

Fact & Fiction in Cosmology

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26 Jan 2005

Outline

- Misconceptions we shouldn't teach our students.
- Misconceptions we shouldn't tell the DoE and NASA.

Fact: Gravity Rules

- Gravity is a long-range, always attractive^[1] force, and dominates the Universe at large scales.
- Newton's law for gravity is $F = -GMm/d^2$.
 - or $g = -GM/d^2$ independent of the nature of the mass “m”.
- Need to know the DISTANCE “d” in order to have an inverse square law.

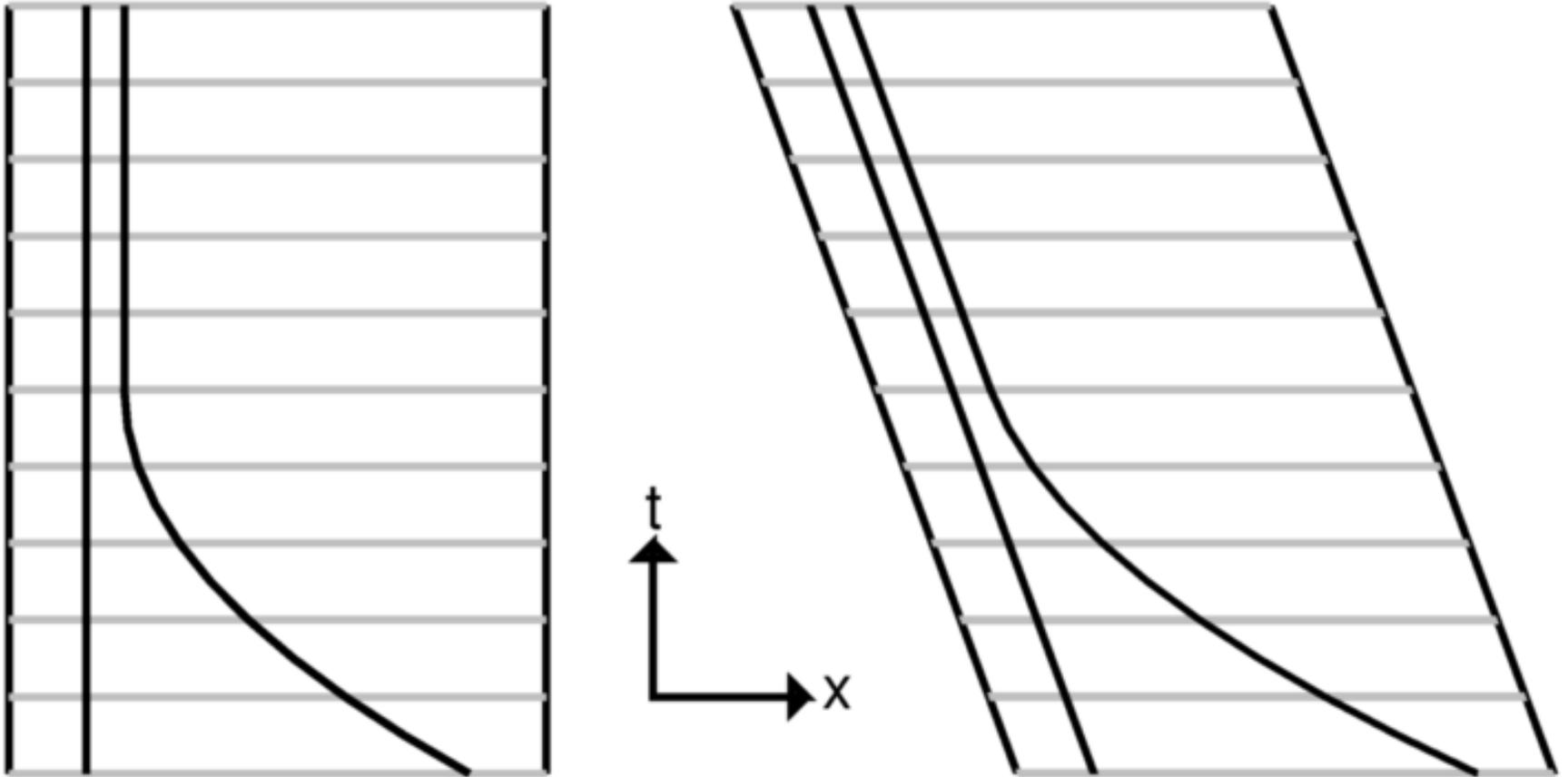
Definitions

- Distance – the spatial separation of the positions of two objects taken at the SAME TIME.
 - $d = \| x_1(t) - x_2(t) \|$
 - $d \neq \| x_1(t_1) - x_2(t_2) \|$ with $t_1 \neq t_2$.
- Recession velocity “v” is the change in the distance during a time interval divided by the duration of the time interval
 - $v = [d(t_2) - d(t_1)] / [t_2 - t_1]$

But, but, but ...

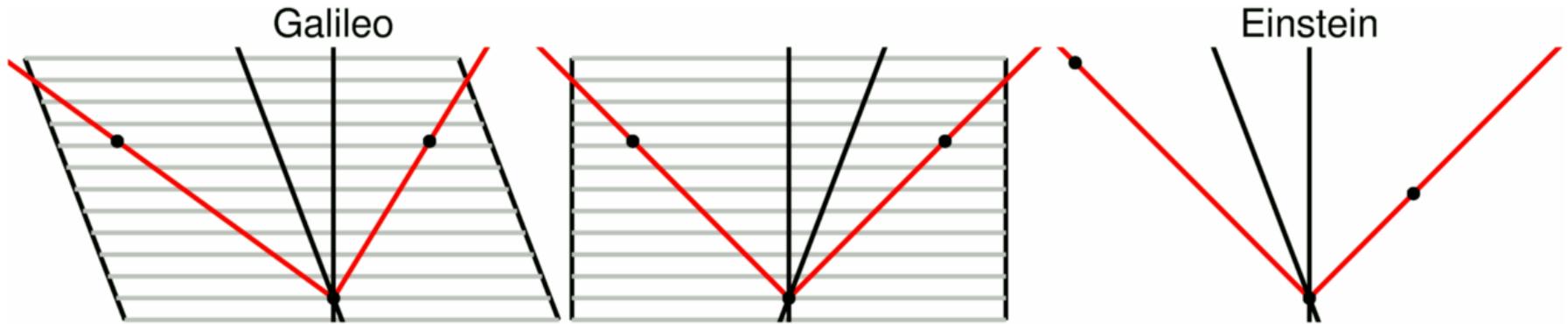
- Special relativity says that the concept of simultaneity for spatially separated events cannot be defined in an invariant manner.
- Time dilation: moving clocks run slow.
- Einstein wanted to replace Newton's inverse square force because the DISTANCE that went into Newton's Law was not defined in SR.
- General relativity was the result. "General" means invariant under general^[2] coordinate transformations.

Galilean Relativity



- Only allowed transformations are “skewing the deck of cards with a straightedge.”

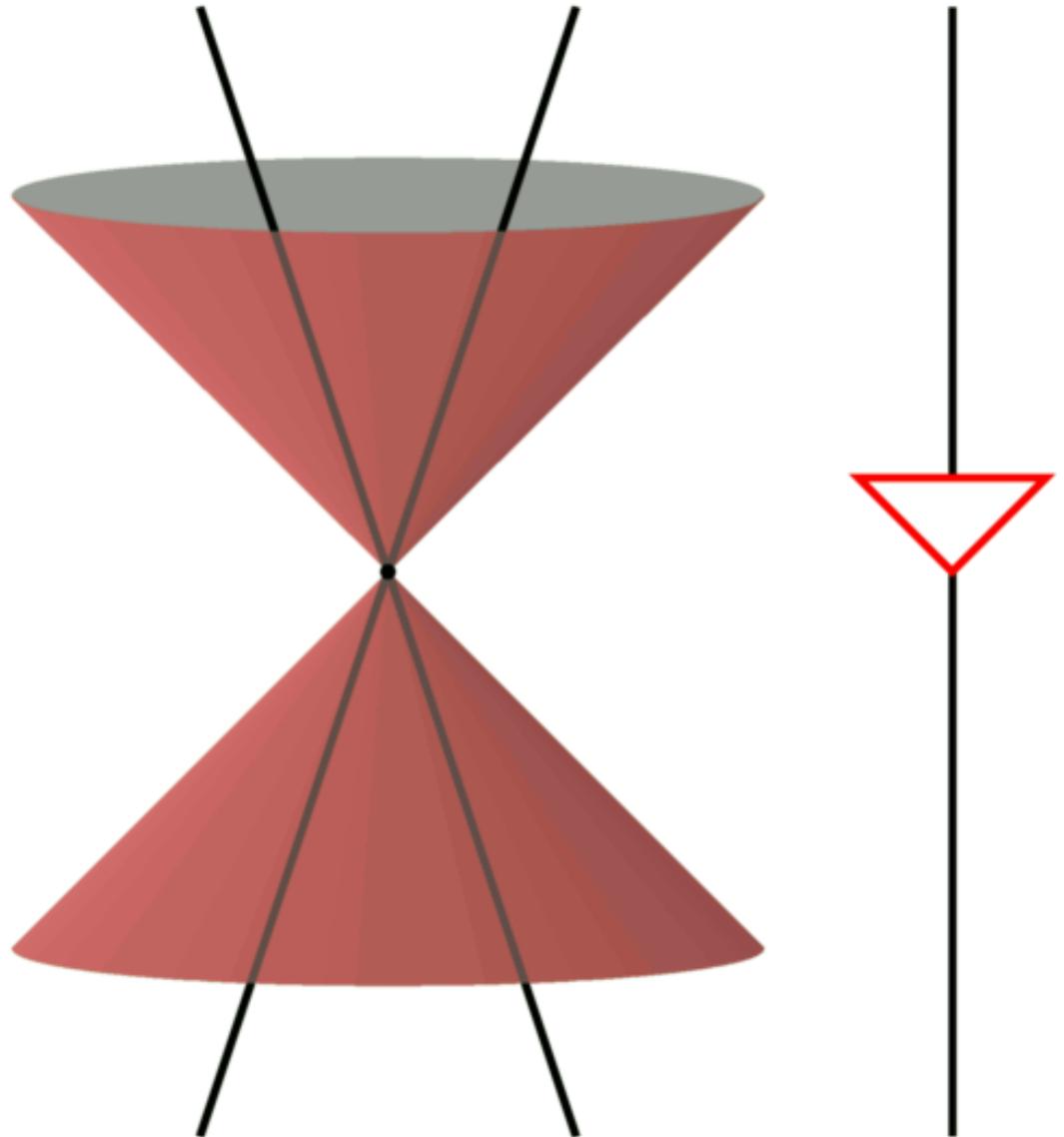
But Let There be Light(speed)



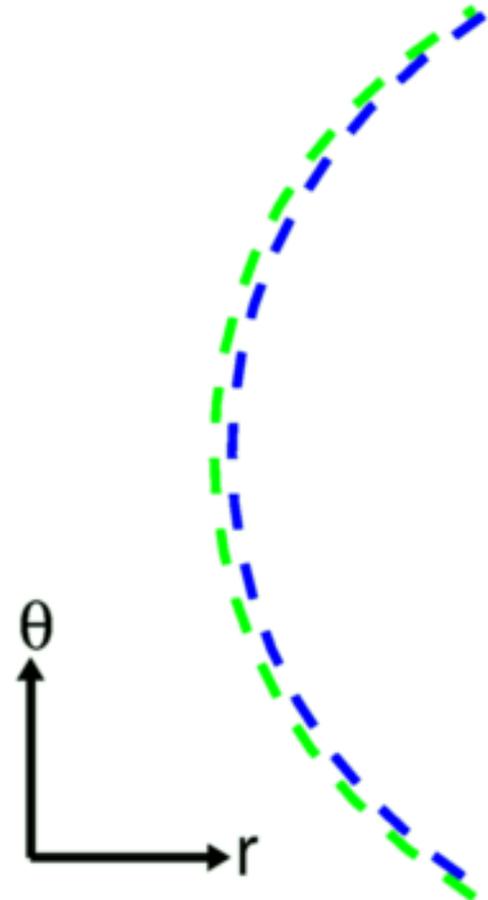
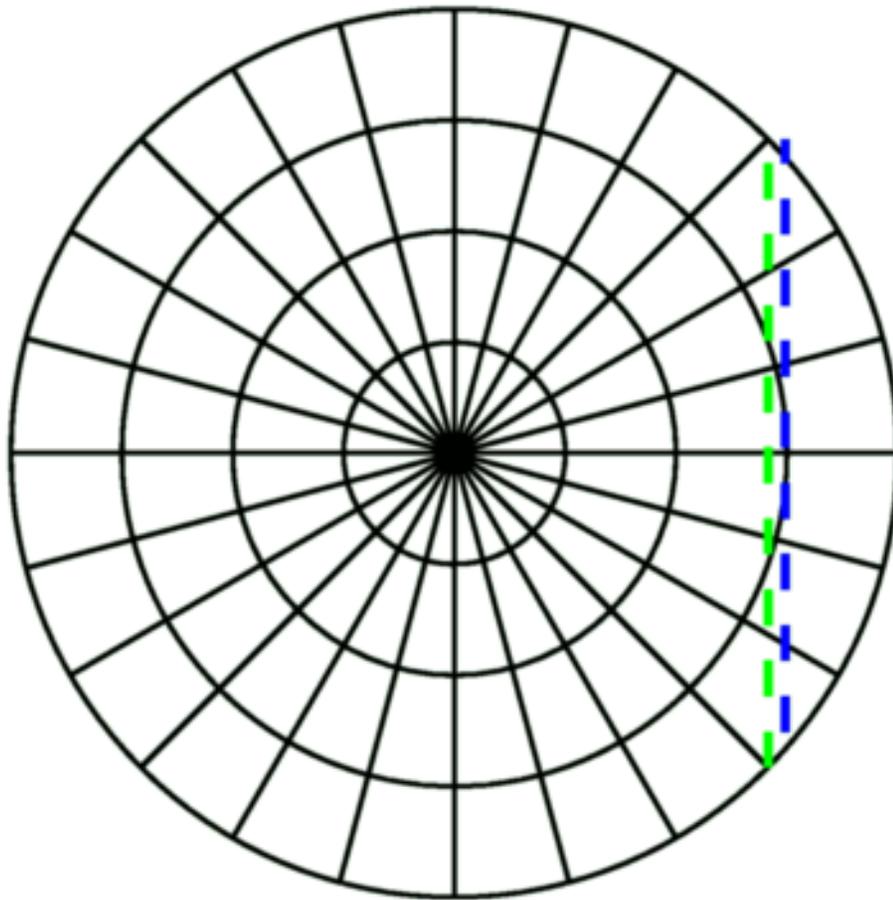
- A constant speed of light violates Galilean relativity, so SR uses Lorentz transformations.
- Middle ST diagram transforms into unequal speeds of light under Galilean transformation [left], while Lorentz transformations [right] preserve the speed of light but not simultaneity.

Lightcones are fundamental

- In SR lightcones transform onto themselves but not in GR: they can tilt or stretch.
- “Speed Limit 300,000 km/sec” only means worldlines of objects have to be inside their local lightcone.



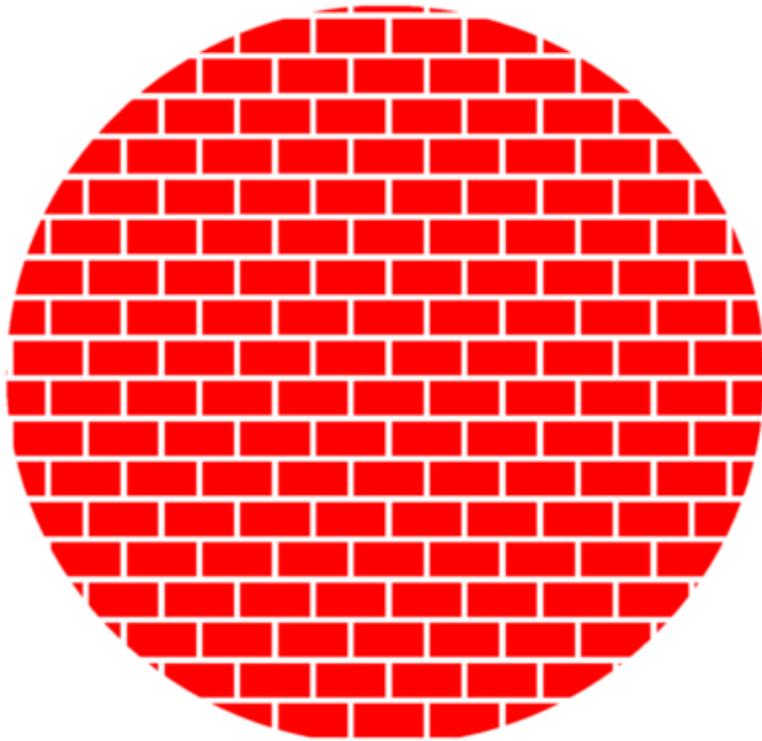
A General Transformation



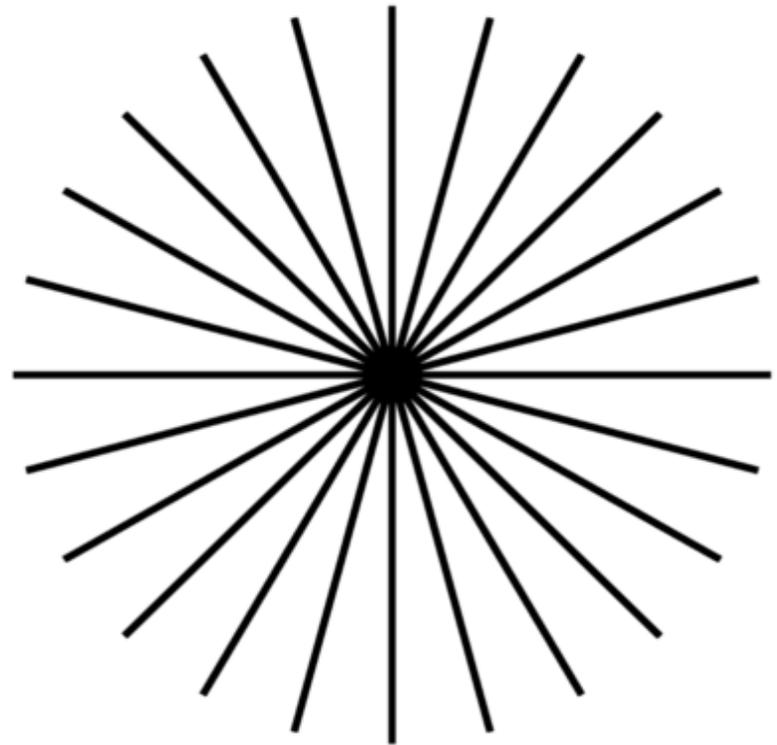
- “Straight” world lines become curved but same acceleration for all objects.

Fact: The Cosmological Principle

- The Universe is homogeneous^[3] and isotropic^[4].



Not isotropic

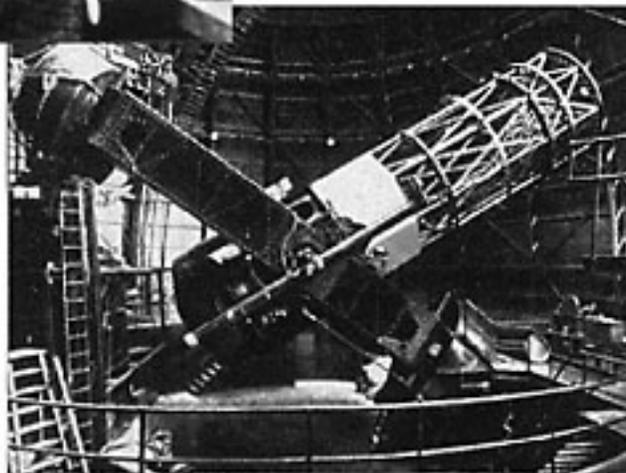
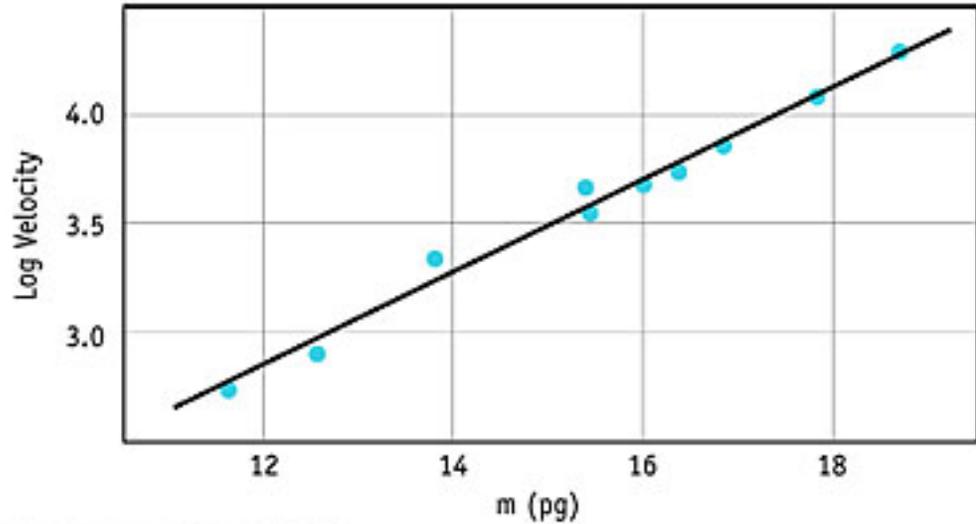


Not homogeneous

Fact: the Hubble Law



Edwin Hubble



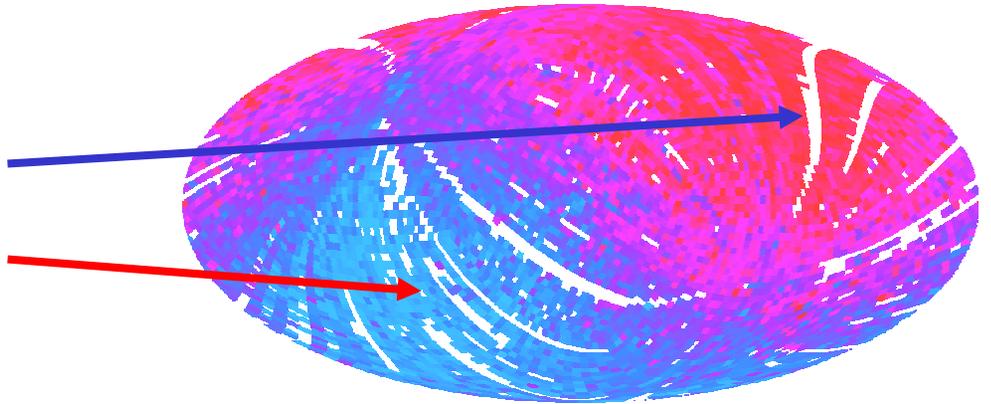
Mt. Wilson
100 Inch
Telescope

Define Cosmic Time

- The Hubble law is only true in one frame of reference, the comoving frame.
- An observer moving with respect to that frame would see excess velocities:

– Blueshifts in front:

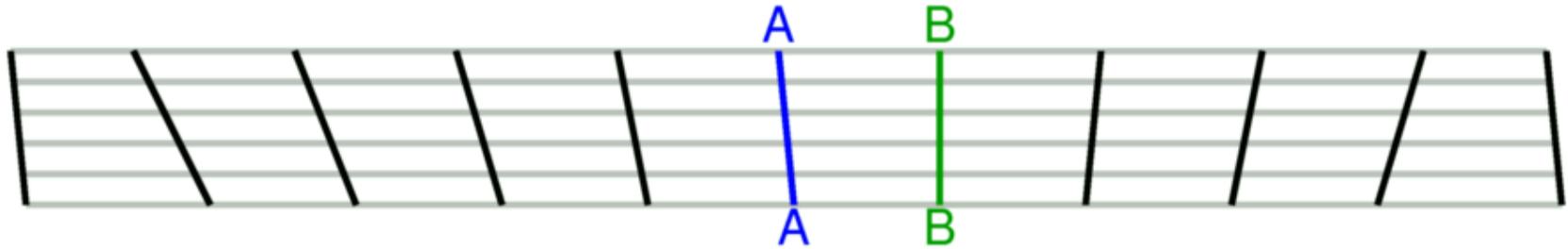
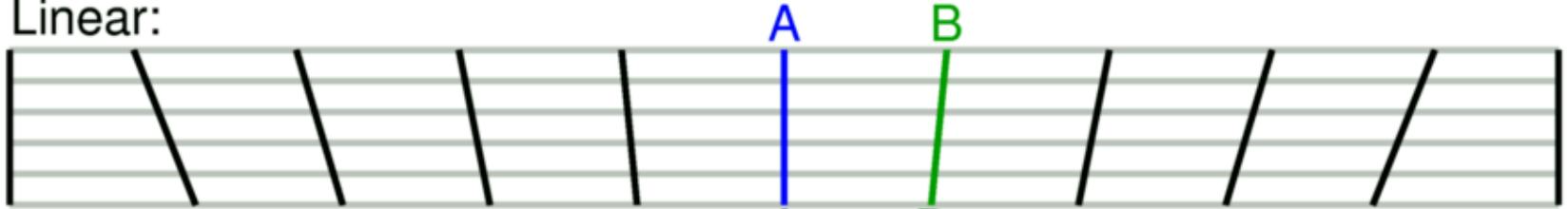
– Redshifts behind:



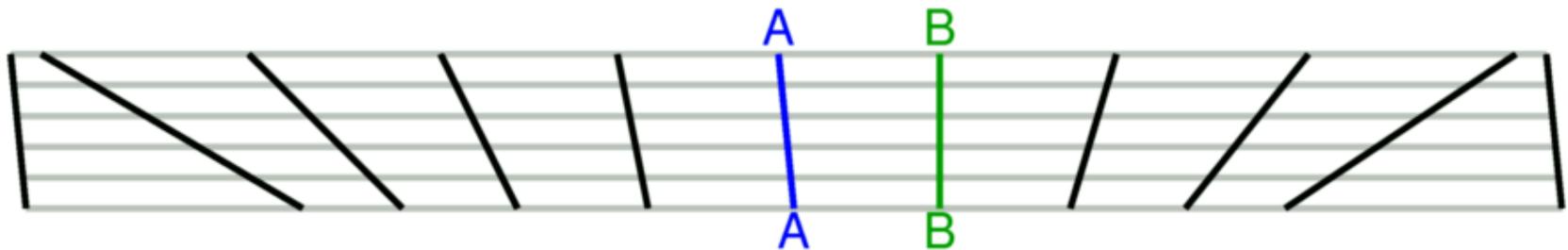
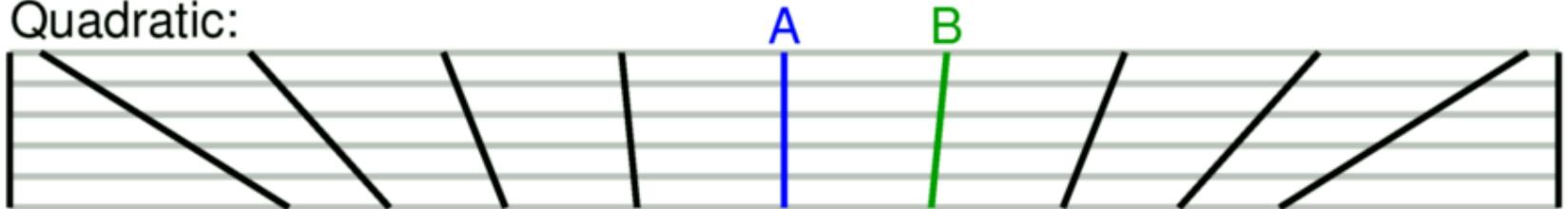
- Therefore the cosmic time, the age of the Universe measured by a comoving observer, can be defined.

