The Standard Cosmology: 10 things to know, triumphs & tests, Hubble troubles, and big questions

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16/17 July 2023

The Standard Cosmology: 10 things to know, triumphs & tests, Hubble troubles, and big questions (lecture 1)

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The Standard Cosmology (ΛCDM) in plain English

… very-early accelerated expansion driven by the potential energy of a scalar field gives rise to a very-large, smooth, spatially flat patch that becomes all that we can see today. Quantum fluctuations during this inflationary phase grow into the seeds for galaxies. The conversion of potential field energy into heat produces the quark soup that evolves a baryon asymmetry and long-lived dark matter particles. The excess of quarks over antiquarks becomes neutrons and protons, later some light elements and finally atoms. The gravity of the dark matter particles drives the formation of structure from galaxies to superclusters and a mere 5 billion years ago the repulsive gravity of dark energy (Λ) again drove accelerated expansion …

MST, The Road to Precision Cosmology and ΛCDM, ARNPS 72, 1 (2022) https://arxiv.org/pdf/2201.04741.pdf

1. Not a model – a real, falsifiable theory that makes precise, testable predictions

- Matter tell space how to curve:

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

- Space tells matter how to move/evolve:

$$T^{\mu\nu}{}_{;\nu} = 0$$

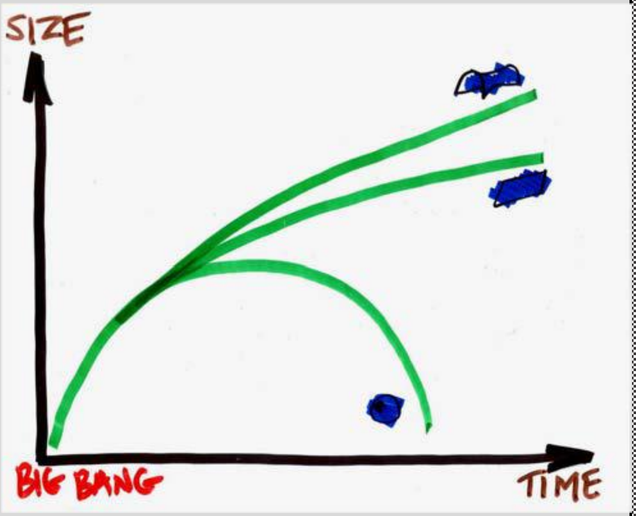
- With the assumption of spatial flatness and isotropy/homogeneity (supported by much evidence) only the composition of the Universe needs to be fixed. Today,
  - Matter (baryons, dark matter, neutrinos): 31% ± 0.6% (Baryons, 4.8 ± 0.06%)
  - Dark Energy (Λ): 69% ± 0.6%
  - Photons (CMB): 0.005%

2. Expansion of space: kinematics

- Spacetime metric:

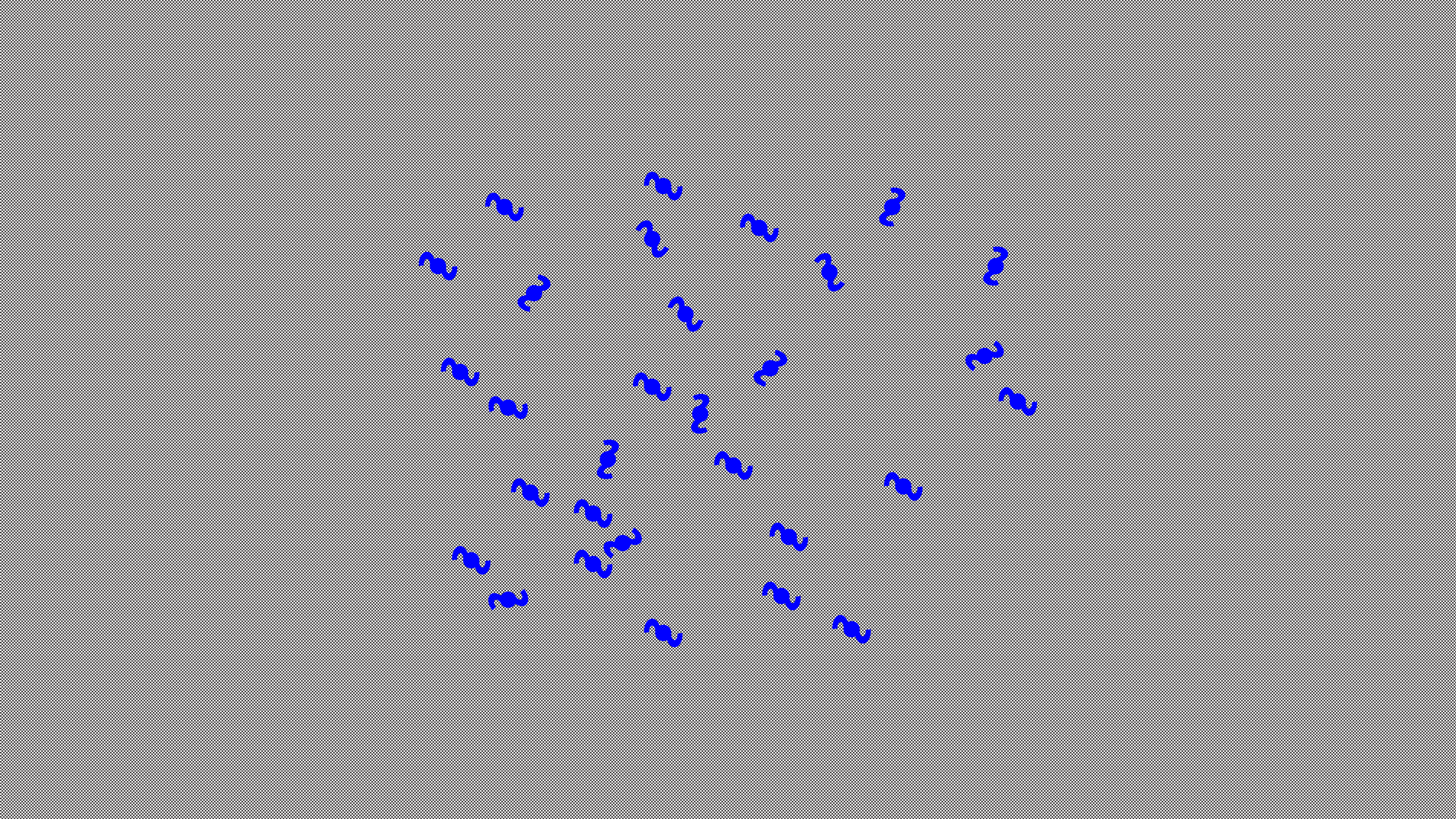
$$ds^2 = dt^2 - a(t)^2[dr^2 + r^2 d\Omega]$$

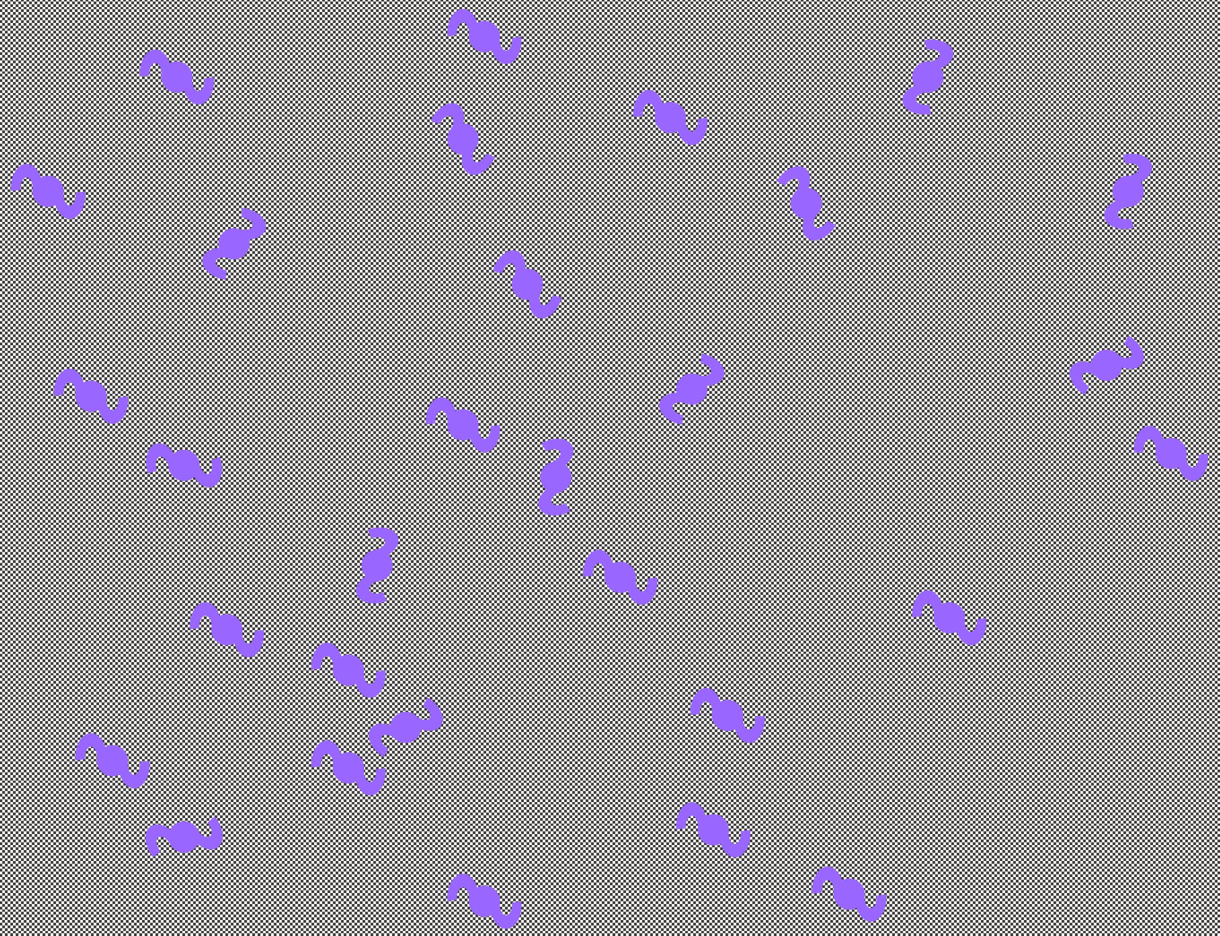
- One dof: the cosmic scale factor a(t) or R(t)

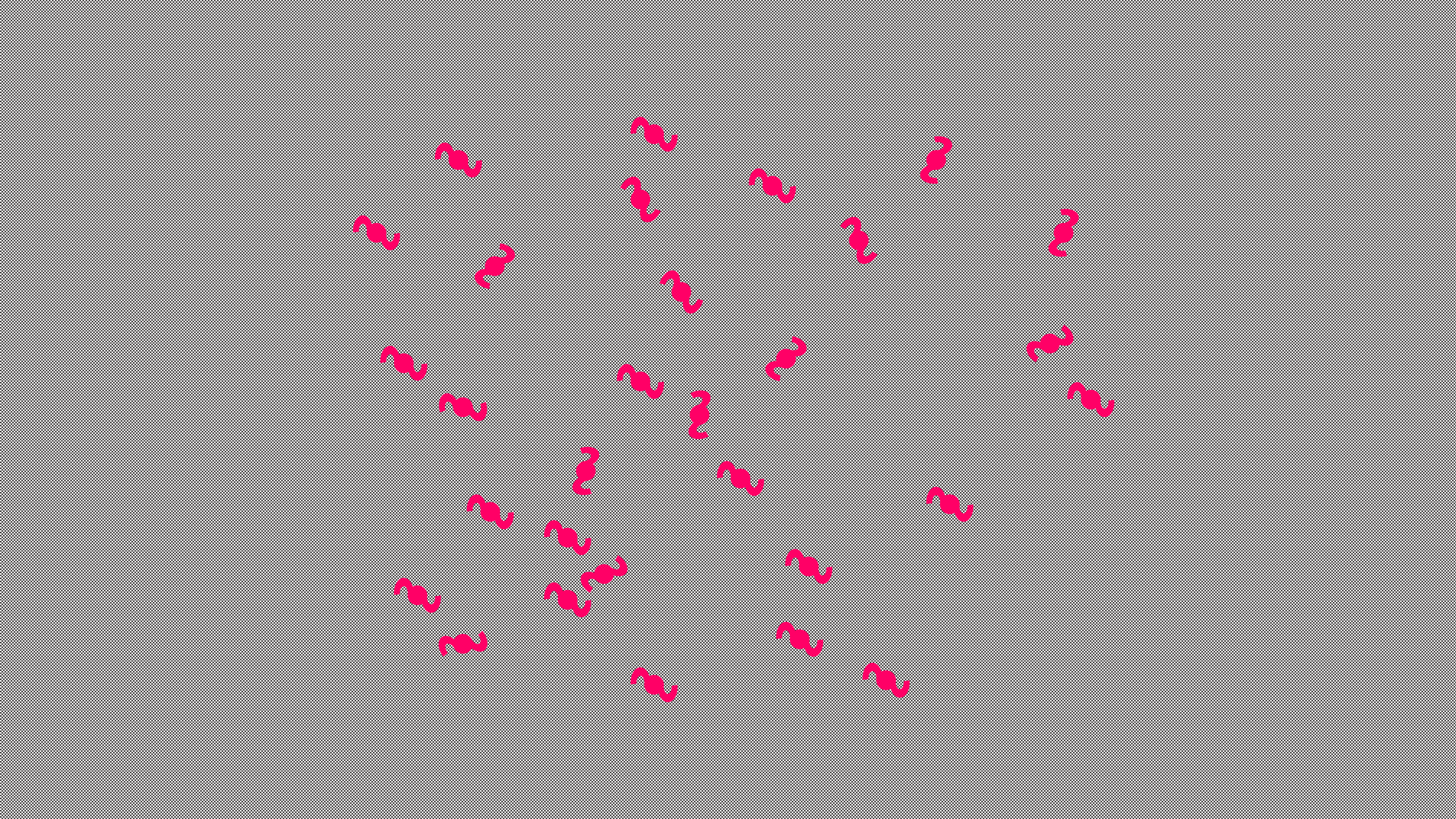


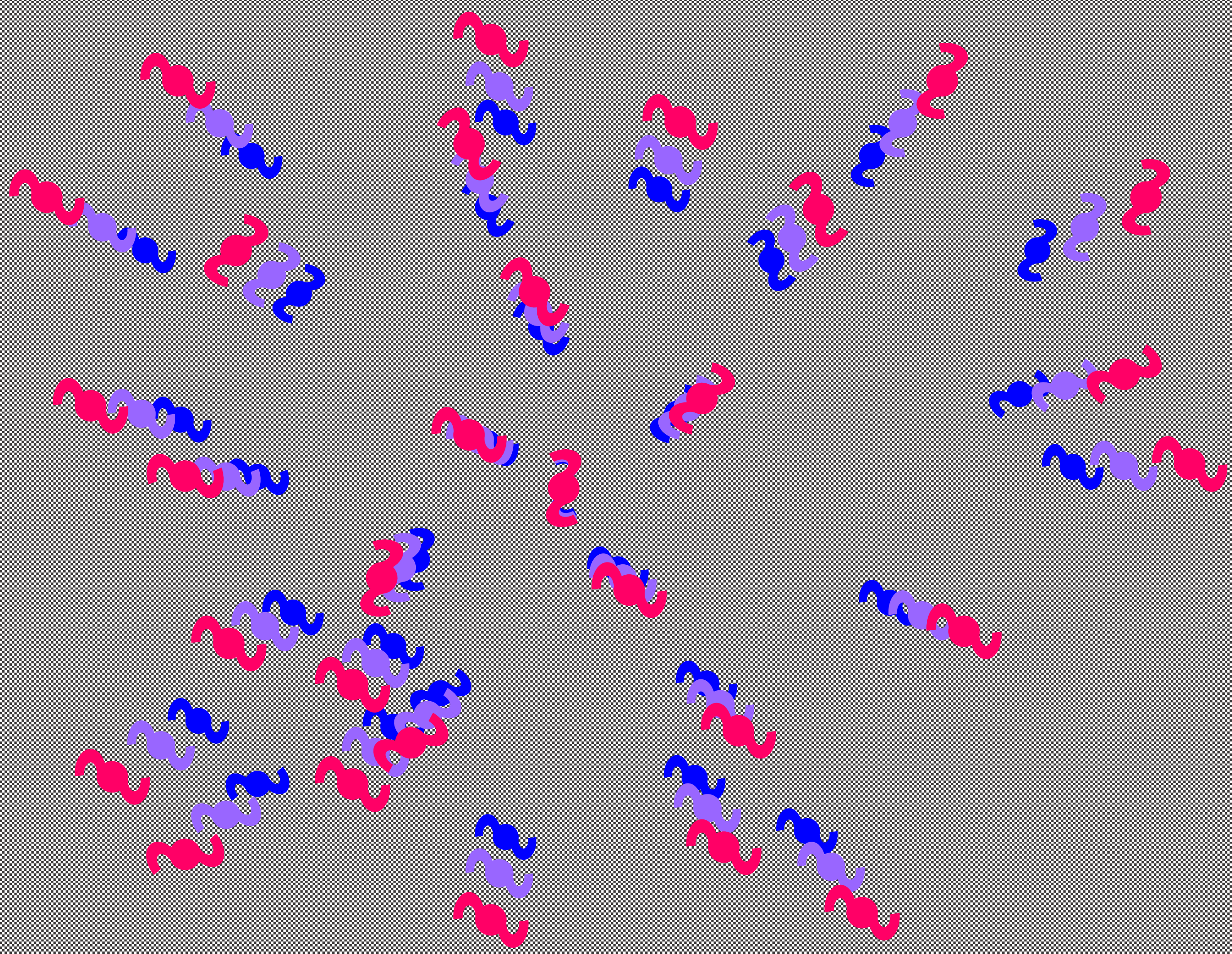
- Expansion of Universe is a scale up
- Big bang is an explosion of space
- Most important number in cosmology Hubble parameter (~1/age)

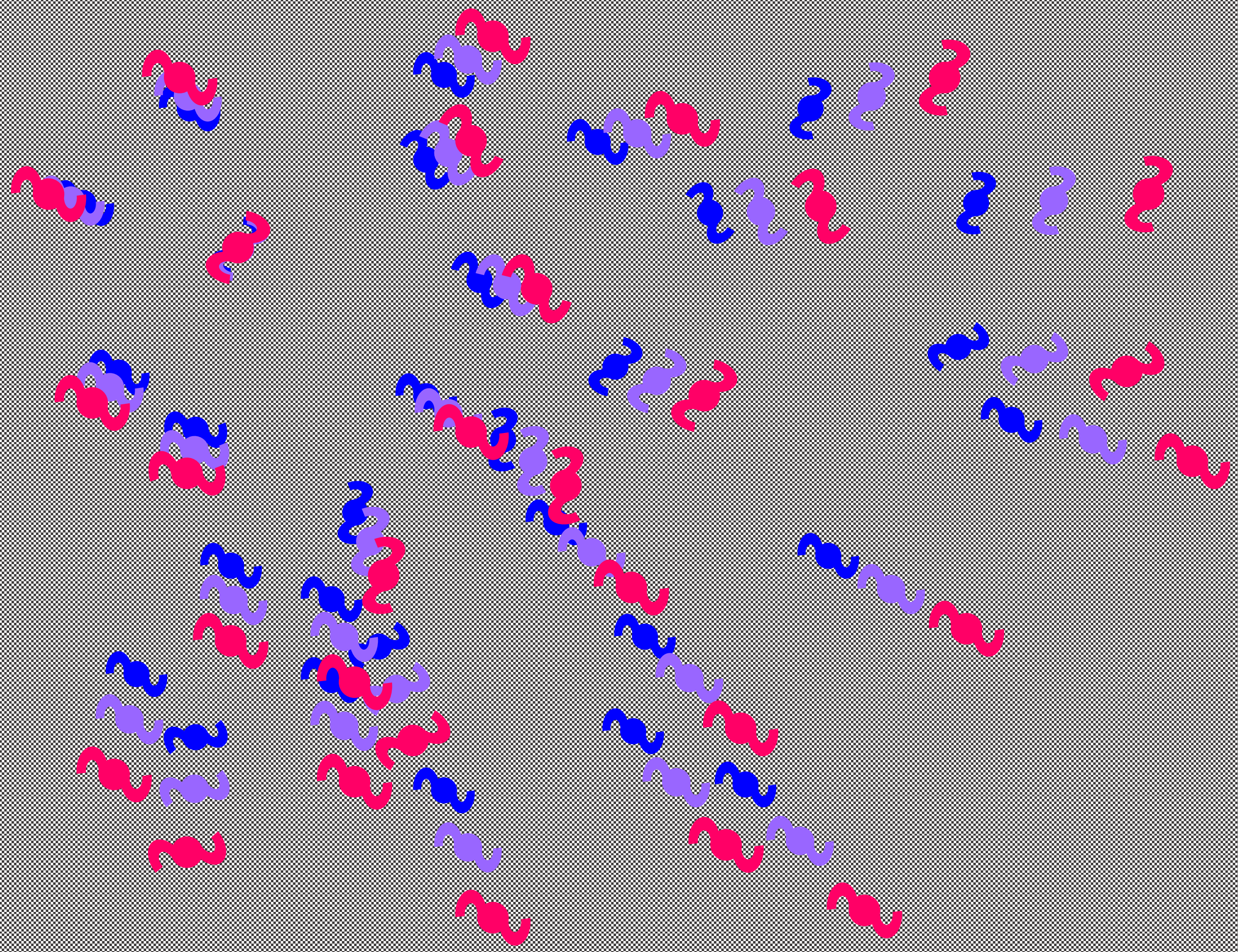
$$H \equiv \frac{\dot{a}}{a}$$

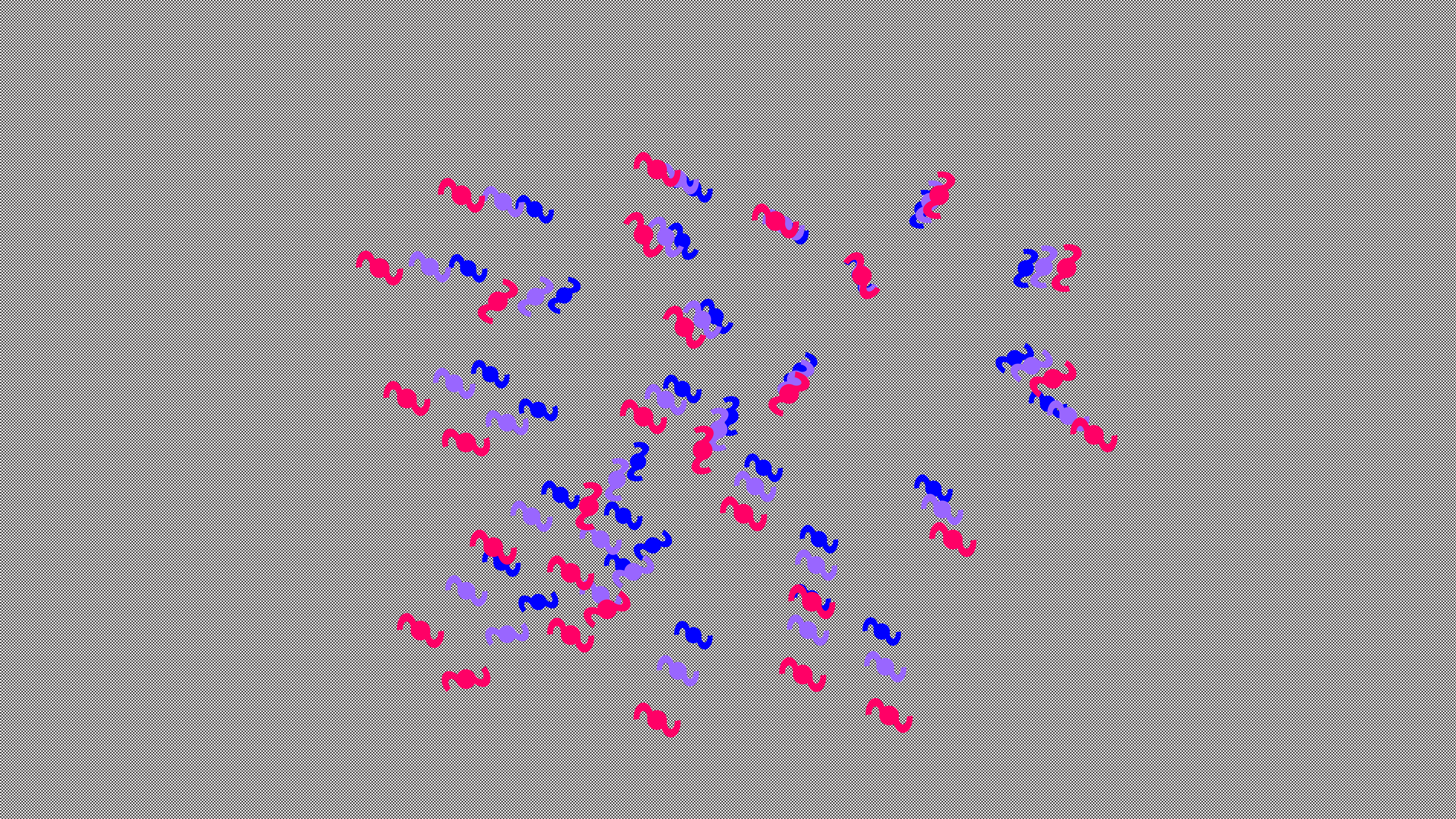








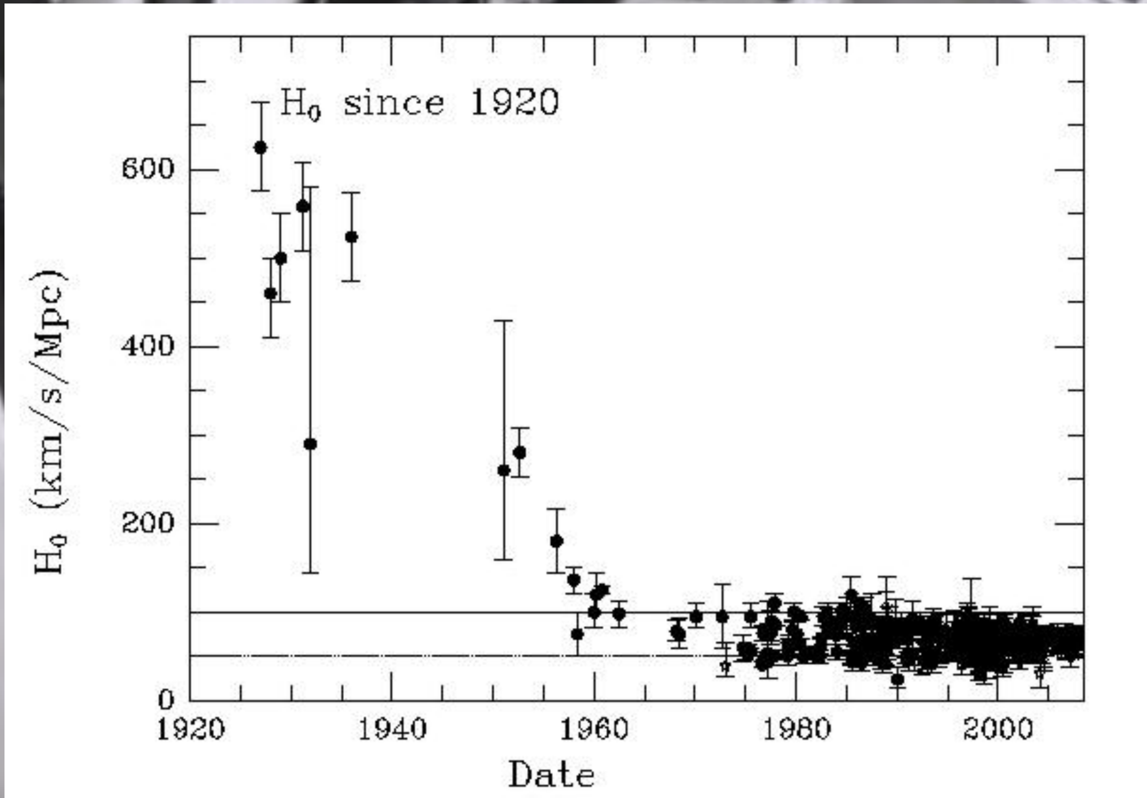


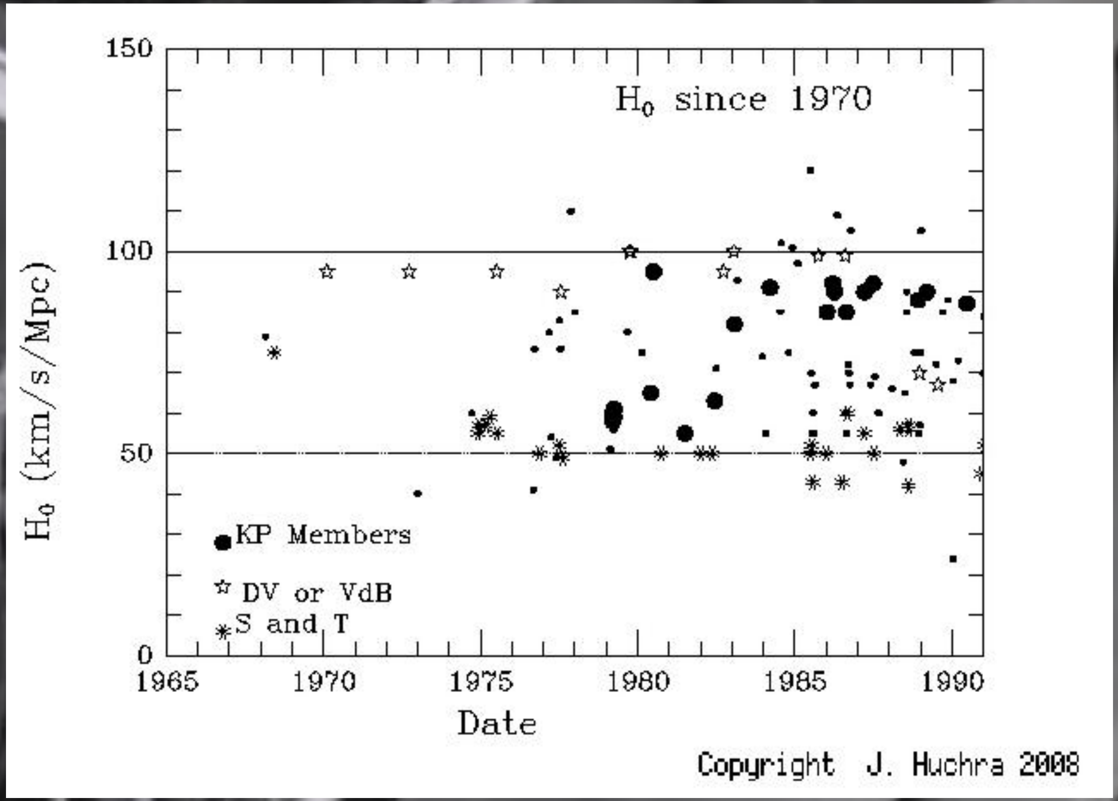


Just like Harvard, everyone is at the center of their Universe

But really, NO CENTER

Hubble troubles, part 1

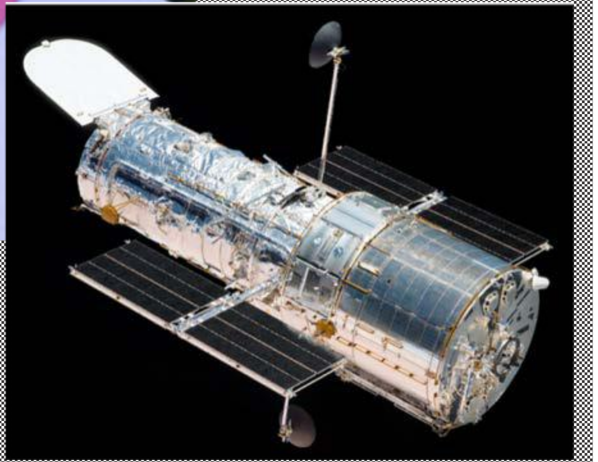


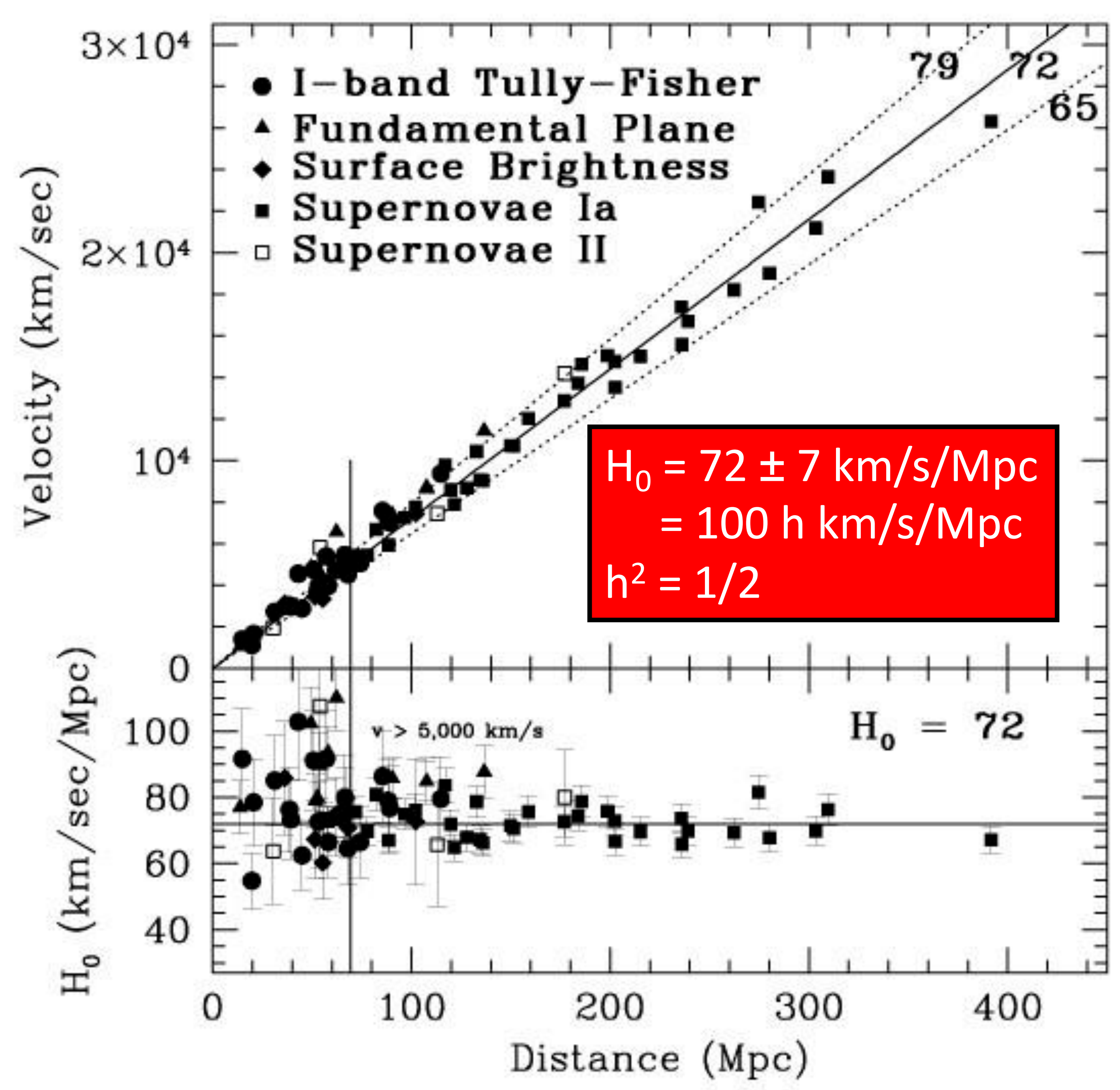


The problem with mirrors ….

Distance is the hardest thing to measure in cosmology

2001: $H_0 = 72 \pm 2 \pm 6$ km/s/Mpc





$H_0 = 72 \pm 7$ km/s/Mpc

$= 100\ h$ km/s/Mpc

$h^2 = 1/2$

Final Results from the *Hubble Space Telescope* Key Project to Measure the Hubble Constant*

Wendy L. Freedman[1], Barry F. Madore[1,2], Brad K. Gibson[3], Laura Ferrarese[4], Daniel D. Kelson[5], Shoko Sakai[6], Jeremy R. Mould[7], Robert C. Kennicutt, Jr.[8], Holland C. Ford[9], John A. Graham[5]

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The Astrophysical Journal, Volume 553, Number 1

Citation Wendy L. Freedman *et al* 2001 *ApJ* **553** 47

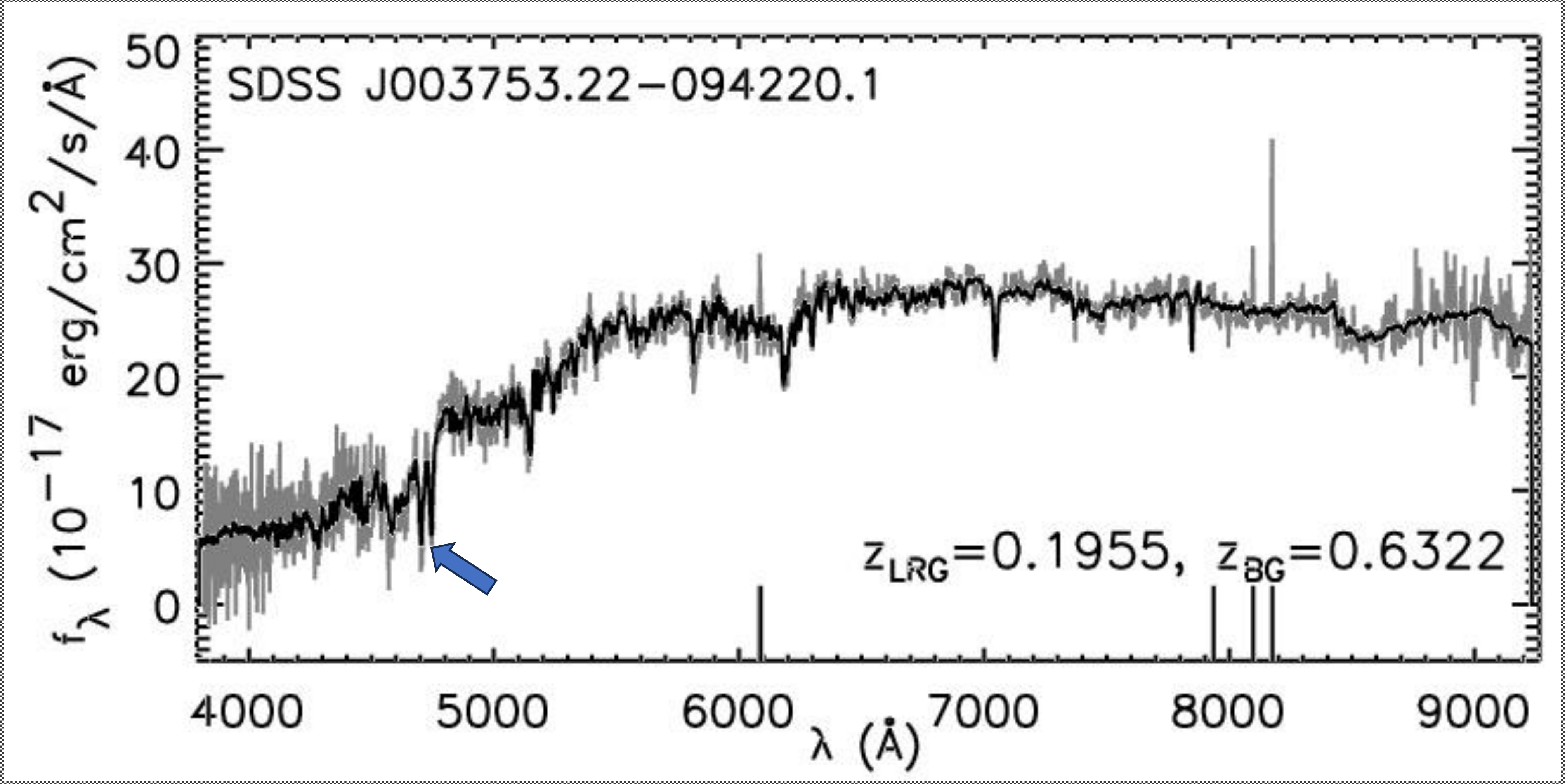
2. More kinematics of the expanding Universe

- Redshift z (IMPORTANT)

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

Redshift is the observable!

