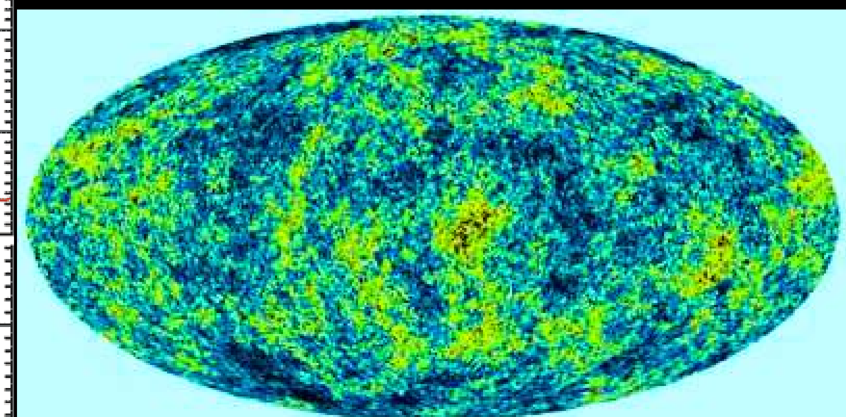
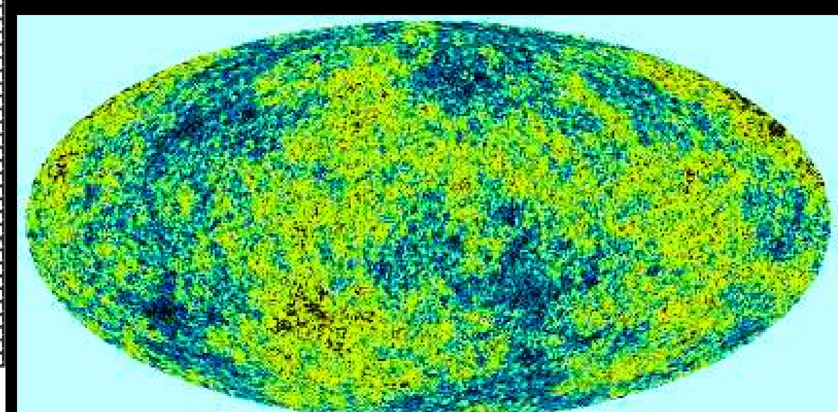
In EdS (linear regime) $D(z) = a$, and therfore $d\Phi/d\tau = 0$

Not in Λ dominated or low density universe !



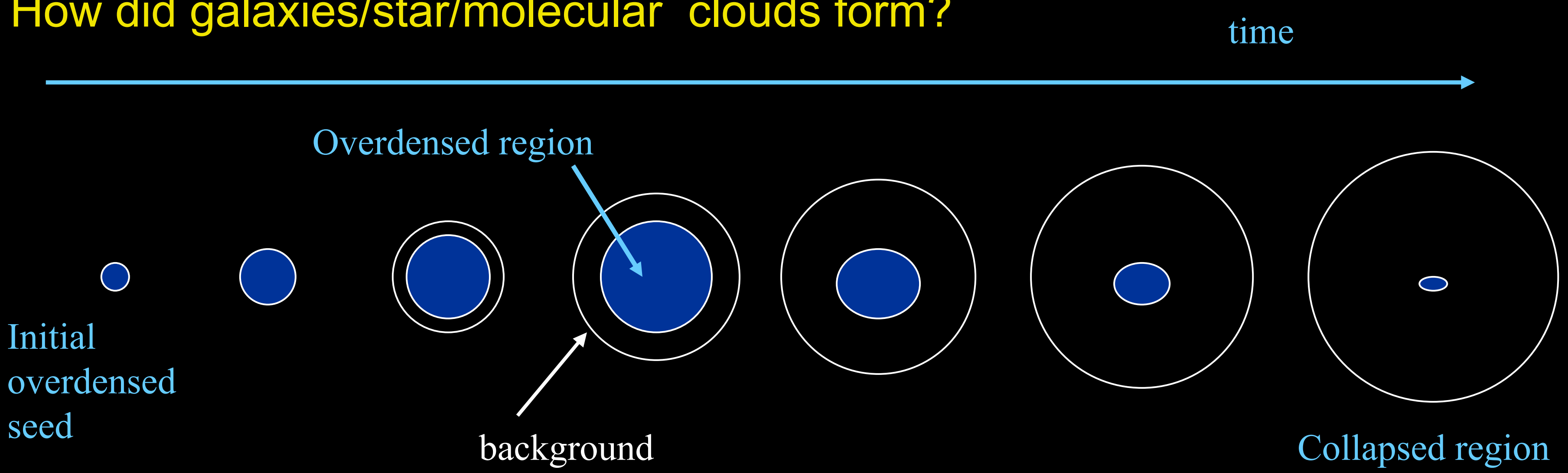
Gamma Rays
X-Rays
Ultraviolet
Visible
Infrared
Microwaves
Radio, TV
MAP
mw ovens
10 -16
10 -14
10 -12
10 -10
10 -8
10 -6
10 -4
10 -2
(1 cm)
10 0
(1 meter)
10 2
Electromagnetic Wavelength (meters)



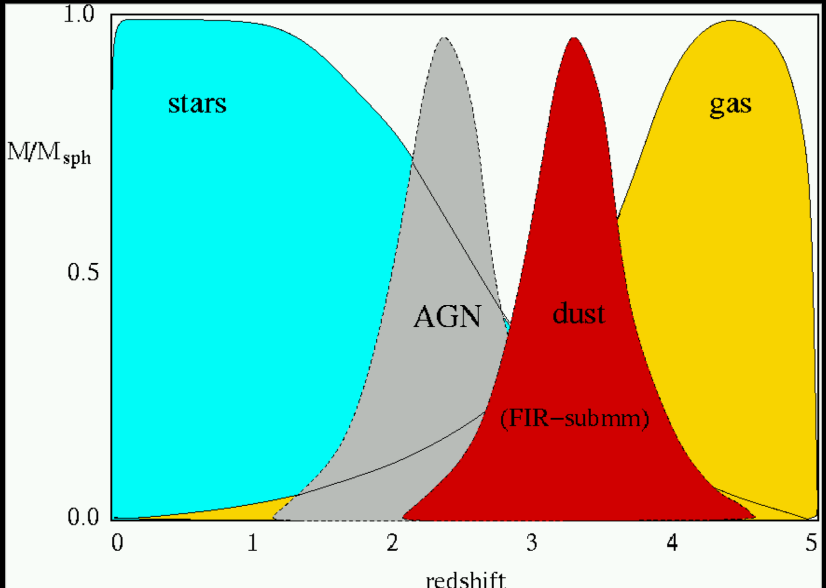

Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)C_l/2π (μK²)
3
2
1
0
-1
Reionization
TE Cross Power Spectrum
(l+1)C_l/2π (μK²)
0
10
40
100
200
400
800
1400
Multipole moment (l)




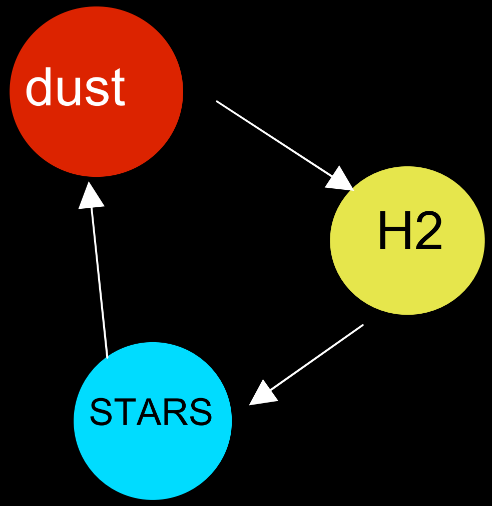
Where does Structure in the Universe come From?

How did galaxies/star/molecular clouds form?

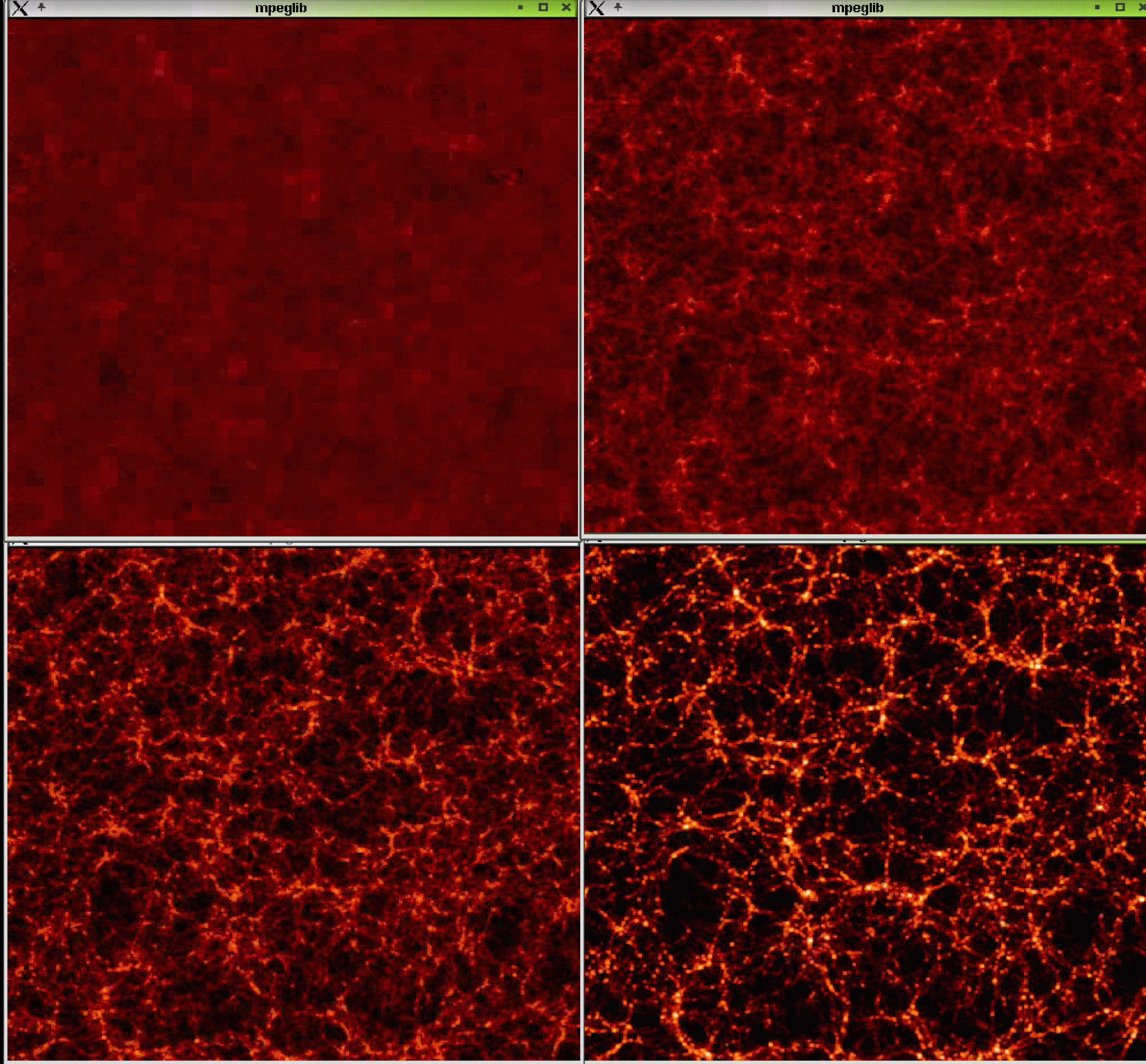


IC + Gravity+ Chemistry = Star/Galaxy (tracer of mass?)





