National Radio Astronomy Observatory

# Dark Energy: Constraints from the Hubble Constant

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Topics:

- What is the Hubble constant $H_0$?
- How can $H_0$ constrain dark energy (DE) and other cosmological parameters?
- How can we measure $H_0$ with higher accuracy?

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Key references:

Freedman et al. 2001, Astrophysical Journal, 553, 47 (HST Key Project measurement of $H_0$)

Hu 2005, "Dark Energy Probes in Light of the CMB," ASP Conf. Ser. Vol. 339, Observing Dark Energy (San Francisco ASP), 215 (astro-ph/0407158)

Lo 2005, "Mega-Masers and Galaxies," Annual Review of Astronomy & Astrophysics, 43, 625

# What is the Hubble Constant?

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

$$h \equiv \frac{H_0}{100 \text{ km s}^{-1} \text{ Mpc}^{-1}} \approx 0.72$$

$H = H(t)$ is the (variable) Hubble parameter measuring the unversal expansion rate

$H_0$ is the present, or local, value of $H$

$H_0 = 72 \pm 7$ km s$^{-1}$ Mpc$^{-1}$ observed for "nearby" galaxies, where 1 Mpc = $3.086 \cdot 10^{19}$ km

$H_0 \approx 1.36 \cdot 10^{10}$ years

# How can $H_0$ constrain DE?

- $H_0$ is *not* needed for relative distances (distance ratios) versus redshift $z$ (e.g., the detection of DE by using SNe 1a as uncalibrated "standard candles").
- $H_0$ *is* needed to convert between relative and absolute quantities (e.g., distance, density), the latter often appearing in CMB results. Consequently,
- "The single most important complement to the CMB for measuring the DE equation of state at $z \sim 0.5$ is a determination of the Hubble constant to better than a few percent." (Hu 2005)

# Example: The Critical Density

A "flat" universe ($k = 0$) implies a critical total (including DE) density depending only on $H_0$:

$$\left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{8\pi G}{3c^2}\rho - k\frac{c^2}{a^2}\right)$$

$$\rho_c = \frac{3H_0^2 c^2}{8\pi G} \approx 10^{-8} \text{ erg cm}^{-3}$$

$$\rho_c / c^2 = \frac{3H_0^2}{8\pi G} \approx 1.0 \times 10^{-29} \text{ g cm}^{-3}$$

