Cosmic Relics:
The nearly thermal universe

Albert Stebbins

Academic Lecture Series

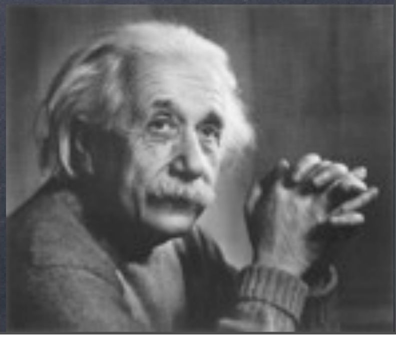
Fermilab 2014-03-04

Some Guiding Principles

- "If you have to guess a number, guess zero, if you can't guess zero guess one." – Frank Shu

More Guiding Principles

- “The hardest thing to understand about the universe is how easy it is to understand.”
- paraphrase of “The most incomprehensible thing about the world is that it is at all comprehensible” - A. Einstein
- Is this a “selection effect”? Maybe we only understand things which are easy to understand?
- The Cosmic Microwave Background is (relatively) easy to understand.



Cosmology 101

AGE OLD QUESTIONS

- QUESTION: How many different places/ages are there in the universe?
  - Many!
- I mean really different!
  - Well actually it's all pretty much the same.
- Was it the same in the past?
  - Probably.
- ANSWER: 1

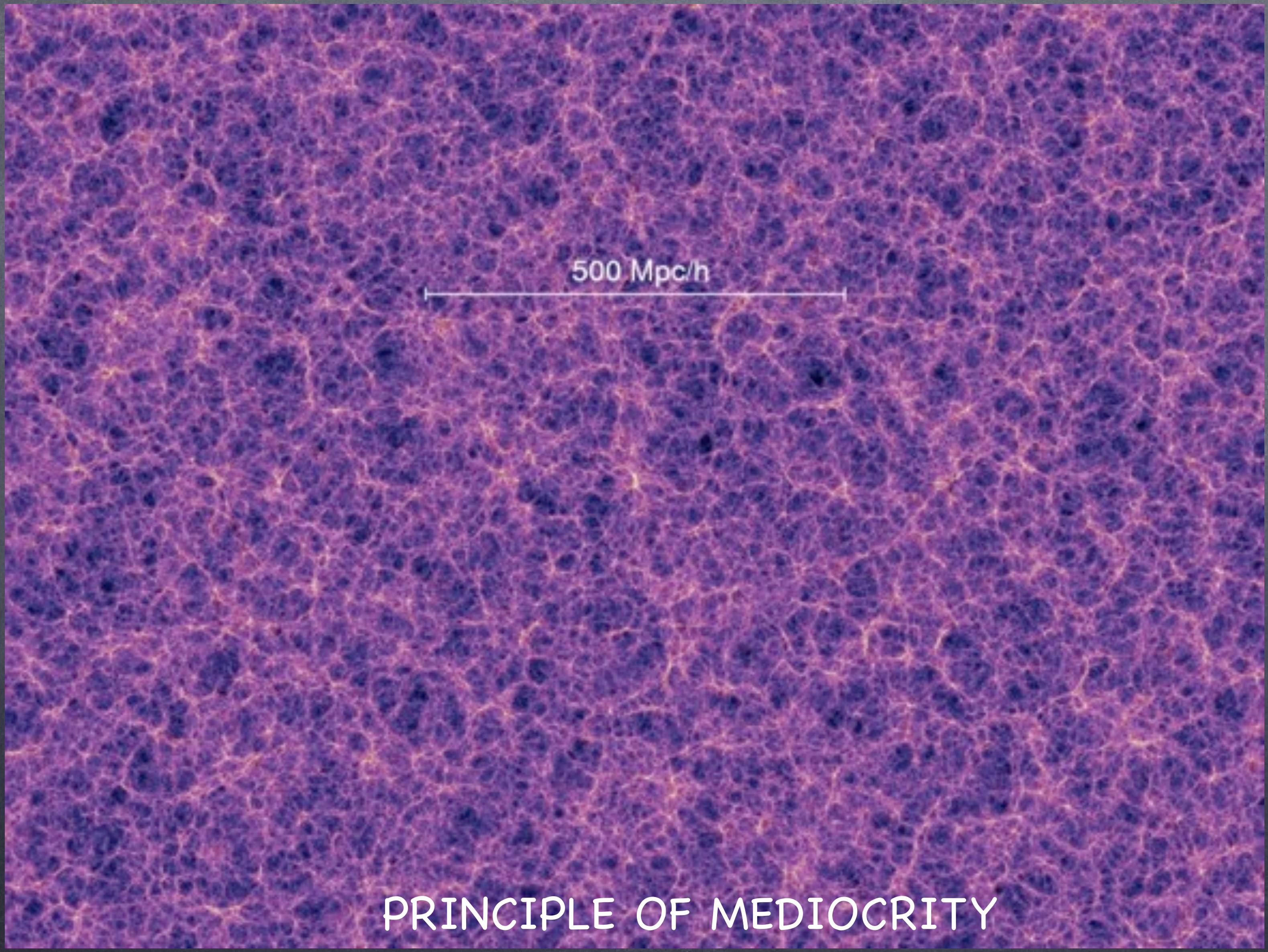
HOMOGENEITY

COSMOLOGICAL PRINCIPLE

PRINCIPLE OF MEDIOCRITY

HOMOGENEITY

COSMOLOGICAL PRINCIPLE



PRINCIPLE OF MEDIOCRITY

ISOTROPY

(about us)

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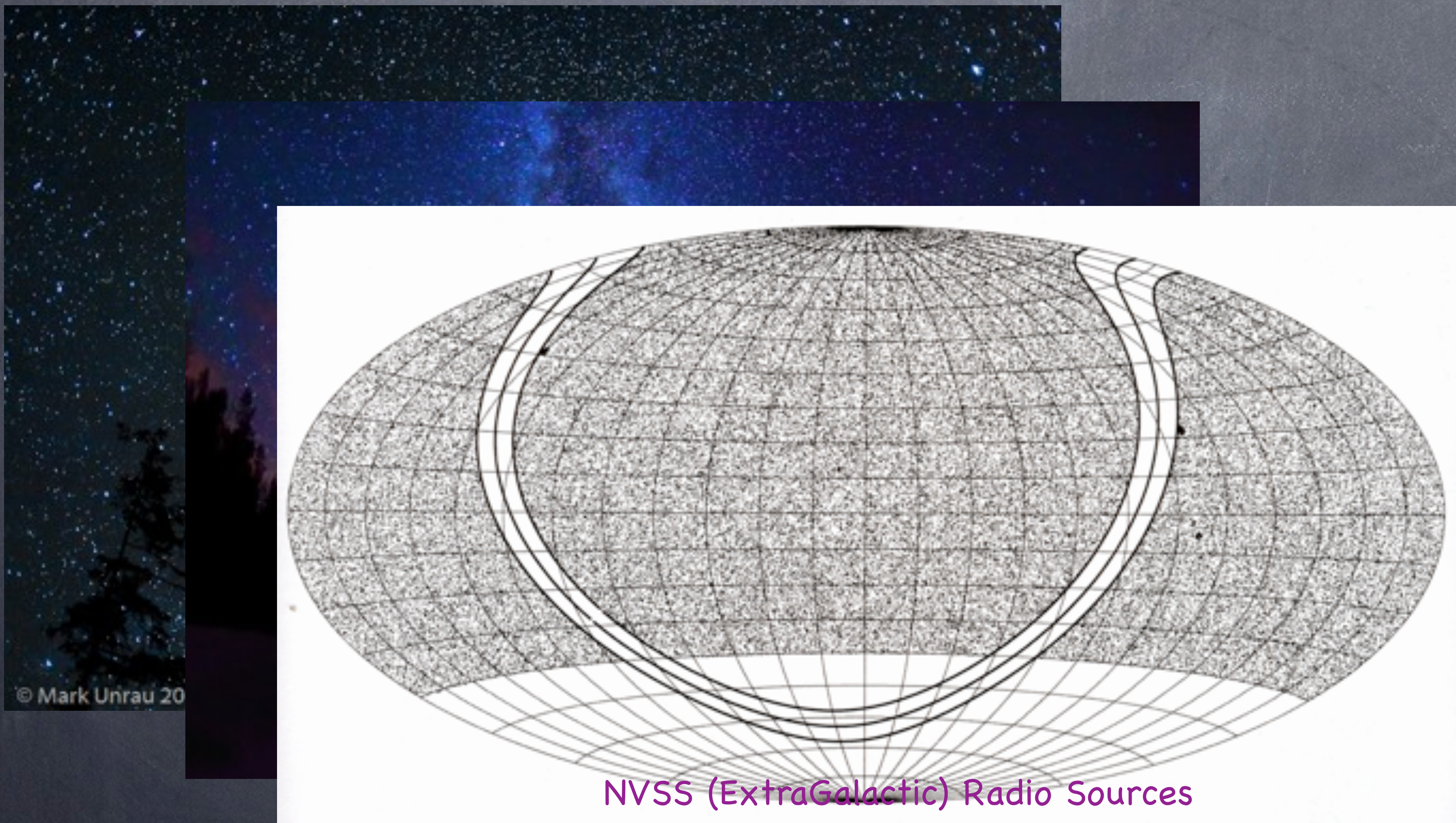

ISOTROPY

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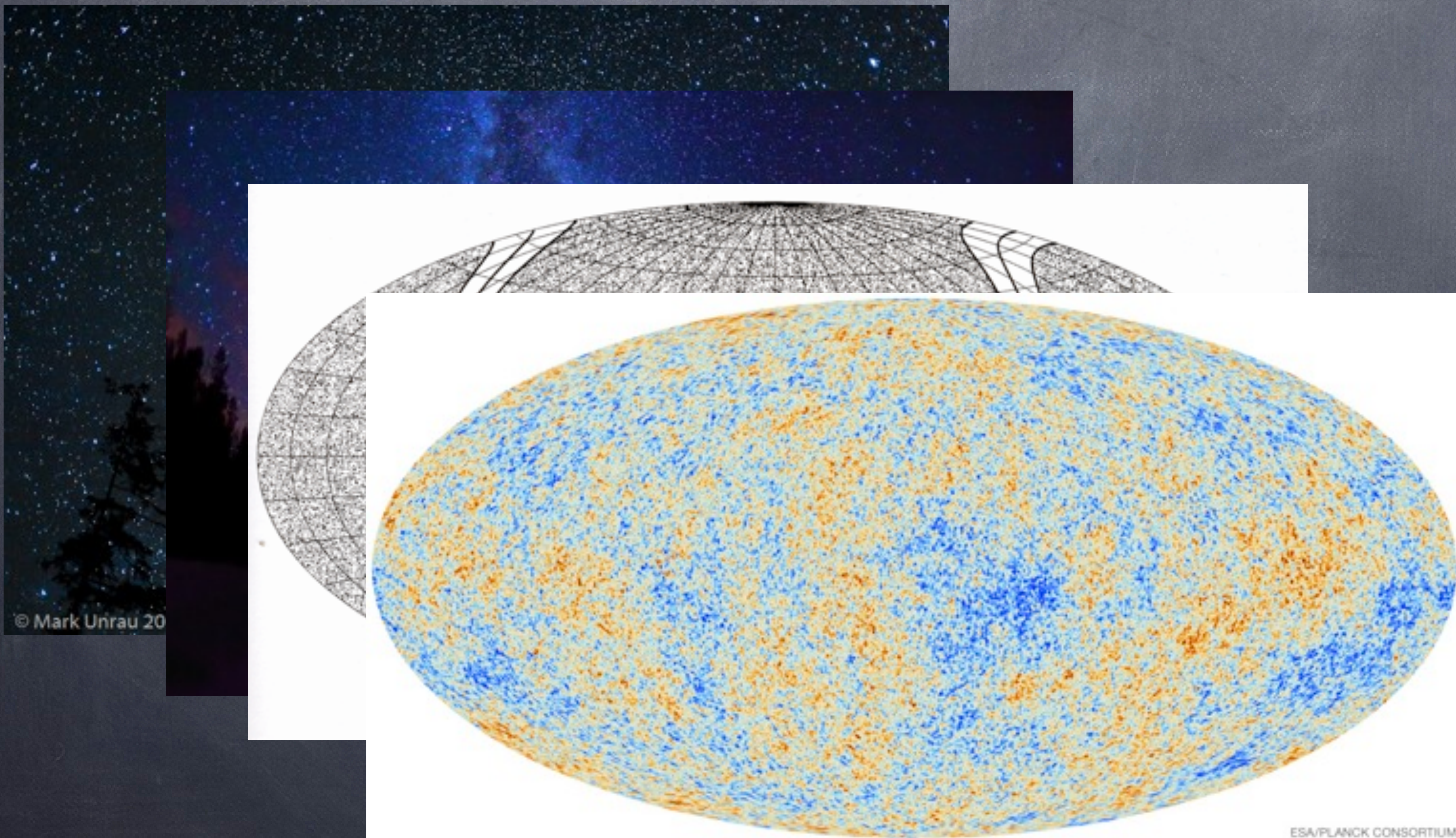


