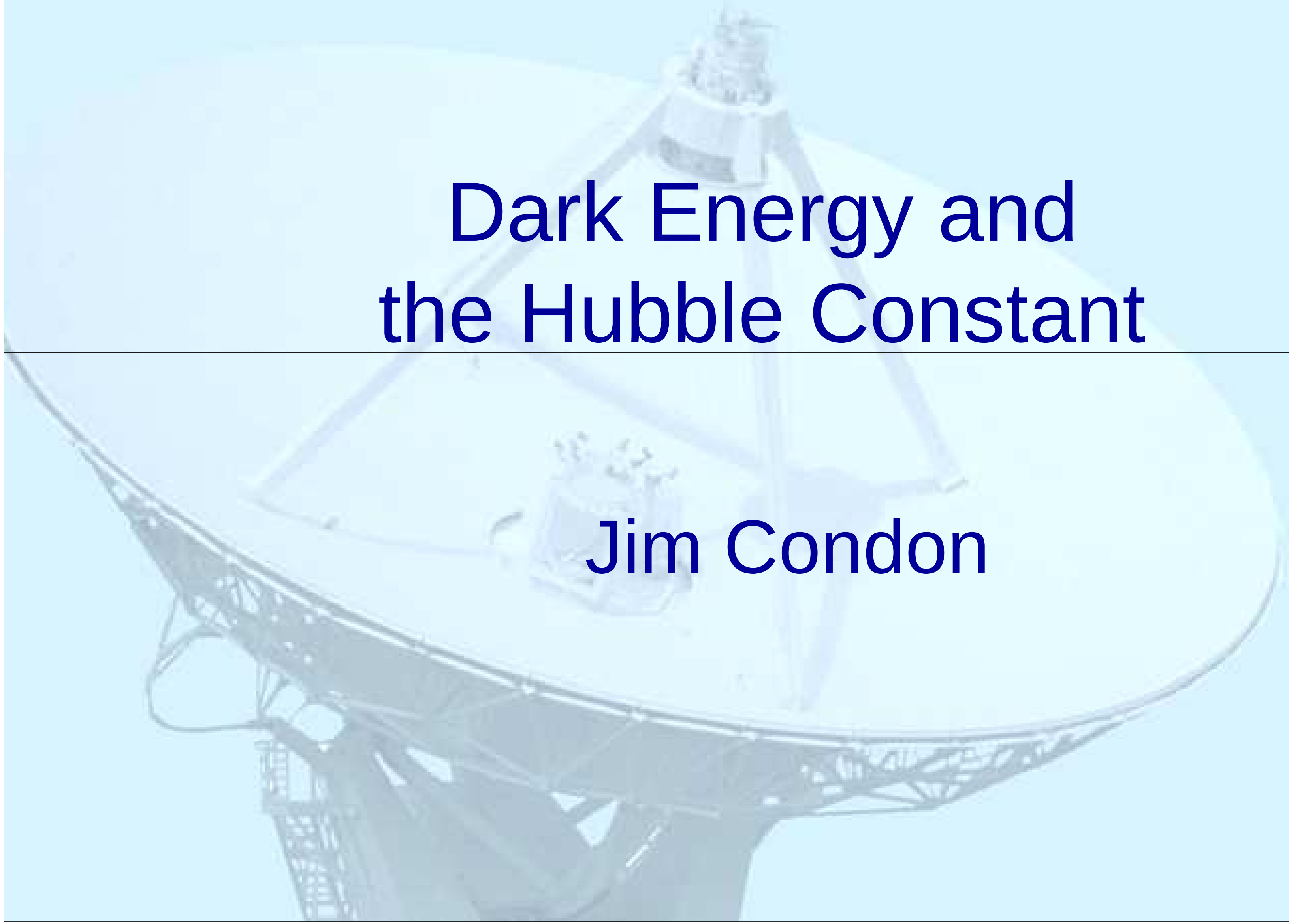
National Radio Astronomy Observatory

UVa – 2009 Sep 25



Dark Energy and the Hubble Constant

Jim Condon

1) What is dark energy (DE)?
2) How does an accurate ($\sigma < 3\%$) local measurement of the Hubble constant H_0 plus CMB data constrain DE?
3) How can radio astrometry determine H_0?
4) Bonus: accurate SMBH masses

The Megamaser Cosmology Project

http://wiki.gb.nrao.edu/bin/view/Main/MegamaserCosmologyProject

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H_0 and the "age problem" if $\Omega_m = 1$

(Carroll, Press, & Turner 1992, ARA&A, 30, 449)

"Matter," defined by $p = 0$, yields <u>de</u>celeration only, so the age of a matter-dominated universe is $t_0 < 1 / H_0$.

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

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

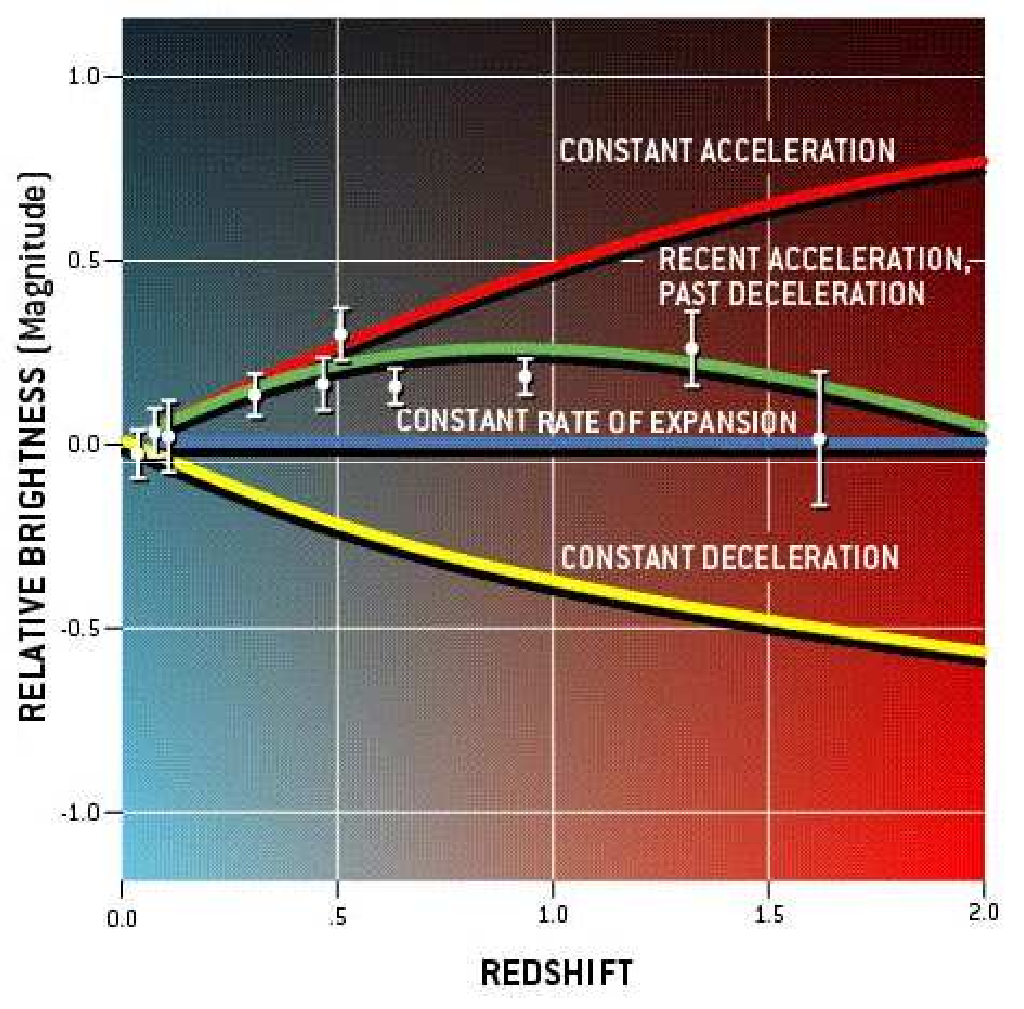
$$\frac{\dot{a}}{a} = H = \frac{2}{3t}$$

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

If $\Omega_m = 1$ and $H_0 = 72$ km s^{-1} Mpc^{-1} = $(13.6 \times 10^9 \text{ yr})^{-1}$, then $t_0 <$ the age of the oldest stars, so

Either H_0 is too high or the expansion is not decelerating as fast as expected.