D.Hughes


mpeglib
mpeglib

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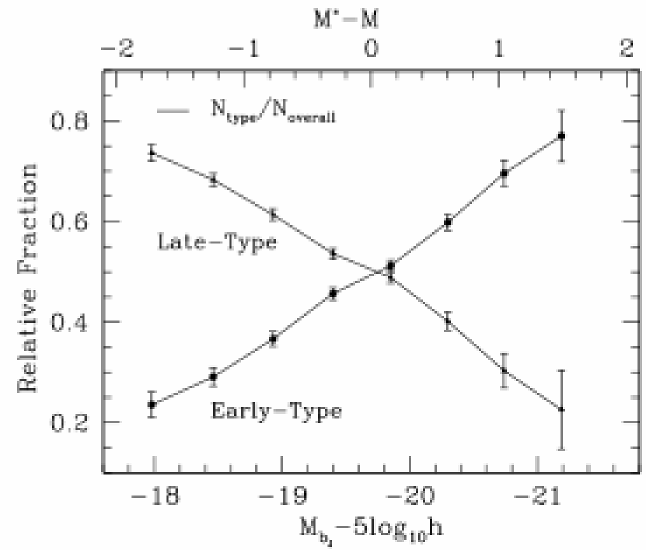
TIFF (Uncompressed) decompressor
are needed to see this picture.



Where does Structure in the Universe come From?

Perturbation theory:

$$\rho = \rho_b (1 + \delta) \quad => \quad \Delta\rho = (\rho - \rho_b) = \rho_b \, \delta$$

$$\rho_b = M / V \quad => \quad \Delta M /M = \delta$$

With : $\delta'' + H \, \delta' - 3/2 \, \Omega_m H^2 \delta = 0$ in EdS linear theory: $\delta = a \, \delta_0$

Gravitation potential:

$$\Phi = - G M /R \quad => \Delta\Phi = G \, \Delta M / R = GM/R \;\; \delta$$

in EdS linear theory: $\delta = a \, \delta_0 => \Delta\Phi = GM \, (\delta/ R) = GM \, (\delta_0/ R_0)$!!

$\Delta\phi$ is constant even when fluctuations grow linearly!

Rms fluctuations

$$\left.\begin{array}{l}\Delta T/T=(SW)=\Delta\Phi/c^2 \\ \Delta\Phi = GM(\delta/R)/c^2\end{array}\right\} \Delta T/T = G\,\rho_m\,4/3\,\pi\,(R/c)^2\,\delta$$

$$\boxed{\Delta T/T = \Omega_m/2\ \ (H_0 R/c)^2\,\delta \sim \Omega_m/2\ \ (R/3000\mathrm{Mpc})^2\,\delta}$$

$$\langle\Delta T/T\rangle \sim 10^{-5}$$ *for* $(R\sim 10\ \mathrm{Mpc}\ ,\ \langle\delta\rangle\sim 1)$

Coincidence #4 :

Concordance: Evidence for Dark Matter

$$\Omega_m = 0.2$$

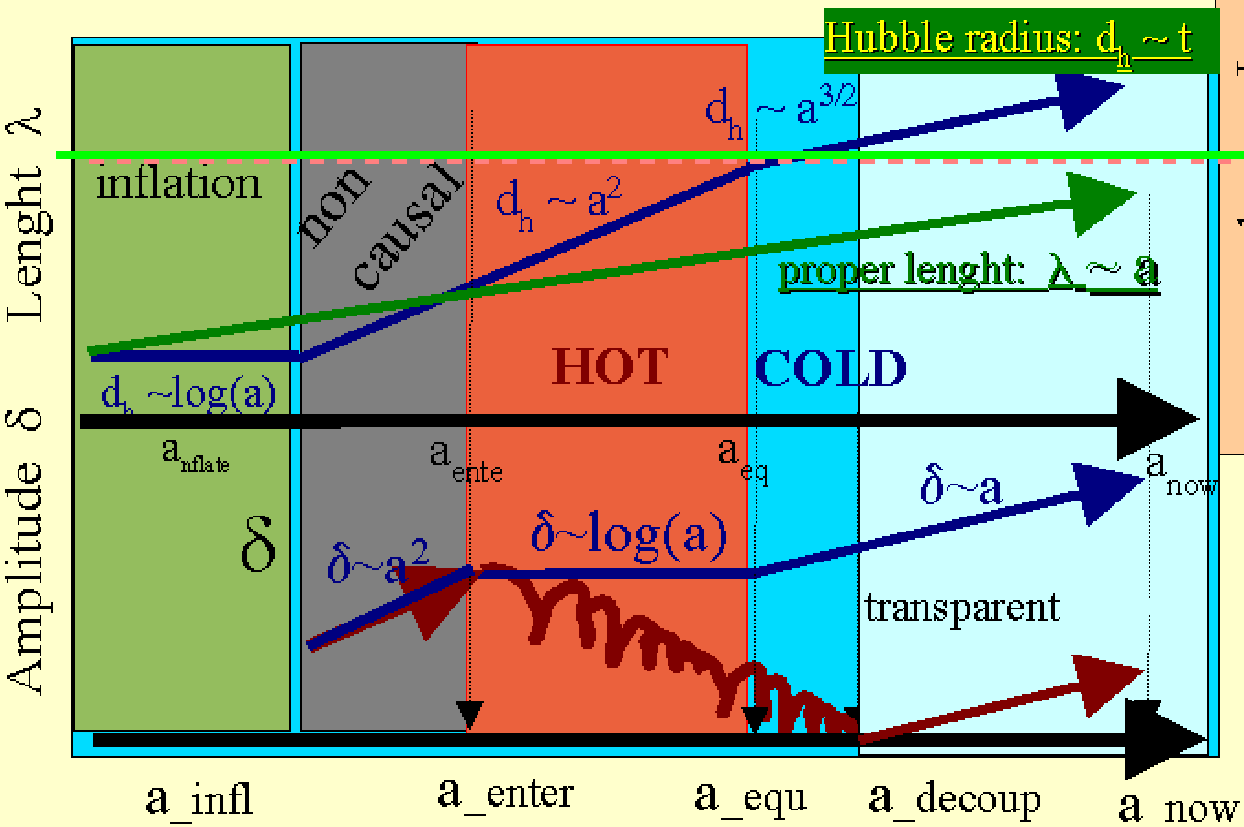
Measurements: dynamics vs P(k)

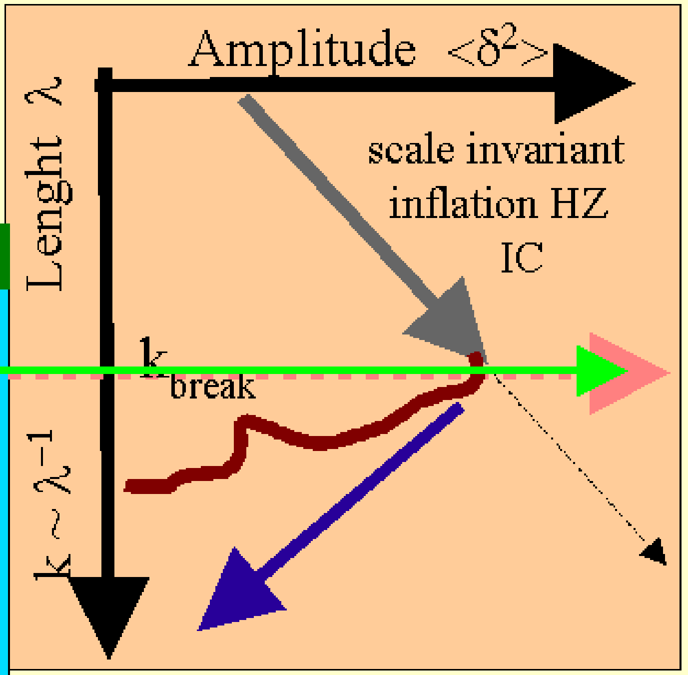
Spectrum of fluctuations

Given IC spectrum: $P_0(k) = <\delta^2> = k$ (HZ)