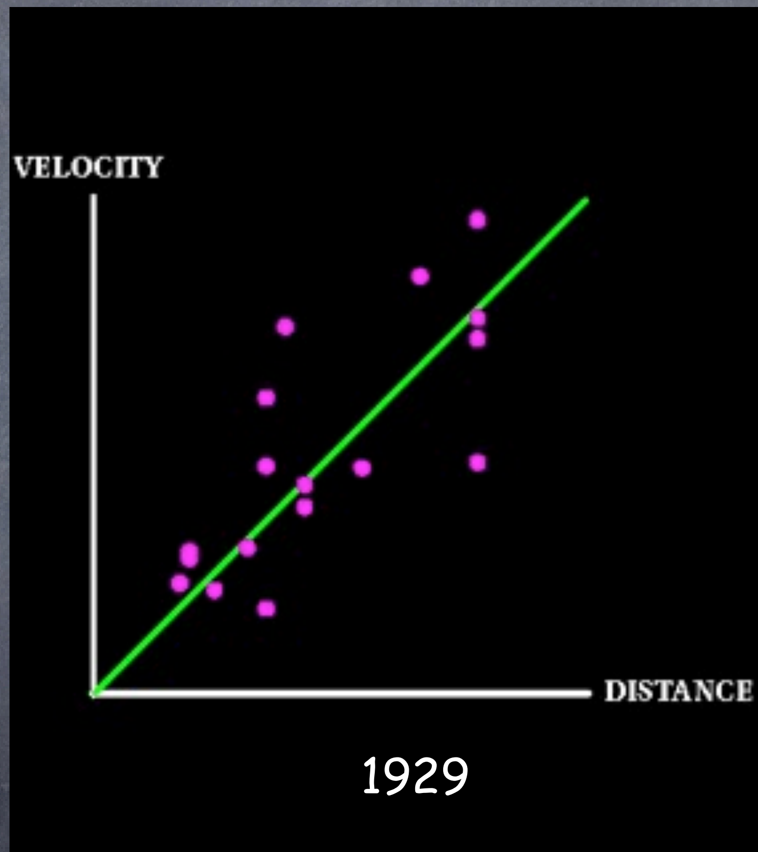
STEADY STATE

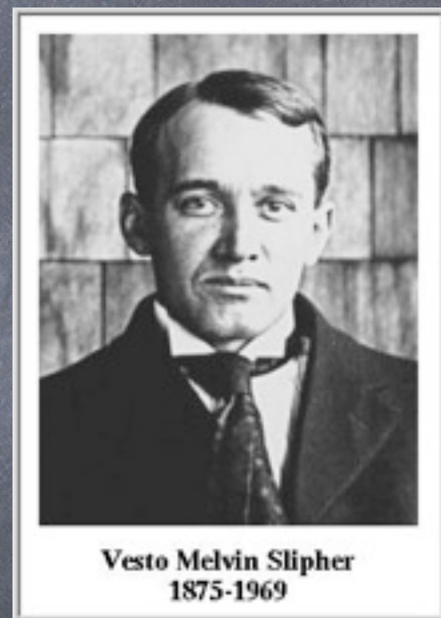
PERFECT COSMOLOGICAL PRINCIPLE

- If the answer was only one (place/age) then the universe is in a STEADY STATE.
  - This has been the philosophically preferred answer over the ages - even until the 20th century.
    - $(\text{age of universe})^{-1} = 0$
- Allowed questions:
  - What's in the universe? (inventory)
  - What's happening? (processes - uniformitarianism).
  - ~~What does the universe do?~~
    - nothing - no dynamics

DYNAMICAL UNIVERSE

IT IS EXPANDING



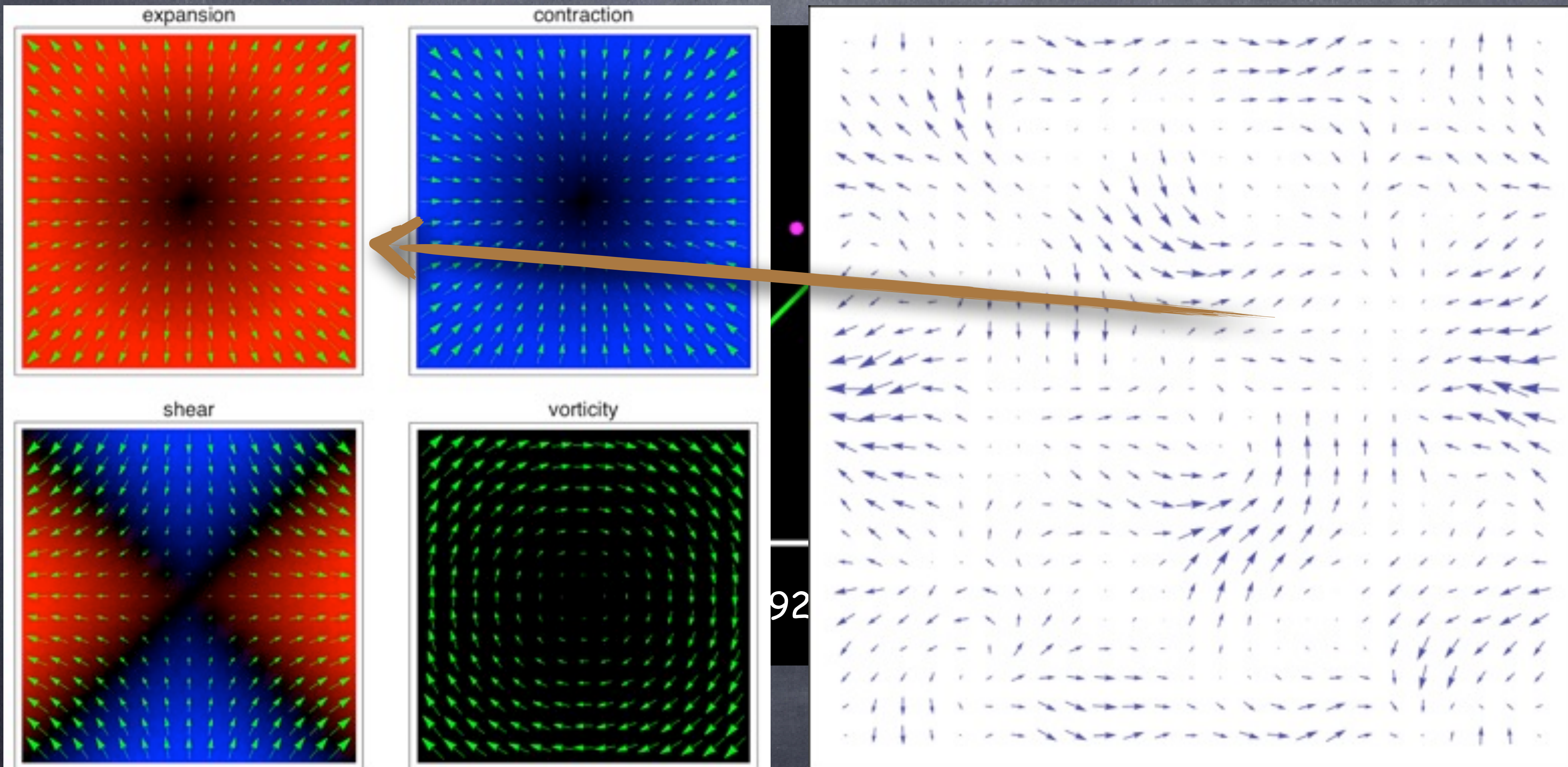


It is difficult to reconcile expansion with steady state

e.g. if matter conserved density should decrease

HUGE EXTRAPOLATION

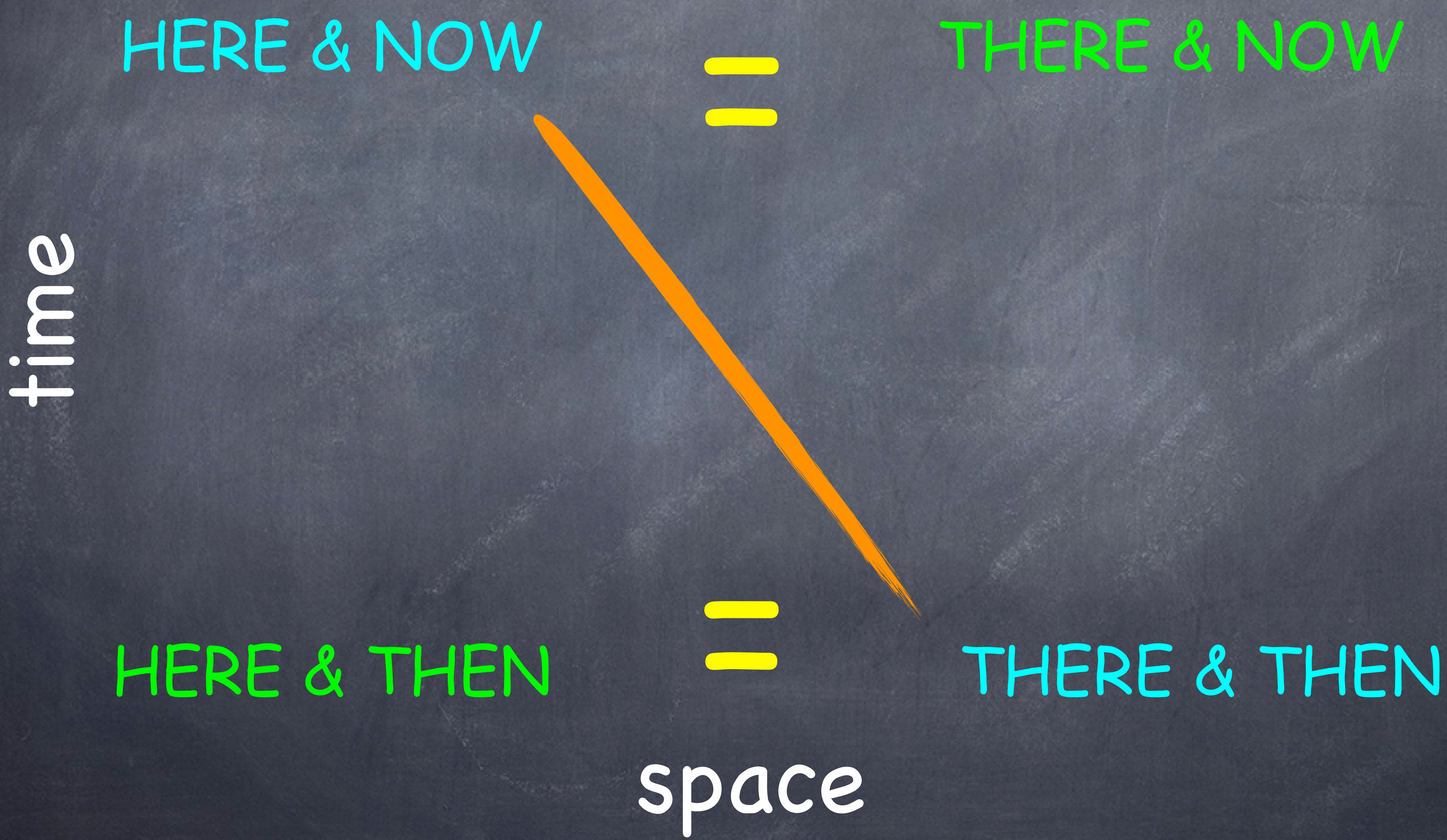
Was Hubble, Einstein, ... incredibly naive?