Acceleration Observed



SNe type Ia used as <u>relative</u> standard candles indicate recent acceleration.

Riess et al. 2004

How can gravity make the universe accelerate?

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

Only energy density ρ and pressure p are relevant. For each constituent of the Universe, define $w \equiv p / \rho$. For nonrelativistic matter, $w = 0$; for radiation, $w = 1/3$. Acceleration requires a sufficiently negative pressure $w < -1/3$; e.g., the quantum vacuum has constant $w = -1$ (but wildly wrong energy density). Is DE a variable “quintessence”? A better H_0 constrains w via the expansion history of the universe.

Conservation of stress-energy and the expansion of the universe

$$\dot{\rho} + 3\left(\frac{\dot{a}}{a}\right)(\rho + p) = 0$$

$$\frac{\dot{\rho}}{\rho} + \frac{3\dot{a}}{a}(1 + w) = 0$$

$$\text{matter } w = 0 \rightarrow \rho \propto a^{-3}$$

$$\text{radiation } w = 1/3 \rightarrow \rho \propto a^{-4}$$

$$\text{constant vacuum energy} \, \dot{\rho} = 0 \rightarrow w = -1$$

Radiation dominates at early times (small *a*), then matter, and finally vacuum energy.

How will it end?

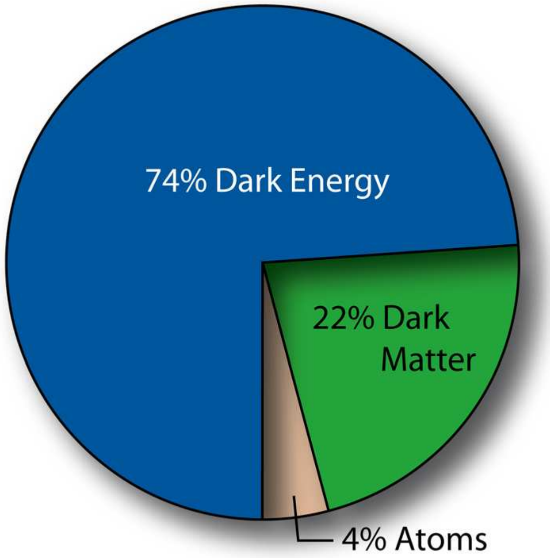
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2 a^3} \quad \rightarrow a \propto t^{2/3} \quad \text{(matter)}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2 a^4} \quad \rightarrow a \propto t^{1/2} \quad \text{(radiation)}$$

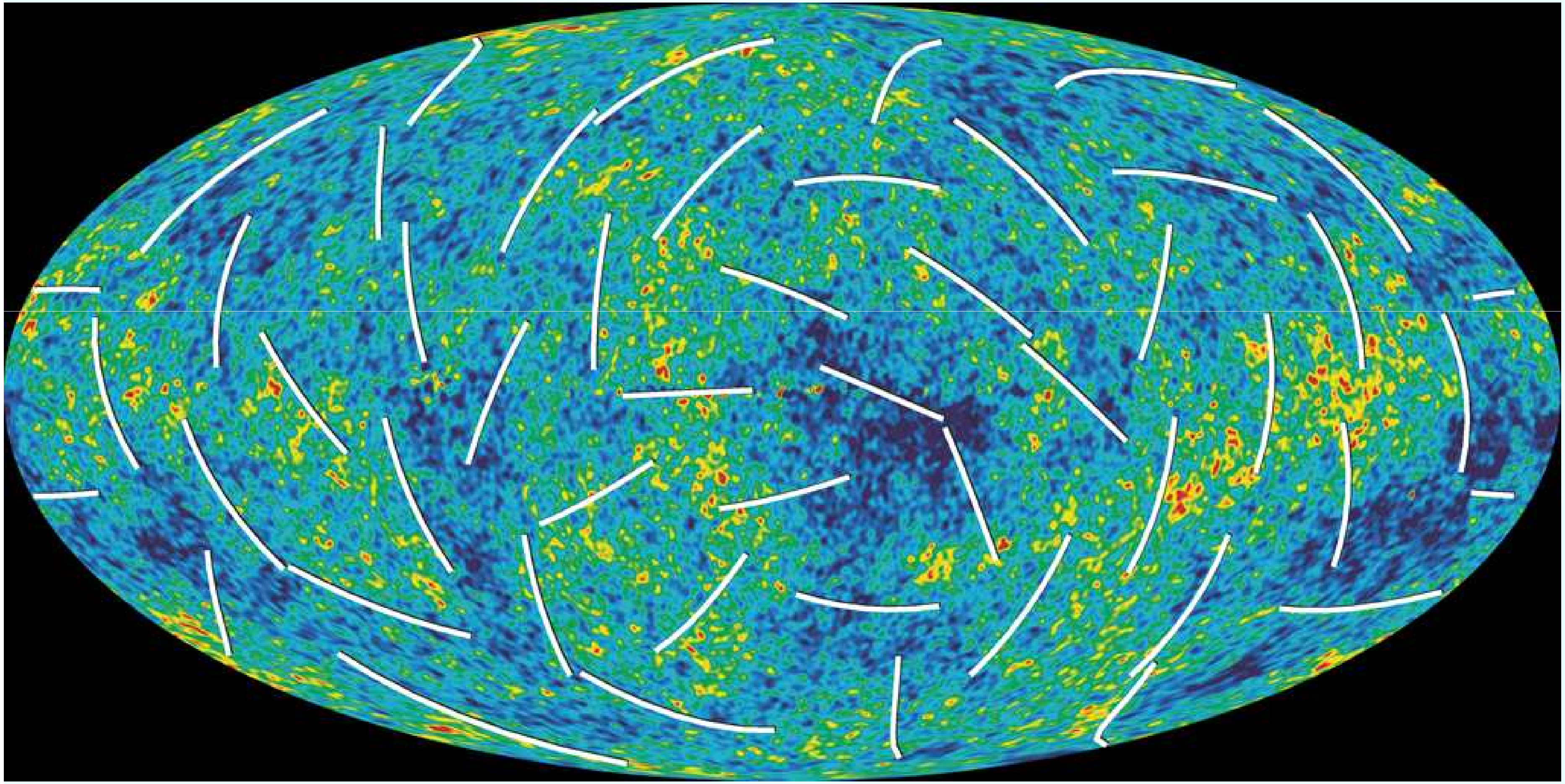
$$\left(\frac{\dot{a}}{a}\right)^2 = \text{constant} \quad \rightarrow a \propto \exp(Ht) \quad \text{(vacuum)}$$