Redshift of H, K lines of Ca
Lab: 3934, 3969 Å
Observed: ~4750 Å
$1 + z = \lambda_{rcvd} / \lambda_{rest} = 4750/3950$
$z = 0.20$



Big redshifts: UV → IR

$$\text{Ly-}\alpha = 1216\,\text{Å}$$

JWST redshift 9.51 galaxy

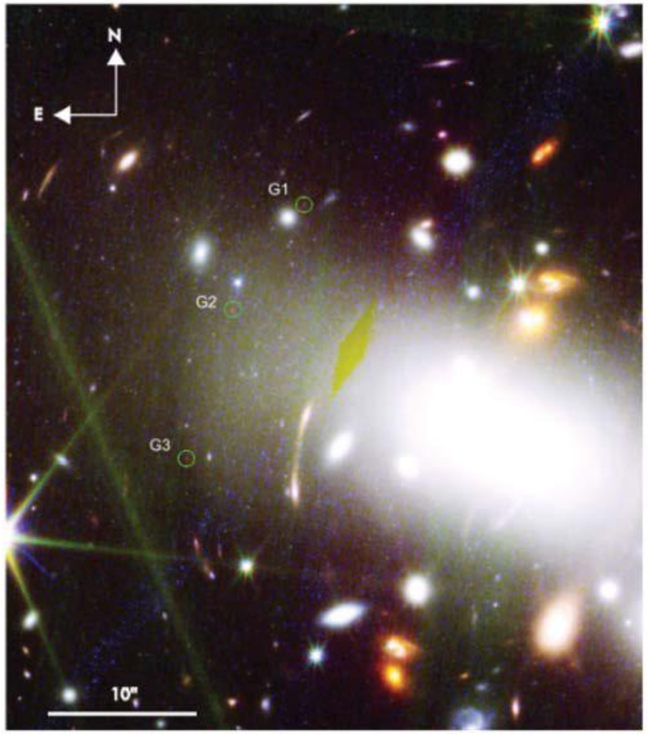


Fig. 1. Color-composite image of part of RX J2129. JWST NIRCam + HST ACS color-composite image of galaxy cluster RX J2129, with three images of the z = 9.51 galaxy circled in green. We obtained spectroscopy of image G2. Filters were assigned to RGB colors as red, JWST F277W+F356W+F444W; green, JWST F115W +F150W+F200W; and blue, HST F606W + F814W. The broad blue and green bands are diffraction spikes caused by foreground stars. The yellow diamond is an artifact caused by a chip gap in the HST ACS camera. The individual red, green, and blue images are shown in figs. S11 to S13.

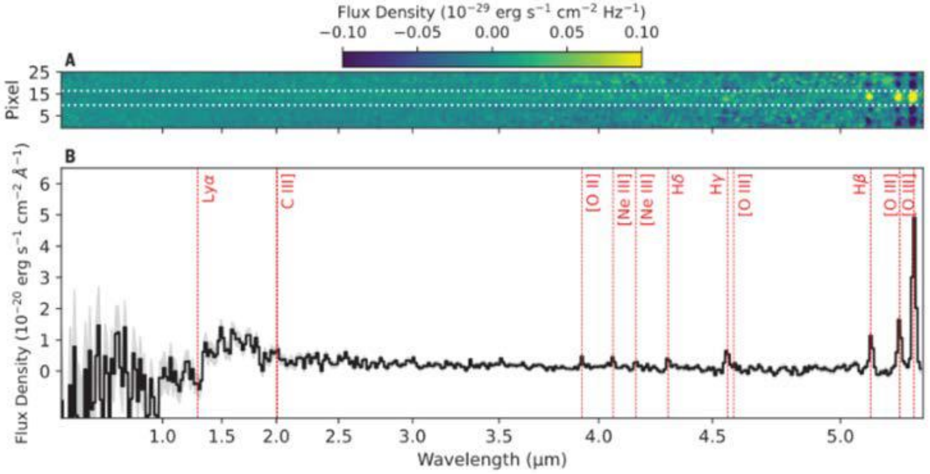
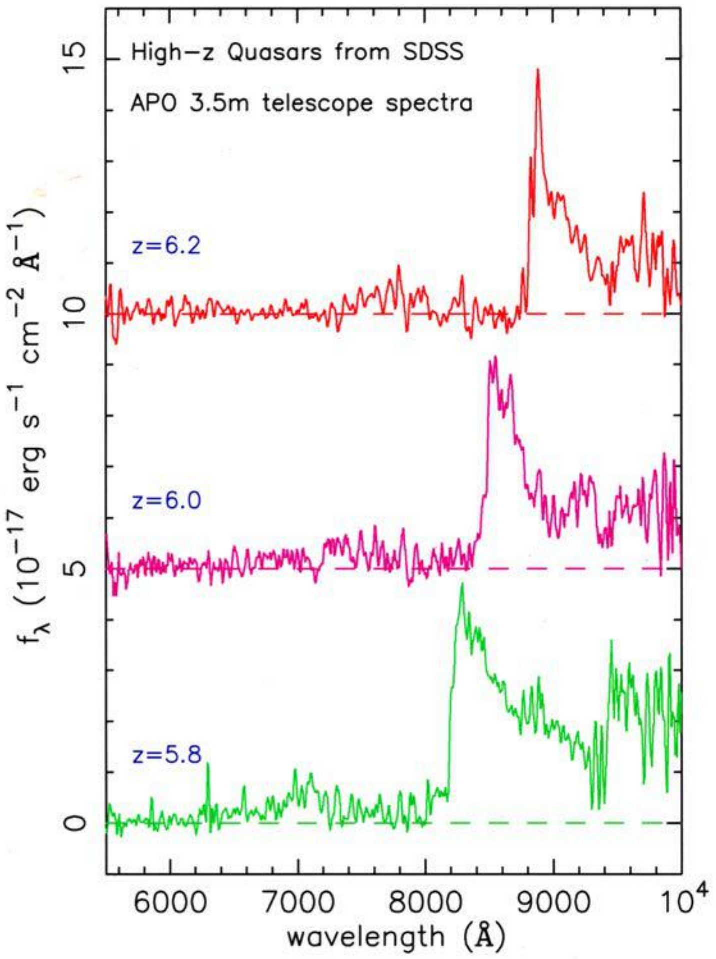


Fig. 2. Observed JWST spectrum of image G2. NIRSpec prism spectrum of image G2 of the z = 9.51 galaxy. This spectrum has not been corrected for magnification from gravitational lensing. (**A**) Two-dimensional spectrum, with flux densities indicated by the color bar. The apparent negative fluxes, in the background near the emission lines, are artifacts produced by the dither pattern used for the NIRSpec observations. The white dotted lines indicate the window used to extract the spectrum in (B). (**B**) One-dimensional spectrum. The black line is the data, with gray shading indicating its 1σ uncertainties. Red vertical lines indicate the expected wavelengths of emission lines for z = 9.51.

SDSS High-z quasars



The Astrophysical Journal Letters, 907:L1 (7pp), 2021 January 20 https://doi.org/10.3847/2041-8213/abd8c6

A Luminous Quasar at Redshift 7.642

Feige Wang[1,15], Jinyi Yang[1,16], Xiaohui Fan[1], Joseph F. Hennawi[2,3], Aaron J. Barth[4], Eduardo Banados[3], Fuyan Bian[5], Konstantina Boutsia[6], Thomas Connor[7], Frederick B. Davies[3,8], Roberto Decarli[9], Anna-Christina Eilers[10,15], Emanuele Paolo Farina[11], Richard Green[1], Linhua Jiang[12], Jiang-Tao Li[13], Chiara Mazzucchelli[5], Riccardo Nanni[2], Jan-Torge Schindler[3], Bram Venemans[3], Fabian Walter[3], Xue-Bing Wu[12,14], and Minghao Yue[1]

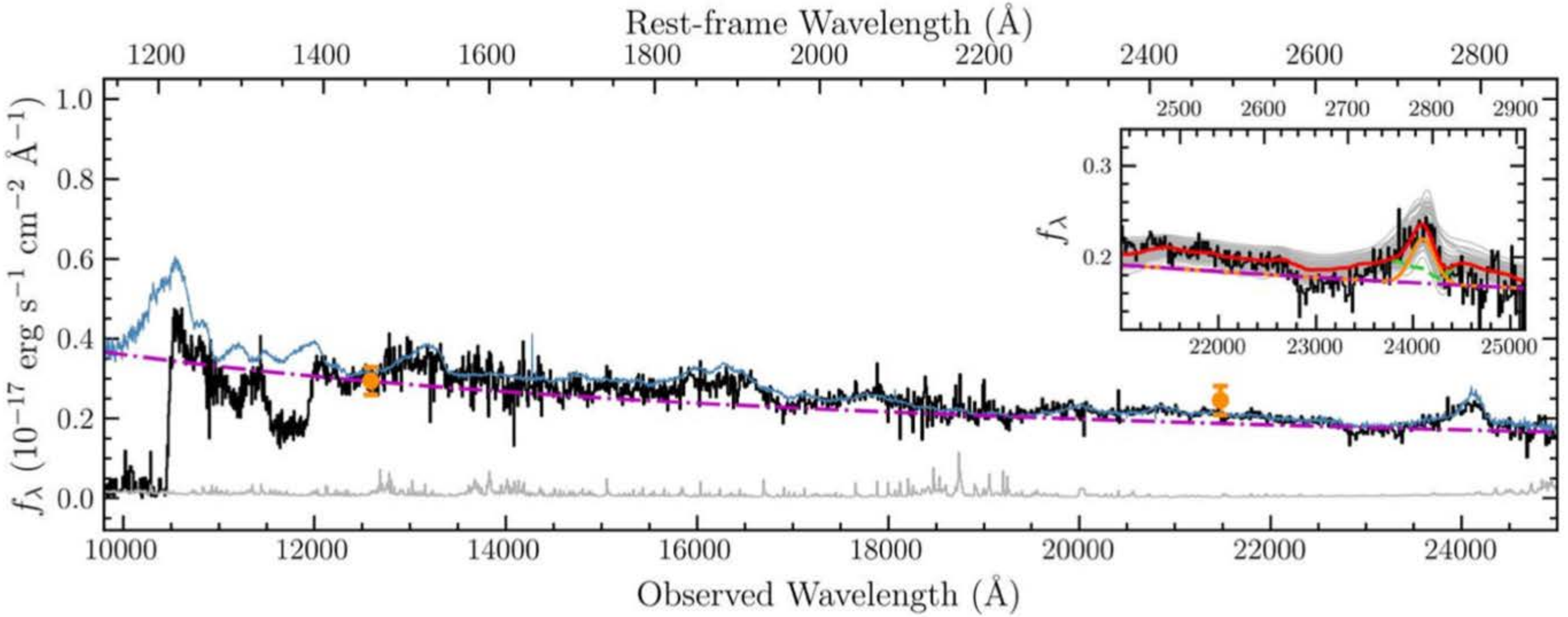


Figure 1. Top panel: image cutouts (20″ × 20″, north is up and east is to the left) for J0313–1806 in PS1 *z*, PS1 *y*, DELS *z*, VISTA *J*, VISTA *K*s, WISE W1, and WISE W2 bands. The photometry is given in Table 1. Bottom panel: the final stacked spectrum of J0313–1806. In the figure, we re-binned the spectrum by two spectral pixels (∼173 km s^{-1}) for illustration purposes. The black and gray lines represent the Galactic extinction-corrected spectrum and the error vector, respectively. The blue line denotes the quasar composite spectrum constructed with Sloan Digital Sky Survey (SDSS) $z \sim 2$ quasars having similar C IV blueshifts and line strengths. The purple dashed line denotes the power-law continuum. The orange points are flux densities determined from photometry in the *J*- and *K*s-bands. The inset panel shows the Mg II line fitting with the purple dotted–dashed line denoting the power-law continuum, the green dashed line denoting the pseudo-continuum model (the sum of power-law continuum, Fe II emission, and Balmer continuum), the orange line representing the Gaussian fitting of the Mg II line and the red line representing the total fit of pseudo-continuum and Mg II line. The thin gray lines in the insert panel represent the spectral fitting of 100 mock spectra as described in Section 3.

Just can't get enough of those high redshift galaxies: z = 10 to 13

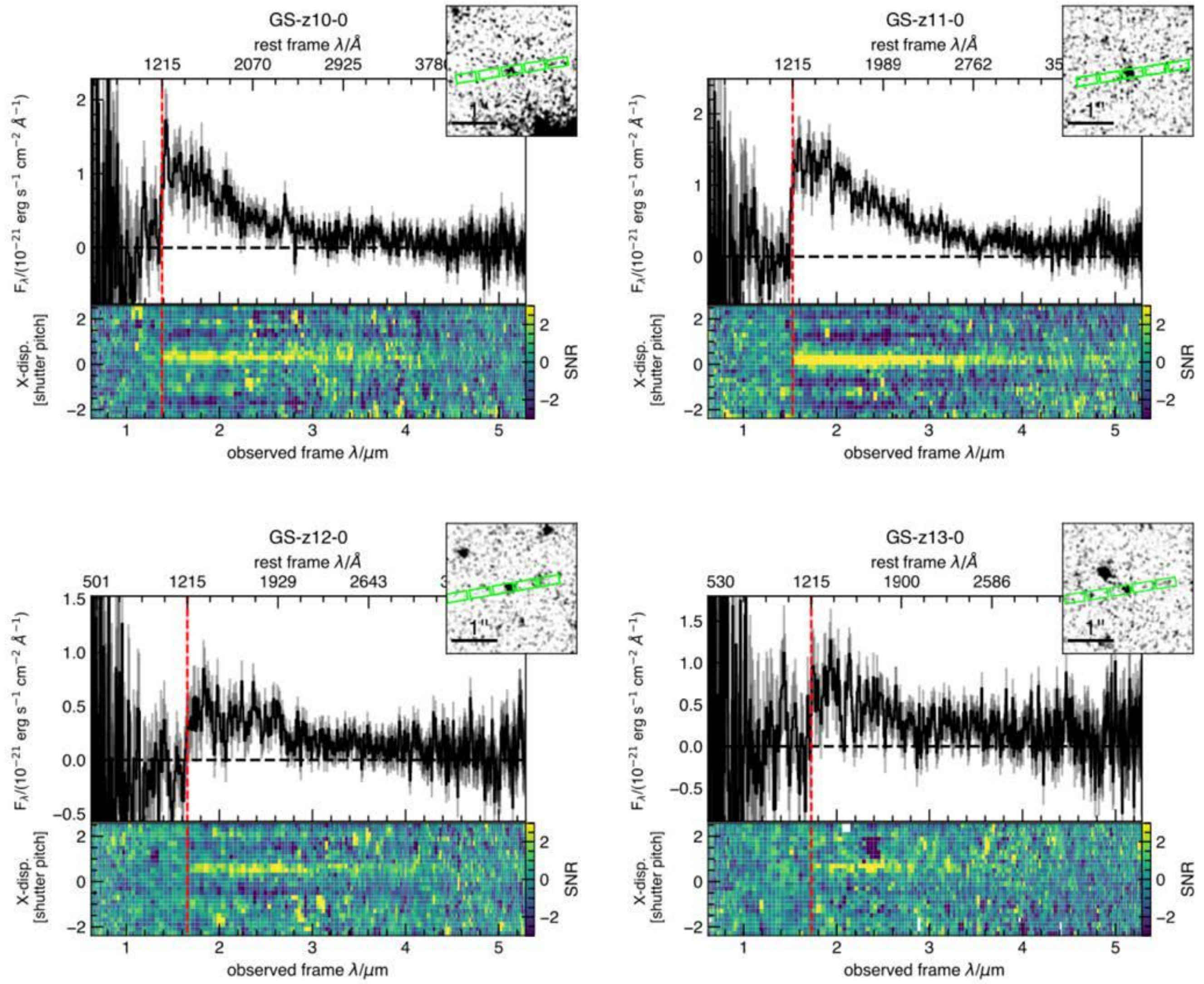


Fig. 1 NIRSpec prism R ~ 100 spectra for the four z > 10 galaxies targeted for the first deep spectroscopic pointing of the JADES survey, JADES-GS-z10-0, JADES-GS-z11-0, JADES-GS-z12-0 and JADES-GS-z13-0. For each galaxy we display the 1D spectrum and associated 1σ uncertainties (which are derived from standard error propagation through the reduction pipeline). In the bottom panel we show the 2D signal-to-noise ratio plot. The 2D plot is binned over four pixels in the wavelength direction to better show the contrast across the break. The inset panel in the top right-hand corner shows the NIRCam F444W filter image with the three nodding positions of the NIRSpec micro-shutter 3-slitlet array aperture shown in green. The red dashed line shows 1215.67Å at the observed redshift z_{1216}.

Spectroscopic confirmation of four metal-poor galaxies at z=10.3-13.2

Emma Curtis-Lake[1*], Stefano Carniani[2†], Alex Cameron[3], Stephane Charlot[4], Peter Jakobsen[5,6], Roberto Maiolino[7,8,9], Andrew Bunker[3], Joris Witstok[7,8], Renske Smit[10], Jacopo Chevallard[3], Chris Willott[11], Pierre Ferruit[12], Santiago Arribas[13], Nina Bonaventura[5,6], Mirko Curti[7,8], Francesco D'Eugenio[7,8], Marijn Franx[14], Giovanna Giardino[15], Tobias J. Looser[7,8], Nora Lützgendorf[16], Michael V. Maseda[17], Tim Rawle[16], Hans-Walter Rix[18], Bruno Rodríguez del Pino[13], Hannah Übler[7,8], Marco Sirianni[16], Alan Dressler[19], Eiichi Egami[20], Daniel J. Eisenstein[21], Ryan Endsley[22], Kevin Hainline[20], Ryan Hausen[23], Benjamin D. Johnson[21], Marcia Rieke[20], Brant Robertson[24], Irene Shivaei[20], Daniel P. Stark[20], Sandro Tacchella[7,8], Christina C. Williams[25], Christopher N. A. Willmer[20], Rachana Bhatawdekar[26], Rebecca Bowler[27], Kristan Boyett[28,29], Zuyi Chen[20], Anna de Graaff[18], Jakob M. Helton[20], Raphael E. Hviding[20], Gareth C. Jones[3], Nimisha Kumari[30], Jianwei Lyu[20], Erica Nelson[31], Michele Perna[13], Lester Sandles[7,8], Aayush Saxena[3,9], Katherine A. Suess[24,32], Fengwu Sun[20], Michael W. Topping[20], Imaan E. B. Wallace[3] and Lily Whitler[20]

2. More kinematics of the expanding Universe

- Redshift z (IMPORTANT)

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

- Age

$$dt = -\frac{dz}{H(z)(1+z)} \quad \Rightarrow \quad t(z) = \int_0^z \frac{dz}{(1+z)H(z)} \;\; \& \;\; t_0 = \int_0^\infty \frac{dz}{(1+z)H(z)}$$

- Luminosity distance

$$F \equiv \frac{\mathcal{L}}{4\pi d_L^2} \quad \Rightarrow \quad d_L(z) = (1+z)r(z)$$

- Comoving distance to z

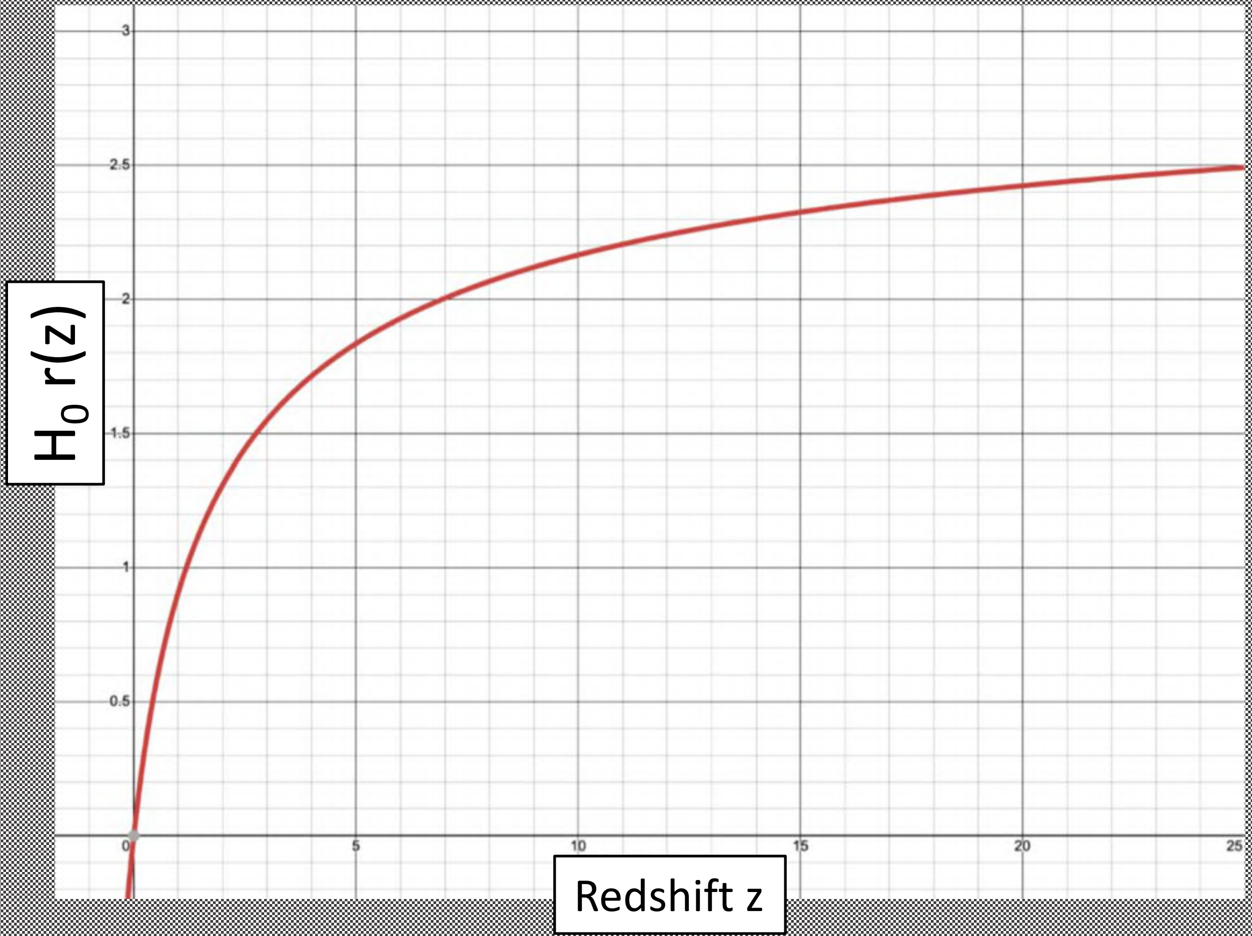
$$dr = dt/a(t) \quad \Rightarrow \quad r(z) = \int_0^z dz/H(z)$$

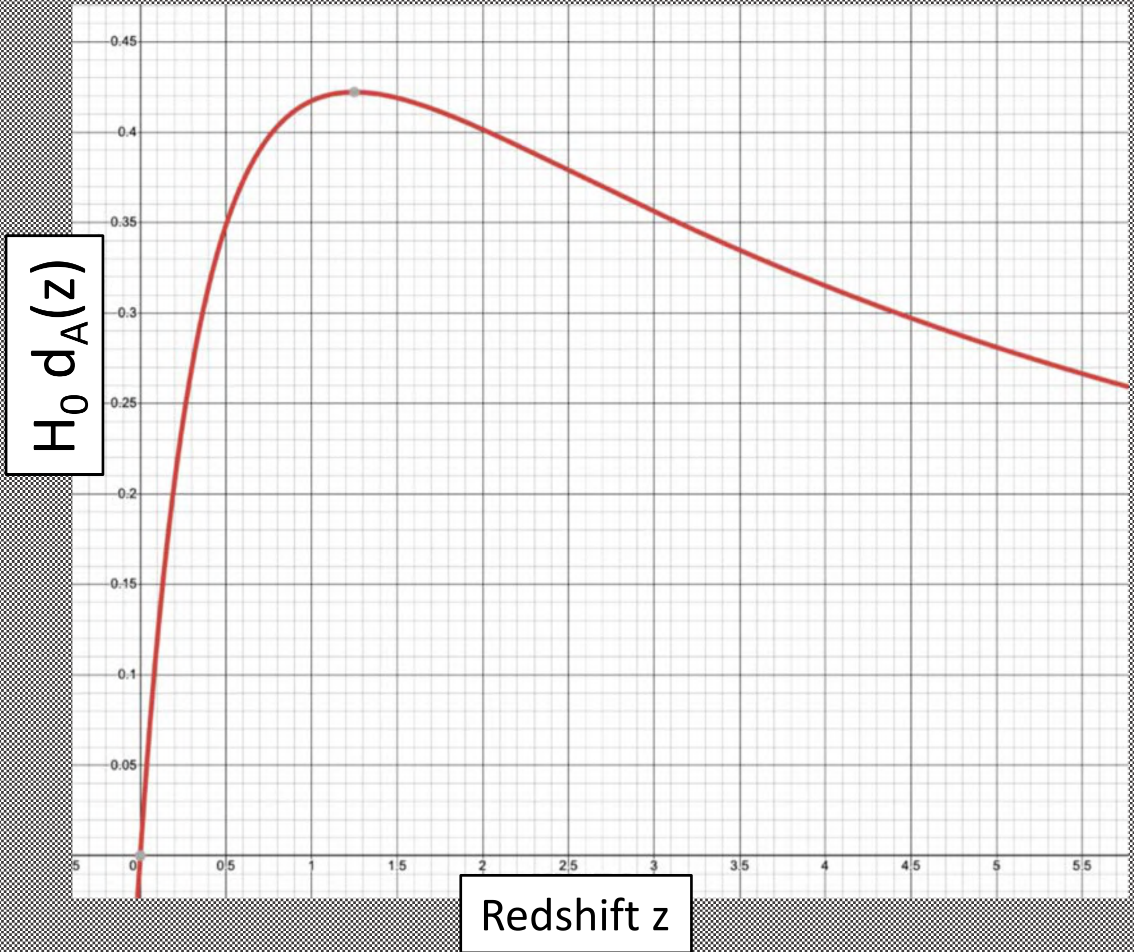
- Angular distance

$$\Delta\theta \equiv \frac{L}{d_A} \quad \Rightarrow \quad d_A = r(z)/(1+z) = d_L/(1+z)^2$$

Back to cosmological distances

- For small z: r, d_A, and $d_L = z\, H_0^{-1}$ (H_0^{-1} = 4300 Mpc = 14 Gyr)
- $r(z)_L$ asymptotes to 3.2 H_0^{-1} and d_A decreases at large z (rulers look bigger!)





3. Matter dynamics

- How free particles move: 3-momenta redshift as 1/a

$$\vec{p} \propto 1/a \qquad \Rightarrow \qquad \mathrm{E} \propto 1/a \;\; \mathrm{UR} \qquad \mathrm{KE} \propto 1/a^2 \;\; \mathrm{NR}$$

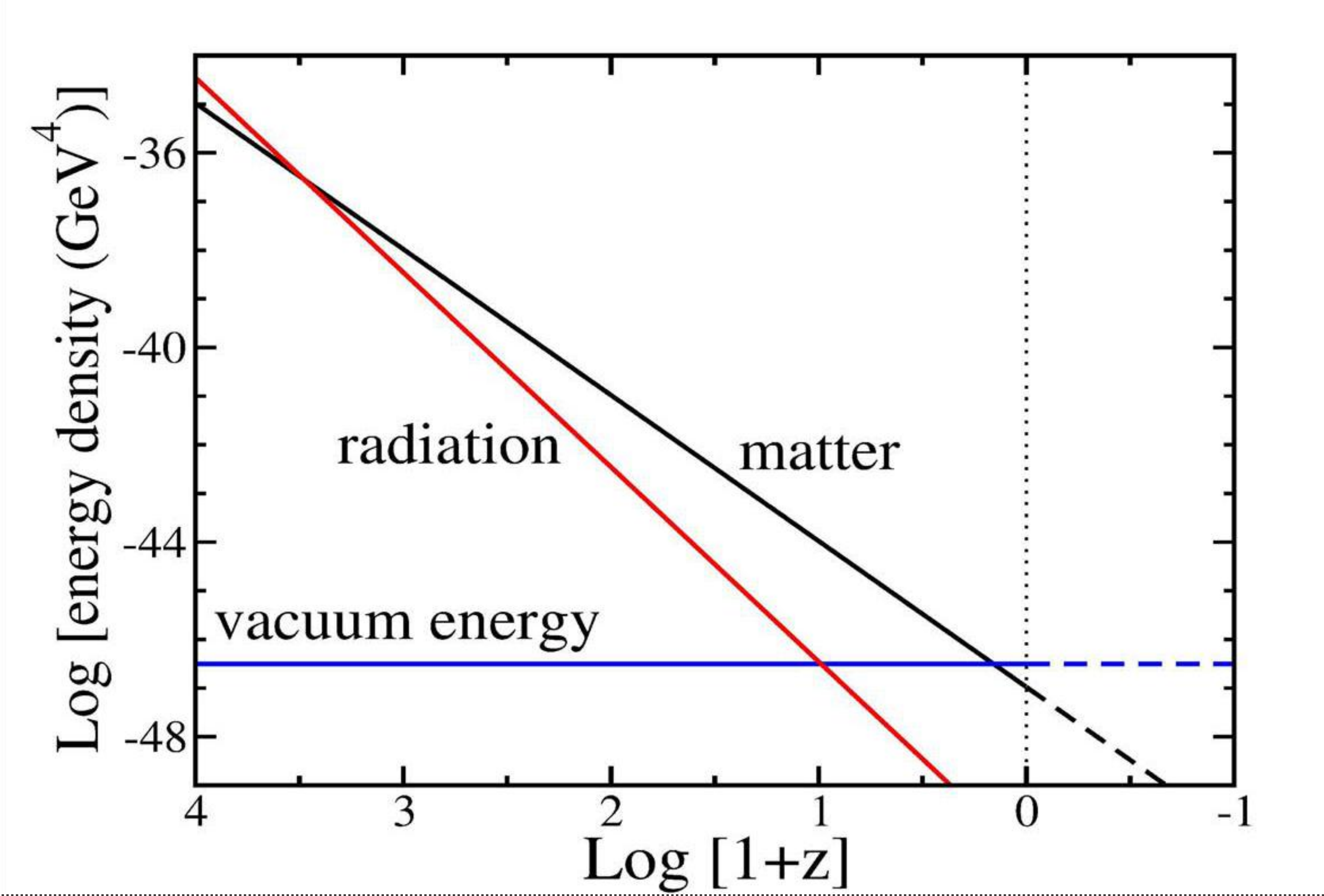
- How "fluids" evolve

$$\begin{aligned} d(\rho a^3) &= -p d(a^3) && \text{“First Law”} \\ \rho &\propto a^{-3(1+w)} && \text{for } p = w\rho \end{aligned}$$

$$\begin{aligned} &\text{Matter } (w=0)\text{: } \rho \propto a^{-3} \qquad \propto (1+z)^3 \\ &\text{Radiation } (w=1/3)\text{: } \rho \propto a^{-4} \qquad \propto (1+z)^4 \\ &\text{Vacuum Energy } \Lambda \ (w=-1)\text{: } \qquad \rho \propto \text{const} \end{aligned}$$

Three epochs: Radiation dominated, Matter dominated, and Dark Energy dominated

- Radiation epoch
  - Thermal bath of particles (quark soup)
  - Origin of dark matter
  - Baryogenesis
  - Inflation
- Matter era
  - Growth of structure
  - Formation of CMB
- Vacuum era
  - Where we find ourselves
  - Unknown future



4. Dynamics: Matter and spacetime together

- Friedmann Equations:

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

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

- Hubble parameter

$$H(z)^2 = H_0^2\left[\Omega_\Lambda + \Omega_M(1+z)^3 + \Omega_R(1+z)^4\right]$$

- Scale factor

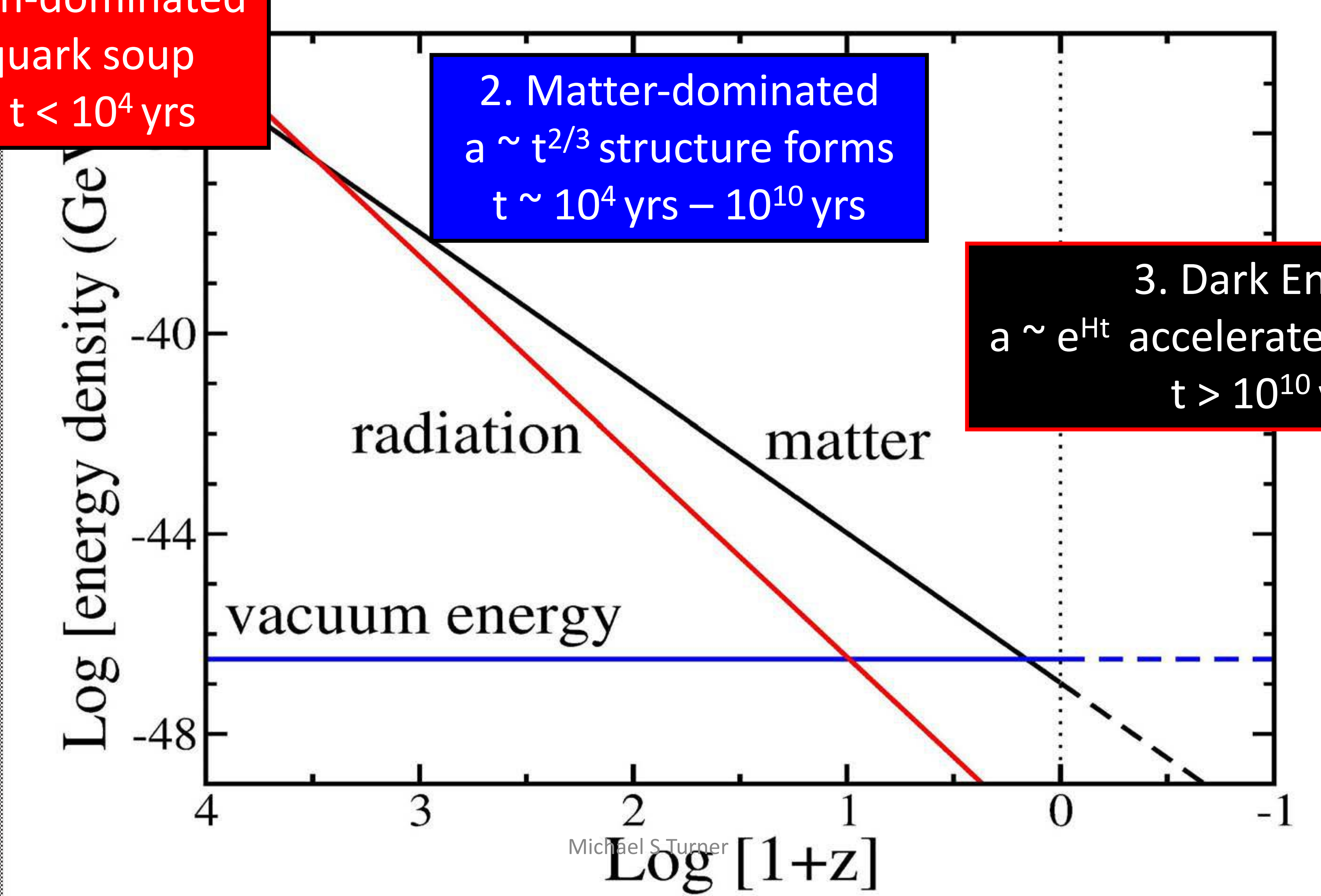
Radiation-dominated $(z > 3000)$: $a \propto t^{1/2}$
Matter-dominated $(3000 > z > 1)$: $a \propto t^{2/3}$
Vacuum-Energy-dominated $(z < 1)$: $a \propto \exp(Ht)$

