N-body Simulations and Photometric Redshifts

Hans Stabenau

12/02/2008

Collaborators

- U. of Penn:
  - Bhuvnesh Jain
  - Mike Jarvis
  - Gary Bernstein
  - Mark Devlin
  - Marie Rex
  - James Aguirre
- U. of Washington
  - Andrew Connolly
- U. of BC
  - Ed Chapin
  - Gaelen Marsden
  - Douglas Scott
  - Guillaume Patanchon

Overview

- Motivation
  - Cosmic acceleration
  - Large-scale structure
- N-Body simulations
- Photometric redshifts
- Submillimeter galaxies (briefly)

Evolution of the Universe

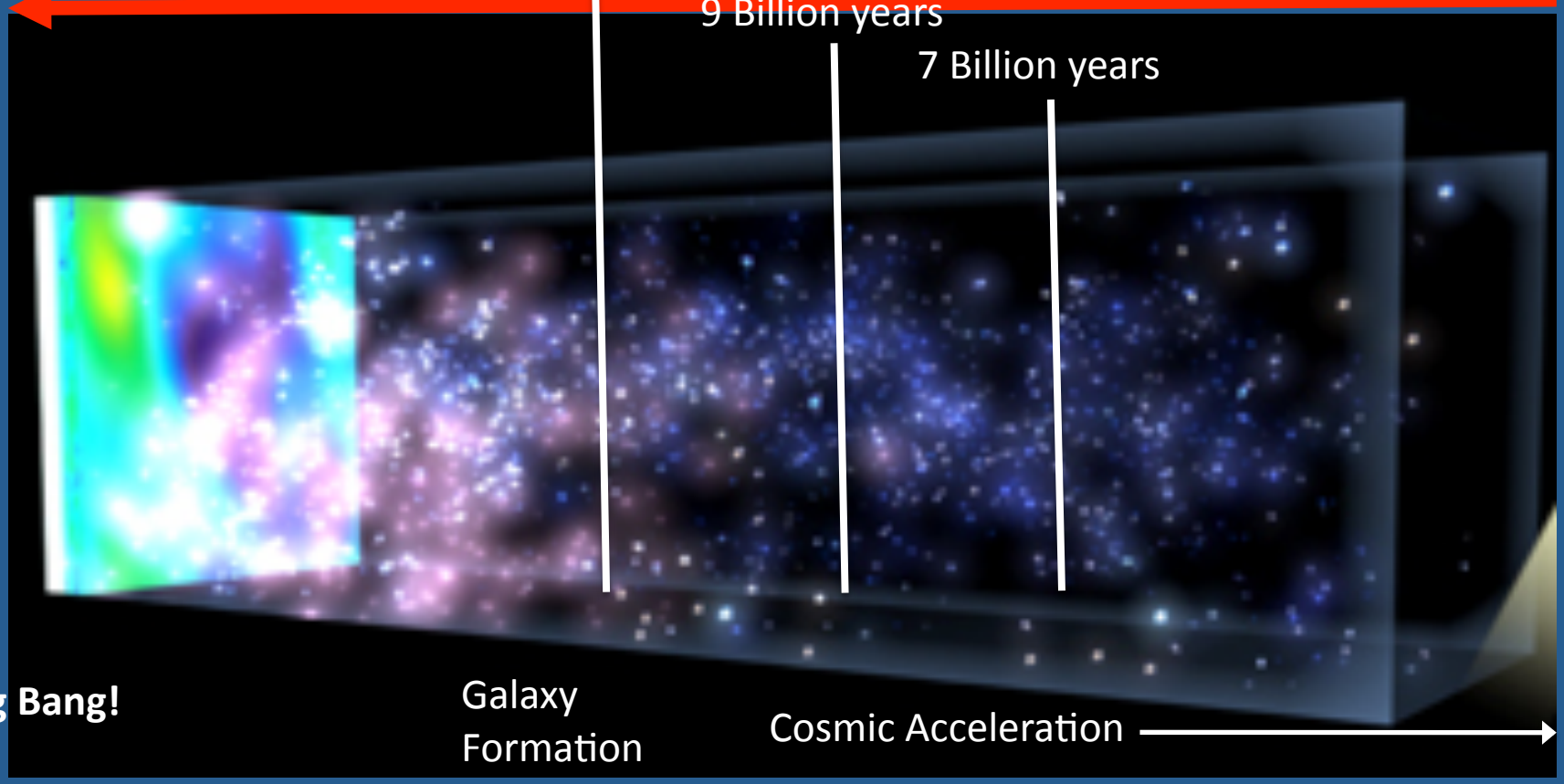


Figure from WMAP Website

Cosmic Acceleration

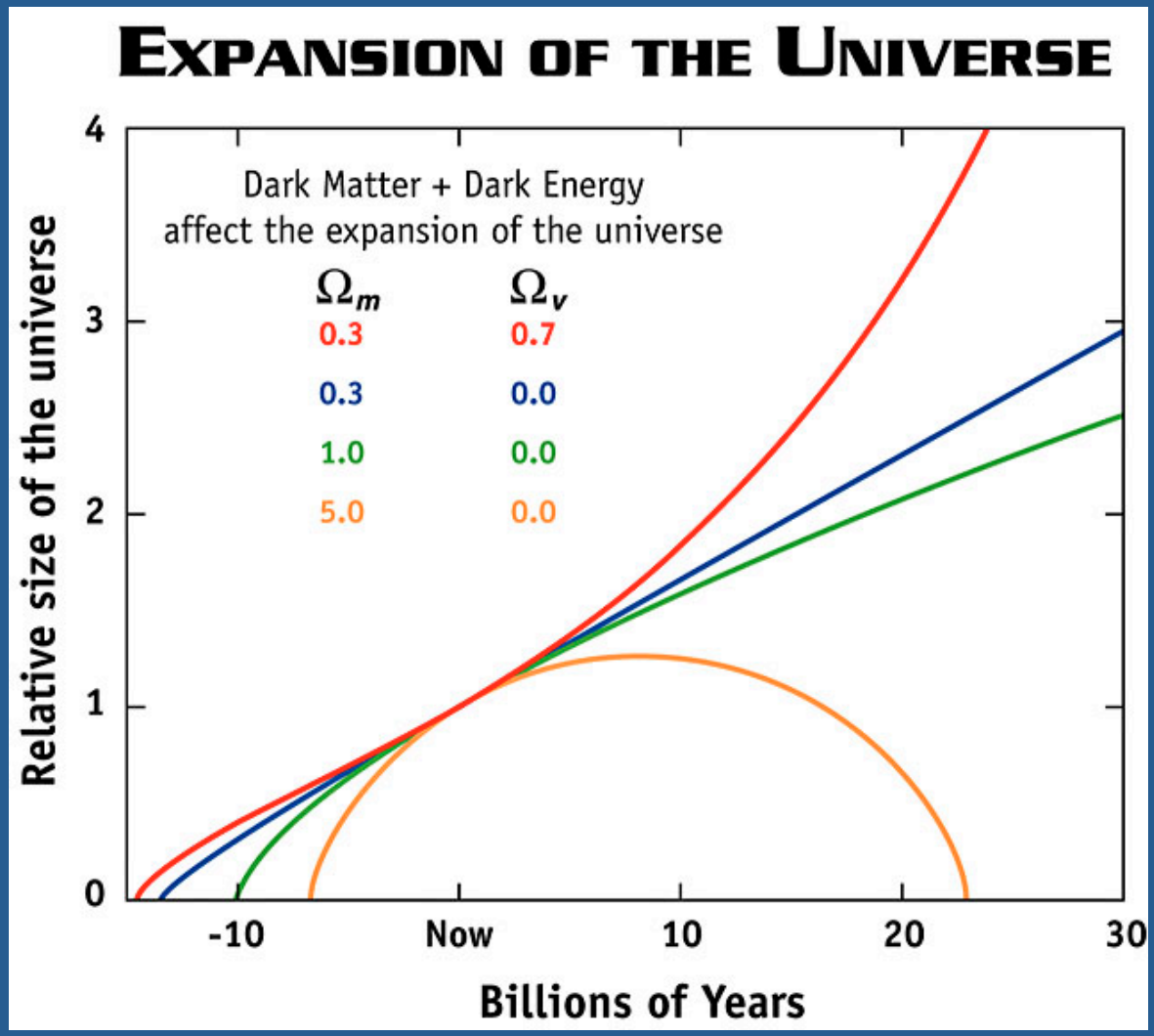


Image credit: NASA

Lightning Review of GR

- Specify action:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R + S_M$$

- Choose coordinates (metric):

$$ds^2 = -dt^2 + a^2(t)dx^2$$

- Equations of motion (Einstein eqn.):

$$R_{\mu\nu} + \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G_N T_{\mu\nu}}{3}$$

- Expansion (Friedmann eqn.):

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho}{3}$$

Deceleration Parameter

- Dimensionless deceleration:

$$q(a) \equiv -\frac{\ddot{a}a}{\dot{a}^2} = \frac{dH^{-1}}{dt} - 1$$

$$q(a) = \frac{1}{2}\left(1 + 3\frac{P}{\rho}\right) = \frac{1}{2}(1 + 3w)$$

- But w controls $\rho(a)$:

$$\rho(a) \propto a^{-3(1+w)}$$

Energy Density Evolution

- Cold Dark Matter: $P = 0$, so $w = 0$

$$\rho_{\mathrm{CDM}}(a) \propto a^{-3}$$

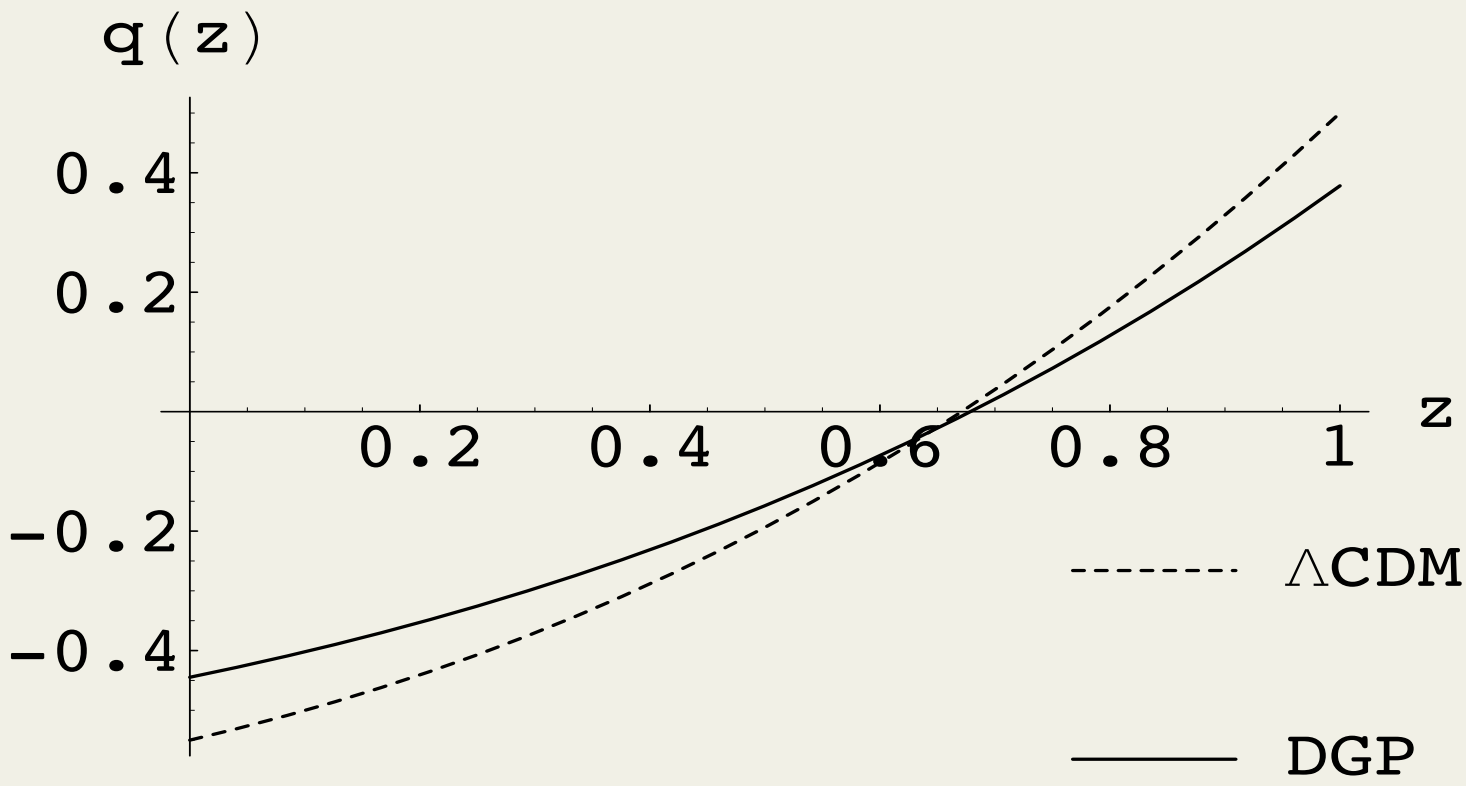
- Radiation: $w = 1/3$

$$\rho_{\gamma}(a) \propto a^{-4}$$

- Dark Energy: $w \approx -1$

$$\rho_{\Lambda}(a) \propto a^{0} \propto \mathrm{const!}$$

A Cosmic Puzzle



Cosmological Timeline

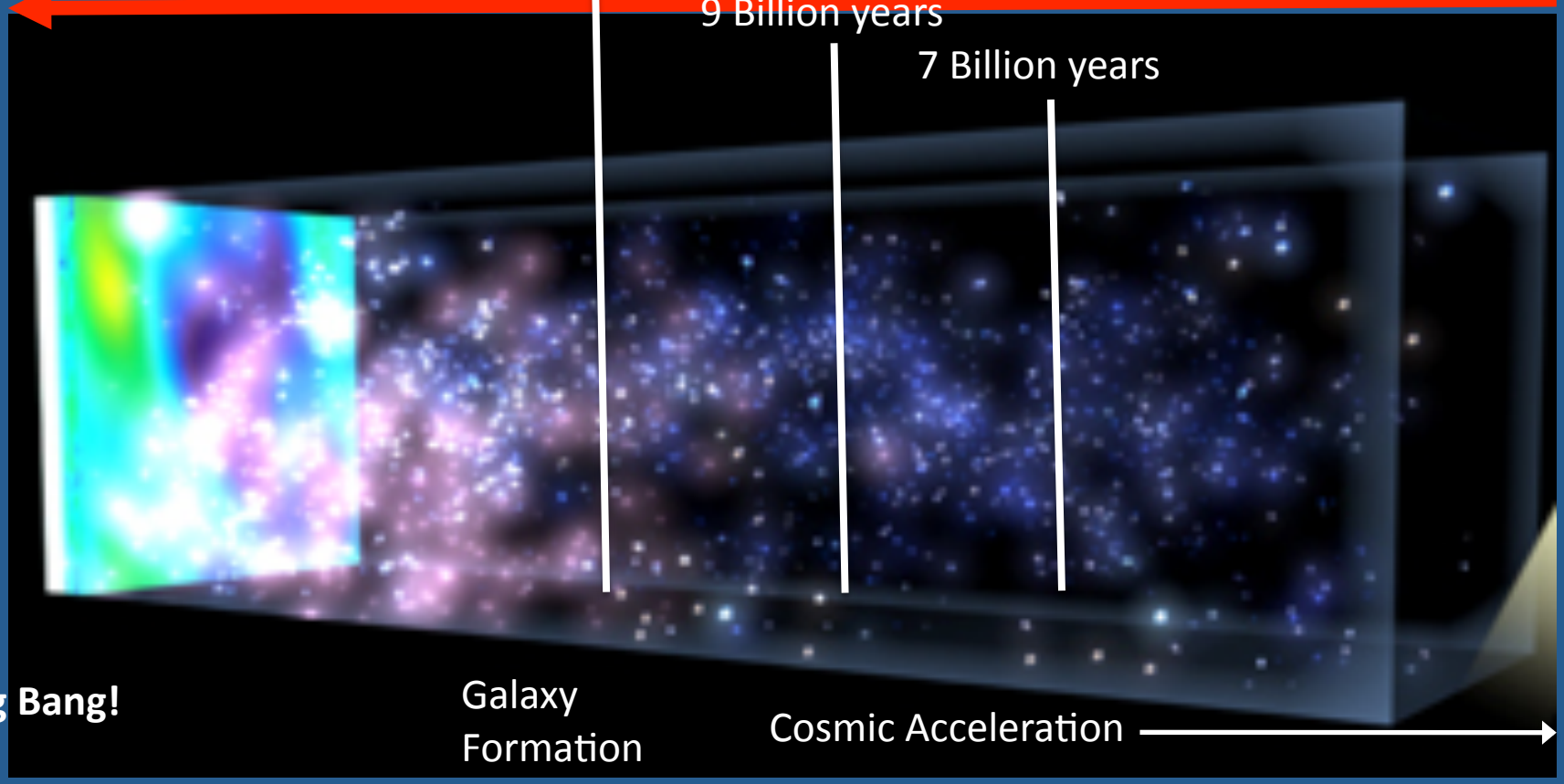


Figure from WMAP Website

Modified Growth

- Perturbed metric

$$ds^2 = -[1+2\Phi]dt^2 + a^2(t)[1-2\Psi]dx^2$$

- Conservation of stress-energy gives

$$\begin{aligned} -k^2\Psi &= a^2 4\pi G_N \rho_{bg} \delta f(k,t) \\ \Psi &= \Phi \eta(k,t) \end{aligned}$$

- Growth factor: $\delta(k,t) = D(t)\,\delta(k)$

$$\ddot{D} + 2H\dot{D} = \frac{3}{2}H_0^2 \frac{\Omega_m}{a} D \left[\frac{f(k,t)}{\eta(k,t)}\right]$$

- For GR, $f = \eta = 1$, so D is <u>scale-independent</u>.

DGP growth factor slide

The Model

- Modification on large scales

$$\tilde{\phi}(k) = \frac{3}{2}\frac{\Omega_{m0}}{a}\frac{\delta_k}{G_k}\left[1+\alpha\frac{1}{1+(2\pi k r_s/a)^2}\right]$$

$$\phi(\mathbf{r}) = -G\int d^3\mathbf{r}'\frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\left[1+\alpha\left(1-e^{-\frac{|\mathbf{r}-\mathbf{r}'|}{r_s}}\right)\right]$$