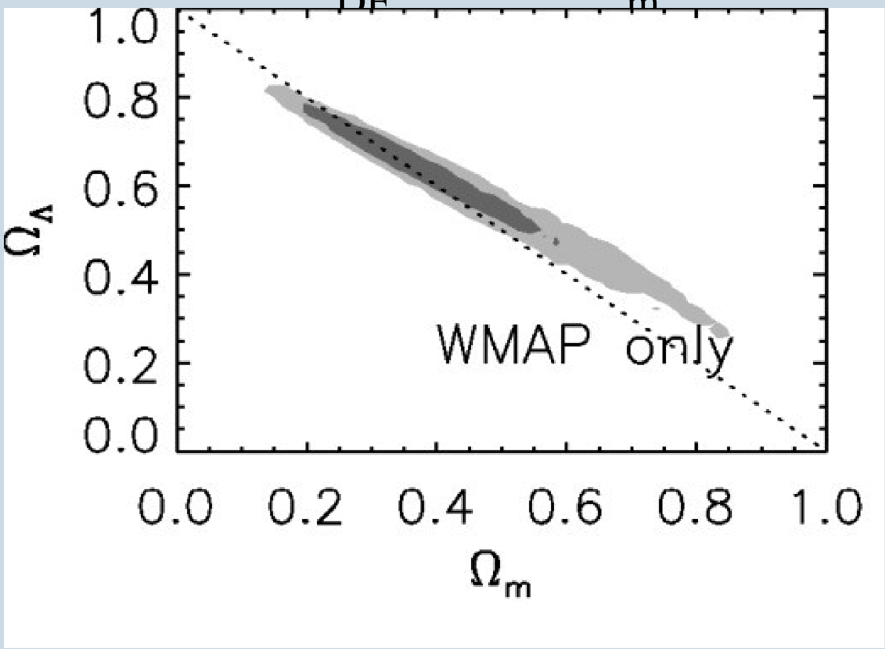
$$\Omega \equiv \frac{\rho}{\rho_c}$$

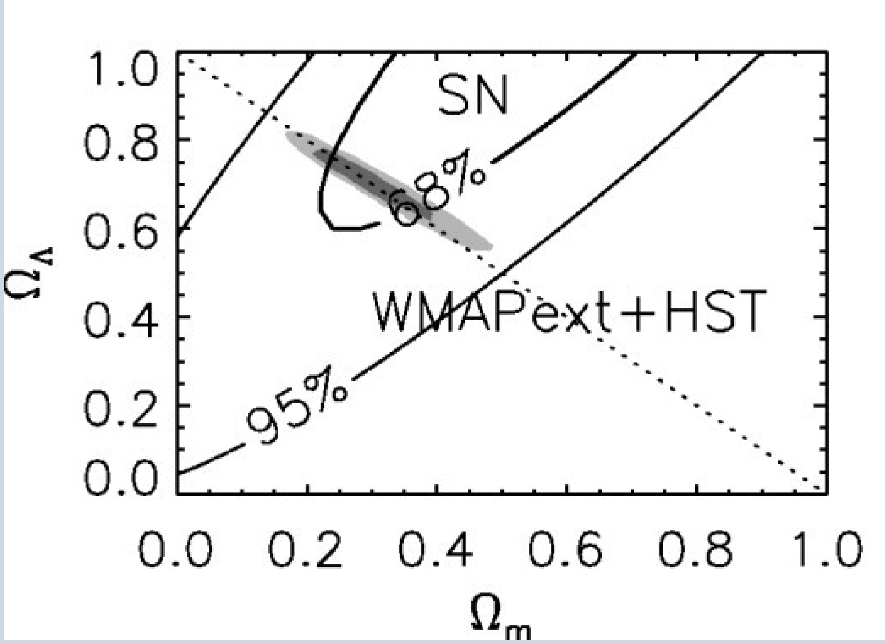
# Example: CMB results from WMAP

$\Omega_b h^2 = 0.024 \pm 0.01$ (baryonic matter)

$\Omega_m h^2 = 0.14 \pm 0.02$ (all matter)

$\Omega_{DE} = 1 - \Omega_m$




(Spergel et al. 2003, ApJS, 148, 175)

# CMB constraints on $H_0$

WMAP gets $h = 0.72 \pm 0.05$ by assuming a flat LambdaCDM model with spectral index $n = 1$. But:

"CMB observations do not directly measure the local expansion rate of the universe...

Thus, local Hubble constant measurements are an important test of our basic [flat CDM] model."

"...$H_0$ measurements could place significantly stronger limits on $w$."

(Spergel et al. 2003, ApJS, 148, 175)

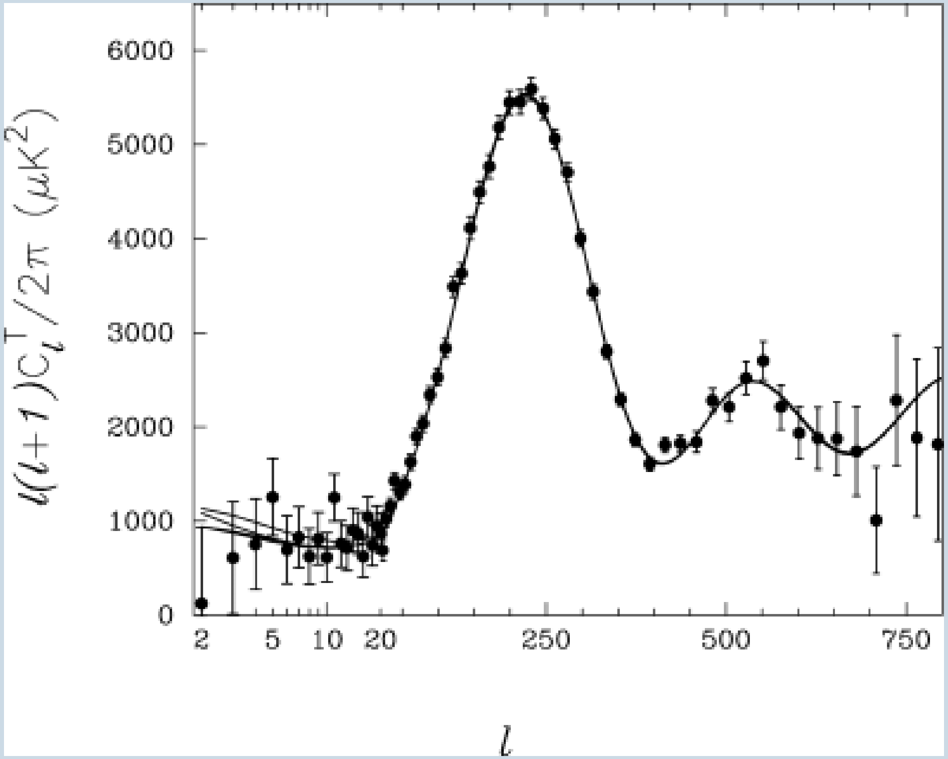
# Example: Is the Universe Flat?