5. The 3 epochs of cosmology

1. Radiation-dominated
$a \sim t^{1/2}$ quark soup
$a < 10^{-4}$, $t < 10^{4}$ yrs

2. Matter-dominated
$a \sim t^{2/3}$ structure forms
$t \sim 10^{4}$ yrs – 10^{10} yrs

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



Age of the Universe

$$t_0 = \int_0^\infty \frac{dz}{(1+z)H(z)}$$

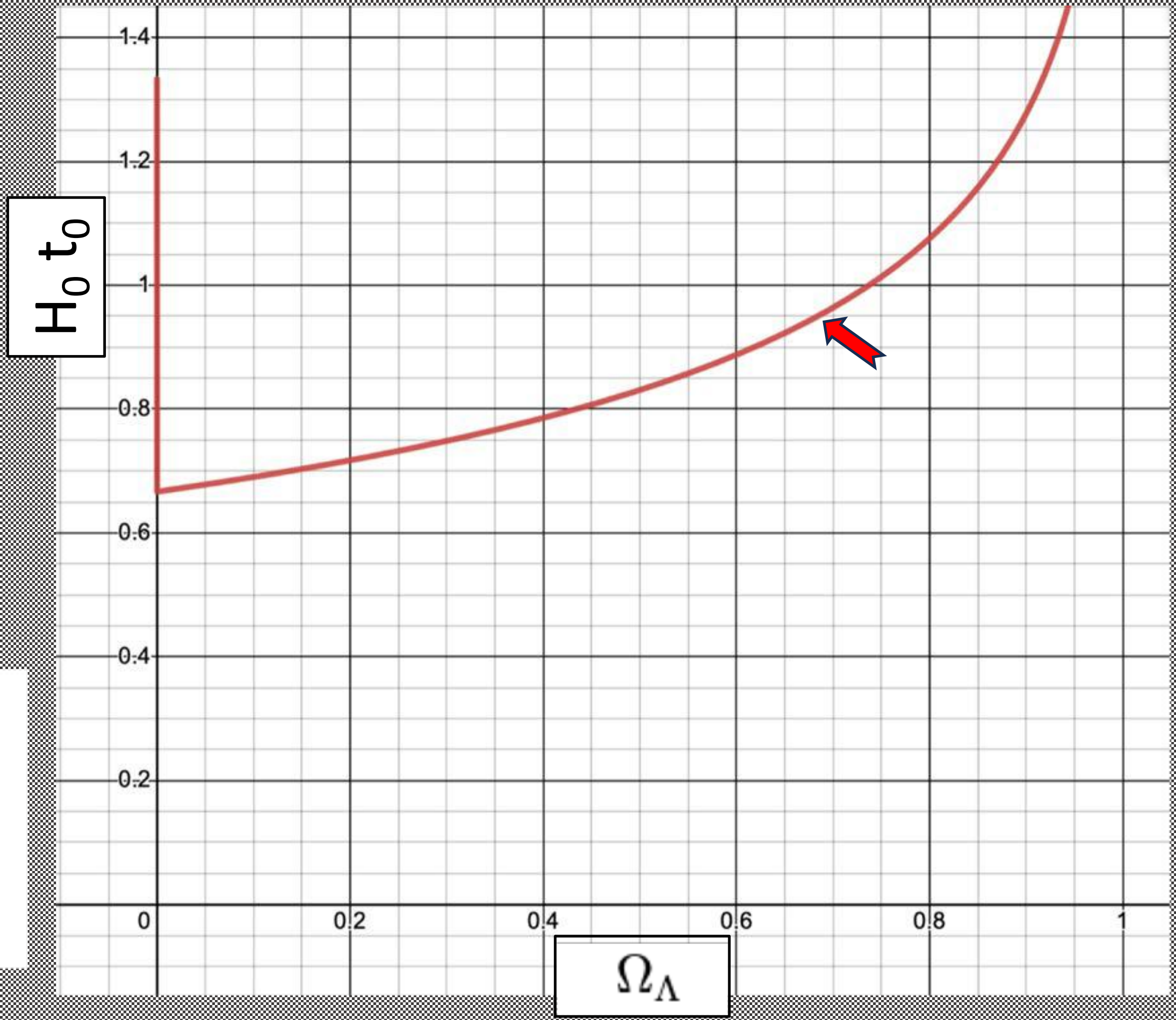
$$H = \dot{a}/a = n/t \quad \text{for} \quad a \propto t^n$$

$$t = 2H^{-1}/3 \quad \text{MD}$$

$$t = H^{-1}/2 \quad \text{RD}$$

$$\text{for } \Lambda\text{CDM } t_0 \simeq H_0^{-1}$$

$$t_0 = \frac{2}{3} H_0^{-1} \Omega_{\text{VAC}}^{-1/2} \ln\left[\frac{1+\Omega_{\text{VAC}}^{1/2}}{(1-\Omega_{\text{VAC}})^{1/2}}\right]$$



One last thing, horizons (how far you can see on a clear day)

- Universe was smaller, but was expanding fast
- Light travels only about c x t since the beginning (mostly in the last Hubble time)

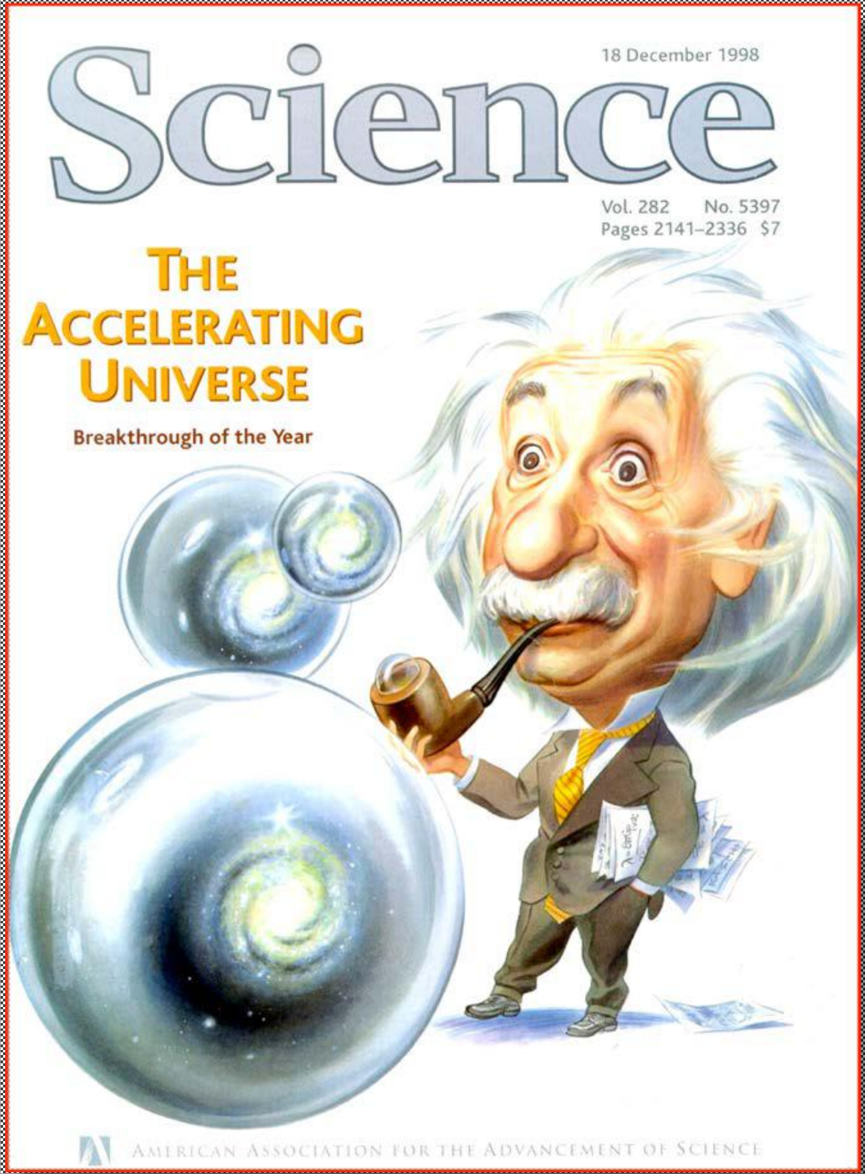
$$d_H(t) \equiv a(t) \int_0^t dr = a(t) \int_0^t \frac{dt'}{a(t')} = \frac{t}{1-n} = \frac{n}{1-n} H^{-1}$$

$$d_H(t) = 3t = 2H^{-1} \quad \mathrm{MD}$$

$$d_H(t) = 2t = H^{-1} \quad \mathrm{RD}$$

- This is known as the “horizon problem”: can’t smooth or create inhomogeneities on very large scales

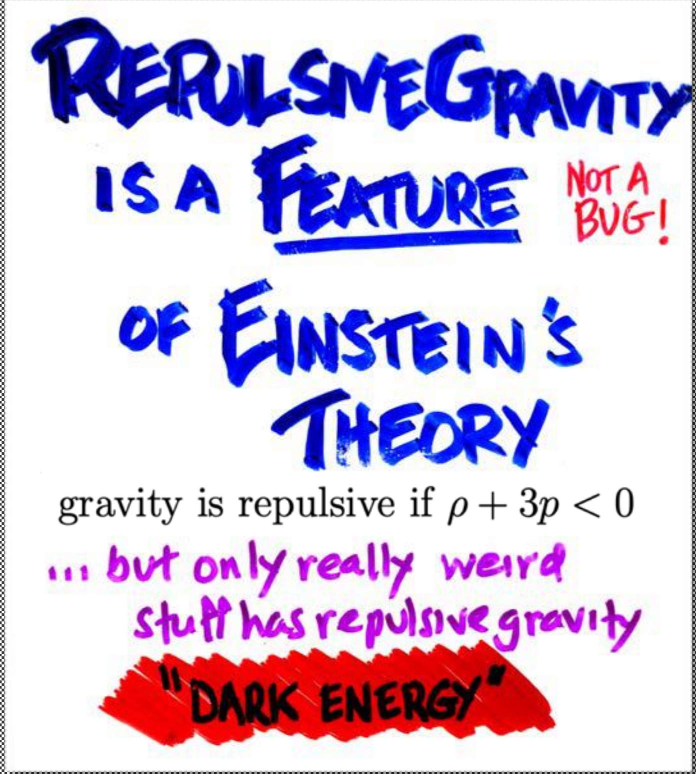
1998: Cosmic speed up and dark energy



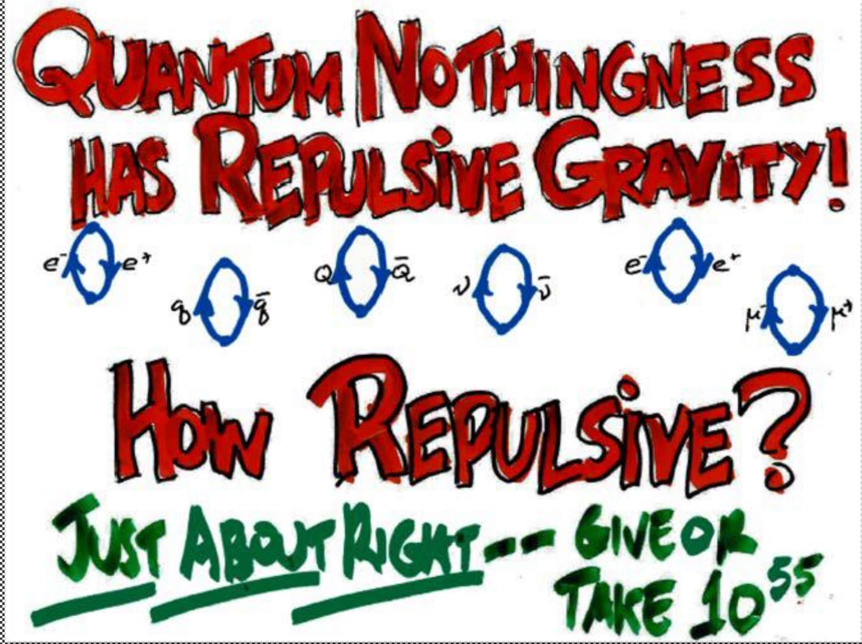
- Λ (vacuum energy) fits the date but why so small?
- Evidence of the rich vacua of string theory and the multiverse?
- Related to inflation (accelerated expansion) or something else?
- Describe by equation-of-state

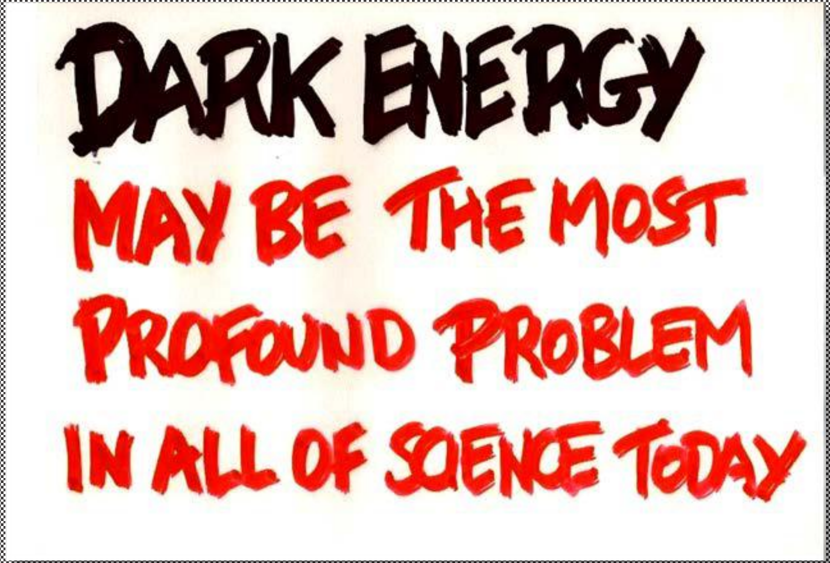
$$p = w\rho$$

$$w = -1.0 \pm 0.04$$



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





Gravity is sourced by energy + 3 x pressure → BHs and repulsive gravity!!!

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Michael S. Turner

UCLA and UChicago

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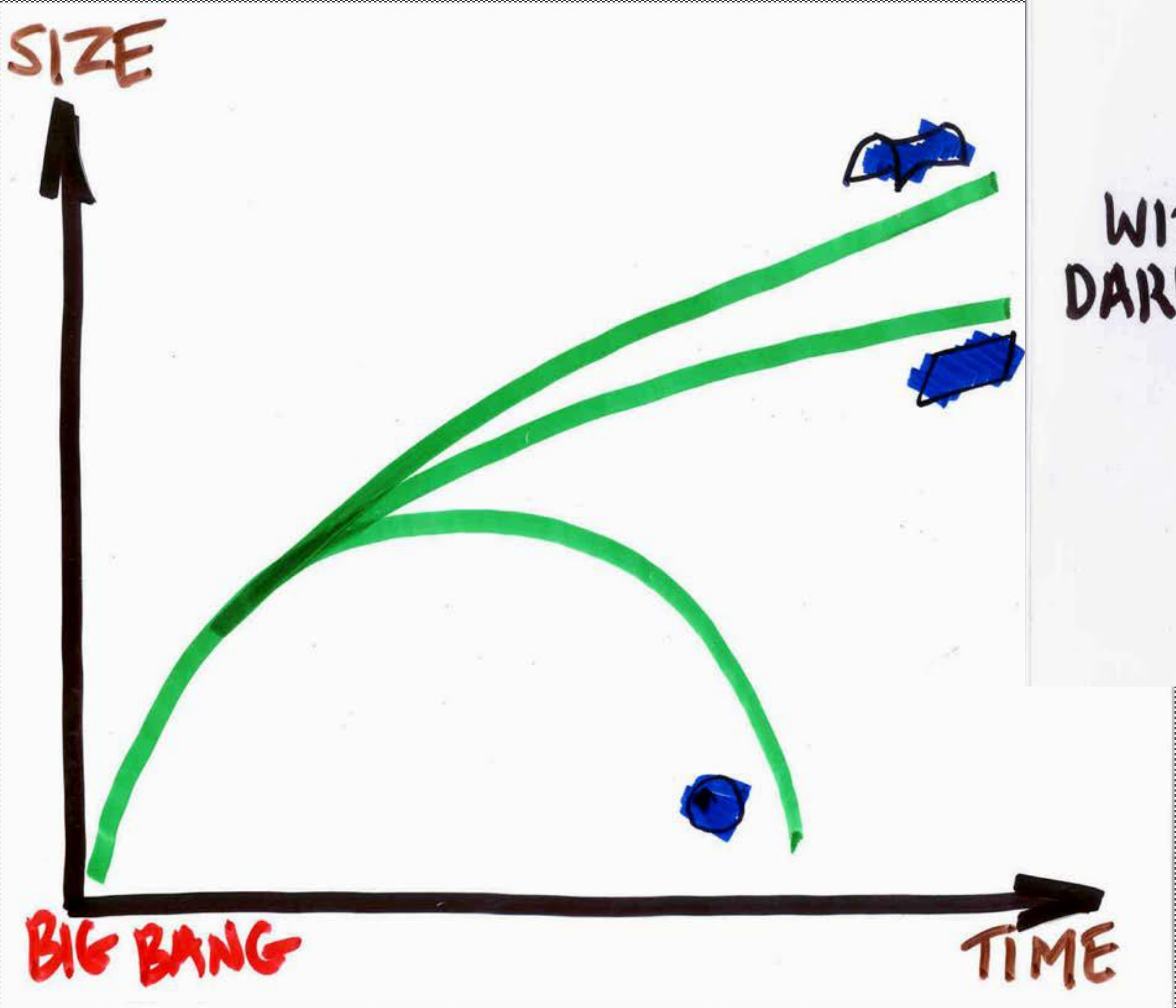
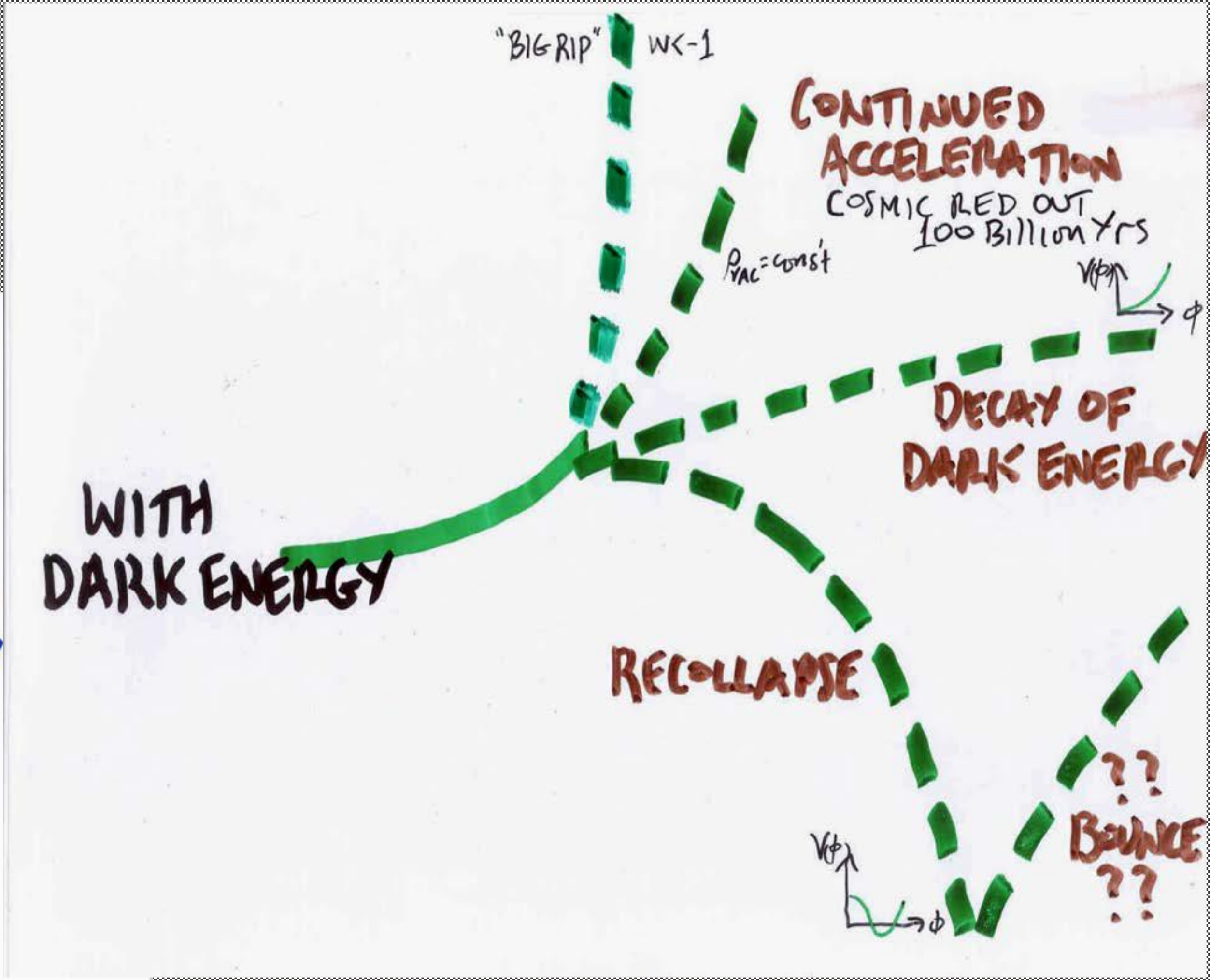
Cosmic Destiny





In the presence of dark energy, a flat Universe can expand forever, re-collapse, or even experience a big rip!

The Standard Cosmology (ΛCDM) in plain English

… very-early accelerated expansion driven by the potential energy of a scalar field gives rise to a very-large, smooth, spatially flat patch that becomes all that we can see today. Quantum fluctuations during this inflationary phase grow into the seeds for galaxies. The conversion of potential field energy into heat produces the quark soup that evolves a baryon asymmetry and long-lived dark matter particles. The excess of quarks over antiquarks becomes neutrons and protons, later some light elements and finally atoms. The gravity of the dark matter particles drives the formation of structure from galaxies to superclusters and a mere 5 billion years ago the repulsive gravity of dark energy (Λ) again drove accelerated expansion …

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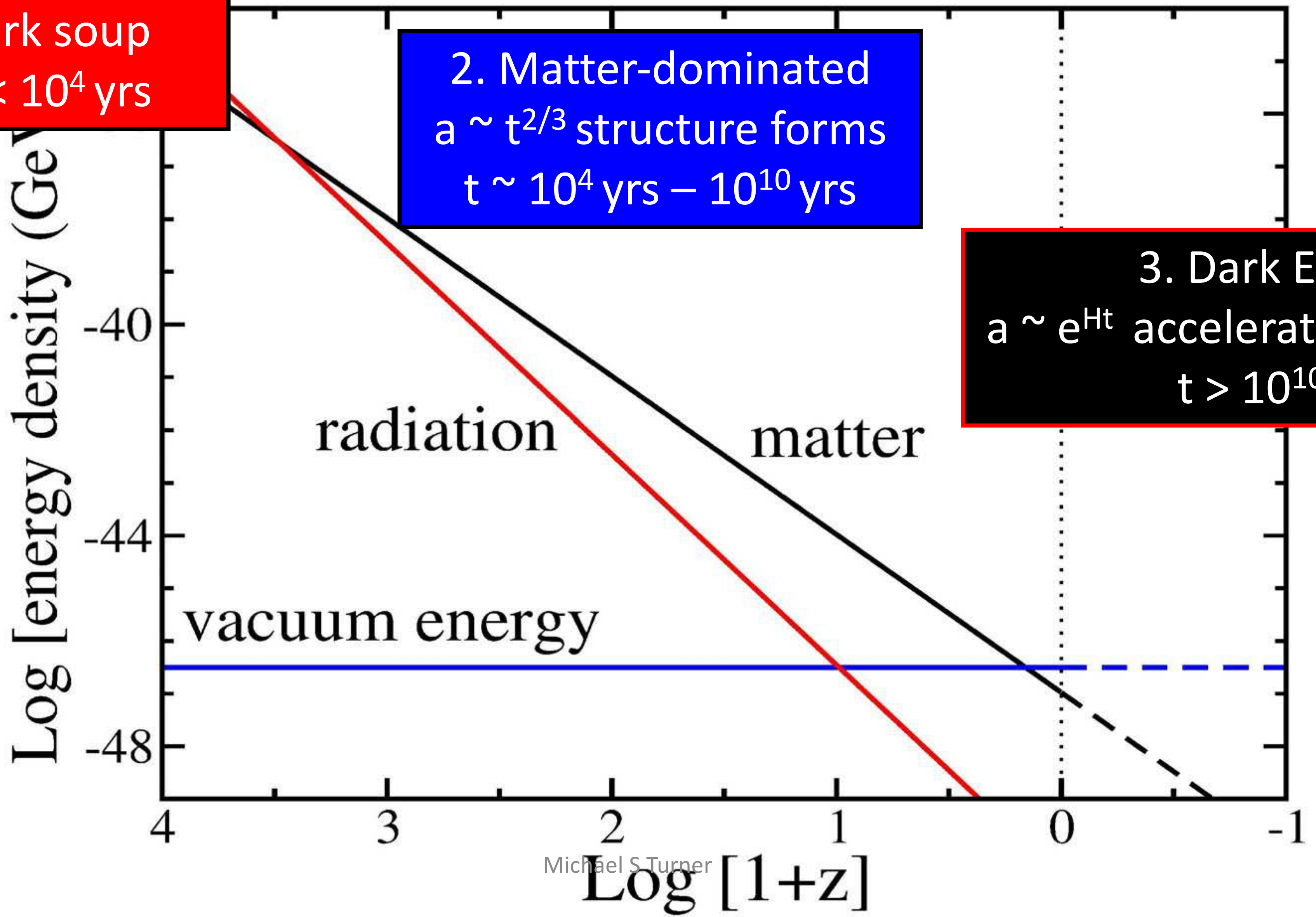
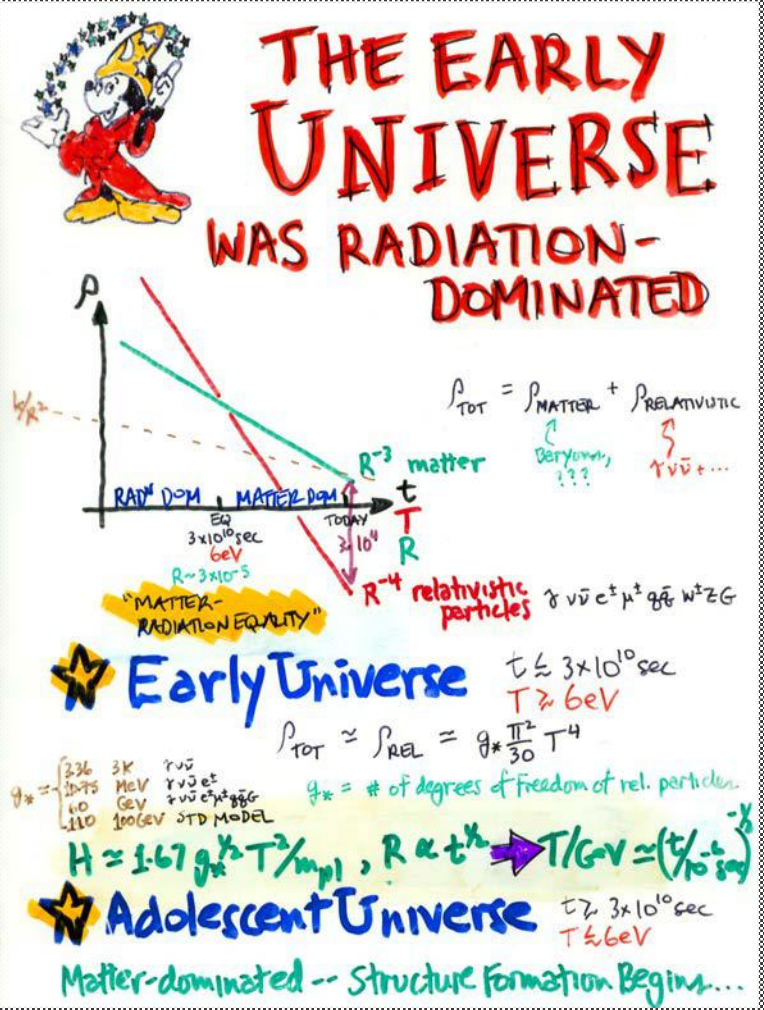
$a \sim e^{Ht}$ accelerated expansion
$t > 10^{10}$ yrs



Michael S Turner

6. Thermodynamics in the early Universe



- Thermal bath of particles
- For kT > mc^2 particle/antiparticle pairs as abundant as photons

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

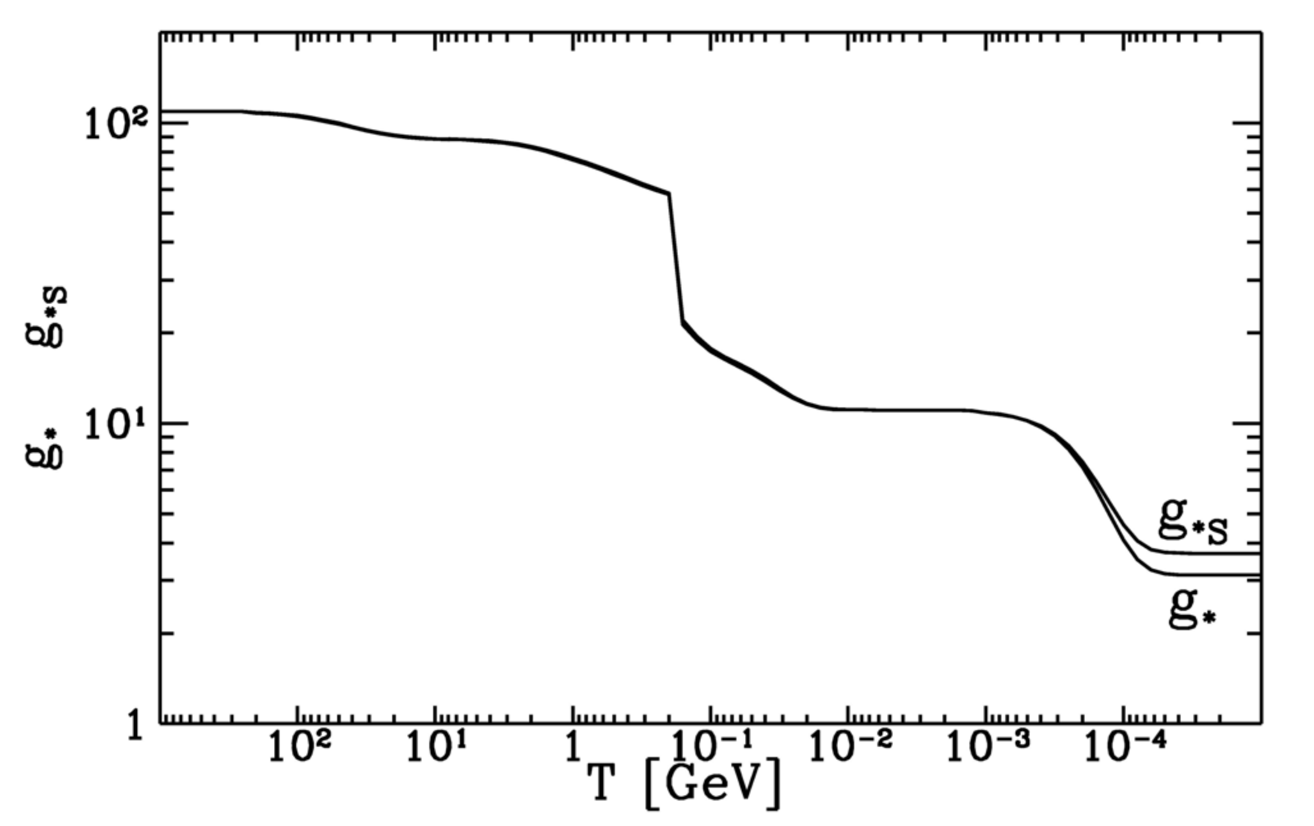
- For most of its early history: thermal equilibrium
- But, departures are very important – not all Fe today


Campbell's
CONDENSED
Quark
WITH LEPTONS AND GAUGE BOSONS
SOUP

$$\rho_{\mathrm{R}} = g_* \frac{\pi^2}{30} T^4 \qquad g_*(T) = \sum_{\text{bosons}} g_i + \frac{7}{8} \sum_{\text{fermions}} g_i$$

$$\Rightarrow \qquad H \simeq 1.67 g_*^{1/2} T^2 / m_{\mathrm{pl}}$$

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



UNITS

BART SEZ:

$\hbar = k_B = c = 1$

$1\,\mathrm{GeV} = (2\times10^{-14}\,\mathrm{cm})^{-1} = (6.6\times10^{-25}\,\mathrm{sec})^{-1}$

$= 1.6\times10^{-3}\,\mathrm{erg} = 1.2\times10^{13}\,\mathrm{K}$

$1\,\mathrm{GeV}^2 = (0.4\,\mathrm{mb})^{-1}$

$1\,\mathrm{GeV}^3 = 1.3\times10^{41}\,\mathrm{cm}^{-3}$

$1\,\mathrm{GeV}^4 = 2.32\times10^{17}\,\mathrm{g\,cm}^{-3}$

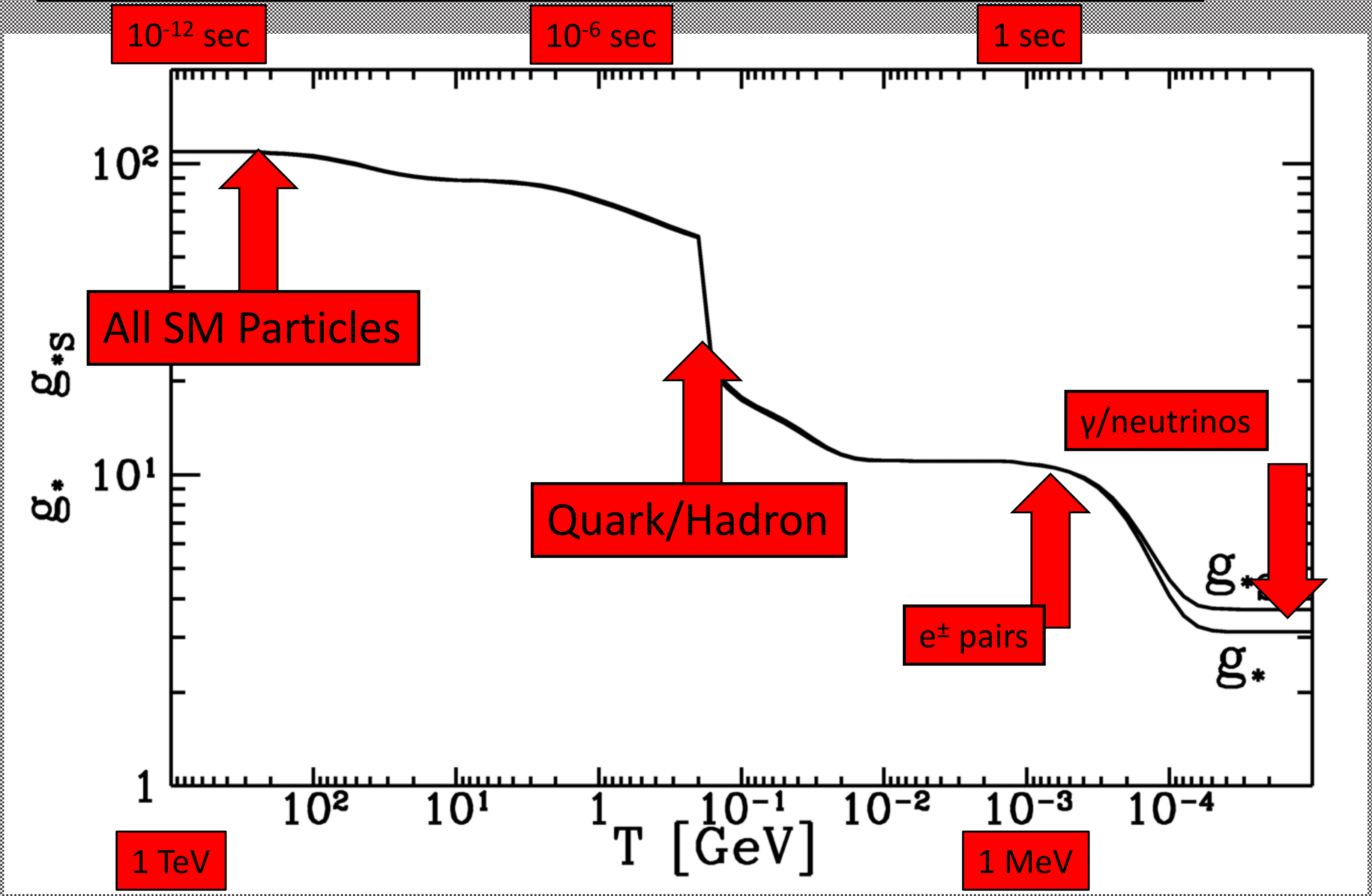
$1\,\mathrm{GeV}^5 = 3.2\times10^{62}\,\mathrm{erg\,cm}^{-3}\,\mathrm{s}^{-1}$

$G \equiv m_{\mathrm{pl}}^{-2} \qquad m_{\mathrm{pl}} = 1.22\times10^{19}\,\mathrm{GeV}$

$1\,\mathrm{Mpc} = 3.1\times10^{24}\,\mathrm{cm} = 1.6\times10^{38}\,\mathrm{GeV}^{-1}$

$H_0 = 2.1\,h\times10^{-42}\,\mathrm{GeV}$

Relativistic Degrees of Freedom



Basic thermodynamics review

- Thermal phase space density

$$f_i = \exp\left[\mu_i - E_i/T\right]$$

- With zero chemical potentials
  - Ultrarelativistic limit

$$n_i \sim T^3$$

  - Non-relativistic limit

$$n_i \sim (mT)^{3/2} \exp[-m_i/T]$$

- Chemical equilibrium establishing by i + j + … ←→ a + b + … occurring "rapidly"

$$\mu_i + \mu_j + \cdots + = \mu_a + \mu_b + \cdots$$

Entropy conservation (in the absence of departures from equilibrium and entropy production)

$$s = \frac{\rho + p}{T} = g_* \frac{2\pi^2}{45} T^3$$

$$S \equiv a^3 s \propto g_* a^3 T^3 = \text{const}$$

$$\Rightarrow a^3 \propto 1/s$$

$$\Rightarrow n_X/s \propto \text{ number of X's per comoving volume}$$

$$\Rightarrow T \propto g_*^{-1/3} a^{-1}$$

High entropy/small baryon number

- When g_* is constant, e.g., since t = 1 sec, $s \simeq 7 n_\gamma \simeq 3000\,\mathrm{cm}^{-3}$
- n_B/s = baryon number per comoving volume = n_b/s (few or no anti-baryons) = (baryon-to-photon ratio $\eta = 6 \times 10^{-10}$)/7 = 10^{-11}
- Note $7/\eta = 10^{11}$ is the entropy per baryon – VERY HIGH – meaning lots of photons per baryon! Cf, newly born neutron star entropy per baryon is a few per baryon. BIG consequences in cosmology!
- The old question: where did all the entropy come from?
- The other way to look at: Where did the small net baryon number $n_B/s = 10^{-11}$ come from? Baryogenesis!

