Joris Van Houtven
2014

COSMOLOGY

H1

0) cosmological principle: homogeneous, isotropic. true if $r > 100\,\mathrm{Mpc}$

1) RW-metric $ds^2 = c\,dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$

2) 1st Friedmann eqn: $\frac{\dot{a}^2}{a^2} + \frac{kc^2}{a^2} = \frac{8\pi G}{3}\rho$
derived from $E = T + V$ and $k \equiv -\frac{2E}{mr^2}$

3) 2nd Friedmann eqn: $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3\frac{P}{c^2}\right)$
derived from time derivative of 1st and $dE + PdV = 0$ (adiabatic?)

4) $k = \begin{cases} -1 & \text{open} \\ 0 & \text{flat} \\ 1 & \text{closed} \end{cases}$ } $\dot{a}$ cannot be zero (1st FE) → positive forever

2nd FE $\xrightarrow[P,\rho>0]{}$ $\ddot{a}$ always negative

⇒ universe is expanding, but slower and slower

5) proper (radial) distance $d_p = a(t)\int_0^r \frac{dr}{\sqrt{1-kr^2}}$ ⇒ $\dot{d}_p = \frac{\dot{a}}{a} d_p$
→ Hubble's law with $H = \frac{\dot{a}}{a}$

6) density parameter $\Omega = \frac{8\pi G\rho}{3H^2}$ as in 1st FE: $\frac{kc^2}{H^2a^2} = \frac{8\pi G}{3H^2}\rho - 1$
critical density $\rho_c = \frac{\rho}{\Omega}$ → then $k = 0$

7) redshift z: $1 + z = \frac{a(t_0)}{a(t)}$ derived from $\int [ds = 0]$

8) deceleration parameter q_0: ~~measures deviation from~~
$q = -\frac{\ddot{a}}{aH^2} = -\frac{\ddot{a}a}{\dot{a}^2}$

9) Always: $\rho \sim \frac{1}{t^2}$ matter dominated: $\begin{cases} a \sim t^{2/3} \\ P = 0 \\ \rho \sim a^{-3} \end{cases}$
radiation: $\begin{cases} \rho \sim a^{-4} \\ P = \rho/3 \\ a \sim t^{1/2} \end{cases}$

derived from $\begin{cases} dU + PdV = 0 \\ U = \rho V \sim \rho a^3 \end{cases}$

(2)

10) age of universe : $t(z) = \frac{1}{H_0} \int_0^{\frac{1}{1+z}} \frac{1}{\sqrt{(1-\Omega_0) + \Omega/x}}$ with $x = \frac{a}{a_0}$

derived from general 1st FE ($\times a^2$ and $\div a_0^2$; $\rho = \frac{\rho_0 a^3}{a_0^3}$)

$\Rightarrow$ ~~$t_0 =$~~ $t(0) = \frac{2}{3H_0}$

11) Einstein eqn with cosmological cst Λ :

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$\rightarrow$ 2nd FE shows now that Λ is an accelerating term.

$\rightarrow$ longer ~~of~~ age of universe

$$\rho \mapsto \rho + \rho_\Lambda \quad \text{with} \quad \rho_\Lambda = \frac{\Lambda c^2}{8\pi G}$$

$\Rightarrow$ negative pressure!

$\rho_\Lambda = -3P_\Lambda$ $\leftarrow$ 2nd FE

12) flatness condition (with $\Omega_\Lambda = \frac{\Lambda c^2}{3H^2}$) : $\Omega + \Omega_\Lambda = 1$

H2

13) Hubble law : $v = H d$

Caution : intrinsic v_{galaxy} component as large as 500 km/s

14) Distance ladder ($cz = H_0 d$: z is easy, now find d to calculate H_0)

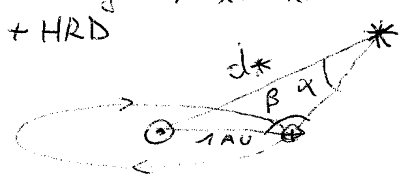
{ type Ia - SN : white dwarf accretes matter and explodes at $M_{Chandr.}$ with high L and very homogeneous (no metallicity dependence). But: $M < M_c$ may happen depending on explosion location and accretion speed.

