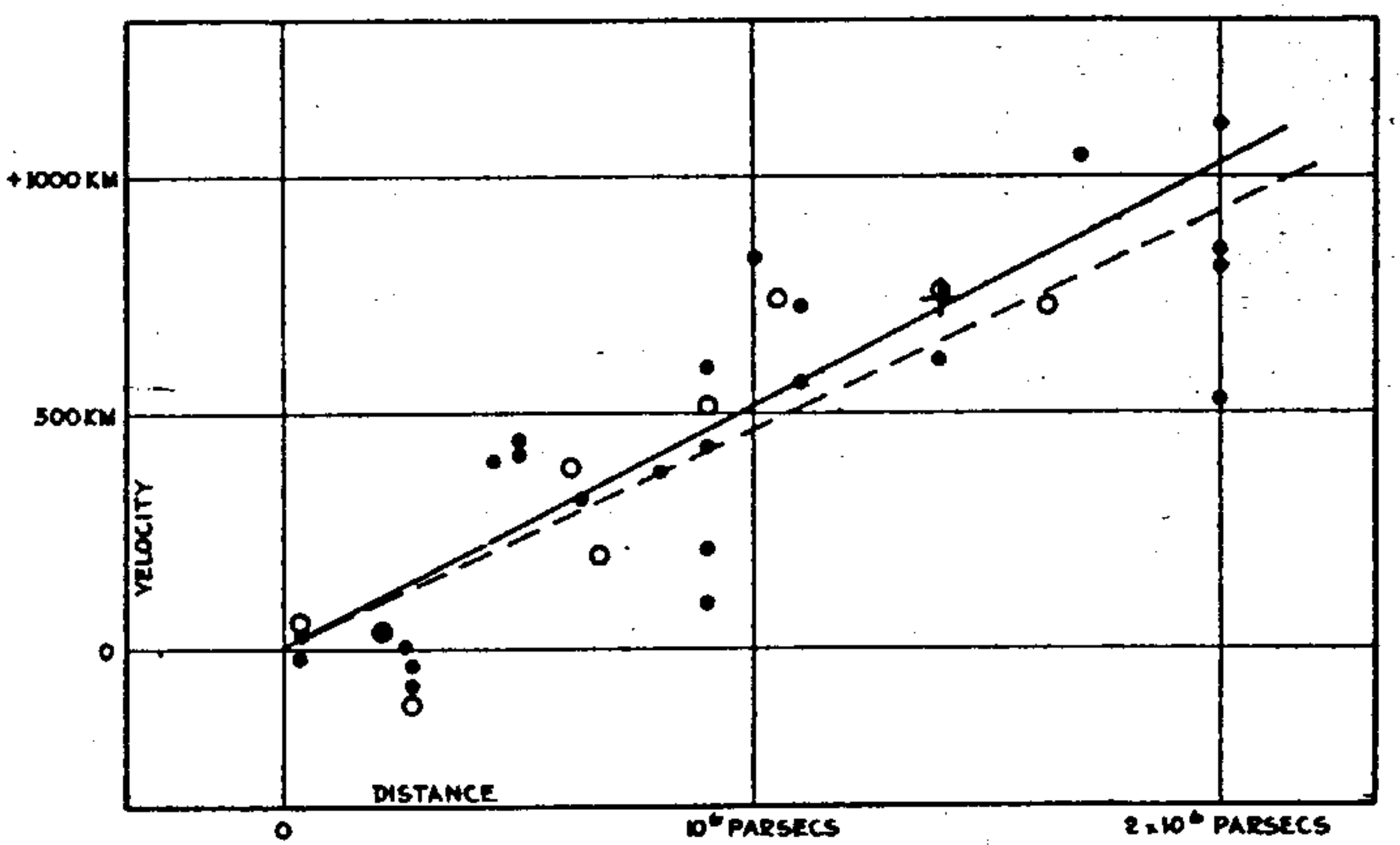

FIGURE 1

Measuring the Hubble constant with GWs

Daniel Holz

The University of Chicago

H_0 is not important

- Just one number
- Gives us the age/size of the Universe. So what?
- Local, $z=0$ measurement, so has nothing to do with dark energy

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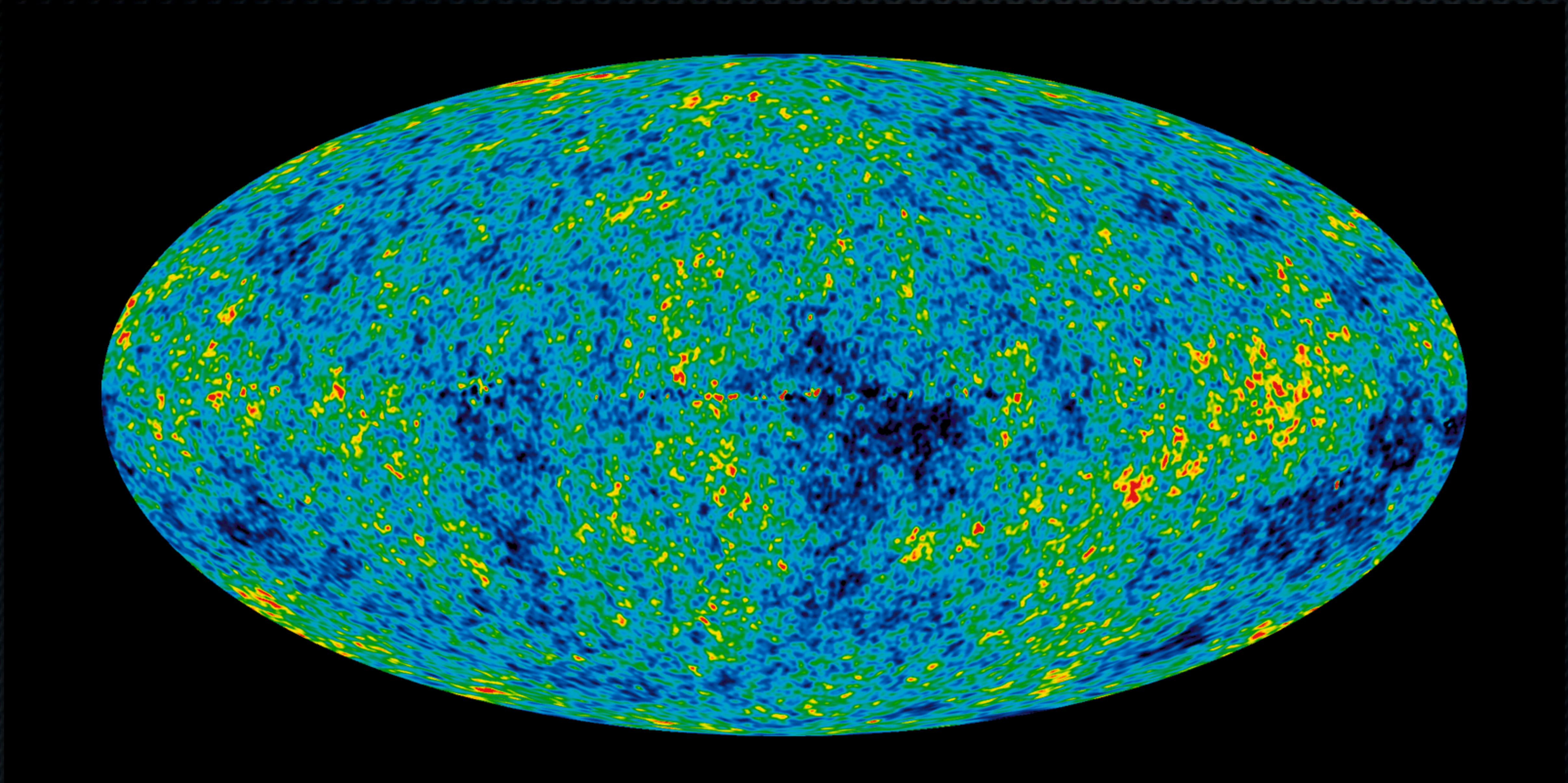
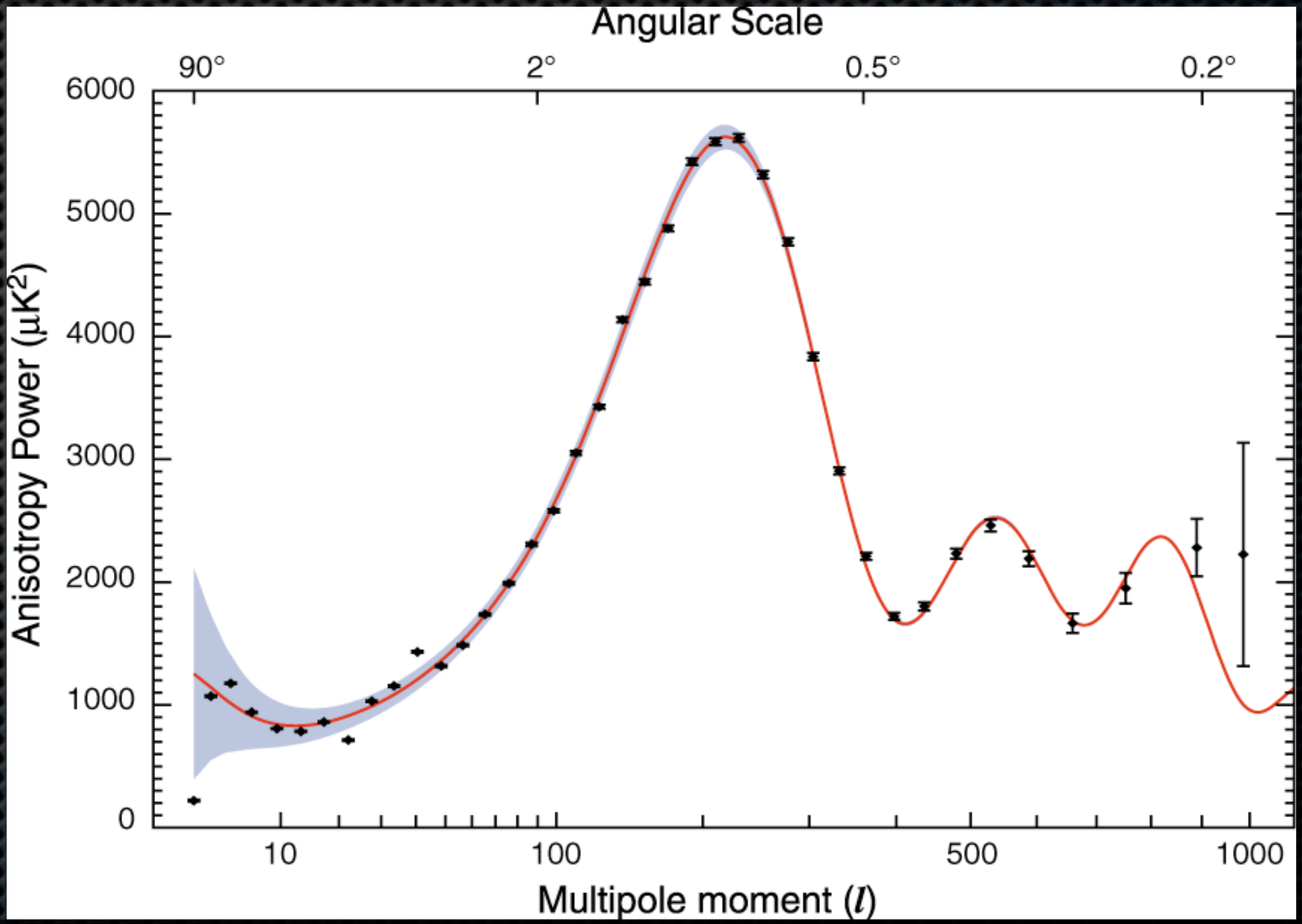