Thermal equilibrium requires rapid interaction rates relative to expansion rate

- Interaction rate
  = number density of targets x cross section x $v_{relative}$

$$\Gamma = n\sigma v$$

- Expansion rate

$$H \simeq T^2/m_{\rm pl}$$

- Expansion time (= 1/H) x interaction rate = number of interactions per "expansion time" (doubling of scale factor, halving of temperature)
- Rapid interaction rate (thermal equilibrium): $\Gamma/H \gg 1$
- Slow interaction rate ("frozen out" reactions): $\Gamma/H \ll 1$

Worked example: decoupling of neutrinos

- Interactions

$$\bar{\nu}\nu \leftrightarrow e^+e^-,\ \nu e \leftrightarrow \nu e, \text{etc.}$$

- Interaction rate

$$\sigma \simeq G_F^2 T^2$$

$$\Gamma_{int} = n\sigma|v| \simeq G_F^2 T^5$$

- Decoupled at T ~ 1 MeV

$$\frac{\Gamma_{int}}{H} \simeq \frac{G_F^2 T^5}{T^2/m_{Pl}} \simeq \left(\frac{T}{1\ \mathrm{MeV}}\right)^3$$

Worked example: neutrino to photon temperature

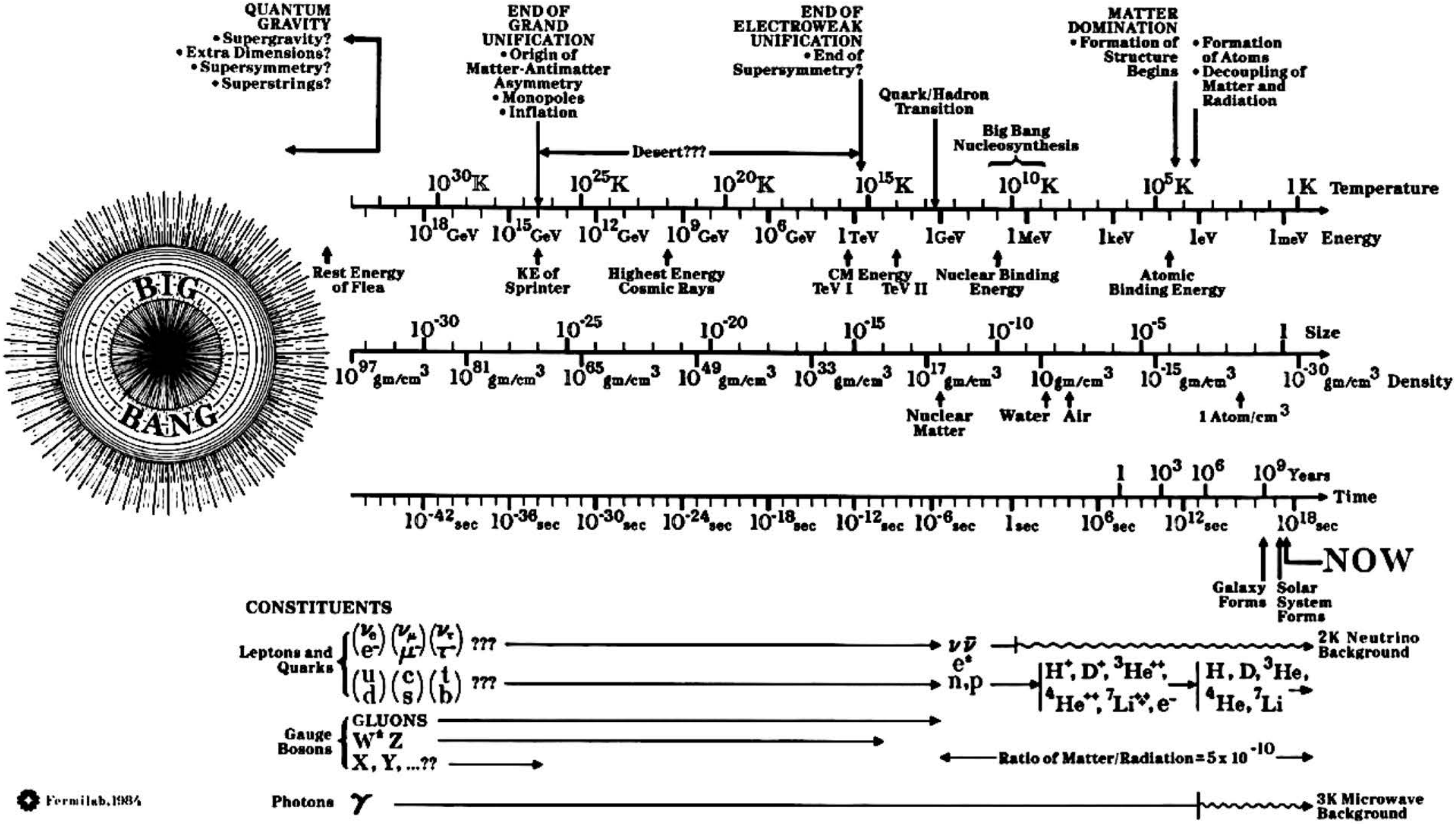
- Universe at 1 sec/1 MeV: photons (g = 2) and electrons/positrons (g = 4 x 7/8 = 3.5)
- Neutrinos decouple and evolve adiabatically
- T < 1 MeV, entropy from electron/positron pairs resides in photons only

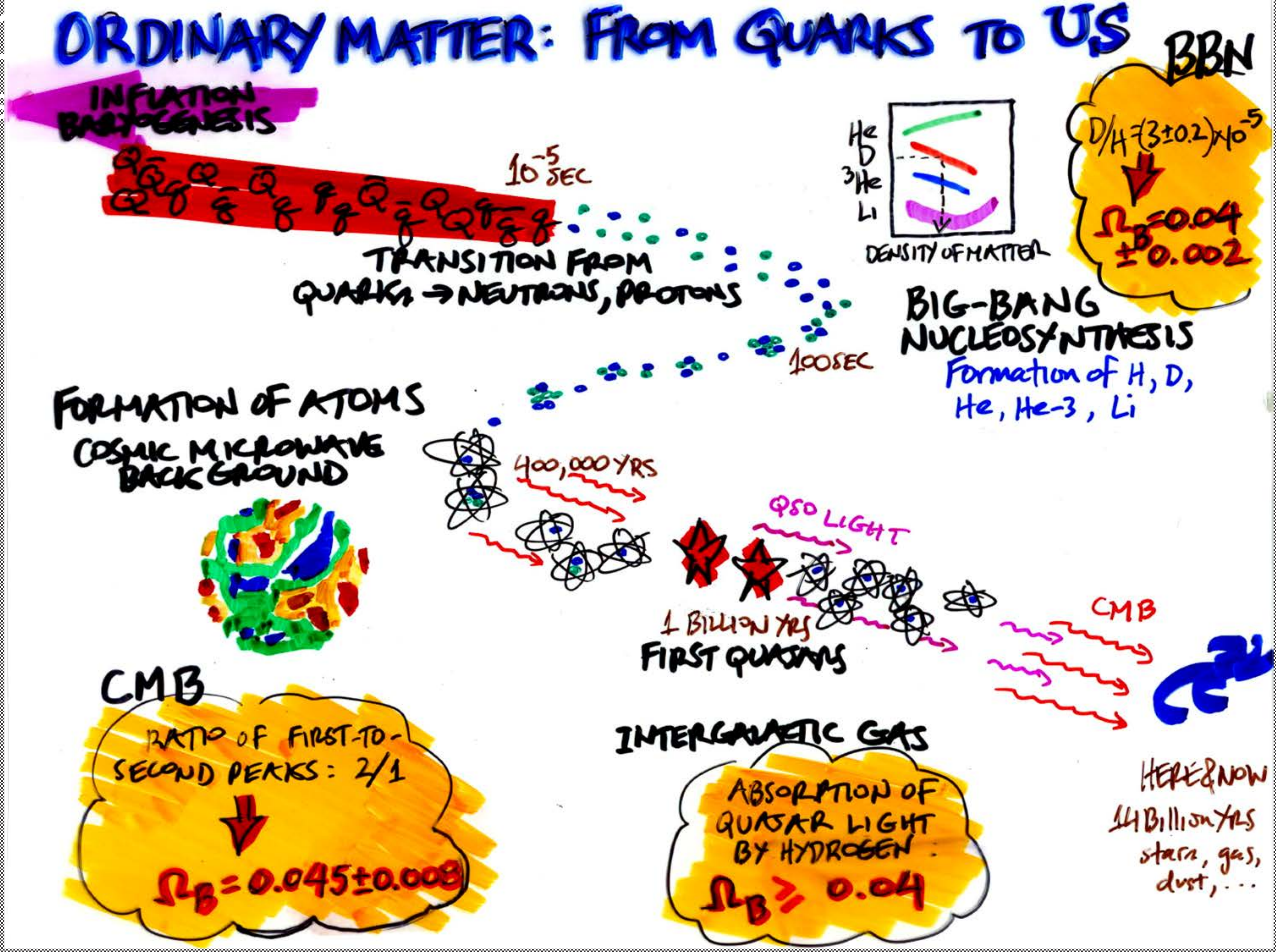
$$T_\nu \propto \frac{1}{a} \qquad T_\gamma \propto \frac{g_*^{-1/3}}{a}$$

$$g_* = 11/2 \to 2 \Rightarrow g_*^{-1/3} = (11/2)^{-1/3} \to (2)^{-1/3}$$

$$\Rightarrow T_\nu/T_\gamma = \left(\frac{4}{11}\right)^{1/3}$$

PS: Neutrinos participate in a small part of the e^+/e^- entropy transfer (about 1%)

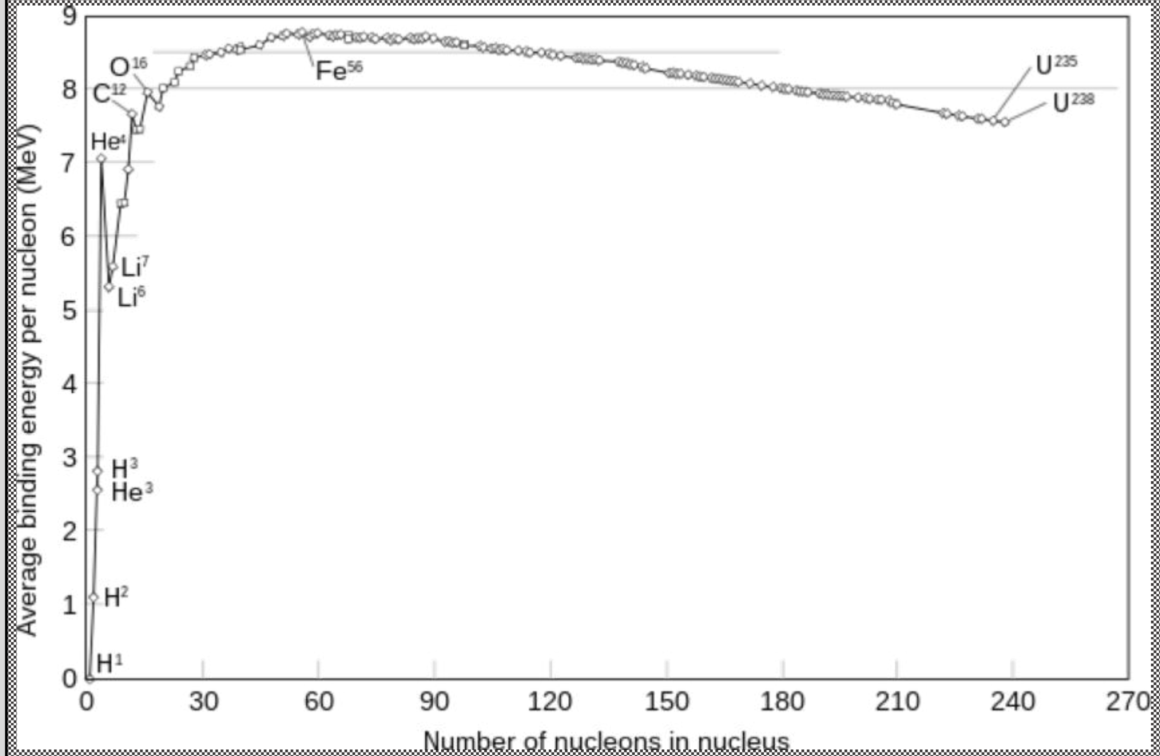

QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
• Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Desert???
10^{30}K
10^{25}K
10^{20}K
10^{15}K
10^{10}K
10^{5}K
1 K
Temperature
10^{18}GeV
10^{15}GeV
10^{12}GeV
10^{9}GeV
10^{6}GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy
TeV I
TeV II
Nuclear Binding Energy
Atomic Binding Energy
BIG BANG
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
Size
10^{97} gm/cm^3
10^{81} gm/cm^3
10^{65} gm/cm^3
10^{49} gm/cm^3
10^{33} gm/cm^3
10^{17} gm/cm^3
10 gm/cm^3
10^{-15} gm/cm^3
10^{-30} gm/cm^3
Density
Nuclear Matter
Water
Air
1 Atom/cm^3
1
10^{3}
10^{6}
10^{9} Years
Time
10^{-42}sec
10^{-36}sec
10^{-30}sec
10^{-24}sec
10^{-18}sec
10^{-12}sec
10^{-6}sec
1 sec
10^{6}sec
10^{12}sec
10^{18}sec
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
$\binom{\nu_e}{e^-} \binom{\nu_\mu}{\mu^-} \binom{\nu_\tau}{\tau^-}$???
$\binom{u}{d} \binom{c}{s} \binom{t}{b}$???
$\nu \bar{\nu}$
$e^{\pm}$
n, p
2K Neutrino Background
H^+, D^+, $^3He^{++}$, $^4He^{++}$, $^7Li^{+++}$, e^-
H, D, ^{3}He, ^{4}He, ^{7}Li
Gauge Bosons
GLUONS
$W^{\pm}$ Z
X, Y, ...??
Ratio of Matter/Radiation = 5 x 10^{-10}
Photons γ
3K Microwave Background
Fermilab,1984


ORDINARY MATTER: FROM QUARKS TO US
INFLATION
BARYOGENESIS
10^-5 SEC
TRANSITION FROM
QUARKS → NEUTRONS, PROTONS
He
D
3He
Li
DENSITY OF MATTER
BBN
D/H = (3±0.2)x10^-5
ΩB = 0.04 ± 0.002
BIG-BANG
NUCLEOSYNTHESIS
Formation of H, D,
He, He-3, Li
100 SEC
FORMATION OF ATOMS
COSMIC MICROWAVE
BACKGROUND
400,000 YRS
QSO LIGHT
1 BILLION YRS
FIRST QUASARS
CMB
CMB
RATIO OF FIRST-TO-
SECOND PEAKS: 2/1
ΩB = 0.045±0.008
INTERGALACTIC GAS
ABSORPTION OF
QUASAR LIGHT
BY HYDROGEN
ΩB ≥ 0.04
HERE & NOW
14 Billion YRS
stars, gas,
dust, . . .

7. BBN and the high entropy of the Universe (small baryon number)

Most “accurate” description of BBN physics https://arxiv.org/pdf/2111.14254.pdf

- Boltzmann equations in the expanding Universe → the results of BBN depend upon the baryon to photon ratio $\eta = 6 \times 10^{-10}$ and nuclear data (cross sections, neutron lifetime) and $N_{neutrinos}$
- Large entropy per baryon (small η) plays a critical role in delaying BBN to a time when Coulomb barriers prevent nucleosynthesis beyond ^{4}He and NSE
- That is a good thing: a tremendous amount of nuclear free energy is left to power stars and life in the Universe 10^{52} ergs per solar mass!



1. BBN begins with NSE (chemical equilibrium), followed by a series of departures from thermal equilibrium

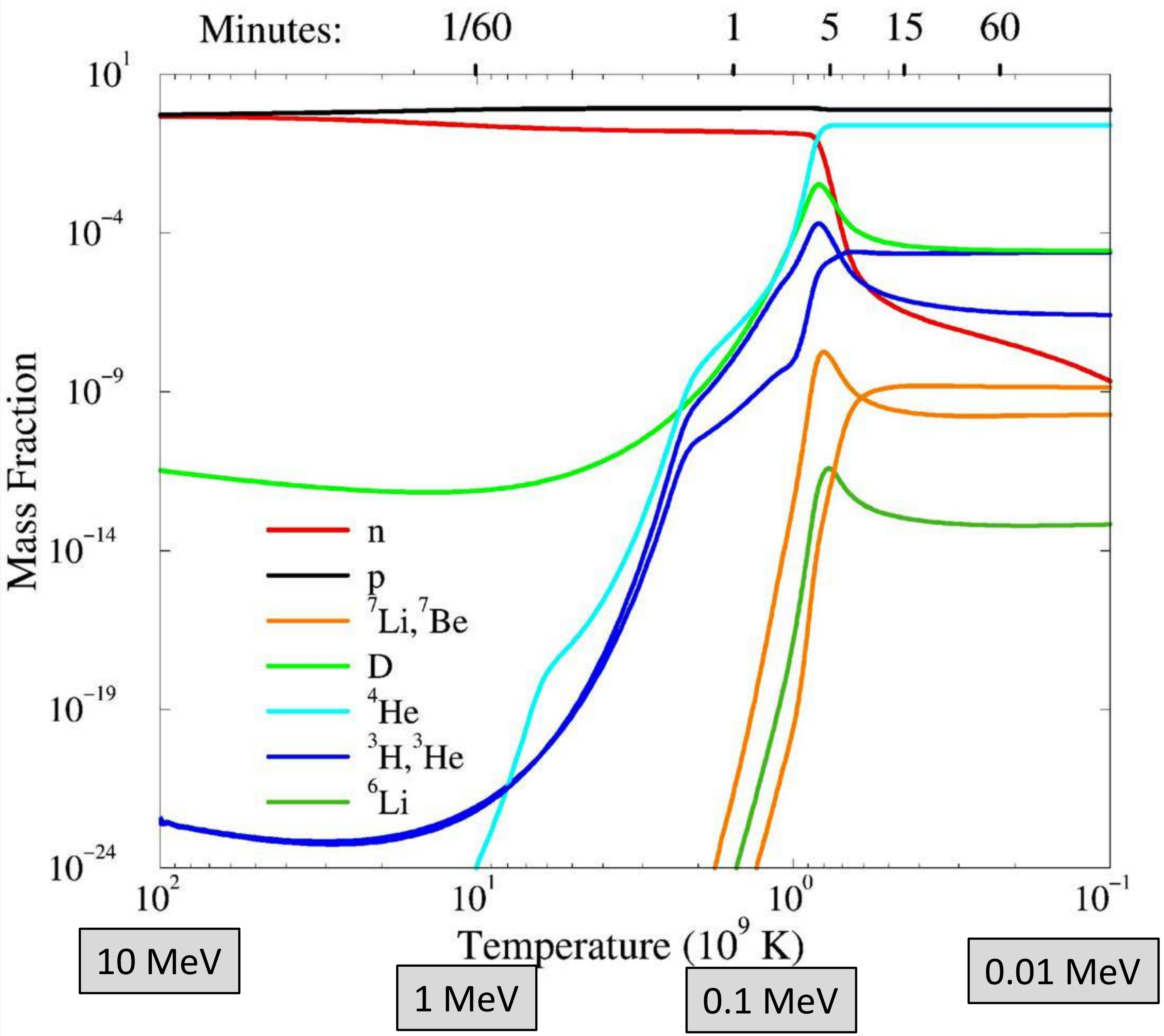
$$T_{\rm nuclei} \simeq \frac{B_A/(A-1)}{\ln\eta^{-1} + 1.5\ln(m/T)} \simeq 0.25\,{\rm MeV}$$

2. n/p ratio freezes in at a value of around 1/7 at T ~ 1 MeV

$$(n/p)_{\rm eq} = \exp[-\Delta m/T]$$

3. Coulomb barriers (T < 0.05 MeV) prevent NSE from being established and significant nucleosynthesis beyond ^{4}He
4. End result, lots of ^{4}He made from free neutrons, a little unburnt D and ^{3}He and a trace amount of ^{7}Li

NB: without the non-thermal neutrons, first step of BBN would have to be p + p → D + gamma (a weak interaction that would have time to take place!



← NSE n/p freeze in |Nuclei favored→ |Coulomb barriers→

Nuclear Statistical Equilibrium

- NSE abundance of ^{Z}A:

$$n_A = g_A \left(\frac{m_A T}{2\pi}\right)^{3/2} \exp\left(\frac{\mu_A - m_A}{T}\right)$$

- Chemical Equilibrium

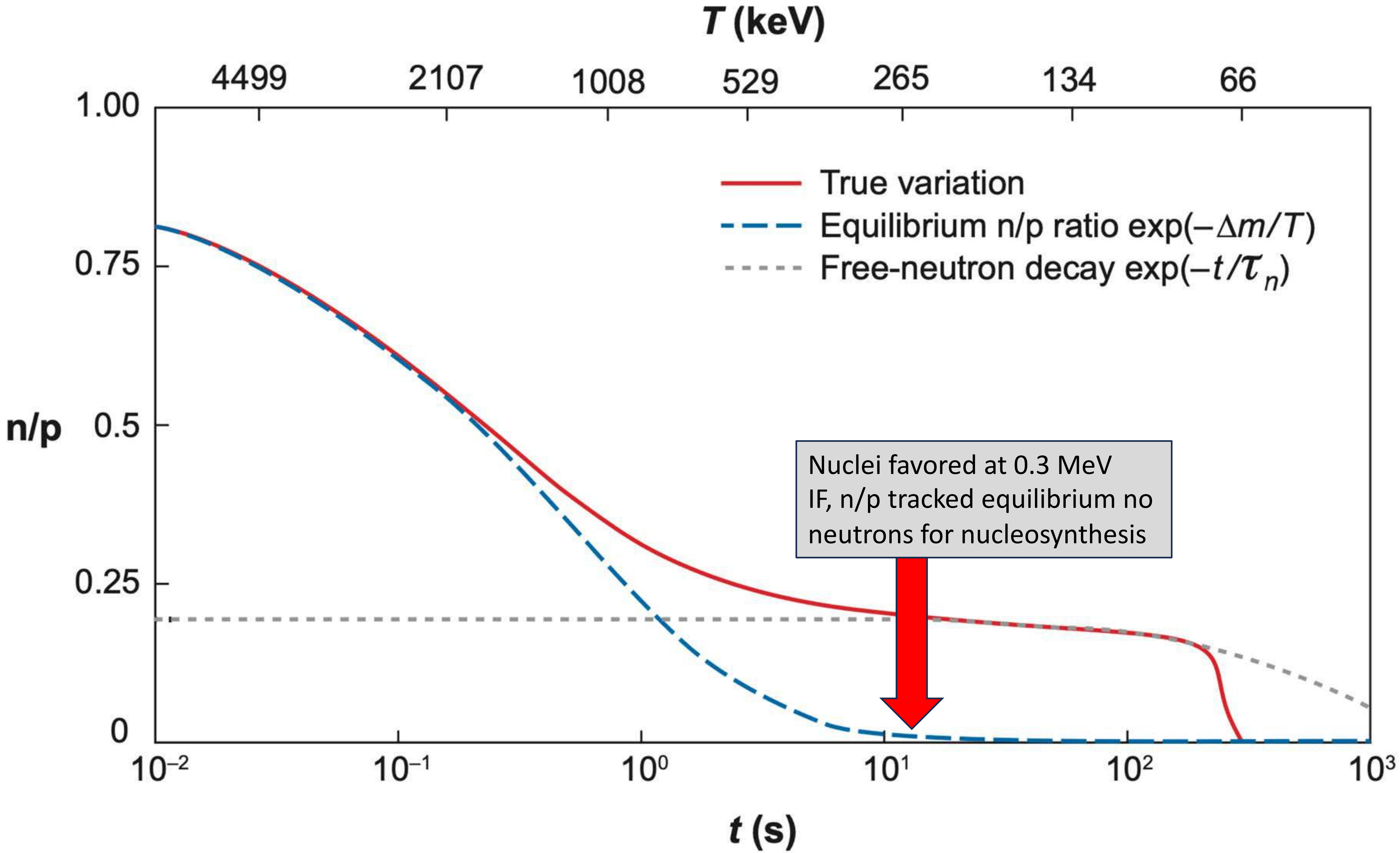
$$\mu_A = Z\mu_p + (A - Z)\mu_n$$

- Binding energy

$$B_A \equiv Zm_p + (A - Z)m_n - m_A$$

- Mass fraction of ^{Z}A in NSE (after algebra)

$$\begin{aligned} X_A &= g_A[\zeta(3)^{A-1}\pi^{(1-A)/2}2^{(3A-5)/2}]A^{5/2}(T/m_N)^{3(A-1)/2} \\ &\times \eta^{A-1} X_p^Z X_n^{A-Z} \exp(B_A/T), \end{aligned}$$


T (keV)
4499
2107
1008
529
265
134
66
1.00
0.75
0.5
0.25
0
n/p
True variation
Equilibrium n/p ratio exp(−Δm/T)
Free-neutron decay exp(−t/τ_n)
Nuclei favored at 0.3 MeV
IF, n/p tracked equilibrium no
neutrons for nucleosynthesis
10⁻²
10⁻¹
10⁰
10¹
10²
10³
t (s)

Two big successes: D/H (vs. CMB) and ^{4}He and one big problem ^{7}Li

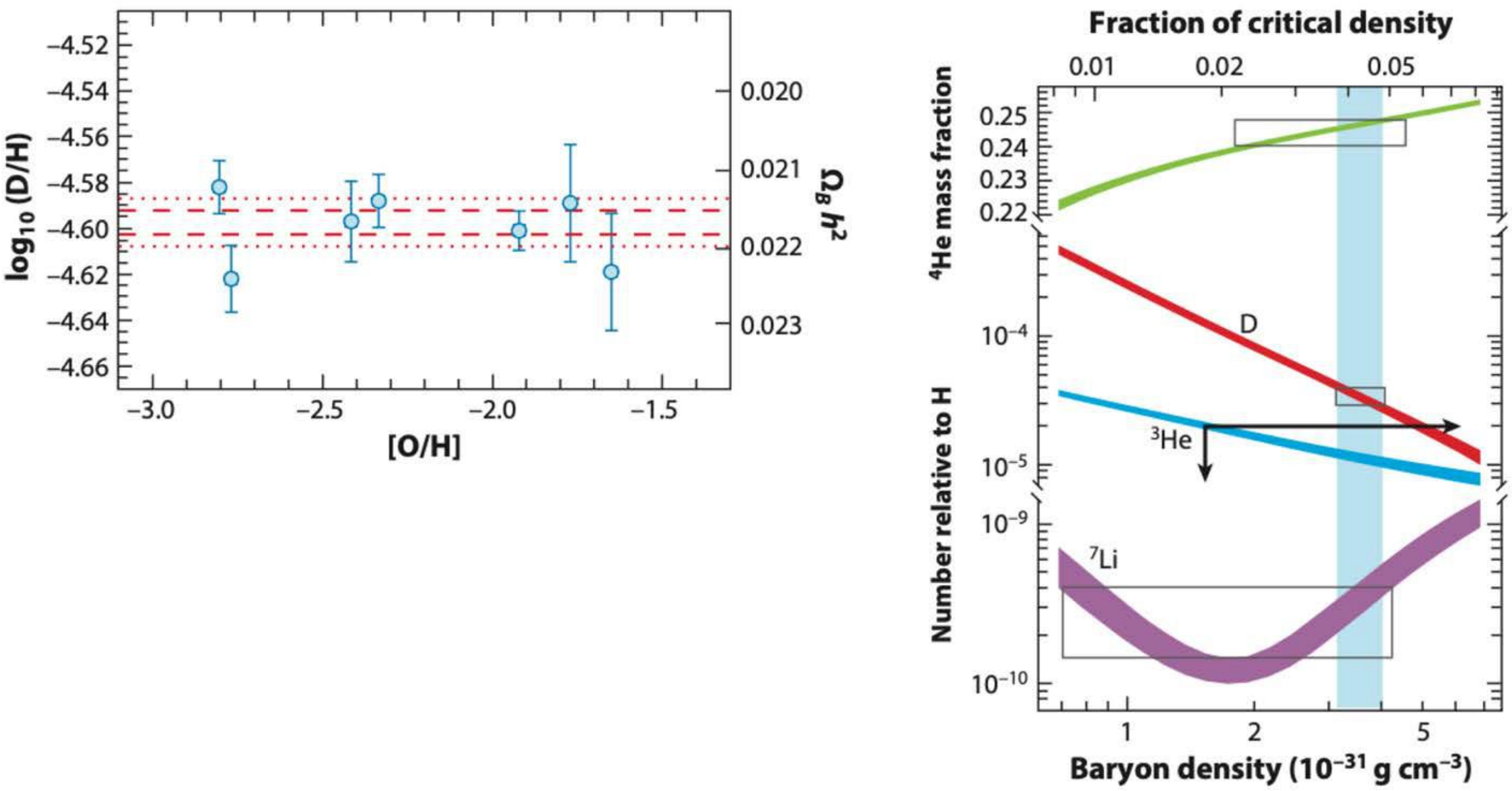


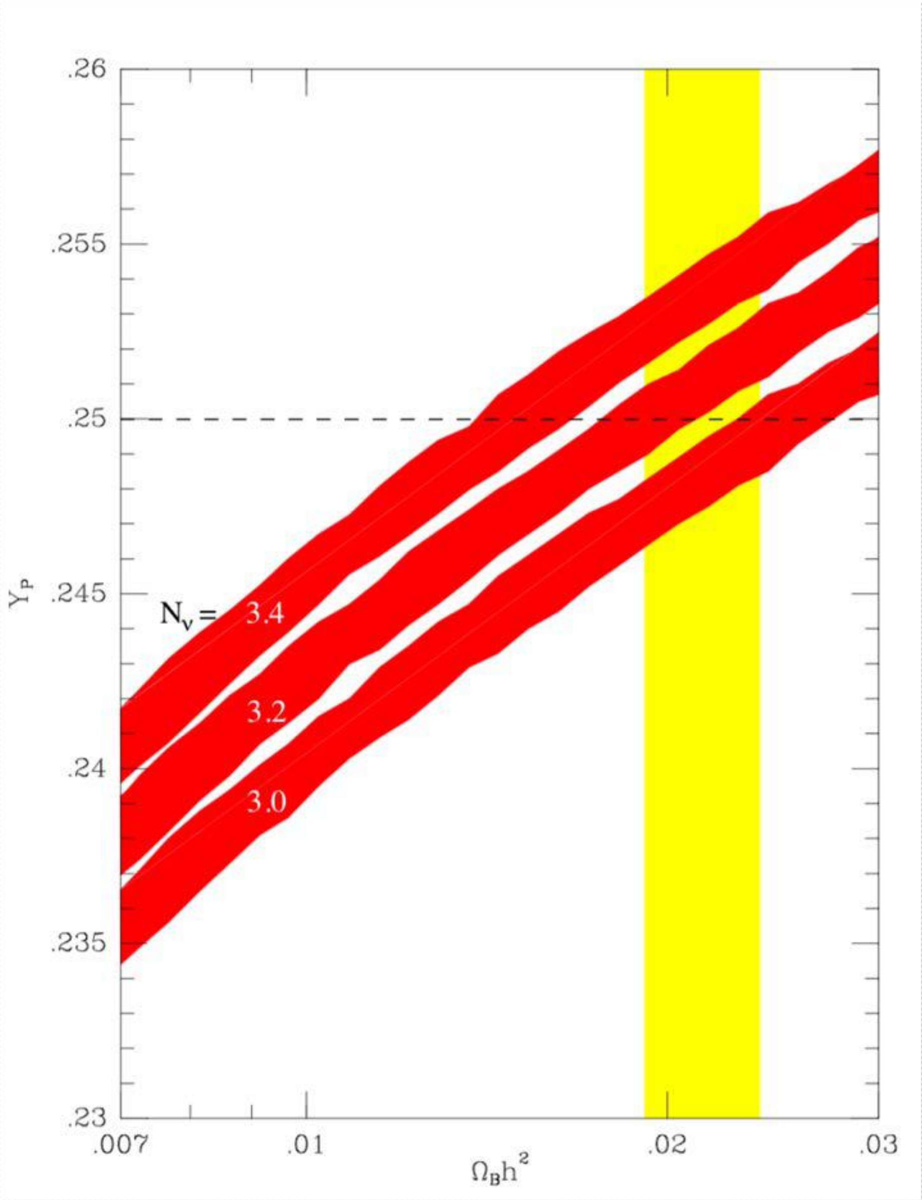
Figure 8

Big bang nucleosynthesis. (*a*) D/H determinations. Panel adapted with permission from Reference 178; copyright 2018 AAS. (*b*) The vertical band is the deuterium-determined baryon density, and the other bands are the 1σ predictions. The heights of the black boxes indicate the measured abundances with error estimates. The upper density scale assumes $H_0 = 65$ km s^{-1} Mpc^{-1}. Panel adapted from Reference 179.

Looking for more dark stuff

- N_{eff}: the number of relativistic species (m << T) expressed in as neutrino species*: portal to the TOE (dark sector, …)
  - BBN: species less massive than 1 MeV & σ_N = 0.05
  - CMB: species less massive 1 eV & σ_N = 0.03
  - Don't have to agree

*Chicago school convention; NB: SM predicts 3.045 for CMB



8. Recombination and CMB last scattering

- Two separate events!
- Recombination (misnomer):
  - Chemical equilibrium: rapid $p + e \leftrightarrow H + \gamma$ ensures $\mu_p + \mu_e = \mu_H$
  - Ionization fraction in thermal equilibrium (X_e), B = 13.6 eV

$$\frac{1 - X_e}{X_e^2} \simeq \eta (T/m_e)^{3/2} \exp(B/T)$$

  - Rec: X_e ~ 0.5 (z = 1300)

$$T_{\rm rec} \simeq \frac{B}{-\ln \eta - 1.5 \ln(T_{\rm rec}/m_e)} \simeq 0.3\,\mathrm{eV}$$

<< 13.6 eV!!

