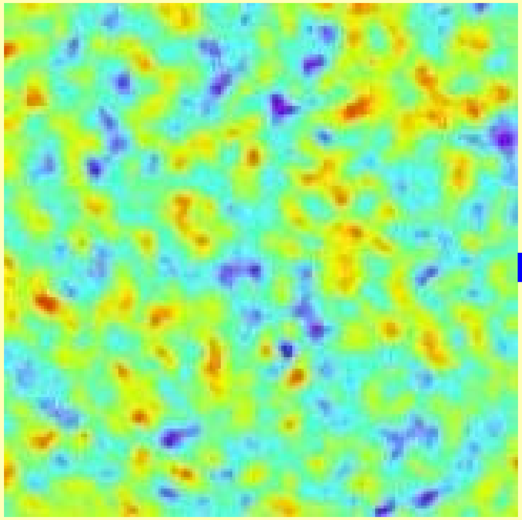
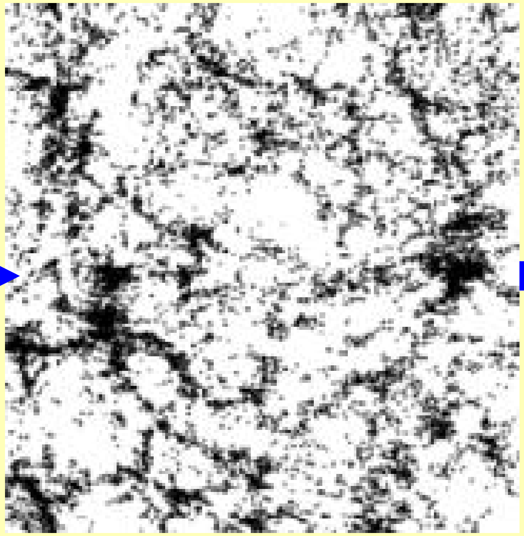
Cosmology now



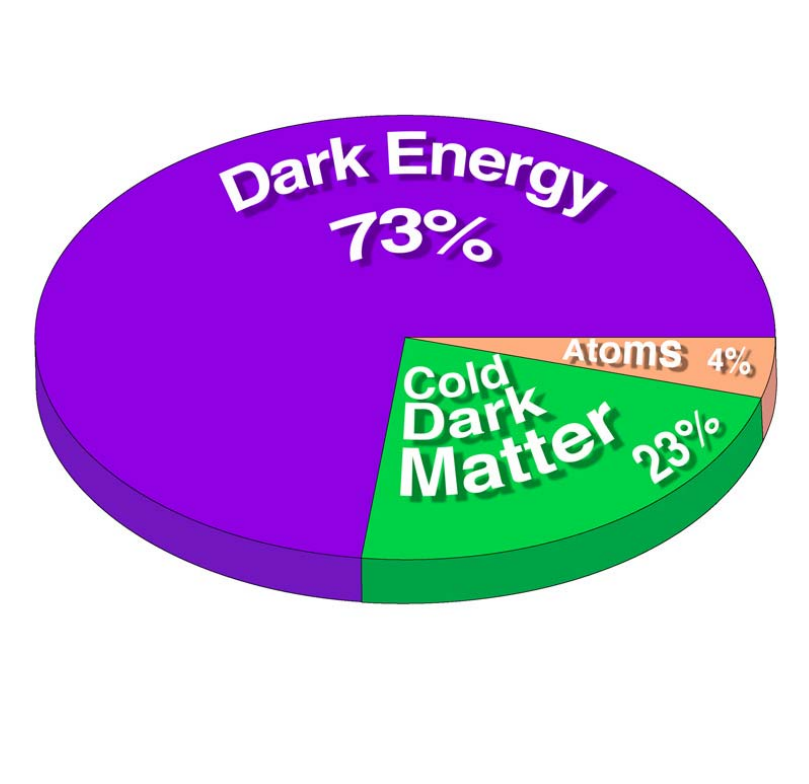


John Peacock

Observing the Dark Universe with Euclid

Estec Nov 17 2009

Outline



- Past ! now
- Open questions
- Issues for the future

Maisie Peacock 1911 – 2009

1913: Redshift (not) of M31

LOWELL OBSERVATORY

BULLETIN No. 58

VOL. II | No. 8

THE RADIAL VELOCITY OF THE ANDROMEDA NEBULA

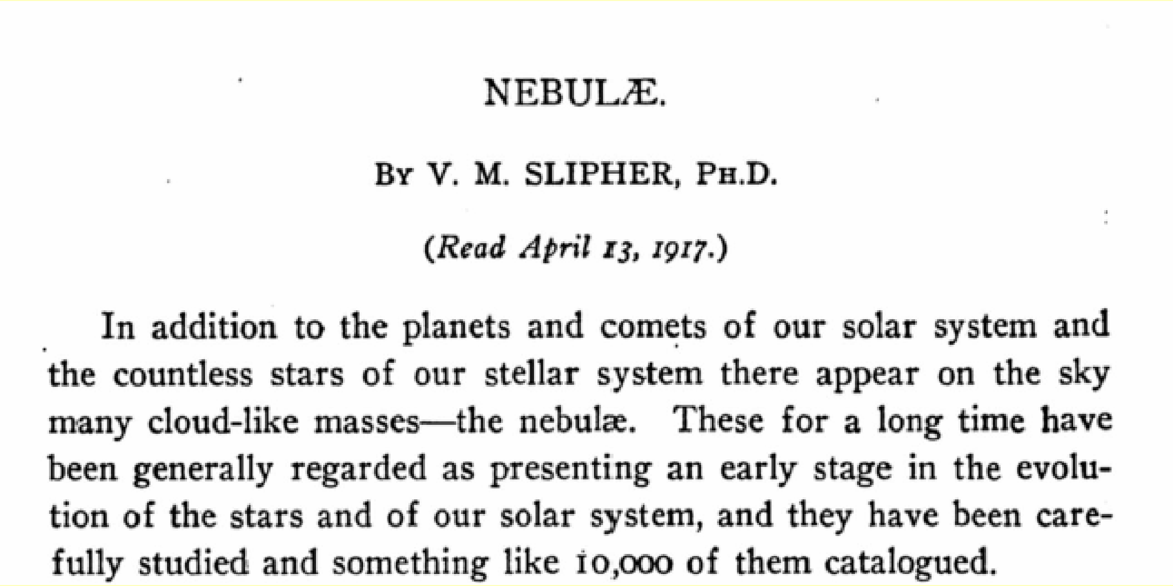
1912,	September	17,	Velocity,	—284 km.
	November	15–16,	"	296
	December	3–4,	"	308
	December	29–30–31,	"	—301
		Mean velocity,		—300 km.

The magnitude of this velocity, which is the greatest hitherto observed, raises the question whether the velocity-like displacement might not be due to some other cause, but I believe we have at the present no other interpretation for it. Hence we may conclude that the Andromeda Nebula is approaching the solar system with a velocity of about 300 kilometers per second.

This result suggests that the nebula, in its swift flight through space, might have encountered a dark "star,"

Vesto Slipher (1875-1969)

1917



NEBULÆ.

BY V. M. SLIPHER, PH.D.

(*Read April 13, 1917.*)

In addition to the planets and comets of our solar system and the countless stars of our stellar system there appear on the sky many cloud-like masses—the nebulæ. These for a long time have been generally regarded as presenting an early stage in the evolution of the stars and of our solar system, and they have been carefully studied and something like 10,000 of them catalogued.

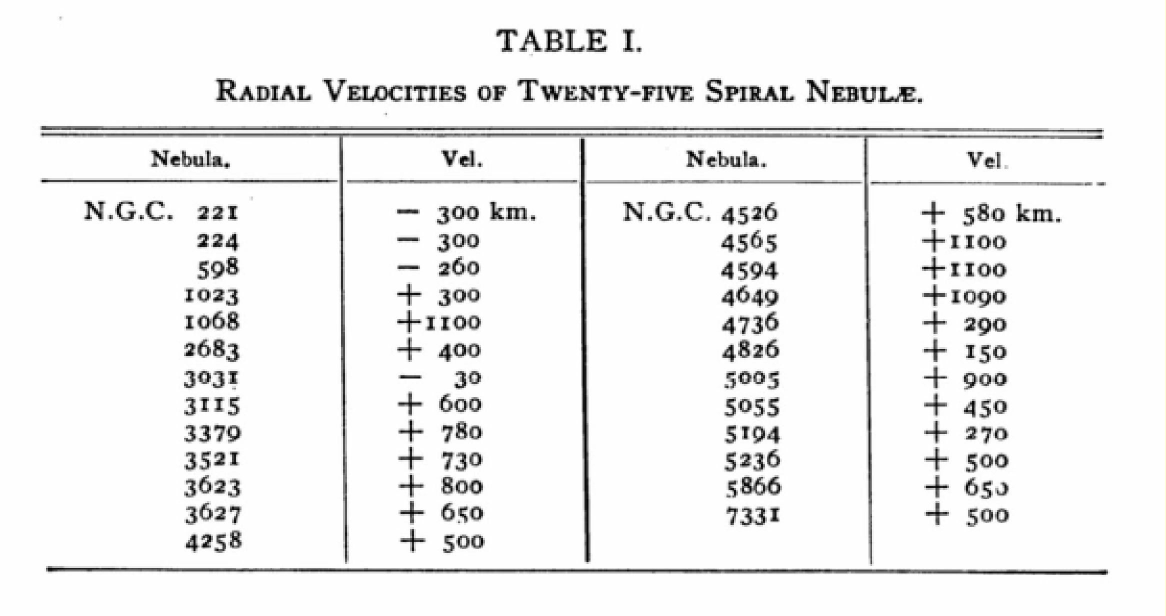


TABLE I.

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

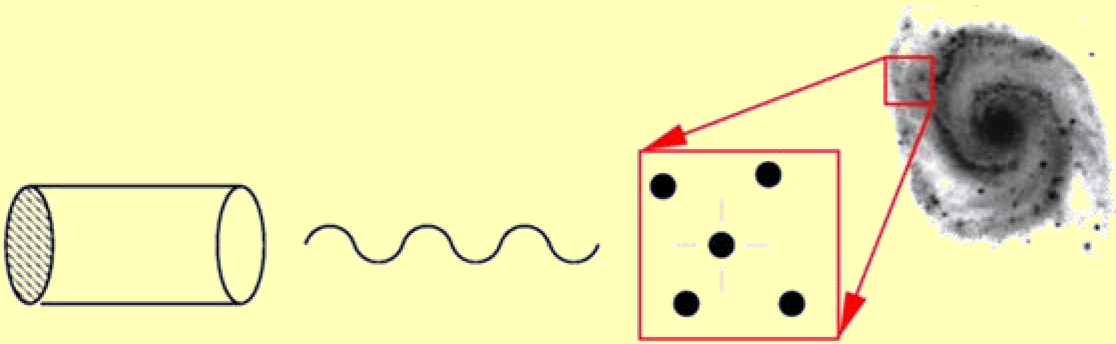
Proc. Amer. Phil. Soc., 56, 403 (1917)

21/25 redshifted

The Great Debate

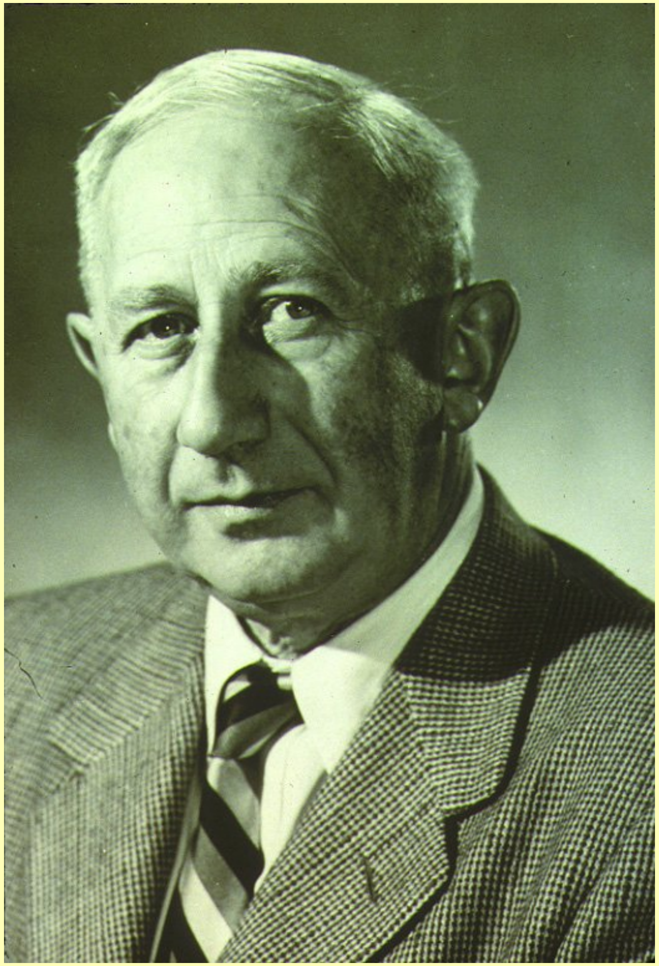
Are nebulae clouds of gas,
or distant systems of stars?

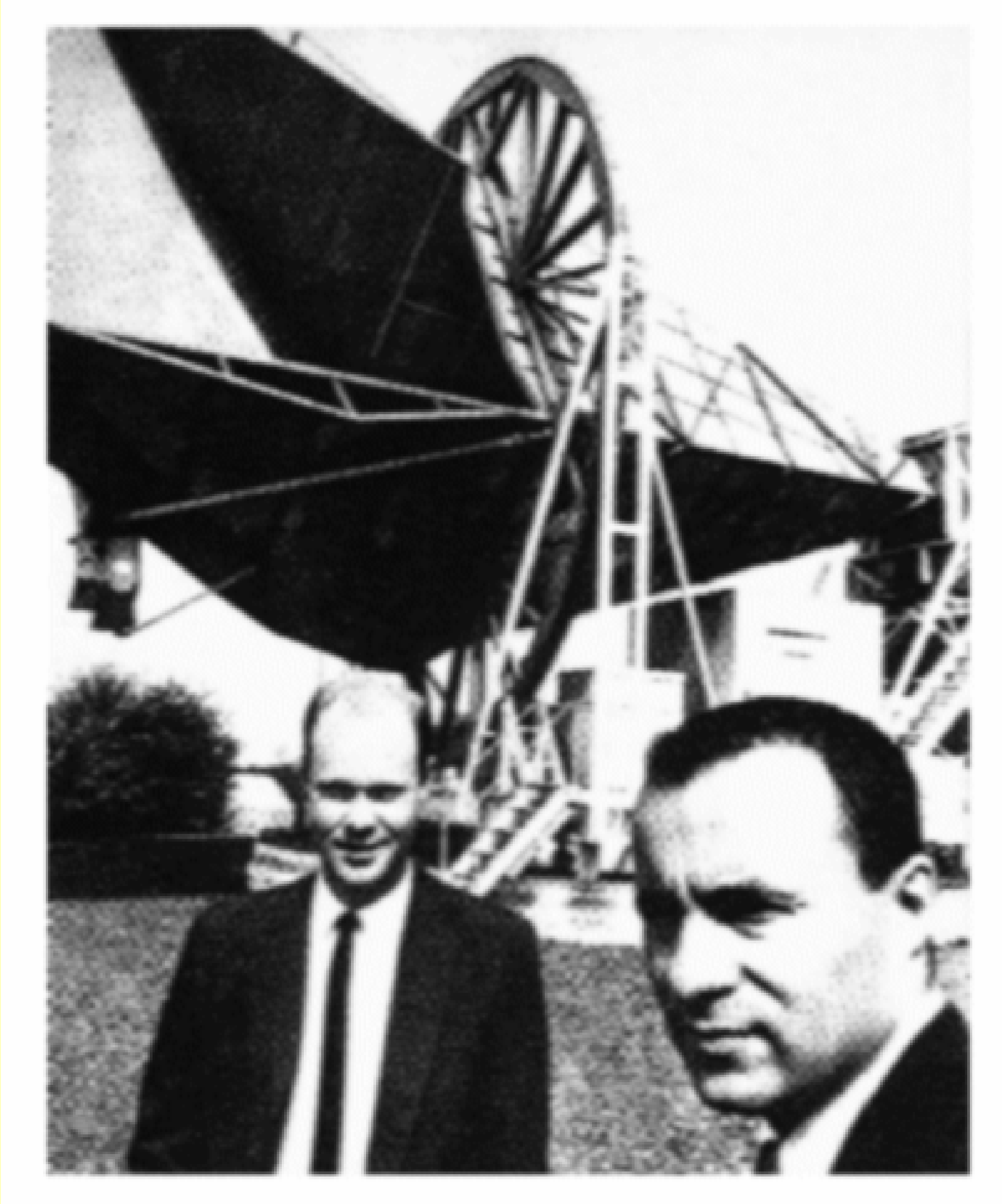
1924: Hubble solves the problem by finding Cepheid variable stars in M31



1 galaxy = 100 billion stars

Stellar Populations



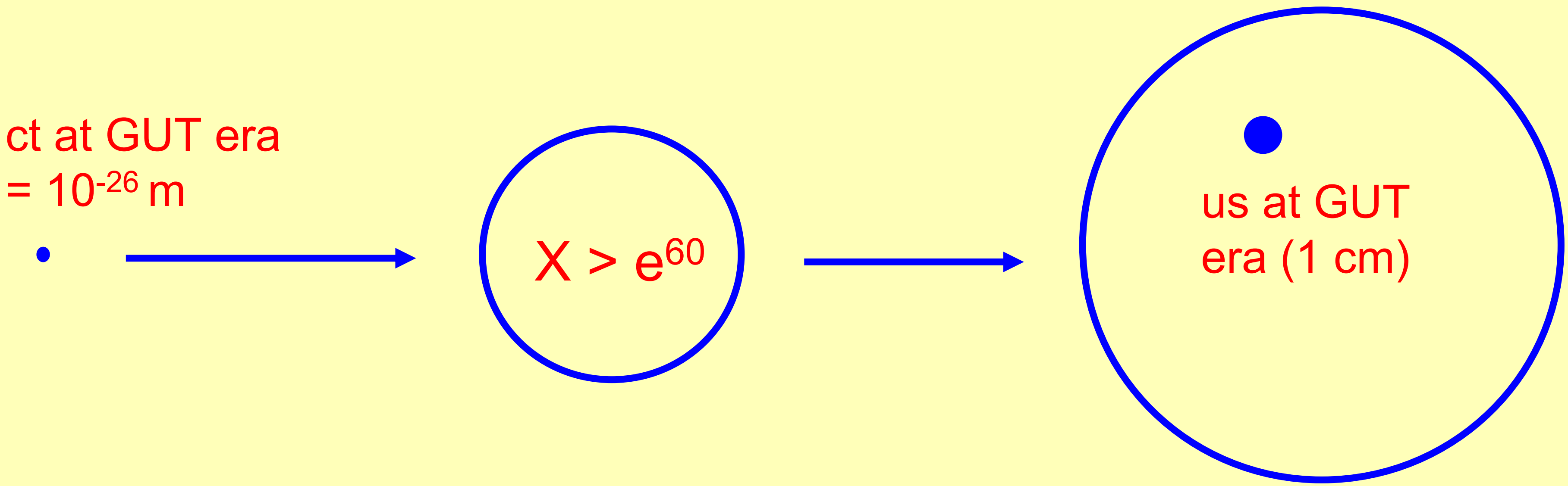


Alan Guth (1947 -)

