

· FLRW metric The Universe is roughly homogeneos & isotropic on large scales. FLRW metric is a good approximation $ds^{2} = -c^{2}dt^{2} + a^{2}(t) \left[dx^{2} + f_{K}^{2}(x) \left(d\theta^{2} + \sin^{2}\theta d\phi^{2} \right) \right]$ Epakial metric c = 1Scale factor (SIAX k = 1 closed $\varphi_{k}(x) = \varphi x$ k=0 flat L sinh x open K = +1

o Measuring the acceleration Want to measure a (2). We observe distances & redsh. Fts (c.f. Hulible). In cosmology there are two main ways of measuring distances · standard candles: objects of known luminosity • II Wers; II II II Site * Example of standard candle: Cepheids Å Puesating stans with stable residic luminolity. Cuminoli in Relation between period & Cuminosity disovered in 1308 by Henzietta Swan Leavitz. Crucial for all cosmologicu observations. period -> Allowed to go from dr 102 Ly. to 1010 light years! In cosmology we need more luminous objets e to define distances in an expanding spacetime: supernovae & luminosty distance

· Luminosity distance : radiated EM energy per vnit time (power) dE Luminosity FIDE : Amount of everyy reaching $F = \frac{L}{A} = \frac{L}{4\pi d^2}$ a durface. Telescopes measure this, In an expanding universe $A = \iint_{A} dS_{2} = a f_{K}^{2}(\chi) \iint_{A} dJ_{2} =$ Induced metric on the sphere = 4TT a gr (2) We use the same definition as in flat space the $F_{obs} = \frac{L_{obs}}{A(t_{obs}, \chi)}; \quad L_{obs} = \frac{dE_{obs}}{dt_{obs}} = \frac{dE_{obs}}{dE_{obs}} \frac{dE_{obs}}{dE_{obs}} \frac{dE_{obs}}{dt_{obs}} \frac{dE_{obs}}{dt_{obs}} \frac{dE_{obs}}{dt_{obs}} \frac{dE_{obs}}{dt_{obs}} = \frac{1}{(1+z)^2} L_{ems}$

Luminosity where dr = (1+2) do fk(x) F = 411 d12 distance We need to find & (comoving distance) Protonc travel along ds=0 => dt = ± a(t)dx X S $a(z) = \frac{ao}{1+z} \qquad da = -\frac{dz}{(H+z)^2} a_0$ with Ho = H (2=0) $\text{Def}: \Sigma_{k,0} \equiv -\frac{k}{a_0 + c} \Rightarrow a_0 = \frac{H_0}{\sqrt{1}\Sigma_{k,0}}$ $d_{L}(z) = (\Lambda + z) \xrightarrow{H_{0}^{-1}} f_{K}(\sqrt{|\Omega_{k_{0}}|}) \xrightarrow{Z} \frac{dz'}{E(z')}$

• For small e:
$$E(z) = \frac{H(z)}{H_0} \propto \frac{H_0}{H_0} = 1$$
: $dL(z) \simeq H_0^{-1} = Hubble hav$
• Supernoyae are found for $z \leq 1$. We can expand for simple \pm .
More over, unput ite today is simple and enters only at third order in z .
Up to believed order in z : (E_X, I_1)
 $dL(z) = (A+z) \int_0^z \frac{dL^2}{H(z)} = dL(0) + dL(z) \Big|_{z=0} + \frac{1}{2} dL'(z) \Big|_{z=0} = z^2 + i$.
 $dL(z) = (A-z) \int_0^z \frac{dL^2}{H(z)} = dL(0) + dL'(z) \Big|_{z=0} + \frac{1}{2} dL'(z) \Big|_{z=0} = z^2 + i$.
 $dL'(z) \Big|_{z=0} = H_0^{-1}; dL'(z) \Big|_{z=0} = H_0^{-1} (A - \frac{a}{H_A}) \frac{1}{2z_0}$
• $\partial e g: traditionally g = -\frac{a}{H^2} = -\frac{a}{a} \frac{dimensionless}{qvantity}$
Acceleration for $q_0 < 0$?
 $the sign is historical: people we expecting to measure $a < 0$?$