Hubble just measured a local velocity gradient

COSMOLOGICAL PRINCIPLES AS INFERENCE ENGINES

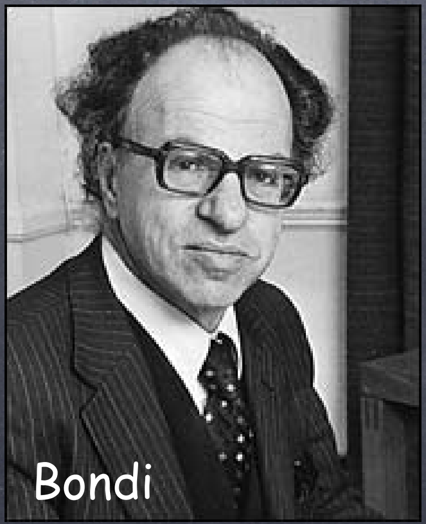
We observe the universe with light



STEADY STATE 2.0

A SYMMETRY TOO FAR

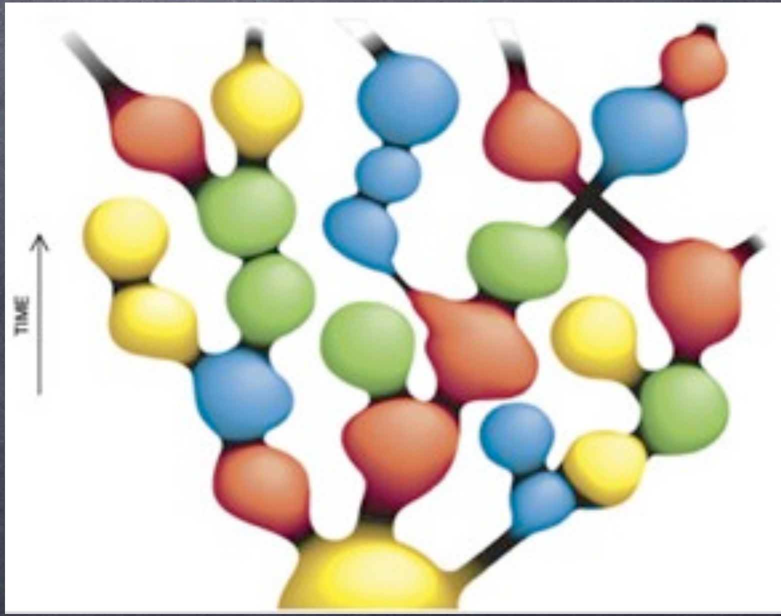
- While a few scientists tried to hang on to the perfect cosmological principle in light of expansion - as we shall see - observational tests of the STANDARD MODEL of an evolving universe make this idea untenable.



STEADY STATE 3.0

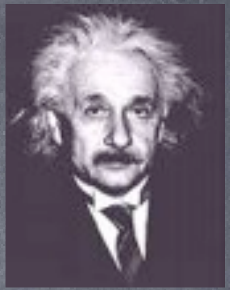
MULTIVERSE - IS THIS SCIENCE?

- Recent ideas (motivate by the highly "successful" model inflation as well as particle models with hugely numerous vacua) suggest
  - with a coarse graining scale (in length and time) beyond what is even in principle observable that the universe may be in some sort of statistical equilibrium.
  - Cyclical universes have also been revived



EXPANDING UNIVERSE

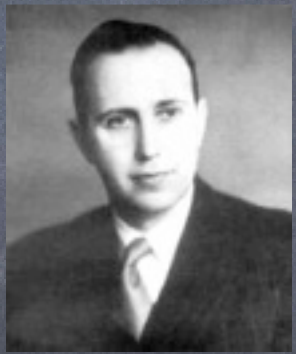
w/ cosmological principle

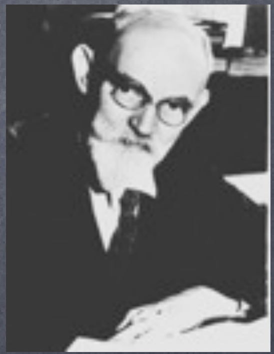


- Newton-Friedman Equations: Concentric Shell Model

$$\ddot{R} = -\frac{G\,M[R]}{R^2} \qquad M = \frac{4\pi}{3}\left(\rho + 3\,\frac{p}{c^2}\right) R^3 \qquad \dot{\rho} = -3\,\frac{\dot{R}}{R}\left(\rho + \frac{p}{c^2}\right)$$

$$a[t] \equiv \frac{R[t]}{R[t_0]} \qquad H_0 \equiv \frac{\dot{a}[t_0]}{a[t_0]} \qquad \Omega_0 \equiv \frac{8\pi G\,\rho[t_0]}{c\,H_0^2} \qquad K \equiv \frac{H_0}{c}(\Omega_0 - 1) \qquad \frac{d}{dt_0}K = 0 \qquad H[t]^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\,\rho}{3} - \frac{K c^2}{a^2}$$



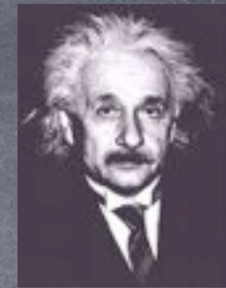


$$ds^2 = -dt^2 + a[t]^2\left(dr^2 + \frac{S[\sqrt{|K|}\,r]^2}{\sqrt{|K|}}\left(d\theta^2 + \mathrm{Sin}[\phi]^2\right)\right)$$

$$S[x] = \begin{cases} \mathrm{Sin}[x] & K > 0 & \mathbb{S}^3 & \text{"closed"} \\ x & K \to 0 & \mathbb{E}^3 & \text{"flat"} \\ \mathrm{Sinh}[x] & K > 0 & \mathbb{H}^3 & \text{"open"} \end{cases}$$

EXPAND... UNIVERSE

w... principle



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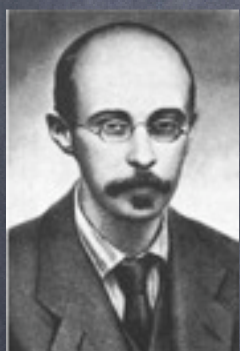

