Evidence for Dark Matter

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see information at

http://particleastro.brown.edu/

http://cdms.brown.edu/ http://xenon.brown.edu/

Thanks

- Thanks for some of slide material
  - Ian Dell'Antonio, Bernard Sadoulet, Rocky Kolb, Joel Primack, Dan Akerib, Max Tegmark, Ted Baltz

- Useful reading
  - Principles of Cosmology, Peebles
  - The Early Universe, Kolb & Turner
  - Cosmological Physics, Peacock
  - Other primary refs given on slides

  - Also see references in Direct Detection of Dark Matter, Gaitskell, Annual Reviews Nuclear and Particle Science, vol 54 (2004), to be published shortly

Rick Gaitskell, Introduction

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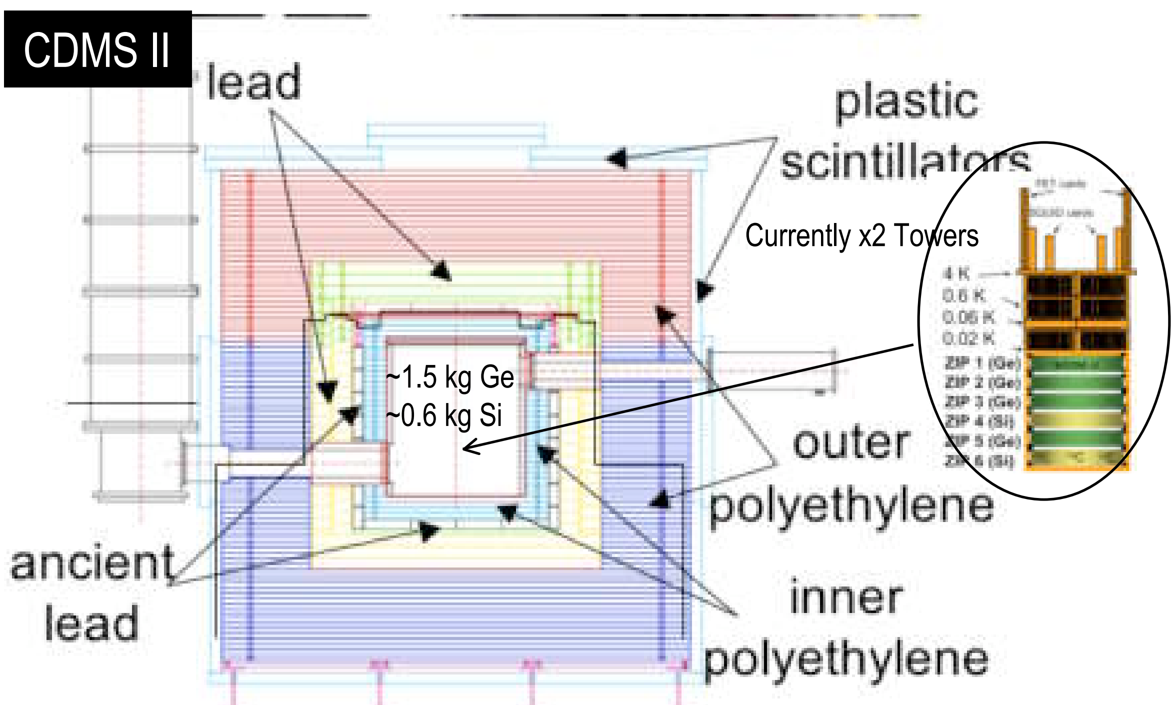
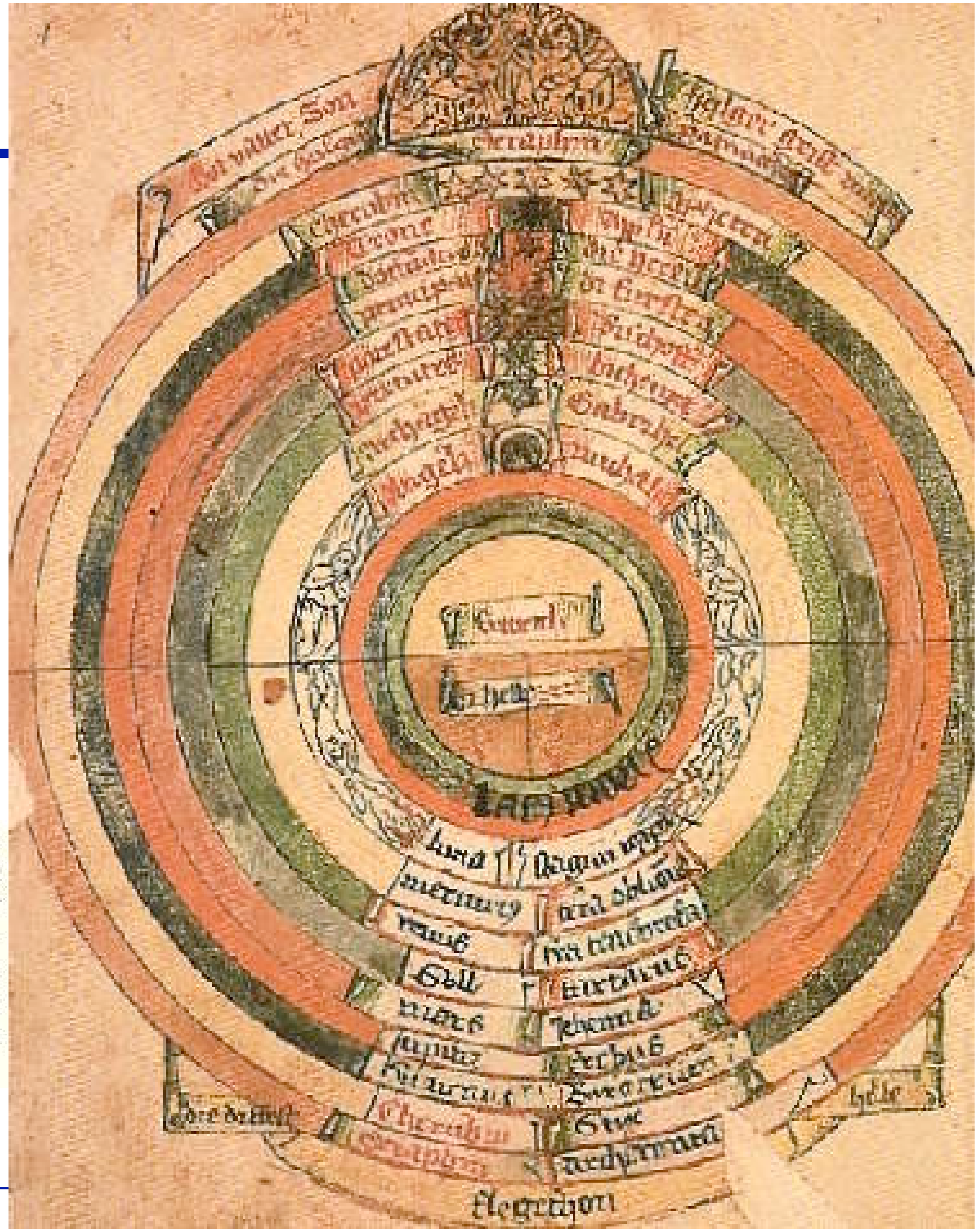
- Head of Particle Astrophysics Group, Dept of Physics, Brown University
  - Previously at University College, London / UC Berkeley, Center for Particle Astrophysics / Oxford University
  - 15 years searching for Dark Matter in the form of WIMPs (Talk: Ted Baltz)
    - CDMS I/II Cryogenic Dark Matter Search Experiment
      - Currently is most sensitive WIMP search (Talk: Blas Cabrera)
    - XENON: Next generation search experiment



Medieval Universe



The geocentric pre-Copernican Universe in Christian Europe. At center, Earth is divided into Heaven (tan) and Hell (brown). The elements water (green), air (blue) and fire (red) surround the Earth. Moving outward, concentrically, are the spheres containing the seven planets, the Moon and the Sun, as well as the "Twelve Orders of the Blessed Spirits," the Cherubim and the Seraphim. German manuscript, c. 1450.

From Joel Primack, UC Santa Cruz

Confession

>95% of the Composition of the Universe is still unknown

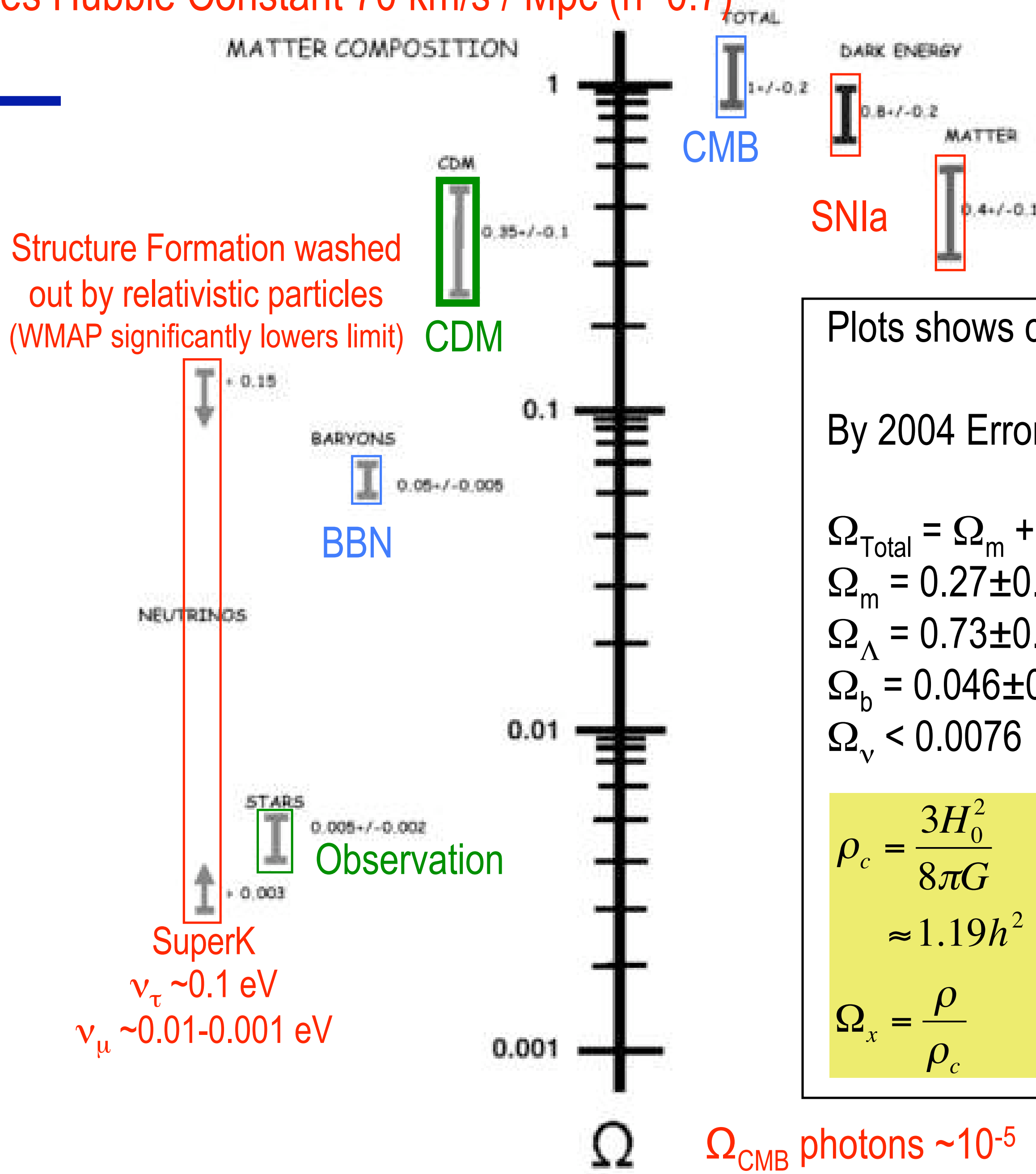
Known Unknowns

- “As we know,
  There are known knowns.
  There are things we know we know.
  We also know
  There are known unknowns.
  That is to say
  We know there are some things
  We do not know.
  But there are also unknown unknowns,
  The ones we don't know
  We don't know."
- -- Donald Rumsfeld, Secretary of Defense,
  February 12, 2002, Department of Defense news briefing

Introduction

- --> 1990's For many a "known known" was that $\Omega_{Total} = 1$
  - This being matter dominated, $\Omega_m = 1$
- We have had to revise this view partially: $\Omega_{Total} = 1$, but $\Omega_m \sim 0.3$
  - Dark Matter now has to share the shadows with Dark Energy
  - Indeed it is convenient to split into 3 Dark Problems
    - Baryonic Dark Matter - Mostly known
    - Non-Baryonic Dark Matter - **Know Unknown**
    - Dark Energy - Only God knows, right now
- It has been a Problem in Cosmology that astrophysical assumptions often need to be made to interpret data/extra parameters
  - Now many independent/increasingly precise techniques are being used
  - This now enables disentanglement of "Gastrophysics" (Sadoulet)
- Ultimately related to Fundamental/Particle Physics
  - Non-baryonic dark matter - New Particles - SUSY, neutrinos, baryogenesis
  - Dark Energy - Gravity / Extra Dimensions