1981: Inflation solves the causal horizon problem

What if the vacuum density was extremely high in the past?
(needs 10^{80} kg m^{-3} to dominate at the GUT era (10^{-26} today)

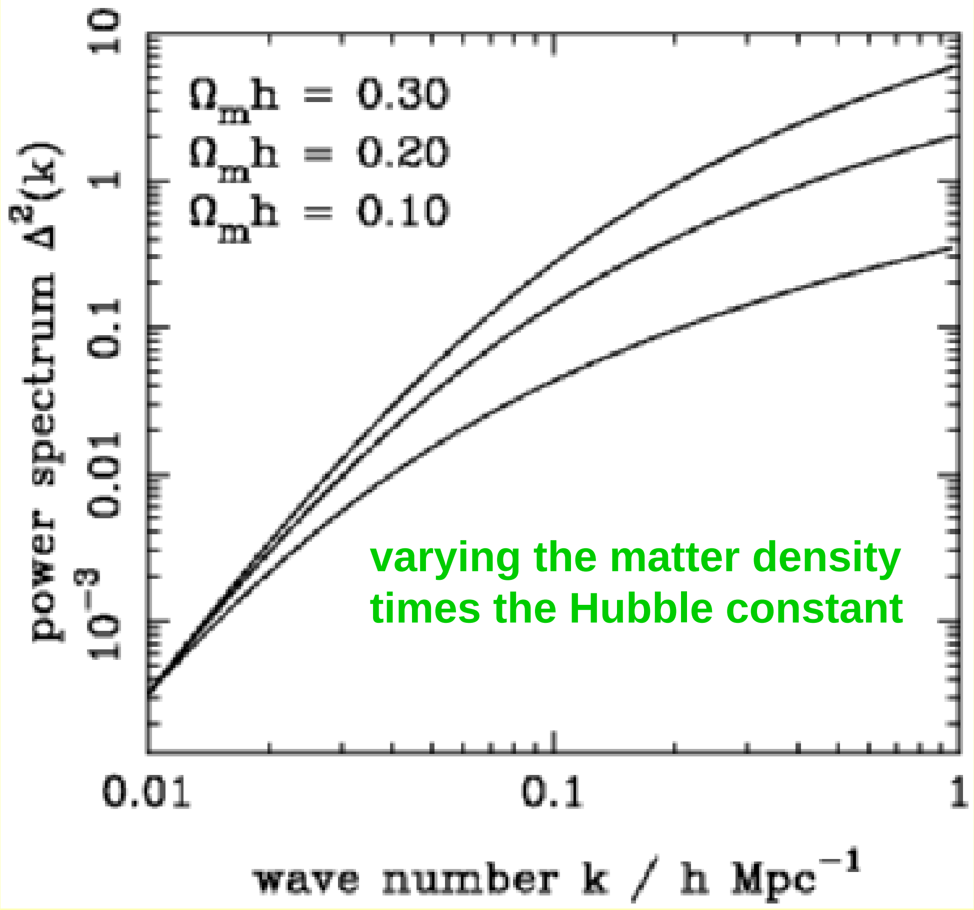
Antigravity can blow a big bubble from a subatomic patch

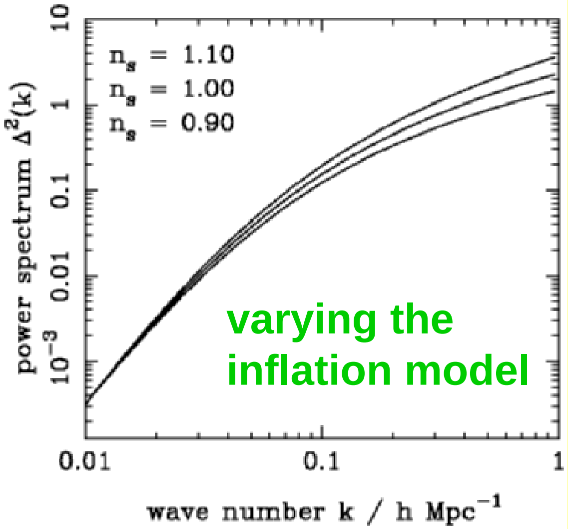


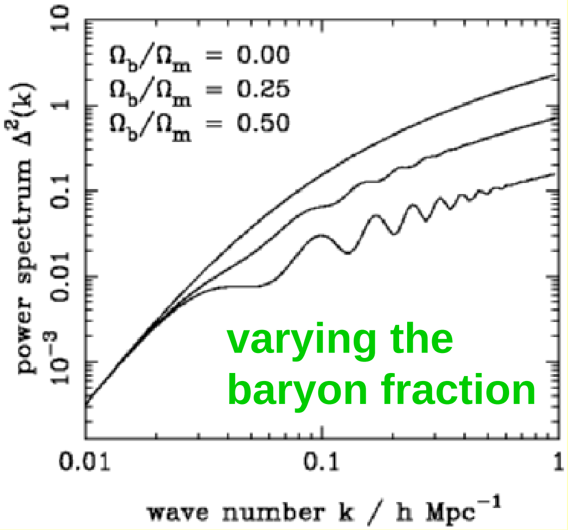
The CDM model (Peebles 1982, Bond & Szalay 1983)

