The Dark Universe:

1. Dark Matter
2. Dark Energy

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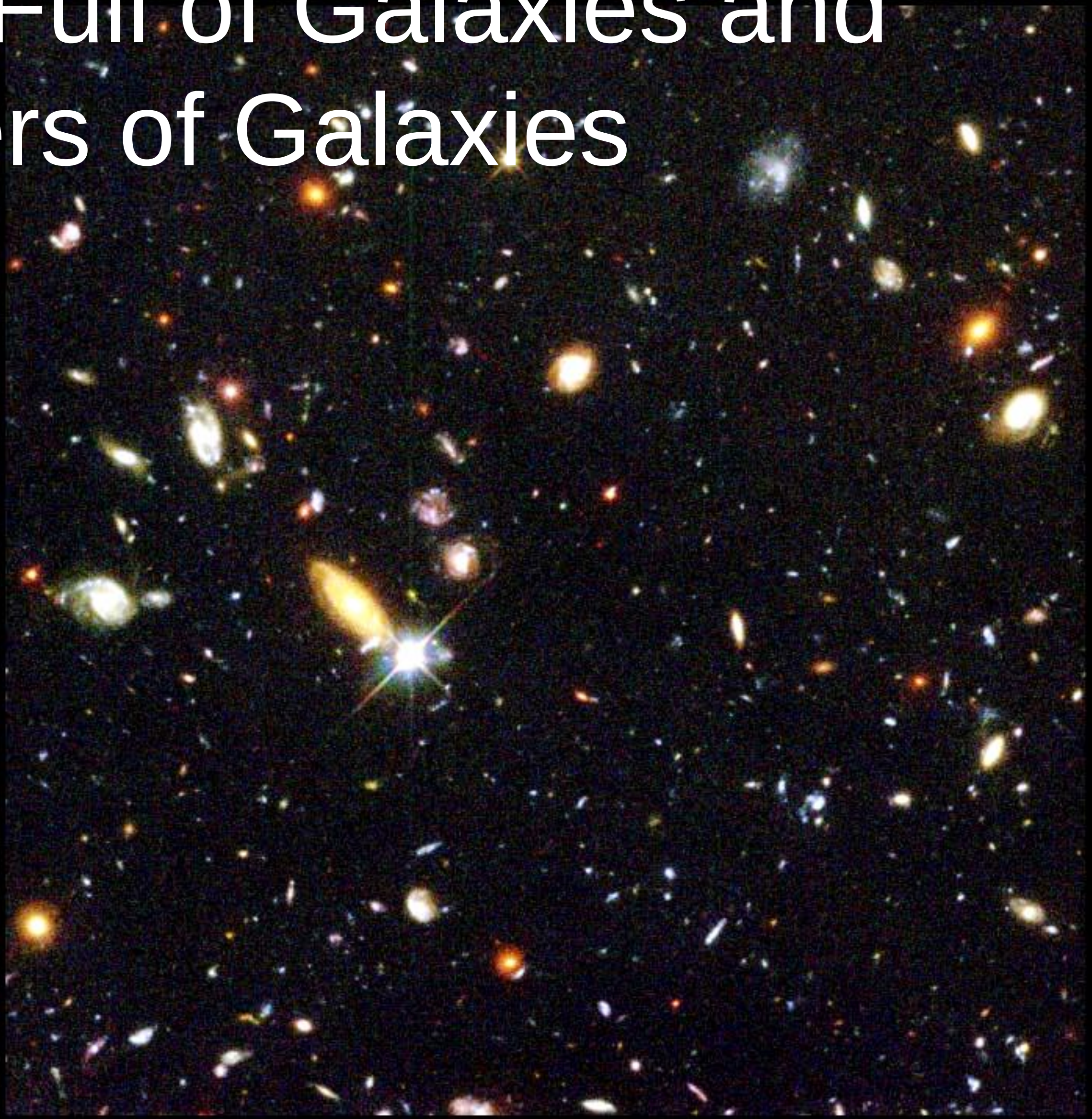
School
IDPASC Dark Matter School
Évora, Portugal, 14-18 December 2011

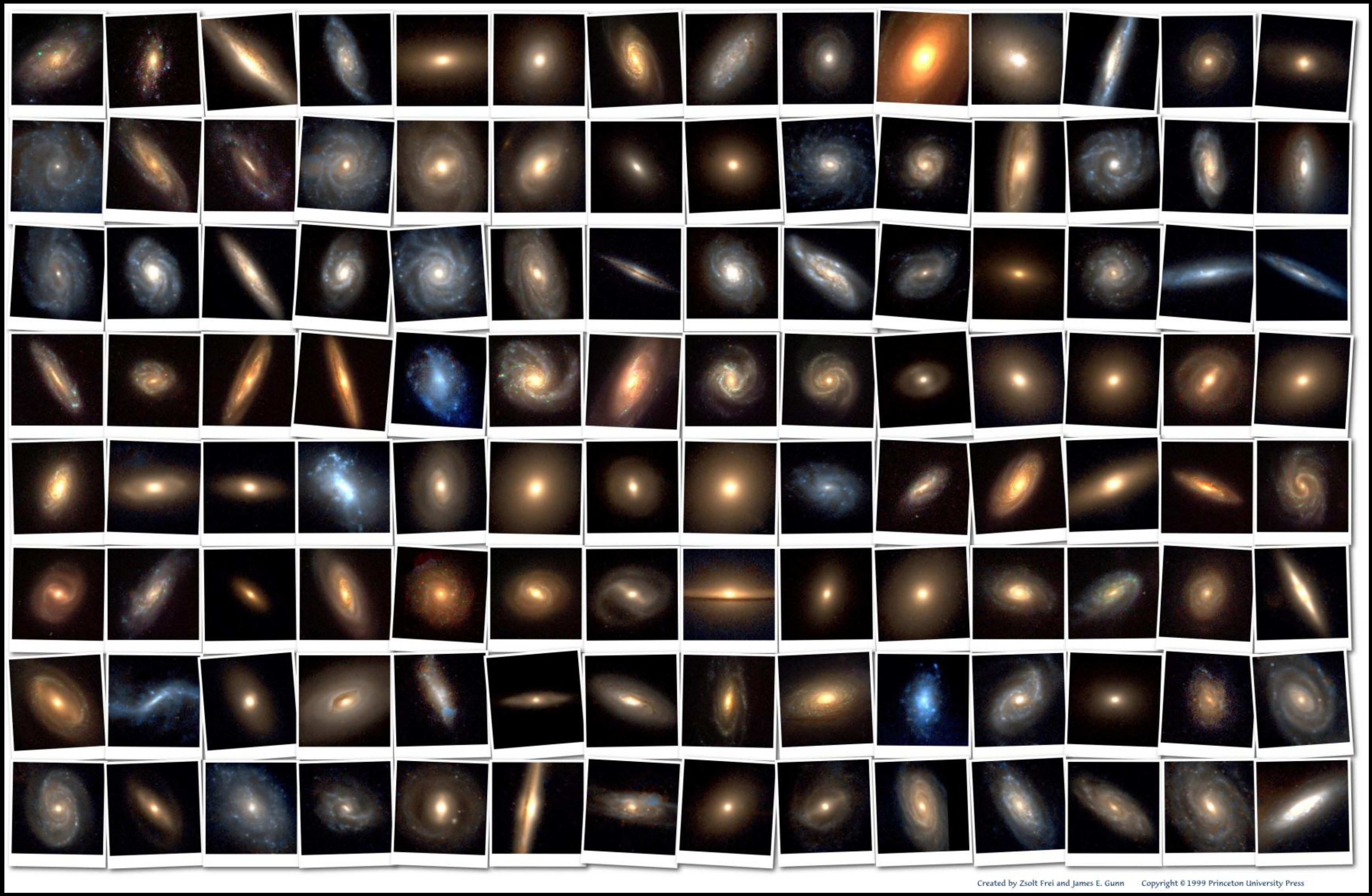
A Universe Full of Galaxies and Clusters of Galaxies

- 10^{11} galaxies!
- Density of galaxies: ~$0.001/\mathrm{Mpc}^3$
- Typical mass 10^{12} solar mass (2×10^{45} g)
- Range: 10^6 to 10^{13} solar masses



Hubble Deep Field HST • WFPC2
PRC96-01a • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA

Galaxies as far as the eye can see!



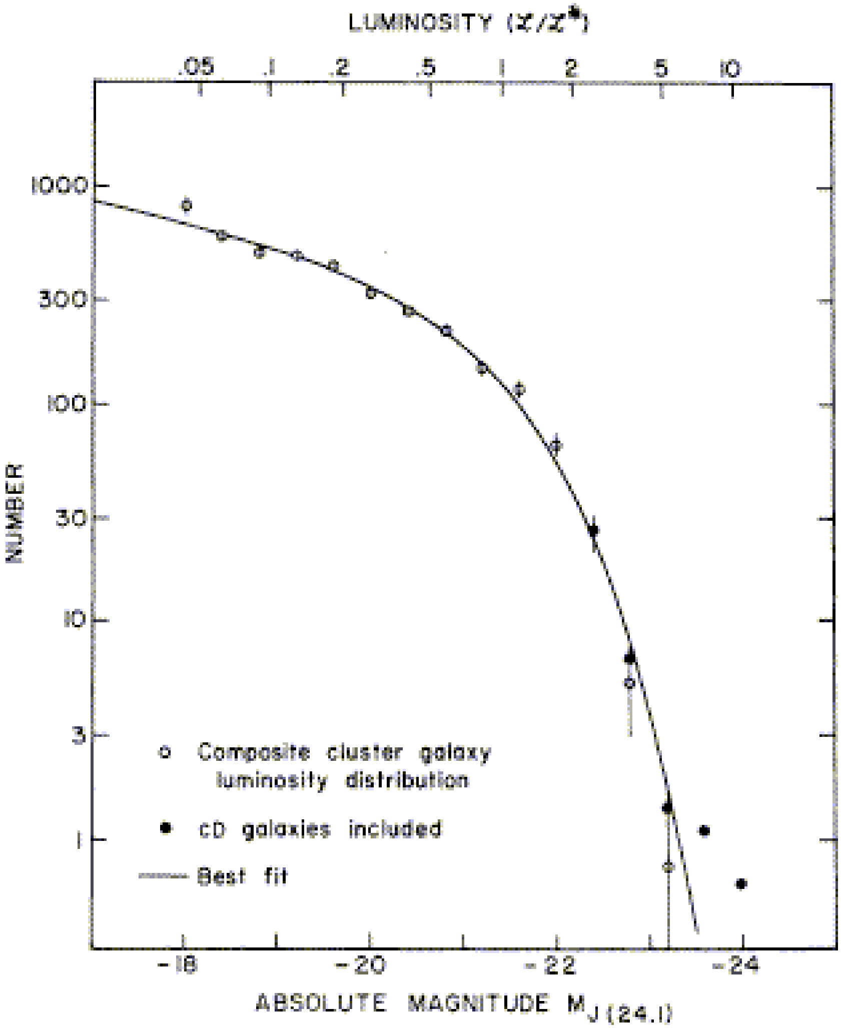


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

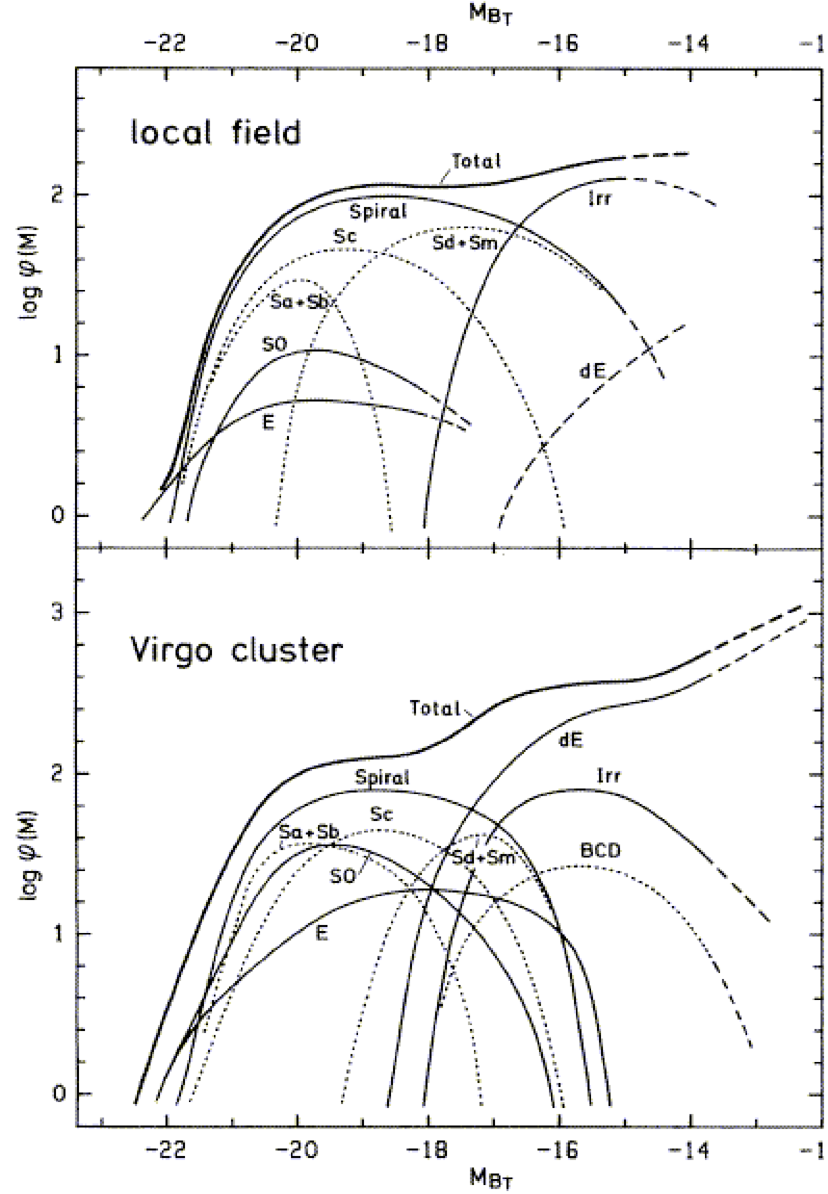
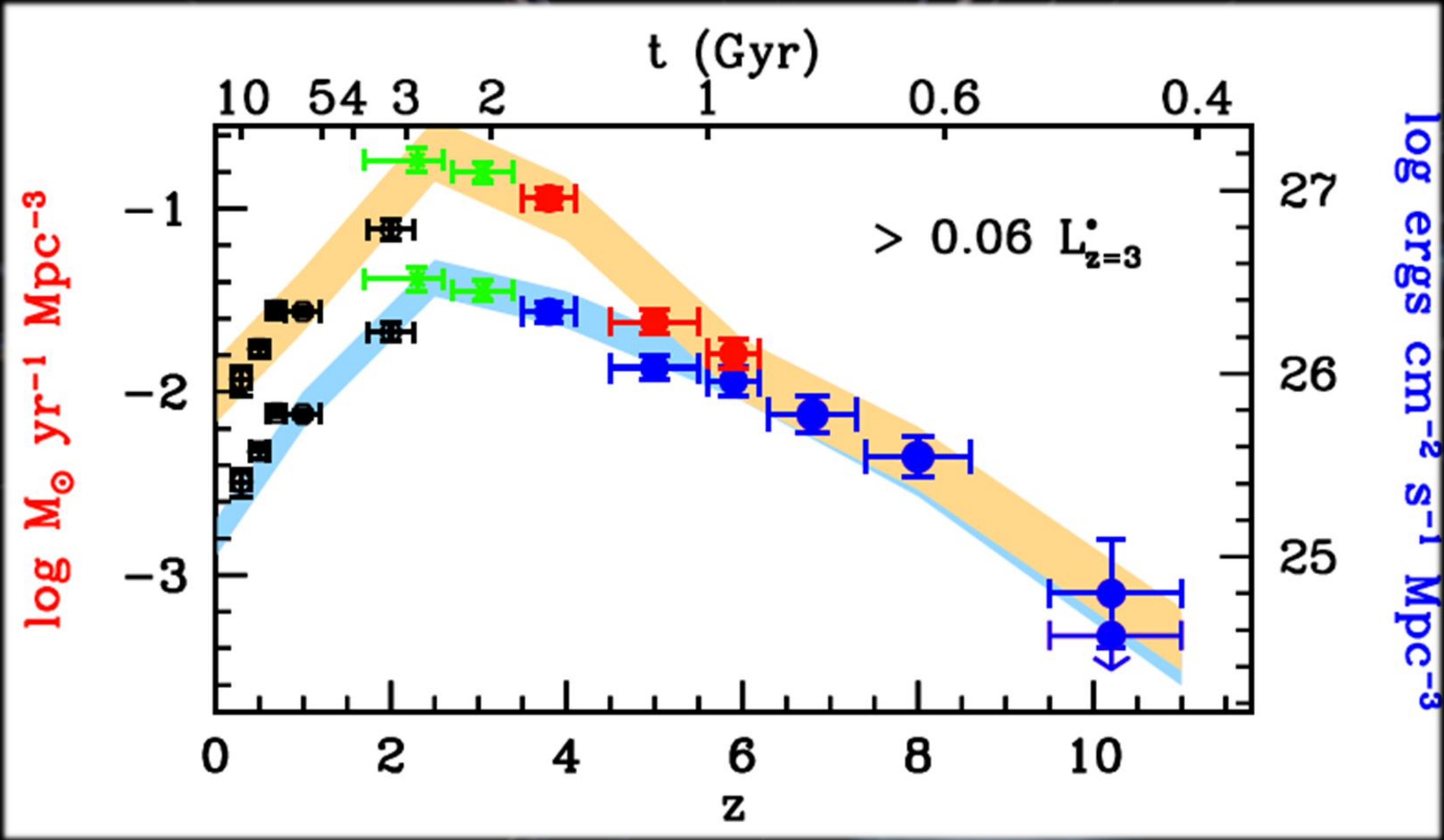


Figure 1 The LF of field galaxies (top) and Virgo cluster members (bottom). The zero point of log $\varphi(M)$ is arbitrary. The LFs for individual galaxy types are shown. Extrapolations are marked by dashed lines. In addition to the LF of all spirals, the LFs of the subtypes Sa + Sb, Sc, and Sd + Sm are also shown as dotted curves. The LF of Irr galaxies comprises the Im and BCD galaxies; in the case of the Virgo cluster, the BCDs are also shown separately. The classes dS0 and "dE or Im" are not illustrated. They are, however, included in the total LF over all types (heavy line).

Star formation

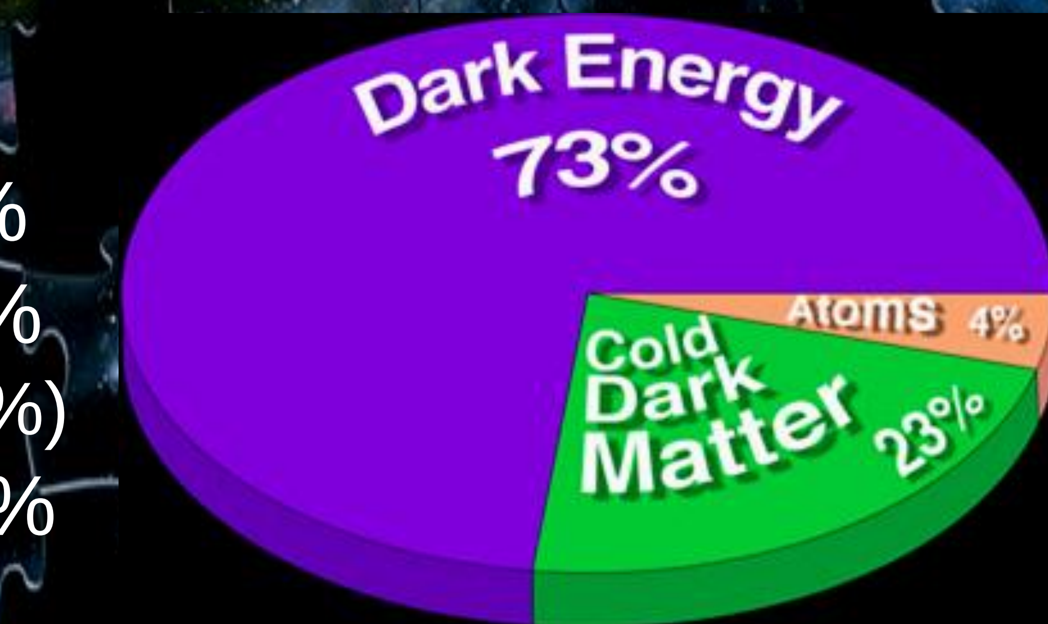
peaked 13 billion years ago, almost done



The Dark Side of the Universe

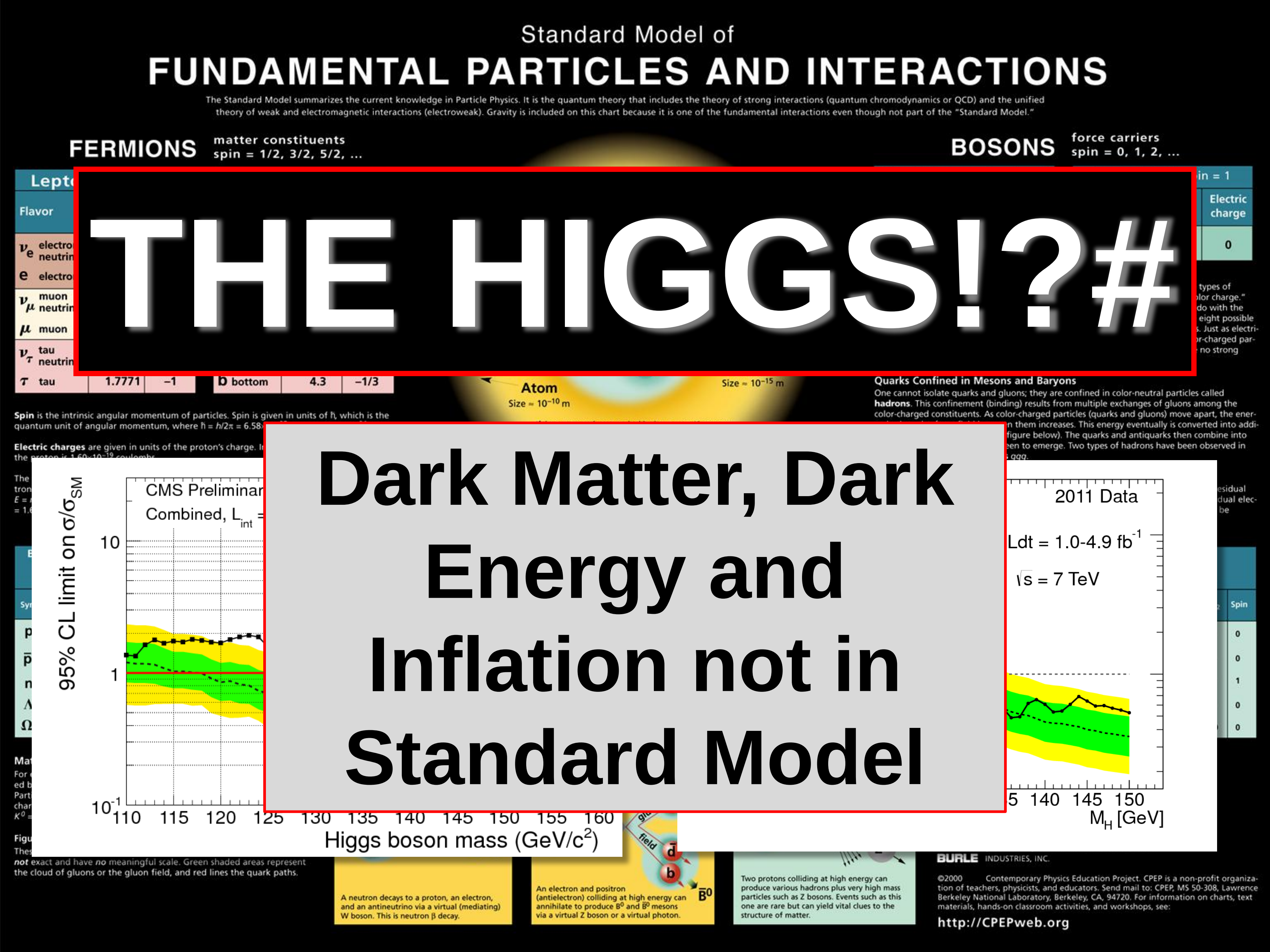
Stuff of the Universe

Stars: 0.5%
Hot Atoms: 4.0%
Dark Matter: 24%
(Neutrinos: few 0.1%)
Dark Energy: 71%



THE HIGGS!?#

Dark Matter, Dark Energy and Inflation not in Standard Model



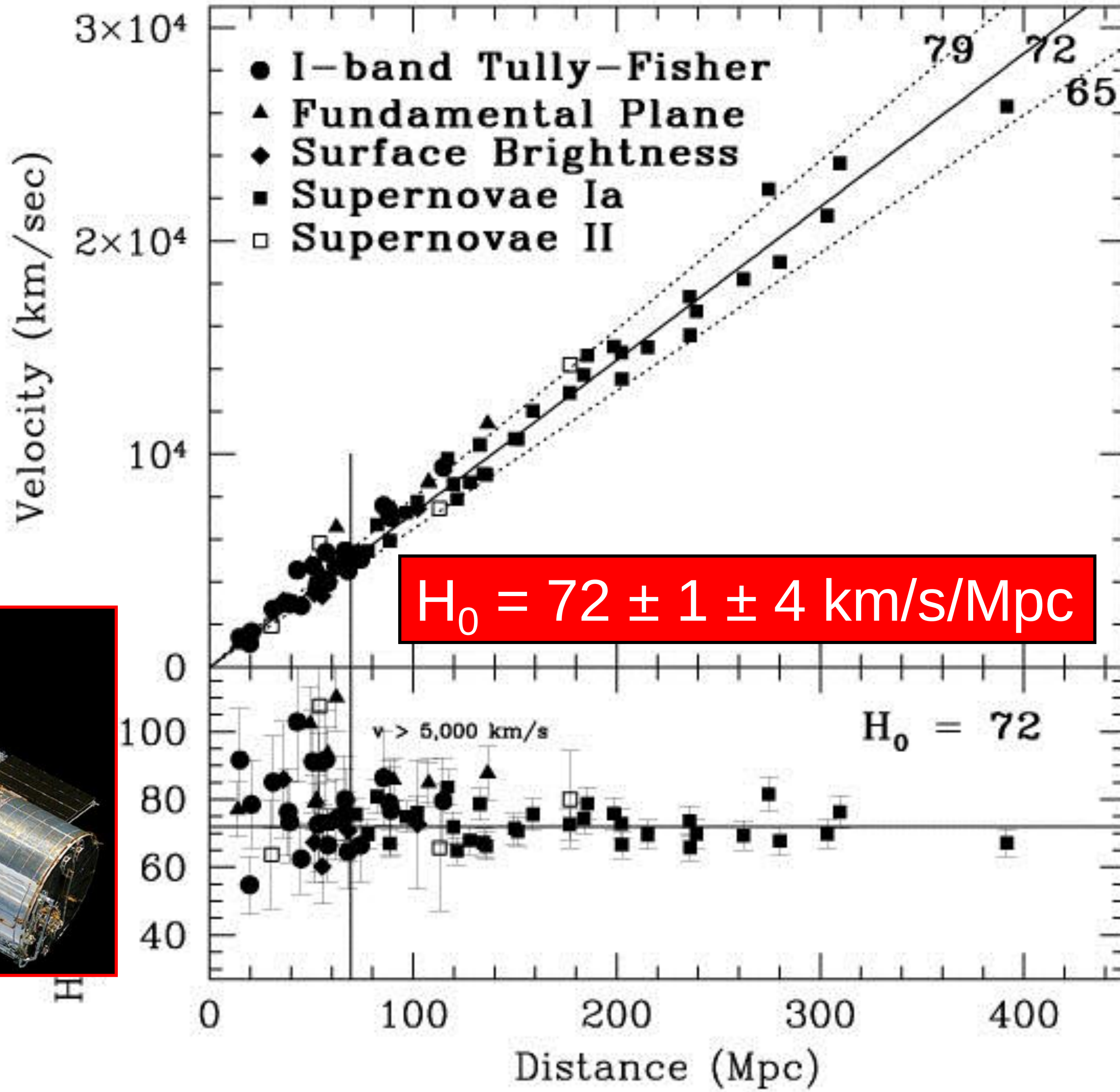
Today’s Cosmology

Rests upon three mysterious pillars

All implicate new physics!