CMB degenerate models

($h^2\Omega_b = 0.024$, $h^2\Omega_m = 0.12$):

| $\Omega_k$ | $\Omega_b$ | $\Omega_{cdm}$ | $\Omega_{DE}$ | $h$ |
|---|---|---|---|---|
| -0.00 | 0.0463 | 0.2237 | 0.73 | 0.72 |
| -0.05 | 0.0806 | 0.3894 | 0.58 | 0.54 |
| -0.10 | 0.1114 | 0.5386 | 0.45 | 0.45 |
| -0.20 | 0.1714 | 0.8286 | 0.20 | 0.37 |

(Efstathiou 2003, MNRAS, 343, L95)



# Example: The Age of a Flat Universe

First hint of Einstein's cosmological constant (Eddington 1930!) and of dark energy (Carroll & Turner 1992, ARA&A, 30, 449)

$$\left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{8\pi G}{3c^2}\rho - k\frac{c^2}{a^2}\right)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3p).$$

"Matter" (defined by $p = 0$) and radiation yield deceleration only. If $k = 0$ and $h \approx 0.7$, then $t_0 <$ age of oldest stars.

$$\frac{\ddot{a}}{a} = \frac{-\dot{a}^2}{2a^2}$$

$$a \propto t^{2/3} \qquad \dot{a} \propto t^{-1/3}$$

$$\frac{\dot{a}}{a} = H = \frac{2}{3t}$$

$$t_0 = \frac{2}{3H_0} \approx 9 \text{ Gyr}$$

# Structure at $z = 0$

$$\sigma_8 \approx \frac{\delta_\zeta}{5.59 \times 10^{-5}} \left(\frac{\Omega_{\rm b} h^2}{0.024}\right)^{-1/3} \left(\frac{\Omega_{\rm m} h^2}{0.14}\right)^{0.563} \times (3.123h)^{(n-1)/2} \left(\frac{h}{0.72}\right)^{0.693} \frac{G_0}{0.76}$$

(Hu 2005, eq. 33), where:

sigma_8 = rms density fluctuation smoothed by a spherical tophat of radius $8h^{-1}$ Mpc (strong scaling with $h$)

delta_zeta = WMAP TT amplitude

n ≈ 1 is the spectral slope

# How can we measure $H_0$ with higher accuracy?

Velocities directly: redshifts (but ± peculiar velocities).

Distances indirectly: use Cepheid variable stars calibrated in our Galaxy and in the nearby LMC. But "metallicity" may affect period-luminosity relation (see Jensen et al. 2004, astro-ph/0304427).

Distances directly: geometry of $H_2O$ masers

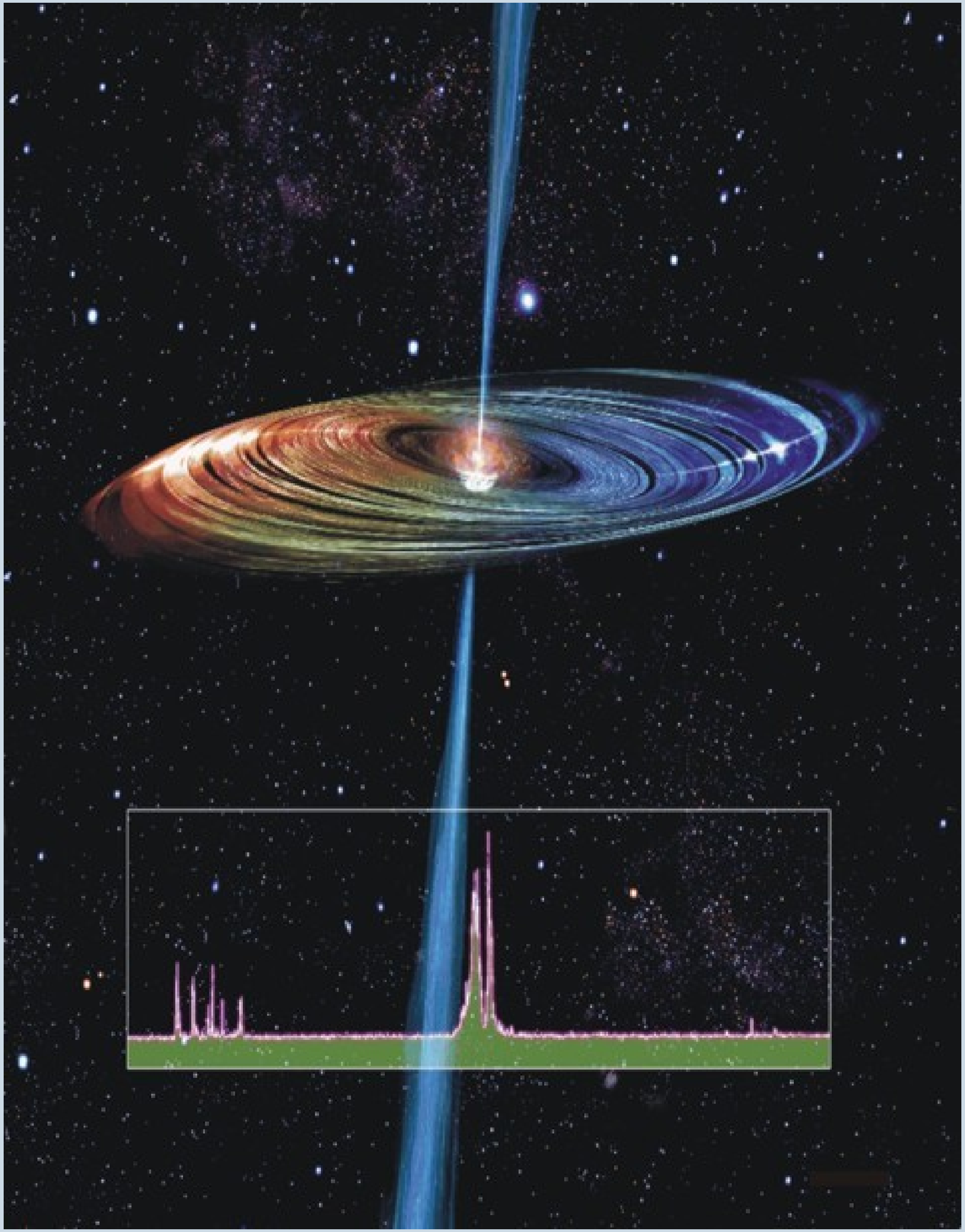
(copyrighted photo of can of worms deleted)