Ω (Plot assumes Hubble Constant 70 km/s / Mpc (h~0.7)



Plots shows consensus in 2000

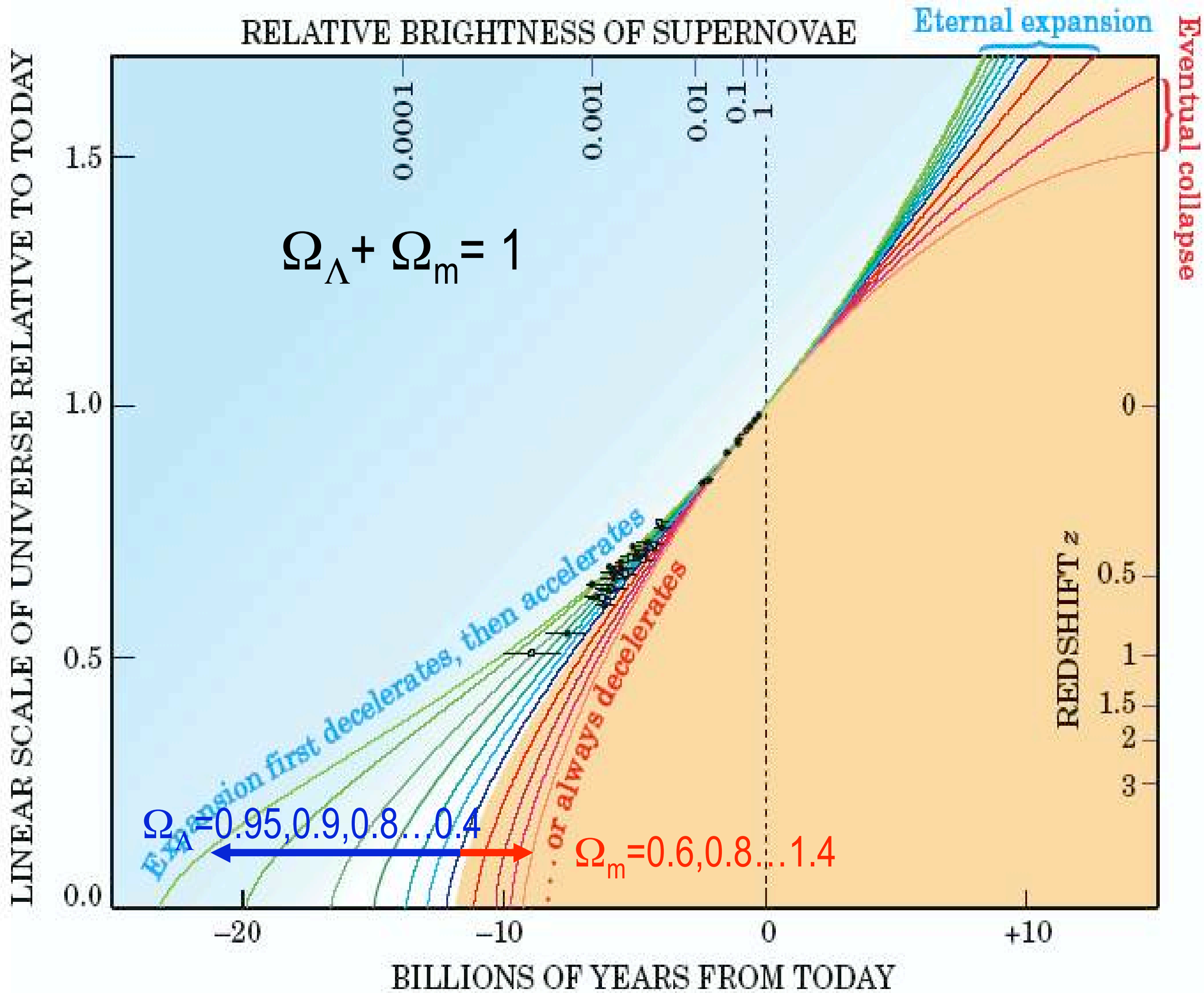
By 2004 Error bars have shrunk !

$\Omega_{Total} = \Omega_m + \Omega_\Lambda = 1.02\pm0.02$
$\Omega_m = 0.27\pm0.02$
$\Omega_\Lambda = 0.73\pm0.04$
$\Omega_b = 0.046\pm0.001$
$\Omega_\nu < 0.0076$

$$\rho_c = \frac{3H_0^2}{8\pi G} \approx 1.19h^2 \text{ GeVc}^{-2}\text{m}^{-3}$$

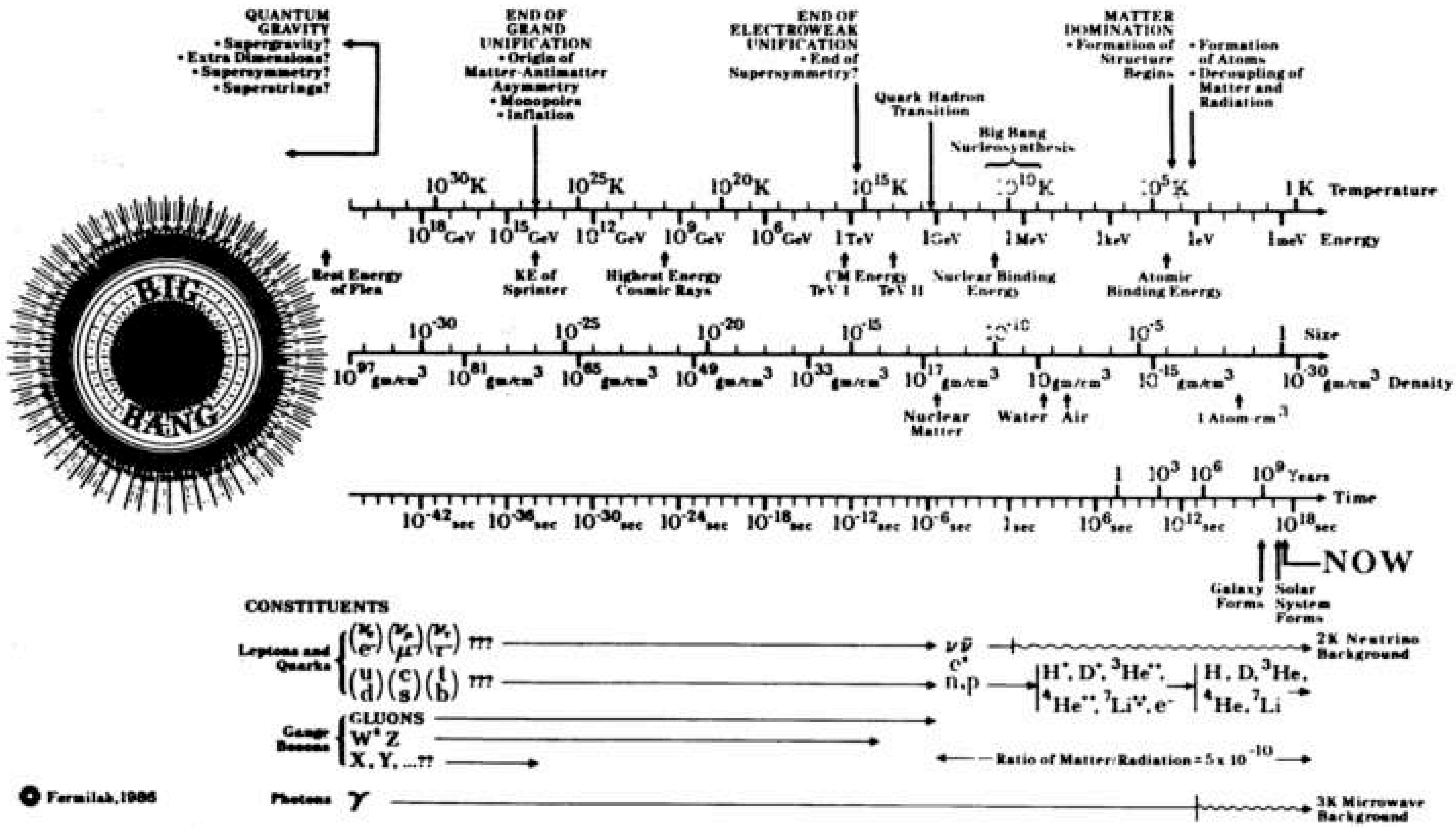
$$\Omega_x = \frac{\rho}{\rho_c}$$

ΛCDM Cosmology Evolution - z vs time



Saul Perlmutter, Physics Today, Apr 2003

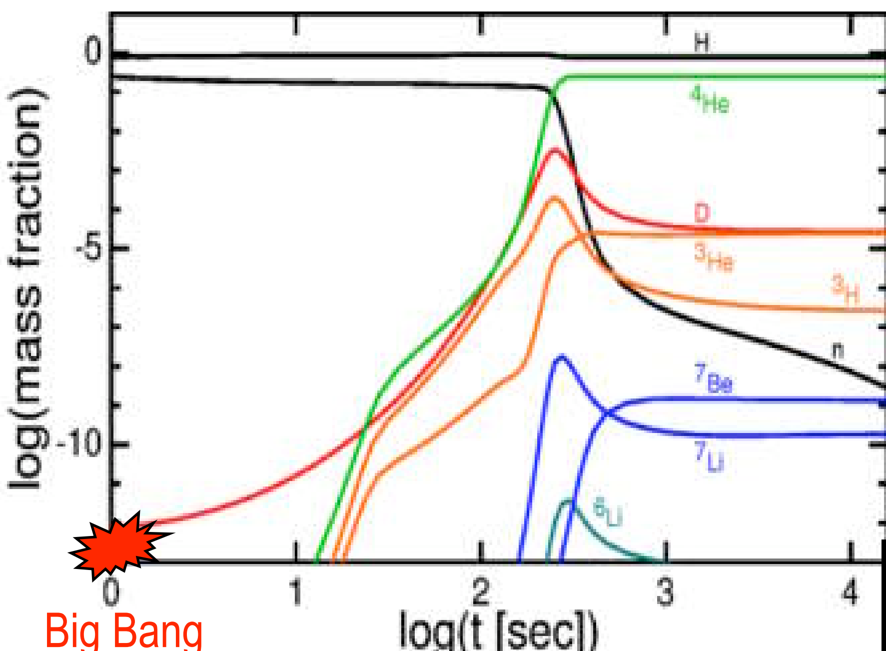
Big Bang Timeline (for reference)

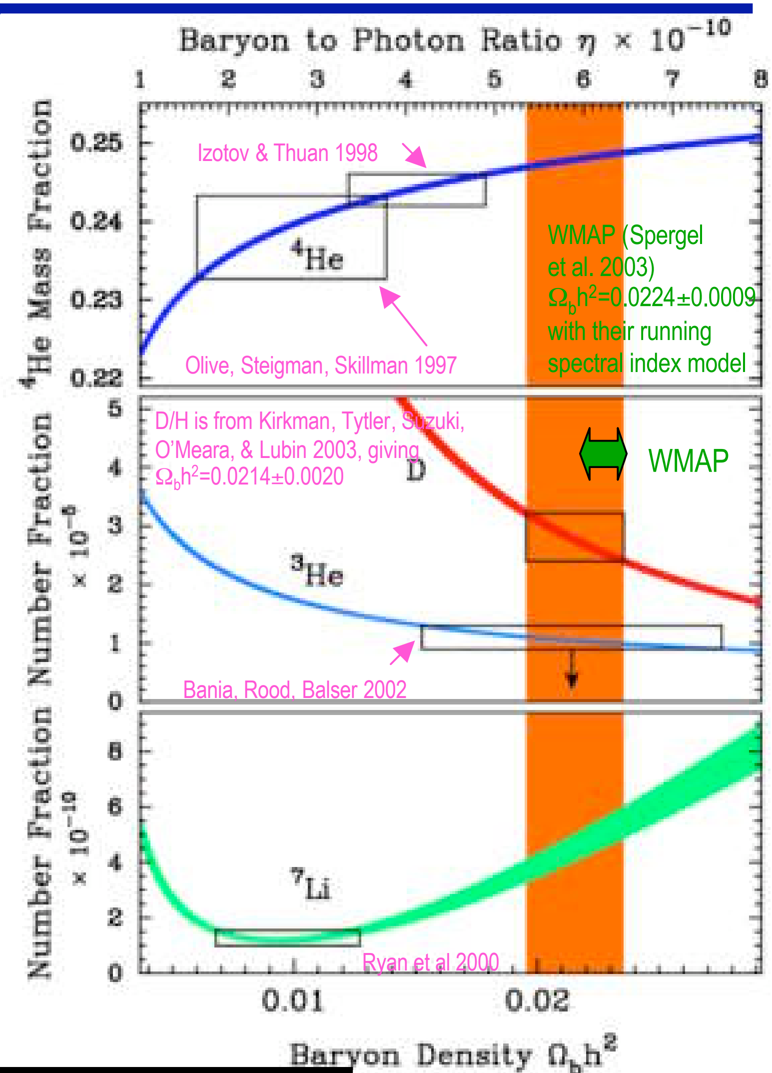


Baryonic Matter: Well determined

Ω_b = 0.046±0.001

- Big Bang Nucleosynthesis
  - Primordial abundances of light elements depend on the number of baryons
  - neutron/proton~1/6 from thermodynamics and freeze-out temp. (# depends on baryon density)
  - 4He has highest binding energy and consumes most of neutrons
    - Depletes D abundance which is very sensitive to initial density