Measuring *H0* is important!

Key point: we have exquisite precision cosmological constraints from the CMB

CMB is good

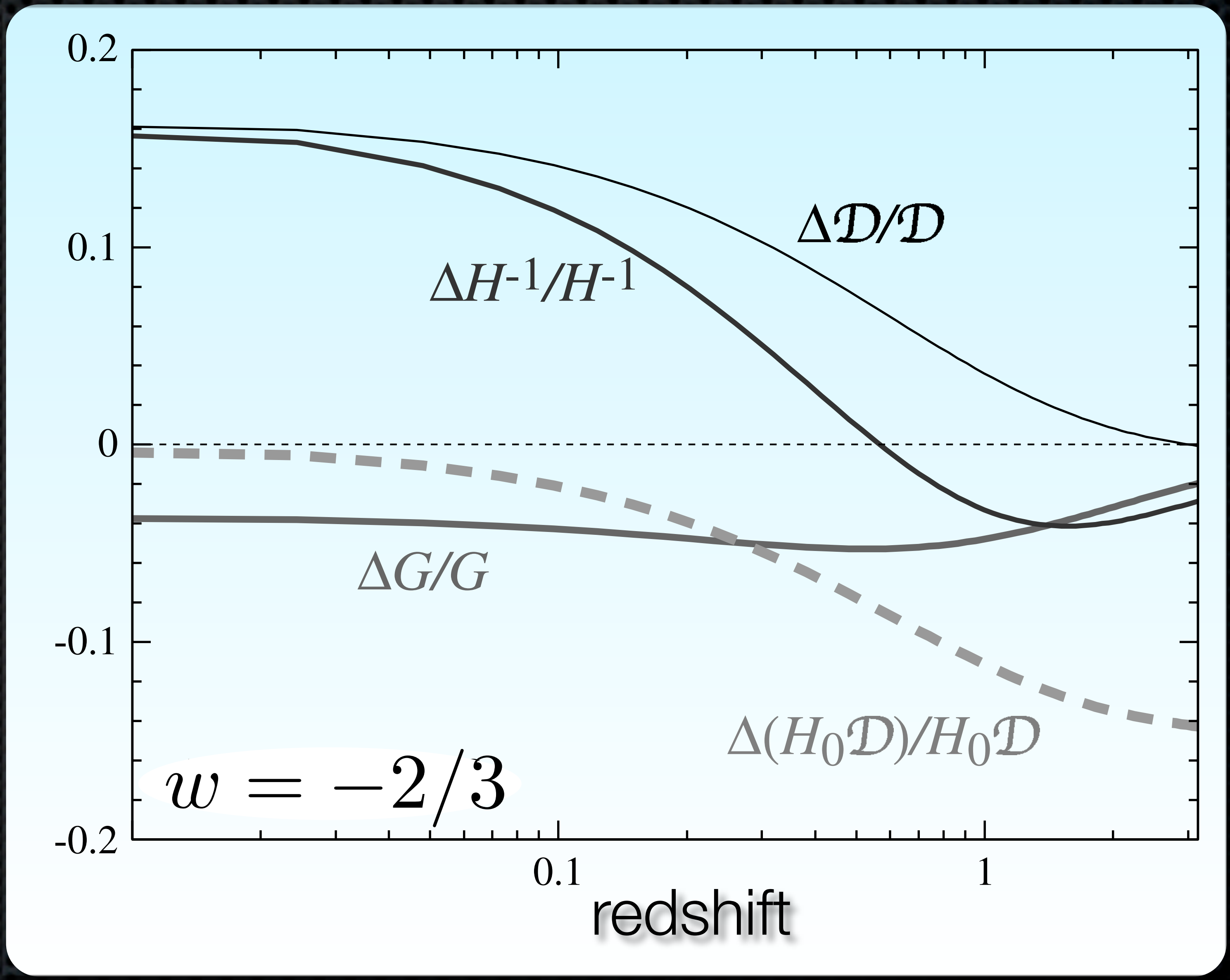
- CMB at $z=1100$
  - standard ruler: sound horizon at recombination
  - standard fluctuation: initial amplitude of fluctuations at $k=0.05\ Mpc^{-1}$



CMB+H_0 is great

Hu 2005
Suyu et al. 2012

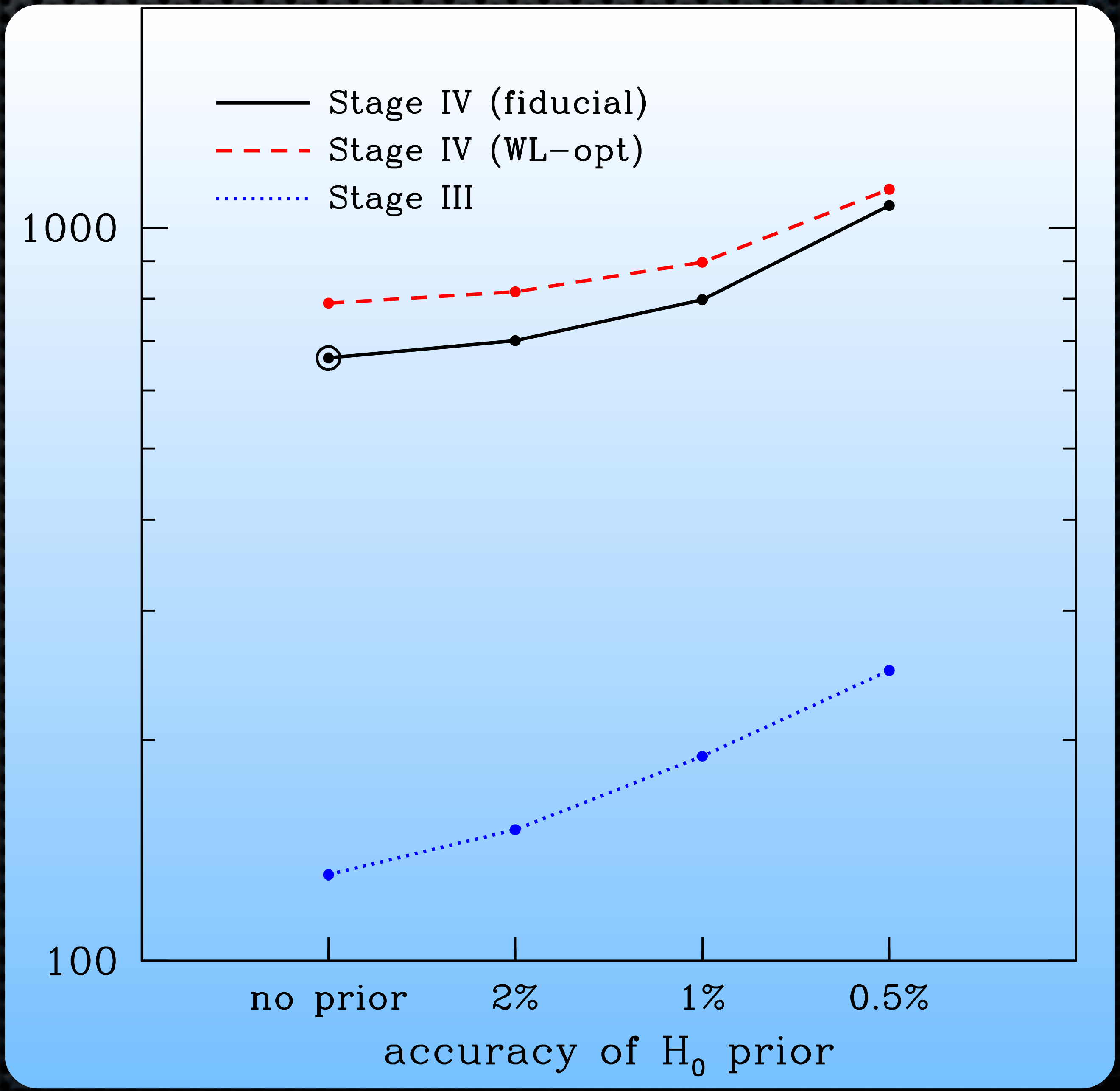
- CMB at $z=1100$
  - standard ruler: sound horizon at recombination
- H_0 at $z=0$
  - tremendous lever arm



In light of CMB, constrain dark energy by measuring H_0

CMB+H_0 is great

- Dark energy figure-of-merit as a function of accuracy of H_0
- Hubble helps all other methods: >40% improvement in constraints
- Errors in CMB dominate when H_0 is known to ~0.5%



Weinberg et al. 2012

Goal: Falsify the cosmological constant

- All we need to do is show

$$w \neq -1$$

- Control of systematics is essential

So how well can we measure H_0?