Linear v vs D law is universal

Linear:



Quadratic:



Linear v vs D law does not distort



$$v \propto D^0$$

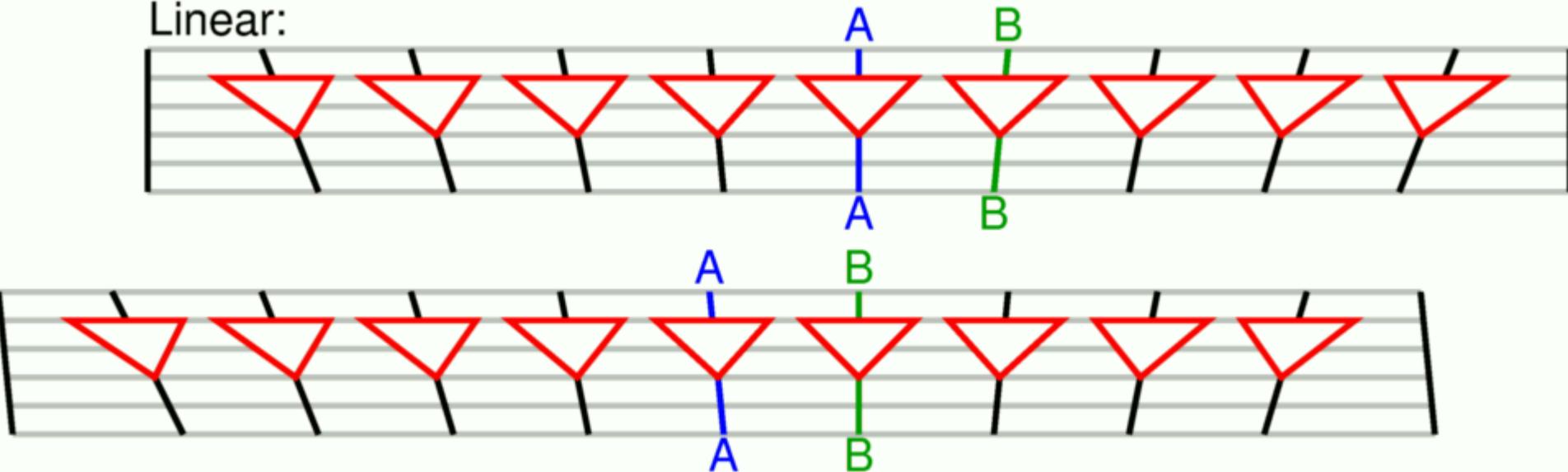
$$v \propto D^1$$

$$v \propto D^2$$

Cosmological Spacetime

- Use proper time since Big Bang for comoving observers as the time variable.
- Use radar distance measured by comoving observers for small distances.
 - Hence light cones are symmetric about worldlines of comoving observers. Speed of light is “c” relative to local comoving observers.

Linear:



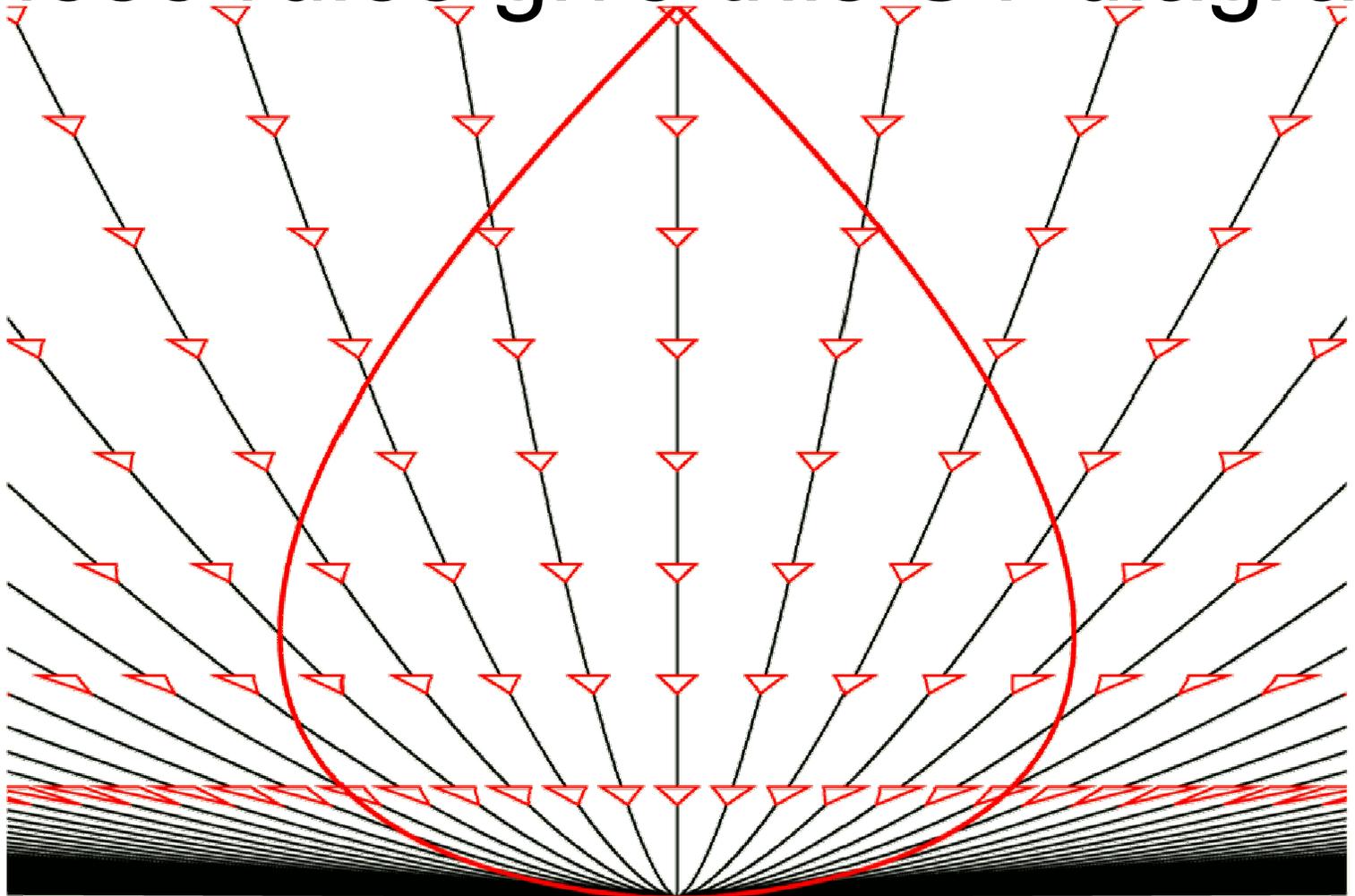
$v > c$ is inevitable

- Over long distances sum up many short distances.
- Hubble law $v = HD$ applies exactly so $v > c$ is inevitable for large distances.



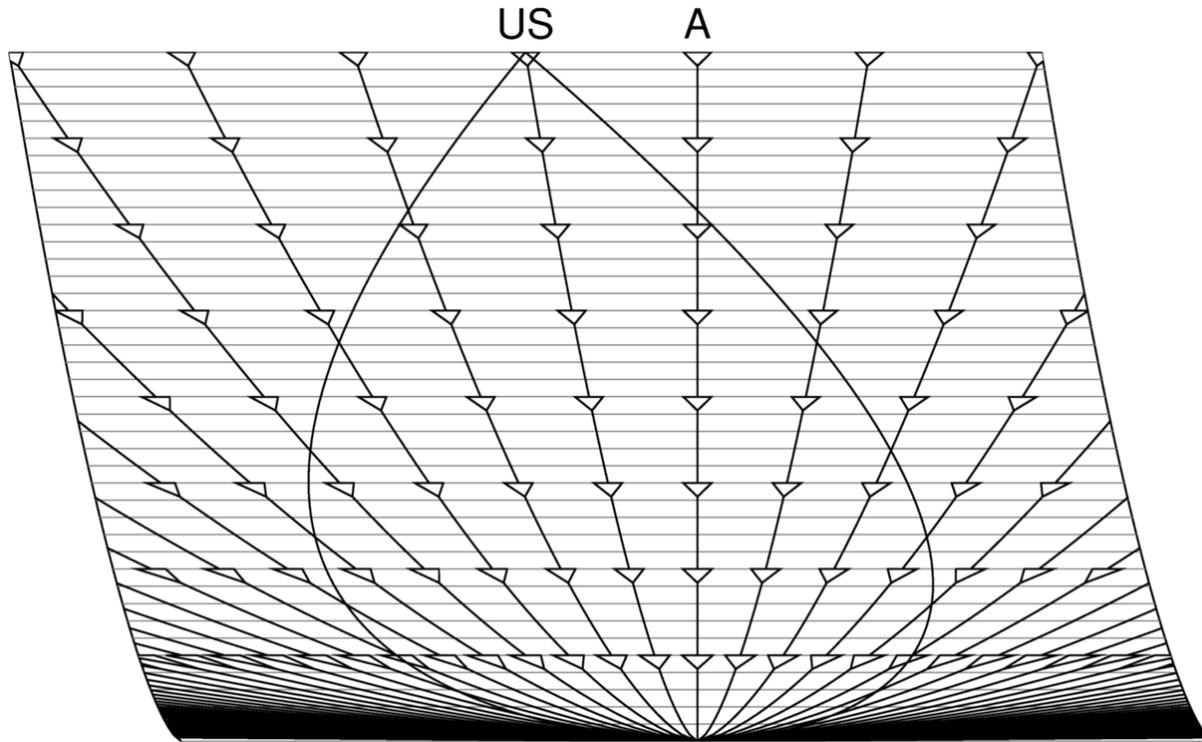
- Where the lightcones are tipped past the vertical, galaxies are receding faster than c .

These rules give this ST diagram



The “teardrop” is always parallel to the sides of the little light cones, so it is our past light cone, and marks the part of spacetime we can see.

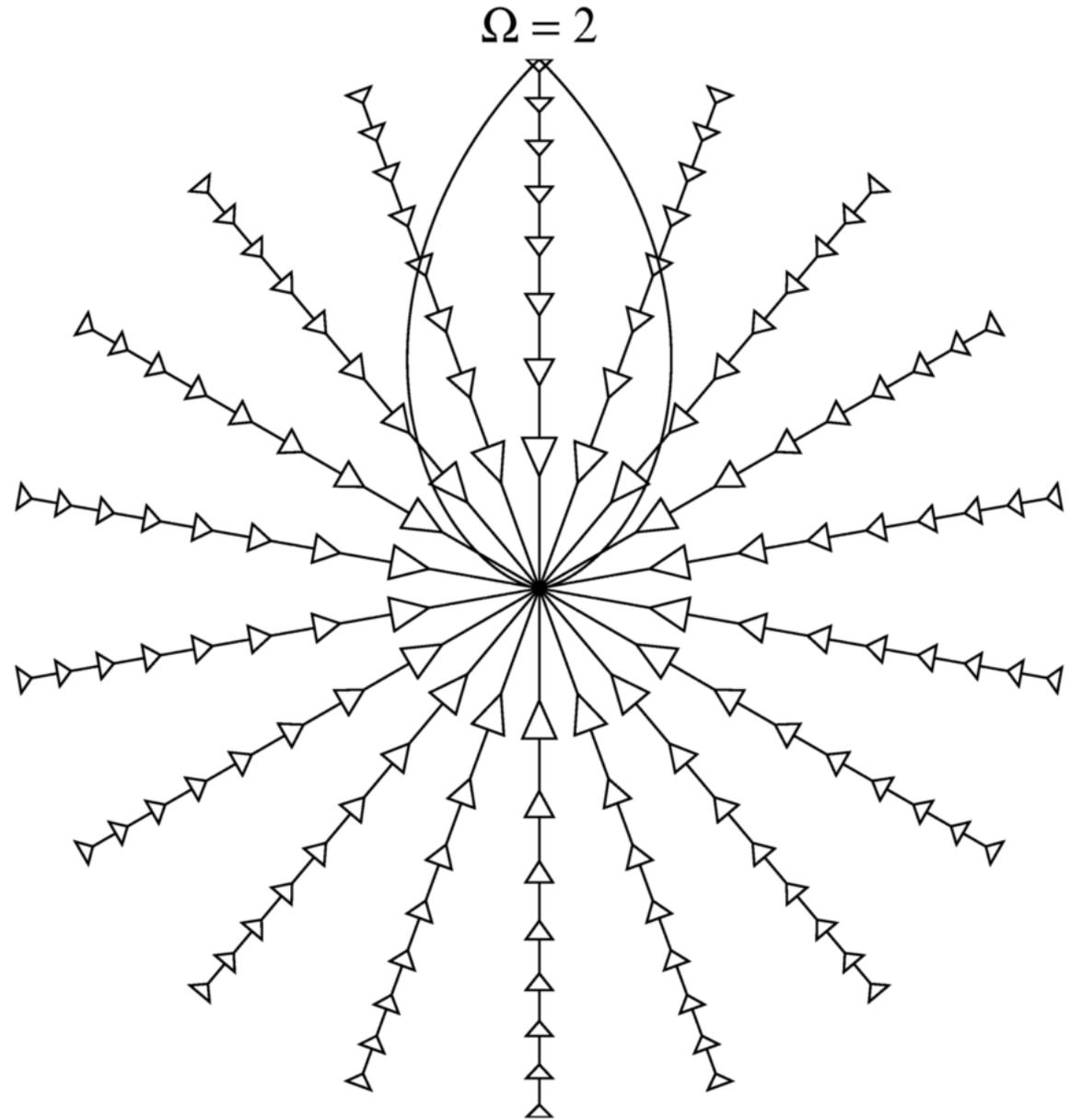
A New Deck of Cards



- With cosmic time we are back to skewing a deck of cards. But now the edge can be curved – it must follow the worldline of a comoving observer.

$$\Omega_m = 2$$

- A natural transformation maps space into angles and time into radius. Here $r = a(t)$.
- This works very well for closed spaces.
- We see half the Universe in this model.



$(v/c)_{\max} = \infty$ for viable models

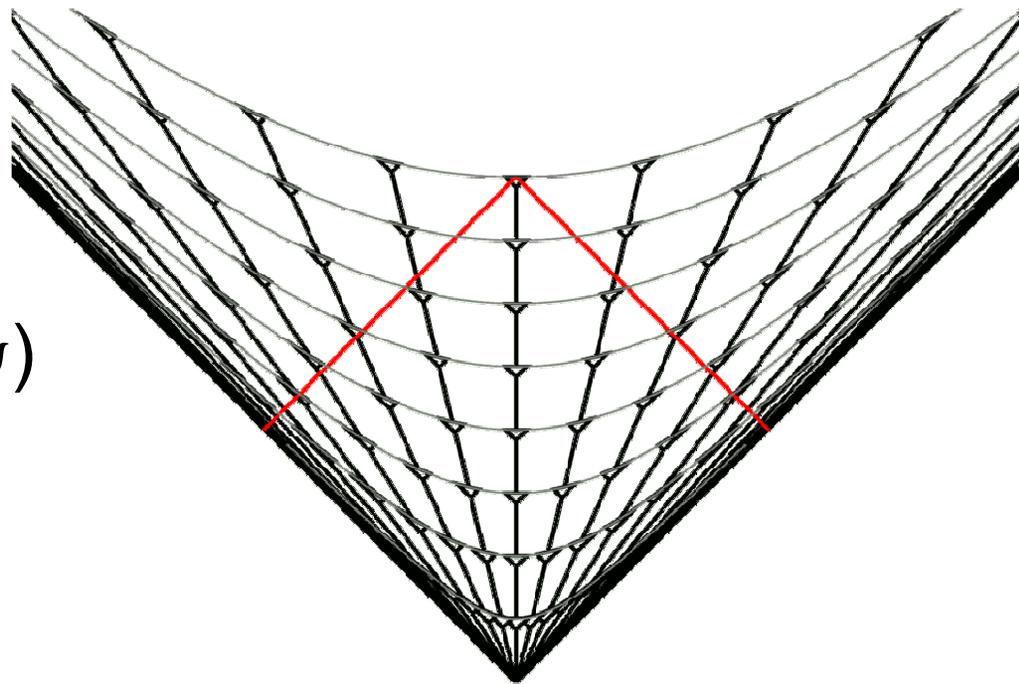
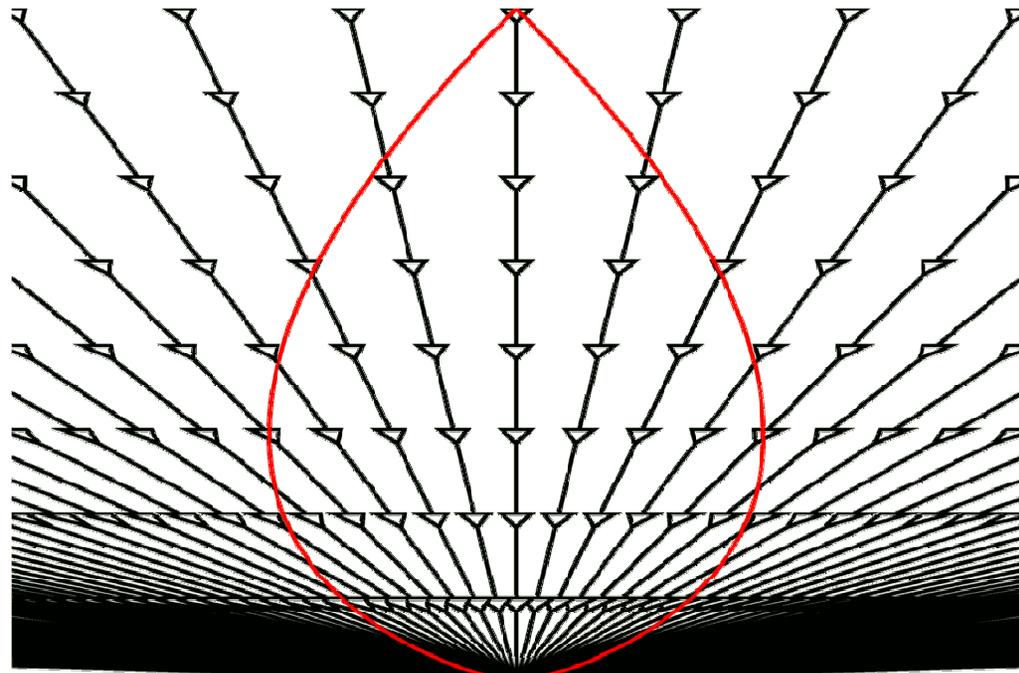
Ω_m	0	0.27	1	6.43	0.27	0
Ω_Λ	0	0	0	0	0.73	1
Max (v/c)	∞	∞	∞	1.35	∞	∞
(v/c) at $z=\infty$	∞	2.91	2	1	3.38	∞

$H_0 = 71, \Omega_r = 0$

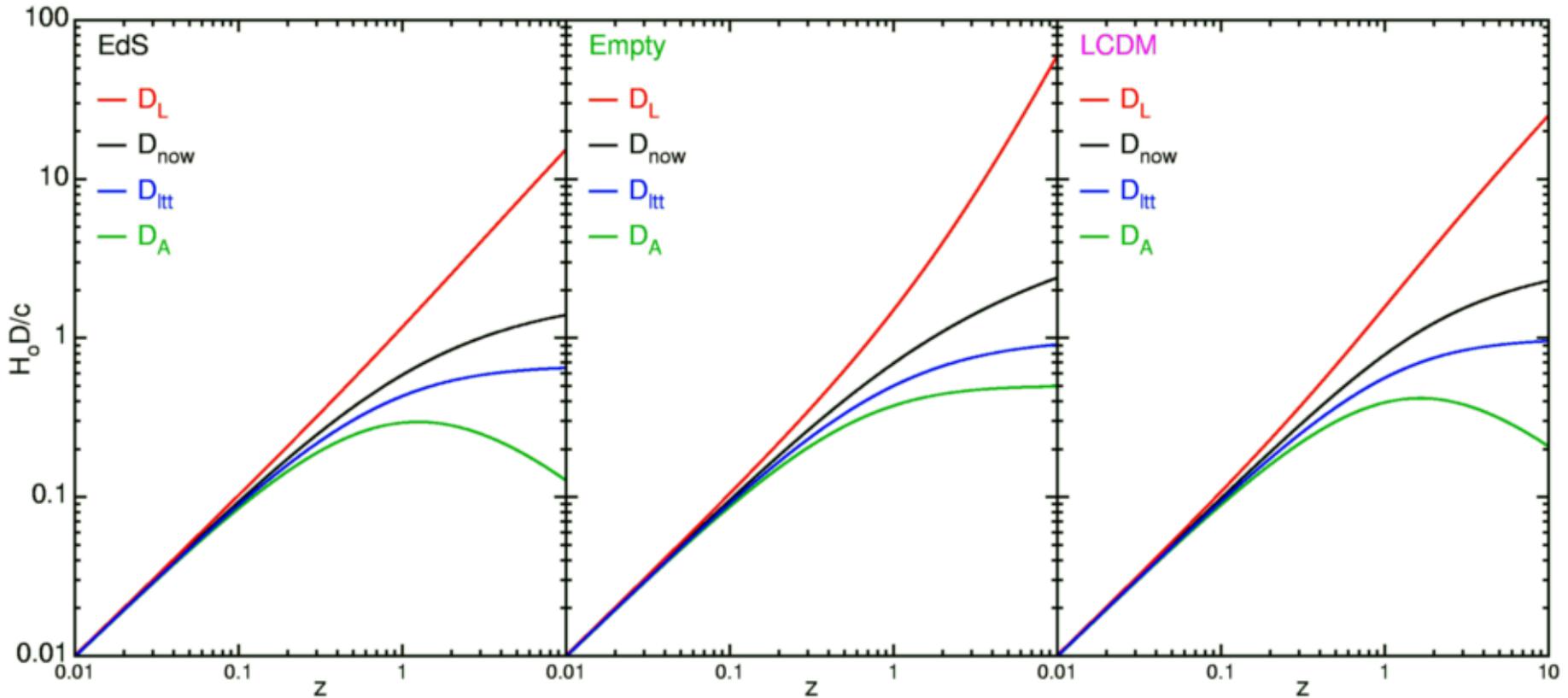
Inflation has nothing to do with it!

Empty Model

- The Milne model with $\Omega_m=0$ & $\Omega_\Lambda=0$ can be transformed to SR coordinates.
- $x_{\text{sr}} = ct^* \sinh(\psi)$
- $t_{\text{sr}} = t^* \cosh(\psi)$
- $D_{\text{now}} = ct\psi$
- $v_{\text{now}} = HD_{\text{now}} = c\psi$
- $v_{\text{sr}}/c = x_{\text{sr}}/ct_{\text{sr}} = \tanh(\psi)$
- $1+z = \exp(|\psi|)$

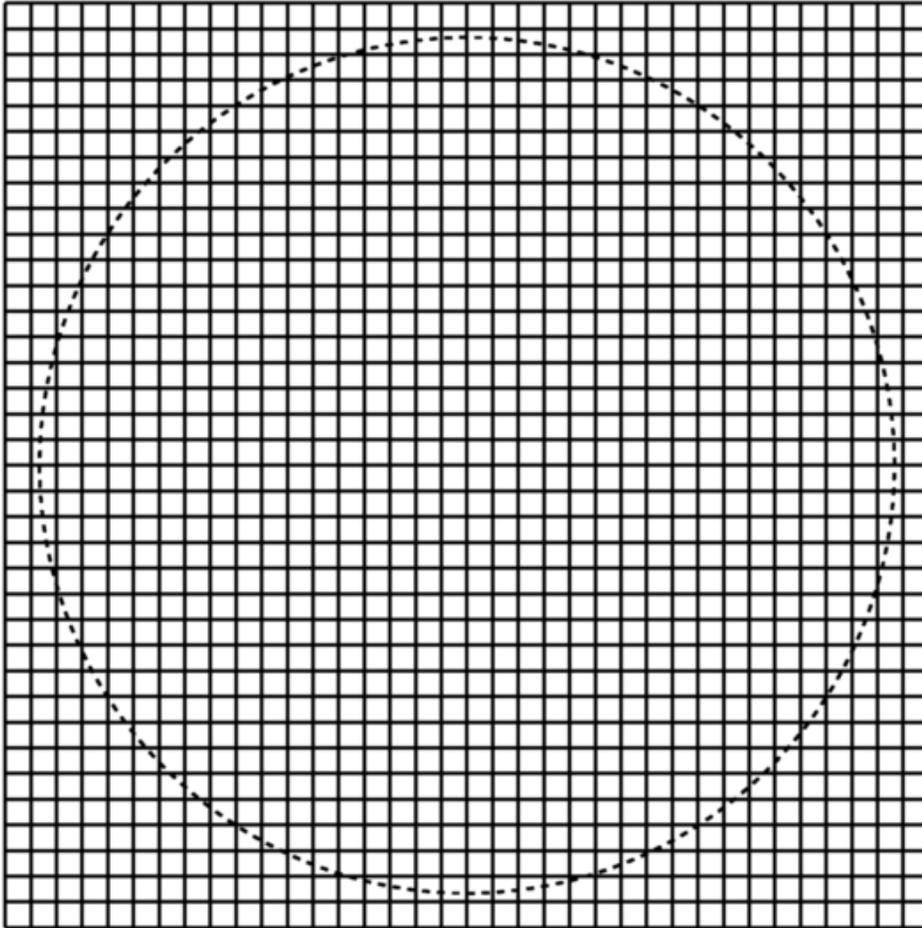


Many Distances



- $D_A = \text{size}/\theta$ $D_L = D_A * (1+z)^2$ cz/H_0
- $D_{\text{ltt}} = c * (t_o - t_{\text{em}})$
- $D_{\text{now}} = \int \sqrt{-ds^2}$ along $t = t_o$

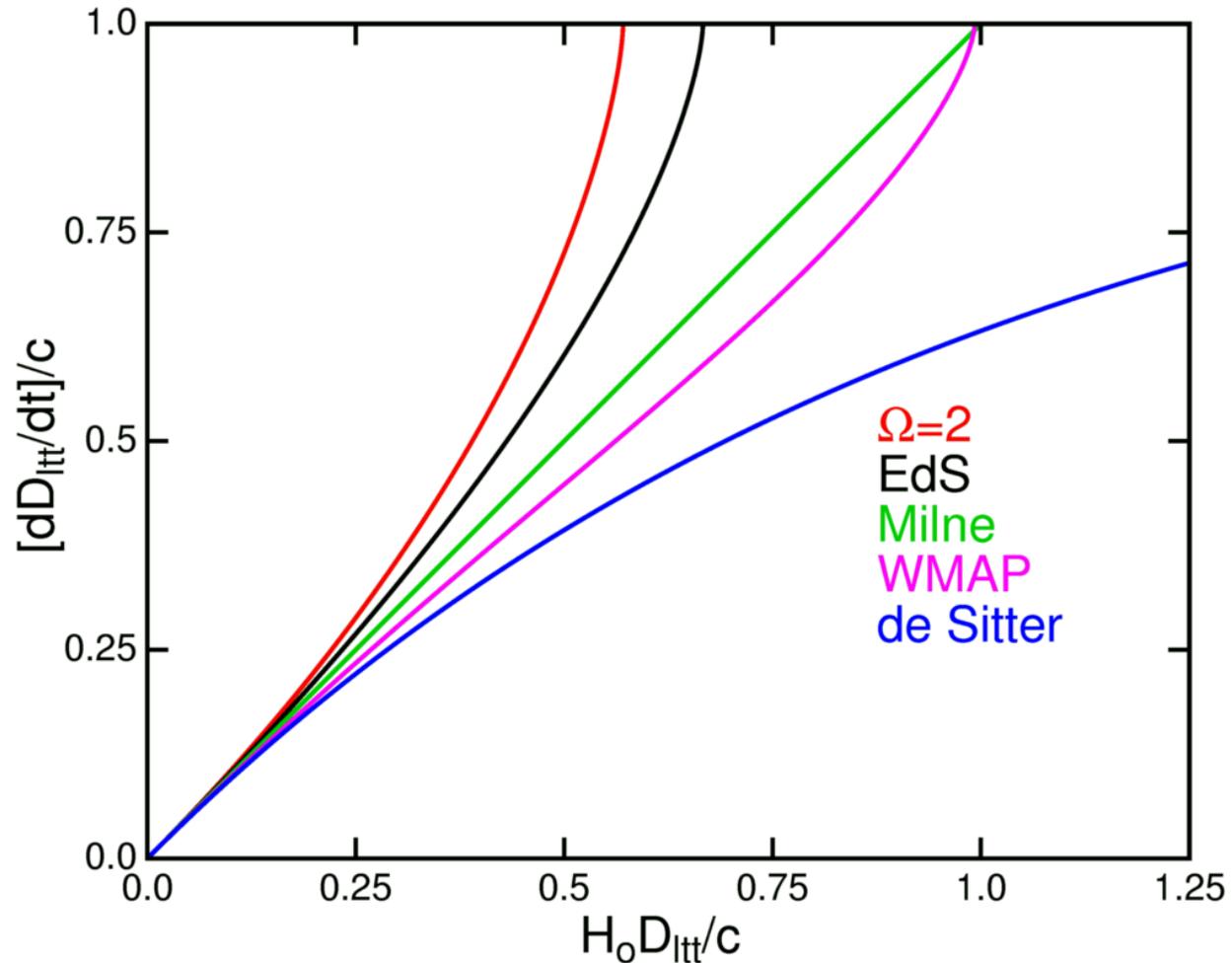
Light travel time: Why D_{ltt} is D_{umb}



- Light travel time distance violates the cosmological principle: the Universe is neither homogeneous nor isotropic.