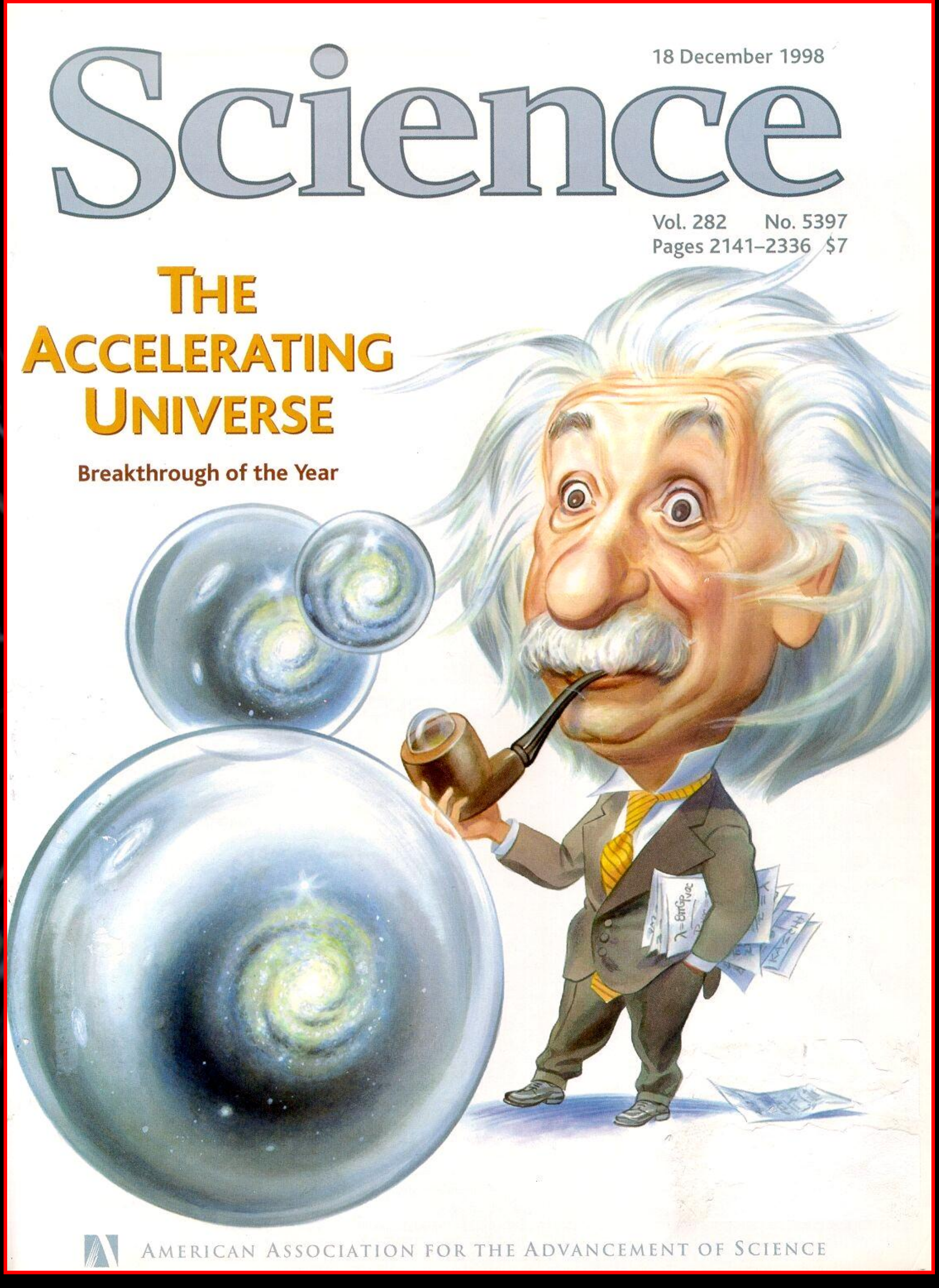
Some key facts about the Universe

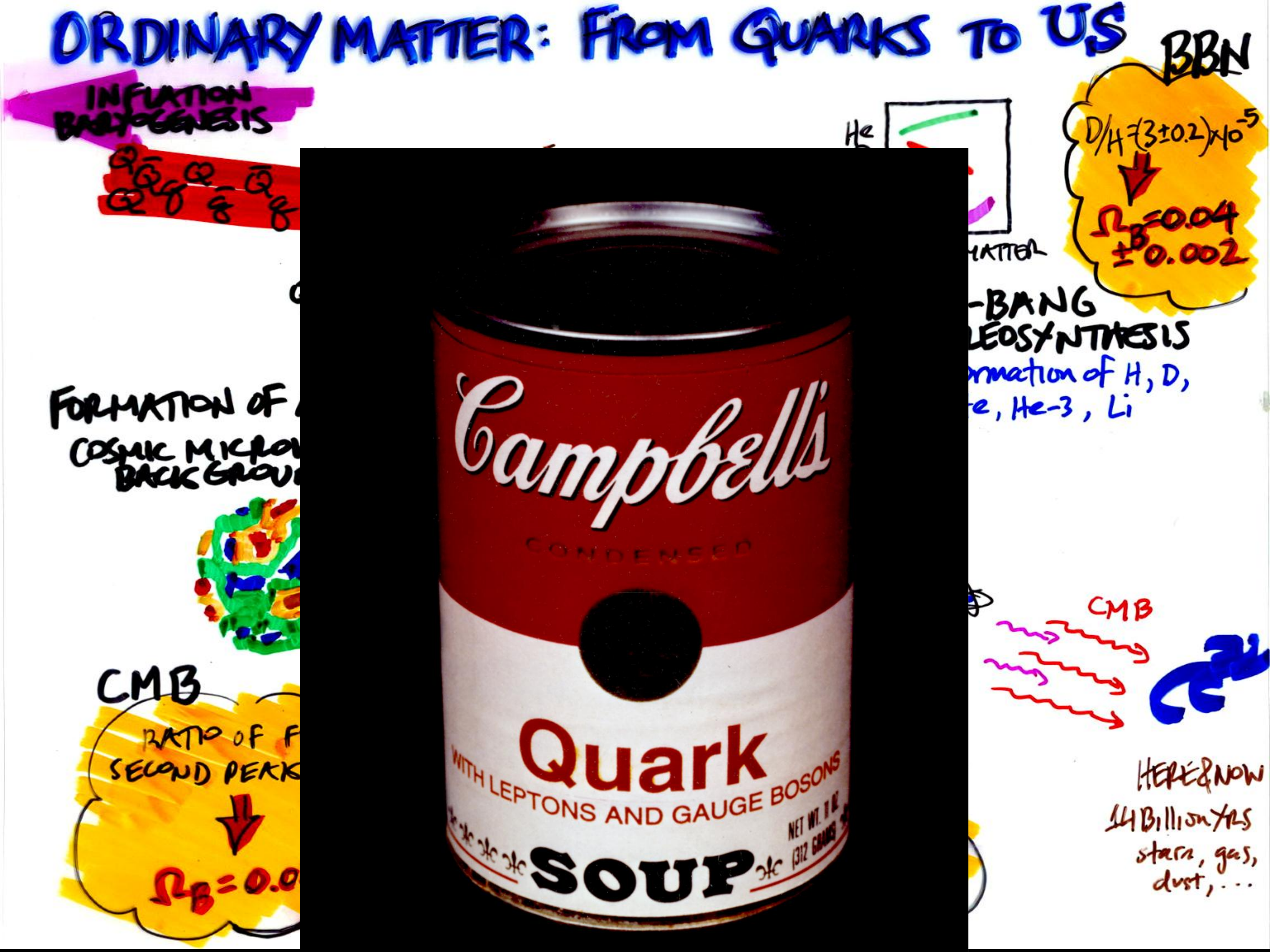
- Expanding (Hubble, 1929)
- Accelerating (Riess, Perlmutter and Schmidt)
- Isotropic and homogeneous (large scales today – > 100 Mpc – and at early times): distribution of galaxies today and CMB
- Hot big bang – quark soup beginning
- Gravity driven structure formation
- Much more than meets the eye
- Precision parameters and cross-checks



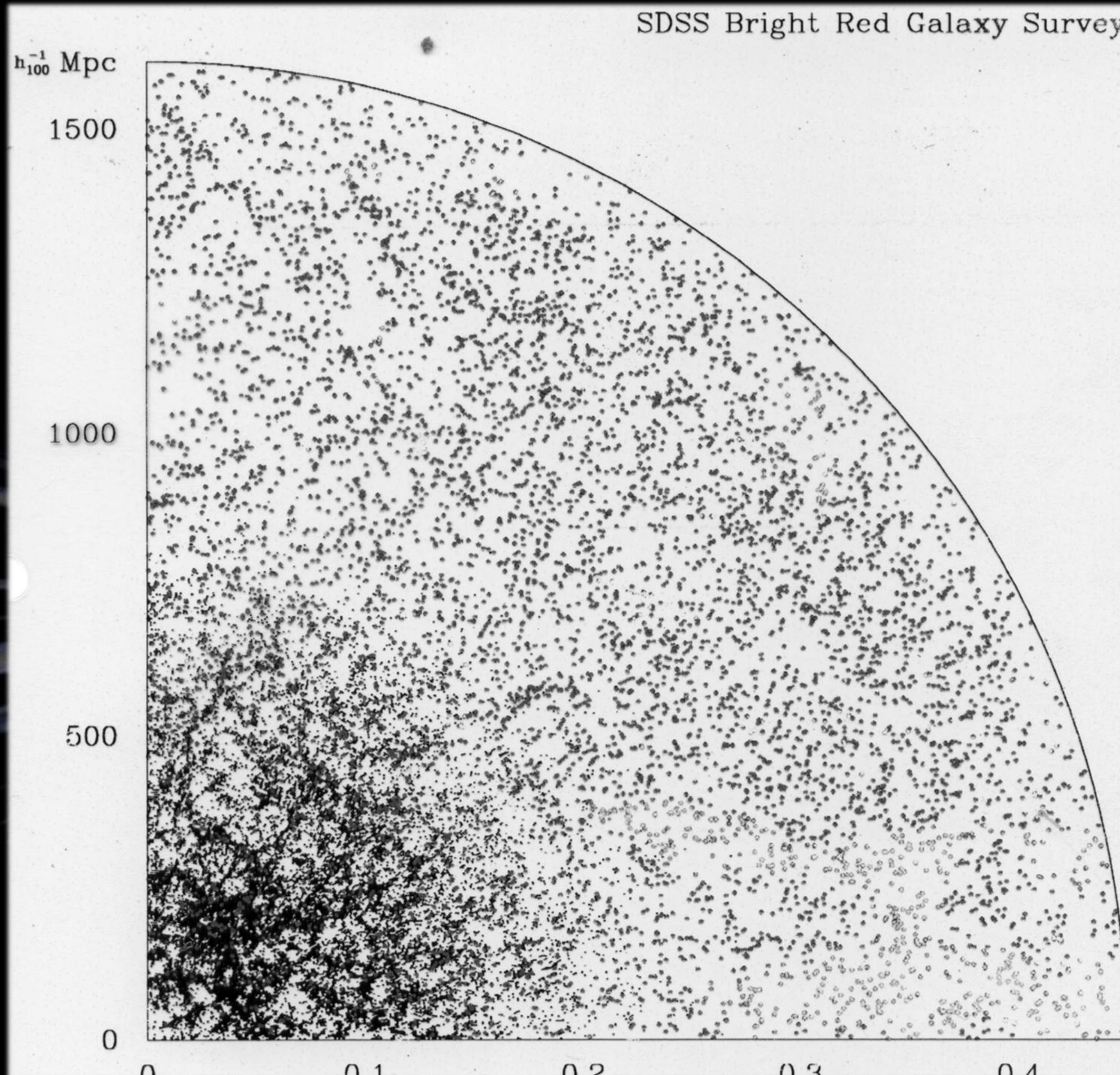
$H_0 = 72 \pm 1 \pm 4$ km/s/Mpc

Expansion is accelerating due to dark energy (something like quantum vacuum energy / cosmological constant

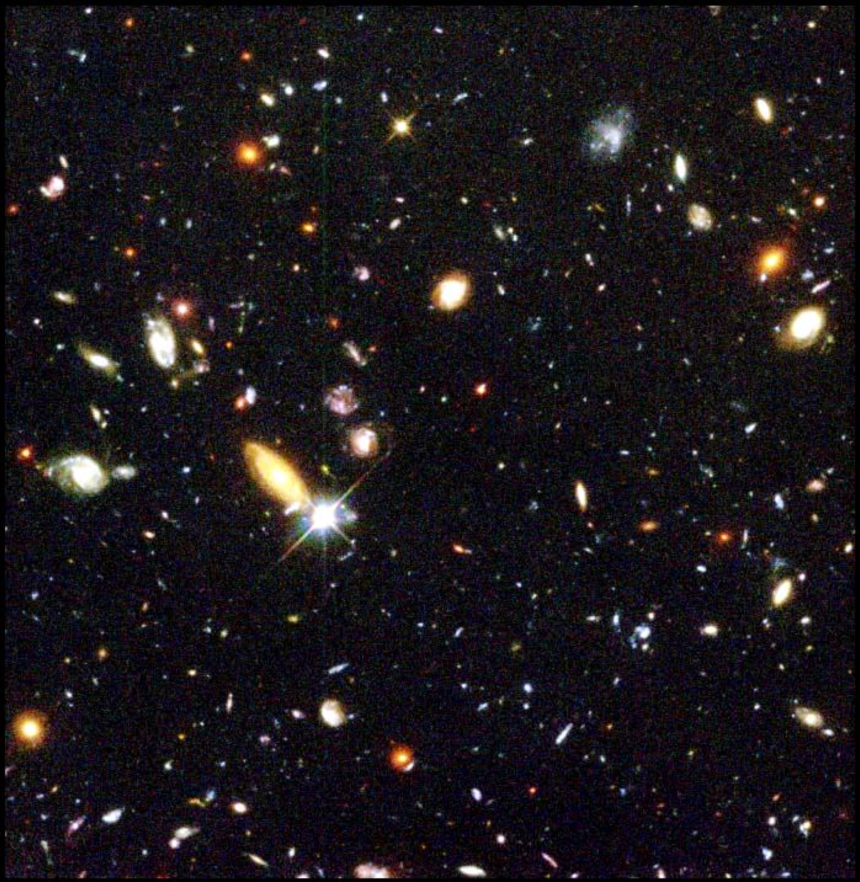



ORDINARY MATTER: FROM QUARKS TO US
INFLATION
BARYOGENESIS
BBN
D/H = (3±0.2)×10^-5
Ω_B = 0.04 ± 0.002
He
BANG
LEOSYNTHESIS
rmation of H, D,
e, He-3, Li
FORMATION OF
COSMIC MICRO
BACKGROU
CMB
RATIO OF F
SECOND PEAK
Ω_B = 0.0
CMB
HERE&NOW
14 Billion YRS
stars, gas,
dust, ...
Campbell's
CONDENSED
Quark
WITH LEPTONS AND GAUGE BOSONS
NET WT. 11 OZ
(312 GRAMS)
SOUP

Sloan Digital Sky Survey
sdss.org



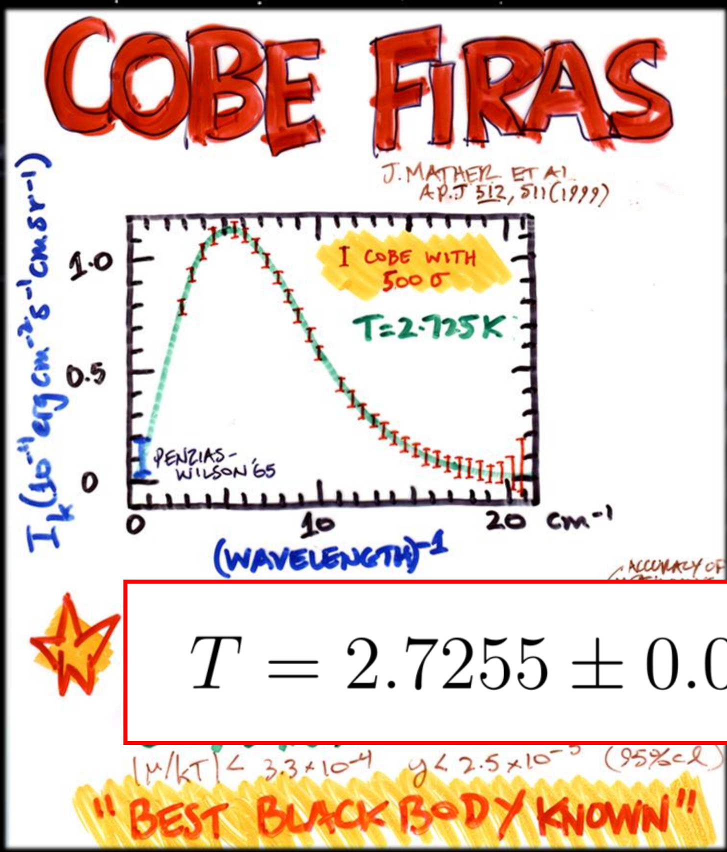
Isotropy (same in all directions): Galaxy Distribution on Sky



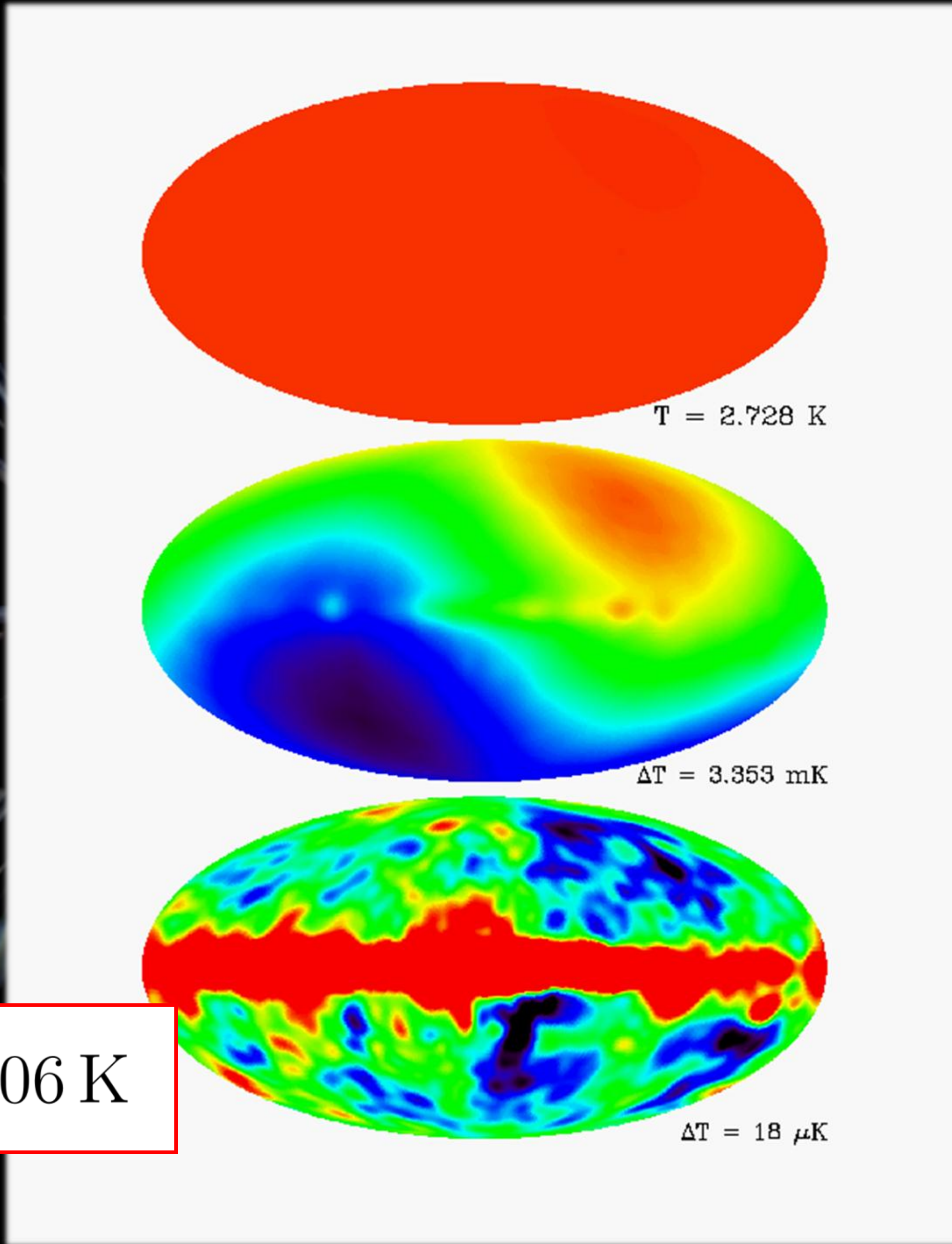
Hubble Deep Field HST • WFPC2
PRC96-01a • ST Scl OPO • January 15, 1996 • R. Williams (ST Scl), NASA

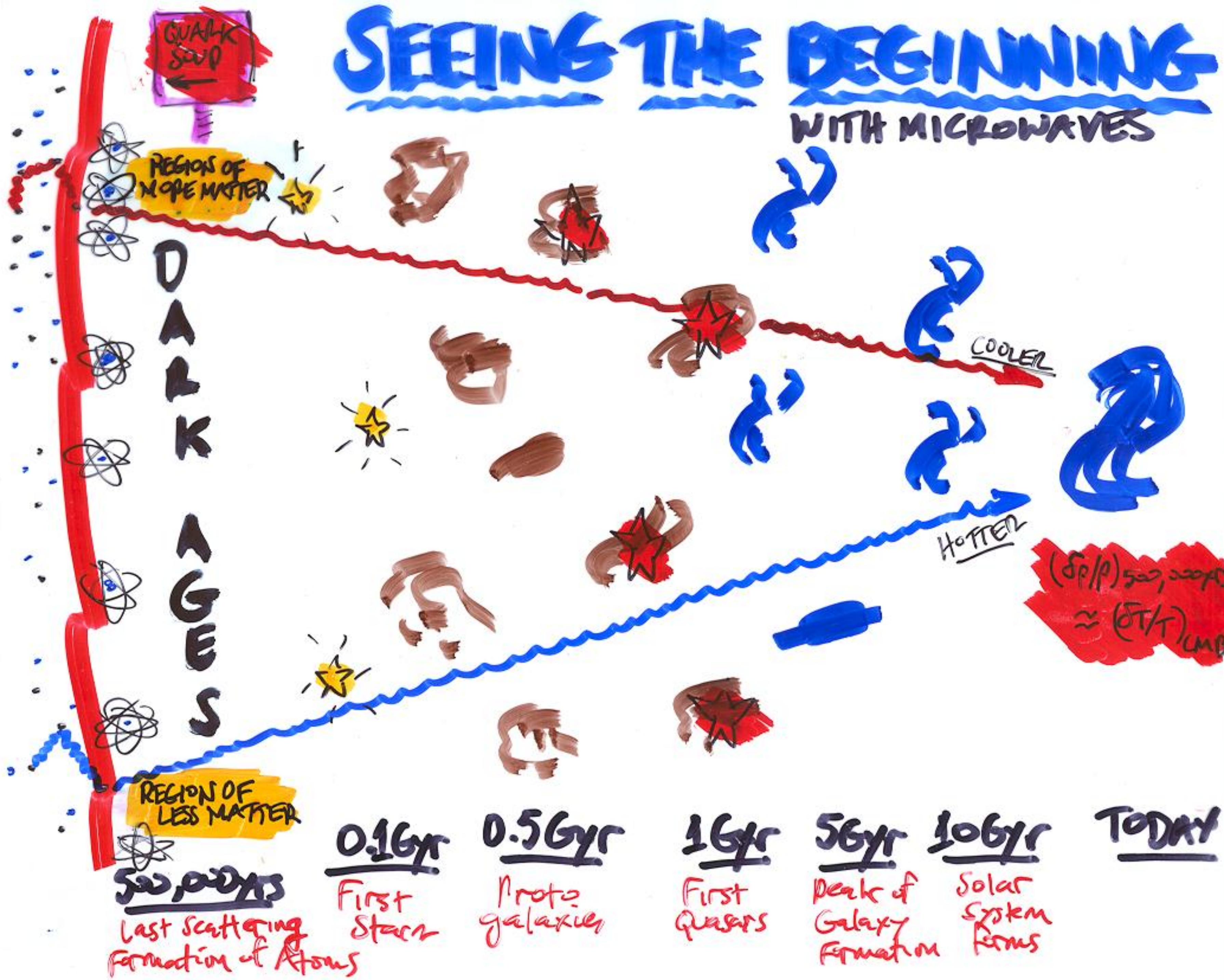
Hubble Deep Field South **HST • WFPC2**
PRC98-41a • STScl OPO • November 23, 1998
The HDF-S Team • NASA

1992: COBE Maps & Blackbody Spectrum



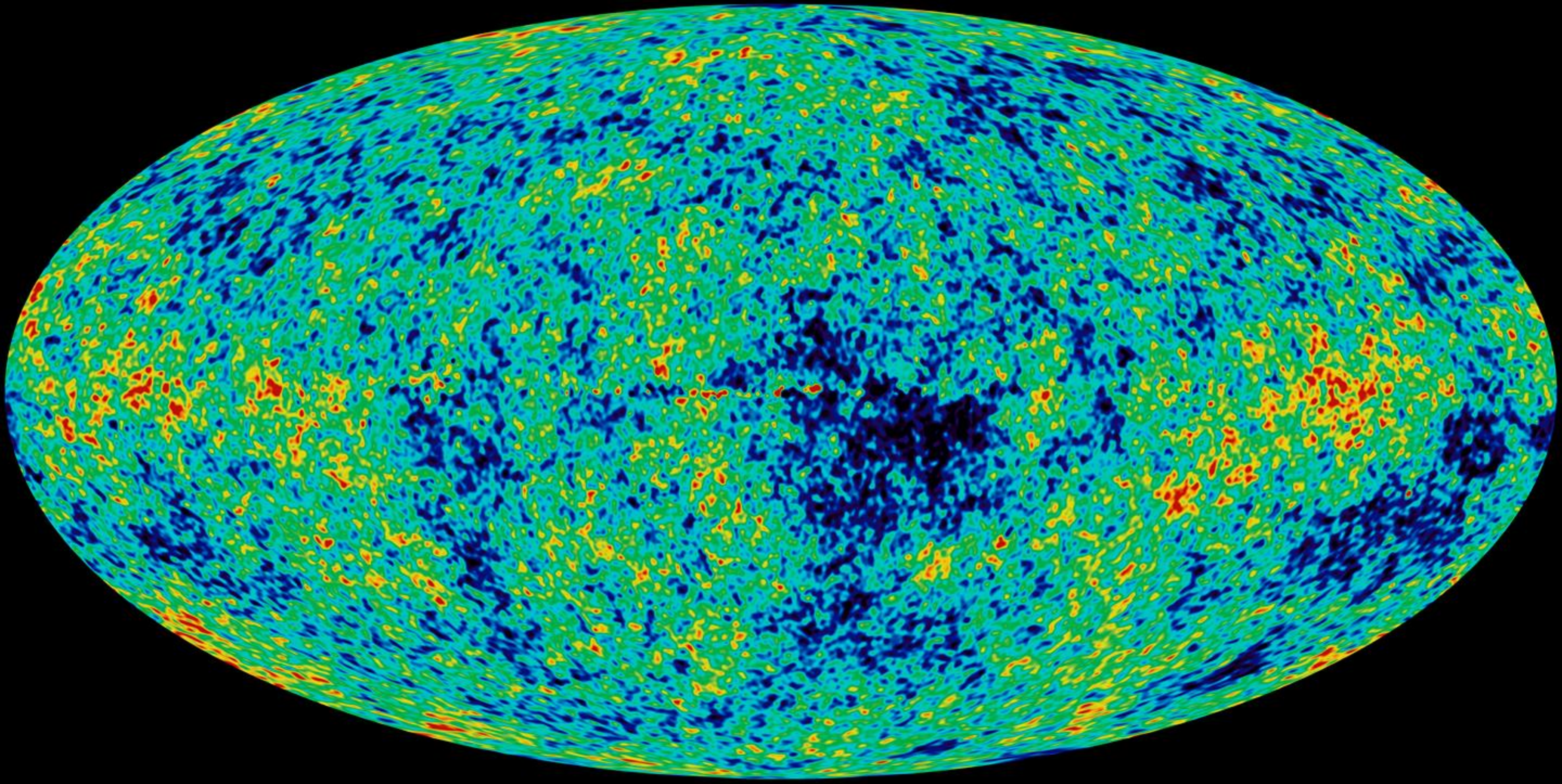
$$T = 2.7255 \pm 0.0006\,\mathrm{K}$$




SEEING THE BEGINNING
WITH MICROWAVES
QUARK SOUP
REGION OF MORE MATTER
DARK AGES
COOLER
HOTTER
$(\delta\rho/\rho)_{500,000\,yrs} \approx (\delta T/T)_{CMB}$
REGION OF LESS MATTER
500,000yrs
Last scattering
Formation of Atoms
0.1Gyr
First Stars
0.5Gyr
Proto galaxies
1Gyr
First Quasars
5Gyr
Peak of Galaxy Formation
10Gyr
Solar System forms
TODAY