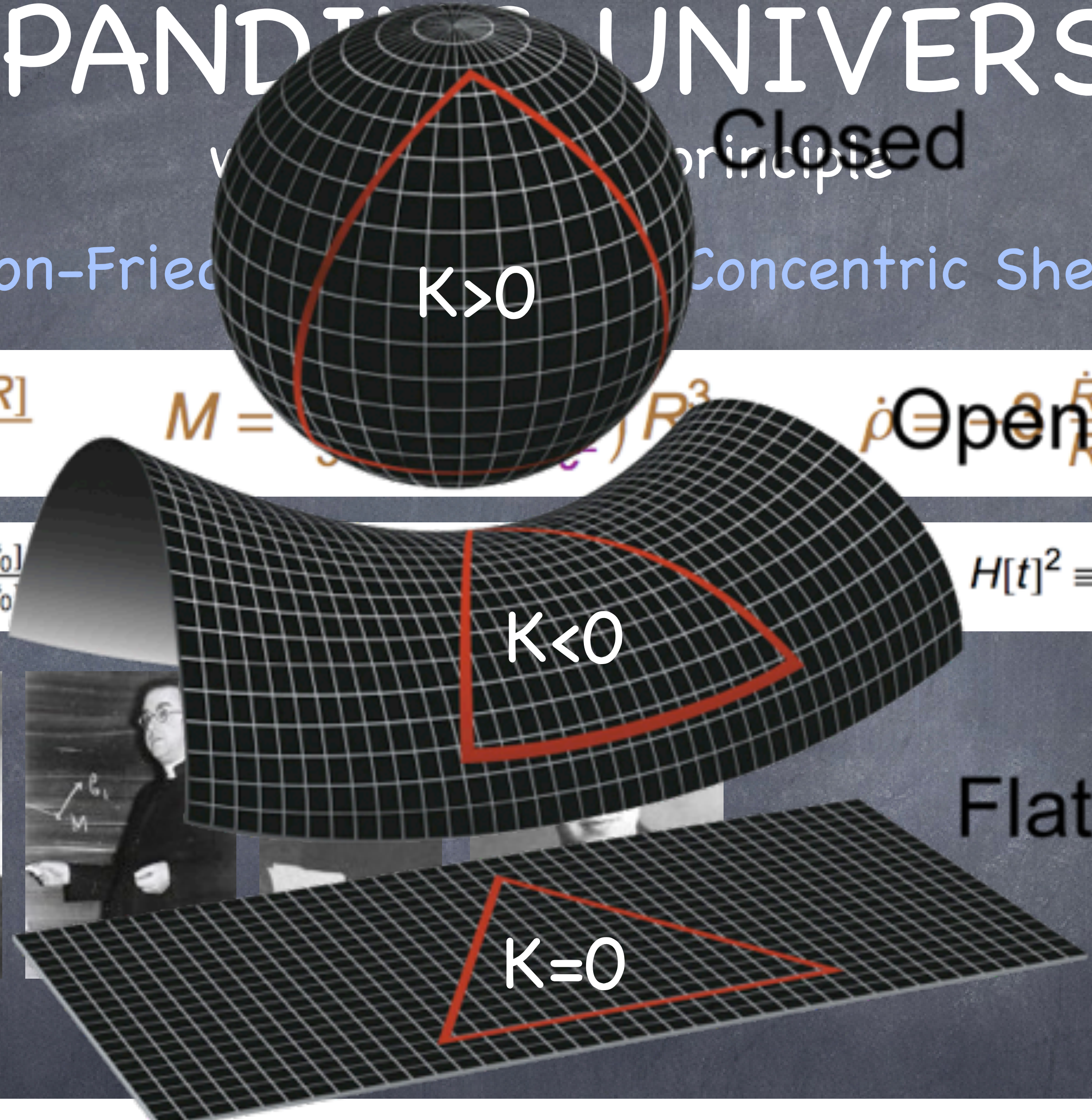

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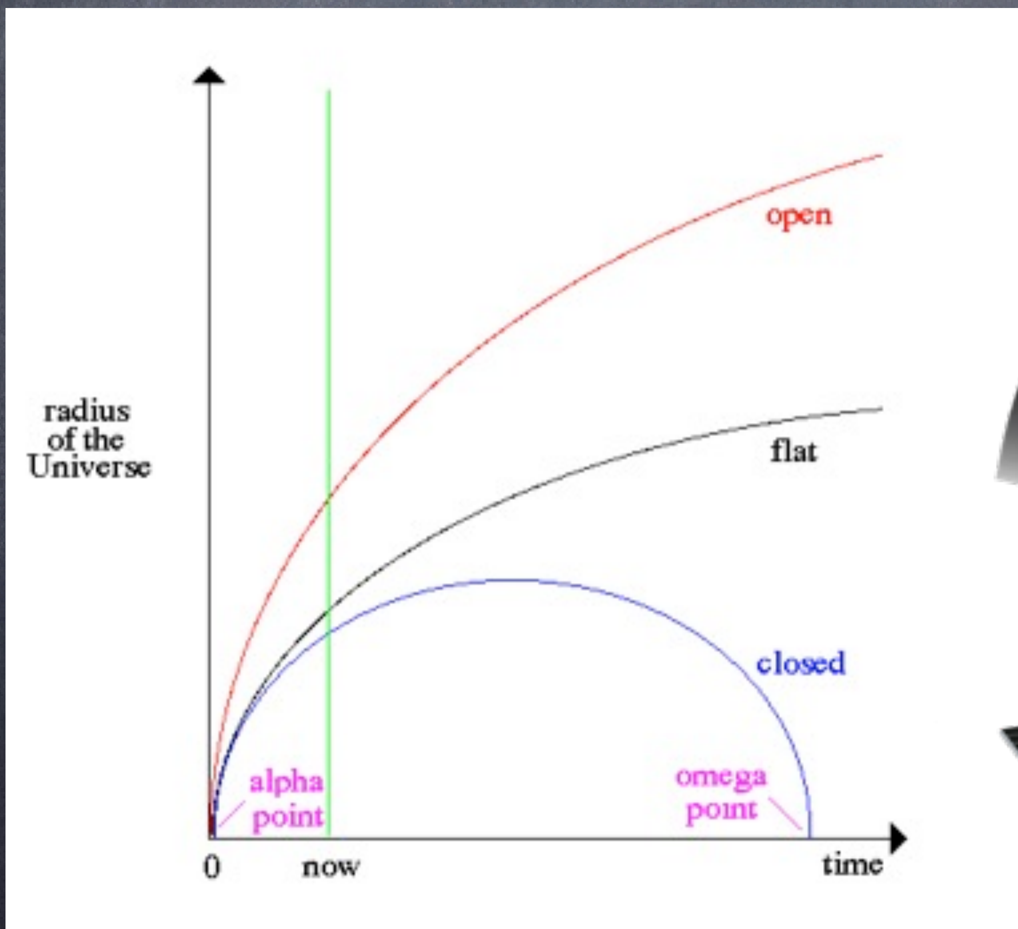
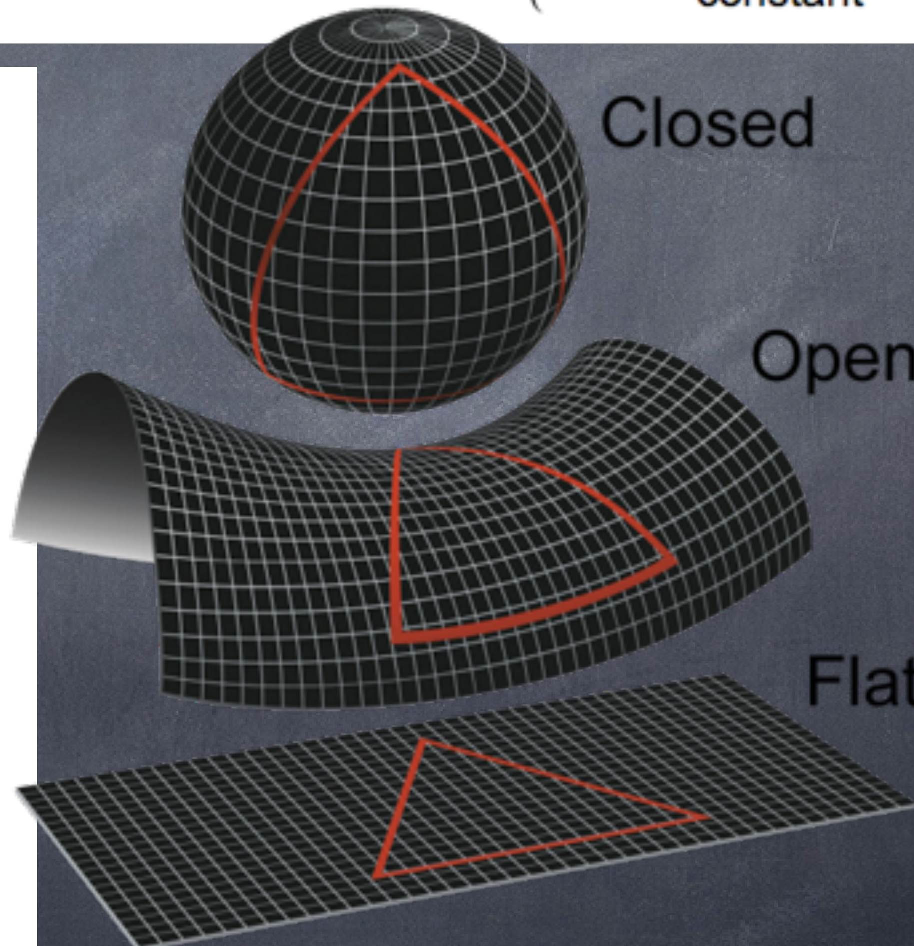
Evolution = Inventory + Geometry

$$\left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{Kc^2}{a^2} \qquad \frac{\dot\rho}{\rho} = -3\,\frac{\dot a}{a}(1+w) \qquad w \equiv \frac{p}{\rho c^2} = \begin{cases} 0 & \text{dust} \\ \frac{1}{3} & \text{radiation} \\ -\frac{1}{3} & \text{curvature} \\ -1 & \text{cosmological constant} \end{cases}$$





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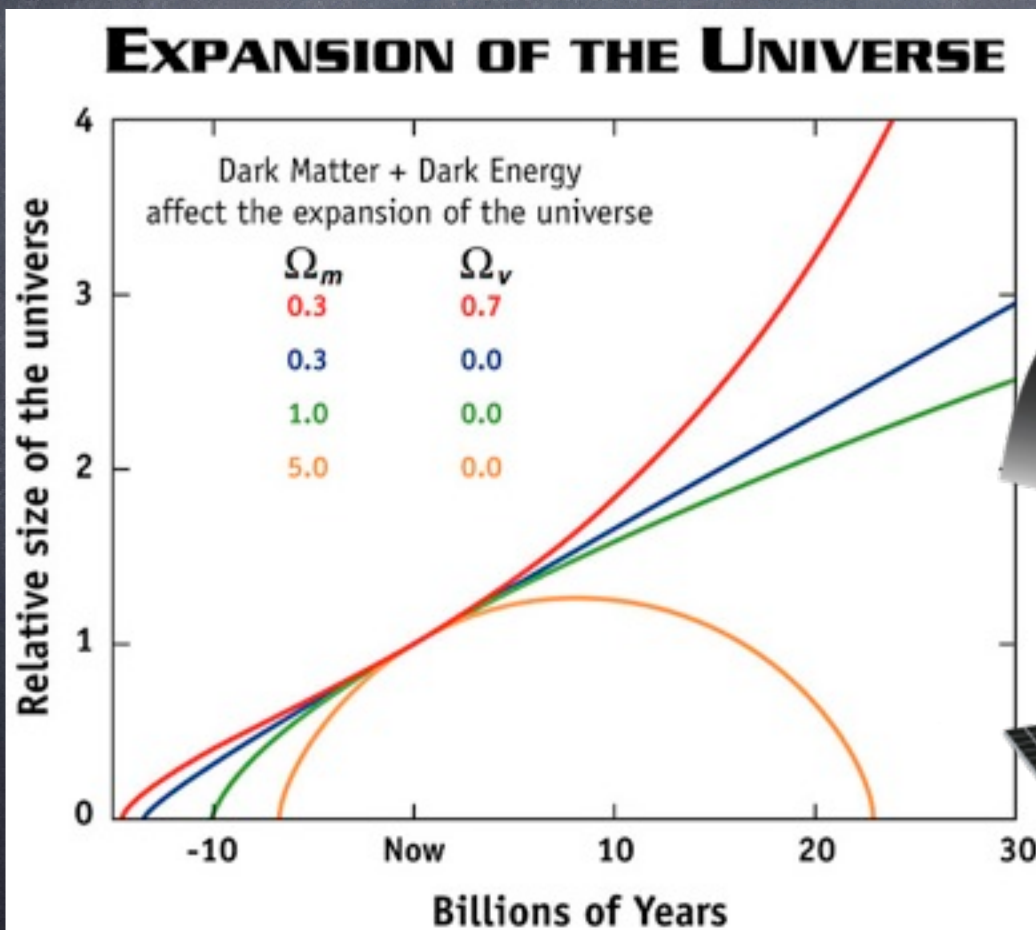