# Present situation:

- The distances to only two galaxies (the LMC and NGC 4258) have been measured directly by geometry, and both are too nearby to measure $H_0$.
- Cepheid measures of $H_0$ are still in dispute (e.g., Paturel & Teerikorpi 2005, A&A, 443, 883 find $h \approx 0.56$) and extend only to D ≈ 25 Mpc (HST).
- Direct distance measurements are needed for galaxies at distances $D \sim 100$ Mpc where peculiar velocities << expansion velocities.

# $H_2O$ maser in the nucleus of NGC 4258

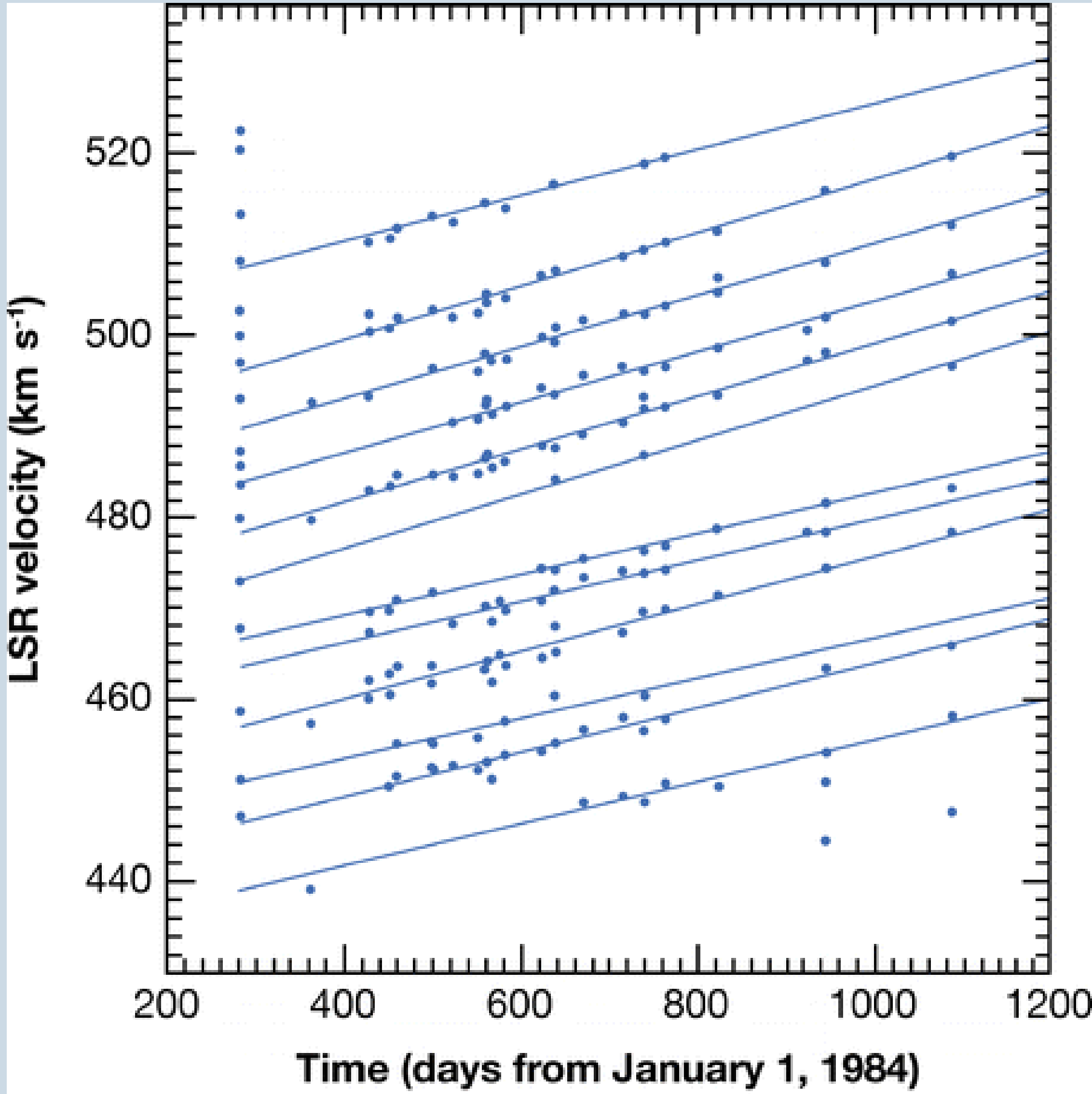
- $H_2O$ maser line emitted at 22.23508 GHz (1.35 cm wavelength)
- "Satellite" lines offset by ± 900 km/s, >> outer disk rotation speed