- Cepheids/Masers
- Type Ia supernovae
- Baryon Acoustic Oscillations

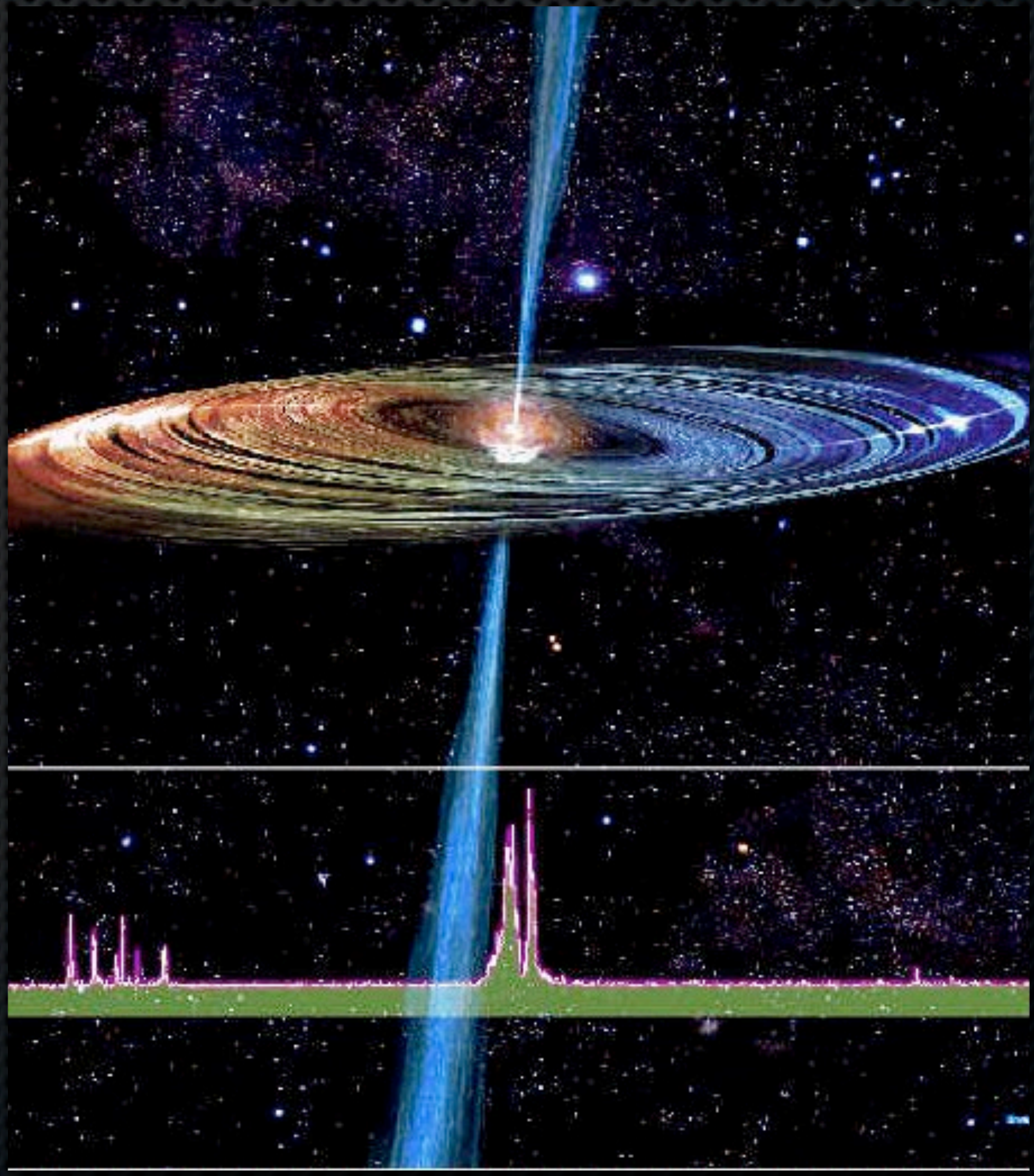
Cepheids

- Absolute calibration of distance ladder, using parallax of nearby ones
- The Hubble Space Telescope Key Project on the Extragalactic Distance Scale
- No revolutionary improvements in foreseeable future

$$H_0 = 72 \pm 8\,\mathrm{km/s/Mpc}$$

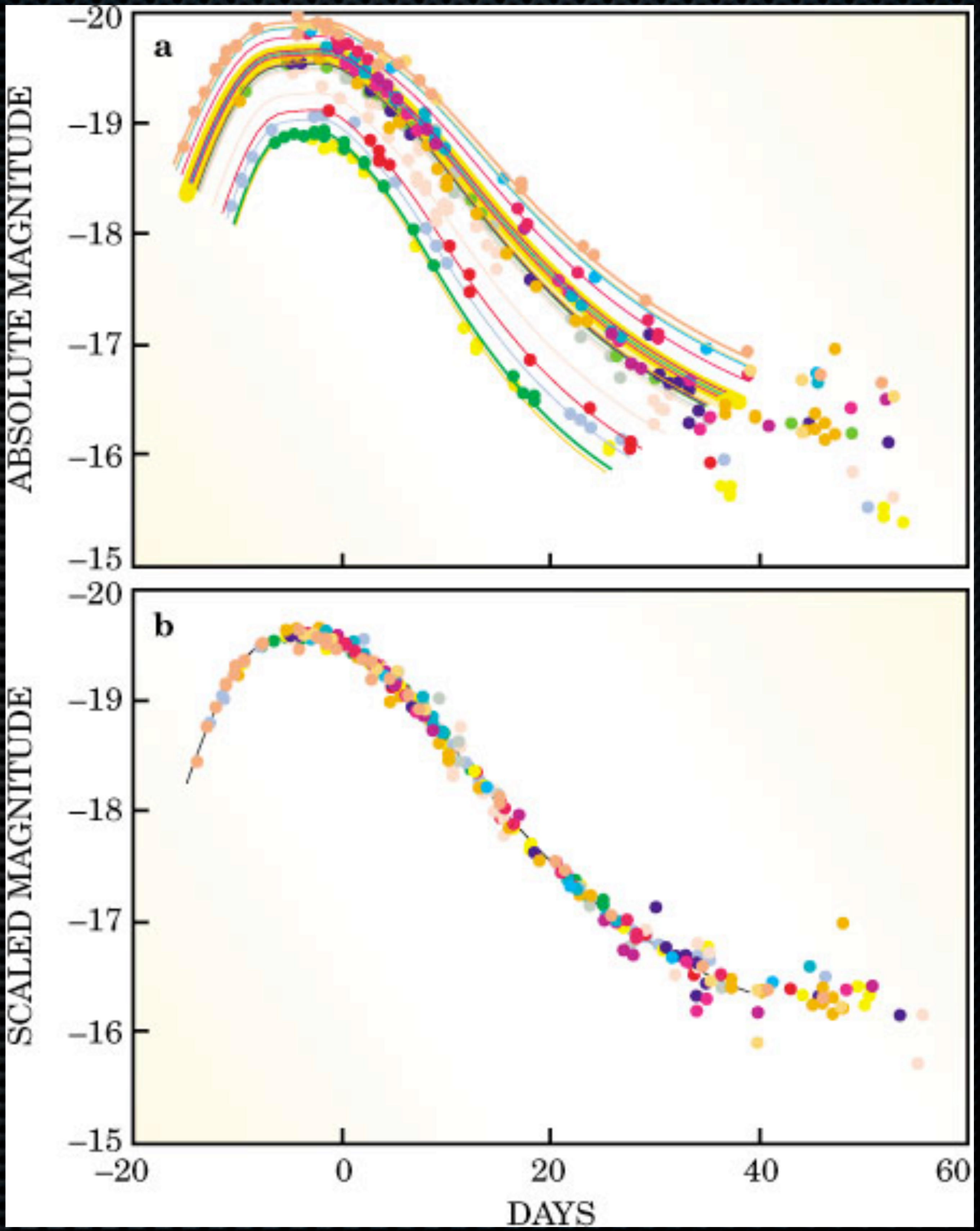
Water Masers

- Geometric measure of distance
- Approaching the Hubble flow
- Limited by local volume, so slow improvements