$$\rho_{\text{vac}} = \frac{3H^2c^2}{8\pi G}, \quad H = H_0$$

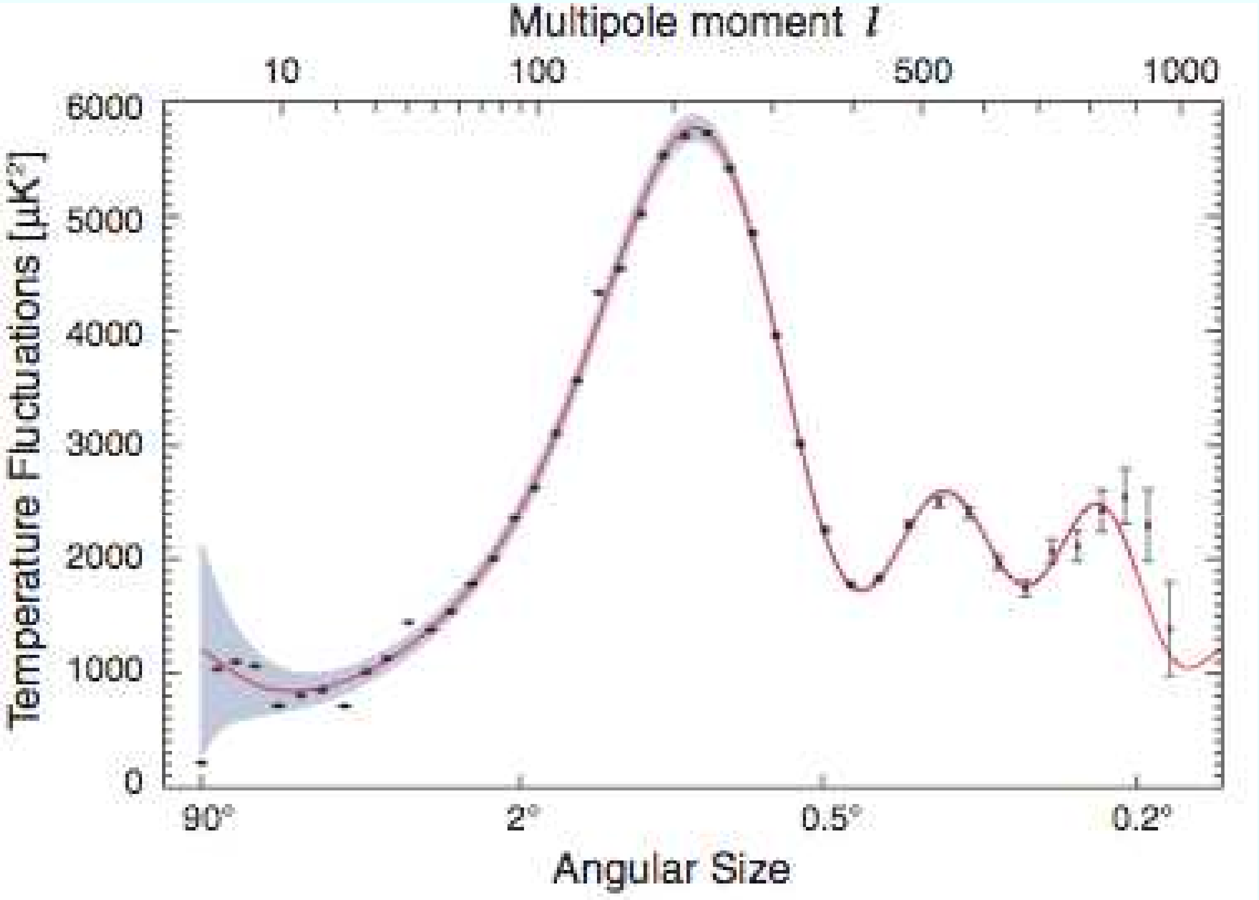


DE dominates the future expansion of the universe, which will double in size every 14 Gyr and become very empty and dark.

Absolute cosmic distances: constraining DE by measuring the expansion of the universe between z ~ 1089 (CMB) and now (H_0)



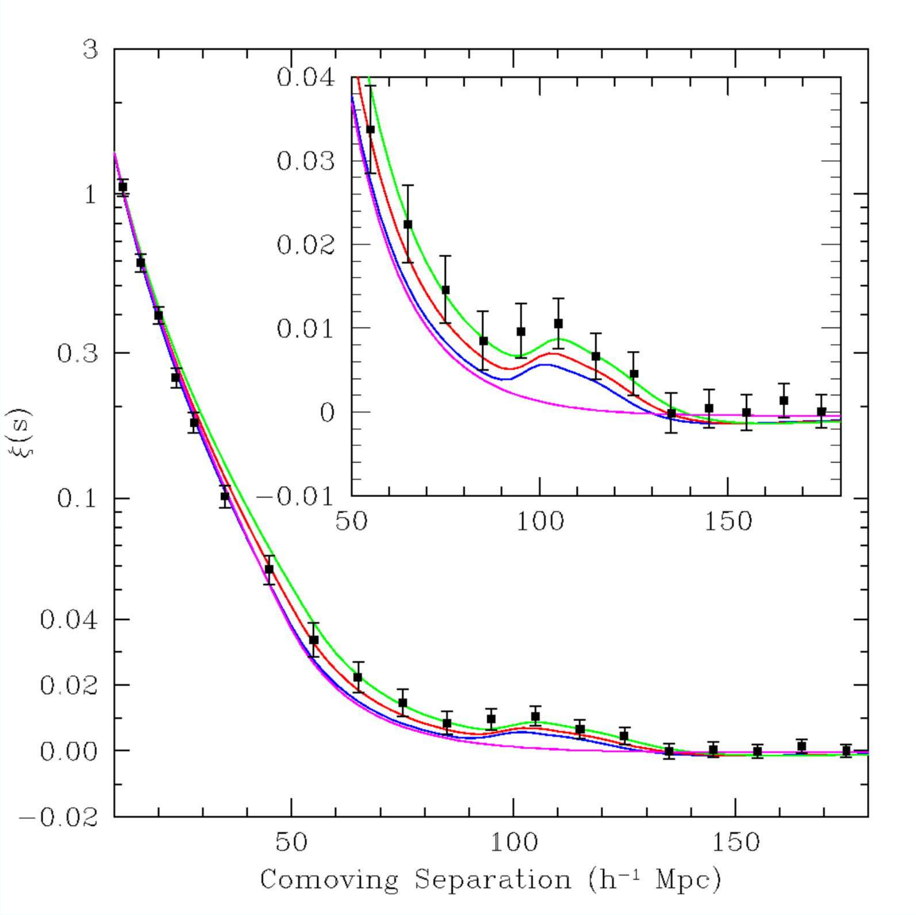
WMAP 5-year TT power spectrum



Absolute angular-size distance to $z \sim 1089$

= linear size (theory) / angular size (observed)

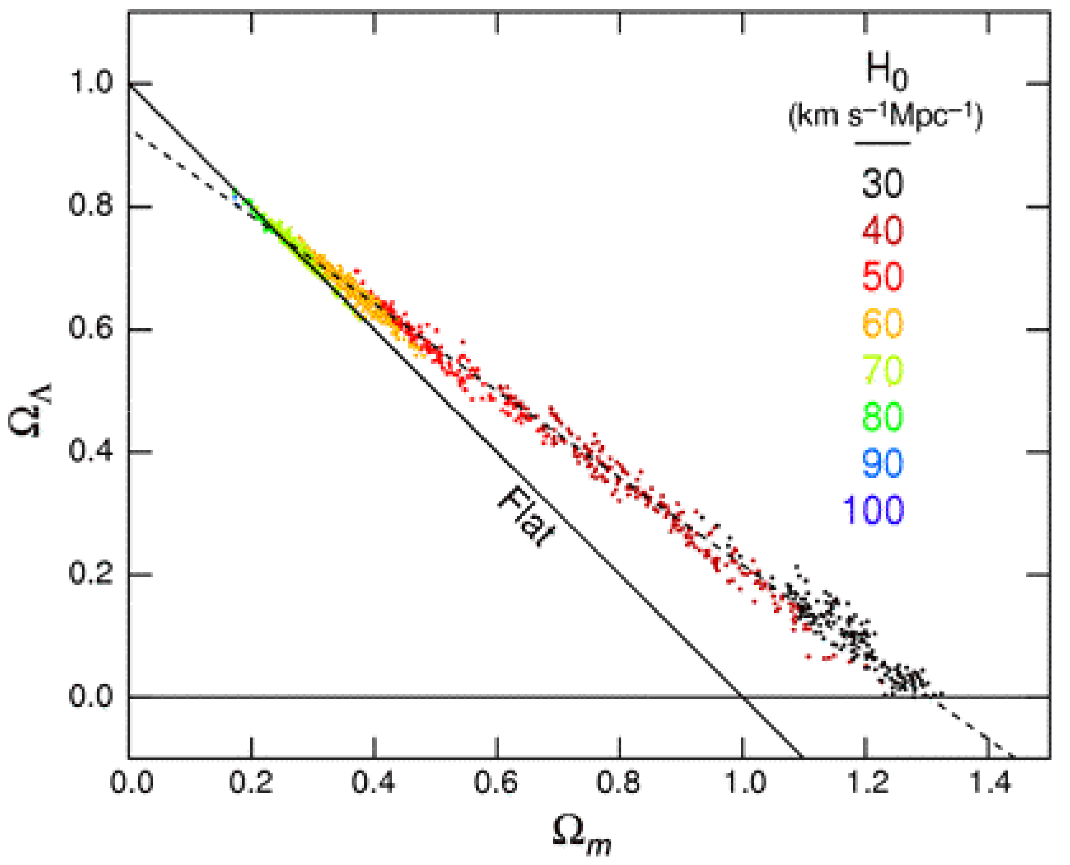
Baryonic acoustic oscillations of galaxies→ statistical measurements of *H* at moderate *z~0.35*