# NGC 4258

systemic acceleration

$$a_{\rm rad} = {\rm d}V_{\rm rad} / {\rm d}t$$
$$= 9.5 \pm 1.1 \text{ km/s/yr}$$
$$= 3 \cdot 10^{-4} \text{ m s}^{-2}$$




Lo, KY. 2005
Annu. Rev. Astron. Astrophys. 43: 625–76

# NRAO's VLBA

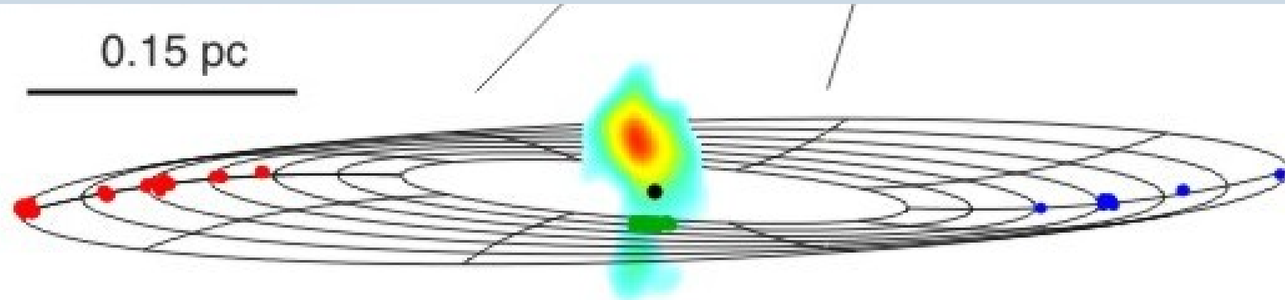
$D \approx 8{,}000$ km

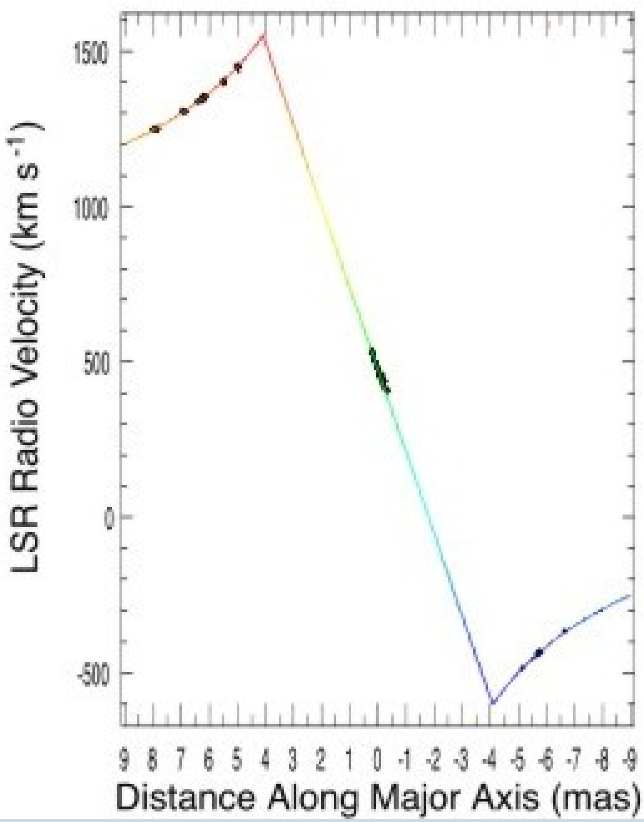
wavelength ≈
1.35 cm

resolution ≈
wavelength / D
$\approx 2 \cdot 10^{-9}$ rad

position error ≈
$10^{-10}$ rad

1 pc ≈ 3.1 · $10^{16}$ m
Keplerian rotation curve,
M ≈ 3.9 · $10^7$ solar masses ≈ 8 · $10^{37}$ kg
Equation below follows from ring geometry:



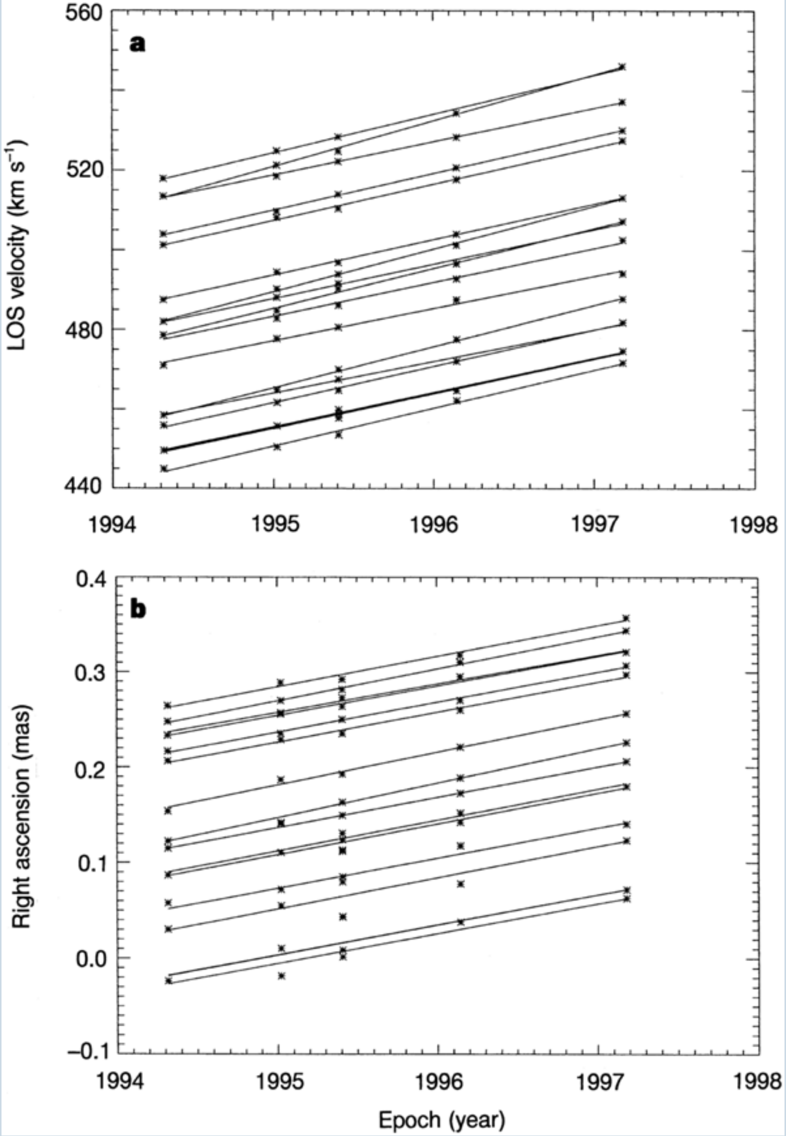



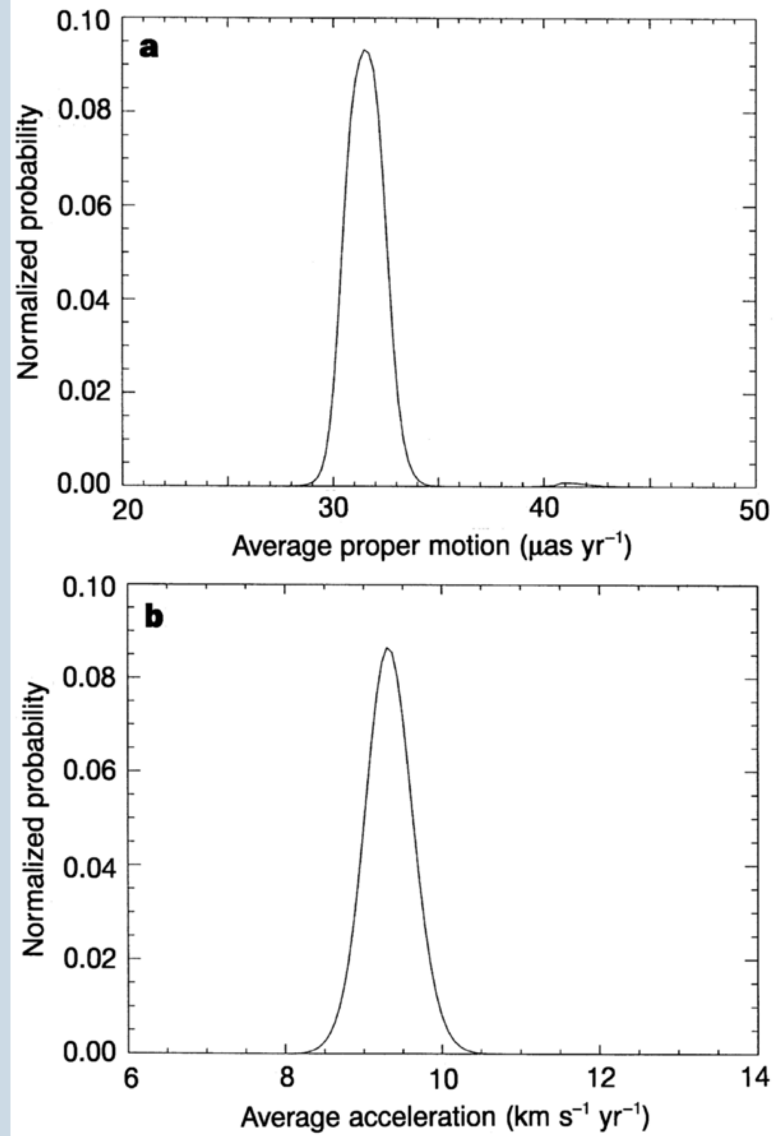

$$D = \frac{\frac{dV_{\rm rad}}{d\theta} V_{\rm rot}}{\frac{dV_{\rm rad}}{dt}}$$

$$\approx \frac{6 \times 10^{13}\ \rm m\ s^{-1} rad^{-1} \times 10^{6}\ m\ s^{-1}}{3 \times 10^{-4}\ \rm m\ s^{-2}}$$