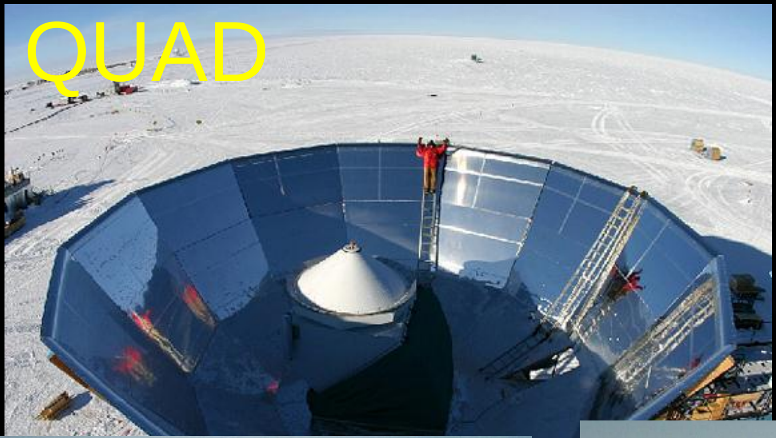
The Universe circa 380,000 yrs

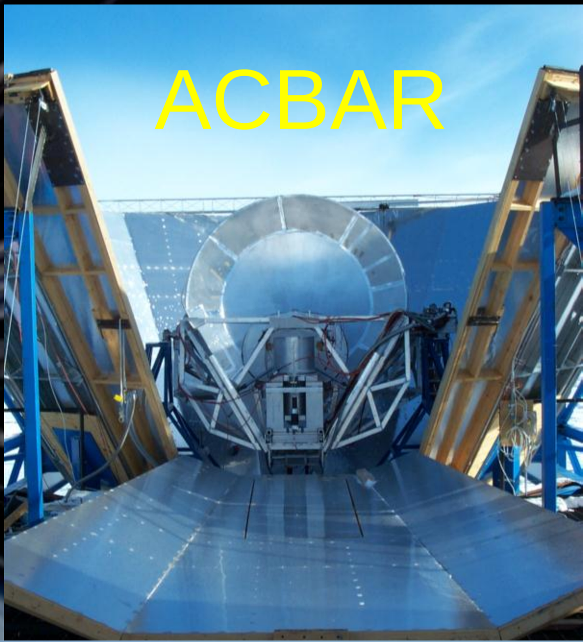
WMAP



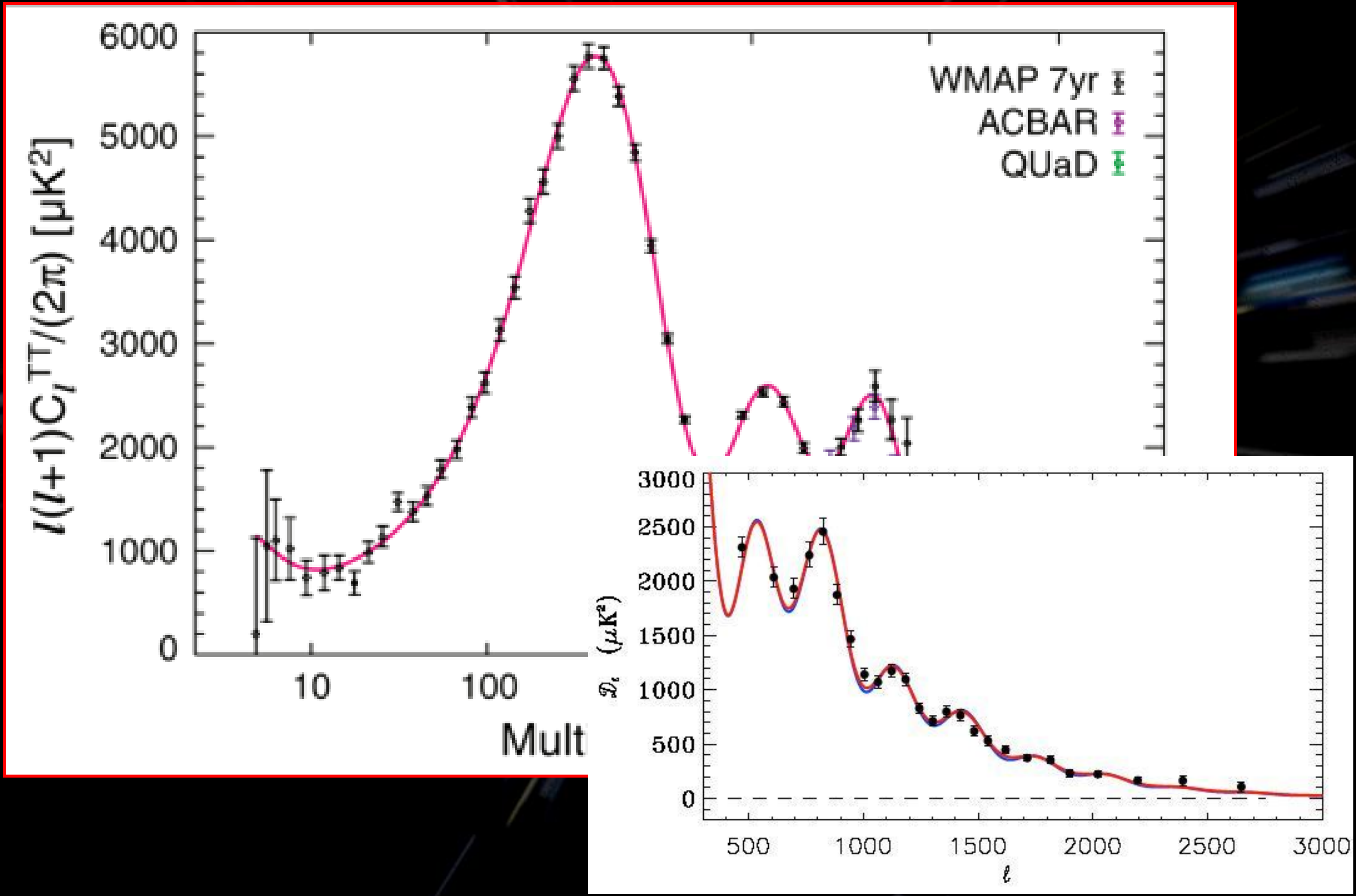
±0.001% Fluctuations

CMB Experiments





Curve = concordance cosmology



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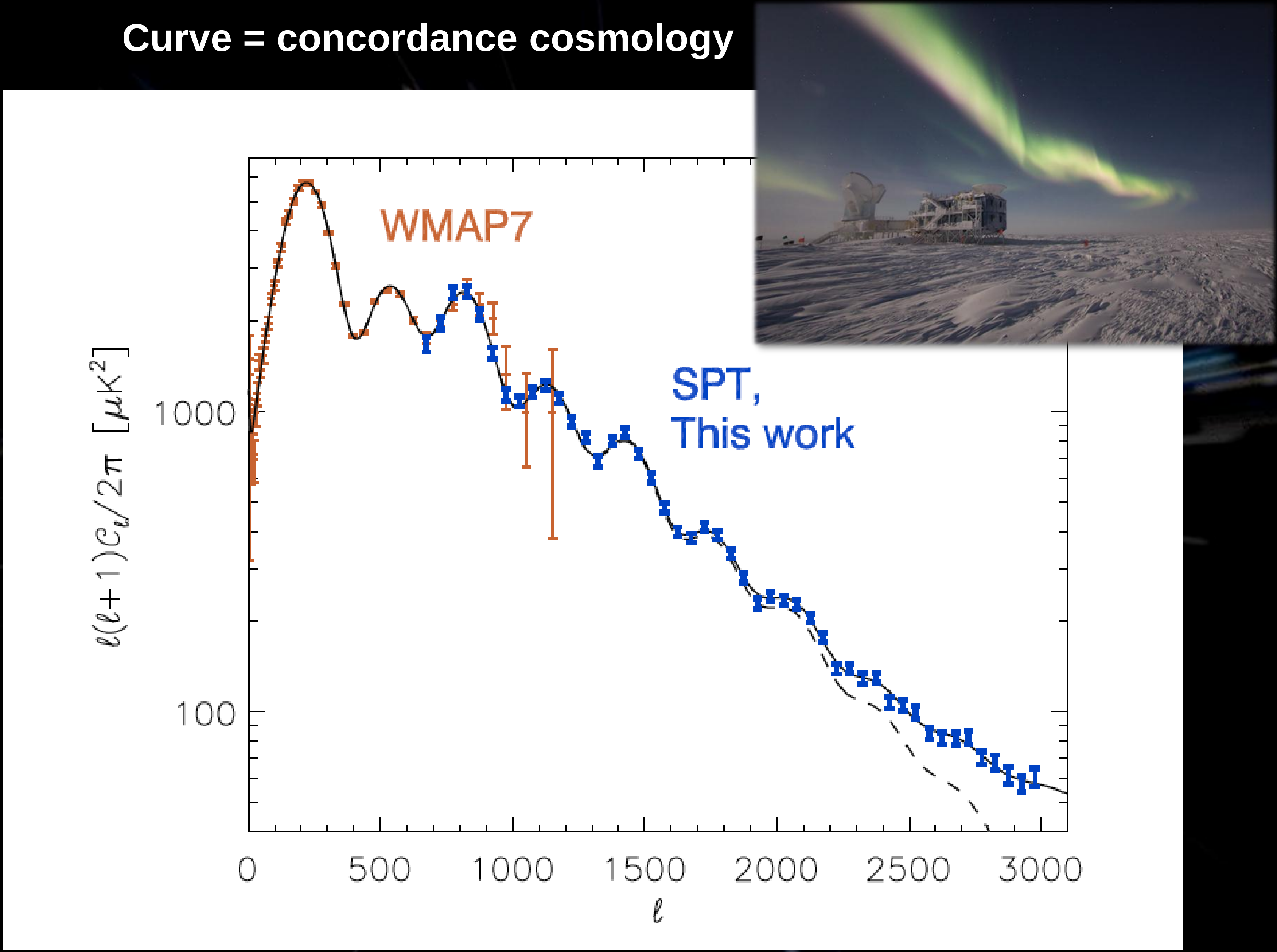
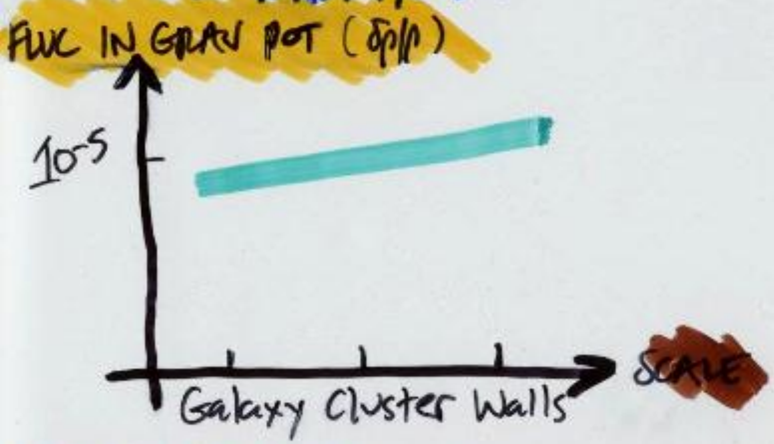
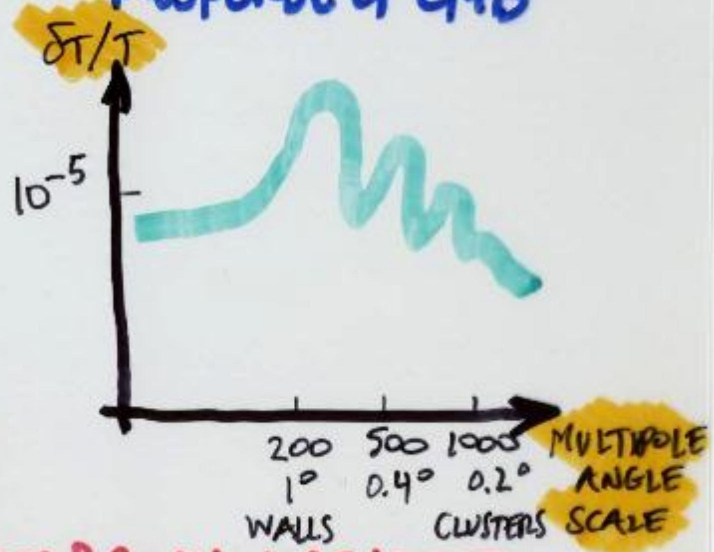


CMB IS A NON TRIVIAL PROBE OF MATTER DENSITY

UNDERLYING DENSITY PERTURBATIONS



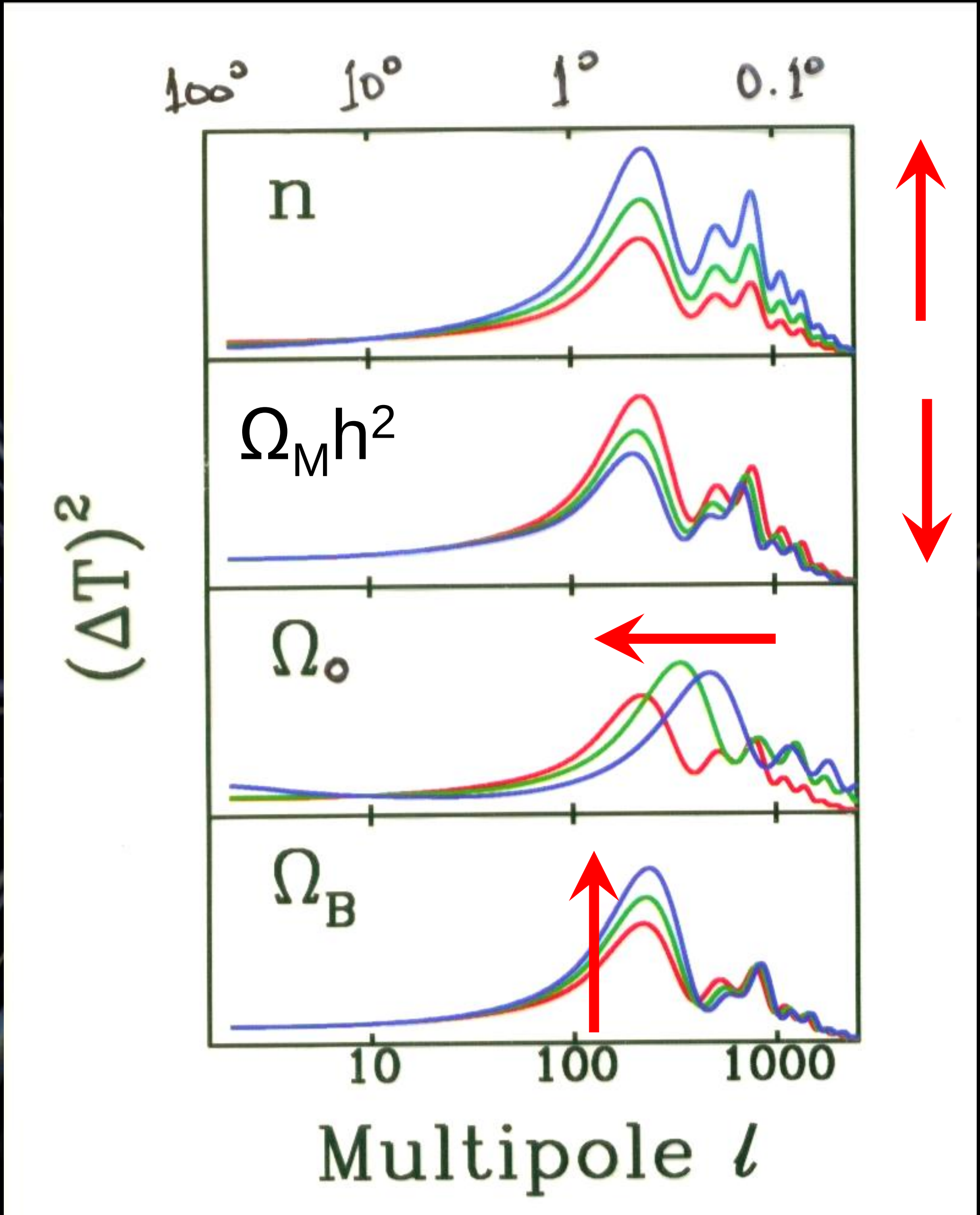
"RESPONSE OF CMB"



RESPONSE DEPENDS UPON: MATTER & BARYON DENSITIES, CURVATURE, DARK ENERGY ... & PRIMEVAL $\delta\rho/\rho$

➡ PROBES COSMOLOGY!

CMB anisotropy is a non-trivial map of density inhomogeneity to temperature fluctuations: Mapping depends upon cosmological parameters (good news!)



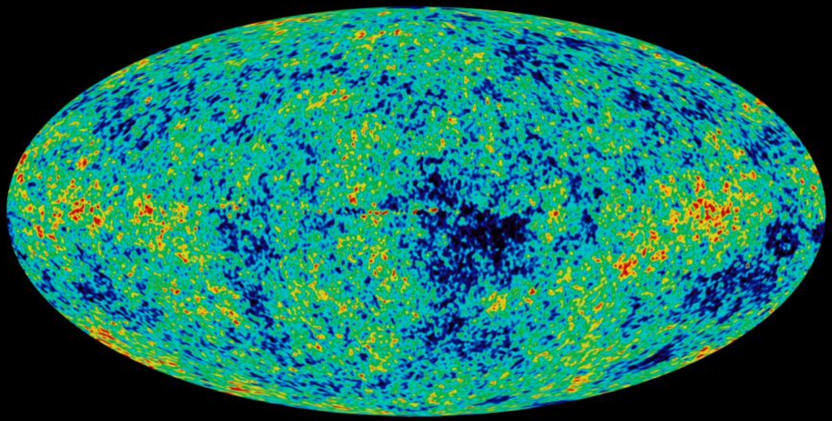
Today's "Consensus Cosmology"

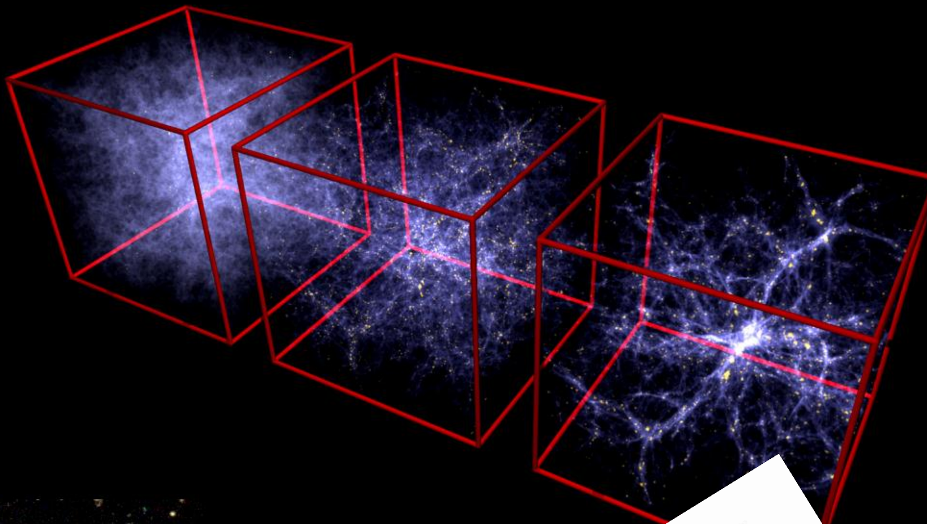
based upon precision measurements

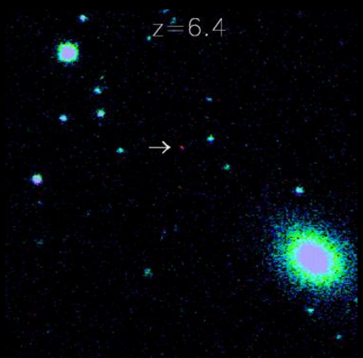
- From quark soup to nuclei and atoms to galaxies and large-scale structure
- Flat, accelerating Universe
- Atoms, exotic dark matter & dark energy
- Consistent with inflation
- Precision cosmological parameters
  - $\Omega_0 = 1.005 \pm 0.006$ (uncurved)
  - $\Omega_M = 0.273 \pm 0.014$
  - $\Omega_B = 0.046 \pm 0.0016$
  - $\Omega_{DE} = 0.73 \pm 0.015$
  - $H_0 = 70.4 \pm 1.3$ km/s/Mpc
  - $t_0 = 13.75 \pm 0.11$ Gyr
  - $N_\nu = 3.86 \pm 0.42$

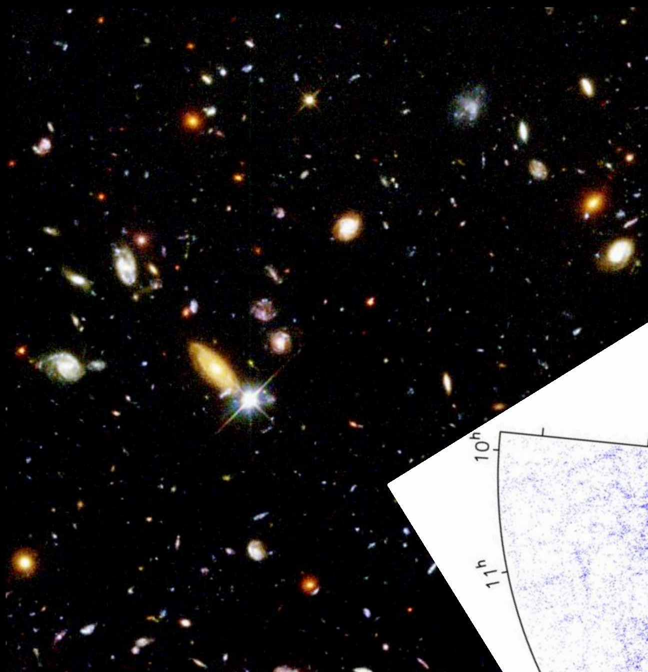
Consistent with all data, laboratory and cosmological!

Tracing the history from a slightly lumpy Universe to galaxies ablaze

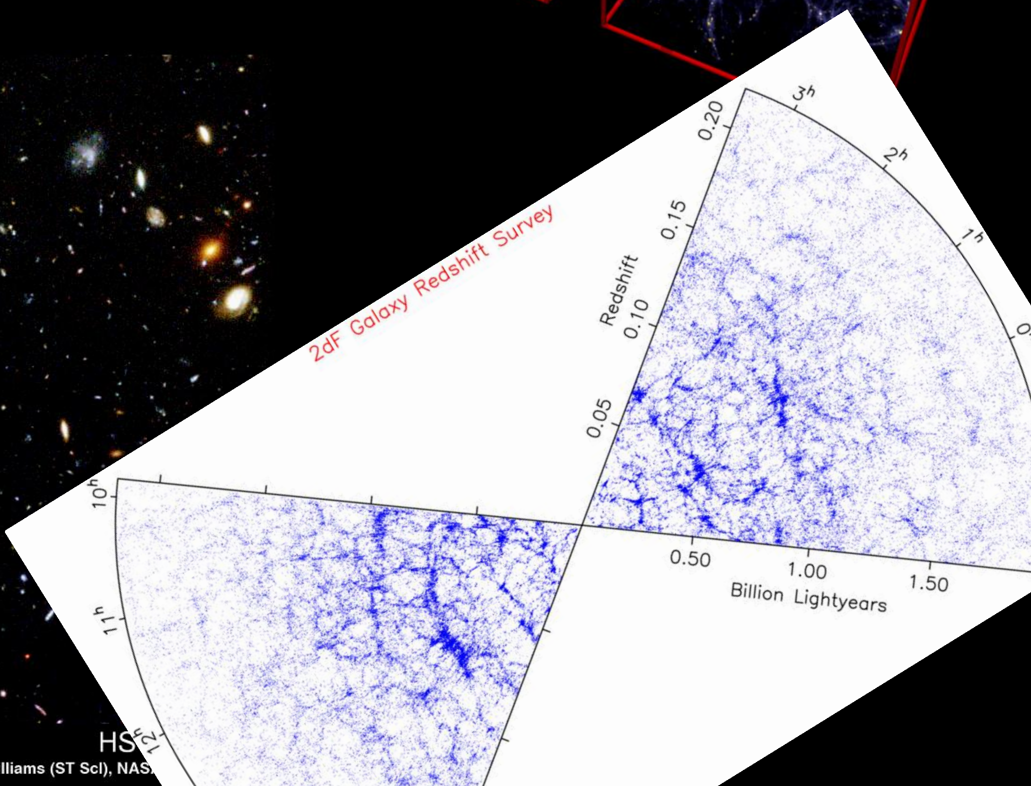






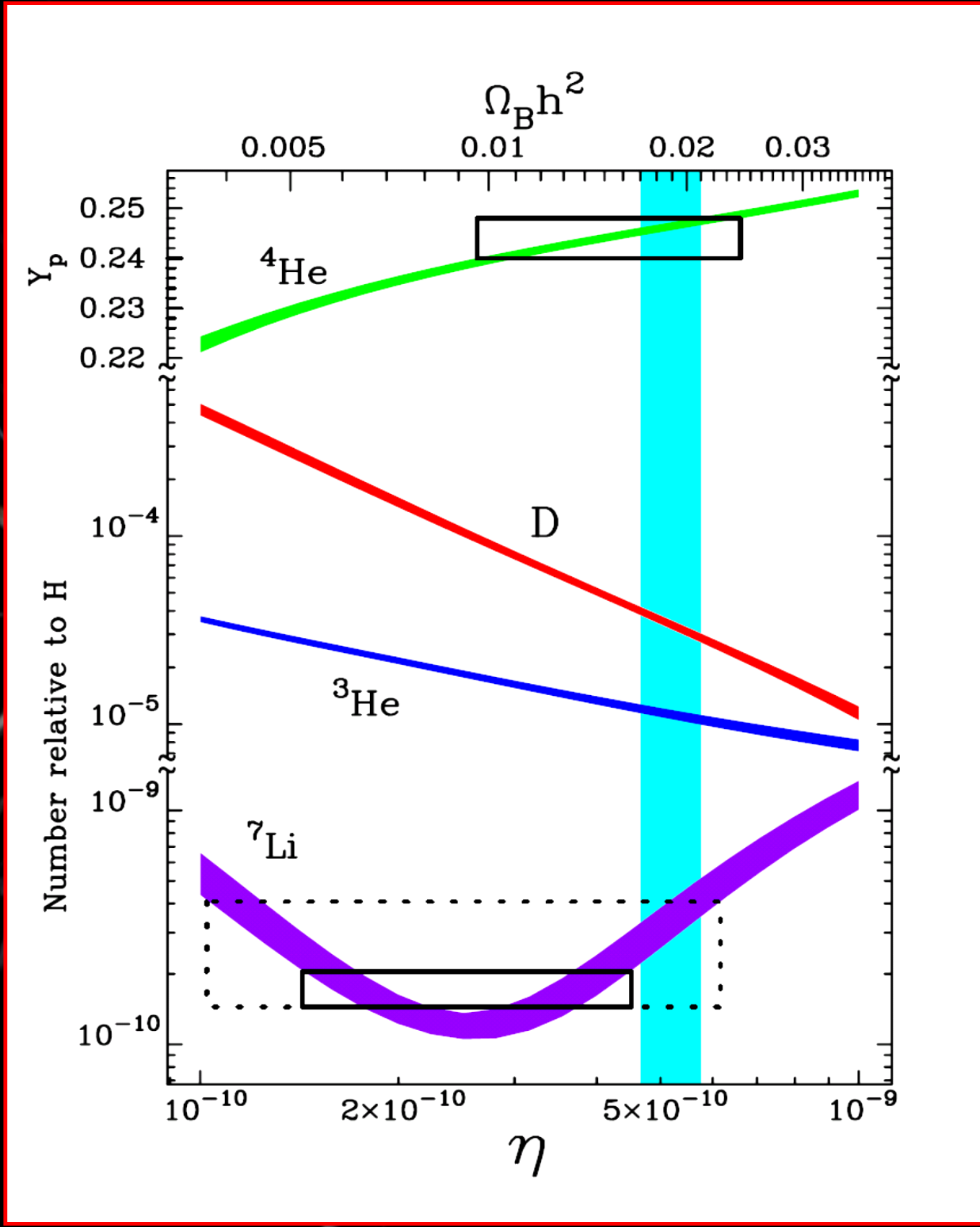


Hubble Deep Field HS
PRC96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NAS

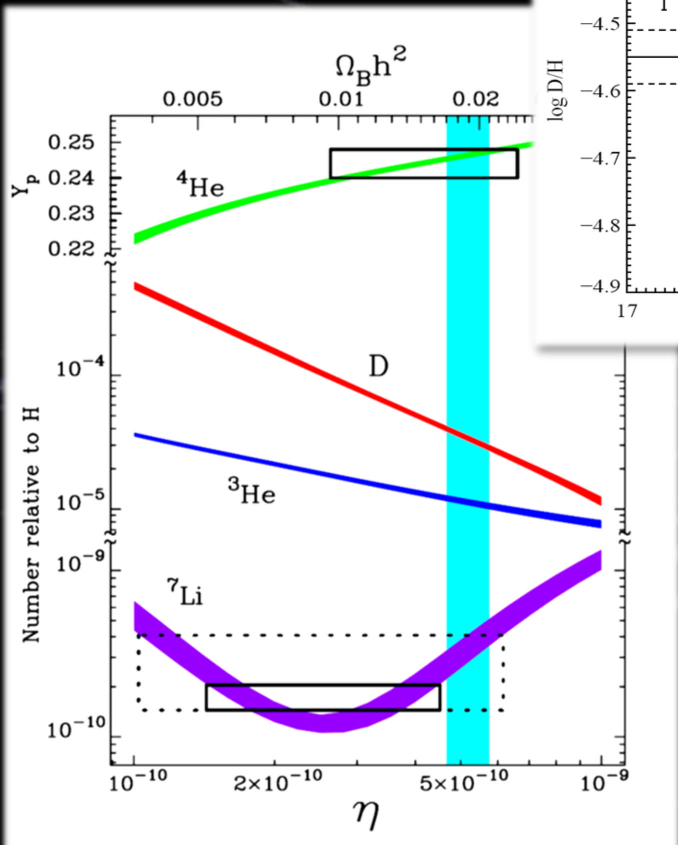


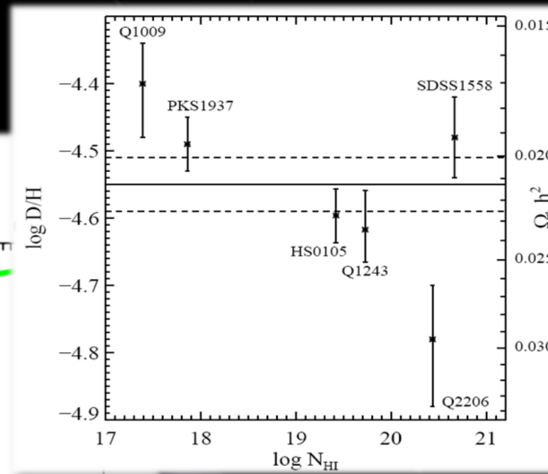
BBN Predictions
(95% cl)

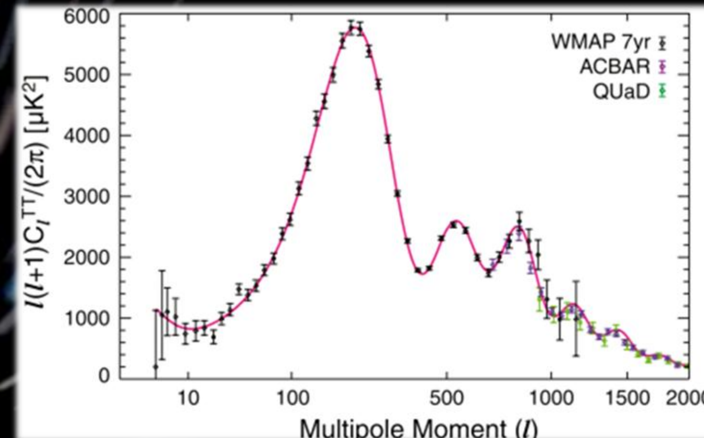
- Deuterium: baryometer!
- He-4: go/no-go test of big bang
- Li-7: consistency test; stellar probe?
- He-3: probe of chemical evolution



Precision Cosmology Indeed!







CMB (first to second peak)

$\Omega_b h^2 = 0.0225 \pm 0.0006$

vs.