Density fluctuation: $\delta = \sum \delta_k e^{(-ikx)}$

$\Delta^2(k) = d\sigma^2/d \ln k \sim k^4 \Phi_{rms}^2$

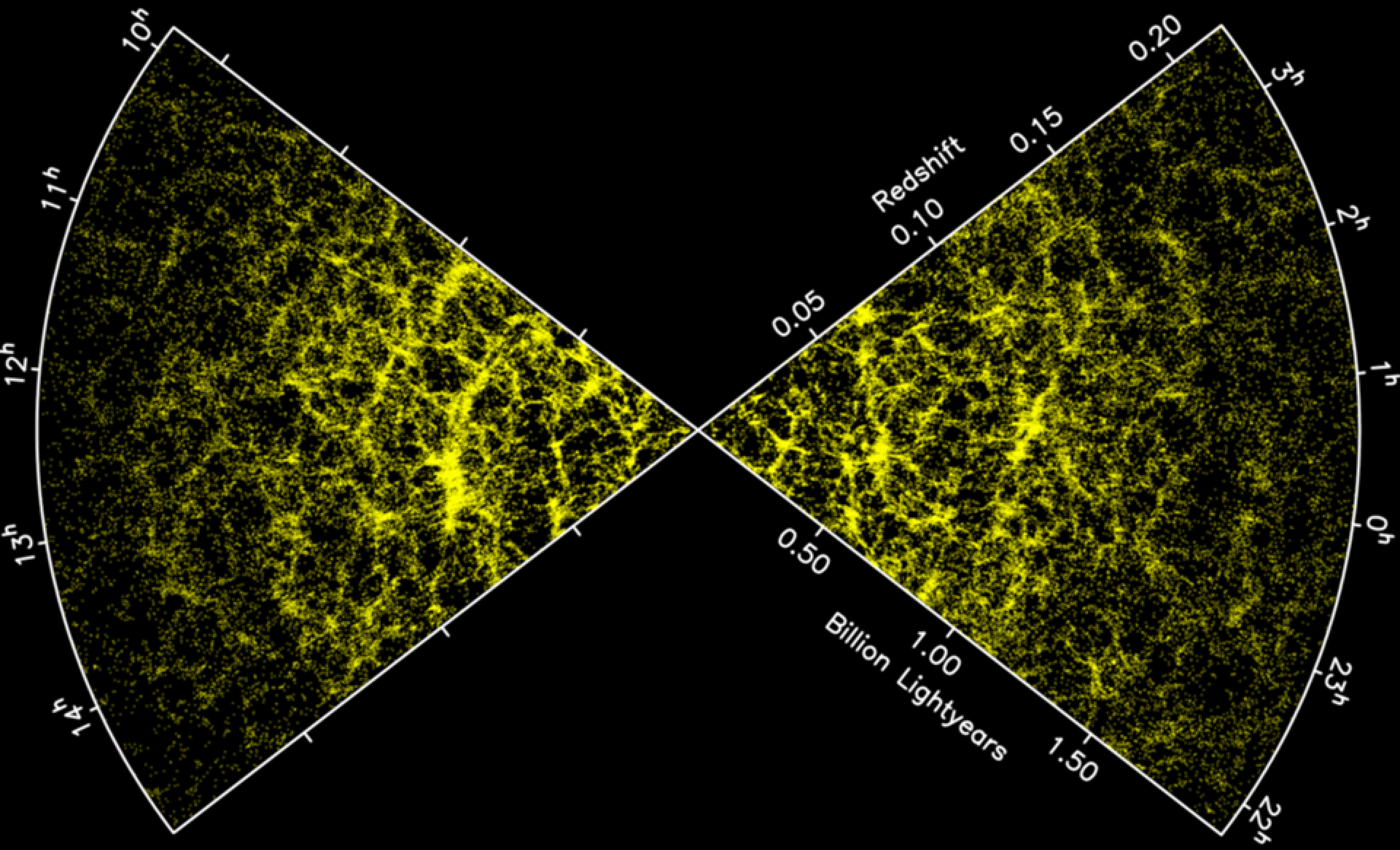






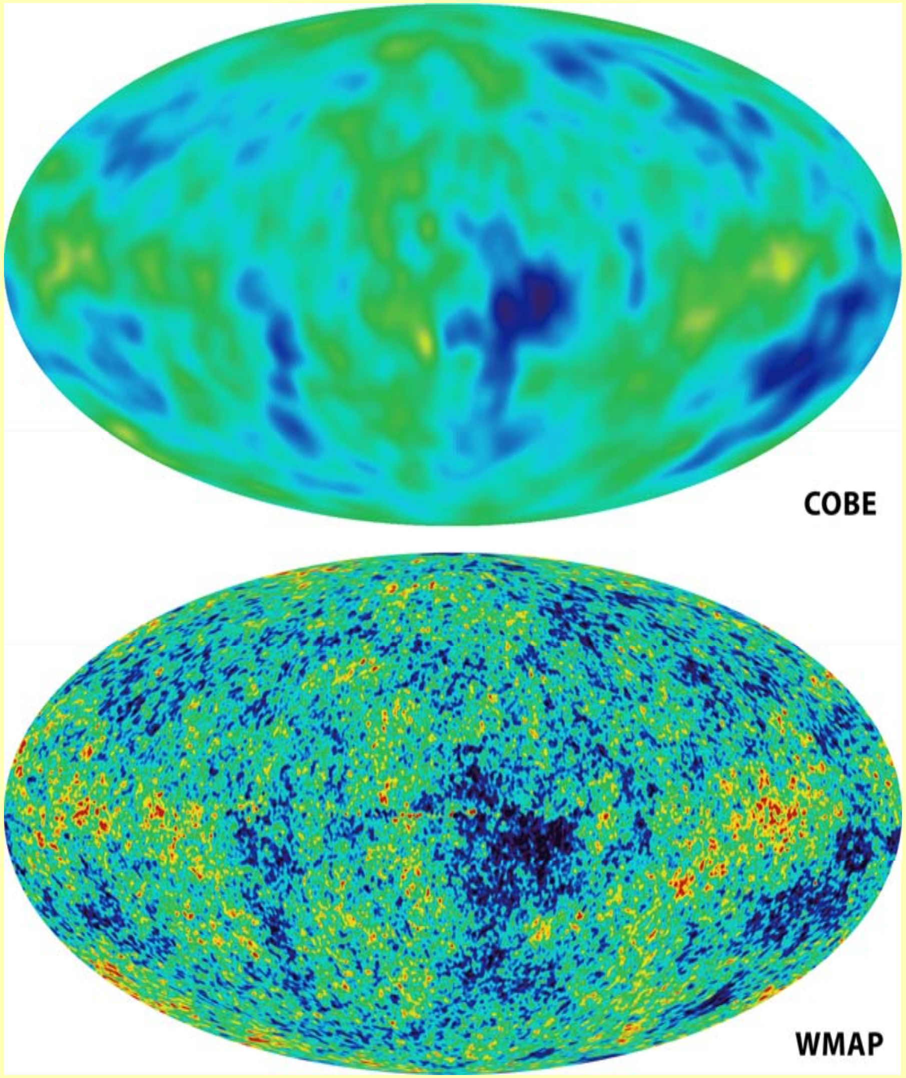
2005

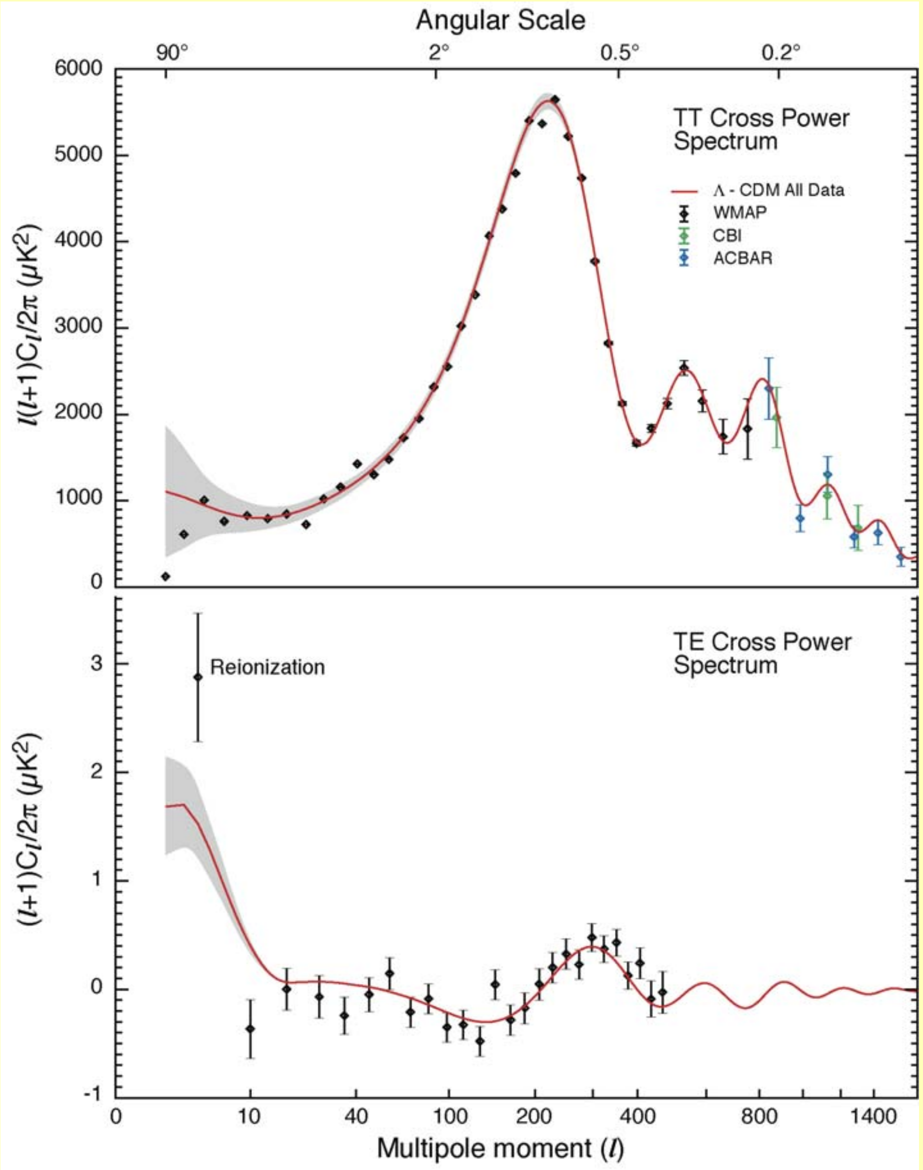
Fair samples of cosmological structure



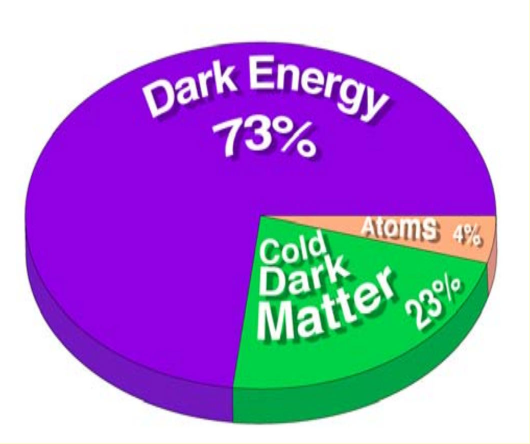
2dFGRS cone diagram: 4-degree wedge

A golden CMB decade: COBE to WMAP

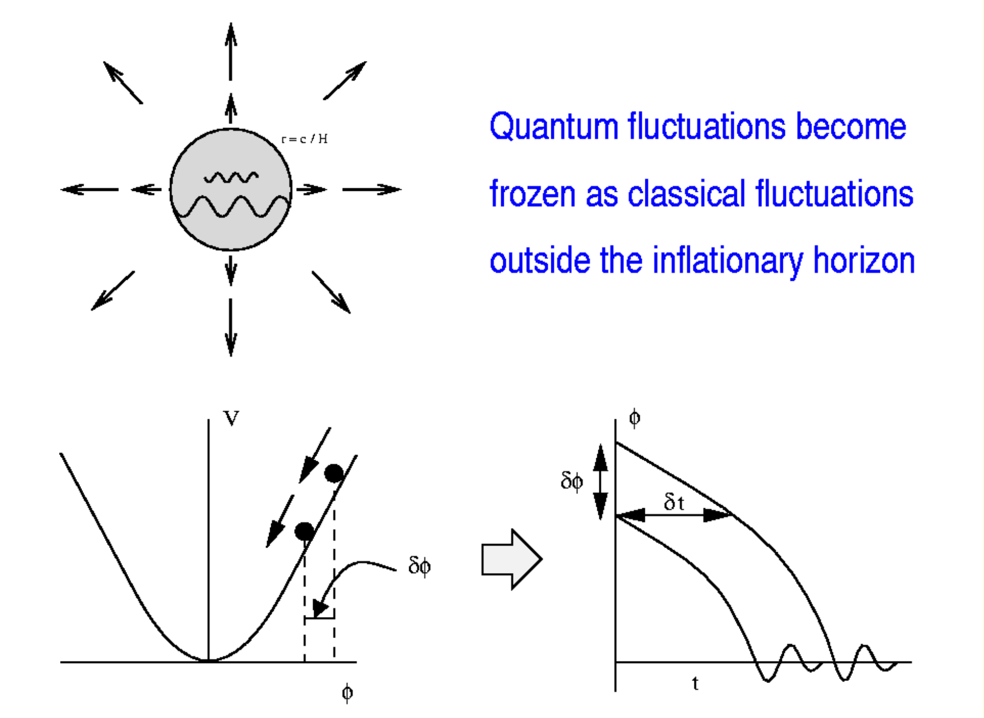




The standard cosmological model



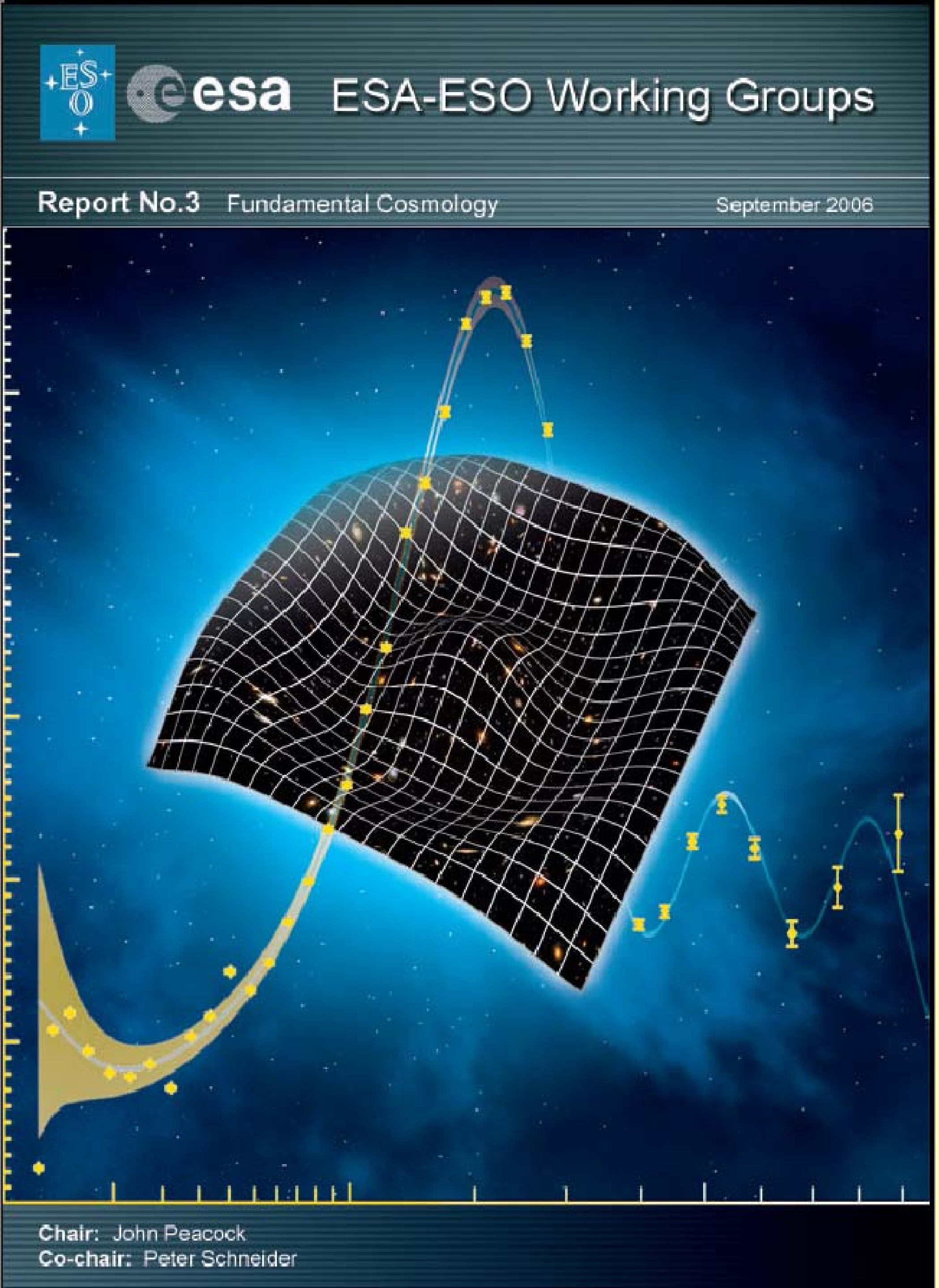
- Normal (baryonic) matter
- Dark matter: collisionless; interacts via gravity only
- Dark energy: a homogeneous component; negative pressure drives an accelerating expansion



- Start of expansion in inflationary phase dominated by energy density of a scalar field, possibly like dark energy
- Quantum fluctuations in field seed structure

So what's the problem?

- It might be right
  - Particle physicists have spent 40 years testing their standard model
- Cosmology is not fundamental: should be able to dissect each ingredient
  - What is the dark matter?
  - What is the dark energy?
  - Why is there a baryon asymmetry?
  - Can we prove that inflation really happened?
- Need to understand formation of stars and galaxies



ESA-ESO Working Group on Fundamental Cosmology

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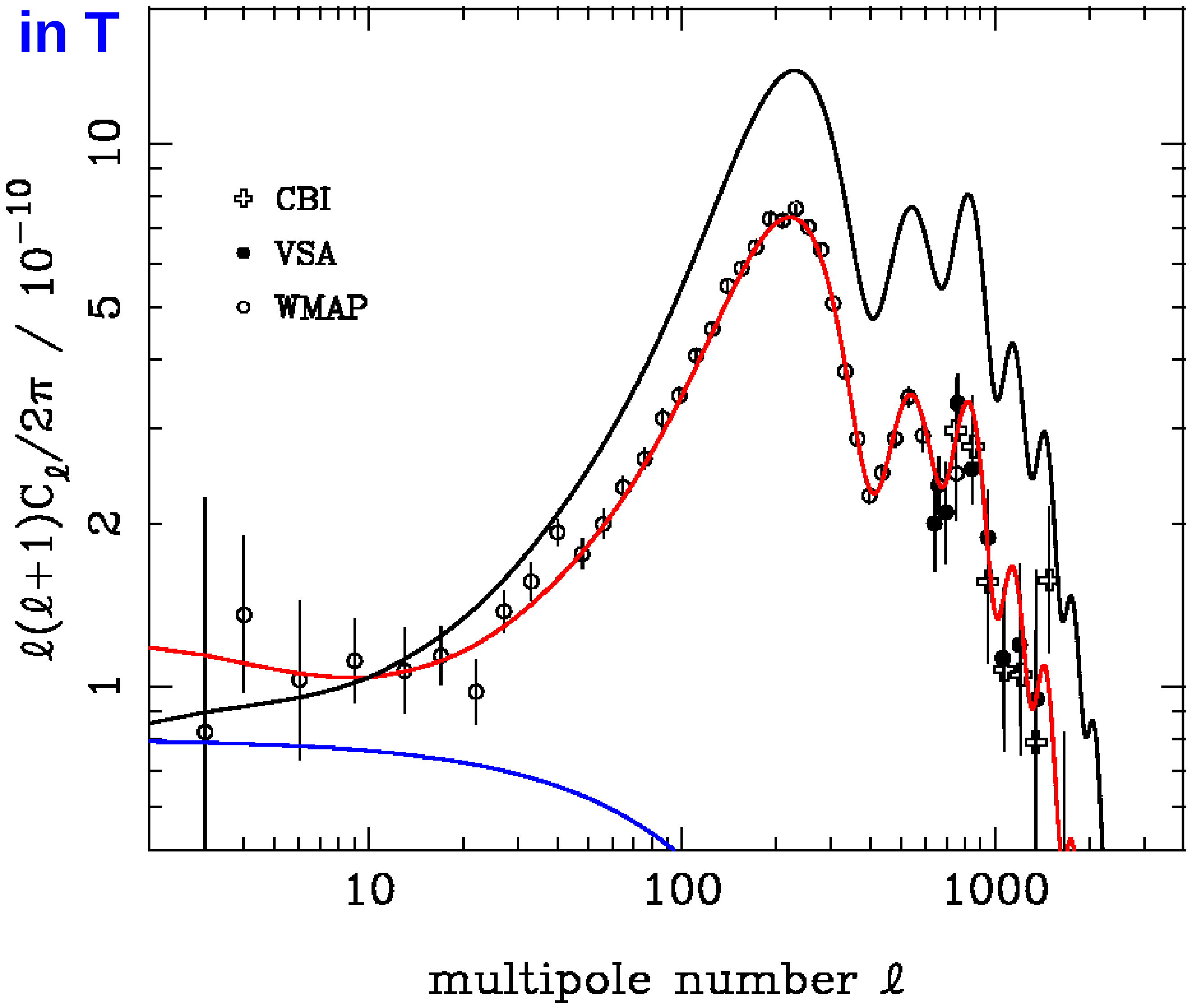
Dark Energy Task Force

Rocky Kolb
Andy Albrecht

CMB: signatures of inflation

variance in T



(1) Tilt:

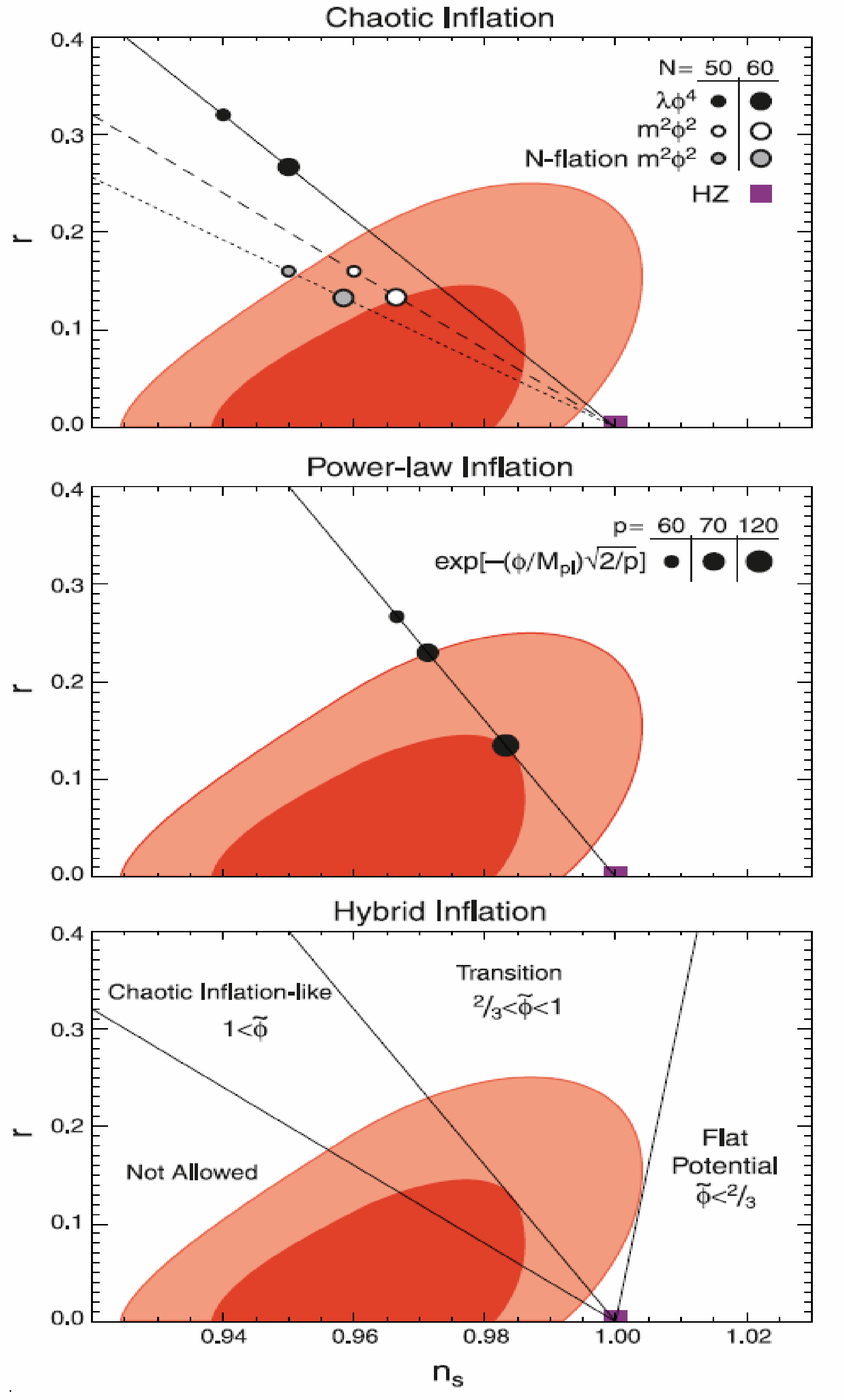
Degenerate with matter content

spectrum / (scale)$^{n-1}$ simple predictions: |n-1| ~ 1%

(2) Tensors:

Primordial gravity waves. Large scales only

now: r = T/S < 0.3
target: r = 10^{-3} – 10^{-5}



Constraints on inflation

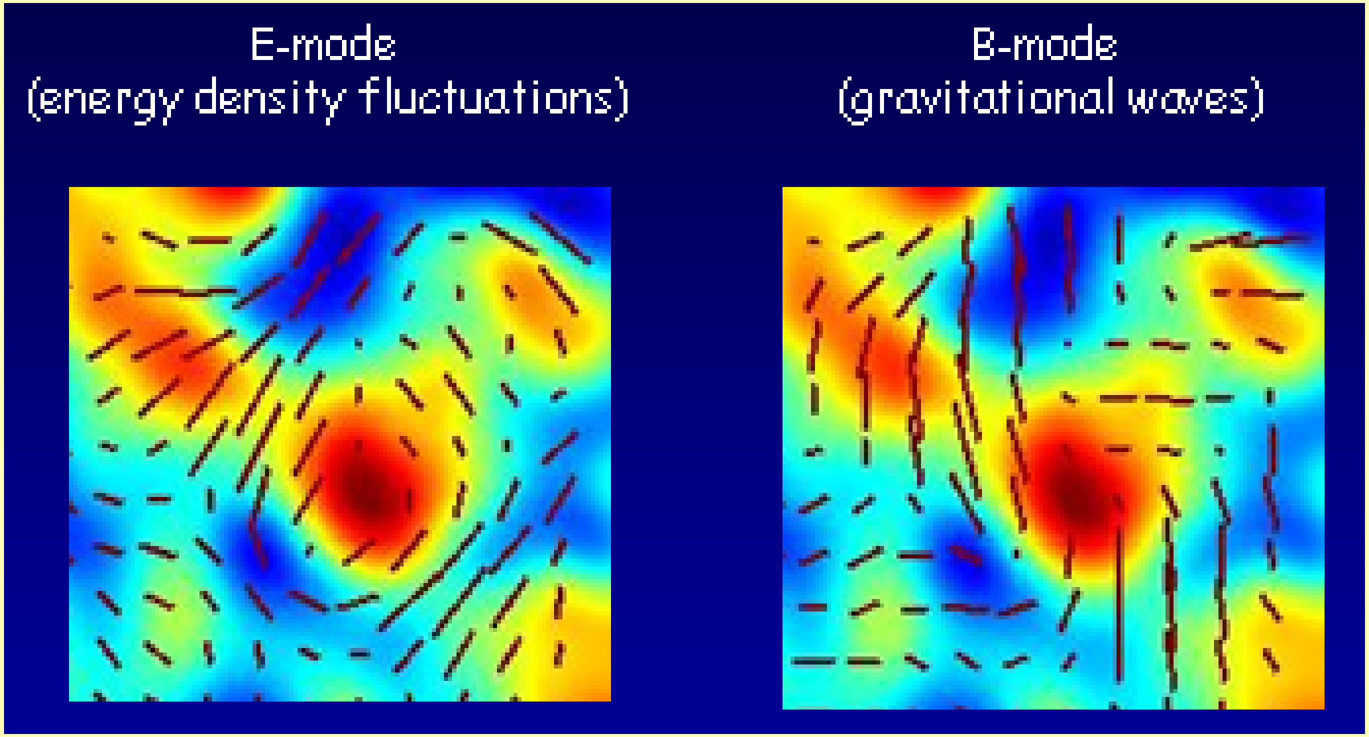
(Komatsu et al. 2008)