Transfer function: $P(k)= P_0(k)\, T^2(k)$

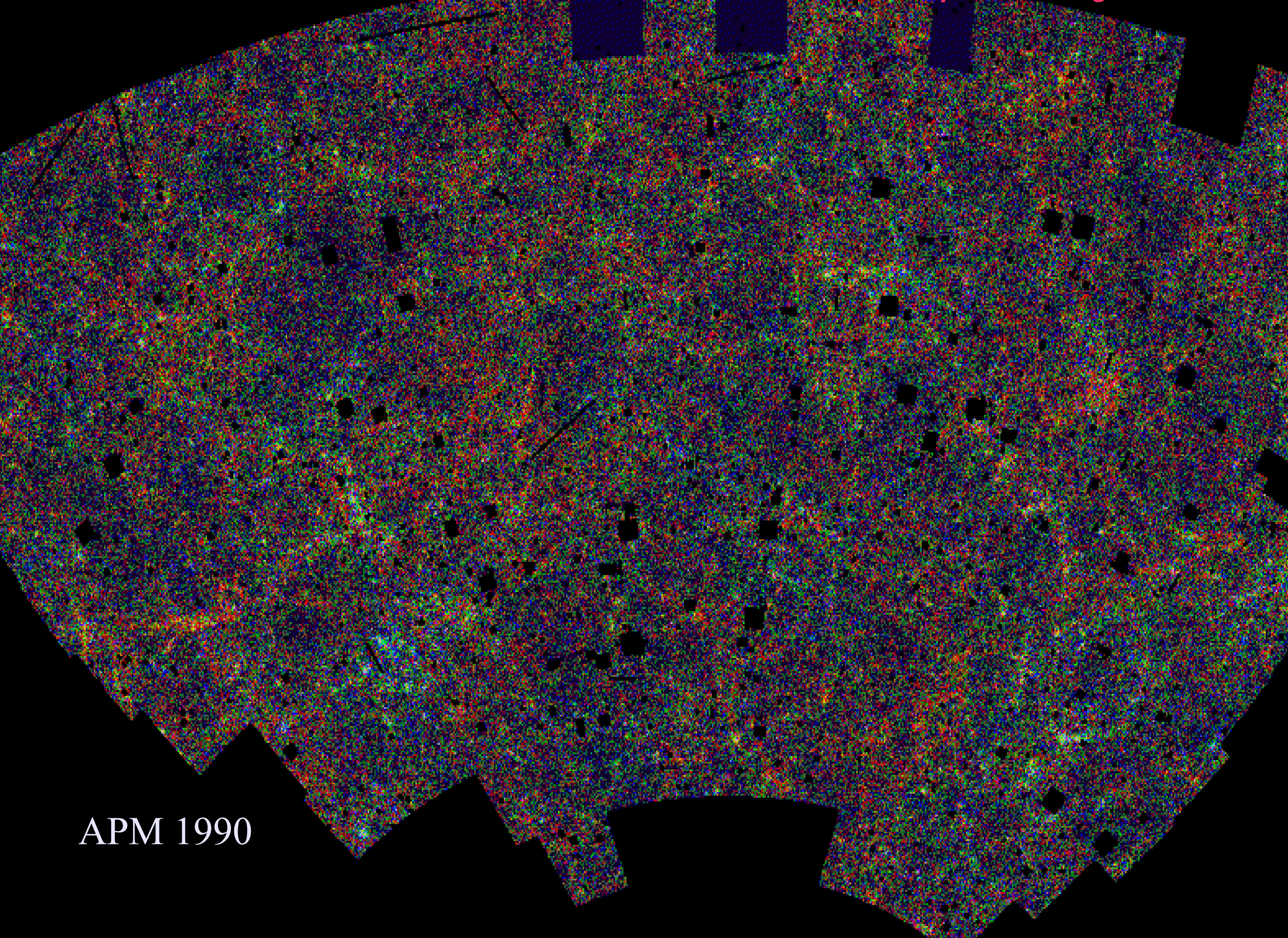
$T^2(k)= F[k,\Gamma]$; $\Gamma = \Omega_0 h\, e^{-[\Omega b(1+2h/\Omega o)0.06]}$



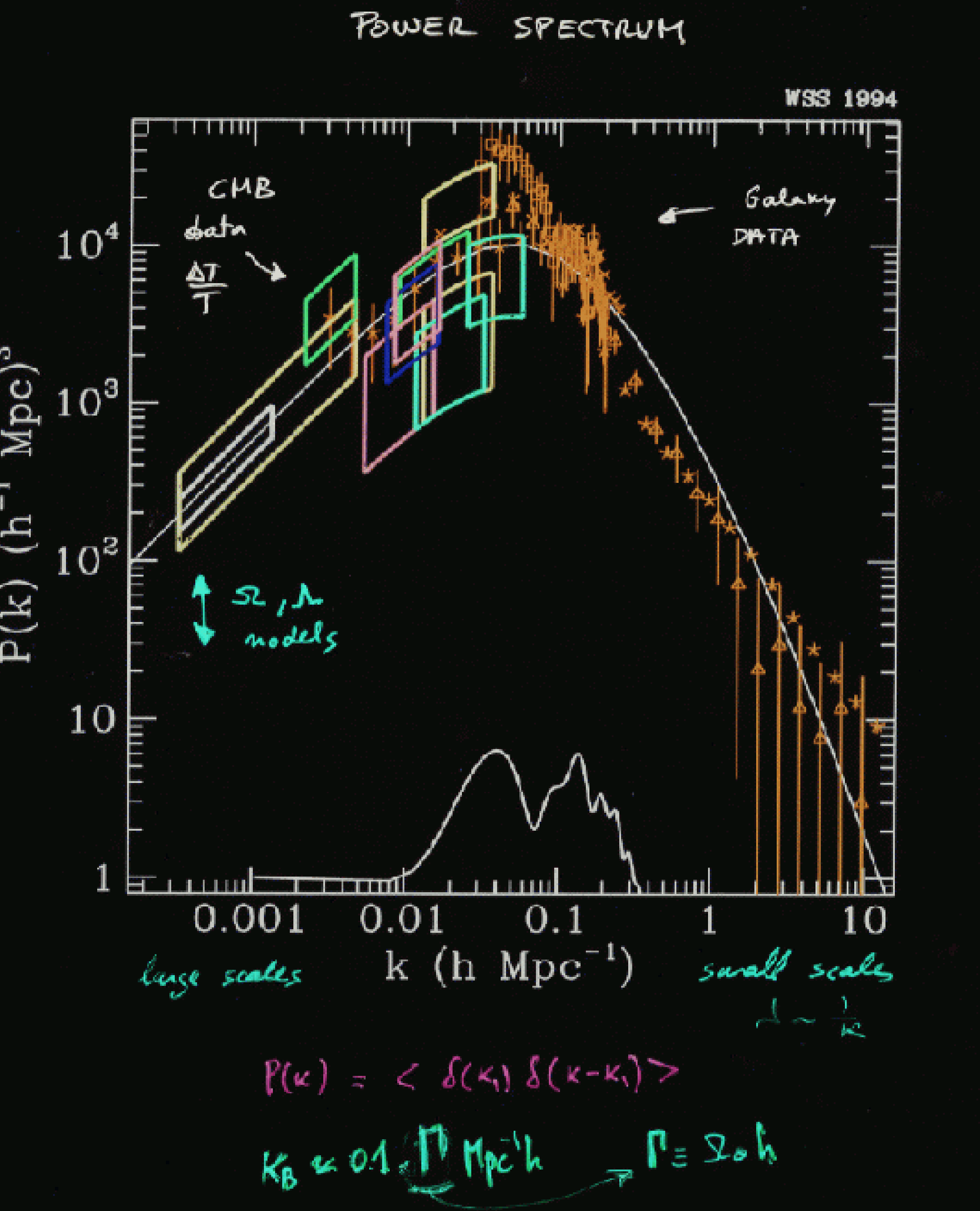


k_{break} = Hubble radius at MD (CDM) ~ 0.1 (Ω_0 h) h/Mpc
$\Rightarrow$ 30 Mpc/h /(Ω_0 h) \Γ

a = scale factor = t^{α}


APM 1990

DM from P(k)



POWER SPECTRUM
WSS 1994
CMB data
ΔT/T
Galaxy DATA
Ω, Λ models
10^4
10^3
10^2
10
1
0.001
0.01
0.1
1
10
P(k) (h⁻¹ Mpc)³
k (h Mpc⁻¹)
large scales
small scales

Coincidence #5:

Cosmic aceleration: Evidence for Dark Energy

$$\rightarrow \; q_0 = -0.5$$

Measurements: SN Ia vs Flat universe

or

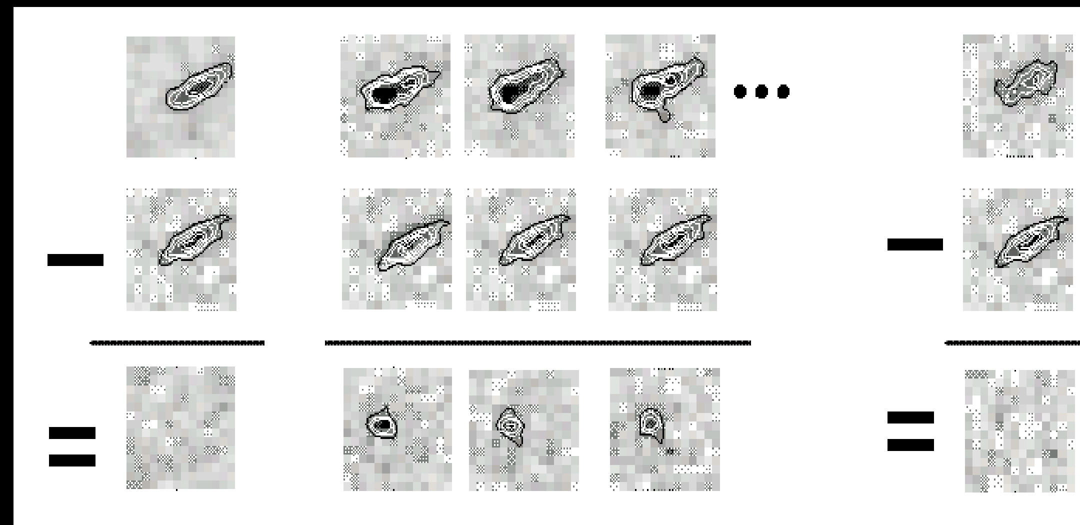
CMB vs P(k)

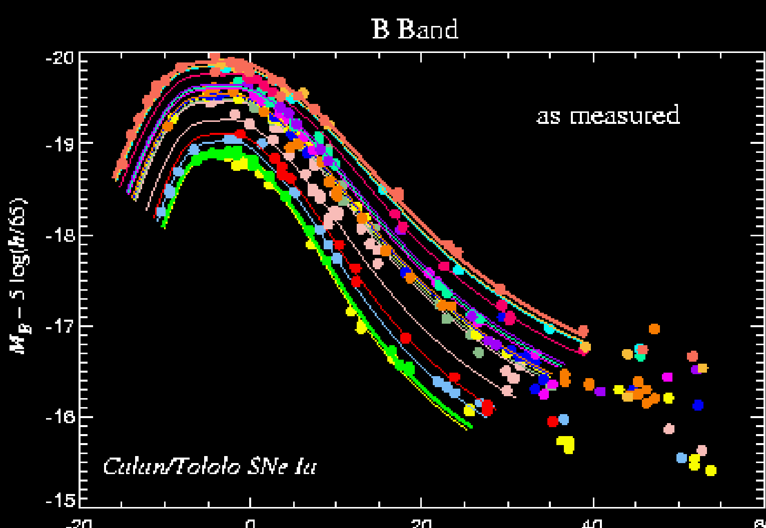
SN Ia vs P(k)

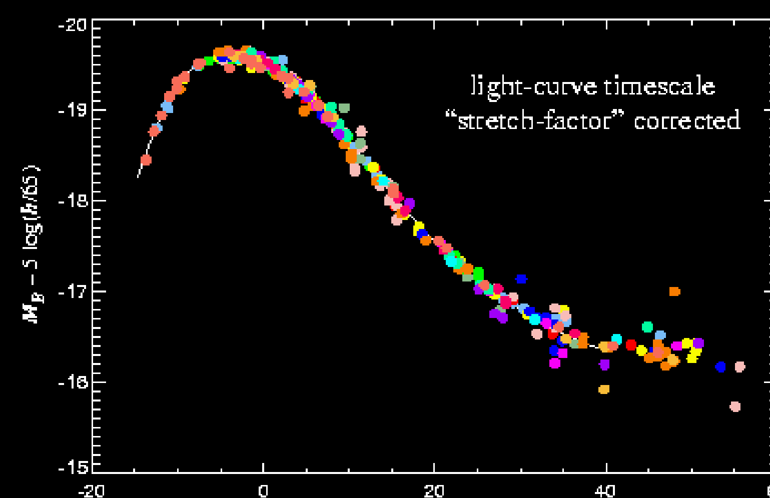
SNIa vs ISW

TYPE I-A SUPERNOVAE

Bright as a galaxy
2 / galaxy / 1000 yr
Rise time ~ 20 days
standard candles?