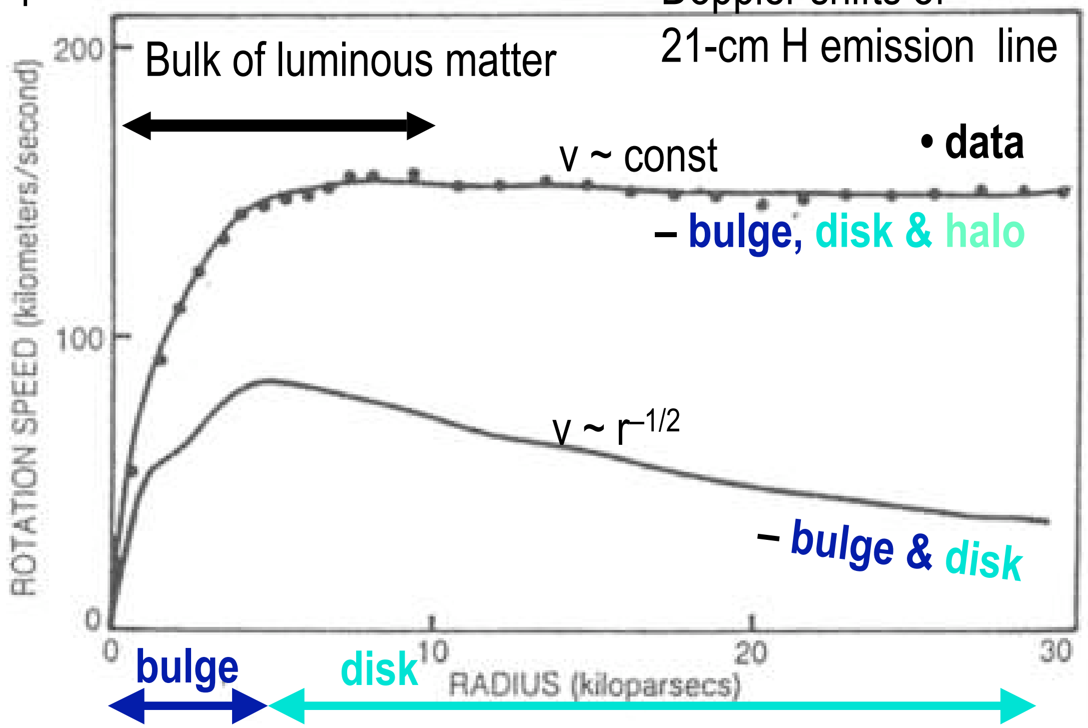


^{4}He and ^{7}Li show some disagreement BUT BEST PROBE, D, GOOD AGREEMENT OTHER EXP.

BBN predictions are from Burles, Nollett, & Turner 2001
see also Joel Primack, DM2004

Dark Matter Dynamical Evidence: Individual Galactic Halos

Spiral Galaxies



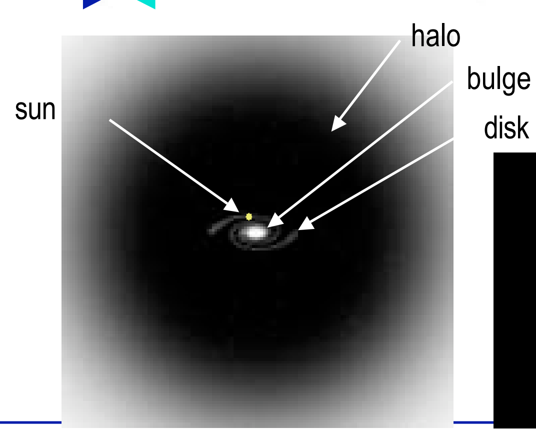
$$F_{\text{centripetal}} = F_{\text{gravity}}$$

$$\frac{mv_r^2}{r} = \frac{GmM_{\text{total}}(r)}{r^2}$$

$$v_r = \sqrt{\frac{GM_{\text{total}}(r)}{r}}$$

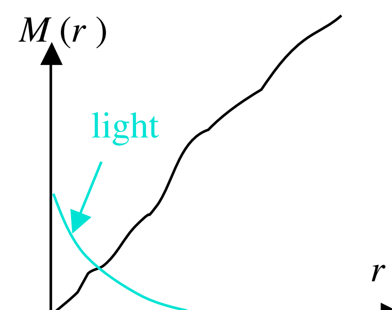
$$\frac{M(r)}{r} \to \text{const} \quad (r >> r_{core})$$

A self gravitating ball of ideal gas at a uniform temperature would have such a profile
(e.g. see J Binney and S Tremaine, Galactic Dynamics, Princeton UP, 1988)

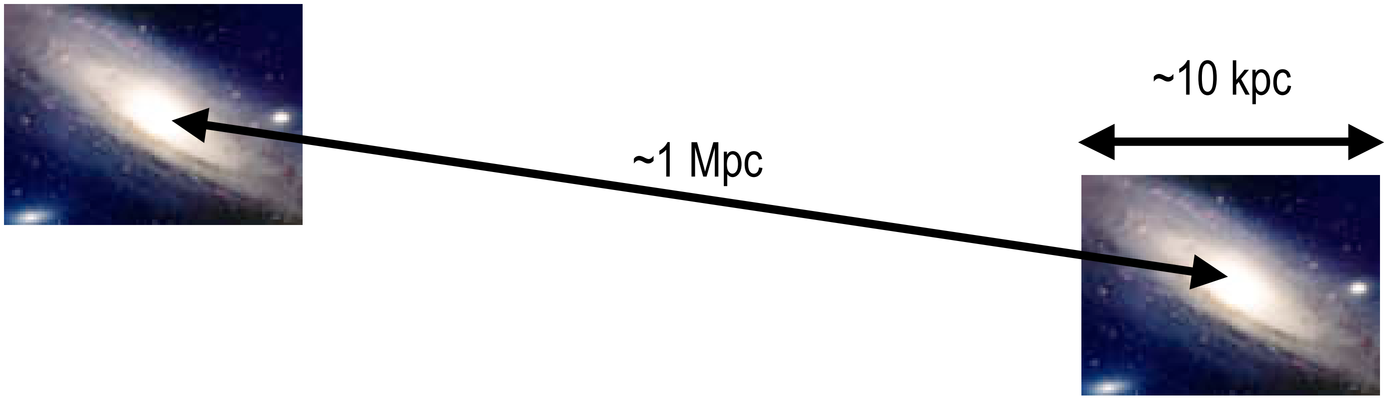


$$M_{\text{dark}} \geq 10 M_{\text{stars}}$$

However, mass from summing all
galactic halos only set lower
limit ~ Ω_m >0.02
NEED TO PROBE LARGER SCALES
INTER-GALACTIC



Inter-Galactic Scales



- 1920's Hubble establishes (using Cepheid variable stars) that spiral nebulae (M31) well outside Milky Way
- Subsequent surveys: Average Galaxy spacing ~1 Mpc
  - How far out do the galactic dark halos extend?
- However apparent that the spatial distribution of galaxies shows range of structure
  - Small Clusters e.g. "Local Group" MW + M31 (Andromeda, 0.8 Mpc) + ~12 smaller galaxies (include Large / Small Magellanic Clouds)
  - Rich Clusters e.g. Virgo or Coma clusters, 1000's galaxies in few Mpc

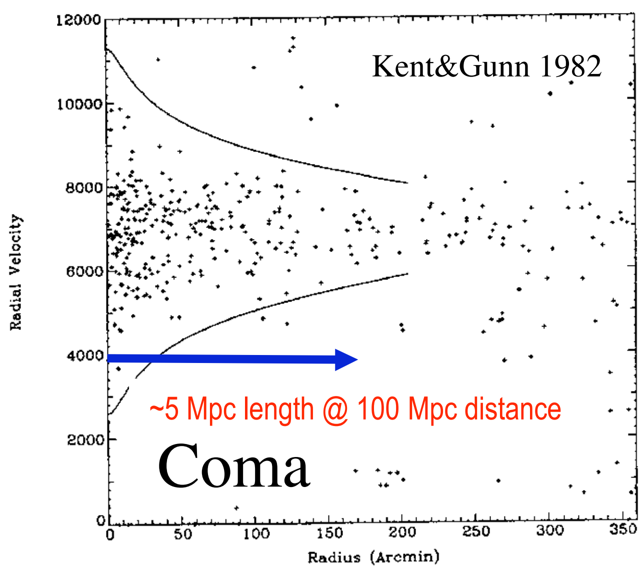
1 pc = 3.26 light-years

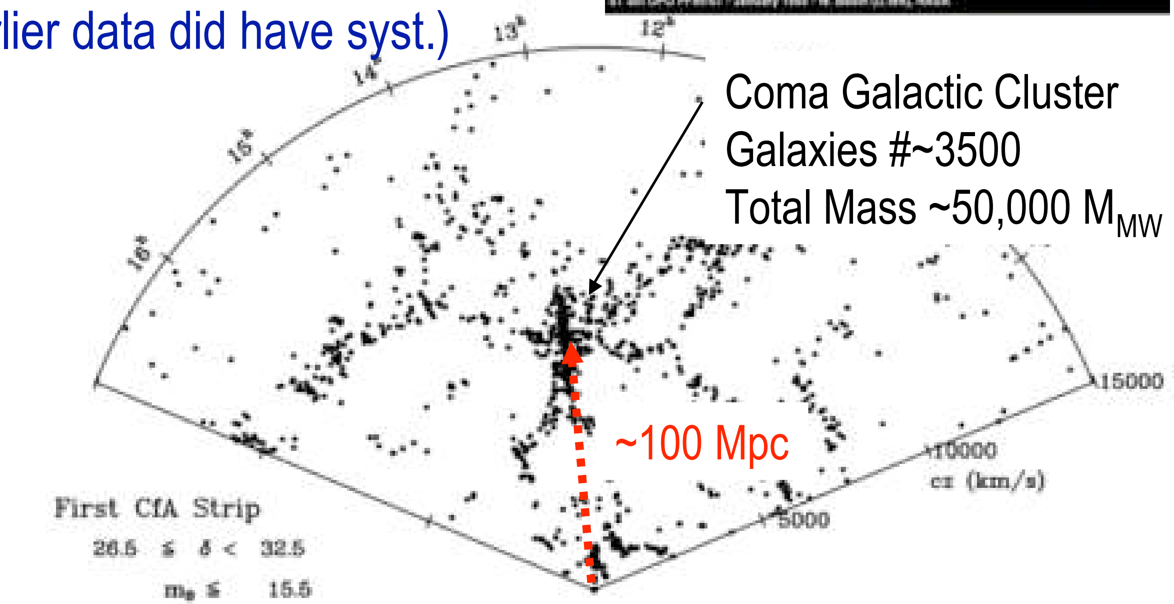
Galactic Velocity Dispersion in Clusters

- Velocities of galaxies in galactic clusters
  - 1936 Fritz Zwicky - first measurement => Dark Matter
    - Measured Velocity Dispersion via Doppler Redshift of 8 galaxies in Coma Cluster
    - Velocities too high to be provide gravitational potential from luminous matter alone (m_{Lum}~0.5% of required)
  - Expect Virialized Velocities

$$\langle KE \rangle = -\frac{1}{2}\langle PE \rangle$$

  - Modern Results - similar (earlier data did have syst.)