D_{ltt} violates the Hubble law

- Velocity is not strictly proportional to distance when using D_{ltt} :
- The deviation depends on the cosmological model.



D_{ltt} is often used in press releases

- The redshift is thought to be too complicated.
- The radial proper distance D_{now} is thought to be too complicated.
- But D_{ltt} only delays the complications long enough to let the presenters at the press conference get out the door.
 - “If we see a quasar 1 billion years after the Big Bang that is 12.7 billion light years away (D_{ltt}), how did it travel 12.7 billion light years in only 1 billion years?”

A Word from our Sponsor...

Ned Wright's Javascript Cosmology Calculator - Mozilla Firefox

File Edit View Go Bookmarks Tools Help

http://www.astro.ucla.edu/~wright/CosmoCalc.html

Customize Links Free Hotmail RealPlayer Windows Marketplace Windows Media Windows

Enter values, hit a button

71 H_0

0.27 Ω_M

999999 z

Open Flat

0.73 Ω_{vac}

General

For $H_0 = 71$, $\Omega_M = 0.270$, $\Omega_{vac} = 0.730$, $z = 999999.000$

- It is now 13.665 Gyr since the Big Bang.
- The age at redshift z was 0.757 yr.
- The [light travel time](#) was 13.665 Gyr.
- The [comoving radial distance](#), which goes into Hubble's law, is 14262.5 Mpc or 46.518 Gly.
- The comoving volume within redshift z is 12152.786 Gpc³.
- The [angular size distance \$D_A\$](#) is 0.014 Mpc or 0.000047 Gly.
- This gives a scale of 0.000 kpc/".
- The [luminosity distance \$D_L\$](#) is 14262502874.5 Mpc or 46518432.798 Gly.

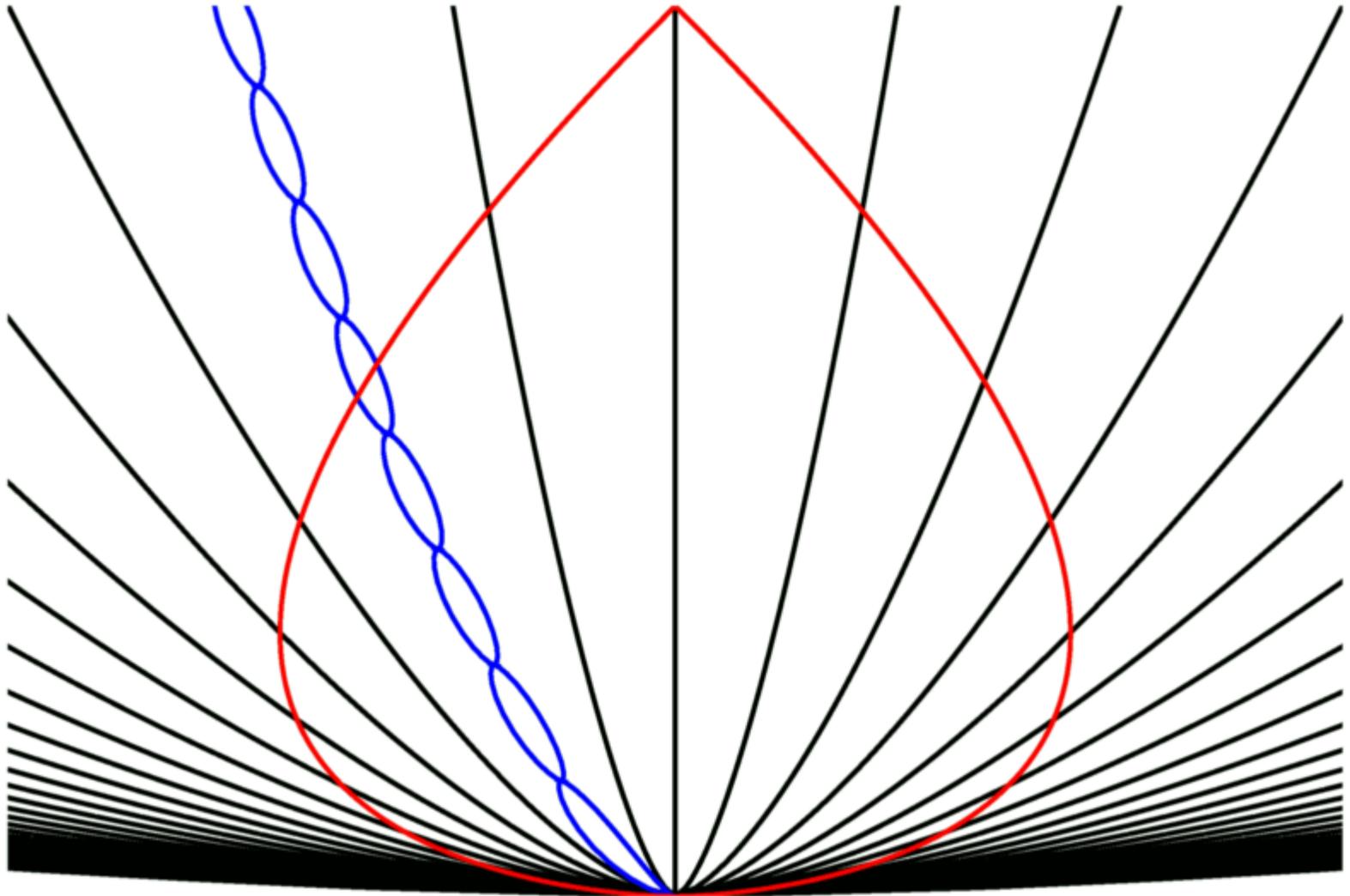
1 Gly = 1,000,000,000 light years or 9.461×10^{26} cm.
1 Gyr = 1,000,000,000 years.
1 Mpc = 1,000,000 parsecs = 3.08568×10^{24} cm, or 3,261,566 light years.

[Tutorial: Part 1](#) | [Part 2](#) | [Part 3](#) | [Part 4](#)
[FAQ](#) | [Age](#) | [Distances](#) | [Bibliography](#) | [Relativity](#)

Great Taste or Less Filling?

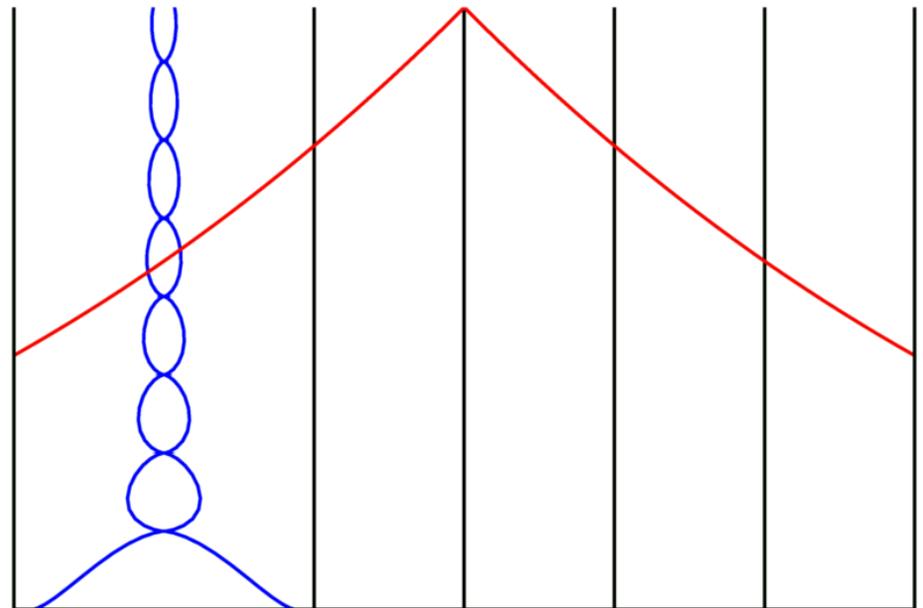
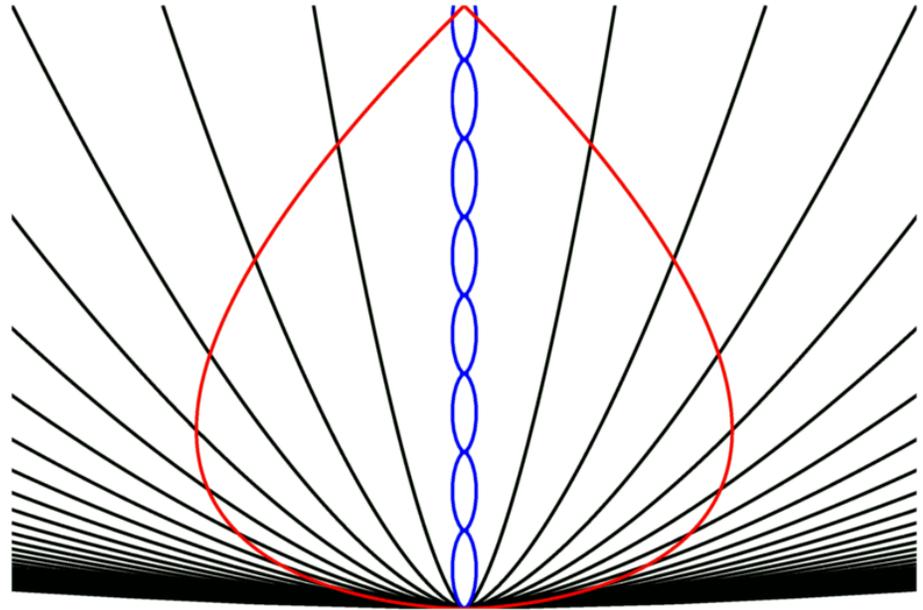
- Is the redshift due to a Doppler shift or is it just the effect of an expansion of space? Please remember that in GR an arbitrary^[5] change in coordinates is allowable.
- So use the coordinates that give the simplest solution. GR guarantees that observables like the redshift will be unchanged so either
 - Fixed comoving coordinates with expanding space, or
 - Proper radial distances with Doppler shift will give the same z if computed correctly.
- But $1+z = ((1+v/c)/(1-v/c))^{0.5}$ is never^[6] right.

A Bound Cluster does not expand



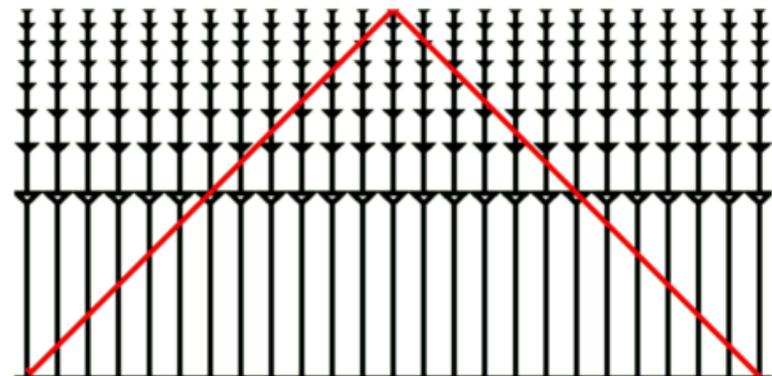
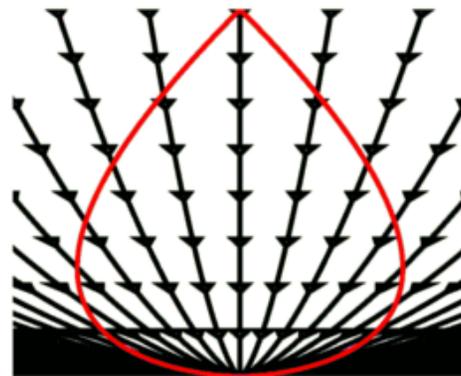
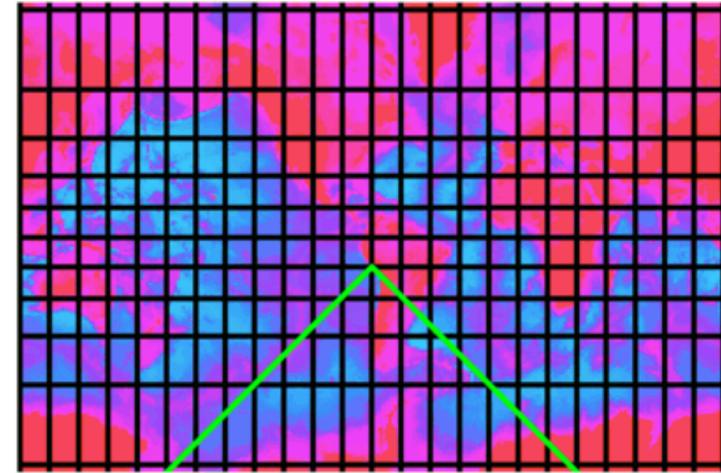
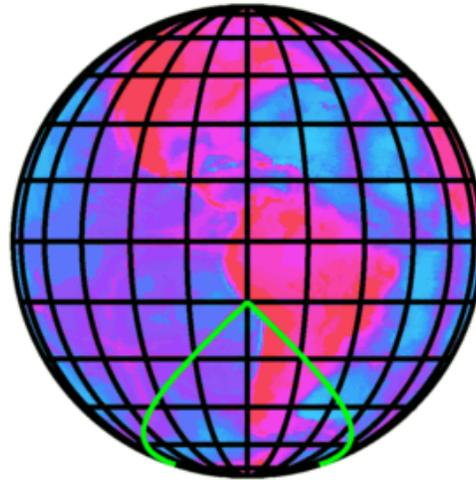
Use the simplest coordinates

- Centered physical coordinates [moving galaxies] allow a simple calculation.
- Comoving coordinates [expanding space] are much more complex here.



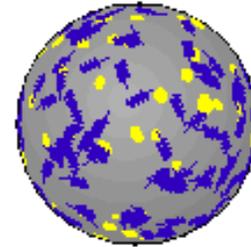
“Normal” vs Conformal ST Diagram

- Constant SE course is a curve on the globe but a straight line on the conformal Mercator map.
- Constant speed-of-light is a curve on the “normal” space-time diagram but a straight line on the conformal diagram.

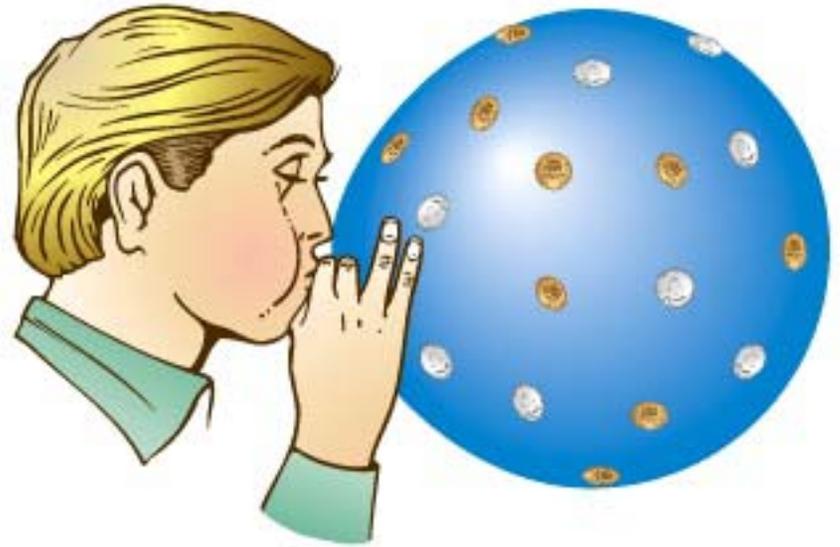


The Balloon Analogy

- Notes that the galaxies DO NOT expand!
- The number density of galaxies goes down.
- The number density of photons goes down.
- The photon energy goes down.



Glue coins to the balloon



On the CN non-discovery

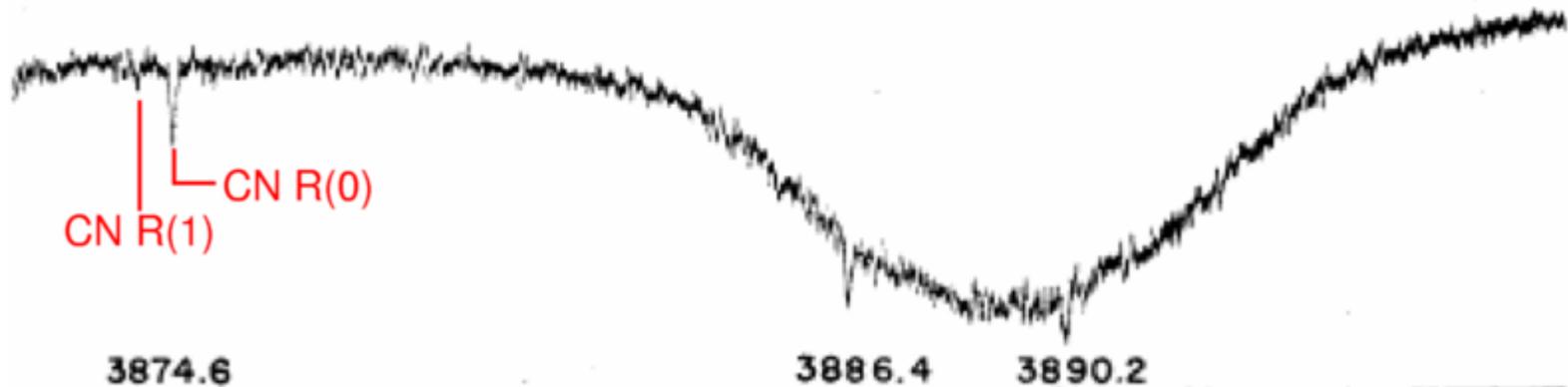


Plate 3 of Adams (1941, ApJ, 93, 11-23) reporting McKellar's work

Herzberg (1950) in *Spectra of Diatomic Molecules*, p 496:

“From the intensity ratio of the lines with $K=0$ and $K=1$ a rotational temperature of 2.3° K follows, which has of course only a **very restricted meaning.**”

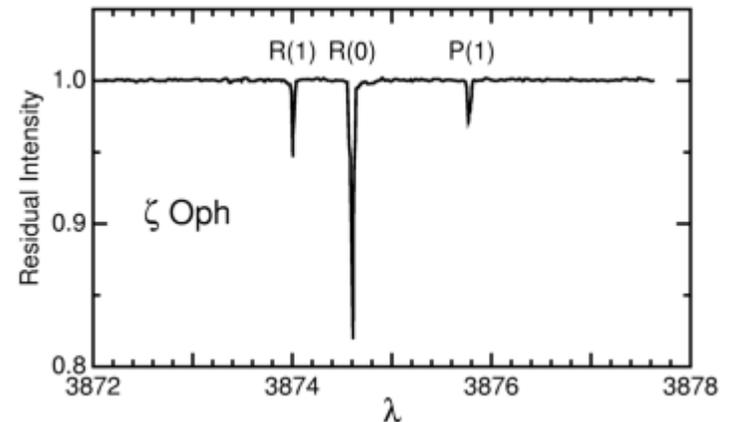
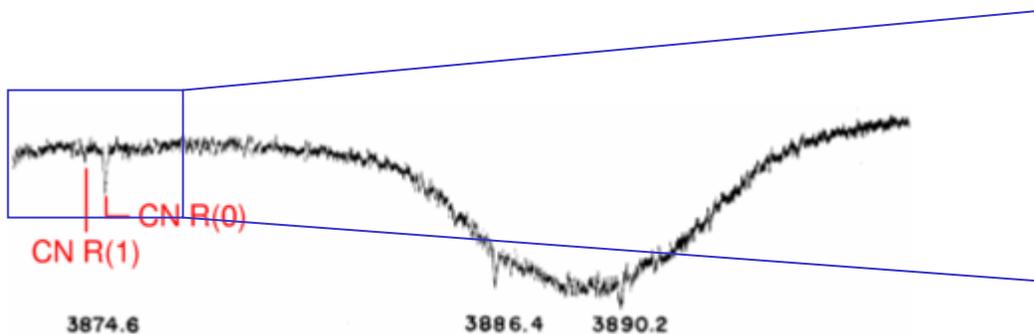
There went Herzberg's [second] Nobel Prize.

Fred Hoyle missed the Nobel Prize

- Hoyle (1950), reviewing a book by Gamow & Critchfield: “[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy.”
- This book implied $T_0 = 11$ K. Gamow in 1956 Scientific American implied 6 K. Alpher & Herman explicitly gave 5 K or 1 K.
- Nobody followed this up!

CN followup after Penzias & Wilson

- Reworking and reobserving the CN lines gave 2.78 ± 0.10 K at 2.64 mm. (Thaddeus, 1972, ARAA, 10, 305-334)
- By 1993, 2.73 ± 0.03 K

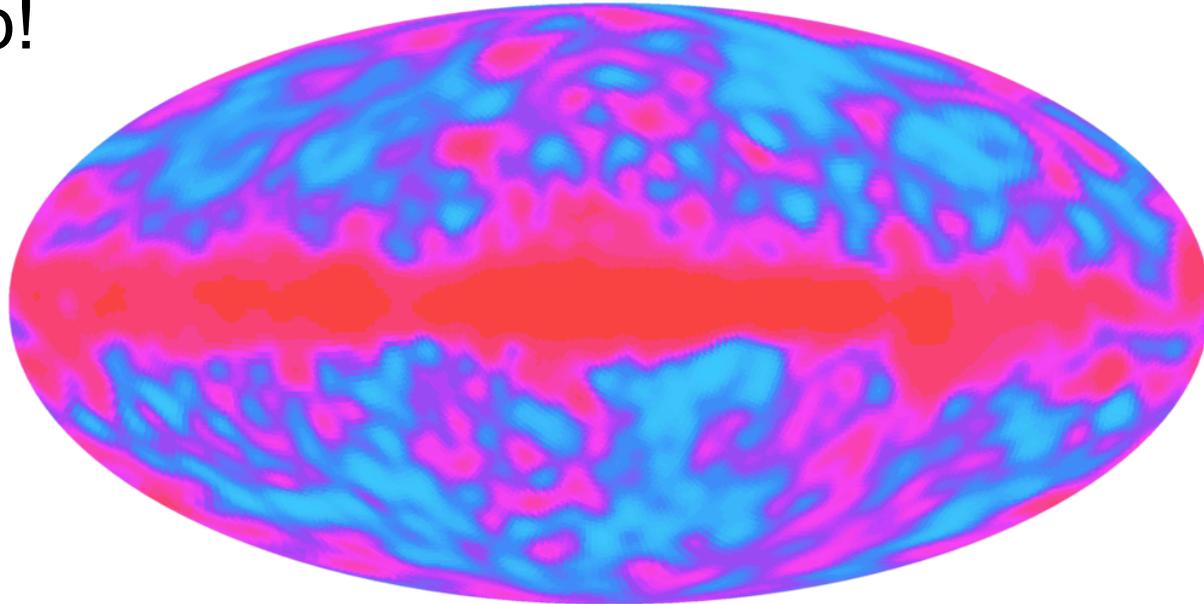


CMB Anisotropy

THE  TIMES

25 April 1992

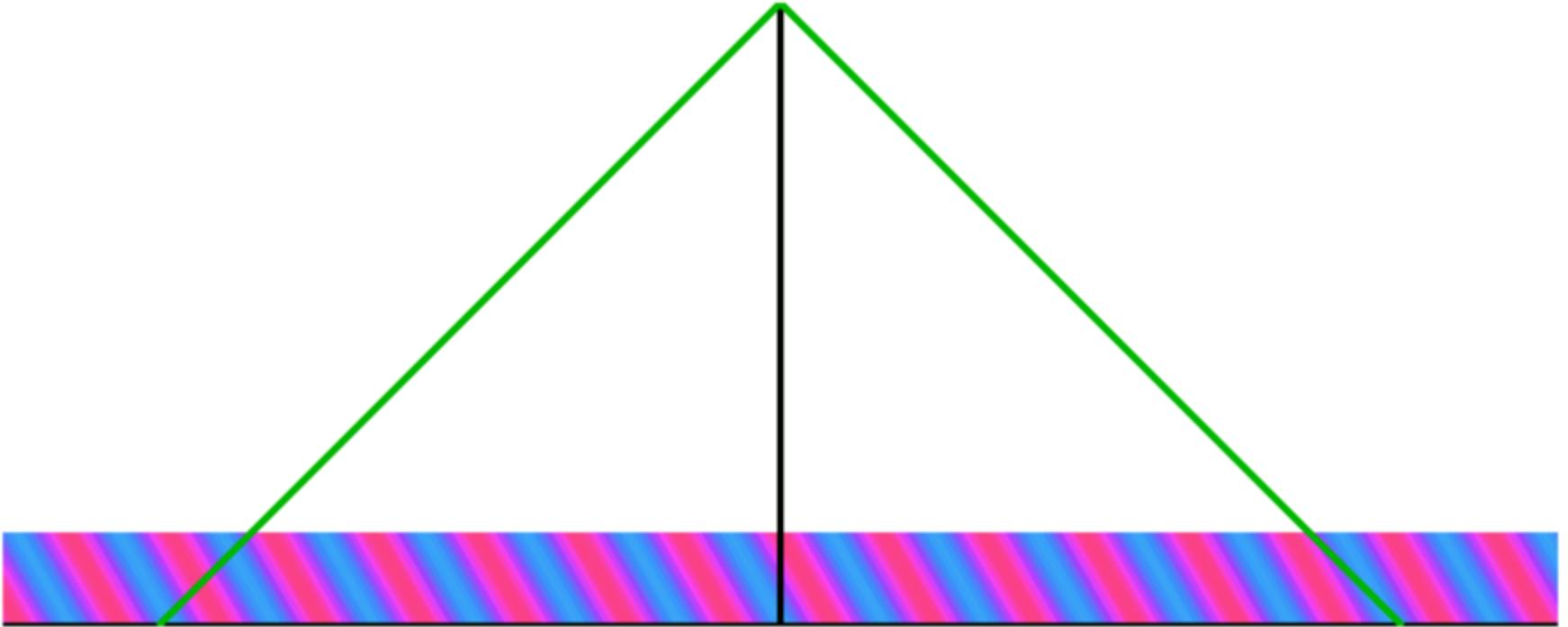
Prof. Stephen Hawking of Cambridge University, not usually noted for overstatement, said: “It is the discovery of the century, if not of all time.” – What a blurb!