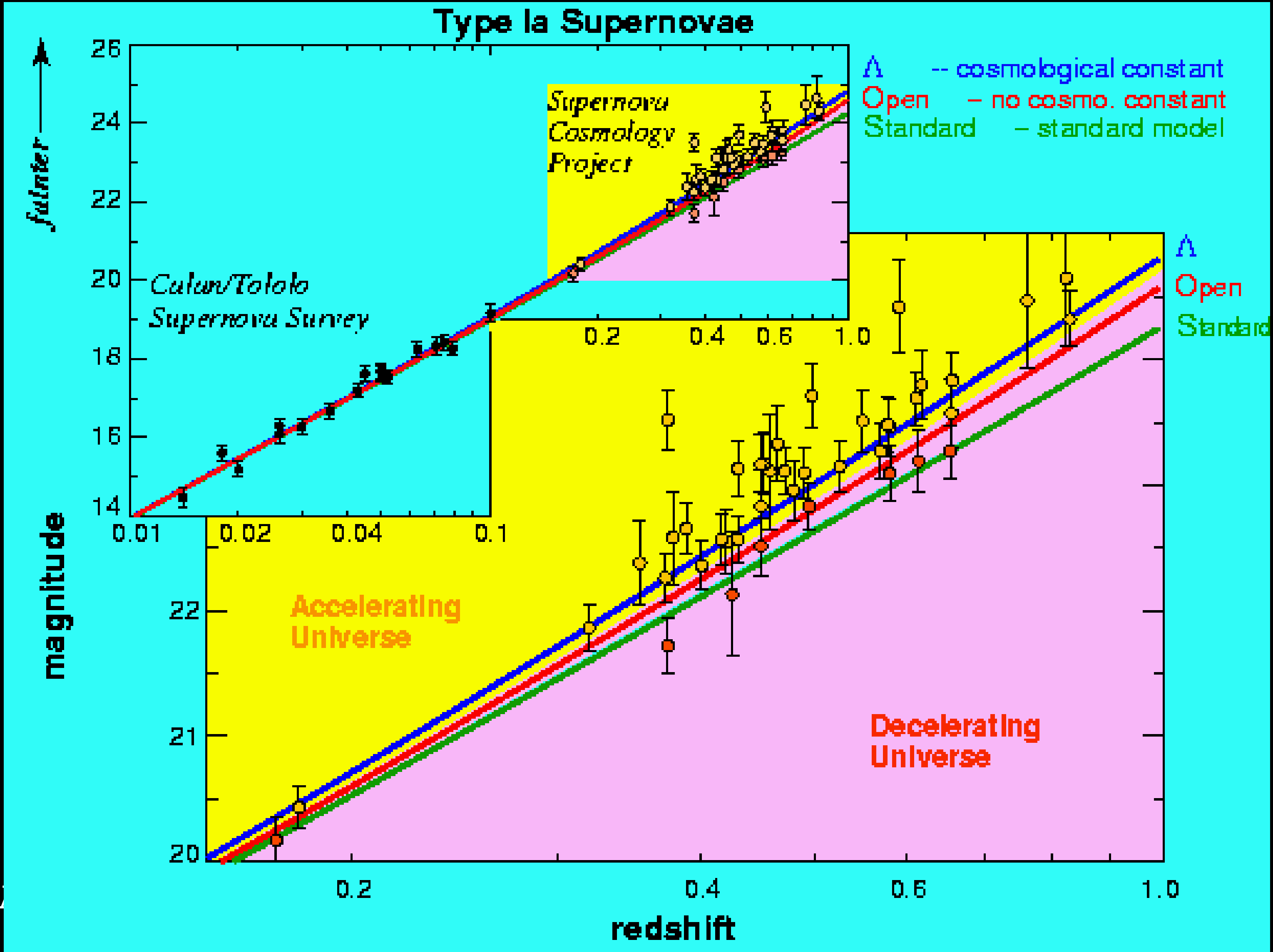


Pierre Astier (Supernovae Cosmology Project) .see http://snfactory.lbl.gov

TYPE I-A SUPERNOVAE

$$q = \frac{1}{2}\,\Omega_T - \Omega_\Lambda = -\,a''/a^2/H^2$$

Using 42 high redshift Type Ia SNe and 18 low redshift SNe, both the Supernova Cosmology Project (Pelmuter et al 1999) and the High-z Supernova Search Team (Ries etal 1998) found that the peak luminosities of distant supernovae appear to be 0.2 magnitude fainter than predicted by a standard decelerating universe :



Pierre

What is Dark Energy?

Whatever makes the Universe to acelerate…

Produced by:

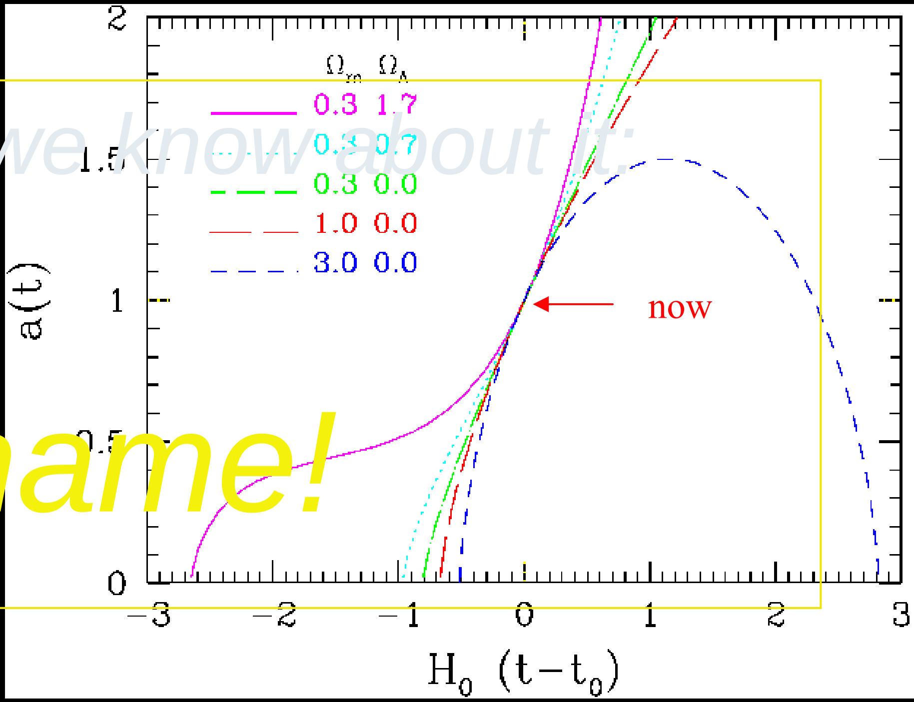
The only thing we know about it:

A - Change the matter contend

B - Change the theory of gravitation

C - Both

it's name!



Causes:

A - a''>0 + transition to a''<0 at z > 1 (ie for Λ case)

B - Older universe (than 1/H, eg in EdS)

C - Larger volumes dV/dz (than EdS) as z increases (in the past)

D - **Stops growth of structures (at z <1?, because a''>0)**

Dark Energy

$$H^2 = (a'/a)^2 = H_0^2 \, (\mathbf{\Omega_m} \, a^{-3} + \mathbf{\Omega_k} \, a^{-2})$$

$\mathbf{\Omega_m} + \mathbf{\Omega_k} = 1$

$\mathbf{\Omega_T} = 1 - \mathbf{\Omega_k}$

EdS $\mathbf{\Omega_k} = 0 \Rightarrow \mathbf{\Omega_T} = 1$

Let's assume: $\rho = \rho_0 \, a^{-3} + \rho_\Lambda$ where ρ_Λ is a constant

$$H^2 = (a'/a)^2 = H_0^2 \, (\mathbf{\Omega_m} \, a^{-3} + \mathbf{\Omega_k} \, a^{-2} + \mathbf{\Omega_\Lambda})$$

$1 = \mathbf{\Omega_m} + \mathbf{\Omega_k} + \mathbf{\Omega_\Lambda}$

$\mathbf{\Omega_\Lambda} = \rho_\Lambda / \rho_c$

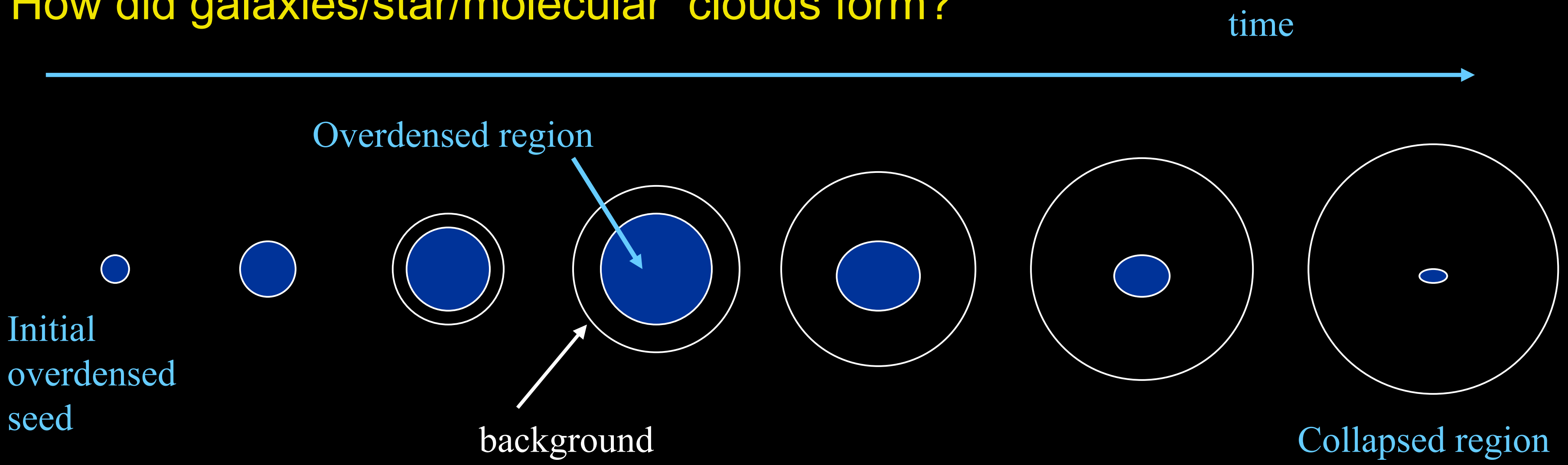
Deceleration $q_0 \equiv - \mathbf{a}_0'' / H_0^2 = \mathbf{\Omega_m}/2 - \mathbf{\Omega_\Lambda} < 0$?