BBN (Deuterium)

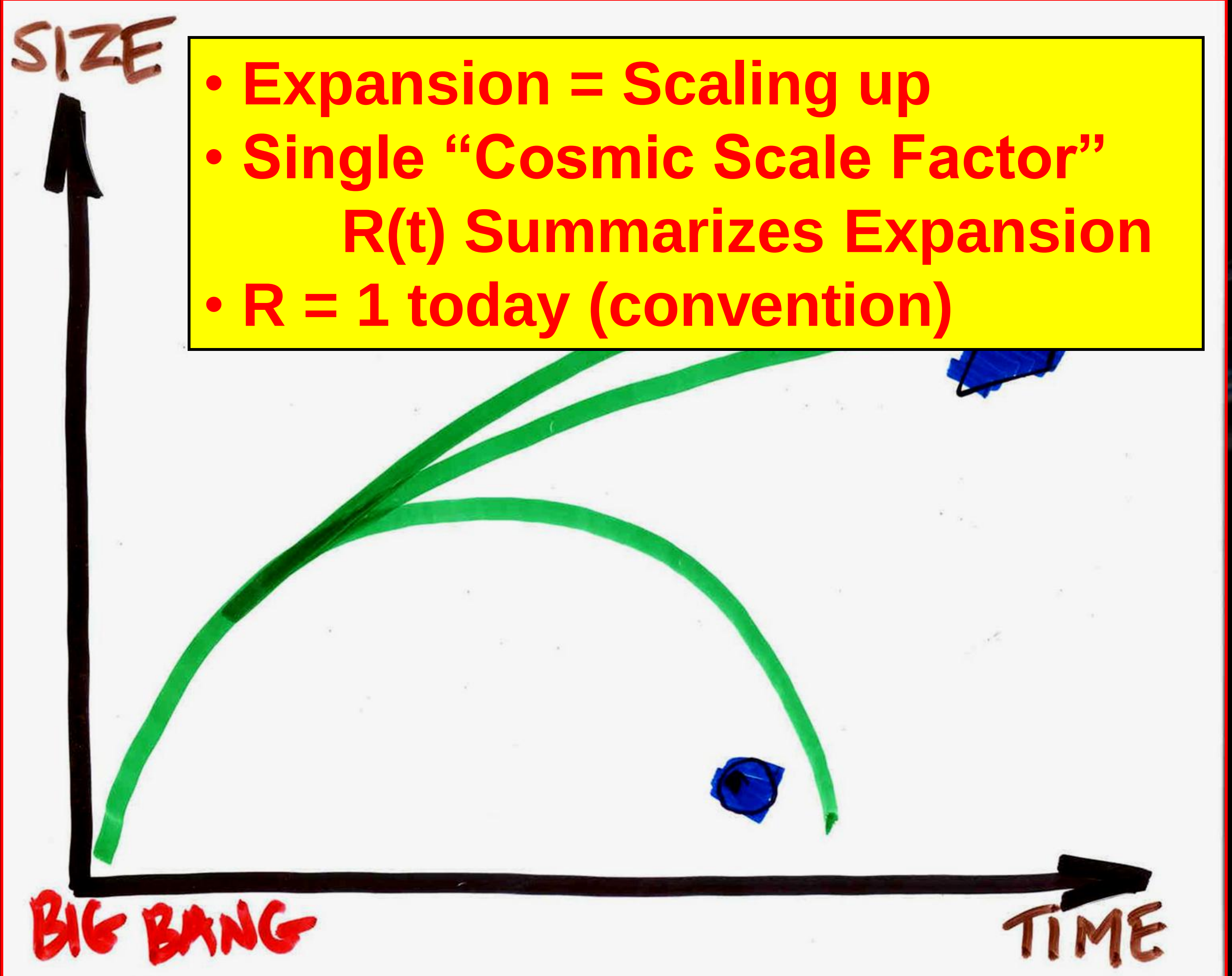
$\Omega_b h^2 = 0.0213 \pm 0.0013$

~5% agreement

$\mathbf{\Omega_b = 0.045 \pm 0.002}$

$h = H_0/100$ km/s/Mpc ~ 0.7

- **Expansion = Scaling up**
- **Single “Cosmic Scale Factor”**
  R(t) Summarizes Expansion
- **R = 1 today (convention)**



Cosmological Redshift

All physical distances get stretched with cosmic scale factor, $R_{today} = 1.0$

- Wavelength of a photon (redshift z)

$$1 + z \equiv \frac{\lambda_{\rm rcvd}}{\lambda_{\rm rest}} = \frac{R_{\rm today}}{R_{\rm emit}} = 1/R_{\rm emit}$$

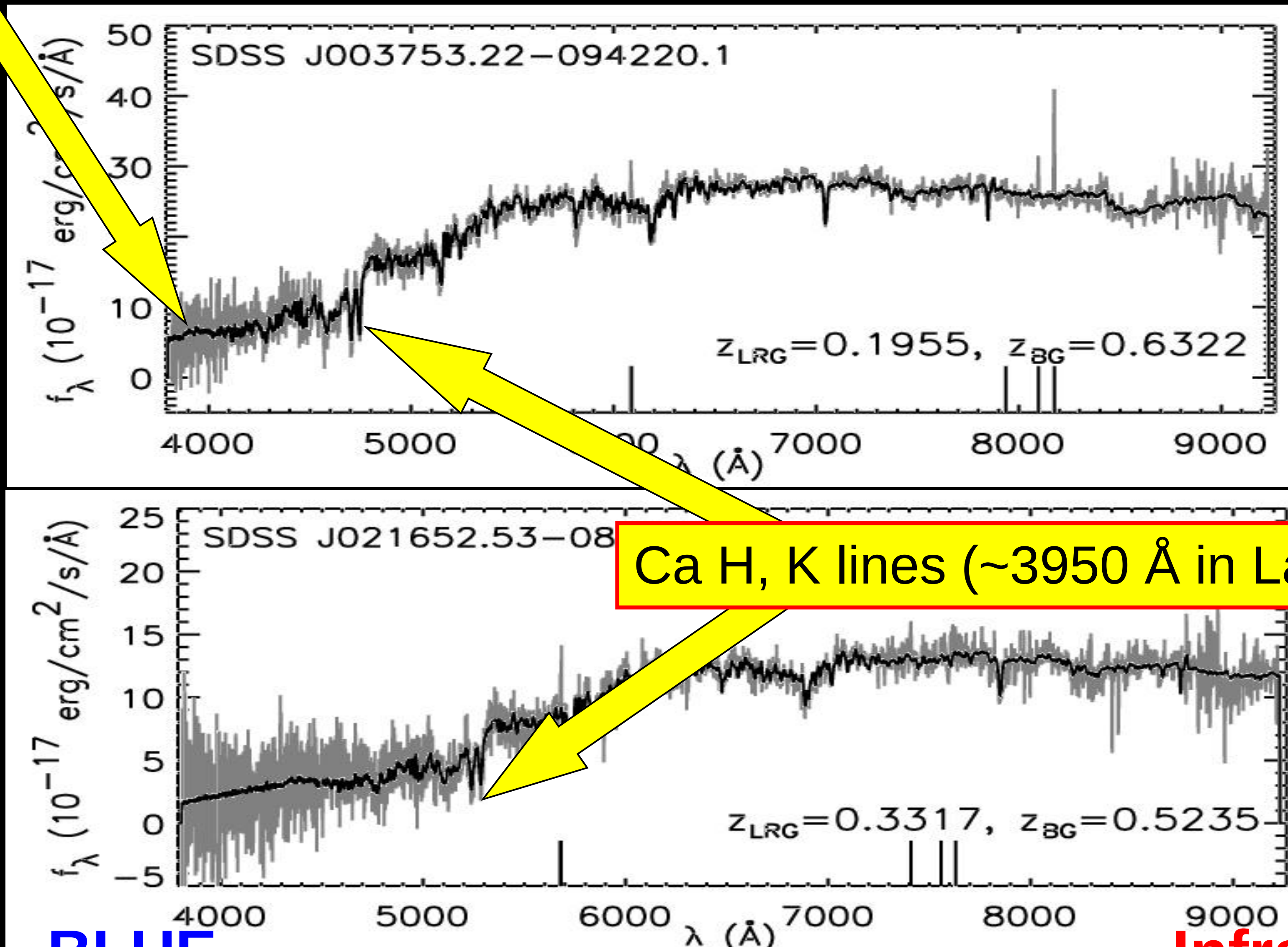
$$dt = \frac{-dz}{(1+z)H(z)} \Rightarrow t(z) = \int_z^\infty \frac{dz}{(1+z)H(z)}$$

- Momenta of particles too: $p \sim 1/R$
- Distance between galaxies

NB: but not the size of self-bound objects (from atoms to stars to galaxies & clusters)

Redshifted Spectra

3950 Å



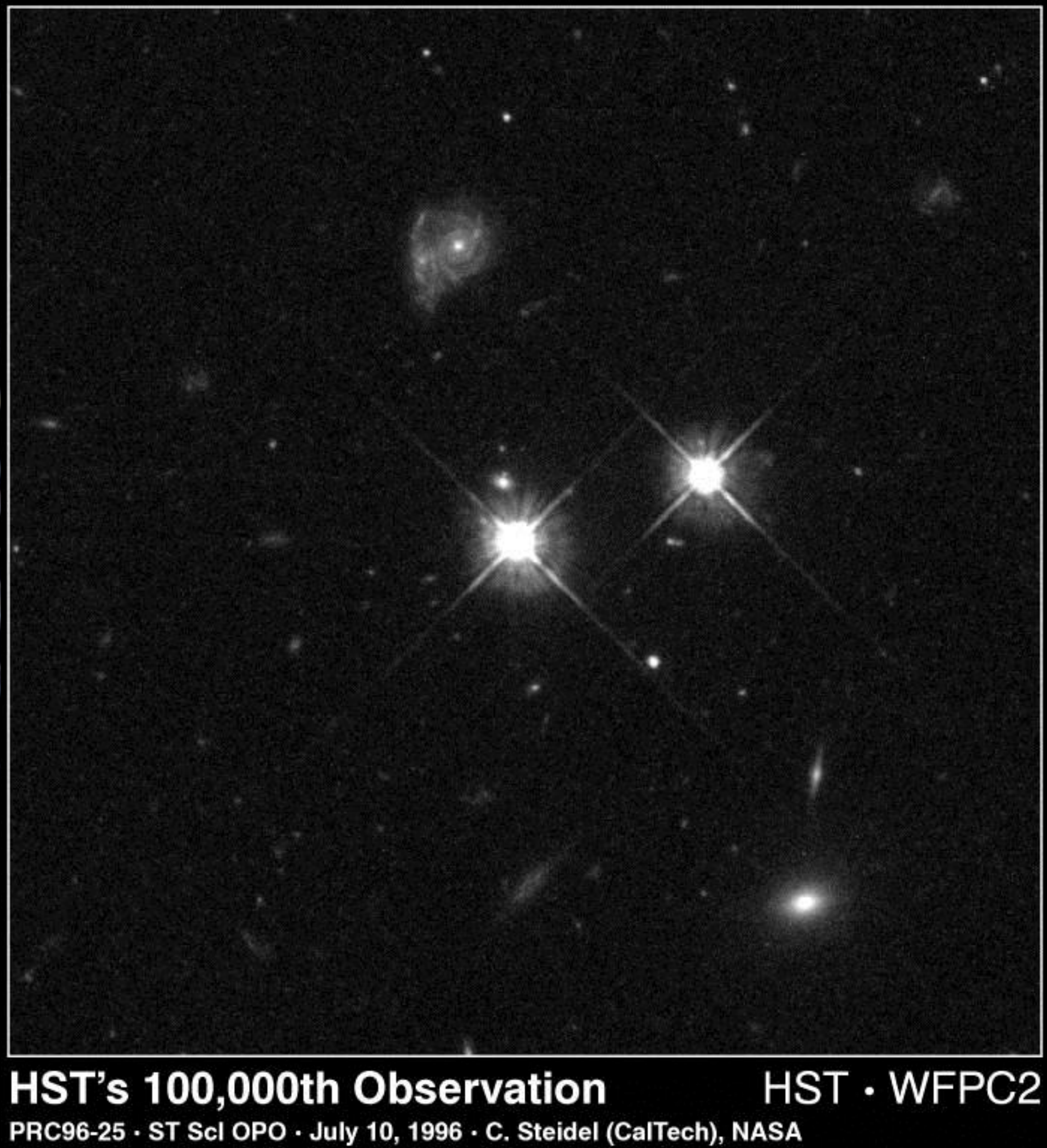
Ca H, K lines (~3950 Å in Lab)

BLUE

InfraRED

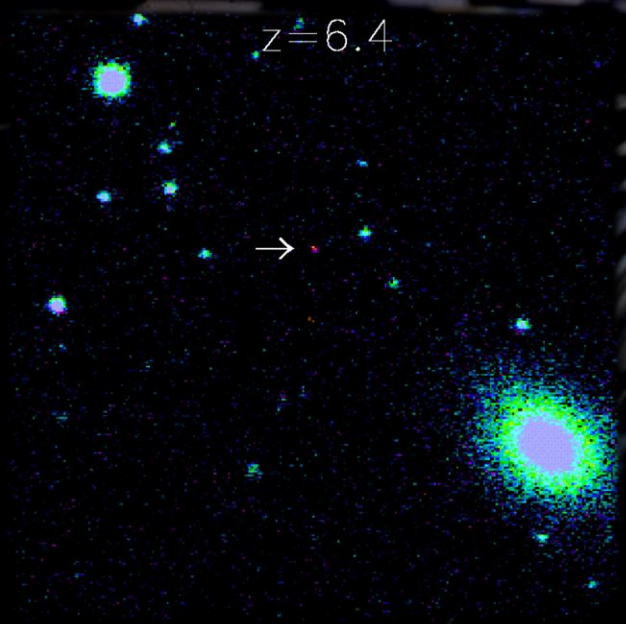
Quasar = Quasi-Stellar Object (QSO)

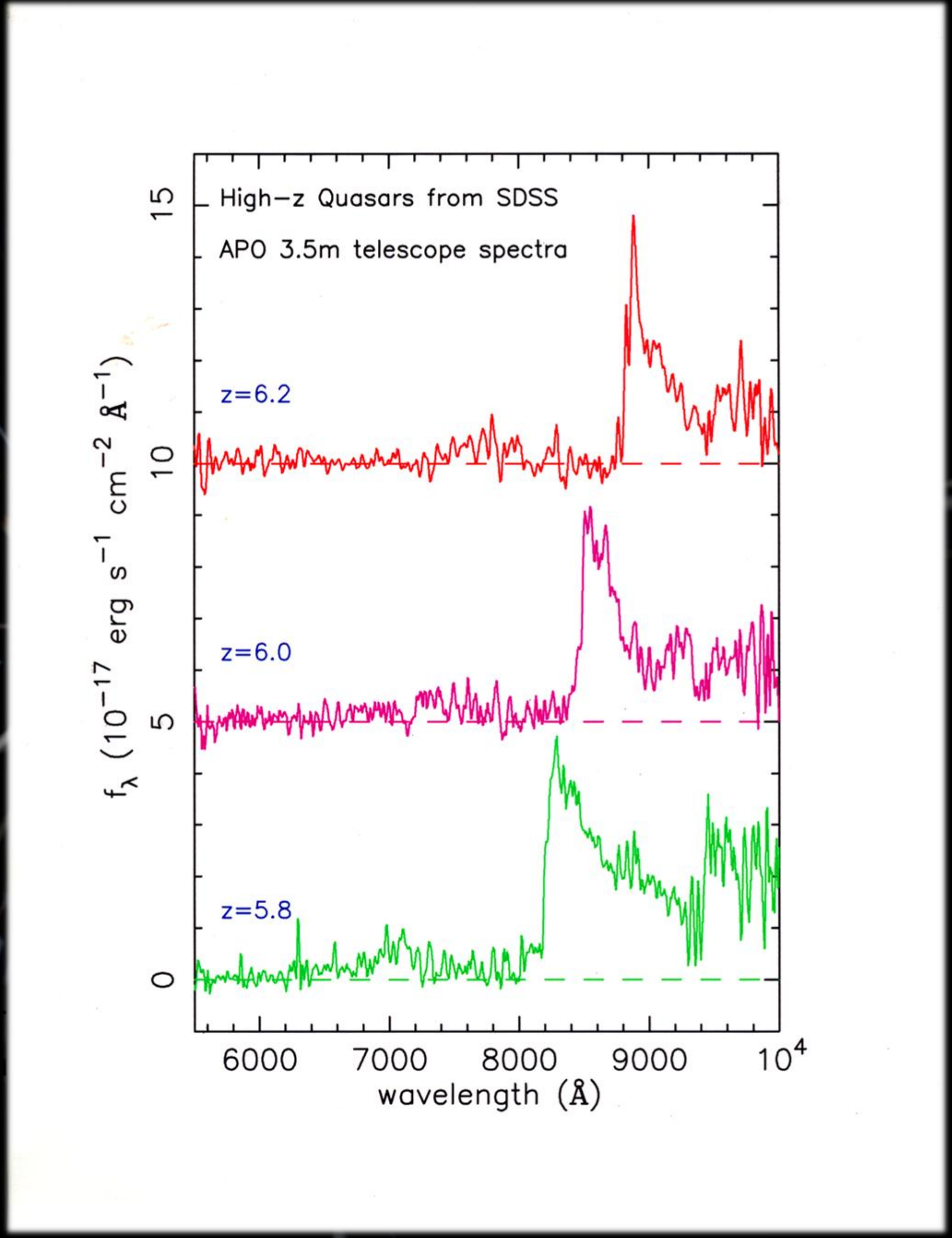
(accreting black hole at center of galaxy)



UV light (1216 Å) from the early Universe redshifted to near IR.

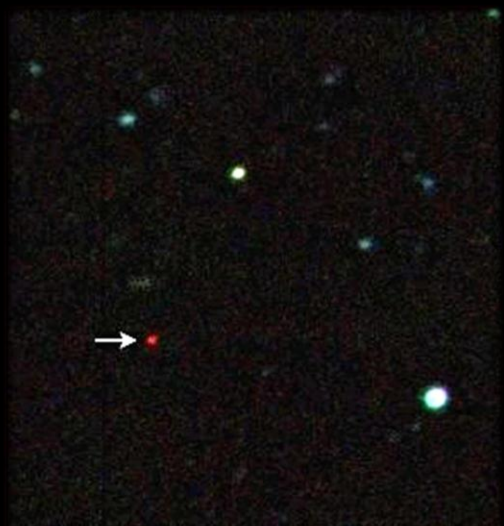
The Universe was ~7 times smaller!

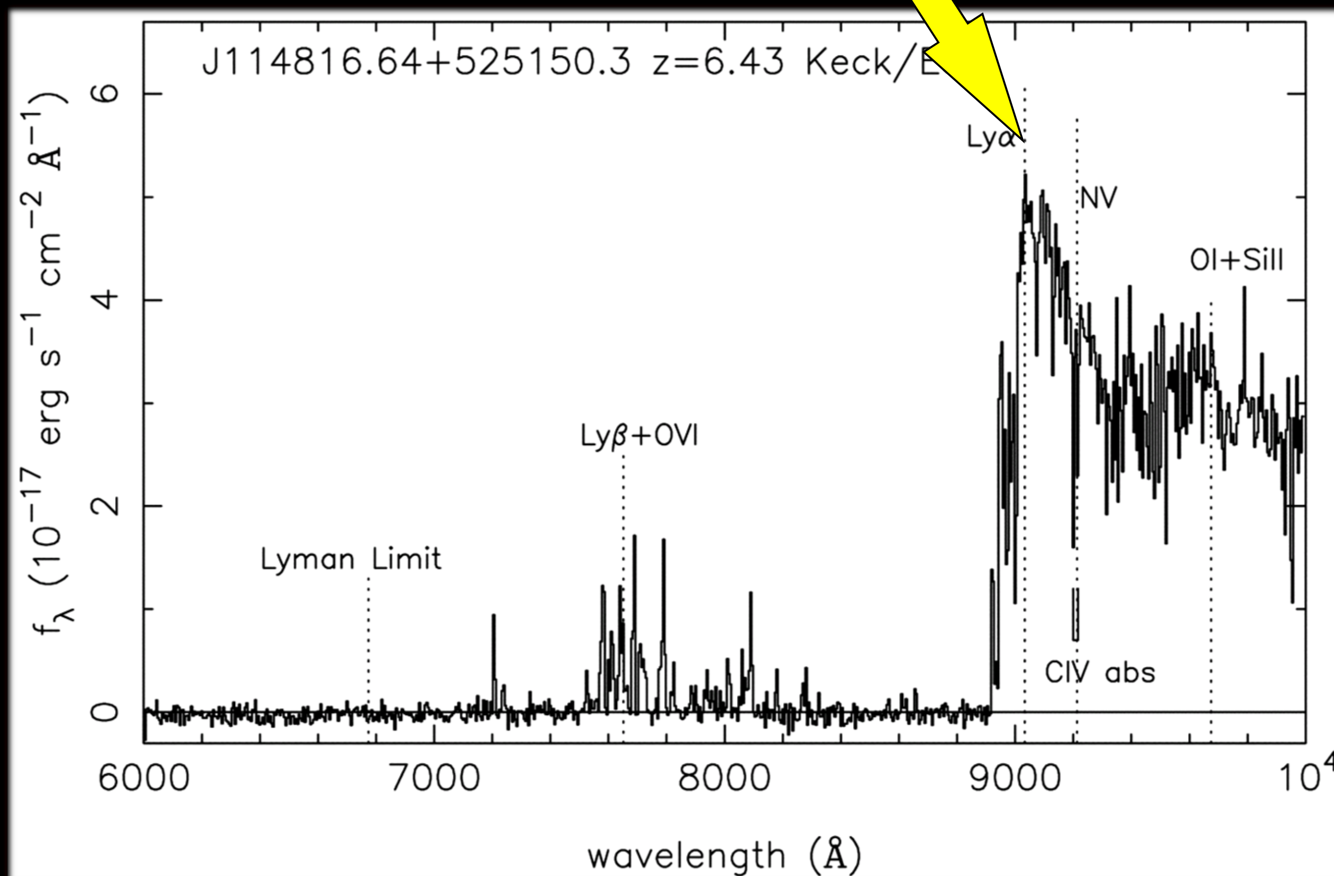




z = 6.43 Quasar!
When the light was emitted,
Universe was 7.43 x smaller!

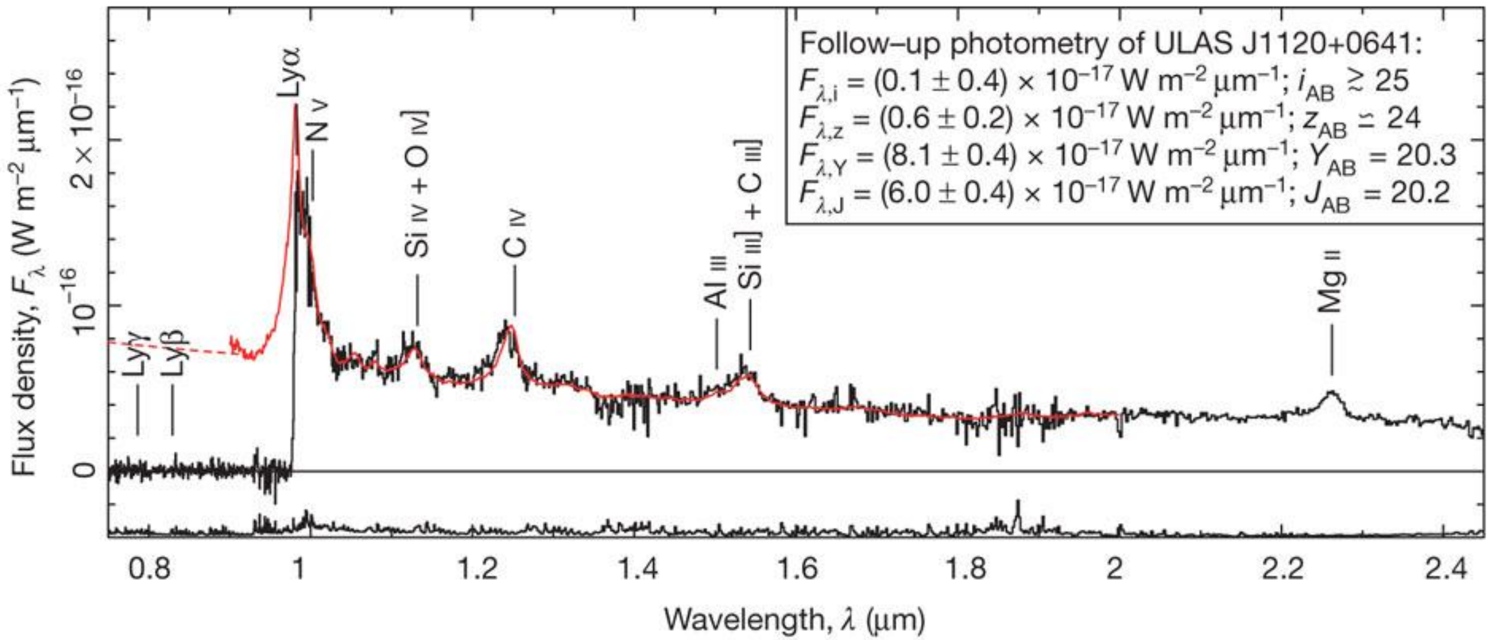
1216 Å





Quasar Redshift Record Holder: z = 7.085

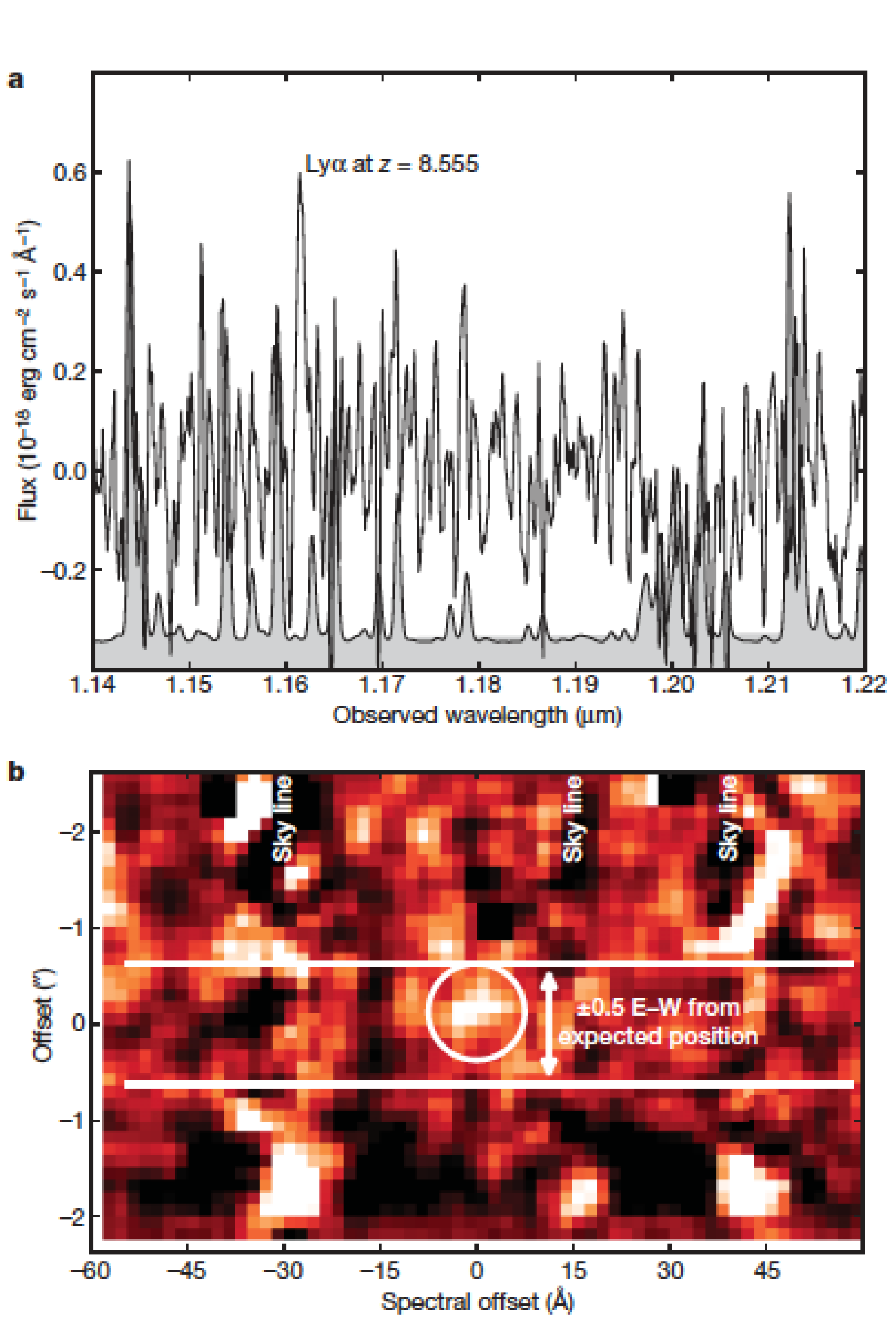
Spectrum of ULAS J1120+0641 and a composite spectrum derived from lower redshift quasars.

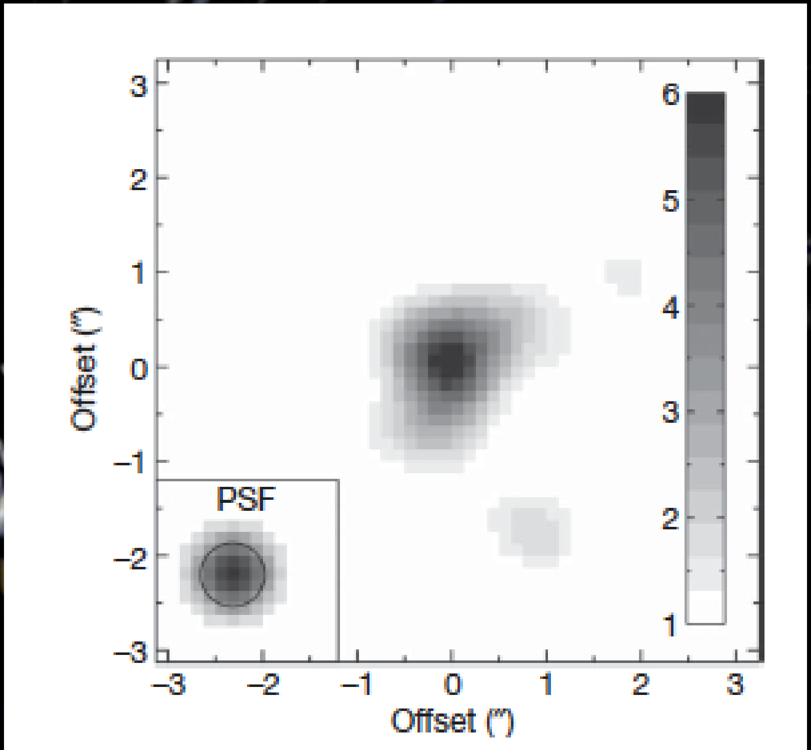


DJ Mortlock *et al*. *Nature* **474**, 616-619 (2011)
doi:10.1038/nature10159

nature

Galaxy record holder: z = 8.6!





Redshift: it's important!