Measures h = 105 Mpc / 144 Mpc = 0.73 and the ratio of distances to *z* = 0.35 and *z* = 1089 to get Ω_m = 0.27.

(Eisenstein et al. 2005, ApJ, 633, 560)

The CMB and H_0



Spergel et al., 2006

"While models with Ω_{DE}=0 are not disfavored by the WMAP data only, the combination of WMAP data plus measurements of the Hubble constant strongly constrain the geometry and composition of the universe" Spergel et al. 2006

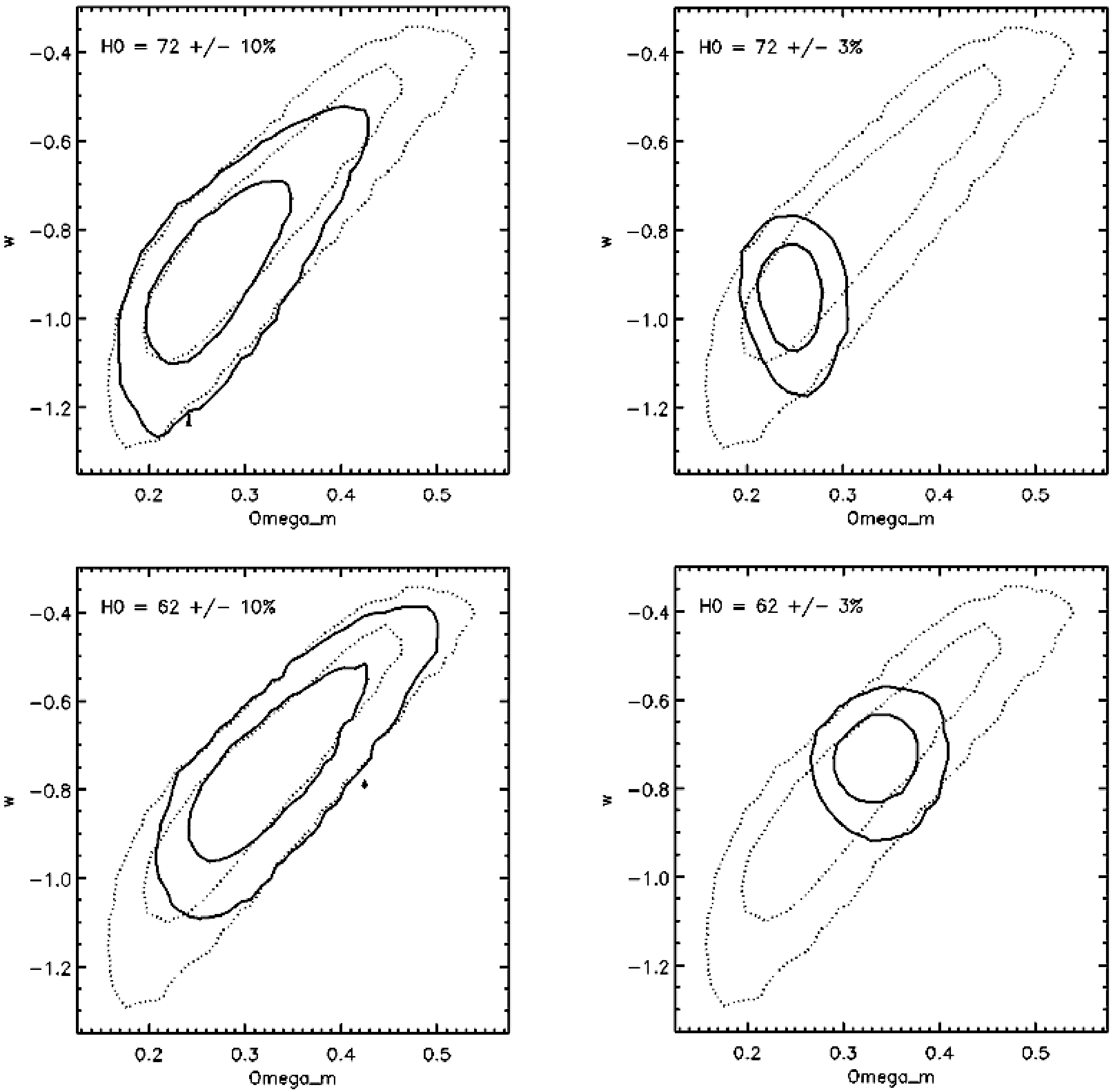
"The single most important complement to the CMB for measuring the DE equation of state at $z \sim 0.5$ is a determination of the [local] Hubble constant to better than a few percent."---Hu, W. 2005, "Dark Energy Probes in Light of the CMB," ASPC 339, 215

The Impact of an H_0 Prior

HST Key Project

$H_0 = 72$

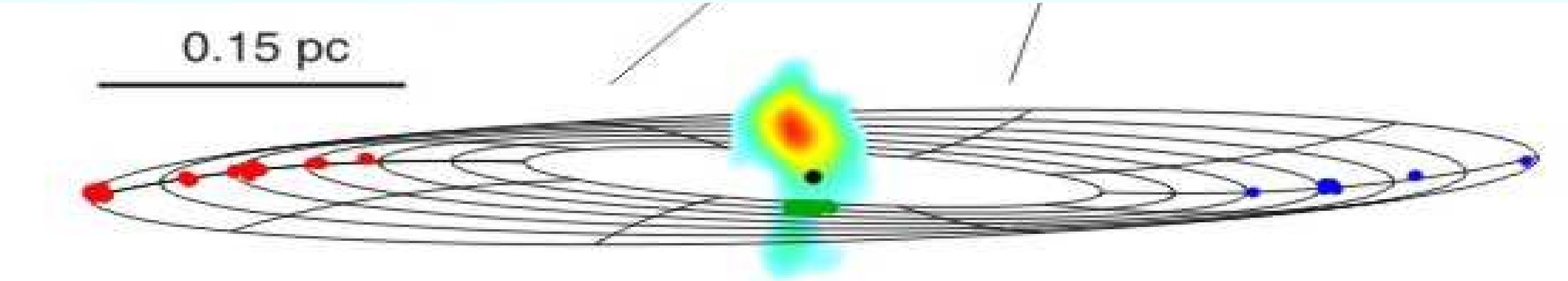
(Freedman et al. 2001)