{ planetary nebulae : relatively homogeneous in terms of mass and L

{ pulsating stars : independent of cause of instability; longer and more diluted stars have longer periods. Cepheids: small T-range for given L : period - density rel. + mass - L rel. = period - luminosity rel.

{ HRD + distance modulus relating $(d, m_\lambda, M_\lambda)$ $\rightarrow$ good for clusters! get M_λ from observed spectrum + HRD

{ parallax : $\sin\alpha = \frac{1 AU}{d_*}$



2× per orbit the angle $\beta = 90°$

{ 1 AU

Bonus : secondary distance indicators, like Tully - Fischer relation, relating L and v_{rot} *

* also: fundamental plane for elliptical galaxies

15) cosmochronology: compare abundances of unstable and stable isotopes. → age of universe

16) age determination from clusters:
* specific HRD: age determination e.g. by MS cutoff point.
* if no heavy metals: $t_{cluster} \to t_{universe}$ (1st gen stars)

rotation neglection may underestimate t_{uni} (rotation → mingle core with shell → extend MS period)

17) proper distance expansion: $d_P = a_0 r = \frac{c}{H_0}\left(z - \frac{1}{2}(1+q_0) z^2 + \dots\right)$

depends on history of universe, and
1) photons are redshifted
2) photon packets smeared out in time

⇒ factor $\left(\frac{a}{a_0}\right)^2$ ⇒ $L \sim \frac{1}{r^2} \mapsto \frac{a^2}{a_0^2 r^2}$

⇒ $d \sim r \mapsto \frac{a_0}{a} r$

so, $d_L = \frac{a_0}{a} d_P$ (luminosity distance)

18) deceleration param q_0 ~ deviation from linear Hubble law
→ need high z measurements. q_0 seems small.

19) to determine Ω we need to estimate matter amounts at scales ≥ 100 Mpc (cosmological principle). Pitfalls:

1) $L \sim M^4$ but IMF $\Phi(M) \sim M^{-2,35}$
→ possibly infinite # low-mass objects?
brown dwarf cutoff + grav. lensing says NO.

2) determination of ~~M~~ M cannot rely on optical alone: 1/3rd of M in spiral galaxy is in the ISM.

3) dark matter

4) unclear how much gas remains in IGM after galaxy formation

But: upper limit for $\rho_{baryon} = 3\% \rho_{crit}$ by ^4He-abundance (see H3)

20) overview
- $\frac{z}{d}$ } → H_0, q_0 (~~the~~ $\frac{c}{H_0}$ is slope of $d_P(z)$)
- rel. abundance, clusters → ages
- density → $\Omega = \rho_0/\rho_c$
- CMB → T_0, $\rho_{radiation}$
- early nucleosynthesis → ρ_{baryon}

21| dark matter proof:

1) peculiar (= intrinsic) velocities of galaxies higher than expected by gravity on basis of ~~present~~ visible mass.
(Zwicky) (virial mass) The cluster could be in non-equil., but it doesn't seem to evolve.

(x-rays) 2) $\rho \bar{\nabla} \Phi = -\bar{\nabla} P$ the pressure gradient measured, corresponds to higher ~~mass~~ gravitating mass than observed.

3) spiral galaxies (spiral traces star formation) would not conserve spiral ~~ity~~ character with so few mass ~~on~~ outer rims ($\rightarrow$ dark matter halo)

(gauss' law) 4) spiral galaxies' rotation speed curves fall off as $r^{-1/2}$. However, at the edge higher rotation speeds are detected: possible with d.m. halo.

Bonus: the unseen matter really is non-baryonic, otherwise nucleosynthesis ~~ele~~ results would have been different than observed and predicted.