  - NB: freeze out of recombination leaves residual ionization of $X_e = 10^{-4}$ or so

Last-scattering (also called decoupling)

- Thomson scattering rate per photon:

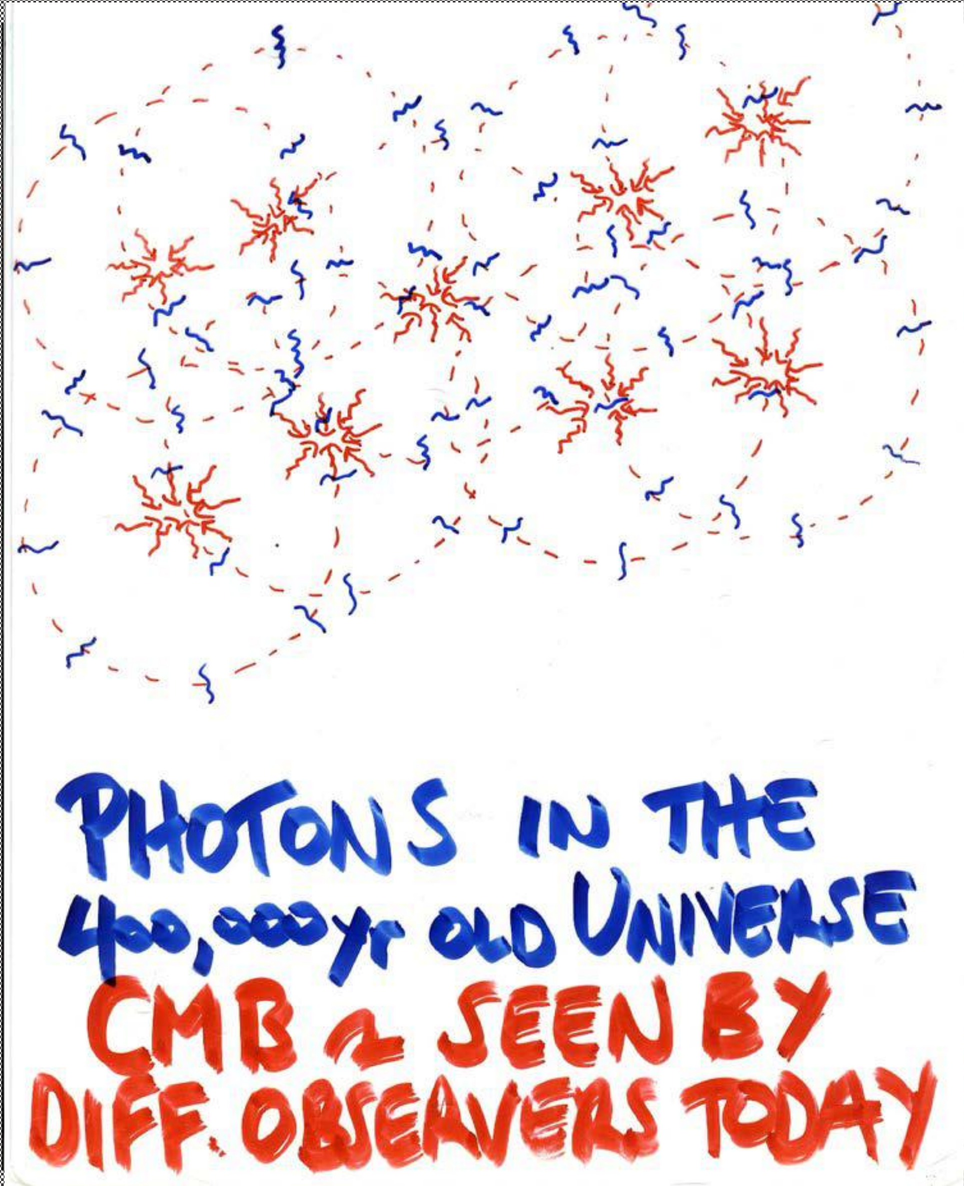
$$\Gamma = n_e \sigma_T \simeq X_e \eta T^3 \alpha^2 / m_e^2$$

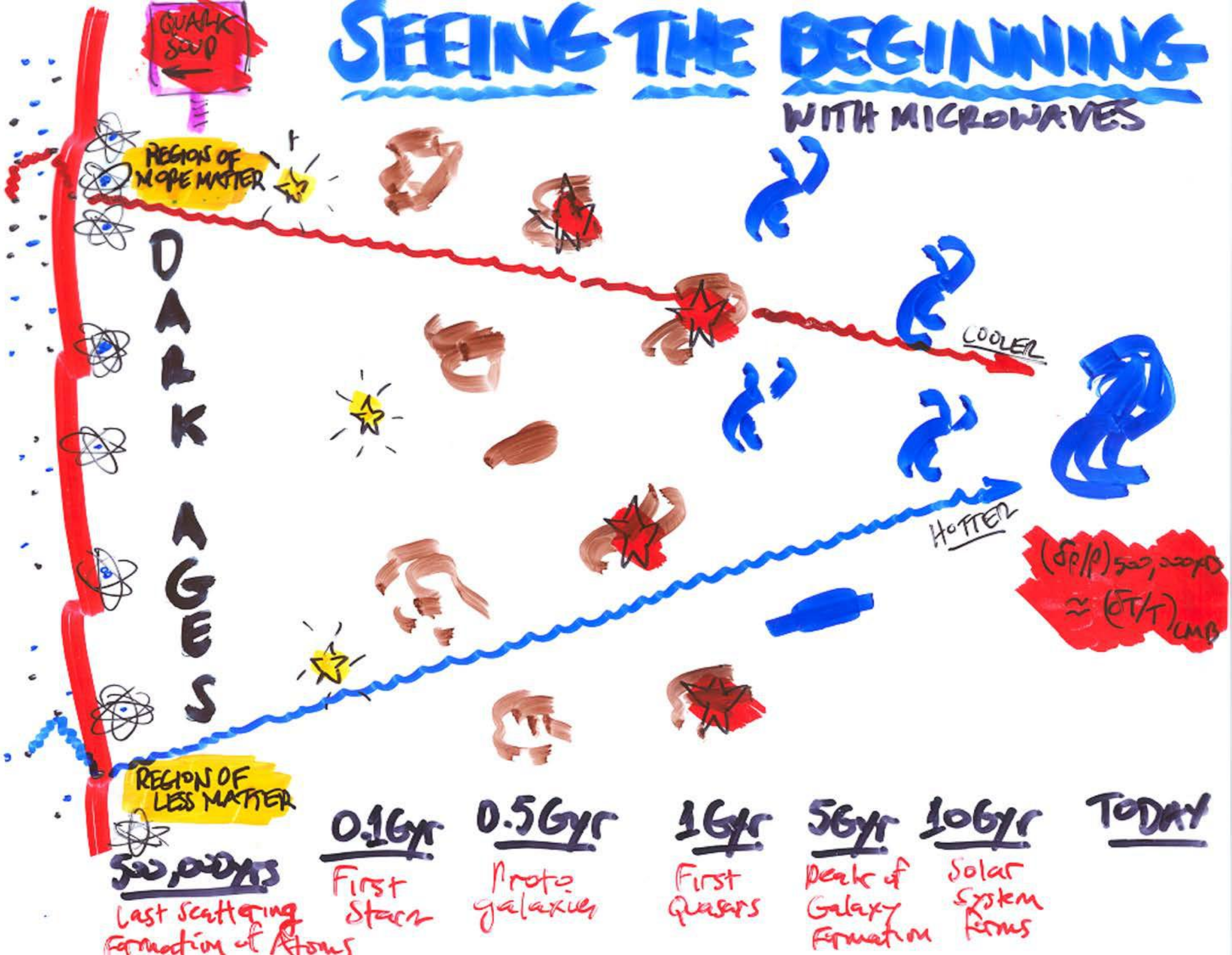
- Decoupling is driven by decreasing X_e

$$\Gamma / H \sim 300 X_e (T/\mathrm{eV})$$

- Last scattering/decoupling occurs at z = 1100, shortly after – and driven by – recombination (z = 1300)


PHOTONS IN THE
400,000yr OLD UNIVERSE

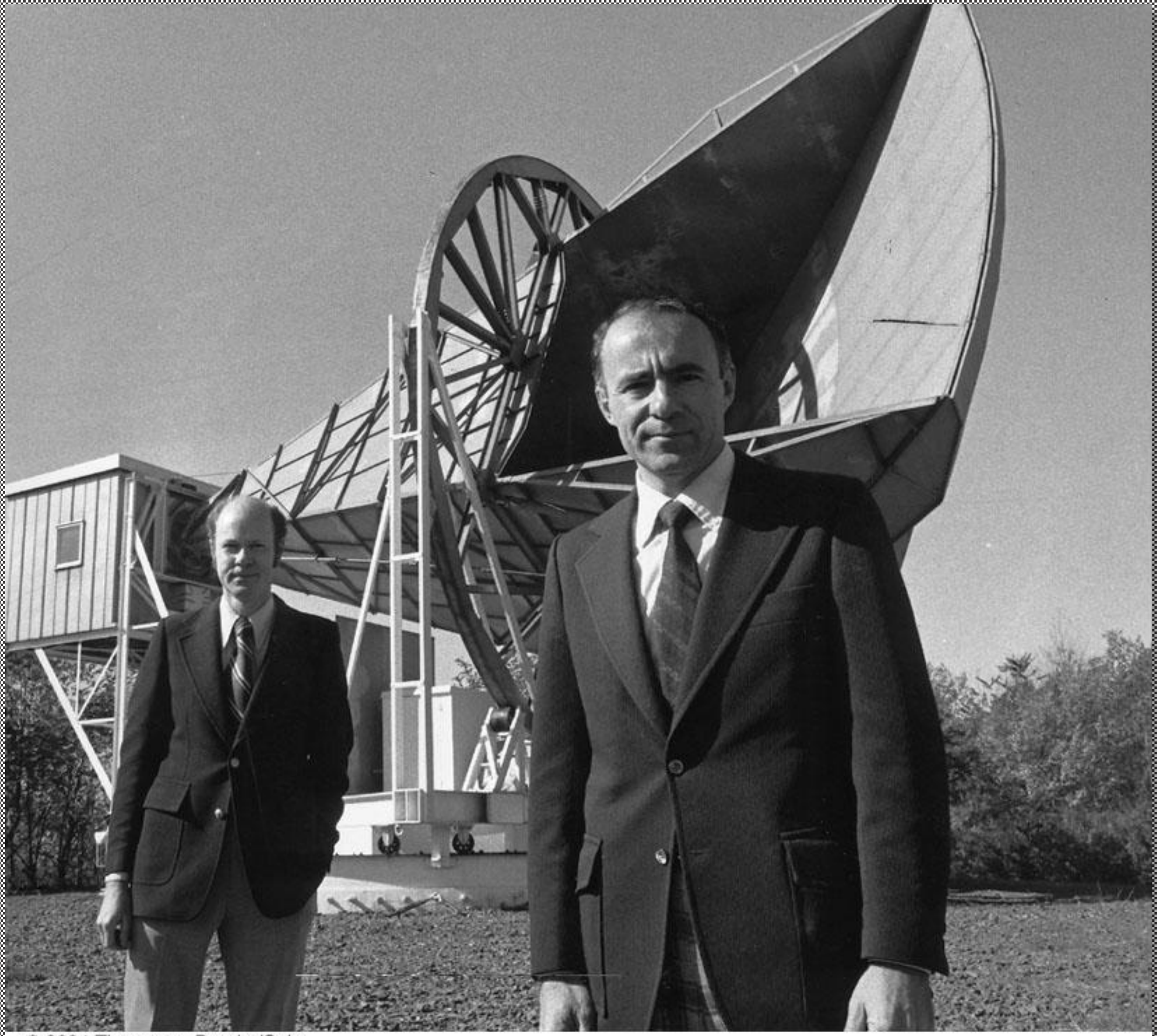

PHOTONS IN THE
400,000yr OLD UNIVERSE
CMB as SEEN BY
DIFF. OBSERVERS TODAY

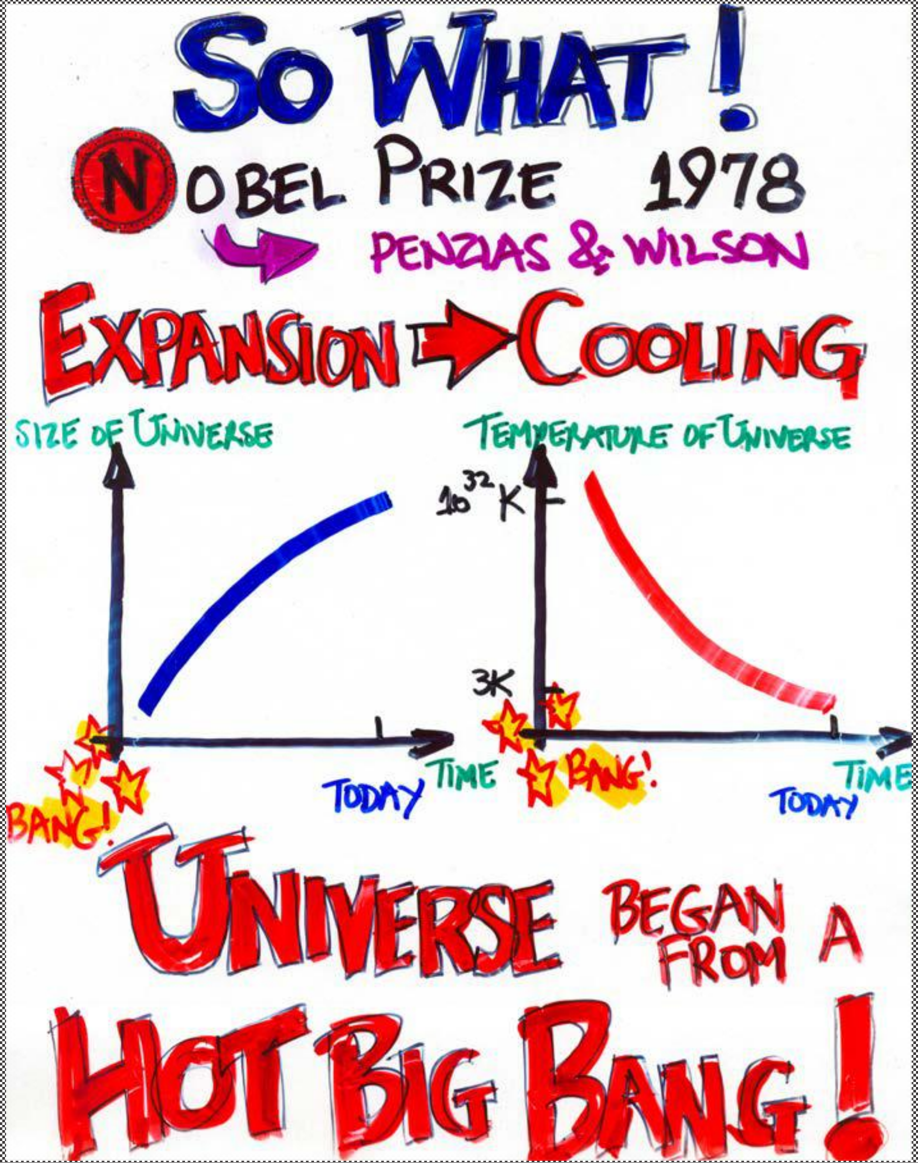


SEEING THE BEGINNING
WITH MICROWAVES
QUARK SOUP
REGION OF MORE MATTER
DARK AGES
COOLER
HOTTER
$(\delta\rho/\rho)_{500,000yrs} \approx (\delta T/T)_{CMB}$
REGION OF LESS MATTER
500,000yrs
Last scattering
Formation of Atoms
0.1Gyr
First Stars
0.5Gyr
Proto galaxies
1Gyr
First Quasars
5Gyr
Peak of Galaxy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

Hot Big Bang!

1964 Arno Penzias & Robert accidentally discover the Cosmic Microwave Background



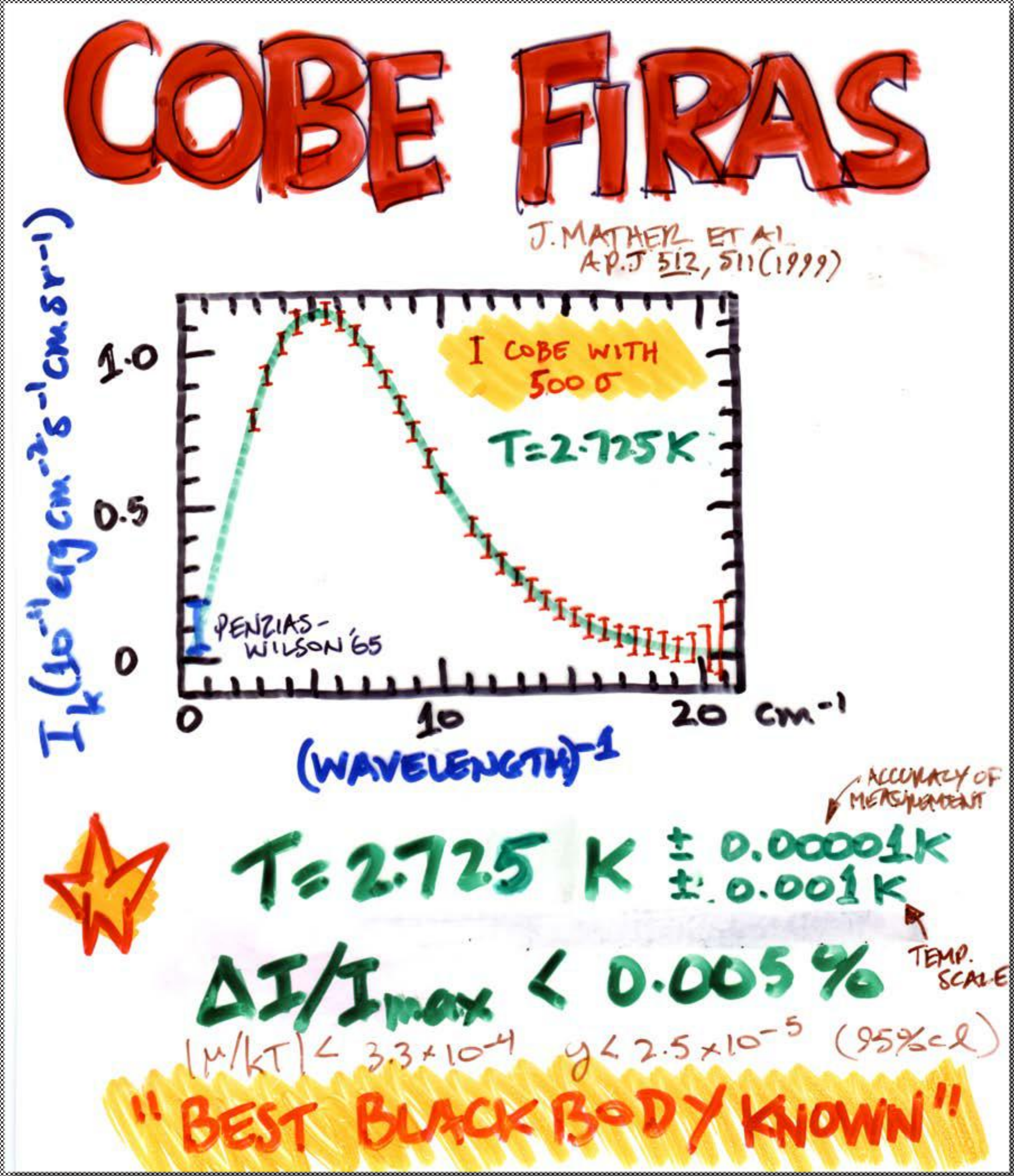


"Perfect" Blackbody

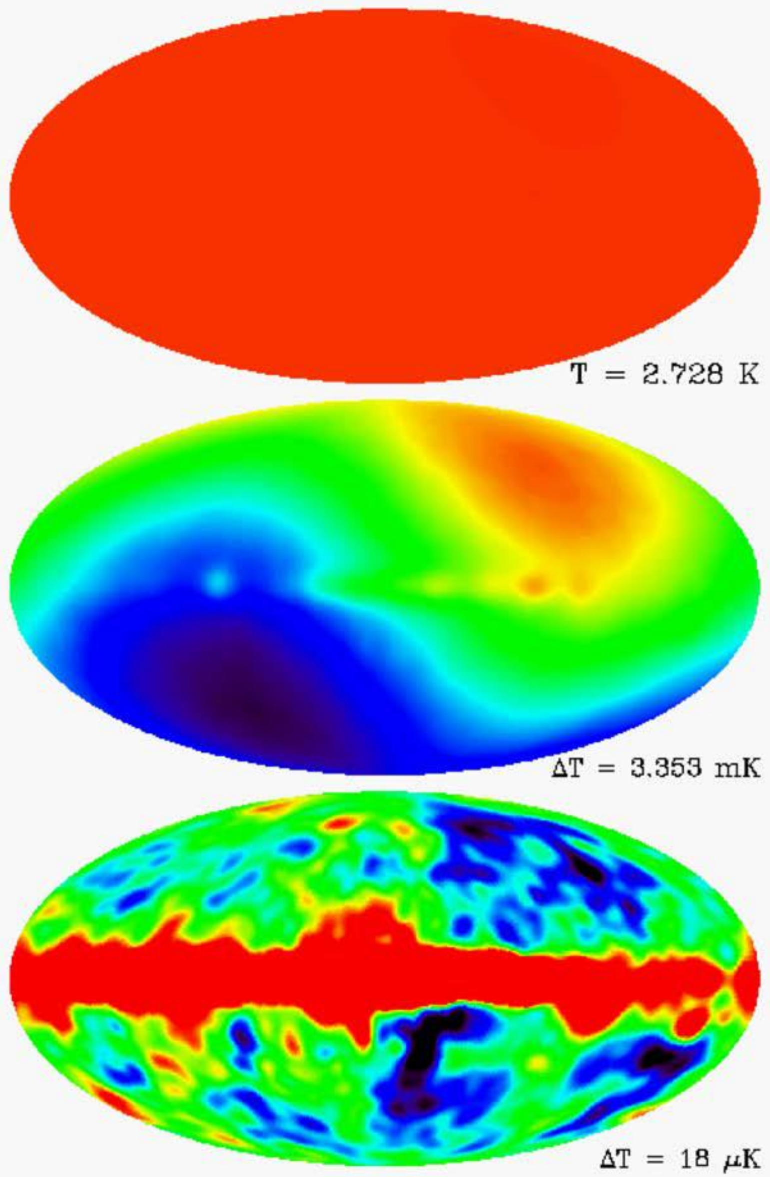
$$T = 2.7255 \pm 0.0006\,\mathrm{K}$$

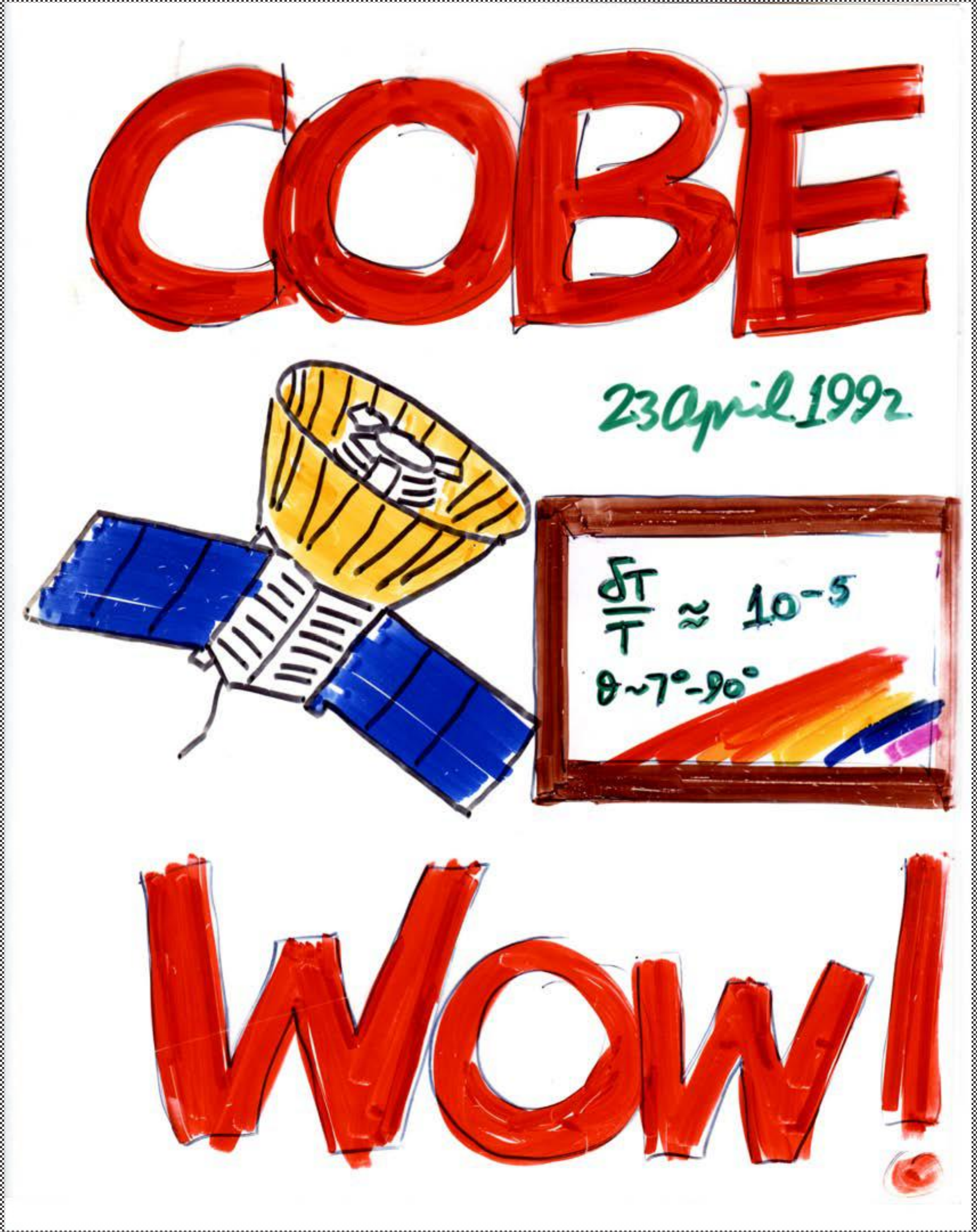
$$n_\gamma = 411\,\mathrm{cm}^{-3}$$

$$\Omega_\gamma \simeq 5 \times 10^{-5}$$



1992: COBE DMR discovers CMB anisotropy





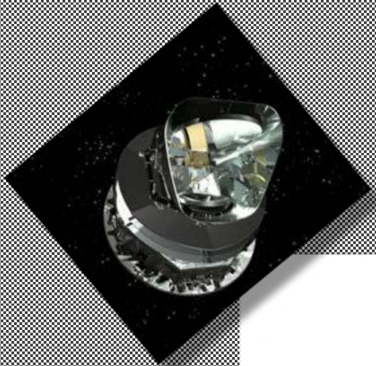
"RIPPLES" IN THE MICROWAVE ECHO

TEMPERATURE VARIATION ≈ 30 μK

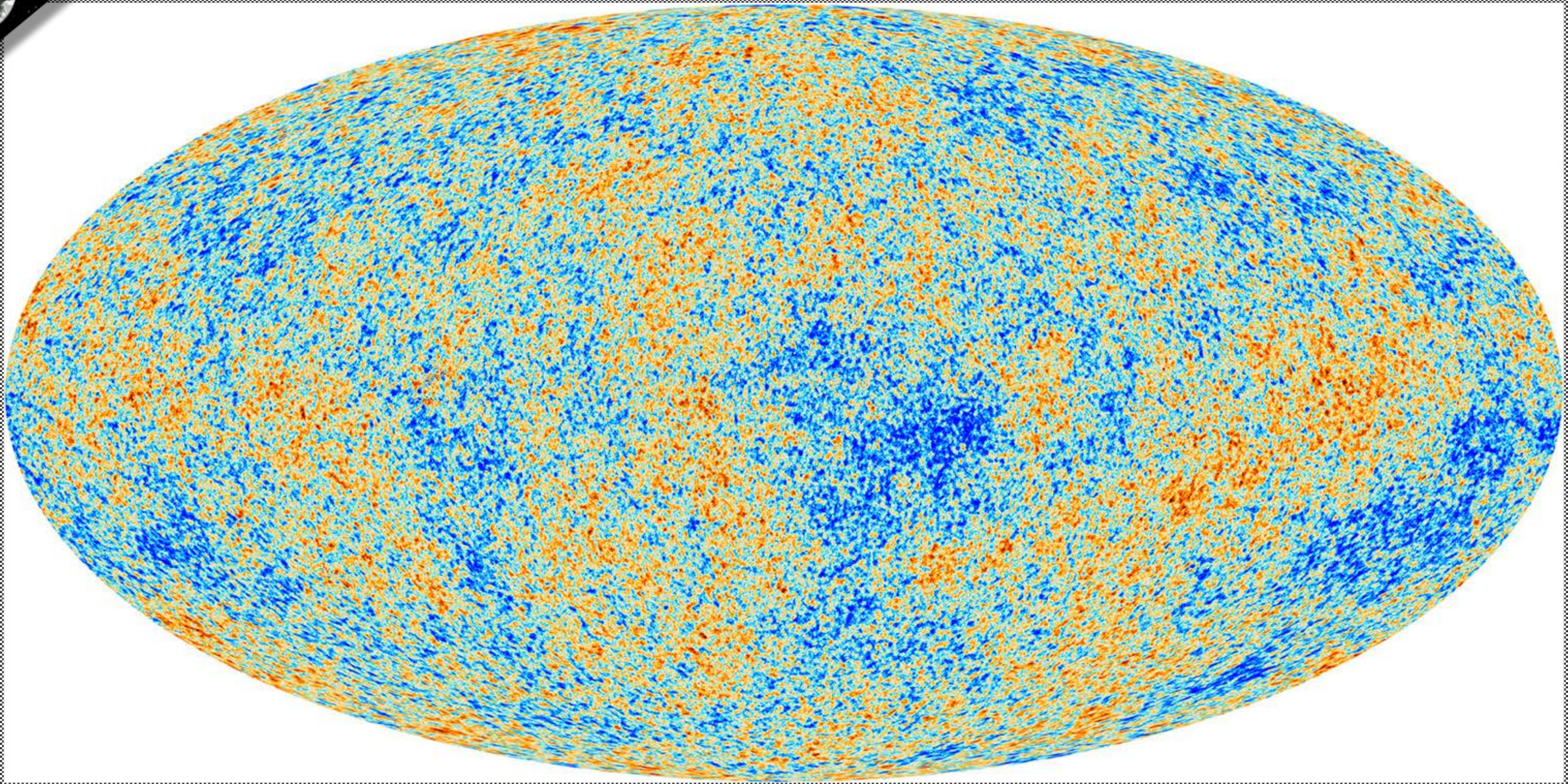
→ EVIDENCE FOR "PRIMEVAL LUMPINESS" THAT SEEDED STRUCTURE (STARS, GALAXIES, CLUSTERS OF GALAXIES, SUPERCLUSTERS VOIDS, WALLS, ...)

S. HAWKING: "GREATEST DISCOVERY OF ALL TIME"

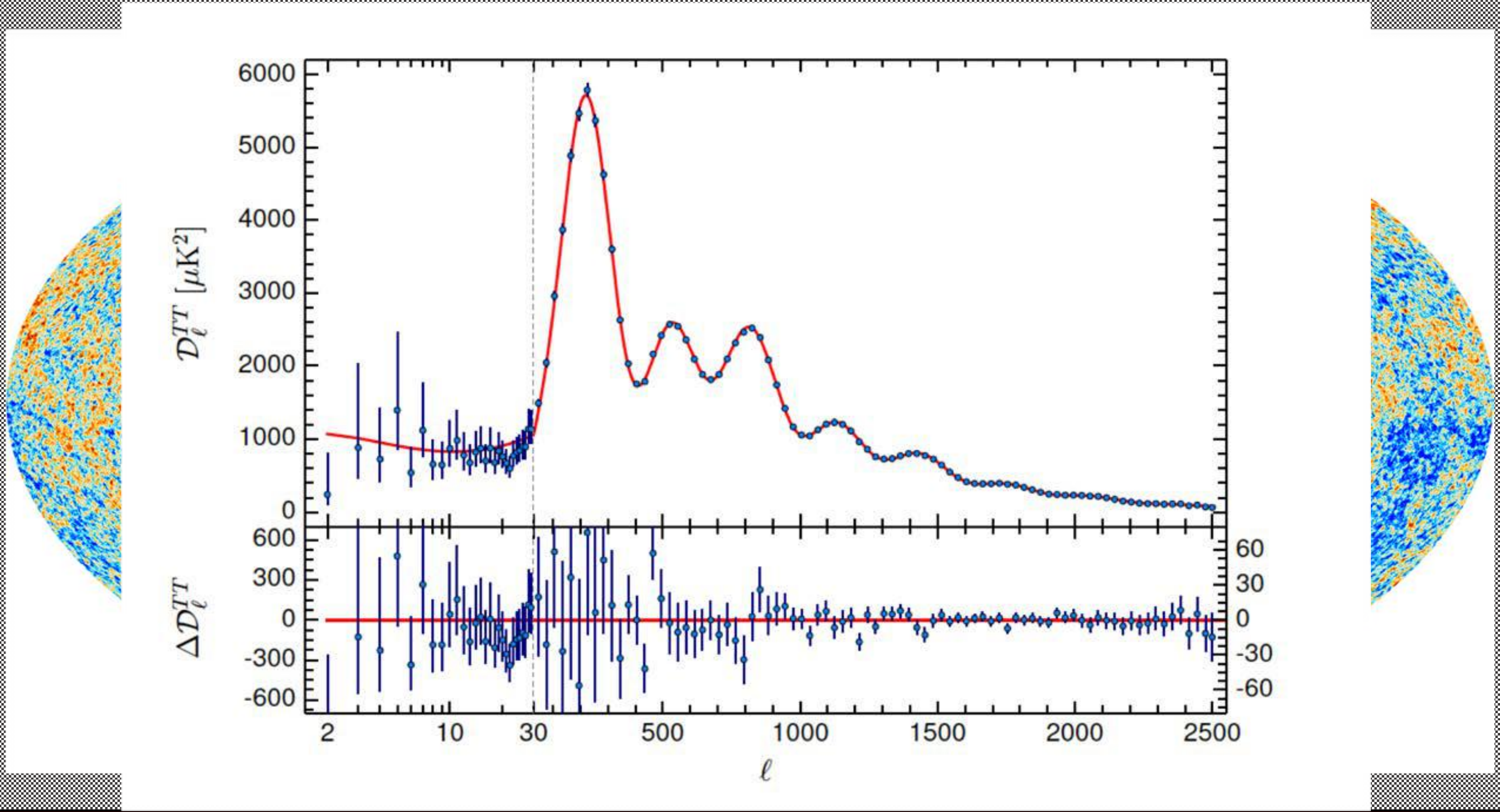
↑ ONLY A SLIGHT OVERSTATEMENT



The Universe at 380,000 years



Best evidence for ΛCDM



6 numbers describe the Universe from the big bang until today

1. Baryon mass density
2. CDM mass density
3. Density perturbation amplitude
4. Tilt
5. Sound horizon
6. Optical depth

$$R_{\text{curv}} \equiv \frac{H_0^{-1}}{\sqrt{\Omega_0 - 1}}$$

$$\rho_{\text{critical}} = \frac{3H_0^2}{8\pi G} \simeq 10^{-29}\,\text{g/cm}^3$$

Our Universe

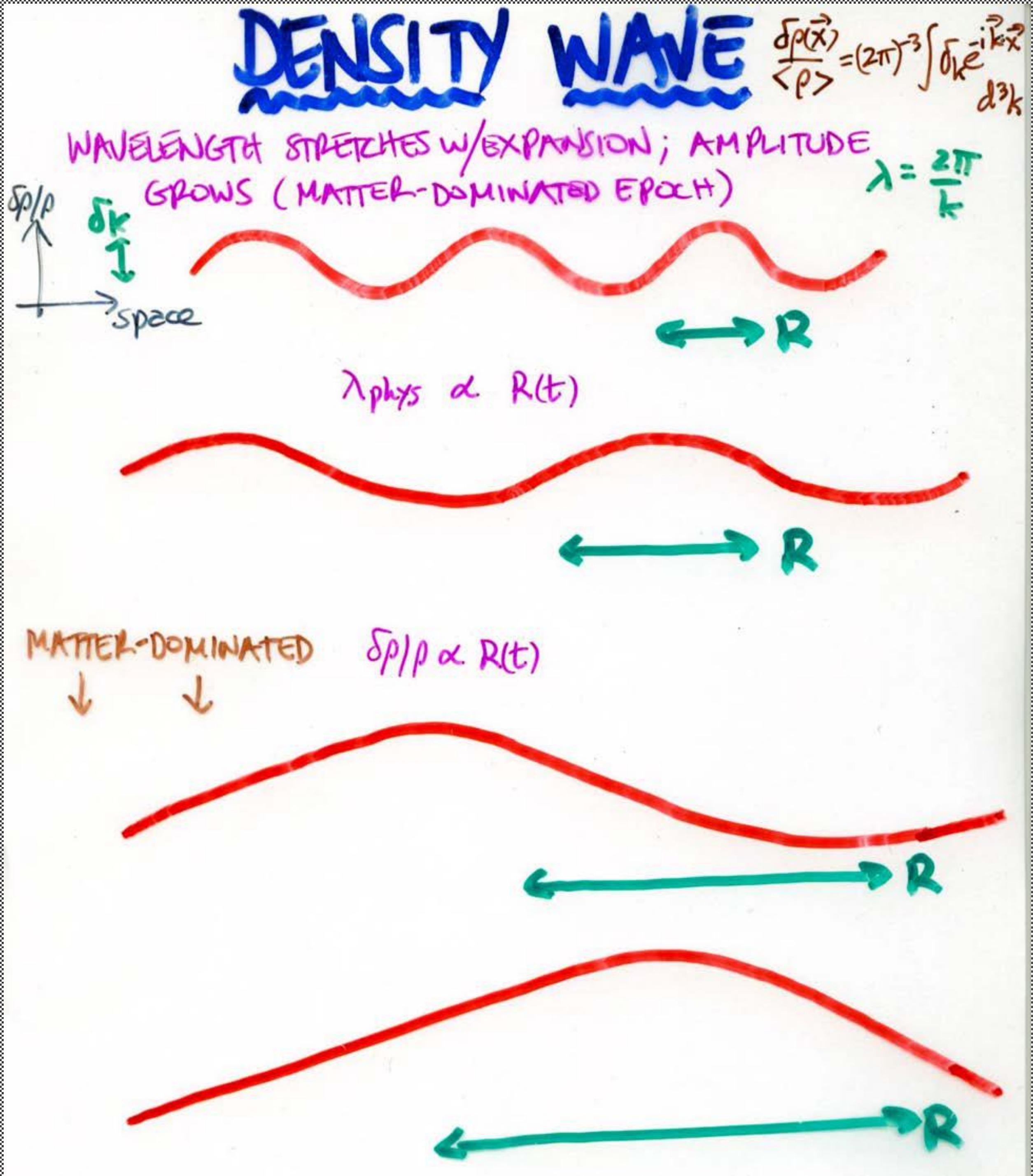
9. The perturbed Universe: beyond homogeneity and isotropy

$$\frac{\delta\rho(\vec{x})}{\bar{\rho}} = \frac{1}{(2\pi)^3}\int \delta_k \exp(-i\vec{k}\cdot\vec{x})d^3k$$

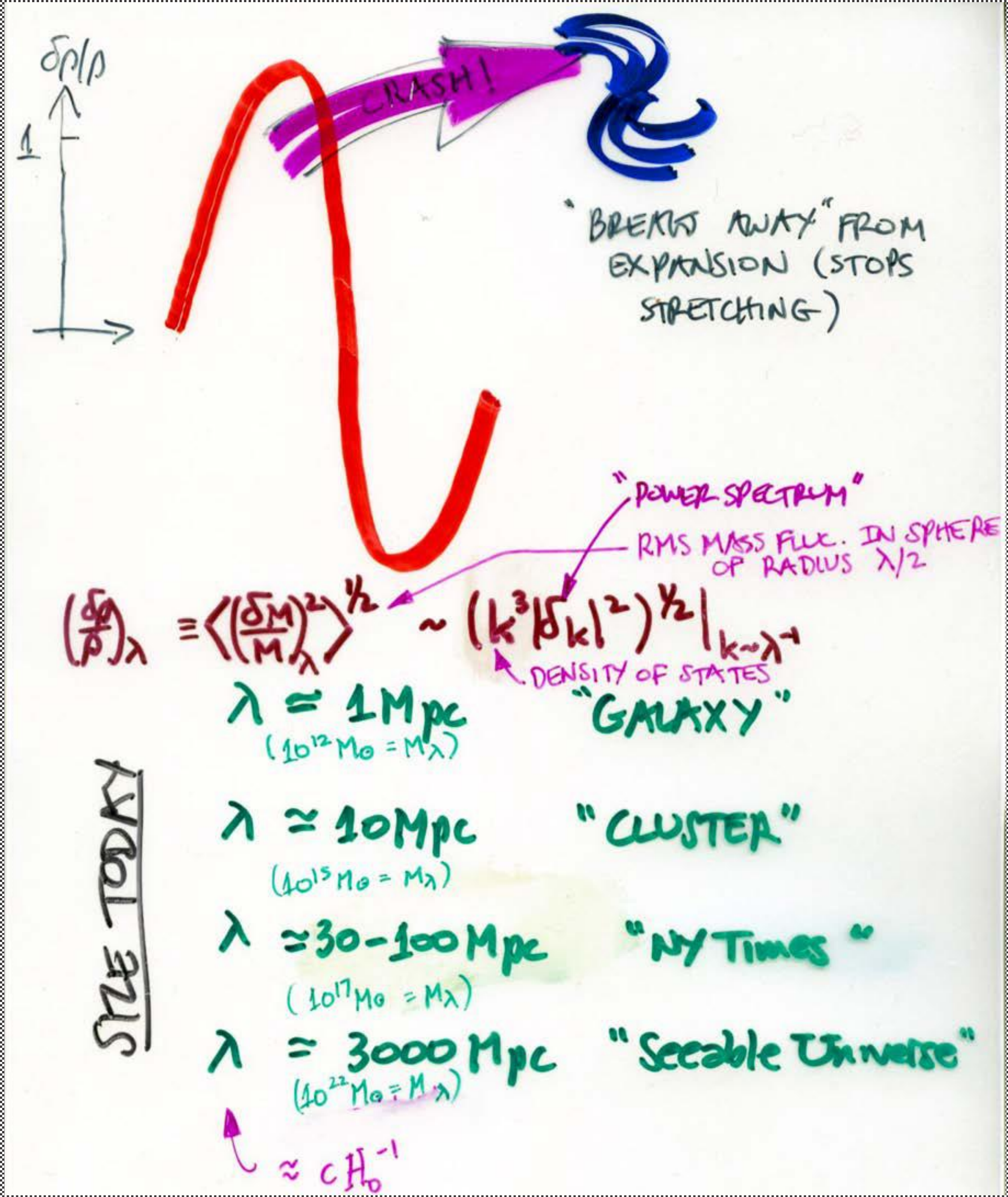
$$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho_M\delta_k = 0$$

1. $H = 0 \Rightarrow \delta_k \propto \exp[(4\pi G\rho_M)^{1/2}t]$ Classic Jeans' instability
2. $H = 2/3t$ (MD) $\delta_k \propto t^{2/3} \propto a(t)$ GROWTH!
3. $H = 1/2t$ (RD) $\delta_k \propto \ln(a)$ No growth
4. $H = const$ (Λ) $\delta_k \propto const$ No growth