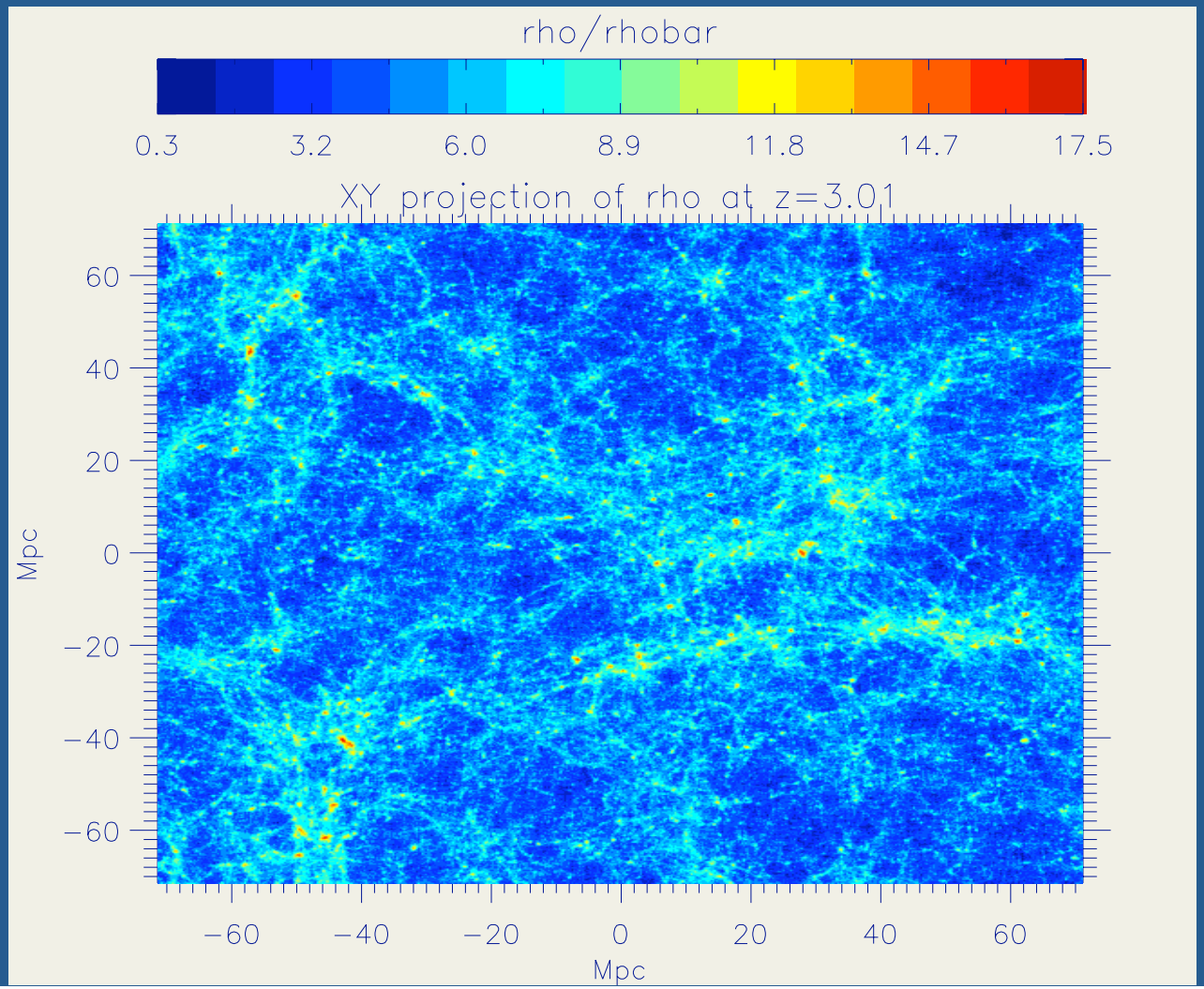
- Gives <u>scale-dependent</u> growth:

$$f(k,t) = 1+\alpha\frac{1}{1+(2\pi k r_s/a)^2}, \quad \eta = 1$$

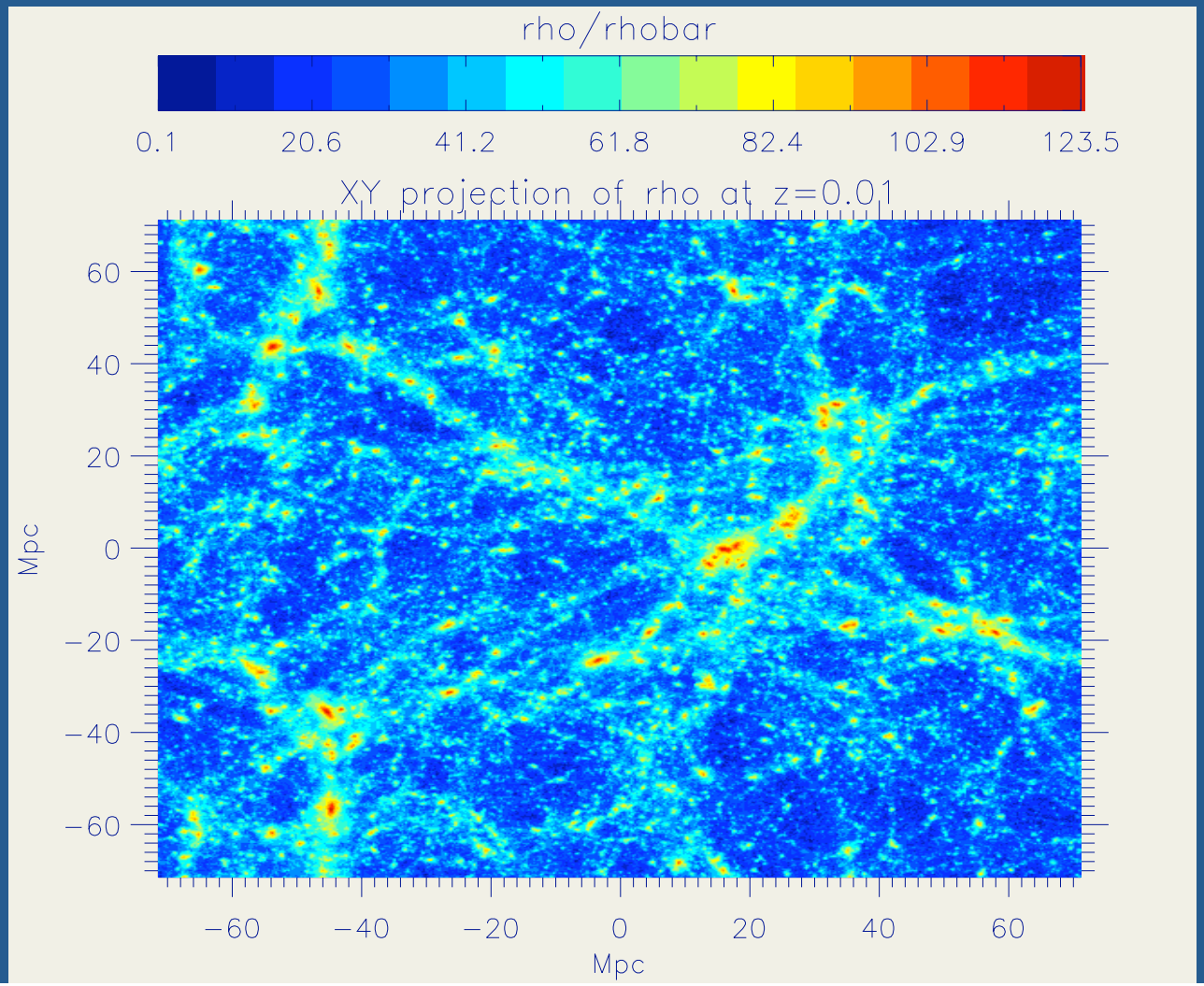
N-Body Simulation

- Put dark matter particles in a box
- Compute all the gravitational forces
- Update positions and velocities
- Repeat for the age of the universee
- Simulation parameters:
  - $N_p = 128^3$
  - $L_{box} = 143$ Mpc
  - $m_p = 1.1 \times 10^{10}\ M_\odot$

