THE STANDARD COSMOLOGICAL MODEL

Winter Meeting 2009

Centro Ciencias Benasque "Pedro Pascual"

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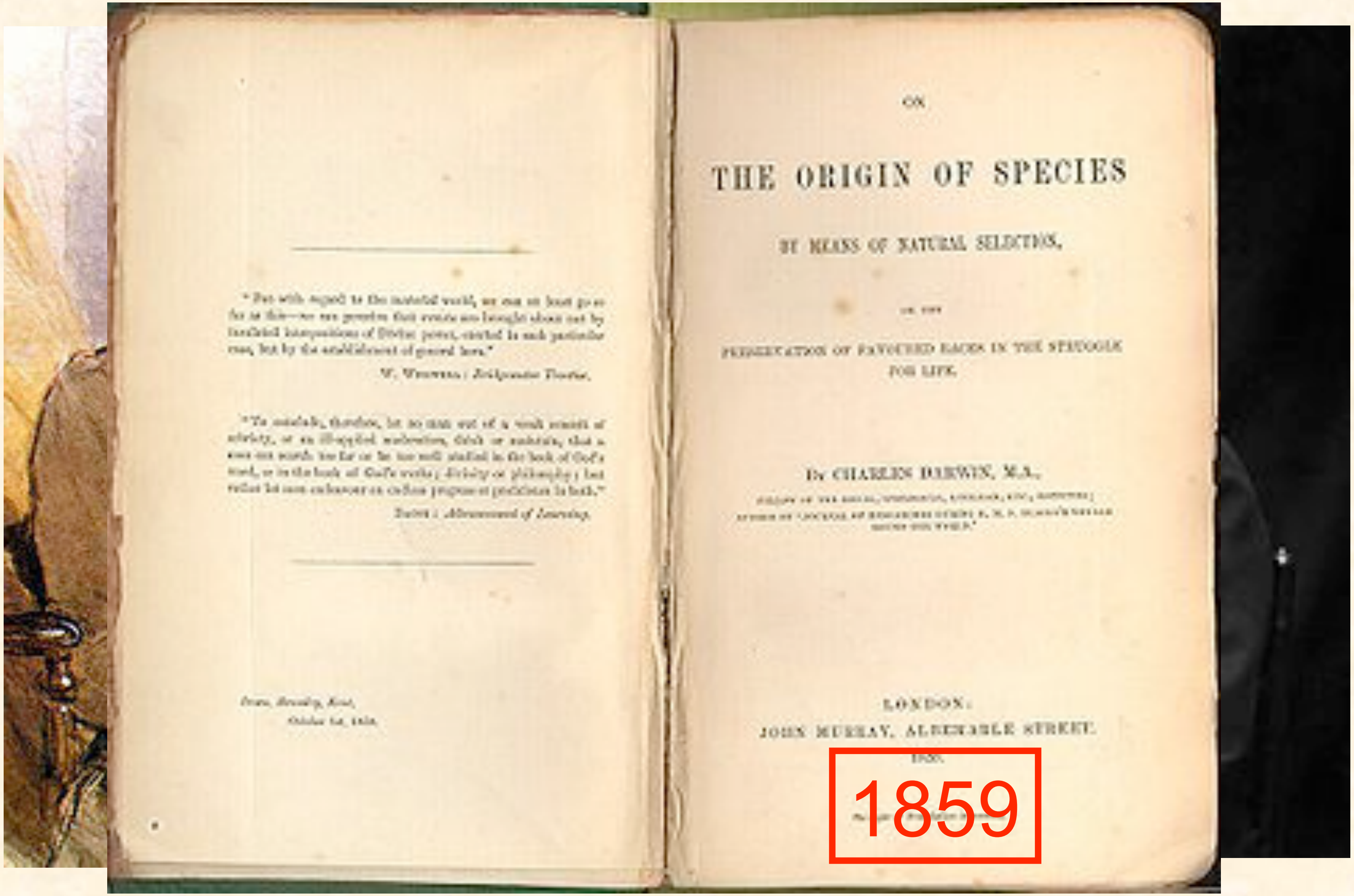
Charles Darwin (1809-1882)



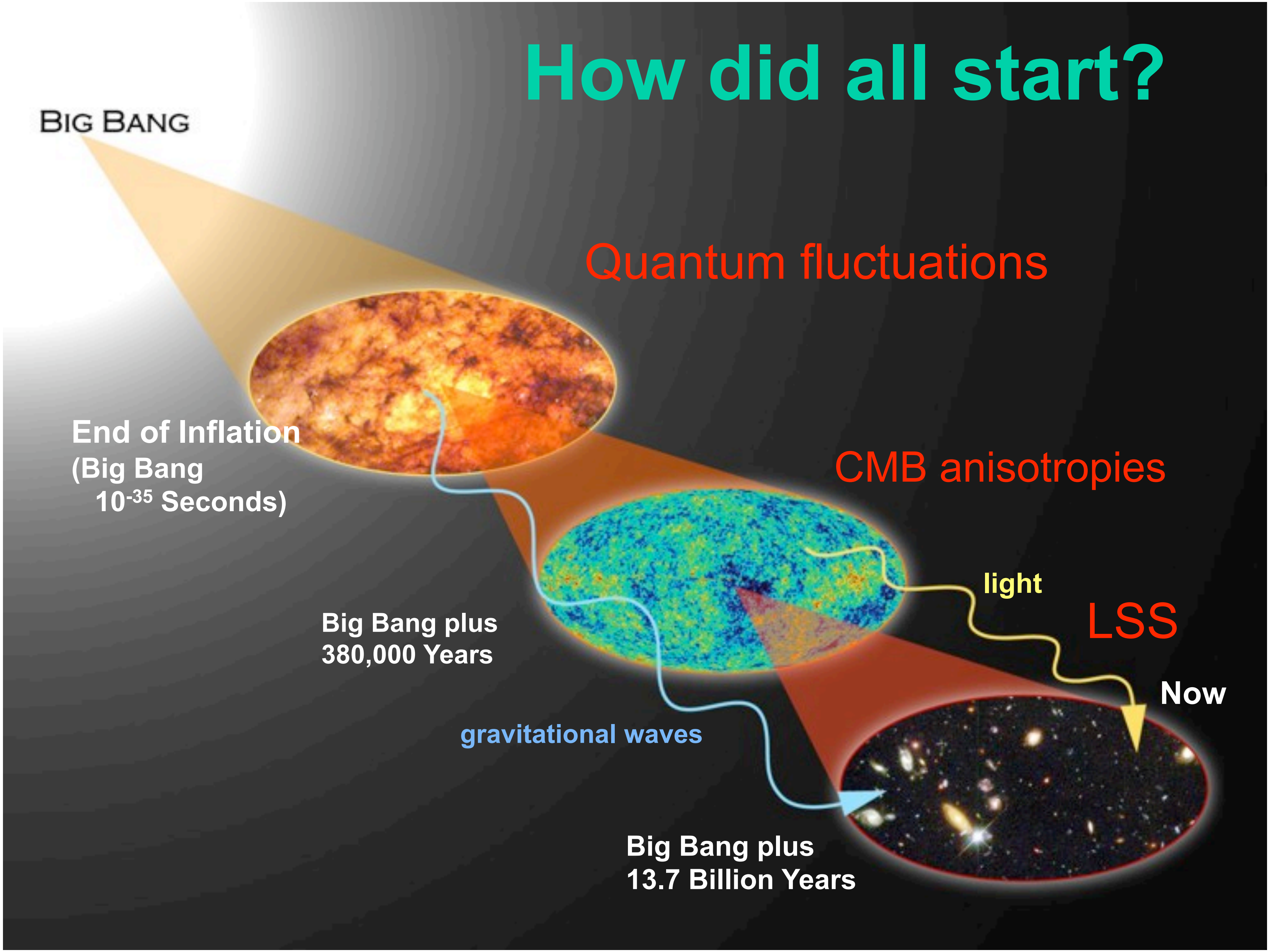
Outline

- The Standard Model of Cosmology
- Recent observations:

  (CMB: T+P aniso., ISW, SZE, Cold spot,

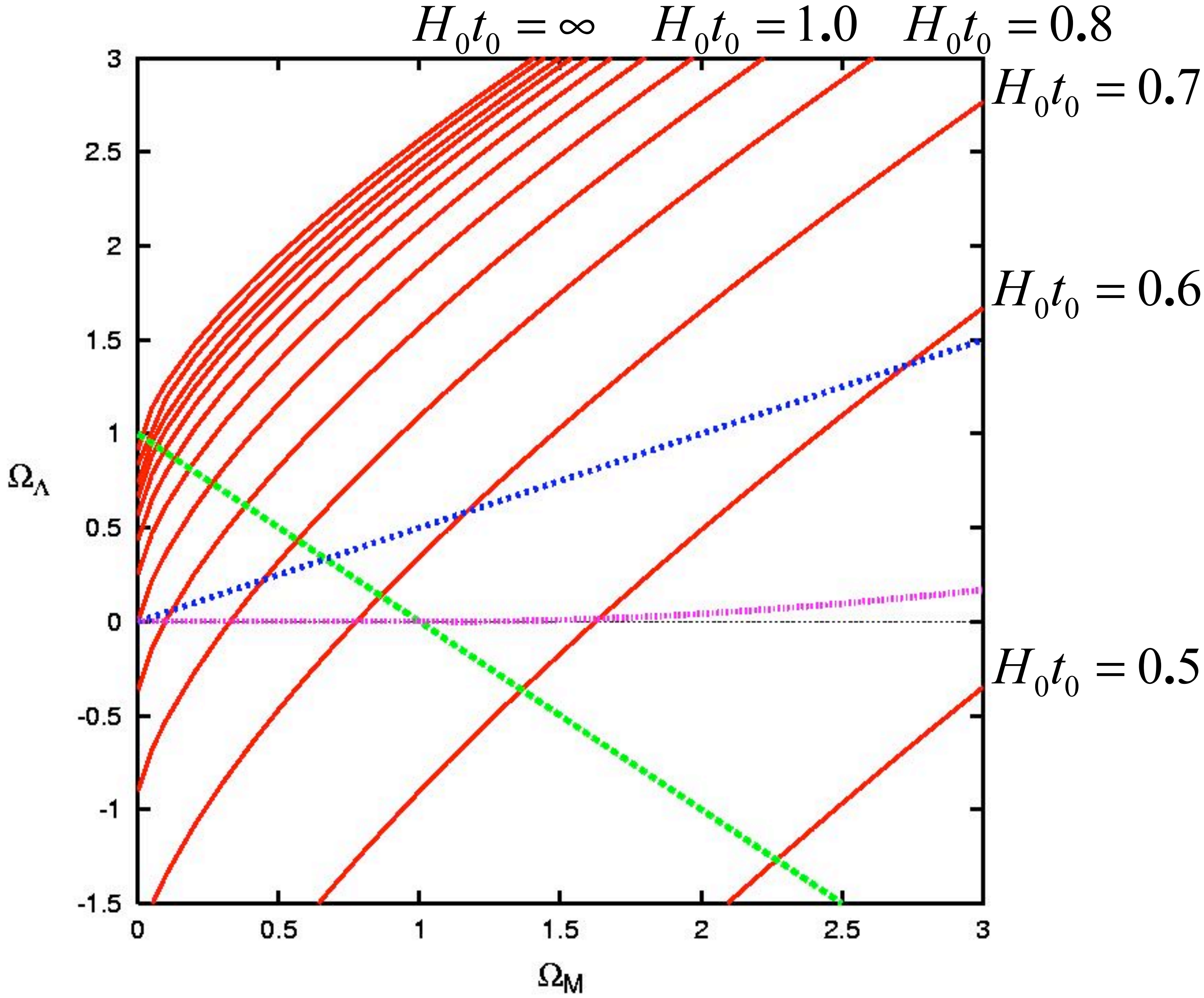
  LSS: BAO, Xray clusters,Bulk flows,

  HST: Ages, Supernovae, Grav. Lensing,…)
- Beyond the Standard Model
- Conclusions

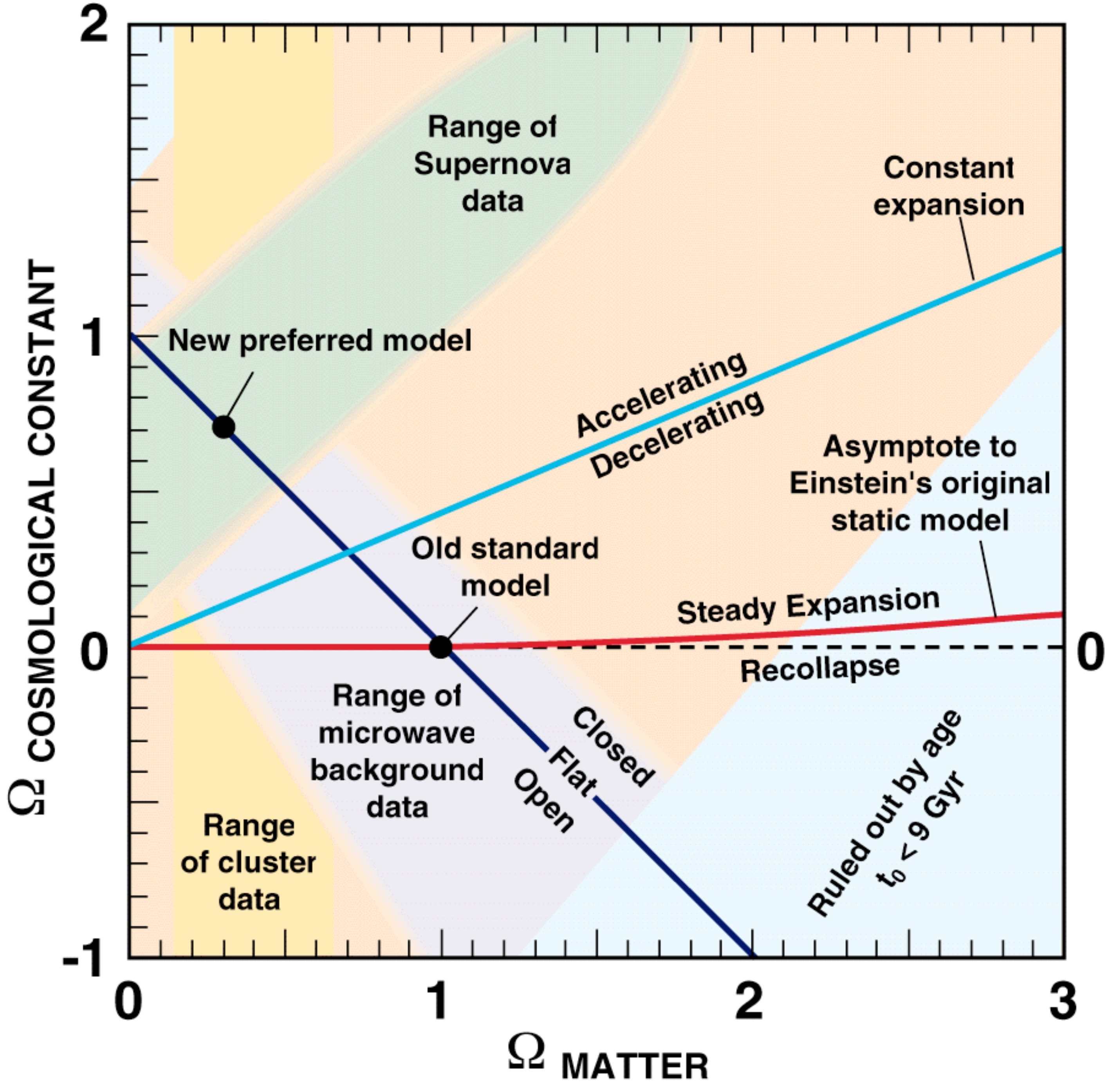

How did all start?
BIG BANG
Quantum fluctuations
End of Inflation
(Big Bang
10-35 Seconds)
CMB anisotropies
light
LSS
Big Bang plus
380,000 Years
Now
gravitational waves
Big Bang plus
13.7 Billion Years

Cosmological Parameters

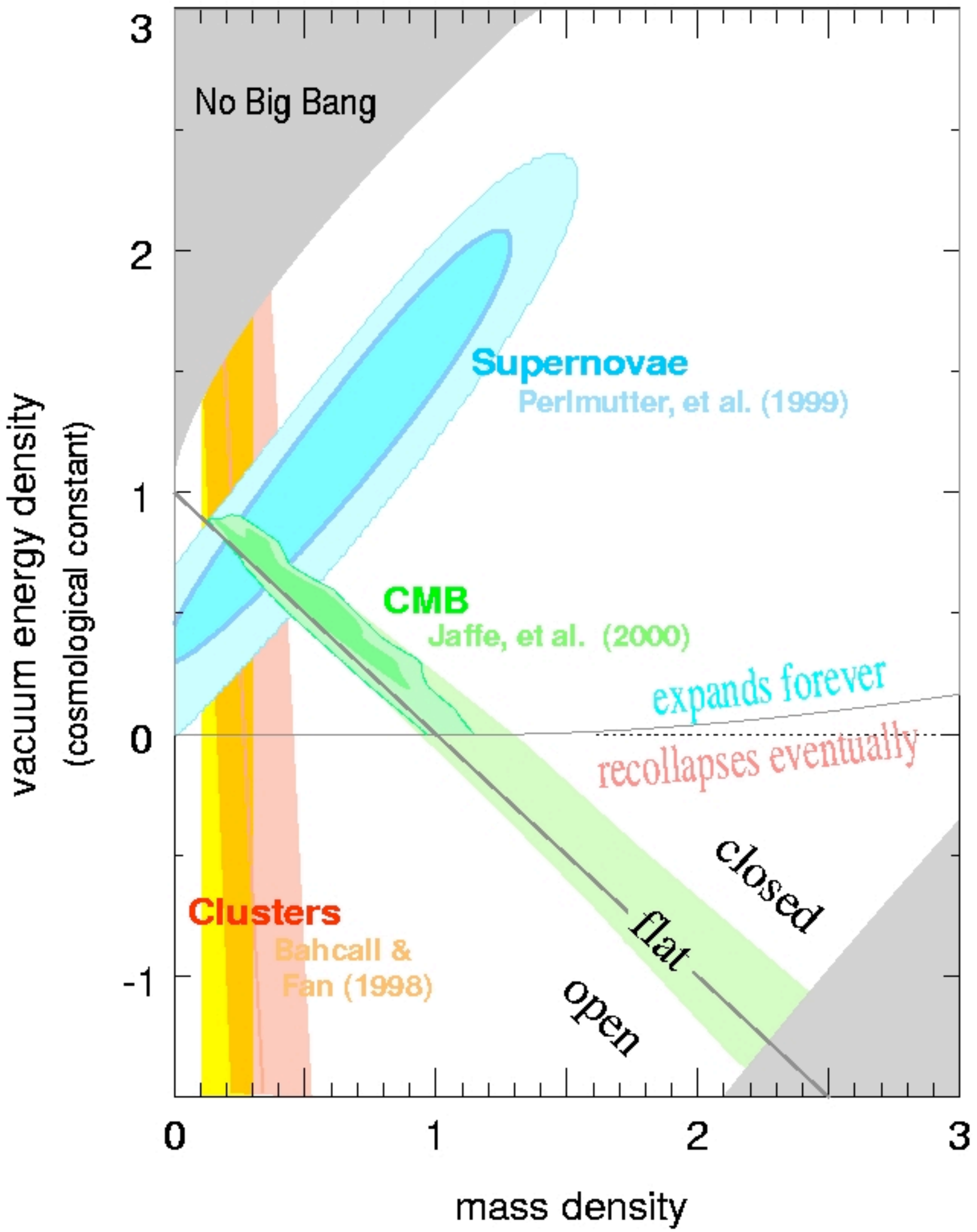
Rate of expansion	$H_0 = 71 \pm 3$ km/s/Mpc
Age of the Universe	$t_0 = 13.7 \pm 0.2$ Gyr
Spatial Curvature	$\Omega_K < 0.01 \quad (95\%\ c.l.)$
Dark Energy Density	$\Omega_\Lambda = 0.73 \pm 0.04$
Equation of state param.	$w = -0.99 \pm 0.05$
Dark Matter Density	$\Omega_{DM} = 0.23 \pm 0.04$
Baryon Density	$\Omega_B = 0.044 \pm 0.004$
Neutrino Density	$\Omega_\nu < 0.0076 \quad (95\%\ c.l.)$
Spectral Amplitude	$A_s = 0.833 \pm 0.085$
Spectral tilt	$n_s = 0.96 \pm 0.03$
Tensor-scalar ratio	$r < 0.65 \quad (95\%\ c.l.)$



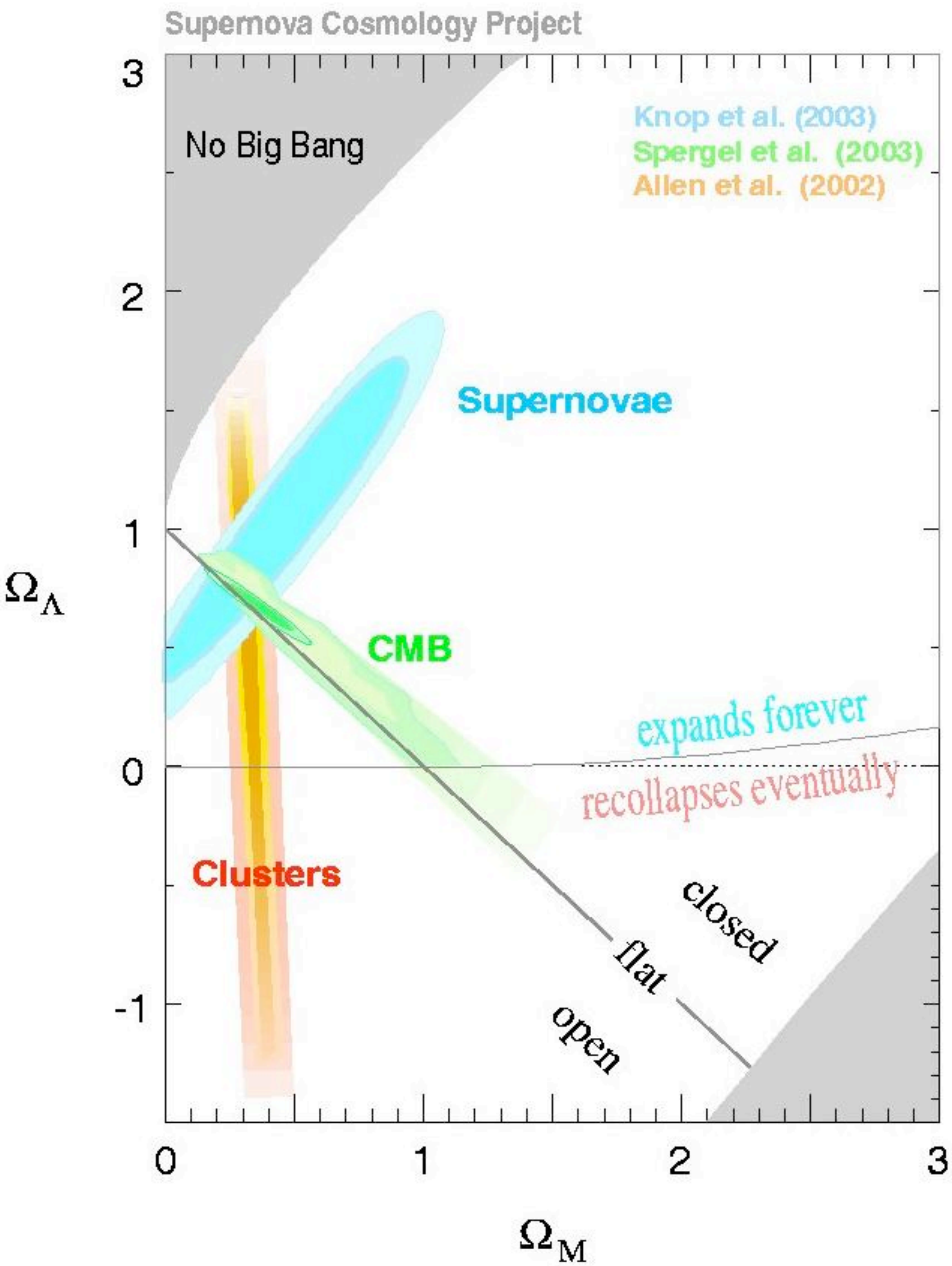
$H_0t_0 = \infty$
$H_0t_0 = 1.0$
$H_0t_0 = 0.8$
$H_0t_0 = 0.7$
$H_0t_0 = 0.6$
$H_0t_0 = 0.5$
Ω_Λ
Ω_M
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3



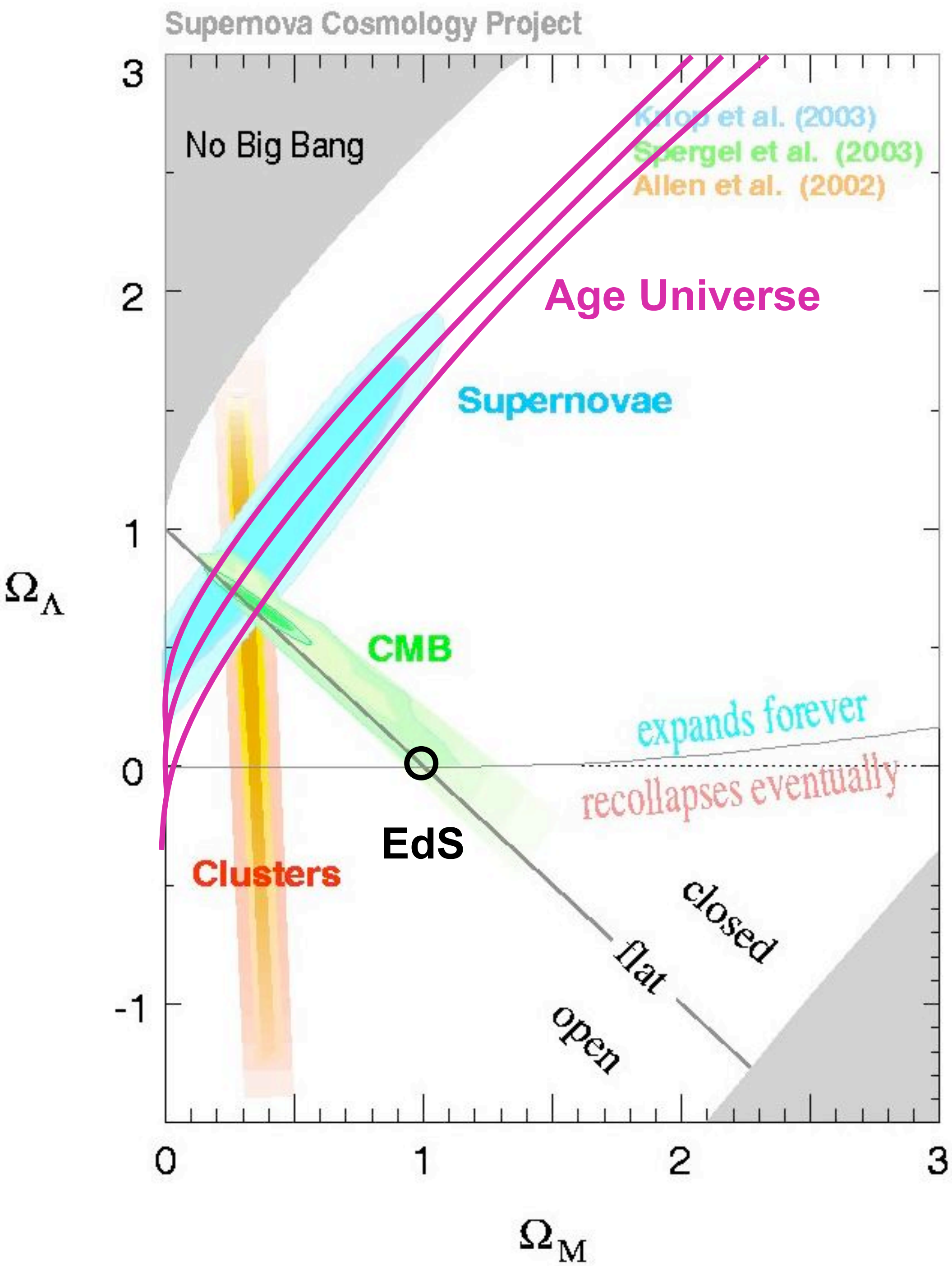
Cosmic Data (1999)



THE CONCORDANCE MODEL (2001)



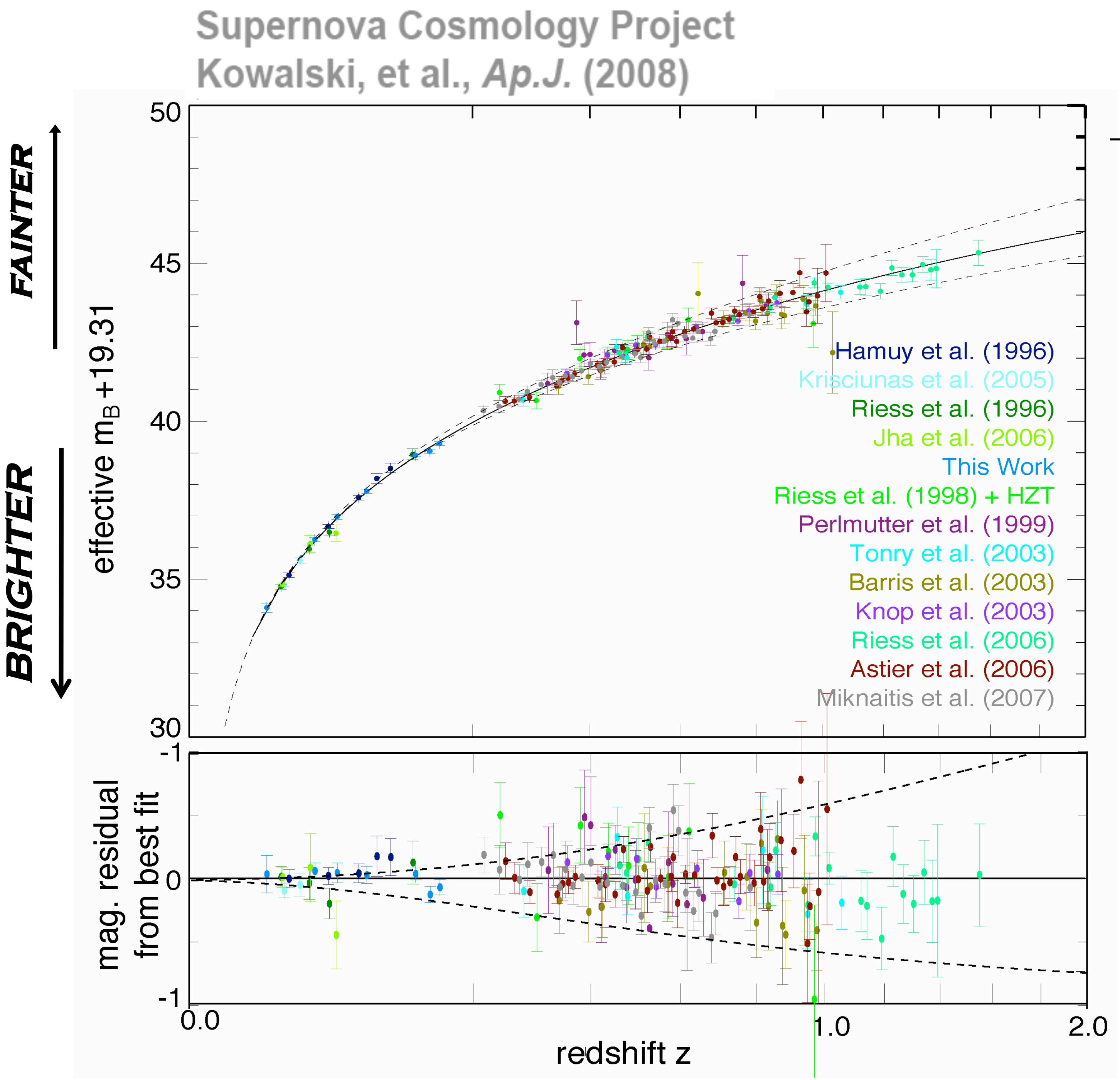
A STANDARD COSMOLOGICAL MODEL? (2003)