First Acoustic peak $\Rightarrow \mathbf{\Omega_k} = 0 \Rightarrow \mathbf{\Omega_\Lambda} \approx 1 - \mathbf{\Omega_m} \approx$ **0.7-0.8** $\Rightarrow$ $q_0 \approx -0.5$! In agreement with SNIa results find $q_0 \approx -0.5$!

Age of universe: 14 Gyr in good agreement with oldest stars.

Where does Structure in the Universe come From?

How did galaxies/star/molecular clouds form?



Perturbation theory:

$$\rho = \rho_b\,(1 + \delta) \quad \Rightarrow \quad \Delta\rho = (\rho - \rho_b) = \rho_b\,\delta$$

$$\rho_b = M / V \quad \Rightarrow \quad \Delta M / M = \delta$$

With : $$\delta'' + H\,\delta' - 3/2\,\Omega_m\,H^2\,\delta = 0$$

in EdS linear theory: $\delta = a\,\delta_0$

$\delta'' + H\,\delta' - 3/2\,\Omega_m\,H^2\,\delta = 0$

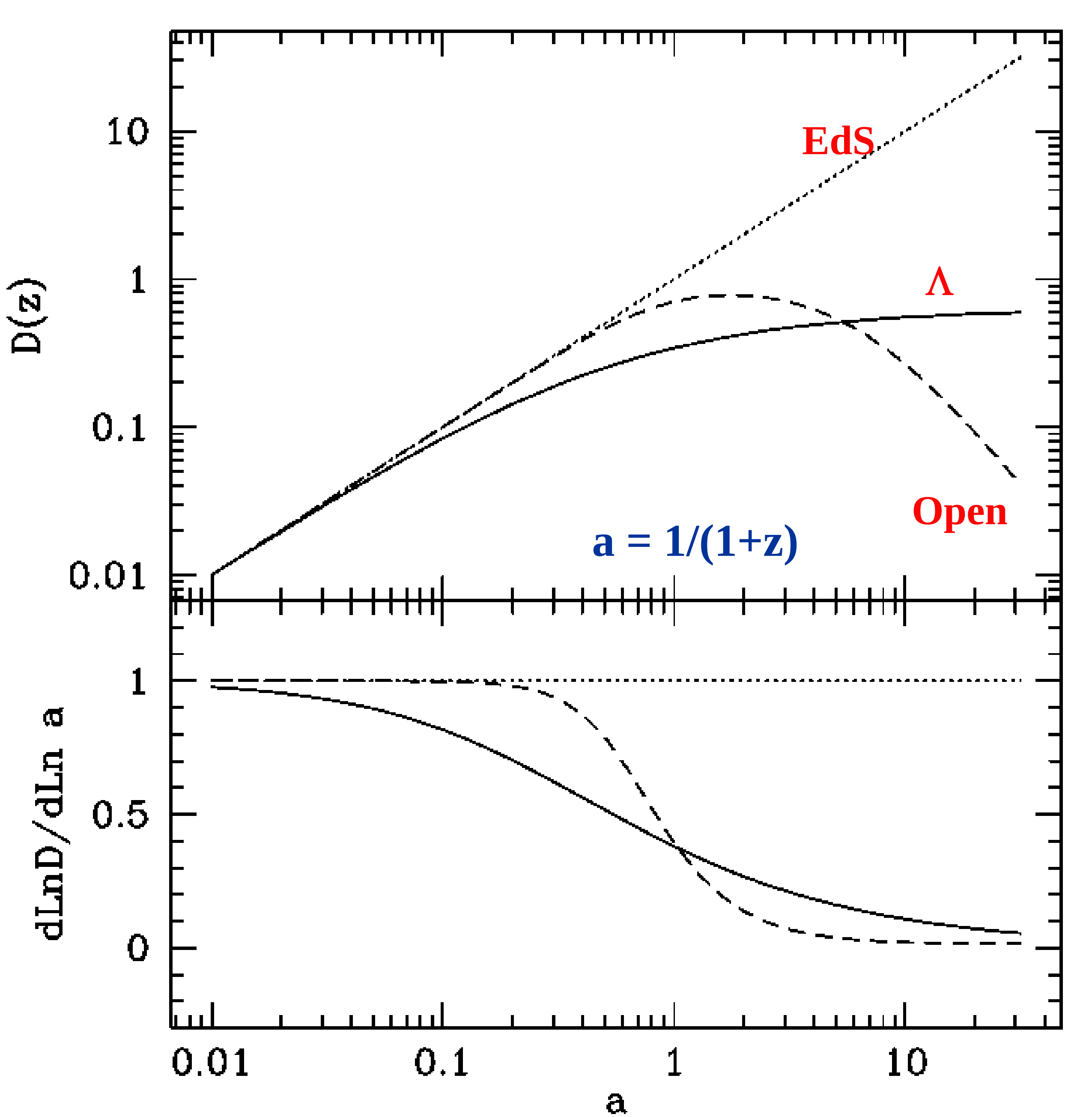
$\delta = D(z)\,\delta_0$

in EdS: $\delta = a\,\delta_0$

$f = dLnD/dLn(a)$

$= \Omega_m^{0.6} + \Omega_\Lambda/70\,(1 + \Omega_m/2)$

in EdS: f=1



Where does Structure in the Universe come From?

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$$\rho_b = M / V \Rightarrow \Delta M / M = \delta$$

With : $\delta'' + H \, \delta' - 3/2 \, \Omega_m H^2 \, \delta = 0$ in EdS linear theory: $\delta = a \, \delta_0$

Gravitation potential:

$$\Phi = - G M / R \quad \Rightarrow \Delta\Phi = G \, \Delta M / R = GM/R \;\; \delta$$

in EdS linear theory: $\delta = a \, \delta_0 \Rightarrow \Delta\Phi = GM \, (\delta / R) = GM \, (\delta_0 / R_0)$!!

$\Delta\phi$ is constant even when fluctuations grow linearly!

PRIMARY & SECONDARY CMB ANISOTROPIES

Sachs-Wolfe (ApJ, 1967)

$$\Delta T/T(n) = [\ 1/4\ \delta\gamma\ (n)\ +\ v.n\ +\ \Phi\ (n)\ ]_i^f$$

Temp. F. = Photon-baryon fluid AP + Doppler + N.Potential (SW)

Φ_i

SZ- Inverse Compton Scattering
-> Polarization

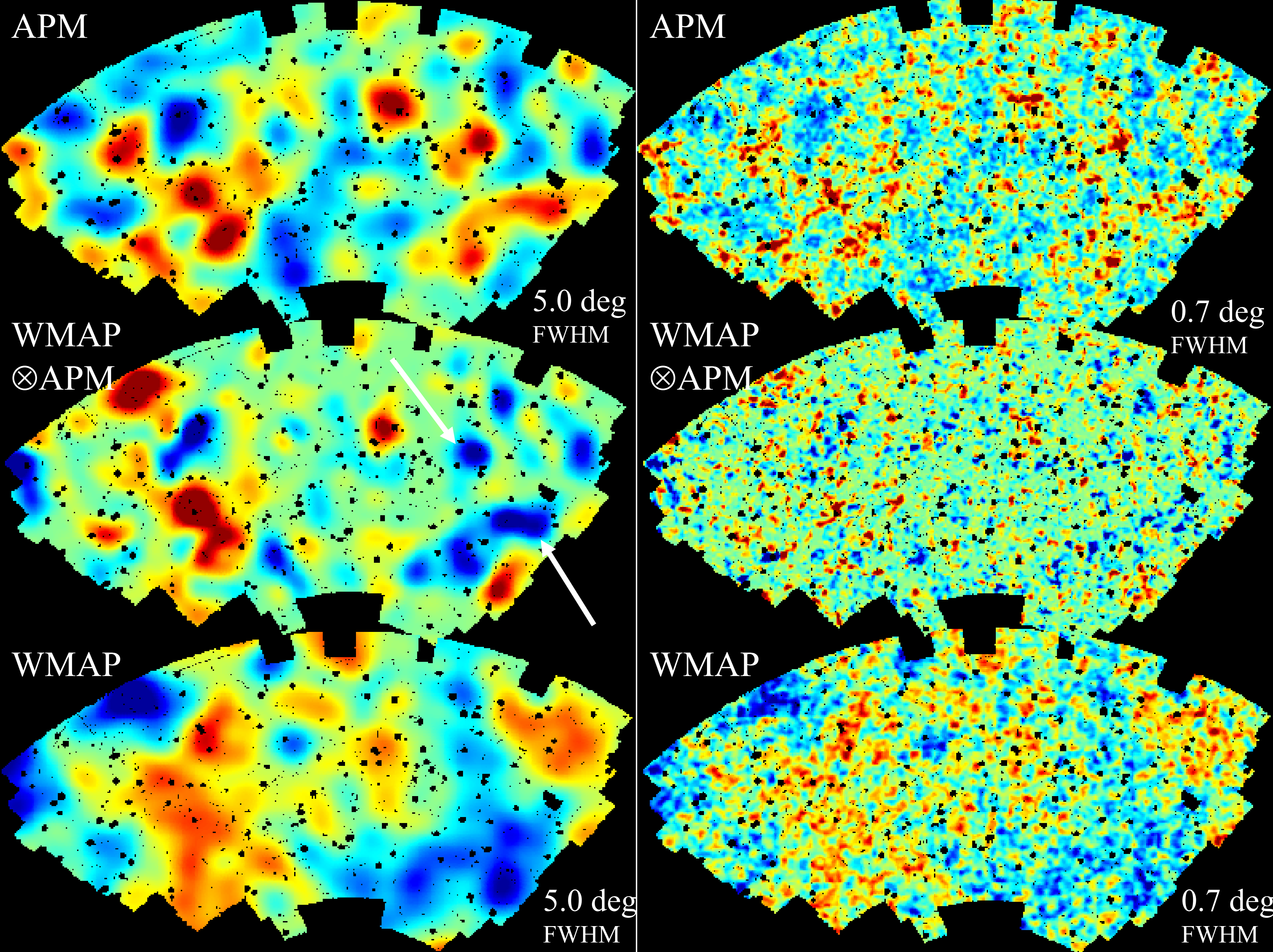
Φ_f

+ Integrated Sachs-Wolfe (ISW) & Rees-Sciama (Nature, 1968) non-linear

$$+\ 2 \int_i^f d\tau\ \ d\Phi/d\tau\ (n)$$

In EdS (linear regime) D(z) = a , and therfore $d\Phi/d\tau = 0$

Not in Λ dominated or low density universe !