- Direct measure of the size of the Universe when the photons were emitted: $R = 1/(1 + z)$

- Time coordinate: "Universe at redshift z = the Universe when a photon emitted then, today has a wavelength larger by 1 + z"

$$1+z = 1/R$$

$$dz = -dR/R^2 = -dt(dR/dt)/R^2 = -dt(1+z)H(z)$$

$$\rightarrow \quad \boxed{t(z) = \int_z^\infty \frac{dz}{(1+z)H(z)}}$$

Friedmann Equations

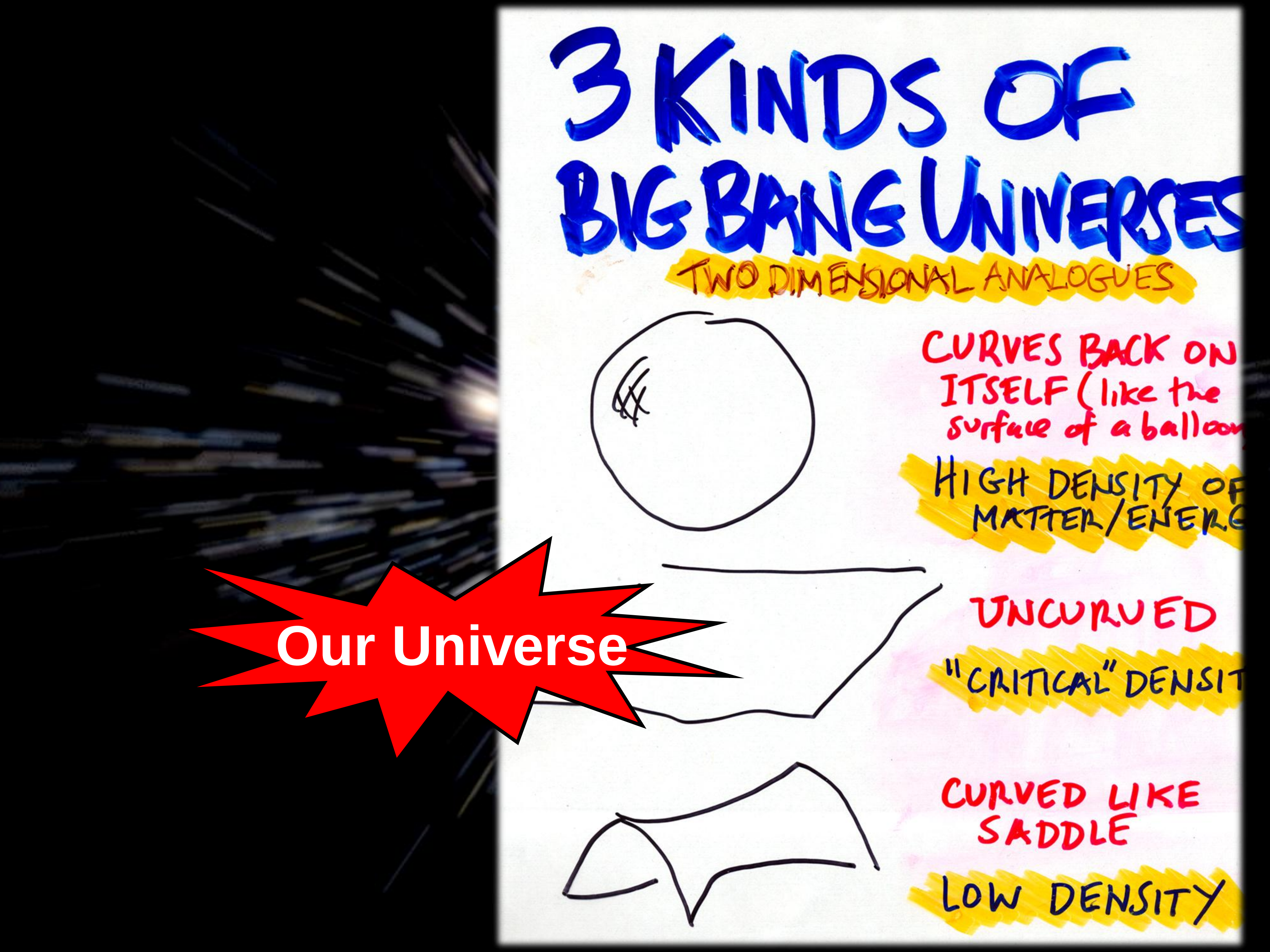
<u>Matter tells space how to bend</u>

("flat", Euclidean Universe)

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 \quad = \quad \frac{8\pi G\rho}{3}$$

- H = expansion rate ("Hubble constant")
- Total energy density ρ and total pressure p
- Solutions:

$$\begin{array}{lll} \rho & \propto & 1/R^n \\ R & \propto & t^{2/n} \qquad H \propto (2/n)/t \qquad t = (2/n)H^{-1} \\ R & \propto & \exp(Ht) \quad H \propto \text{const} \qquad \text{for } n = 0 \end{array}$$


3 KINDS OF
BIG BANG UNIVERSES
TWO DIMENSIONAL ANALOGUES
CURVES BACK ON ITSELF (like the surface of a balloo
HIGH DENSITY OF MATTER/ENERG
Our Universe
UNCURVED
"CRITICAL" DENSIT
CURVED LIKE SADDLE
LOW DENSITY

Cosmological Parameters

NB: $h^2 \cong 0.5$

$$H_0 = 100h\,\mathrm{km/s/Mpc} = h/9.78\,\mathrm{Gyr}$$
$$\simeq 70\,\mathrm{km/s/Mpc} \simeq 1/14\,\mathrm{Gyr} \quad 1/1.3\times10^{28}\,\mathrm{cm}$$
$$\Omega_0 \equiv \frac{\rho_0}{\rho_{\mathrm{critical}}} = \sum_i \Omega_i$$

Ω

ρ … m^3

$$q_0 = -\frac{\ddot{R}_0/R_0}{H_0^2} = \frac{\Omega_0}{2}(1+3w)$$

$\sum_i$

$$T_0 = 2.725 \pm 0.001\,\mathrm{K} \qquad n_\gamma = 410\,\mathrm{cm}^{-3}$$
$$\Omega_\gamma = 2.47h^{-2}\times10^{-5} \simeq 5\times10^{-5}$$
$$\Omega_{\mathrm{R}} = 4.15h^{-2}\times10^{-5} \simeq 8.3\times10^{-5}$$

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Evolution of Matter/Energy

<u>space tells matter how to move</u>

$$d(\rho R^3) = -p d(R^3) \qquad \text{“First Law”}$$

$$\rho \propto R^{-3(1+w)} \qquad \text{for } p = w\rho$$

Matter ($w = 0$): $\rho \propto R^{-3}$ $R \propto t^{2/3}$

Radiation ($w = 1/3$): $\rho \propto R^{-4}$ $R \propto t^{1/2}$

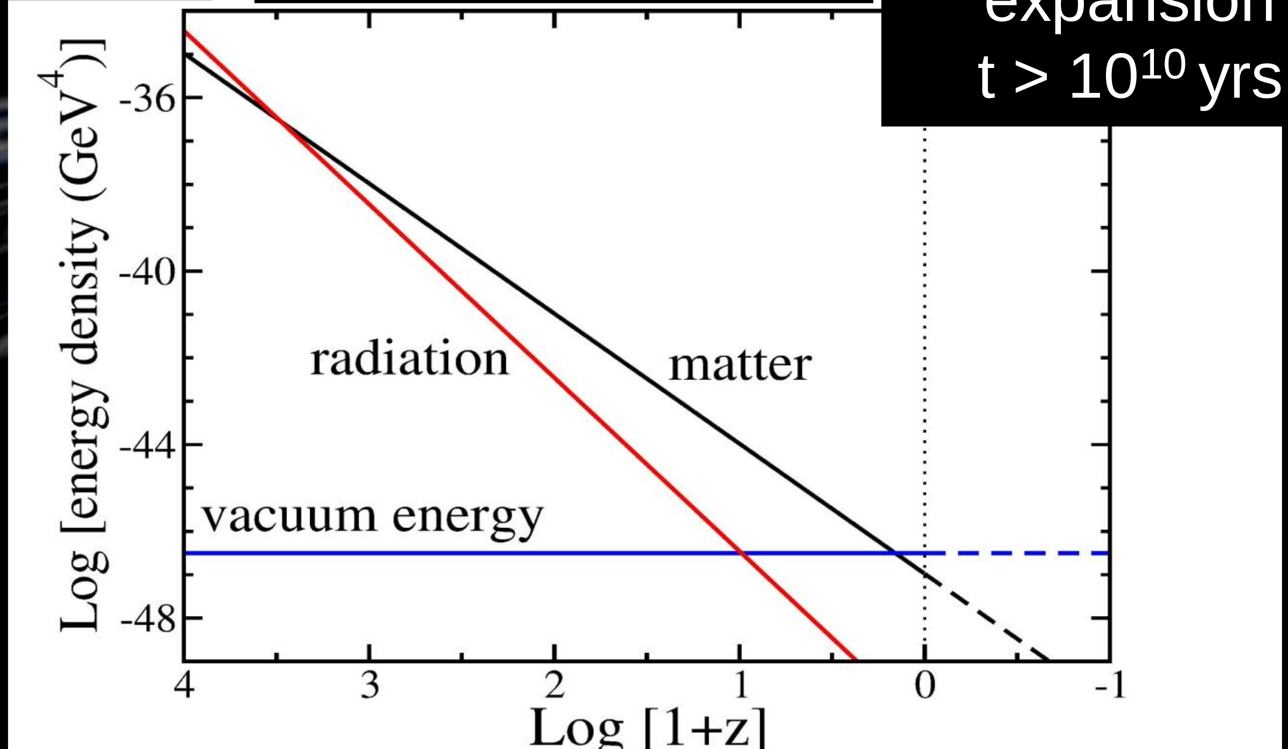
Vacuum Energy ($w = -1$): $\rho \propto \text{const}$ $R \propto \exp(Ht)$

Three Epochs Dominated by Different Forms of Energy

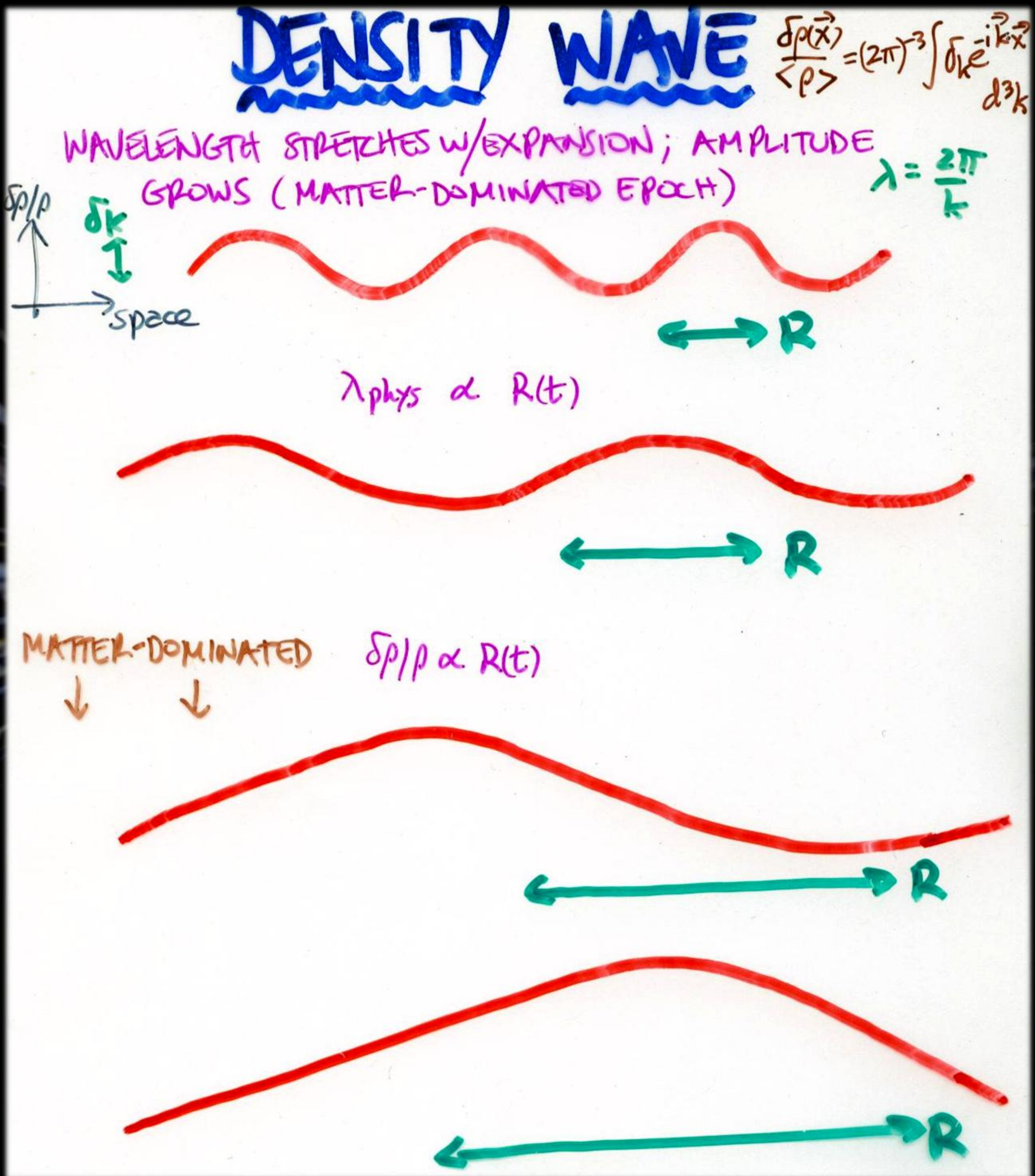
1. Rad dominated
$R \sim t^{1/2}$ thermal bath
$R < 10^{-4}$, $t < 10^{4}$ yrs

2. Matter dominated
$R \sim t^{2/3}$ struc. forms
$t \sim 10^{4}$ yrs – 10^{10} yrs

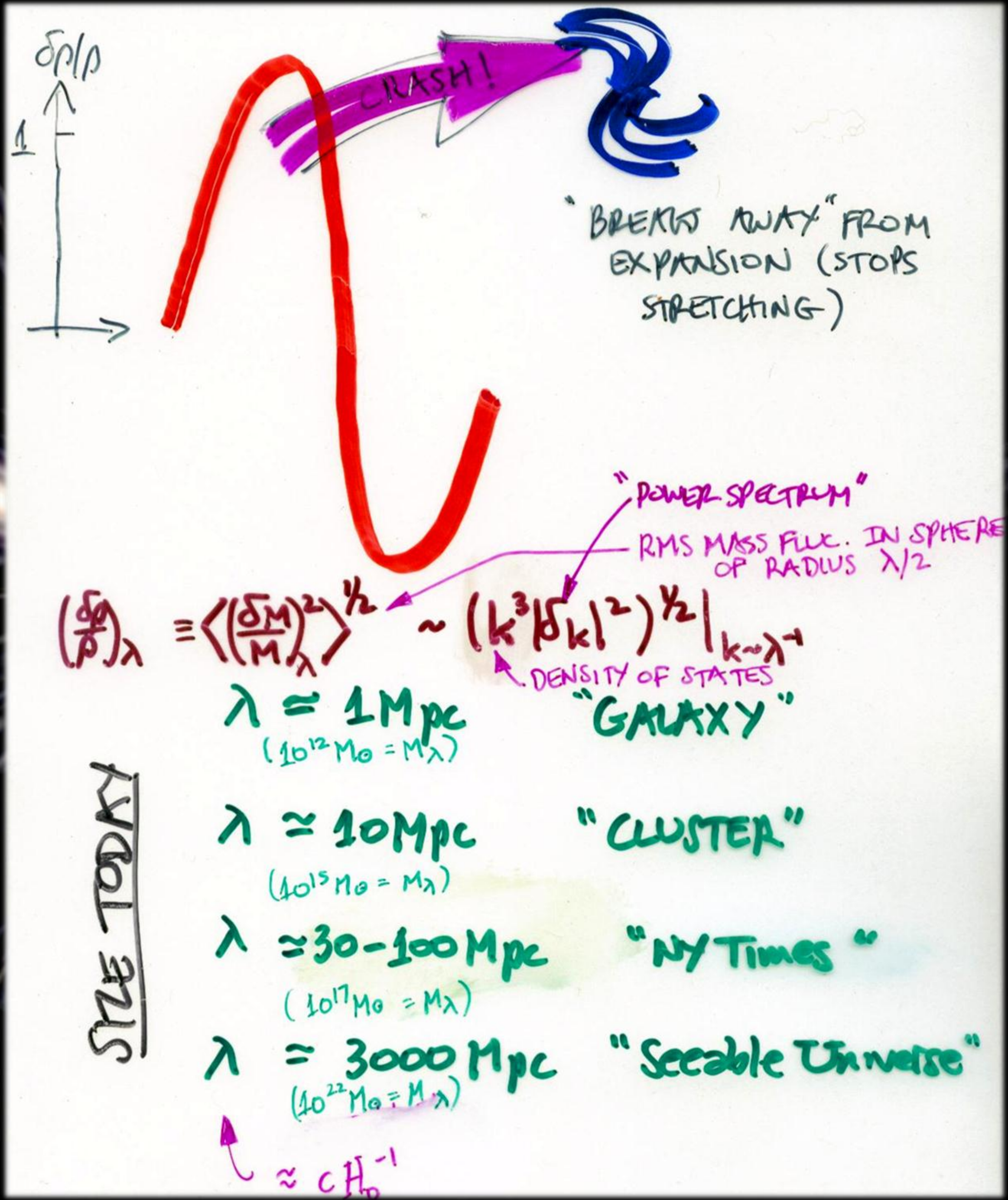
3. Dark Energy
$R \sim e^{Ht}$
accelerated
expansion
$t > 10^{10}$ yrs



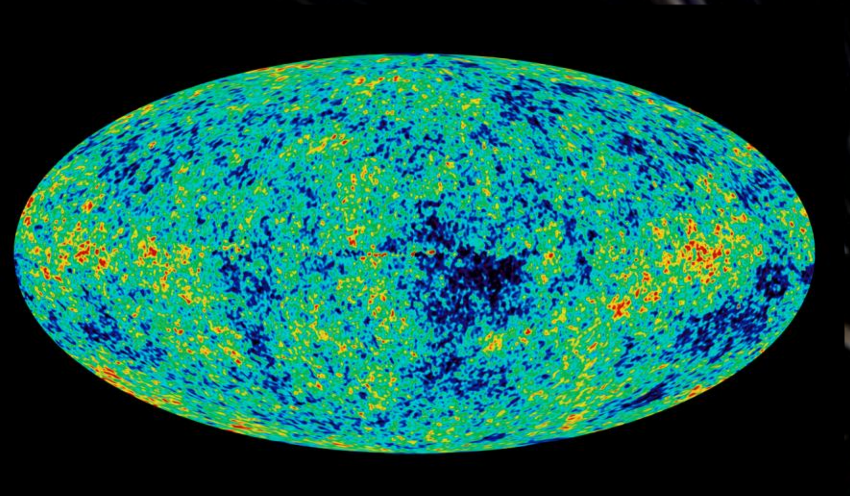
Expand density field in comoving fourier components (which contain fixed amount of matter) but whose physical wavelength grows with time



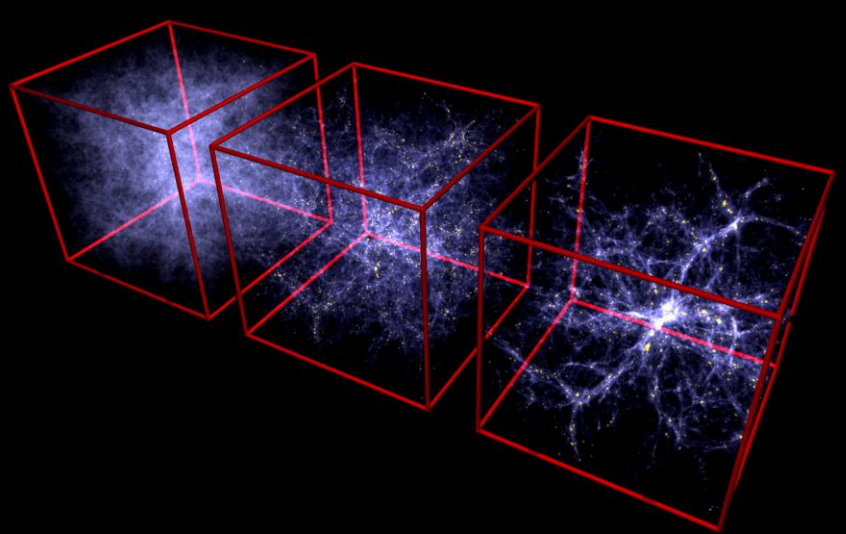
During matter-dominated era, wave amplitudes grow with time (as the scale factor), reach unity and bound structures form and cease expanding



Structure Formation



Gravitational amplification of small (few parts in 10^5) density inhomogeneities to the structure seen today during matter dominated epoch, $\delta\rho/\rho \propto R(t)$

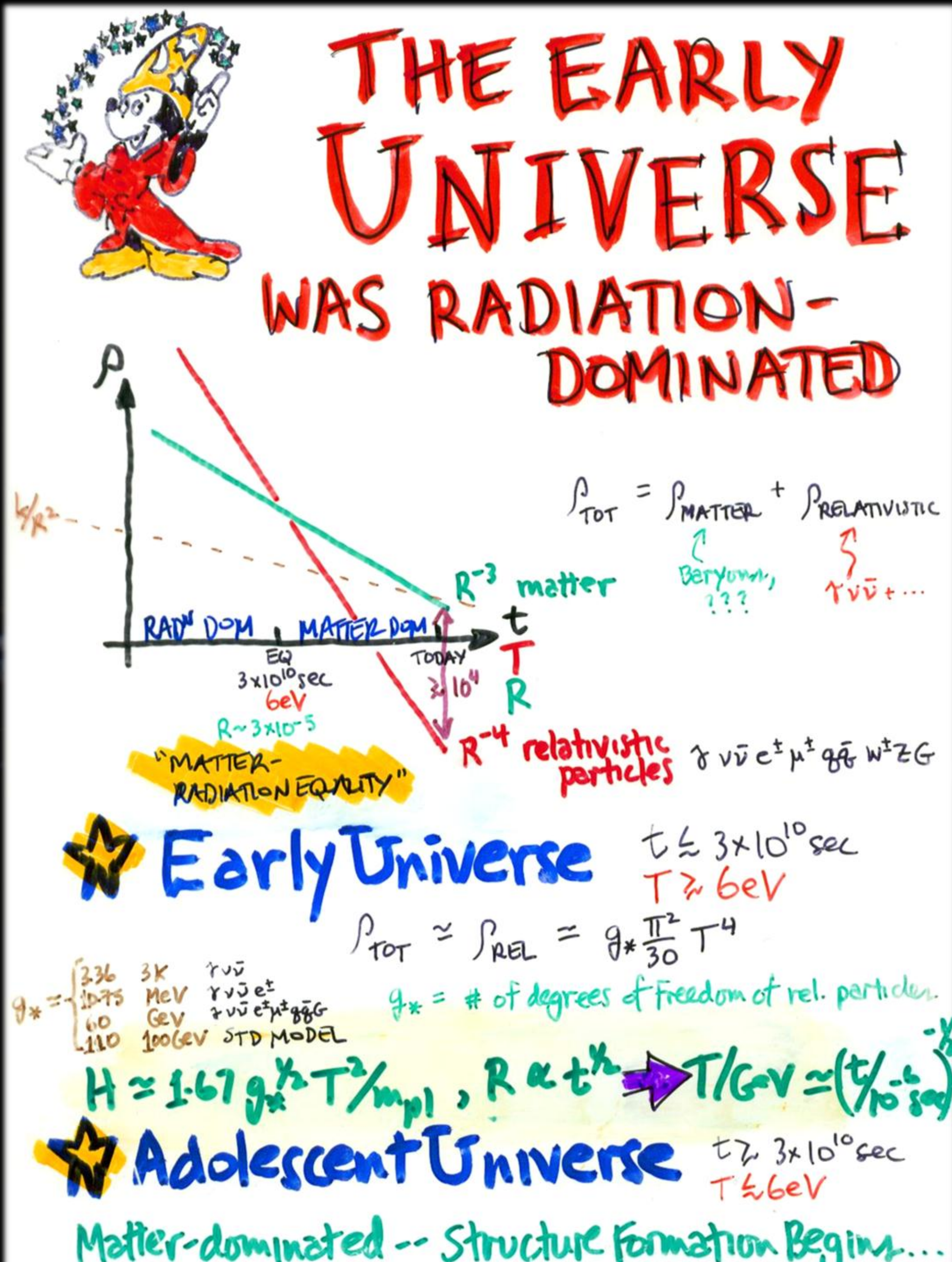


"Jeans' Equation"

$$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho_M\delta_k = 0$$

<u>Solutions</u>

1. $H = 0$: $\delta_k \propto \exp[(4\pi G\rho_M)^{1/2}t]$
   Classic Jeans' Instability
2. $H = 2/3t$ (MD): $\delta_k \propto t^{2/3} \propto R(t)$
3. $H = 1/2t$ (RD): $\delta_k \propto \ln(R)$
4. $H = \text{const}$: $\delta_k \propto \text{const}$ (no growth)



Thermal Bath

For most of its early history: thermal equilibrium (departures are very important – not all Fe today!)

- For $kT > mc^2$ particle/antiparticle pairs as abundant as photons
- Energy density:

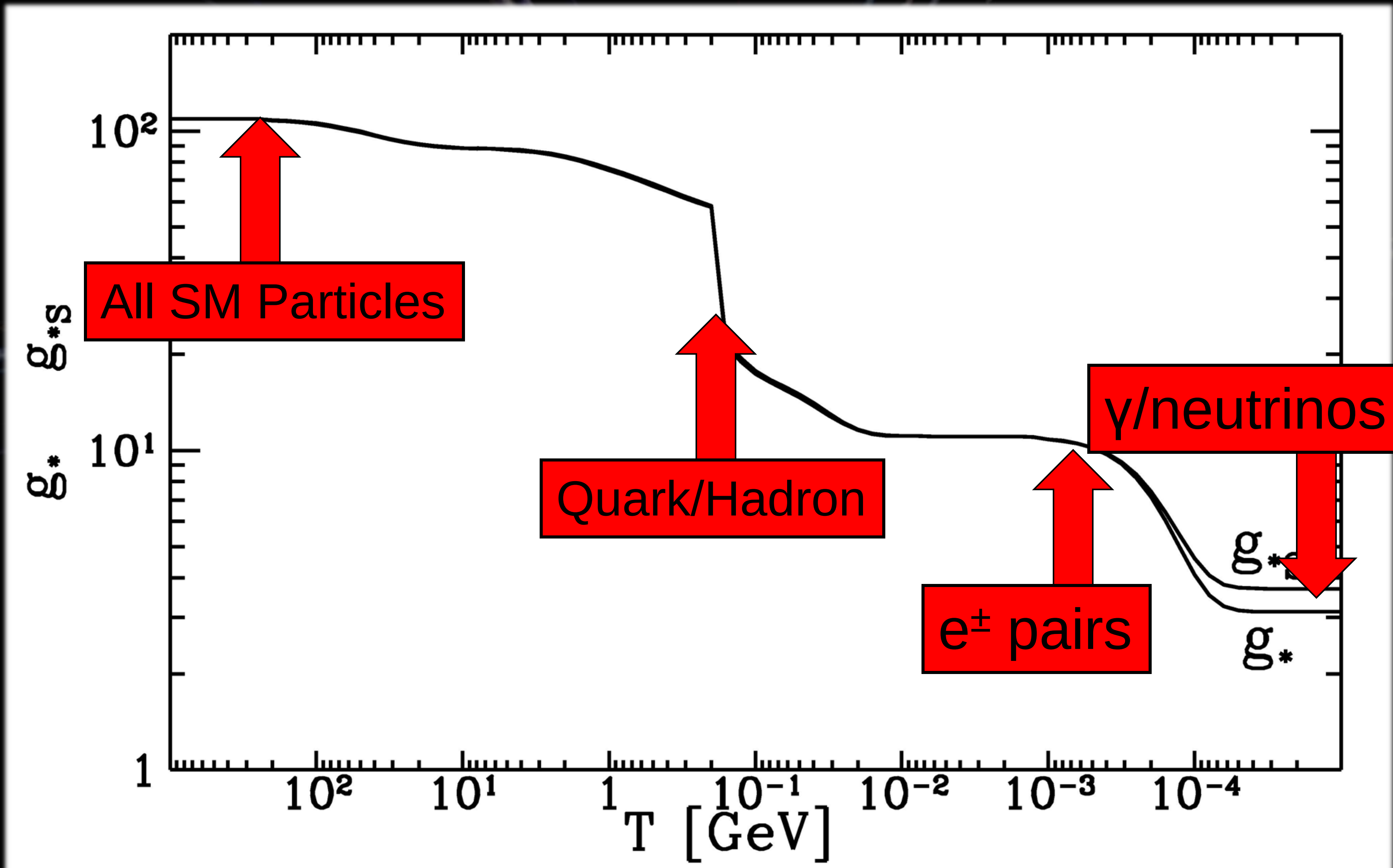
$$\rho = g_*\pi^2 T^4/30$$

g_* counts dof

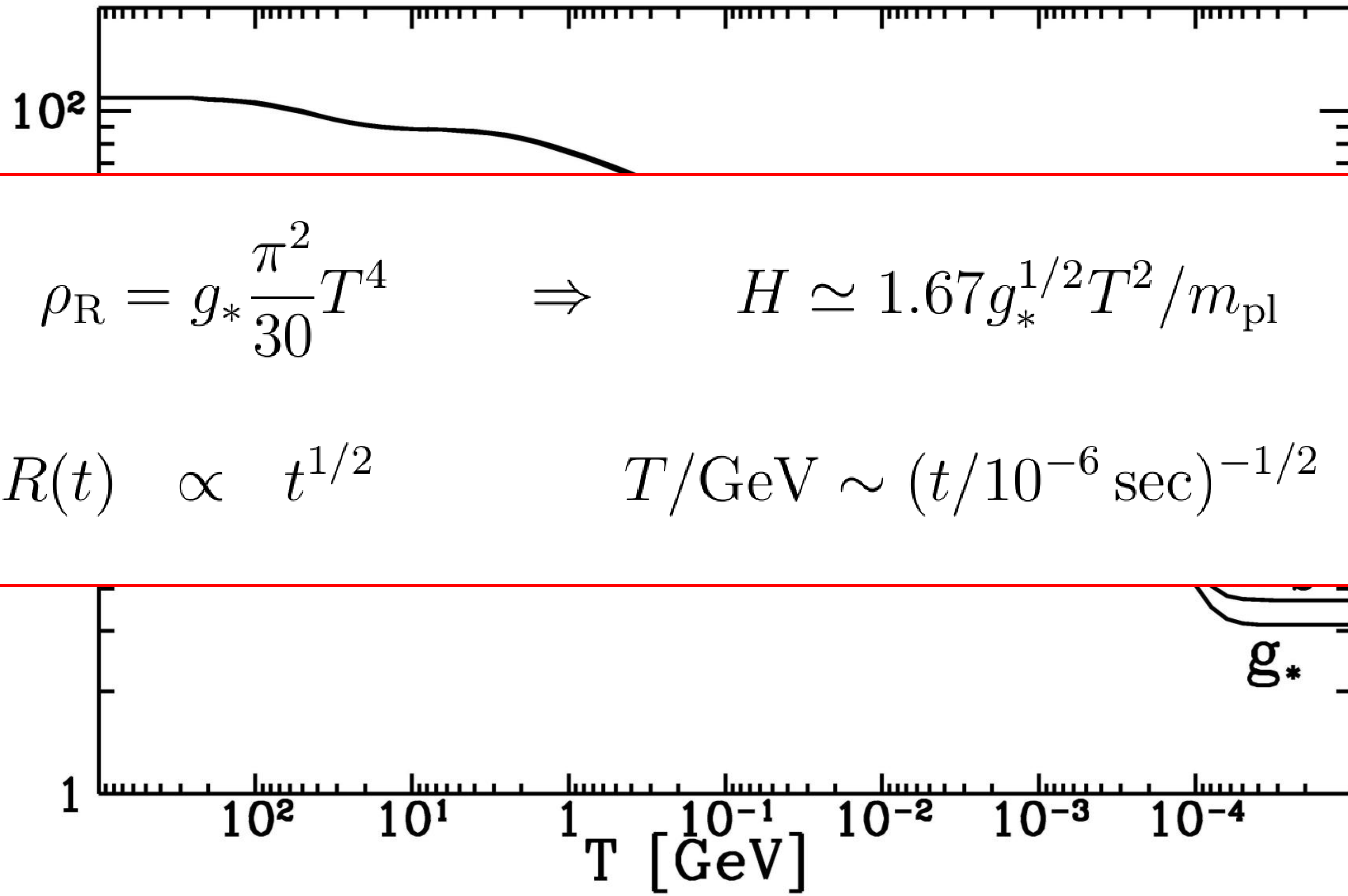
$$\rho_\gamma = \frac{\pi^2 T^4}{15} \qquad n_\gamma = \frac{2\zeta(3)T^3}{\pi^2}$$


Campbell's
CONDENSED
Quark
WITH LEPTONS AND GAUGE BOSONS
SOUP

Relativistic Degrees of Freedom



Radiation-dominated Universe



$$\rho_{\mathrm{R}} = g_* \frac{\pi^2}{30} T^4 \qquad \Rightarrow \qquad H \simeq 1.67 g_*^{1/2} T^2 / m_{\mathrm{pl}}$$

$$R(t) \quad \propto \quad t^{1/2} \qquad\qquad T/\mathrm{GeV} \sim (t/10^{-6}\,\mathrm{sec})^{-1/2}$$

EVIDENCE for DARK MATTER

ITS GRAVITY IS:

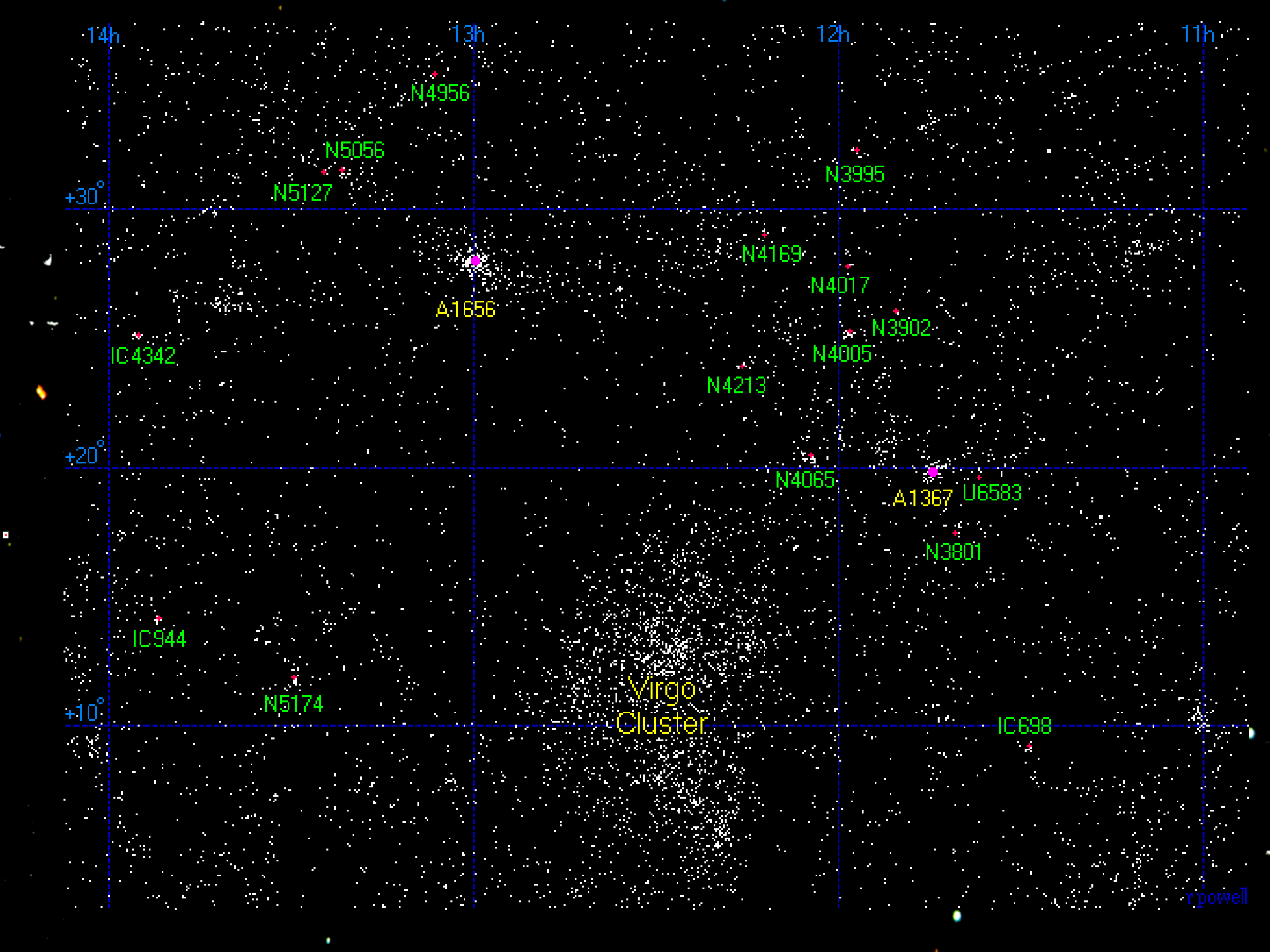
NEEDED TO HOLD GALAXIES TOGETHER

V. RUBIN ET AL '70s.

NEEDED TO HOLD CLUSTERS TOGETHER

ZWICKY '35

1935: Zwicky, Coma and Dark Matter



14h
13h
12h
11h
+30°
+20°
+10°
N4956
N5056
N5127
N3995
N4169
N4017
A1656
N3902
IC4342
N4005
N4213
N4065
A1367
U6583
N3801
IC944
N5174
Virgo Cluster
IC698
r powell

rms velocities ~ 1000’s km/s

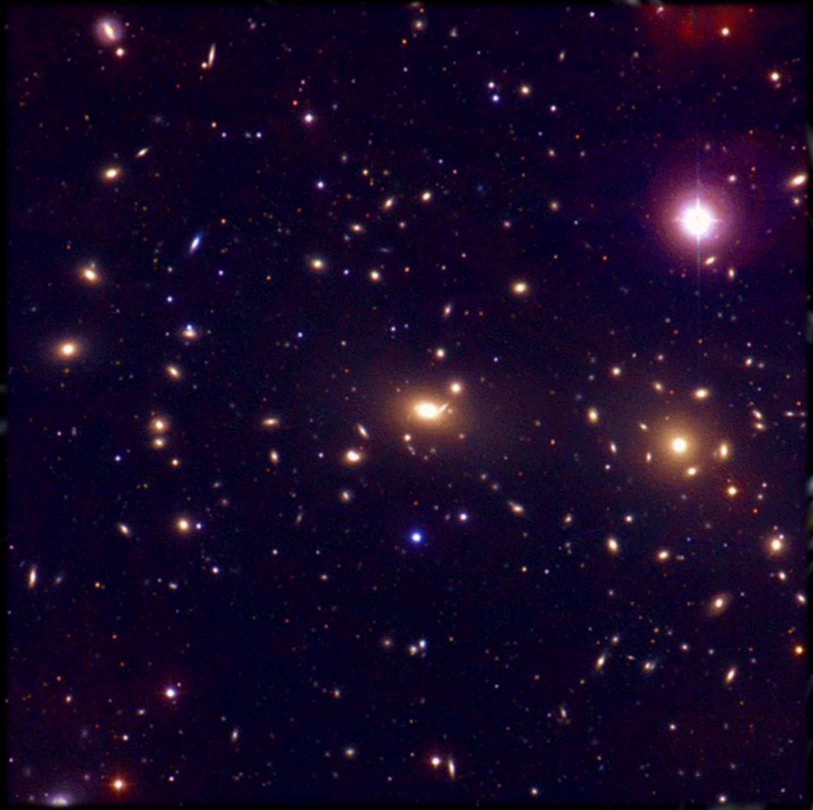
The Gravity of the Stars is not Enough to Hold Clusters Together (off by factor of 60)

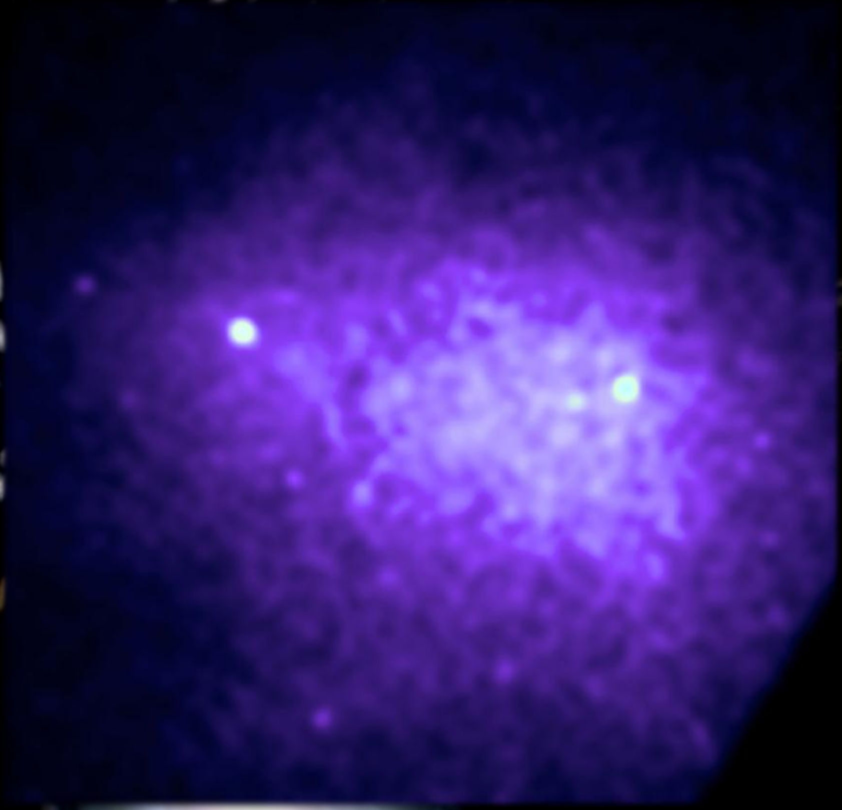
$$M_{grav} = R\langle v^2\rangle/G \gg M_{stars}$$

Clusters Must be Held Together by the Gravity of Unseen

“Dark Matter”

Coma Cluster of Galaxies

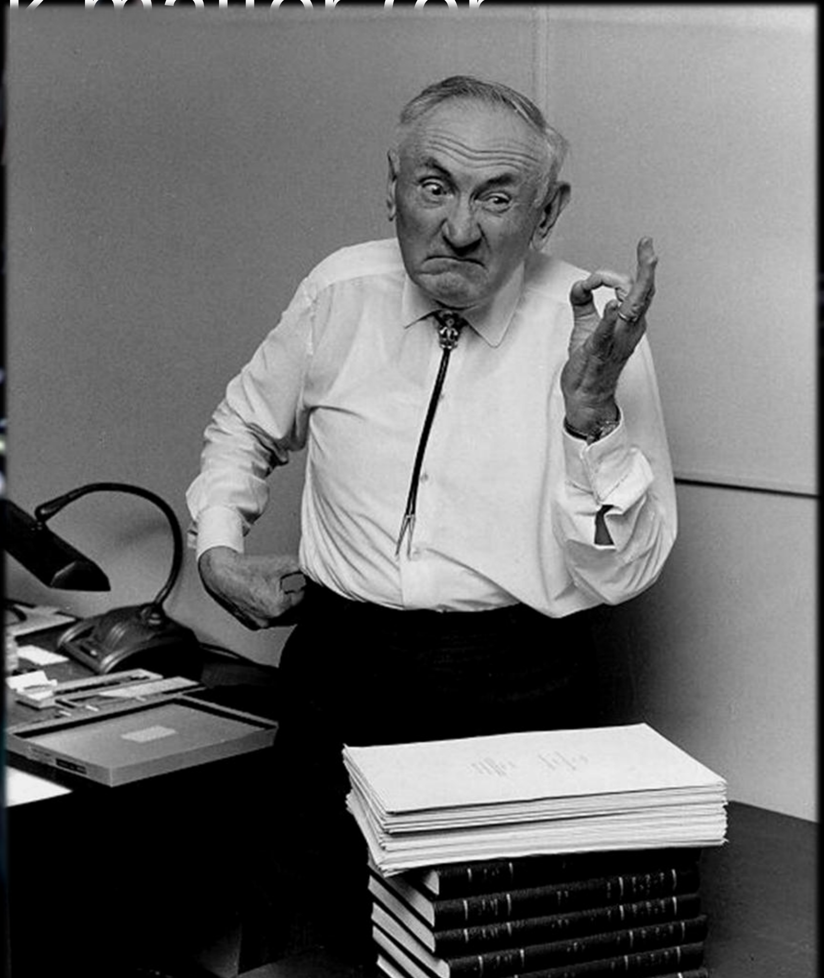




Hot gas accounts for 7x more than stars

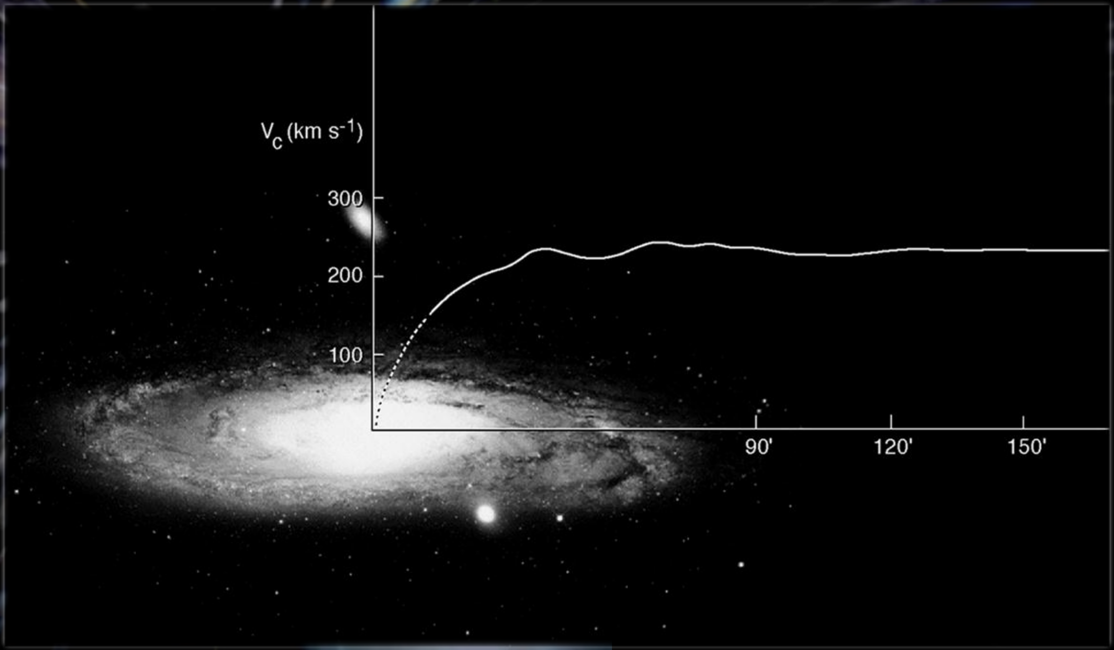
Still factor of 8x less than required dark matter

Cosmology was very young, clusters were new, and astronomy was not ready for dark matter (or most of Zwicky's

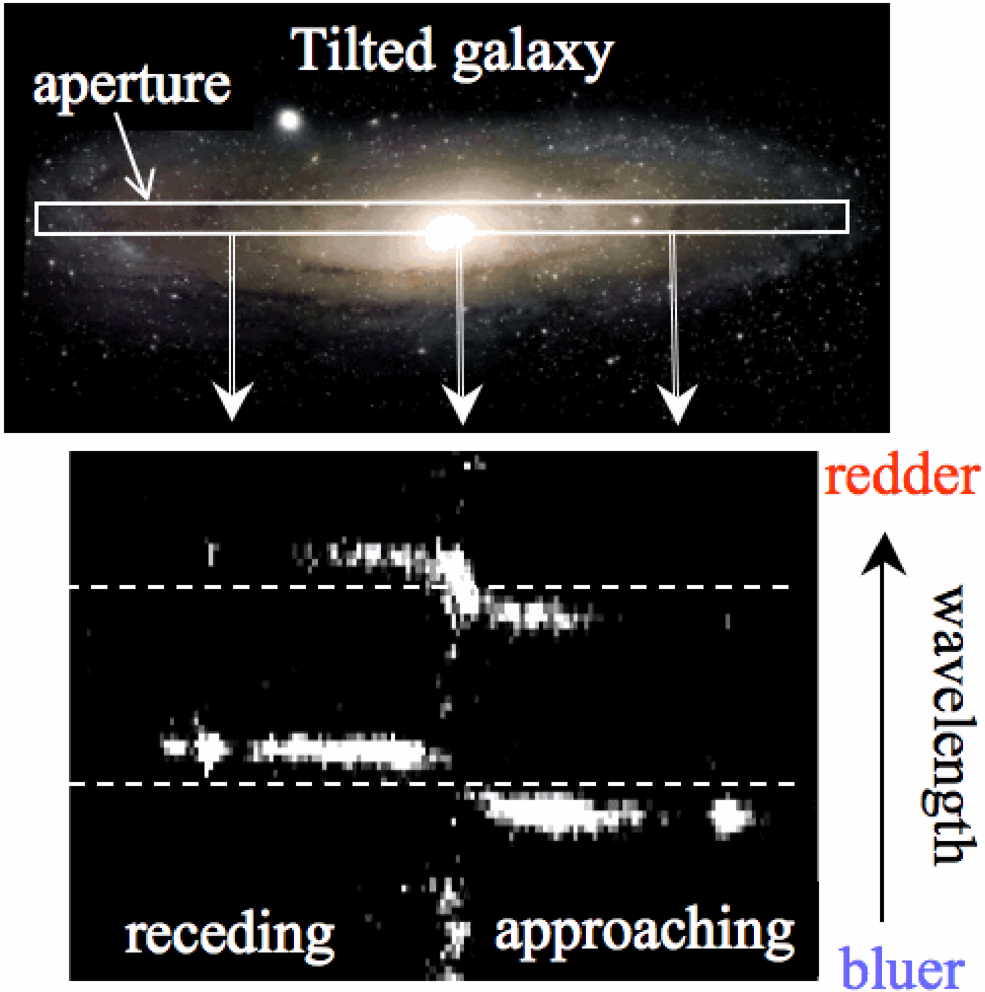


1970s: Vera Rubin and Flat Rotation Curves

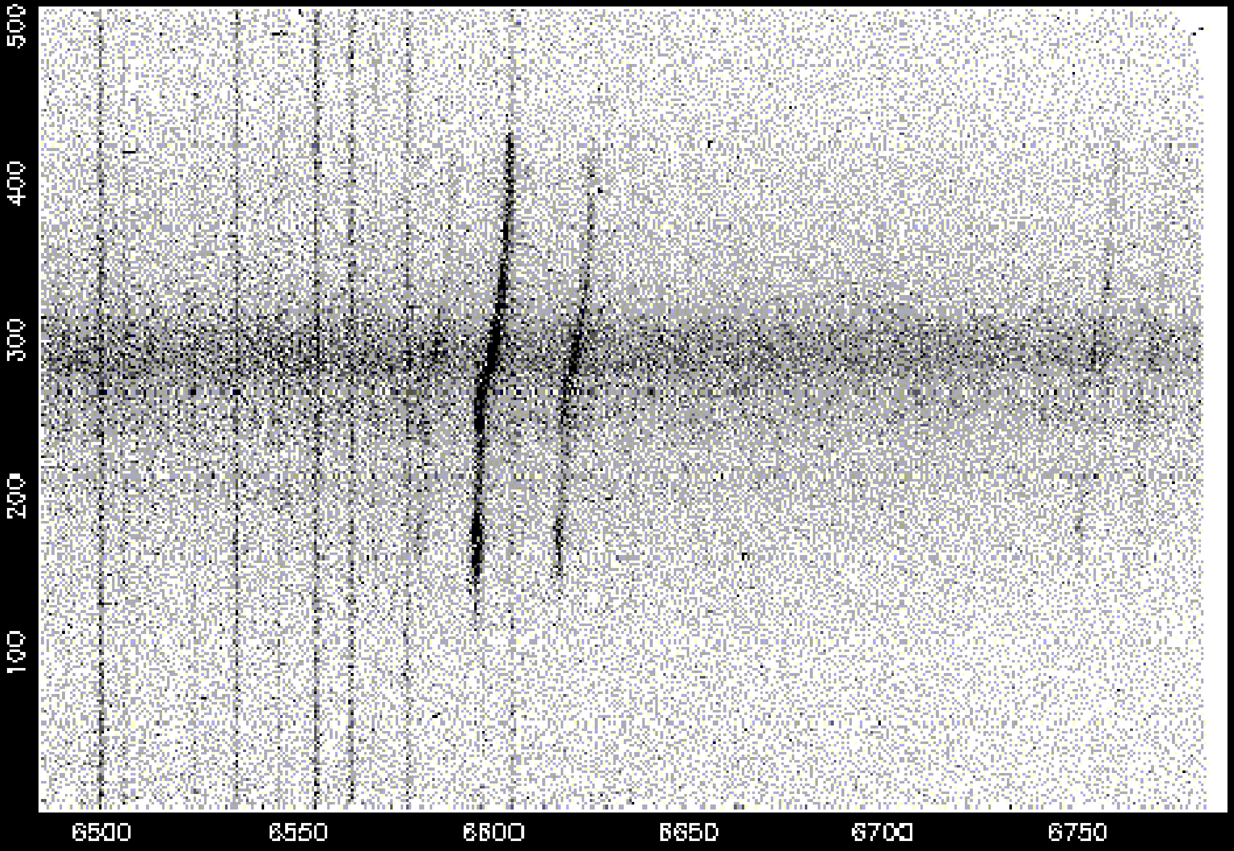
Dark Matter Close to Home



Vera Rubin measuring galaxy rotation curves (~1970)

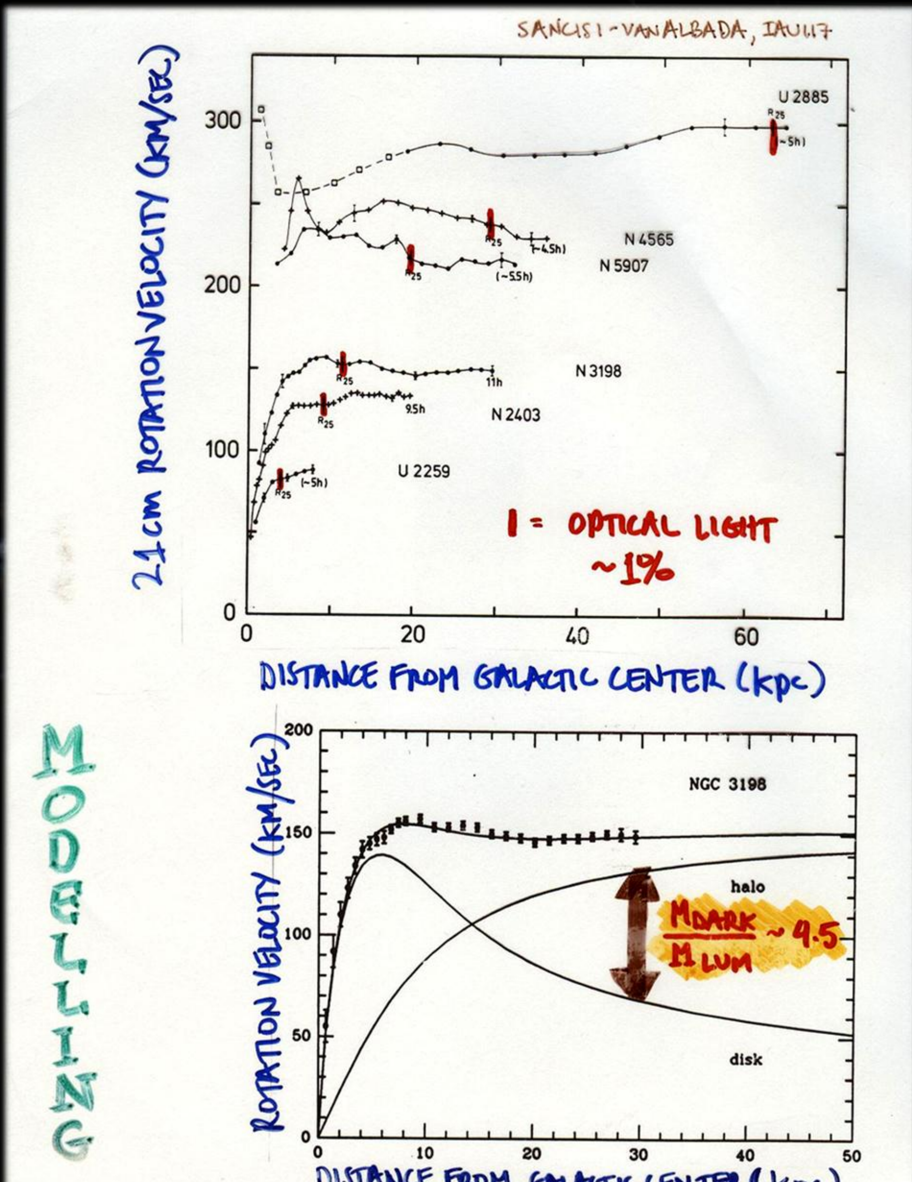


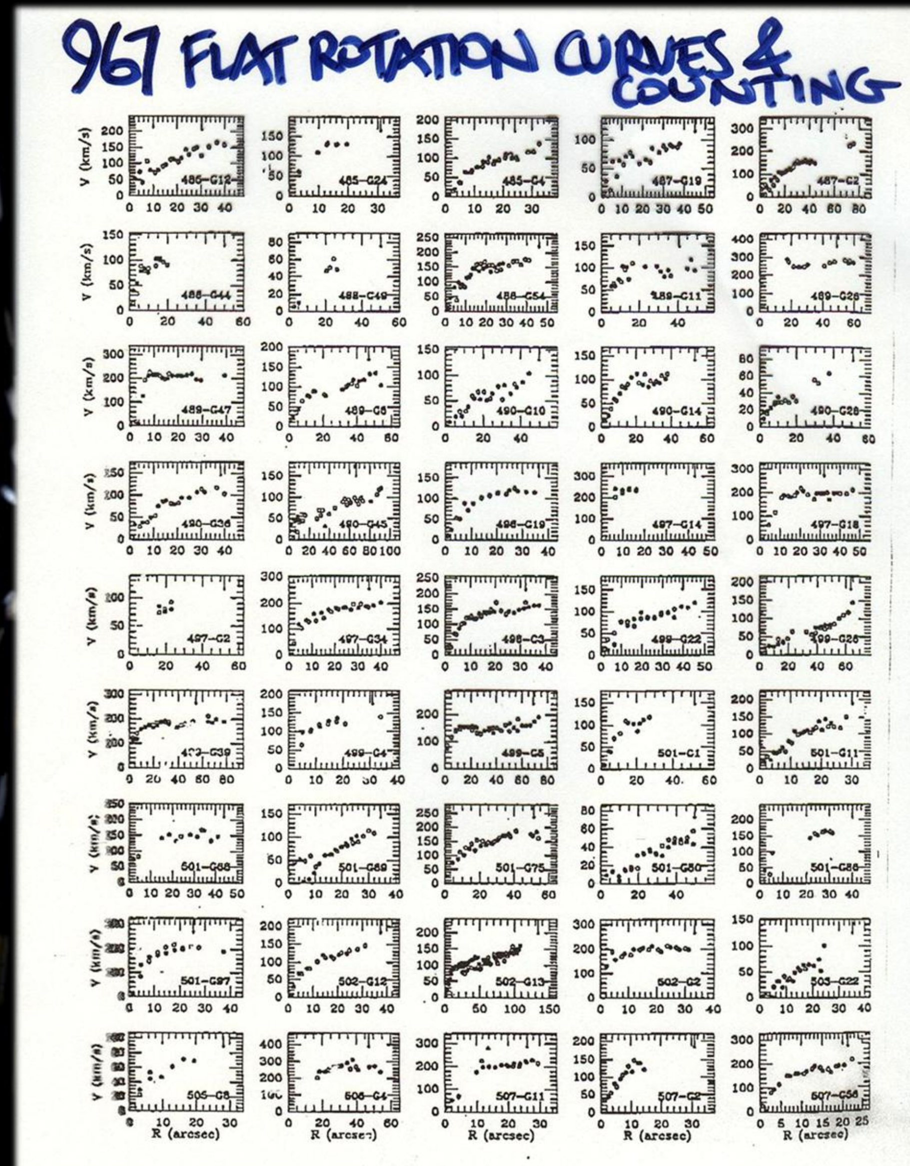
Resulting spectrum of light within aperture



500
400
300
200
100
6500
6550
6600
6650
6700
6750

1000s of Flat Rotation Curves!



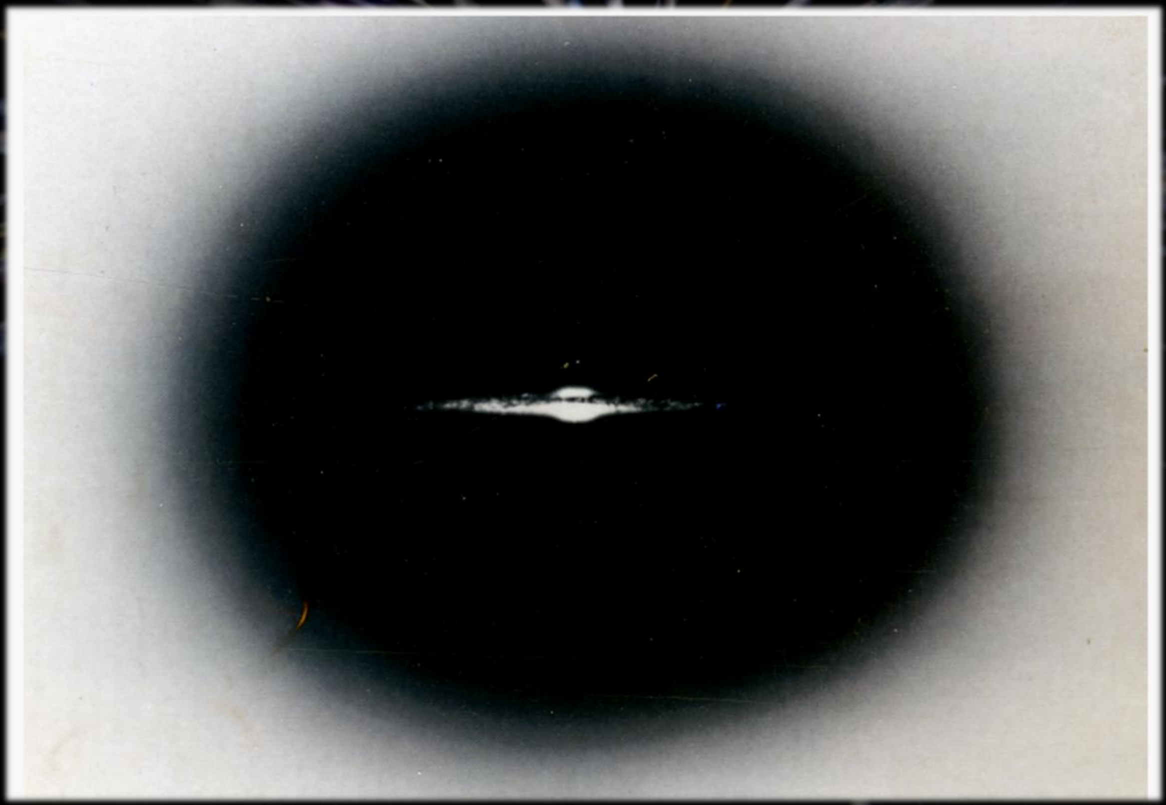


Flat rotation curves imply galaxies are immersed in giant halos with

$$\rho_{halo} \quad \alpha \quad 1/r^2$$

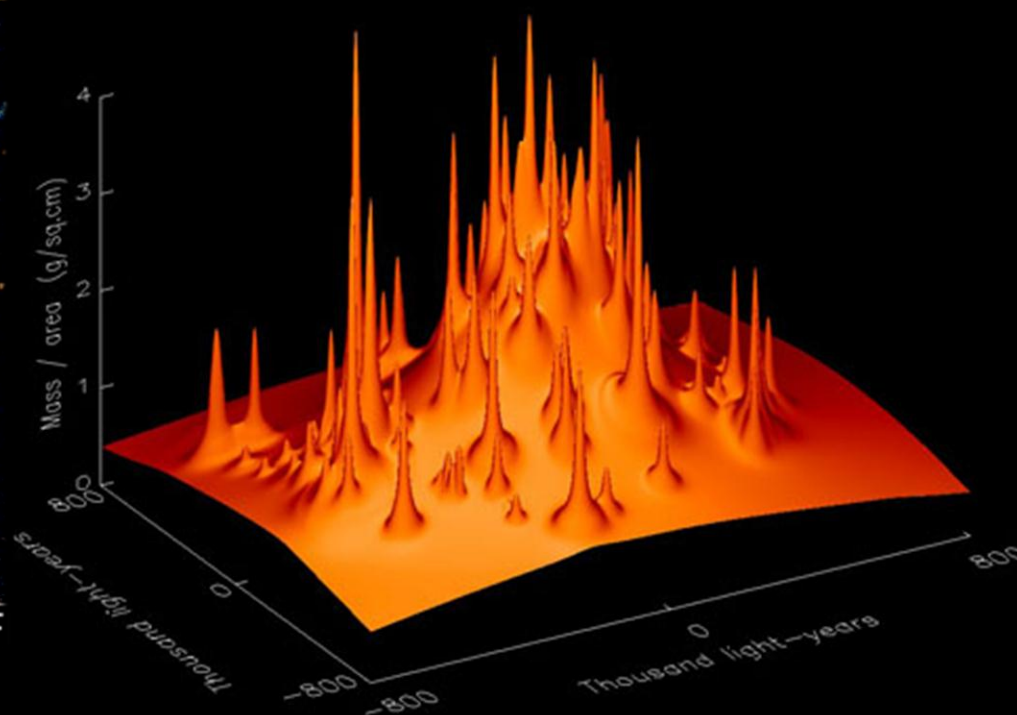
Local halo density: $0.9 \pm 0.3 \times 10^{-24}$ g/cm^3

(local disk density about 10x greater)



Mapping Dark Matter

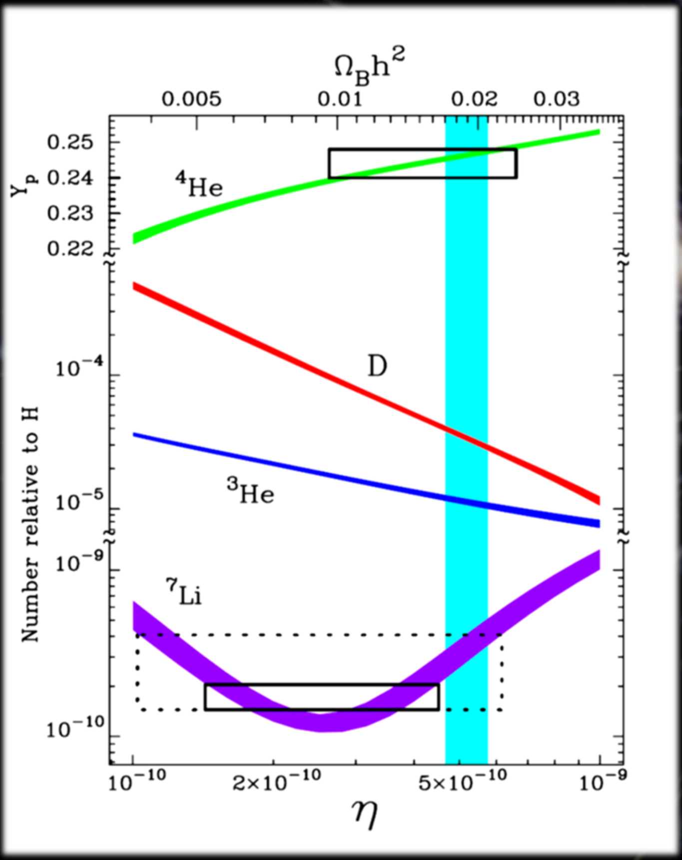
Gravitational Lens HST • WF
Galaxy Cluster 0024+1654
PRC96-10 • ST ScI OPO • April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA

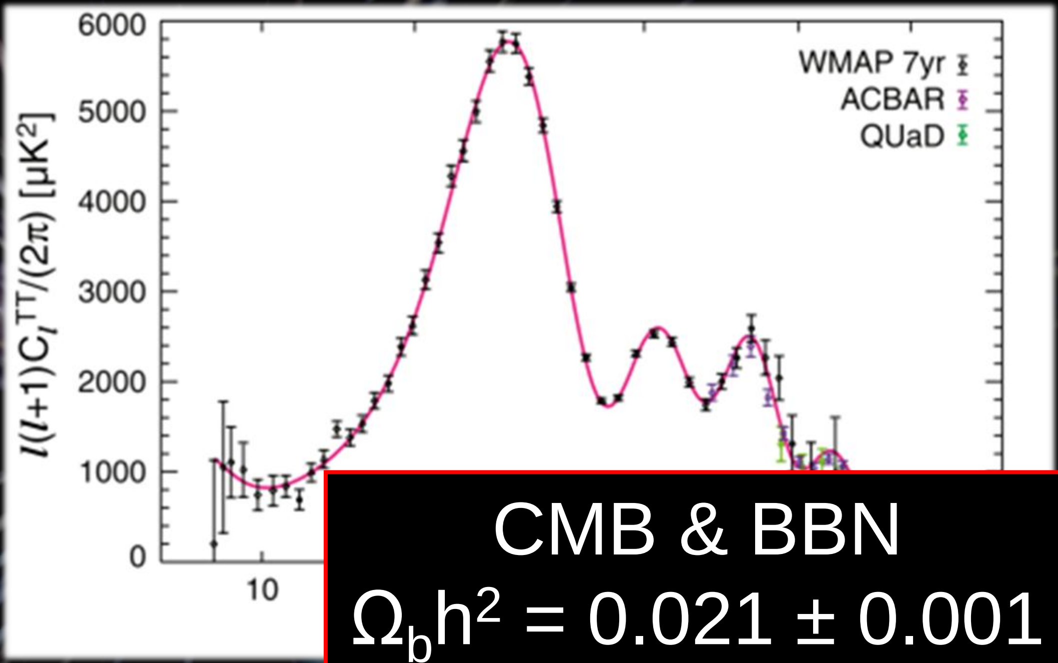


Overwhelming Evidence for Dark Matter

- Flat rotation curves of galaxies (galaxies have large, dark halos)
- Clusters are held together by dark matter (galaxy motions, lensing maps, x-ray gas)
- CMB/BBN census of stuff in the Universe (20 σ)
- Without gravity of dark matter cannot make observed structure
- CDM has most of the truth

Airtight Evidence for Nonbaryonic Dark Matter





CMB & BBN

$\Omega_b h^2 = 0.021 \pm 0.001$

vs.