STANDARD COSMOLOGICAL MODEL (2005)

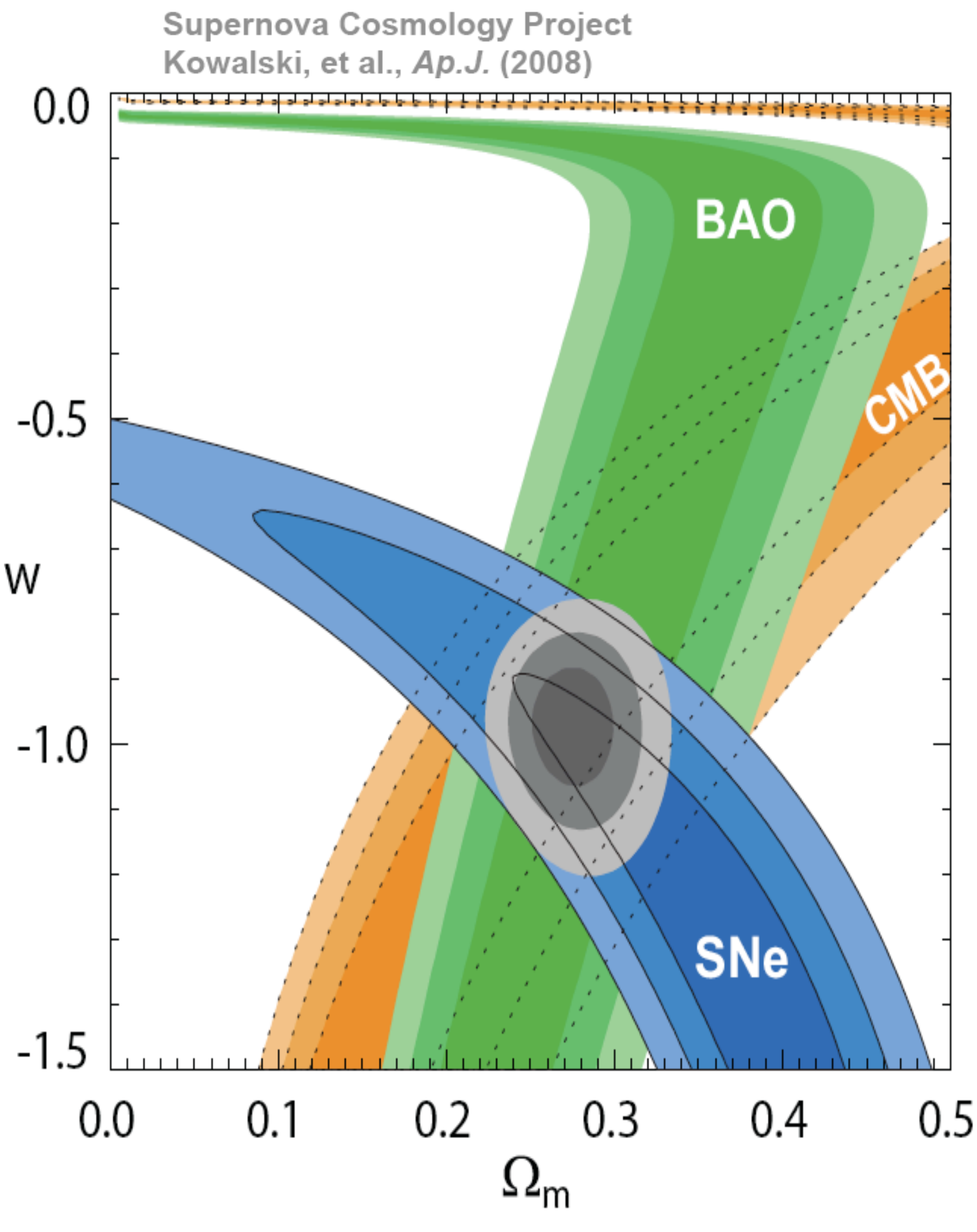
“Precision Cosmology”

Errors < 5%



Flat

Ω_Λ	Ω_M
1	0
0.72	0.28
0	1



A STANDARD COSMOLOGICAL MODEL (2009)

$$\Omega_M = 0.26 \pm 0.03$$

$$\Omega_\Lambda = 0.74 \pm 0.03$$

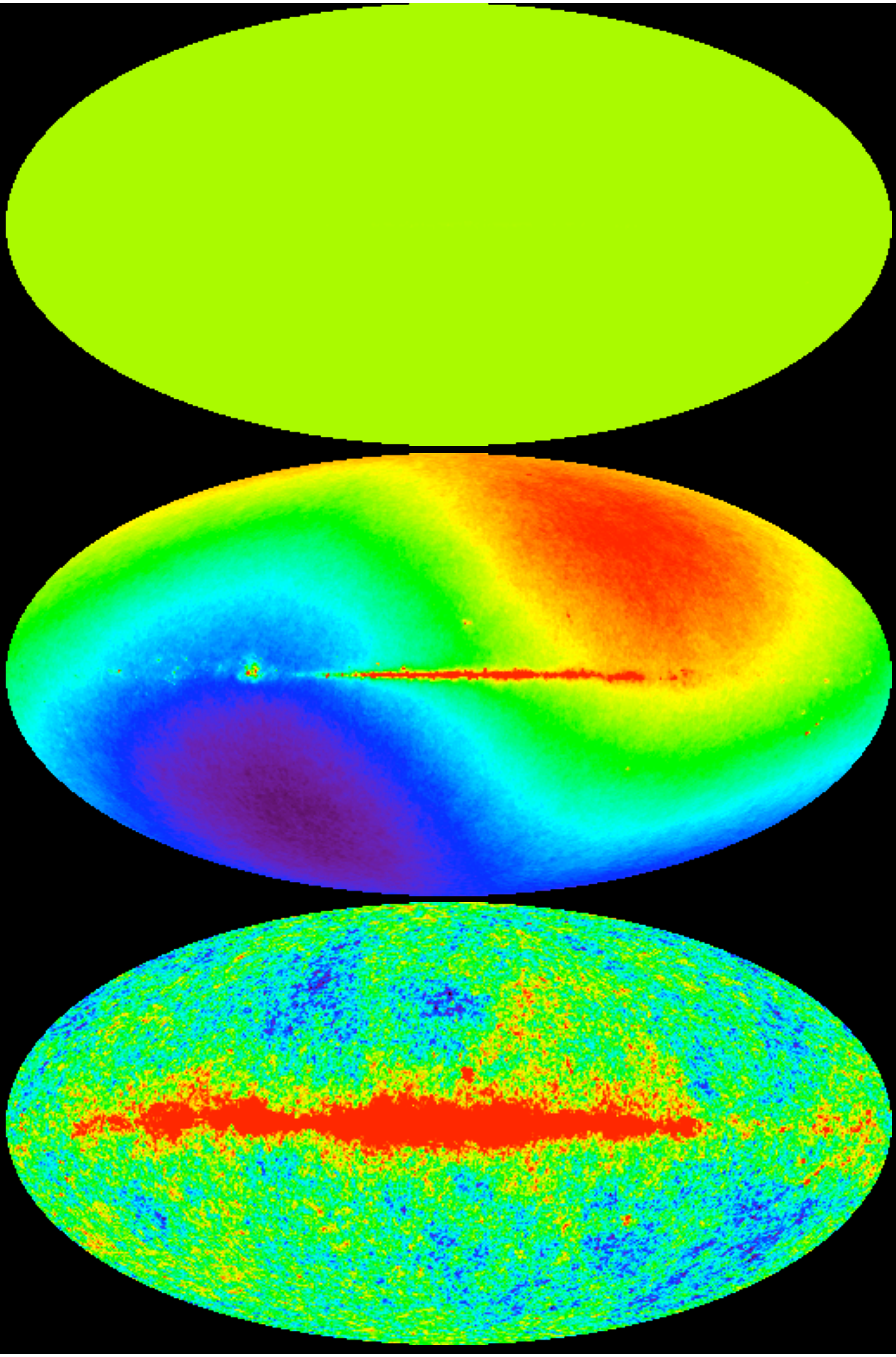
$$\Omega_0 = 1.005 \pm 0.006$$

$$\Omega_B = 0.044 \pm 0.003$$

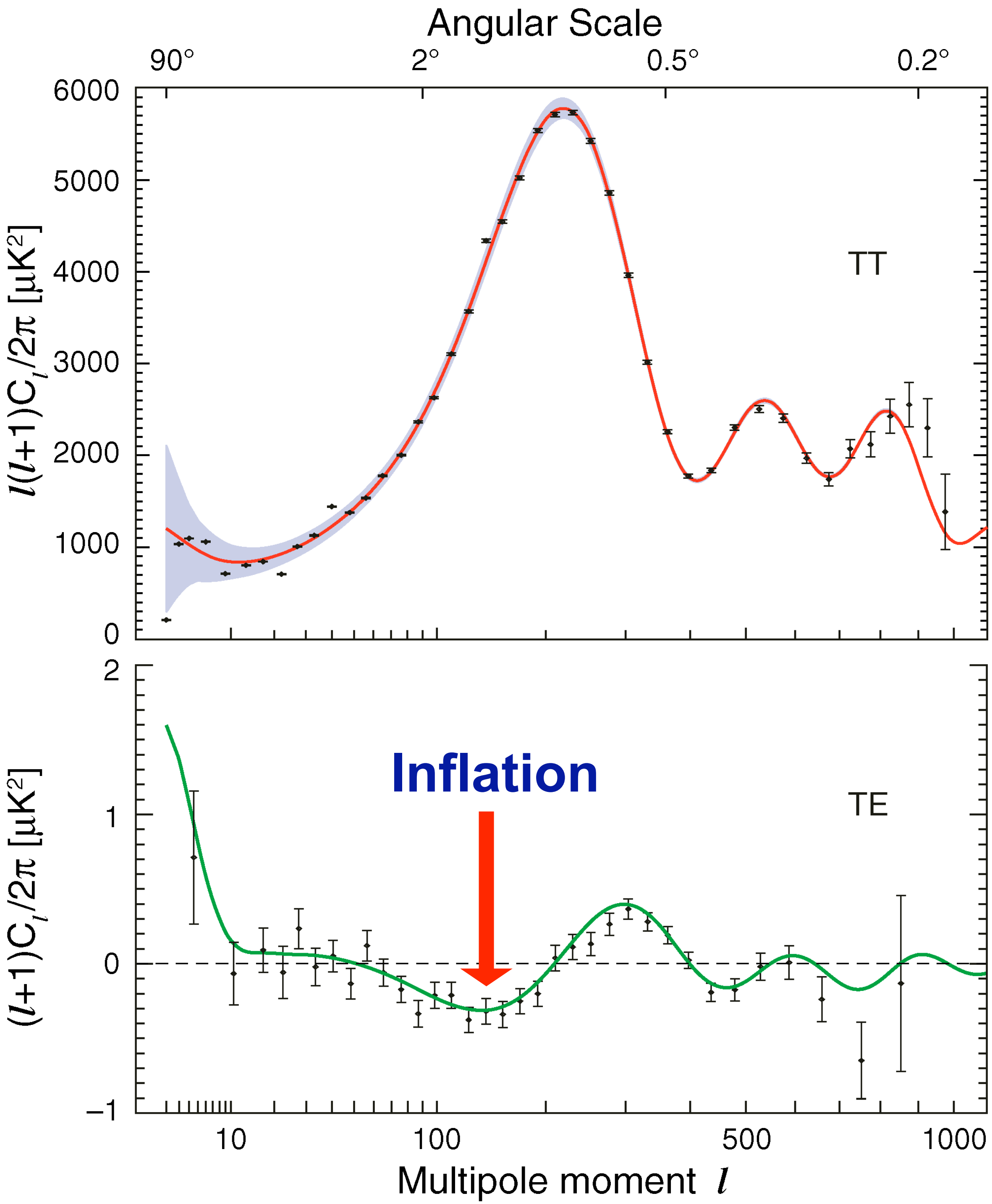
$$H_0 = 71 \pm 3 \text{ km/s/Mpc}$$

$$t_0 = 13.7 \pm 0.3 \text{ Gyr}$$

$$w = -0.99 \pm 0.15$$



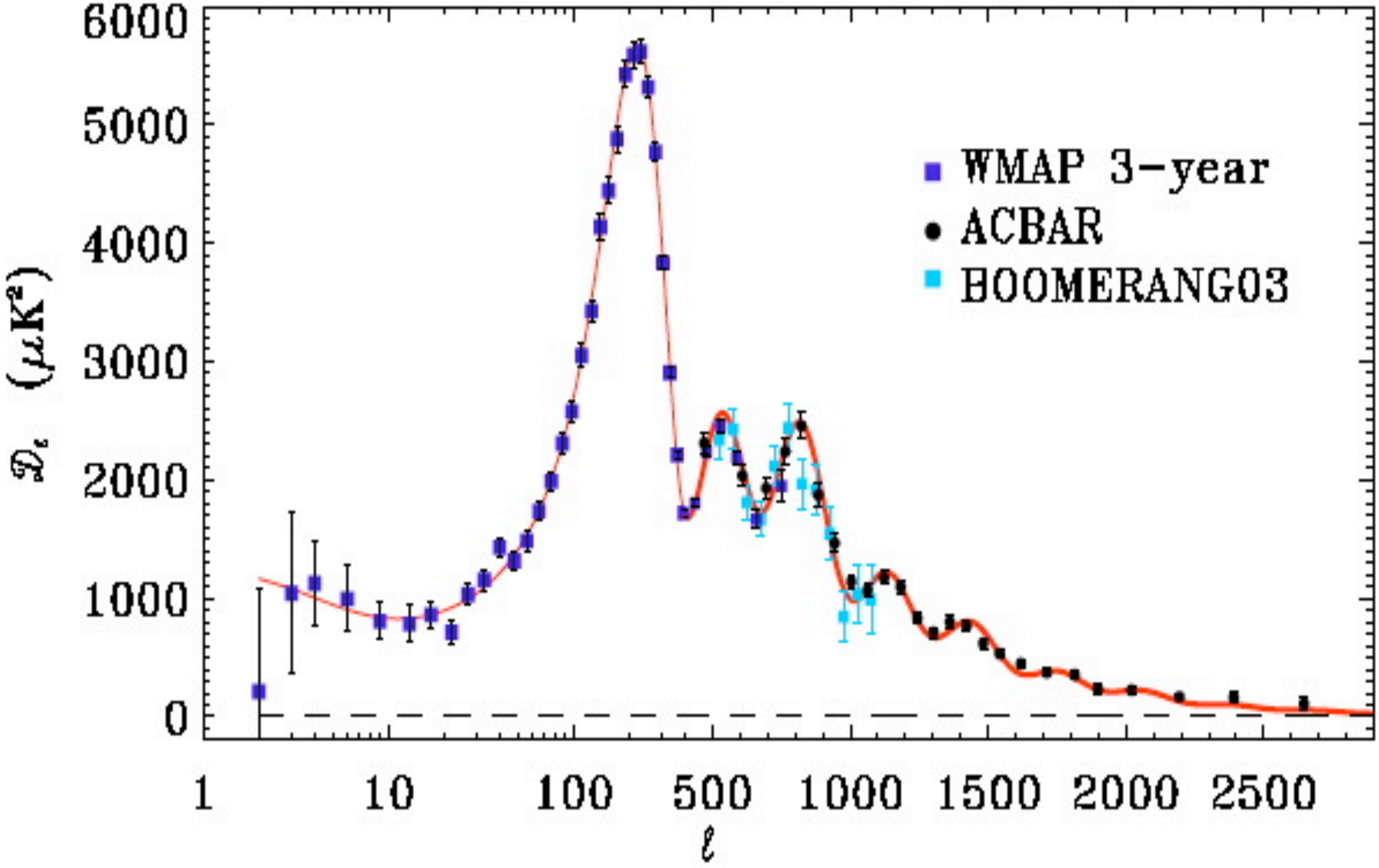
Wilkinson Microwave Anisotropy Probe



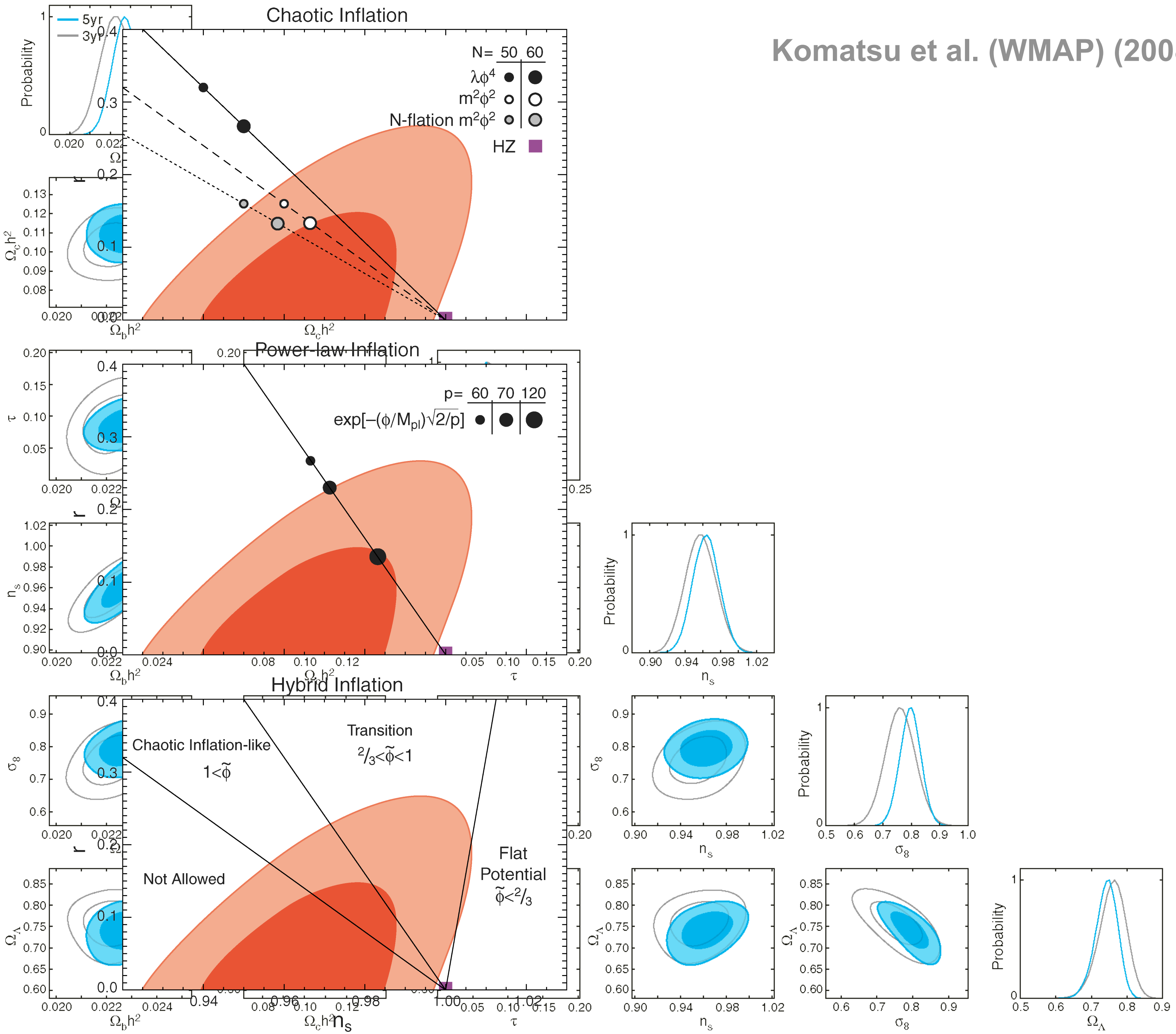
Spergel et al. (2008)

WMAP-5yr

Reichardt et al. (ACBAR), 2008

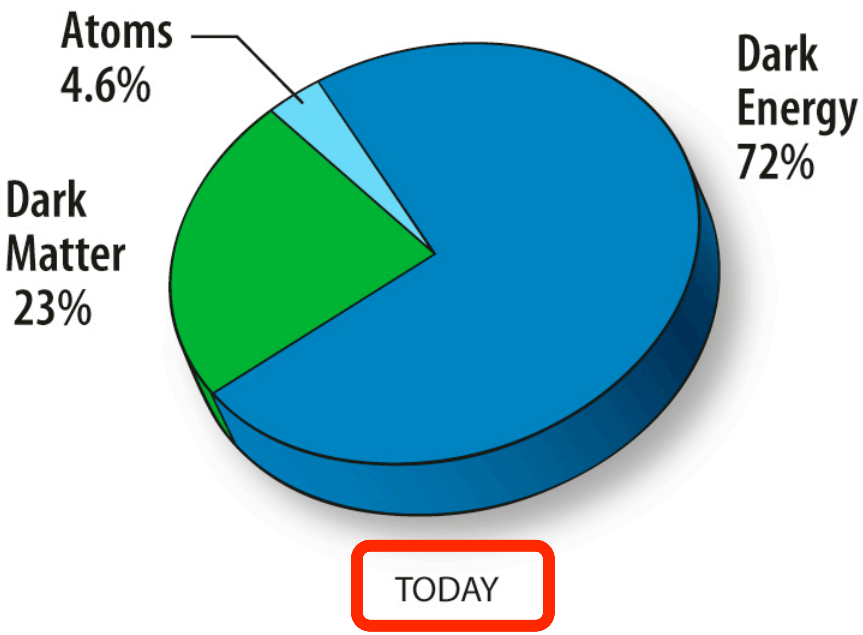


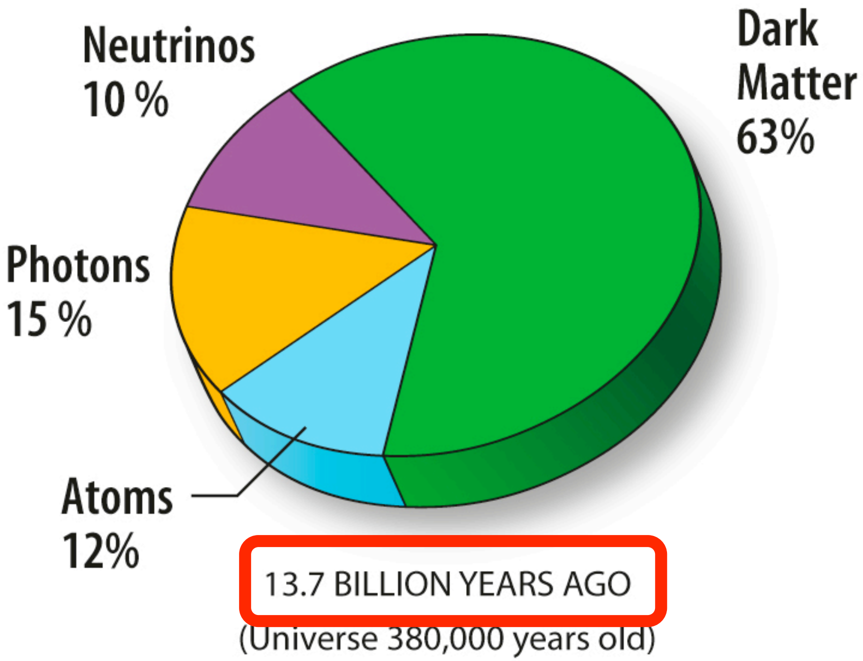
Komatsu et al. (WMAP) (2008)



Cosmological Parameters WMAP5+all

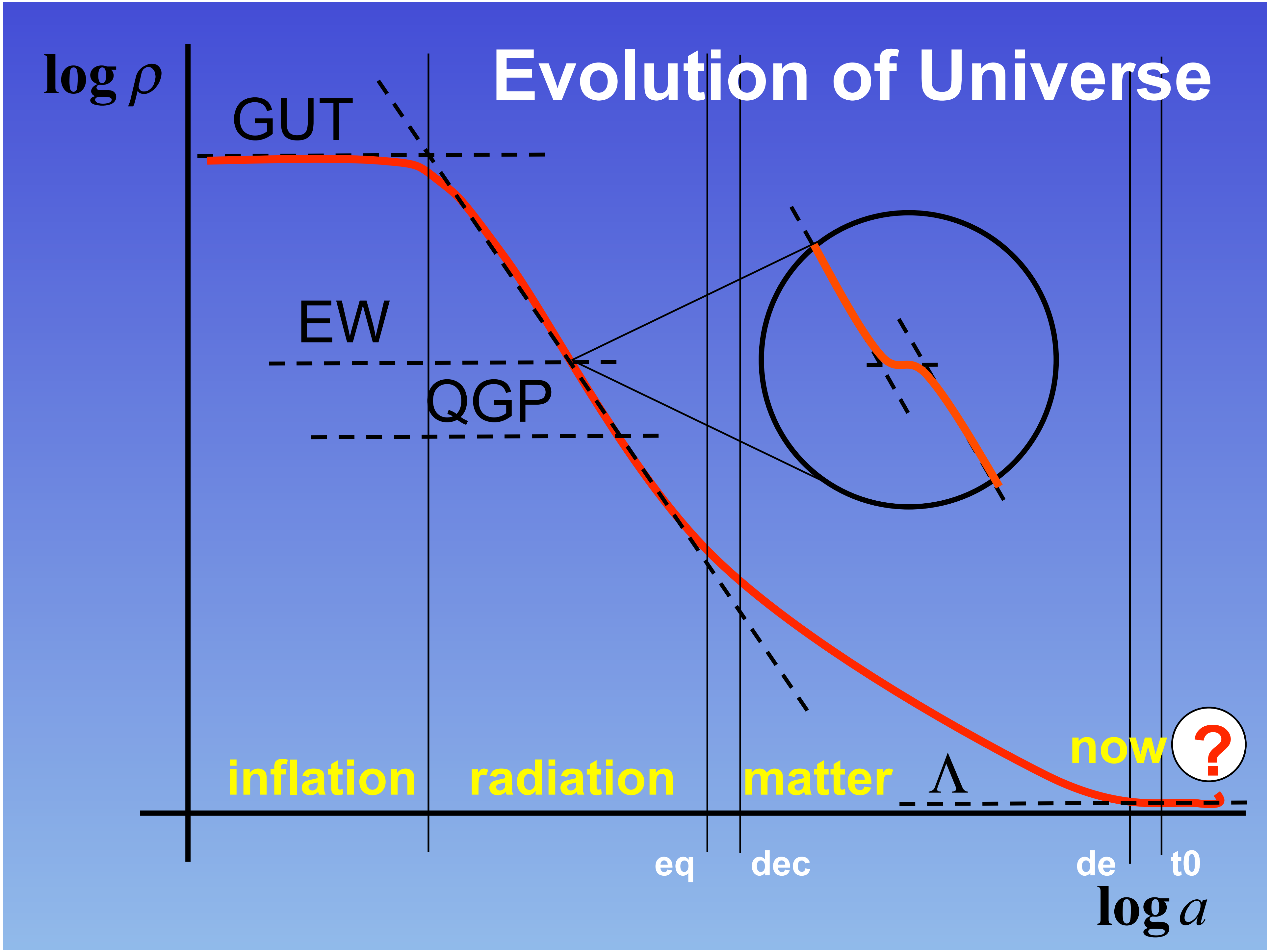
$10^2\Omega_b h^2$	2.273 ± 0.062	$1 - n_s$	$0.037^{+0.015}_{-0.014}$
$1 - n_s$	$0.0081 < 1 - n_s < 0.0647$ (95% CL)	$A_{\rm BAO}(z = 0.35)$	0.457 ± 0.022
C_{220}	5756 ± 42	$d_A(z_{\rm eq})$	14279^{+186}_{-189} Mpc
$d_A(z_*)$	14115^{+188}_{-191} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.41 \pm 0.11) \times 10^{-9}$
h	$0.719^{+0.026}_{-0.027}$	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
$k_{\rm eq}$	0.00968 ± 0.00046	$\ell_{\rm eq}$	136.6 ± 4.8
ℓ_*	$302.08^{+0.83}_{-0.84}$	n_s	$0.963^{+0.014}_{-0.015}$
Ω_b	0.0441 ± 0.0030	$\Omega_b h^2$	0.02273 ± 0.00062
Ω_c	0.214 ± 0.027	$\Omega_c h^2$	0.1099 ± 0.0062
Ω_Λ	0.742 ± 0.030	Ω_m	0.258 ± 0.030
$\Omega_m h^2$	0.1326 ± 0.0063	$r_{\rm hor}(z_{\rm dec})$	286.0 ± 3.4 Mpc
$r_s(z_d)$	153.3 ± 2.0 Mpc	$r_s(z_d)/D_v(z = 0.2)$	0.1946 ± 0.0079
$r_s(z_d)/D_v(z = 0.35)$	0.1165 ± 0.0042	$r_s(z_*)$	146.8 ± 1.8 Mpc
R	1.713 ± 0.020	σ_8	0.796 ± 0.036
$A_{\rm SZ}$	$1.04^{+0.96}_{-0.69}$	t_0	13.69 ± 0.13 Gyr
τ	0.087 ± 0.017	θ_*	0.010400 ± 0.000029
θ_*	$0.5959 \pm 0.0017\ ^\circ$	t_*	380081^{+5843}_{-5841} yr
$z_{\rm dec}$	1087.9 ± 1.2	z_d	1020.5 ± 1.6
$z_{\rm eq}$	3176^{+151}_{-150}	$z_{\rm reion}$	11.0 ± 1.4
z_*	1090.51 ± 0.95		