Simple scale-invariant n=1 spectrum without relic gravity waves ruled out

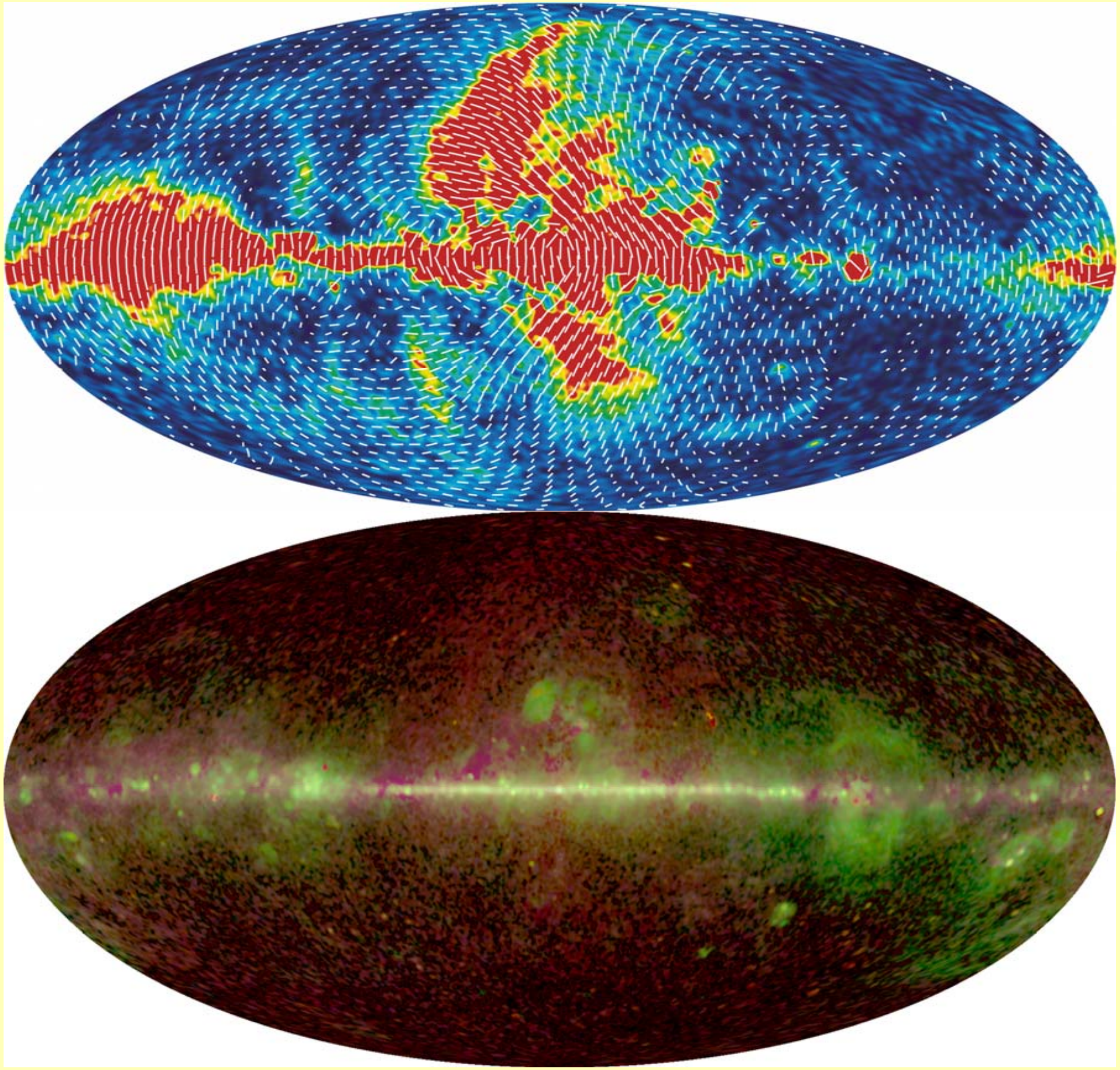
Tensors from B-mode polarization

Vector: $\mathbf{V} = \nabla\Phi + \nabla\wedge\mathbf{A}$

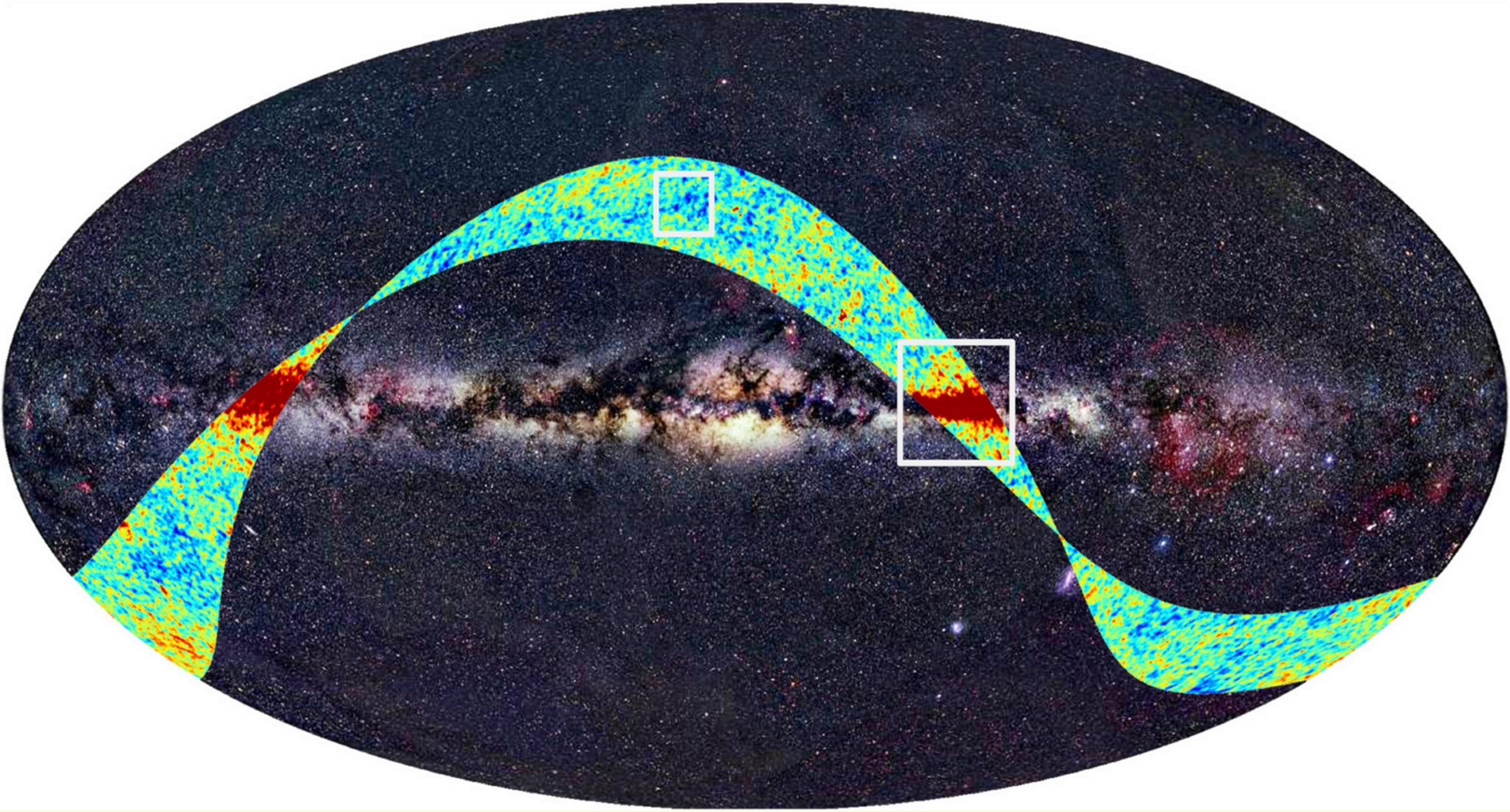
Polar: $\gamma_{ij} = \partial_i\partial_j\Phi_E + \frac{1}{2}(\epsilon_{ki}\partial_k\partial_j + \epsilon_{kj}\partial_k\partial_i)\Phi_B$



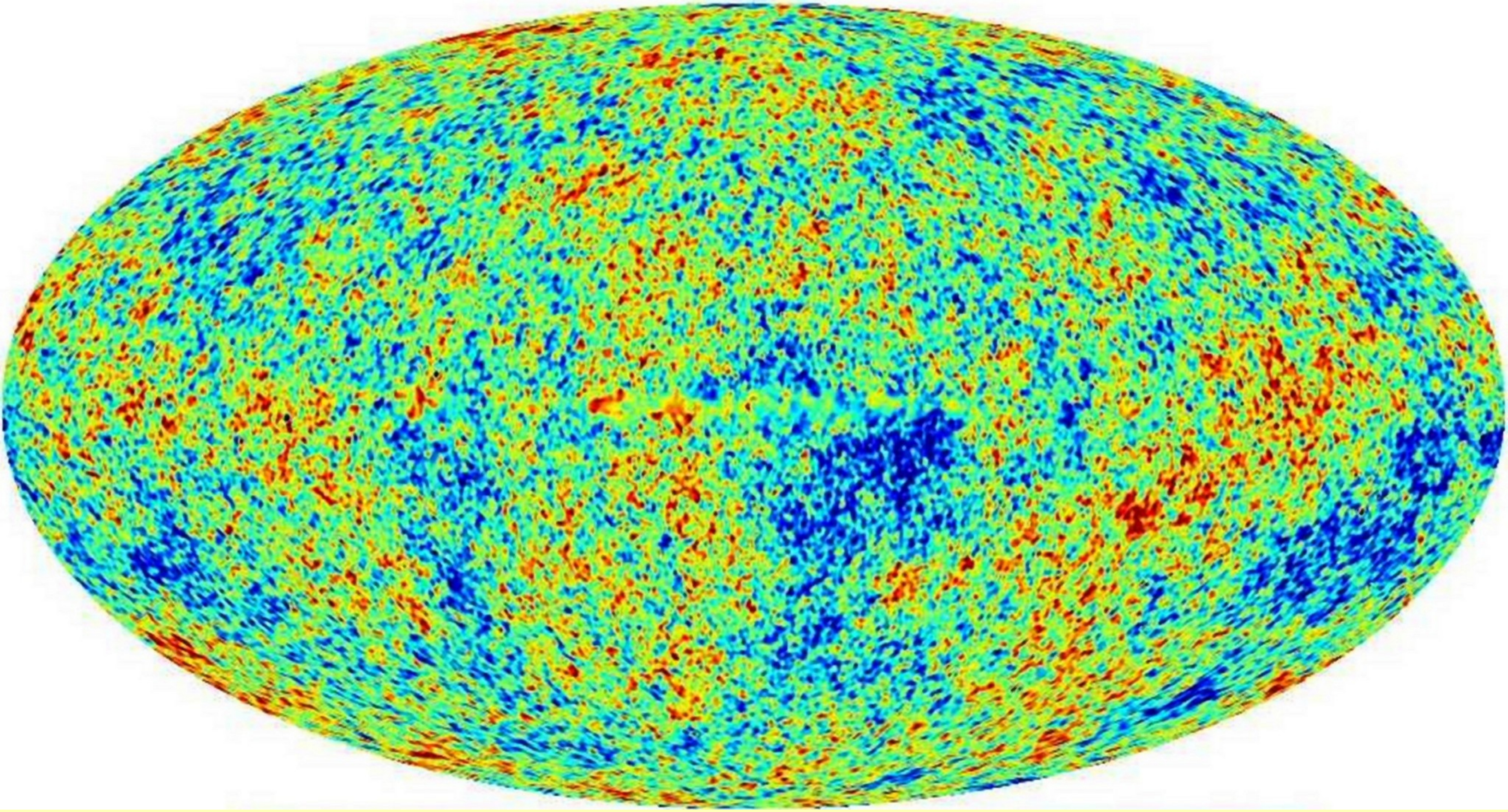
Polarization foregrounds from WMAP3



2009 – 2012: Planck

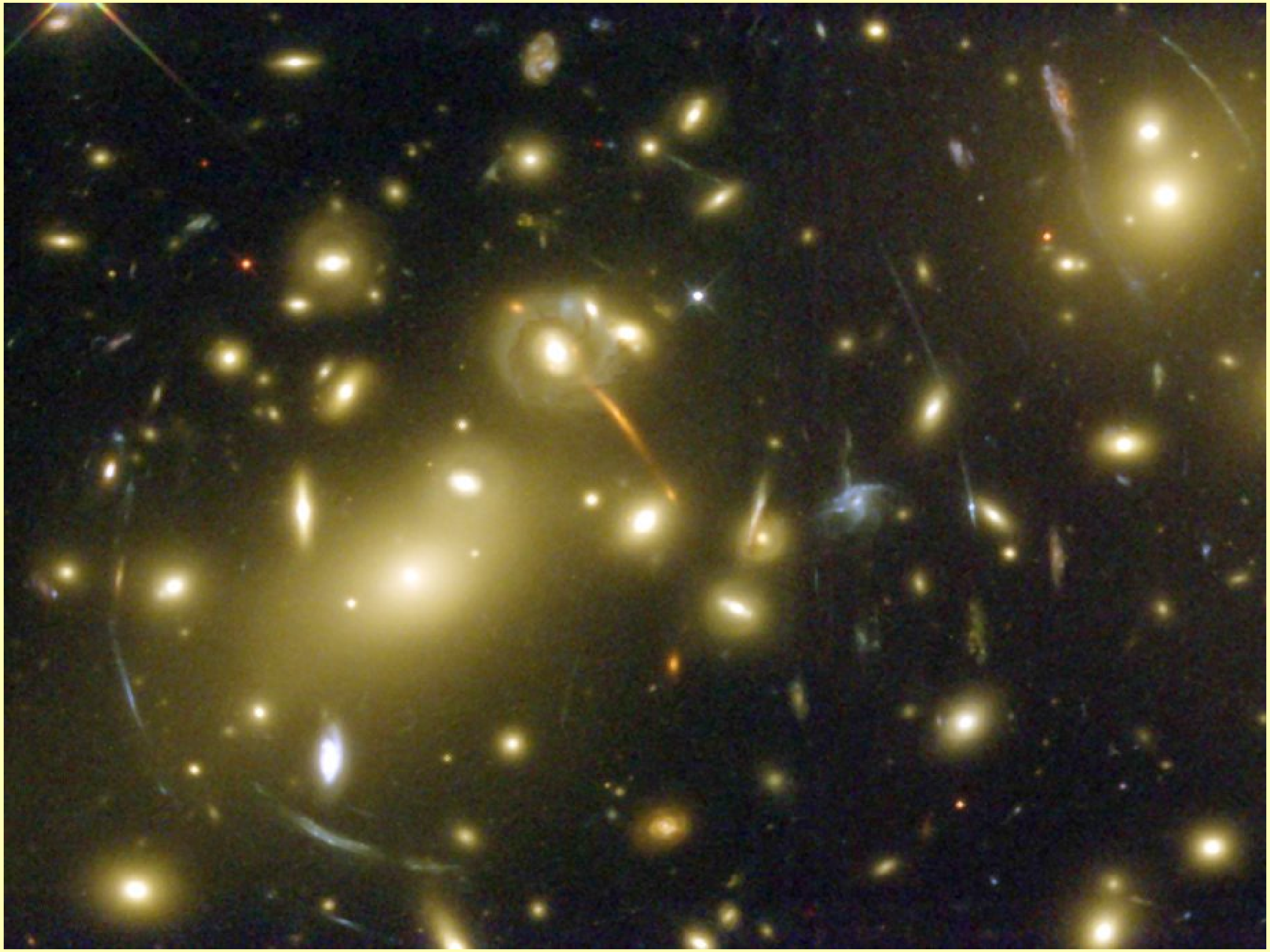


2009 – 2012: Planck



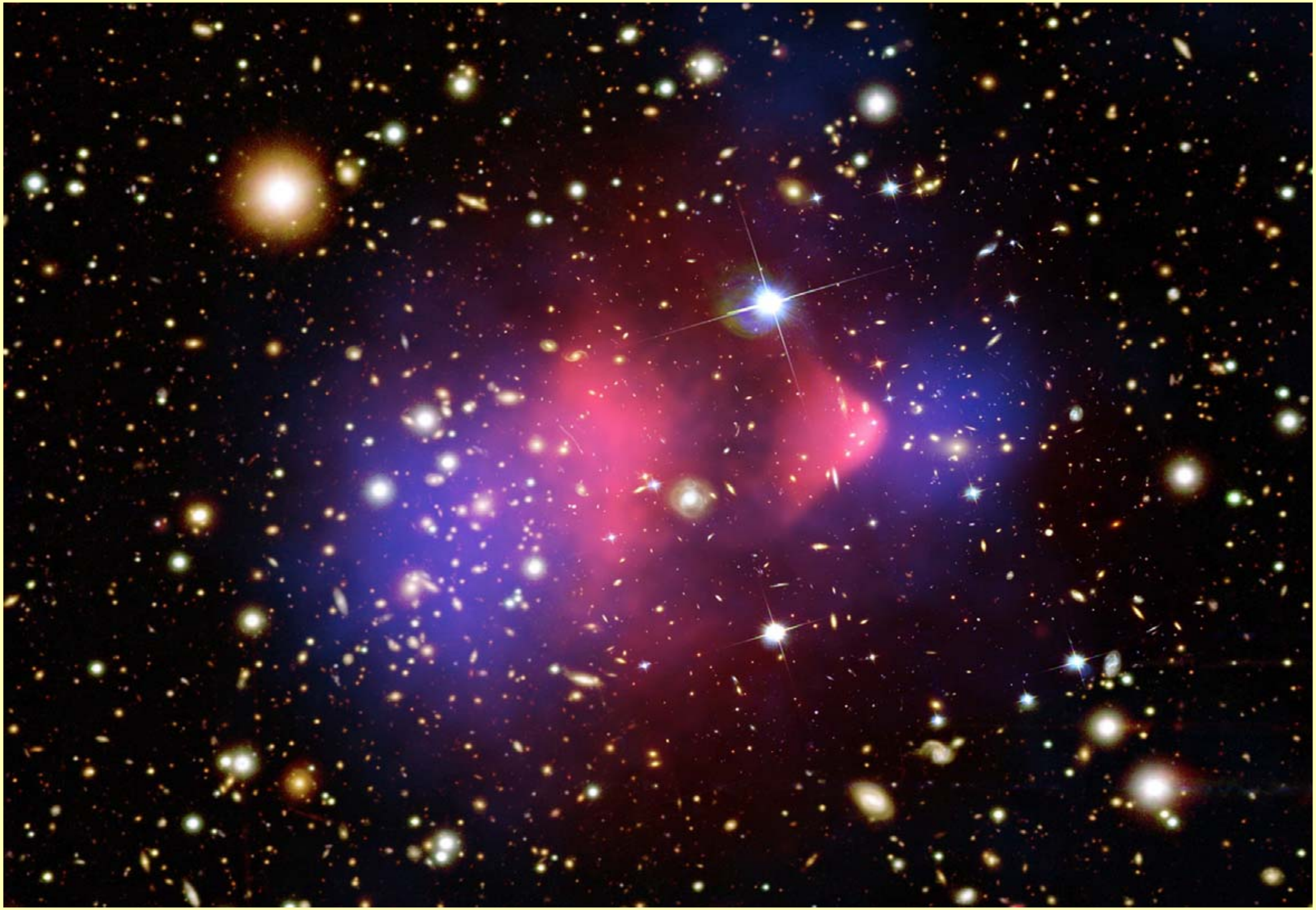
Dark matter

Dark Matter since Zwicky 1933

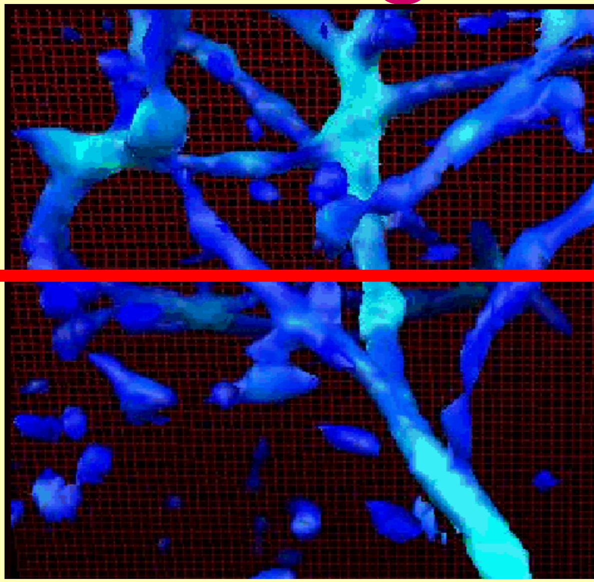


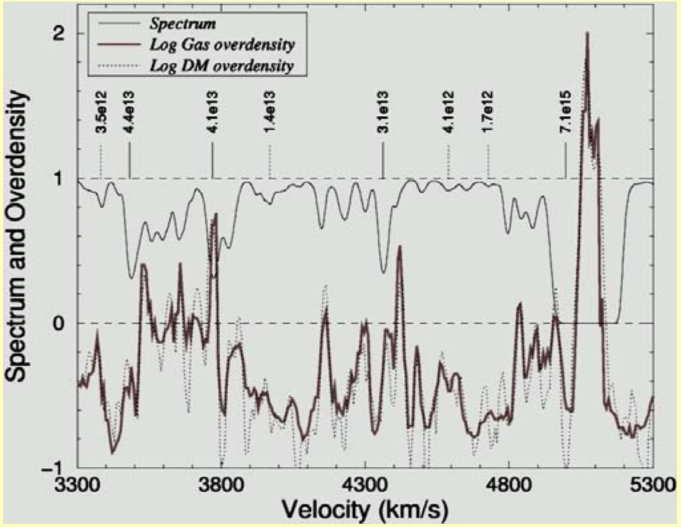
Gravitational Lensing: total mass ~ 5 x (stars + gas)

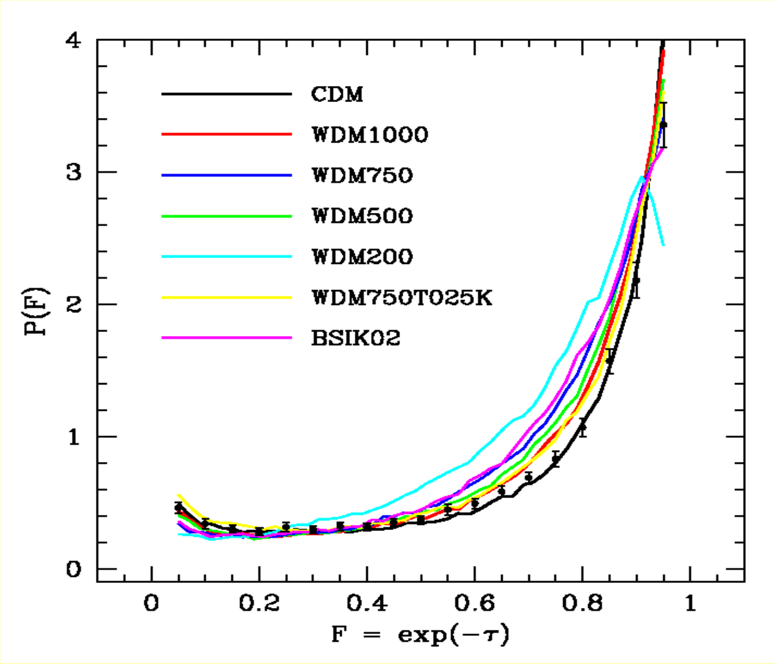
Bullet cluster: DM looks collisionless



Testing CDM: intergalactic gas





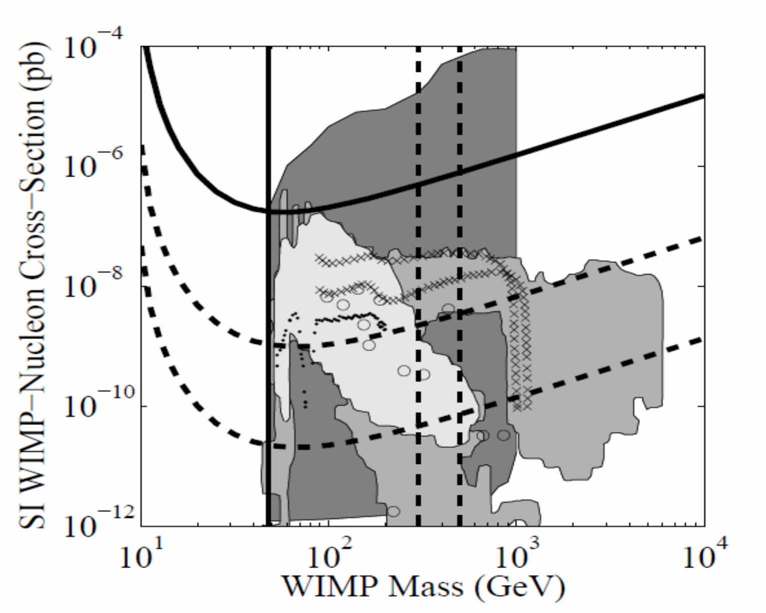


Probe smallest scales (<1Mpc):