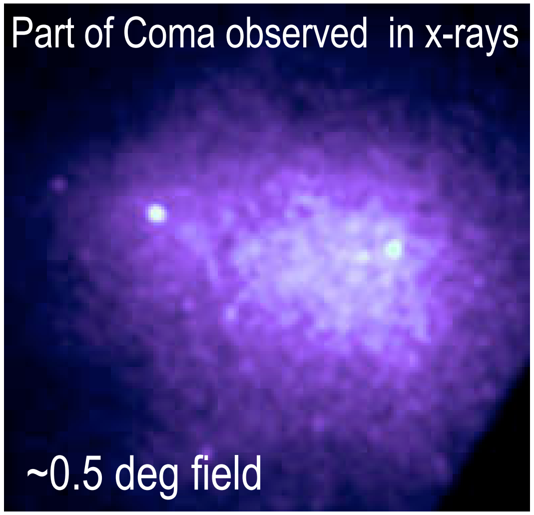


X Ray Emission From Intra Cluster Medium

- X-ray emission
  - Intra Cluster Medium in hydrodynamic equilibrium - internal temperature balanced by gravitational potential

$$\frac{3}{2}k_B T \approx -\frac{1}{2}\langle PE\rangle \quad \text{Hydrodynamic equilibrium}: \rho_T(\vec{r}) = \sqrt{-\frac{\nabla_{\vec{r}}^{\,2}\, p[\rho_b(\vec{r}), T_e(\vec{r})]}{4\pi G}}$$

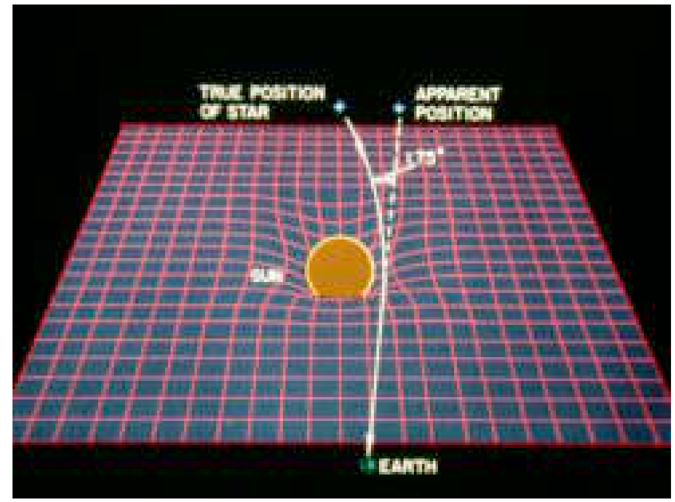
  - Observe emissions (uaing satellite) => $T \sim 10^7$ K
    - Bremsstrahlung up to 10 keV,coming from hot electrons scattering from hot protons
    - High resolution x-ray spectroscopy also able to see lines from highly stripped atoms e.g. Fe14+. Ratio of line intensities also indicates eqm temperature of intra cluster gas
    - $M_{ICM\ gas} \sim$ 2-3x M_{gal} (Ω_{gas}~0.05 Still Baryonic Dark Matter)
    - $M_{Cluster} \sim$ 5x M_{gas} (=>Ω_m~0.3 > Ω_{baryon})

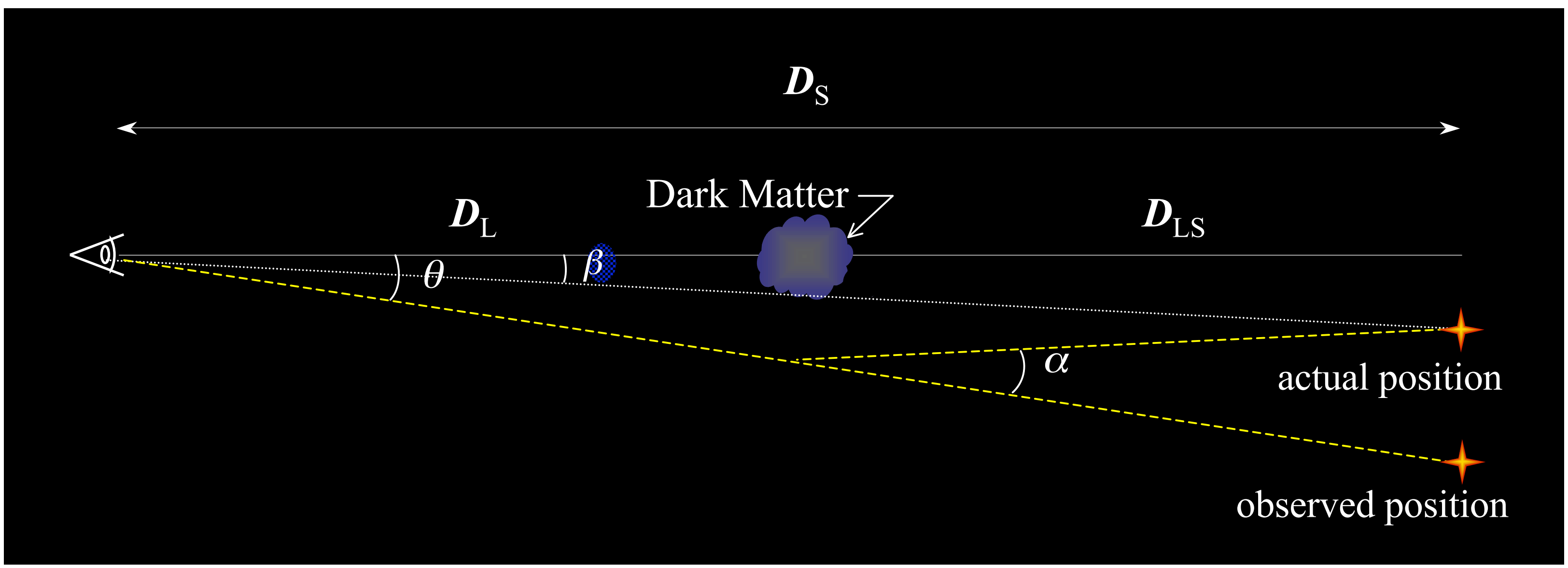


Also Sunyaev Zel'dovich up-scattering of Cosmic Microwave photons

Measurement of Cluster Mass by Strong Lensing

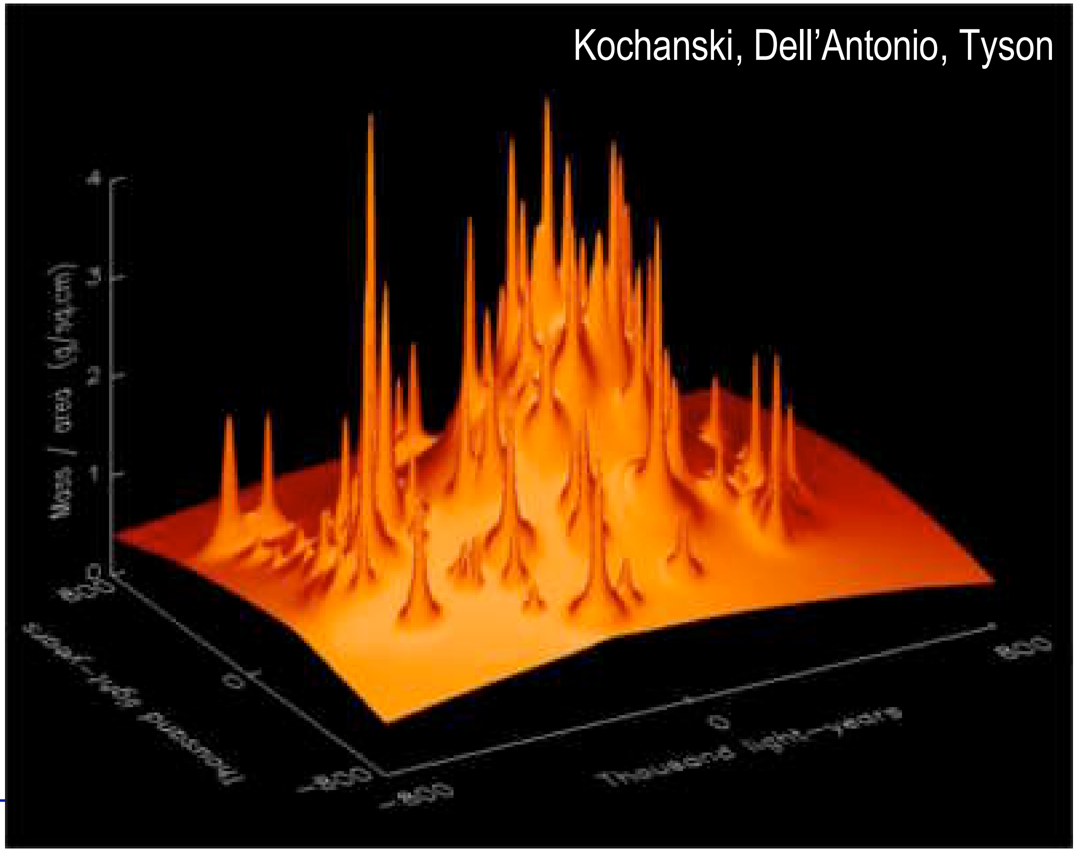
- Matter bends space time, which alters the path of light
- Basic Equation
  - Geometry gives $$\theta = \beta + \frac{\alpha D_{LS}}{D_S}$$
  - A point mass gives $$\alpha = \frac{4GM}{c^2 R}$$
  - Mass distribution Σ(R) gives $$\boldsymbol{\alpha} = \frac{4G}{c^2} \int \frac{\Sigma(\mathbf{R})}{R^2} d\mathbf{R}$$





Measurement of Cluster Mass by Strong Lensing (2)

- If the deflection angle is large there are multiple images - strong lensing
- Requires close alignment of source and center of lens distn e.g. CL0024+1654
  - Foreground galaxy cluster z=0.39 (false yellow = Near Infrared)
  - Background galaxy source z=1.6 (blue, color due to star formation, young galaxy)
    - Einstein Ring ~100 kpc radius @ z=0.39
  - Mass Distribution deconvolved from Hubble Image (galaxies=spikes, DM=hump dominant mass)



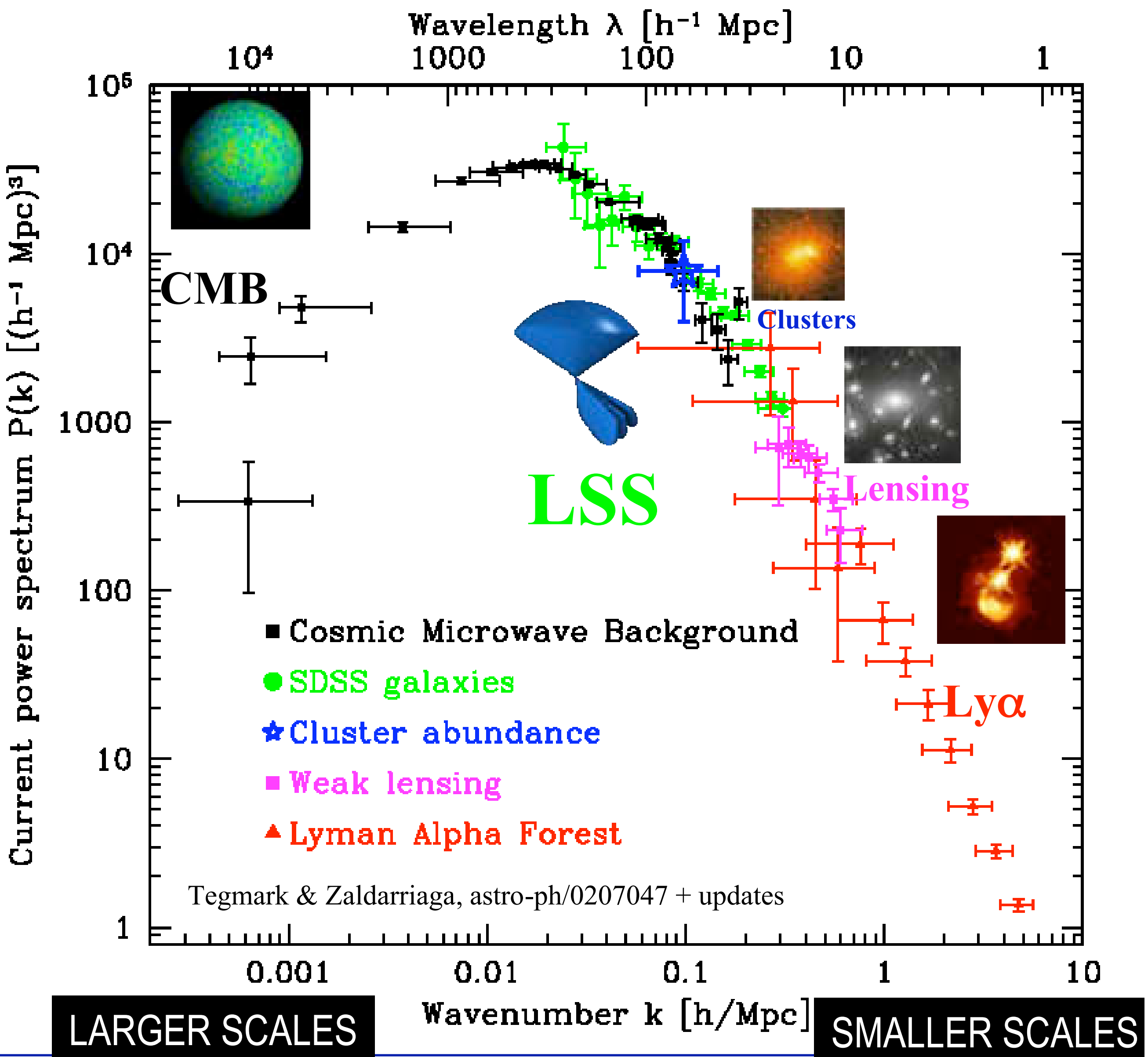
Mass Measurement at Cluster Scales Agree

- All cluster mass measurements have a firm lower limit of $\Omega_m > 0.15$, so majority of mass must be some new non-baryonic form
  - Remembering $\Omega_b = 0.045$
- It is also now clear that $\Omega_m < 1$
  - Clusters/Superclusters are the largest "structures" in the Universe, so there is no greater scale to study dynamics of objects. If they don't contain mass then must turn to diffuse Dark Energy to provide remaining energy to flatten space-time.