APM
5.0 deg
FWHM
WMAP
⊗APM
WMAP
5.0 deg
FWHM
APM
0.7 deg
FWHM
WMAP
⊗APM
WMAP
0.7 deg
FWHM

Data Compilation

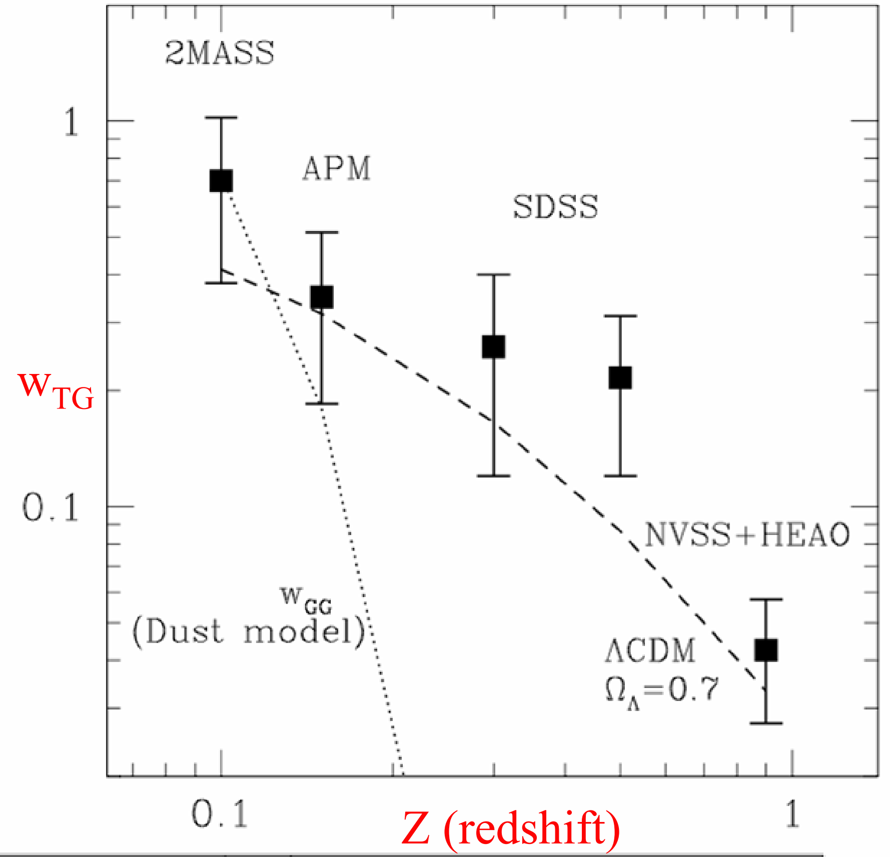
EG, Manera, Multamaki (astro-ph/ 0407022)

Coverage: *z= 0.1 - 1.0*

Area 4000 sqrdeg to All sky

Bands: *X-ray,Optical, IR, Radio*

Sytematics: *Extinction & dust in galaxies.*



$\bar{z}$	w_{TG}/b	b	catalog, Band
0.1	0.70 ± 0.32	1.1	2MASS, infrared ($2\mu m$)
0.15	0.35 ± 0.17	1.0	APM, optical (b_j)
0.3	0.26 ± 0.14	1.0	SDSS, optical (r)
0.5	0.216 ± 0.096	2.4	SDSS high-z, optical (r+colors)
0.9	0.043 ± 0.015	1-2	NVSS+HEAO, Radio & X-rays

TABLE I: Compilation of observed cross correlation w_{TG}/b (averaged for $\theta \simeq 4 - 10^\circ$.) of WMAP anisotropies with different catalogs. Error in w_{TG}/b includes 20% uncertainty in b.

WMAP team (Nolta et al., astro-ph/0305467) and Boughm & Crittenden (astro-ph/0305001). Radio Galaxies (NVSS) + X-ray HEAO (both at z =0.8-1.1)

APM (Fosalba & EG astro-ph/05468)

z=0.15-0.3

SDSS (Fosalba, EG, Castander, astro-ph/0307249) z=0.3-0.5

SDSS team (Scranton et al 0307335)

2Mass (Afshordi et al 0308260) z=0.1

Data Compilation

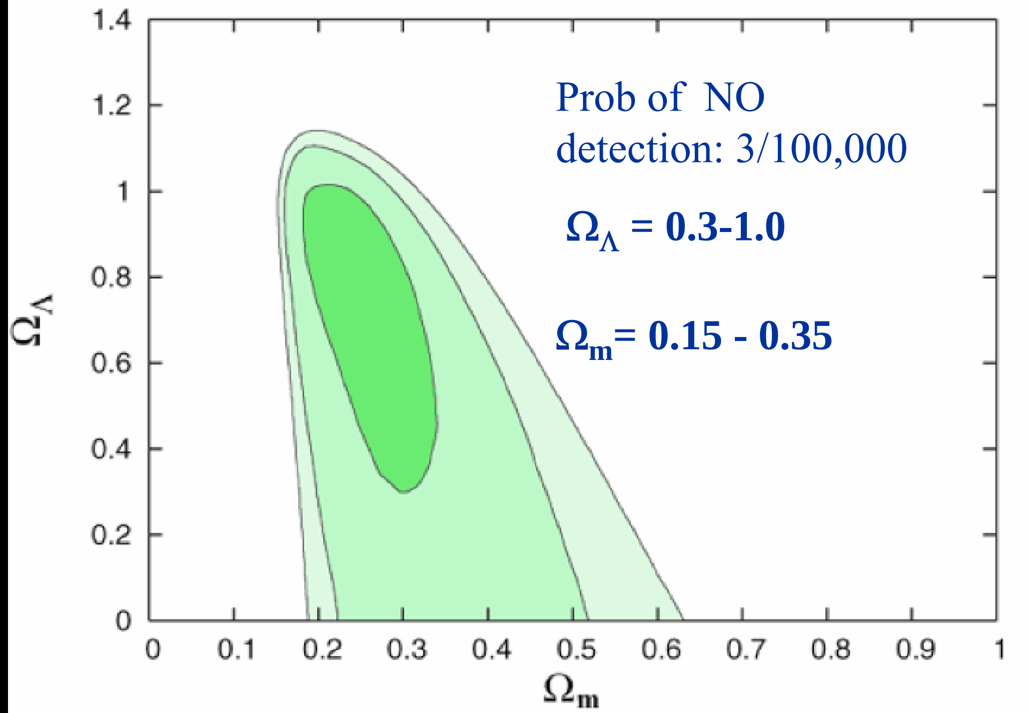
EG, Manera, Multamaki (astro-ph/ 0407022)

Marginalized over:

- -h=0.6-0.8
- -relative normalization of P(k)

Normalize to sigma8=1 for CM

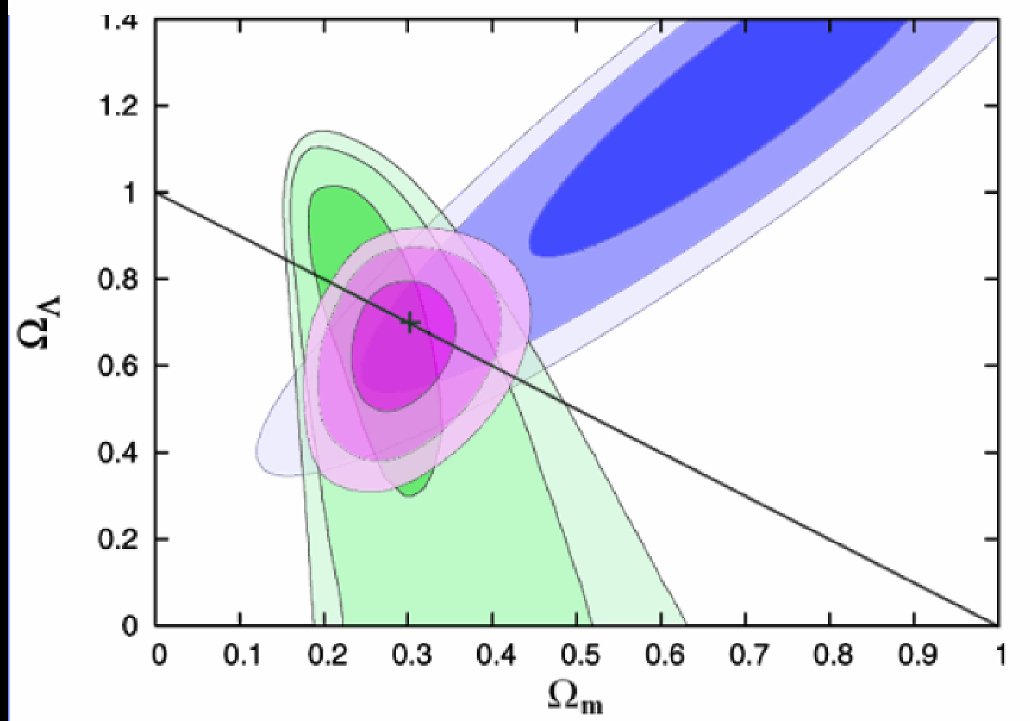
Bias from Gal-Gal correlation



With SNIa:

$\Omega_\Lambda = 0.65$ +/- 0.15

$\Omega_m = 0.25$ +/- 0.05

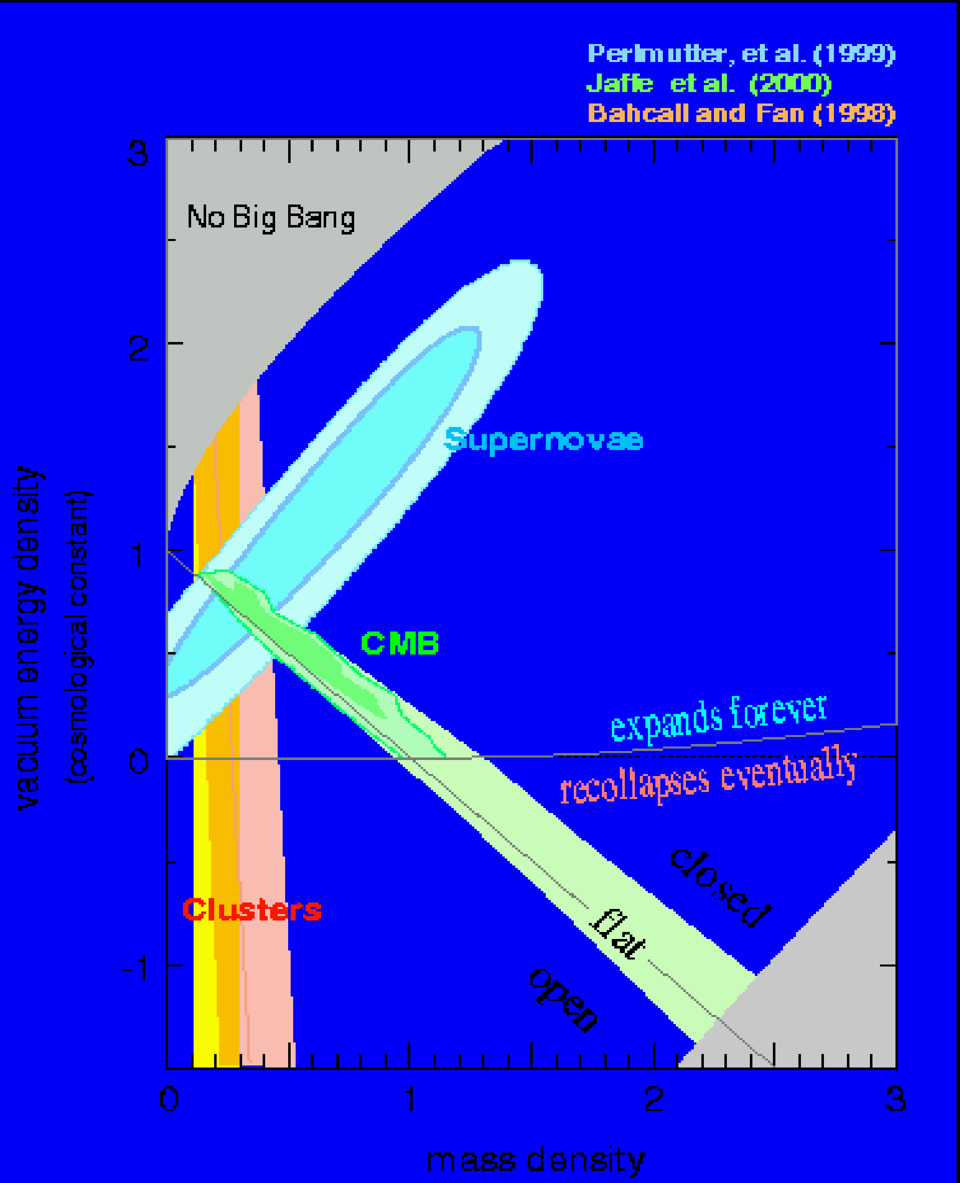


Another set of coincideces:

->Why is Ω_Λ becoming dominant just today?

->Gravity needs to be tested on these same (mm scales).

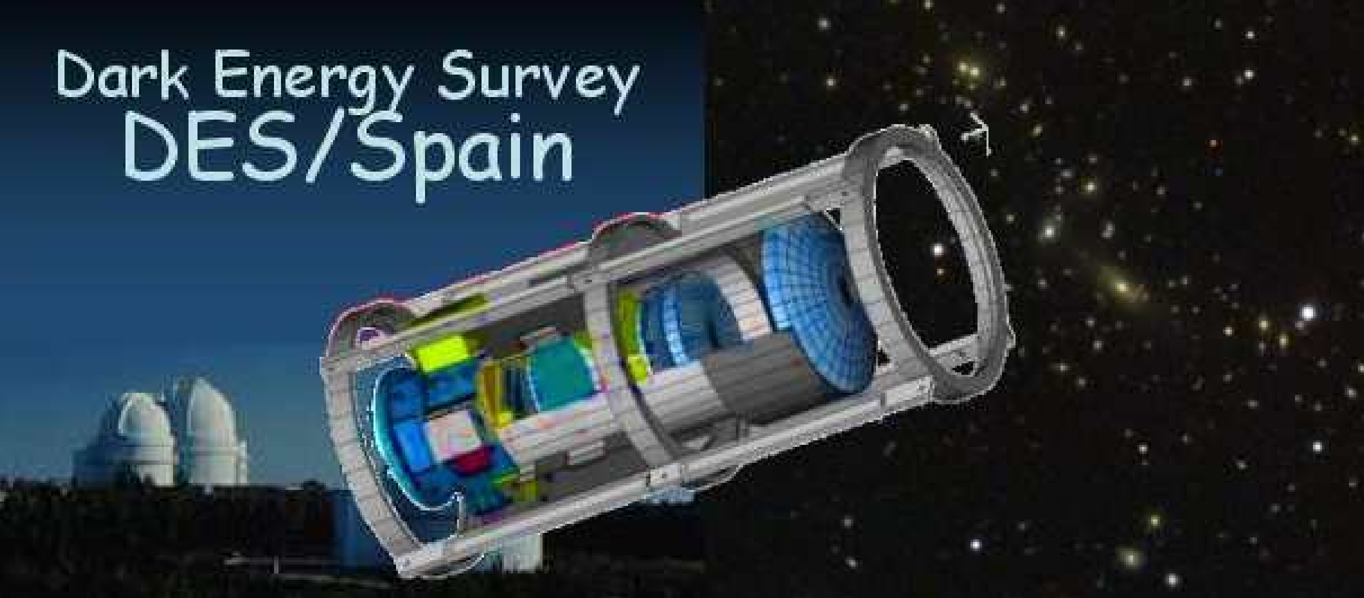
Precision Cosmology



How can we do better?

We need to understand the systematics. We need to build better resolution CMB maps and deeper and wider galaxy samples with redshift.

THE
DARK ENERGY
SURVEY



QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

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Photometric redshifts

CCDs more sensitive on red (z-band)

5000 sqr degrees to z=1 matches SPT CMB data

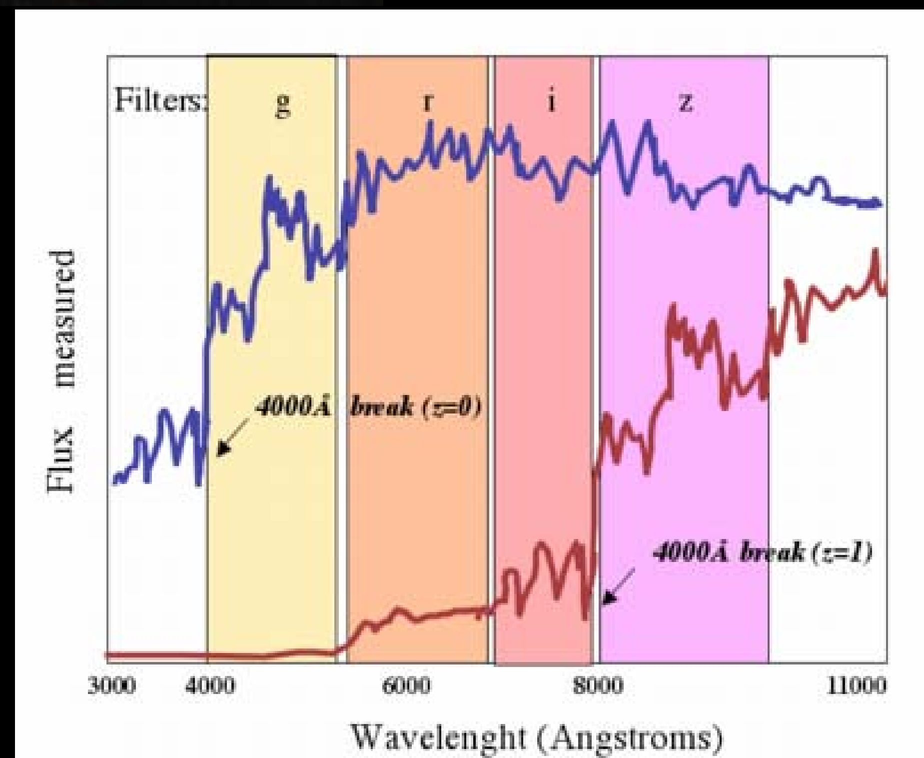
Key projects (systematics!):

-Cluster Abundaces (SZ effect)

-Galaxy clustering evolution (Acustic peaks)