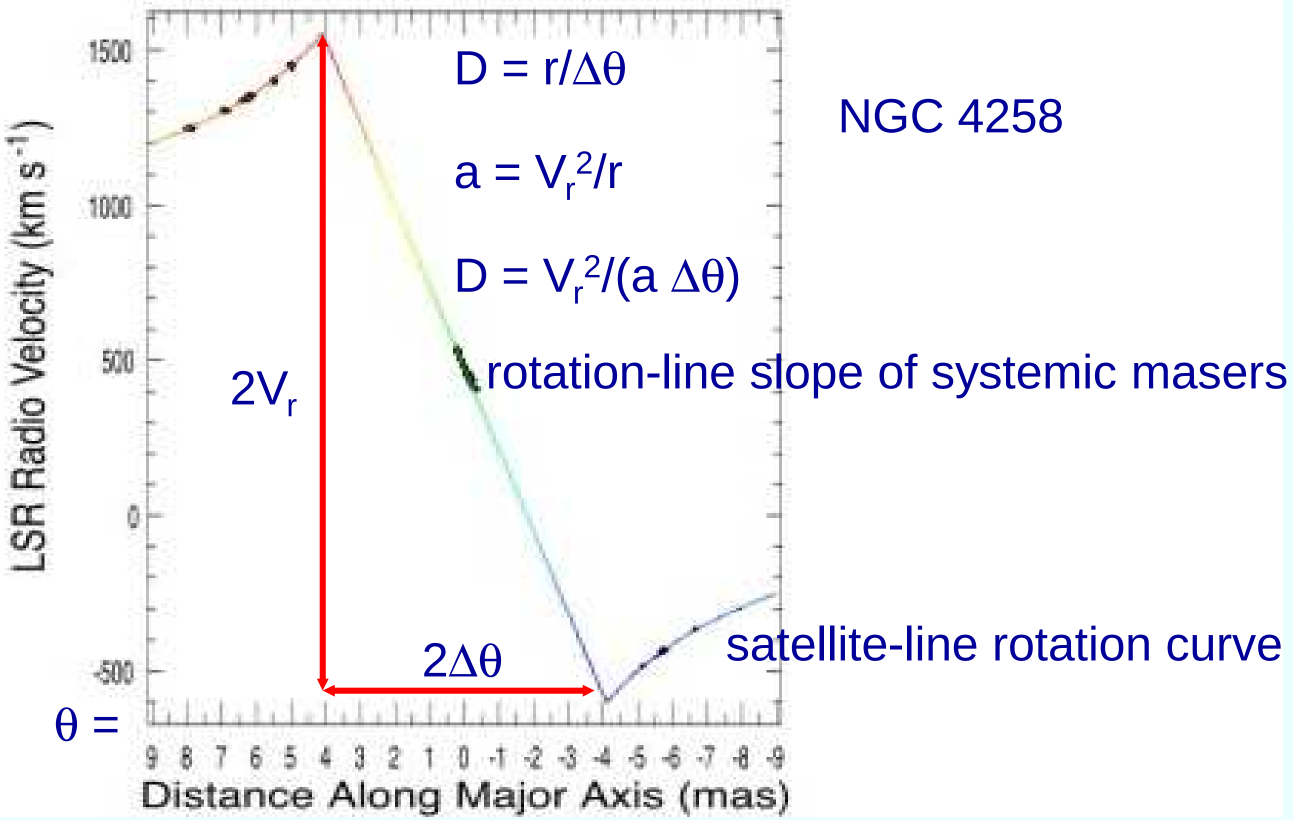


Sandage et al. (2006)

$H_0 = 62$

Geometric Distances to H_2O Megamasers





$D = r/\Delta\theta$

$a = V_r^2/r$

$D = V_r^2/(a\ \Delta\theta)$

NGC 4258

rotation-line slope of systemic masers

satellite-line rotation curve

$2V_r$

$2\Delta\theta$

$\theta =$

r

Two methods to calculate the distance D

Rotation curve of satellite-line masers:

$v_{sat}^2 \propto M/(D\theta_{sat}) \rightarrow M/D$

Rotation-line slope of systemic masers:

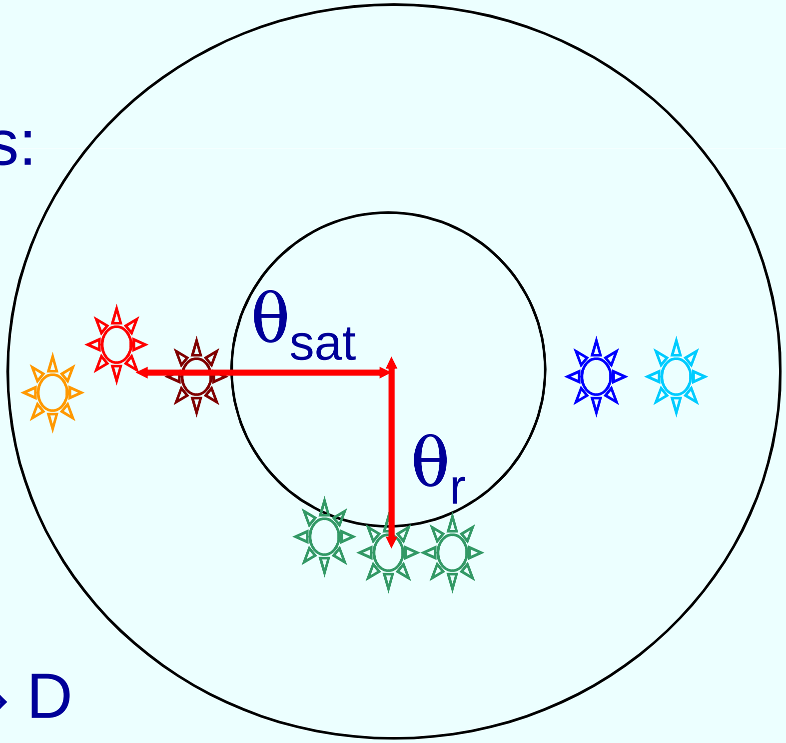
$dv_{sys} / d\theta \propto [M/(D\theta_r^3)]^{1/2} \rightarrow \theta_r$

Acceleration of systemic masers:

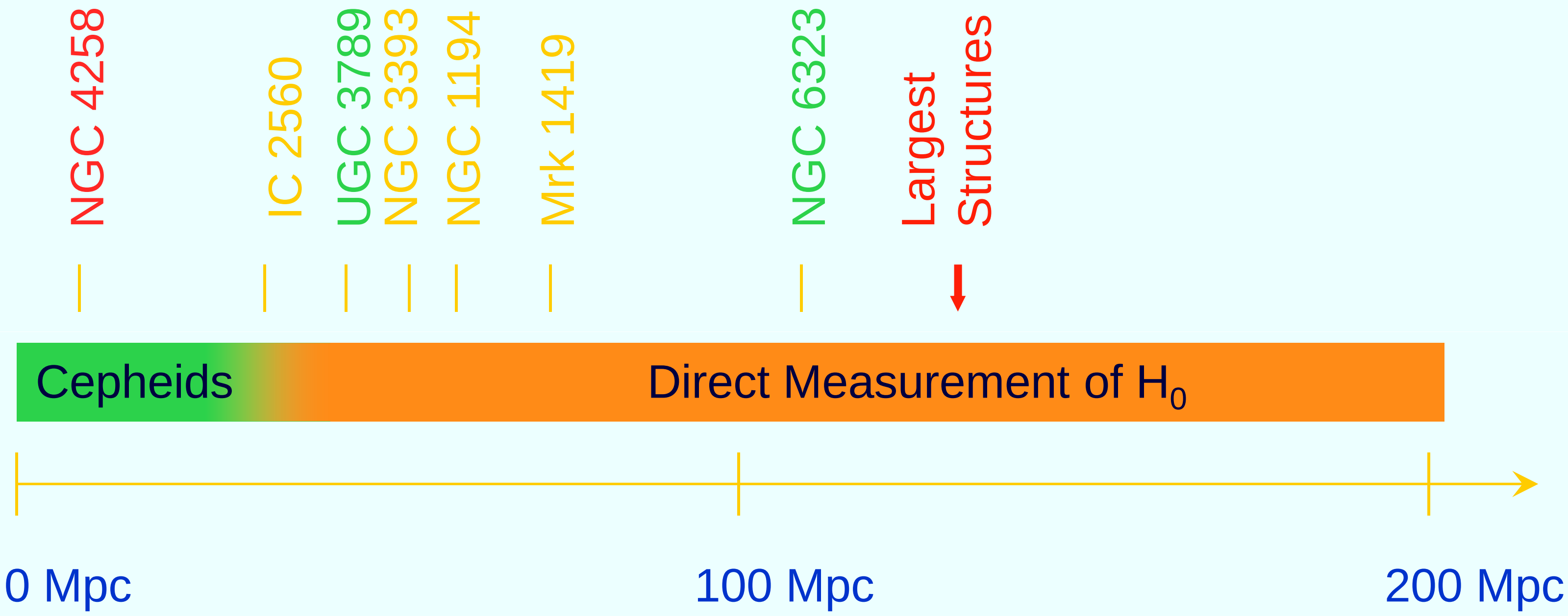
(1) $a_r \propto v_{sys}^2/(D\theta_r) \rightarrow D \rightarrow M$