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

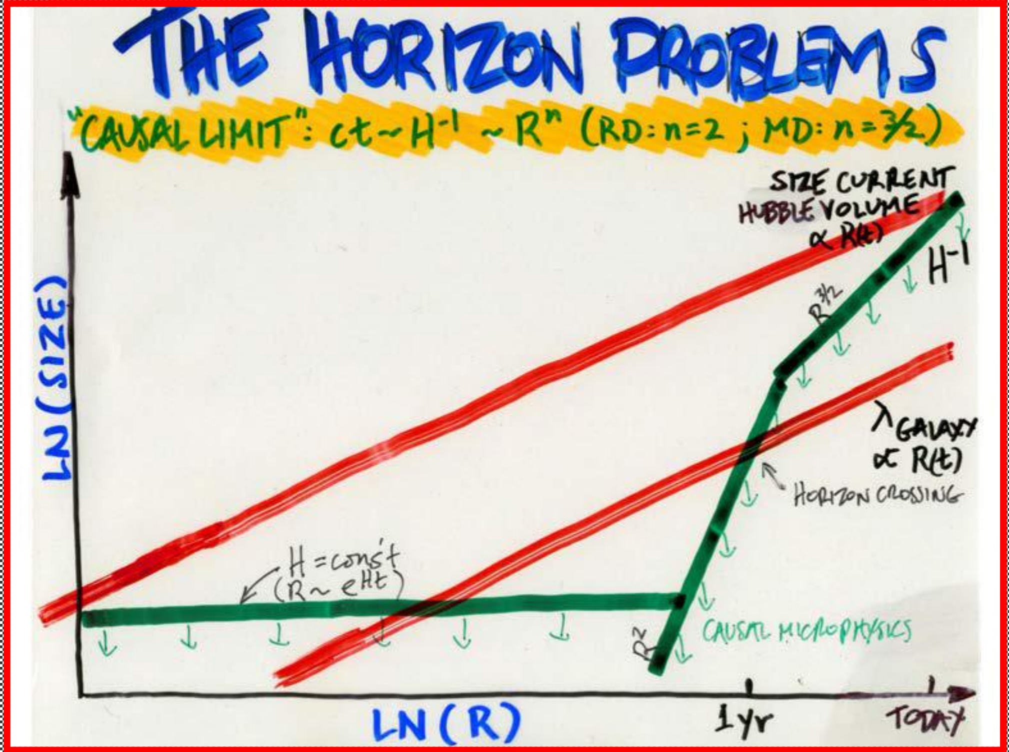


The Physics of Structure Formation (simplified)

1. Creation of Density Inhomogeneities

Inflation

2. Outside Horizon
$\lambda > H^{-1}$
Kinematic



3. Inside Horizon
$\lambda > H^{-1}$
Dynamic Evolution

$$\ddot{\delta}_k + 2H\dot{\delta}_k \;[+(v_s^2 k^2/R^2)\delta_k] - 4\pi G\rho_M \delta_k = 0$$

10. Inflation! The most important idea since the big bang and a pillar of ΛCDM

- “Original intent” (Guth, 1981): First-order phase transition can
  - Solve the horizon, flatness and monopole problems
  - Add on: create the seed inhomogeneities for structure formation (1983)
- Remarkable paper: also proved his idea didn’t work (and then proven it in more detail and rigor with Erick Weinberg, 1983!)
- The slow-roll work around (Linde and Albrecht & Steinhardt, 1982)

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Inflationary universe: A possible solution to the horizon and flatness problems

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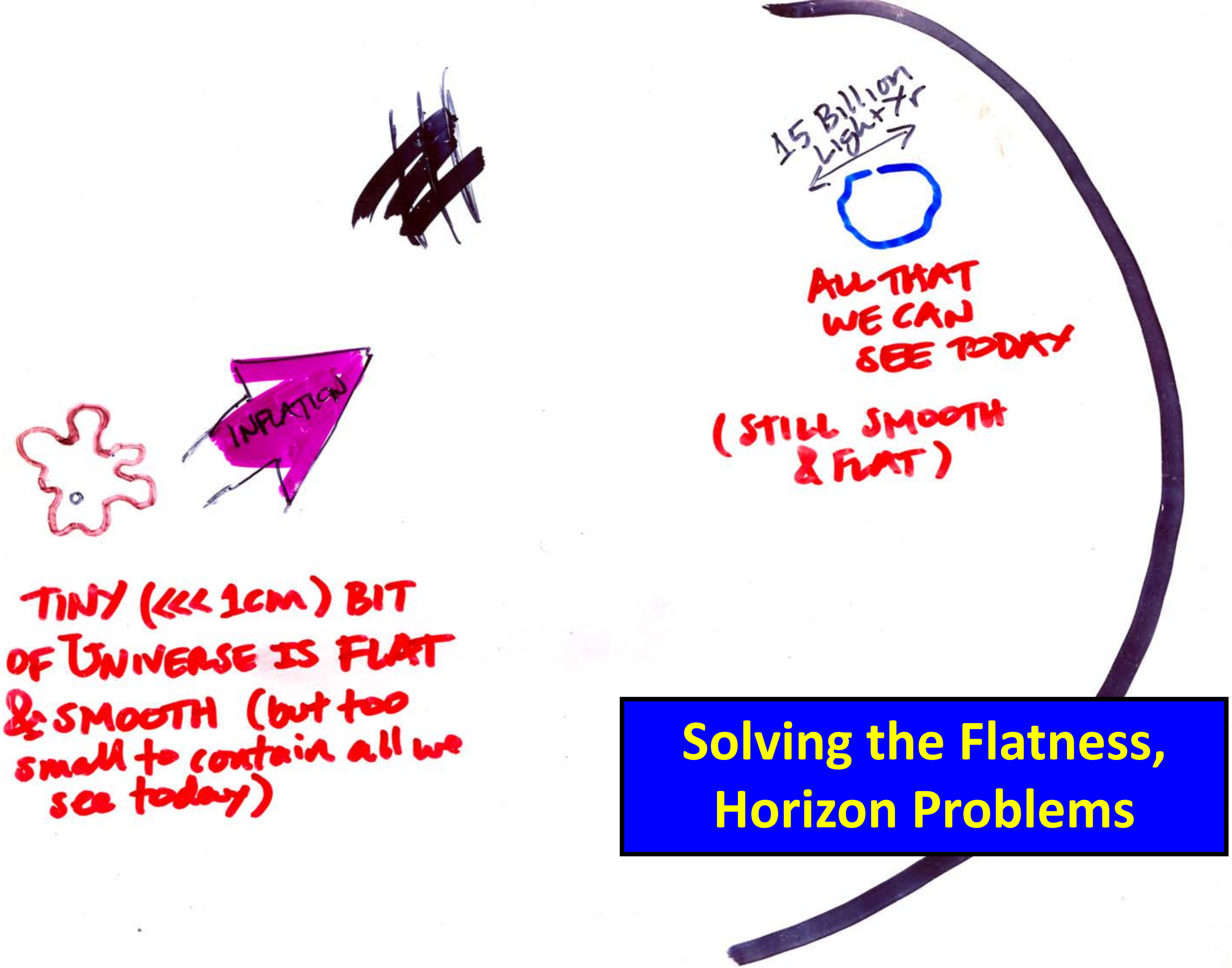
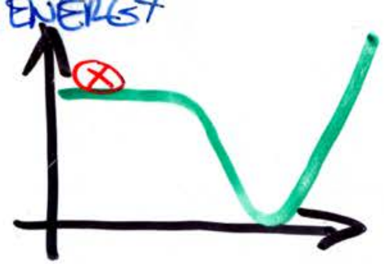
(Received 11 August 1980)

The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

Solving the Flatness, Horizon Problems



COSMIC INFLATION



Guth; Linde; Albrecht-Steinhardt

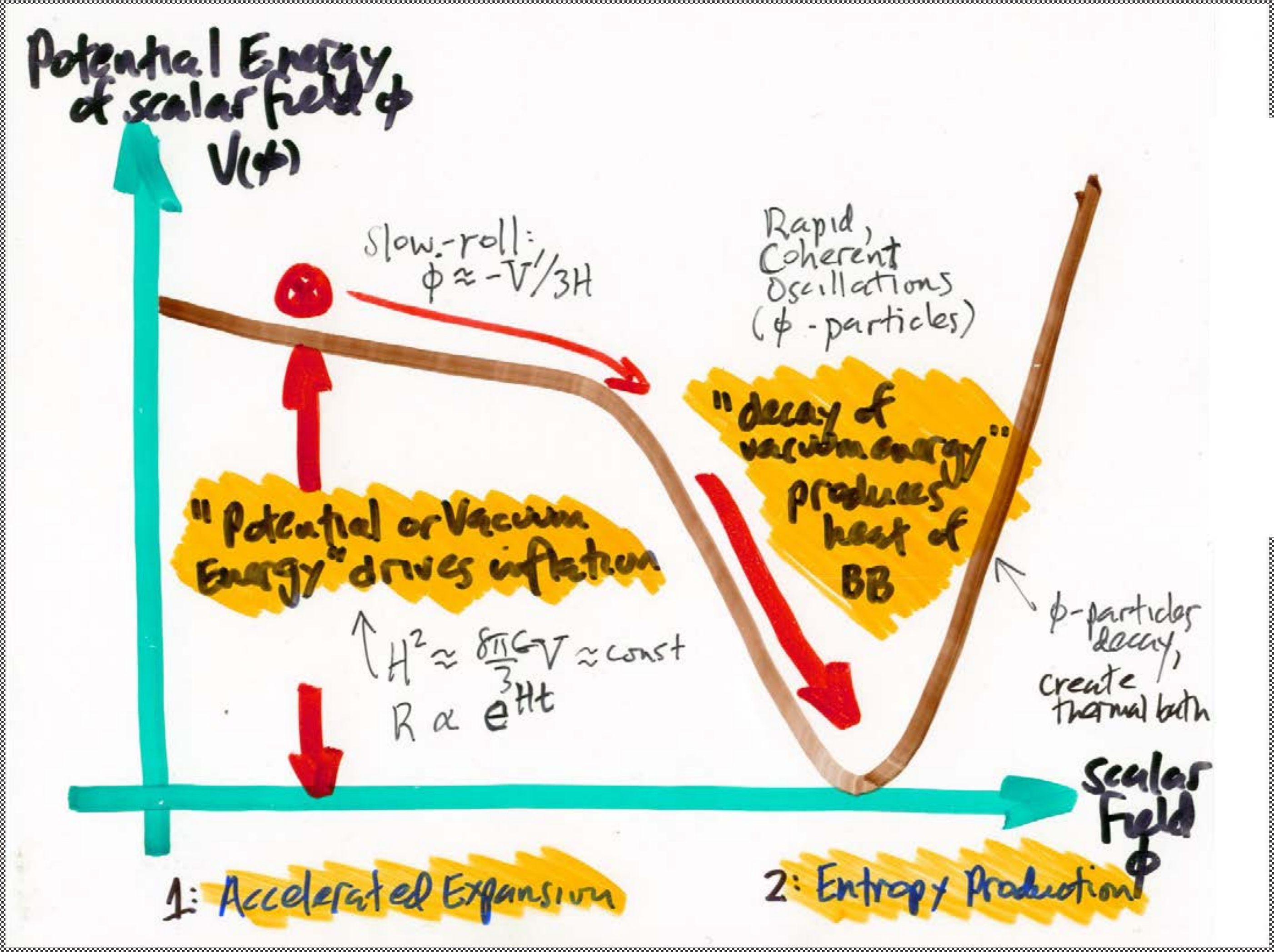
SHORT PERIOD OF RAPID EXPANSION DRIVEN BY "FALSE-VACUUM" ENERGY

- MORE EXPANSION IN 10^{-32} SEC THAN NEXT 15 Byr

- OBSERVED UNIVERSE BEGAN FROM INCREDIBLY SMALL PATCH → FLAT & SMOOTH

- MICROSCOPIC PHENOMENA (QUANTUM FLUCTUATIONS) CAN INFLUENCE MACROSCOPIC SCALES → QUANTUM ORIGIN OF "LUMPINESS"

Slow-roll inflation: scalar-field dynamics



$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

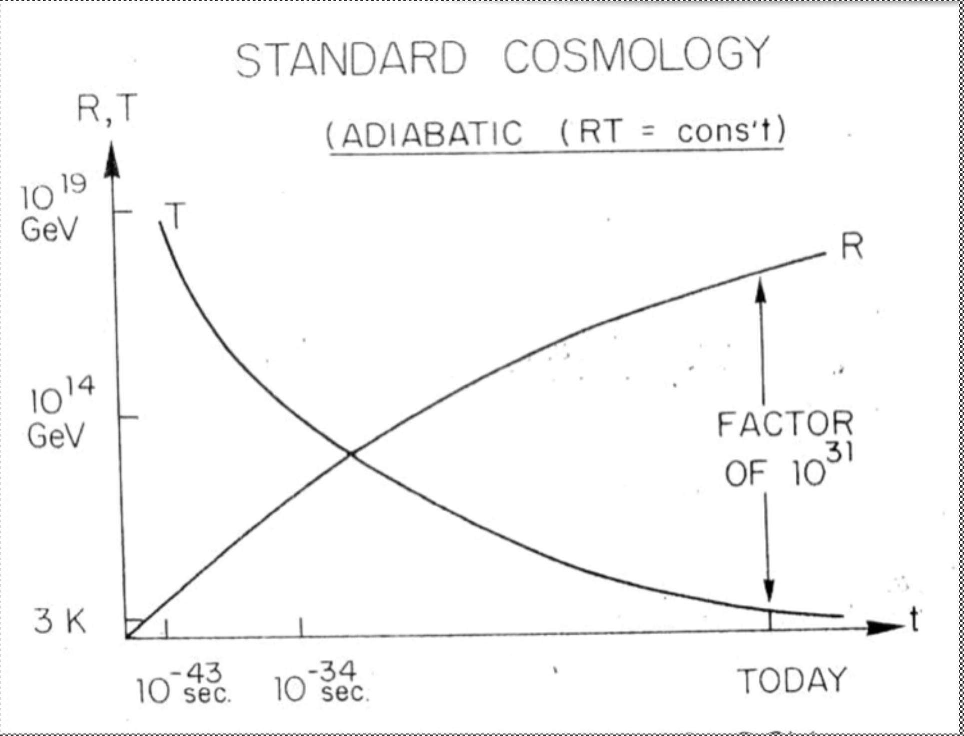
≈-1

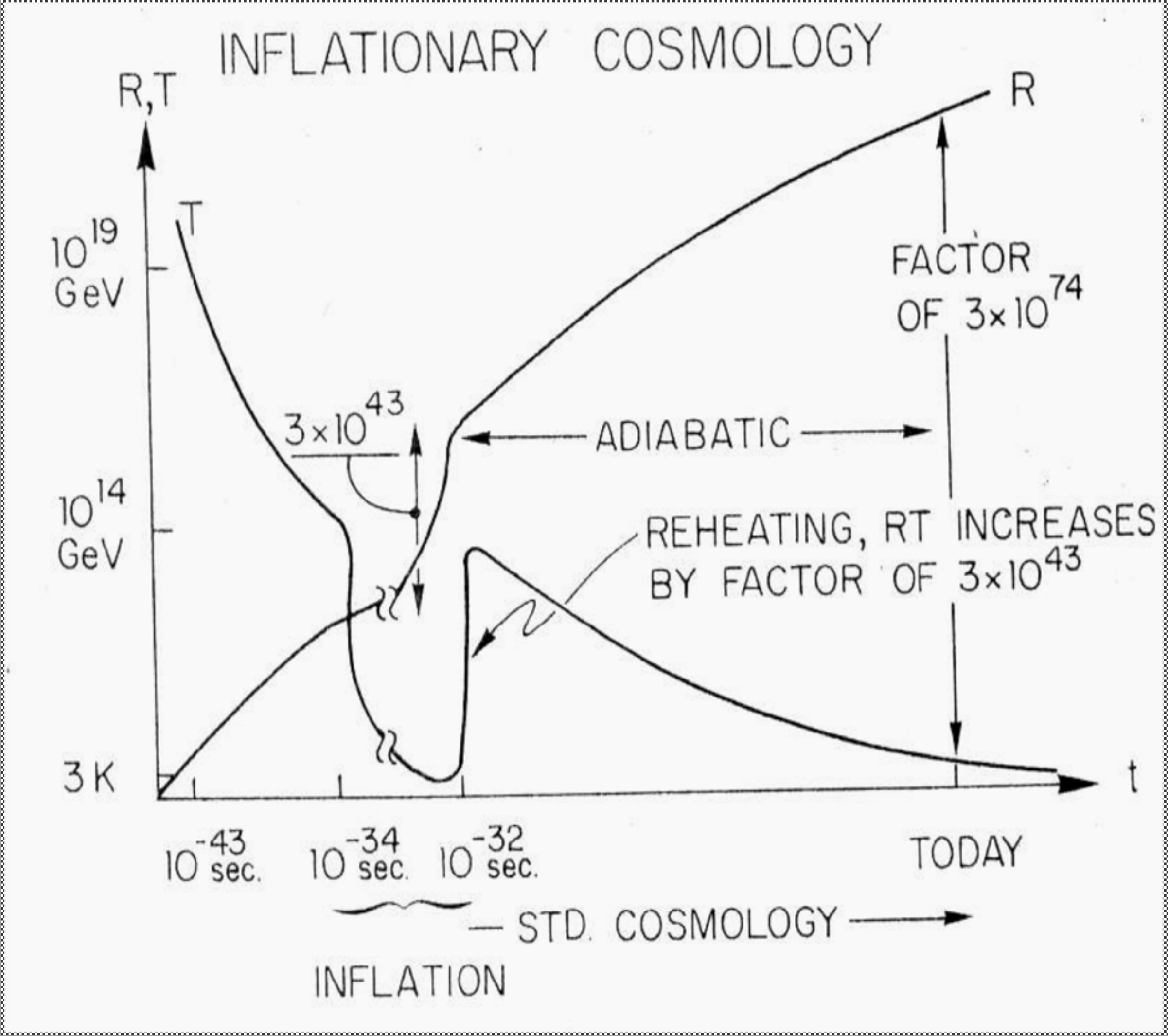
$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) \quad [+\Gamma\dot{\phi}] \quad = 0$$

Entropy Production/Reheating

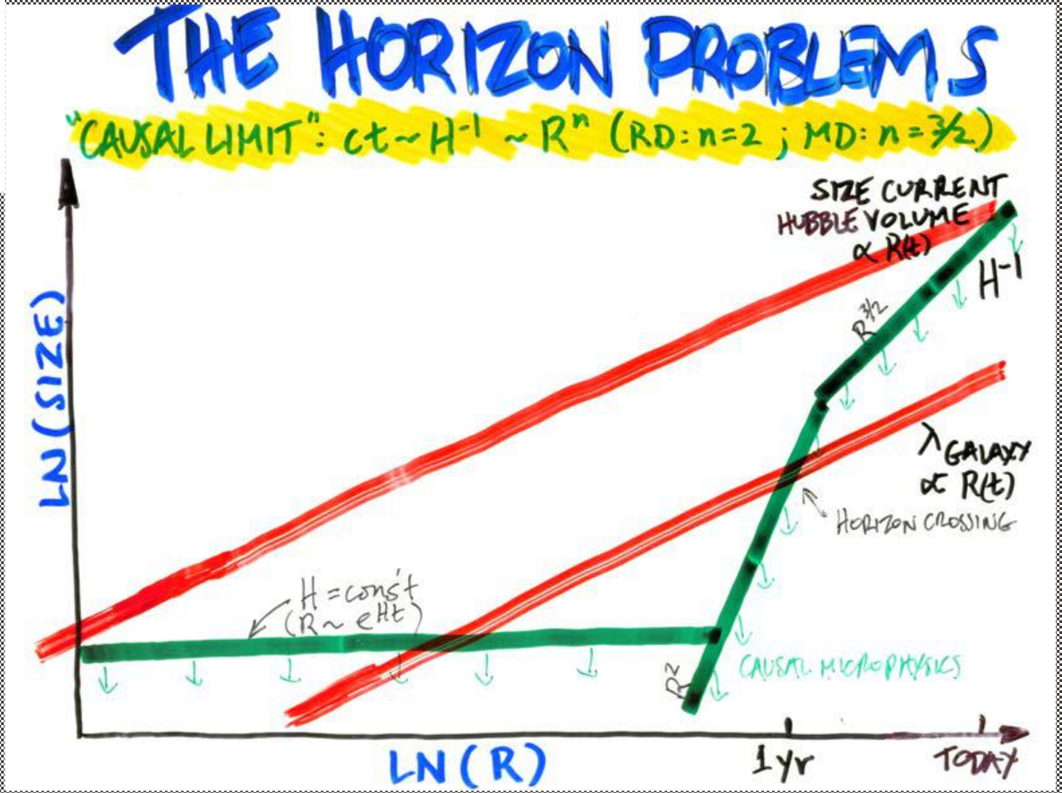
Recall: entropy per comoving volume ~ R^3T^3

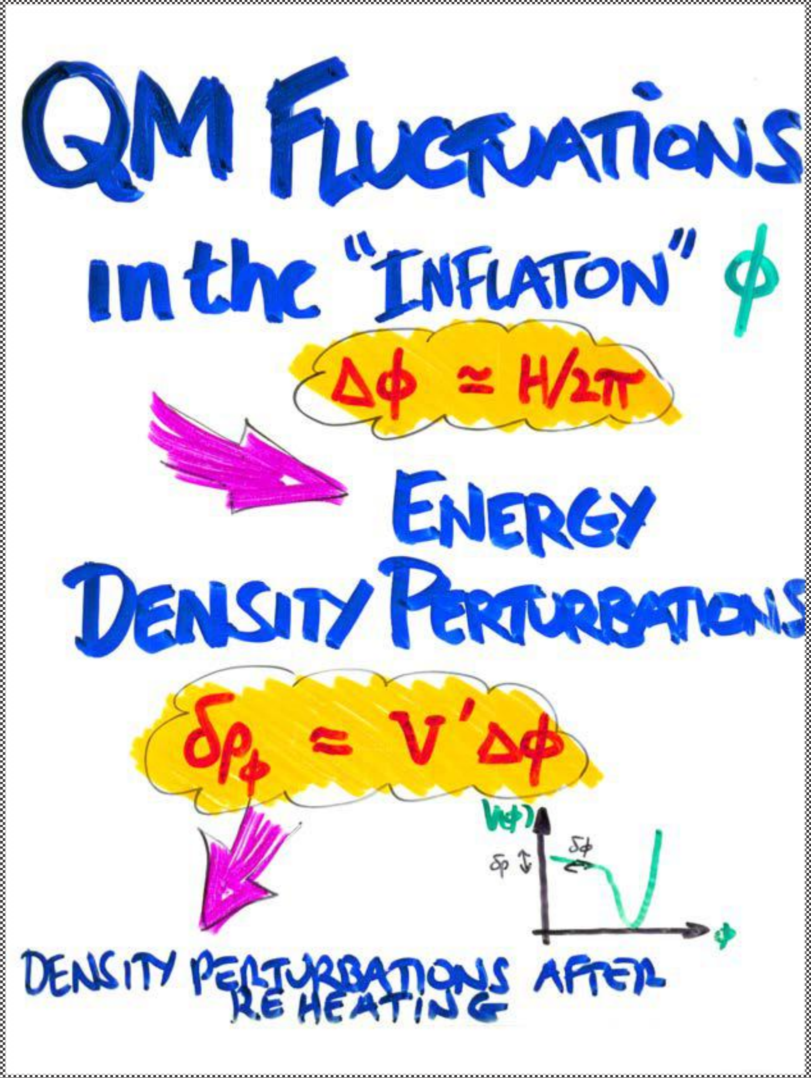




Adiabatic: Constant Number of Photons per co-moving Volume, i.e., RT = const

Quantum Fluctuations Seed Density Perturbations

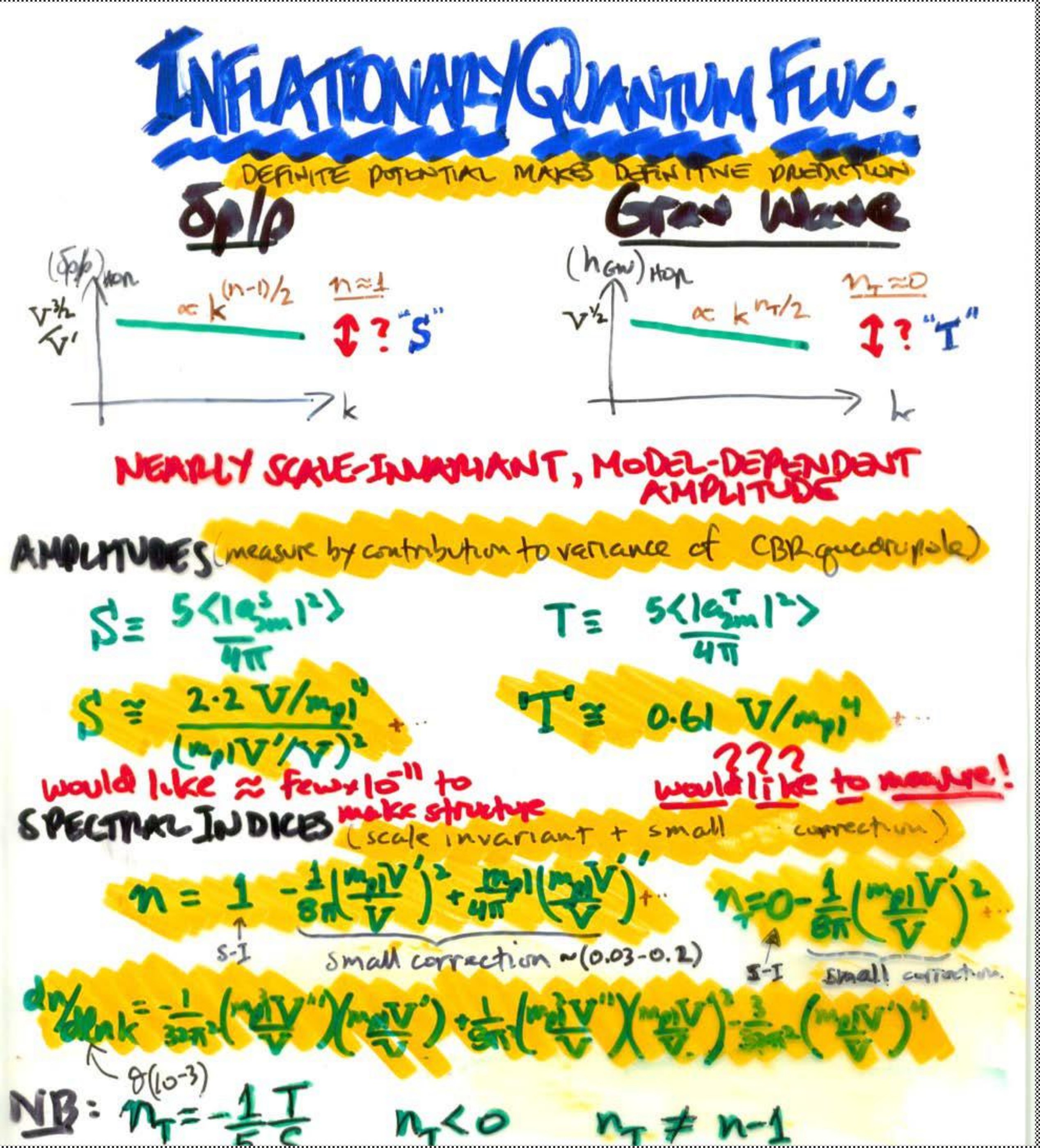




Good news, bad news:

Given a scalar potential V(ϕ),

can compute all observables in terms of V, V’ and V’’



Inflation's predictions

$$P(k) = \frac{1024\pi^3}{75}\frac{k}{H_0^4}\frac{V_*^3}{m_{\rm Pl}{}^6 V_*'^2}\left(\frac{k}{k_*}\right)^{n-1} T^2(k)$$

$$n-1 = -\frac{1}{8\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 + \frac{m_{\rm Pl}}{4\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)'$$

$$\frac{dn}{d\ln k} = -\frac{1}{32\pi^2}\left(\frac{m_{\rm Pl}{}^3 V_*'''}{V_*}\right)\left(\frac{m_{\rm Pl}V_*'}{V_*}\right) + \frac{1}{8\pi^2}\left(\frac{m_{\rm Pl}{}^2 V_*''}{V_*}\right)\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 - \frac{3}{32\pi^2}\left(m_{\rm Pl}\frac{V_*'}{V_*}\right)^4$$

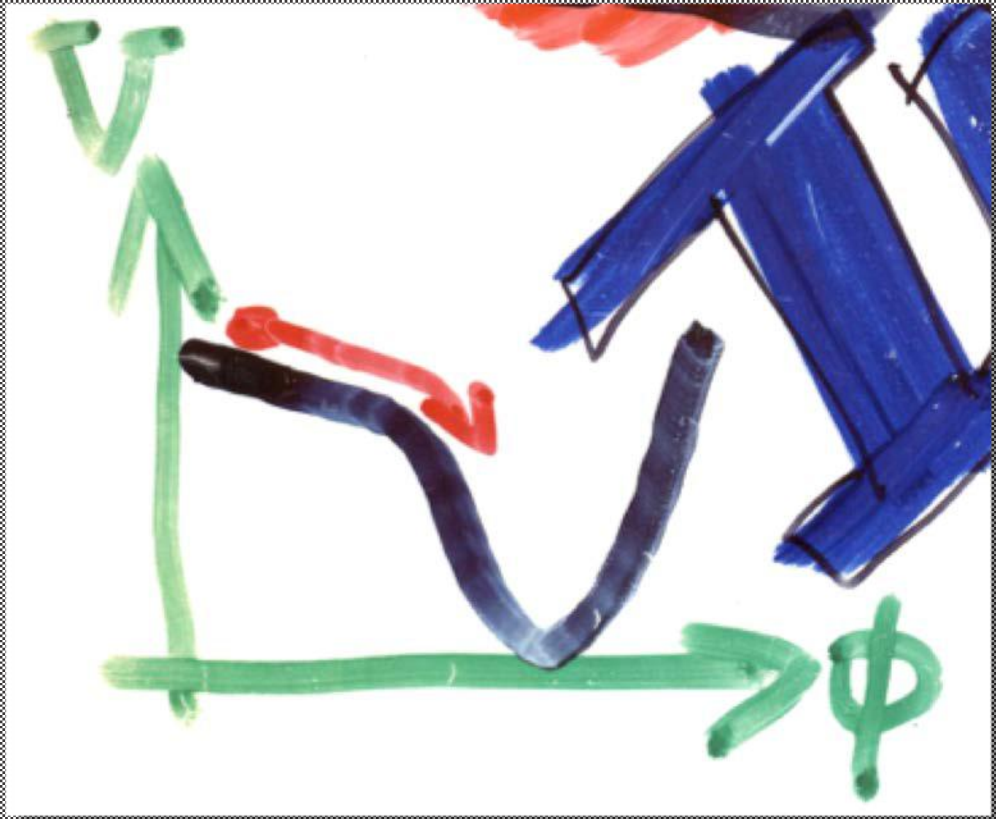
$$T(q) = \frac{\ln(1+2.34q)/2.34q}{[1+3.89q+(16.1q)^2+(5.46q)^3+(6.71q)^4]^{1/4}},$$

$$P_T(k) \equiv \langle |h_k|^2\rangle = \frac{8}{3\pi}\frac{V_*}{m_{\rm Pl}{}^4}\left(\frac{k}{k_*}\right)^{n_T-3} T_T^2(k)$$

$$n_T = -\frac{1}{8\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2$$

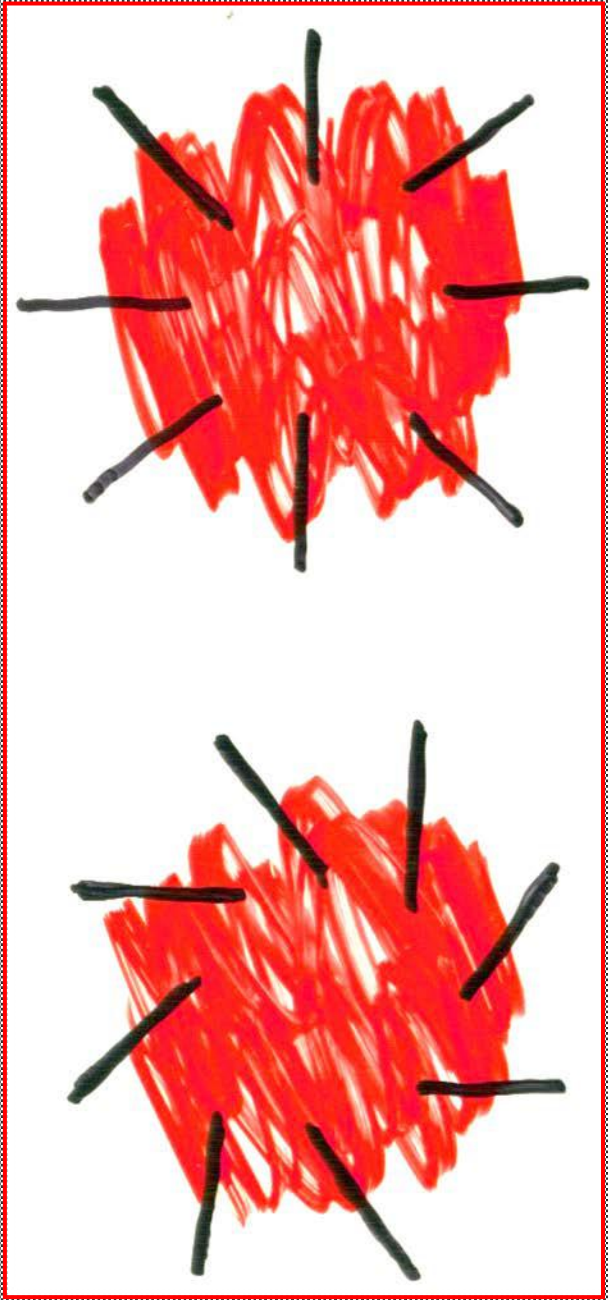
$$\frac{dn_T}{d\ln k} = \frac{1}{32\pi^2}\left(\frac{m_{\rm Pl}{}^2 V''}{V}\right)\left(\frac{m_{\rm Pl}V'}{V}\right)^2 - \frac{1}{32\pi^2}\left(\frac{m_{\rm Pl}V'}{V}\right)^4 = -n_T[(n-1)-n_T]$$

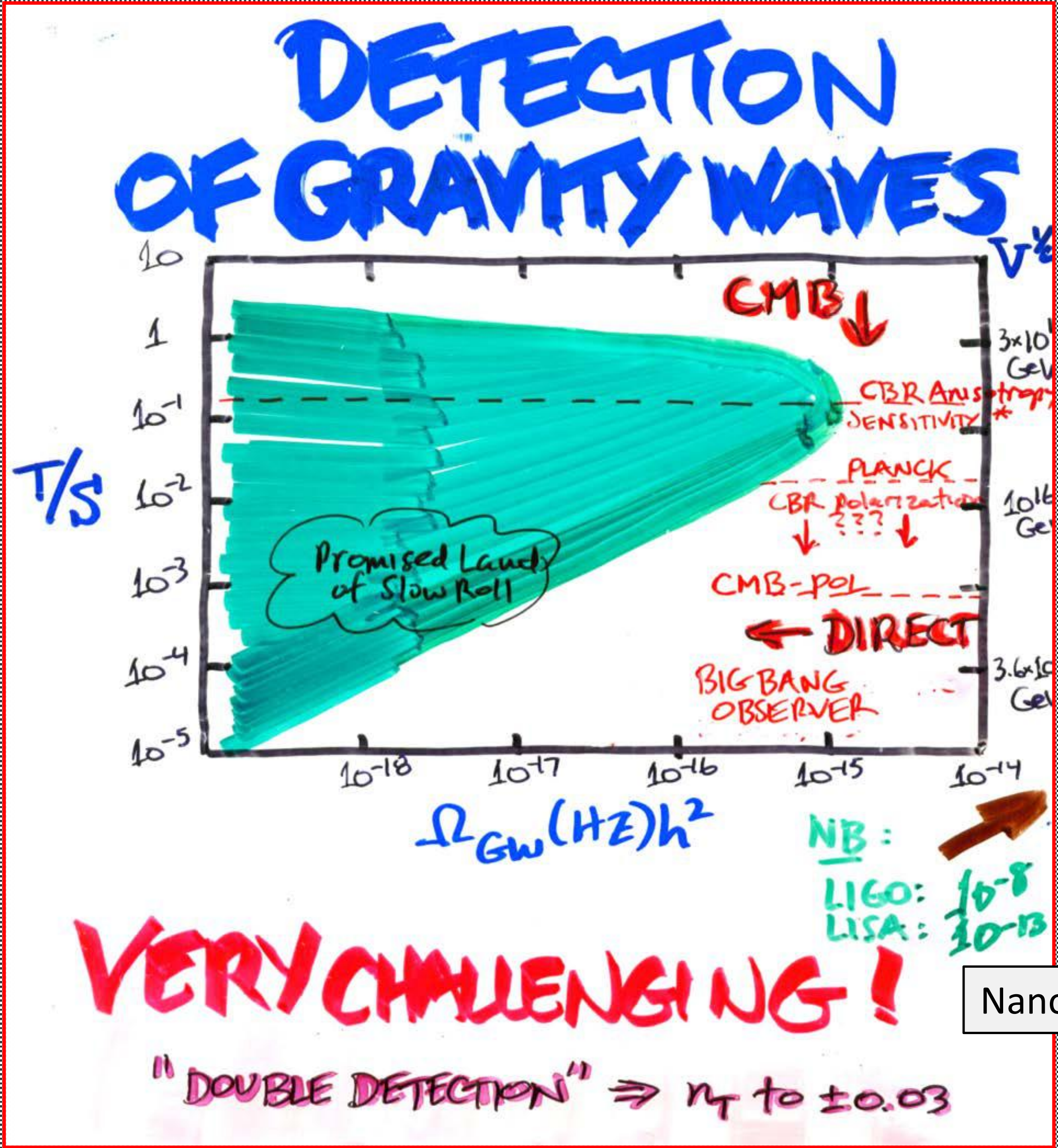
$$T_T(k) \simeq \left[1+\frac{4}{3}\frac{k}{k_{\rm EQ}}+\frac{5}{2}\left(\frac{k}{k_{\rm EQ}}\right)^2\right]^{1/2},$$



Key predictions of inflation

- Flat Universe (at a time when the data said: Ω_0 = 0.1!)
- Almost scale-invariant, Gaussian curvature perturbations (not precisely a power-law and n not precisely 1.0)
- Almost scale-invariant spectrum of GWs: in the B-mode polarization
- Consistency relationship: $T/S = 7n_T$
- … and it explains the isotropy/homogeneity, quark soup and absence of superheavy magnetic monopoles
- BUT, it is an incomplete theory: no std model, temporary fix, what about the BB singularity, and on and on



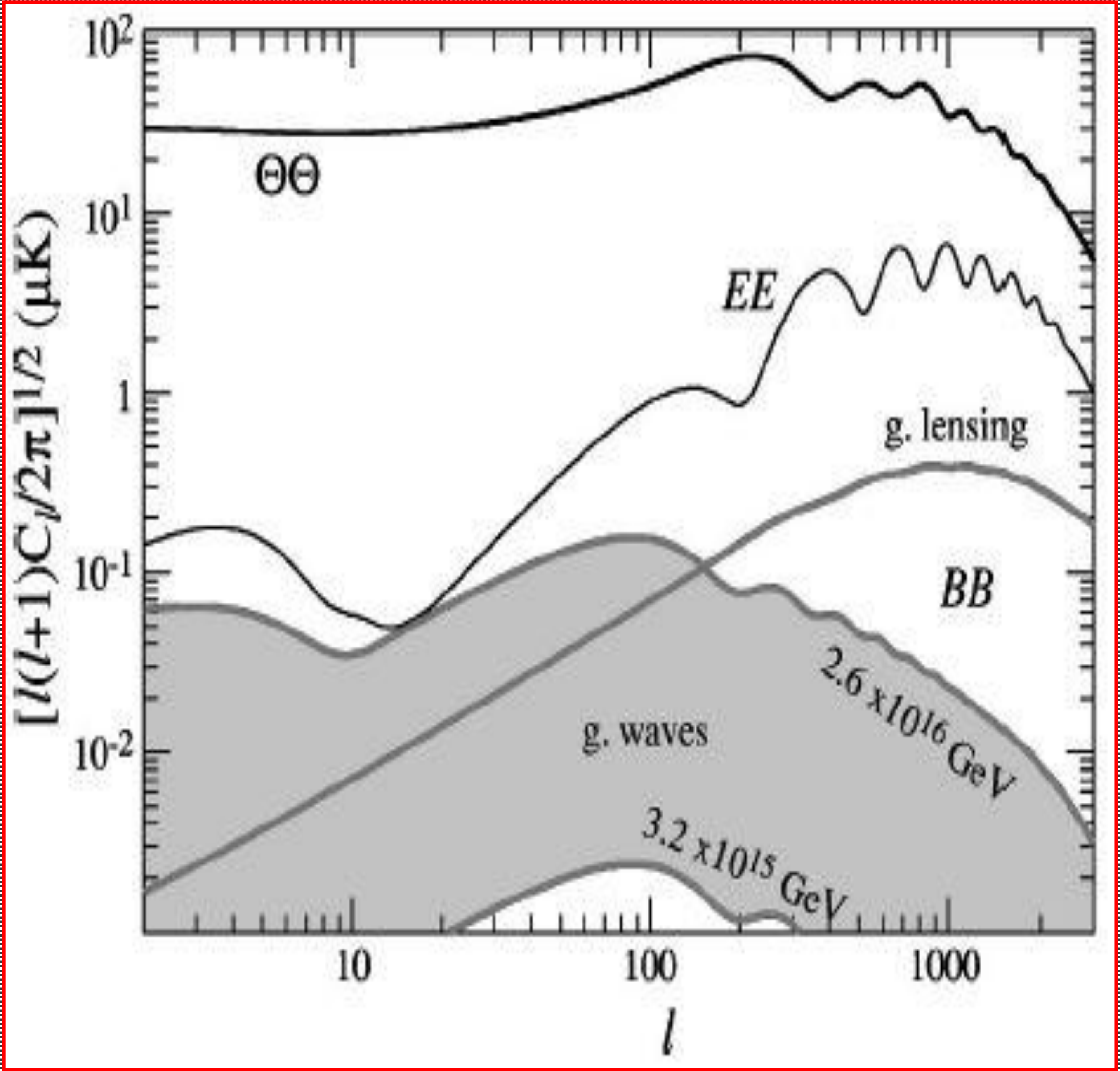


NanoGrav: 10^{-8} at 10^{-9} Hz

CMB Anisotropy from Gravity Waves

- ΘΘ = GW temp
- EE = E mode (scalar)
- g lensing: grav lensing of EE
- BB/g waves = GW B-mode

- nanoKelvin cosmology!