Type Ia supernovae

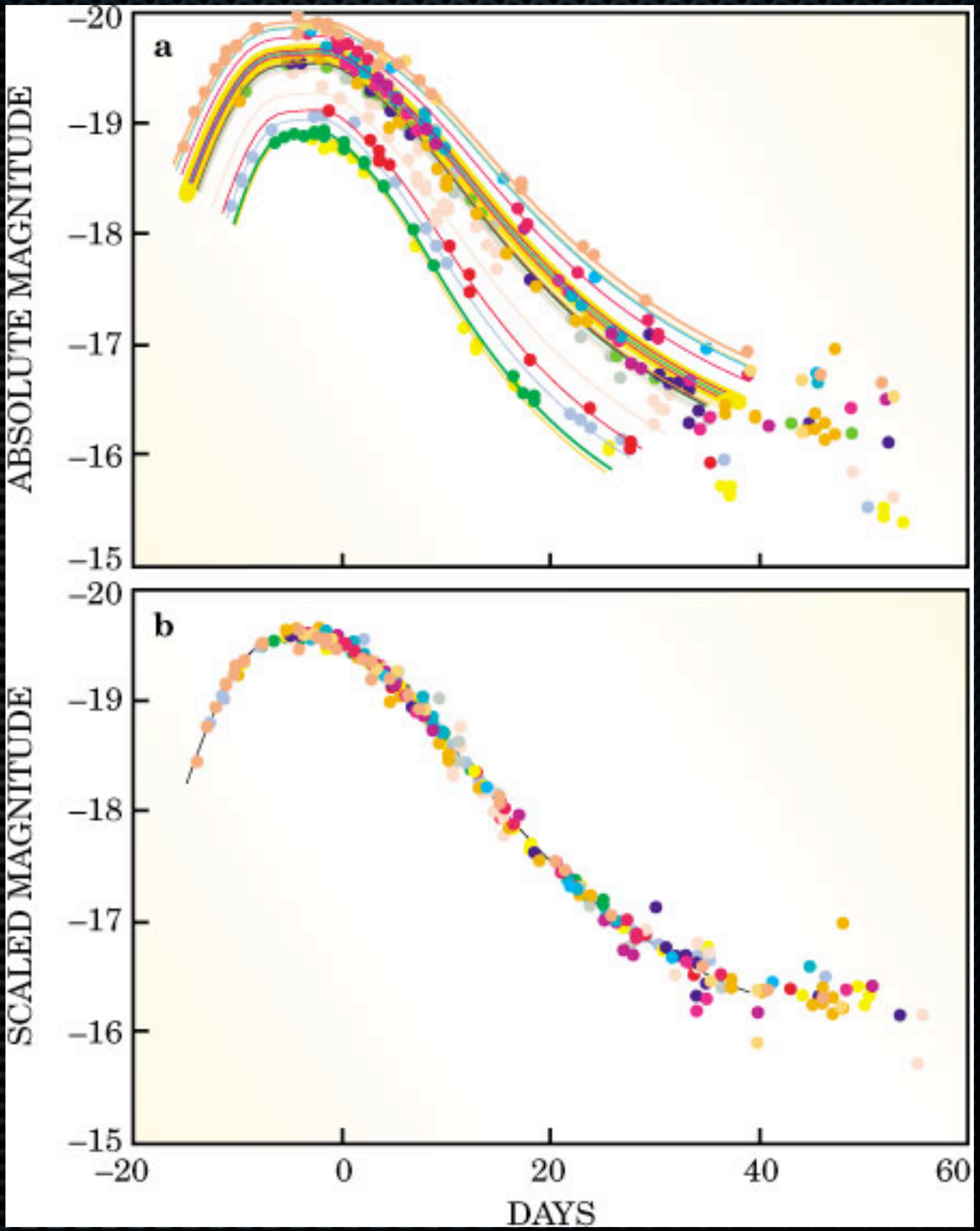
- Absolute distance calibrated by cepheids
- Phenomenological standard candle. No first-principles, physics understanding.
- Fantastic data, high statistics



$$H_0 = 73.8 \pm 2.4\,\mathrm{km/s/Mpc}$$

Type Ia supernovae

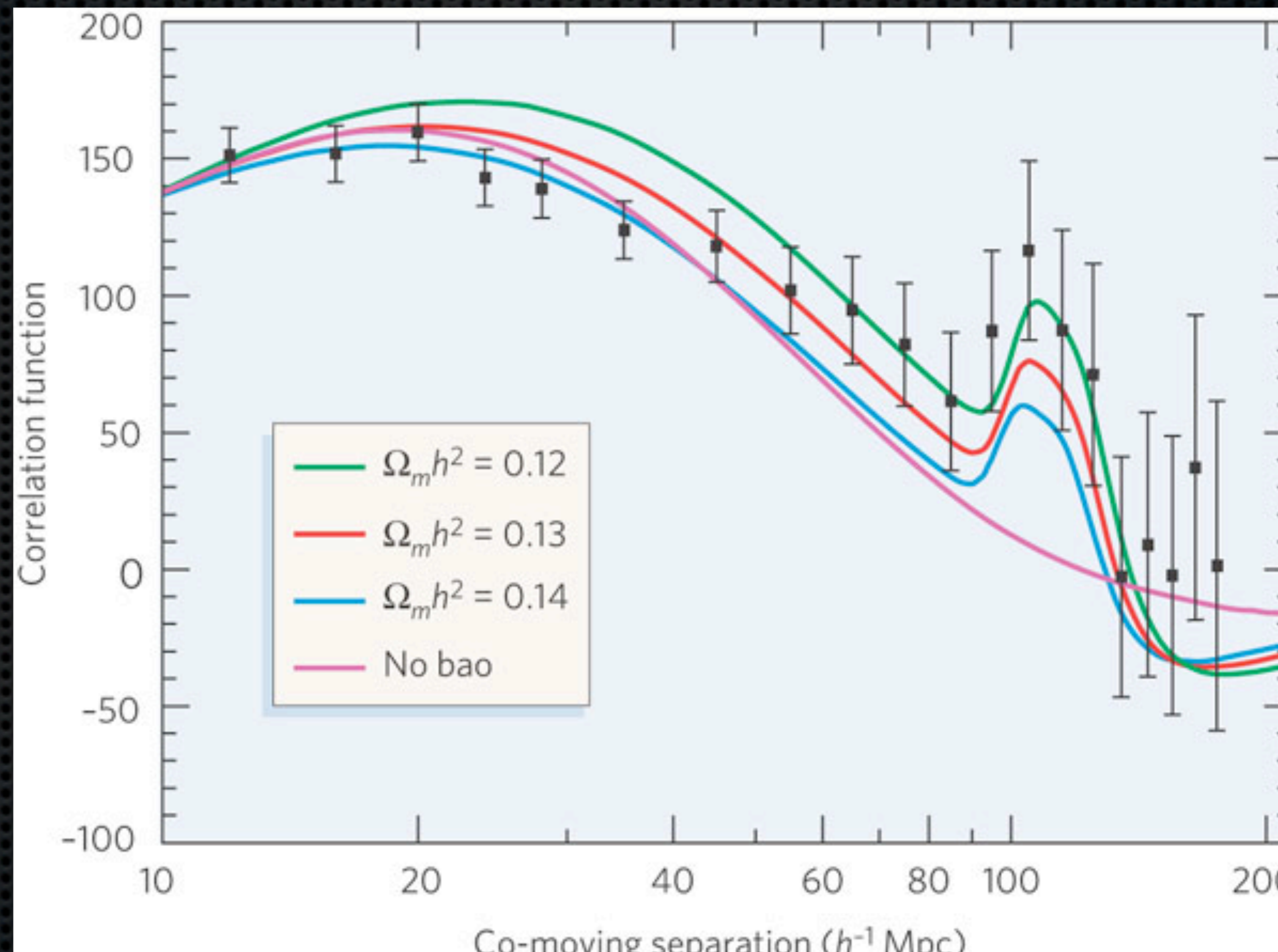
- Can you believe something you don't understand?
- Possible systematics include metallicity, different populations/ delay times, correlations with line widths



$$H_0 = 73.8 \pm 2.4\,\mathrm{km/s/Mpc}$$

Baryon acoustic oscillations

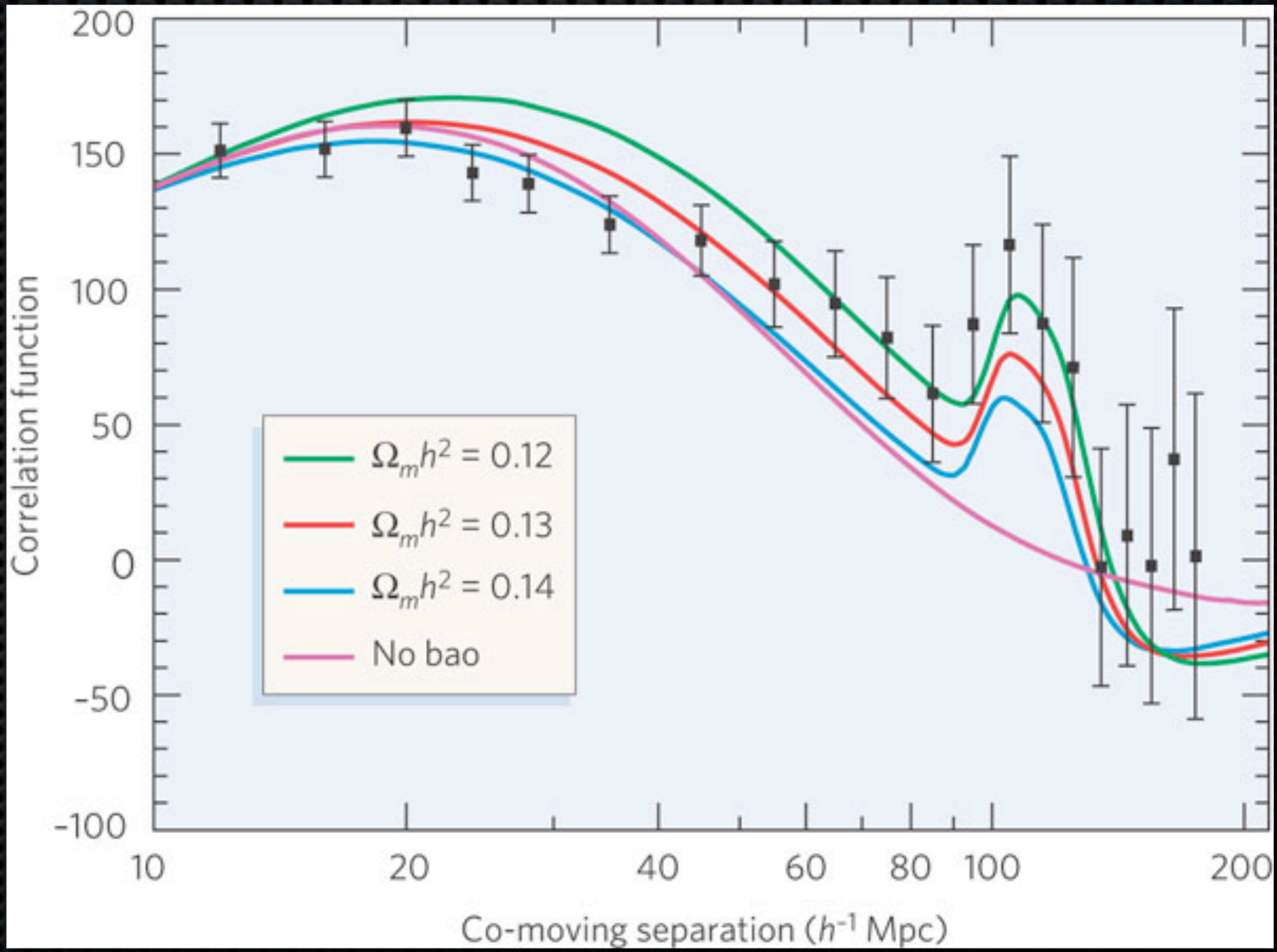
- Bump in CMB turns into bump in galaxy distribution: standard ruler (*150 Mpc*)
- Can calculate CMB bump very accurately. Can calculate galaxy bump almost as well. Physics is understood.