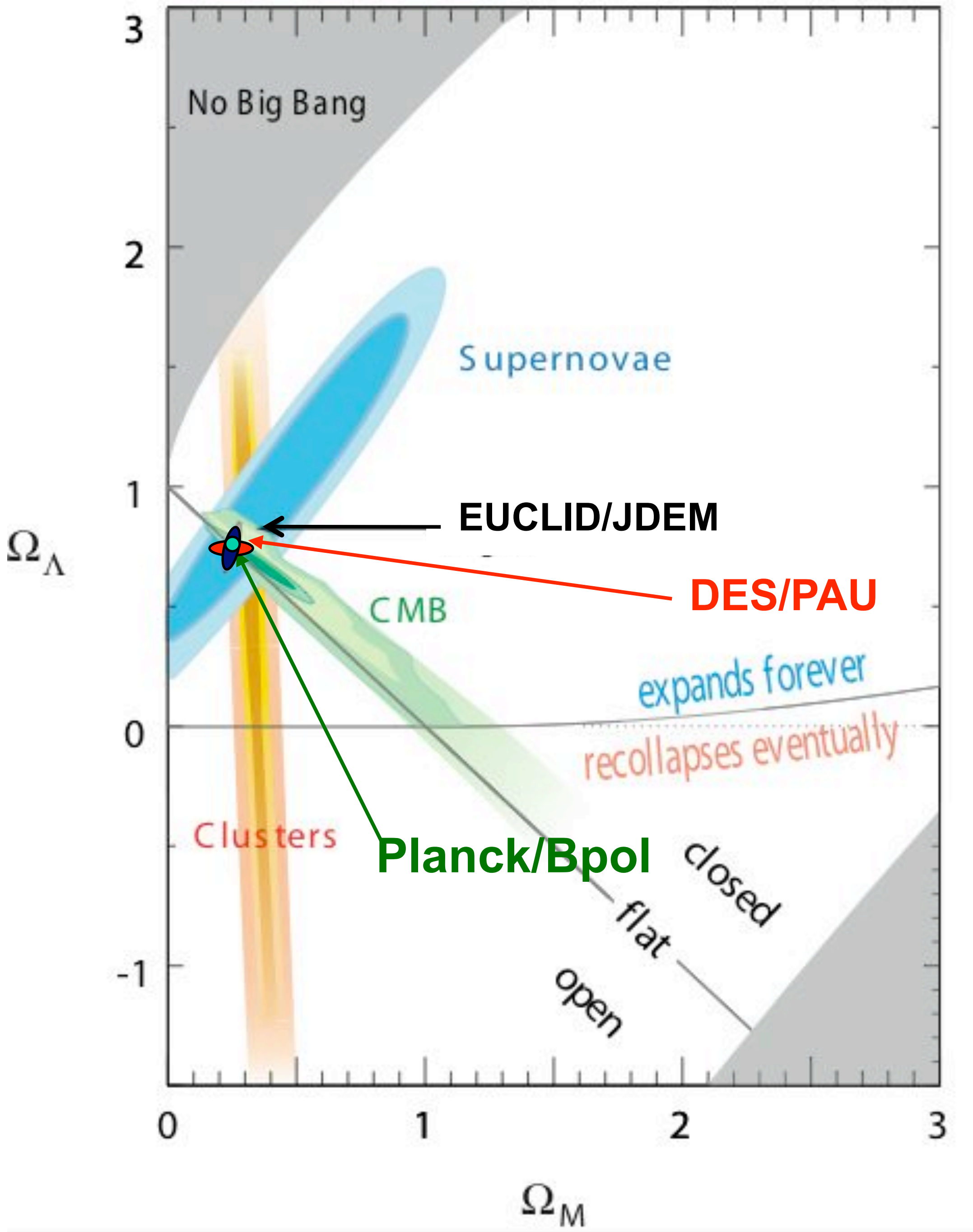




THE MATTER-ENERGY CONTENT OF UNIVERSE

TODAY AND AT PHOTON DECOUPLING


Evolution of Universe
log ρ
GUT
EW
QGP
inflation
radiation
matter
Λ
now
?
eq
dec
de
t0
log a



THE FUTURE?

A STANDARD MODEL OF COSMOLOGY (2010-2015)

precision <1%

Standard?
DM? DE?

Dark Matter

- Axion : mass ~ 1-10 μeV
- massive neutrino : mass ~ 10 keV
- WIMP : mass ~ 100 GeV
- Primordial BH : mass ~ 100 $M_\odot$

…

what about Dark Energy?

Dark Energy

- Cosmological constant : Λ
- Quintessence field : $V(\phi)$
- Higher curvature terms : $f(R)$
- Massive graviton : g_{μν}
- String Theory Landscape
- Brane cosmology : extra dim.
- Huge voids : Inhomogeneous Univ.

Basics of
Differential Geometry

Metric signature: $(-,+,+,+)$

velocity $u^\mu \equiv \dfrac{dx^\mu}{d\tau}$, normalization $u_\mu u^\mu = -1$

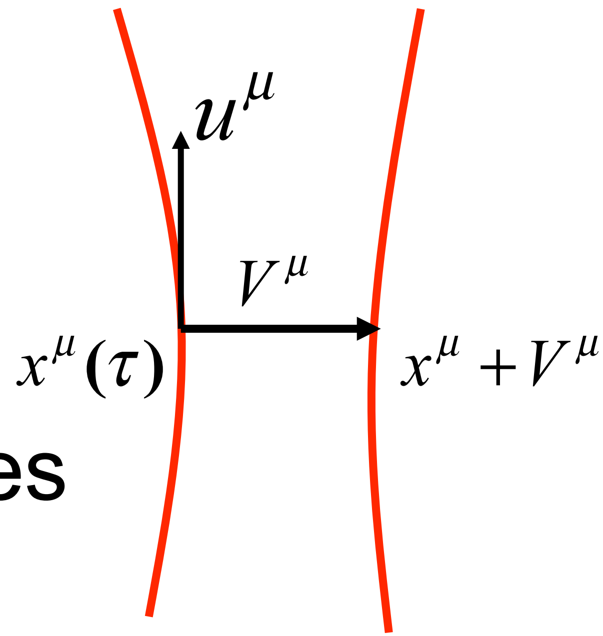
$$\boxed{\frac{Du^\mu}{d\tau} \equiv \frac{du^\mu}{d\tau} + \Gamma^\mu_{\nu\lambda}\, u^\nu u^\lambda = 0}$$

Geodesic Eq.

Geodesic Deviation

$$\frac{D^2 V^\mu}{d\tau^2} \equiv R^\mu{}_{\nu\lambda\rho}\, u^\nu u^\rho\, V^\lambda$$

tidal forces



Congruence of timelike geodesics

$$\frac{DV^{\mu}}{d\tau} = u^{\nu} D_{\nu} V^{\mu} \equiv \Theta^{\mu}_{\ \nu} V^{\nu}$$

Describes the extent to which neighbouring geodesics deviate from remaining parallel

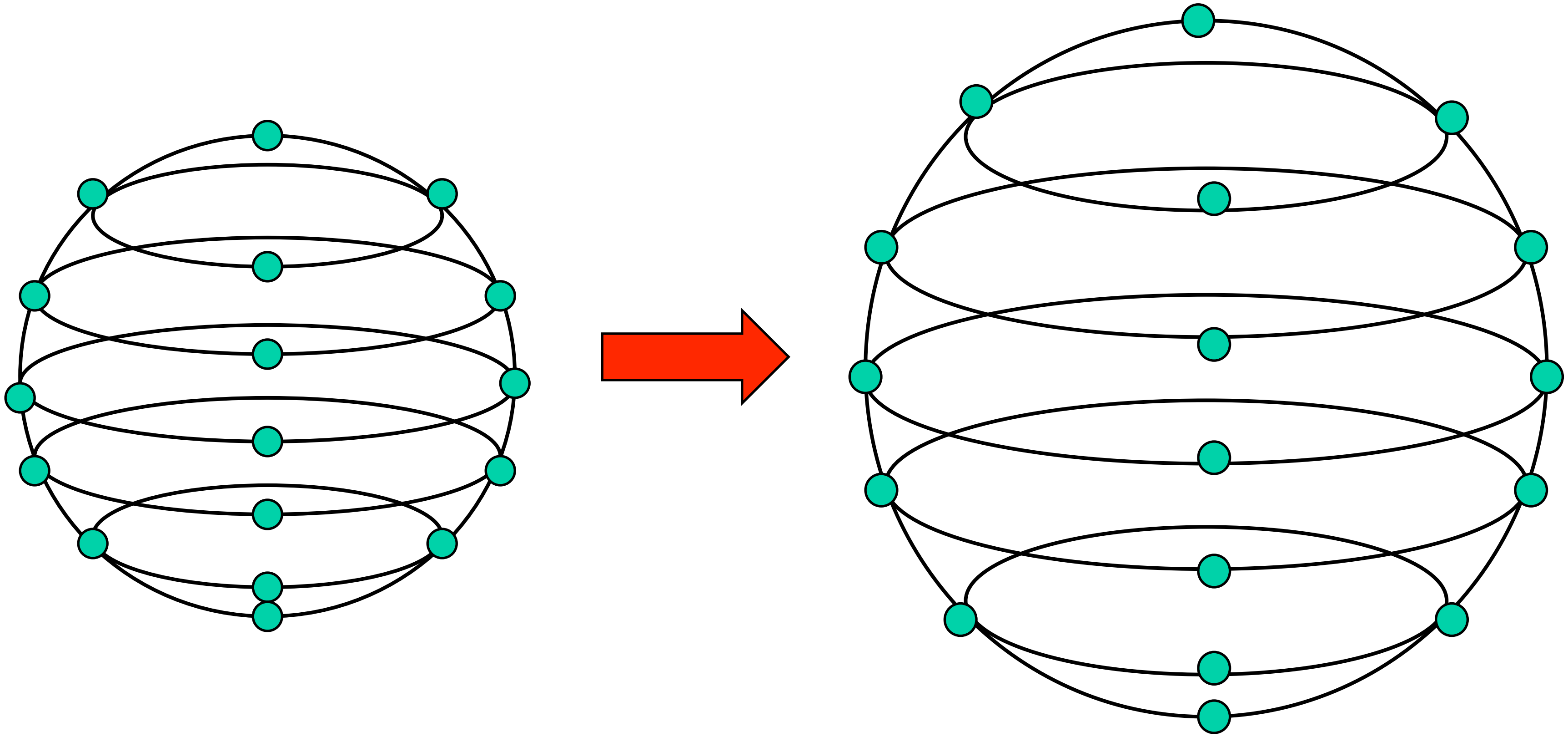
$$\Theta_{\mu\nu} = \frac{1}{3}\Theta P_{\mu\nu} + \sigma_{\mu\nu} + \omega_{\mu\nu}$$

$$\Theta = D_{\mu} u^{\mu}$$ trace

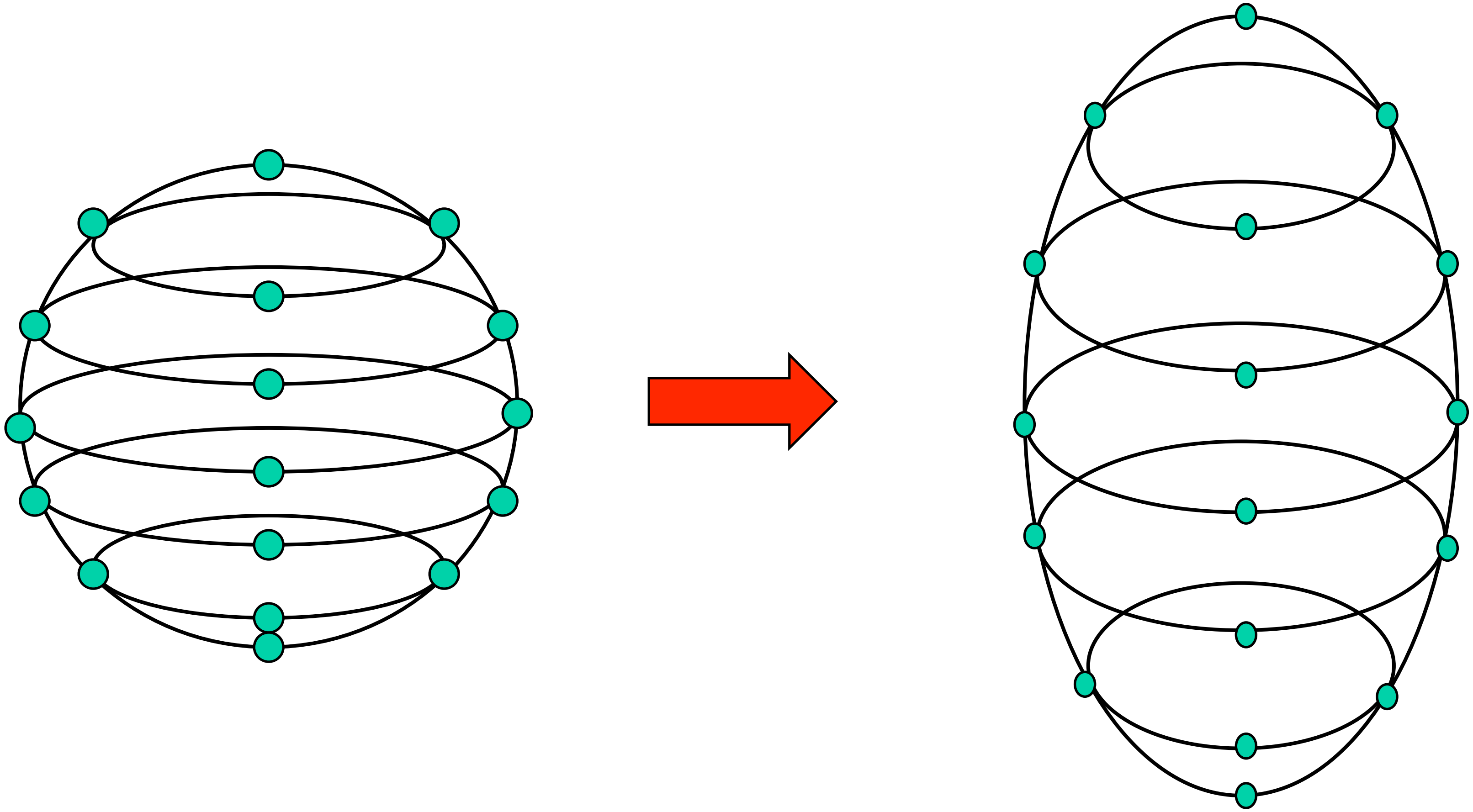
$$\sigma_{\mu\nu} = \Theta_{(\mu\nu)} - \frac{1}{3}\Theta P_{\mu\nu}$$ traceless symmetric

$$\omega_{\mu\nu} = \Theta_{[\mu\nu]}$$ antisymmetric

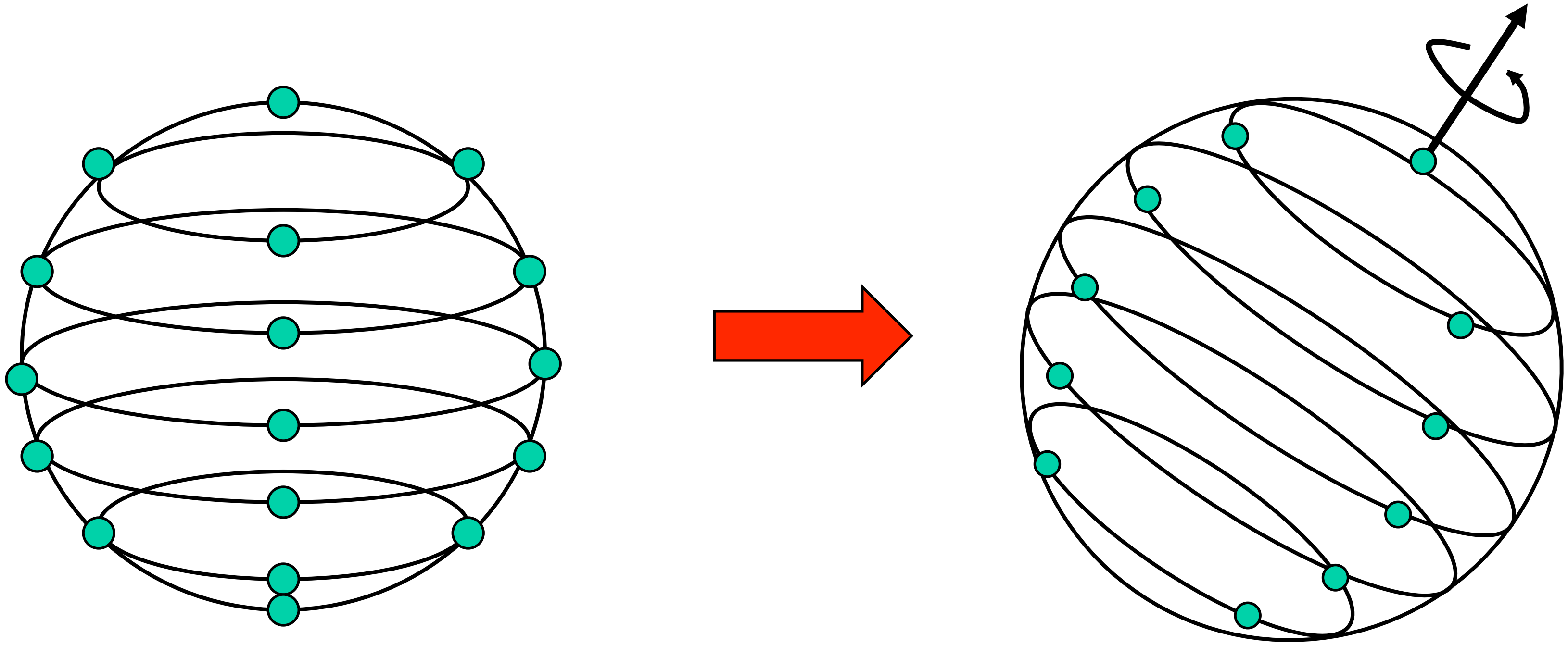
Θ expansion of congruence



$\sigma_{\mu\nu}$ shear of congruence



$\omega_{\mu\nu}$ vorticity of congruence



Evolution of Congruence

$$\frac{D}{d\tau}\Theta_{\mu\nu} = u^{\sigma} D_{\sigma} D_{\nu}\, u_{\mu} = u^{\sigma} D_{\nu} D_{\sigma}\, u_{\mu} + u^{\sigma} R^{\lambda}_{\ \mu\nu\sigma}\, u_{\lambda}$$

$$= -\Theta^{\sigma}_{\nu}\, \Theta_{\mu\sigma} - R_{\lambda\mu\sigma\nu}\, u^{\sigma} u^{\lambda}$$

Raychaudhuri Equation (trace)

$$\boxed{\frac{d\Theta}{d\tau} = -\frac{1}{3}\Theta^{2} - \sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}\, u^{\mu} u^{\nu}}$$

$\sigma_{\mu\nu}\sigma^{\mu\nu} \geq 0,\quad \omega_{\mu\nu}\omega^{\mu\nu} \geq 0,$ spatial tensors

Expanding Universe

$$H(t,\bar{x}) = \frac{1}{3}\Theta = \frac{1}{3}D_\mu u^\mu$$ Hubble parameter

$$q = -1 - H^{-2} u^\mu D_\mu H$$ deceleration parameter

R.E. $\Rightarrow \; qH^2 = \frac{1}{3}(\sigma_{\mu\nu}\sigma^{\mu\nu} - \omega_{\mu\nu}\omega^{\mu\nu}) + \frac{1}{3}R_{\mu\nu}\, u^\mu u^\nu$

Eins.Eq. ↓ Perf.Fluid ↓

$$R_{\mu\nu}\, u^\mu u^\nu \doteq 8\pi G(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T)u^\mu u^\nu \doteq 4\pi G(\rho + 3p)$$

$$-\frac{\ddot{a}}{a} = \frac{4\pi G}{3}(\rho + 3p)$$ Homogeneous Universe

Conditions for acceleration

One of the following must be violated:

1. The Strong Energy Condition is satisfied:

$$(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T)\, u^\mu u^\nu \geq 0, \quad u^\mu \text{ timelike}$$

2. Gravity is described by General Relativity:

$$R_{\mu\nu} = 8\pi\, G\, (T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T)$$

3. The universe is homogeneous and isotropic:

$$T^{\mu\nu} = p(t) g^{\mu\nu} + (\rho(t) + p(t))\, u^\mu u^\nu$$

Conditions for acceleration

Usually one drops assumptions 1. or 2. not 3.

1. The SEC for a homogeneous universe:

$$(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T) u^\mu u^\nu = \rho + 3p \geq 0$$

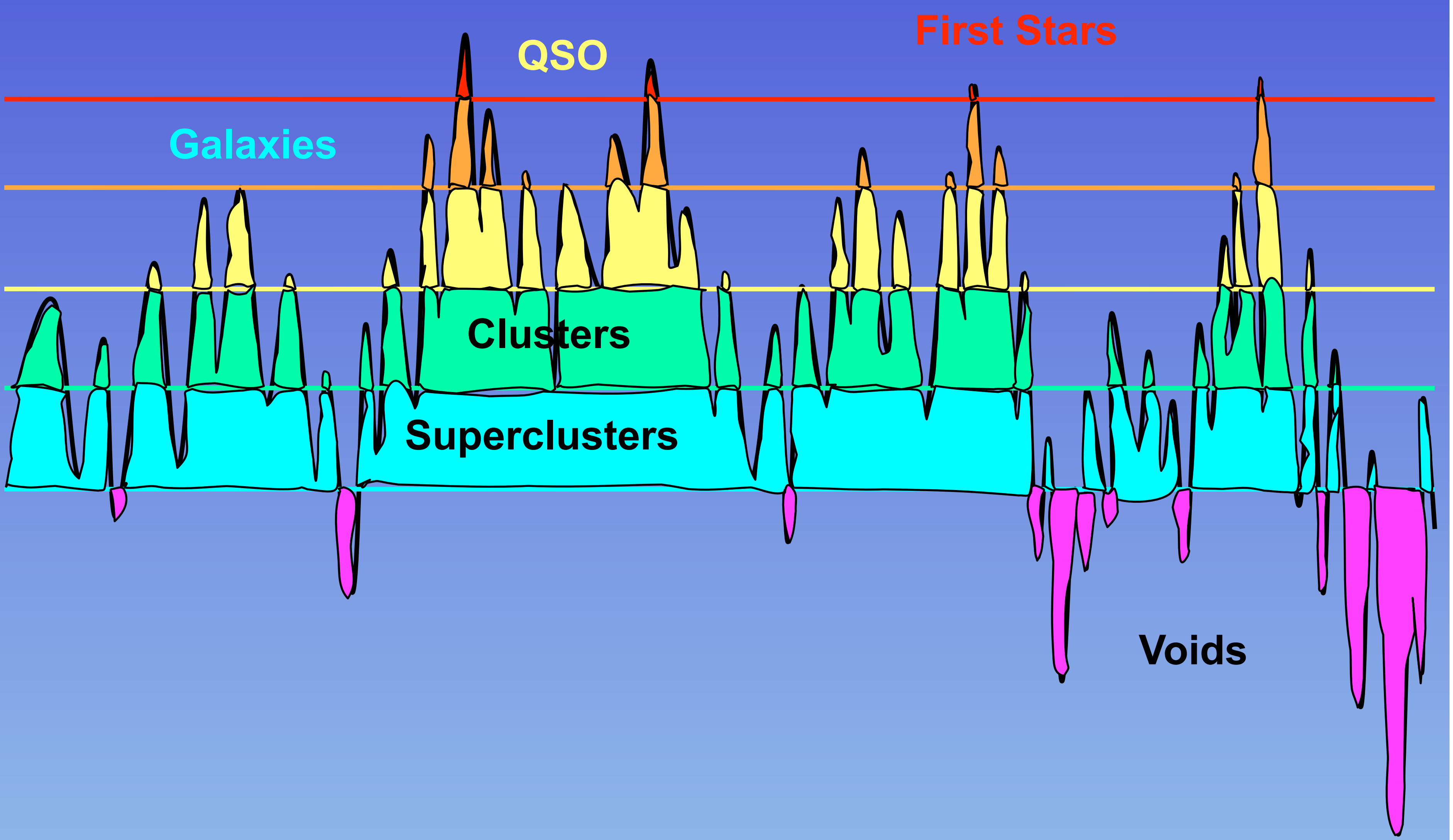
Dark Energy violates SEC: $p = -\rho \Rightarrow \rho + 3p < 0$

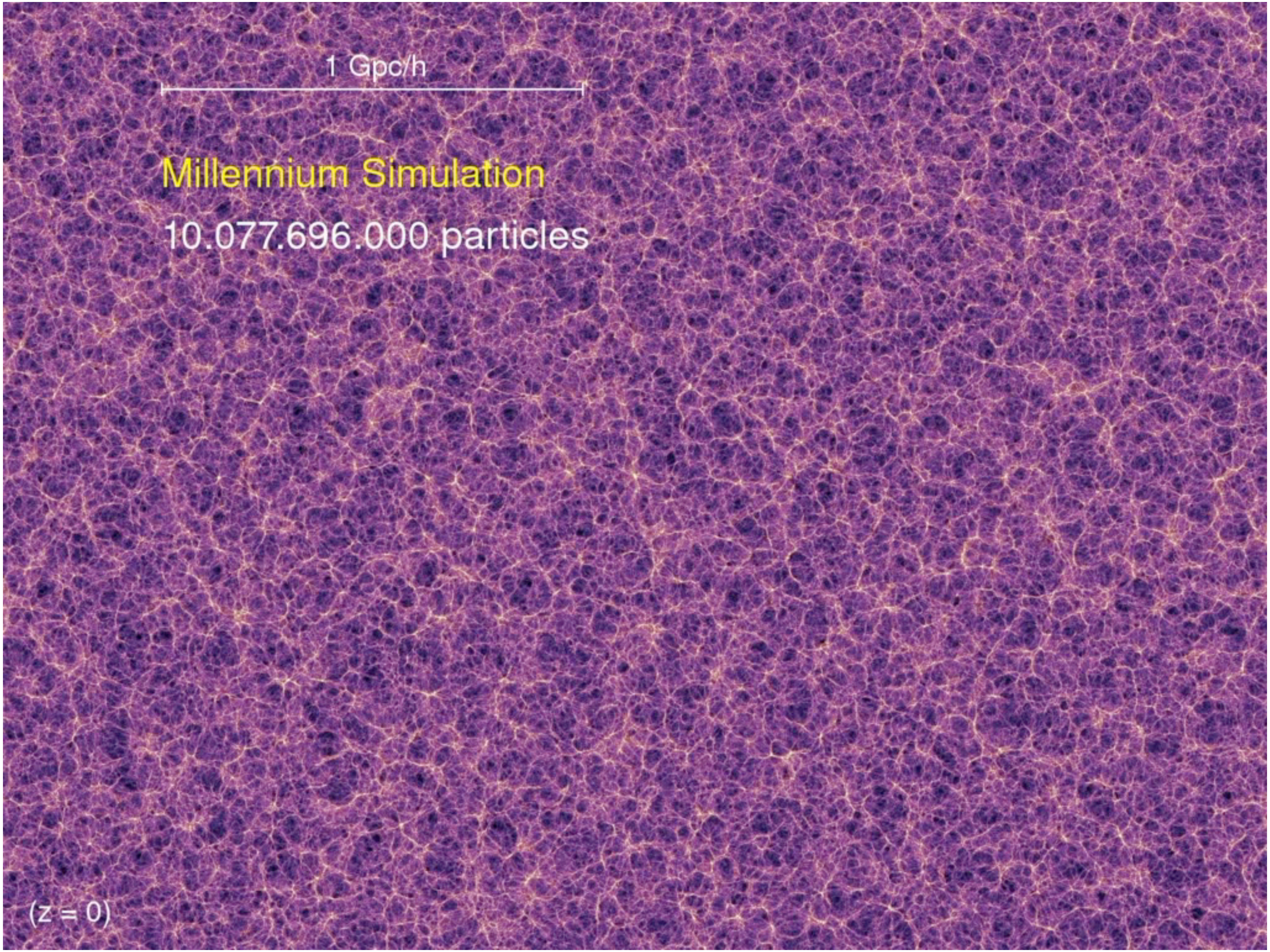
2. Modified Gravity on large scales (quantum eff.?)