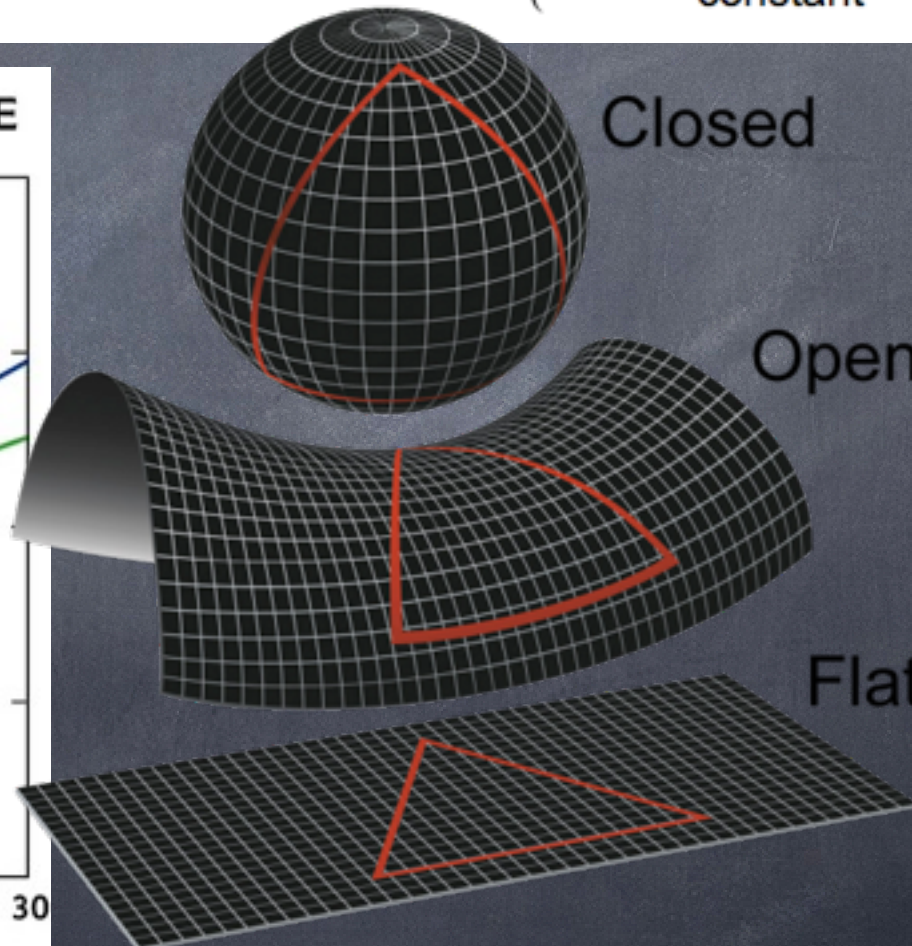

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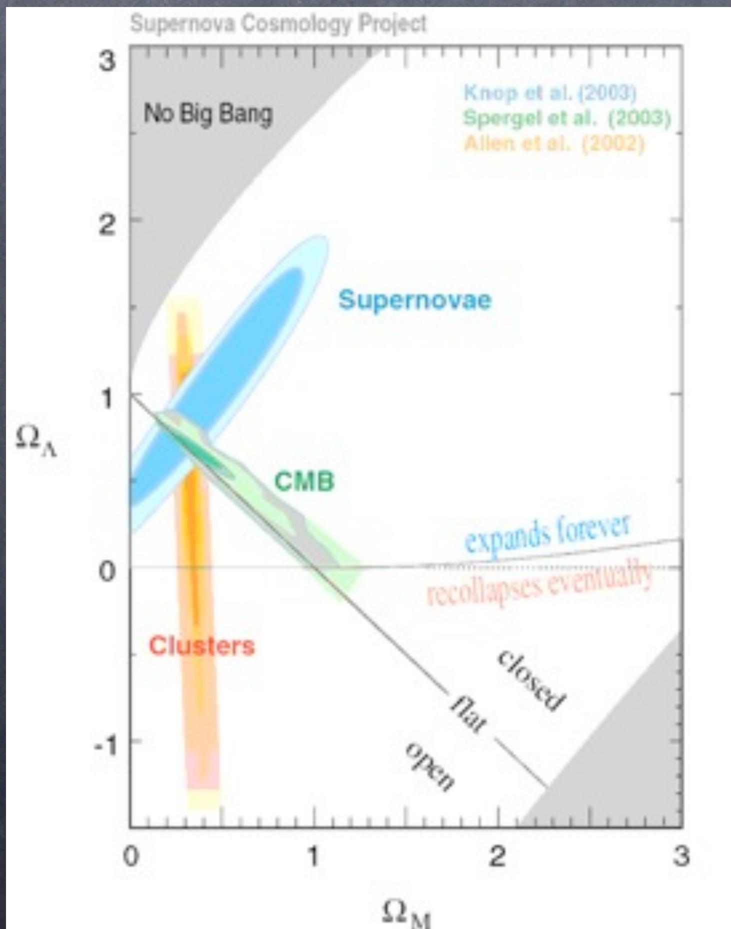
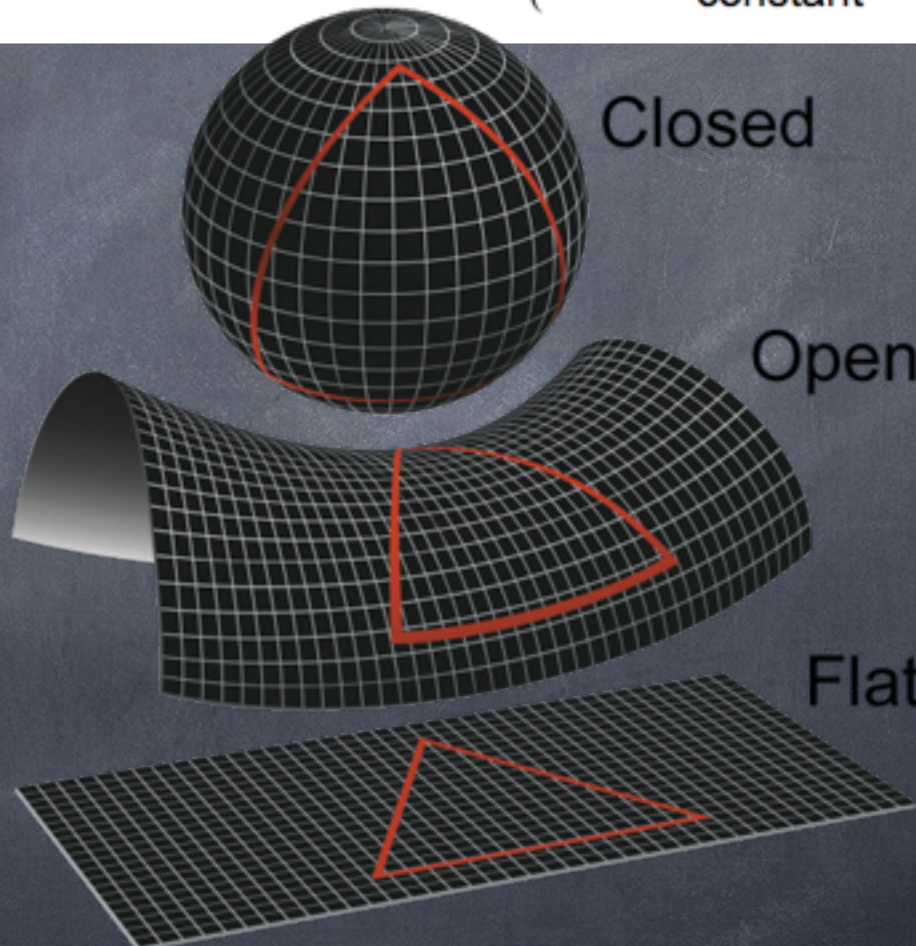
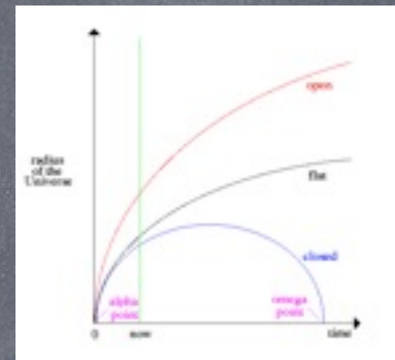




Equation of State, Horizons, Eschatology

- w and K determines: 1) future of universe:

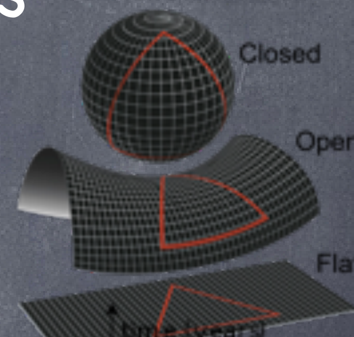
$$\rho \propto a^{-3(1+w)} \qquad \begin{array}{lll} w > -\frac{1}{3} & \text{curvature will dominate} & \begin{cases} \text{recollapse} & K>0 \\ & K=0 \\ \text{becomes empty} & K<0 \end{cases} \\ w < -\frac{1}{3} & \text{density will dominate} & \\ w < -1 & \text{density will increase} & \end{array}$$



- 2) knowledge of the past of distant regions

$$\text{Hubble Length:} \quad \lambda_H \equiv \frac{a_0}{a}\frac{c}{H}$$

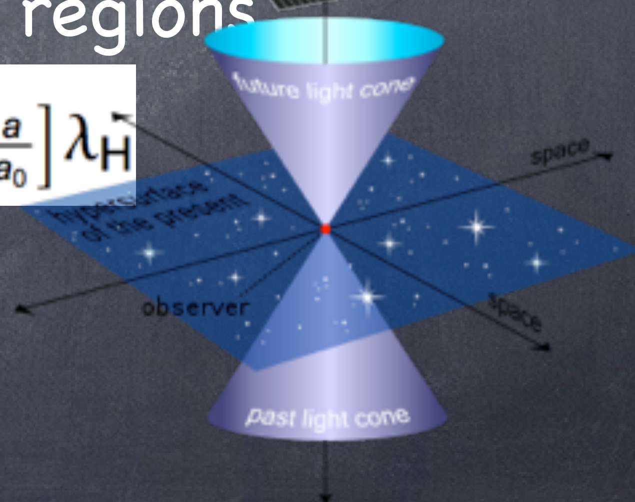
$$\text{comoving particle horizon} : \lambda_- \equiv \int_0^t \frac{a_0}{a} c\, dt = \int_{-\infty}^{0} d\ln\left[\frac{a}{a_0}\right] \lambda_H$$



- 3) ability to effect future of distant regions

$$\text{comoving event horizon} : \lambda_+ \equiv \int_t^\infty \frac{a_0}{a} c\, dt = \int_0^\infty d\ln\left[\frac{a}{a_0}\right] \lambda_H$$

$$\begin{array}{ll} w > -\frac{1}{3} & \lambda_- < \infty \\ w < -\frac{1}{3} & \lambda_+ < \infty \end{array}$$



Was the Universe Cold?

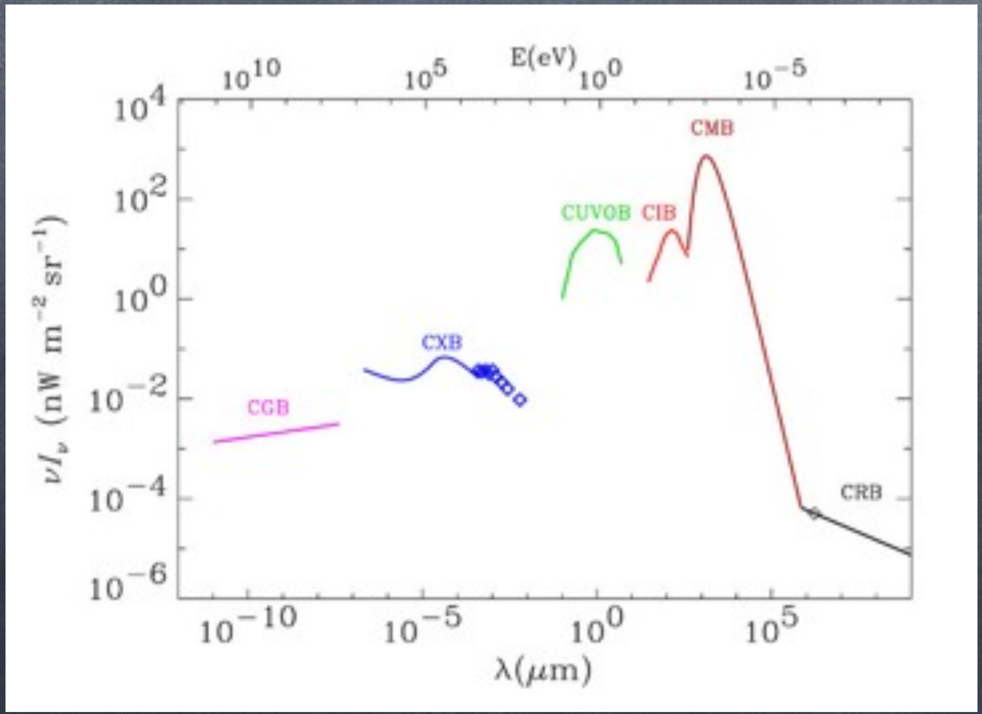
- At present $w \ll 1$
  - non relativistic galaxy velocity dispersion
  - $kT \ll m_p c^2$
- Was it always so?
  - a small amount of radiation today could dominate at early times: $\rho_{rad}/\rho_{dust} \propto a^{-1}$
- Until the 1960s all of the known radiations could have been produced recently by non-relativistic matter.

David Layzer

No! The universe was hot.

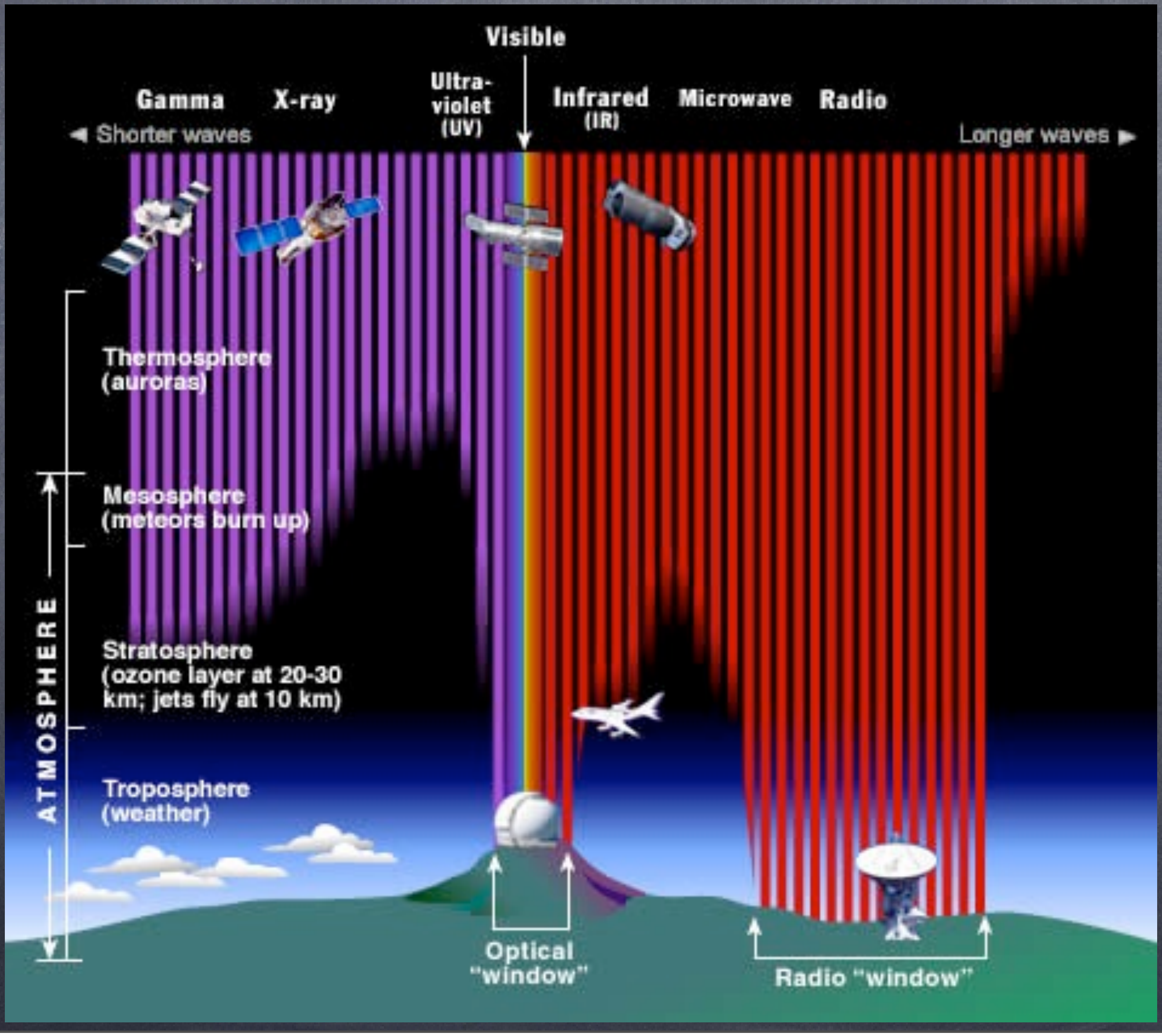
- 1st evidence for this was from stellar abundance of Helium explained by BBN (see below)