Dark Matter after 3 Gyr



Dark Matter after 13.7 Gyr



Dark Matter Simulation

- Numerically Integrate EOM:

$$
\begin{aligned}
d\mathbf{r}/dt &= \mathbf{u} \\
d\mathbf{u}/dt &= -\nabla\Phi \\
\nabla^2\Phi &= 4\pi G\rho - \Lambda
\end{aligned}
\qquad
\begin{aligned}
d\mathbf{x}/da &= \left(\frac{H_0}{\dot{a}}\right)\mathbf{p}/a^2 \\
d\mathbf{p}/da &= -\left(\frac{H_0}{\dot{a}}\right)\nabla_x\phi \\
\nabla_x^2\phi &= \frac{3}{2}\Omega_{m0}\delta/a
\end{aligned}
$$

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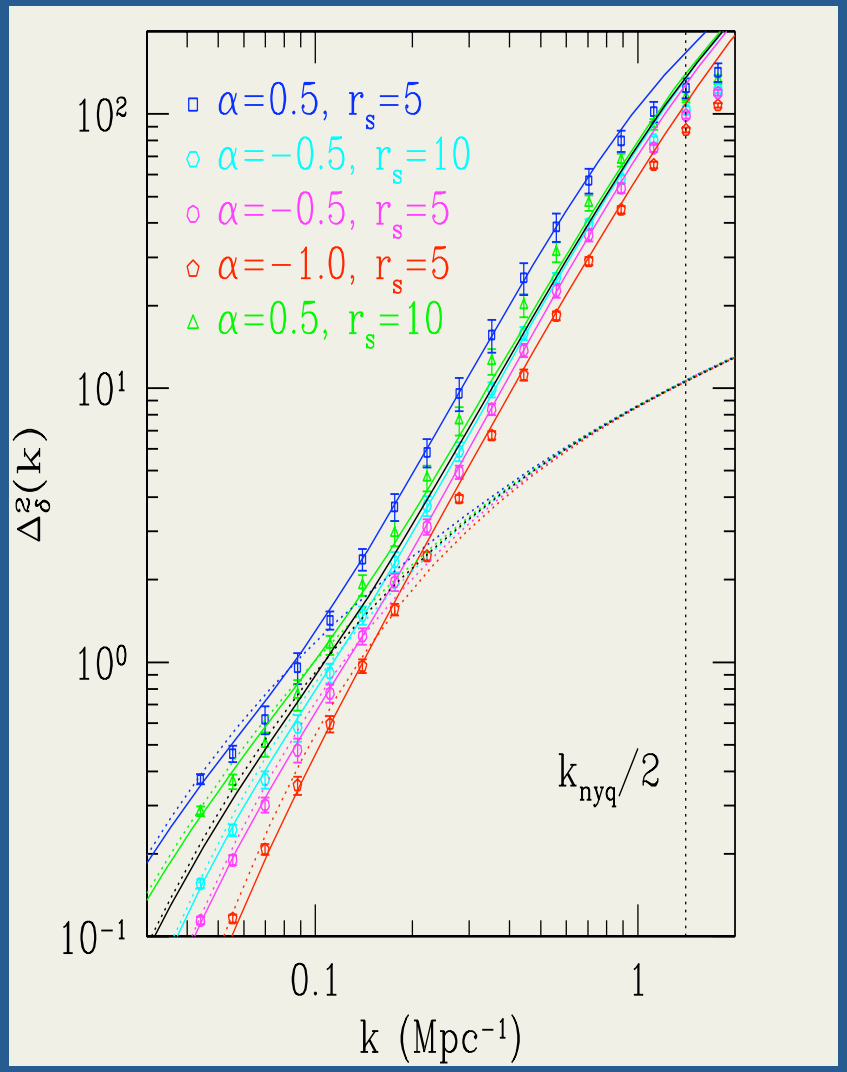
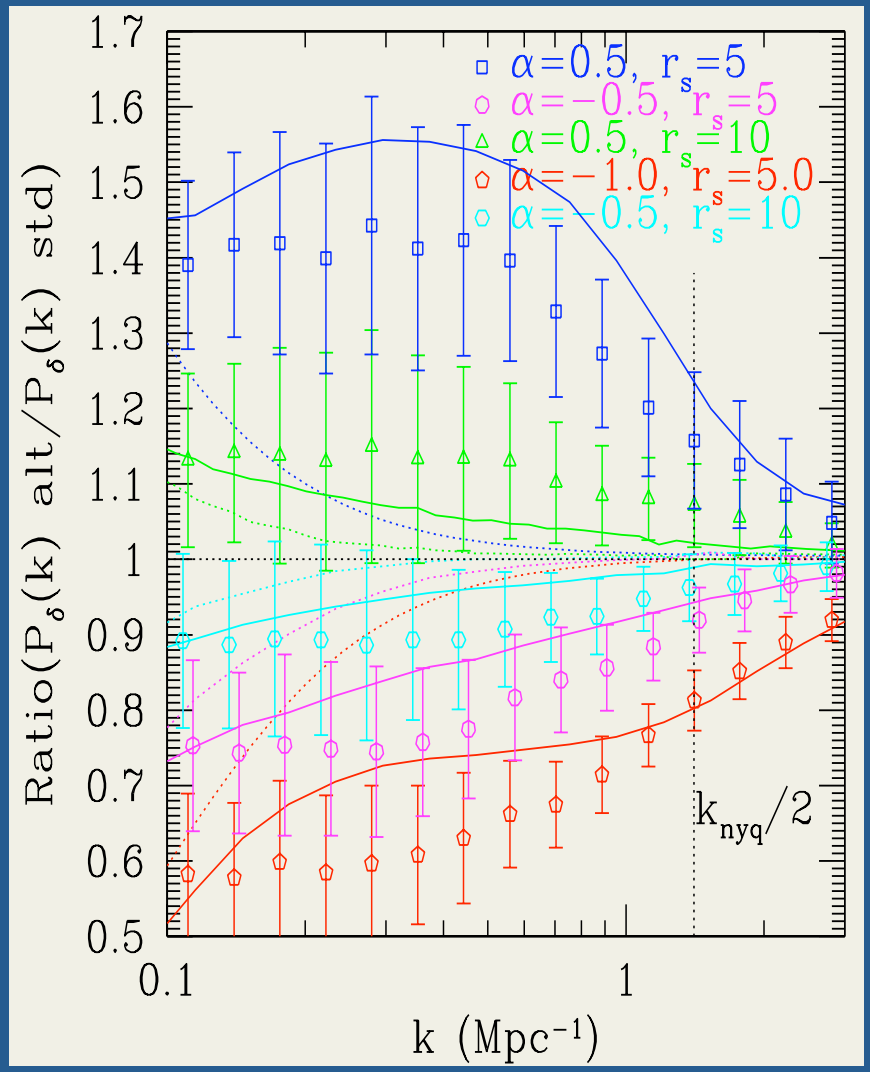
\boxed{\nabla_x^2\phi = \frac{3}{2}\Omega_{m0}\delta/a}
\end{aligned}
$$