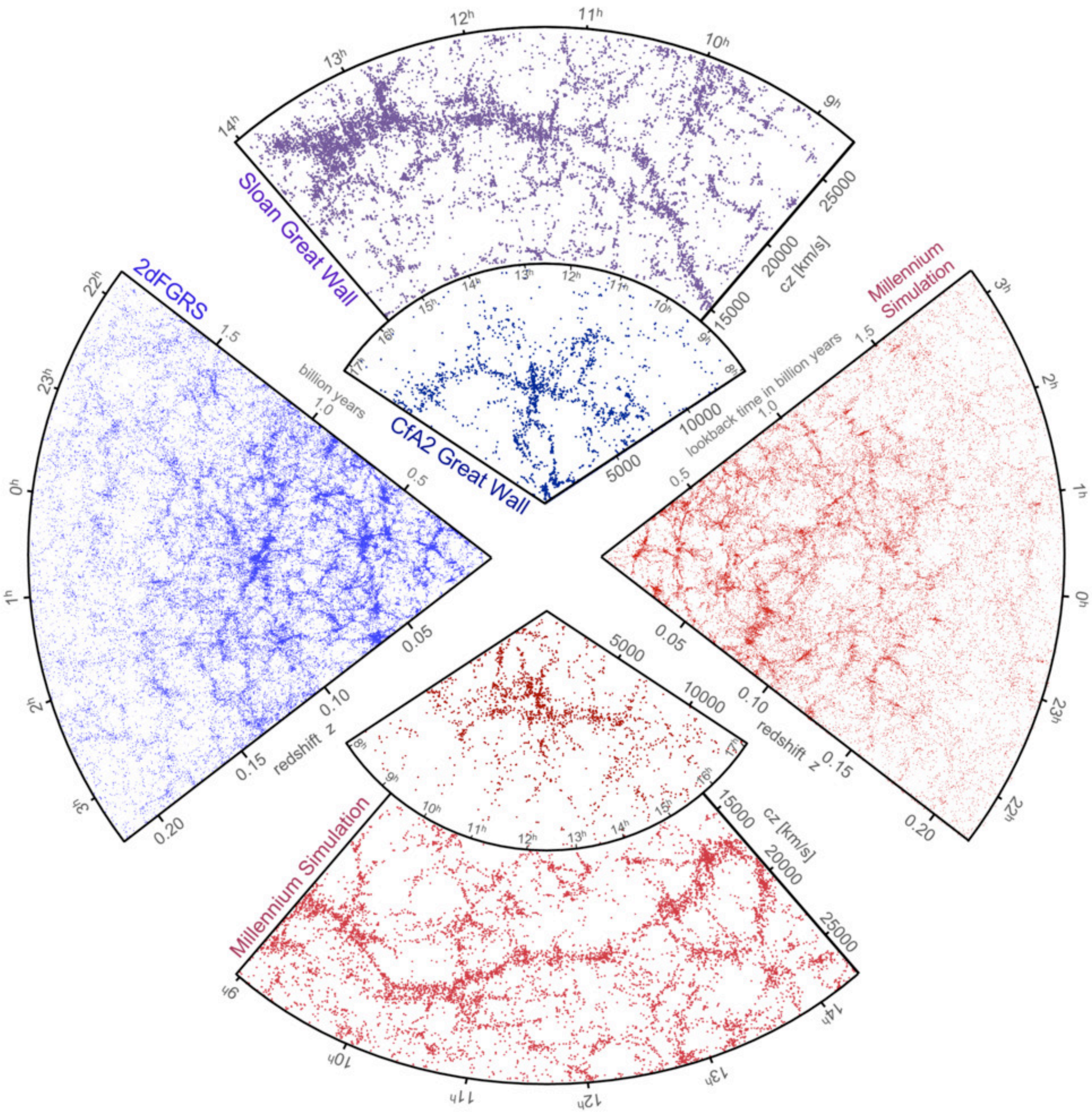
Both are unsatisfactory (new physics is involved) and there is no other experimental evidence in favor

However, assumption 3. is not exactly valid in the real Universe, although inhomogeneities are supposed to be small on the scales of interest

Density contrast thresholds

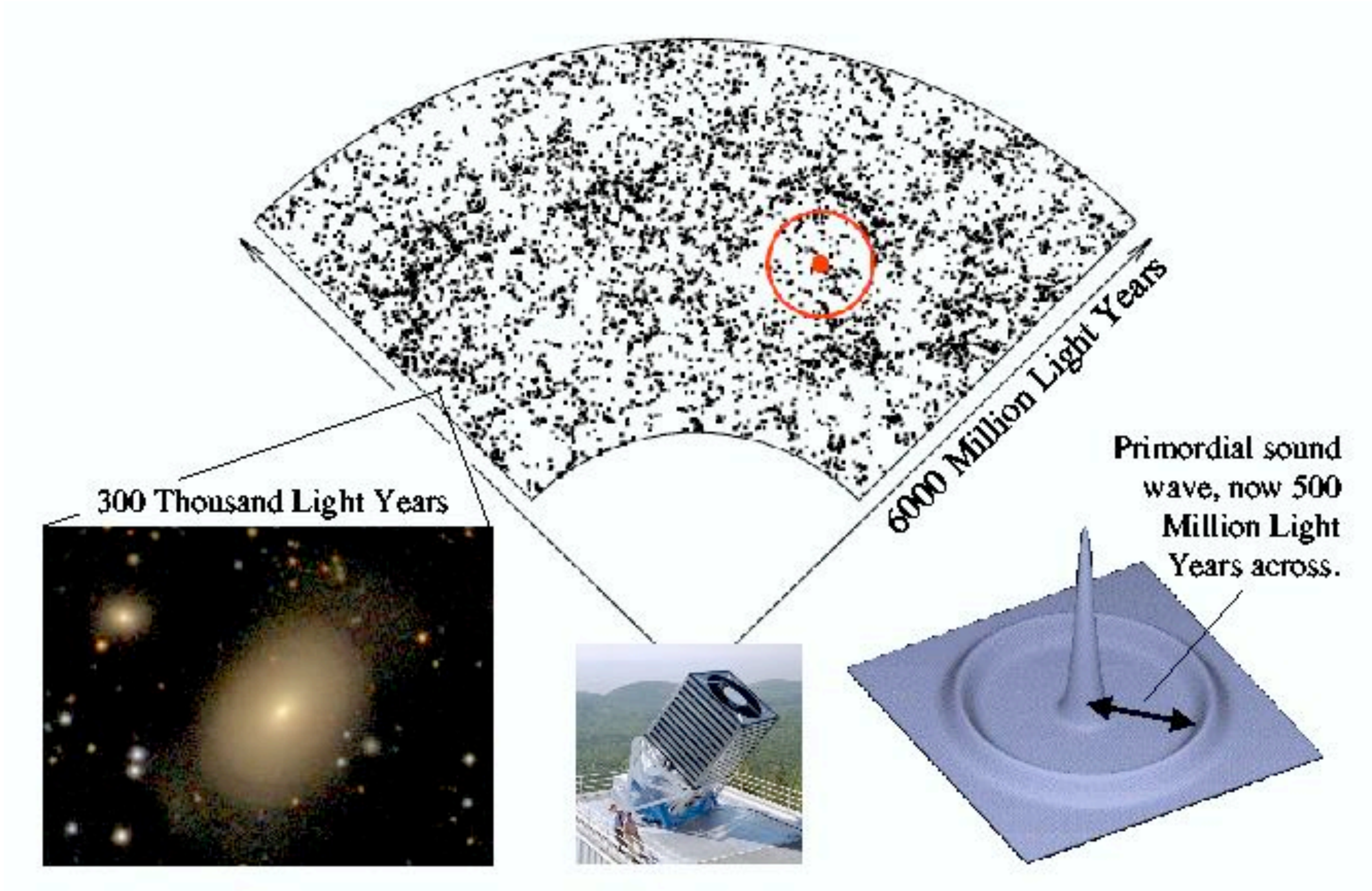



1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

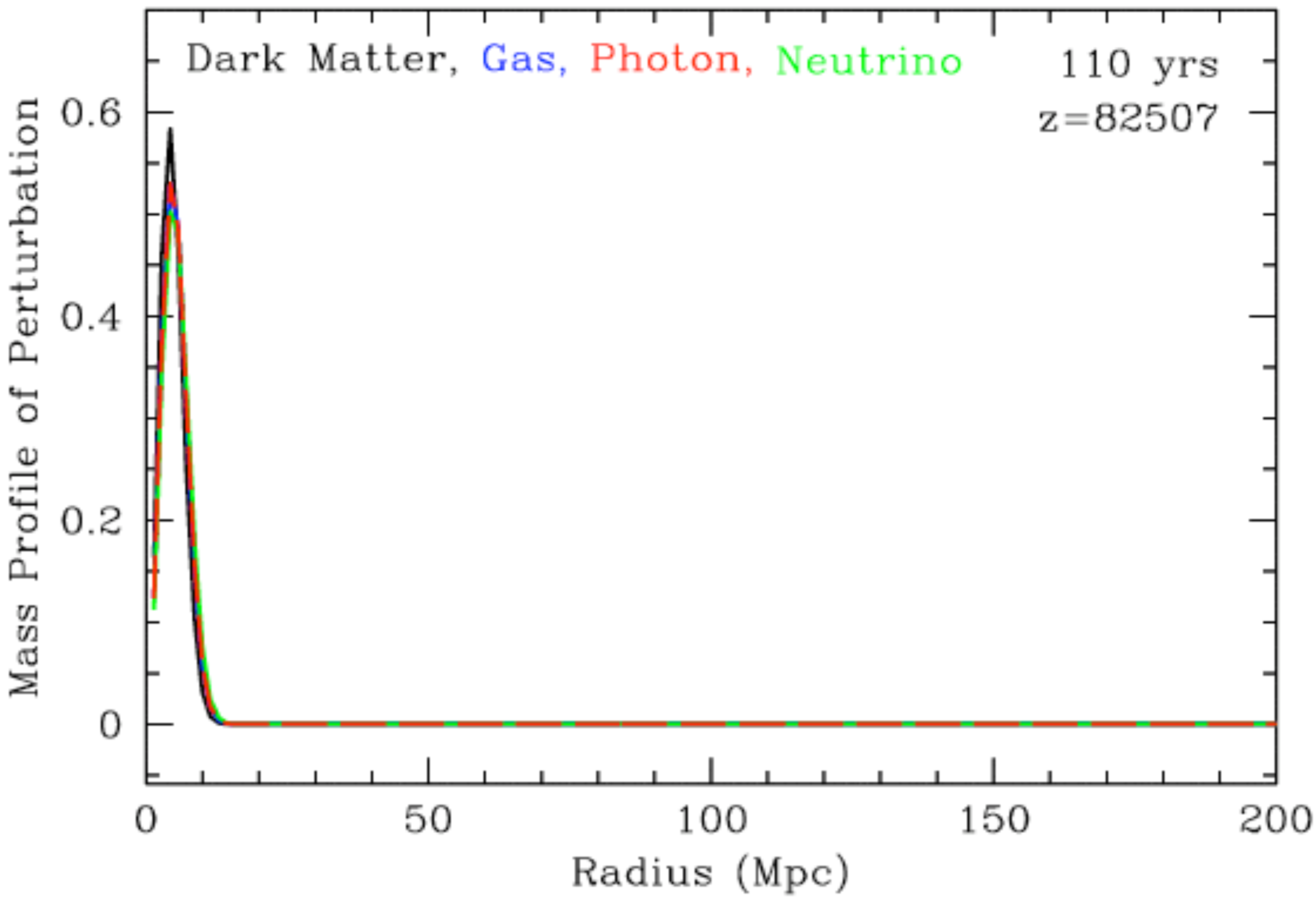


Sloan Great Wall
CfA2 Great Wall
2dFGRS
Millennium Simulation
Millennium Simulation
cz [km/s]
lookback time in billion years
billion years
redshift z

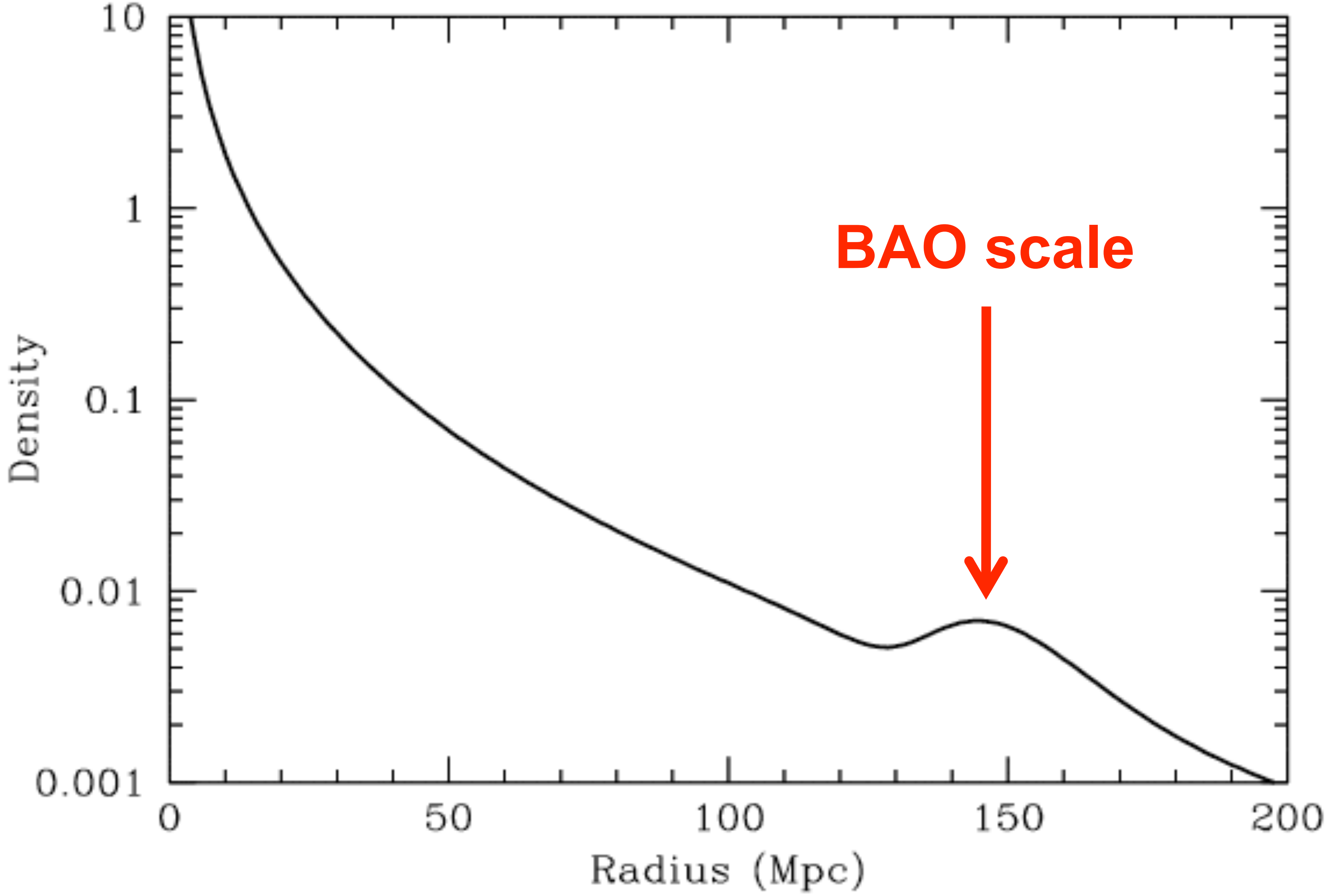
Baryon Acoustic Oscillations

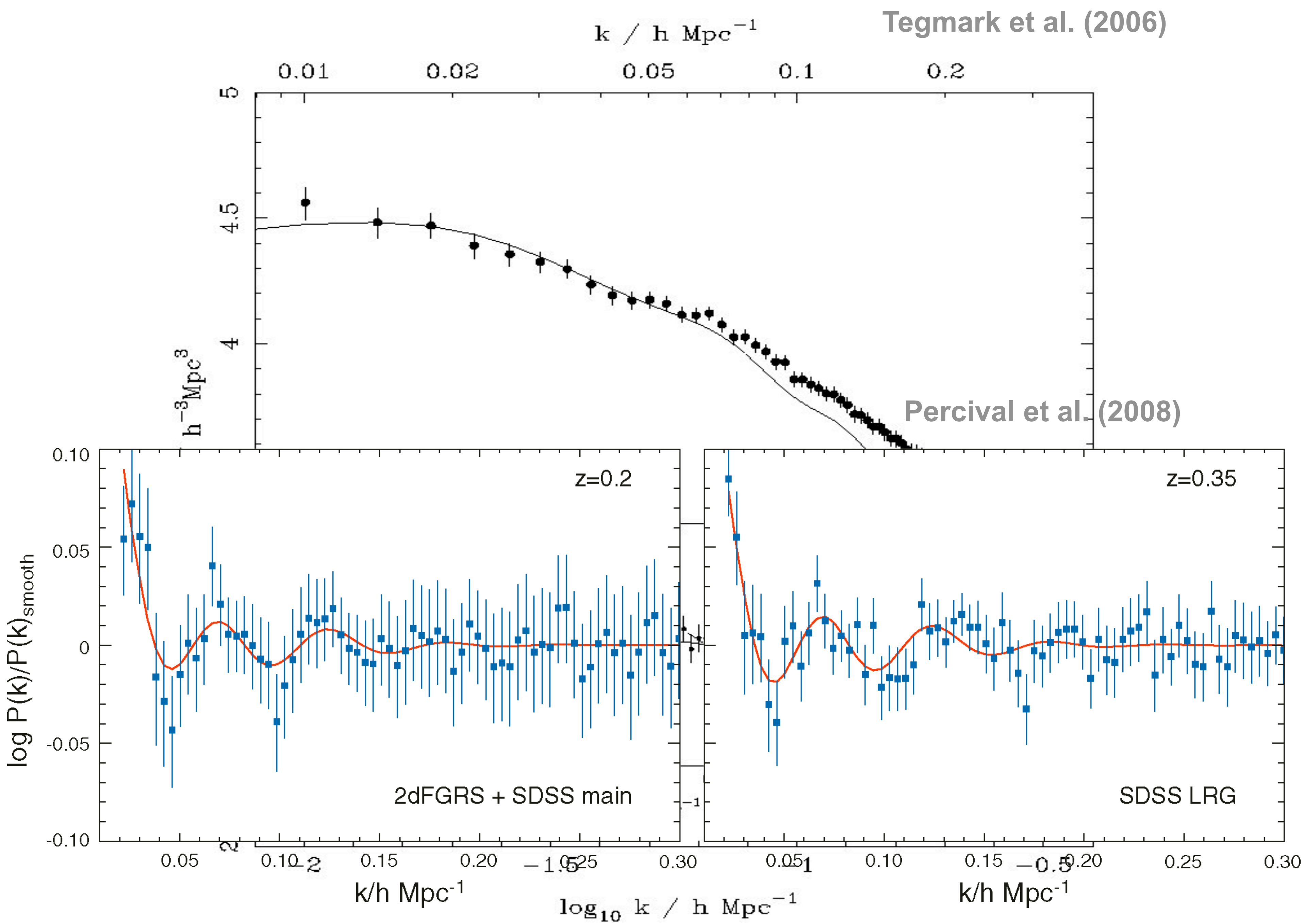


Evolution Baryon Acoustic Oscillations



Evolution Baryon Acoustic Oscillations





Tegmark et al. (2006)
k / h Mpc^{-1}
0.01
0.02
0.05
0.1
0.2
5
4.5
4
h^{-3}Mpc^{3}
log$_{10}$ k / h Mpc^{-1}
Percival et al. (2008)
log P(k)/P(k)$_{smooth}$
0.10
0.05
0
-0.05
-0.10
z=0.2
2dFGRS + SDSS main
0.05
0.10
0.15
0.20
0.25
0.30
k/h Mpc^{-1}
z=0.35
SDSS LRG
0.05
0.10
0.15
0.20
0.25
0.30
k/h Mpc^{-1}

The radial Baryon Acoustic Oscillation scale

Gaztañaga, Cabré & Hui (2008)

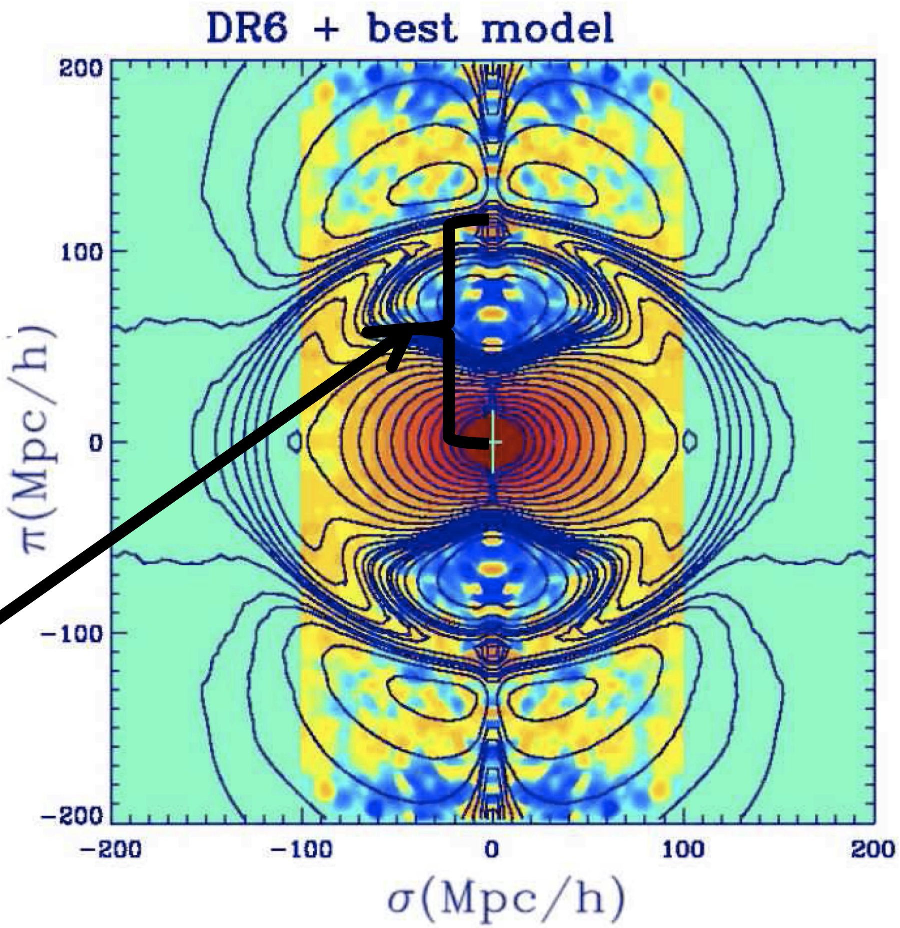
2D correlation: $\xi(\sigma, \pi)$

monopole: $\xi_0(r) = \int_0^1 \xi(\sigma, \pi) d\mu$

$$r = \sqrt{\sigma^2 + \pi^2} \quad \mu = \pi / r$$

BAO peak: $\pi \simeq 110 \text{ Mpc/h}$

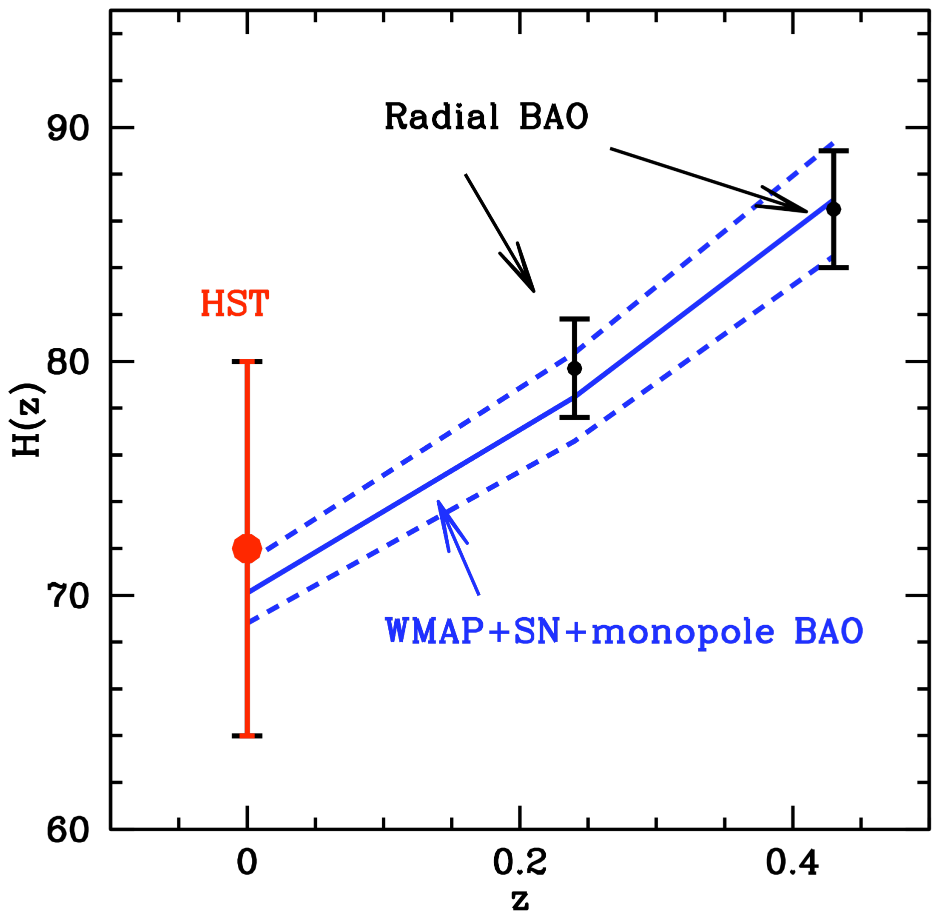
$\sigma < 5 \text{ Mpc/h}$



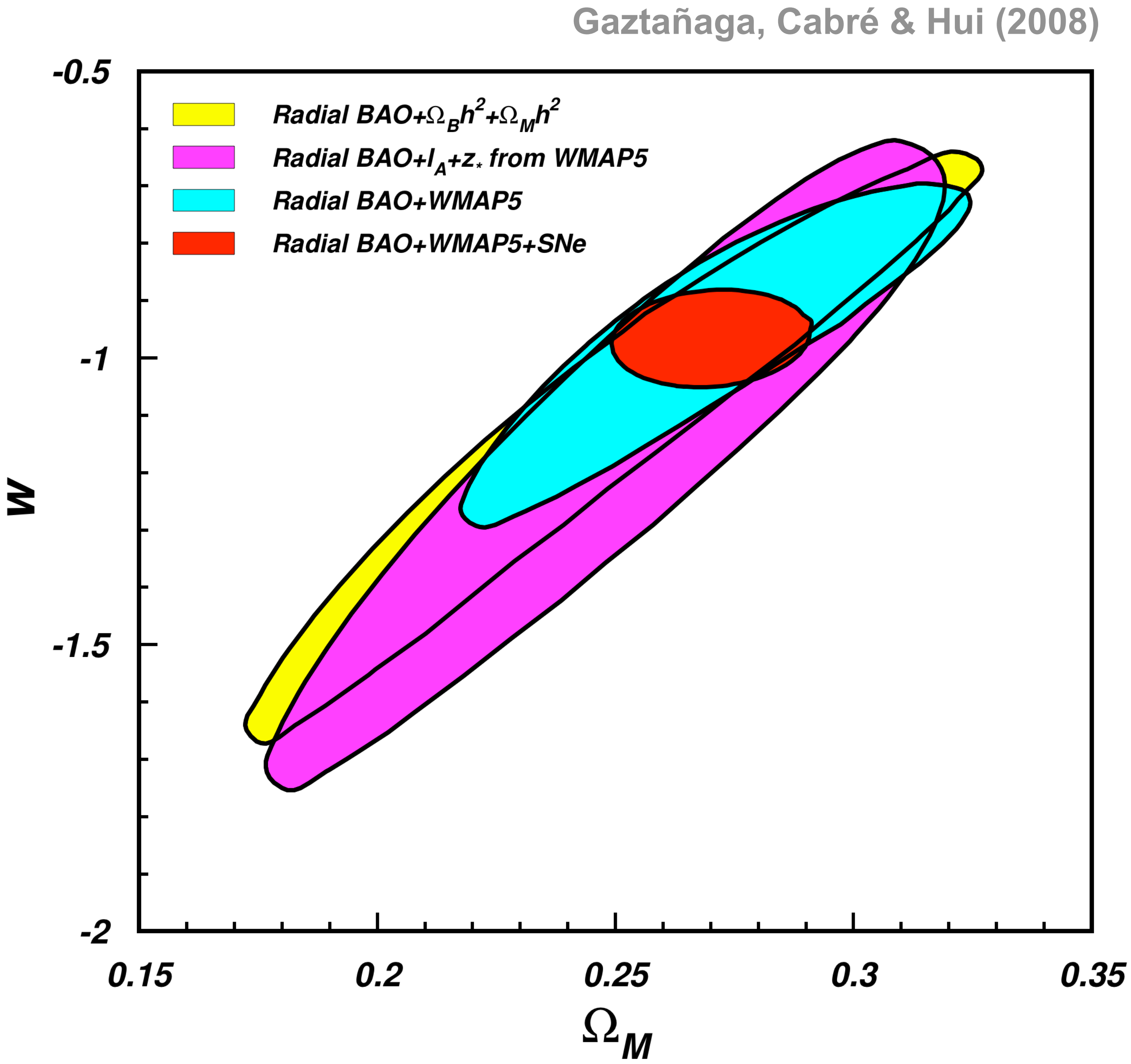
Gaztañaga, Cabré & Hui (2008)

Radial BAO & ΛCDM

$$\Delta z_{BAO}(z_i) = \frac{H(z_i) r_s}{c}$$

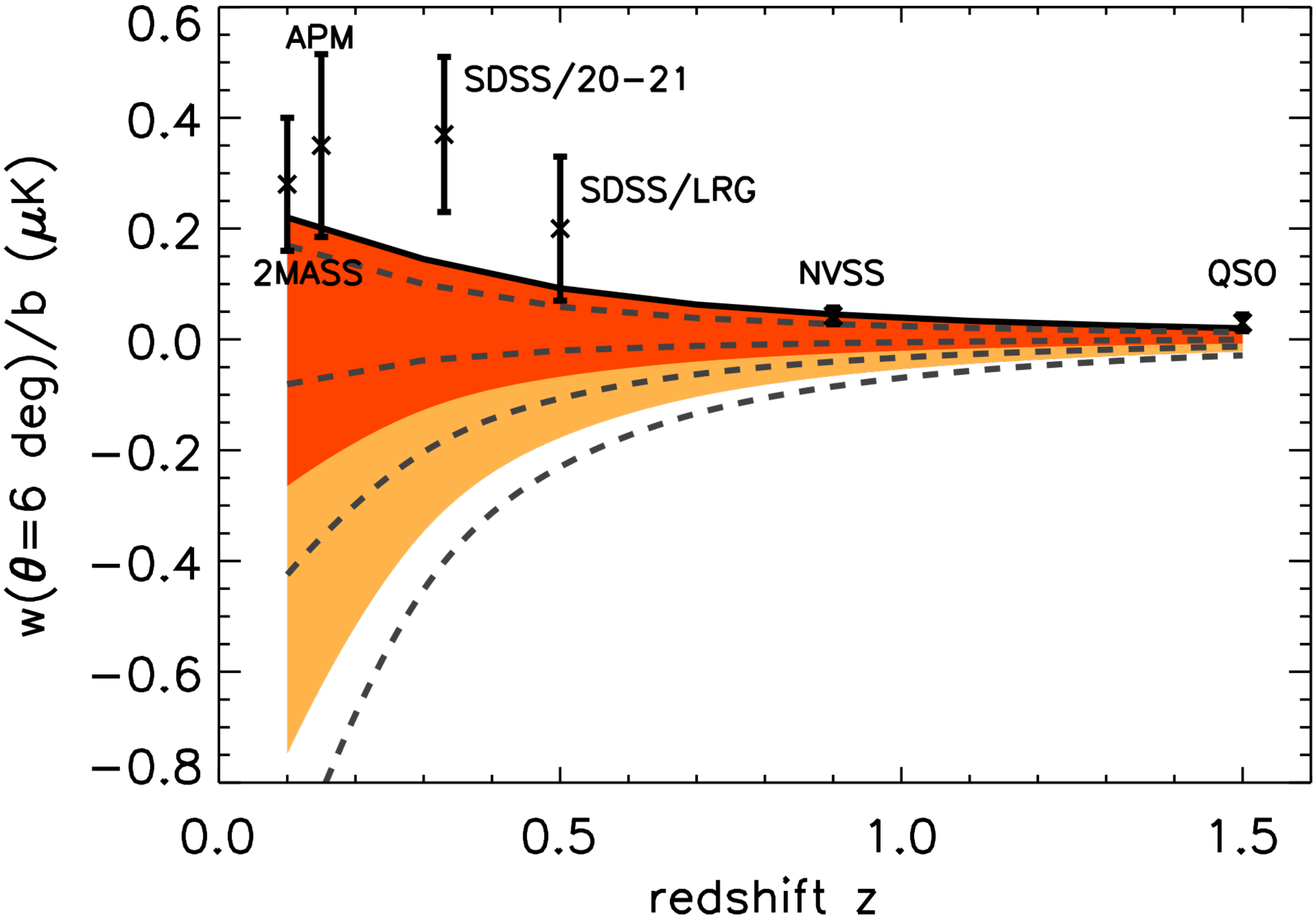


Sample z range	z_m	r_{BAO} Mpc/h	σ_{st}	σ_{sys}	H(z) km/s/Mpc	σ_{st}	σ_{sys}
0.15-0.30	0.24	110.3	2.5	1.35	79.7	2.1	1.0
0.40-0.47	0.43	108.9	2.8	1.22	86.5	2.5	1.0