- Direct evidence came from discovery of the Cosmic Microwave Background Radiation (CMBR), serendipitously. Penzias & Wilson 1964



CMBR is Easy To See:

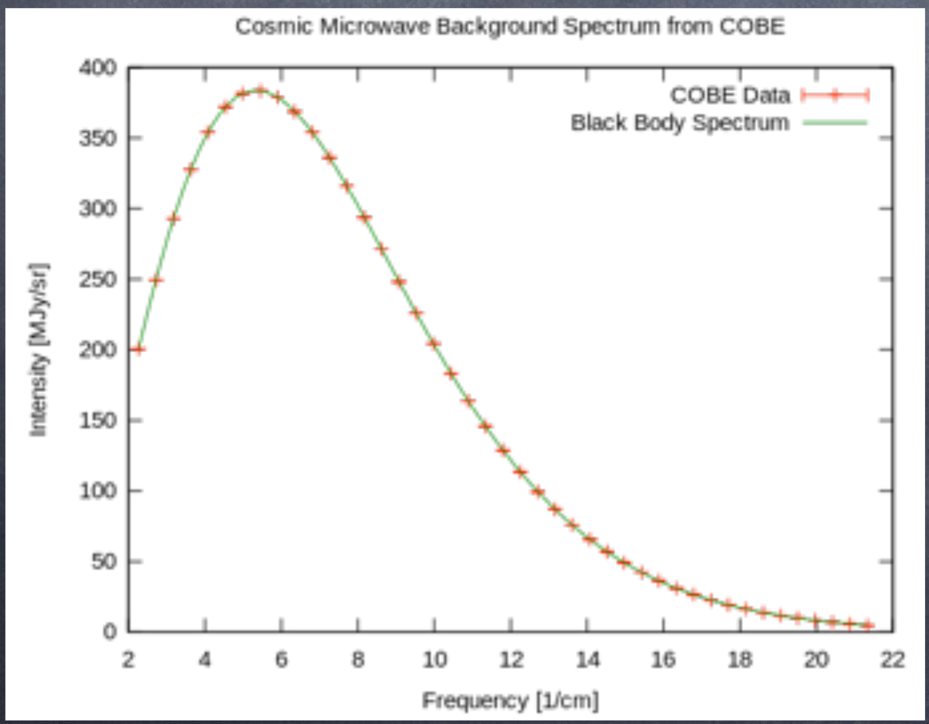
From the Ground



Primordial Origin

- It seem impossible that in the age of the universe that normal astrophysical process could produce so many photons: $n_\gamma/n_b \sim 10^{10}$

- Normal astrophysical processes do not produce near perfect blackbody spectrum (especially in the radio)



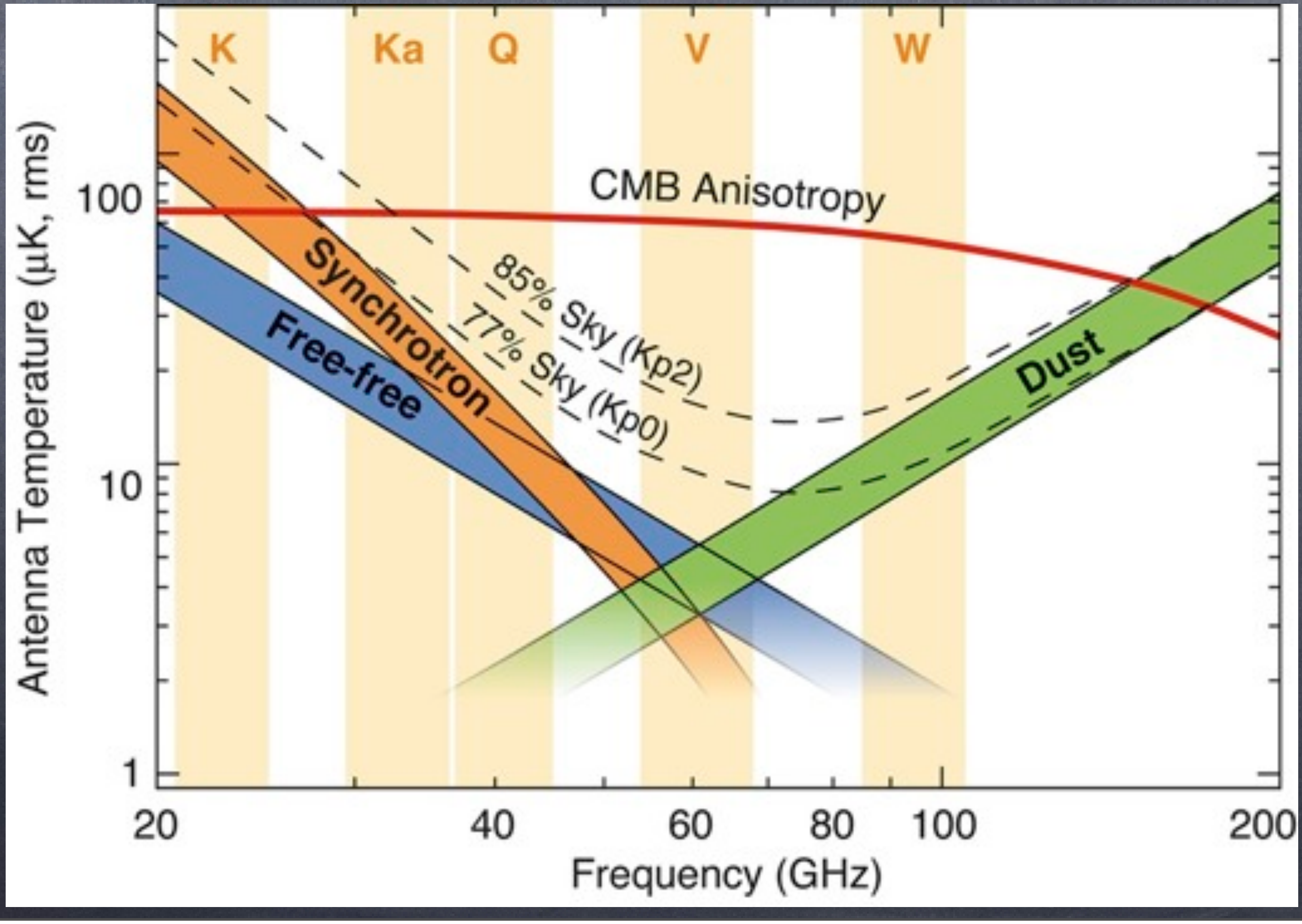
T_{CMBR} = 2.72548±0.00057 K

COBE FIRAS (+ WMAP)

$\delta \ln[B_\nu] < 10^{-4}$

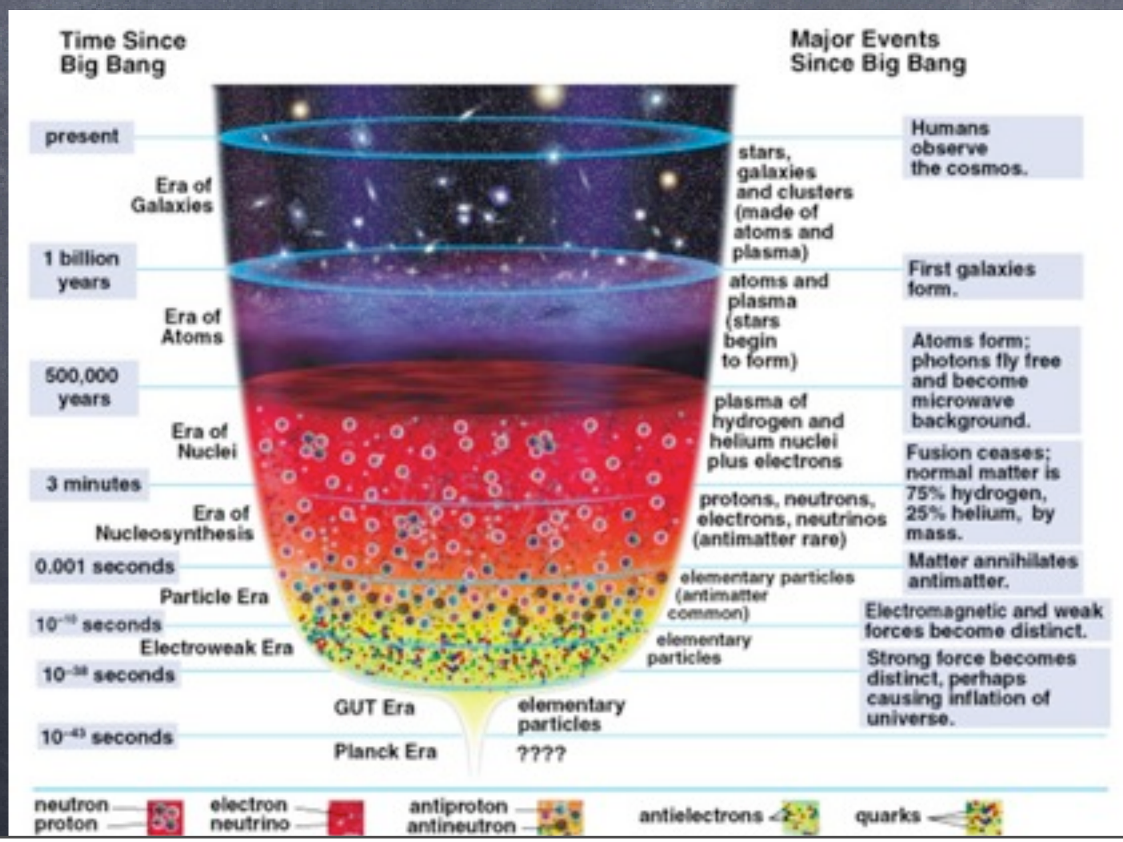
CMBR Very Clean!

- Over much of it's frequency range and most of the sky the primordial photons suffer very little contamination from other (foreground) sources.