- Solve for the forces via FFT

Power Spectra





Stabenau and Jain, Phys.Rev. D74 (2006) 084007

Gravitational Lensing

- Dark matter is not directly observable
- But, GR predicts that mass bends light:

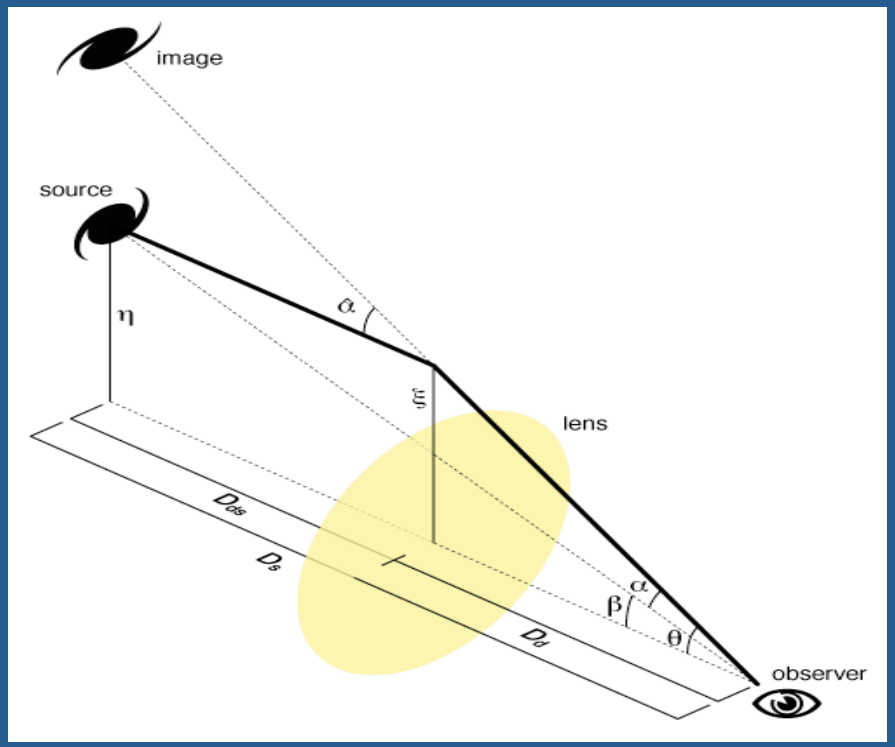


Image credit: Michael Sachs (Wikipedia)

Cosmological Timeline

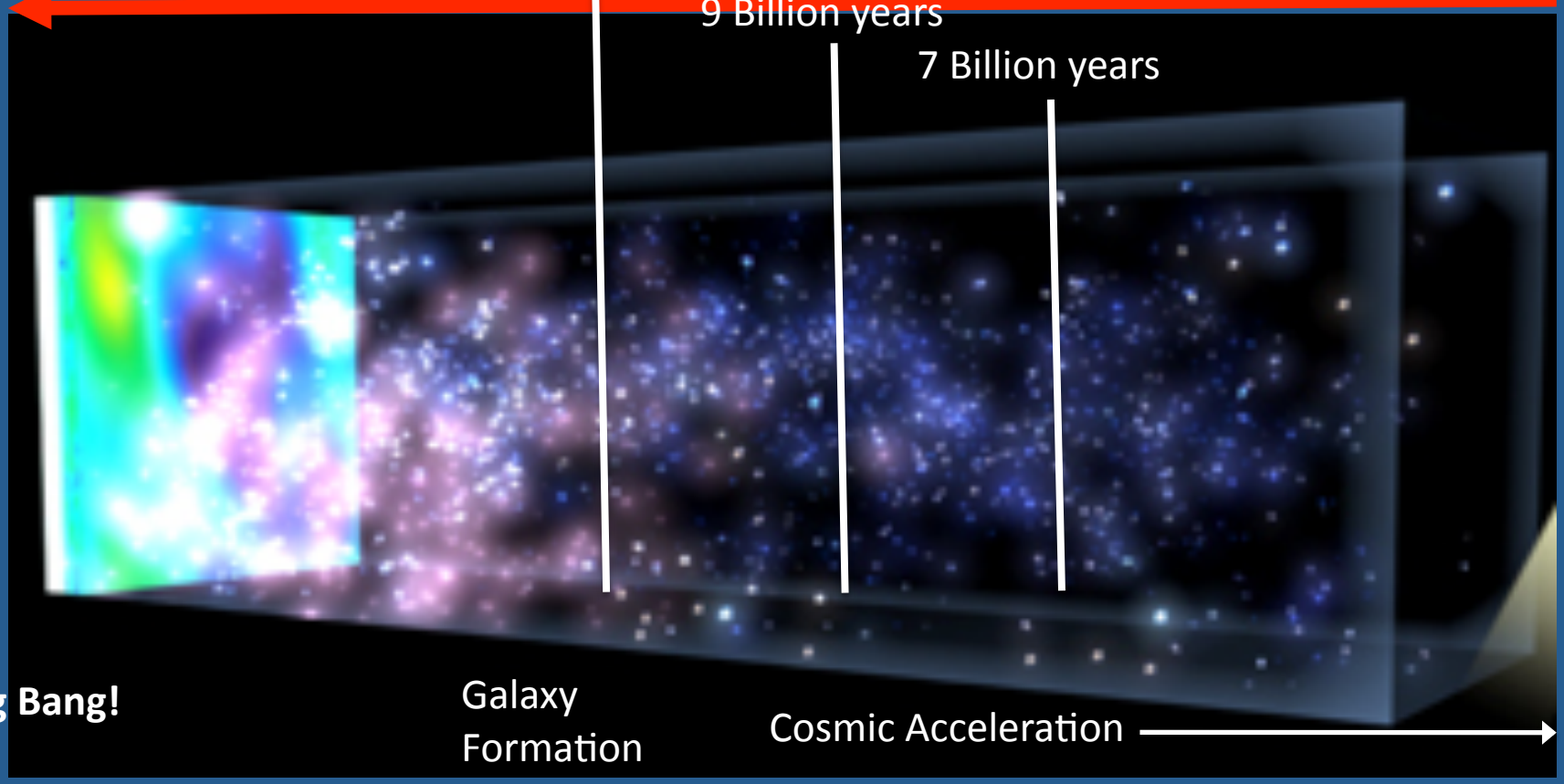
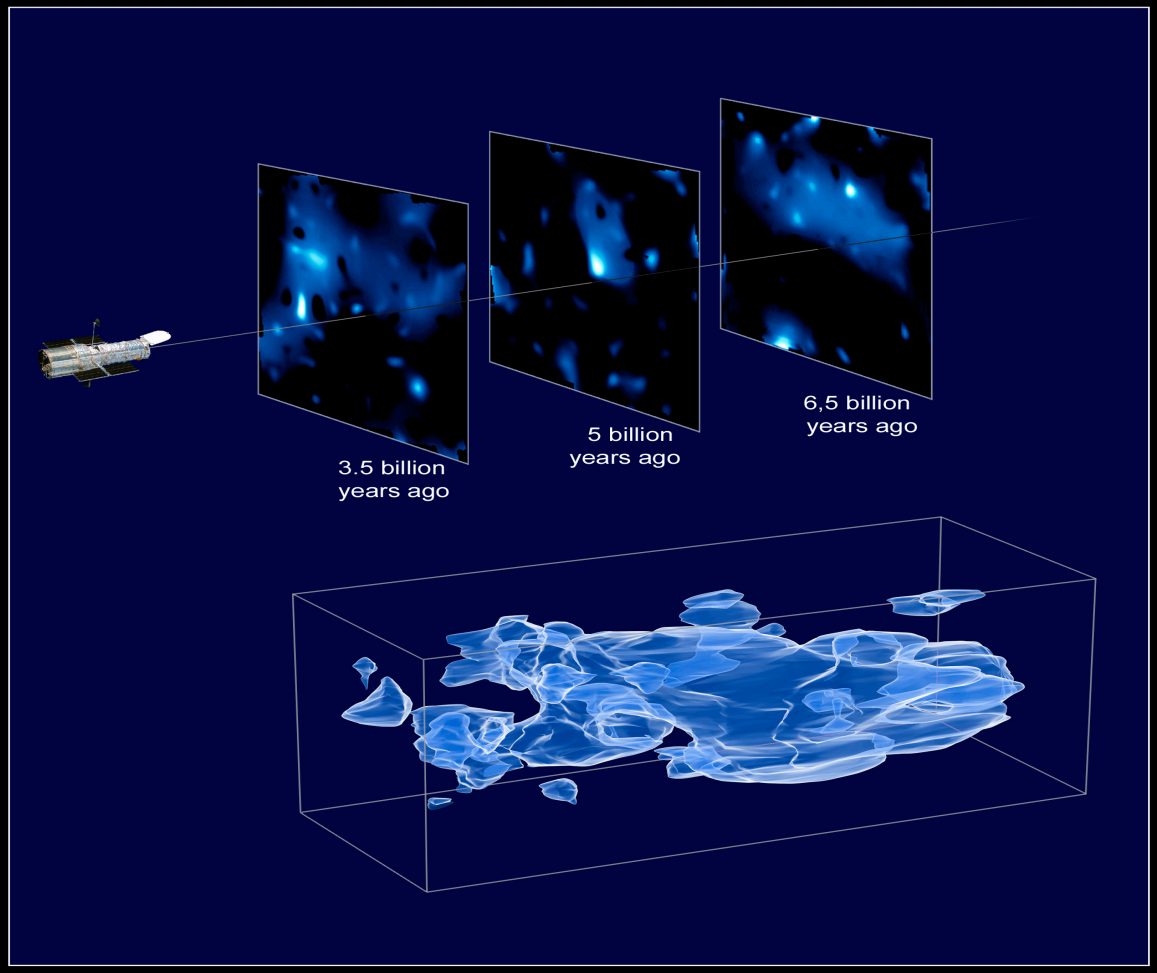