GWs and B-mode CMB polarization

n = 1 n = 0.85

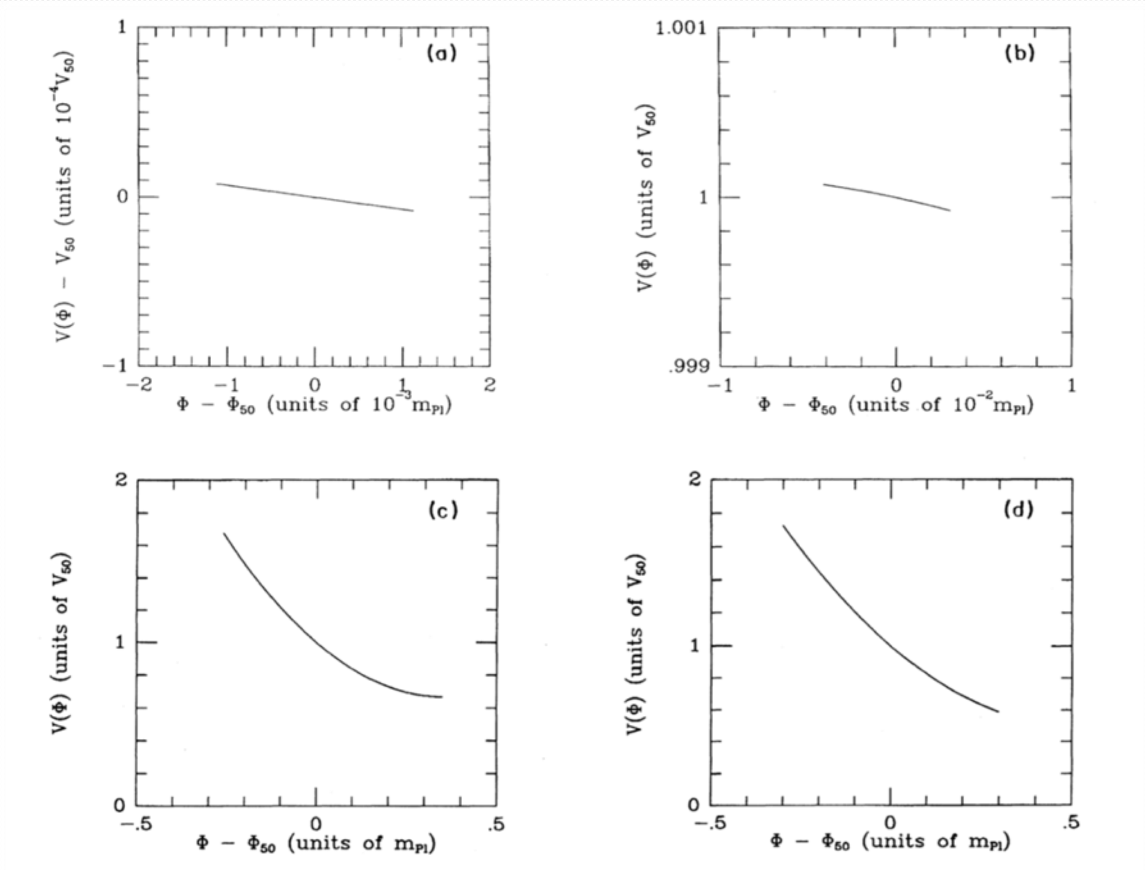
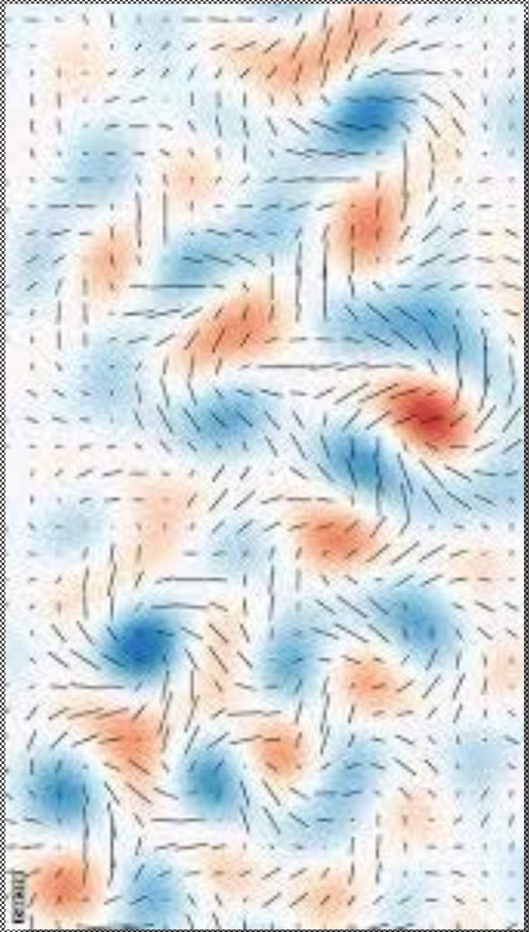


FIG. 5. The four generic inflationary potentials: (a) $n-1=-2\times10^{-6}$ and $T/S=1.4\times10^{-5}$, with the COBE DMR normalization $V_{50}^{1/4}=2.0\times10^{15}$ GeV; (b) $n=0.85$ and $T/S=1.4\times10^{-4}$, $V_{50}^{1/4}=3.6\times10^{15}$ GeV; (c) $n=1$ and $T/S=1$, $V_{50}^{1/4}=2.9\times10^{16}$ GeV; and (d) $n=0.85$ and $T/S=1$, $V_{50}^{1/4}=2.9\times10^{16}$ GeV. (a)–(d) correspond to cases (1)–(4) in the text.

r << 1

r = 1



PHYSICAL REVIEW D VOLUME 48, NUMBER 12 15 DECEMBER 1993

Recovering the inflationary potential

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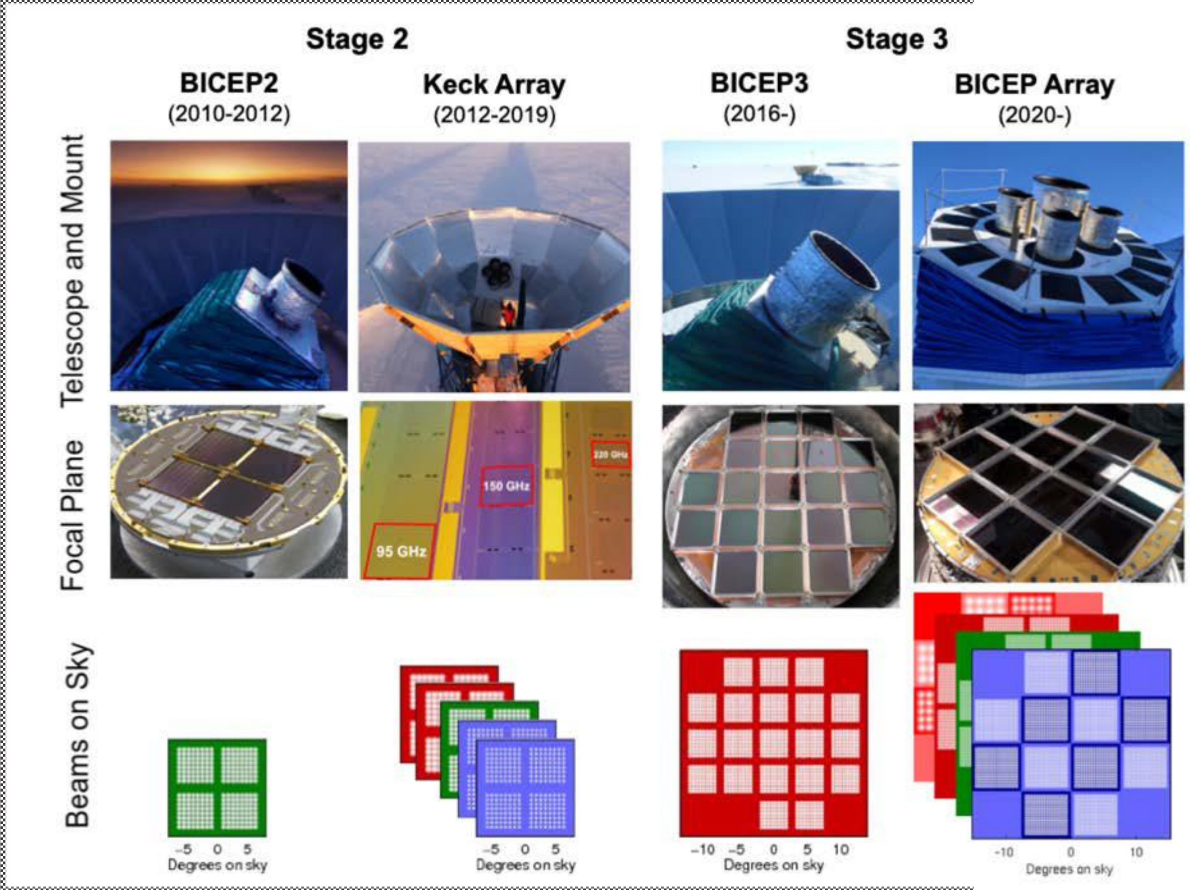
(Received 27 July 1993)

A procedure is developed for the recovery of the inflationary potential over the interval that affects astrophysical scales (≈ 1 Mpc to 10^4 Mpc). The amplitudes of the scalar and tensor metric perturbations and their power-spectrum indices, which in principle can be inferred from large-angle CBR anisotropy and other cosmological data, determine the value of the inflationary potential and its first two derivatives. From these, the inflationary potential can be reconstructed in a Taylor series and the consistency of the inflationary hypothesis tested. Examples are presented, and the effect of observational uncertainties is discussed.

BICEP/Keck leading the way



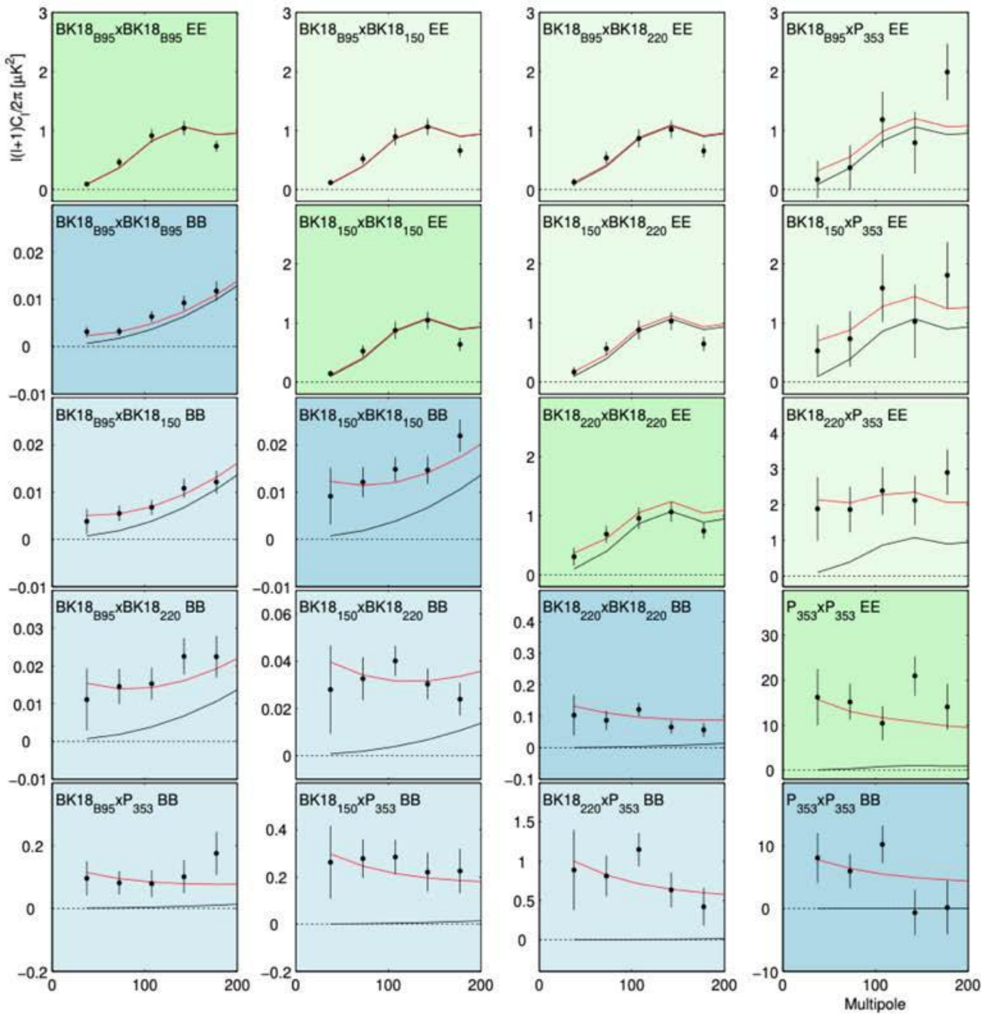


Figure 4. BB (blue) and EE (green) auto- and cross-spectra from BICEP3 95 GHz, BICEP2/*Keck* 150 GHz, *Keck* 220 GHz and *Planck* 353 GHz maps. The black lines are the ΛCDM model expectation values, while the red lines are the ΛCDM+foreground expectation values from the foreground best fit of our previous BK15 analysis. The EE spectra are computed as a demonstration under the assumption $EE/BB = 2$ for dust. EE spectra are not included in our likelihood analysis.

The Latest Constraints on Inflationary B-modes from the BICEP/Keck Telescopes

The BICEP/*Keck* Collaboration: P. A. R. Ade[a], Z. Ahmed[b], M. Amiri[c], D. Barkats[d], R. Basu Thakur[e], C. A. Bischoff[f], D. Beck[b,g], J. J. Bock[e,h], H. Boenish[d], E. Bullock[i], V. Buza[j], J. R. Cheshire IV[i], J. Connors[d], J. Cornelison[d], M. Crumrine[k], A. Cukierman[g,b], E. V. Denison[l], M. Dierickx[d], L. Duband[m], M. Eiben[d], S. Fatigoni[c], J. P. Filippini[n,o], S. Fliescher[k], C. Giannakopoulos[f], N. Goeckner-Wald[g], D. C. Goldfinger[d], J. Grayson[g], P. Grimes[d], G. Hall[k], G. Halal[g], M. Halpern[c], E. Hand[f], S. Harrison[d], S. Henderson[b], S. R. Hildebrandt[e,h], G. C. Hilton[l], J. Hubmayr[l], H. Hui[e], K. D. Irwin[g,b,l], J. Kang[g,e], K. S. Karkare[d,j], E. Karpel[g], S. Kefeli[e], S. A. Kernasovskiy[g], J. M. Kovac[d,p], C. L. Kuo[g,b], K. Lau[k,*], E. M. Leitch[j], A. Lennox[n], K. G. Megerian[h], L. Minutolo[e], L. Moncelsi[e], Y. Nakato[g], T. Namikawa[q], H. T. Nguyen[h], R. O'Brient[e,h], R. W. Ogburn IV[g,b], S. Palladino[f], M. Petroff[d], T. Prouve[m], C. Pryke[k,i], B. Racine[d,r], C. D. Reintsema[l], S. Richter[d], A. Schillaci[e], R. Schwarz[k], B. L. Schmitt[d], C. D. Sheehy[s], B. Singari[i], A. Soliman[e], T. St. Germaine[d,p], B. Steinbach[e], R. V. Sudiwala[a], G. P. Teply[e], K. L. Thompson[g,b], J. E. Tolan[g], C. Tucker[a], A. D. Turner[h], C. Umiltà[f,n], C. Vergès[d], A. G. Vieregg[t,j], A. Wandui[e], A. C. Weber[h], D. V. Wiebe[c], J. Willmert[k], C. L. Wong[d,p], W. L. K. Wu[b], H. Yang[g], K. W. Yoon[g,b], E. Young[g,b], C. Yu[g], L. Zeng[d], C. Zhang[e], and S. Zhang[e]

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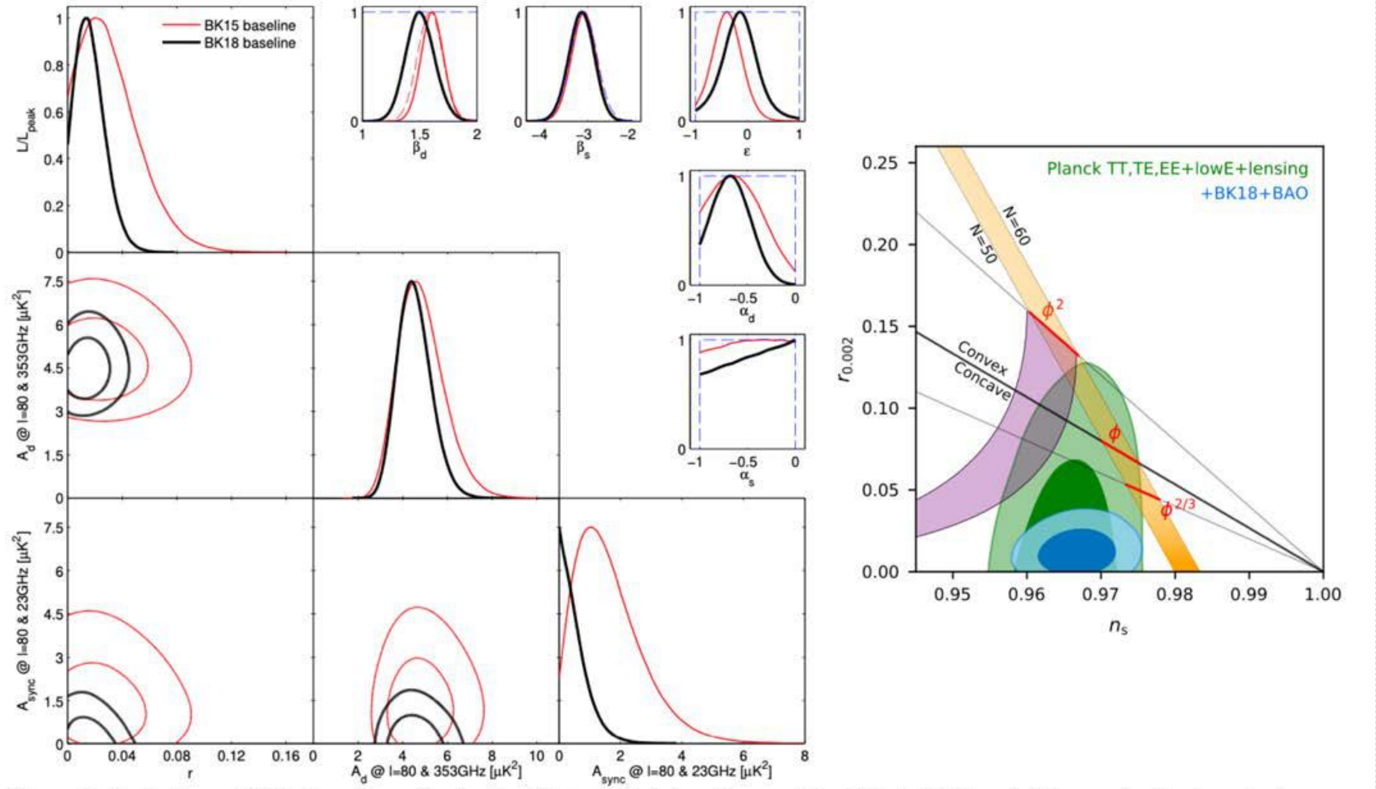
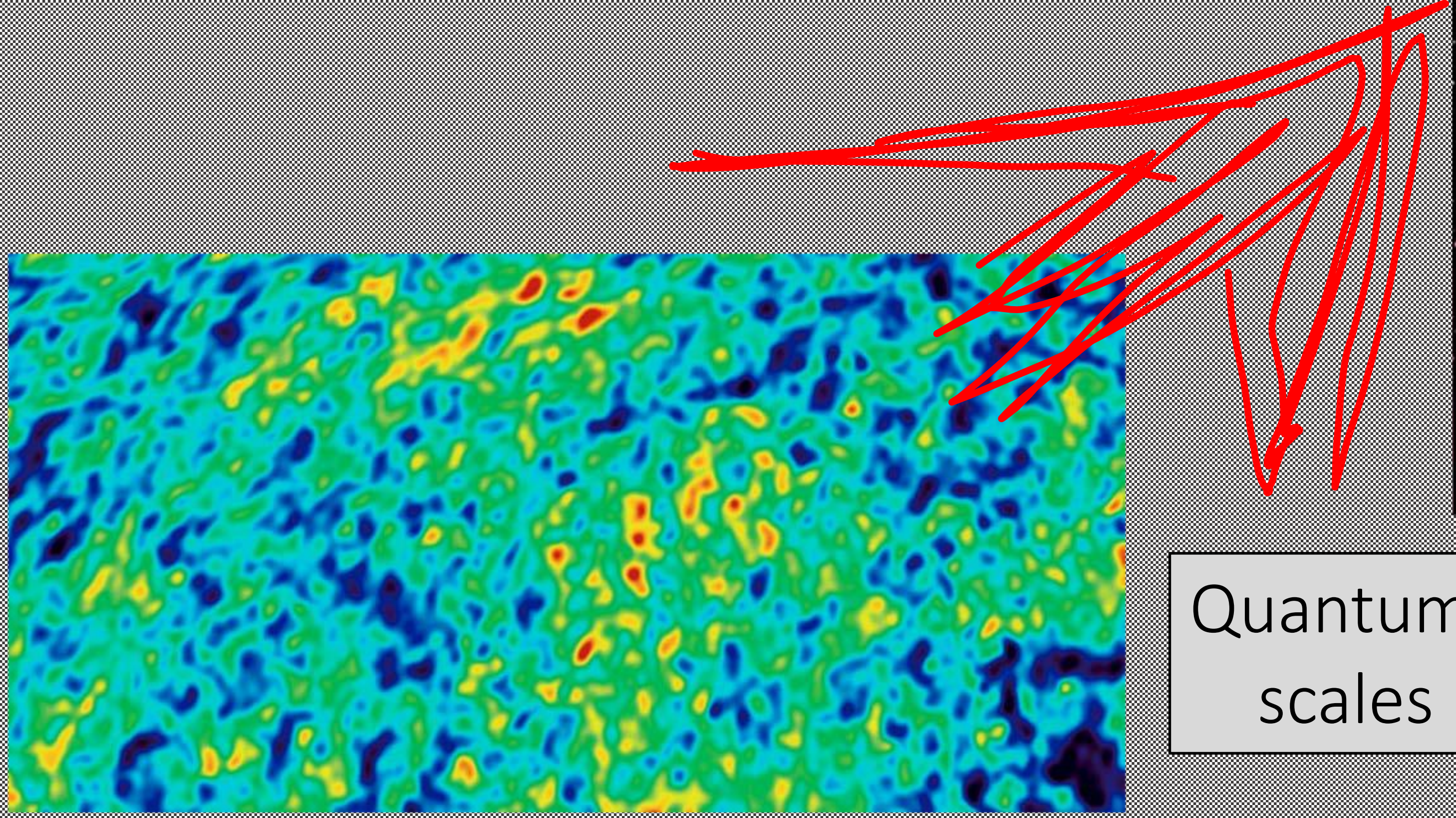


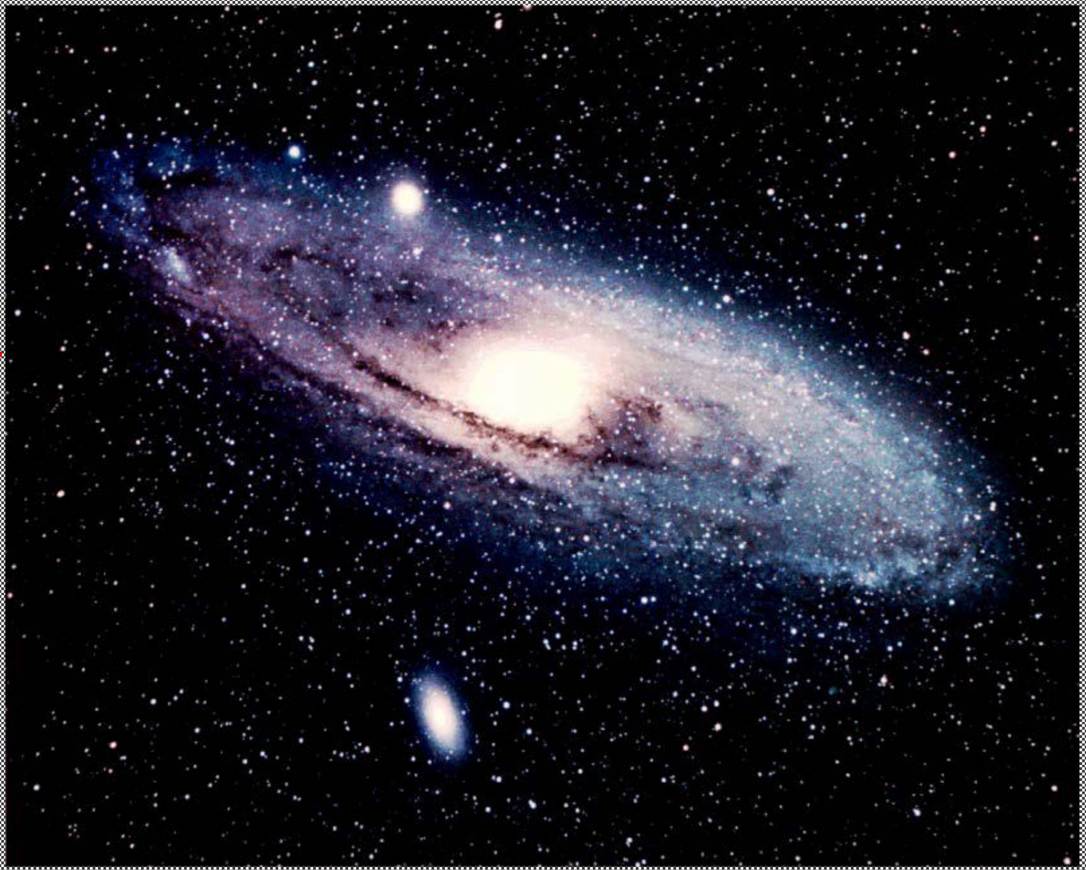
Figure 5. *Left*: **CosmoMC** likelihood results for the BICEP/*Keck* baseline model. Selected 1D and 2D marginalized posteriors are shown. The red faint curves are the results from BK15 while the black solid curves are the results of BK18. The dashed blue and red lines show priors on foreground parameters. The analysis method is the same as in BK15, except the β_d prior based on *Planck* data from other regions of the sky is removed this time due to the improved sensitivity of BK18. *Right*: Constraints in the r vs. n_s plane. The purple and orange bands are natural inflation and monomial inflation respectively. The blue contour shows the updated constraint after adding BK18 and BAO data to the *Planck* baseline analysis. The r posterior is tightened from $r_{0.05} < 0.11$ to $r_{0.05} < 0.035$ at 95% confidence.

Triumphs and tests

- Big bang nucleosynthesis (no need to posit large primordial ^{4}He abundance) and predicted ^{4}He ($Y_P = 0.2469 \pm 0.0002$) vs observed ($Y_P = 0.245 \pm 0.00034$) vs CMB inferred ($Y_P = 0.242 \pm 0.024$)
- BBN baryon density ($\Omega_B h^2 = 0.02166 \pm 0.00015$) and CMB baryon density ($\Omega_B h^2 = 0.02237 \pm 0.00015$)
- Structure formation: perturbations measured in CMB + gravity (numerical simulation) = the Universe we see today
- Crosschecks: H_0, σ_8 and others (tensions and opportunities??)
- Basic predictions of inflation verified: almost scale-invariant, Gaussian curvature fluctuations, flat Universe, and coming soon GWs
- Precision set of cosmological parameters

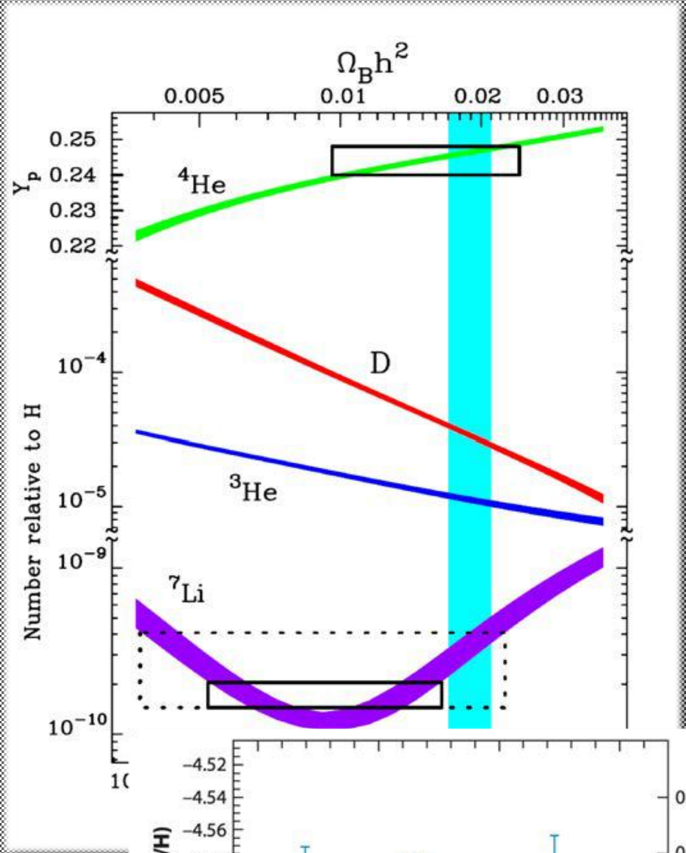
The grand connection between big and small

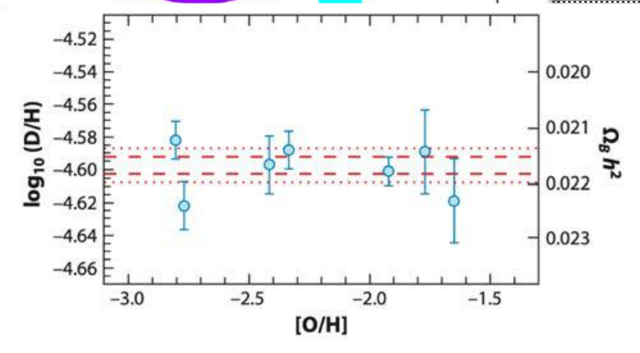


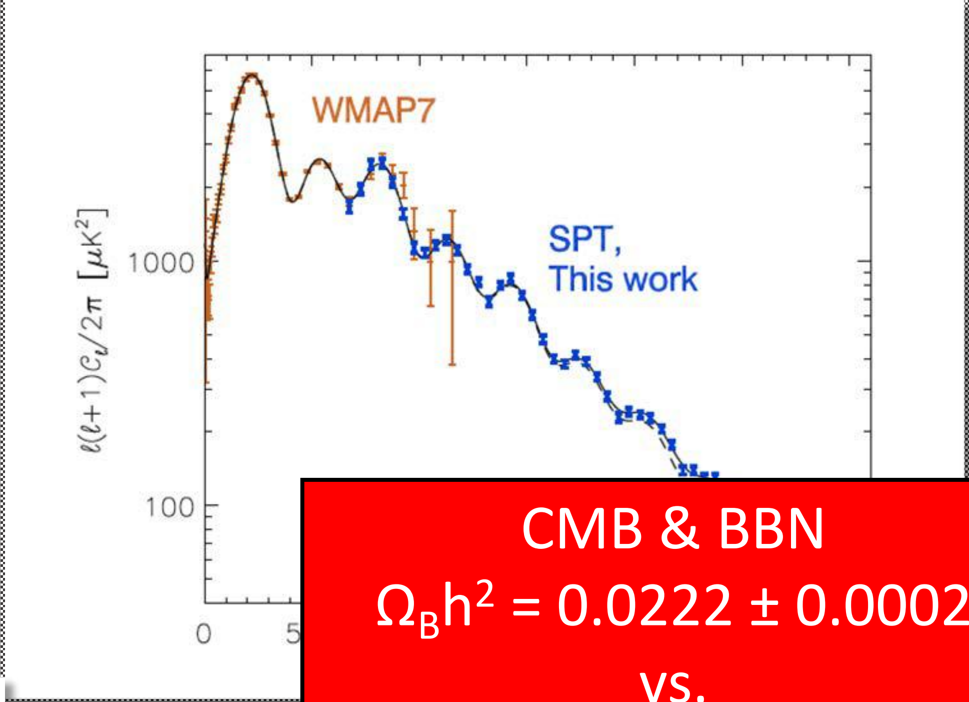


Quantum fluctuations on unimaginably small scales lead to structure on cosmic scales

The airtight evidence for nonbaryonic DM







CMB & BBN

$\Omega_B h^2 = 0.0222 \pm 0.0002$

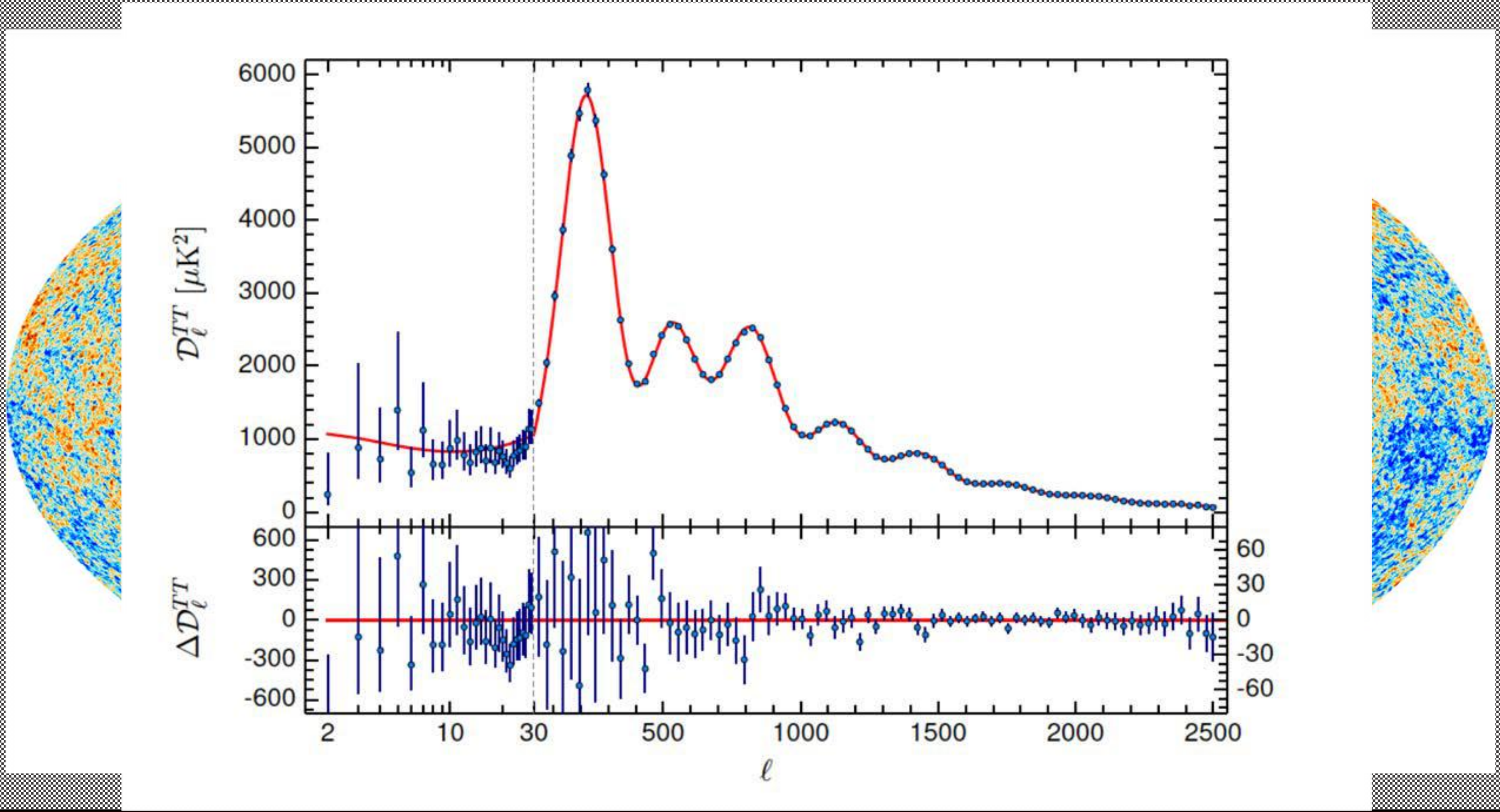
vs.