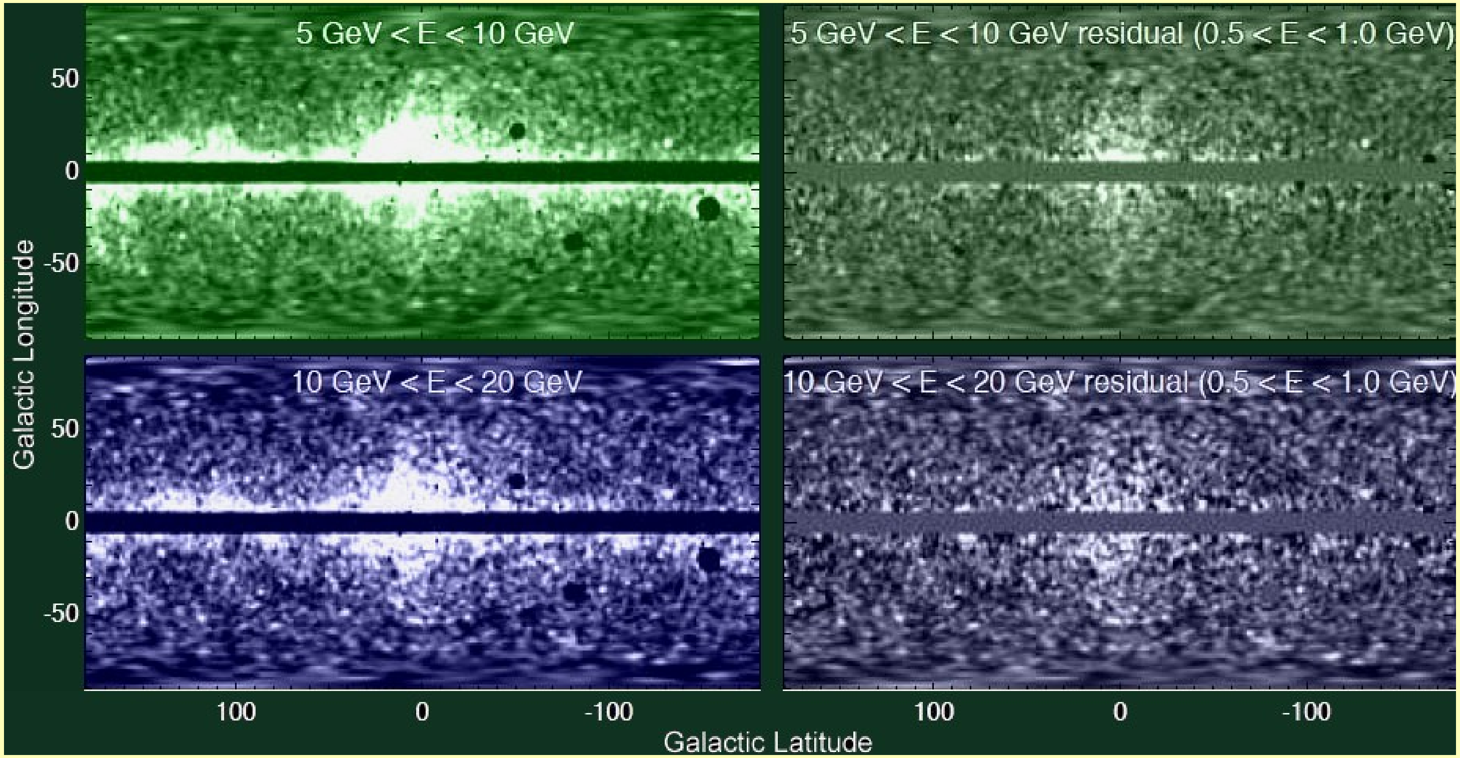
Limit tilt and free-streaming damping

⇒ m_{DM} > 8 keV

(Boyarsky 0812.0010)

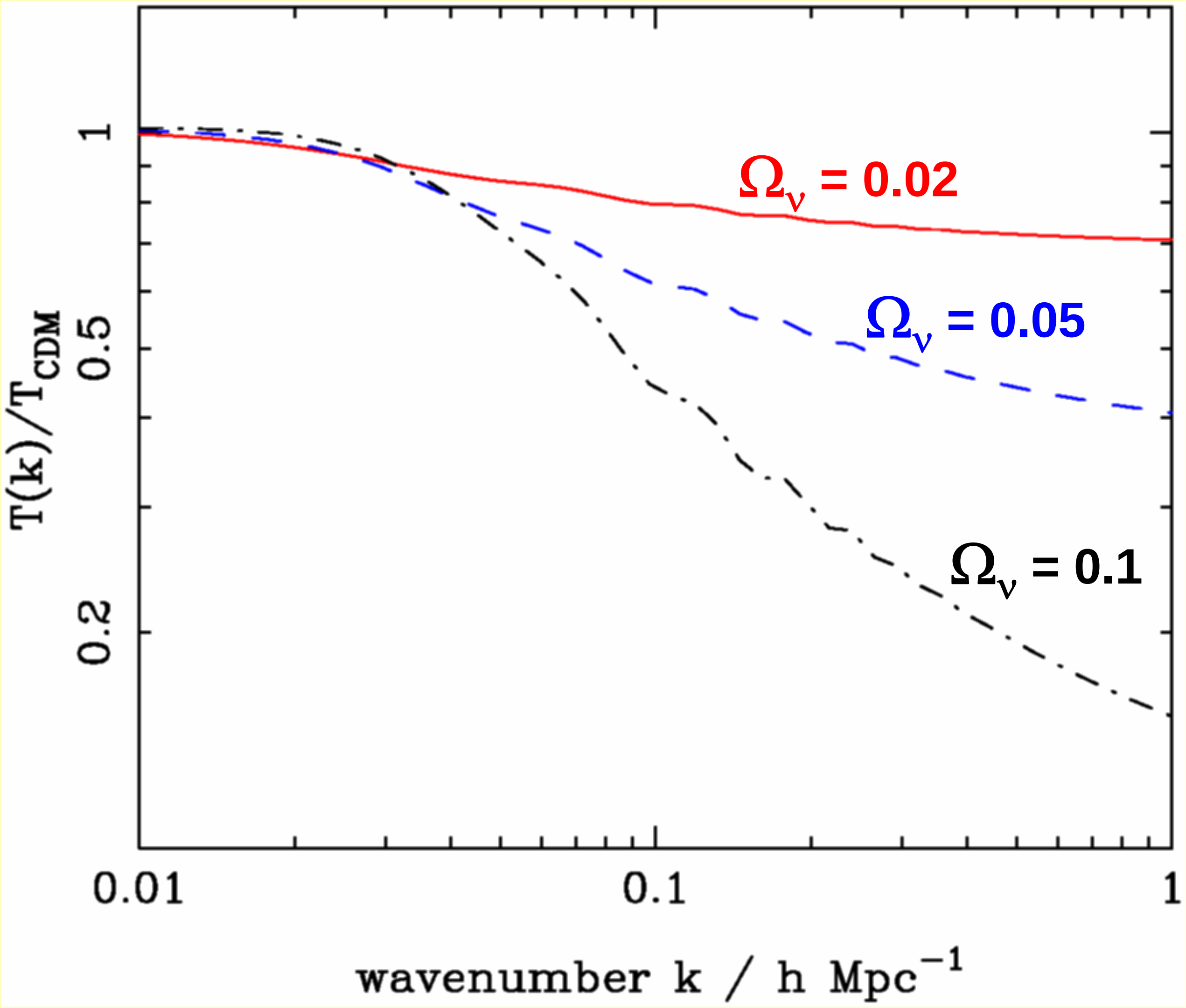


(almost) direct detection



Fermi Haze

Effect of massive neutrinos

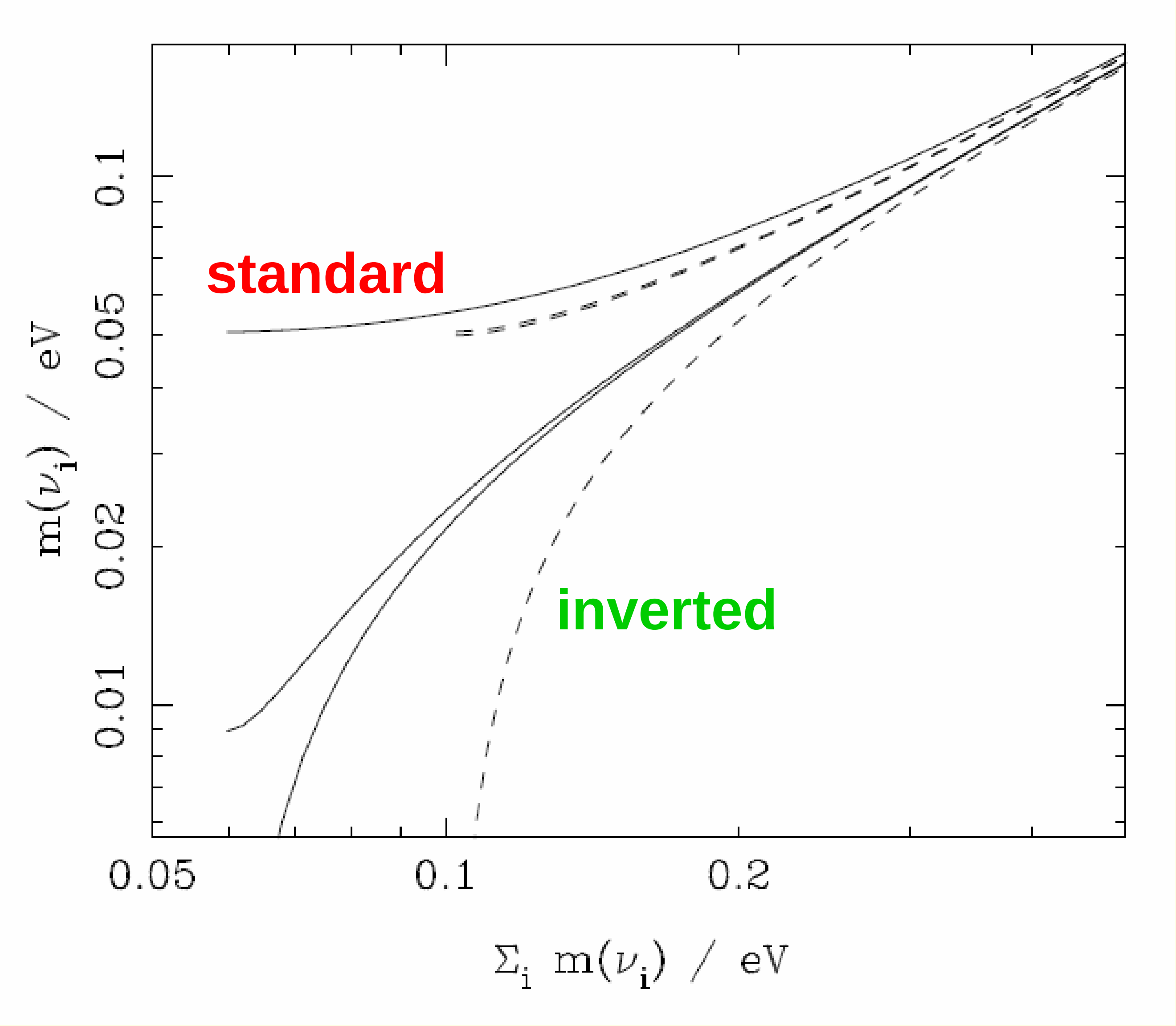


Free-stream length:
80 $(M/eV)^{-1}$ Mpc

($\Omega_m h^2 = M / 93.5$ eV)

M ~ 1 eV causes lower power at almost all scales, or a bump at the largest scales

Discriminating neutrino hierarchies

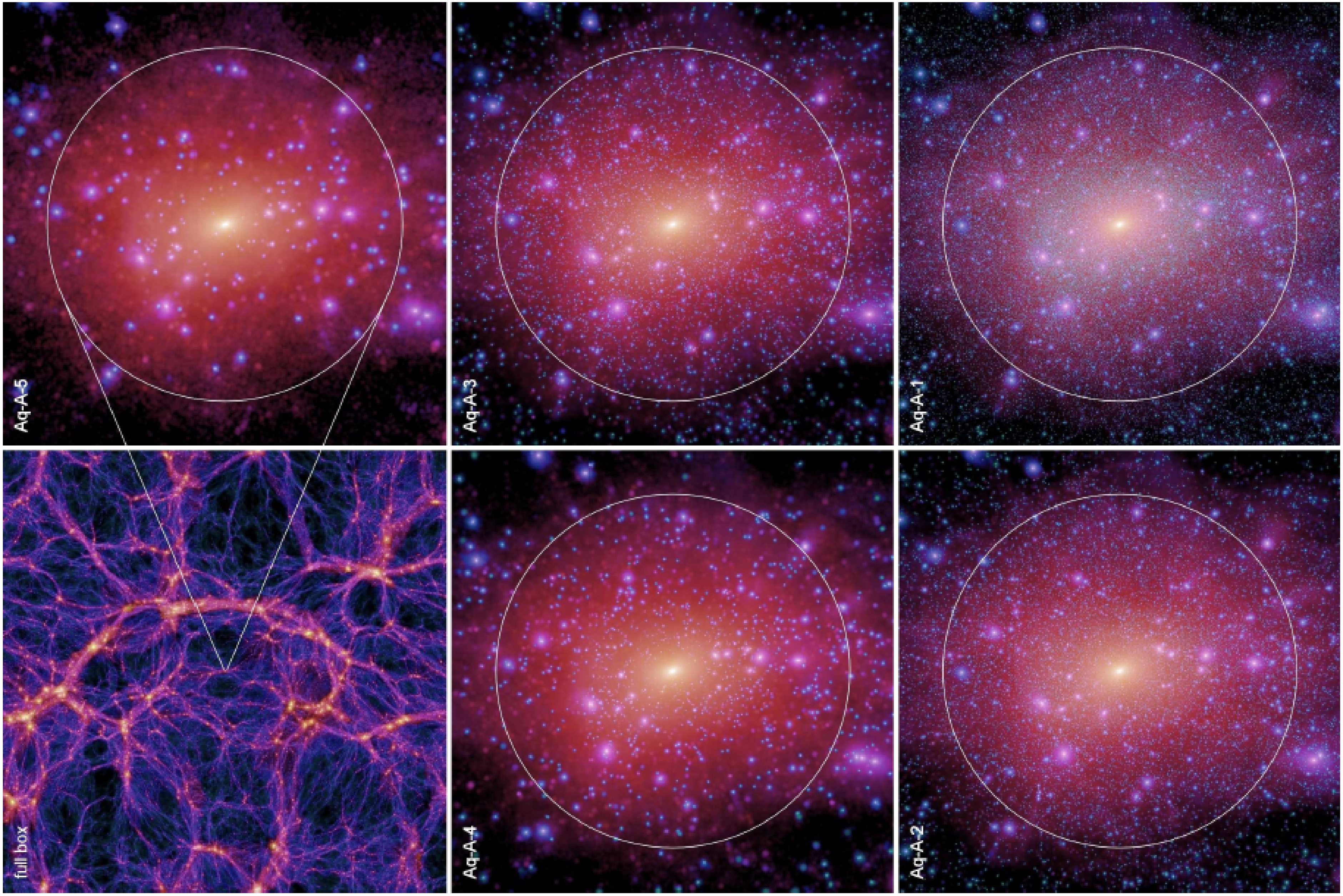


Major target: limit below 0.1eV on summed masses (or detection):

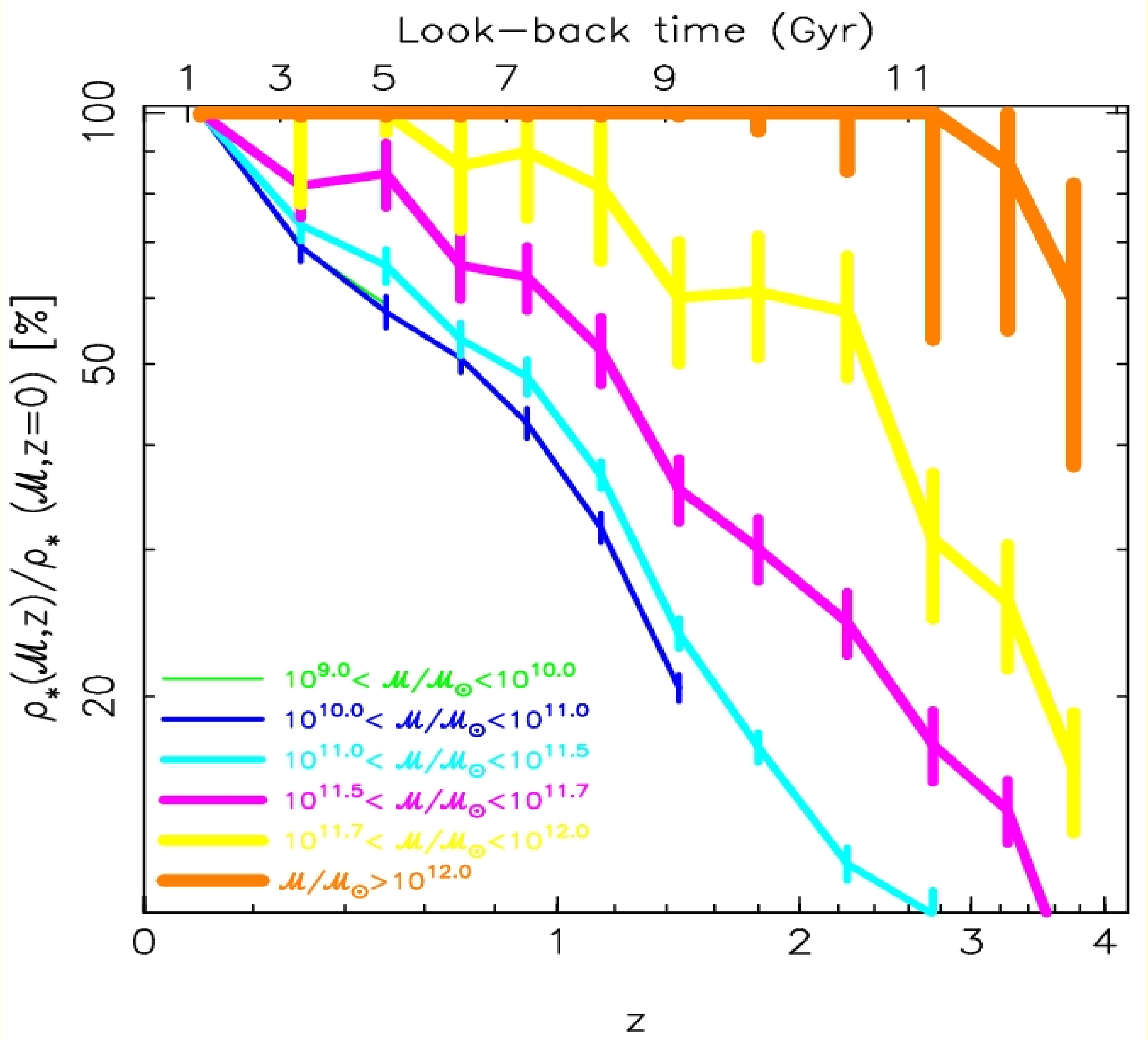
Factor » 5 improvement

Do we understand galaxy formation and evolution within the DM?