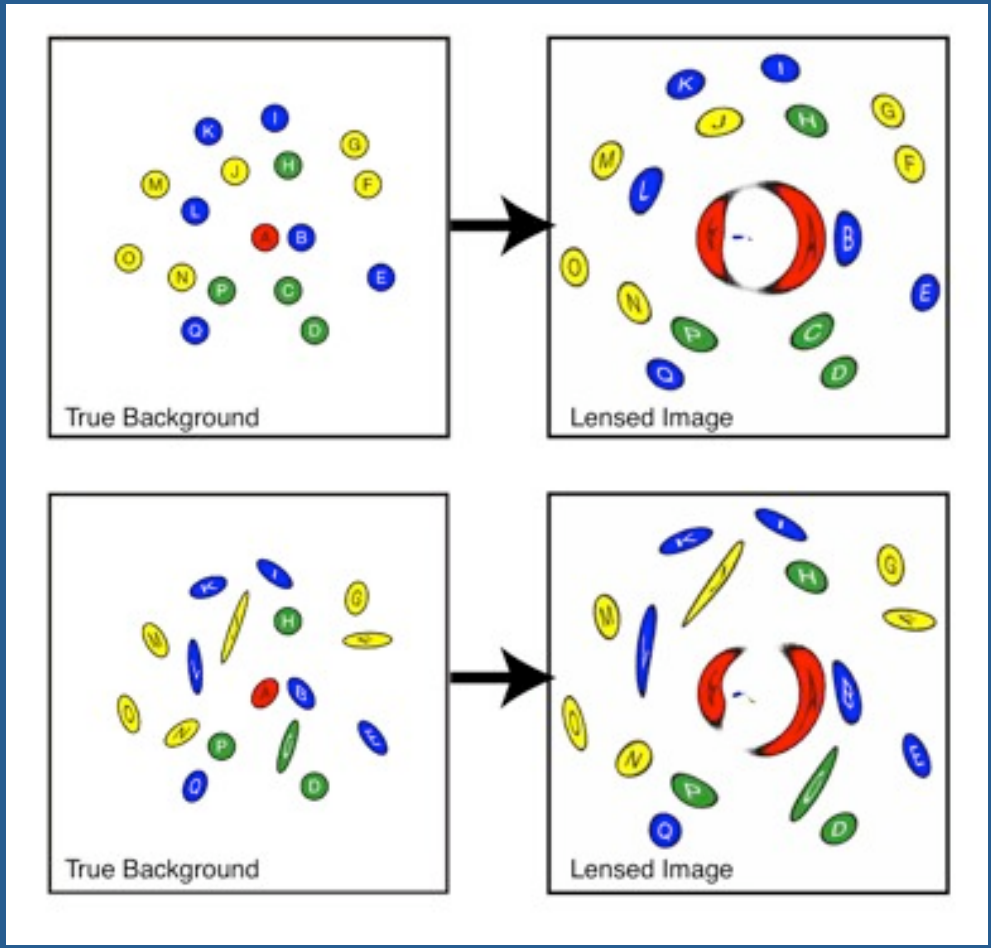
Figure from WMAP Website

Ray Tracing

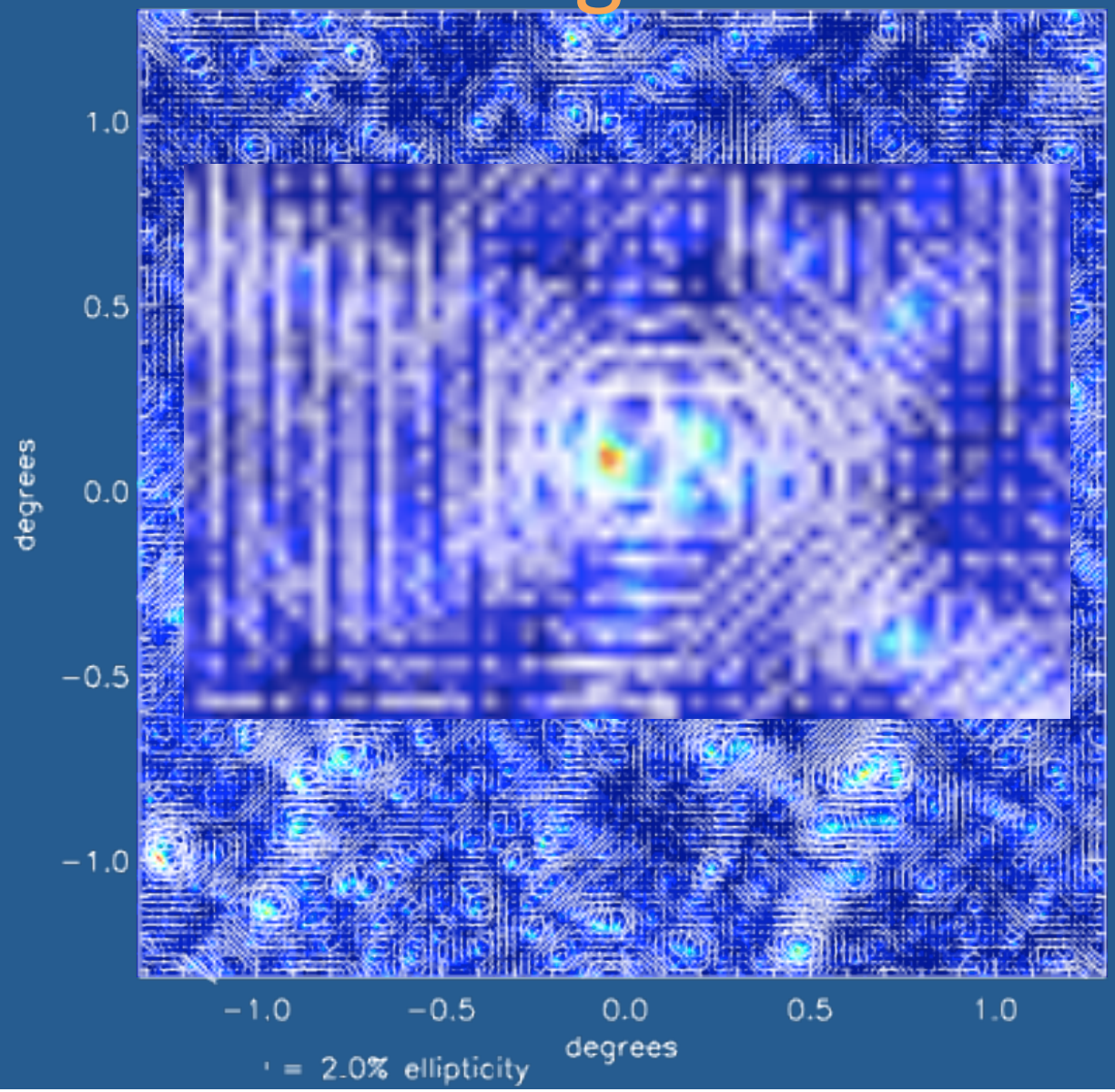


Massey et al 2007

Lensing Distortions



Lensing Results



Weak Lensing

- Convergence and shear

$$\kappa = \frac{1}{2}\int_0^{\chi_H} d\chi W(\chi)\nabla^2(\Phi+\Psi)$$