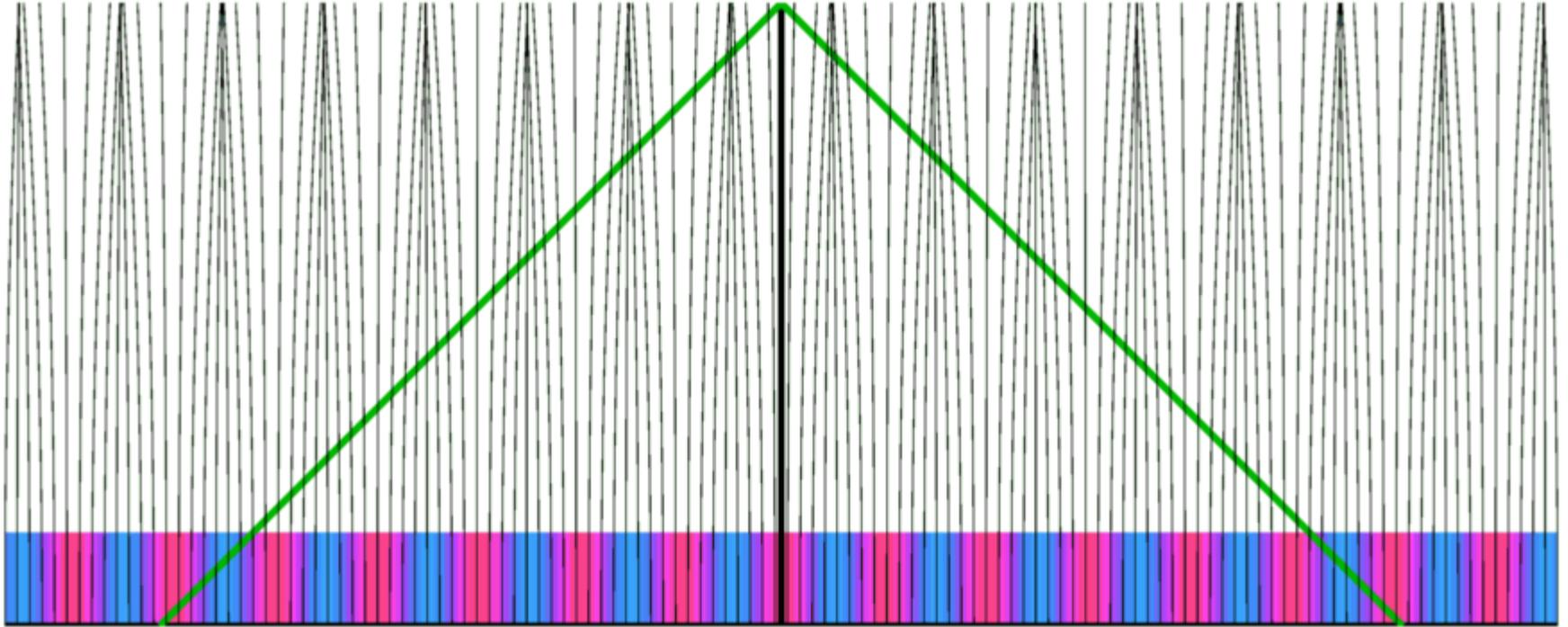
Two Fluids in the Early Universe

- Most of the mass is dark matter
 - 80-90% of the density
 - Zero pressure
 - Sound speed is zero
- The baryon-photon fluid
 - baryons are protons & neutrons = all ordinary matter
 - energy density of the photons is bigger than c^2 times the mass density of baryons
 - Pressure of photons = $u/3 = (1/3)\rho c^2$
 - Sound speed is about $c/\sqrt{3} = 170,000$ km/sec

Traveling Sound Wave: $c_s = c/\sqrt{3}$



Stay at home Dark Matter

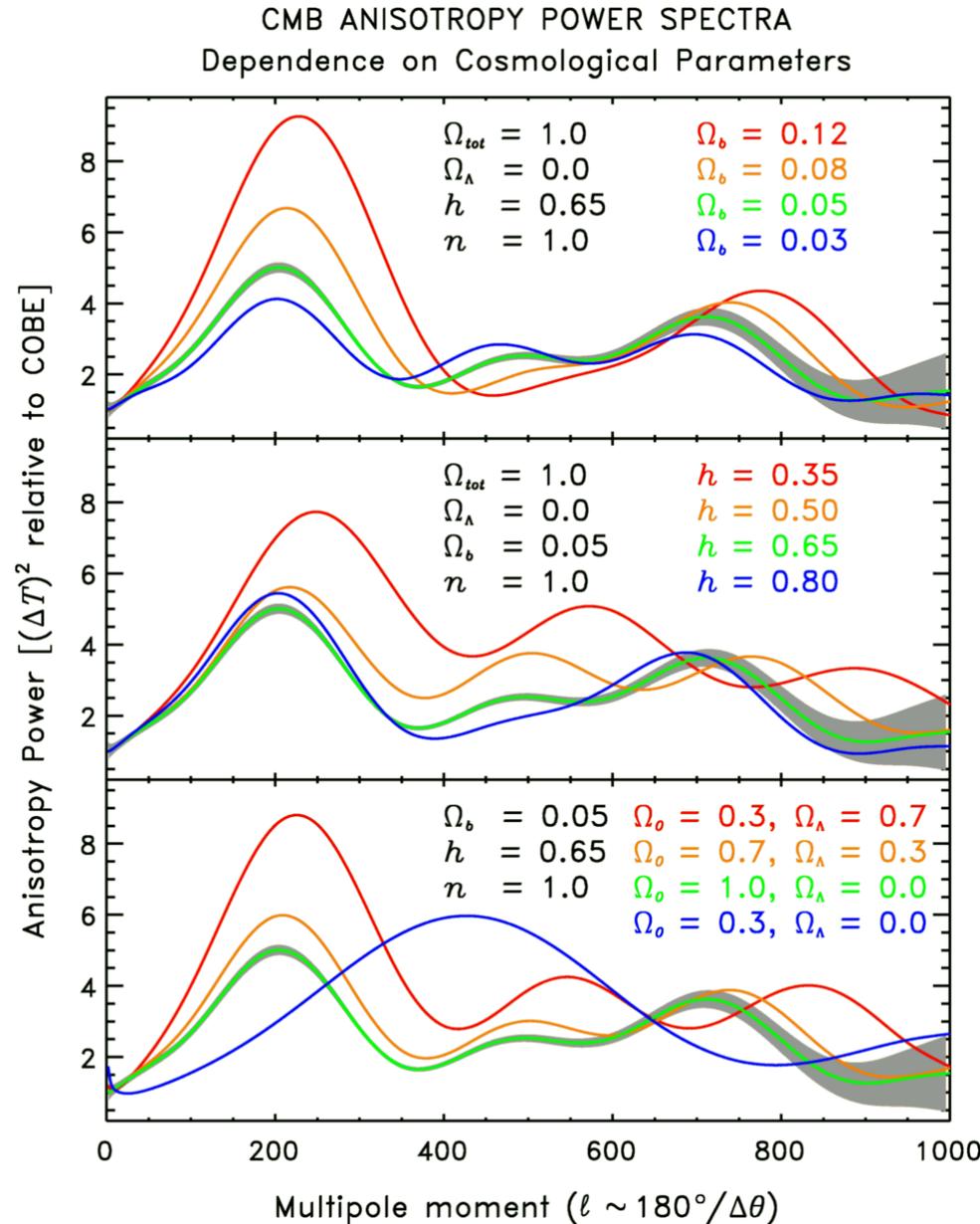


Interference at last scattering

- For the wavelength illustrated [$1/2$ period between the Big Bang and recombination], the denser = hotter effect and potential well = cooler effect have gotten in phase.
- For larger wavelengths they are still out of phase at recombination.

Many parameters to measure

- Careful measurements of the power at various angular scales can determine the Hubble constant, the matter density, the baryon density, and the vacuum density.



COBE View was Blurry



Sometimes higher resolution...



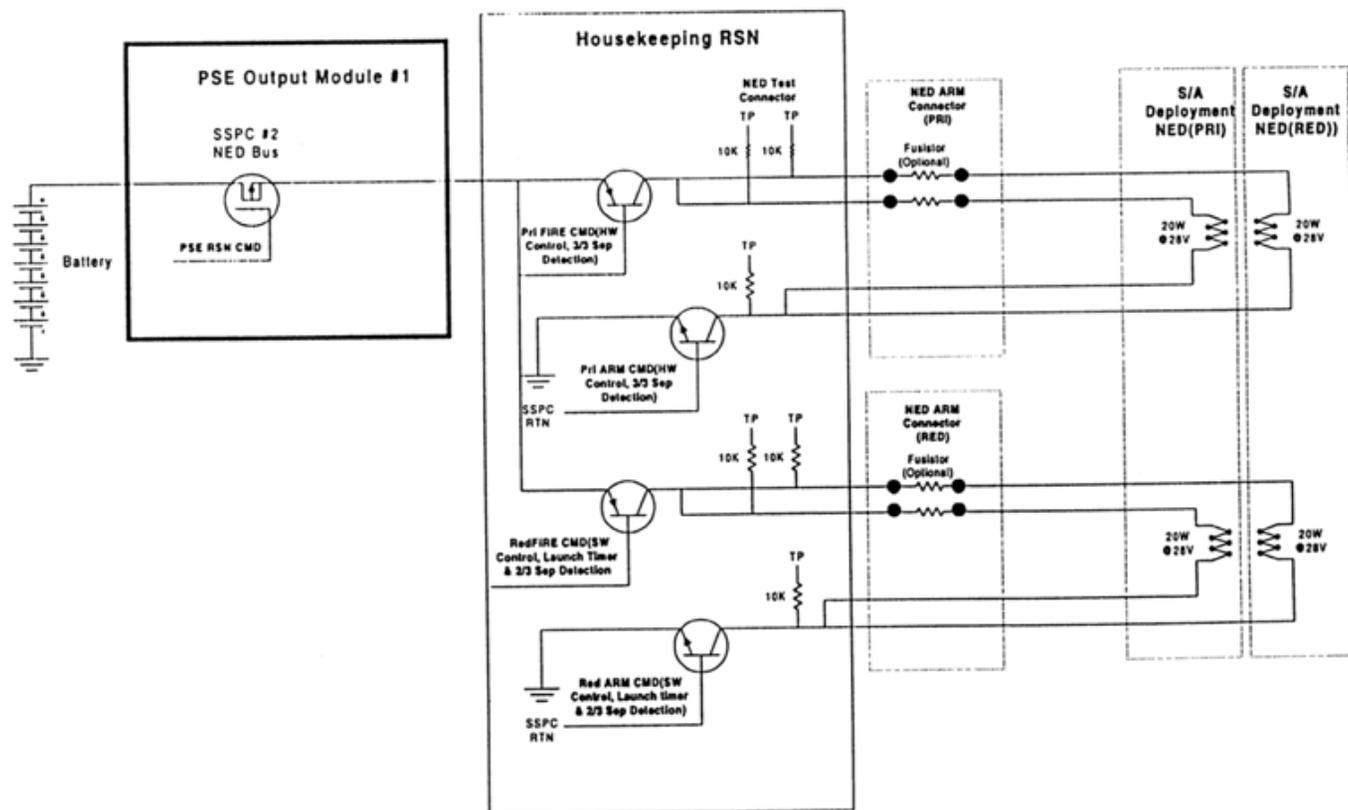
reveals the secret of the Universe

WMAP Status on 30 Jun 2001

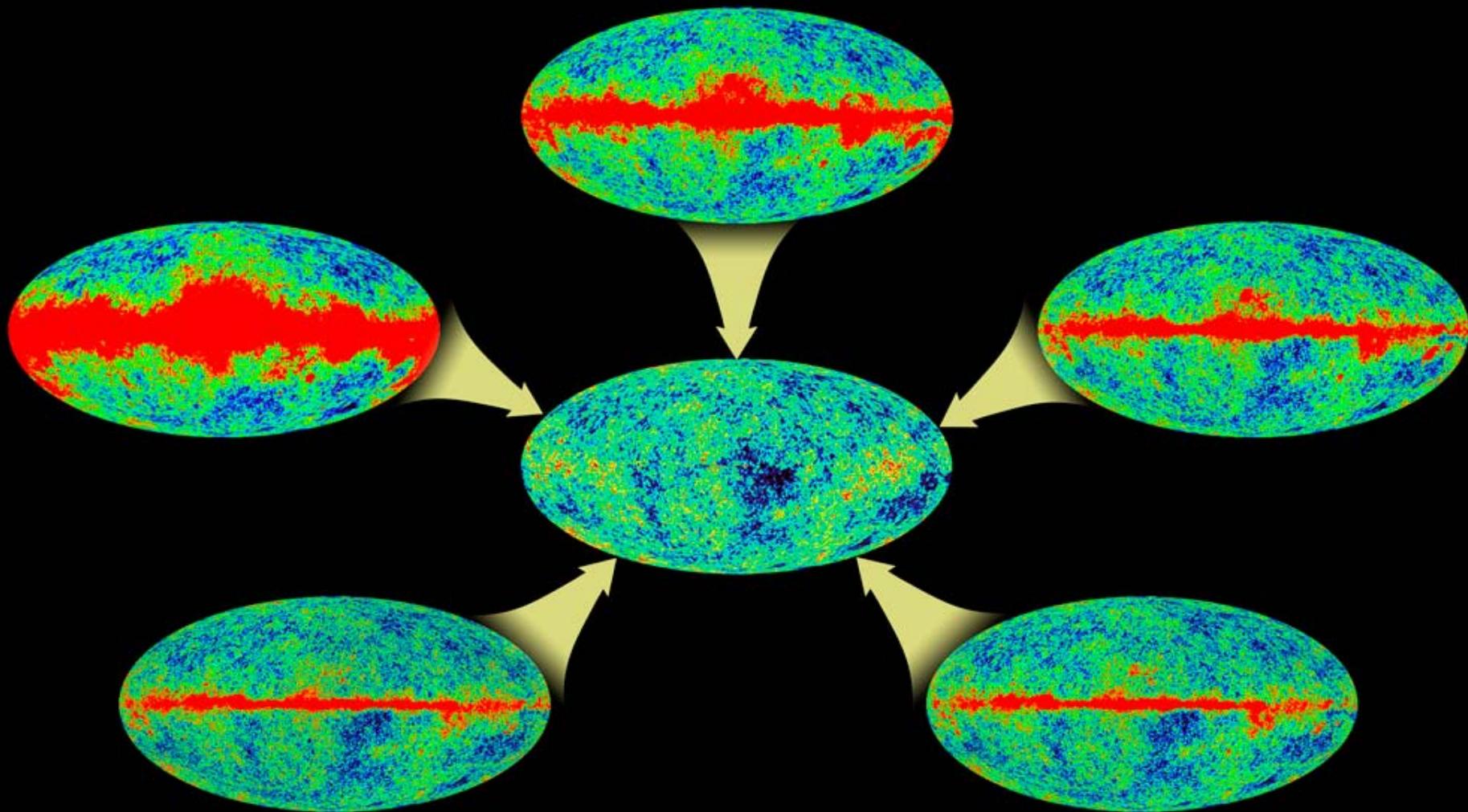


and WMAP has a NED Controller!

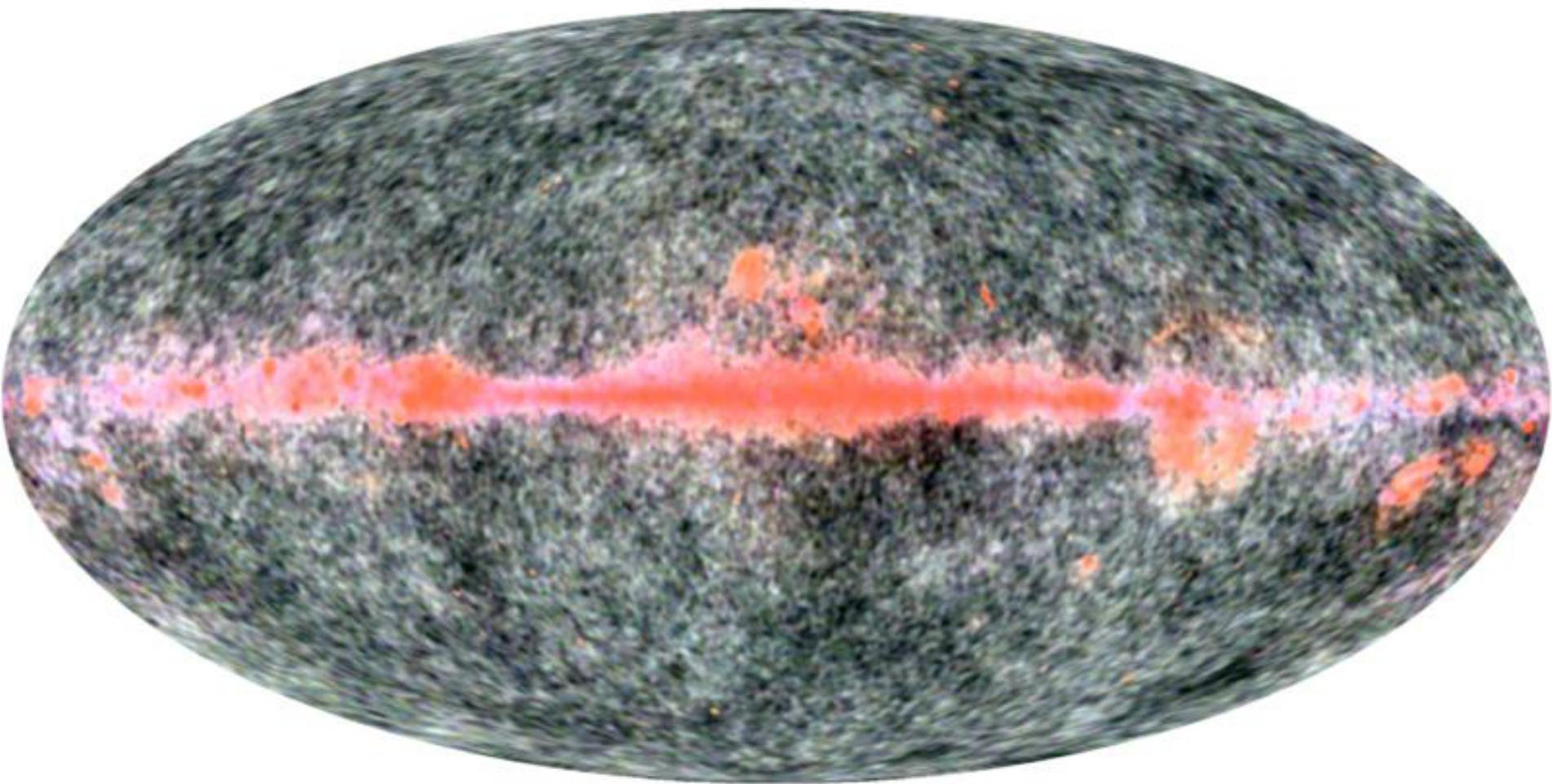
S/A Deployment NED Control



Combination to remove foreground

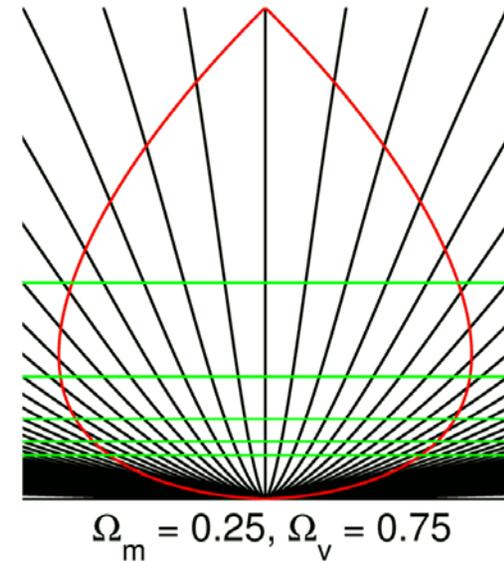
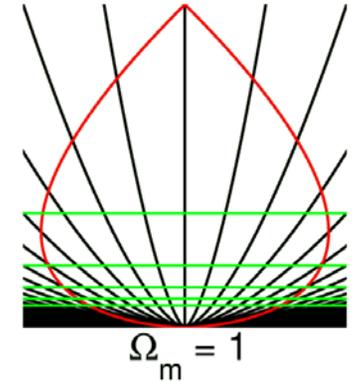
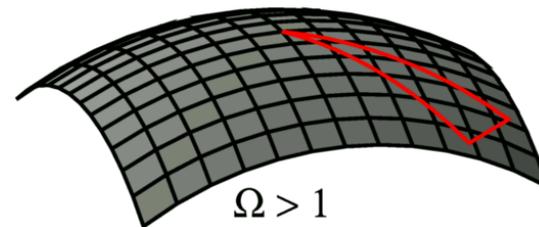
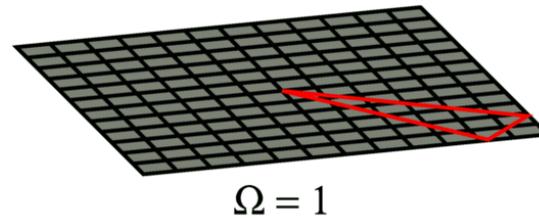
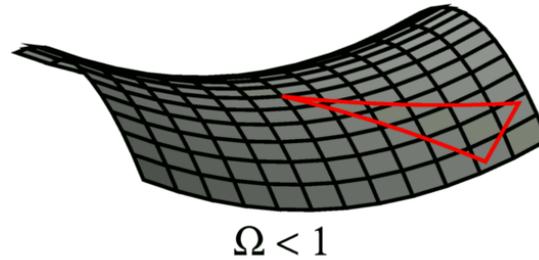


QVW as RGB



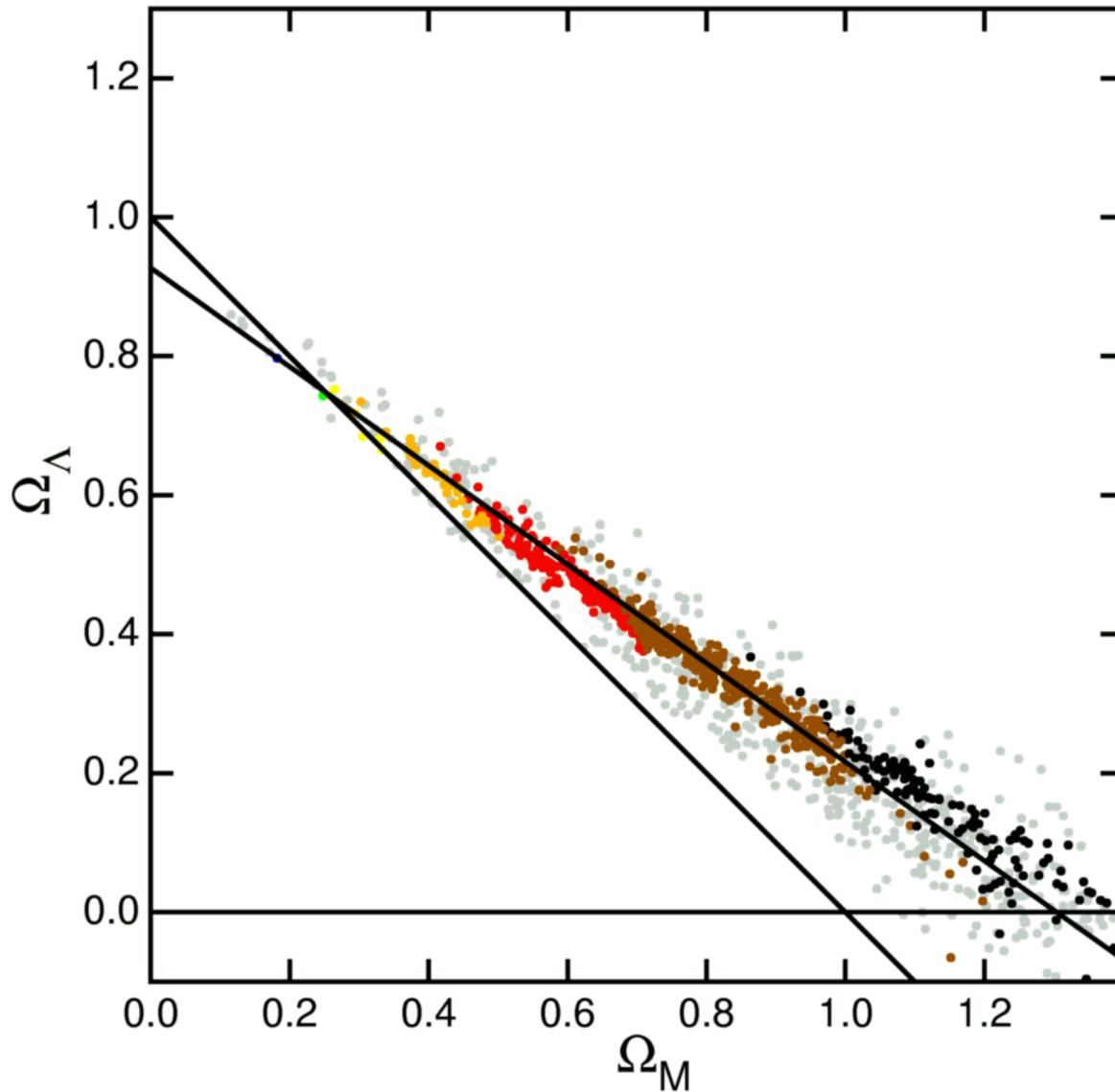
Effects on Peak Position: l_{pk}

- + Open or vacuum dominated Universes give larger distance to last scattering surface
- + High matter density gives smaller wavelength