- We can now go on to look in greater detail at the matter distribution power spectrum (size of fluctuations vs scale)
  - Permit "precision" test, $\Omega_m \sim 0.27 \pm 0.02$ is strongly preferred
  - Extraordinary degree of concordance in many separate techniques

Power Spectrum of Structure

- Consider the Fourier Transform of 2-point correlation of matter distribution
  - Measured by a variety of techniques that overlap in distance scale
  - Show good agreement
    - This is a recent occurence
  - For some data theory approximations/ assumptions required to get to Power Spec, but with larger surveys/precision of data, able to test models directly
  - How do we explain overall shape?



What Determines Structure Power Spectrum?

- Suggest that primordial matter distribution fluctuations are "scale invariant" i.e. fractal, no length scale preferred
  - => $P(k) \sim k^n$, with n=1 , space-time has same "wrinkliness" on each resolution scale
  - This is physics at energy scales yet to be observed - challenge remains to explain details of this mechanism
- Growth of fluctuations calculated by solving eqns of fluid in an expanding Universe, taking into account
  - Gravity
  - Pressure, arising from EM interactions of relativistic component
- At early times, high z
  - Perturbations are small, so possible to linearize
  - Work in "comoving" coordinates to track final k's as Univ. expands
- In absence of fluid pressure and expansion
  - Over densities would grow exponentially
  - In an expanding Univ. exp() become power laws
- Pressure term
  - Provides a restoring force against collapse
  - However, max size at which this can operate is set by "speed of oscillations c_s" in medium
  - Smaller scales: $\lambda < \tau\, c_s$ fluctuations oscillate, where τ is time for gravitational collapse
  - Larger scales: collapse occurs unimpeded, fluctuations grow

What Determines Structure Power Spectrum? (2)

δ_k is size of fluctuations

- Two epochs in early universe

Jeans Length $\lambda_J = \sqrt{\pi} c_s (G\rho)^{-\frac{1}{2}}, \quad c_s = \frac{c}{\sqrt{3}}, \quad (G\rho)^{-\frac{1}{2}}$ is collapse time of sphere density ρ

  - Radiation dominated
    - Pressure is important

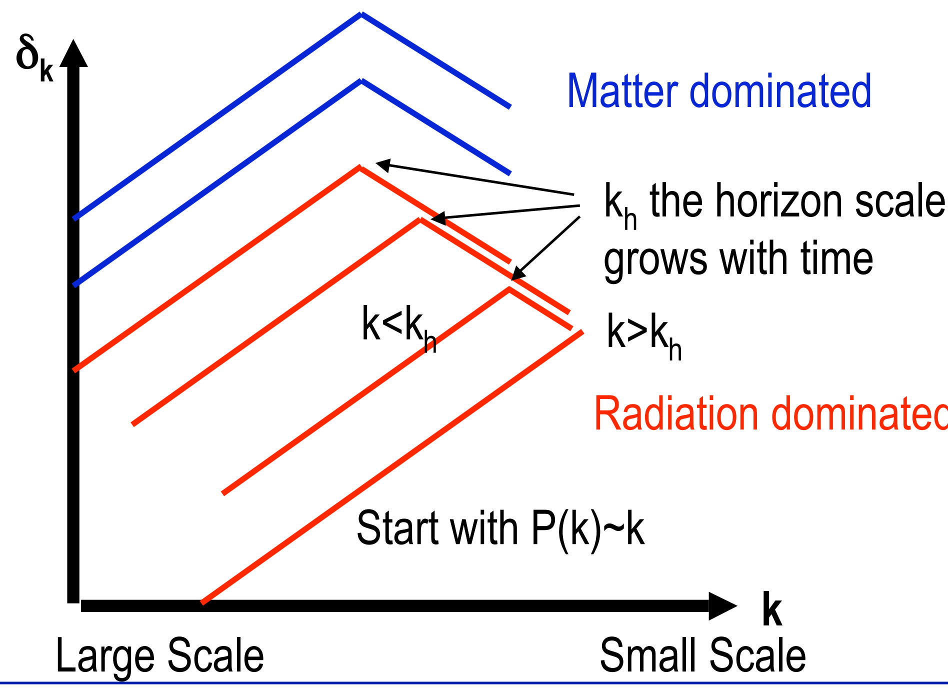
$\lambda < \lambda_J \qquad \delta_k \propto (1+z)^0$, constant, or even decay

$\lambda > \lambda_J \qquad \delta_k \propto (1+z)^{-2}$, fluctuations grown as z falls

  - Matter dominated
    - Pressure no longer important

$\delta_k \propto (1+z)^{-1}$, all fluctuations grow as z falls

- Transition radiation to matter dominated occurs at $z_{eq} \sim 10^4$
  - Reason for transition is that Ω's are diluted by expansion scale expansion $a(t) \sim (1+z)^{-1}$
  - Radiation $\Omega_{rad} \sim a(t)^4$ (think of it as wavelength being stretch as well as volume term)
  - Matter $\Omega_m \sim a(t)^3$ (volume dilution)



Power Spectrum of Structure

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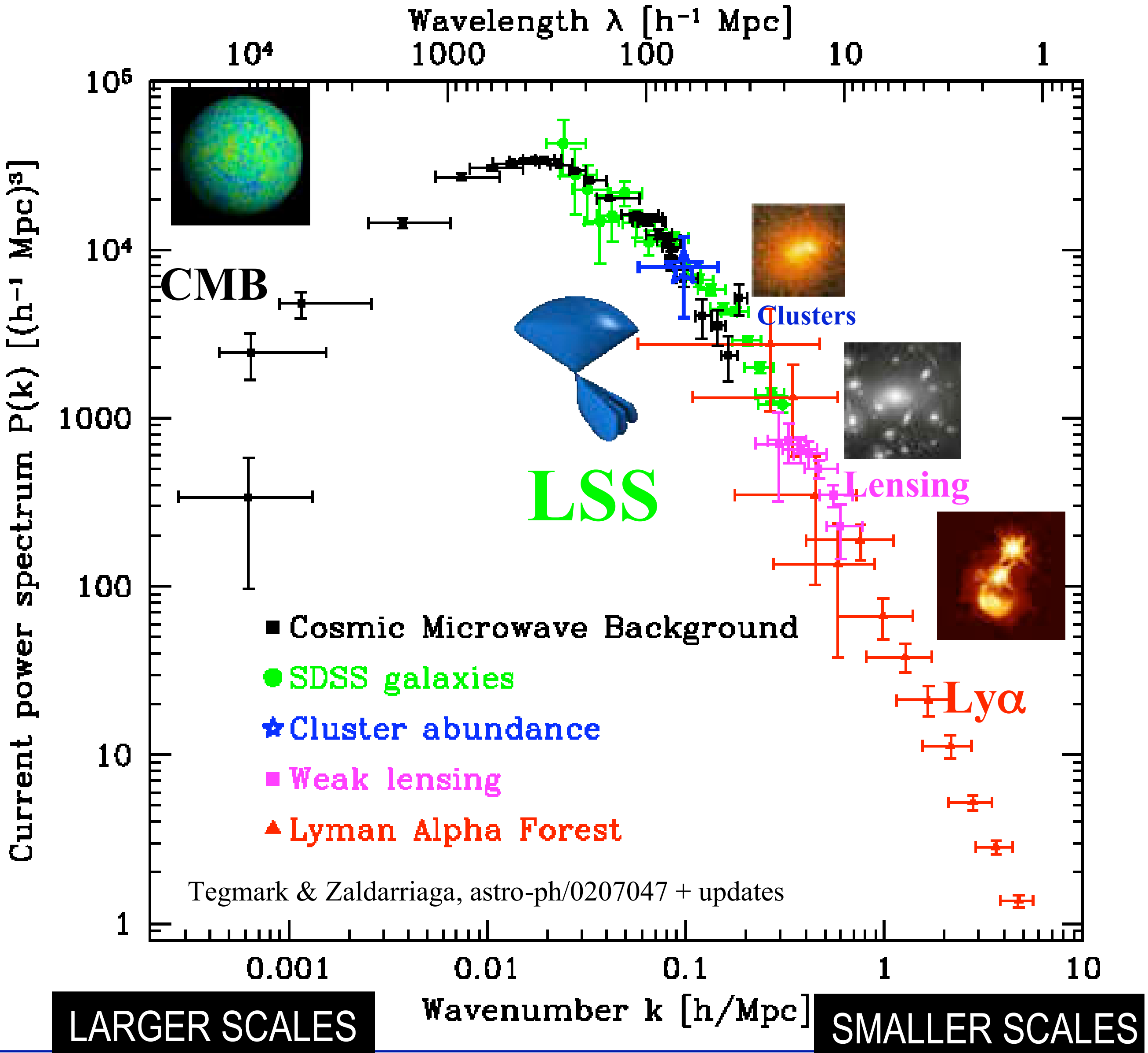
  - How do we explain overall shape?



Directly Measuring Large Scale Structure

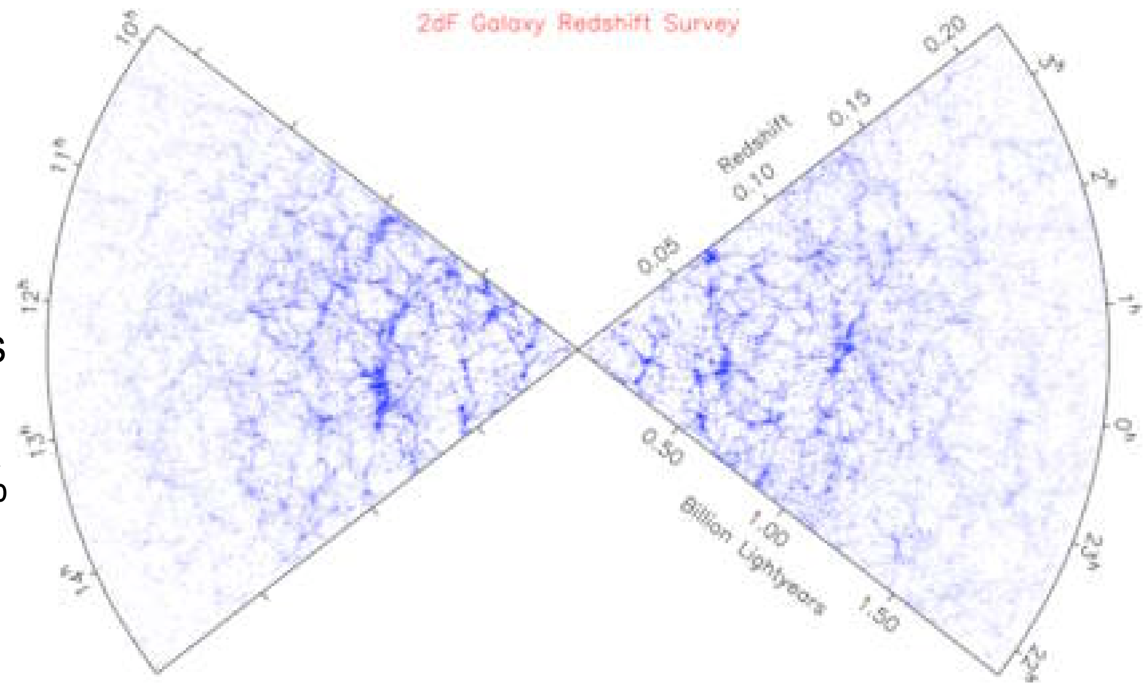
- Galaxy Redshift Surveys
  - Measure angular position and distance using redshift

- CfA (1980's) 30,000 galaxies, out to z~0.05 (v≤15,000 km/s)
  - See Voids, bubble, sheets filaments

- Las Campanas (1990's) additional +26,000 galaxies, out to v≤60,000 km/s

- 2dFGRS (2000's) 250,000 galaxies, 5% of sky (shown)