Aquarius: high-resolution haloes

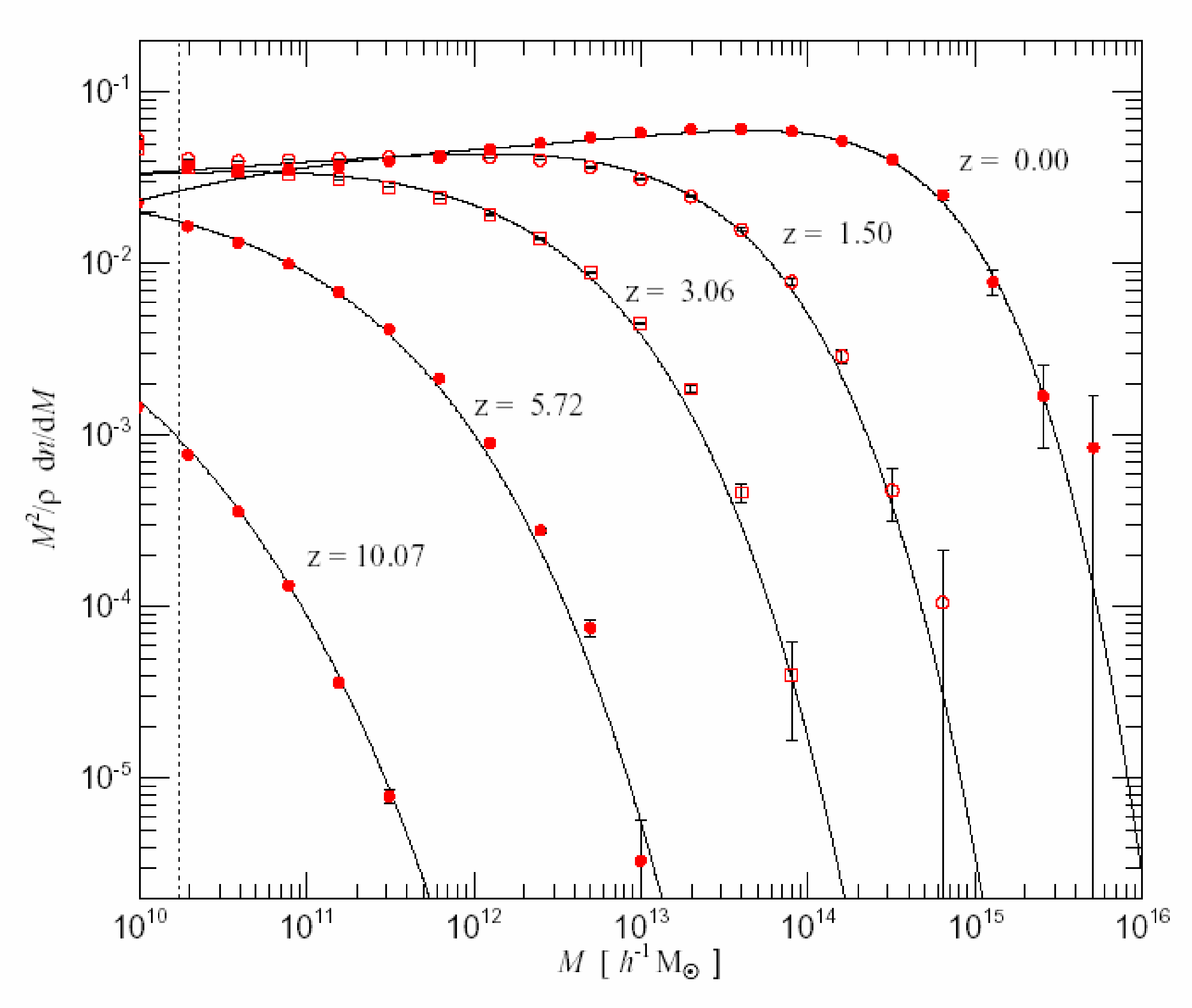


Galaxy assembly: upside-downsizing



Pérez-González et al. (2008)

Opposite to buildup of virialized haloes (ρ = 200 <ρ>)



Dark energy

The concept of vacuum energy

(1) Einstein (1917): want static universe. Introduce cosmological constant as curvature of vacuum

$$\rho,\ \Phi \text{ constant} \Rightarrow$$
$$\nabla^2\Phi = 4\pi G\rho \rightarrow \nabla^2\Phi + \lambda\Phi = 4\pi G\rho$$

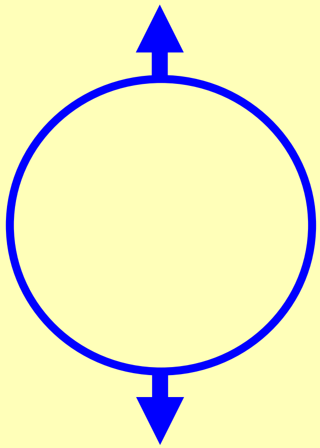
$$G^{\mu\nu} + \Lambda g^{\mu\nu} = -8\pi G T^{\mu\nu}$$

(2) Zeldovich: regard as vacuum energy density

$$G^{\mu\nu} = -8\pi G (T^{\mu\nu} + \Lambda g^{\mu\nu}/8\pi G)$$

(3) Must have antigravity properties

$$GM/r \propto \rho_{\text{vac}} r^3/r \propto r^2$$



– but is DE just a problem with gravity?

Inference of DE comes from assuming Friedmann:

$$H^2(a) = H_0^2 \left[\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_{\mathrm{DE}} a^{-3(1+w)}\right]$$

Extra term

Is DE a physical component, or a failure of Einstein gravity? (not of GR)

$$d\tau^2 = (1+2\Psi)\, dt^2 - (1-2\Phi)\, R^2(t) \left(dr^2 - r^2 d\psi^2\right)$$

Einstein: $\Psi = \Phi;\ \nabla^2\Phi = 4\pi G\bar{\rho}\delta$

$\Rightarrow f_g(a) \equiv d\ln\delta(a)/d\ln a = \Omega_m(a)^\gamma;\ \gamma = 0.55$

Lensing measures sum of potentials; clustering tests perturbation growth law (measure °)

How can we tell?

(1) Dark Energy equation of state

- Ratio of pressure to energy density $w = P / \rho c^2$
- $w = -1$ for cosmological constant
- Linear model $w(a) = w_0 + w_a(1-a)$ $a = 1 / (1+z)$

(2) Evolution of density fluctuations

- $\delta\rho/\rho$ measures small-scale gravity
- Growth at a different rate to DE prediction indicates need for modified gravity

Observing scales in redshift space

(1) Matter-radiation horizon:

$123\ (\Omega_m h^2 / 0.13)^{-1}$ Mpc

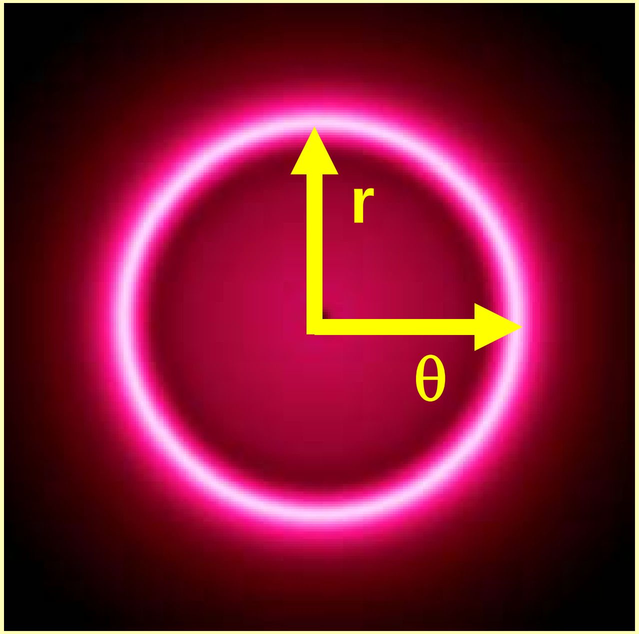
(2) Acoustic horizon at last scattering :

$147\ (\Omega_m h^2 / 0.13)^{-0.25} (\Omega_b h^2 / 0.024)^{-0.08}$ Mpc

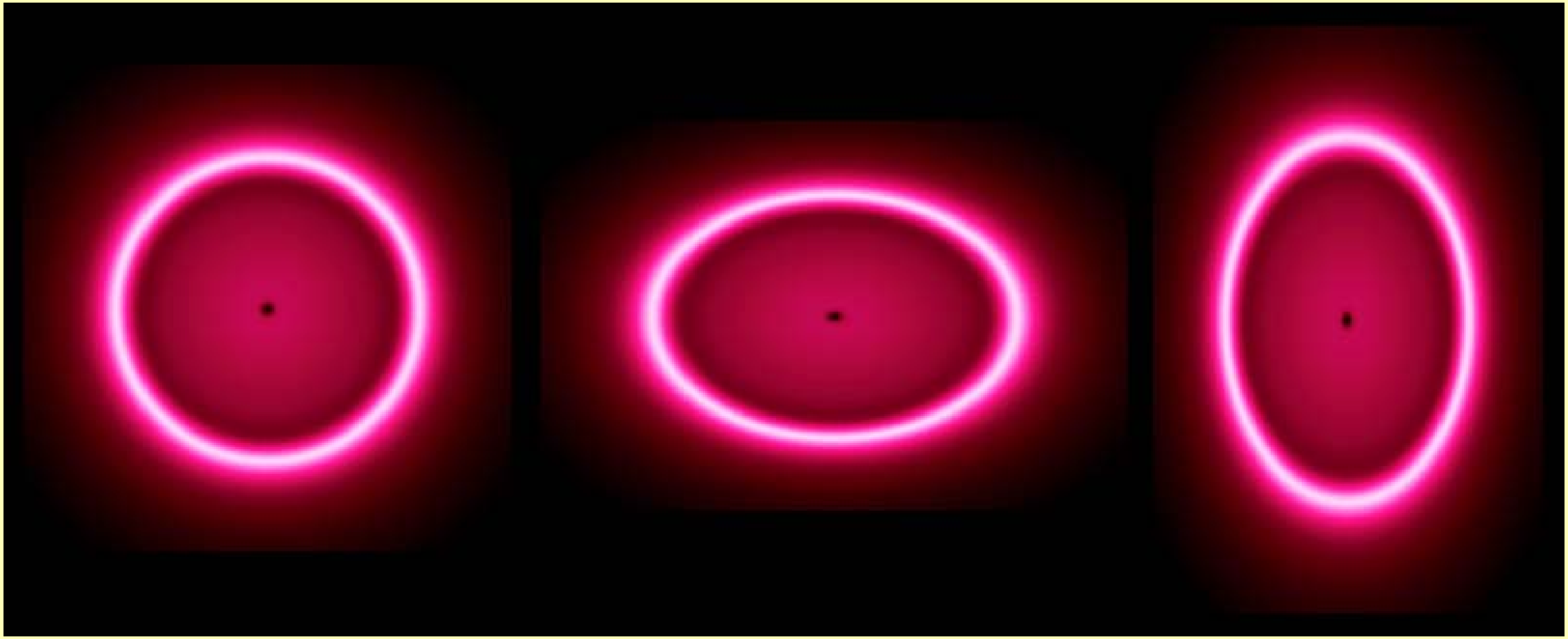
Observe transversely or radially:

$\mu = L / D(z)$ or $dz = L / [c/H(z)]$

Assume average scale depends on $D_V=(D^2[c/H])^{1/3}$



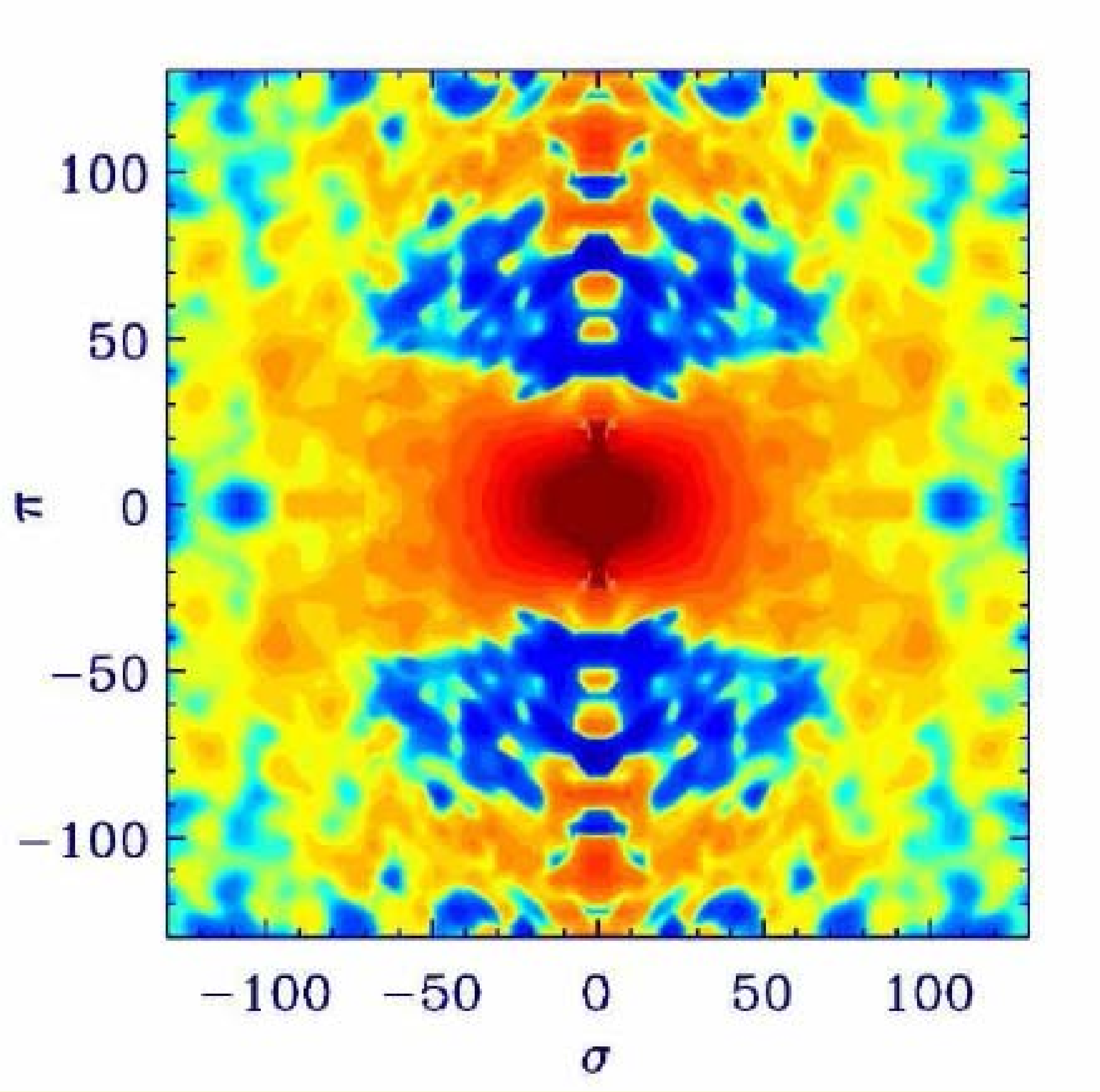
Alcock-Paczynski distortions



$H(z) = H_0[\Omega_v(1+z)^{3+3w} + \Omega_m(1+z)^3 + (1-\Omega)(1+z)^2]^{1/2}$
$D(z) = \int_0^z \frac{c}{H(z)}\, dz$

Radial/Transverse scalings: $f_\perp = D/D_{\rm ref}$, $f_\parallel = H_{\rm ref}/H$
Flattening factor: $F = f_\perp / f_\parallel$

Combining BAO and RSD

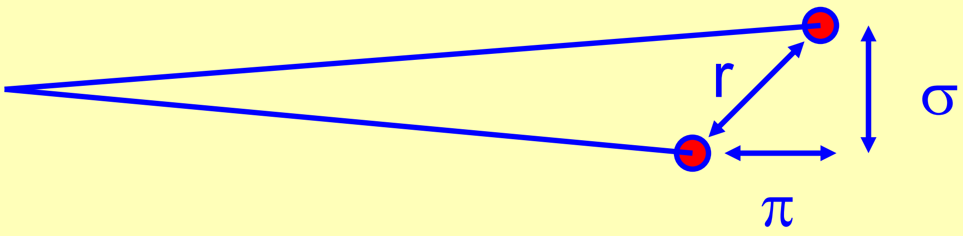


SDSS LRG Redshift-space 2D $\xi(\sigma,\pi)$ Gaztanaga et al. 0807.3551

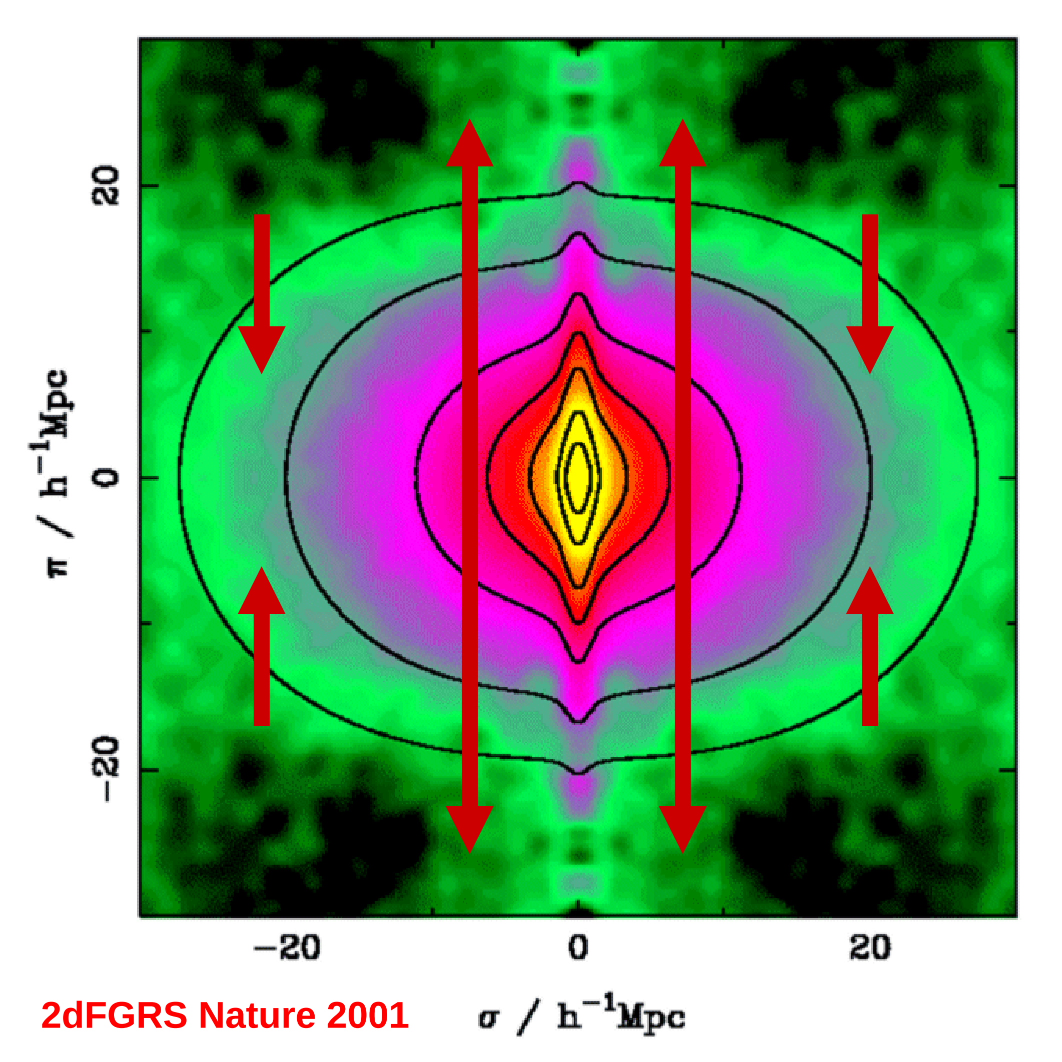
Kaiser flattening at ~ 10-20 Mpc from peculiar velocities.