Results With WMAP

H_0 : 30 40 50 60 70 80 90 100

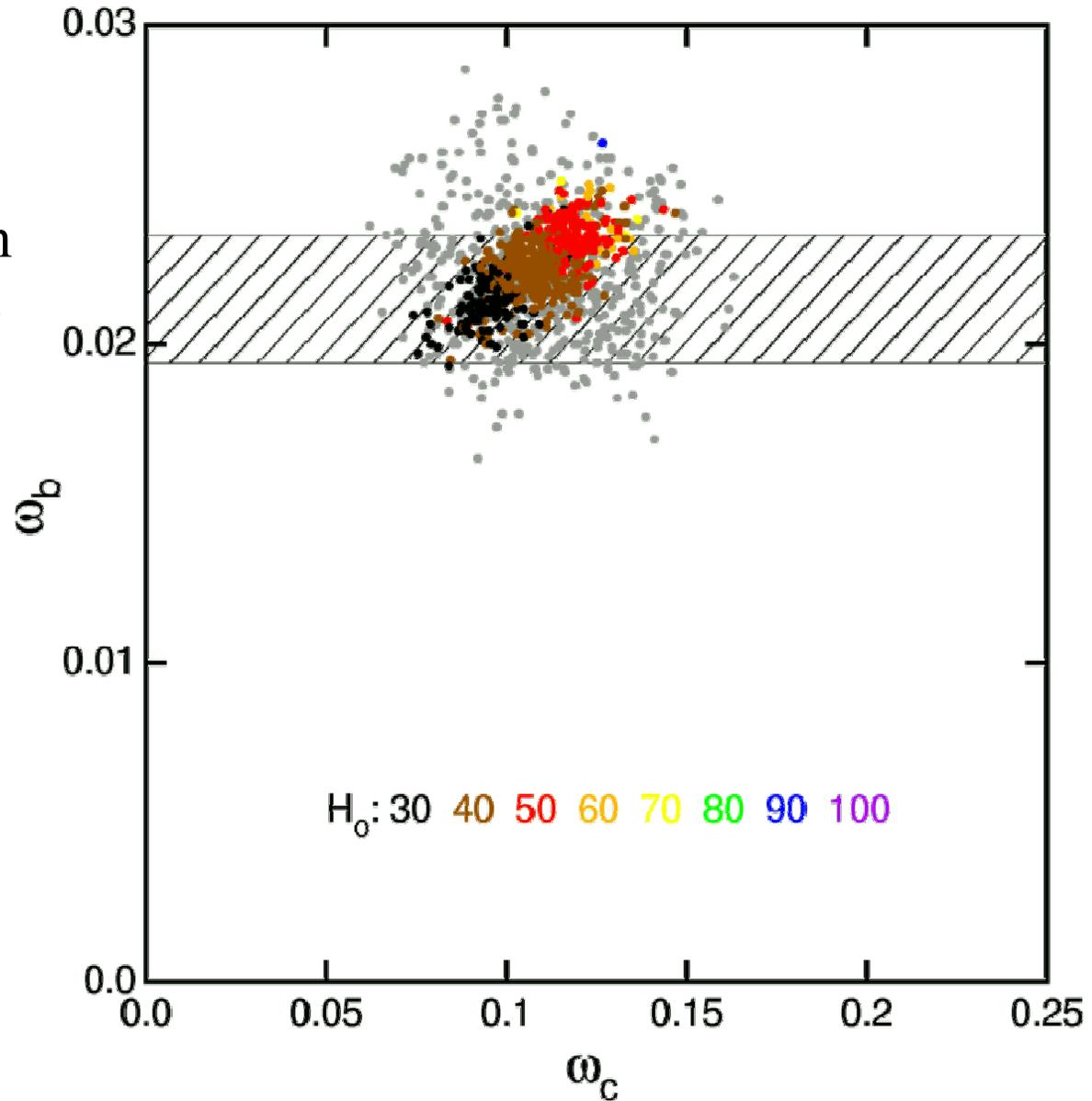


Info from peak & trough heights

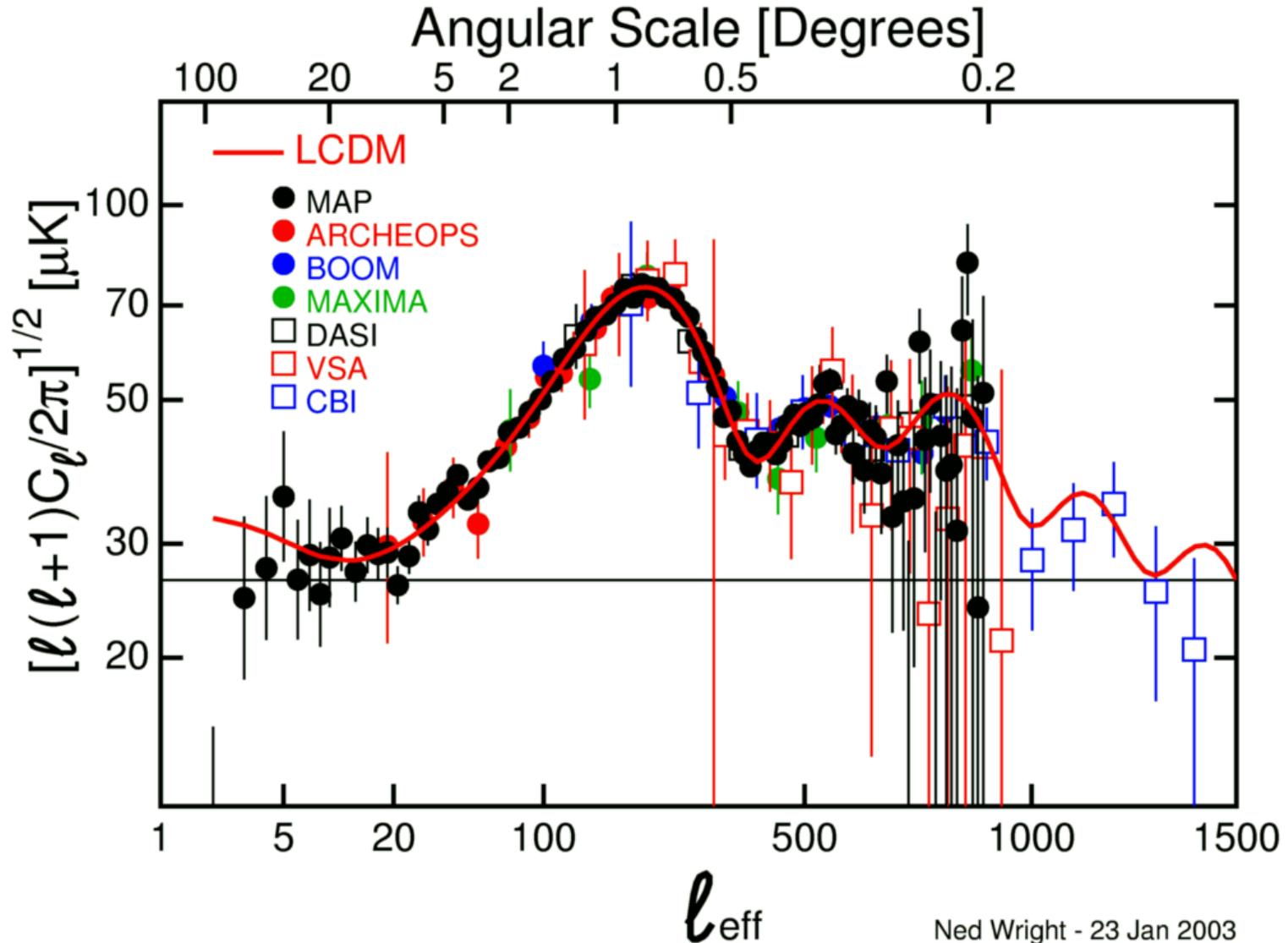
- Overall Amplitude of the perturbations
 - Agrees with large scale structure if almost all the dark matter is COLD dark matter
- Primordial power spectrum power law spectral index: $n = 0.99 \pm 0.04$ without running index.
 - EPAS inflationary prediction is $n = 1$
- Baryon/photon and DM/baryon density ratios
 - $\rho_b = 0.42 \text{ yoctograms/m}^3 = 0.42 \times 10^{-30} \text{ gm/cc}$
 - $\rho_{\text{cdm}} = 2.1 \text{ yg/m}^3$ [$\omega \equiv \Omega h^2 = \rho / \{18.8 \text{ yg/m}^3\}$]

Results With WMAP

Note the new
BBNS value from
astro-ph/0302006



Λ CDM is a Good Fit

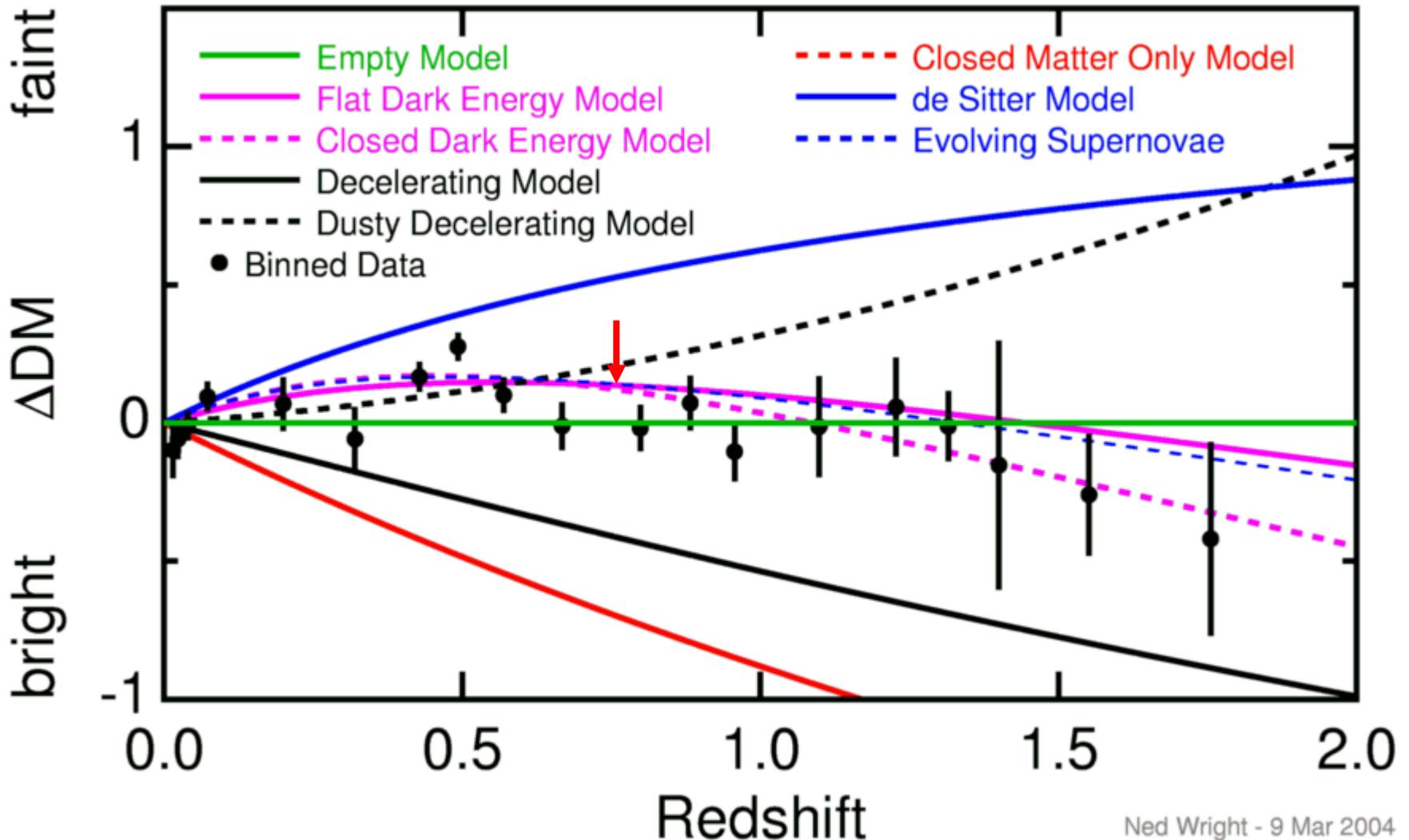


$$H_0 = 71, \Omega_\Lambda = 0.73, \Omega_b h^2 = 0.0224, \Omega_m h^2 = 0.135, \Omega_{\text{tot}} = 1$$

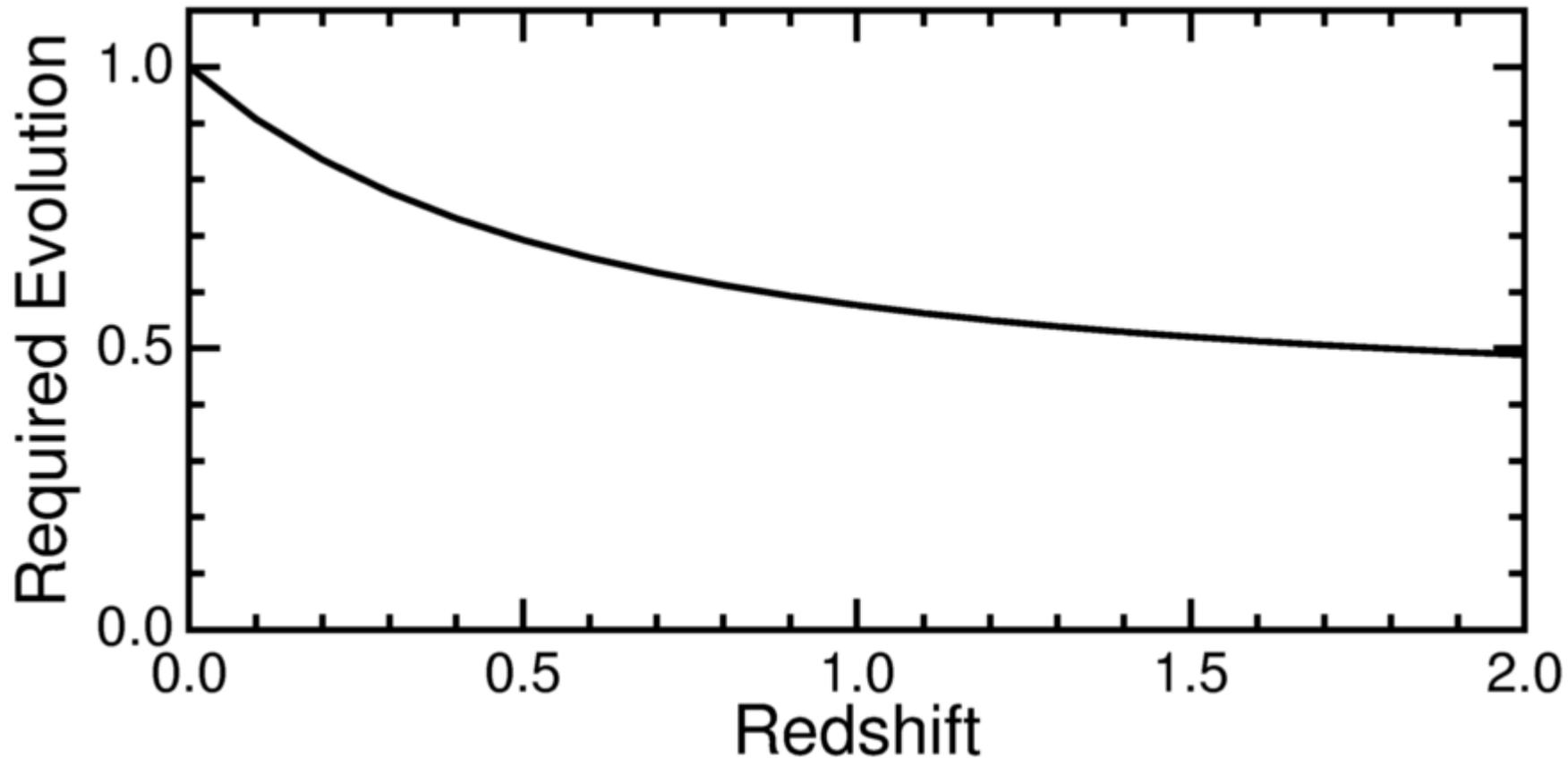
The latest from supernovae

- Several new $z > 1$ SNe, and a great data table in Riess *et al.*, astro-ph/0402512
- Contrary to STScI propaganda, these do not rule out evolution models. Evolution as an exponential of cosmic time in an EdS model is a nearly perfect match to Λ CDM.
- Furthermore, supernovae are fainter than expected in any model with matter, and high- z SNe are “more fainter”. There is no “cross-over” when q changes sign.

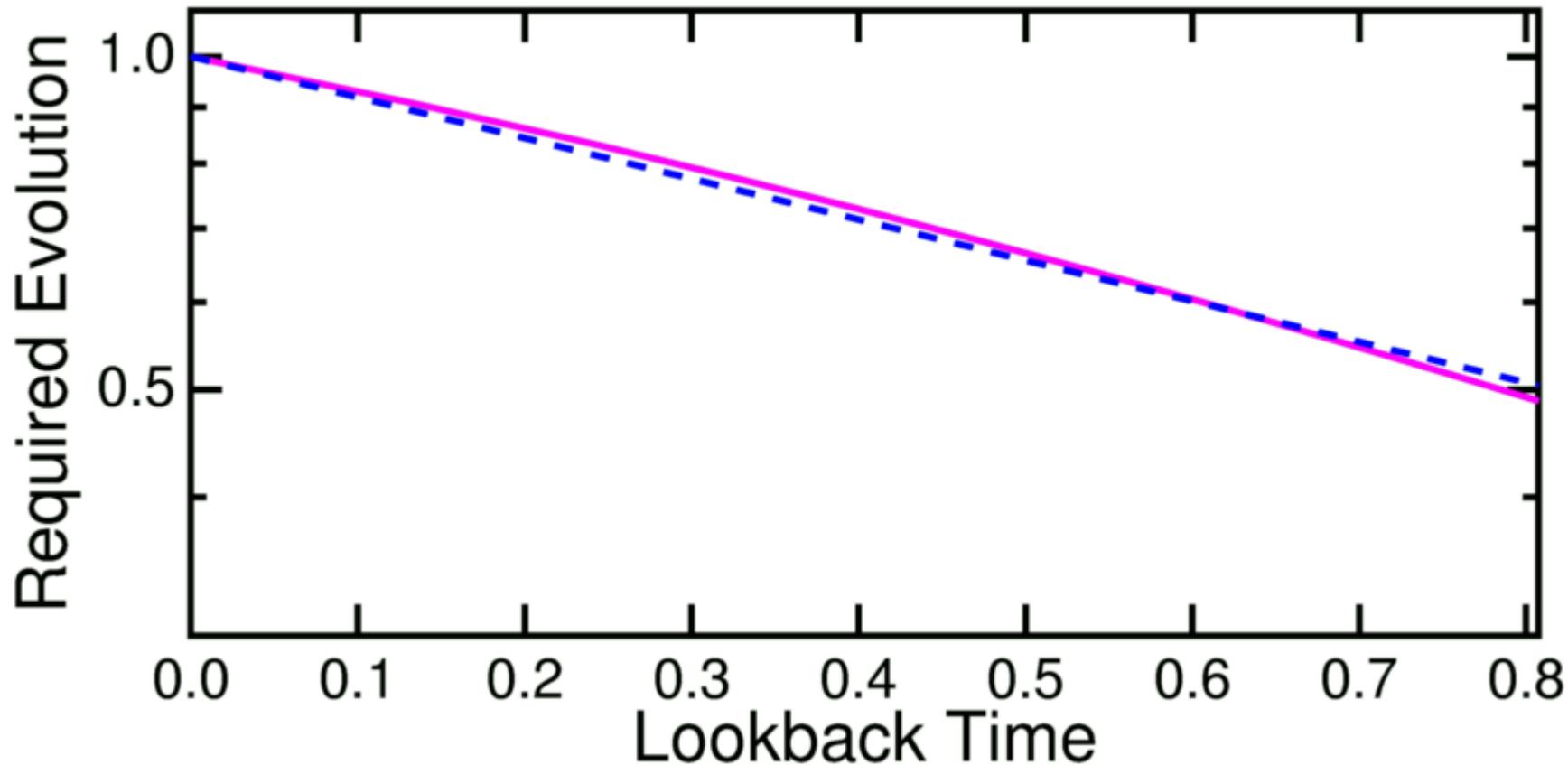
Distance Modulus wrt empty model



Dimming relative to $\Omega_m=1$



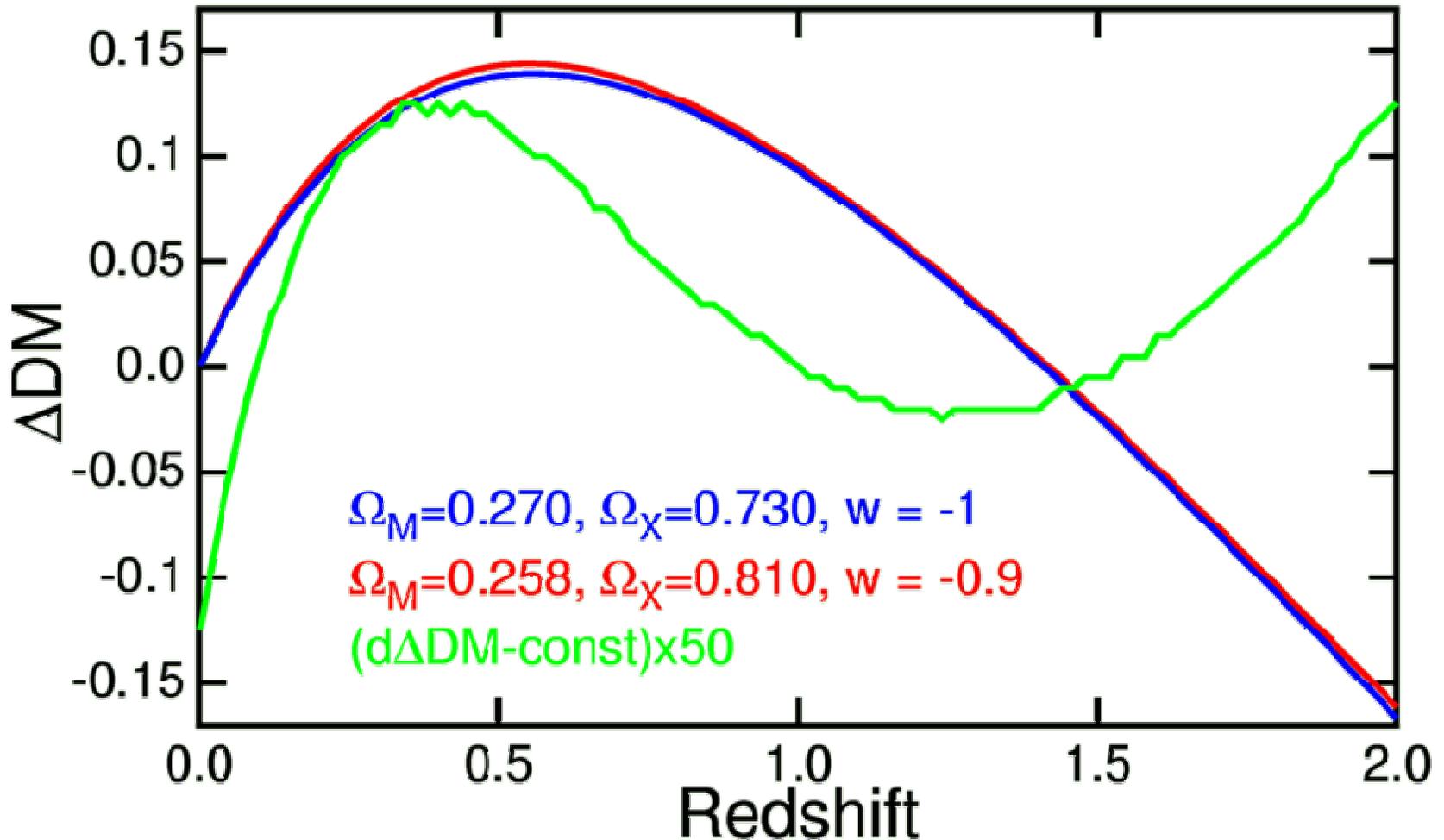
Dimming relative to $\Omega_m=1$



$\Omega_m h^2$ is known, not Ω_m

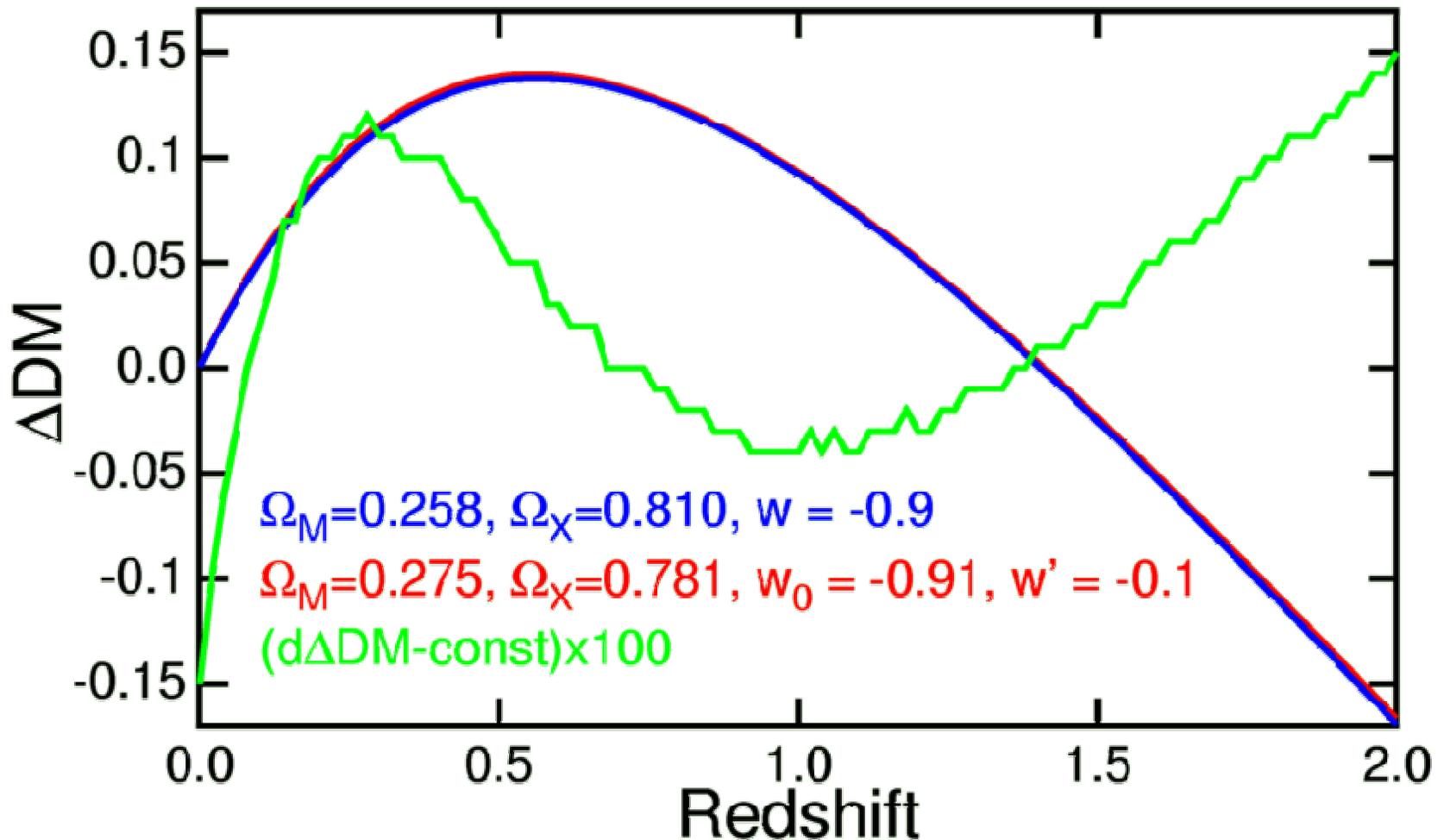
- This makes the H_0 contours vertical lines
 - Contours of $\Gamma = \Omega_m h$ are also vertical lines which are consistent with the HST Key Project Hubble constant.
-
- There is actually a small tilt because $\Omega_m h^2$ shifts when the CMB fit is forced far from the ridgeline.