Proper motion of systemic masers:

(2) $d\theta/dt = v_t/D \propto (M/D^3)^{1/2}\,\theta_r^{1/2} \rightarrow M \rightarrow D$



H_0

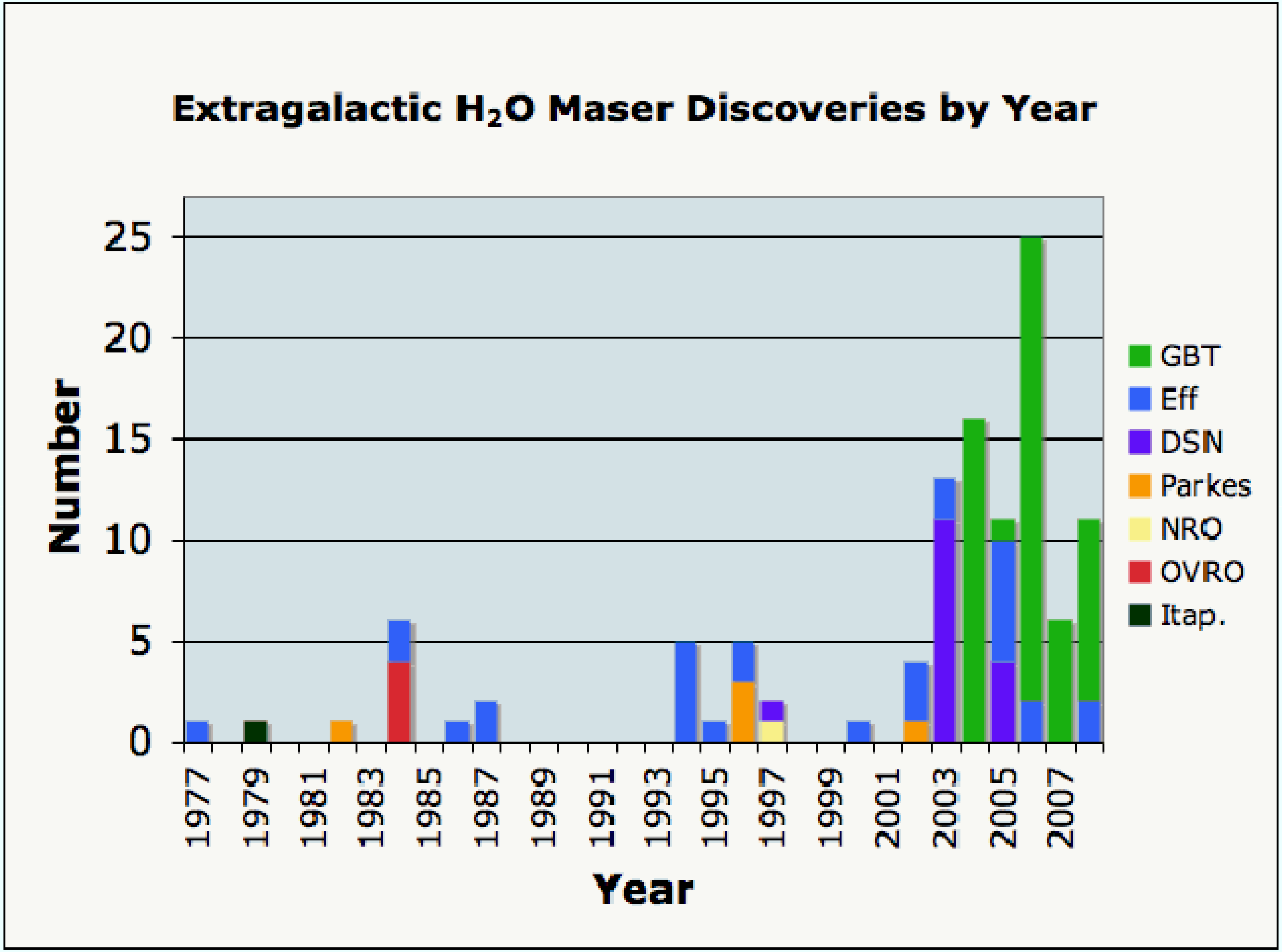


- One method covers all scales out to the size of largest structures
- Maser distances can be used to calibrate other distance methods e.g. Cepheids, SN Ia, Tully-Fisher

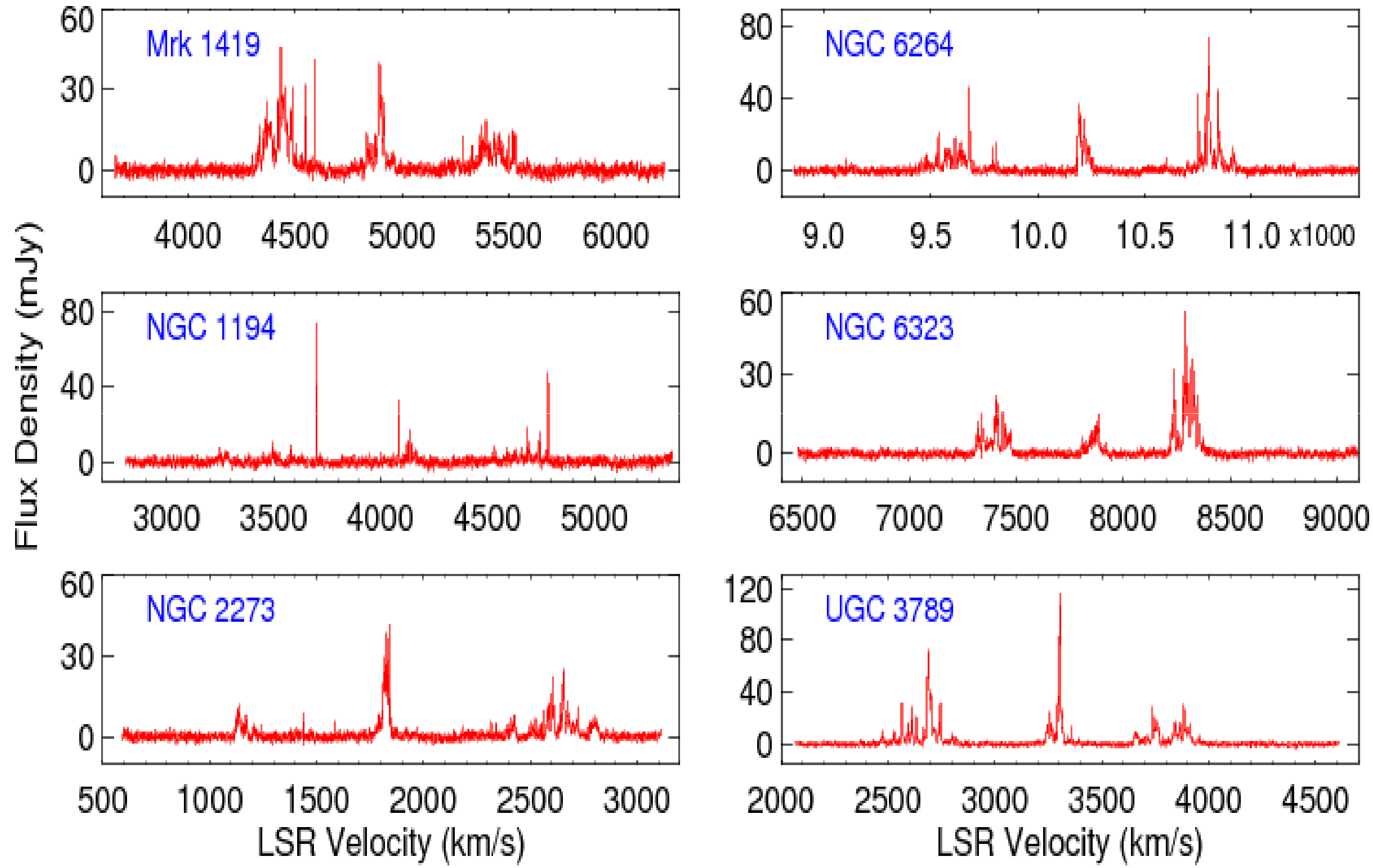
Megamaser Cosmology Project goals:

- Detect $N > 10$ suitable H_2O megamasers (strong enough for VLBA+GBT, in edge-on disks) at distances $D \sim 100$ Mpc (in Hubble flow) around the sky and measure their recession speeds
- Measure their geometric distances to ~10% each via acceleration, mapping, and proper motion. Correct for known velocity fields to determine the average H_0 within 3%, assuming random errors.

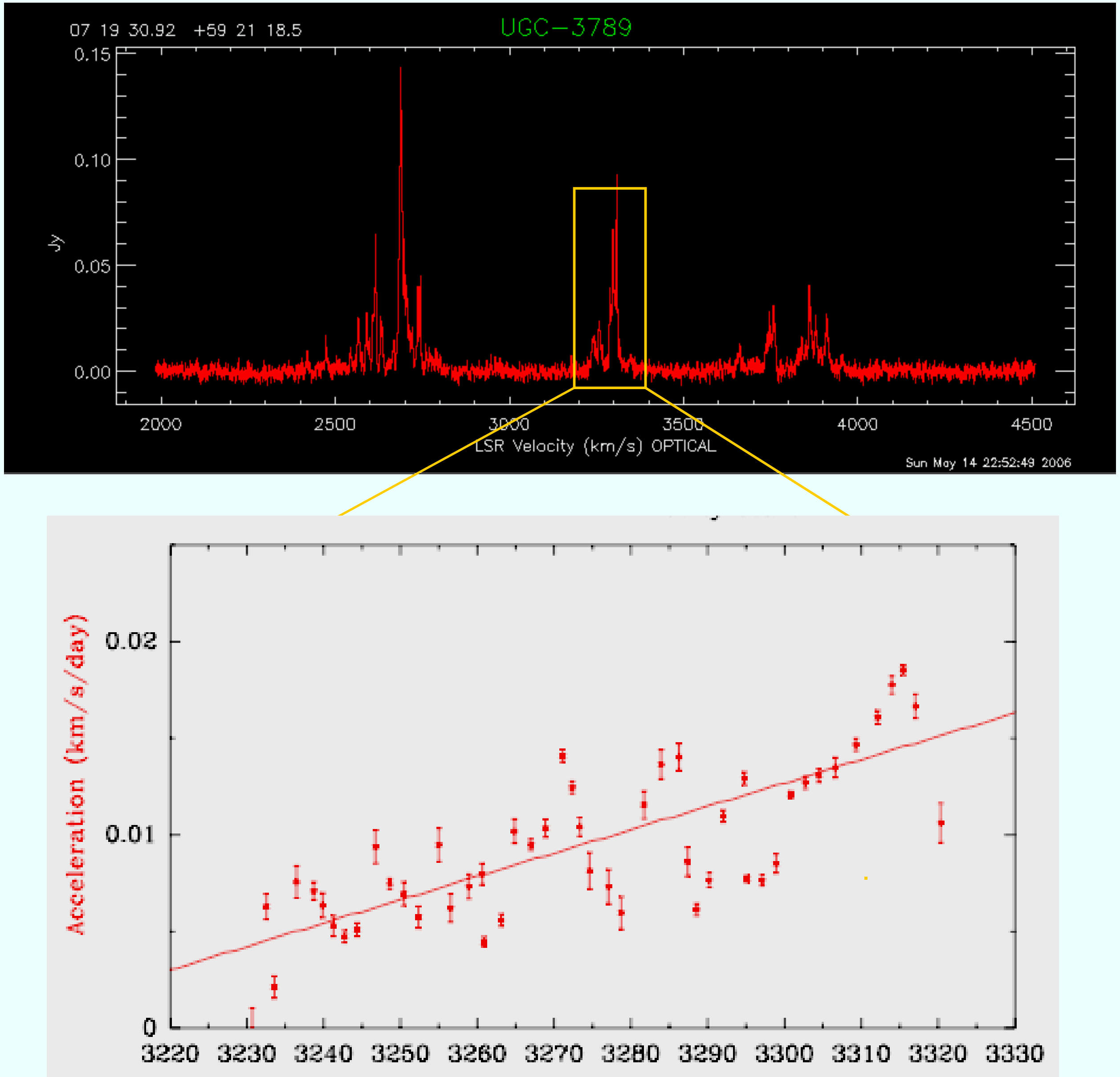
Step 1: Detections and velocities


Extragalactic H_2O Maser Discoveries by Year
Number
0
5
10
15
20
25
Year
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
GBT
Eff
DSN
Parkes
NRO
OVRO
Itap.

GBT Spectra of Some Maser Disks



Step 2: Measure Accelerations



V (km/s)