Gaztañaga, Cabré & Hui (2008)
Radial BAO+$\Omega_B h^2$+$\Omega_M h^2$
Radial BAO+l_A+z_* from WMAP5
Radial BAO+WMAP5
Radial BAO+WMAP5+SNe
-0.5
-1
-1.5
-2
w
0.15
0.2
0.25
0.3
0.35
Ω_M

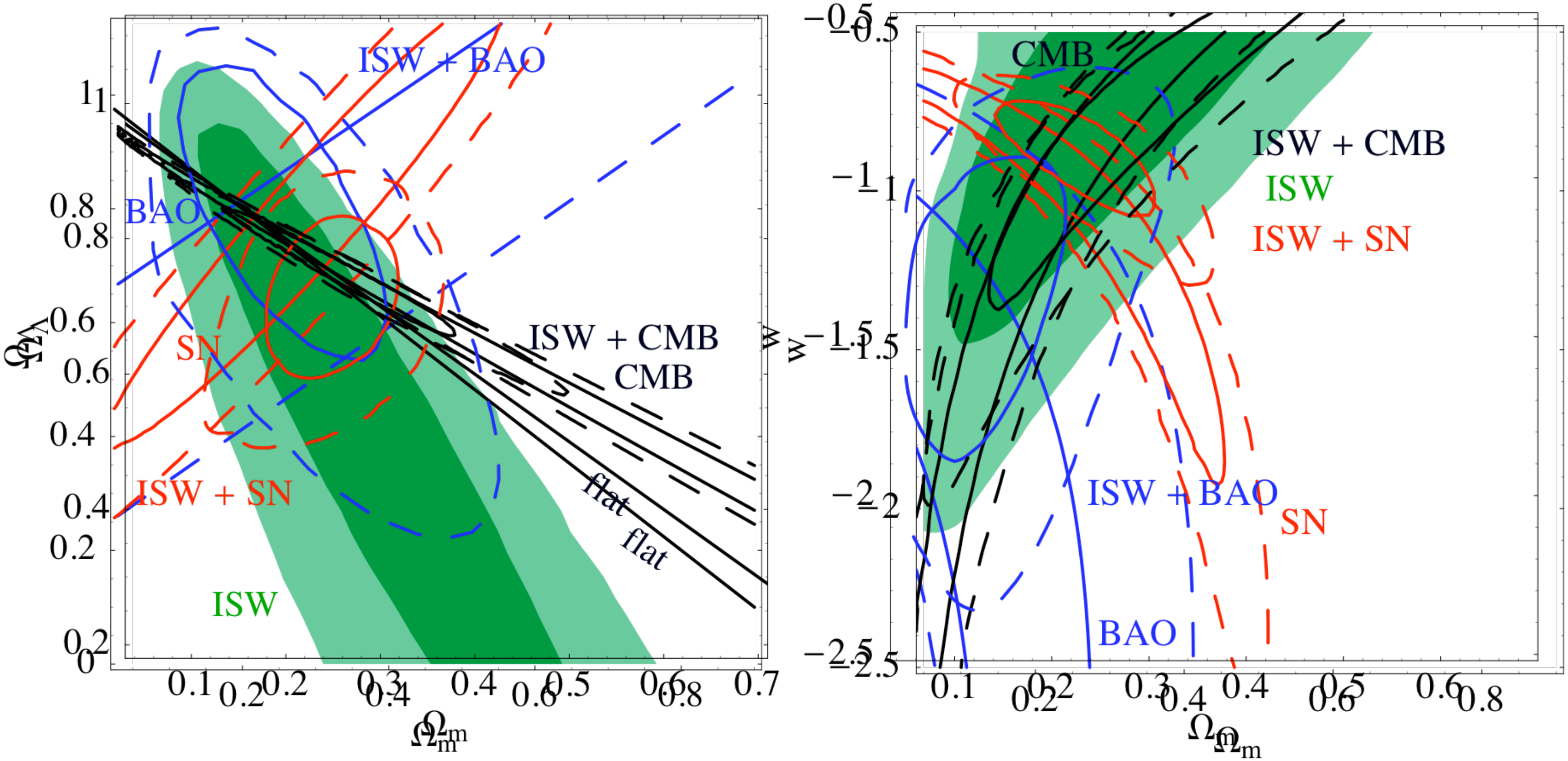
ISW-LSS anticorrelation

Song, Peiris & Hu (2007)

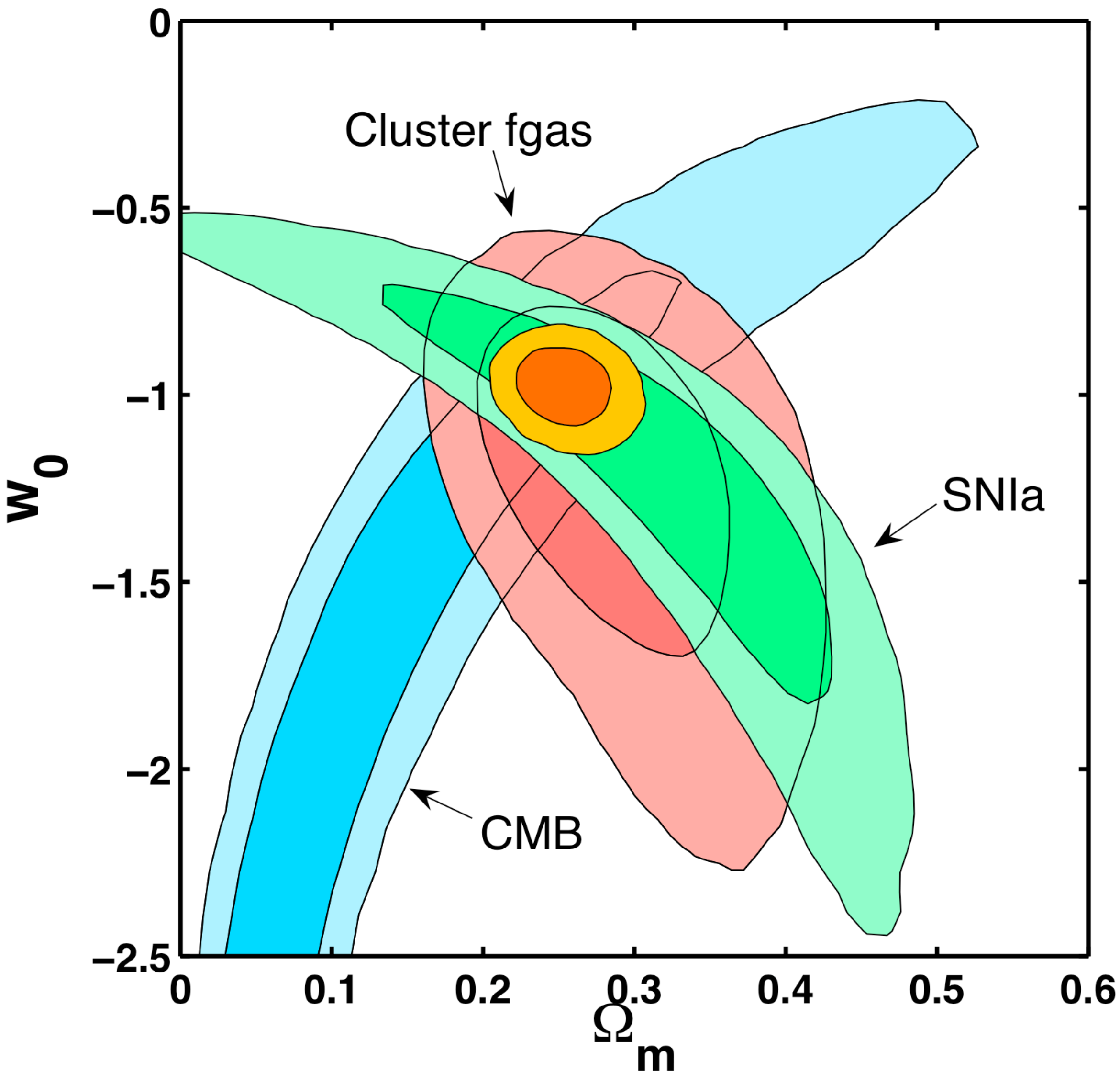


ISW-LSS anticorrelation

Giannantonio et al. (2008)

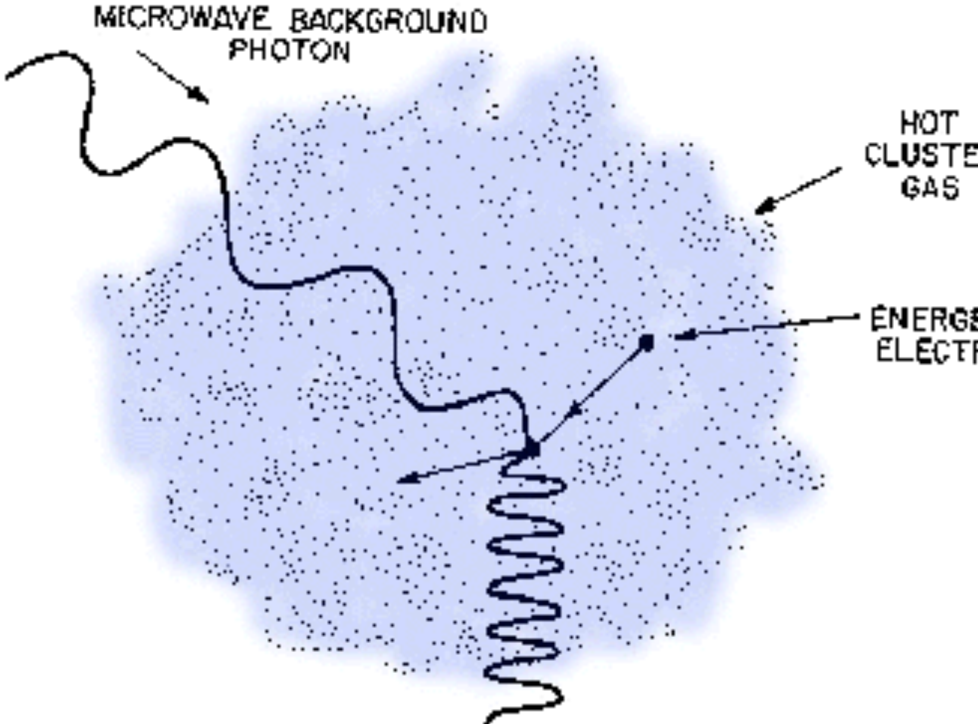


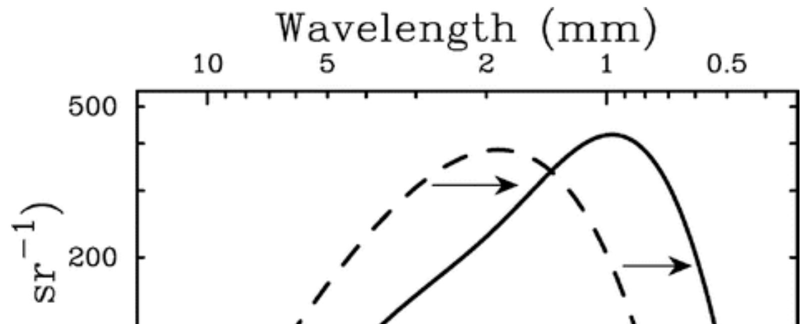
Vikhlinin et al. (2009)

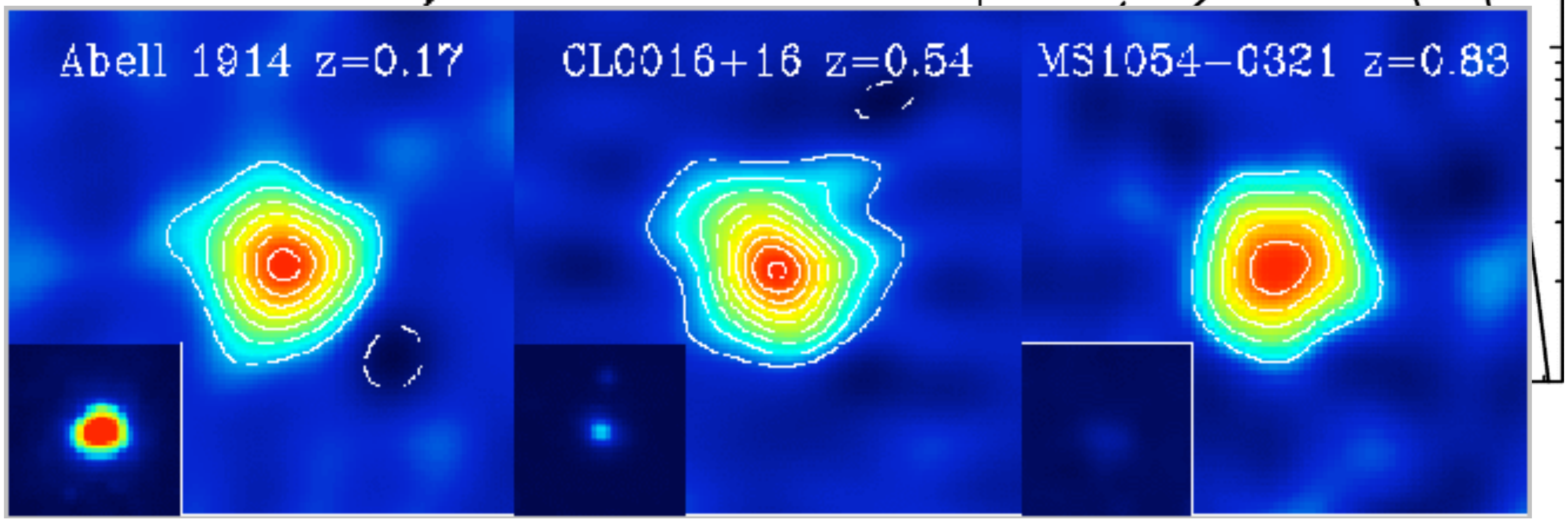


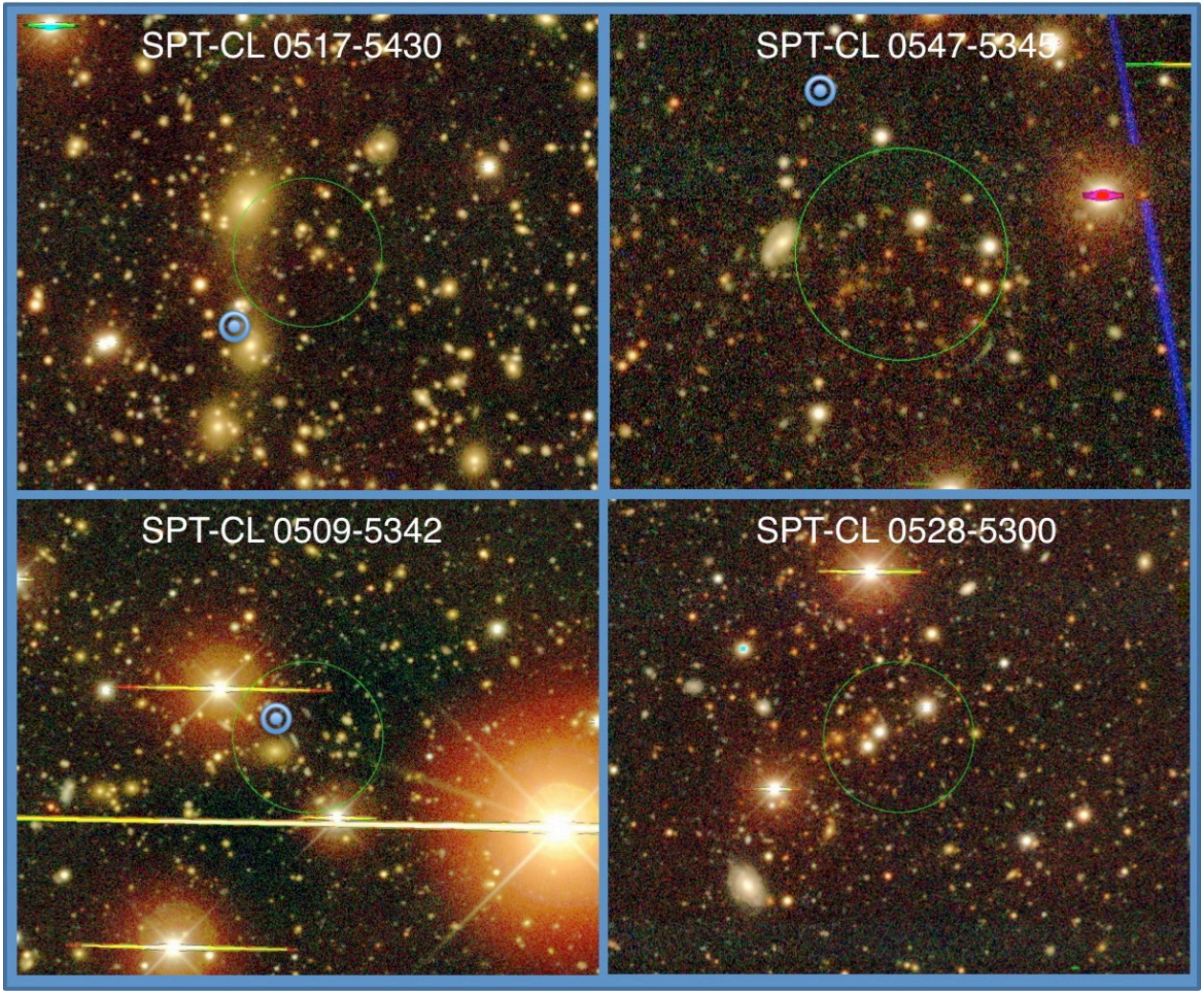
Chandra (Xrays) Cluster Mass Fraction

Suyaev-Zel'dovich effect (1970)








SPT-CL 0517-5430
SPT-CL 0547-5345
SPT-CL 0509-5342
SPT-CL 0528-5300

The kinematic Sunyaev-Zeldovich effect

- The intra cluster gas works as a mirror rescattering photons from all directions into the line of sight
- If the cluster is moving, the Doppler effect gives a change in intensity due to the direction dependence of Compton scattering

$$\frac{\Delta I_\nu}{I_\nu} = -\frac{xe^x}{e^x - 1} \int \sigma_T n_e \frac{\boldsymbol{v}_p}{c} \cdot d\boldsymbol{l}$$

- where $x = h\nu/(kT_0)$ is the normalised ferquency, v_p is the peculiar velocity of the cluster, and the integral is along the line of sight weighted with the optical depth of the gas: $\sigma_T n_e$.

kinematic Sunyaev-Zeldovich effect

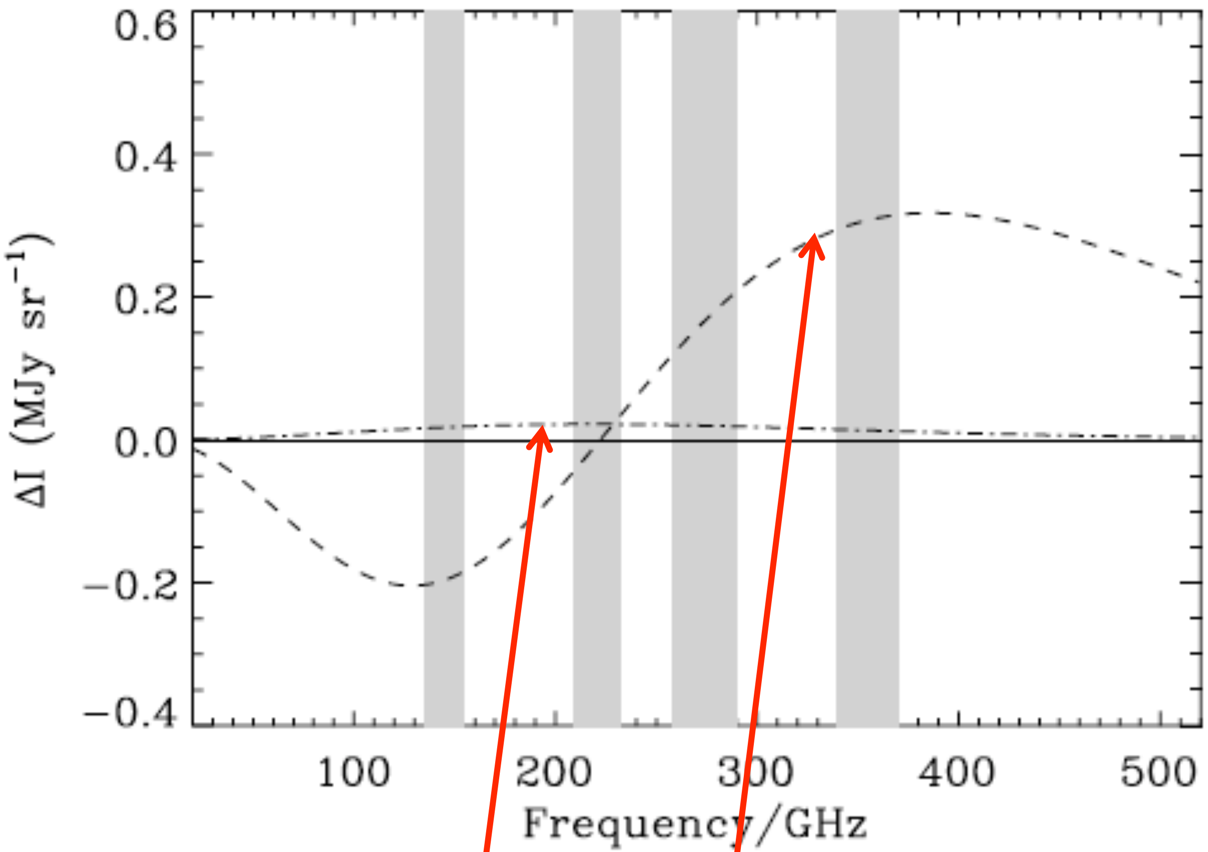
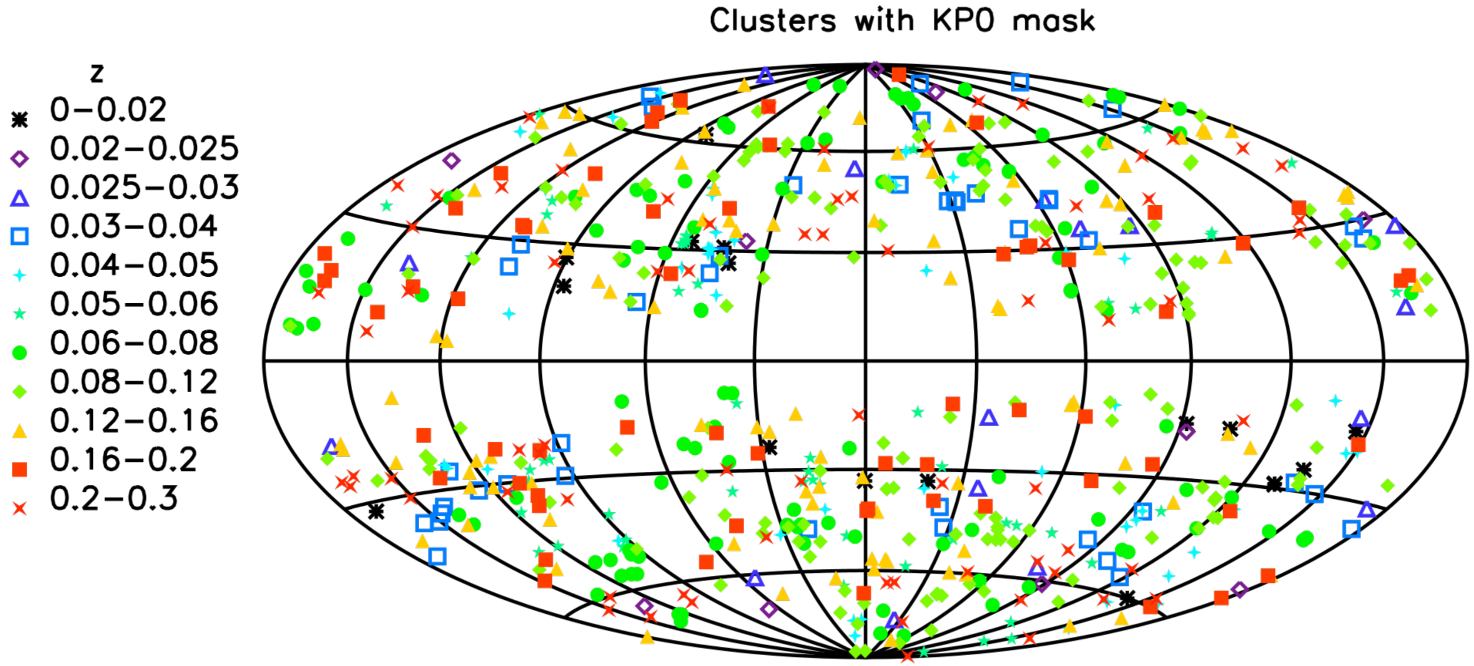


FIG. 1.—Frequency dependence of the SZ effect for a cluster with optical depth $\tau = 0.01$, gas temperature 10 keV, and a peculiar velocity of -500 km s^{-1} (toward the observer). The thermal SZ spectrum is indicated by the dashed line, the kinematic effect by the dot-dashed line. The shaded regions indicate the bands in which SuZIE II observes.