- SDSS, Sloan Digital Sky Survey (on going) ~1 Mgalaxies, 25% of sky



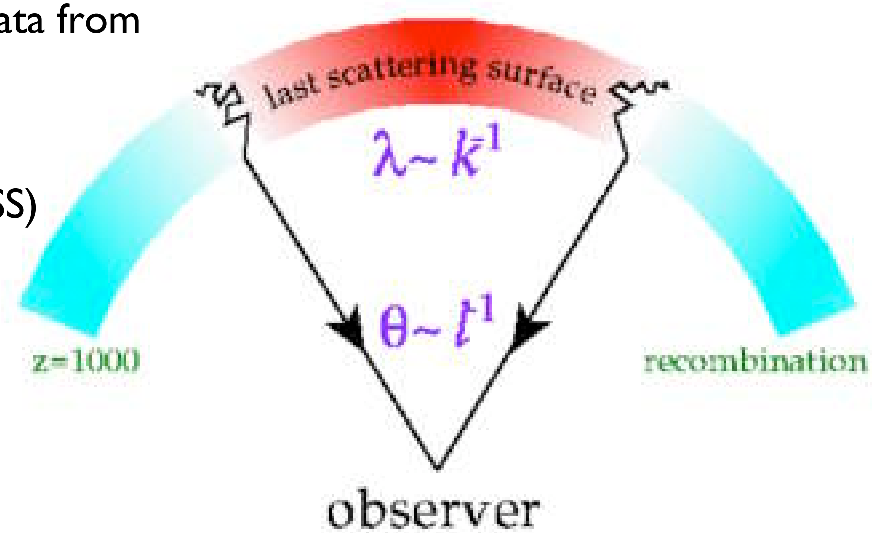
Cosmic Microwave Background

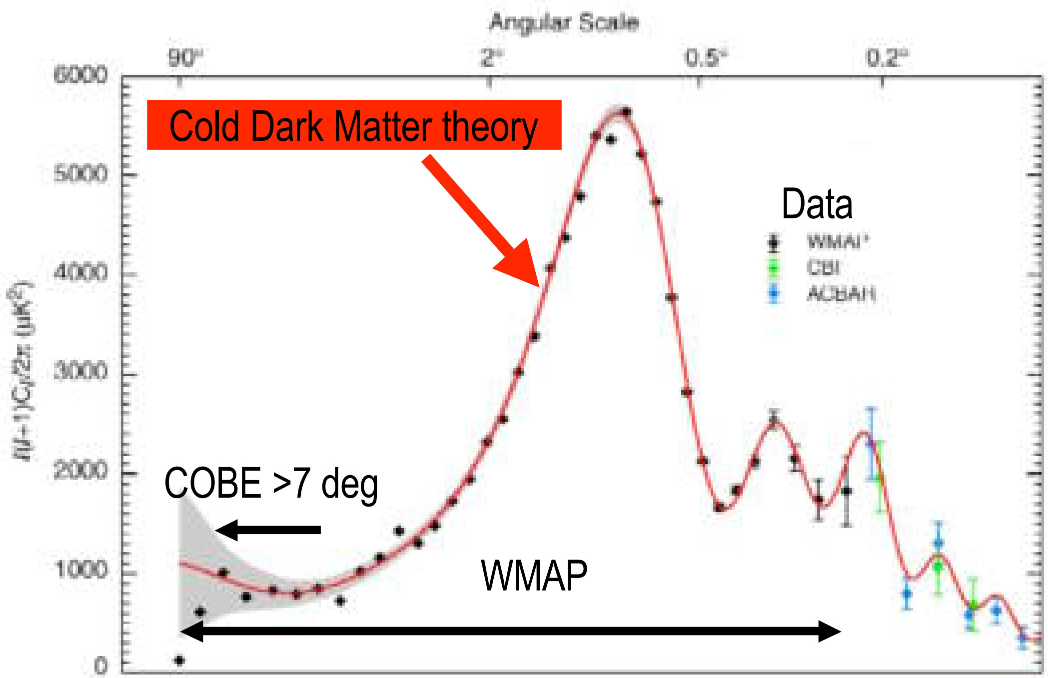
- CMB traces fluctuations in baryons at $z \sim 10^3$
  - This is the time when protons and electron combined into neutral hydrogen and became transparent to photons
  - Large angular scales correspond to smaller k
    - Based on model assumptions able to relate CMB fluctuation to Matter Power Spectrum
  - Note that $\Delta T/T \sim 10^{-5}$ would be too small to create structure power spectrum observed today
    - Require Cold Dark Matter fluctuations to be forming earlier, with larger δk than seen in baryons at time of last scattering
    - CDM weakly interacting/not EM, decoupled from baryonic component /photons
    - Baryons subsequently fall into gravitational potential wells/structure of CDM

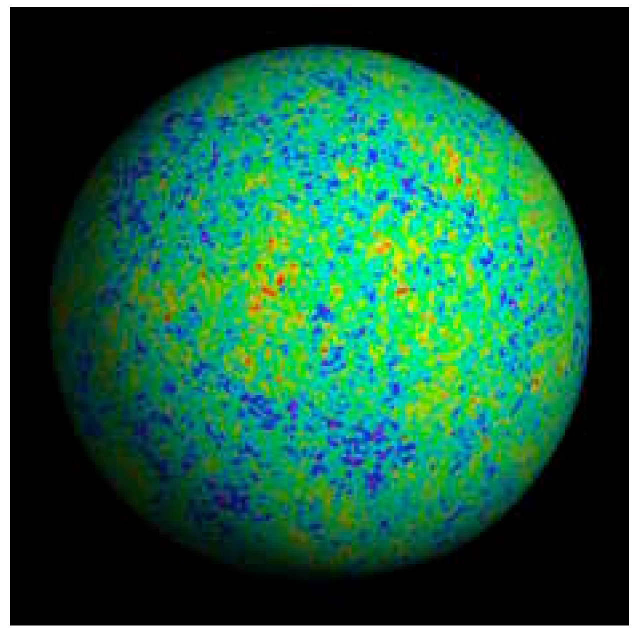
WMAP/CMB: 1st Year data: Best fit cosmological model

Ω_{tot} = 1.02 +/- 0.02
Ω_m = 0.27 +/- 0.04
Ω_b = 0.044 +/- 0.004
Ω_Λ = 0.73 +/- 0.04
h = 0.71 +0.04 -0.03
τ_U = 13.7 +/- 0.2 Gyr

consistent with data from
HST Key project
weak lensing
D measurements
LSS (2dFGRS/SDSS)
Type Ia SN





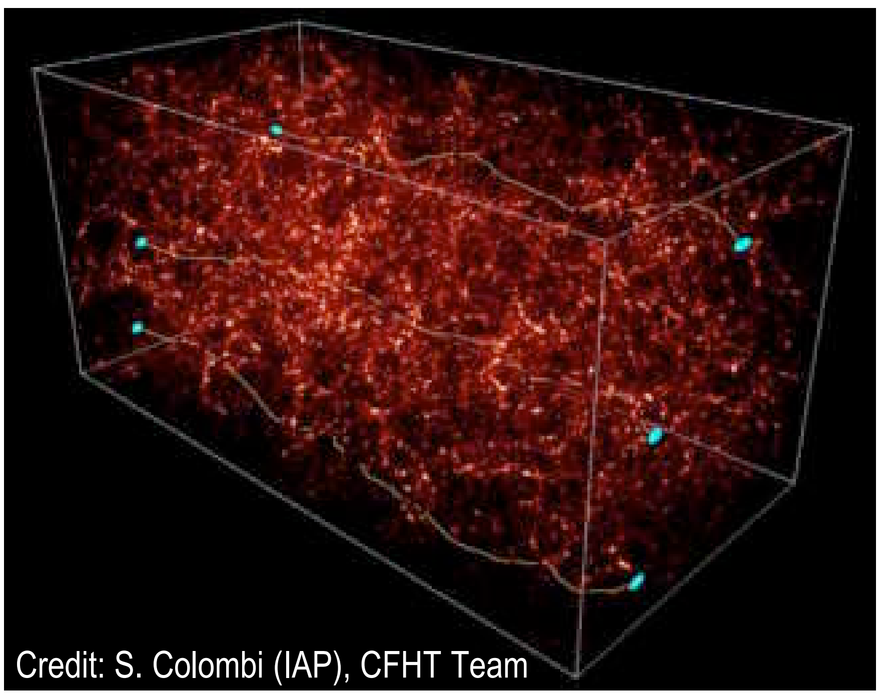


Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496

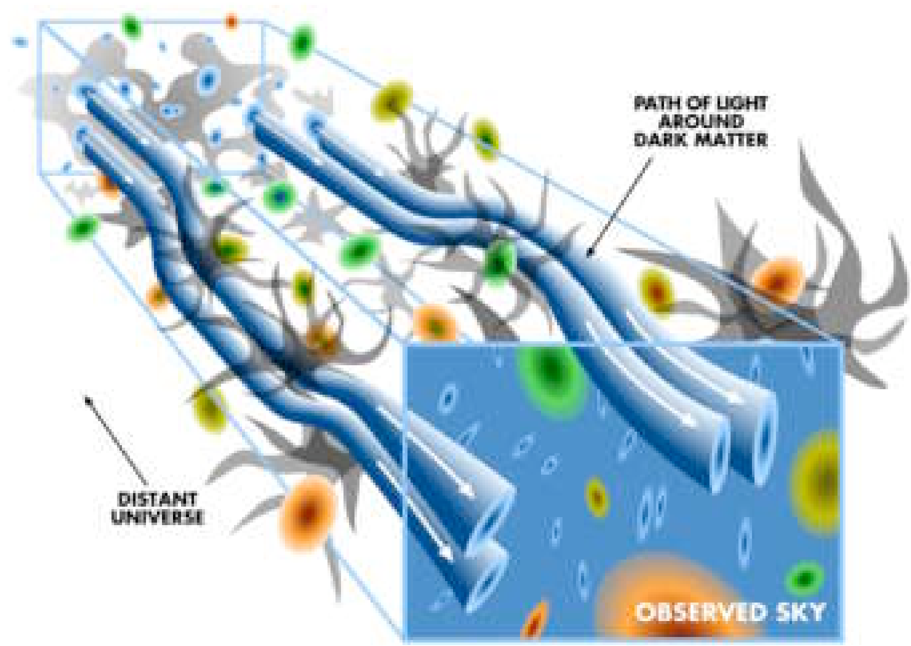
Spergel et al. ApJS 148 (2003) 175

Measurement of Large Scale Structure by Weak Lensing

- If there is only one image of a given background object, there is no way to find unlensed position, so deflection cannot be measured directly (see later talk by A. Refregier)
  - However, if the lensed object is extended can measure shape
  - Shear induced by lense metric
- Problem
  - Background Galaxies aren't round, however, their orientations should be random
  - This should average out if many lensed galaxies are measured