$$H_0 = 69.8 \pm 1.2\,\mathrm{km/s/Mpc}$$

Baryon acoustic oscillations

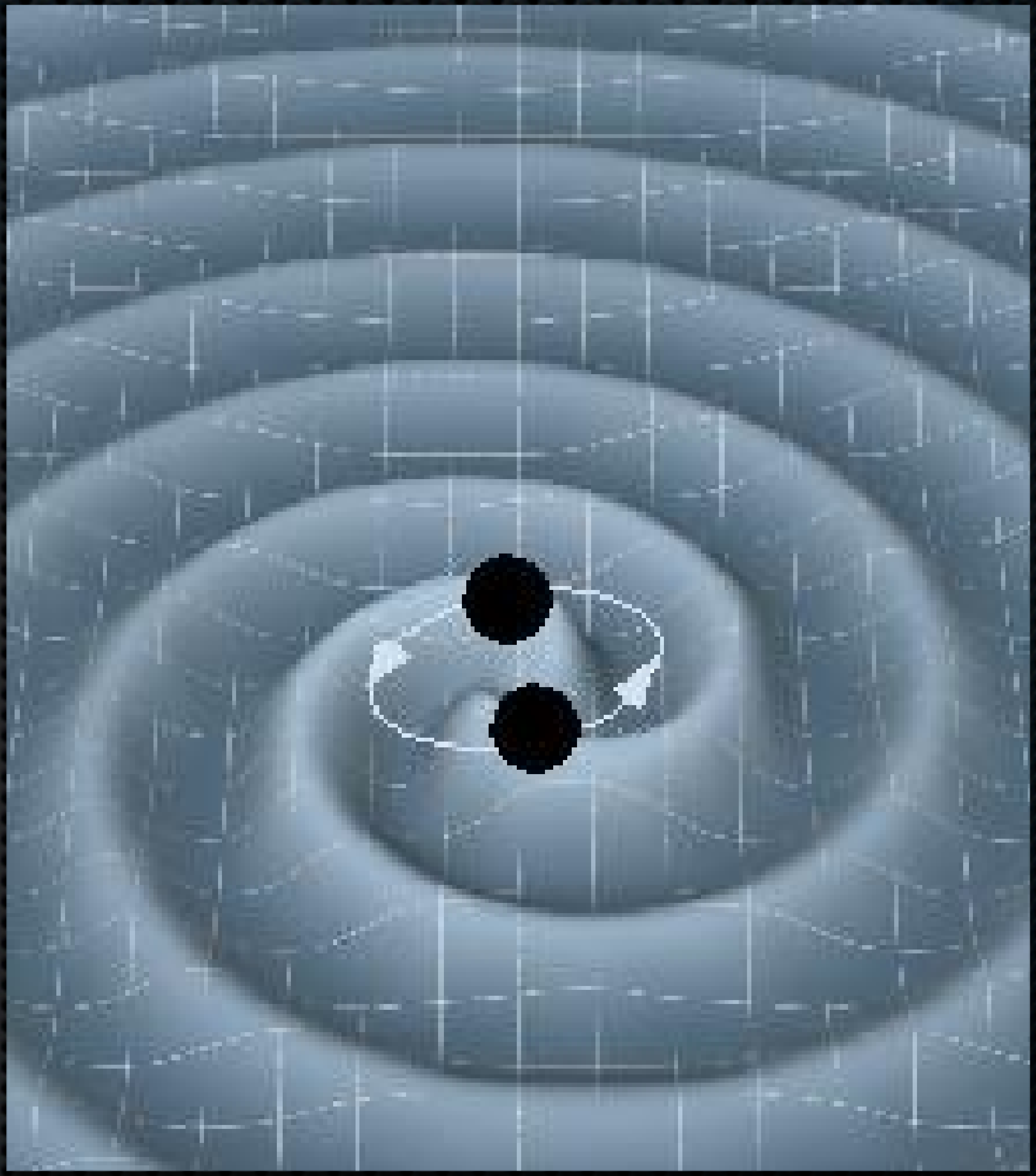
- Requires connecting dark matter and galaxies.
- Requires observing >million galaxies over large fields
- Cosmic variance at low z
- Peculiar velocity, bias, redshifts, etc.



$$H_0 = 69.8 \pm 1.2\,\mathrm{km/s/Mpc}$$

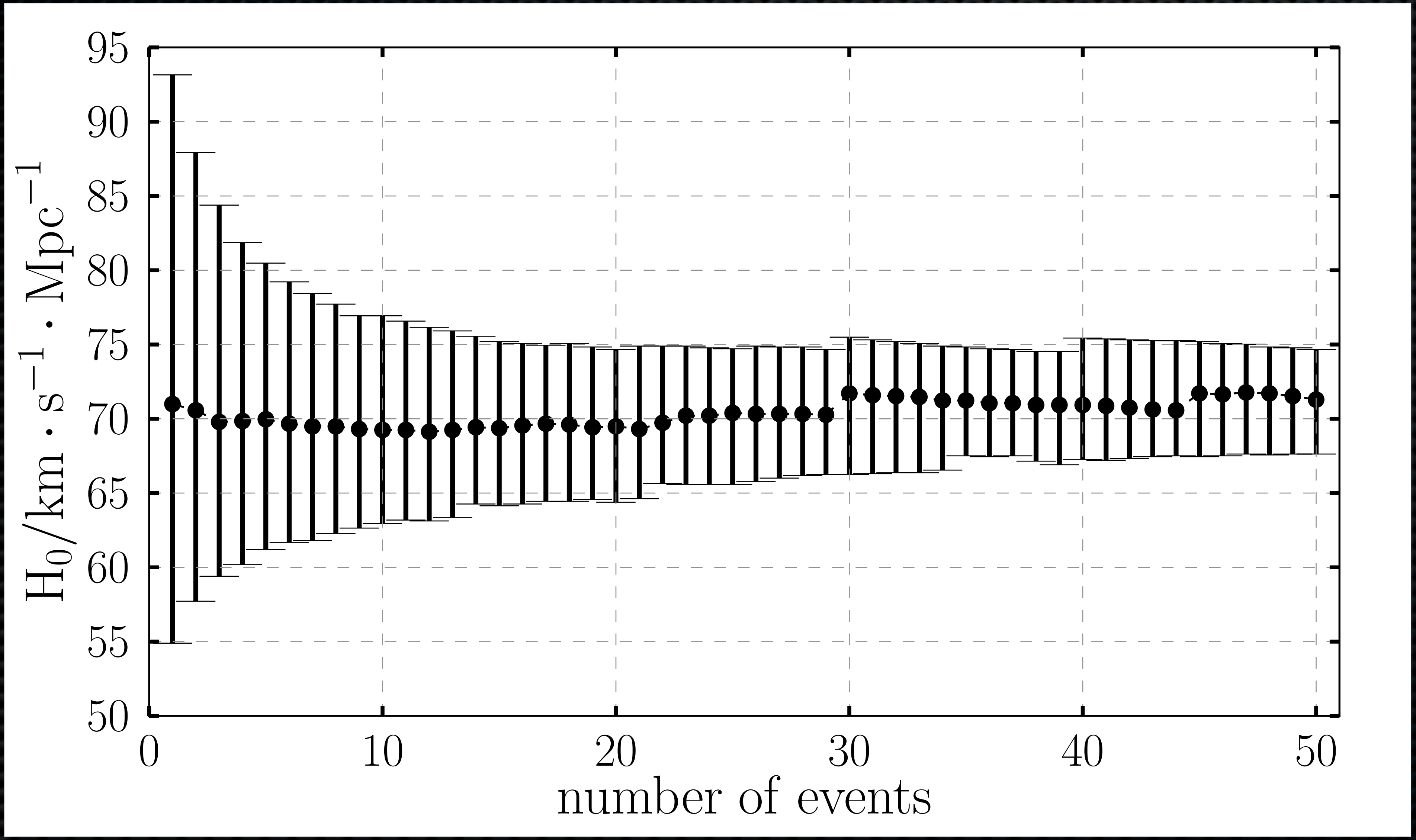
Standard sirens

- Black holes are “simple”
- Physics is understood
- Black hole inspiral is well modeled
- Distance, but NOT redshift
  - need an EM counterpart



Schutz 1986, Nature
DH & Hughes 2005, ApJ
Dalal, DH, Hughes, & Jain 2006, PRD
Cutler and DH 2009, PRD
Nissanke et al. 2010, ApJ