Large bulk flows from kSZ effect

Kashlinsky, Atrio-Barandela, Kocevski & Ebeling (2008)



Xray catalog with 674 clusters from REFLEX, eBCS & CIZA catalogs, z<0.3

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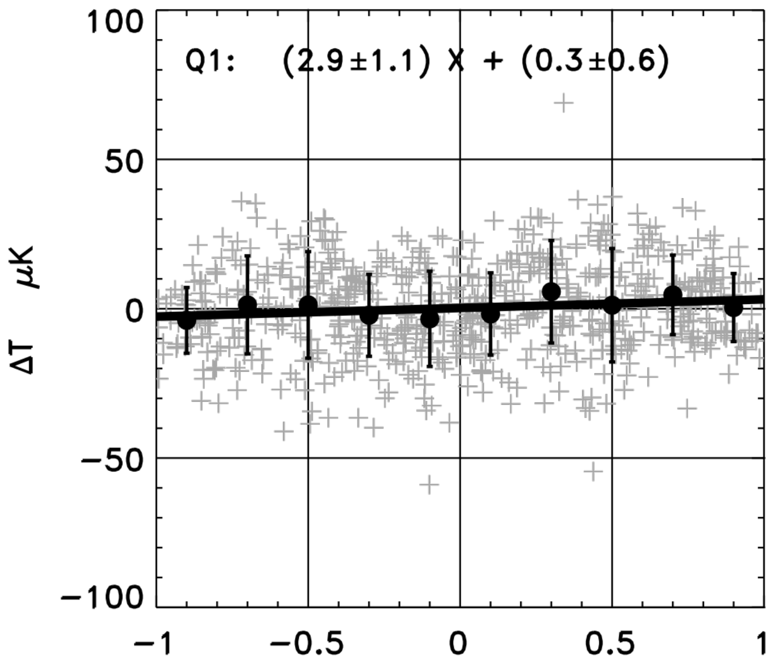
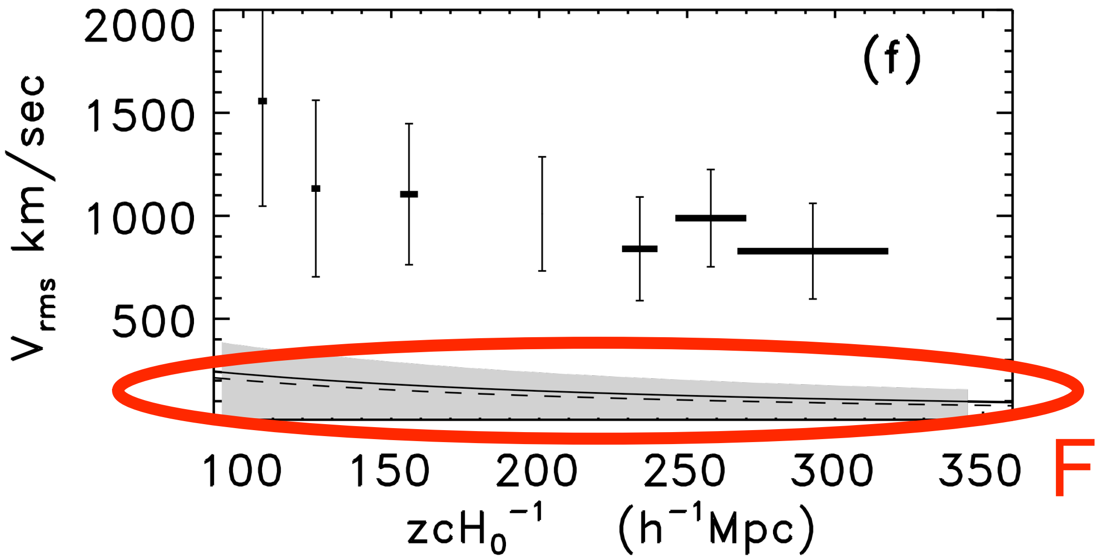


X

Kashlinsky et al. (2008)



FRW-ΛCDM

X = cos μ

(11) (l,b) deg
$(295, 14) \pm 13$
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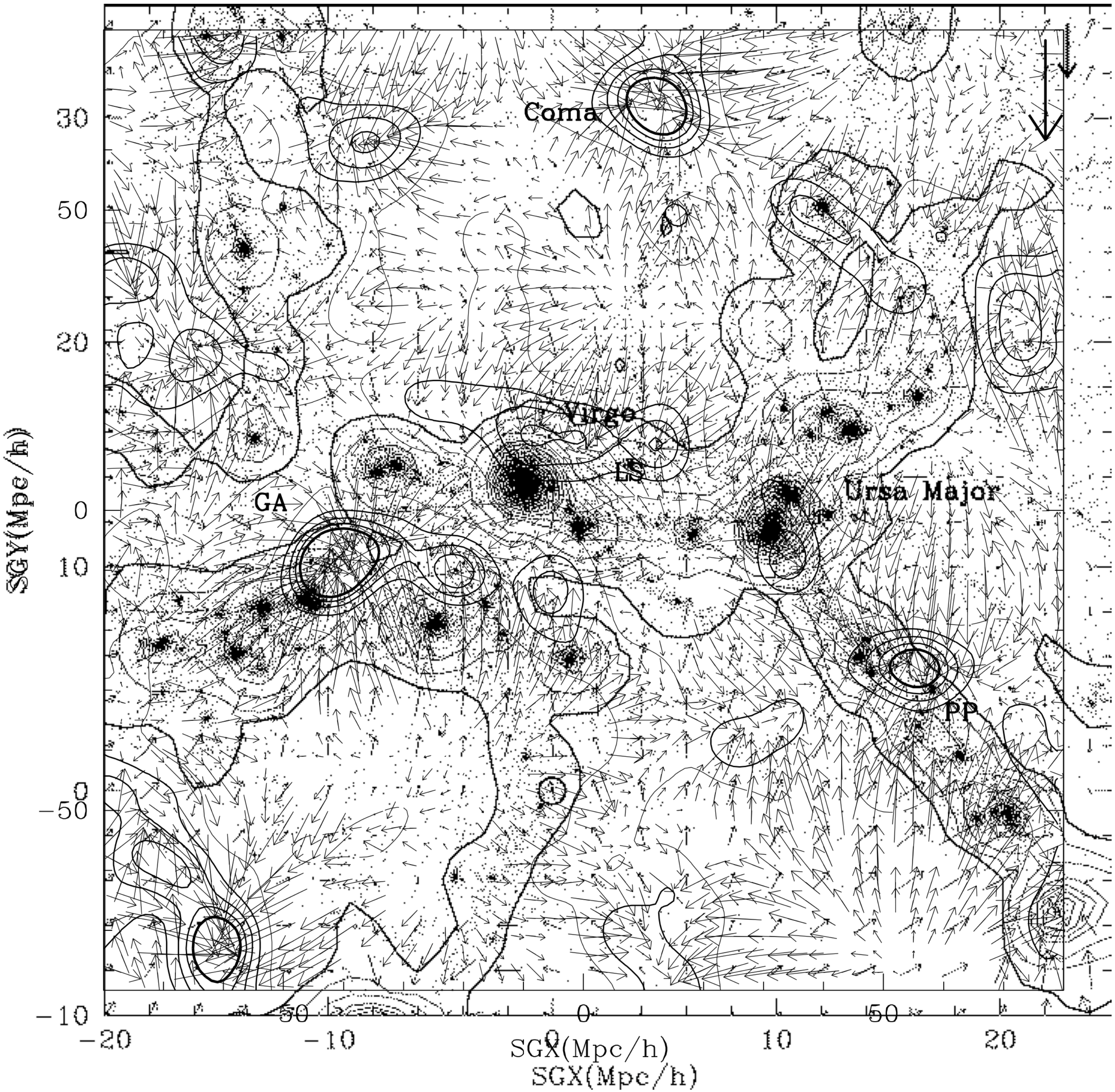
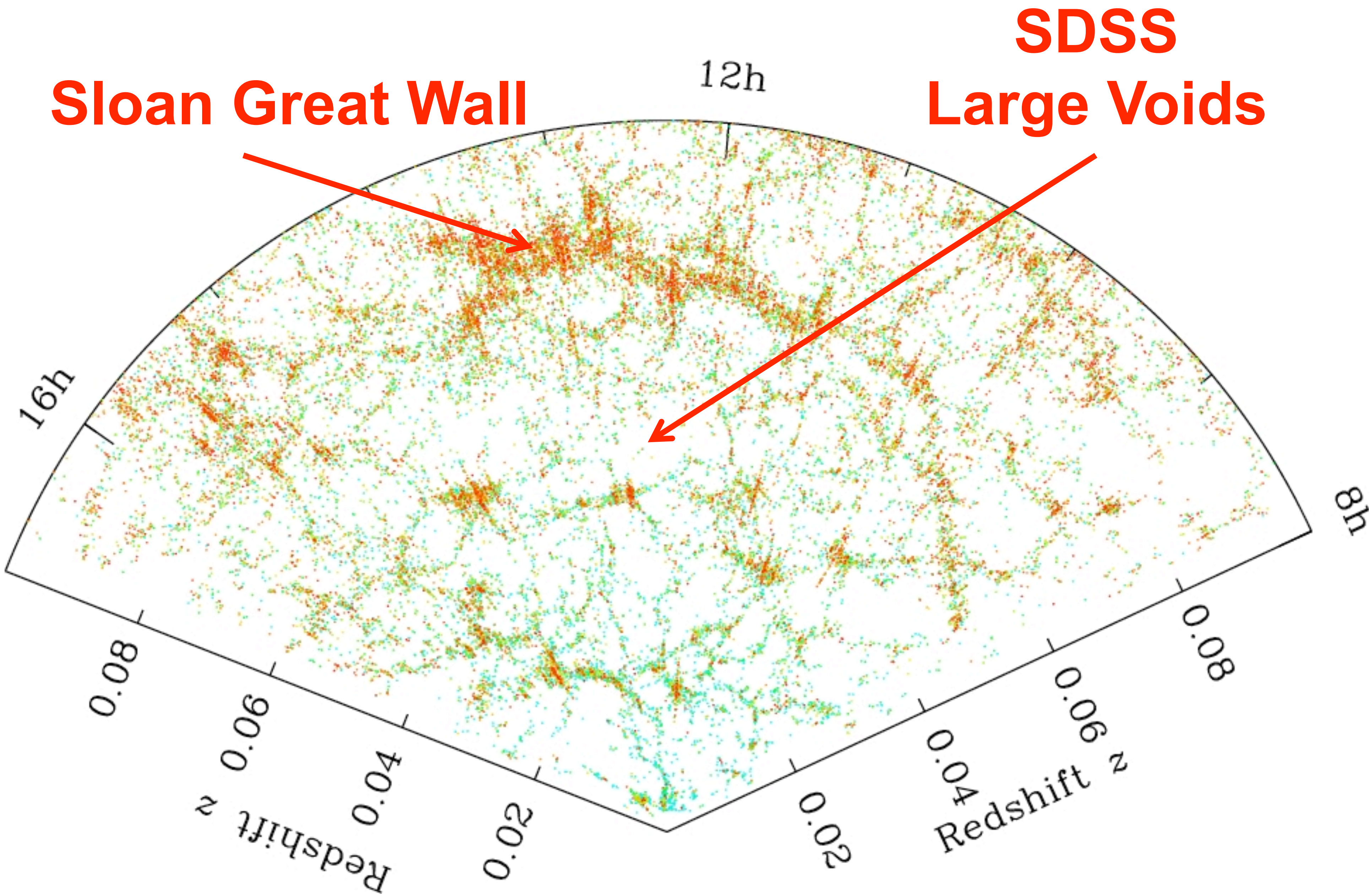


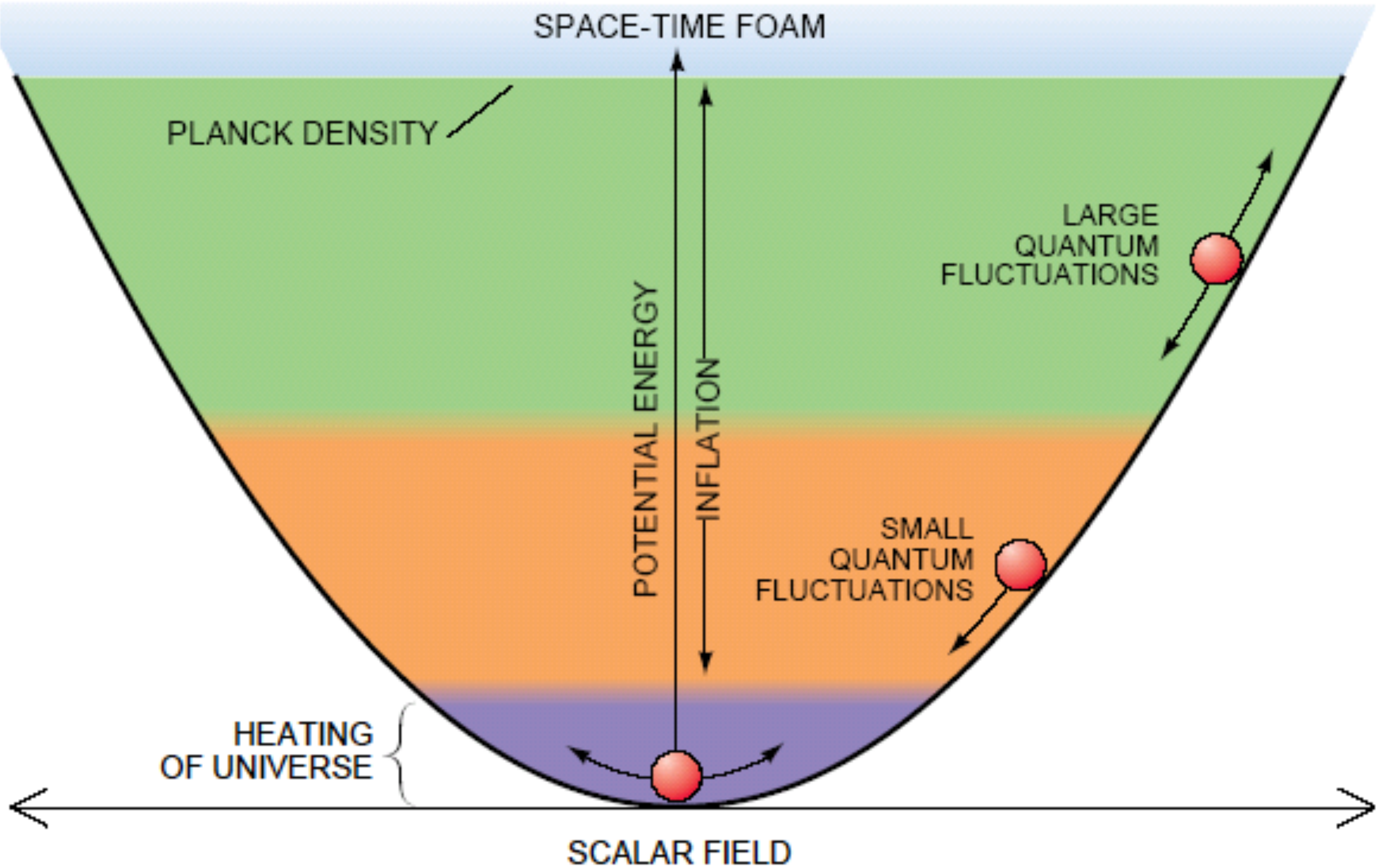
Coma
Virgo
LS
Ursa Major
GA
PP
SGY(Mpc/h)
SGX(Mpc/h)
SGX(Mpc/h)
30
50
20
0
10
−50
−10
−20
−10
0
10
20
50

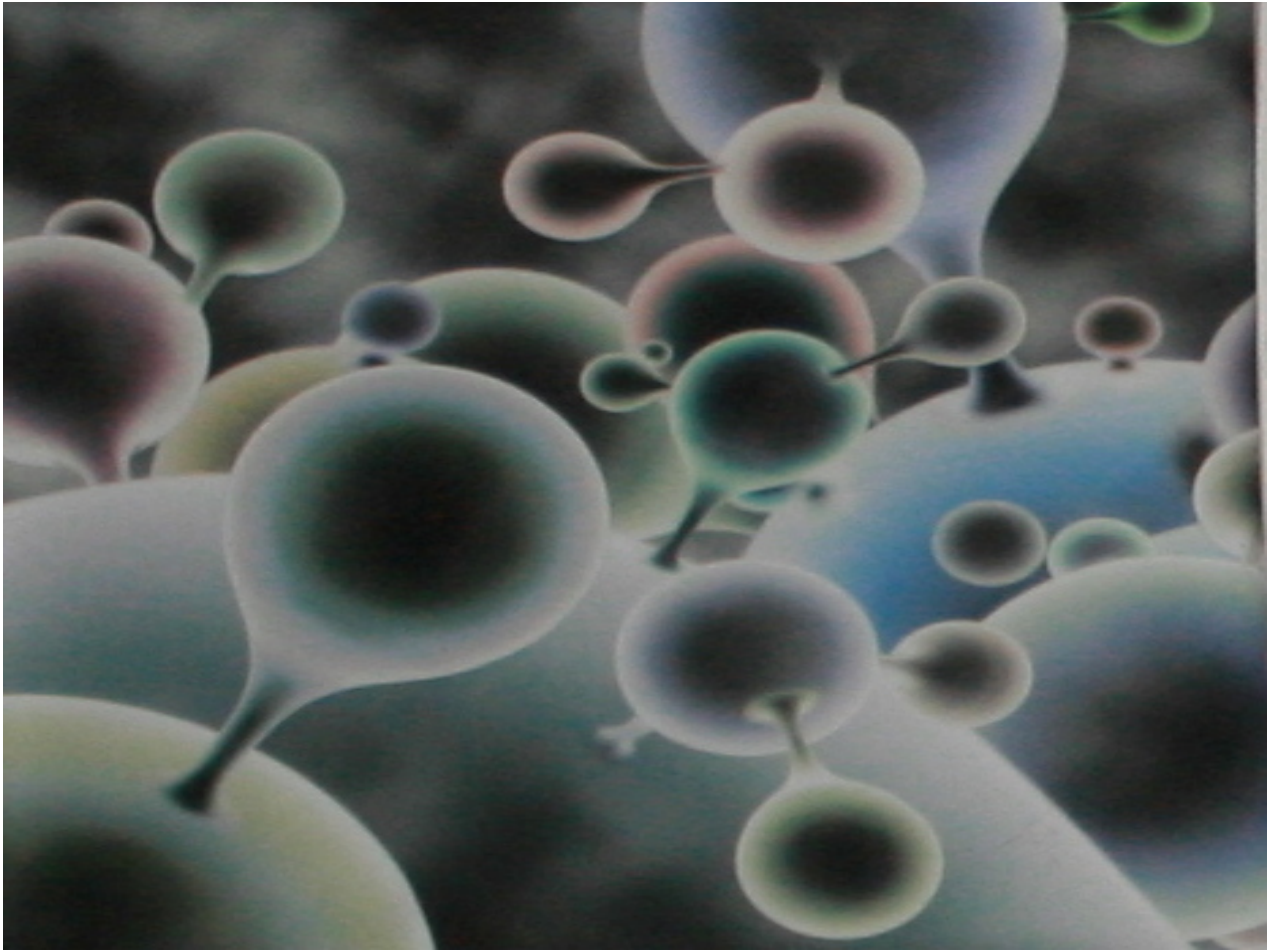

Sloan Great Wall
SDSS
Large Voids
12h
16h
8h
0.08
0.06
0.04
0.02
Redshift z
0.02
0.04
0.06
0.08
Redshift z

If we live in an inhomogeneous Universe…

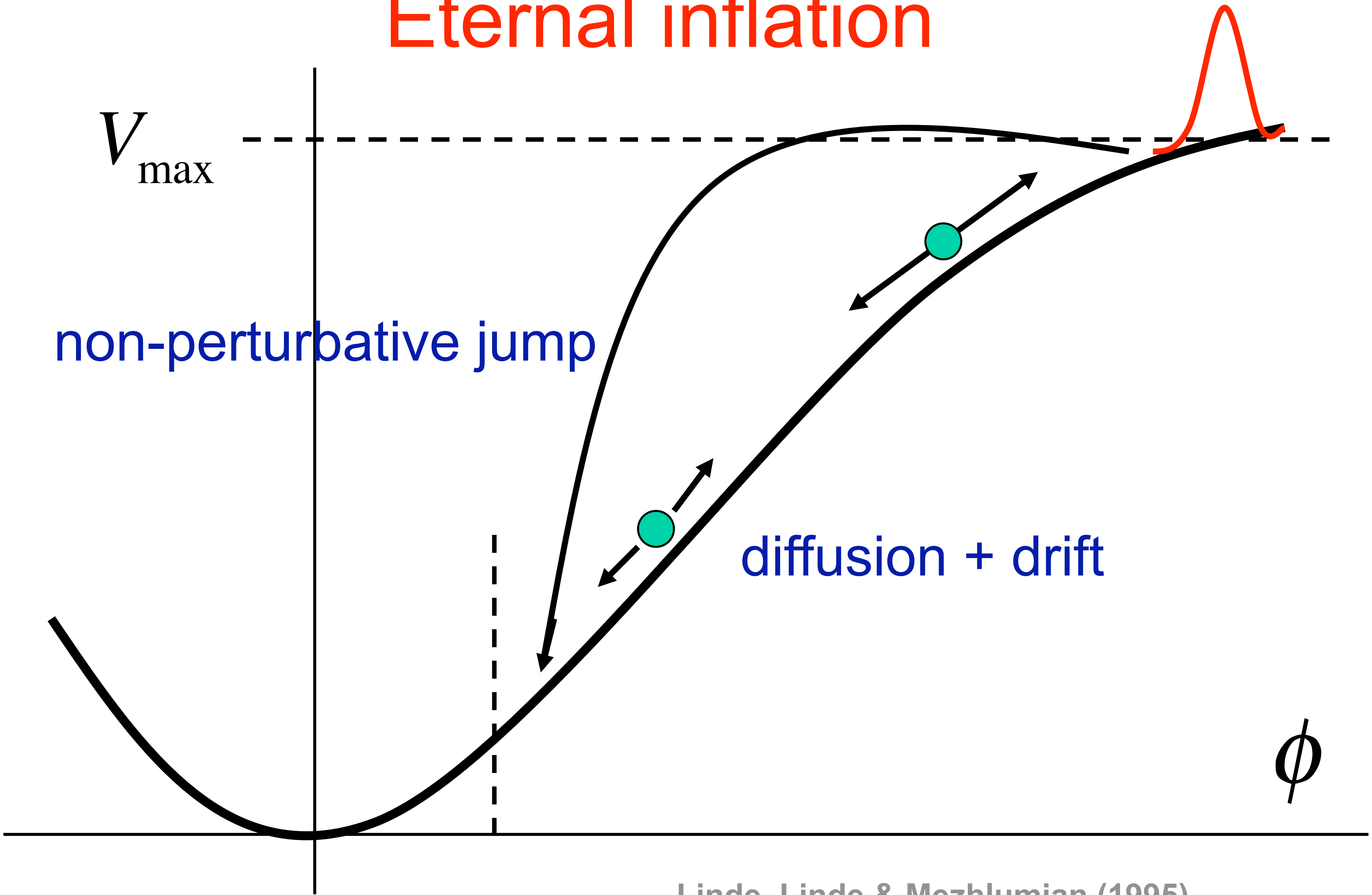
What is the origin of fluctuations?

Chaotic Inflation



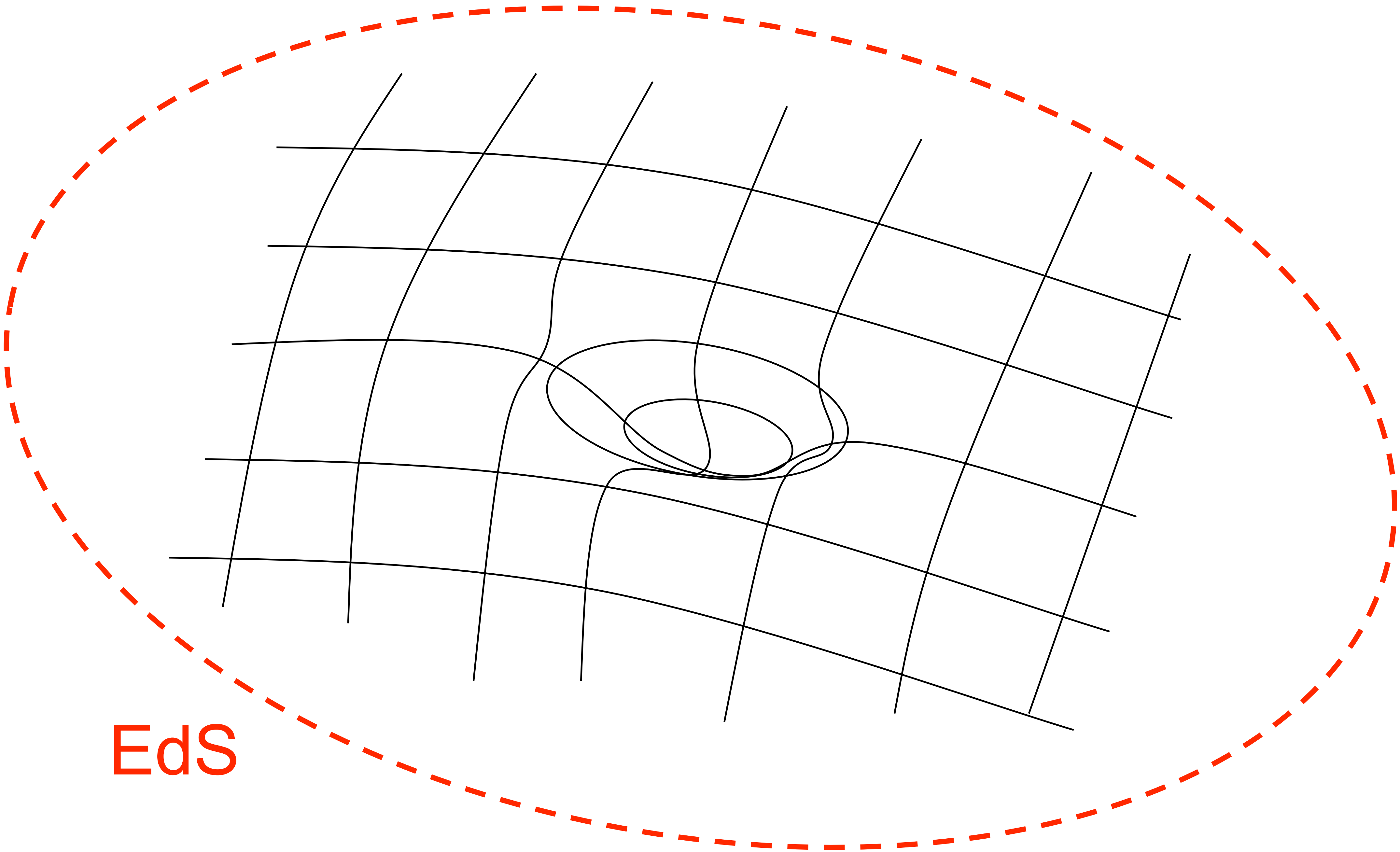


Eternal inflation

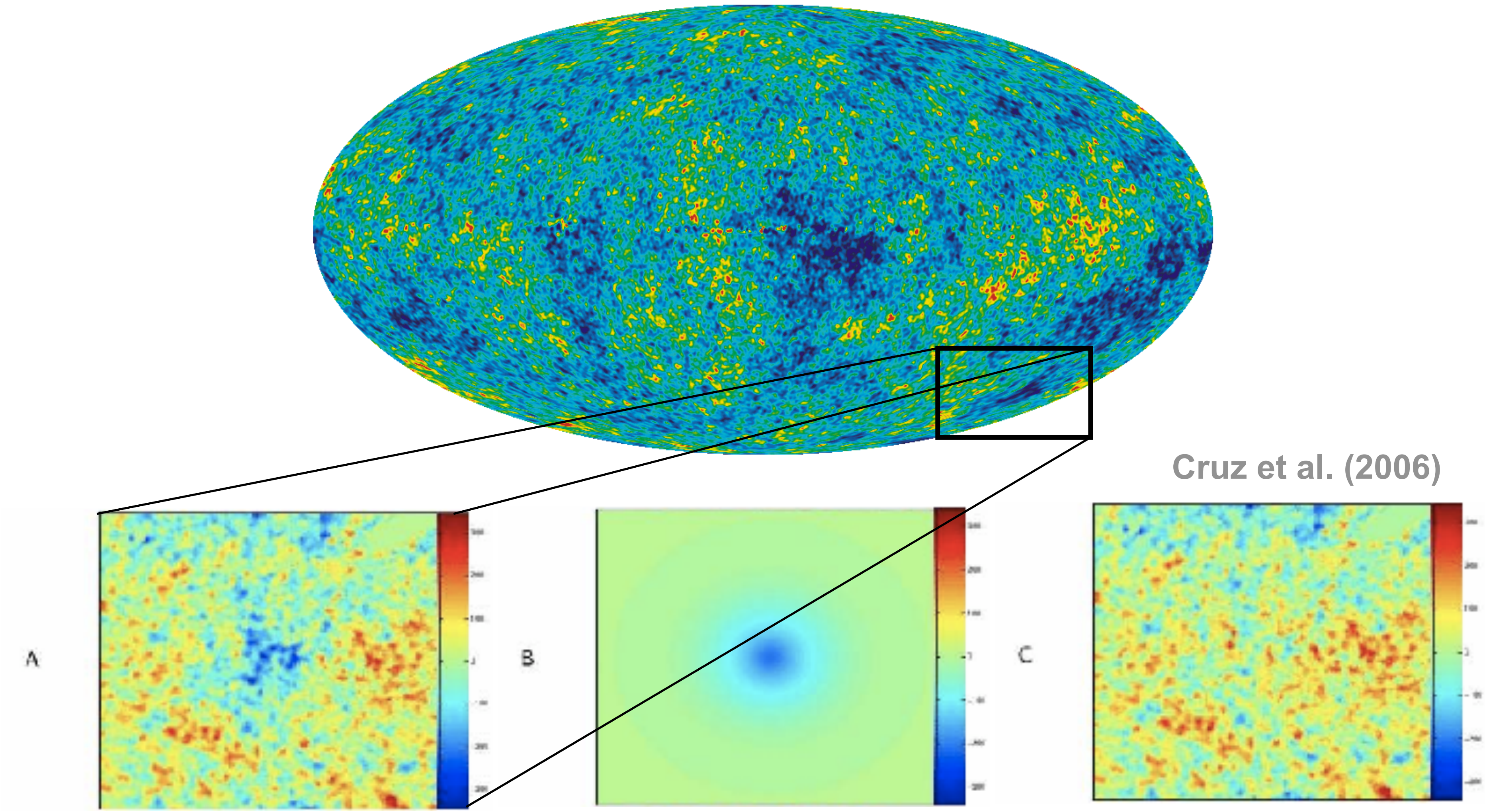


Linde, Linde & Mezhlumian (1995)

The Infloid = LTB Model



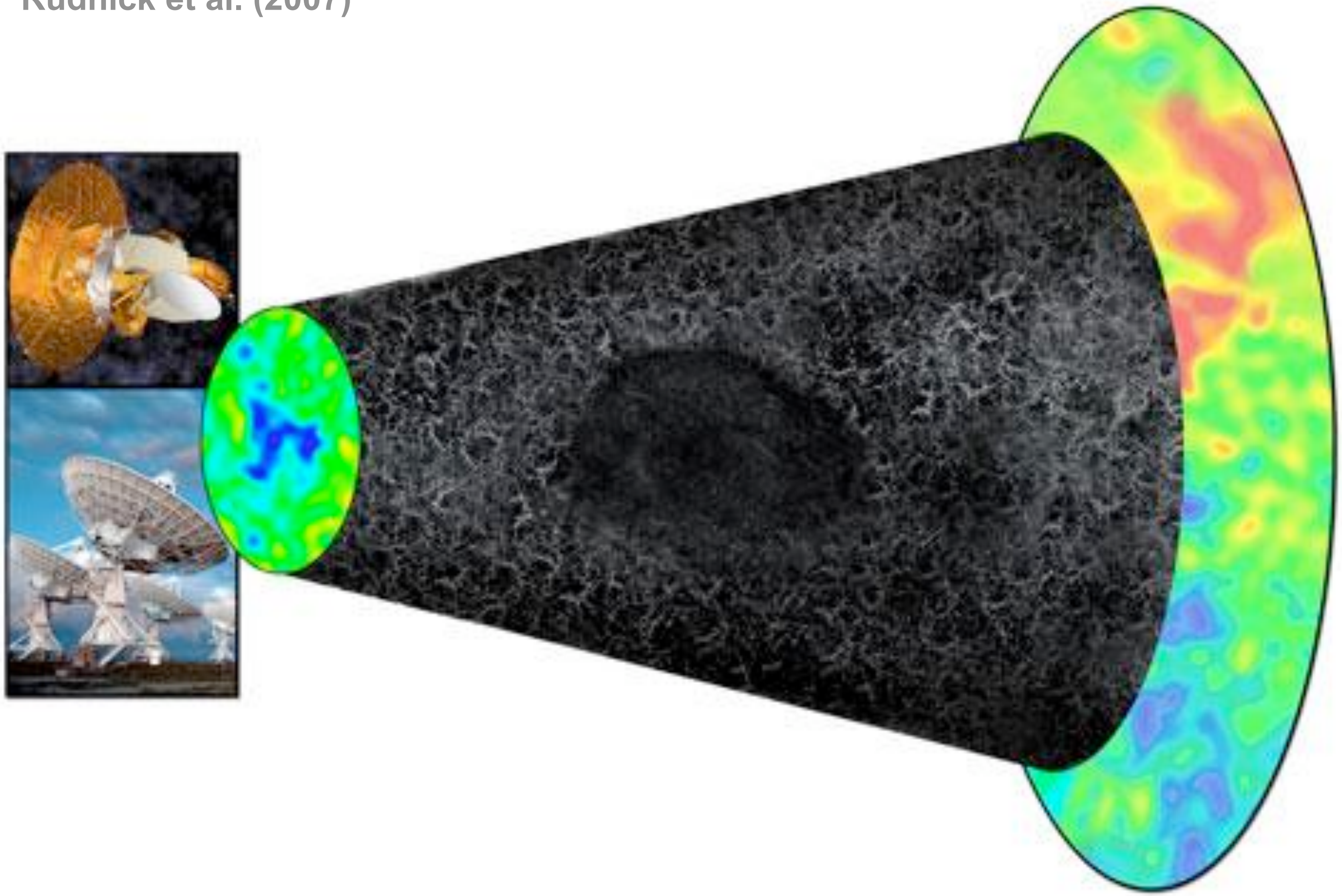
Could the Cold Spot in CMB be an "infloid" ?