Little affect on BAO ring

Redshift-Space Distortions



- RSD due to peculiar velocities are quantified by correlation fn ξ(σ,π).
- Two effects visible:
  - Small separations on sky: ‘Finger-of-God’;
  - Large separations on sky: flattening along line of sight.



Kaiser and A-P degeneracy

Simple theory (linear + FoG):

$$P_{\rm gal}(k) = b^2 P_m(k)\ \left[1 + \beta\mu^2\right]^2 D\left(k\mu\sigma_p\right); \quad \beta \equiv f_g/b$$

But Kaiser dynamical flattening is approximately degenerate with A-P geometrical flattening: ¯$_{\rm eff}$=(F-1)/2

$$\begin{aligned} P'_{\rm gal}(k') = & \frac{1}{f_\perp^2 f_\parallel} b^2 P_m\left(\frac{k'}{f_\perp}\sqrt{1+\mu'^2\left(\frac{1}{F^2}-1\right)}\right) \\ & \times \left[1+\mu'^2\left(\frac{1}{F^2}-1\right)\right]^{-2} \\ & \times \left[1+\mu'^2\left(\frac{\beta+1}{F^2}-1\right)\right]^2 D\left(\frac{k'_\parallel \sigma_p}{f_\parallel}\right), \end{aligned}$$

Ballinger et al. 1996

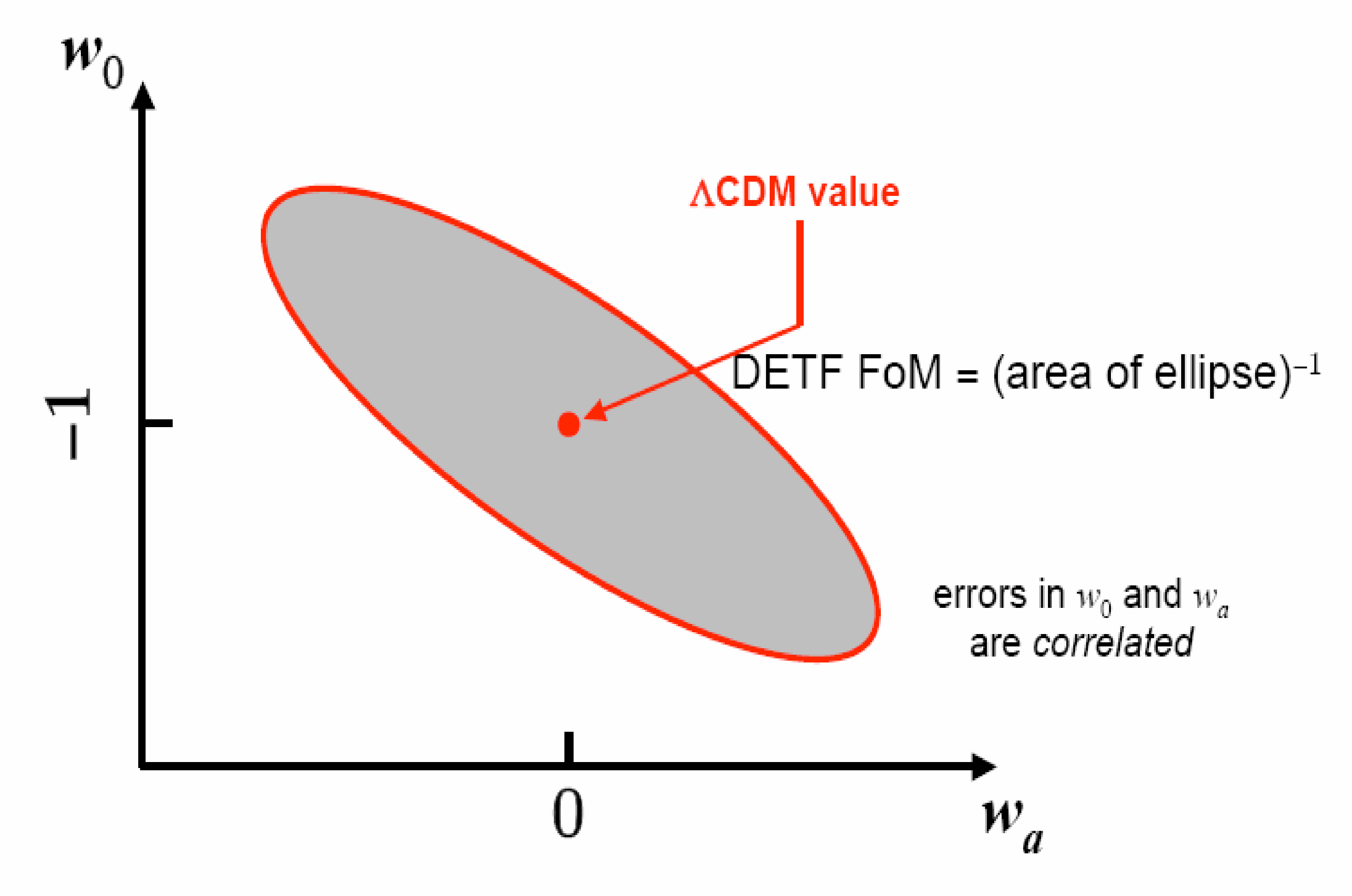
Measuring the growth rate

- Peculiar velocities come from $f_g(a)=d \ln \delta / d \ln a$
- But measure ¯ = f_g /b
  - b from bispectrum?
- Safer to say b = **¾$_{gal}$ / ¾$_{m}$**(CMB | pars)
  - But remember **¾$_{gal}$** is affected by A-P

DETF figure of merit

$w(a) = w_0 + w_a(1 - a)$: $w = w_0$ today & $w = w_0 + w_a$ in the far past

Marginalize over all other parameters and find uncertainties in w_0 and w_a



2008: add higher order w(a) variations plus quote error on γ

Figures of merit

- DE is just a term in Friedmann: probing non-GR is at least as important as measuring w
- But most people are happy not to consider $\gamma(a)$; thus should avoid too much emphasis on variation in w
- $w = w_0 + w_a\,(1-a)$ is better regarded as measuring w_p. Rejection of $w = -1$ less likely from poorly measured w_a
- PCA of w(a) interesting, but not a strong driver
- Suggests focus on $\gamma - w_p$ plane

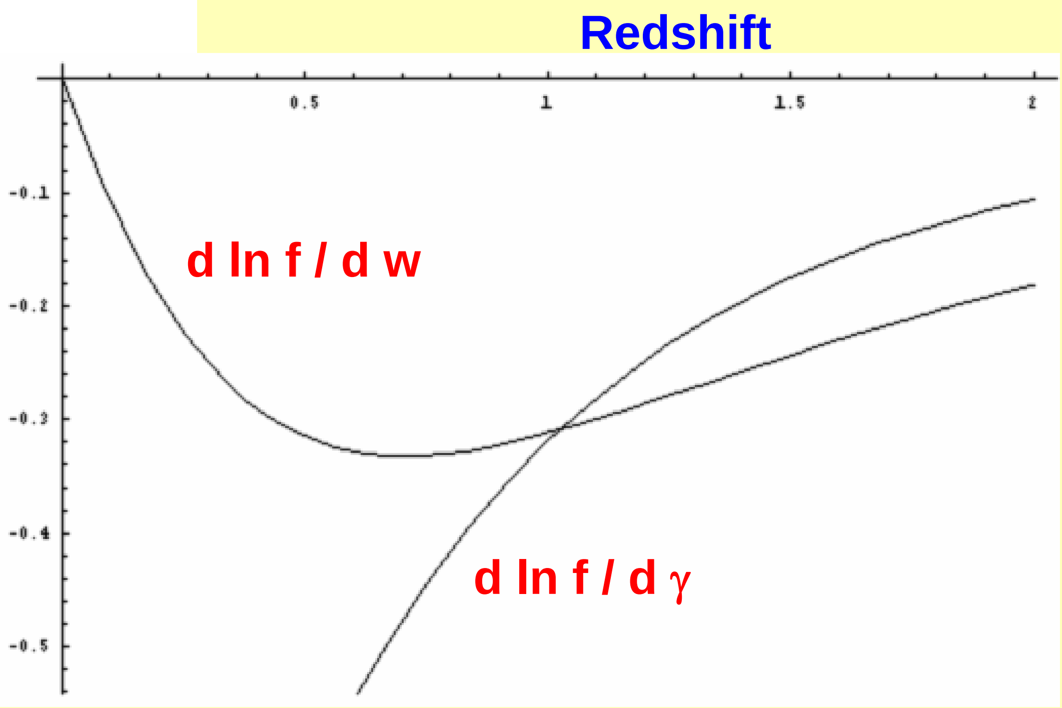
Combining RSD and BAO

BAO depend on just w if matter content is known (assumed from CMB). RSD depend on both w and γ.

$$f \equiv \frac{d \ln \delta}{d \ln a} = \Omega_m(a)^\gamma \quad \Rightarrow$$

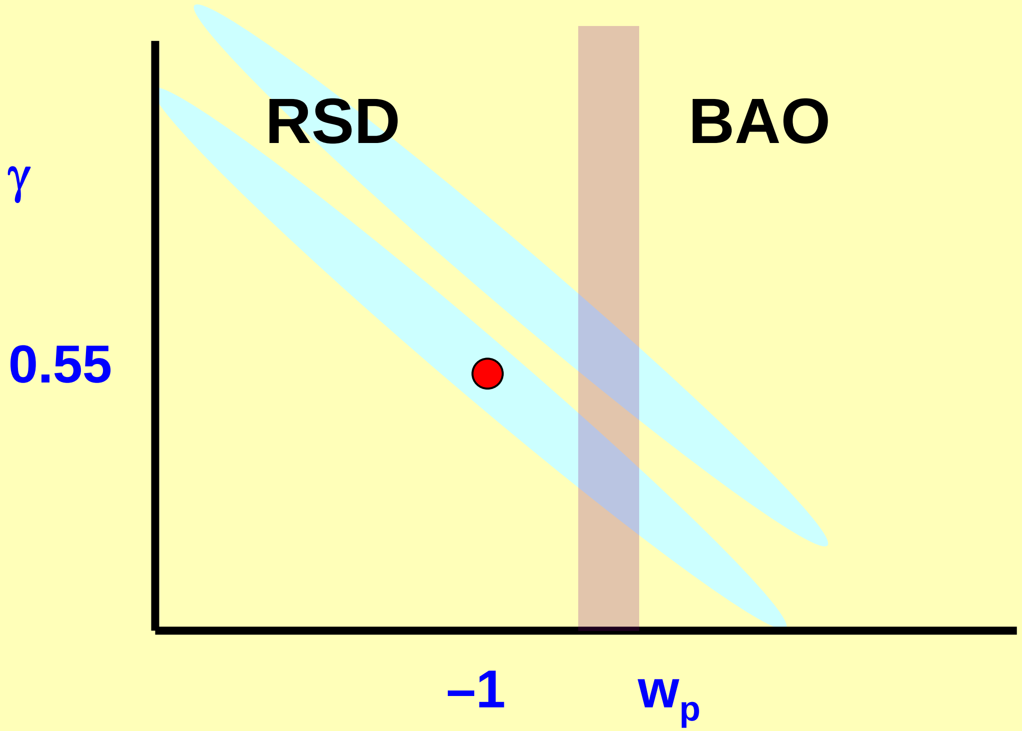
$$\frac{\partial \ln f}{\partial \gamma} = \ln \Omega_m(a)$$

$$\frac{\partial \ln f}{\partial w} = \gamma \frac{\partial \ln \Omega_m(a)}{\partial w}$$



Both derivatives around -0.3 at z = 1

DE-gravity degeneracy



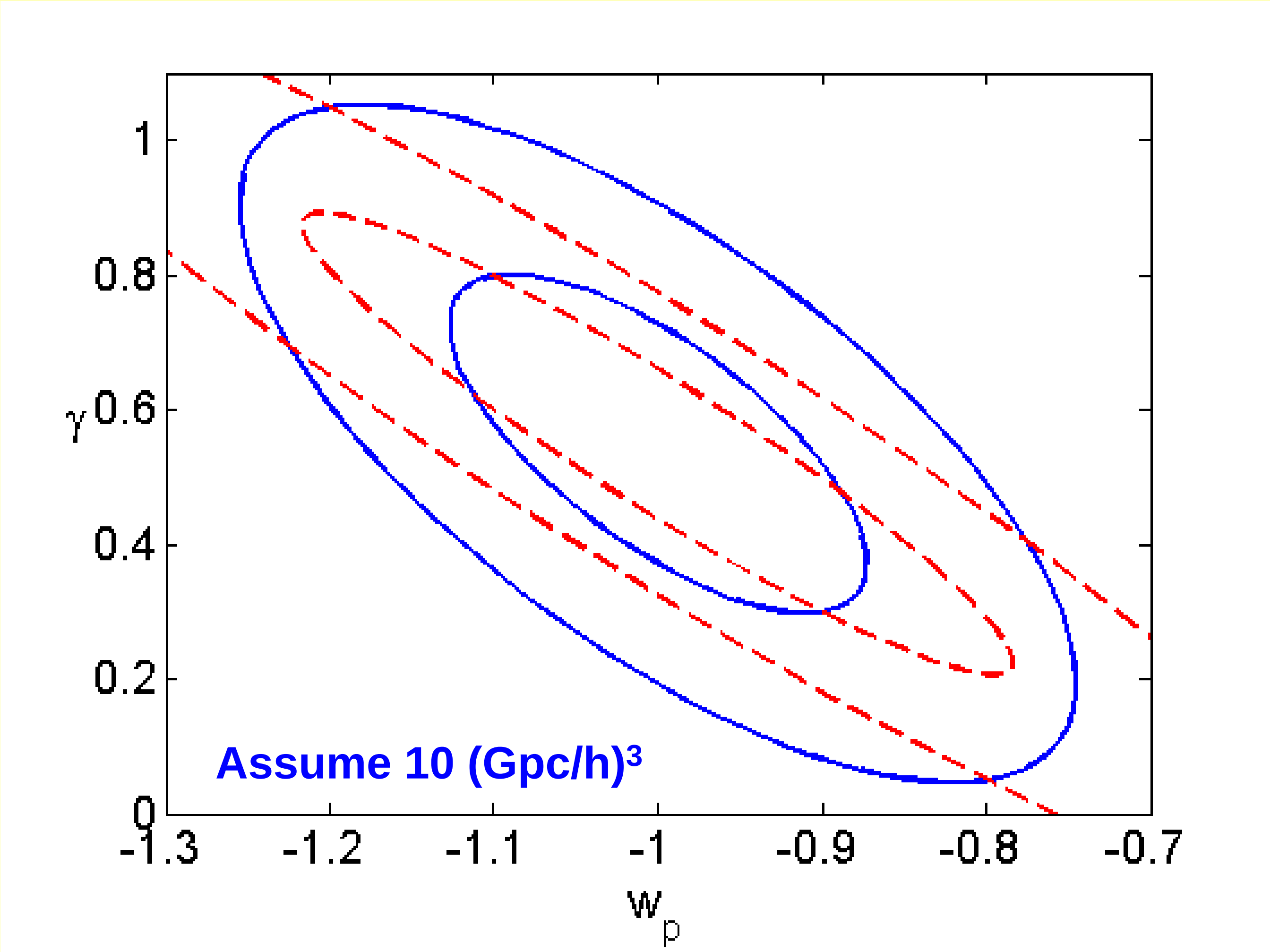
γ + w = x1 § y1

w = x2 § y2

Good to have both errors comparable.