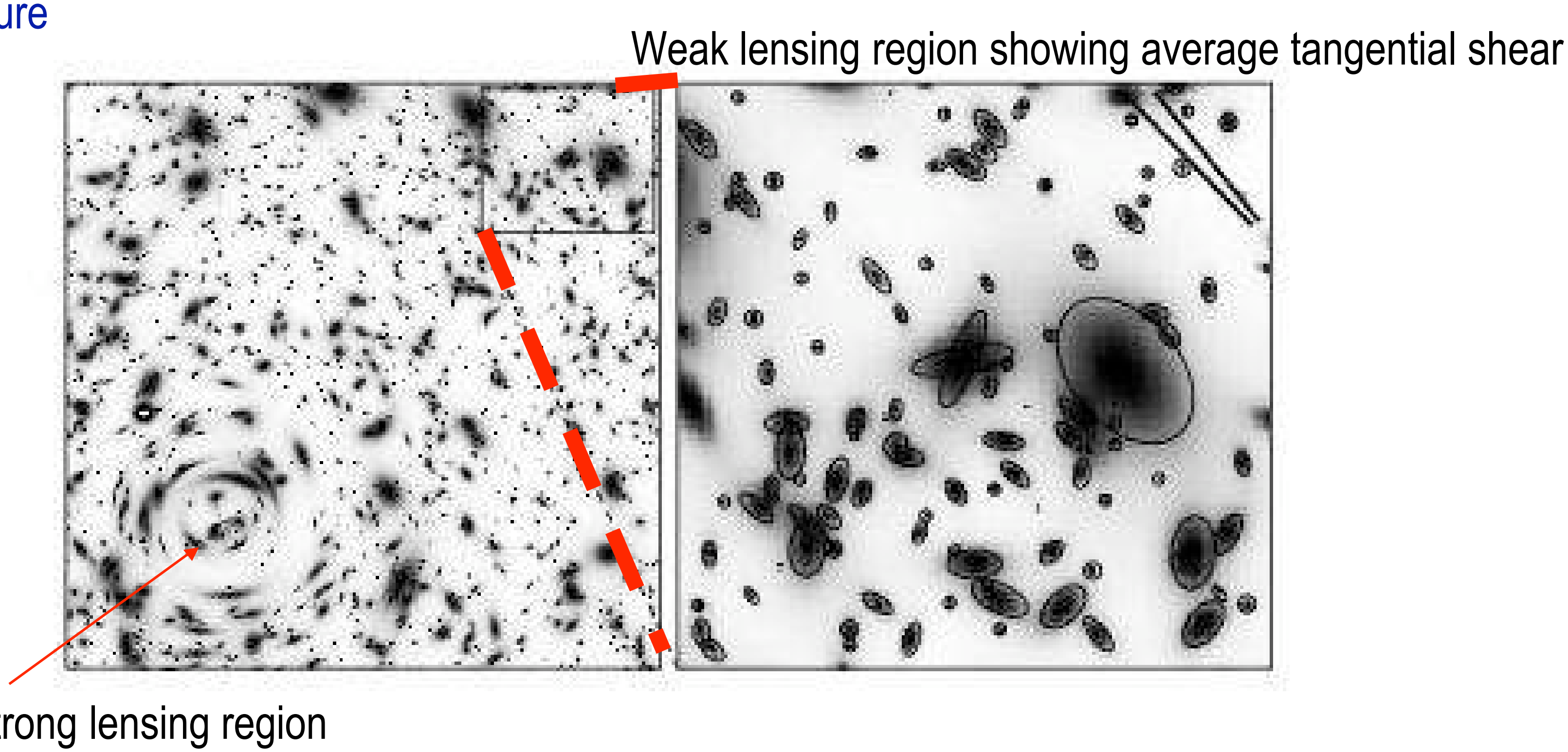


Credit: S. Colombi (IAP), CFHT Team



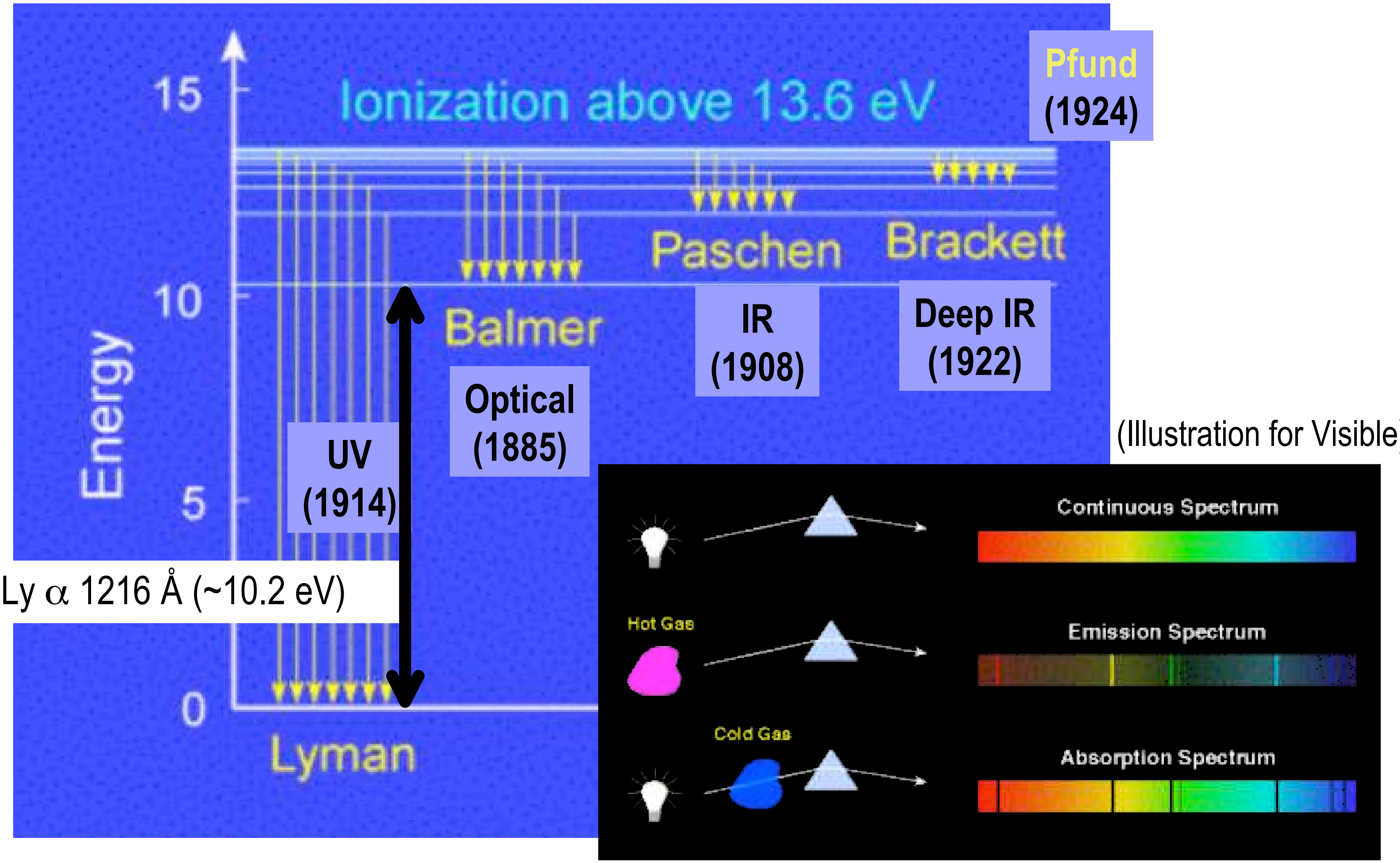
Measurement of Large Scale Structure by Weak Lensing (2)

- Outside of the huge and rare mass overdensities of rich clusters of galaxies, the mass contrast is much lower
  - However, this is where most of dark matter exists
  - Shear values <1%
  - Weak gravitational lensing will measure both the geometry of the universe and the growth rate of structure



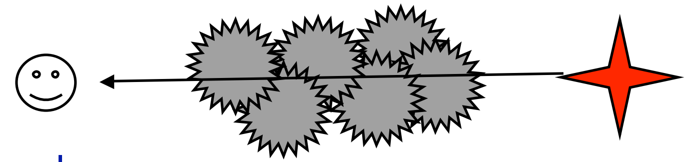
Probing the Universe with Weak Lensing, Y. Mellier
Annual Review of Astronomy and Astrophysiscs Vol. 37 / astro-ph/9812172

Hydrogen Lines (Recap for Lyman α)



Lyman α Forest Absorption Lines

- Observation of continuum spectrum from QSO's
  - Absorbed by Lyα line in intervening hydrogen clouds
  - Probe density/distribution of over dense regions of intergalactic gas along line of site
  - Traces cosmic gas distn @ early times (z~2–4, ~10–20% age of Universe)
    - Over densities are modest, so physics can be simulated to give underlying matter power spectrum



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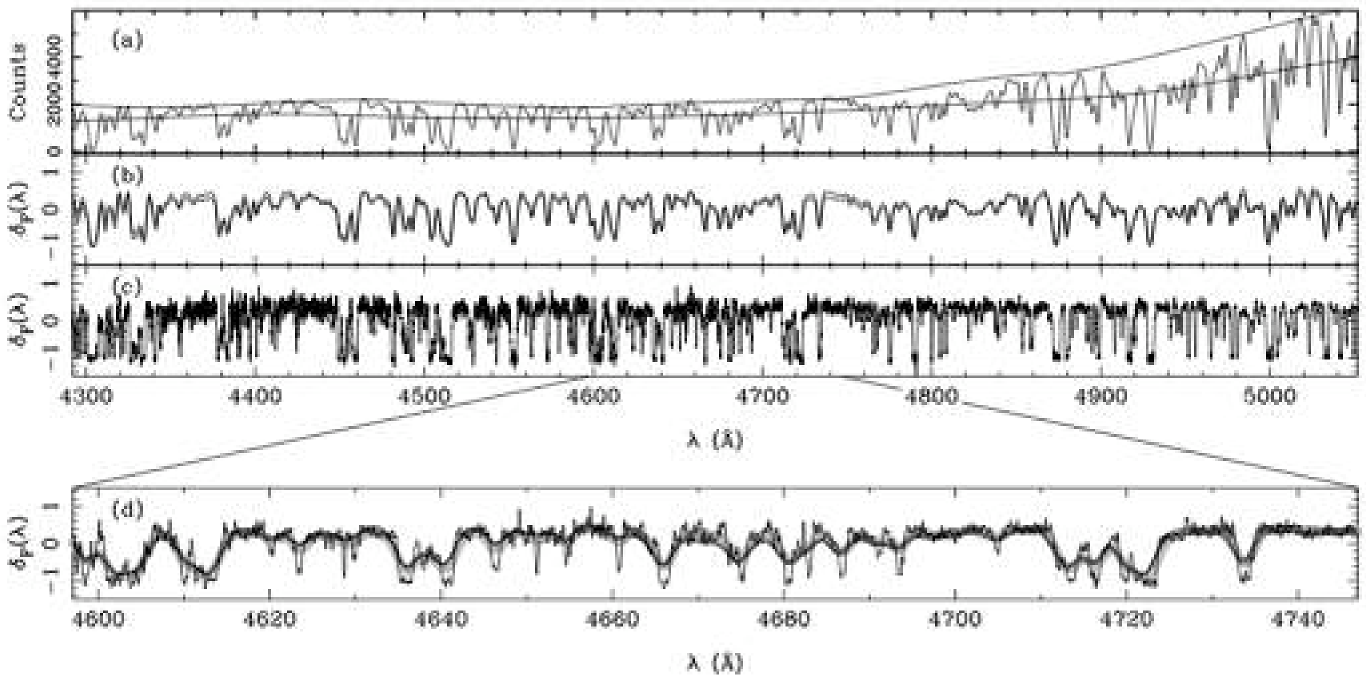


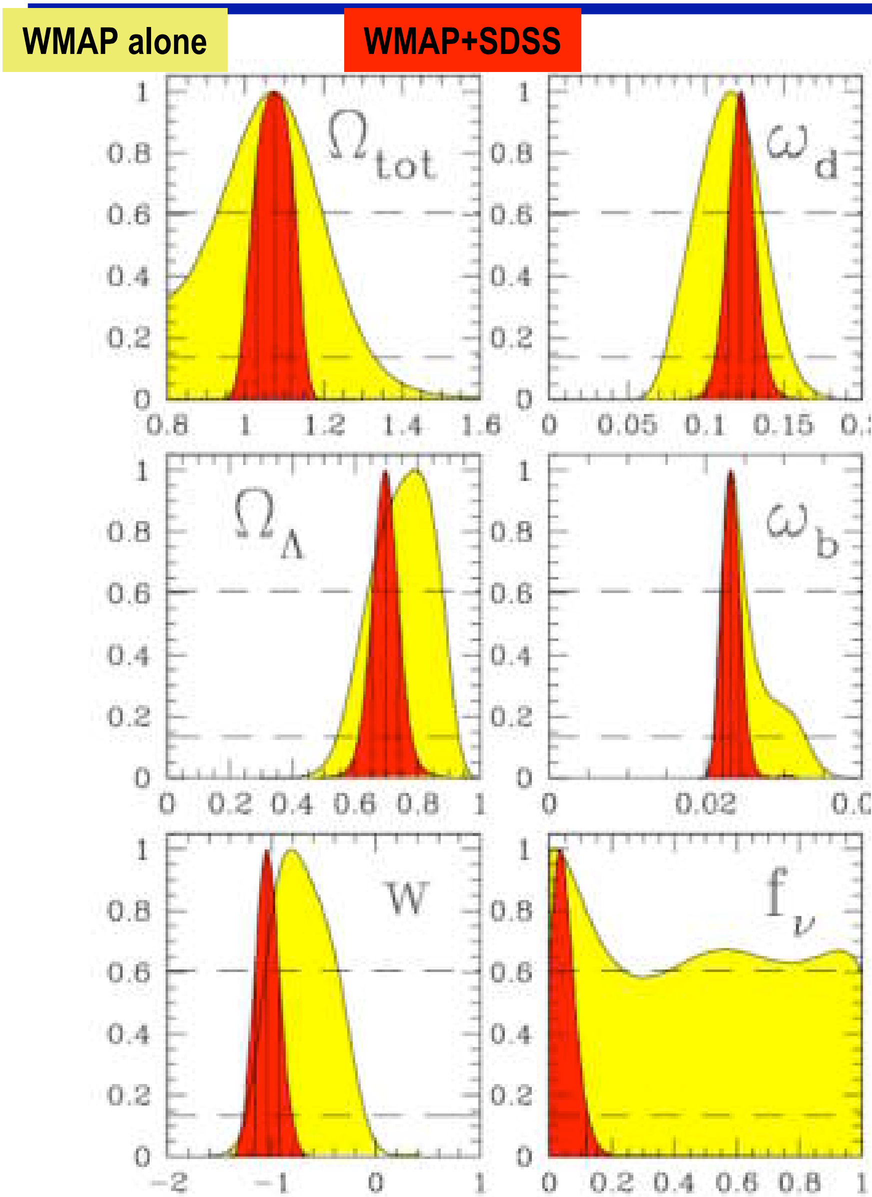
Keck LRIS

Keck HIRES

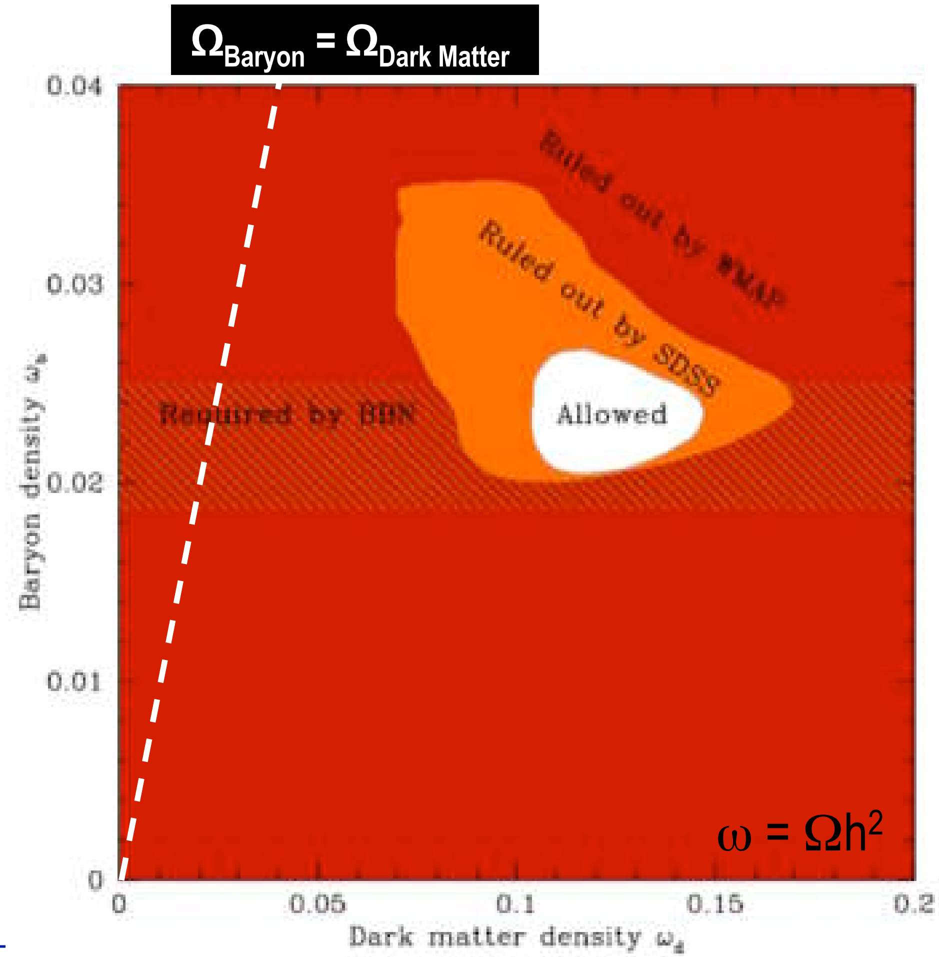
RAC Croft et al astro-ph/0012324

WMAP only & WMAP + SDSS "6 param Vanilla model"