A large void, approximately 2 Gpc in size

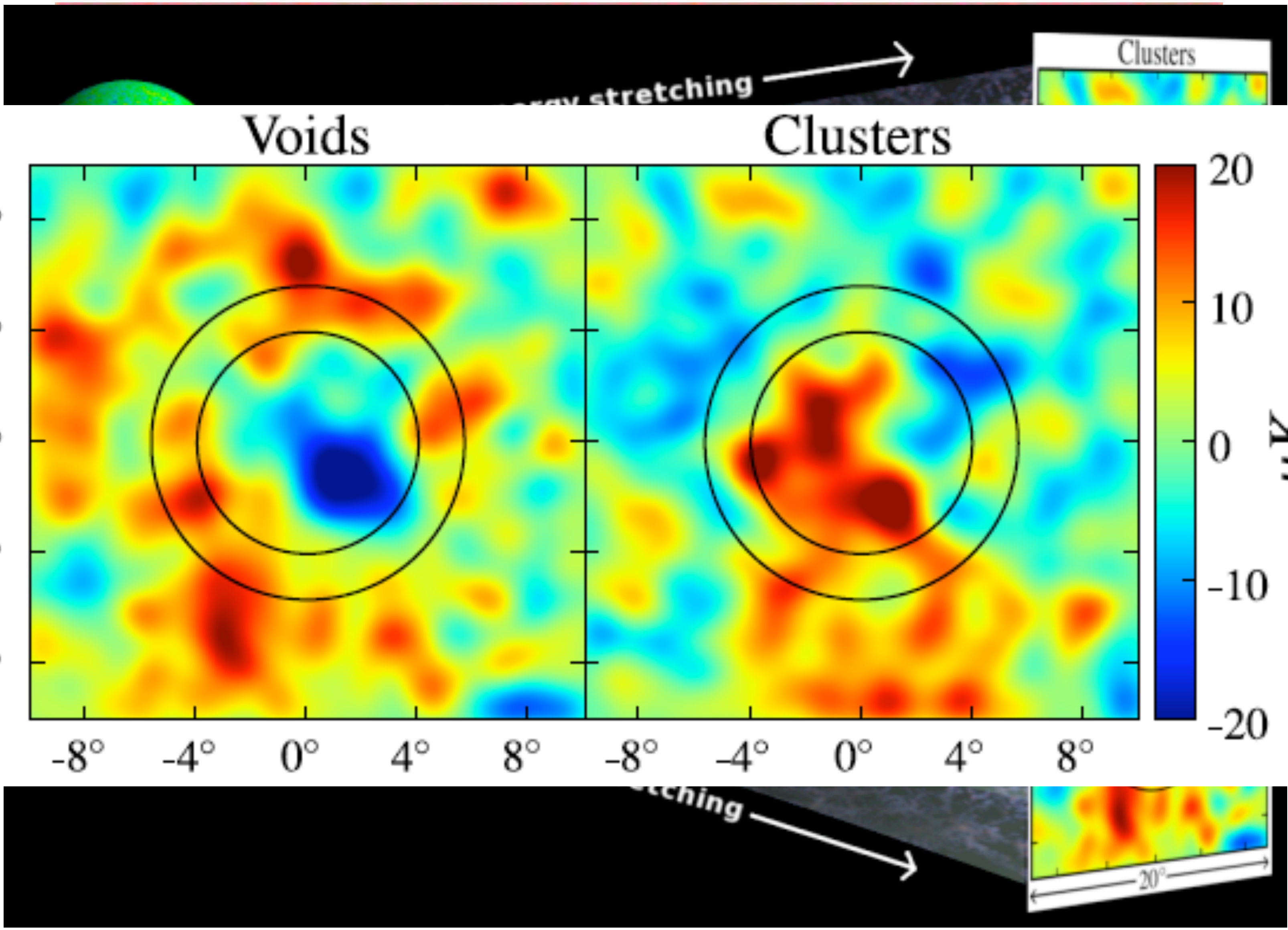
Could the Cold Spot in CMB be an “infloid” ?

Rudnick et al. (2007)



Voids and Superclusters in SDSS

Granett et al. (2008)



The Lemaître-Tolman-Bondi Model

- Describes a space-time which has spherical symmetry in the spatial dimensions, but with time and radial dependence:

$$ds^2 = -dt^2 + X^2(r,t)\,dr^2 + A^2(r,t)\,d\Omega^2$$

- From the 0-r part of the Einstein-Equations we get:

$$X(r,t) \quad = \quad A'(r,t)/\sqrt{1-k(r)}$$

- One can recover the FRW model setting:

$$A(r,t) = a(t)\,r \qquad k(r) = k\,r^2$$

Celerier (1999), Tomita(2000), Moffat (2005), Alnes et al. (2005), Enqvist & Mattsson(2006)

The Lemaitre-Tolman-Bondi Model

- Matter content:

$$T^{\mu}_{\nu} = -\rho_M(r,t)\,\delta^{\mu}_{0}\,\delta^{0}_{\nu}$$

- The other Einstein equations give:

$$\frac{\dot{A}^2 + k}{A^2} + 2\frac{\dot{A}\dot{A}'}{AA'} + \frac{k'(r)}{AA'} = 8\pi\, G\, \rho_M$$

$$\dot{A}^2 + 2A\ddot{A} + k(r) = 0$$

- Integrating the last equation:

$$\frac{\dot{A}^2}{A^2} = \frac{F(r)}{A^3} - \frac{k(r)}{A^2}$$

The Lemaitre-Tolman-Bondi Model

García-Bellido & Haugbølle (2008)

- All we need to specify:

$$F(r) = H_0^2(r)\,\Omega_M(r)\,A_0^3(r)$$

$$k(r) = H_0^2(r)\Big(\Omega_M(r) - 1\Big)\,A_0^2(r)$$

- Then the Hubble rate can be integrated to give A(r,t):

$$H^2(r,t) = H_0^2(r)\left[\Omega_M(r)\left(\frac{A_0(r)}{A(r,t)}\right)^3 + (1-\Omega_M(r))\left(\frac{A_0(r)}{A(r,t)}\right)^2\right]$$

Light Ray Propagation

- By looking at the geodesic equation, we can find the equation of motion for light rays:

$$\frac{dt}{dN} = -\frac{A'(r,t)}{\dot{A}'(r,t)} \qquad \frac{dr}{dN} = \frac{\sqrt{1-k(r)}}{\dot{A}'(r,t)}$$

where N = ln(1+z) are the # e-folds before present time.

- The various distances as a function of redshift are:

$$d_L(z) = (1+z)^2 A[r(z), t(z)]$$

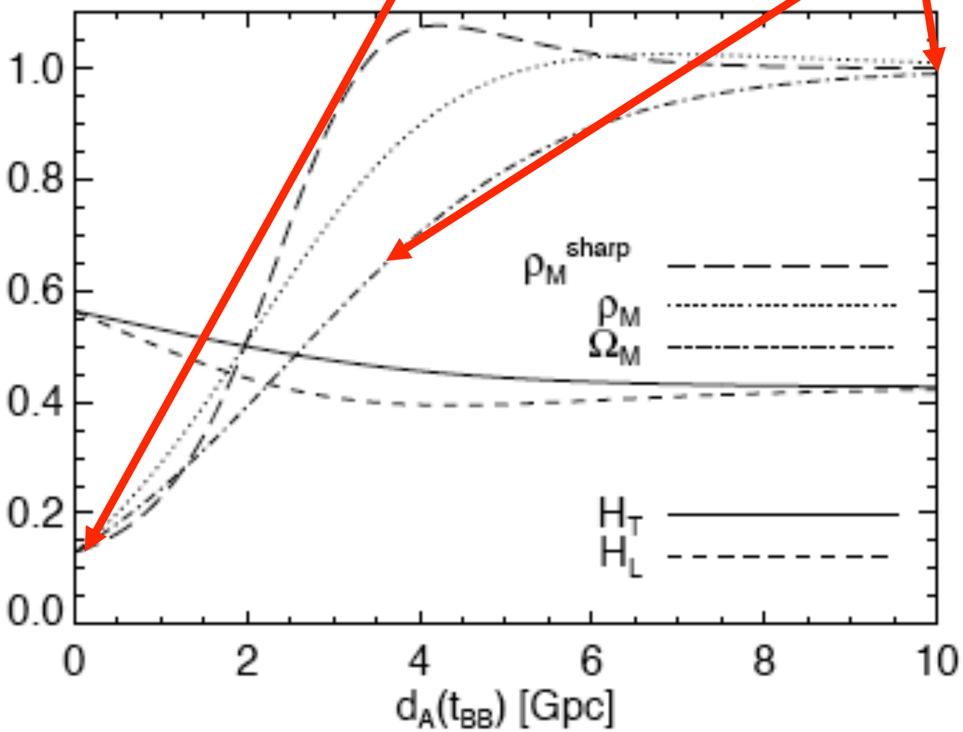
$$d_C(z) = (1+z)\, A[r(z), t(z)]$$

$$d_A(z) = A[r(z), t(z)]$$

The LTB-GBH model

$$\Omega_M(r) = \Omega_{\rm out} + \left(\Omega_{\rm in} - \Omega_{\rm out}\right)\left(\frac{1 - \tanh[(r - r_0)/2\Delta r]}{1 + \tanh[r_0/2\Delta r]}\right)$$

$$H_0(r) = H_{\rm out} + \left(H_{\rm in} - H_{\rm out}\right)\left(\frac{1 - \tanh[(r - r_0)/2\Delta r]}{1 + \tanh[r_0/2\Delta r]}\right)$$



- If we assume asymptotic flatness, then the model has **5** parameters
- If we require a homogeneous Big Bang then the model has **4** parameters

García-Bellido & Haugbølle (2008)

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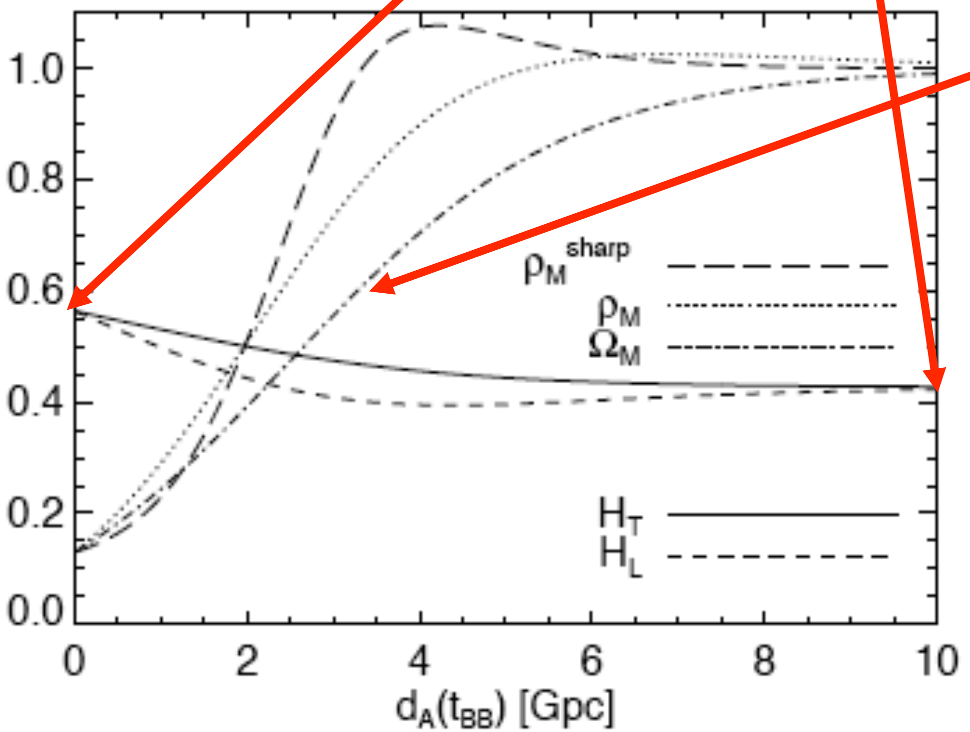

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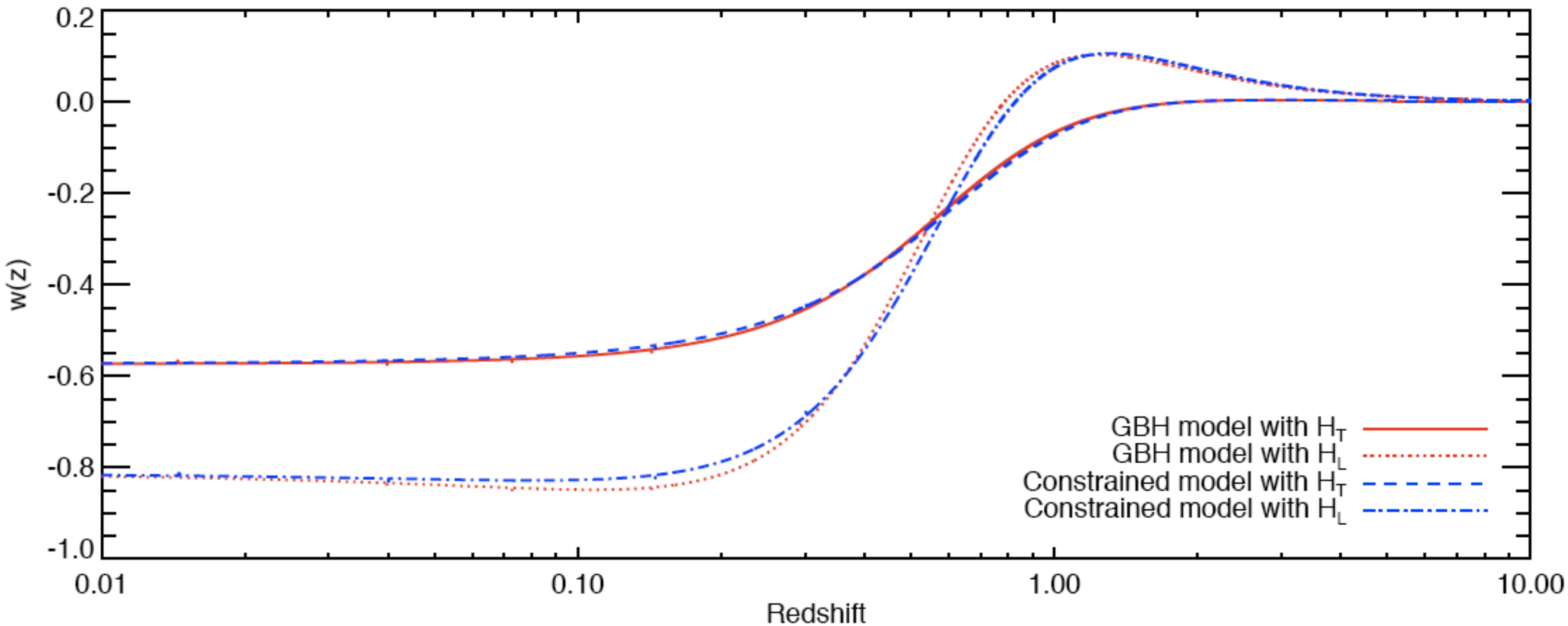
García-Bellido & Haugbølle (2008)

LTB-GBH model

- Effective equation of state parameter:

$$w_{\rm eff}^{T,L}(z) = -1 + \frac{1}{3}\frac{d\log\left[\frac{H^2_{T,L}(z)}{H^2_{\rm in}} - (1+z)^3\Omega_{\rm in}\right]}{d\log[1+z]}$$

García-Bellido & Haugbølle (2008)

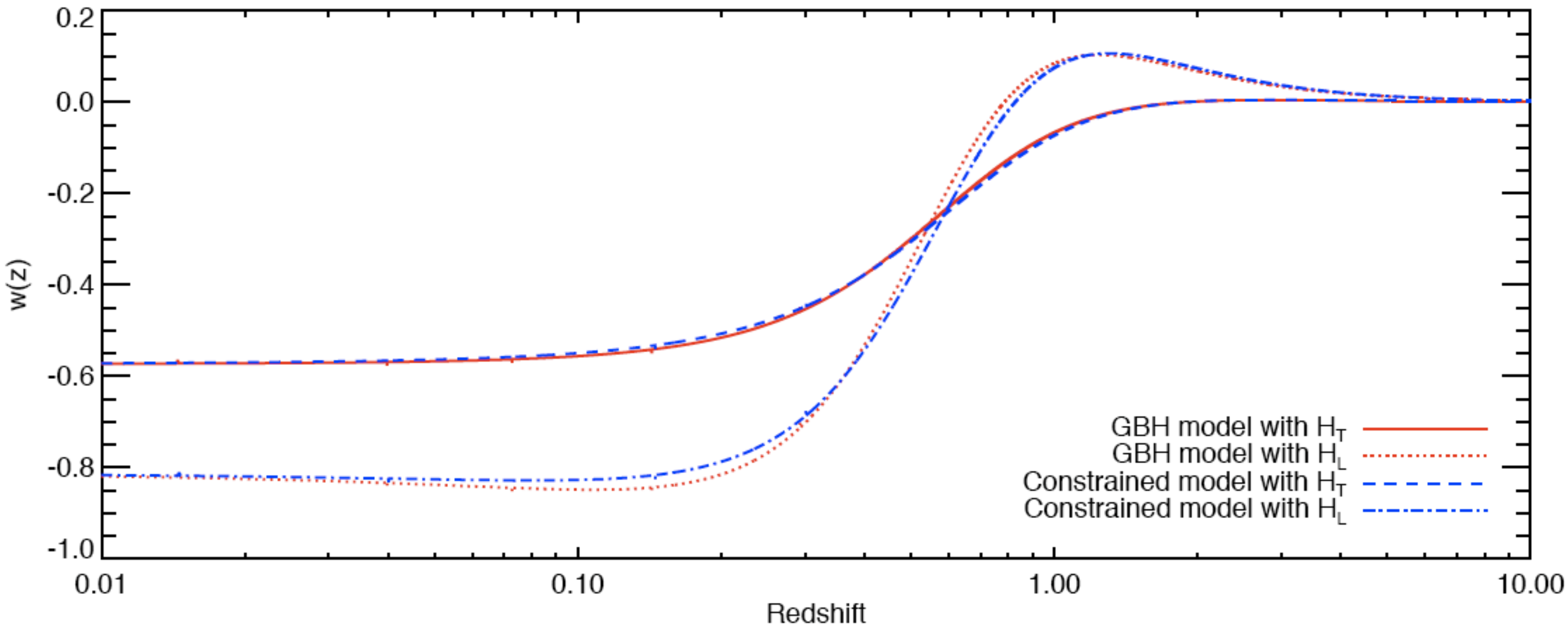


LTB-GBH model

- Effective equation of state parameter:

$$w_{\rm eff}^{T,L}(0) = \begin{cases} -\frac{1}{3} + \frac{2}{3}\frac{cH_0'(0)}{(1-\Omega_{\rm in})H_{\rm in}^2} & \text{if} \quad H = H_T \\ -\frac{1}{3} + \frac{4}{3}\frac{cH_0'(0)}{(1-\Omega_{\rm in})H_{\rm in}^2} & \text{if} \quad H = H_L \end{cases}$$

García-Bellido & Haugbølle (2008)



Constraining Cosmological Data

- Type Ia Supernovae: 307 SNIa Union Supernovae

  Simple to do since we just fit against $d_L(z)$

- 1^{st} acoustic peak in the CMB: $d_C(z_{rec})$, sound horizon $r_s(z)$

- Baryon Acoustic Oscillations:

  Sound horizon $$D_V(z) = \left[d_A^2(z)(1+z)^2 \frac{cz}{H_L(z)} \right]^{1/3}$$

- Other constraints:
  - $f_{gas} = \rho_b / \rho_m = \omega_b / (\Omega_m h^2)$
  - Hubble key project: $H_0 = 72 \pm 8$ km/s/Mpc (1σ)
  - Globular cluster lifetimes ($t_{BB} > 11.2$ Gyr)

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3 distances

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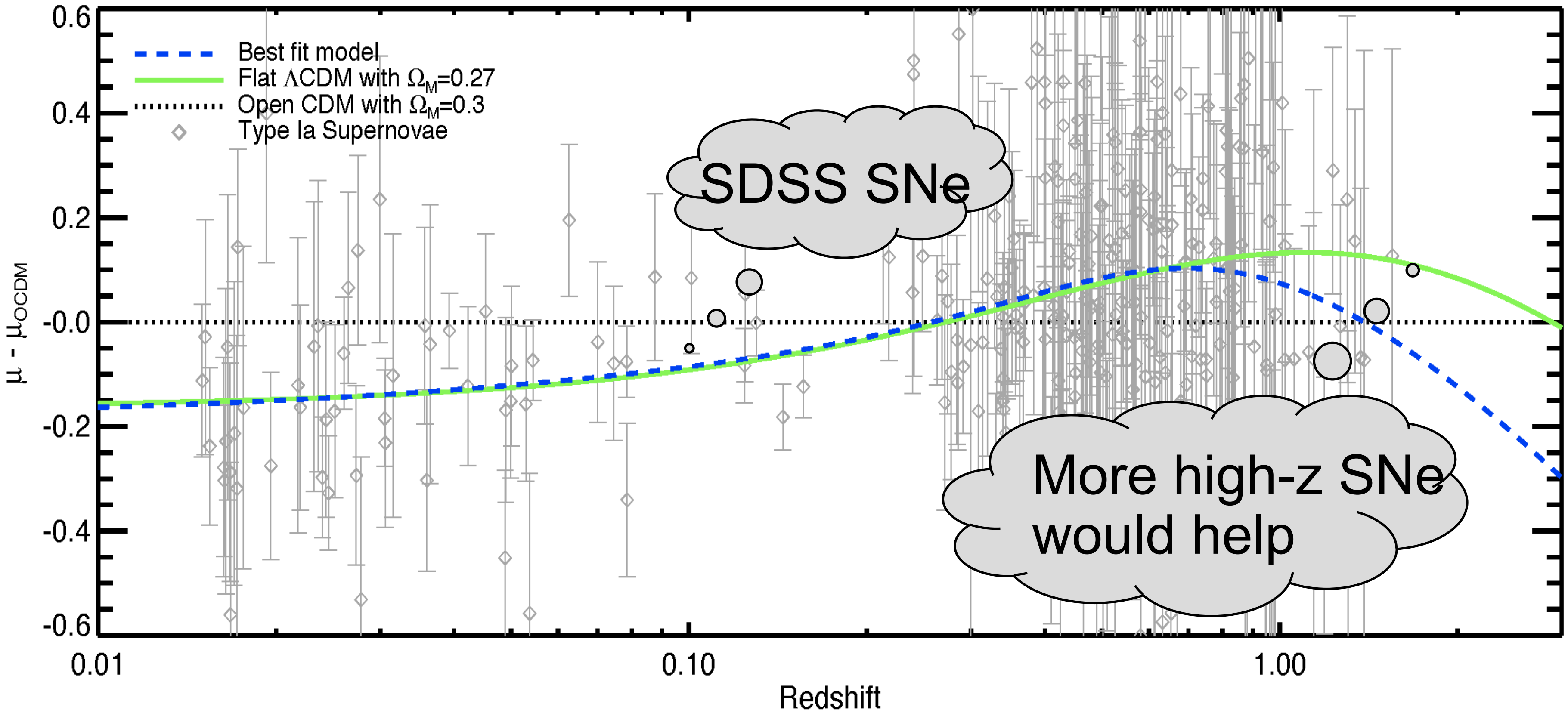
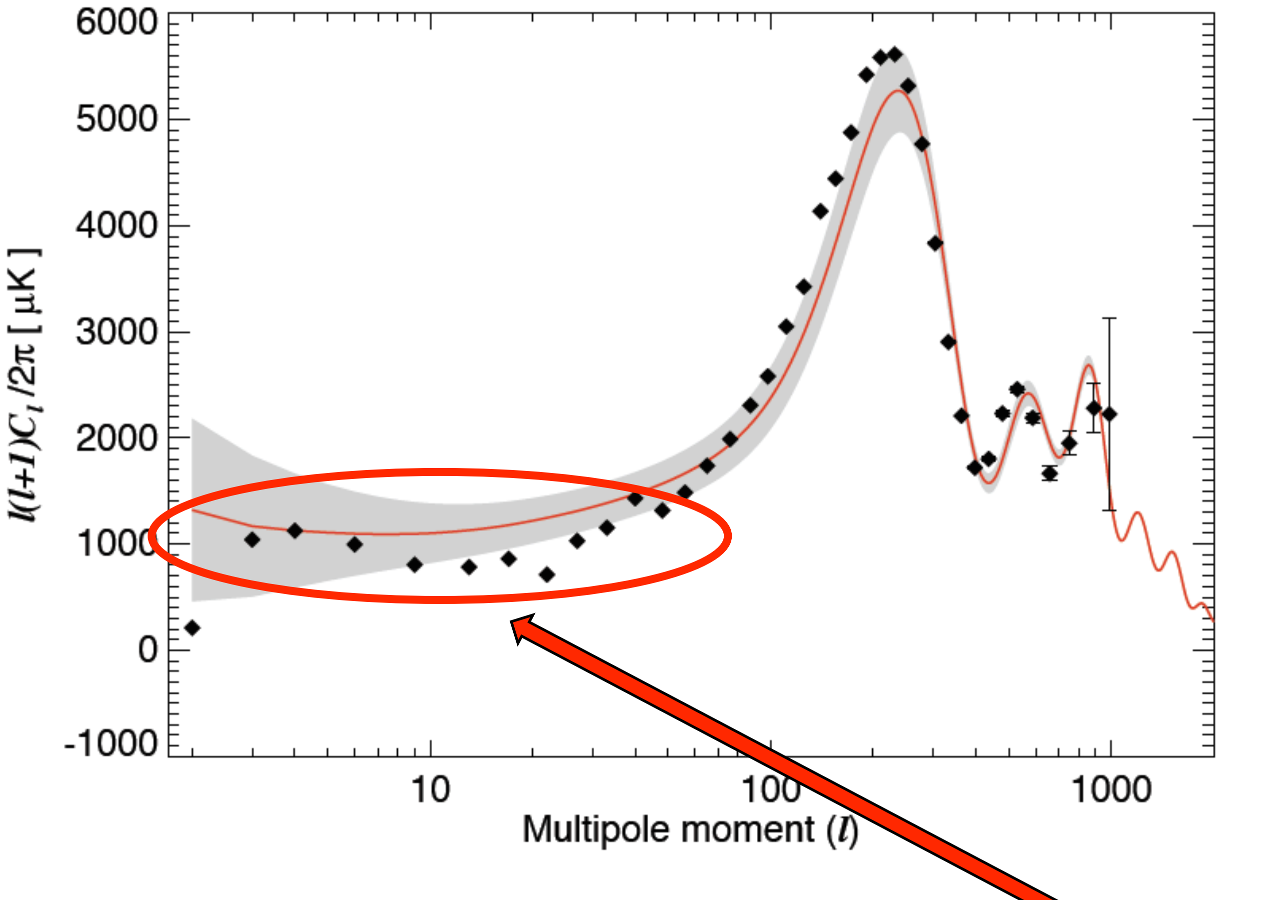
Fitting the Union Supernovae

- The best fit GBH-model has no problem with SNe Ia
- One can always find a void model that fits SNe as ΛCDM

García-Bellido & Haugbølle (2008)



Fitting the 1st peak in the CMB



- The fit to the *first* peak is OK - we did *not* try to fit all data!
- LTB perturbation theory (work in progress) to explain low *l* (ISW)