SNe alone can't measure w



- Model with $w = -1$ and $w = -0.9$ agree to within ± 2 millimag

SNe alone can't measure w'

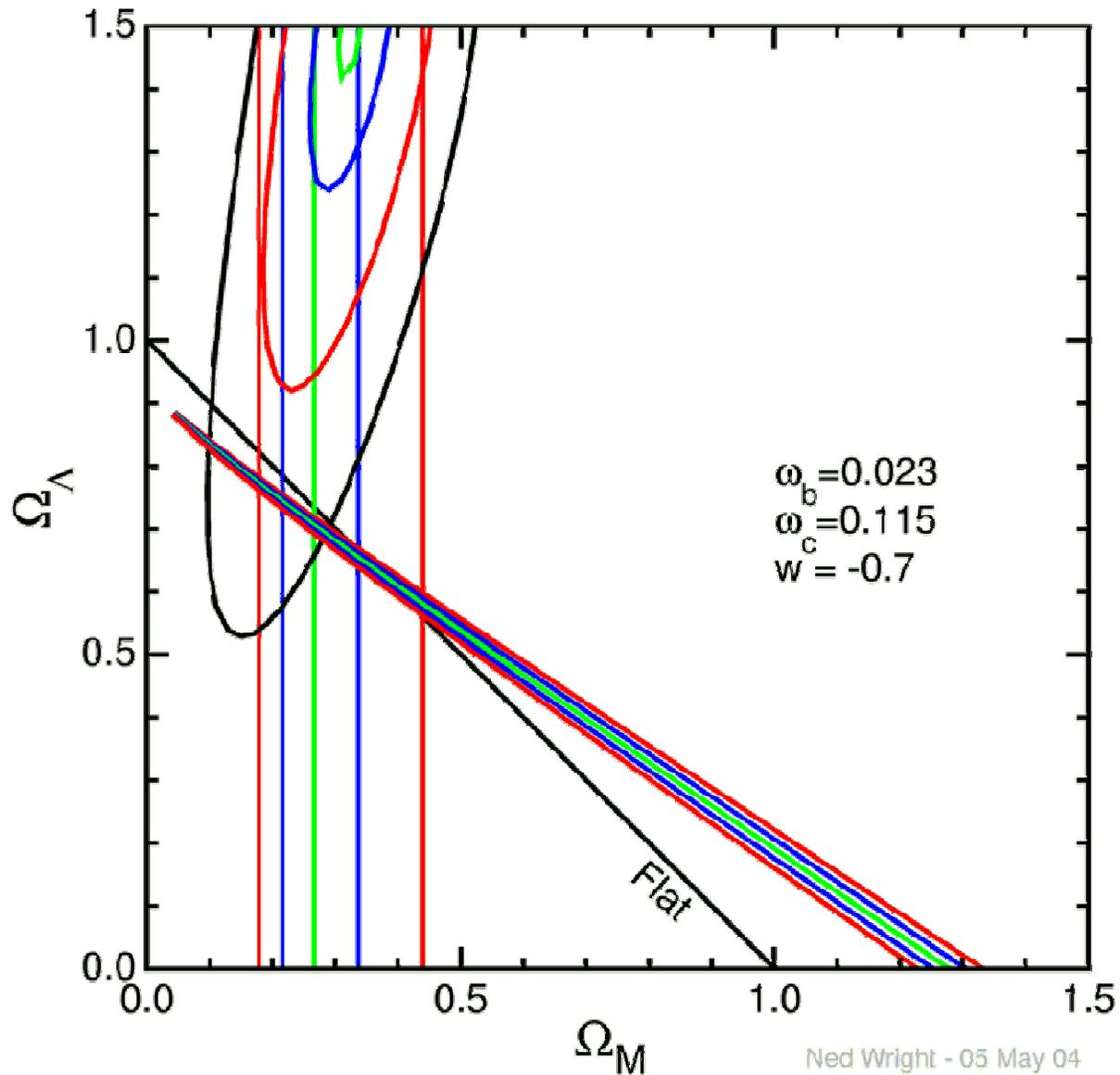


- Model with $w' = 0$ and $w' = -0.1$ agree to within ± 1 millimag

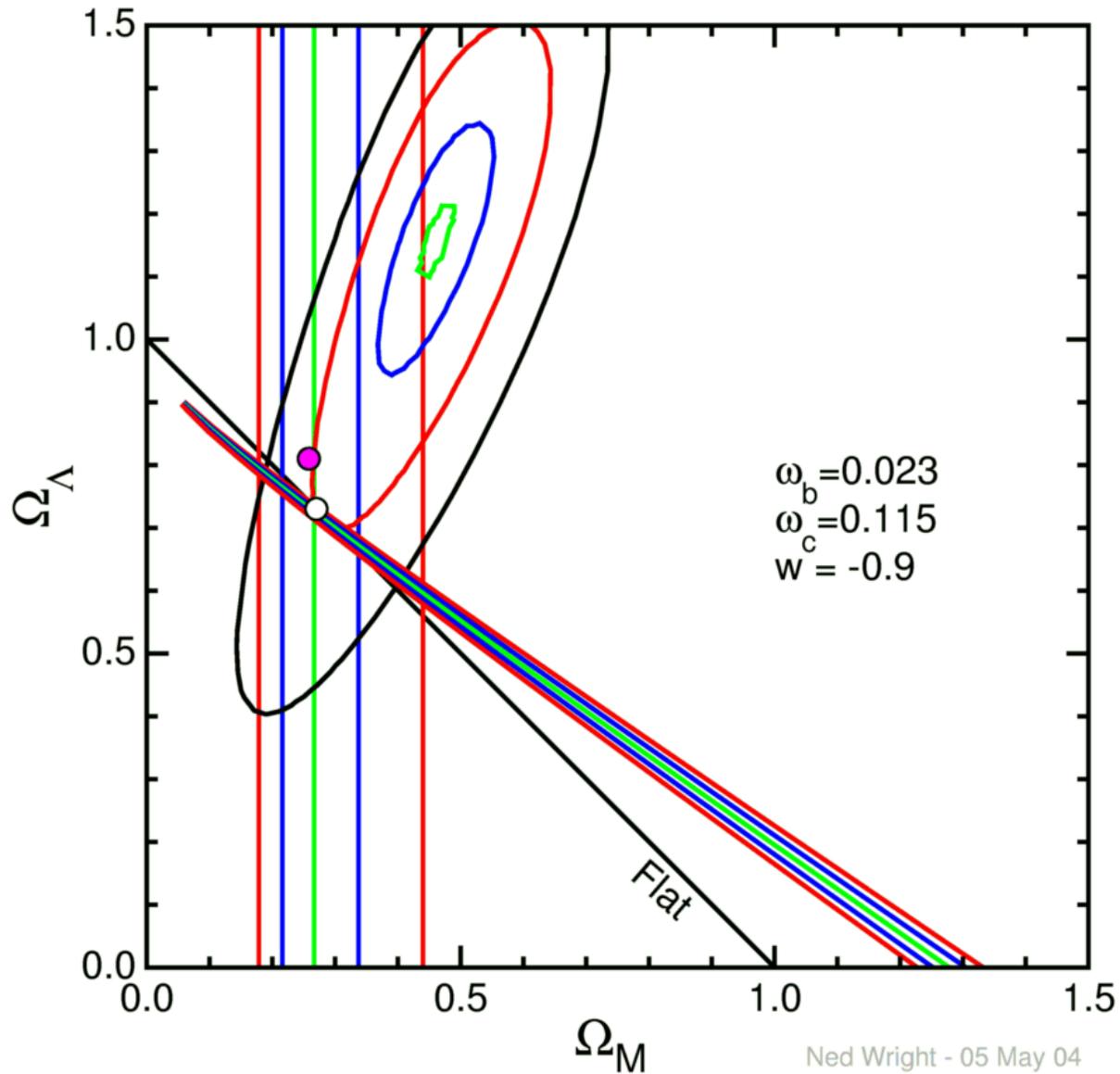
Non-supernova data needed for w

- Following charts show an actual fit to the SNe data, but only an approximation based on the acoustic scale for the CMB.
- The physical matter density is fixed at the value given by WMAP 1-year data.
- But if $w \neq -1$ then the dark energy will be dynamic, have spatial inhomogeneities, and change the angular power spectrum of the CMB by more than just a change in peak position.

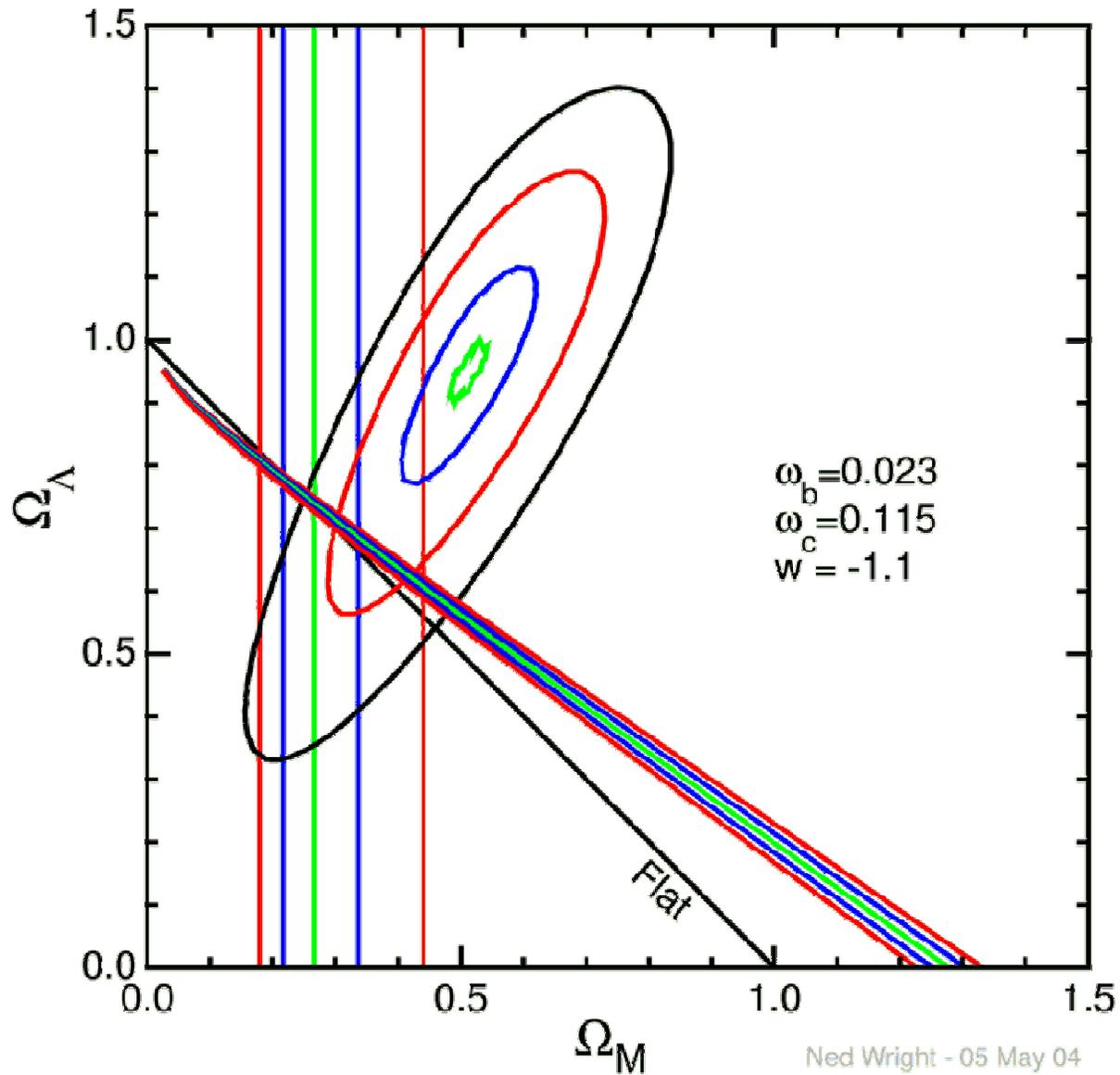
Can we measure $w = P/\rho c^2$?



Can we measure w ?



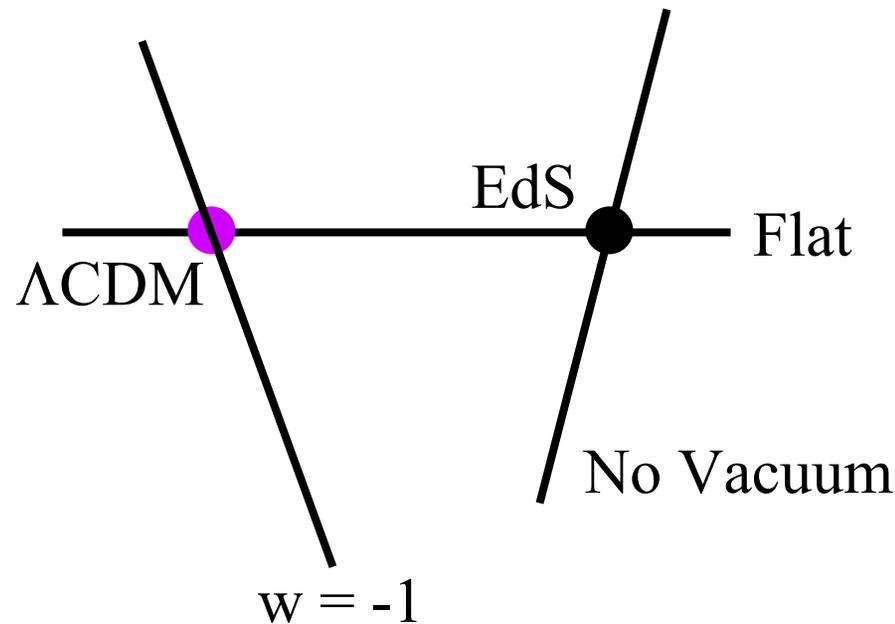
Can we measure w ?



The Three Simplificities

- $\Lambda = 0$ but this probably is not correct.
- $\Omega_{\text{tot}} = 1$.
- $w = -1$ if there is dark energy.
 - Note that if $w = -1$, the dark energy is Lorentz invariant, but if $w \neq -1$ observers can measure their velocity with respect to the dark energy so the dark energy has to be a dynamical thing that will react to inhomogeneities in the Universe. Thus w will be a function of space and time.
 - The assumption that $w = f(z)$ is silly.

Generalized non-flat dynamic fluctuating quintessence.



SN data pushed us off the simplest EdS model. If more data pushes us off the ΛCDM model, there is little reason to expect that a flat (w, w') model will be correct.

We should prove flatness.

- The success of the flat model with $w = -1$ can not be used to justify assuming flatness when trying to find w and w' .
- Certainly $\Omega_{\text{tot}} = 1$ is simpler, but
 - $\Omega_{\text{X}} = 0$ is simpler, no CDM is simpler & $w = -1$ is simpler
- But the model consistent with both the CMB and SNe data moves as w is varied, and is most consistent with the Hubble constant from the HST Key Project when w is close to -1 . So w can be measured ***using all data combined*** but be suspicious of priors on Ω_{tot} or Ω_{M} .

If $\Omega = 1$, then $w = -1$ is a good fit to all the data. If $w = -1$, then flat Λ CDM is a good fit to all the data.

Observational systematic errors

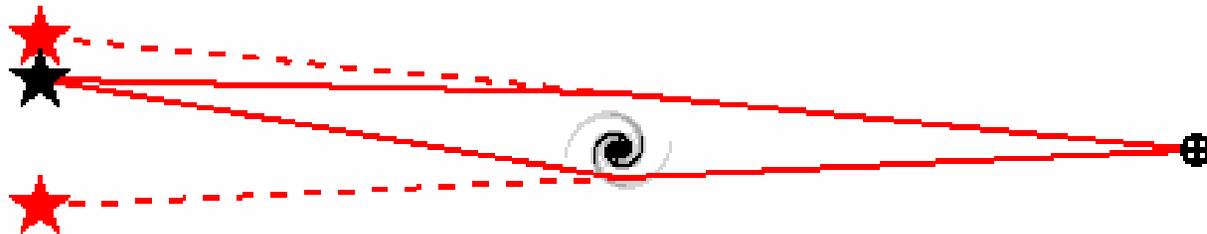
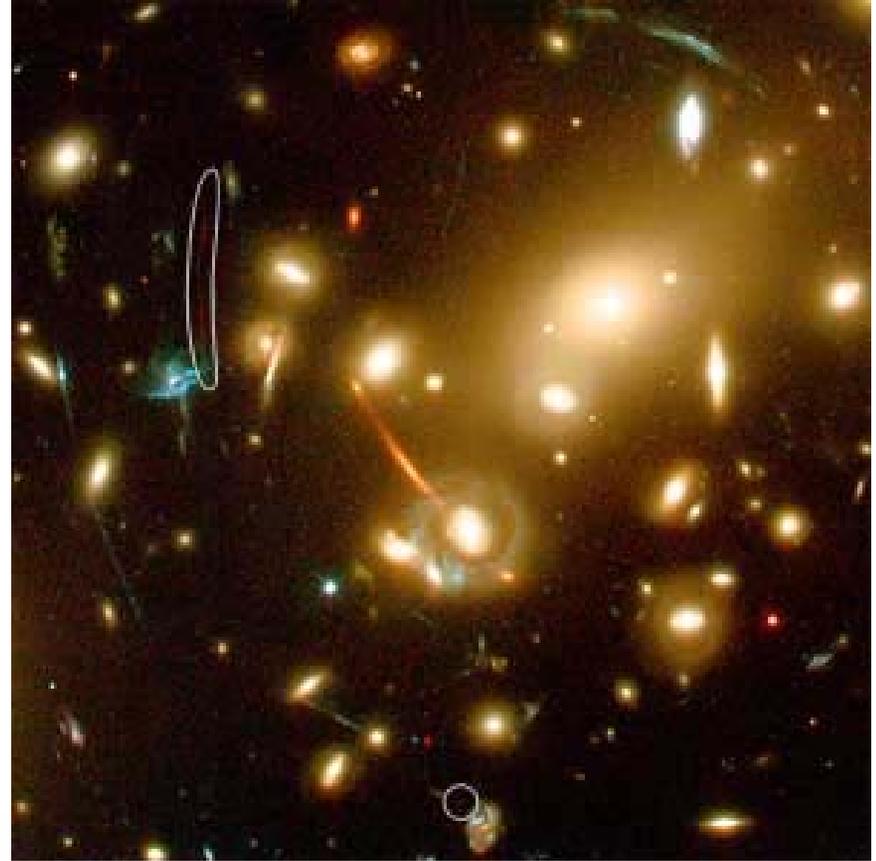
- Absolute calibration of photometry. A 1% error is the ratio of 0th mag fluxes between V (550 nm) and H (1.6 μm) would be as big as the effects being sought.
- A 1 K error in the absolute temperature of a 2800 K calibration lamp would cause an effect bigger than the residuals from $\Delta w = 0.1$ with Ω_M & Ω_{DE} free.
- Perhaps NIST should join the JDEM collaboration.

Astrophysical Systematic Errors

- Evolution with age of the Universe of any of the parameters that control the big bright=slow eigenvector of the Type Ia SNe
- Lensing
- Contamination by SNe II or Ib varying as a function of z .
- And the ever popular gray dust. A “steady state” dust model with constant physical dust density is a better fit to the current SNe data than Λ CDM.

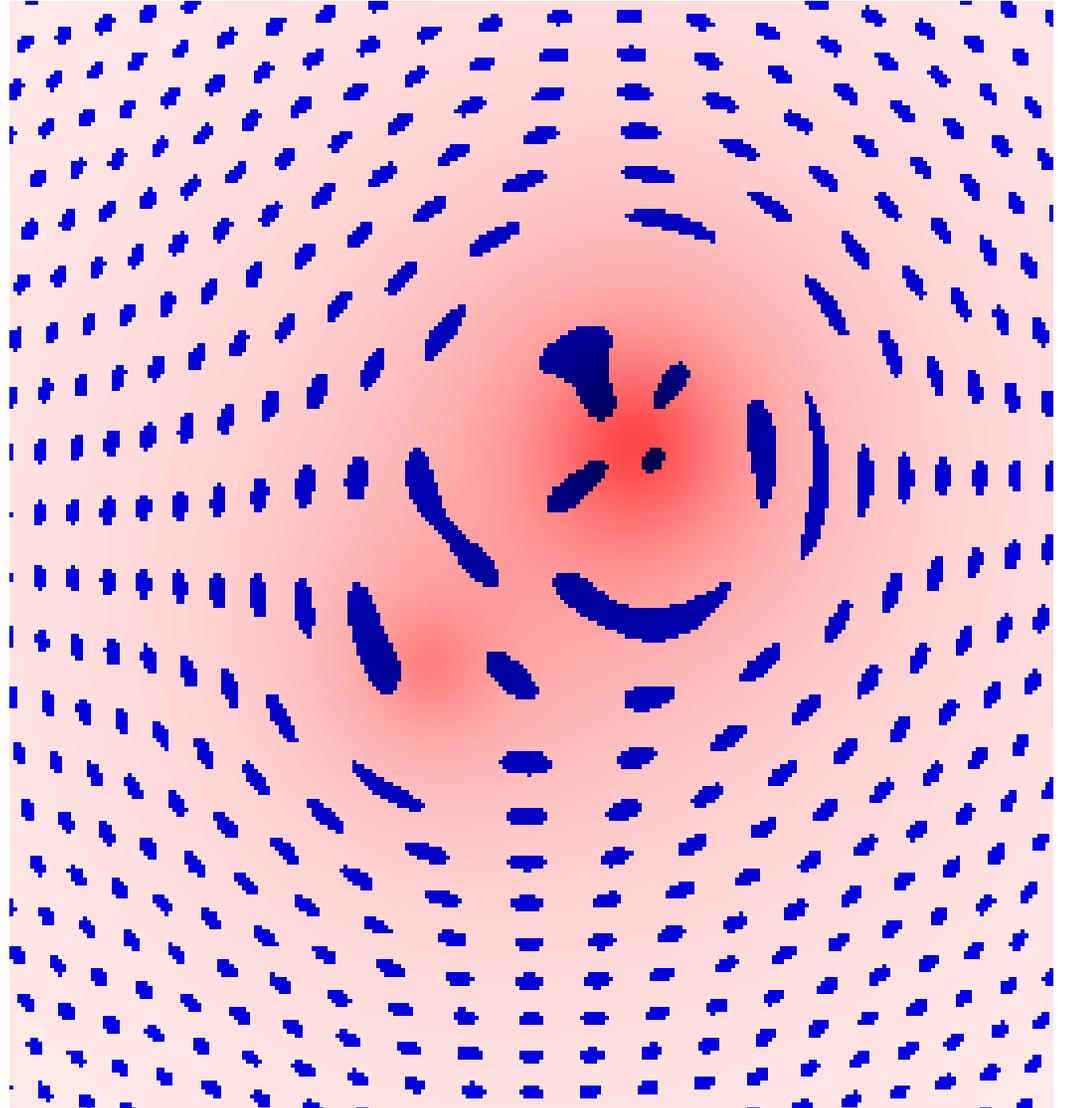
Gravitational Lensing

- Light is bent by a cluster of galaxies.
- For a symmetric cluster a small faint galaxy can be made into a long and much brighter arc or even a complete ring: the “Einstein ring”

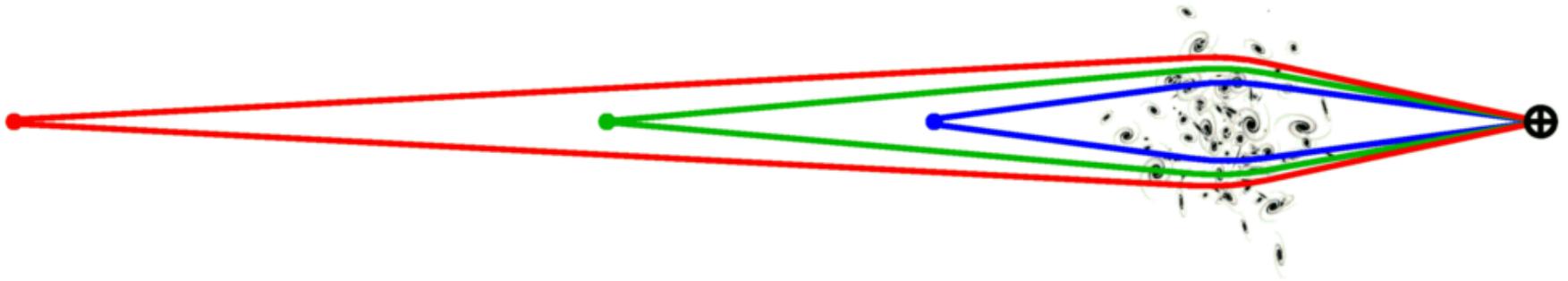


Cluster Lensing

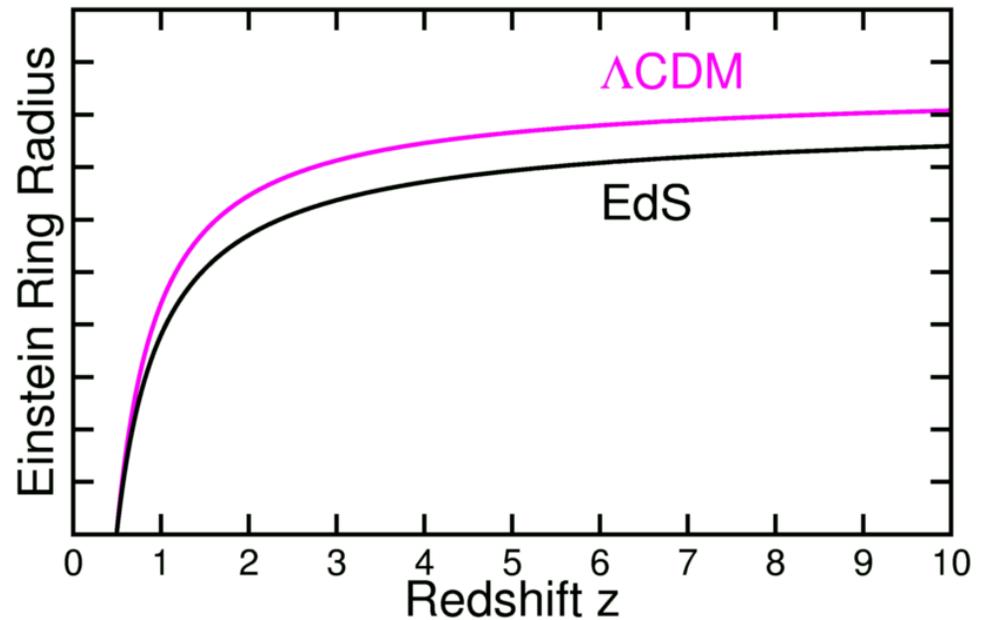
- This animation shows a foreground cluster of galaxies with the pink showing the projected mass density. It has two separate clumps.
- The blue background galaxies slide behind the cluster to illustrate the range of images that can be produced.