Tegmark et al. Astro-ph/0310723



$$(\tau, \Omega_\Lambda, \omega_d, \omega_b, A_s, n_s)$$



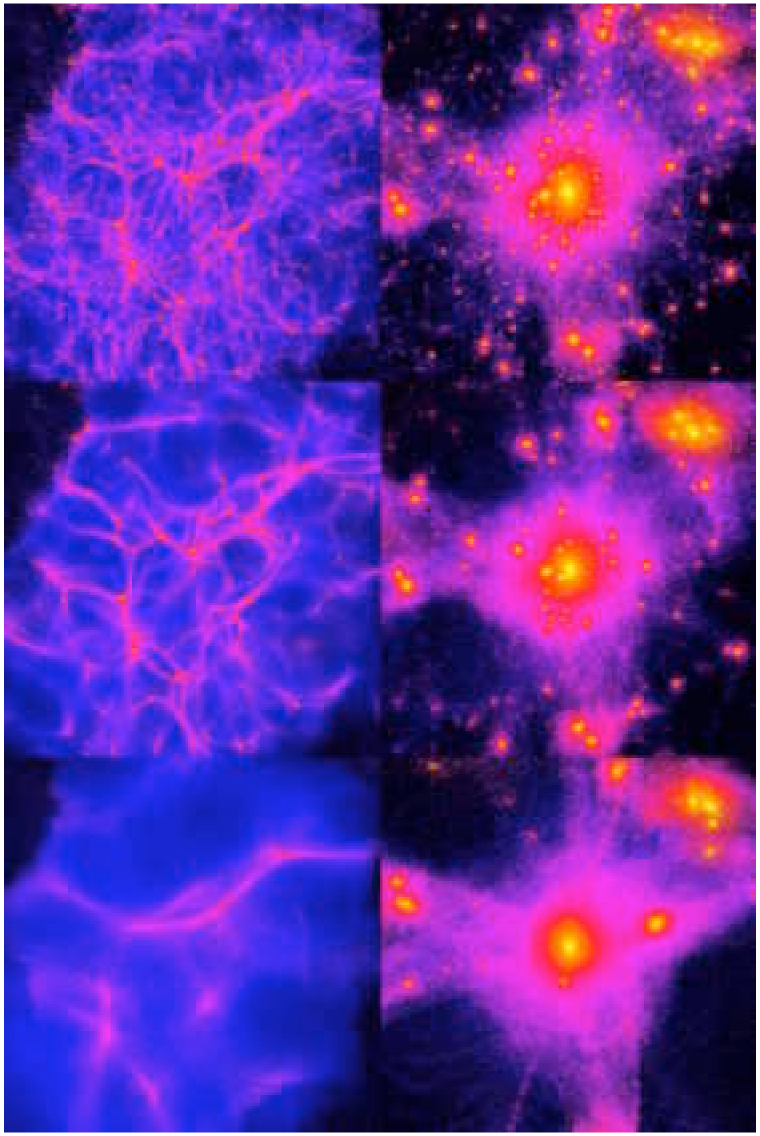
Dark Matter Halo Simulations

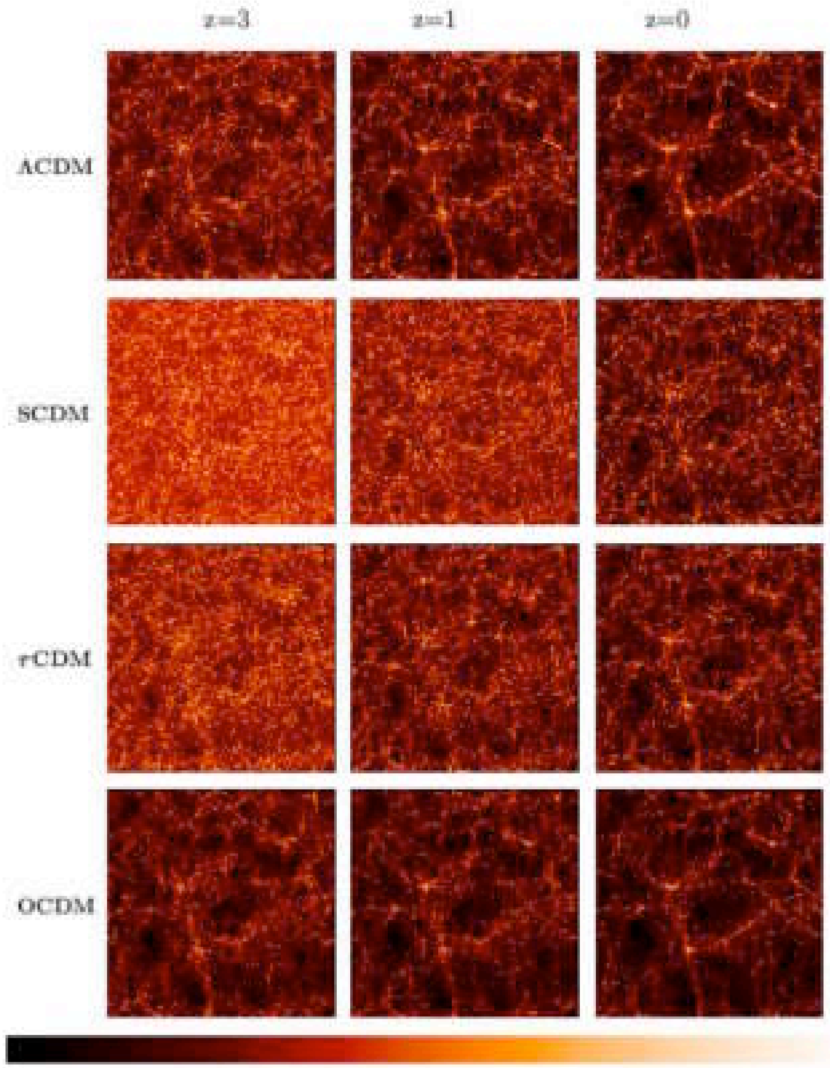
- Dark Matter Halo Sim z=10 -> 0
  - Non-linear, hence numerics
  - Each point is ~10^9 M_{sun}
  - Galaxy is ~10^{11} M_{sun}
- Understanding smaller scale structure inside galactic halos
  - remains a challenge for both observation and simulation

J. Diemand, J. Stadel and B. Moore, U. Zurich
http://krone.physik.unizh.ch/~diemand/clusters/

(Λ)CDM Best Fits Observed Halo Structure

- Cold Dark Matter
  - Cold means at times of structure formation the particles are non relativistic
  - CDM simulations most closely map observed structure
- Warm Dark Matter
  - Compromise reasonably motivated in 1990's to help fit Matter Power Spectrum, however, introduction of LCDM cosmology now makes this unnecessary
- Hot Dark Matter
  - e.g. Light Neutrinos
  - Streaming of relativistic particles washes out smaller scale structure
  - WMAP/LSS Provides hard upper limit
    $\Omega_\nu < 0.0076$ (Spergel et al., 2003)





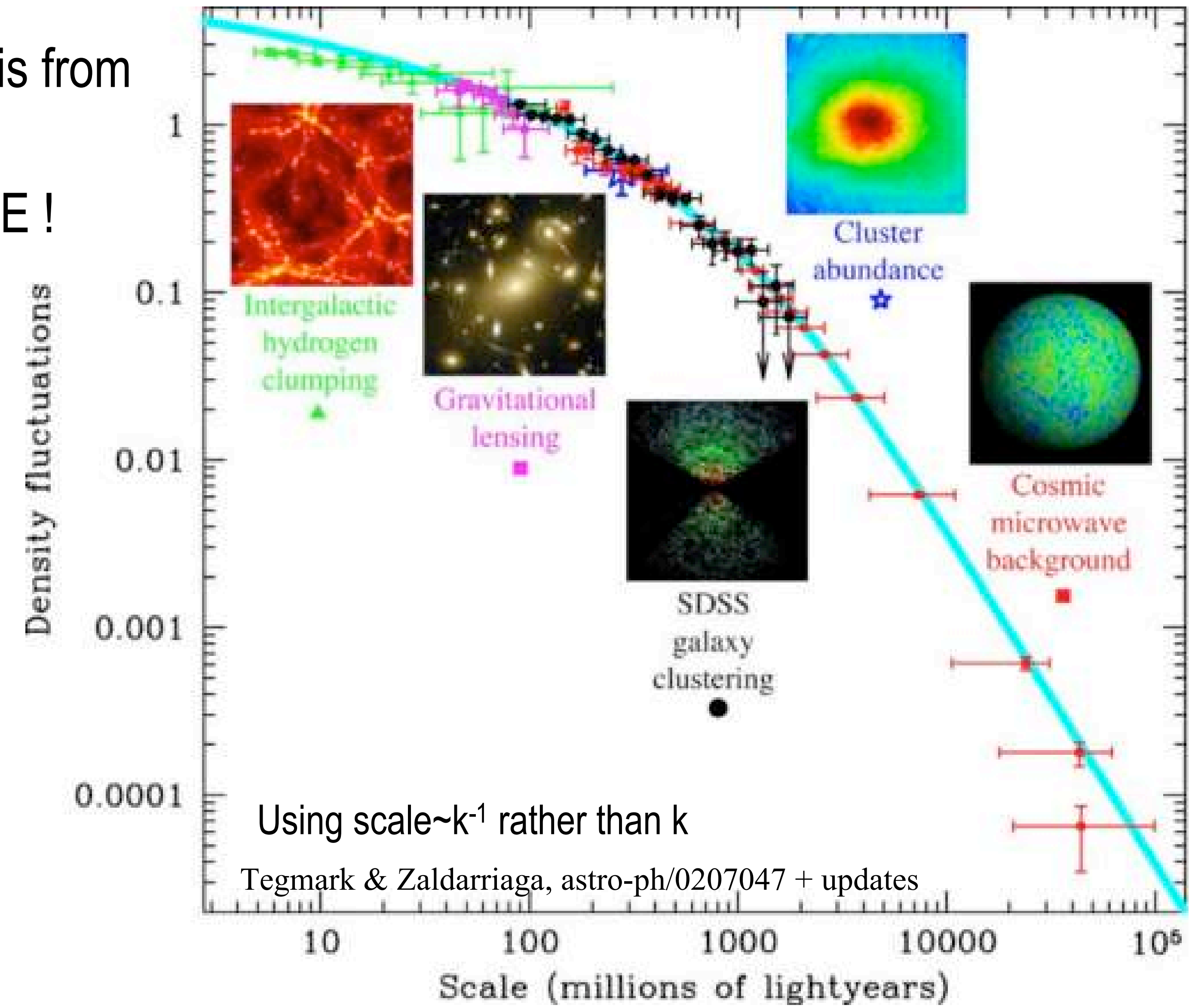
The VIRGO Collaboration 1996

http://www.mpa-garching.mpg.de/Virgo/virgopics.html

Reparameterize Structure as Density Fluctuations

- Line - fit to data is from ΛCDM Model

  CONCORDANCE !



Conclusion

- Concordance Model (ΛCDM) fits data extremely well
  - Seems probable that model will be around for sometime to come
  - Currently no good alternatives to it
    - Need to invent new ones!!
- >95% still unidentified, "Known Unknown"
  - General Properties known and allow precision fit of data
  - Concordance
  - Challenge will be discover physics that generates Dark Matter/Dark Energy
  - Why is Universe so & what created initial conditions?

$$\Omega_{Total} = 1$$
$$\Omega_m = 1/3$$
$$\Omega_\Lambda = 2/3$$