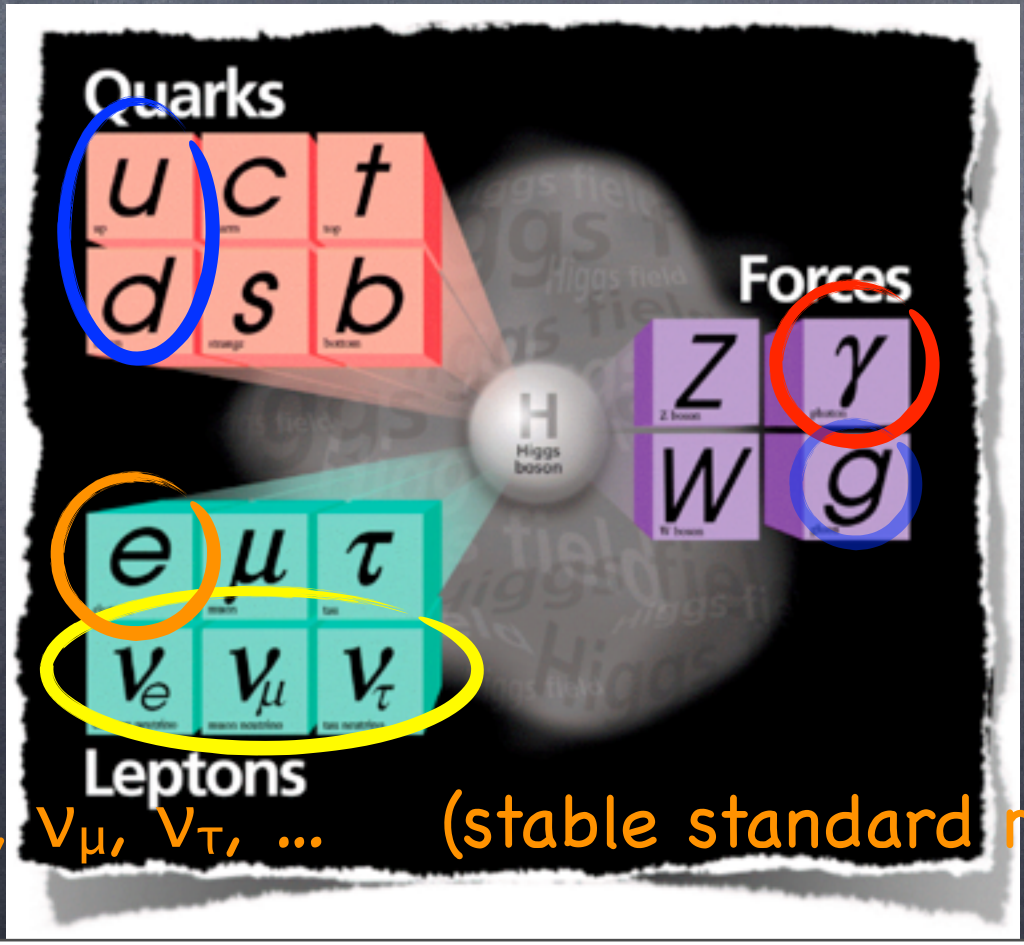
A Tale of Two Relics

- Likely that CMBR photons and the baryons have pre-existed since very early cosmological times.
- From these two relics one can write a history of a thermal universe:



Additional Relics

- As $a \rightarrow 0$: $kT \propto a^{-1}$, $n \propto a^{-3}$: all particles produced.
- As universe cools relics will include all stable particles
  - massive particles thermodynamically suppressed



- p^+, e^-, ν_e, ν_μ, ν_τ, ... (stable standard model particles)

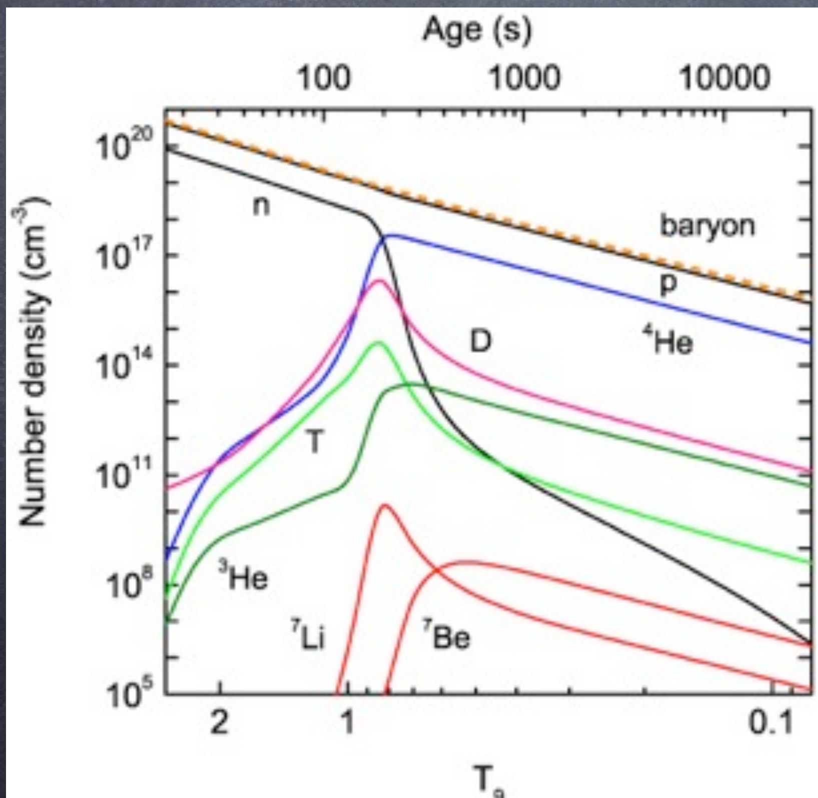
Thermal Universe Timeline

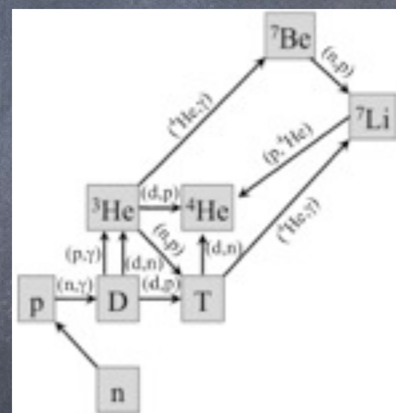
(in reverse)

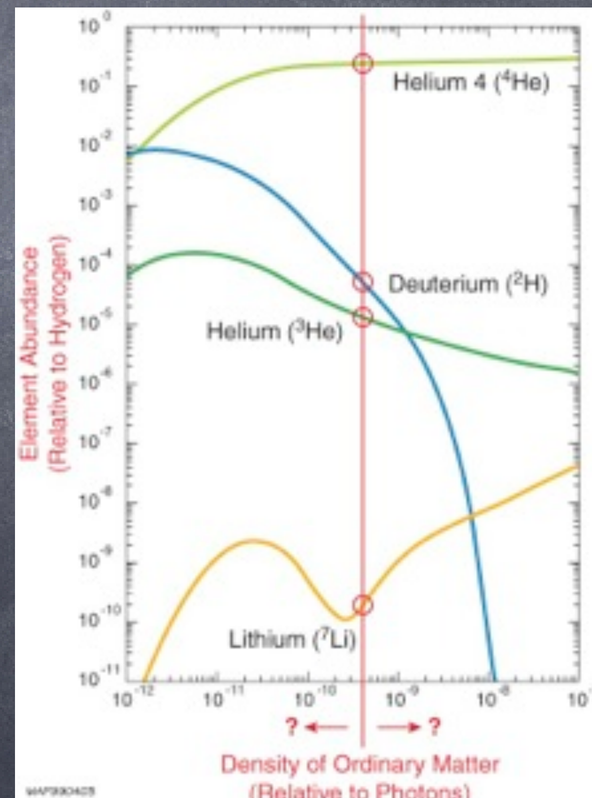
- 0.3eV - recombination: $e^- - {}_1H^+ - {}_4He^+ - \ldots \rightarrow HI - {}_4HeI - \ldots$ Universe becomes transparent
- 10eV - CMBR spectrum freeze-out (photon thermalization inefficient)
- 100keV - nucleosynthesis: $e^- - p^+ - n \rightarrow e^- - {}_1H^+ - {}_2H^+ - {}_3He^+ - {}_4He^+ - \ldots$
- 500keV - $e^\pm$ annihilation: $e^\pm - e^-$
- 2.5MeV - neutrino freeze out (weak interactions inefficient)
- 200MeV - QCD confinement: $q_x - g_x \rightarrow n - p^+ - \pi^\pm - \pi^0 - \ldots$
- 10^xGeV - dark matter genesis?
- 0.1TeV - electroweak symmetry breaking: $H - W^\pm - Z^0 - l_x \rightarrow e^\pm - \mu^\pm - \tau^\pm - \nu_x$
- 10^xTeV - baryogenesis: $b - \bar{b} \rightarrow b$?
- ?? inflation - smooth geometry += gravitational perturbations (density, waves)

Big Bang Nucleosynthesis

- Alpher, Bethe, Gamow 1948 suggested Hot Big Bang could explain Helium abundance if $T_\gamma \sim 5K$.
- For allowed range of n_γ / n_b isotopic ratios goes out of equilibrium yielding only ~24% ^4He by weight + …







Neutrino Freeze Out

- Entropy versus Particle Number Conservation

$$\text{constant} = \begin{cases} \frac{s}{a^3} & \text{equilibrium} \\ \frac{n}{a^3} & \text{decoupled} \end{cases} \quad \frac{s}{k_B} = \frac{4}{3}\,\frac{\pi^2}{30}\left(\frac{k_B\,T}{\hbar\,c}\right)^3 g_* \quad T_{\text{eq.}} \propto \frac{a}{\sqrt[3]{g_*[a]}} \quad T_{\text{dec.}} \propto a$$

- If $mc^2 \gg kT$ then $g_{f,b} \ll 1$, if $mc^2 \ll kT$ then

$$g_* = \sum_i^{\text{bosons}} g_b + \frac{3}{4}\sum_i^{\text{fermions}} g_f$$

$$\int_0^\infty \frac{x^2}{e^x+1}\,dx = \frac{3}{4}\int_0^\infty \frac{x^2}{e^x-1}\,dx$$

$$g_\gamma = (2\text{ polarizations}) = 2$$
$$g_{e^\pm} = (2\text{ charges})\times(2\text{ spins}) = 4$$
$$g_{\nu' s} = (3\text{ flavors})\times(2\text{ helicities}) = 6$$
$$g_{g' s} = (8\text{ colors})\times(2\text{ helicities}) = 16$$
$$g_{q' s} = (3\text{ colors})\times(2\text{ charges})\times(2\text{ spins})\times(6\text{ flavors}) = 72$$

- If neutrino freeze-out was well before $e^\pm$ annihilation

$$\frac{T_\nu}{T_\gamma} = \left(\frac{2}{2+\frac{7}{8}\times 4}\right)^{\frac{1}{3}} = \left(\frac{4}{11}\right)^{\frac{1}{3}} \Rightarrow \left(\frac{4}{11}\,\frac{N_\nu^{\text{eff}}}{3}\right)^{\frac{1}{3}} \qquad \text{S.M.}:\ N_\nu^{\text{eff}} = 3.046$$

- Thermal model gives density history for T<1MeV

$$\rho = \frac{3\,H_0^2}{8\,\pi\,G}\,\frac{\Omega_{m0}}{a^3} + \frac{\pi^2}{30}\,\frac{(k_B\,T_{\gamma 0})^4}{(\hbar\,c)^3\,c^2}\,\frac{2+\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}(2\,N_\nu^{\text{eff}})}{a^4}$$

Constraints from Planck and other CMB datasets (95% c.l.)

$$\text{Planck alone (no pol.)} \quad N_{eff}^{\nu} = 4.53^{+1.5}_{-1.4}$$

$$\text{Planck} + \text{WP} \quad N_{eff}^{\nu} = 3.51^{+0.80}_{-0.74}$$

$$\text{Planck} + \text{WP} + \text{Lensing} \quad N_{eff}^{\nu} = 3.39^{+0.77}_{-0.70}$$

$$\text{Planck} + \text{WP} + \text{highL} \quad N_{eff}^{\nu} = 3.36^{+0.68}_{-0.64}$$

$$\text{Planck} + \text{WP} + \text{highL} + \text{Lensing} \quad N_{eff}^{\nu} = 3.28^{+0.67}_{-0.64}$$

Conclusions:

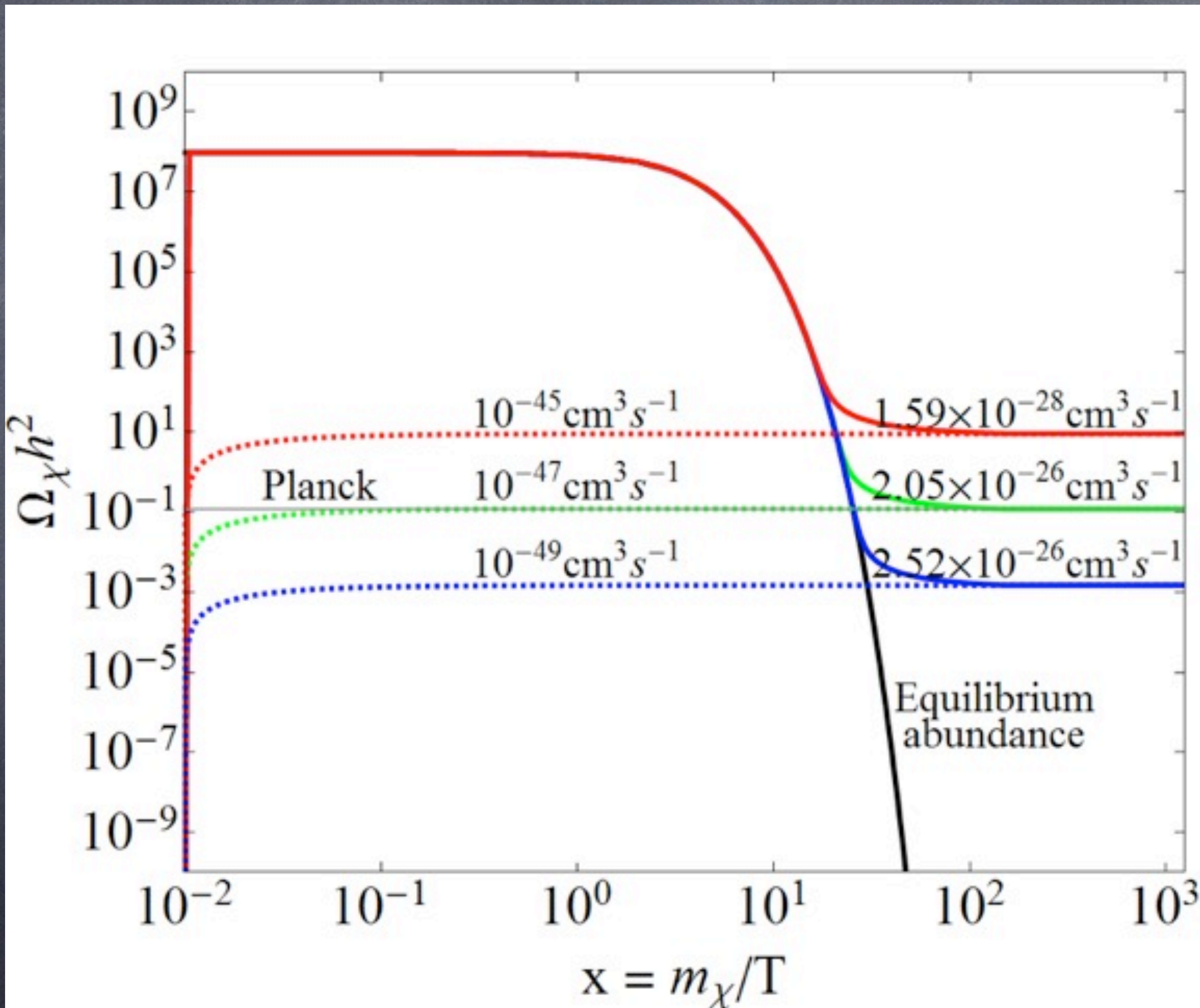
- $N_{eff}=0$ is excluded at high significance (about 10 standard deviations). We need a neutrino background to explain Planck observations !

- **No evidence** (i.e. > 3 σ) for extra radiation from CMB only measurements.

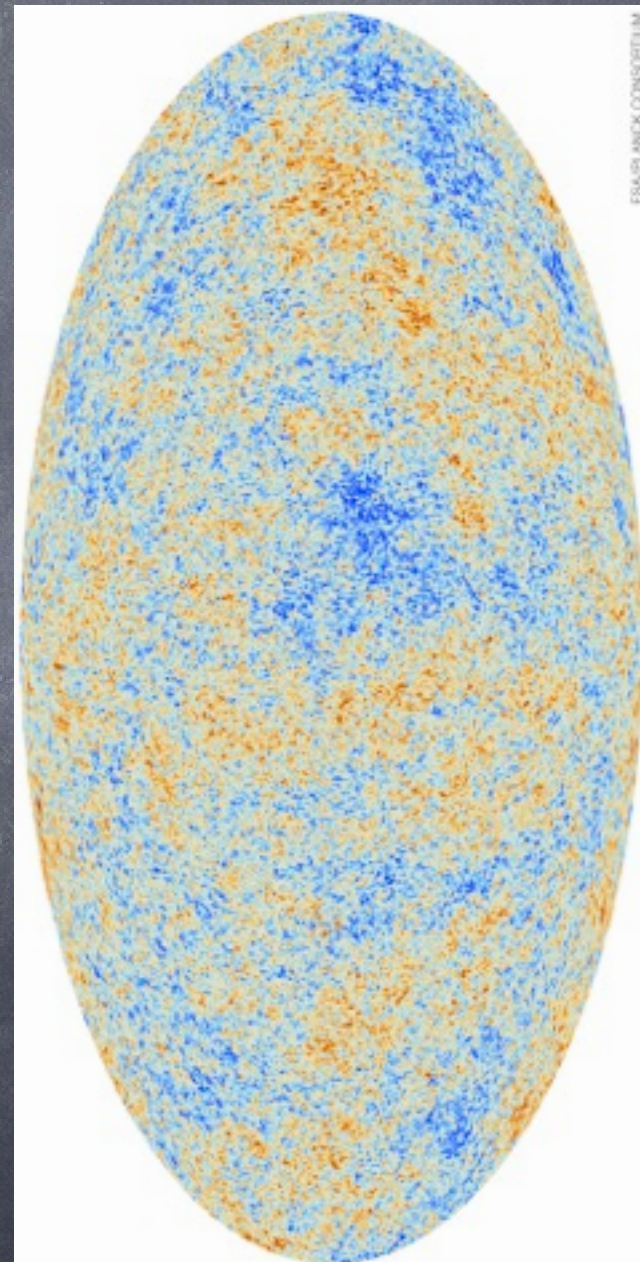
- $N_{eff}=4$ is also consistent in between 95% c.l.

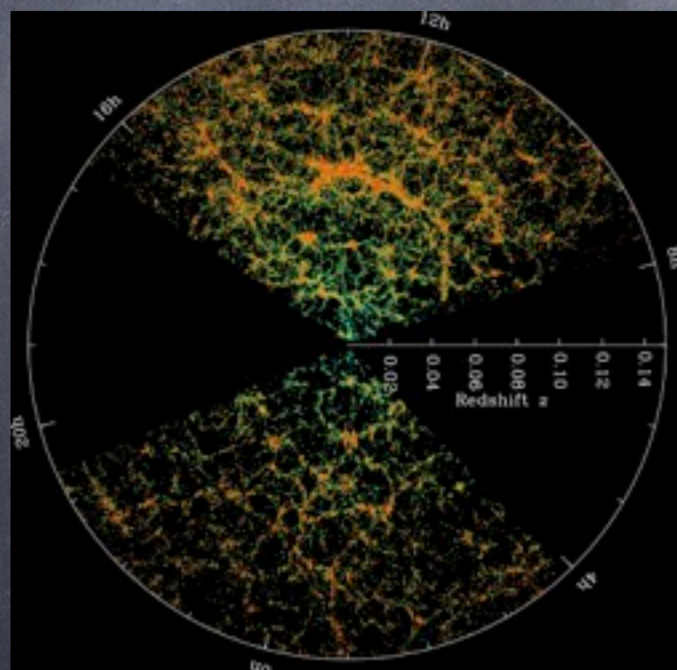
- $N_{eff}=2$ and $N_{eff}=5$ excluded at more than 3 σ (massless).

Dark Matter Genesis



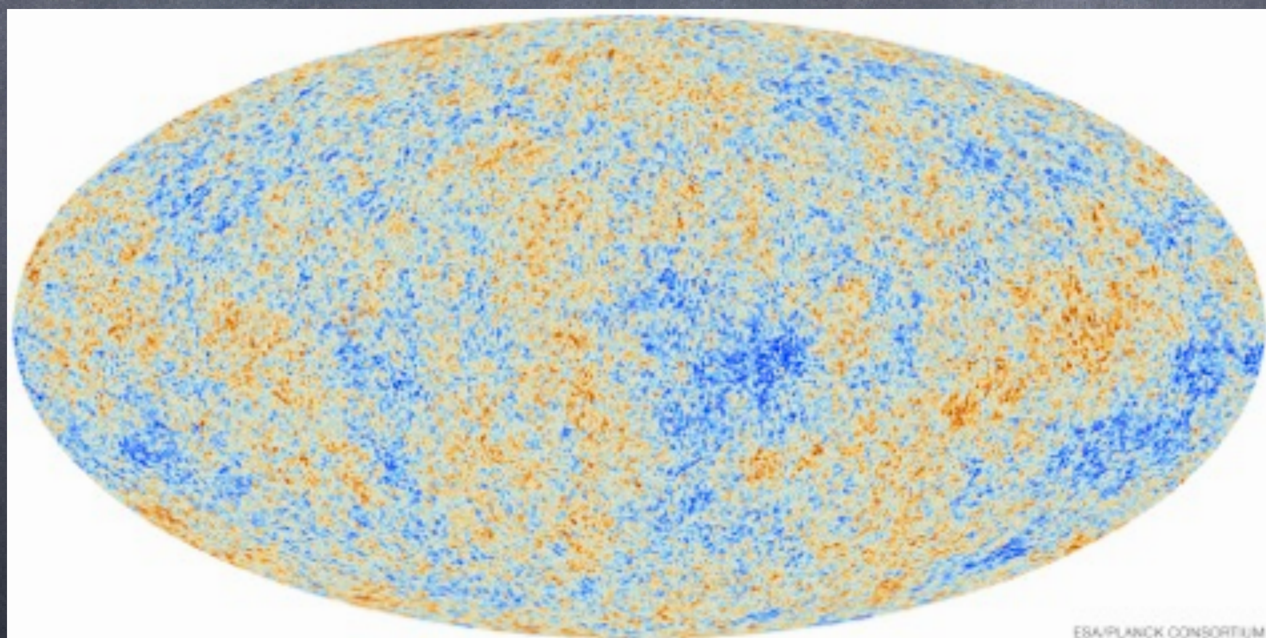
What's Missing – Us!





Cosmological Conundrums

- Horizon Problem:
  - CMBR show correlations on scales > 2Gpc
  - At recombination 2 x particle horizon: $\lambda_{-} < 300$Mpc
  - Where do these correlations come from?



Inflationary Paradigm

- Solution: Make Horizon Bigger: Guth, Starobinsky, Linde, Albrecht, Steinhardt
  - At some early time in past $w<-\frac{1}{3}$
  - $w \cong -1$ is a natural value for scalar fields
    - $\rho=\frac{1}{2}(\partial\phi/\partial t)^2+\frac{1}{2}(\nabla\phi)^2+V[\phi]$
    - $p=\frac{1}{2}(\partial\phi/\partial t)^2+\frac{1}{2}(\nabla\phi)^2-V[\phi]$
  - uniform ϕ: $\partial^2\phi/\partial t^2+3H\,\partial\phi/\partial t+V'[\phi]=0$
    - slow roll: $\varepsilon=(V'[\phi]/V[\phi])^2/(16\pi G)\ll 1$ $\quad \eta=V''[\phi]/V[\phi]/(8\pi G)\ll 1$
    - slow roll: $\partial\phi/\partial t \cong -\frac{1}{3}H^{-1}V'[\phi]$ $\quad H^2 \cong 8\pi G V[\phi]/3$
    - flat potential: $p/\rho \cong -1+\frac{2}{3}\varepsilon$

Other Implications

- Quantum fields fluctuate in (highly) curved space-time
  - deSitter space: $T_H=H^{-1}$
    - fluctuations in scalar modes: inflation: $\delta\phi$
    - fluctuation in tensor modes: $\delta g_{\mu\nu}$
  - Reheating: $\delta\rho_{rad}$, $\delta g_{\mu\nu}$ superhorizon scales $\lambda \gg H^{-1}$
  - $(\delta\rho/\rho)[k]^2 = 32/75\ V[\phi]/M_{pl}^4/\varepsilon \propto k^{ns}$
  - $n_s \cong 1-6\varepsilon-2\eta$
  - $(\delta g_{GW})[k]^2 = 32/75\ V[\phi]/M_{pl}^4 \propto k^{nt}$
  - $n_t \cong -2\varepsilon$

Cosmic Relics:

- Photons: The 2.725K CMBR
- Neutrinos: (difficult to see directly) expect T_ν=1.955K
- Baryons: (origin of baryon anti-baryon asymmetry unknown)
- Dark Matter: (origin unknown)
- Scalar Perturbation: inhomogeneities
- ?Tensor Perturbations: gravitational radiation
- Dark Energy (origin unknown - only important recently?)