Statistical standard sirens

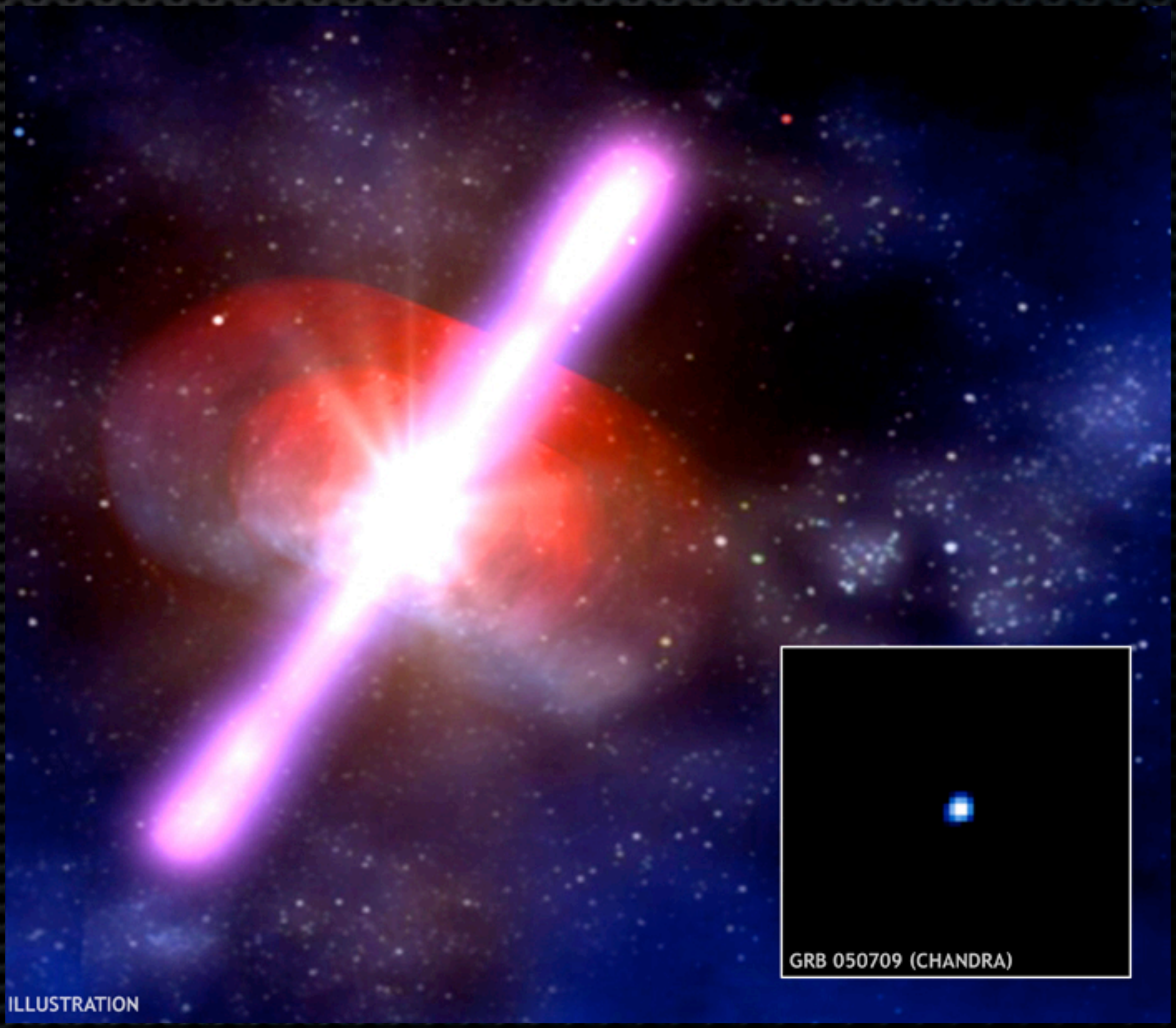


- Statistically matching possible host galaxies
- Converges for sufficient numbers of sirens

Schutz, 1986
Del Pozzo, 2012

Gamma-ray Burst Standard Sirens

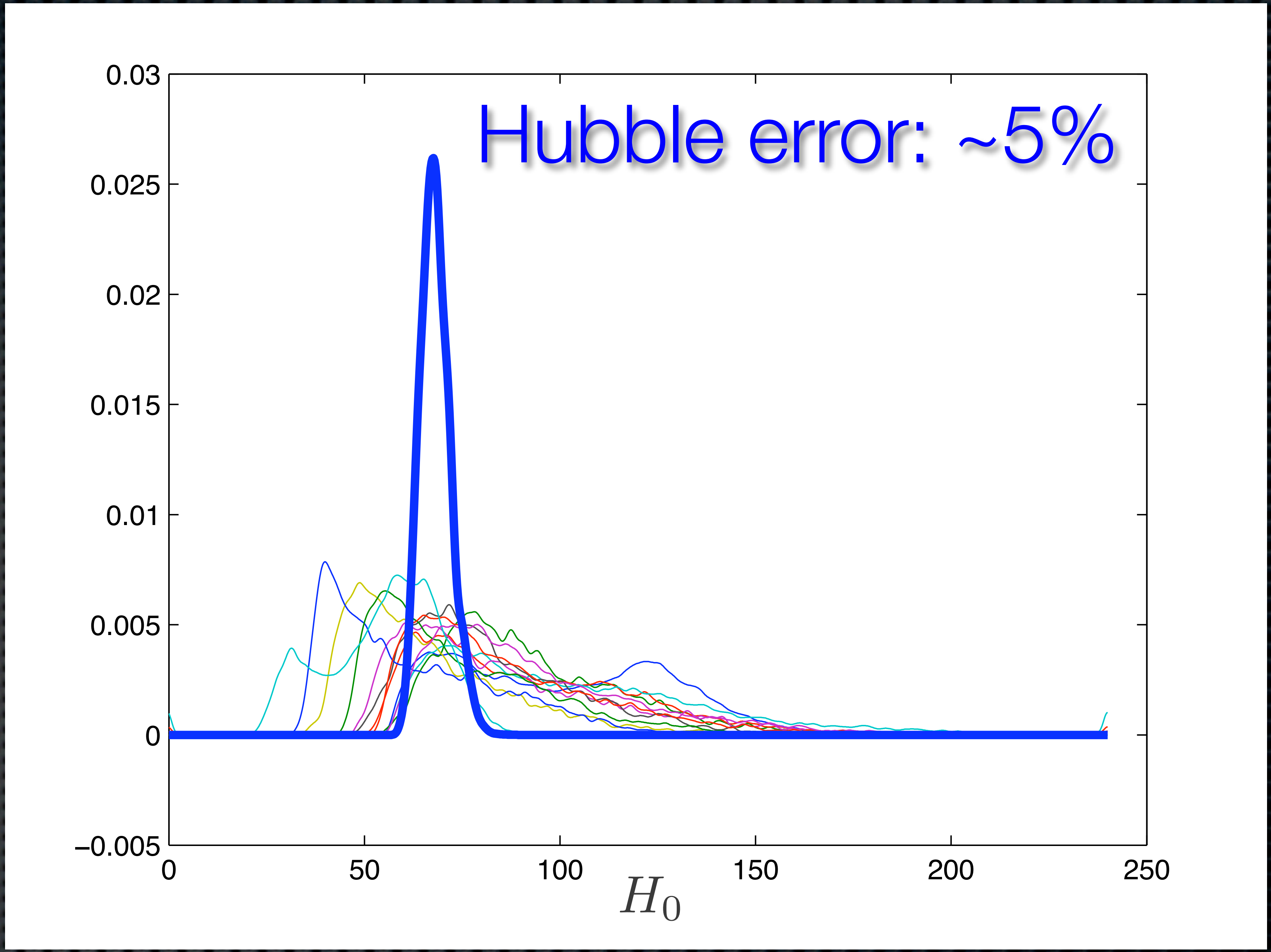
- Short GRBs are known to occur at low redshift ($z < 0.2$)
- Short GRBs are thought to be the result of binary mergers (NS or BH)
- Will be seen by aLIGO. Perfect standard siren!



Systematic “free”, absolute distance

LIGO measurement of Hubble

LIGO+VIRGO
NS/NS binary
15 GRBs
unbeamed



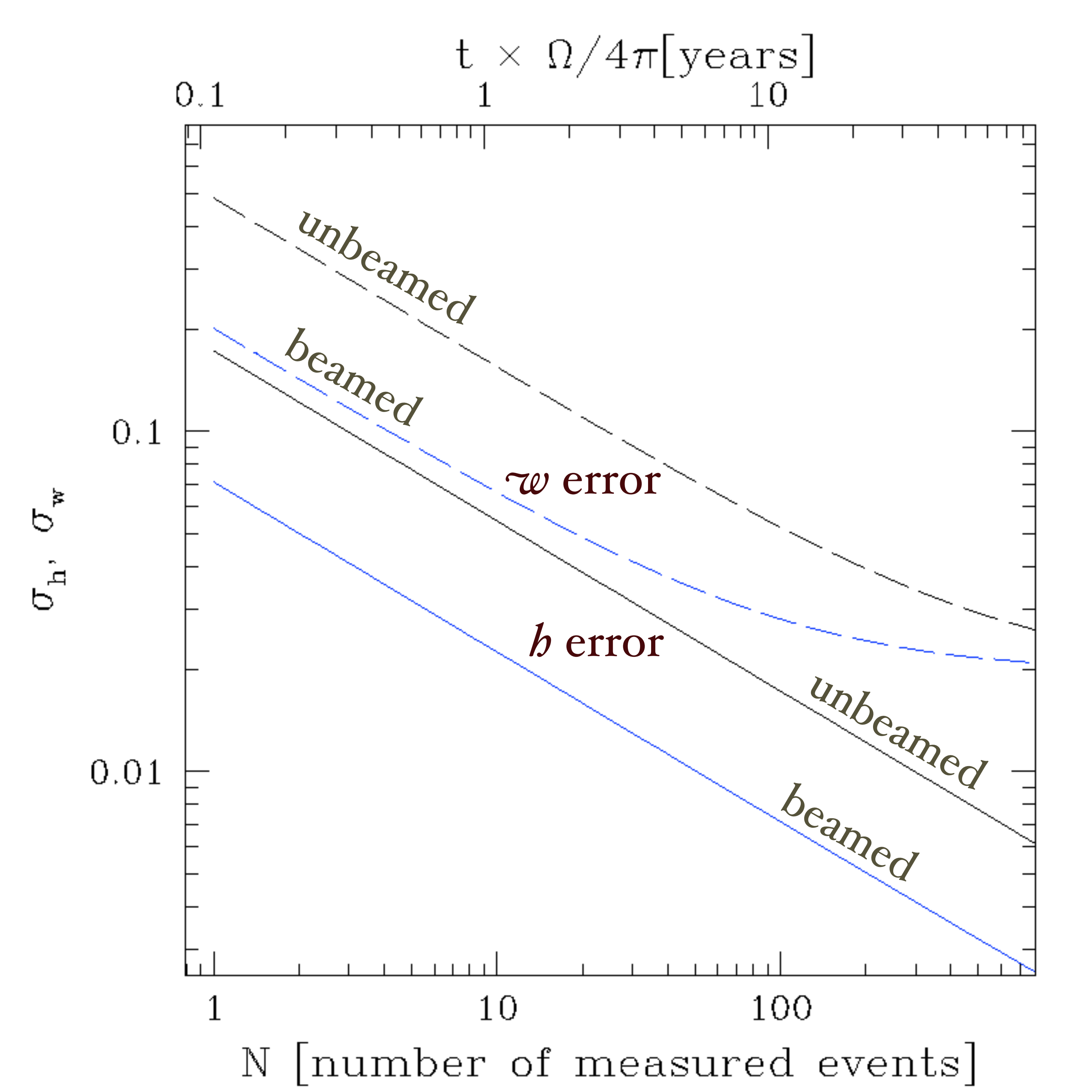
add IndIGO+KAGRA: factor ~2
if GRBs are beamed: factor >2
NS-NS⇒NS-BH: factor ~4