Radial BAO & LTB

$$\Delta z_{BAO}(z_i) = \frac{H(z_i) r_s}{c}$$

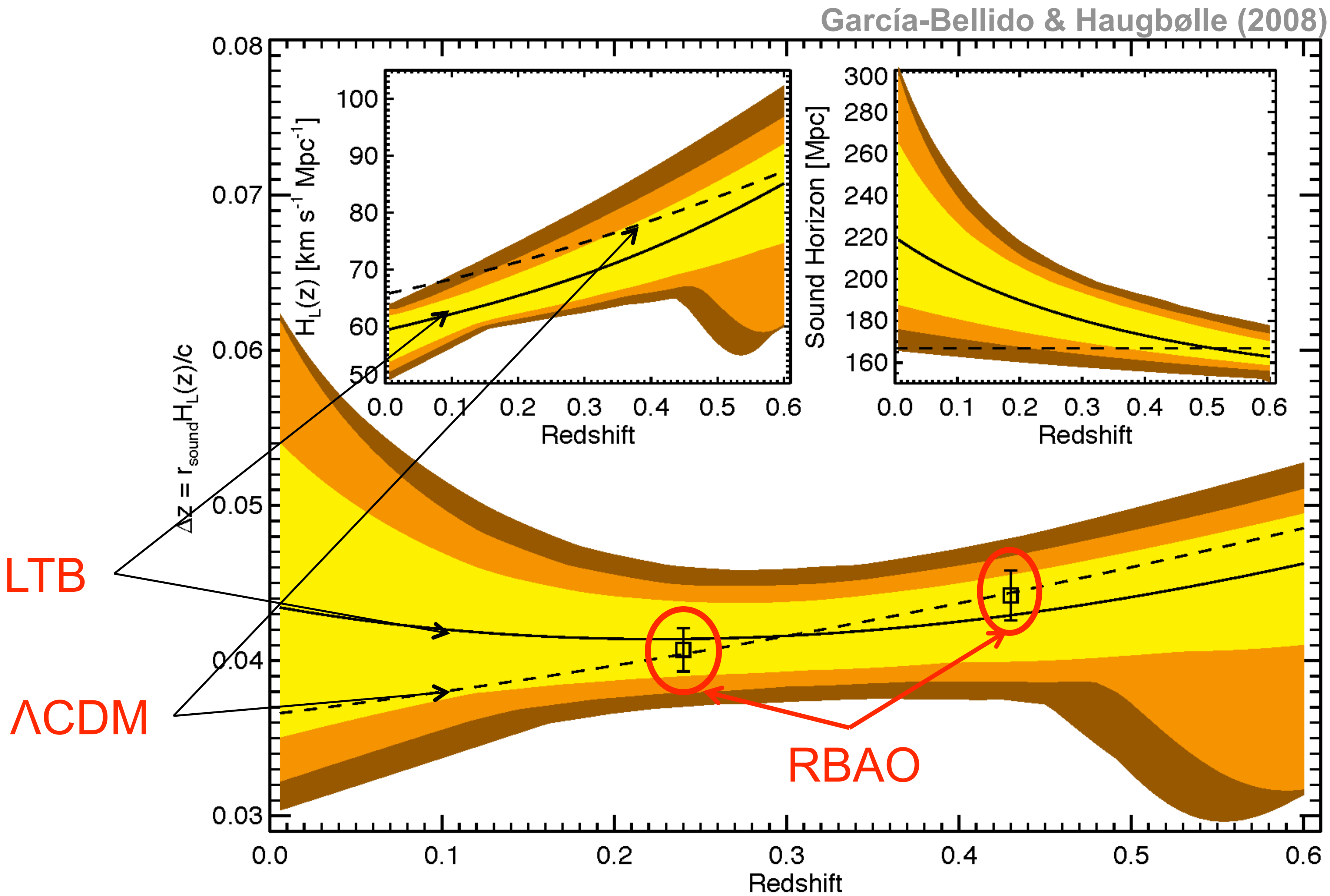
$$\Downarrow$$

scaled distances: $$\Delta z_{LTB} = \frac{H_L(z) r_s(z)}{c}$$

r_s = sound horizon at recombination

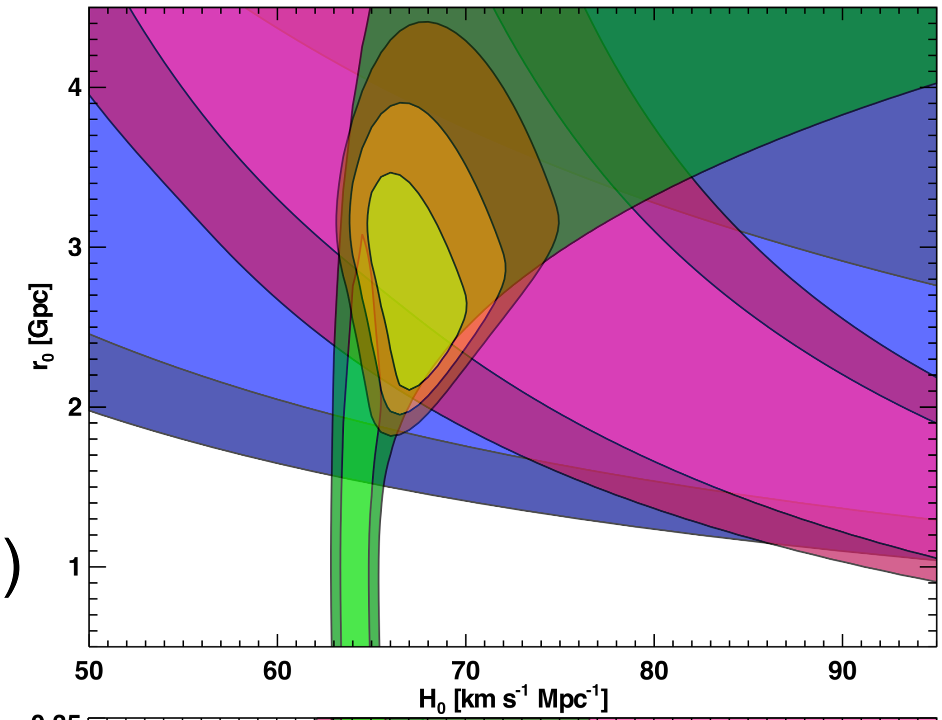
Sample z range	z_m	r_{BAO} Mpc/h	σ_{st}	σ_{sys}	Δz_{BAO}	σ_{st}	σ_{sys}
0.15-0.30	0.24	110.3	2.5	1.35	0.0407	0.0009	0.0005
0.40-0.47	0.43	108.9	2.8	1.22	0.0442	0.0011	0.0005

Sound horizon and line of sight rate of expansion

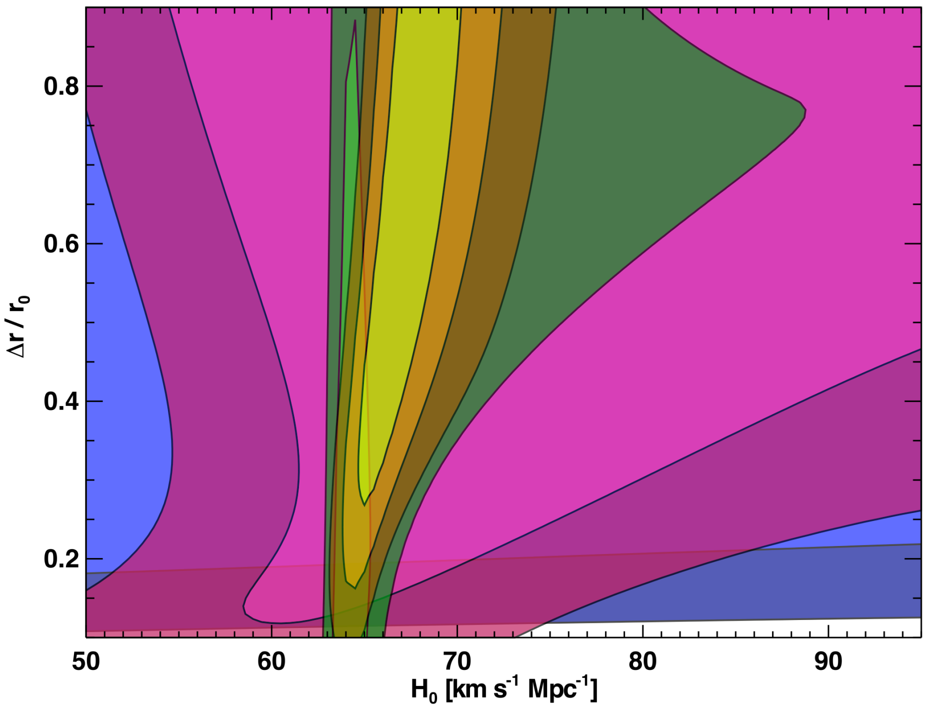


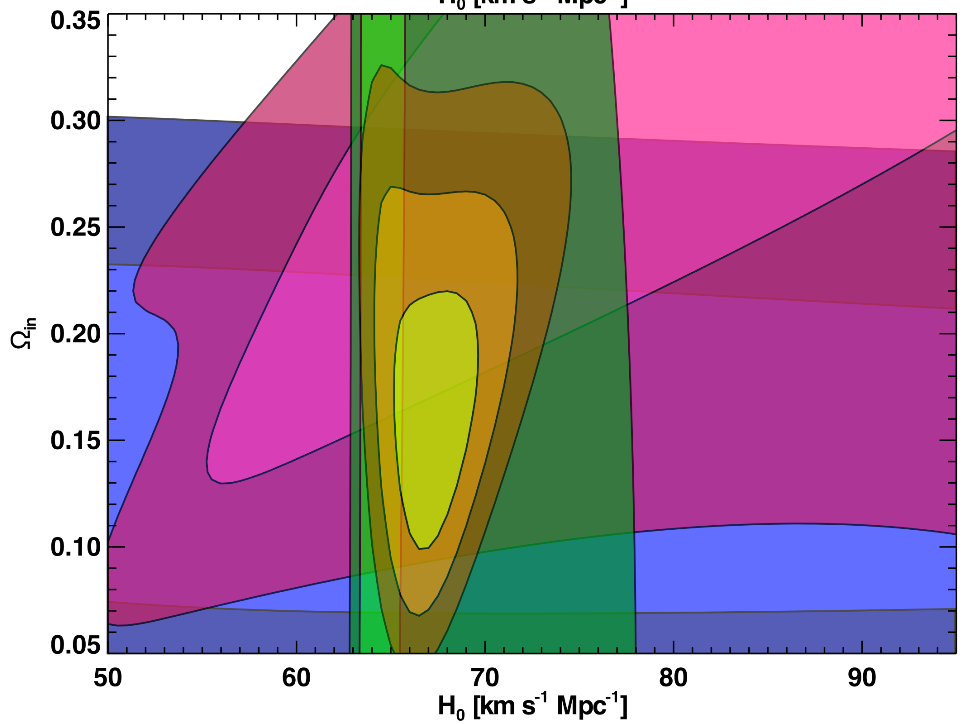
Scanning the model

- Yellow: Everything, Blue: SNe .
- Green: CMB. Purple: BAO
- Supernovae constrain Ω_{matter}
- CMB constrains the H_0, (Ω_{out}=1)

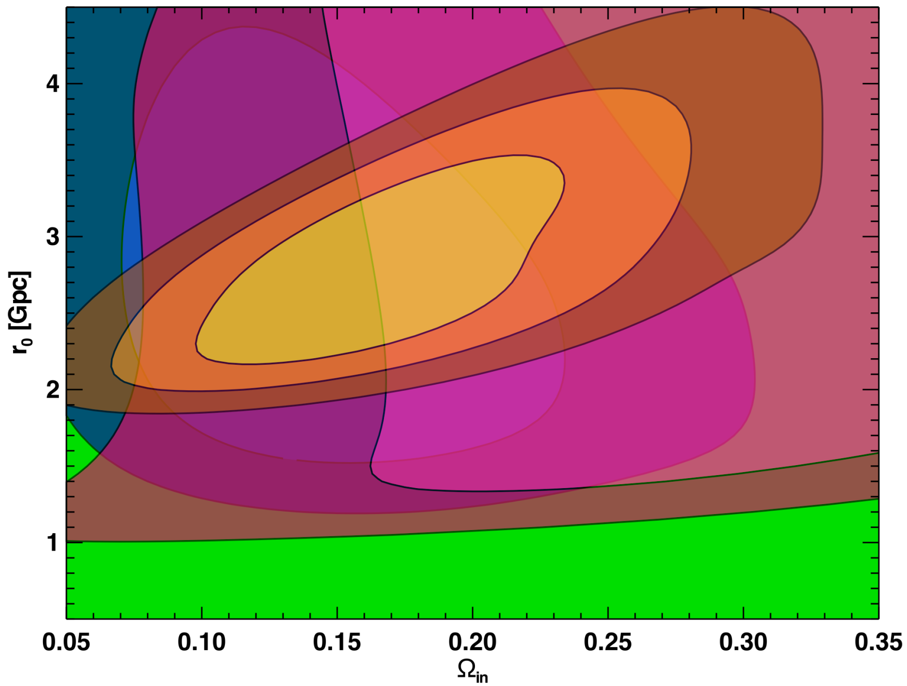


García-Bellido & Haugbølle (2008)





- The SNe and BAO pushes the void size to r_0 > 1.8 Gpc
- Some tension between RBAO and SNe (waiting for high-z SNe)
- Large degeneracy between r_0 and $\Delta r/r_0$



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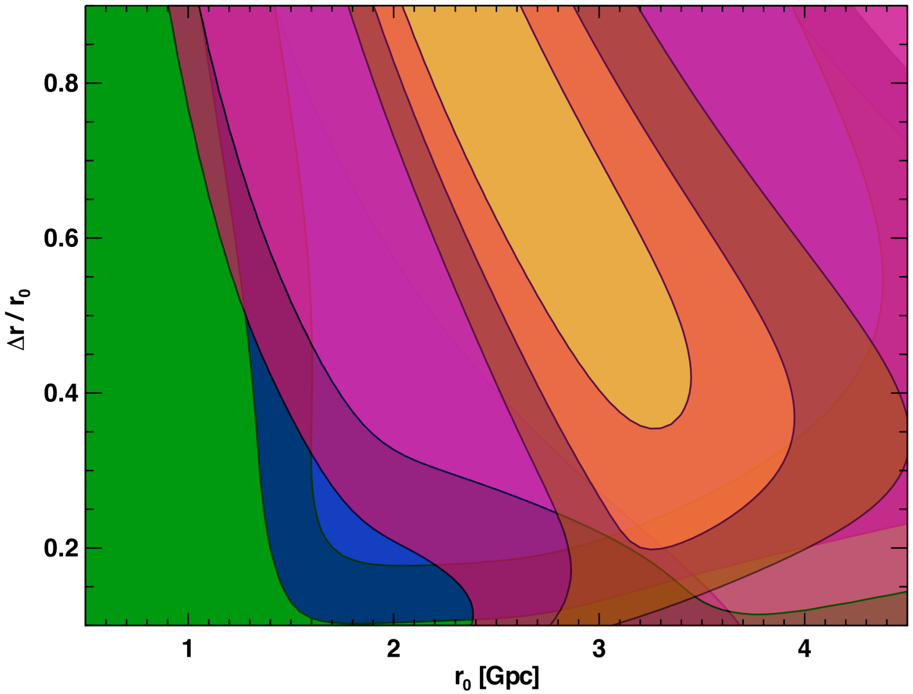

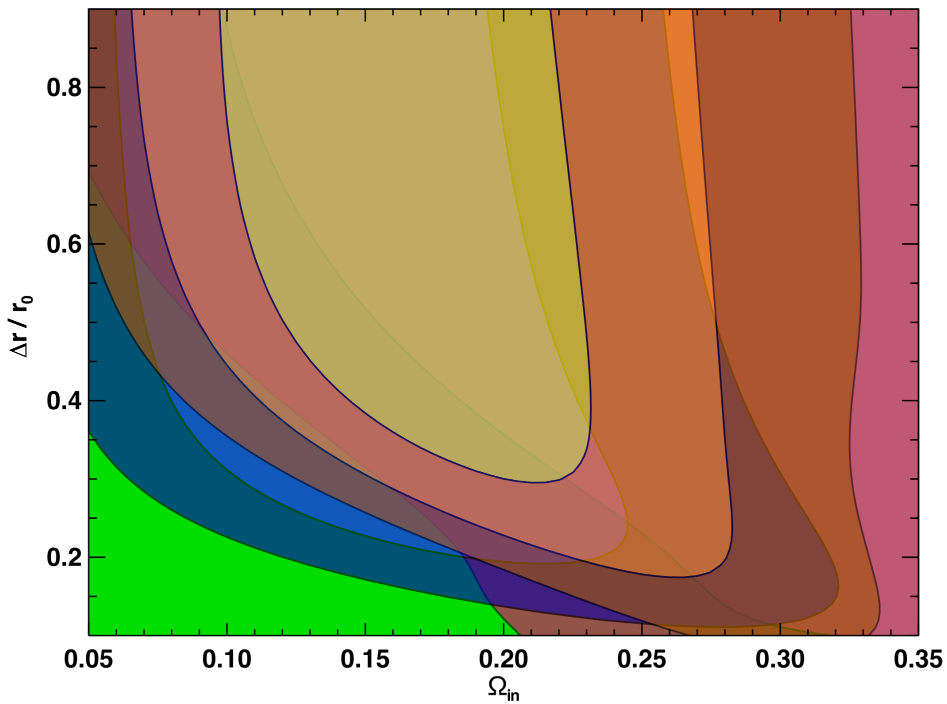

Marginalized errors

García-Bellido & Haugbølle (2008)

Model	H_0	$H_{\rm in}$	$H_{\rm out}$	$H_{\rm eff}$
units		100 km s^{-1} Mpc^{-1}		
GBH	–	0.58±0.03	0.49±0.2	0.43
Constrained	0.64±0.03	0.56	0.43	0.42

Model	$\Omega_{\rm in}$	r_0	Δr	t_{BB}
units		Gpc	r_0	Gyr
GBH	0.13±0.06	2.3±0.9	0.62(>0.20)	14.8
Constrained	0.13±0.06	2.5±0.7	0.64(>0.21)	15.3

!!

$\chi^2_{\Lambda CDM} / d.o.f. = 1.021$ $\chi^2_{LTB-GBH} / d.o.f. = 1.036$

Bayesian analysis

- Posterior distribution for param θ, given model M & data D

$$\mathcal{P}(\theta,\mathcal{M}|\mathbf{D}) = \frac{\mathcal{L}(\mathbf{D}|\theta,\mathcal{M})\,\pi(\theta,\mathcal{M})}{E(\mathbf{D}|\mathcal{M})}$$

- Bayesian evidence: average likelihood L over priors π

$$E(\mathbf{D}|\mathcal{M}) = \int d\theta\;\mathcal{L}(\mathbf{D}|\theta,\mathcal{M})\,\pi(\theta,\mathcal{M})$$

- Bayes factor between competing models { i, j } :

$$B_{ij} \equiv \frac{E(\mathbf{D}|\mathcal{M}_i)}{E(\mathbf{D}|\mathcal{M}_j)}$$

Jeffreys' scale

- Occam's razor: Arbitrary scale on log Bij with unit steps

$$\ln B_{ij} = 0$$ undecisive

$$\ln B_{ij} = 1$$ weakly disfavoured

…

$$\ln B_{ij} = 5$$ strongly ruled out

- LTB-GBH model versus FRW-ΛCDM

$$\ln E(\Lambda CDM) = -103.1$$

$$\ln E(GBH) = -106.7$$

$$\ln B_{12} = 3.6$$

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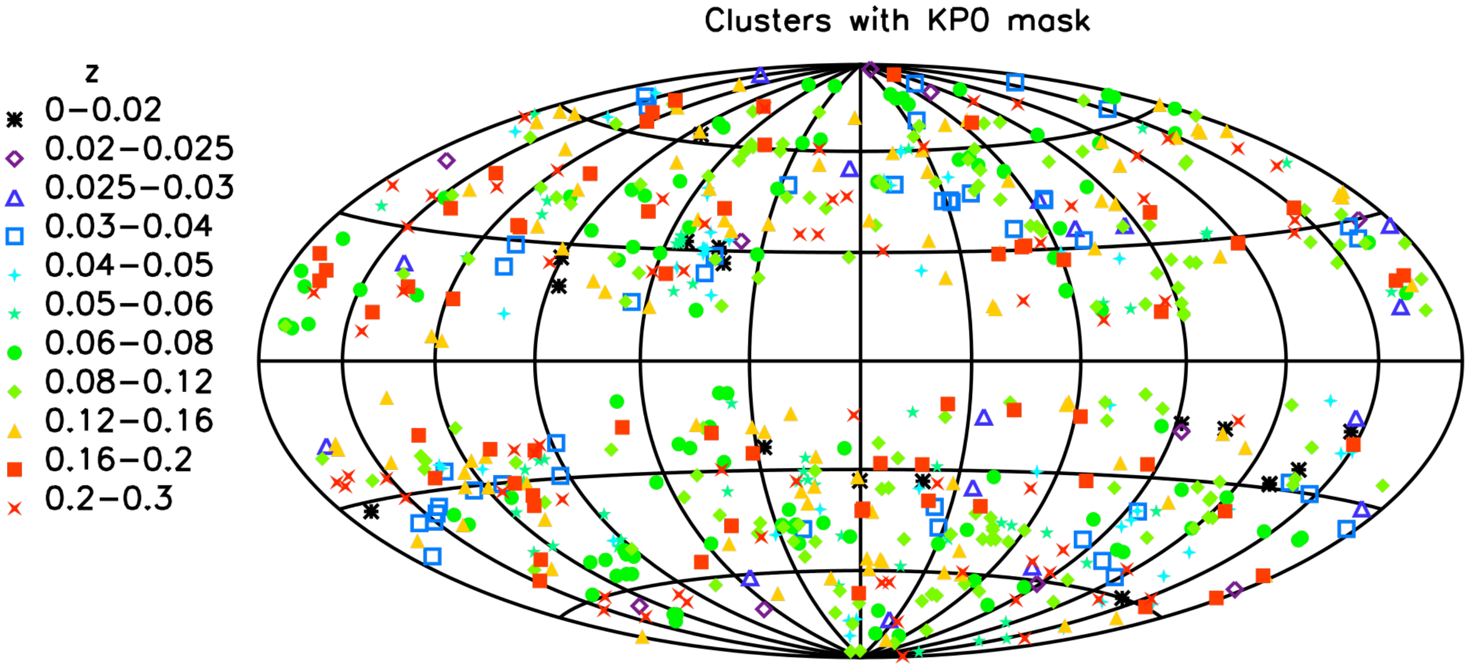
Kashlinsky, Atrio-Barandela, Kocevski & Ebeling (2008)



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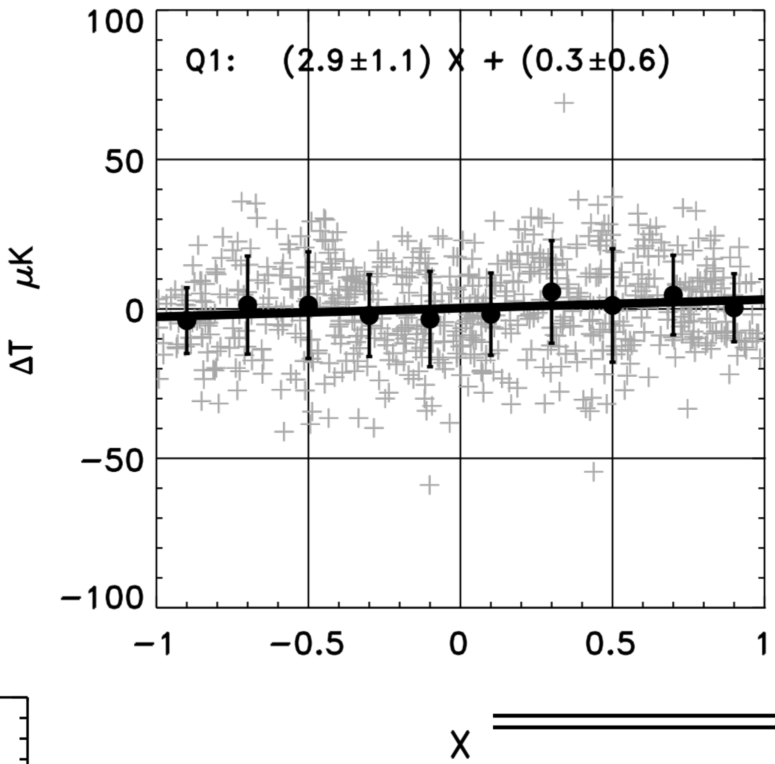

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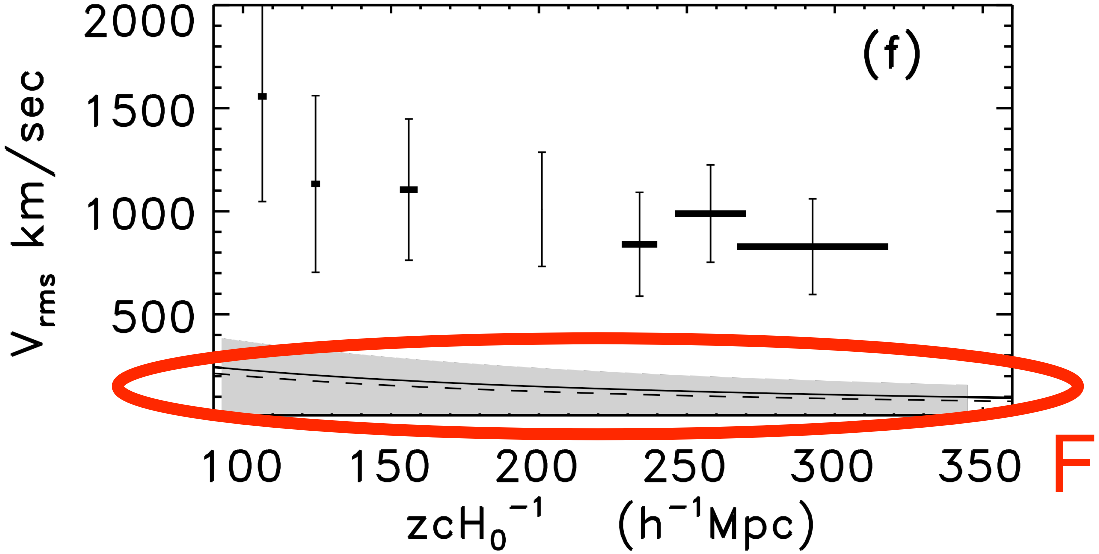


FRW-ΛCDM

$X = \cos \mu$

(11) (l,b) deg
$(295, 14) \pm 13$
$(267, 34) \pm 15$

Preliminary Conclusions

- LTB models are in mild contradiction with current kinetic Sunyaev-Zeldovich observations.

- In a years time or so the ACT/SPT will report their first results, and either large scale voids are ruled out or confirmed.

- It seems clear that kSZ measurements will put by far the strongest observational constraints on LTB models compared to other cosmological data.

- There is maybe a large scale flow in the local universe, naturally explained in the void model, but in conflict with the standard ΛCDM model.

A new observable: cosmic shear

$$\frac{d\Theta}{d\tau} = -\frac{1}{3}\Theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}n^\mu n^\nu$$

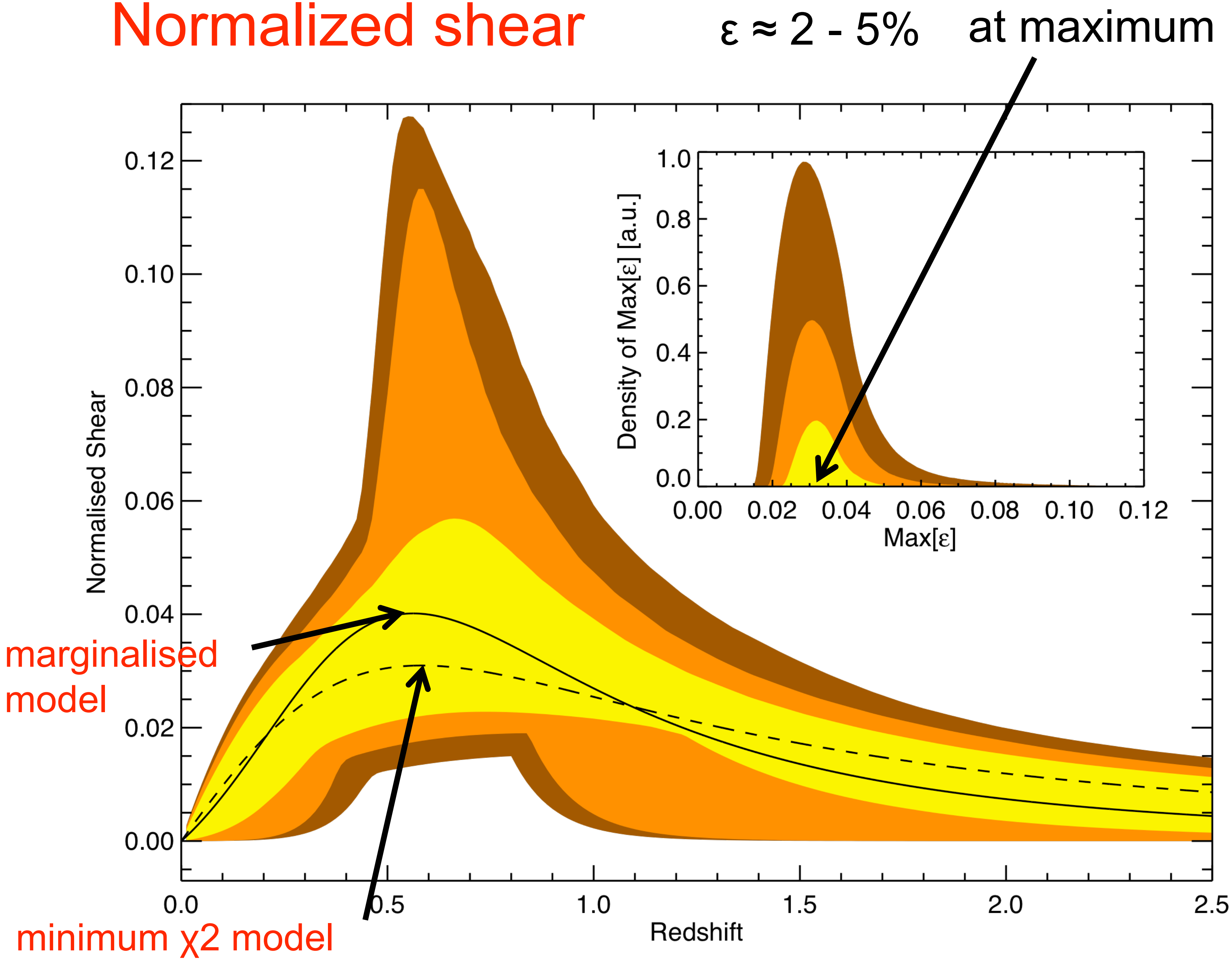
$$\varepsilon \equiv \sqrt{\frac{3}{2}}\frac{\sigma}{\Theta} = \frac{H_T - H_L}{H_L + 2H_T}$$ normalized shear

$$\boxed{\varepsilon(z) = \frac{1 - H_L(z)[(1+z)\, d_A(z)]'}{3H_L(z)d_A(z) + 2 - 2H_L(z)[(1+z)\, d_A(z)]'}}$$

FRW: $H_L = H_T = H$ shearless

$(1+z)d_A = \int dz/H(z)$ $\quad \varepsilon(z) = 0$

Normalized shear



Discussion

- Void models, observationally, seem a real alternative to the standard model. While they break away from the Copernican Principle, they do not need dark energy!
- There is no coincidence problem either! It was there always

  The “Why Now?” becomes “Why Here?” !

- A void model with a size of ~ 2 Gpc yields a perfect fit to observations constraining the geometry of the universe.

- The final test will be comparing the model to observations:
  - Large scale shear + bulk flows near z~0.5 (DES, PAU)
  - CMB, and matter power spectra (More theory: ISW)
  - Remote measurements of the CMB: The kinematic Sunyaev Zeldovich effect (ACT, SPT, Planck)

Conclusions

Present observations do not exclude the possibility that we live close to the center of a large (Gpc size) void.

Such voids could arise from eternal Inflation via non-perturb. fluctuations

Perhaps there is no need for
Dark Energy / Cosmological Constant
We could tell by making observations of cosmic shear in future surveys