Supernovae type la

· Supernovae type ta Supermoval type Ia can be used as Tandard Candles : very bright! Ideal to measure acceleration Eacreating white dwarf, sustained by electron prostuze (m < 1.44 M.O) Gompanien STAR Mass of white dwarf increases by accreation. Internal temperature raises, carbon storts fusing : C+C -> heavier elements Runaway substion : violent process, carbon detonation! This happens at the chitiche (Chandrasekhar) mass 1.44 Mo, when fearing overcomes electron degeneracy pressure.

Supernovae type la





Supernovae type la

Characteristic luminosity vs time light-curve:



$v_H = c z$ The distance ladder





Luminosity distance/redshift relation



Luminosity distance/redshift relation



· STAndard Sirens Use GW instead of light. BH Dinaries instead of GN $h_{+1} \sim \frac{4}{d_{L}} (G_{M_{c}})^{\frac{5}{3}} (\pi t)^{\frac{2}{3}} = G_{W} f_{t} q_{venus}$ MZ $\frac{1}{G_{W}} = \frac{1}{G_{W}} + \frac{1}{G_{W}} +$ the child mass can be inferred from f: df ~ 96 18/3 (GMc) 5/3 f 1/3 (from quadwoode for mula) Advantage the system is seef-calibrated (and can go at high 2 if Me is large). towever, impossible to deduce & without an associated optical counterpart (e. A. Gw 170817): mass-redshift degeneracy Same signal from MA, 2 at Z=0 & MI, 2 at Z

analysis (blue consults). Shading fer Ho from Grand os ι from the joint GW-ENA.4% (2therastreety biohostaticentation) of the set of th 2 analysis (blue contours). Shading levels are drawn lat and 2 the contract source the optimate source optimate source the optimise optimate source optimate so pansion rate of the Universe. At nearby distances and 2 are sensitive to a number for the Universe. At nearby distances $(d \leq 50 \text{ Mpc})$ it is well approximated by the ex_{et al.} 2016). As noted in the texchores of current galax peculiar velocities; pression^{0.04} – $(d \leq 50 \text{ Mpc})$ it is well approximated by the ex_{et al.} 2016). As noted in the texchores of current galax peculiar velocities; near 180 deg (cost the need for cledicated follow-up surveys, the matching the method of the defector. (1) gular moasenwells asti-parategoitothselection front for Ho. The $v_H = H_0 d,$ $v_H = H_0 d$, (1) gular modernværtis astreparatingenotins electron rom setts 499 e system recting for local orivalue with the mining the source of the detected 2013). In what follows we exploit around the location of NGC 4993 as the detected 2013). In what follows we exploit the source of the identification of NGC 4993 as the hosting at the hostin completeness of casten figadaity distance and comoving distance) difESO-508005 os Detater of mass or sign select the group velocity by 310 d for dedicated for the converse of v_H/c where c is the speed of ty relative to the frame of the CMB (Hinshaw et the coherent bulk flow (Springod et al.). nge of selection **lightetis** (Sviegsen $\sim 1\%$ for GW170817 we do not 2009) is (Crook et al. 2007) 3327 ± 72 km s⁻¹. We pernova measurements from the order of the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the Grant of the GW data associated with GW 1708217 and the GW 1708217 and to perform a state structure as in a and p_A MethodsisettyoisfthelecoirsecThensteledaof gravetydetainsetslikom Hubble constant (Holøbtalinuhe Hubble flow velocity at the posiour estimate of the weculier relogity nice fested in the plant of the measurer al. 2006; Nissation of GW2008,17, we use the optical identification of the bulk flow motion that have been a component of the point of the bulk flow motion that have been a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bulk flow motion and be a component of the bul ates for the pazadimensionfalt projected offset and is independent s_{al}^{-1} Mb (s_{al}^{-1}) style to the side of the duboration of the comparison of the comparison of the set of the structure of the set of the structure of the set of the structure of the set of the he assumption contained avalue of H₀. The position and red the pecultar velocity all the Odcan of the NGC NPOR od soft entry tematic uncertain at present for a systematic ect model of gravity (Abthin galaxy allow us to estimate the appro-and fold this into our estimate of the uncertainty e most interested priateviding of the Hubble flow velocity. Because v_H . From this, we obtain a Hubble velocity and established EM-based An analysis of the GW data alone finds that finds that much remarked upon, the on on the luminotity solution interview in the remarked upon, the Fronts. and established EM-based Errors: clination angle. Forothenenafysikaxies, known as peculiar velocities, T) Hubble flow velocity: need to account for the location of velocities, cauted by interpentent error from the location of velocities, cauted by interpentent error from the location of velocities, cauted by interpentent error from the location at velocities, cauted by interpentent error from the location at velocities, cauted by interpentent error from the location at velocities, cauted by interpentent error from the location at velocities, cauted by interpentent error from the location at velocity velocity in the minimal width 68 3% credible inter-net of the location at velocity velocity in the minimal width 68 3% credible inter-noise in detectors in the first error from the location at velocity velo 017). See the Method Method $show s^{-1}$. from that in other studies (Abbott et al. 2017a), The original standard siren proposal (Schutz since here we assume that the optical counter- γ_{π}