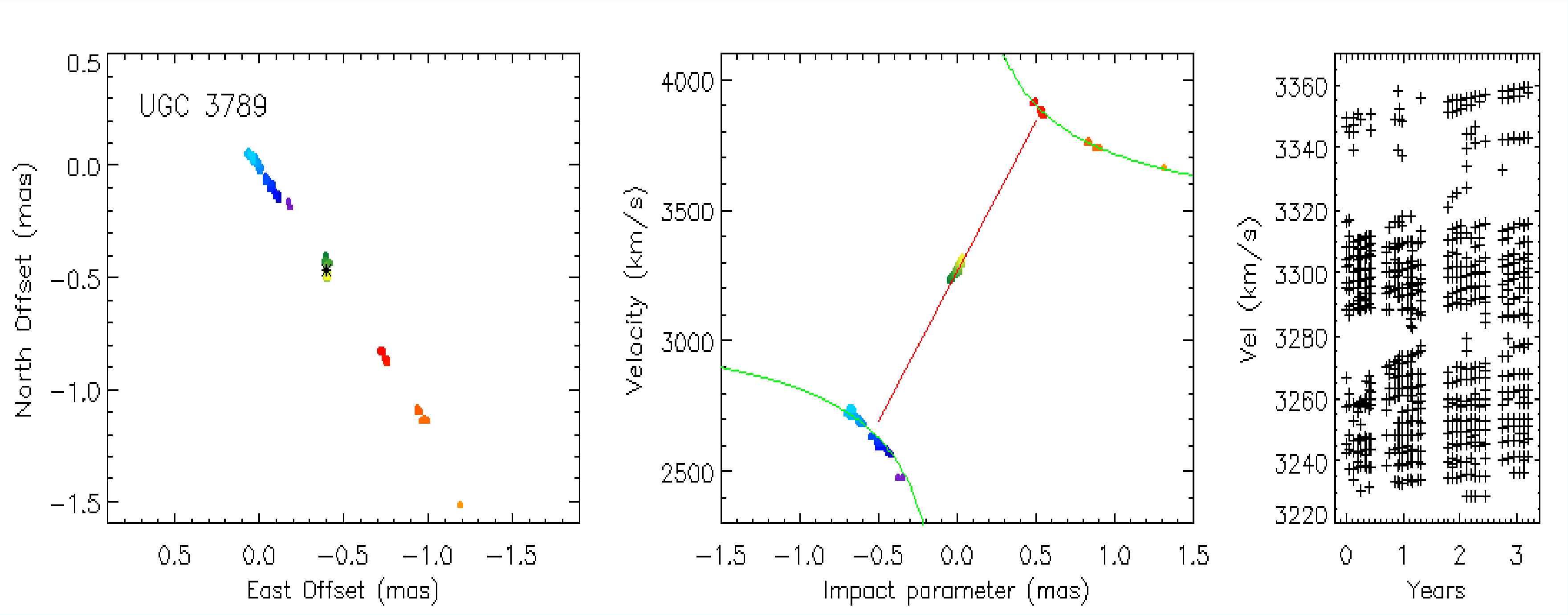
Step 3: Imaging GBT + VLBA

The GBT lets us:

Image fainter (more distant) H_2O masers

Use fainter (closer on the sky) continuum phase calibrators or even line self-calibration (NGC 1194 S > 500 mJy during flares)

UGC 3789 Results



R ~ 0.09 - 0.20 pc (0.40 - 0.87 mas)
V ~ 750 - 450 km/s
M_{bh} ~ 1.2 x 10^7 M_{sun}
a ~ 3.6 km s^{-1} yr^{-1} (mean value)

D ~ 50 Mpc ± 13%
H_0 ~ 71 ± 10 km s^{-1} Mpc^{-1}

Supermassive black hole?

Or dense "star" cluster?

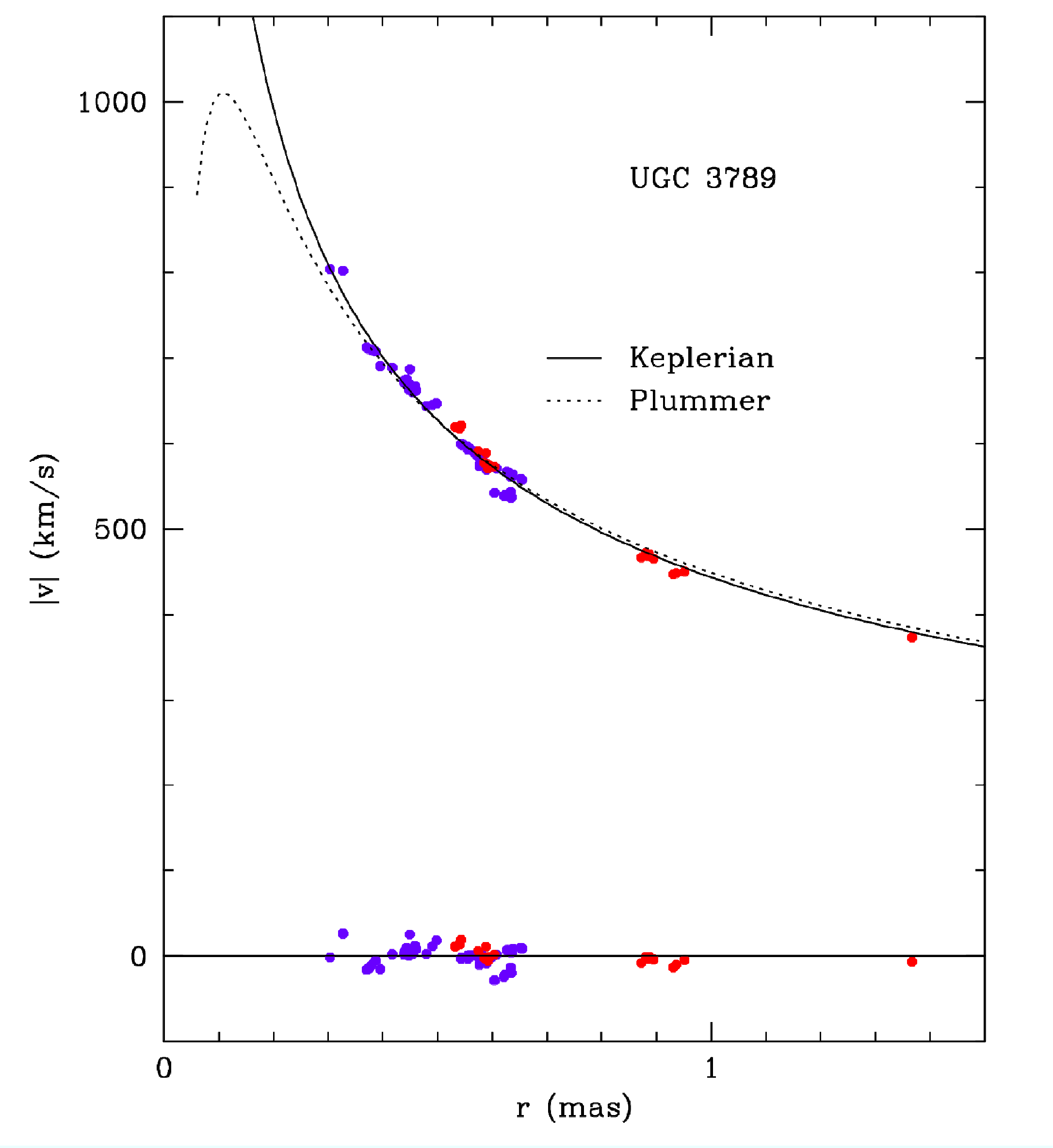
Plummer distribution:

$\rho(r) = \rho_0\ (1 + r^2/\ c^2)^{-5/2}$

1. Evaporation if N small
2. Collisions if N large

$\rho_0 > 4\ X\ 10^{11}\ M_{sun}/pc^3$

$m_* < 0.08\ M_{sun}\quad N > 10^8$



Direct measurements of SMBH masses

Galaxy	**Radius (pc)**	**M_{bh} (M_{sun})**
Mrk 1419	0.05 – 0.30	7.5×10^6
NGC 1194	0.58 – 1.41	6.6×10^7
NGC 2273	0.03 – 0.08	7.6×10^6
NGC 6264	0.23 – 0.78	2.5×10^7
NGC 6323	0.11 – 0.29	1.0×10^7
UGC 3789	0.08 – 0.30	1.1×10^7

Summary

- An accurate (< 3%) measurement of H_0 independent of the CMB and other techniques (e.g. distance ladder) is critical for characterizing dark energy, testing the flat ΛCDM model, and fixing fundamental cosmological parameters (e.g. deriving Ω_m from the CMB observed $\Omega_m h^2$).
- Recent observations of megamaser disks support the feasibility of using the GBT and VBLA to measure H_0 directly.
- Accurate masses of SMBHs

Summary

- An accurate (< 3%) measurement of H_0 independent of the CMB and other techniques (e.g. distance ladder) is critical for characterizing dark energy, confirming the flat ΛCDM model, and fixing other cosmological parameters (e.g. deriving Ω_m from the observed $\Omega_m h^2$).

- Recent observations of megamaser disks support the feasibility of using the GBT and VBLA to measure H_0 directly.