CMB/SDSS

$\Omega_M h^2 = 0.143 \pm 0.001$

<u>> 50σ discrepancy</u>

Best evidence for ΛCDM



6 numbers describe the Universe from the big bang until today

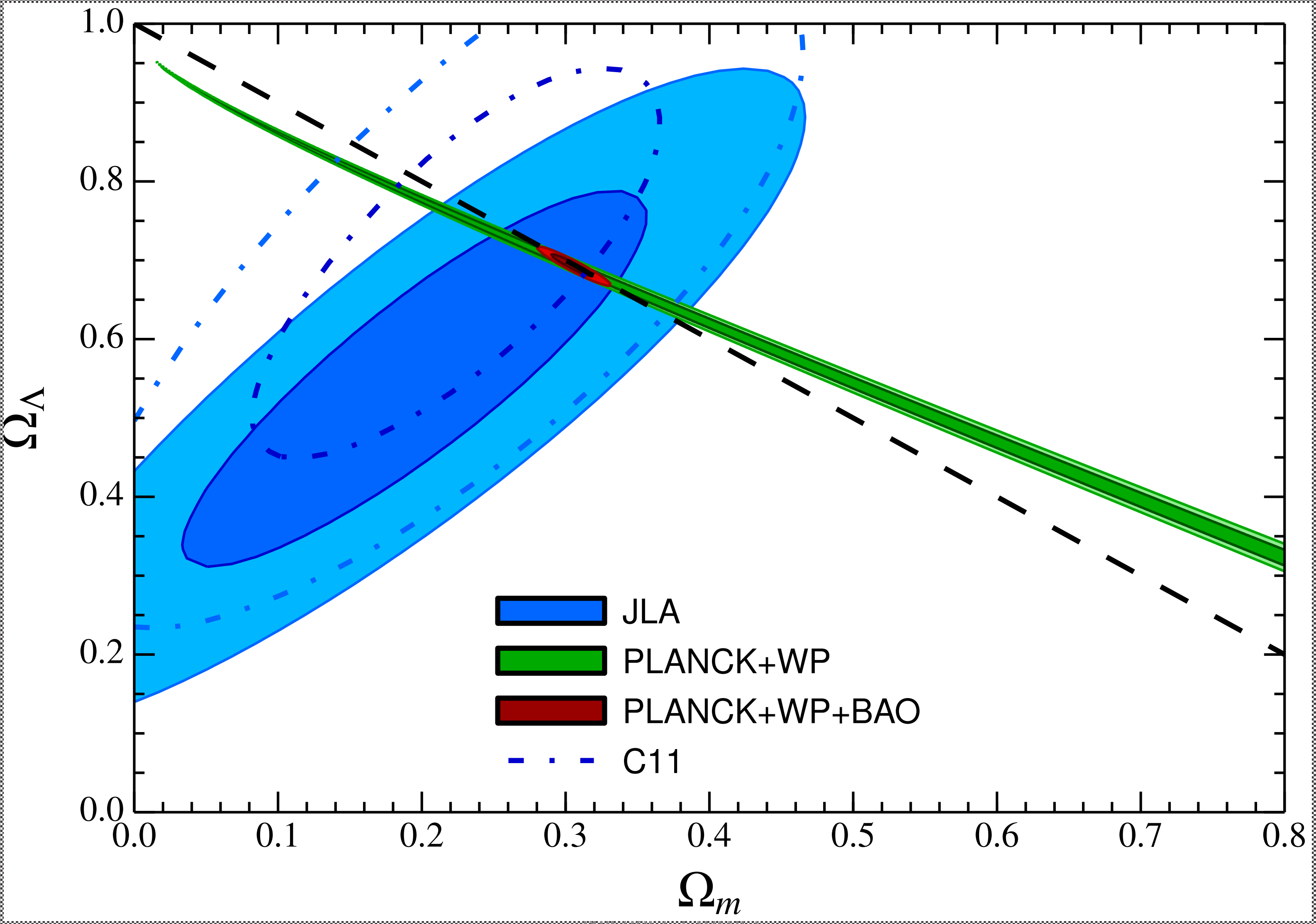
1. Baryon mass density
2. CDM mass density
3. Density perturbation amplitude
4. Tilt
5. Sound horizon
6. Optical depth

Era of Precision Cosmology (plenty of well measured numbers)

$$
\begin{aligned}
T_0 &= 2.7255 \pm 0.00057\,\mathrm{K} \\
t_0 &= 13.8 \pm 0.02\,\mathrm{Gyr} \\
\Omega_0 &= 1.00 \pm 0.002 \\
H_0 &= 67.4 \pm 0.5\,\mathrm{km/s/Mpc} \\
H_0 &= 73.5 \pm 2\,\mathrm{km/s/Mpc} \\
N_\nu &= 2.99 \pm 0.17 \\
n_s &= 0.965 \pm 0.004 \\
r &< 0.07 \pm 0.03 \\
w &= -1.03 \pm 0.04 \\
w_a &= -0.22 \pm 0.41 \\
\Omega_B h^2 &= 0.0222 \pm 0.0002 \\
\Omega_M h^2 &= 0.142 \pm 0.0013 \\
\sigma_8 &= 0.811 \pm 0.006 \\
\theta_{MC} &= 1.04092 \pm 0.0003 \times 10^{-2} \\
\tau &= 0.0544 \pm 0.0073 \\
A_S &= 2.10 \pm 0.03 \times 10^{-9} \\
z_{rec} &= 1090 \pm 0.2 \\
z_{eq} &= 3387 \pm 27 \\
\cdots &= \cdots
\end{aligned}
$$

and more to come – more tests and hopefully some surprises

Λ fits perfectly!



We have come a long way since 1970, when Allan Sandage said:

COSMOLOGY:
A SEARCH FOR TWO NUMBERS

Precision measurements of the rate of expansion and the deceleration of the universe may soon provide a major test of cosmological models

ALLAN R. SANDAGE

Allan Sandage has been a staff member at the Mount Wilson and Palomar Observatories since he received his PhD from Cal Tech in 1953. His main interests are stellar evolution, observational cosmology, form of the redshift laws, quasars and distance scales. In 1960 Sandage and Thomas Matthews were the first to isolate the quasars.

36 • FEBRUARY 1970 • PHYSICS TODAY

Hubble troubles, part 2

Direct: 73 ± 1.1 vs. Indirect: 67.5 ± 0.4 km/s/Mpc

- Direct measurement:
  - NB: "v easy, d hard"
  - Distance ladder: standard candles – Cepheids, TRB, SNe1a
  - Time delay (jump ladder)
  - Both agree

$$H_0 = \frac{\dot{\mathrm{R}}}{\mathrm{R}} = \frac{\text{galaxy velocity}}{\text{galaxy distance}} \qquad \mathrm{R} = \text{size of Universe}$$

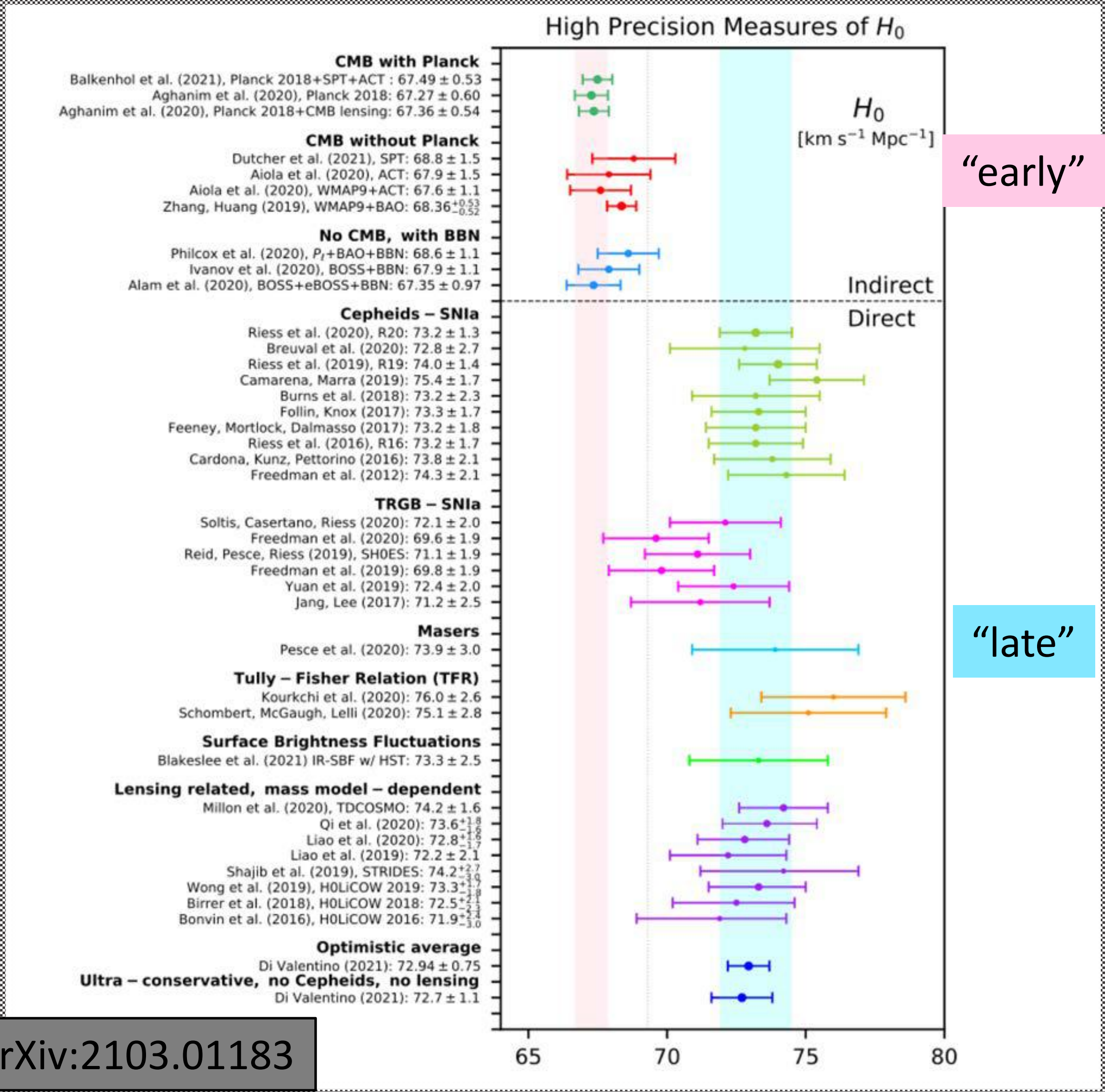
$$\text{distance} \sim \frac{\text{time delay}}{\theta^2}$$

- Indirect (CMB)

$$d_{\mathrm{CMB}} = \frac{v_{\mathrm{sound}} t_{\mathrm{CMB}}}{\theta_{\mathrm{sound}}} = H_0^{-1} \int \frac{dz}{[\Omega_M (1+z)^3 + \Omega_\Lambda]^{1/2}}$$

- Direct and indirect could both be correct and paradigm wrong! Or, one or both measurements could be wrong and ΛCDM correct

Hubble troubles or opportunities!



"early"

"late"

arXiv:2103.01183

- Indirect (pink): **67.5 ± 0.5** km/s/Mpc

George Efstathiou (Planck)

- Direct (cyan): **73.2 ± 1.3** km/s/Mpc

Adam Riess (SHoES)

- 5-sigma difference!

DRAFT VERSION JULY 20, 2022
Typeset using LATEX default style in AASTeX631

A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the *Hubble Space Telescope* and the SH0ES Team

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ABSTRACT

We report observations from the *Hubble Space Telescope* (*HST*) of Cepheid variables in the host galaxies of 42 Type Ia supernovae (SNe Ia) used to calibrate the Hubble constant (H_0). These include the complete sample of all suitable SNe Ia discovered in the last four decades at redshift $z \leq 0.01$, collected and calibrated from ≥ 1000 *HST* orbits, more than doubling the sample whose size limits the precision of the direct determination of H_0. The Cepheids are calibrated geometrically from *Gaia* EDR3 parallaxes, masers in NGC 4258 (here tripling that sample of Cepheids), and detached eclipsing binaries in the Large Magellanic Cloud. All Cepheids in these anchors and SN Ia hosts were measured with the same instrument (WFC3) and filters (*F555W*, *F814W*, *F160W*) to negate zeropoint errors.

We present multiple verifications of Cepheid photometry and six tests of background determinations that show Cepheid measurements are accurate in the presence of crowded backgrounds. The SNe Ia in these hosts calibrate the magnitude–redshift relation from the revised Pantheon+ compilation, accounting here for covariance between all SN data and with host properties and SN surveys matched throughout to negate systematics. We decrease the uncertainty in the local determination of H_0 to 1 km s^{-1} Mpc^{-1} including systematics. We present results for a comprehensive set of nearly 70 analysis variants to explore the sensitivity of H_0 to selections of anchors, SN surveys, redshift ranges, the treatment of Cepheid dust, metallicity, form of the period–luminosity relation, SN color, peculiar-velocity corrections, sample bifurcations, and simultaneous measurement of the expansion history.

Our baseline result from the Cepheid–SN Ia sample is $H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1}, which includes systematic uncertainties and lies near the median of all analysis variants. We demonstrate consistency with measures from *HST* of the TRGB between SN Ia hosts and NGC 4258, and include them *simultaneously* to yield 72.53 ± 0.99 km s^{-1} Mpc^{-1}. The inclusion of high-redshift SNe Ia yields $H_0 = 73.30 \pm 1.04$ km s^{-1} Mpc^{-1} and $q_0 = -0.51 \pm 0.024$. We find a 5σ difference with the prediction of H_0 from *Planck* CMB observations under ΛCDM, with no indication that the discrepancy arises from measurement uncertainties or analysis variations considered to date. The source of this now long-standing discrepancy between direct and cosmological routes to determining H_0 remains unknown.

$H_0 = 73 \pm 1$ km/s/Mpc

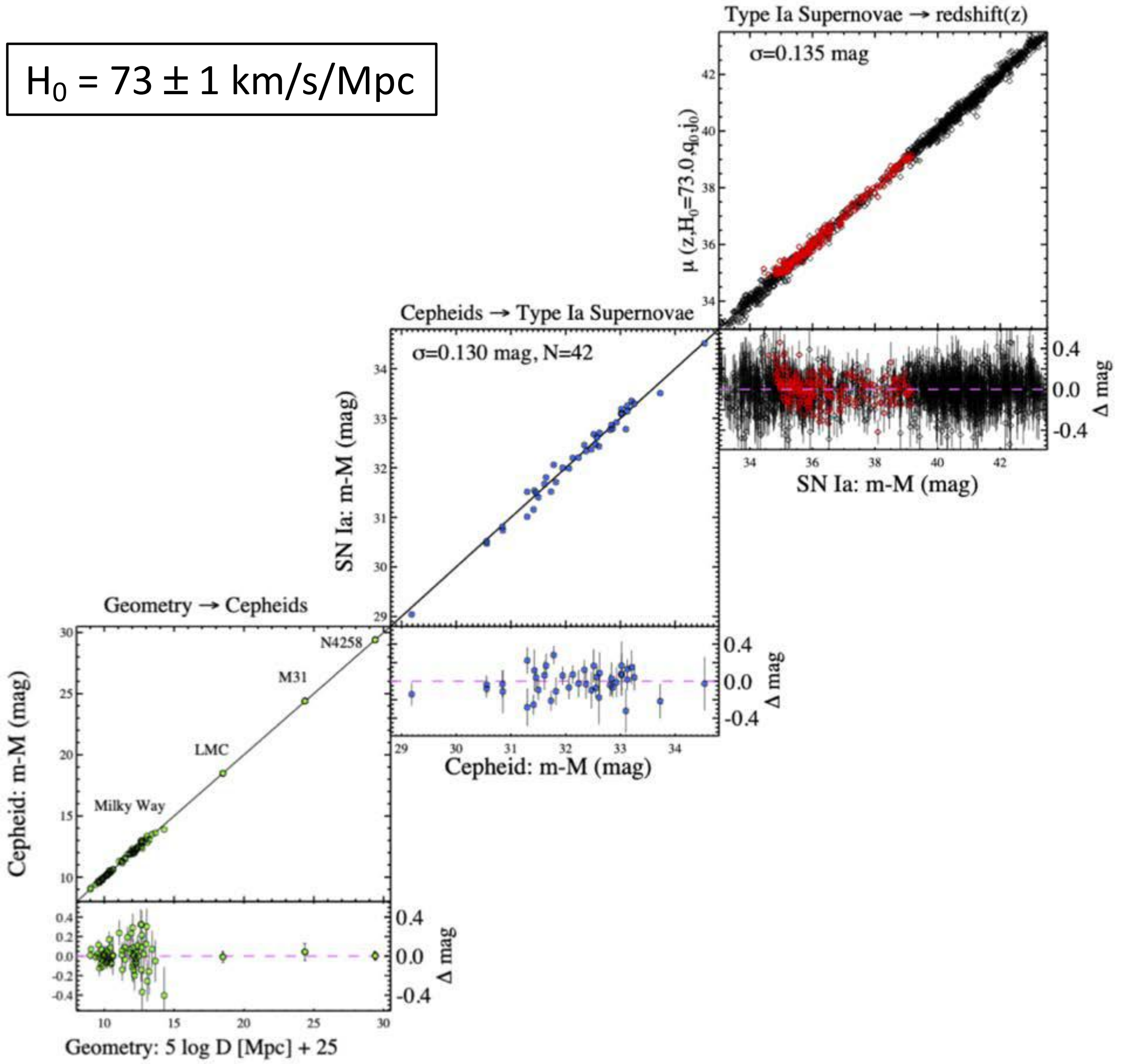


Figure 12. Complete distance ladder. The simultaneous agreement of distance pairs: geometric and Cepheid-based (lower left), Cepheid- and SN-based (middle), and SN- and redshift-based (top right) provides the measurement of H_0. For each step, geometric or calibrated distances on the abscissa serve to calibrate a relative distance indicator on the ordinate through the determination of M_B or H_0. Results shown are an approximation to the global fit as discussed in the text. Red SN points are at $0.0233 < z < 0.15$, with the lower-redshift bound producing the *appearance* of asymmetric residuals when plotted against distance.

“New physics”

- The two discrepant measurements could both could be right if ΛCDM is wrong!
- New ingredient(s) to ΛCDM
  - Early dark energy
  - Extra radiation
  - None compelling yet

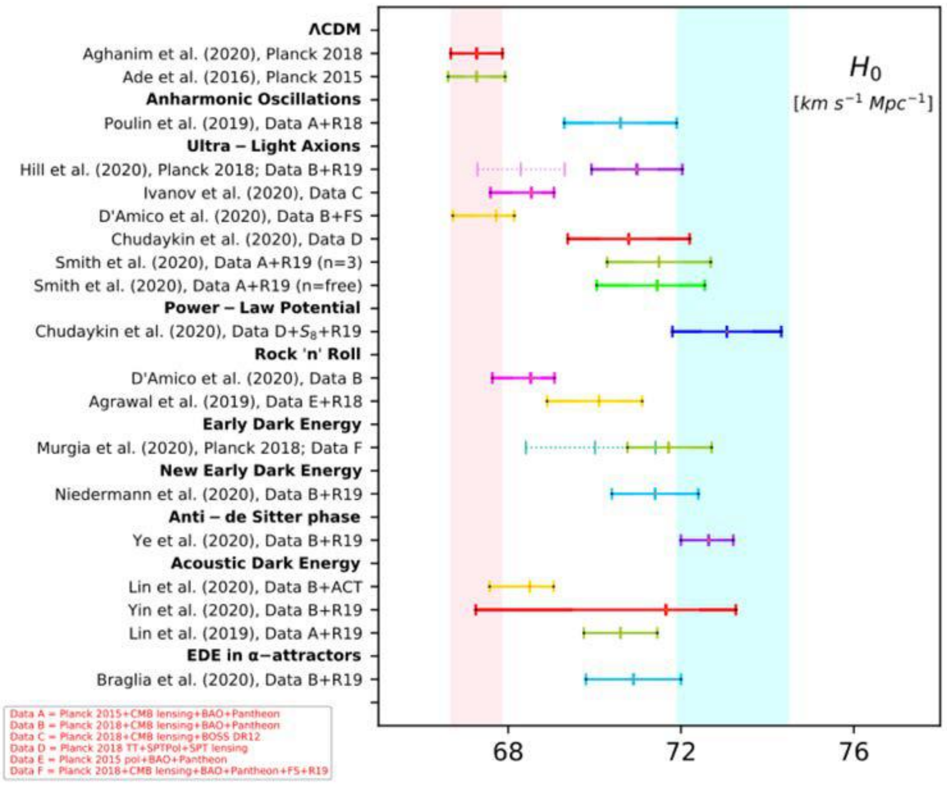


Figure 4. Whisker plot with the 68% marginalized Hubble constant constraints for the models of Section 4. The cyan vertical band corresponds to the H_0 value measured by R20 [2] and the light pink vertical band corresponds to the H_0 value estimated by *Planck* 2018 [11] in a ΛCDM scenario. For each line, when more than one error bar is shown, the dotted one corresponds to the *Planck* only constraint on the Hubble constant, while the solid one to the different dataset combinations reported in the red legend, in order to appreciate the shift due to the additional datasets.

Or one or both measurements could be wrong or NEW PHYSICS! Big mystery; stay tuned!

ΛCDM paradigm shift: adding ONE (odious) thing, solved FIVE problems with Inflation + CDM. H_0 fixes not as compelling – yet!

General Relativity and Gravitation, Vol. 27, No. 11, 1995

The Cosmological Constant Is Back†

Lawrence M. Krauss[1] and Michael S. Turner[2,3]

A diverse set of observations now compellingly suggest that the universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the favored value for the cosmological constant corresponds to a very tiny vacuum energy density. We discuss future observational tests for a cosmological constant as well as the fundamental theoretical challenges — and opportunities — that this poses for particle physics and for extending our understanding of the evolution of the universe back to the earliest moments.

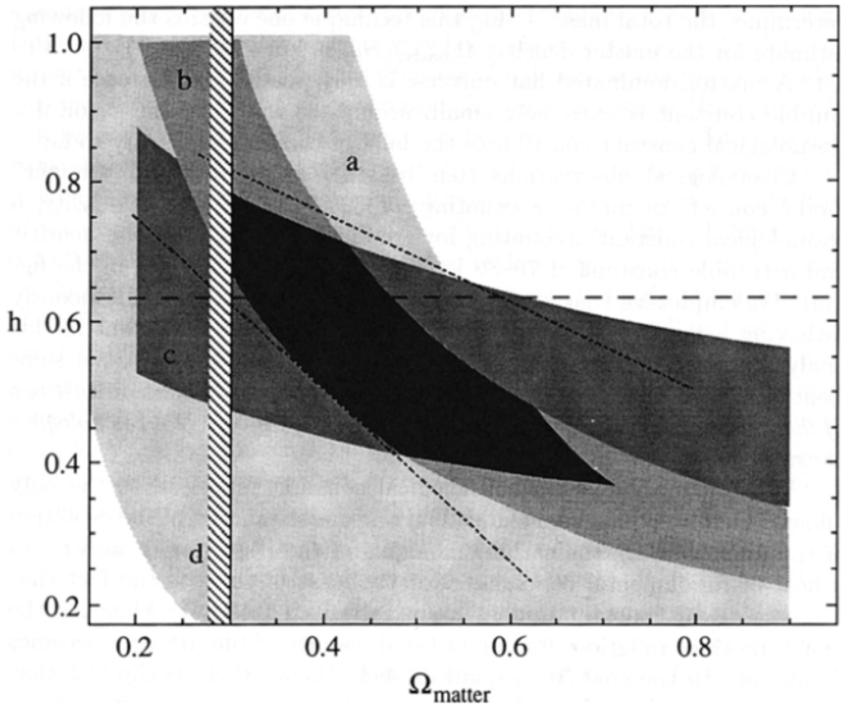


Figure 1. Constraints on the matter density in a flat universe as a function of the Hubble constant $H_0 = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Shaded regions indicate allowed regions of parameter space. Region (a) comes from combining big-bang nucleosynthesis limits with x-ray observations of clusters, (b) arises from considerations of clustering on large scales, (c) is based on age determinations of globular clusters, (d) is a lower limit based on virial estimates of the density of clustered matter on large scales. The horizontal dashed line is a one sigma lower limit on the Hubble constant from recent Hubble Space Telescope measurements. The diagonal dashed lines represent the allowed limits of phase spaced based on combining COBE normalization of cold dark matter models with estimates of matter density fluctuations on galactic and cluster scales. The dark shaded region indicates the region allowed by all constraints.

Big questions and grand aspirations

… the pillars of the ΛCDM paradigm!

- Don’t understand **Dark Energy (69** ± 0.6%) and why Λ (quantum vacuum energy) is so small
- The physics of **Inflation** or when it took place
- What **Dark Matter** (31% ± 0.6% less baryons) is comprised of
- How **Baryons** (4.8 ± 0.06%) survived annihilation (baryogenesis)

?!

Both!

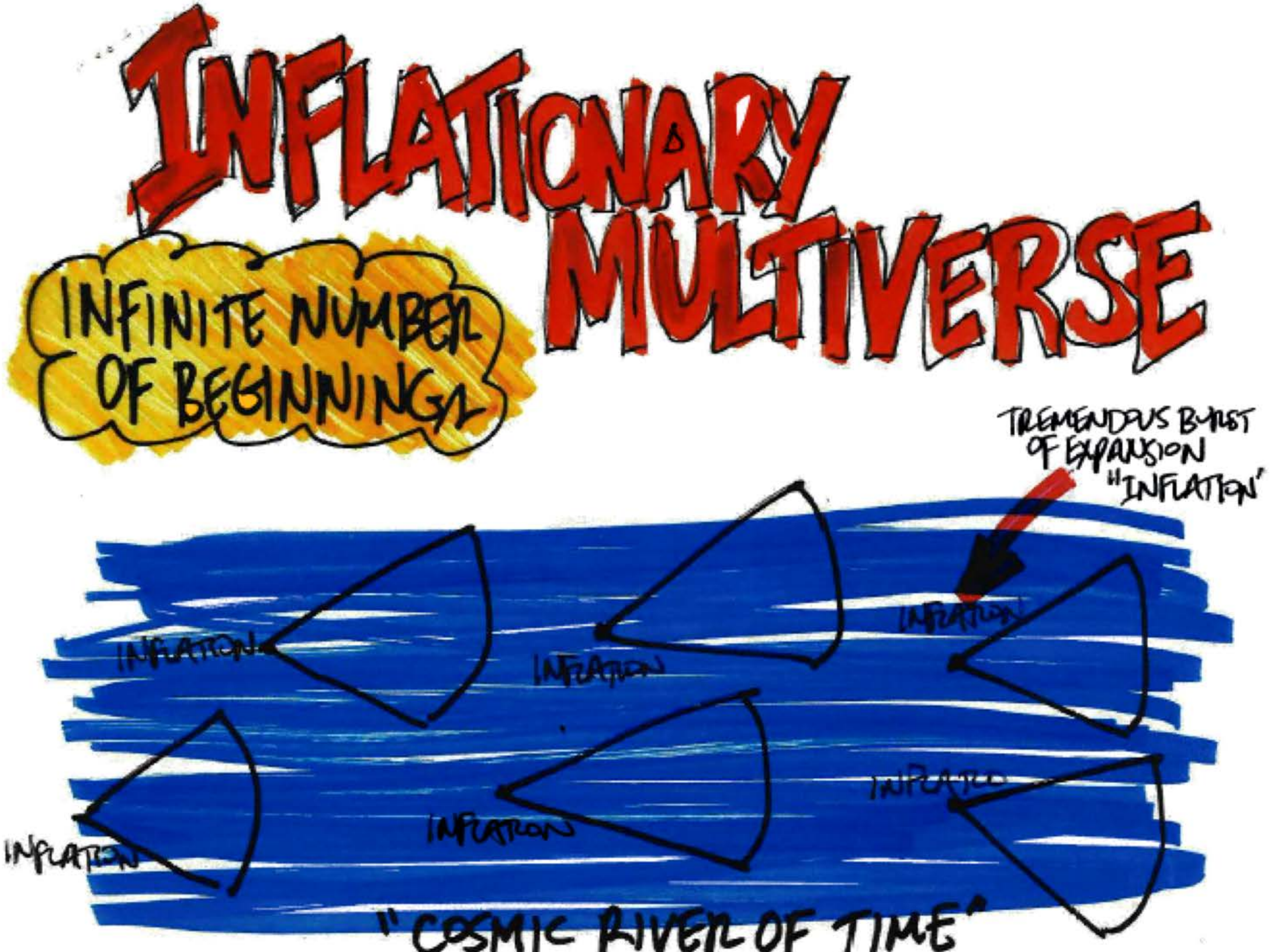
Cosmic acceleration

- How often?
- When?
- Why?
- Something beyond GR needed?
- Opportunity to unify inflation and dark energy?

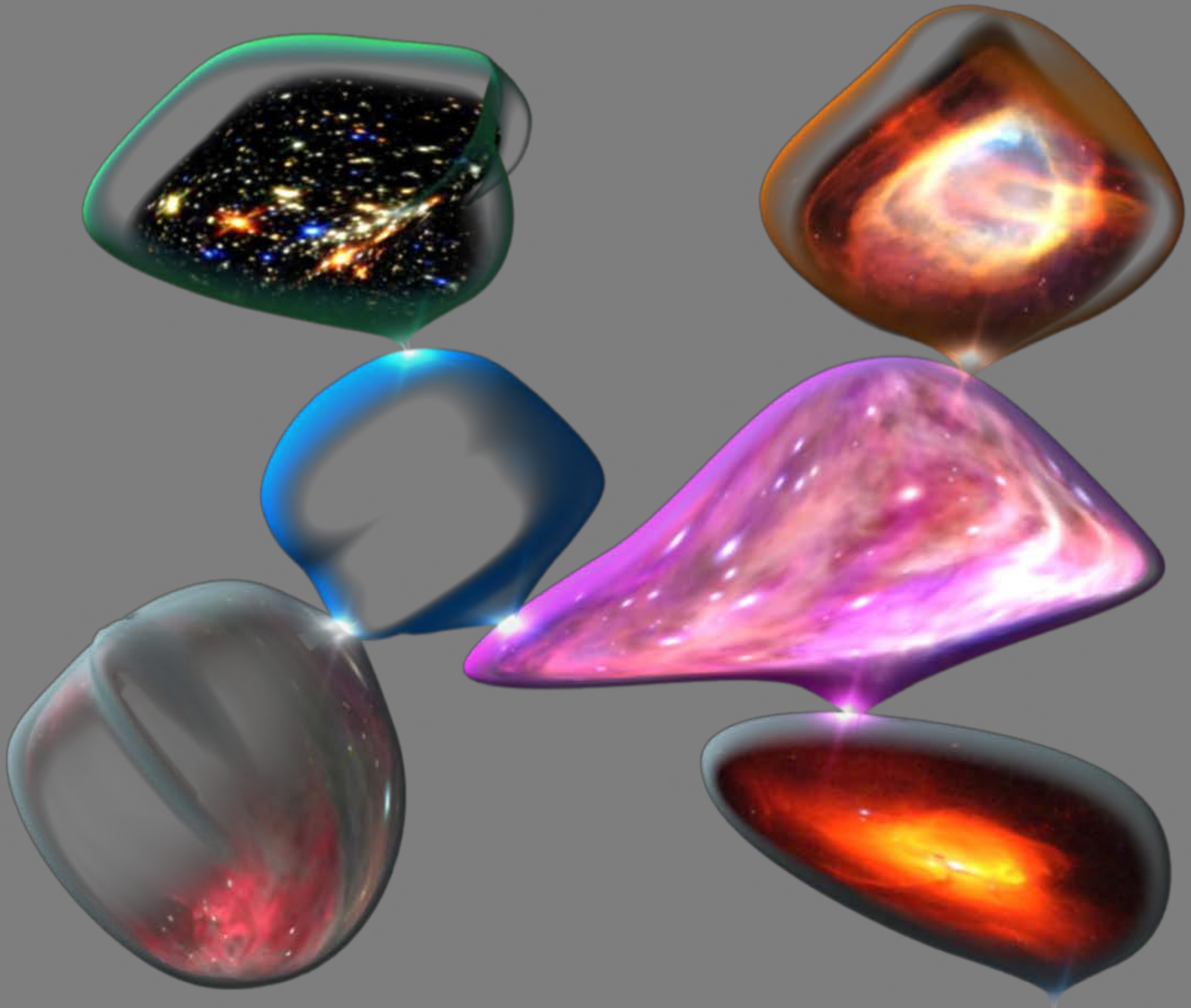
Grand aspirations

1. Origin of the space, time and the Universe
2. Before the big bang (related to #1?)
3. Destiny of the Universe
4. Self-booting Universe (given the TOE, everything else follows automatically)
5. Making sense of the multiverse or getting rid of it
6. Why something rather nothing and, where did the laws of physics come from?

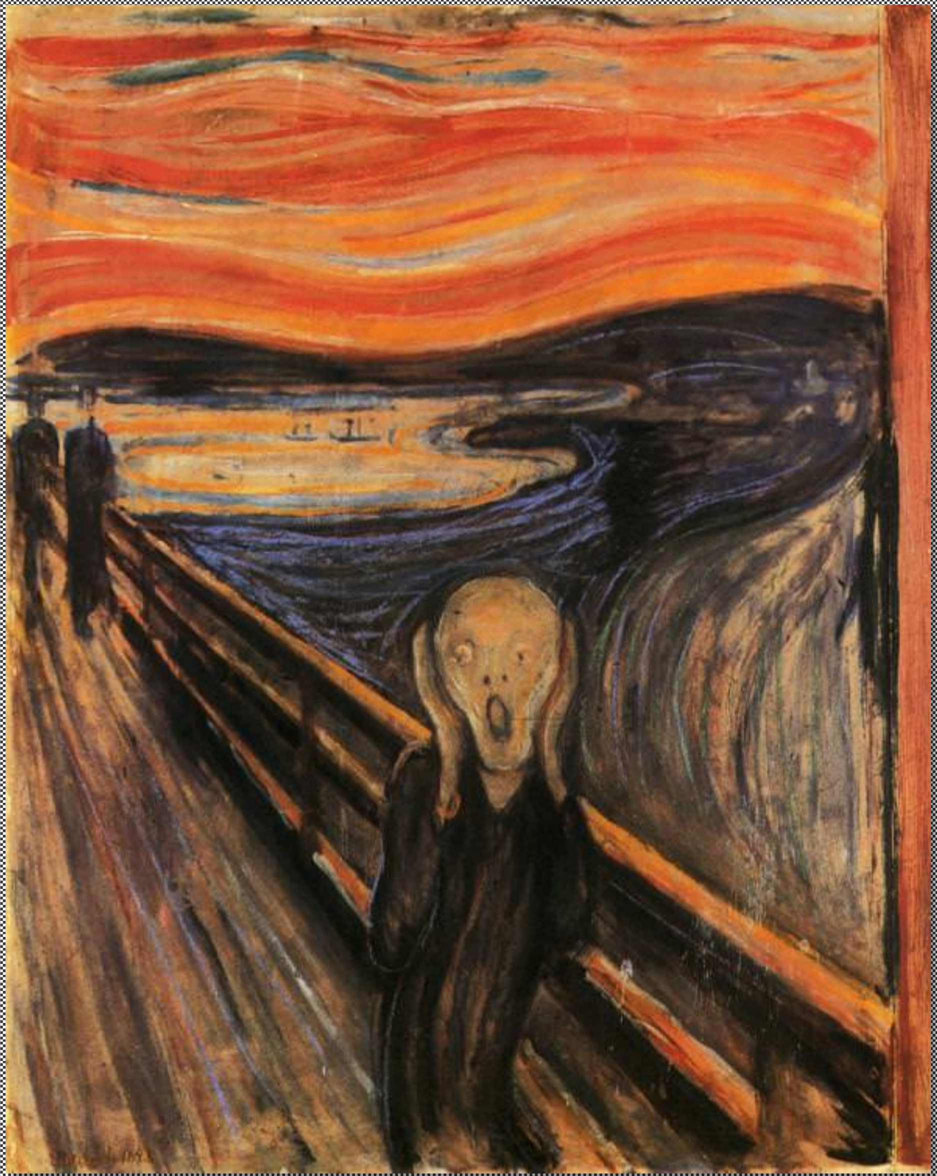
Einstein got the right answer for the wrong reason?


INFLATIONARY MULTIVERSE
INFINITE NUMBER OF BEGINNINGS
TREMENDOUS BURST OF EXPANSION "INFLATION"
INFLATION
INFLATION
INFLATION
INFLATION
INFLATION
INFLATION
"COSMIC RIVER OF TIME"

The multiverse



What to do about the multiverse



- Most important "discovery" since Copernicus?
- But is it science? (not testable – yet)