several ways of determining the redshift

· Direct EM wonterpart with 2 measured (aw 170817) · Schutz 86 · Collection of galaxies localized in the GW bunkitation volume · Knowledge of the source frame muss distribution (peaks mass gaps, etc.) o Tidal deformability breaks mush-redshift degeneracy (for NS) Potentially interesting in the future

Conclusions Lecture 1

- To measure the expansion rate we need to measure distances and redshifts: Iuminosity distance and angular diameter distance. We have derived the dependence of the luminosity distance on the deceleration parameter, which can be measured by standard candles.
- **Type la supernovae** are very bright and their brightness depends on the timeluminosity relation: They are ideal standard candles to go at high redshifts. They have been used to measure the expansion at high redshifts and **discover the cosmic acceleration**. Concordance with other observations. Standard sirens potentially useful on the future.

EXERCISES 1.1 Verify $d_{L}(2) = H_{0}^{-1} Z \int I + \frac{1}{2} (I - q_{0}) Z + \cdots$ SOLUTION: $d_{L}(z) = (\Lambda + 2) \int_{-\pi}^{2} \frac{dz'}{H(z')} = d_{L}(o) + d_{L}(z)|_{z=0} + \frac{1}{2} \frac{d_{L}''(z)|_{z=0}}{z=0} + \frac{1}{2} \frac{d_{L}''(z)|_{z=$ and plug: $\frac{dL'(z)}{dL'(z)} = \int_{0}^{z} \frac{dz'}{H(z')} + \frac{1+z}{H(z)} \Rightarrow \frac{dL'(z)}{z} = H_{0}^{-1}$ $d_{L}^{''}(x) = \frac{1}{H} + \frac{1}{H} + \frac{d}{dx} + \frac{1}{H} + \frac{1}{H}$ $\frac{dz}{dt} = \frac{A}{at}\left(\frac{a_0}{a}\right) = -\frac{a_0}{a^2} = -\frac{A}{(1+2)} = -\frac{1}{4}\left(2 - \frac{1+q}{1+4}\right)$ = 9

1,2 If you have never done it, play with Friedmann eqs. by showing funt the first is equivalent to the second upon use of the conservetion eqn. 1.3 Generalize the expression of E(z) to the one of WDE(z) 1. 4 Show that the compuning distance to z= or for 52, =0 is $\chi(\infty) = 2 \operatorname{acsinh} \int \frac{JL_K}{JL_M}$. Use the replacement $1+z = y^{-2}$ to solve $\frac{JL_M}{L_M}$