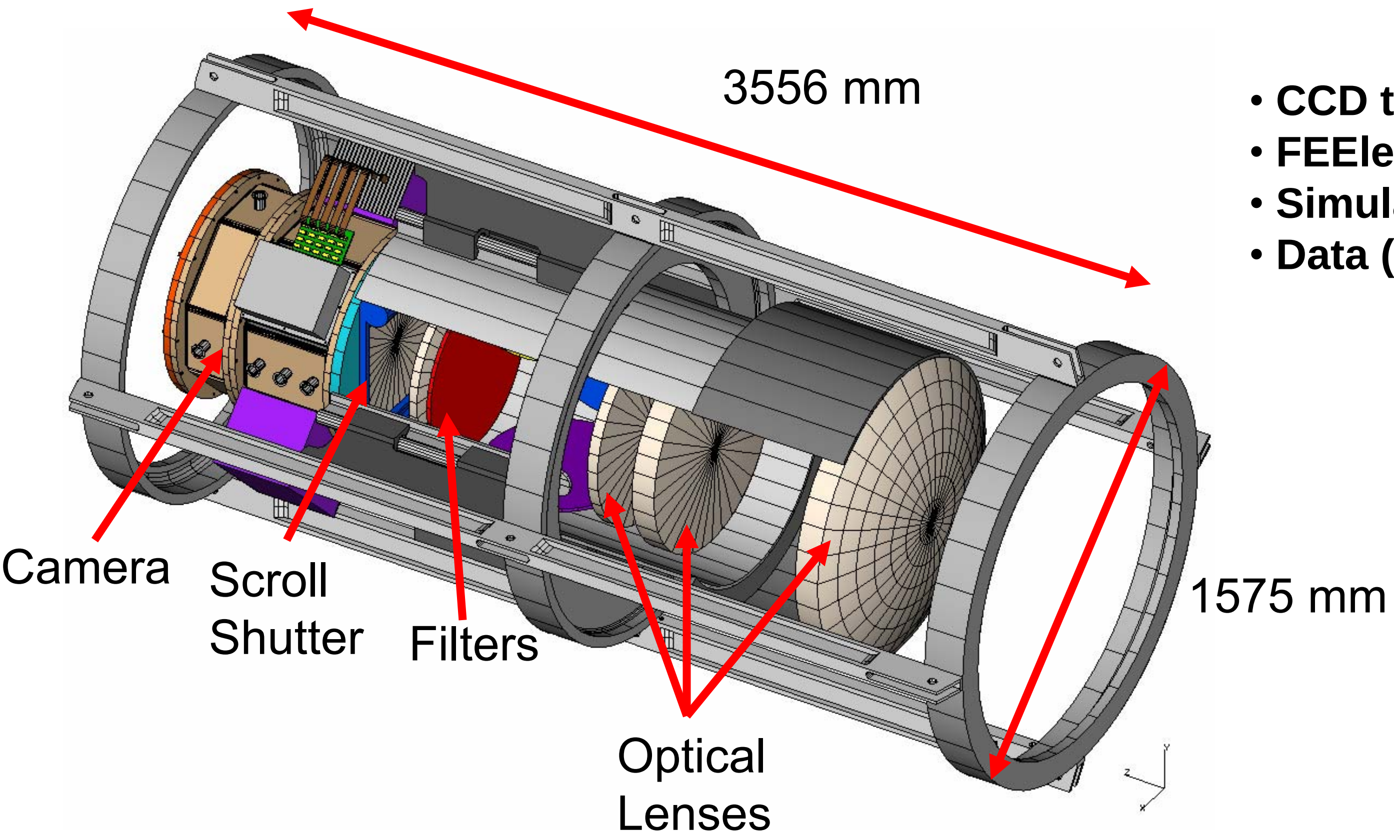
-Weak and strong lensing (Cluster mass)

-SNIa



DE: Dark Energy Instrument @Fermilab

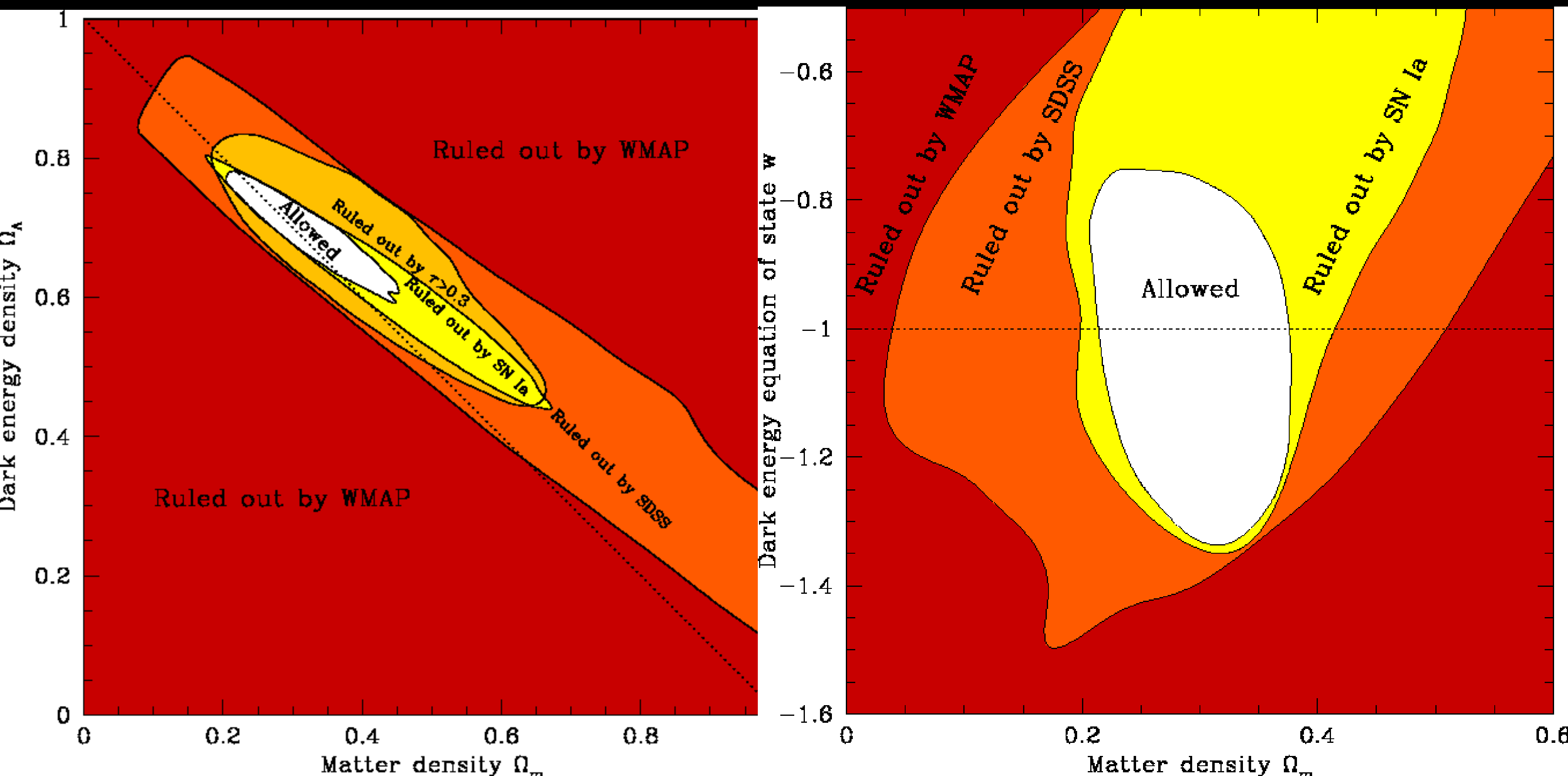
IFAE &IEEC/CSIC



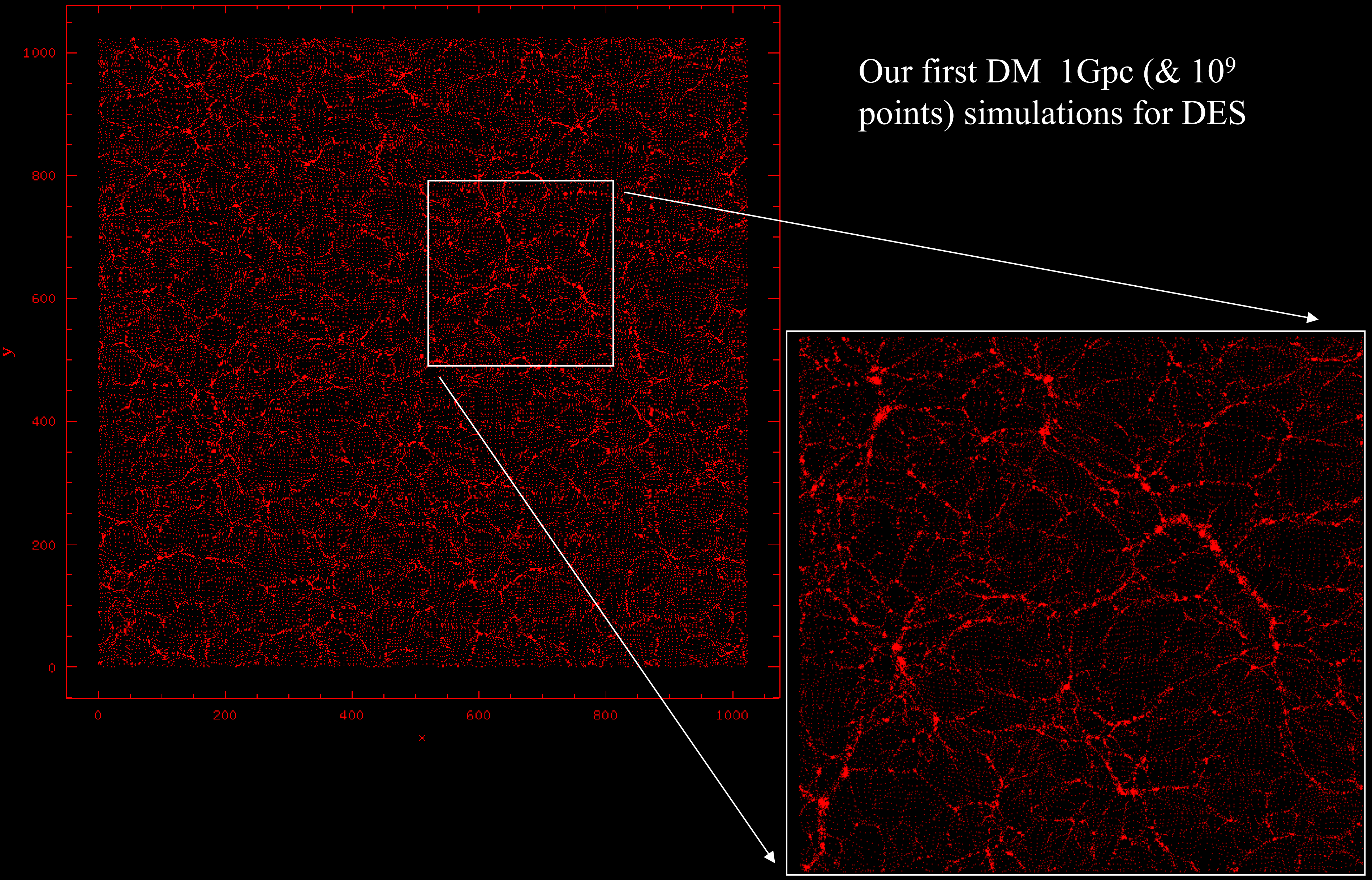
- **CCD testing -> SNAP/LSST**
- **FEElec & DAQ**
- **Simulations: science**
- **Data (Grid/Pipes)**

Equation of Esta for Dark Energy: $p = w\rho$

$\rho_{DE} = a^{-3(w+1)}$



Our first DM 1Gpc (& 10^9 points) simulations for DES



CONCLUSION

Classical cosmological test are built around a few but remarkable order of magnitude coincidences.

We are now entering a new era of "precission cosmology" and we face the much harder task of understanding systematic errors in our experiments and in our theories!