$$\approx 2 \times 10^{23}\ \rm m \approx 7\ Mpc$$

1 mas ≈ 5 · $10^{-9}$ rad



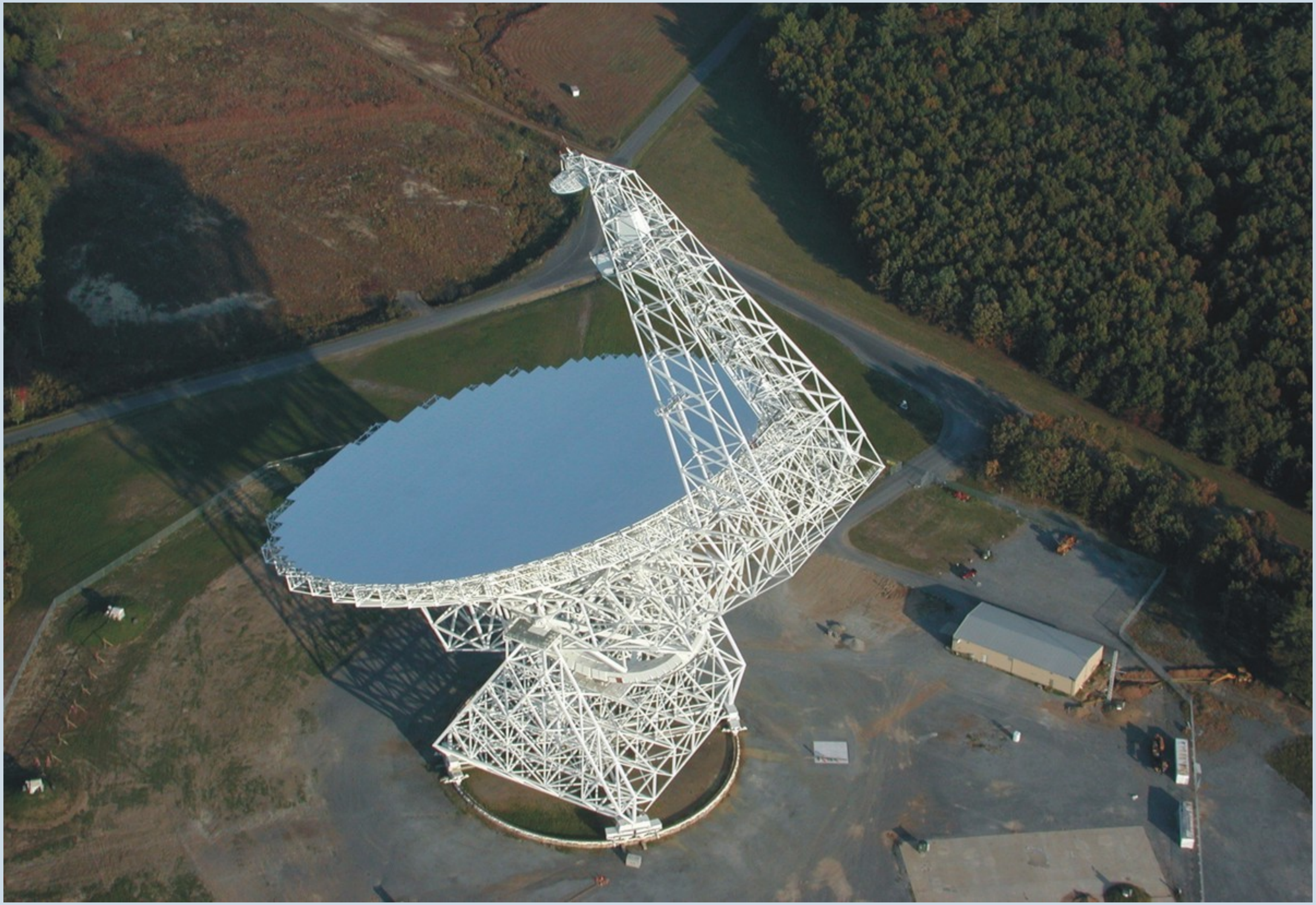




D(proper motion) = 7.2 Mpc, D(acceleration) = 7.1 Mpc
(Herrnstein et al. 1999, Nature, 400, 539)