CMB/SDSS

$\Omega_M h^2 = 0.13 \pm 0.005$

<u>20σ discrepancy</u>

Dark Numbers

- Stars: ~0.5%
- Atoms: 4.5 ± 0.2%
- Dark Atoms: ~4% (90% of atoms)
- Exotic Dark Matter: 23 ± 1.5%
- Neutrinos: 0.1% to 2%

…. the rest is dark energy

Clusters: Nature's Fair Sample

What Astrophysics Tells Us About Dark Matter

- Need for DM comes at different length scales (constant $a = v^2/r \sim H_0$ – Milgrom Miracle)
- Less concentrated → weakly interacting (uncharged) particles
- Cold (small velocity dispersion) – structure formation
- Non baryonic (accounting + don't see it)
- "Isothermal halo" – $\rho \propto 1/r^2$ with $\langle v^2 \rangle \sim (270\ \text{km/s})^2$

Big Surprise? – No Dark Matter

ASTRONOMY

Seeing Through Dark Matter

Stacy McGaugh

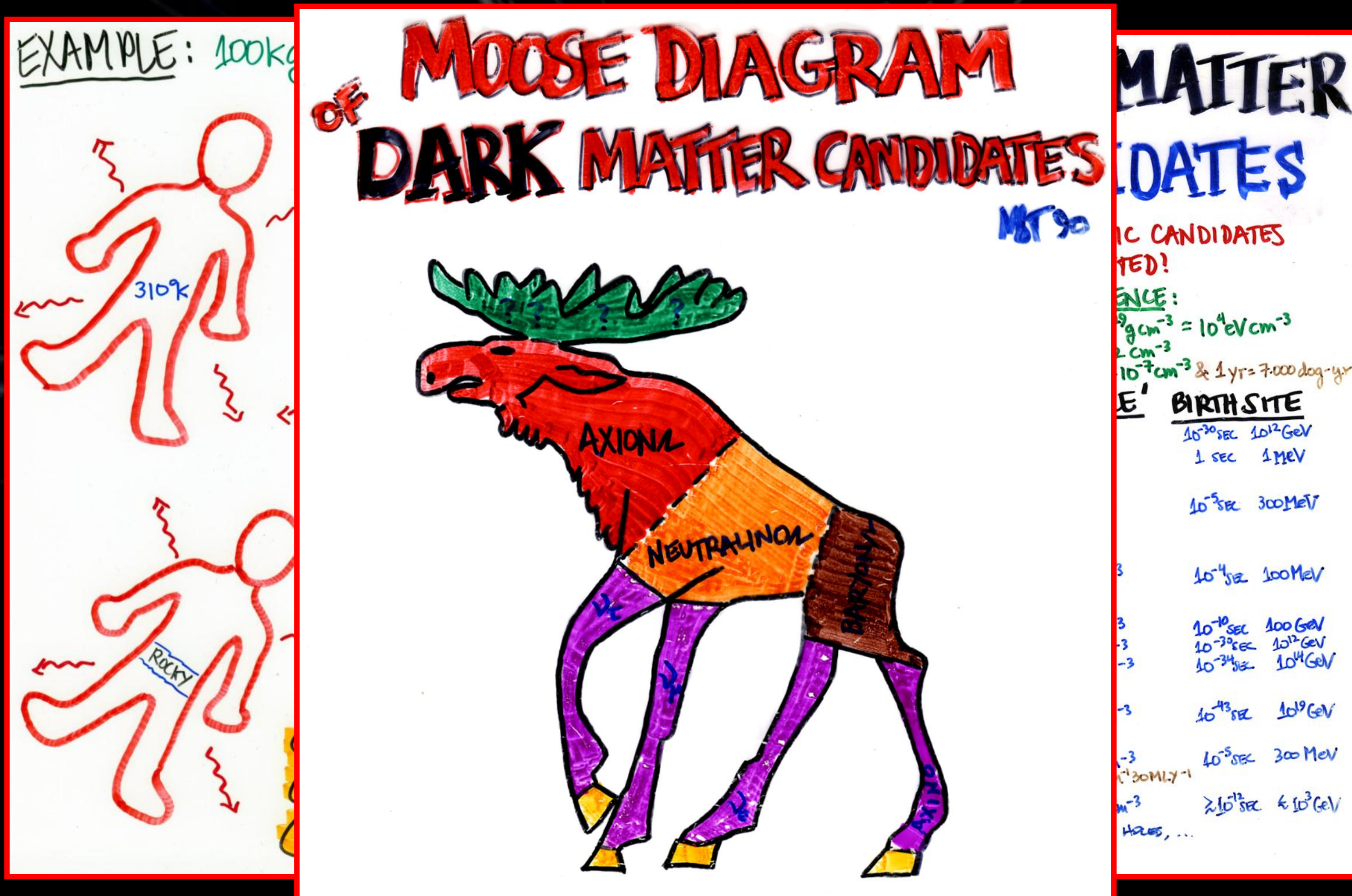
If MOND is Right I'll Eat My Powerpoint (laptop included)!

This lack of corroboration, con... increasing complexity and "prepo... nature of a once simple and elegant cosmology, leads one to wonder if perhaps instead gravity is to blame.

Simply changing the force law on some large length scale does not work (2). One

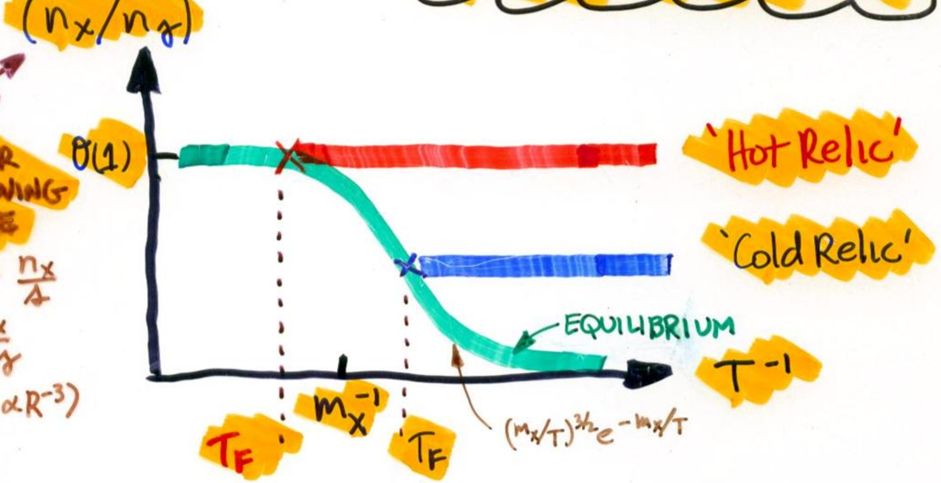
...case after case, MOND ...maps the observed mass to the observed dynamics. Why would such a direct mapping exist between visible and total mass if in fact dark matter dominates? Moreover, MOND's explicit predictions for low surface brightness galaxies have been realized (5). In contrast, the dark matter par-

Dark Matter Candidates



THERMAL RELICS

EARLY UNIVERSE WAS VERY HOT ⇒ ALL KINDS OF EXOTIC PARTICLES WE STRUGGLE TO PRODUCE WERE PRESENT IN GREAT ABUNDANCE



NUMBER PER COMOVING VOLUME

$n_X R^3 = \frac{n_X}{s} \simeq \frac{n_X}{n_\gamma}$

(Recall $s \propto R^{-3}$)

★ EQUIL. ABUNDANCE MAINTAINED WHEN

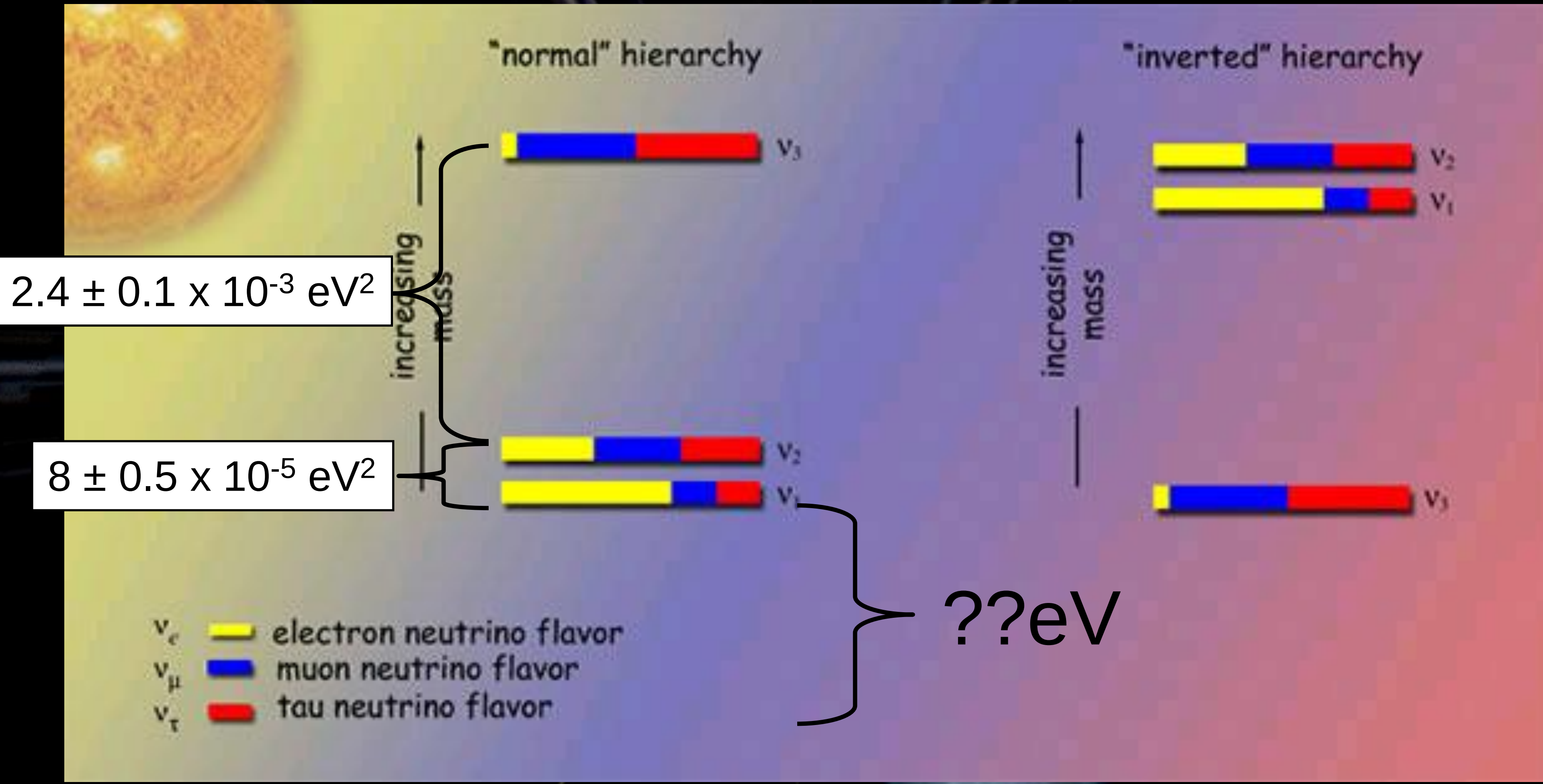
$$\Gamma_{\substack{\text{creation}\\ \text{annihilation}}} \gtrsim H = |\dot{T}/T|$$

★ "FREEZE OUT": $\Gamma(T_F) \simeq H(T_F)$

thereafter: $(n_X/n_\gamma) \simeq (n_X/n_\gamma)|_{T_F}$

HOT: $T_F > m_X \Rightarrow \left(\frac{n_X}{n_\gamma}\right) \simeq \mathcal{O}(1)$ COLD: $T_F < m_X \Rightarrow \left(\frac{n_X}{n_\gamma}\right) \simeq \left(\frac{m_X}{T_F}\right)^{3/2} e^{-m_X/T_F} \ll 1$

Neutrinos have mass!



Neutrinos and Cosmology

Relic abundance, lab measurements, and cosmology imply

$$n_{\nu\bar{\nu}} = 113\,\mathrm{cm}^{-3}\ \text{per species}$$

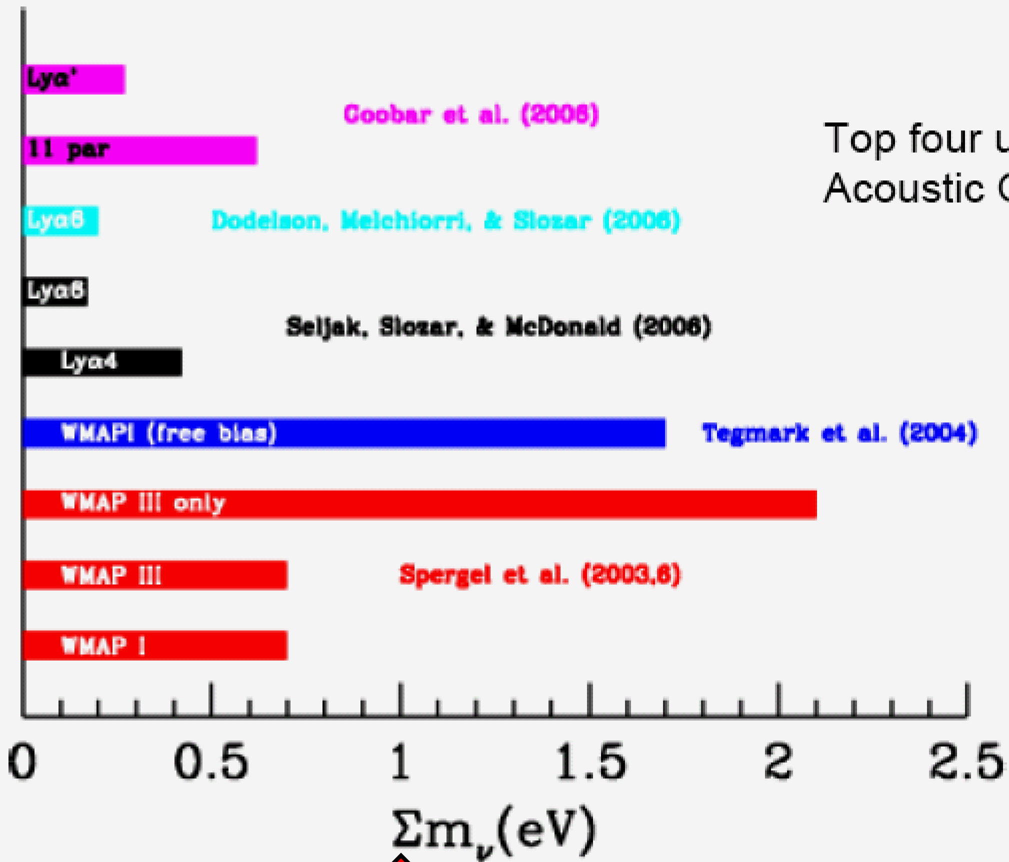
$$\Omega_\nu = \frac{\sum_i m_i}{91 h^2\,\mathrm{eV}}$$

$m_{\nu_e} < 2.2\,\mathrm{eV}$ (Mainz) $\quad m_{21}^2 \simeq 8 \times 10^{-5}\,\mathrm{ev}^2 \quad m_{23}^2 \simeq 3 \times 10^{-3}\,\mathrm{eV}^2$

0.13 (direct) > 0.02 (structure) $> \Omega_\nu > 0.001$

Neutrinos are a cosmic spice, but more importantly a “proof of principle “

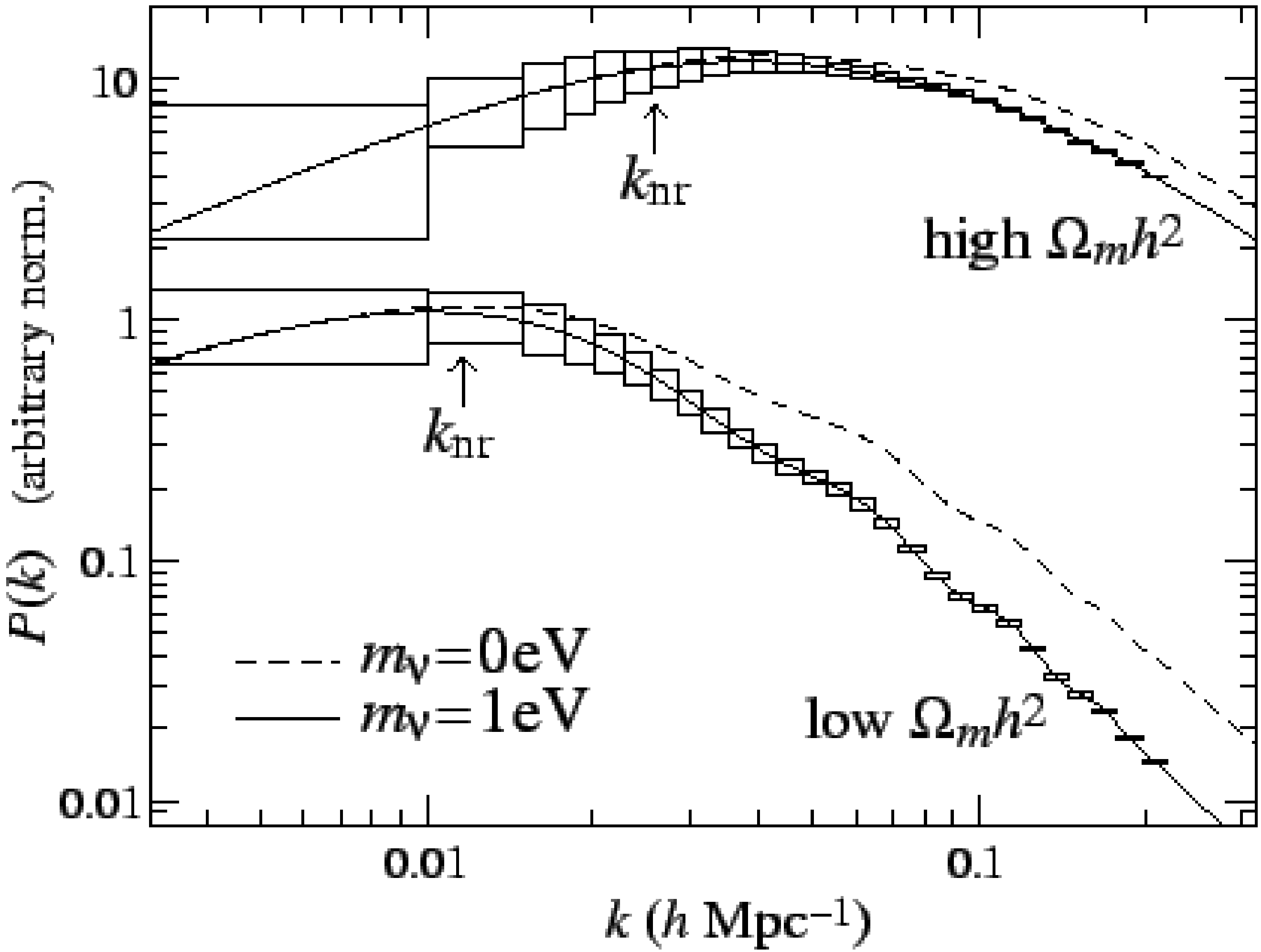
Neutrino Mass constraints are typically sub-eV



Top four use Baryon Acoustic Oscillations

$\Omega = 0.02$

Neutrinos suppress power on small scales



Origin of WIMP™ Dark Matter: Incomplete Annihilation

Thermal Equilibrium

T >>

phot

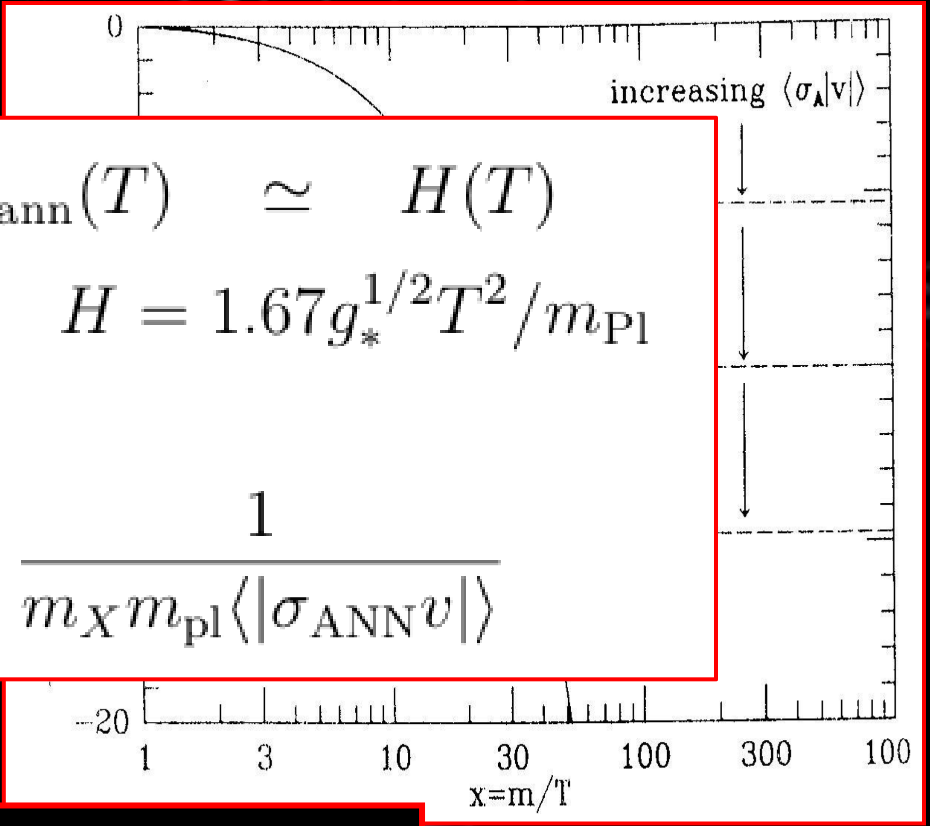
T <<

rare

… bu

incor

abundance:



$$\textbf{Freeze Out :} \quad \Gamma_{\rm ann}(T) \simeq H(T)$$

$$\Gamma_{\rm ann} = n_{\rm EQ}\langle|\sigma_{\rm ANN} v|\rangle \qquad H = 1.67 g_*^{1/2} T^2 / m_{\rm Pl}$$

$$\Rightarrow (n_X/n_\gamma)_{\rm F} \sim \frac{1}{m_X m_{\rm pl}\langle|\sigma_{\rm ANN} v|\rangle}$$

WIMP Miracle

$\Omega \sim 0.3$ for $\sigma v \sim 10^{-36}$ cm^2

The WIMP Miracle

big hint or misdirection

- $\Omega \sim 0.3$ for $\sigma \sim 10^{-36}$ cm^2

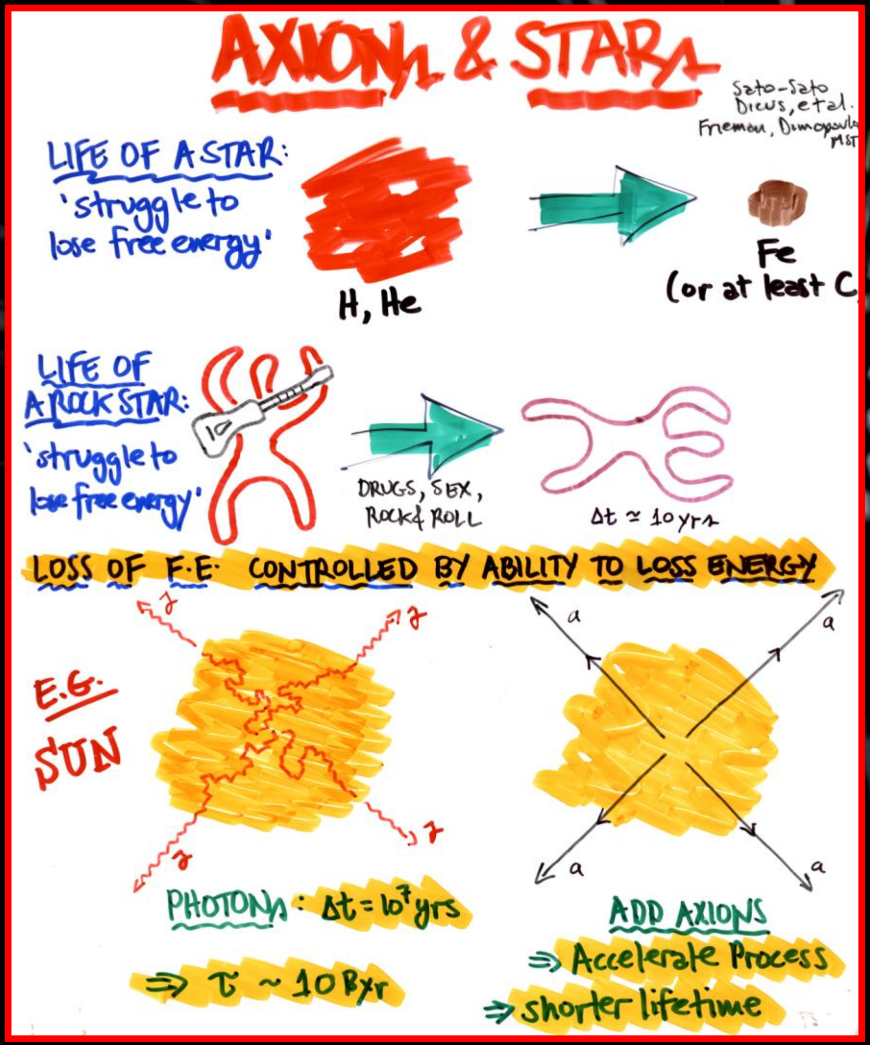
- This implies weak production cross section (at accelerator), weak scattering in matter (direct detection), and weak annihilation rate (indirect detection)

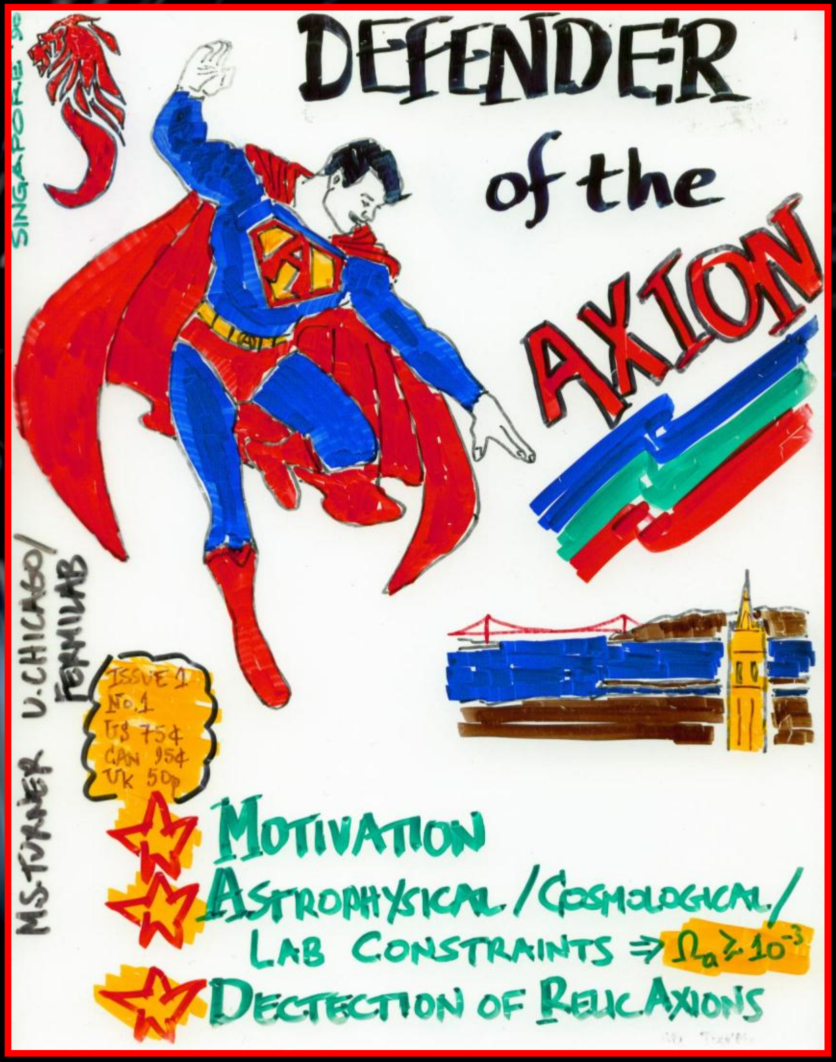
- → Decade of the WIMP!