22| CMB characteristics:

1) isotropic $\rightarrow$ CMB comes from universe itself.
2) intense $\leftarrow$ spread out across whole sky
$\rightarrow$ must be the whole universe itself.
3) blackbody spectrum. with $T \approx 2,7\,K$
since ~~ρ~~ $\rho \sim T^4$ for a BB and also $\rho_{rad} \sim a^{-4}$ we have $T \sim a^{-1}$.

$\hookrightarrow$ proof: clear absorption lines corresponding to CMB spectrum at higher T. in an ISM spectrum at high z

Bonus: contains: multipole anisotropy (very small: fluctuations)
dipole (doppler shift) (600 km/s)
foreground (visible objects in sky)

23| Hubble law $\Rightarrow$ expanding universe
But: RW metric $\Rightarrow$ Hubble law
and cosmological principle $\Rightarrow$ RW metric
So: cosmological principle $\Rightarrow$ expanding universe

24| To understand the universe's evolution, we need not know it's history; just like thermodynamical equilibrium allows us to ascribe properties to a system

25| Early history of universe is one of phase transitions.
Different eras:

1) hadronic era: $t < 10^{-4}$ s ; $T > 10^{12}$ K
hadron - antihadron pairs; inflation.

2) leptonic era: $10^{-4}\,s < t < 1\,s$; $10^{12}K > T > 10^{10}K$
electron - positron pairs; neutrino's decouple at the end $\Rightarrow$ no more β - decay
$\Rightarrow \frac{m_n}{m_p}$ frozen in at 0,17

3) radiation era: $1\,s < t < ?$; $10^{10}K > T > 10^{4}K$
$\downarrow$
$z \approx 1500$
$\rho_{rad} \gg \rho_m$
first 3 minutes: nucleosyntesis, but all is still ionised.
ρ_m: $1kg/l \rightarrow 10^{-20} kg/l$ and thus (Thomson scattering) mean free path of radiation from $\sim$ cm $\rightarrow \sim$ kpc. Still "small"
$\rightarrow$ "BB radiation"

4) matter era: t? ; $10^{4}K > T$.
Hydrogen in increasingly neutral state.
$\rightarrow$ (until $T = 10^3 K$) recombination epoch
from $10^3K > T$: decoupling epoch: all H is neutral.
(inner and outer surface of last scattering)

After decoupling there's barely any radiation pressure
$\rightarrow$ gravity starts shaping the universe

26] Chemical evolution of a galaxy:
1st gen stars contain no ~~heavy~~ heavy elements.
G-dwarf problem: no zero metallicity star is known.
Though He is produced ~~also~~ in stars, like heavy elements, its relative abundance is very high (26% He, 72% H, 2% metals)
so 24% He needs another explanation → primordial nucleosynthesis

27] explaining relative abundances of heavy metals:
1) most are α-elements, others are products of secondary reactions
2) beyond iron: explosive nucleosynthesis from core-collapse SN
via r-process — rapid n° capture
p — p⁺ capture
s — slow n° capture
3) iron peak: mostly Ia SN where the explosion is thermonuclear.

28] After leptonic era, $\frac{n^\circ}{n_p}$ frozen out at 0,17, but T was not yet low enough for nucleosynthesis and $\tau_{n^\circ} \approx 10$ min.
→ $\frac{n^\circ}{n_p}$ fell back to $1/7 \approx 0{,}14$

29] $n + p \rightarrow {}^2H + \gamma$ and other reactions $\rightarrow {}^4He$ } primordial nucleosynthesis
All neutrons are soaked up into ^4He nuclei;
rel. mass fraction $(1/7 + 1/7) / (1 - 1/7) \approx 0{,}25$ which explains the extra 24%
No higher elements yet because of unstable ^8Be.

30] Though, the amount of ^4He formed depends on ρ.
Also, tiny bits of ^7Li can be made ~~if ρ is high enough~~,
($\rho_{crit,uni} \approx 10^{-30}$ g/cm³)
low ρ: $^4He + {}^3H \rightarrow {}^7Li$
high ρ: $e^- + {}^4He + {}^3He \rightarrow e^- + {}^7Be \rightarrow {}^7Li$ dominates.
which explains the sudden rise in fig 3.1 p53.