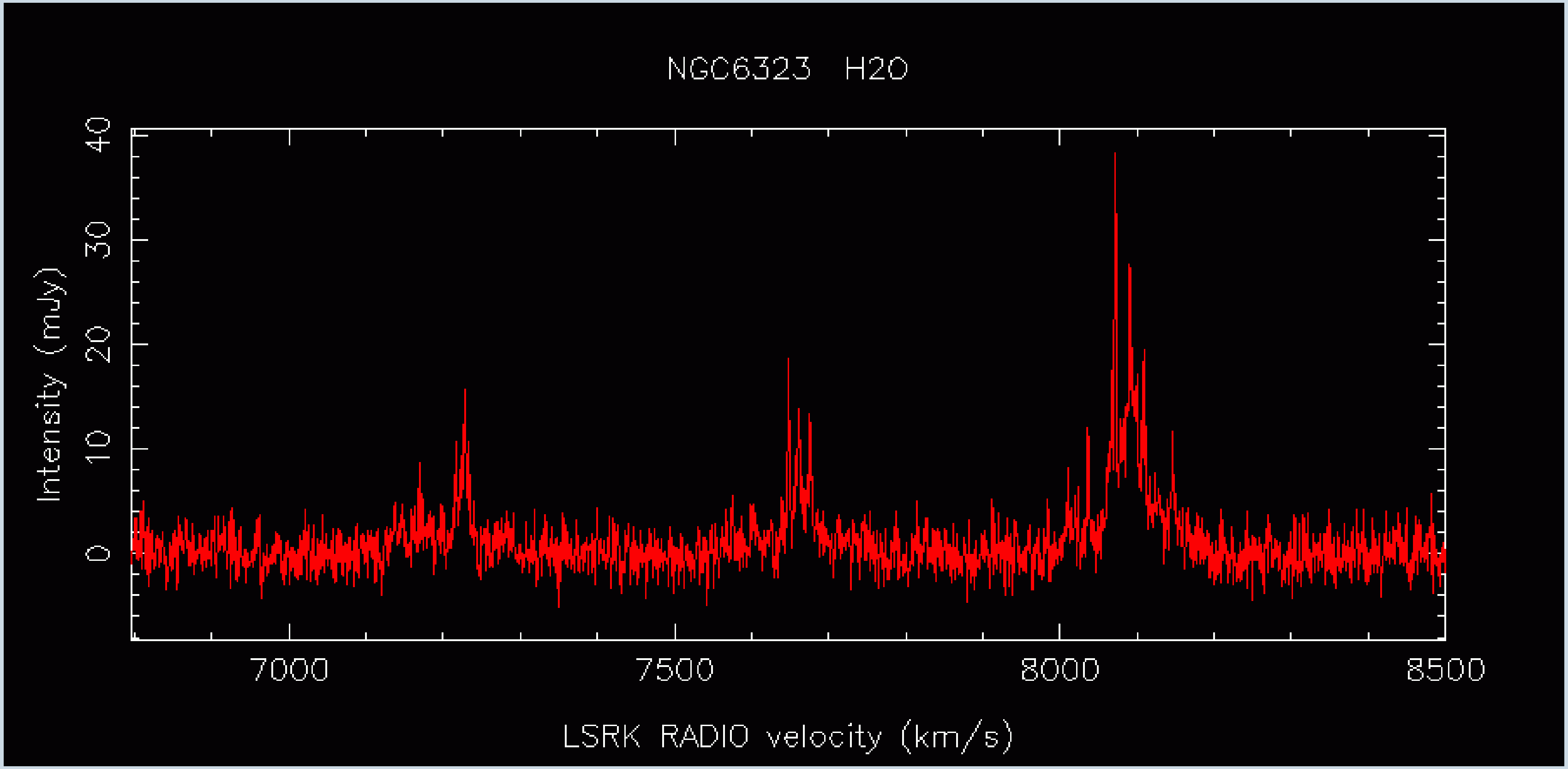
# A Legacy Project to measure $H_0$ directly and accurately (<3%)

- Detect N > 10 suitable $H_2O$ megamasers (strong enough for VLBA/HSA, in edge-on disks) at distances D ~ 100 Mpc (in Hubble flow) and measure their recession speeds
- Measure their geometric distances to ~10% each via acceleration and/or proper motion
- Correct for known velocity fields, calculate average $H_0$

# Detections: GBT



# NGC 6323 at $v_r \approx 7700$ km/s




Braatz et al. 2004, ApJ, 617, L29

# Galaxy samples to search:

- Narrow-line AGN at $z < 0.05$, N = 277 in SD2 sample, N ~ 2000 potentially in SDSS
- Bright nearby galaxies not known to be Seyfert 2
- Heavily absorbed X-ray galaxies from Swift

Need S > 20 mJy $H_2O$ lines to detect with HSA

Need S > 200 mJy for line self-calibration, else nearby (< 2º) continuum source with correlated S > 30 mJy

# VLBA/HSA multiepoch imaging

- Locate candidate flat-spectrum phase-calibration sources near $H_2O$ masers using NVSS/GB6/PMN surveys
- Image masers having suitable calibrators and geometries 3 X per year for ~ 5 years using the GBT+VLBA+(VLA)

# Upcoming NRAO colloquia:

- Lyman Page (Princeton WMAP group) "Observing the CMB: Status and Future Directions" 4 PM, Thursday, Feb. 9
- Wayne Hu (University of Chicago) [dark energy and cosmology] 4 PM, Thursday, Feb. 23

http://www.cv.nrao.edu/colloq/cvlocalcolloq.php