Nissanke et al., in prep

Measurement of dark energy

- Short GRB rate: $10\,\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$
- *PLANCK* CMB priors
- 4 aLIGO detectors

10% measure of dark energy parameters



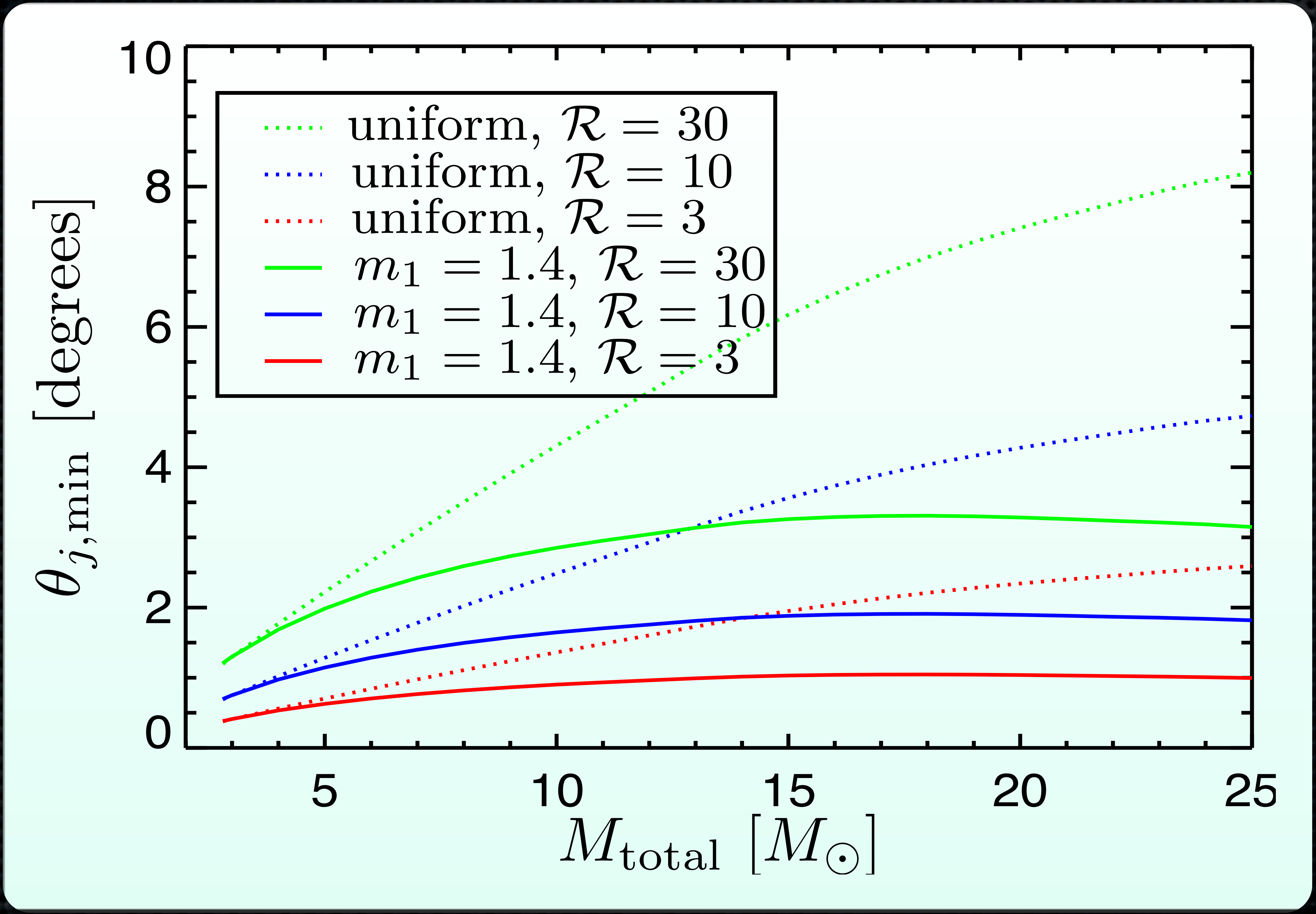
Dalal, DH, Hughes, & Jain 2006, PRD

GRB beaming and GWs

- Assume short GRBs are binary systems
  - no supernova
  - far from center of host galaxy
  - not associated with star formation
- Assume the *observed* rate of short GRBs is $10\,\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$