31] observed He-abundance is strongest evidence of ~~BB for~~ big bang primordial nucleosynthesis.
But: hard to constrain:
1) old stars are too cool and have no He-absorption lines
2) hot old stars have evolved too far and have made their own He
→ globular clusters: compare HRD with theoretical isochrones

32) But there are 3 better methods to obtain primordial abundances:

1) He-absorption lines in ISM (HII-regions, near young massive stars)
The He-abundance there scales with ^{16}O-abundance and can be extrapolated towards zero ^{16}O-content.

2) ^{2}H-abundances in the ISM by shifted absorption spectra (best for Hydrogen)
But: Stark broadening makes for inaccuracies.

c) ^{7}Li: has a strong resonance in the visual band.
^{7}Li is easily destroyed by mixing and thus disappears in metal-rich stars.
For old stars (spanning 2 orders of magn. in metallicity) a constant abundance is found (Spite plateau)
→ unmixed stars → primordial value.
But: value found is quite low. Need gravitational diffusion

33) BB-model issues:

1) flatness problem: $\Omega_0 \approx 10^{-5}$ so at nucleosynthesis $\Omega \sim 10^{-13}$ which seems an odd coincidence

2) horizon problem: CMB at same temperature everywhere, even though points had no causal contact.
Horizon / Hubble distance $d_H = 3ct$ (matter dom.)
$2ct$ (rad. dom.)
derived from d_p definition and $ds = 0$ (RW)

3) monopole problem: phase transitions should produce relic particles (with mass) though still the universe was dominated by radiation.

34) inflation: suppose $\ddot{a} \gg 0$ temporarily.
($P < -e/3$) 1st FE now implies a negative $P_{infl.}$ because strong energy condition $e + P > 0$ is abandoned.
(in the vacuum!) Through $T_{00} = 0$ this implies $P_{vac} = -\rho_{vac} c^2$, so the 1st FE becomes $\frac{\ddot{a}}{a} = \frac{8\pi G}{3}\rho \Rightarrow a(t) \sim \exp\left[\left(\frac{8\pi G}{3}\right)^{1/2} t\right]$

35) inflation solves the BB-problems:

1) inflation washes out deviations from $\Omega = 1$
because 1st FE: $\Omega = 1 + \sim \frac{1}{\dot{a}}$

2) inflation ~~causes~~ allows the local universe to expand more rapidly than c

Bonus: inflation models can be adapted for a nonzero Λ

36) slow-roll inflation by scalar field inflaton φ.
with energy tensor of perfect fluid:

$$\begin{cases} \rho = \frac{1}{2}\dot{\varphi} + V(\varphi) \\ P = \frac{1}{2}\dot{\varphi} - V(\varphi) \end{cases} \underset{P<-\rho/3}{\Longrightarrow} \dot{\varphi}^2 < V(\varphi)$$

moreover, if $\dot{\varphi}^2 \ll V(\varphi)$, then $a(t) \sim e^{Ht}$

Slow-roll requires $V(\varphi)$ to be flat. When that ends the inflaton energy converts to massive particles. (and radiation)

37) Density perturbations in early universe have a QM origin, and wavevectors have Gaussian distr.

Power spectrum: $\delta_f^2(k) = \frac{k^3 \sigma_k^2}{2\pi^2}$

$$f(\vec{x}) = \int \frac{d^3k}{(2\pi)^{3/2}} f_k \, e^{i\vec{k}\cdot\vec{x}}$$

38) inflationary perturbations are nearly scale-invariant (i.e. independent of k)!

$$\sigma_k^2 = \left(H^2\tau^2 + \frac{H^2}{k^2}\right) \approx \frac{H^2}{2k^3}, \text{ so } \delta_{\delta\varphi}^2(k) = \frac{H^2}{4k^2}$$

This is because the integral of the power spectrum will mainly get contributions from small k, because high k's cancel eachother out.