Einstein Ring Radius vs Distance

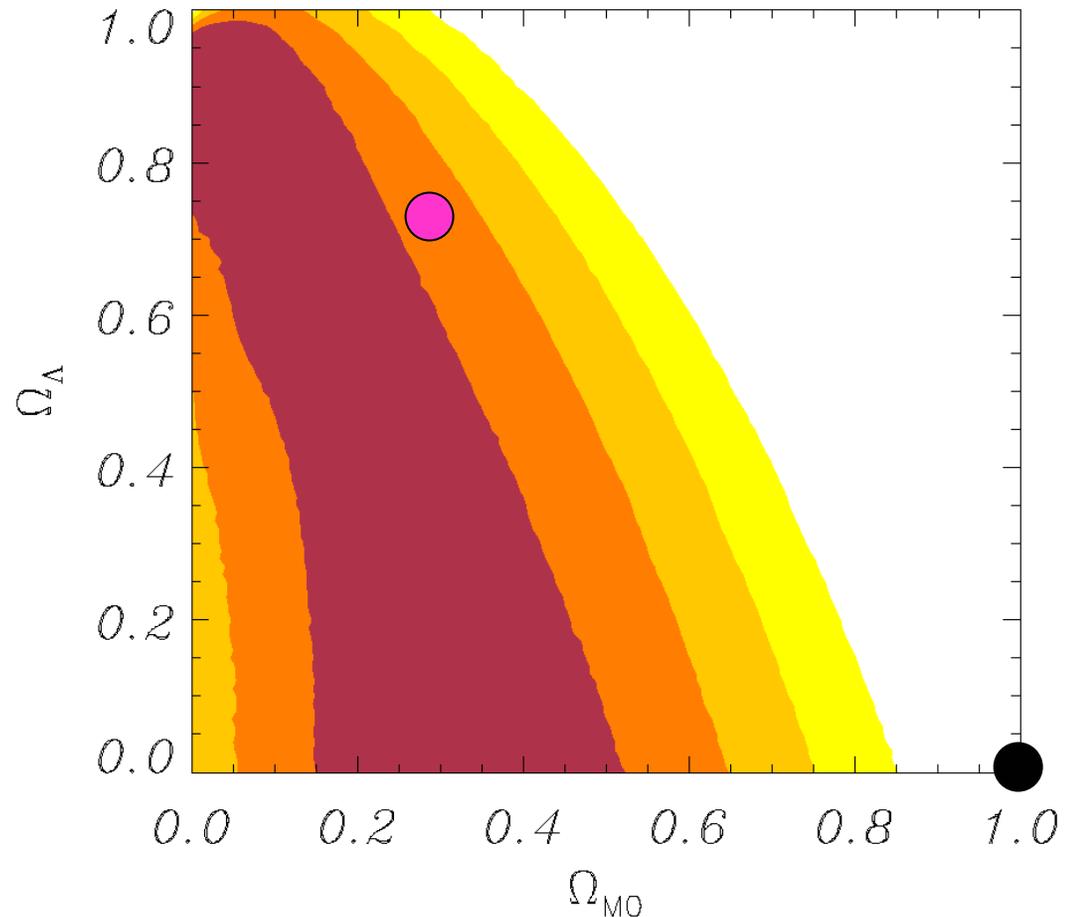


- Radius depends on distance.
- Distance depends on redshift and the geometry of the Universe.

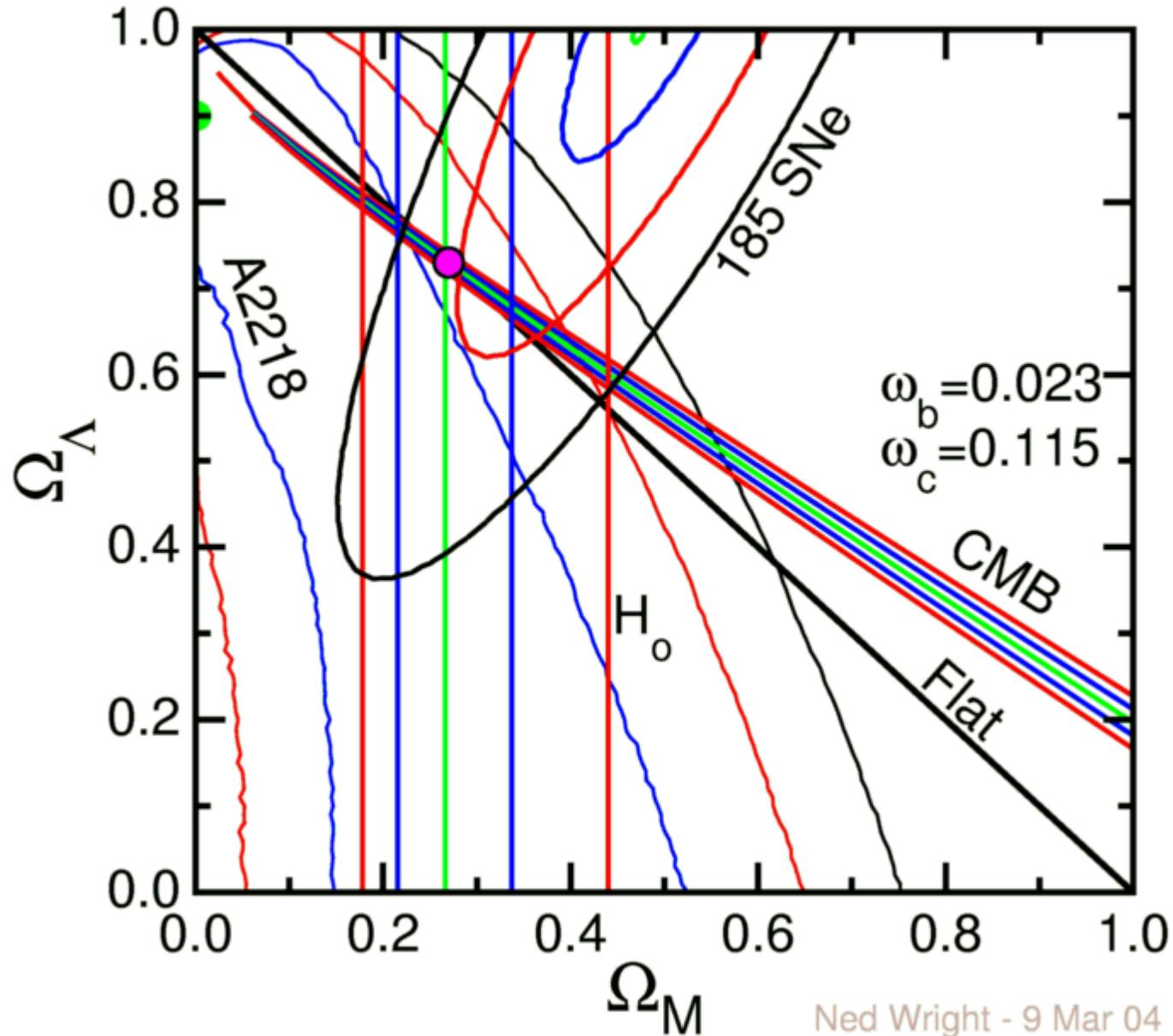


Can be used to measure Universe

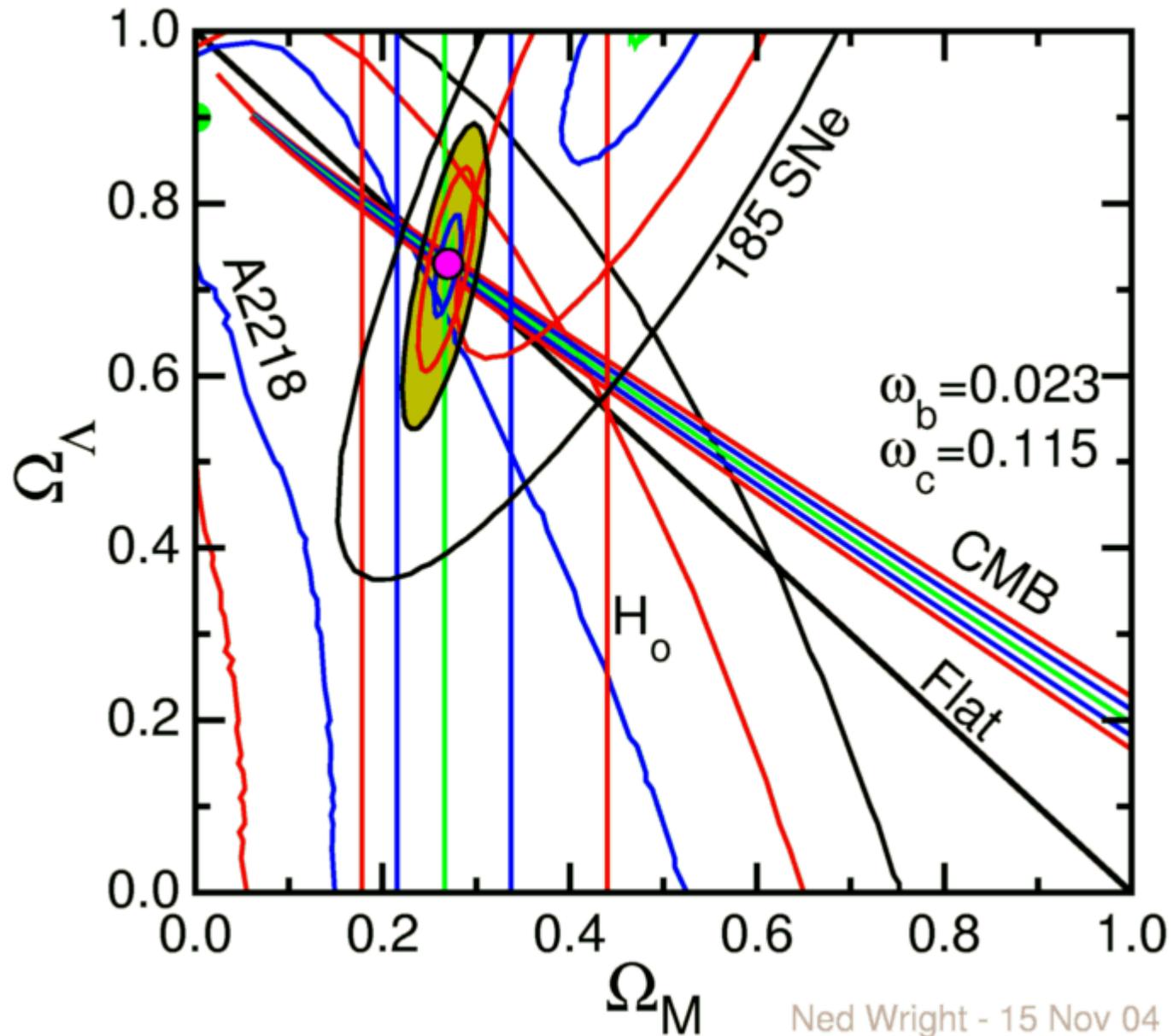
- 4 arcs with well-known redshifts in Abell 2218.
- These arc radii agree more-or-less with the **accelerating Universe** from SNe.



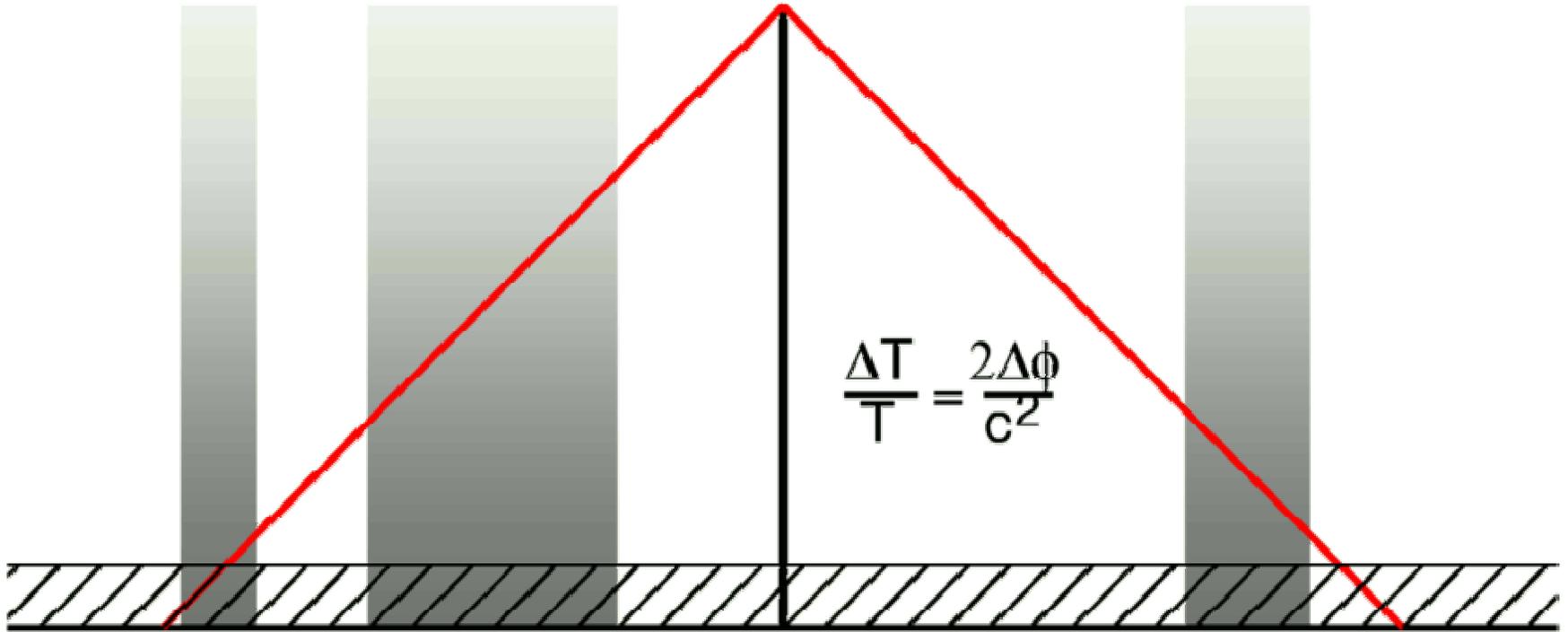
With known baryon & DM density



After a “SNAP”-like mission

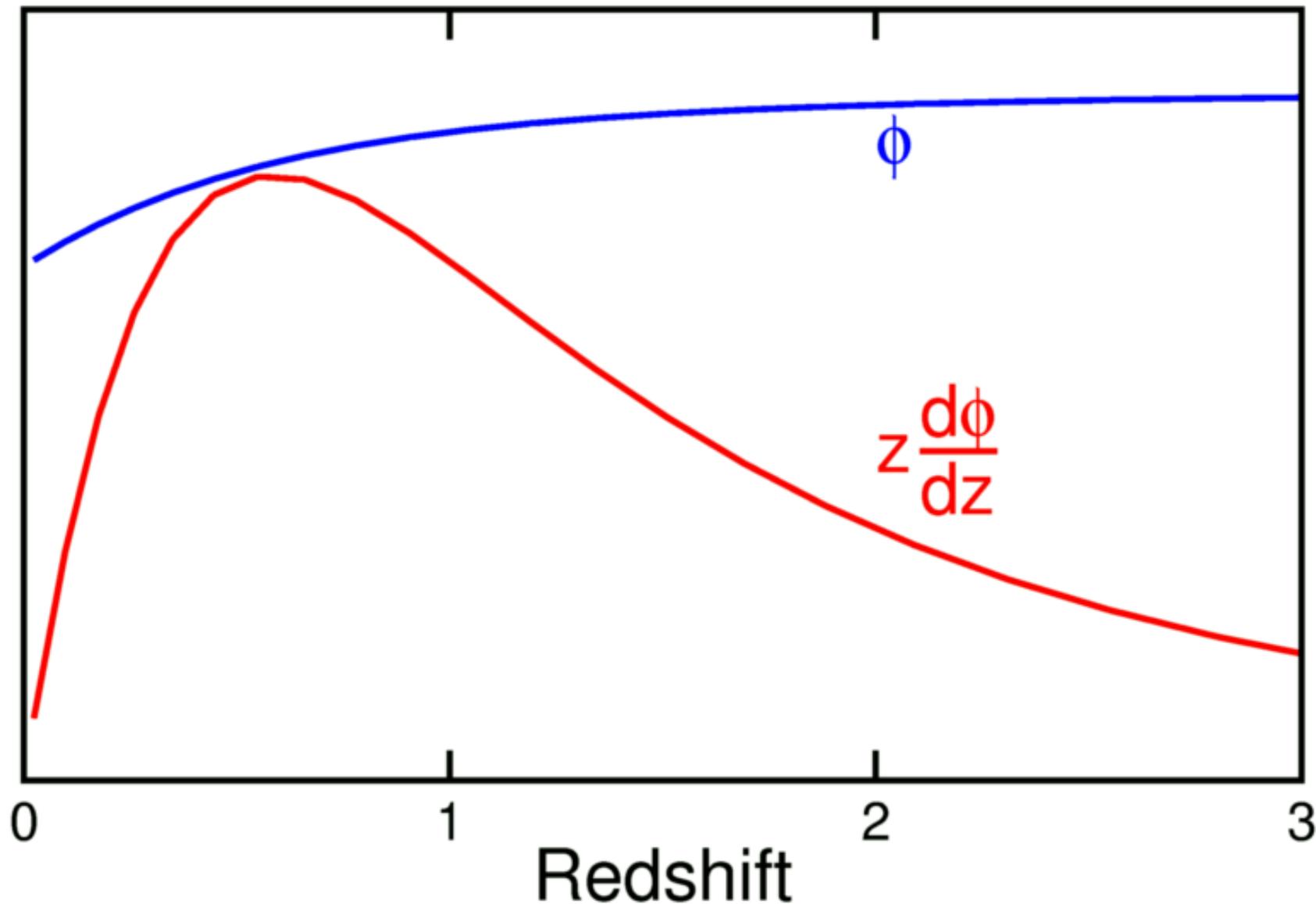


Late ISW Effect



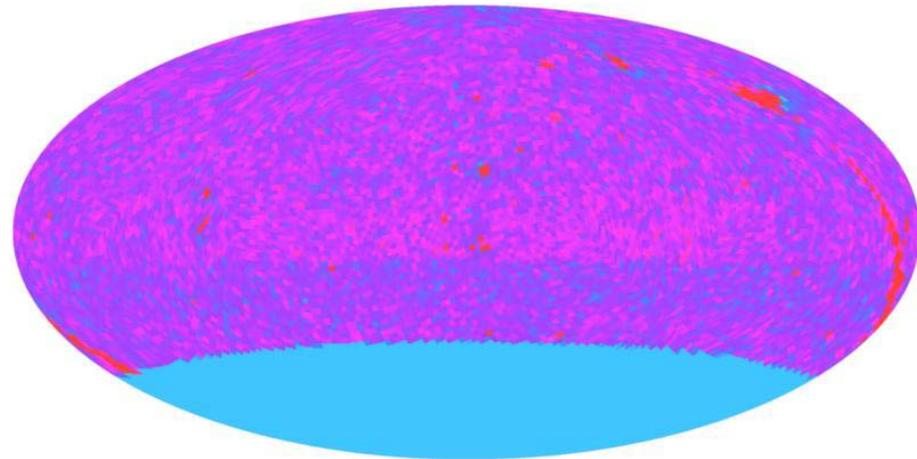
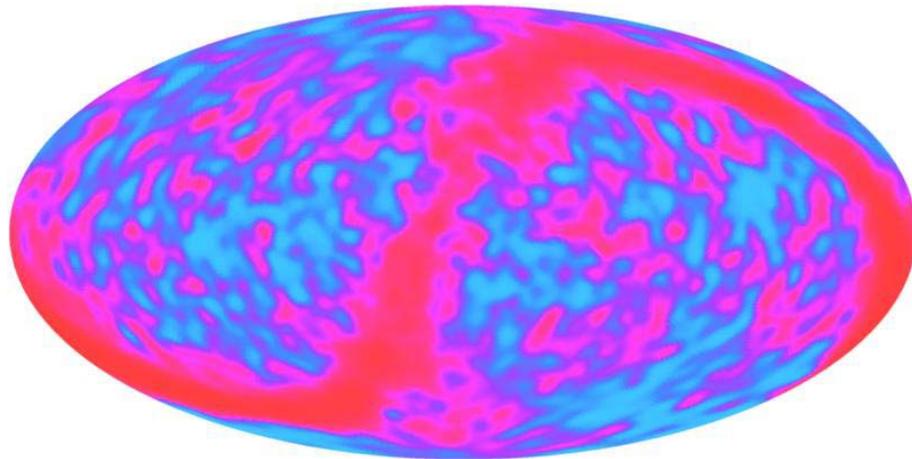
Potential only changes if $\Omega_m \neq 1$ (or in non-linear collapse, but that's another story [Rees-Sciama effect]).

Potential decays at $z \approx 0.6$



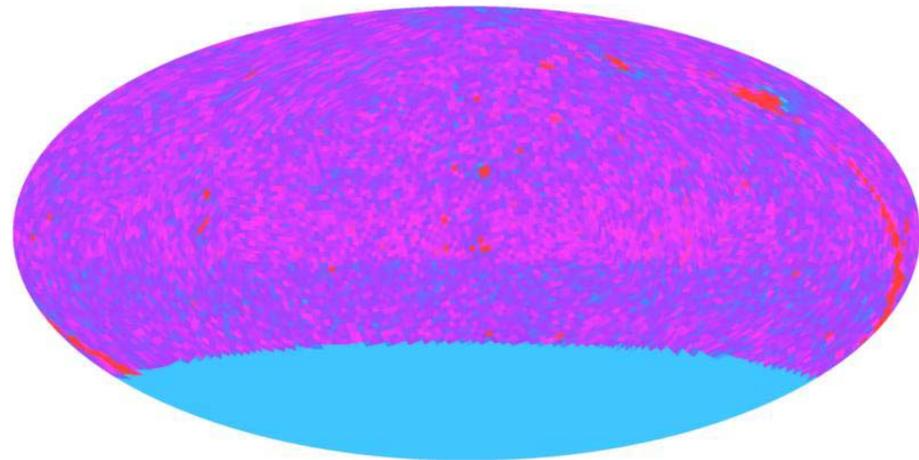
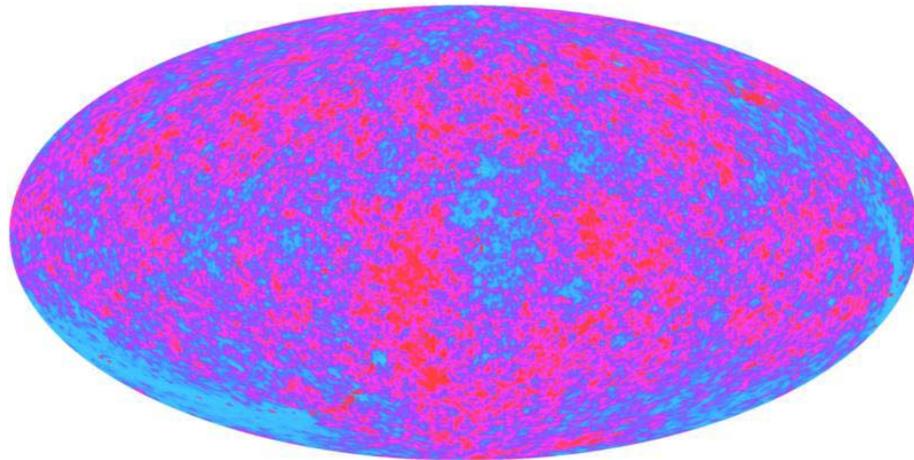
Correlated with Observed LSS

- This late ISW effect occurs on our past light cone so the ΔT we see is due to structures we also see.
- Search for correlation between LSS at $z=0.6$ and the CMB anisotropy: see Boughn & Crittenden, astro-ph/0111281
 - Expected 0.035 cross-correlation between NVSS sources and COBE DMR
 - observed -0.003 ± 0.025

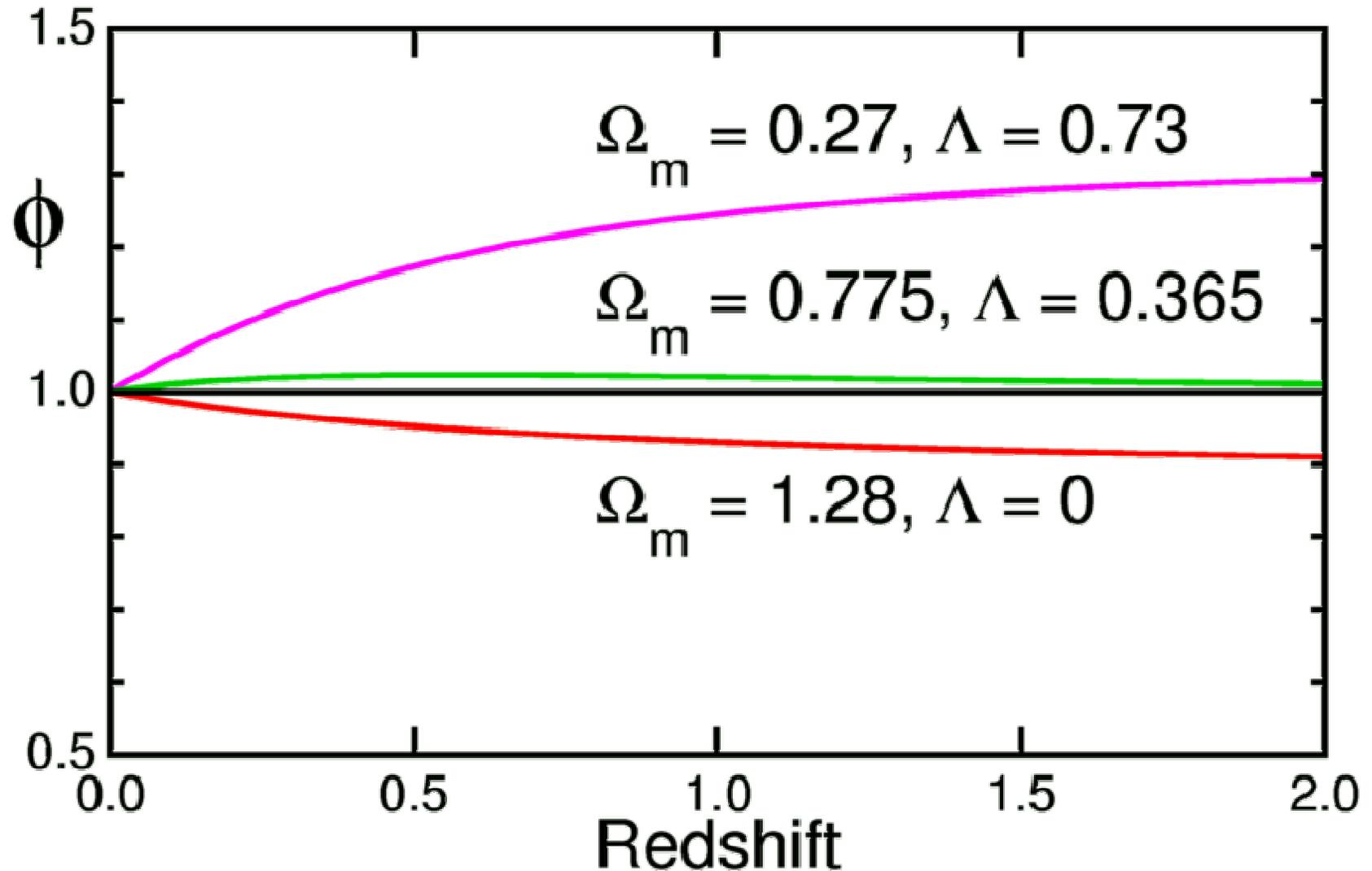


Correlation is seen with WMAP

- Correlation between WMAP and LSS seen by:
 - Boughn & Crittenden (astro-ph/0305001) at 2.75σ with hard X-ray background and 2.25σ with NVSS
 - Nolta et al. (astro-ph/0305097) at 2σ with NVSS