Good case for FoM based on joint area of confidence ellipsoid in this plane

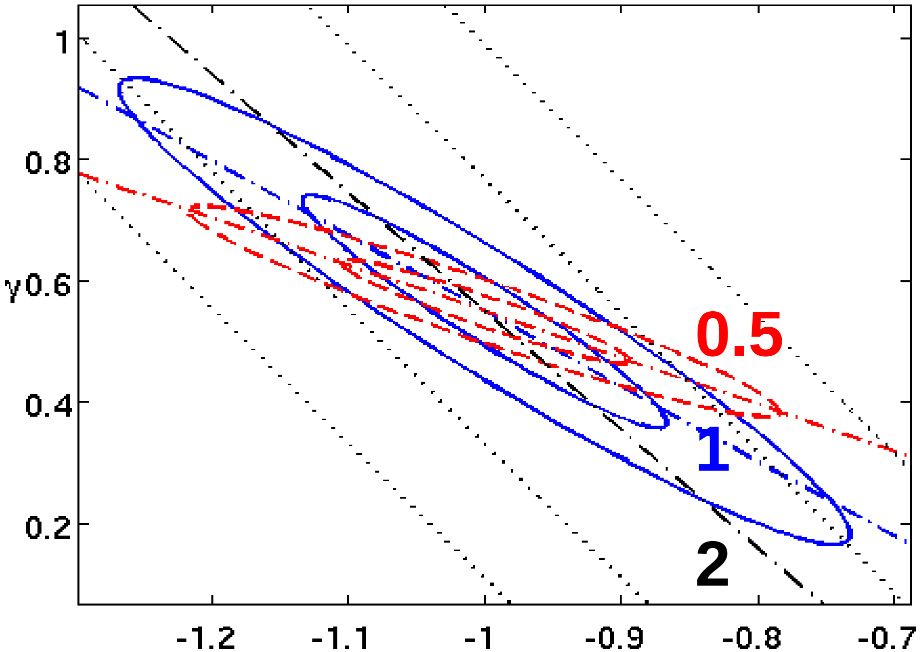
Allowing for Alcock-Paczynski



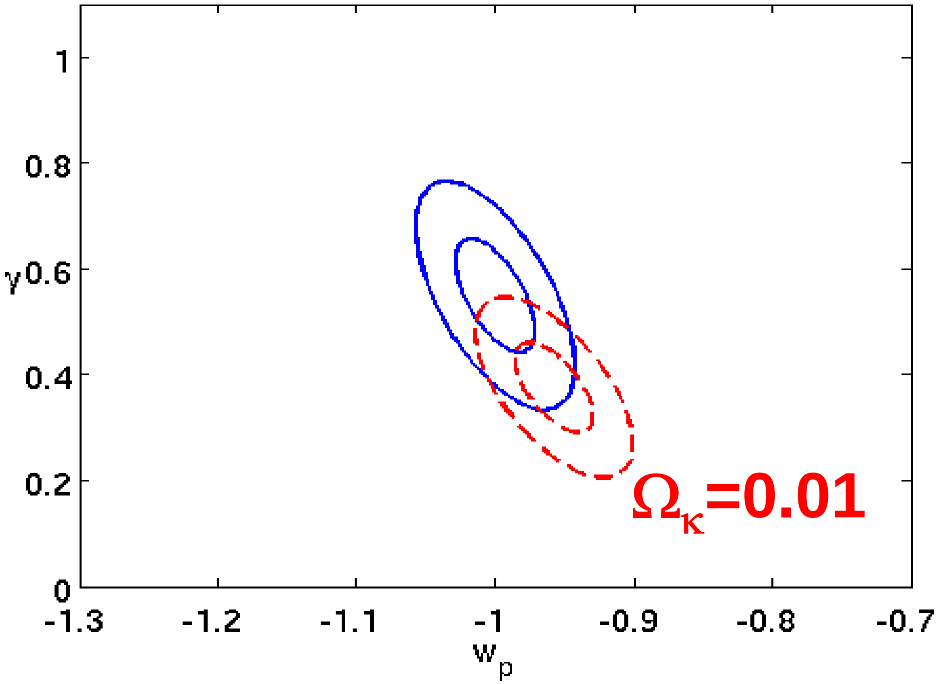
Fergus Simpson + JAP:

Overall uncertainty in γ can be ~2.5 x figure for w = -1

Base FoM on area in γ–w plane



Effect of redshift on degeneracy direction



Effect of assuming flat

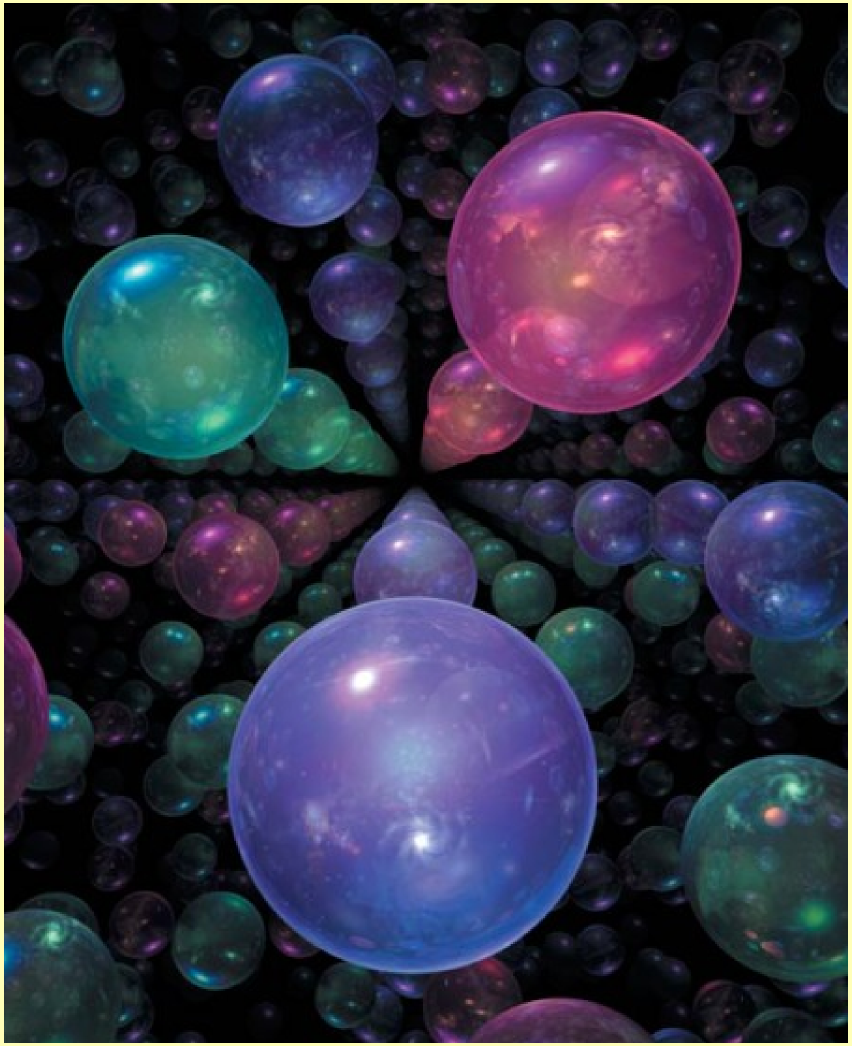
The really big question:

Universe or Multiverse?

Classes of Multiverse (Tegmark)

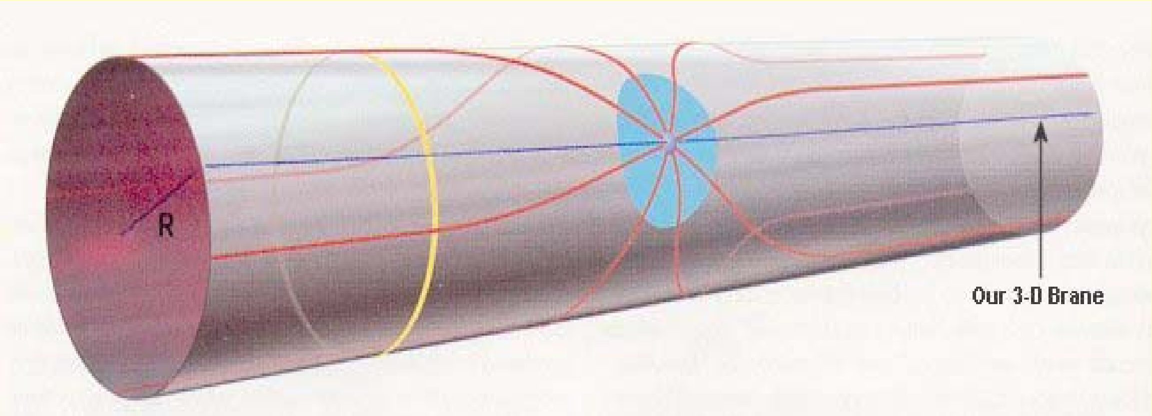
- Type 1: Distant regions
- Type 2: Physically distinct universes (inflationary bubbles; branes)
- Type 3: QM many worlds

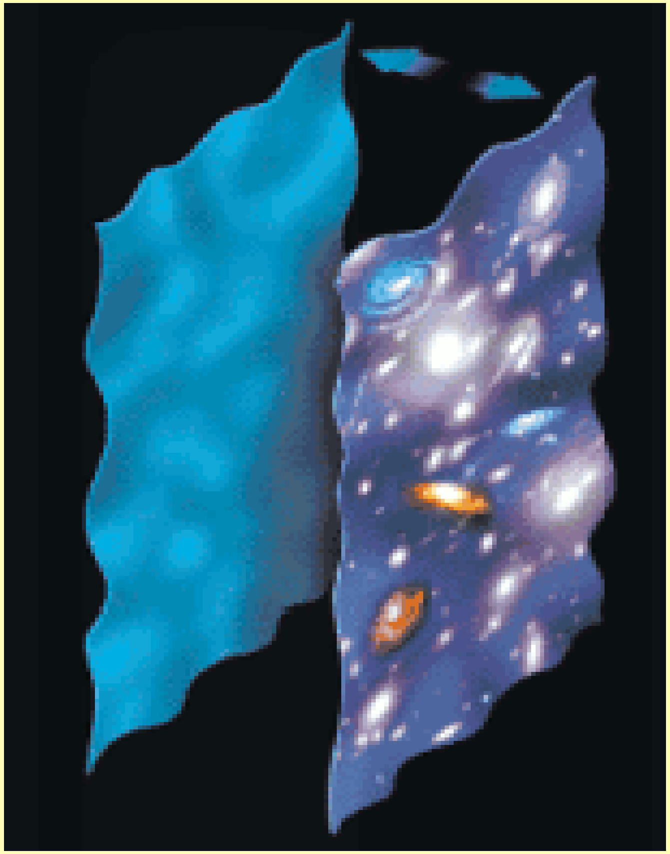
Type 2 most interesting, as physics can vary (landscape)



Extra dimensions

$$S = -\frac{1}{16\pi G}\int \left(R + e^{-2\phi}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi\right)\ \sqrt{g}\,d^4x^{\mu}$$

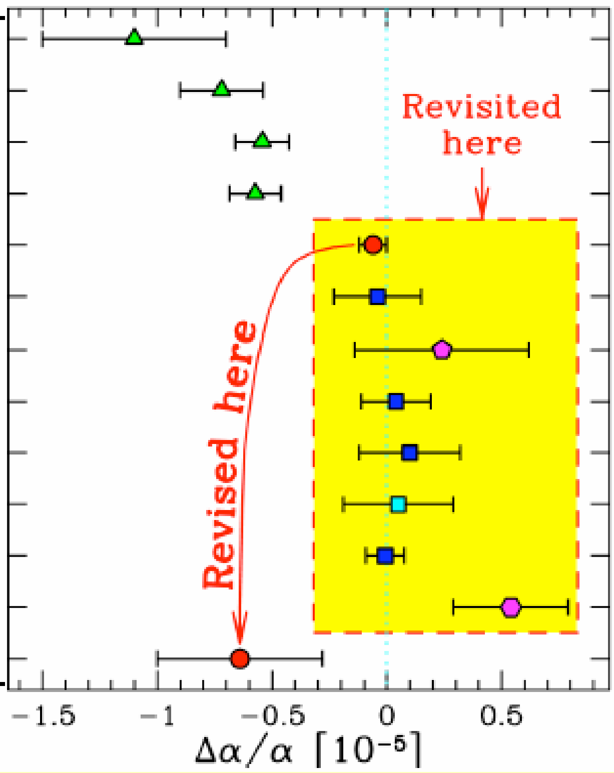




$$\frac{\dot{\alpha}}{\alpha} \sim -\frac{\dot{R}_{\text{extra}}}{R_{\text{extra}}}$$

Possible test: varying constants

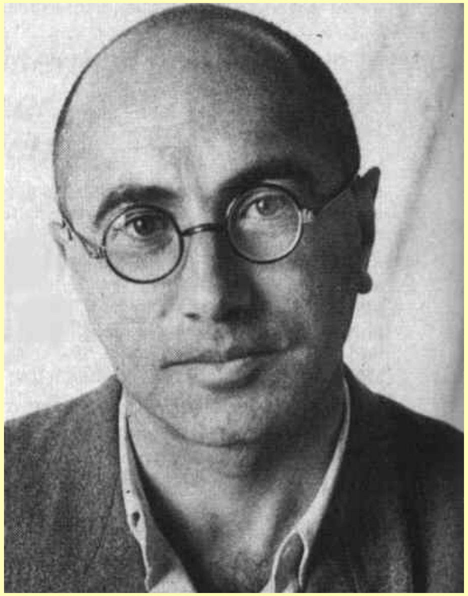
Instrument	N_{abs}	z_{abs}	$\Delta\alpha/\alpha$ [10^{-5}]	Reference
HIRES	30	0.5–1.6	−1.100 ± 0.400	Webb et al. (1999)
HIRES	49	0.5–3.5	−0.720 ± 0.180	Murphy et al. (2001a)
HIRES	128	0.2–3.7	−0.543 ± 0.116	Murphy et al. (2003)
HIRES	143	0.2–4.2	−0.573 ± 0.113	Murphy et al. (2004)
UVES	23	0.4–2.3	−0.060 ± 0.060	Chand et al. (2004)
UVES	1	1.151	−0.040 ± 0.190 ± 0.270	Quast et al. (2004)
UVES	1	1.839	+0.240 ± 0.380	Levshakov et al. (2005)
UVES	1	1.151	+0.040 ± 0.150	Levshakov et al. (2005)
UVES	1	1.151	+0.100 ± 0.220	Chand et al. (2006)
HARPS	1	1.151	+0.050 ± 0.240	Chand et al. (2006)
UVES	1	1.151	−0.007 ± 0.084 (± 0.100)	Levshakov et al. (2006)
UVES	1	1.839	+0.540 ± 0.250	Levshakov et al. (2007)
UVES	23	0.4–2.3	−0.640 ± 0.360	This work



$$\Delta \ln(m_p/m_e) = 2.6 \pm 3.0 \times 10^{-6}$$

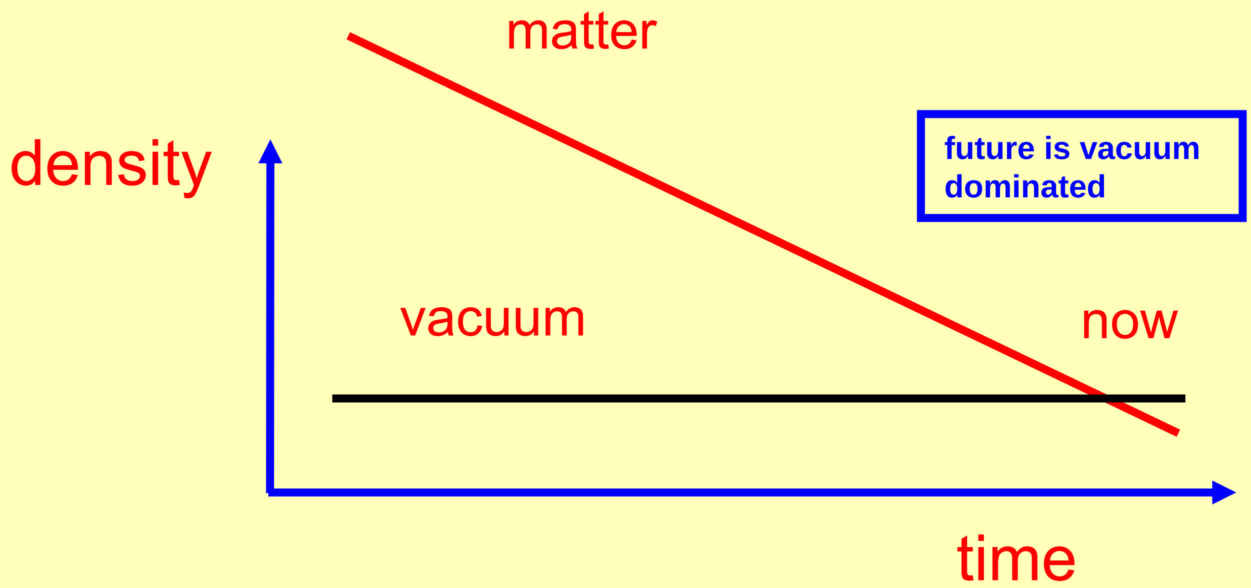
Cosmic puzzles if DE is Λ

$$\rho_{\mathrm{vac}} = \sum_{0}^{E_{\mathrm{max}}} \hbar\omega/2 \sim E_{\mathrm{max}}^4$$



Zeldovich 1967

The Scale Problem: Surely E_{max} is > 100 GeV, not 2.4 meV?

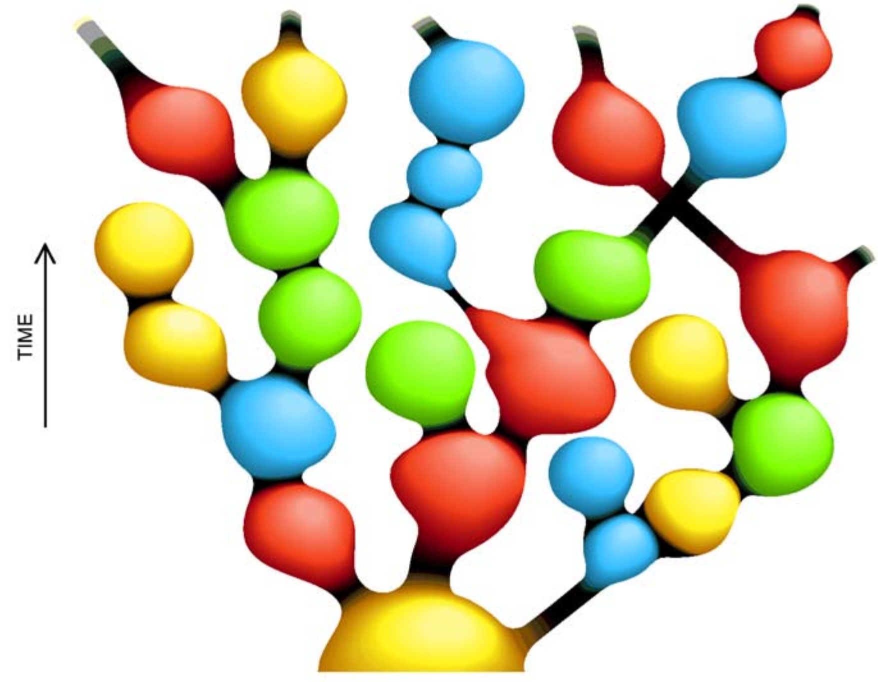


The why now problem

The answer to 'why now' must be anthropic

- One-universe anthropic
  - Life (structure) only after matter-radiation equality
  - Not controversial
  - k-essence would do
  - But need to solve classical Λ=0 problem

- Many-universe anthropic
  - Predates landscape, but requires new physics for variable Λ
  - Can we 'detect' the ensemble?
  - Sound logic (exoplanets)



Weinberg's prediction

The cosmological constant problem*

Steven Weinberg

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Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles. After a brief review of the history of this problem, five different approaches to its solution are described.

Reviews of Modern Physics, Vol. 61, No. 1, January 1989

A large cosmological constant would interfere with the appearance of life in different ways, depending on the sign of λ_{eff}. For a large *positive* λ_{eff}, the universe very early enters an exponentially expanding de Sitter phase, which then lasts forever. The exponential expansion interferes with the formation of gravitational condensations, but once a clump of matter becomes gravitationally bound, its subsequent evolution is unaffected by the cosmological constant. Now, we do not know what weird forms life may take, but it is hard to imagine that it could develop at all without gravitational condensations out of an initially smooth universe. Therefore the anthropic principle makes a rather crisp prediction: λ_{eff} must be small enough to allow the formation of sufficiently large gravitational condensations (Weinberg, 1987).

This result suggests strongly that if it is the anthropic principle that accounts for the smallness of the cosmological constant, then we would expect a vacuum energy density $\rho_V \sim (10-100)\rho_{M_0}$, because there is no anthropic reason for it to be any smaller.

Is such a large vacuum energy density observationally allowed? There are a number of different types of astronomical data that indicate differing answers to this question.

Conclusions

- Galaxy clustering and the CMB define a standard model for structure formation
- Next-generation surveys will either rule out Λ or prove w = –1 to 1%, and will test gravity up to 100 Mpc
- Must consider exotic DE and modified gravity equally
    - e.g. must not claim new gravity if w=-1 is assumed
- Galaxy surveys probe BAO+RSD combination
    - Result is w-° anticorrelation
- Either way, need a solution to the classical Λ problem, or will have to accept a multiverse picture