39) vacuum energy corresponds to a cosmological cst.
Cosmological constant: quantum corrections to its value are an order of magnitude larger than what is observed. Perhaps slow-roll inflation (which mimics vacuum energy) is a solution?

40| gravitational instability: in a contracting cloud there is no immediate rise in P or T: radiative cooling prevents significant T increase at low ρ (isothermal)

41| Jeans criterion for isothermal perturbations to the e.o.m, e.o.s, Poisson's and continuity eqn; and assuming solutions proportional to exp $(i(kx+\omega t))$:

$$\lambda > \left(\frac{\pi}{G\rho}\right)^{1/2} c_s = \lambda_J$$ with dispersion relation $\omega^2 = k^2 c_s^2 - 4\pi G\rho$ and $k = \frac{2\pi}{\lambda}$

Jeans mass (contained in a sphere with radius $\frac{\lambda_J}{2}$):

$$M_J = \frac{\pi}{6}\rho\lambda_J^3 \sim P^{3/2}\rho^{-2}$$

42| In the case of an expanding universe (ρ and v not cst) and assuming Fourier expansion solutions with time dependent coefficients, one finds a power dependence of the perturbations on time rather than exponential; with a decaying rotational mode $\sim t^{-1}$ and a growing mode $\sim t^{2/3}$.

43| Two types of density perturb.; distinction only makes sense before decoupling

A) adiabatic: entropy per comoving volume = cst: structuring of matter ($S\downarrow$) accompanied by heating ($S\uparrow$)
Radiation pressure dominates and $P = c_s^2\rho$ with $c_s = \frac{c}{\sqrt{3}}$
High c_s responsible for high $M_J \sim \rho_m c^3 \rho_{tot}^{-3/2}$

$\Rightarrow M_J$ increases wit time

M_J at decoupling was $10^{15} M_\odot \approx$ mass of clusters of galaxies.

B) isothermal: $c_s \sim \sqrt{\frac{kT}{m_P}}$ sound velocity $\approx$ 500 km/s
100 times less than $c/\sqrt{3}$!!

→ once matter and radiation ~~couples~~ decouple, M_J drops to the isothermal value

44| fluctuation effects that influence macro structure:

1) variation of M_J with time: first increase, then rapid drop.
2) horizon mass (= m within horizon distance) is smaller than M_J for adiabatic case (only relevant before decoupling)
3) energy diffusion; diffusion of ρ by Silk damping → small scale fluctuations disappeared fast. Silk mass $10^{12} M_\odot \approx m_{\text{galaxy cluster}}$.

45| Two scenario's:

A) top-down: clusters of galaxies form first, then separate into individual galaxies. Adiabatic perturb.

B) bottom-up: small structures (globular clusters, dwarf galaxies) form first, and galaxies follow as assemblies. Isothermal fluctuations because otherwise Silk damping (also: smaller structures assemble faster).

Two problems:

a) models achieving structure within reasonable time predict anisotropies $> 10^{-4}$, but in CMB only $< 10^{-5}$ found
b) deep surveys show hints of structure beyond even superclusters of galaxies.

46| Two dark matter solutions:

α) d.m. halos can form well before decoupling, so baryons can immediately fall into grav. wells after decoupling → top-down possible
β) d.m. is thus not affected by Silk damping or radiation pressure, so small fluctuations are not erased → bottom-up possible in adiabatic, coupled epoch!

47| If d.m. particles have long mean free path, this erases structure on smaller scales, just like photons.

Yes) top-down favored: hot dark matter; nonzero ν masses can close the universe.

No) bottom-up still possible: cold d.m. (CDM) scenario. With a cosm. cst., the Λ-CDM scenario predicts large scale structures pretty well.