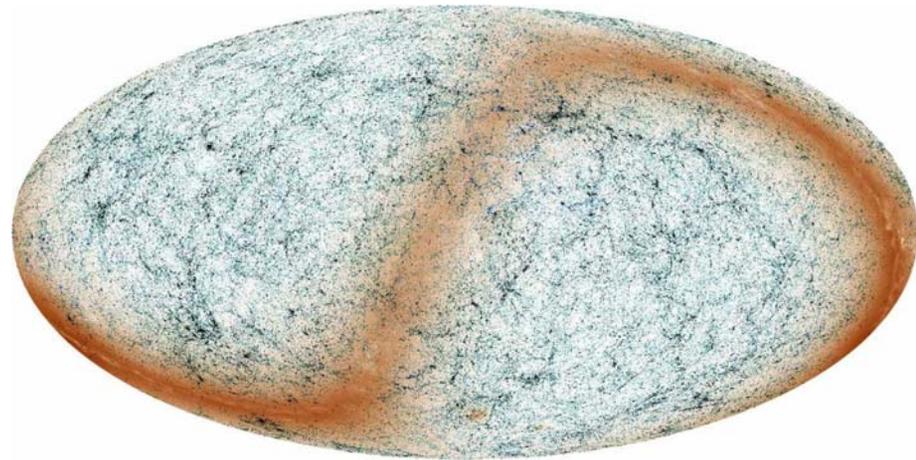
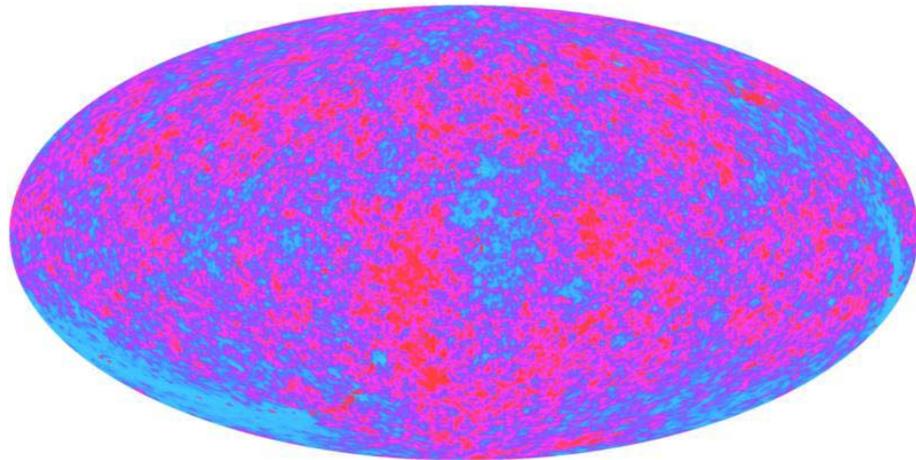


Λ CDM is OK, s SCDM fails at 3σ

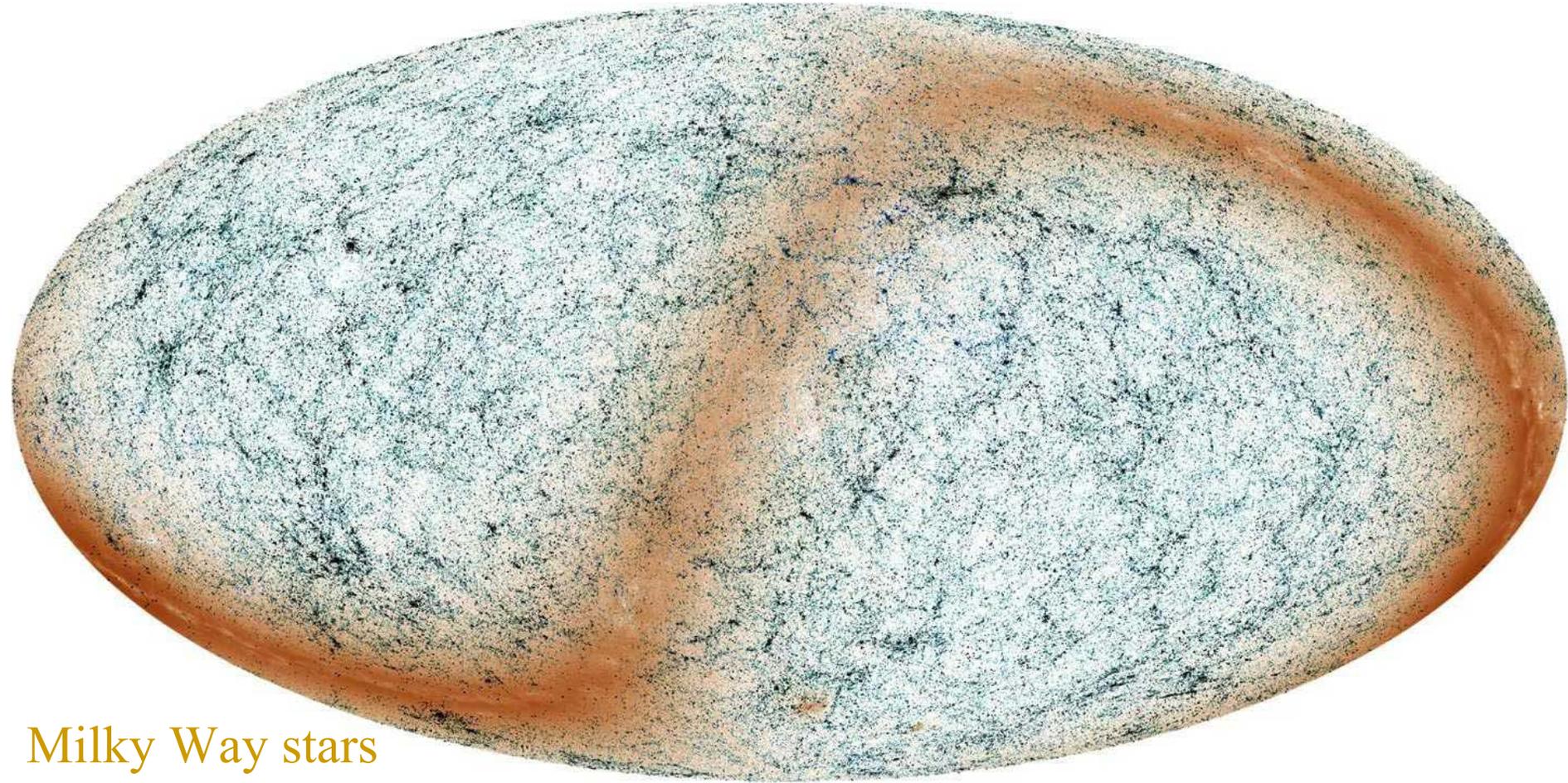


Possible Improvements?

- ✓ Less noisy and higher resolution CMB data.
 - WMAP is correlated with NVSS & XRB.
- Use a better tracer of LSS. IR surveys trace old stars and thus are close to a mass survey.
- Ashfordi et al (astro-ph/0308260) found 2.5σ ISW correlation between WMAP & 2MASS.



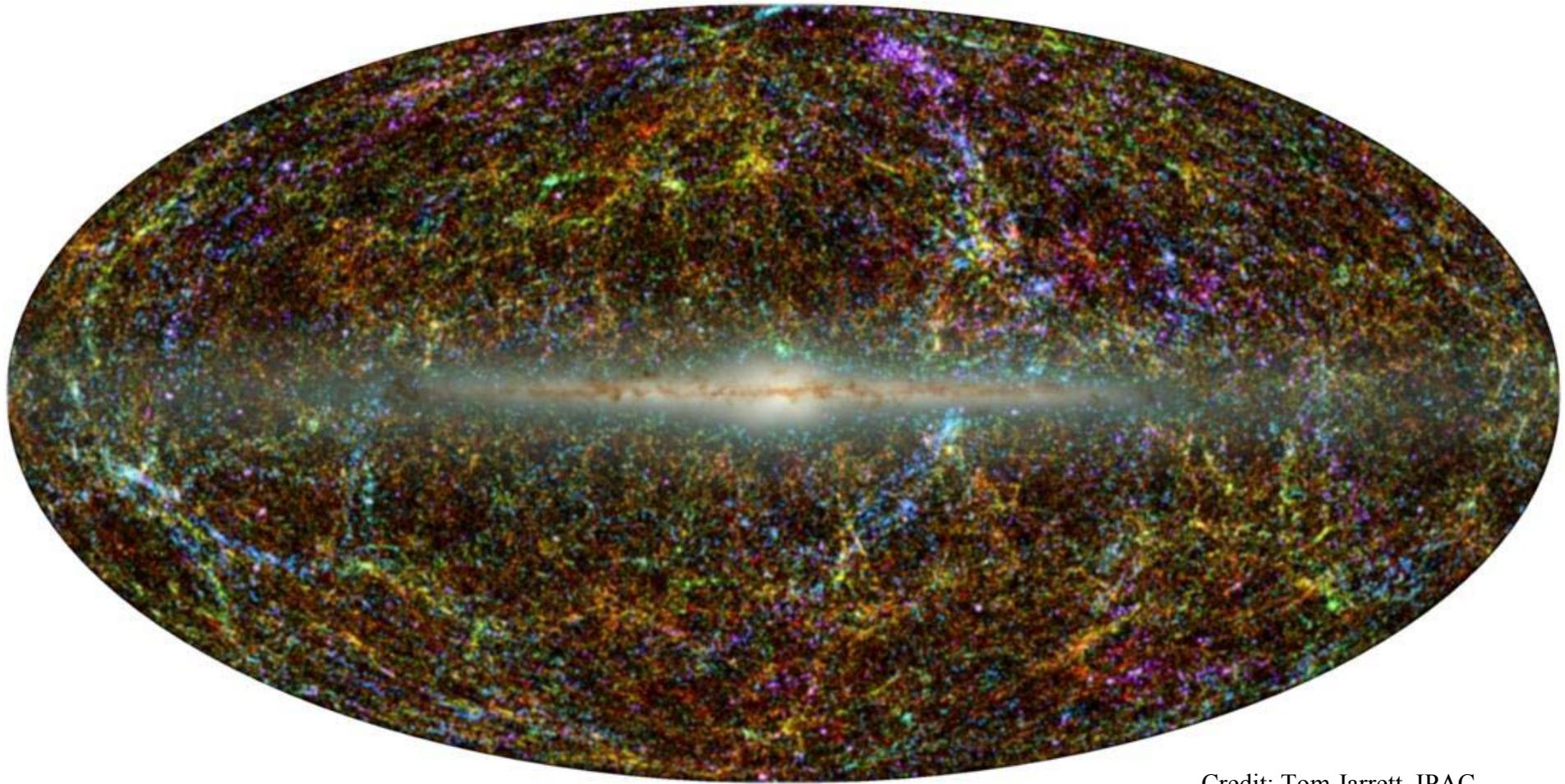
2MASS Galaxies at $z \leq 0.15$



Milky Way stars

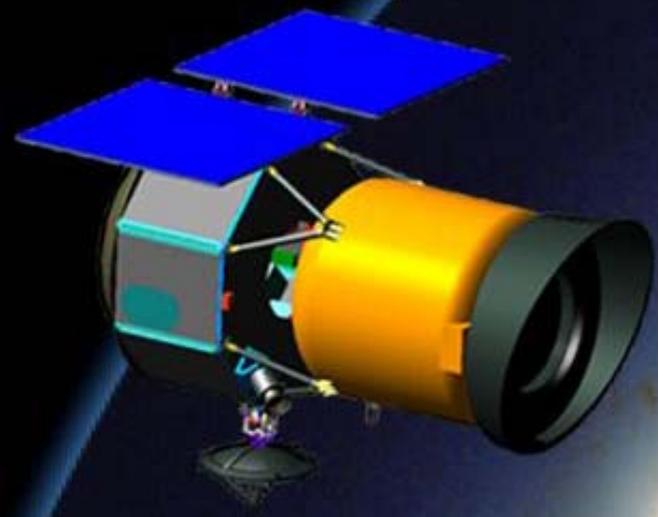
To get a deeper sample, use WISE in 2008

Photometric Redshifts are Good Enough



Credit: Tom Jarrett, IPAC

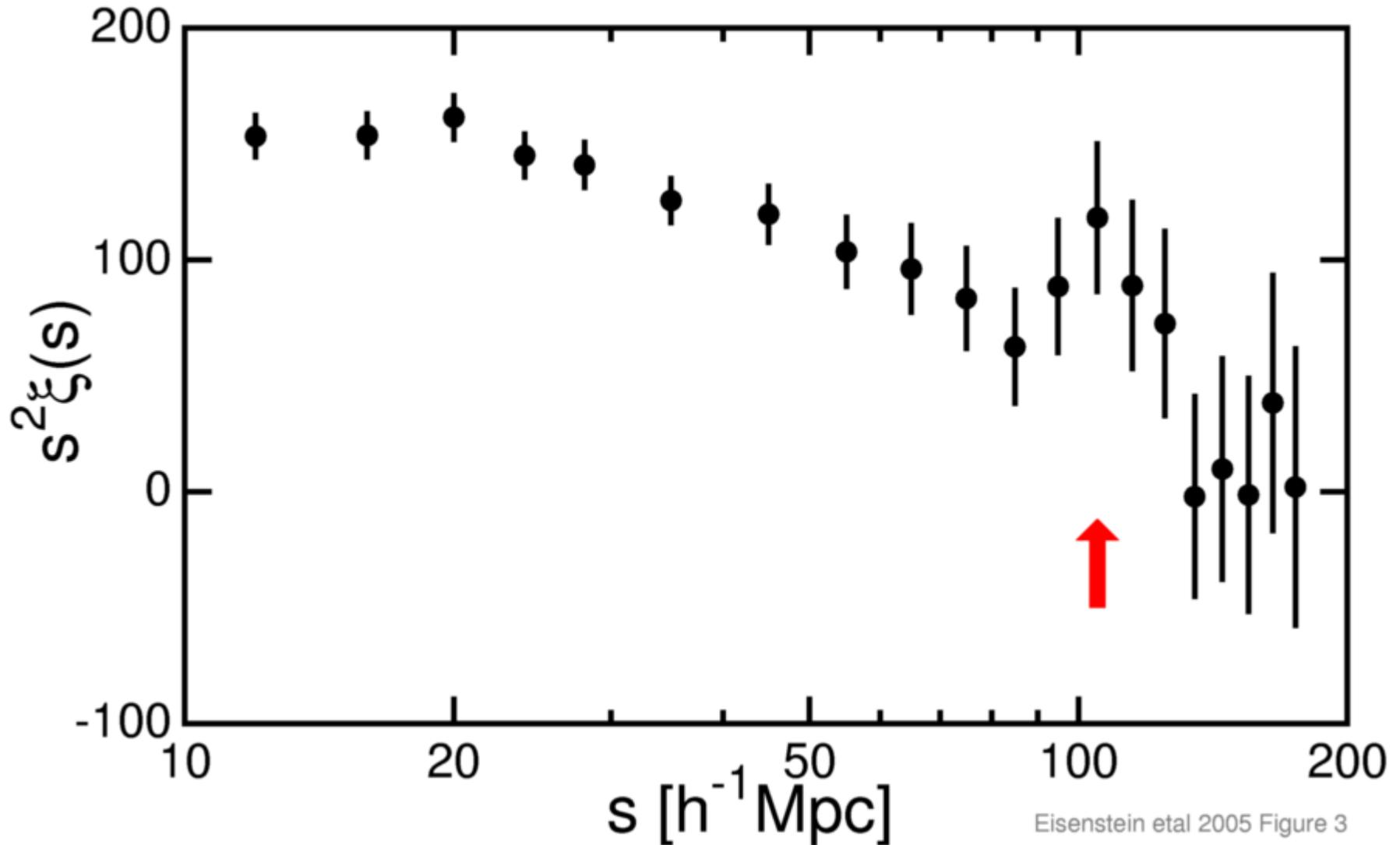
WIDE-FIELD INFRARED SURVEY EXPLORER



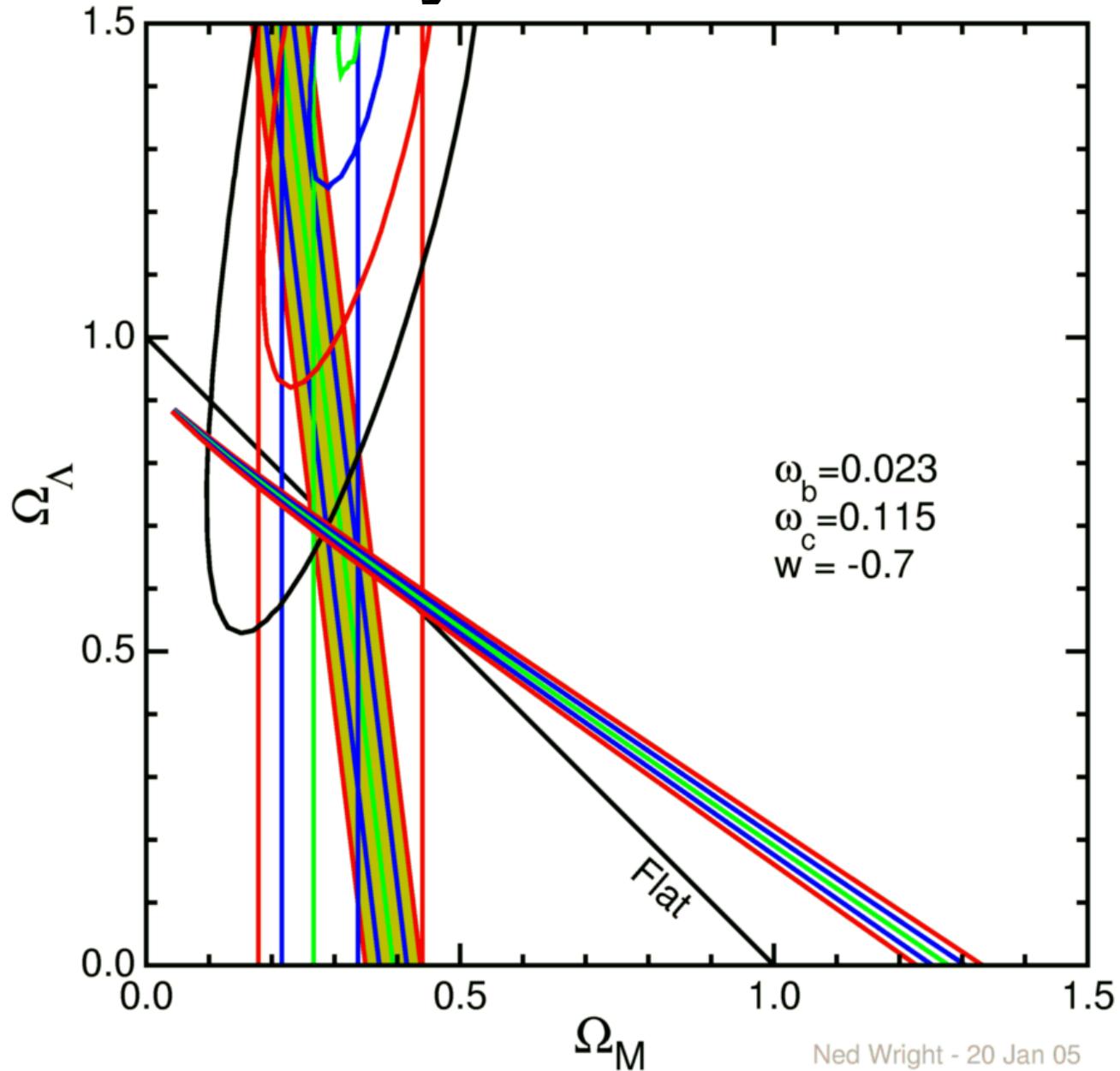
I am the PI on a MIDEX proposal for WISE, an all-sky survey in 4 bands from 3 to 24 μm . WISE will find and study the closest stars to the Sun, the most luminous galaxies in the Universe, and also map the large-scale structure out to redshift $z=0.7$, covering the era when the late ISW effect should be generated.

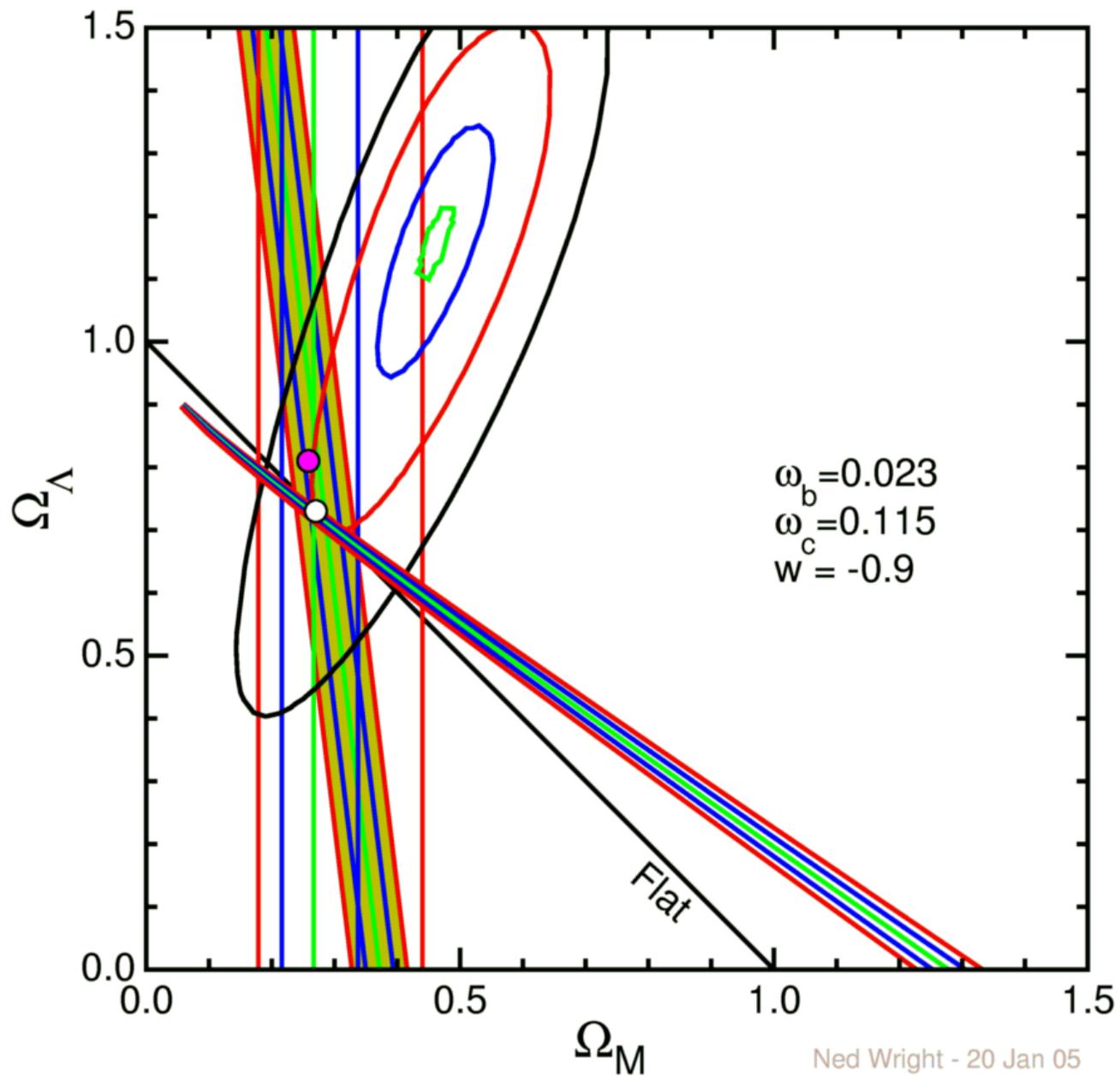
Now in phase B, WISE will fly in 2008.

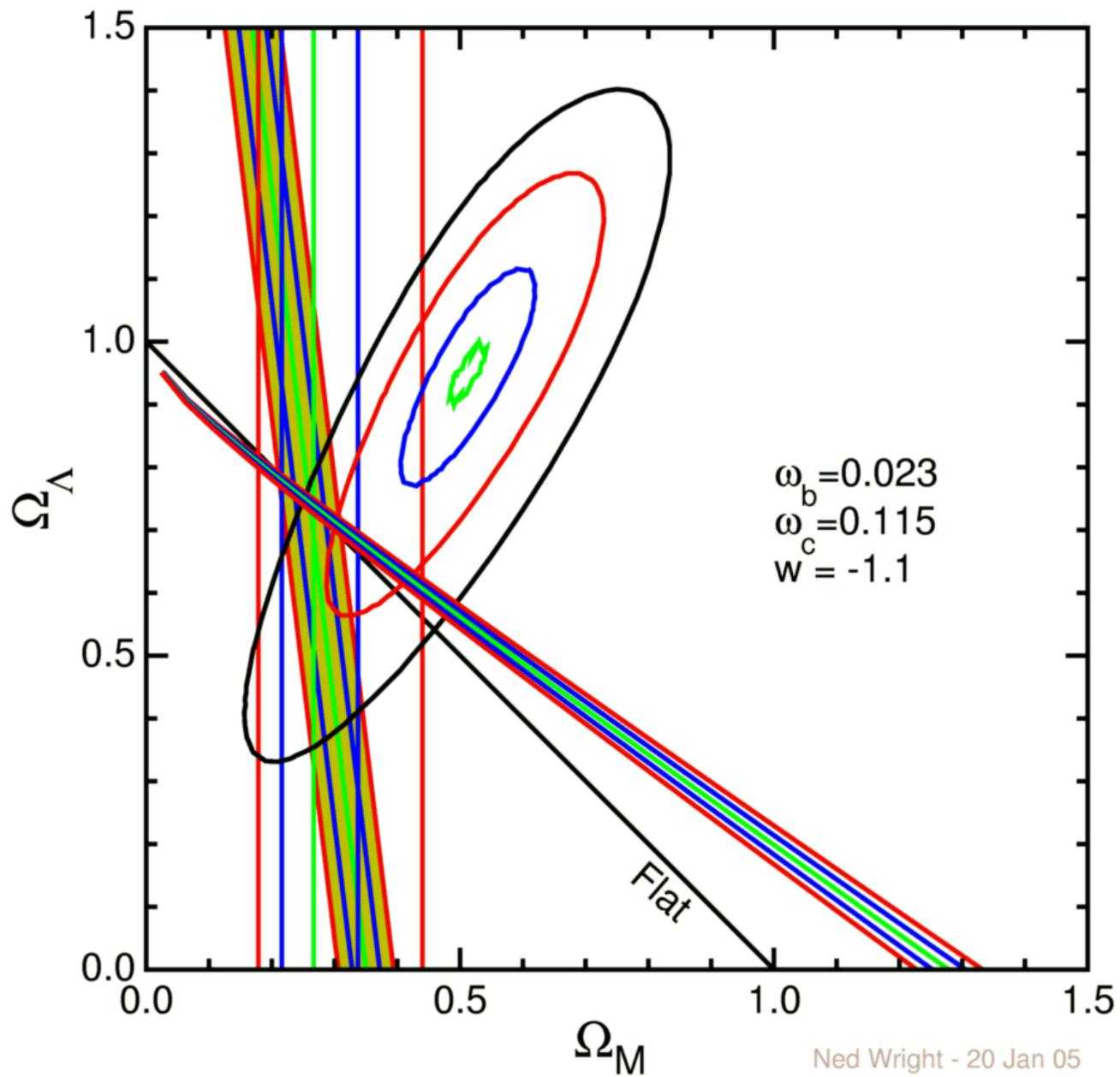
Baryonic Oscillations in SDSS LRGs



With baryon oscillations







Conclusion

- Dark energy is fact: confirmed by
 - Strong lensing
 - Late ISW effect
 - CMB & HST
 - CMB & LSS
 - CMB & Baryonic Oscillations
 - CMB & SNe
- Discussions of dark energy are rife with fiction:
 - Hidden assumptions
 - Conclusions promoted to priors
 - Double & triple counted datasets

End Notes

- 1) Almost
- 2) Almost
- 3) Almost
- 4) Almost
- 5) Almost
- 6) Almost