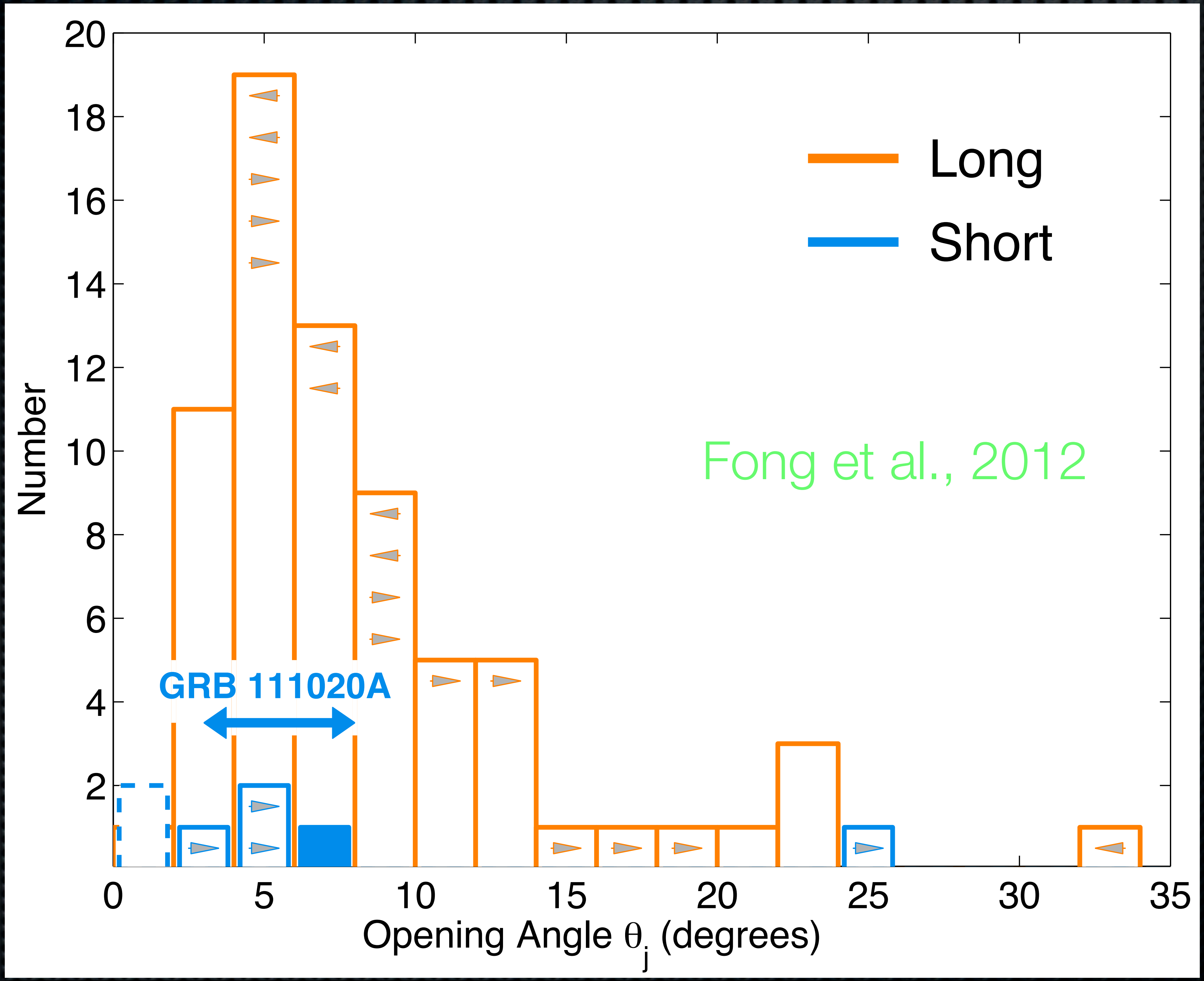
Chen & DH, 2012

GRB beaming and GWs



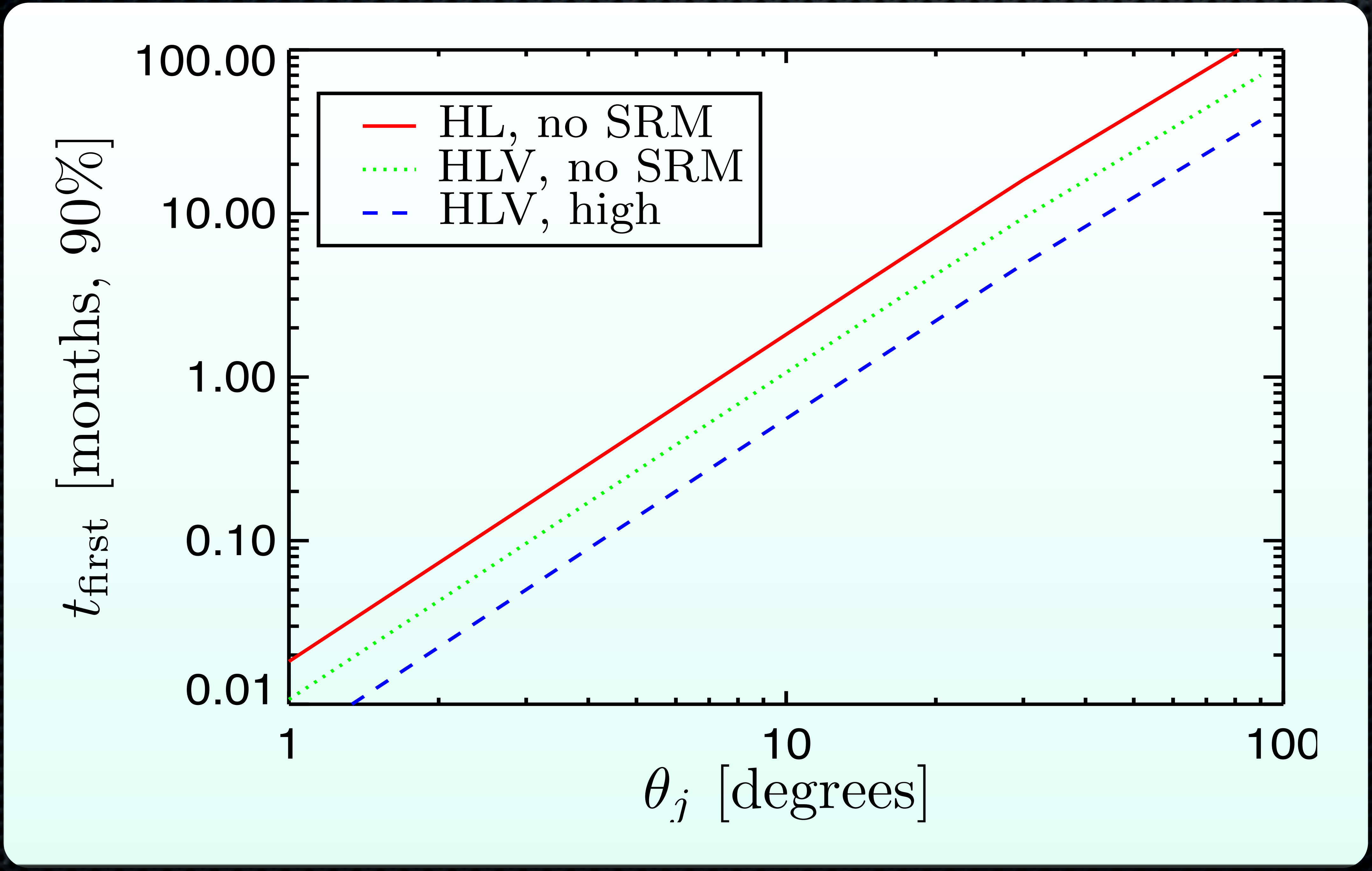
- LIGO S6/V2 didn't see any binaries: constrains beaming

Short GRBs are beamed



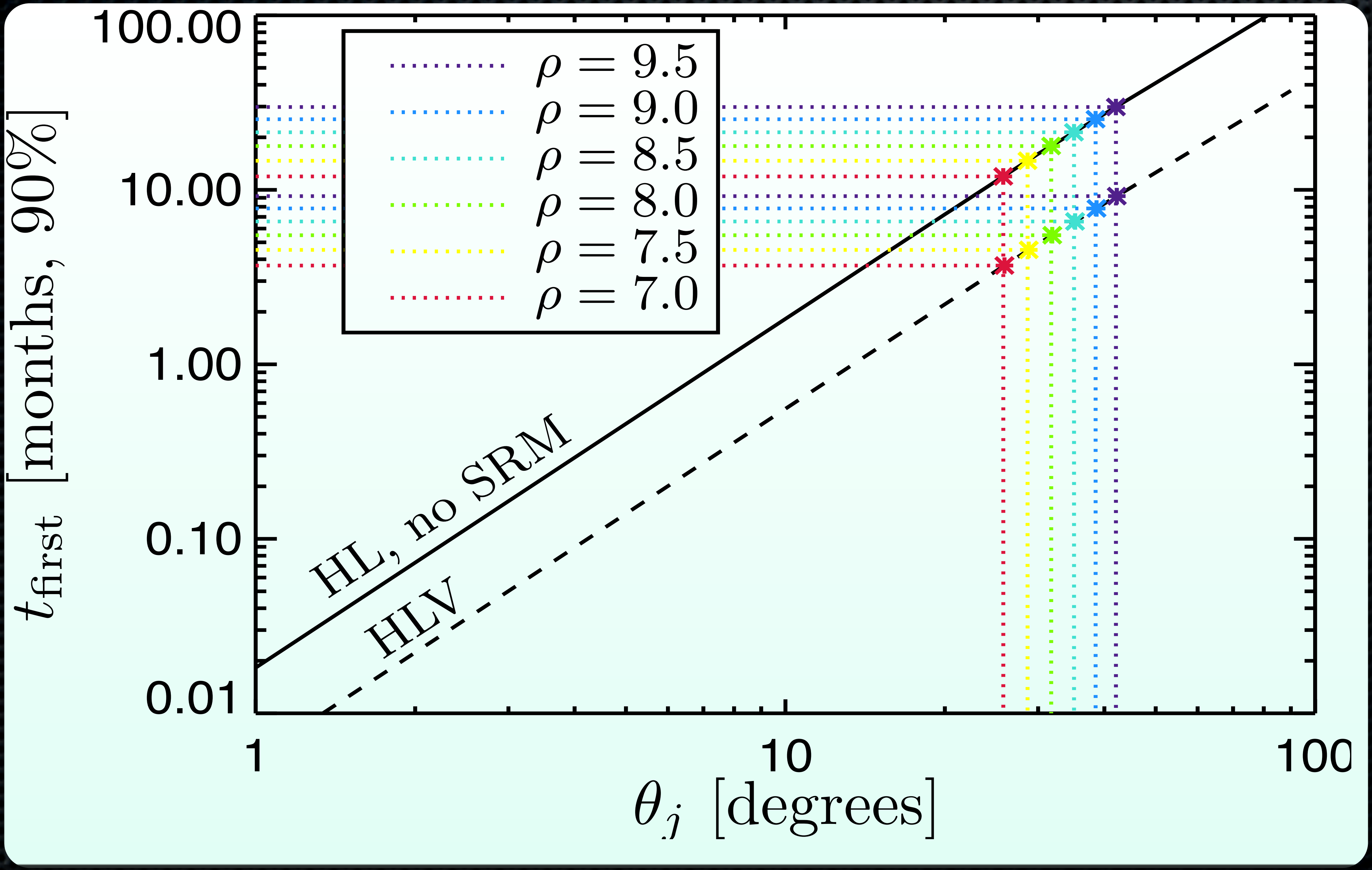
- GRB051221A: $\theta_j \sim 7°$
- GRB111020A: $\theta_j \sim 3$–$8°$

aLIGO will see short GRBs



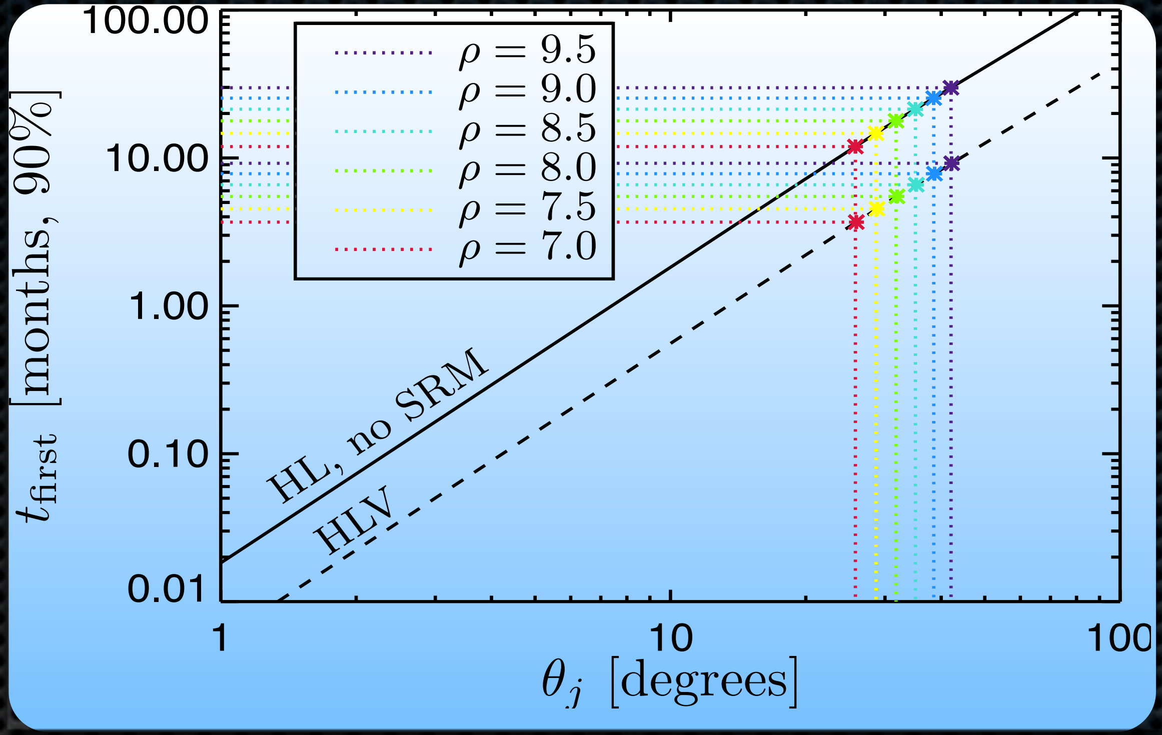
- First binary within ~1 year for HL, ~1 month for HLV

Untriggered before triggered



- If $\theta_j \lesssim 30^\circ$ we will see untriggered binary progenitors before we see GRB triggered bursts

Summary



- Measuring H_0 to percent level is important
- GW standard sirens offer a uniquely clean and powerful way to measure H_0
- Short GRBs are ideal standard sirens for aLIGO
- Based only on GRB observations, aLIGO will see ~6/year (at 30º) and ~50/year (at 10º)
- With 50 events, aLIGO measure H_0 to ~3%, w to ~10%