H5

48 | COBE detected also the ~~small~~ large scale anisotropies in the CMB. Because of scale-invariance, small scale " also predicted and then detected by WMAP and fitted with the Λ-CDM model. One can decompose them into spherical harmonics.

49 | The ~~...~~ power spectrum in terms of angular size / multipole moment - because of the oscillatory density waves - shows acoustic peaks; at decoupling density contrasts are frozen in. Modes that attained extrema at $t = 330{,}000$ yrs dominate the spectrum: i.e. those of sizes $\frac{1}{n} \times \frac{ct}{\sqrt{3}}$ sound travel distance

50 | From the CMB spectrum we can determine:

1) angular size of object of $\frac{1}{\sqrt{3}} \cdot 330{,}000$ light yr at $z_{decoupling}$. This depends on H_0 and Ω, ~~...~~ and especially location of first peak!
   → determine Ω if H_0 separately known.

2) baryon-to-photon ratio (10^{-9}) by inspecting relative amplitudes of the peaks (~~small~~ peaks affected by Silk damping)
   → determine Ω because ρ_{rad} is known from CMB temperature

3) dark matter content from the relative magn. of successive peaks: d.m. favours odd peaks, but prohibits restoration (even peaks) (contraction)
   → determine Ω_{tot} if $\Omega_{baryons}$ is known.

4) Λ is found by comparing Ω_{dm} and $\Omega_{baryons}$.
   Also by the integrated Sachs-Wolfe effect: photon falls into gravity well (λ↓) and ~~...~~ on very large scales when it comes back out: λ↑ not as much, because of expansion of universe.
   For nonzero Λ this would have led to flattening of CMB spectrum towards low l.

5) overall spectrum yields exponents n_s of power spectrum of fluctuations

But: these diagnostics are not independent.
e.g. location of 1^{st} peak depends on H_0,
and matter density. ⇒ full data fits needed
to lift degeneracies, but if so, one can also derive H_0!
Bonus: primordial He-abundance: He neutralises first → decrease in Silk damping

51| Planck and WMAP data do not fully agree. Probably because the CMB contains a lot of noise:
- foreground emission
- dipole (doppler)
- mean is large compared to anisotropies

But they agree on the Λ-CDM model and inflation, and anomalies like low quadrupole term, low values for $l \in [20,30]$ too.

WMAP also detected polarization of CMB, which can occur if e^- density was not isotropic at last (Thomson) scattering.

52| Re-ionization: after decoupling, all matter neutral. First stars all very heavy → quasars formed
→ universe exposed again to UV-radiation → re-ionisation.

53| ~~Proof~~ Proof that first stars were massive:
1) non-zero metallicity of ~~old~~ globular (old) clusters: there must have been a previous, short-lived (and thus massive) generation that polluted them.
But: pollution by their own massive stars also possible.
Anyhow: metal enrichment of galaxies was rapid.
2) γ-ray burst sources (heavy) occur more often at high z.
Probably seeds of super massive black holes.

54| ~~...~~ Re-ionisation occurs when ~~...~~ the universe had become locally anisotropic.
→ polarisation in CMB stronger than before.
WMAP detects maximal polarisation power at length scale of 10°, or ~~...~~ $z \approx 14$. (reduced by expansion of polarized CMB until re-ionisation)
But Gunn-Peterson troughs already disappear at $z = 6$.
⇒ the notion of instantaneous re-ionisation needs refinement.

55] · Gunn – Peterson through:
neutral H absorbs at Ly-α line. Because of H-clouds at all different z-values on line of sight of observer, one gets a "through" of redshifted Ly-α lines

~~Gunn Peterson through: after reionisation~~
Ly-α forest: at (partial) reionisation, some (the ionised) H-clouds don't absorb anymore, and one gets a "forest" of Ly-α lines.

56] gravitational lensing: heavy mass between source and observer deflects light. Applications:

1) like a magnifying glass: observe much more light from distant objects. Very luminous galaxies all have peaks around 100 μm, and redshifting neatly compensates for light dimming due to large distance → bright 100 μm objects are lensed galaxies.