Full Court Press!!

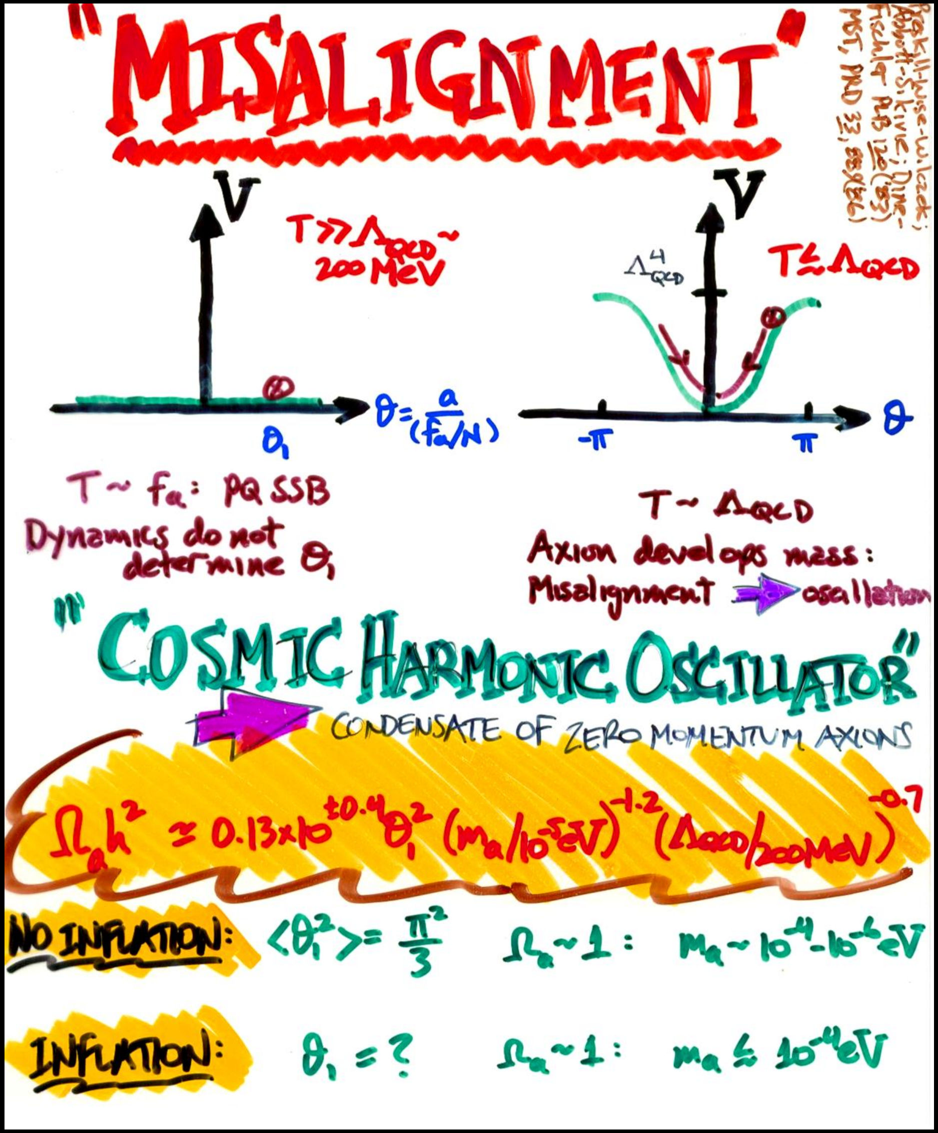
- Produce at LHC
- Detect particles in our halo
- Detect annihilation products

The neutralino is very attractive, but don't forget the axion



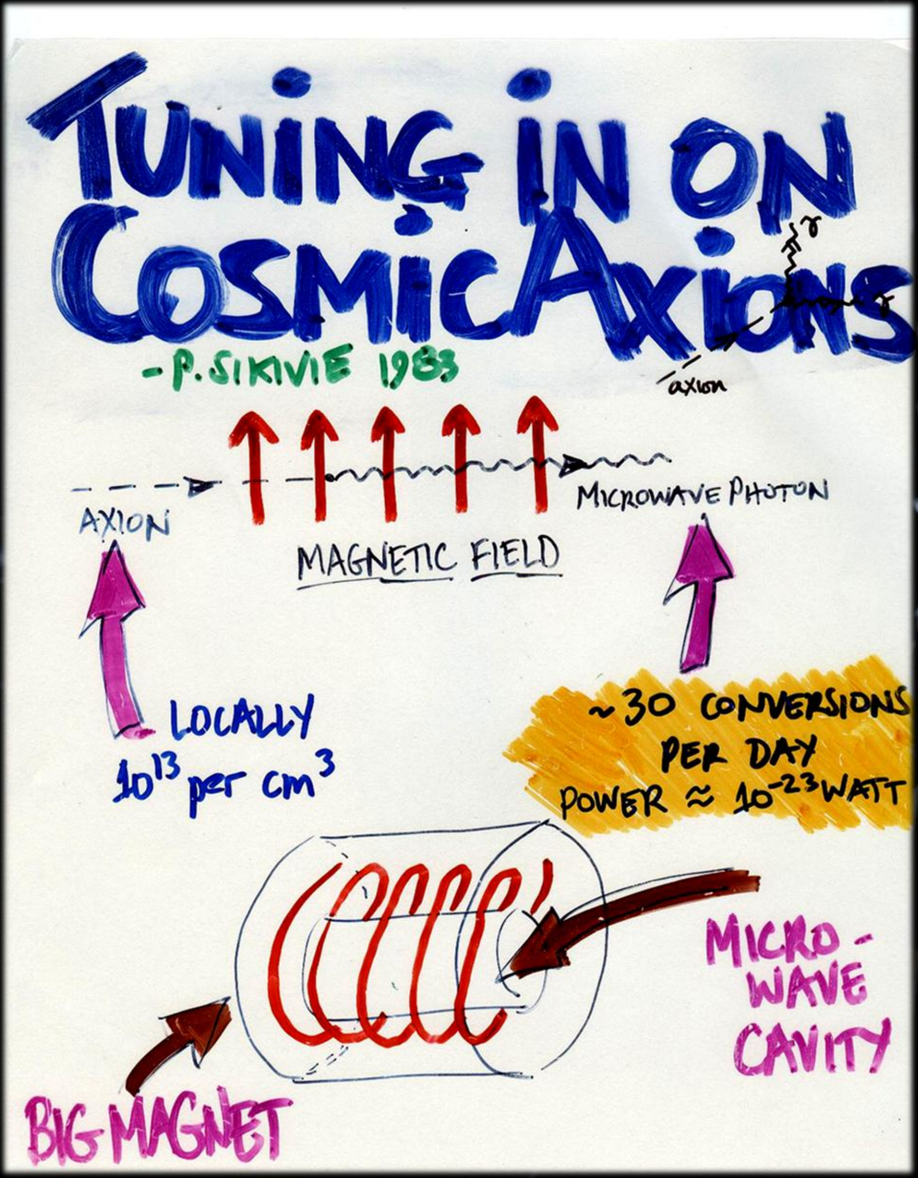


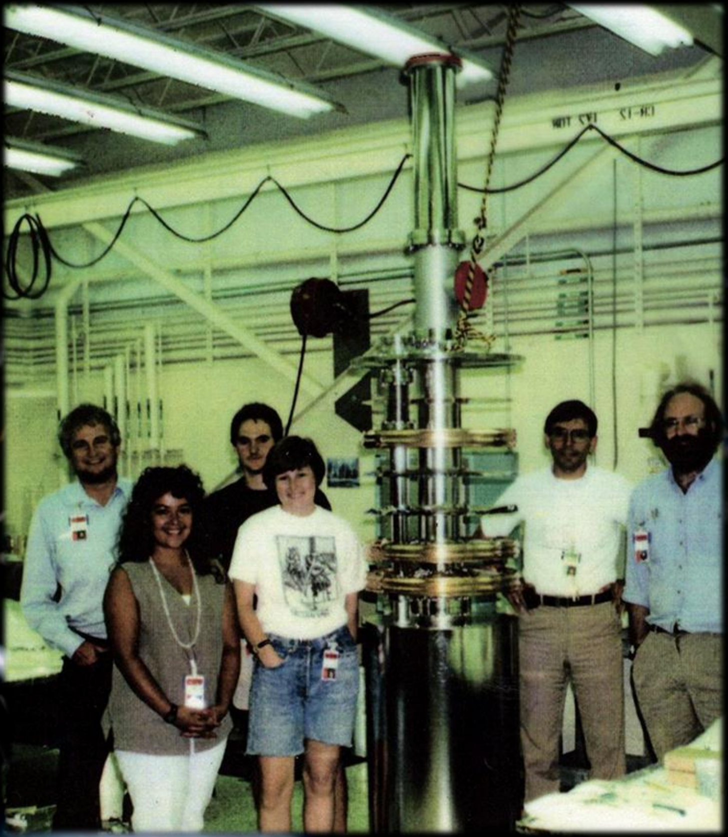
Axion non thermal production

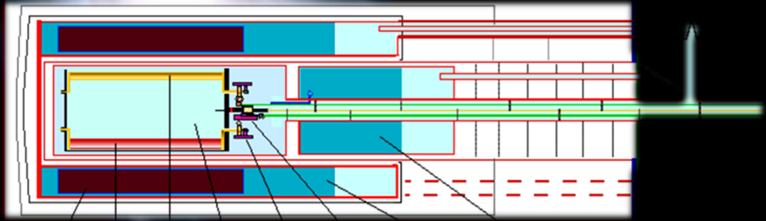


Axion = almost massless N-G boson of PQ symmetry; acquires small mass due to chiral symmetry breaking (QCD effects)

Detecting Cosmic Axions

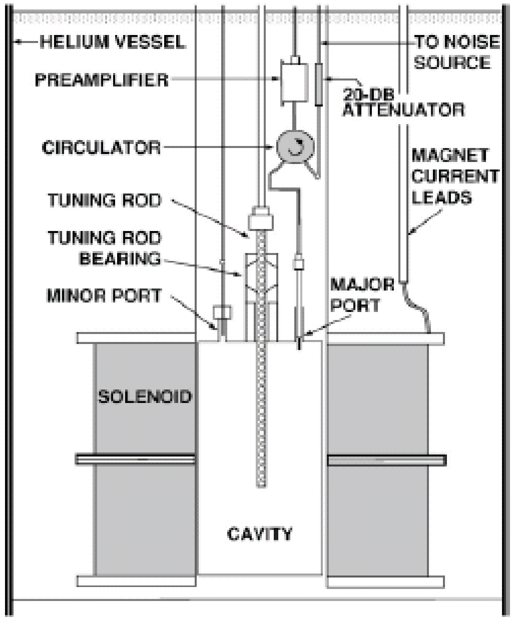




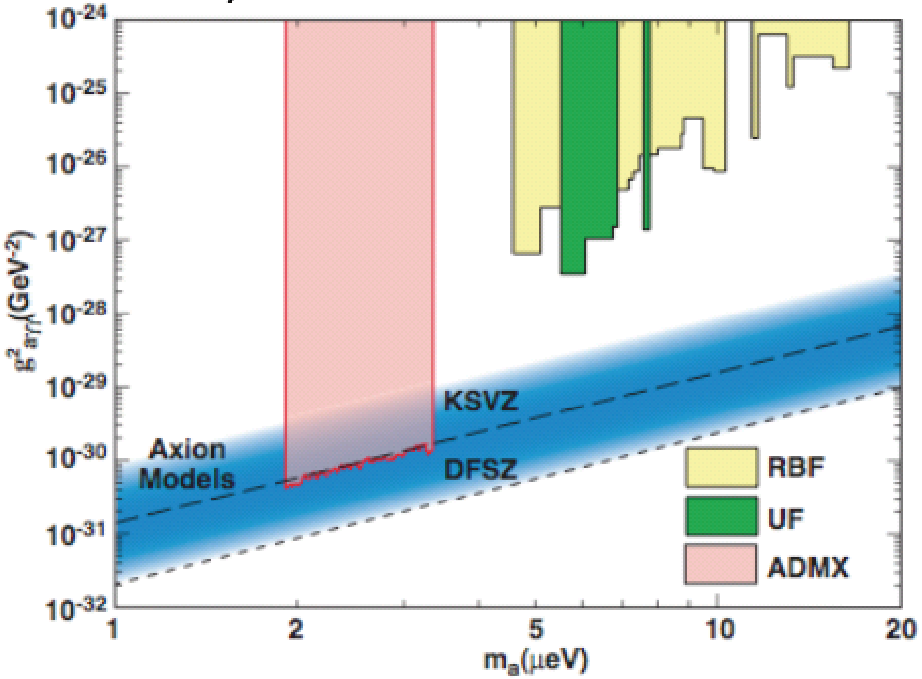


ADMX performed as designed – scanned in the model band

From W. Wuensch *et al.*,
Phys. Rev. D40 (1989) 3153



PRL 80 (1998) 2043
PRD 64 (2001) 092003
PRD 69 (2004) 011101(R)
ApJ Lett 571 (2002) 27



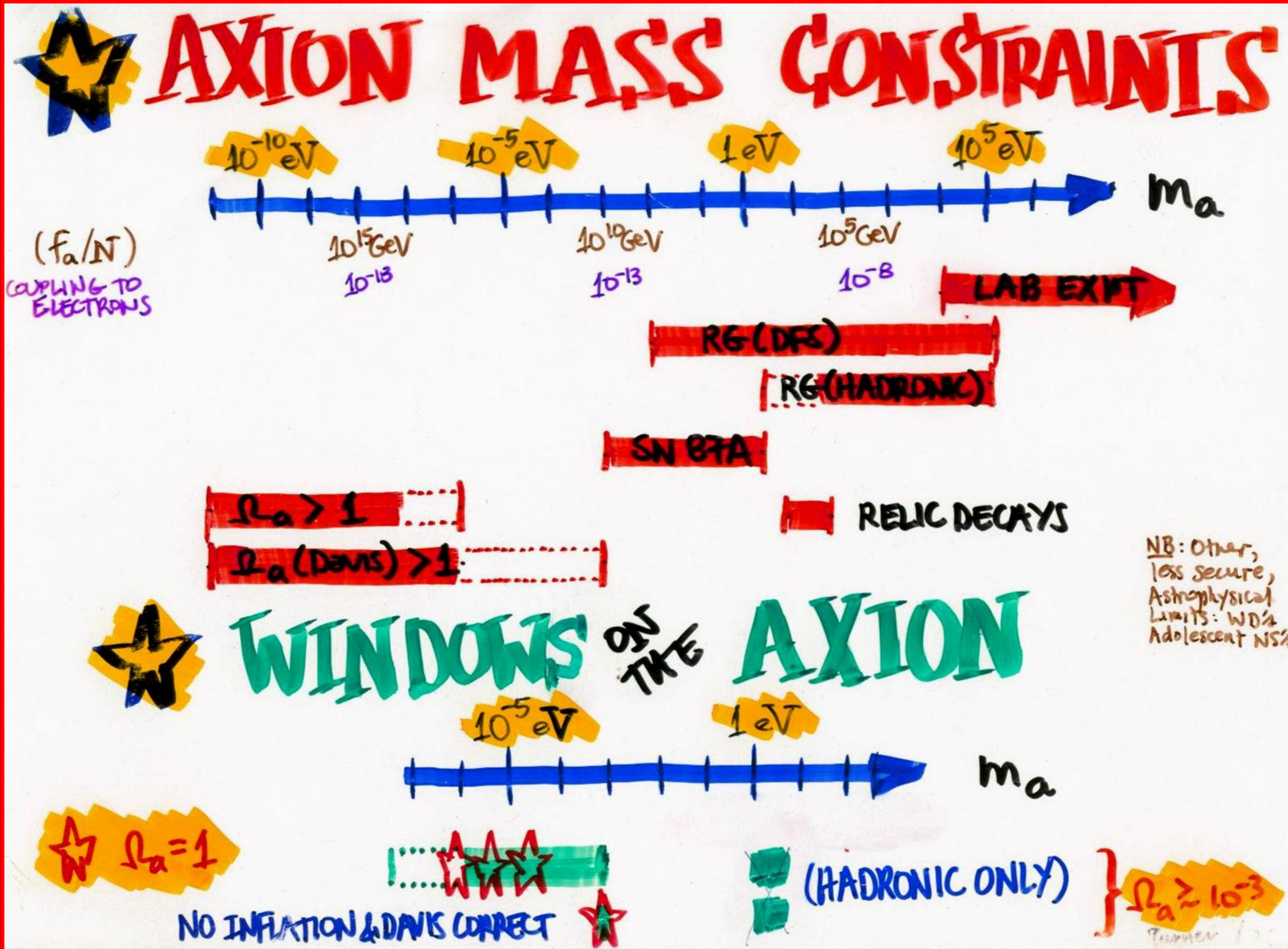
We learned much from the first-generation exp'ts (~ liter volume)
Already came within a factor of 100-1000 of the desired sensitivity

Lecture 1 take homes

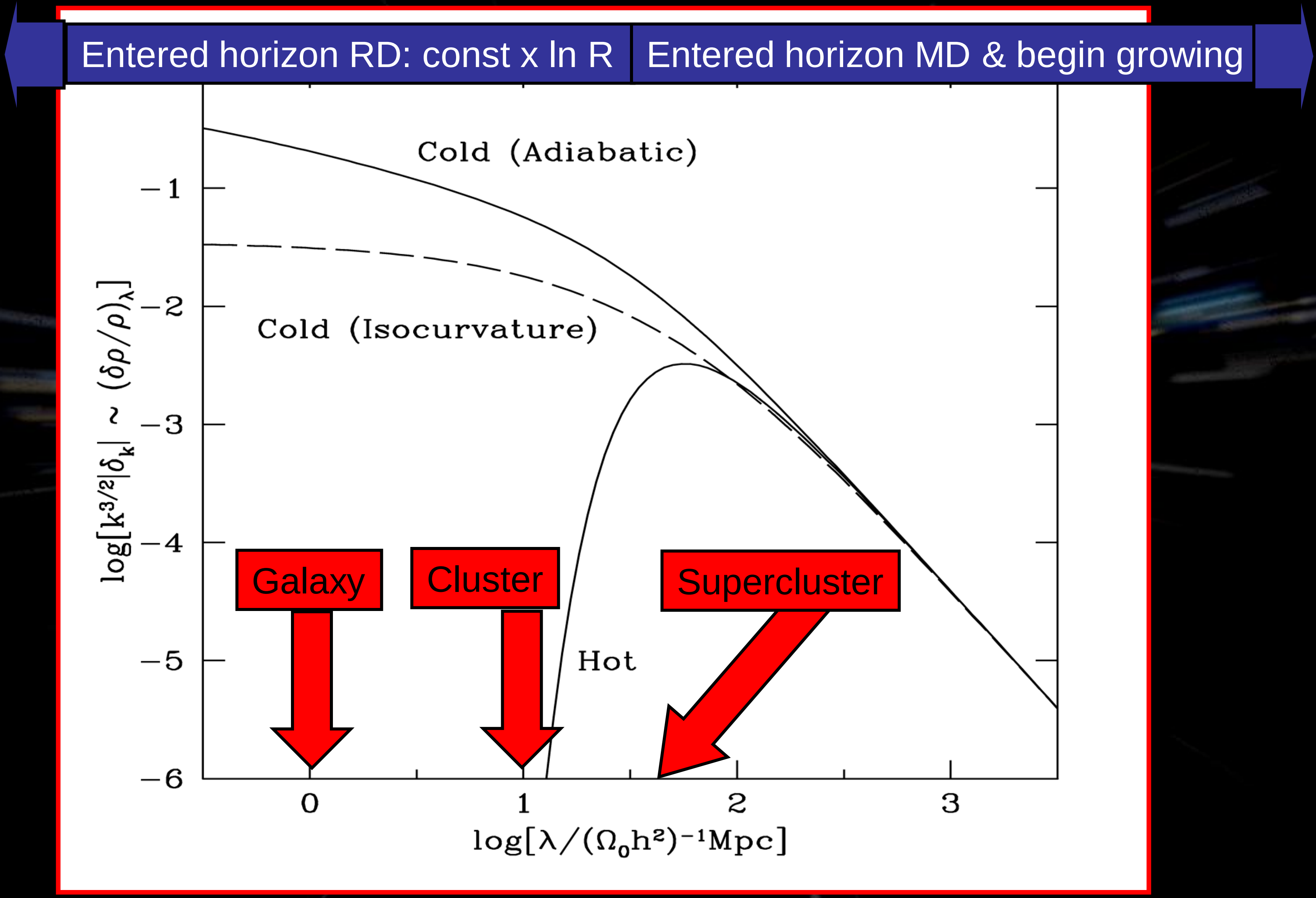
- Consensus cosmology requires dark matter and dark energy
- Precision cosmology is not an oxymoron
- Redshift: stretching by expansion
- Friedmann equations
- Three cosmic epochs
- 20 sigma evidence for non-baryonic dark matter (CMB/LSS/BBN)
- Early universe production of dark matter and WIMP miracle
- Dark matter right here! (~10^{-24} g/cm^3)
- And don’t forget the axion

The Dark Matter Decade

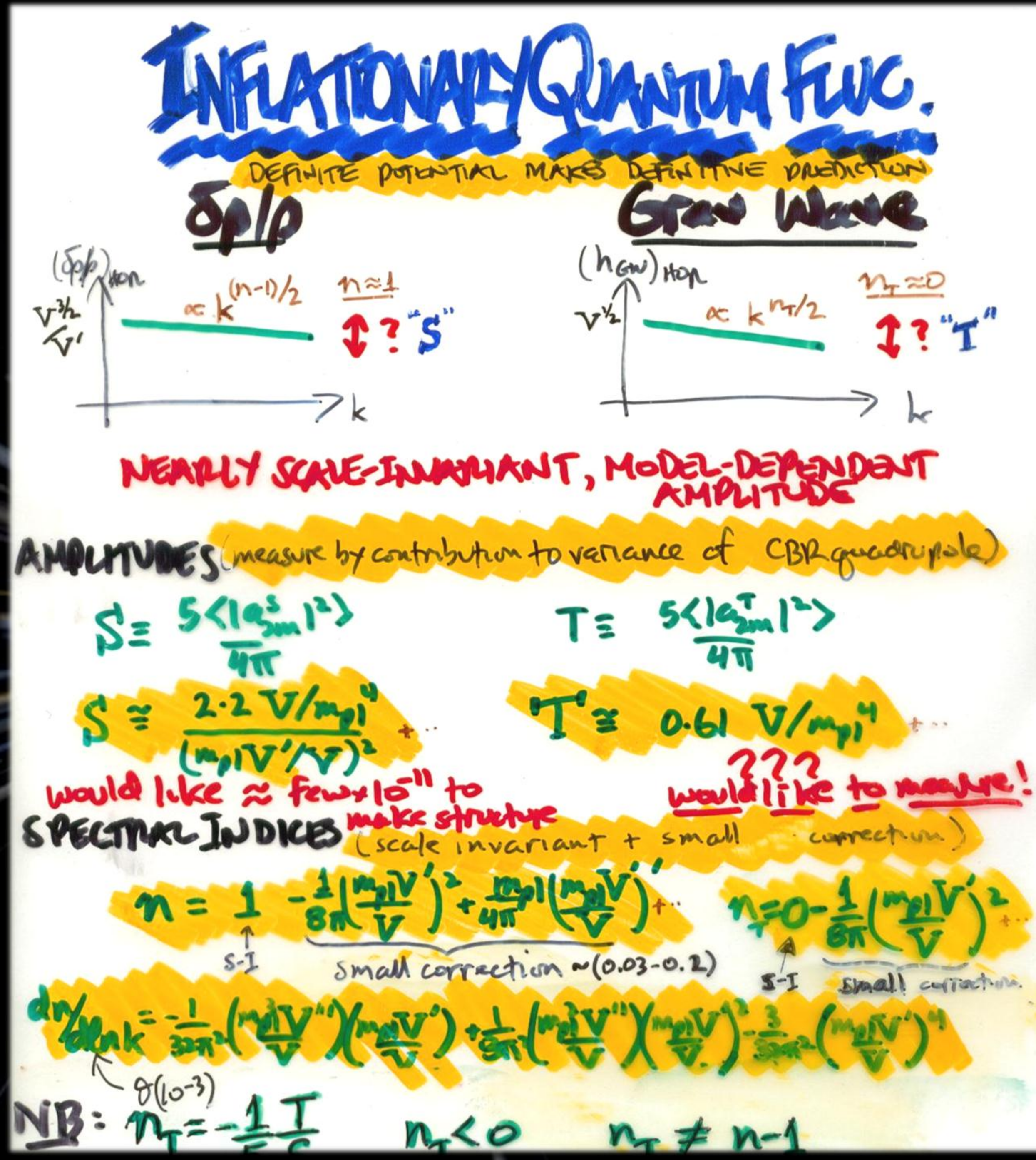
- Hints (and distractions) in the air: Pamela (TeV), WMAP Haze, ATIC, CDMSII; FGST, CRESST, CoGeNT and DAMA (10 GeV)
- New capabilities: LHC, Xenon100, Fermi, COUPP50, SuperCDMS …
- Prediction: "WIMP™ hypothesis (thermal relic, mass < 1 TeV) will tested this decade"


AXION MASS CONSTRAINTS
10^{-10} eV
10^{-5} eV
1 eV
10^{5} eV
m_a
(f_a/N)
10^{15} GeV
10^{10} GeV
10^{5} GeV
COUPLING TO ELECTRONS
10^{-18}
10^{-13}
10^{-8}
LAB EXPT
RG (DFS)
RG (HADRONIC)
SN 87A
$\Omega_a > 1$
Ω_a (Davis) > 1
RELIC DECAYS
NB: Other, less secure, Astrophysical Limits: WD's Adolescent NS's
WINDOWS ON THE AXION
10^{-5} eV
1 eV
m_a
$\Omega_a = 1$
(HADRONIC ONLY)
$\Omega_a \gtrsim 10^{-3}$
NO INFLATION & DAVIS CORRECT

Inflationary Spectra

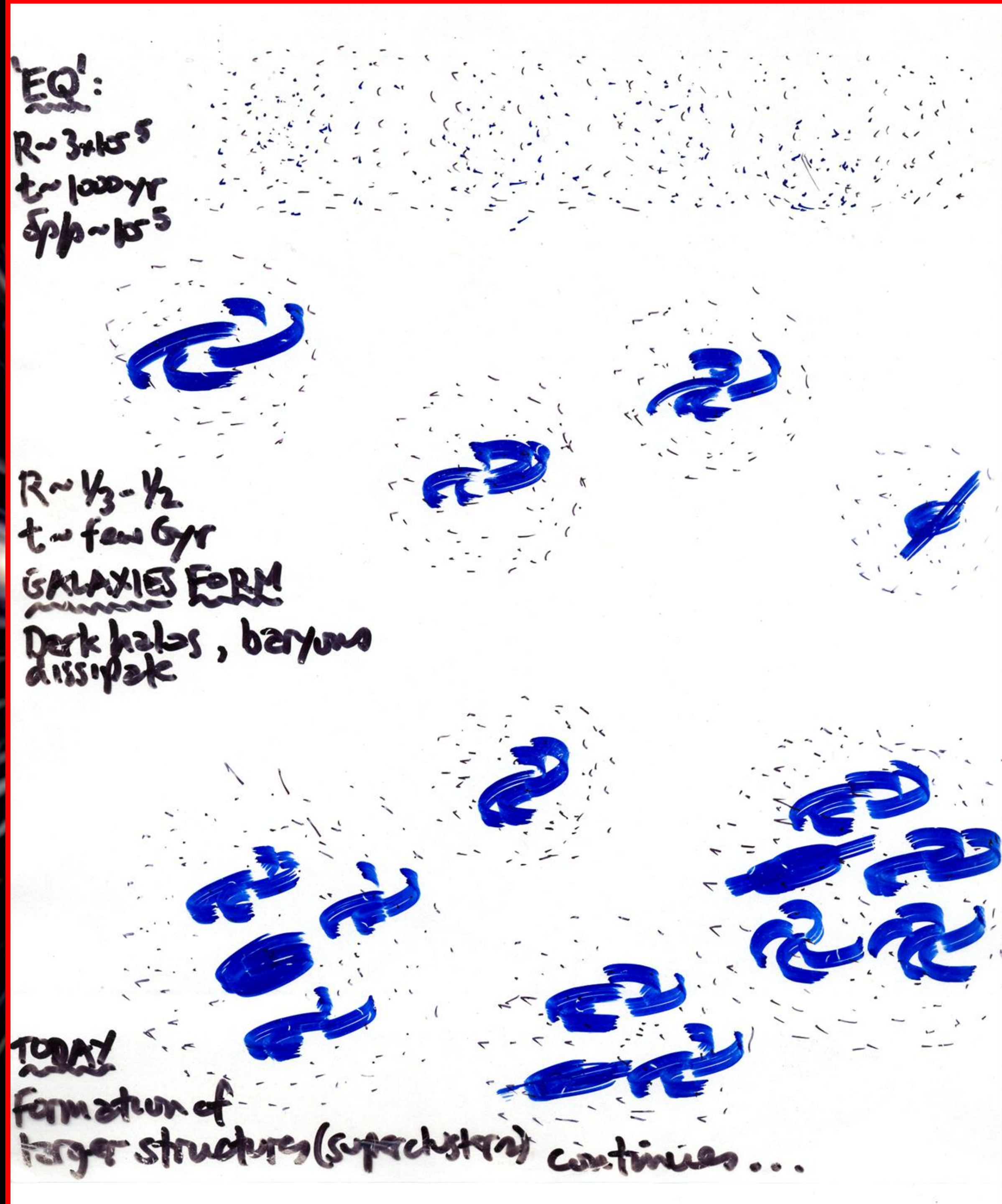


Given scalar potential V(φ), can compute all observables in terms of V, V’ and V’’



Structure Forms From the Bottom Up:

First Stars (z ~ 10 -20)
Galaxies (z ~ 2 – 5),
Clusters (z ~ 0 - 2), and
Superclusters (z ~ 0)



Summary of Tests of CDM Power Spectrum