2) lensing ~~~~ helps locating matter in universe
weak lensing: deflections by some ~~~~ object on large # of galaxies must statistically cancel out. When that is observed, the ~~~~ systematic pattern reveals the unseen deflecting mass.
e.g.: Bullet cluster where dark and baryonic matter are separated.

57] To map the universe, we need ground and space observations!

1) whole relevant wavelength range: ground only good ~~~~ for UV-optical-IR, but not ~~for~~ infrared and for radio and higher E.

2) 2D map of the sky: angular resolution depends on wavelength and telescope size, which ~~~~ is favoured by space and ground observations respectively

3) radial dimension: ~~~~ observing all z-values: high z means faint objects: high collecting power (ground) vs less diffuse background (space)

⇒ 2-step approach: space surveys followed up by ground

58) surveys from ground ~~are~~ are booming:
1) advances in optics combine collecting power with large FOV
2) ICT developments ease data acquisition and storage.

59) deep, shallow surveys to probe earlier epochs,
less deep, broad surveys to probe large scale structure
- deep: ~~bulk~~ X-ray background of first X-ray survey resolved into individual sources: distant galaxies and clusters
- broad: galaxies up to large scales are not distributed homogeneously: 2D bubbles surrounding less dense regions.

60) "Millennium Survey", using the ΛCDM model, confirms filamentary structure, but predicts more dwarf galaxies. Explanation: all gas blown away by early, large supernovae → ~~no~~ star formation impeded → invisible.

61) * Space ~~[illegible]~~ survey ambitions:
- map matter distribution using weak lensing
- follow baryonic acoustic oscillations in time ($\Omega(t)$)
- bonus: a lot of distant SN's will be revealed, constraining high-order terms in Hubble law
→ better understanding of dark energy component

* ground surveys might bring meaningful weak-lensing studies by active optics.

62) Galaxies treated as ~~[illegible]~~ gas particles, not ~~of~~ entirely correct:
- density is very dilute compared to a ~~[illegible]~~ H-gas.
- no galaxy is identical to another, unlike atoms.

63) Cosmological significance of chemical evolution of galaxies

1) Evolution from zero metallicity is not linear.
Initial enrichment very rapid: after 10% age, already half the metallicity

2) G-dwarf problem: no zero-metallicity star found yet
→ 1st gen of massive stars OR 1st gen low mass stars were polluted

3) study of relative abundancy trends can determine the evolution of production with time and reveal info about IMF and star-forming intensity

4) identify intruders by deviating element ratio's.
→ ω Centauri is dwarf galaxy swallowed by our system

5) luminosity function of white dwarfs estimates age of galactic disk: L↓ ⇒ age↑

64) chemical evolution shows evidence for ΛCDM model; (bottom-up scenario)
~~early universe contains~~ many merged galaxies like giant elliptical ones

↳ during collision, all ISM gas is used for star formation → "starburst" galaxies

↳ swallowed a lot of galaxies

65) Chicken-or-egg: first black hole or first the starburst? They reinforce eachother.
Black holes speed up galaxy formation, starburst helps accumulating matter.

66) ways to detect high-z galaxies:

1) Lyman break (discontinuity): galaxies seen only at large wavelengths (beyond Ly-limit) have high z.
2) red objects
3) deep X-ray surveys: hot IGM traces cluster mass.
4) lensed features near massive clusters
5) parent galaxies of γ-ray bursts

67) Convergence model based on 3 approaches:
1) CMB restricts total energy density (location 1st peak)
2) Hubble diagram (Ia – SN) constrains Λ
3) X – ray output of galaxy clusters traces total (vis + dark) matter.

68) "dark energy" ~~because~~ (= cause of acceleration) may refer just to a cosmological cst Λ.
Λ's possible variance with time (less than 6% since decoupling) could indicate another varying scalar field describing vacuum.
→ to know this we need to further study acceleration
→ need more ~~obs~~ higher z observations
→ need deep surveys.