$$\gamma_1 = \frac{1}{2}\int_0^{\chi_H} d\chi W(\chi)[\partial_1\partial_1 - \partial_2\partial_2](\Phi+\Psi)$$

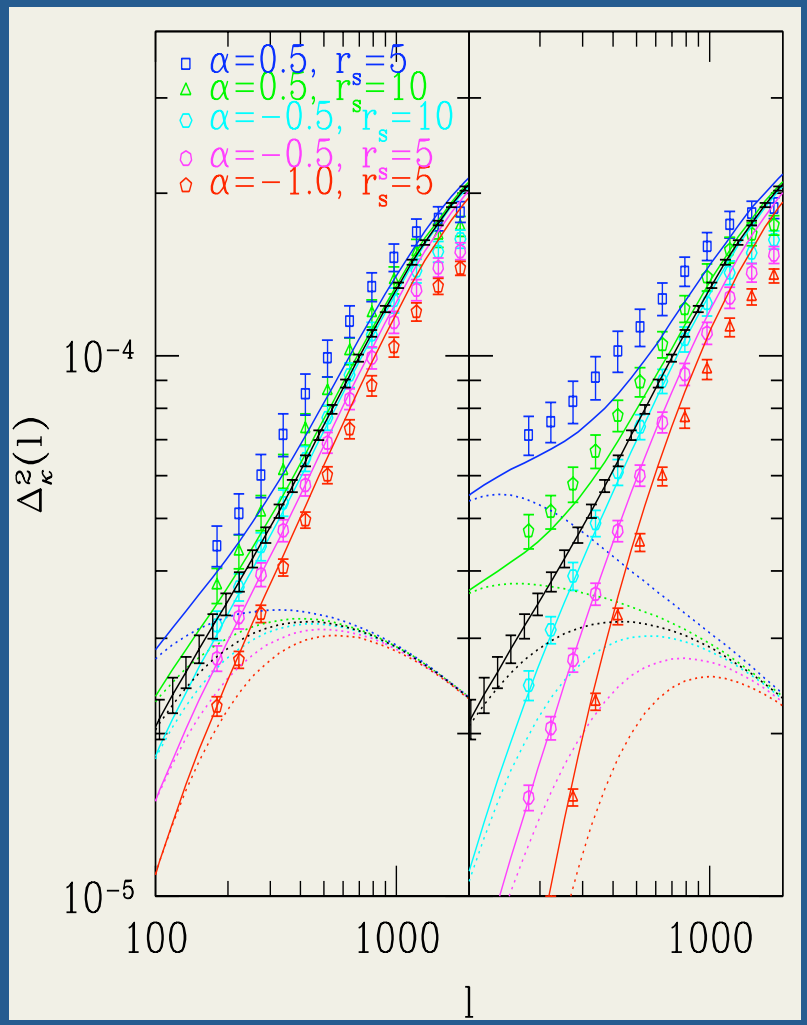
$$\gamma_2 = \int_0^{\chi_H} d\chi W(\chi)\partial_1\partial_2(\Phi+\Psi)$$

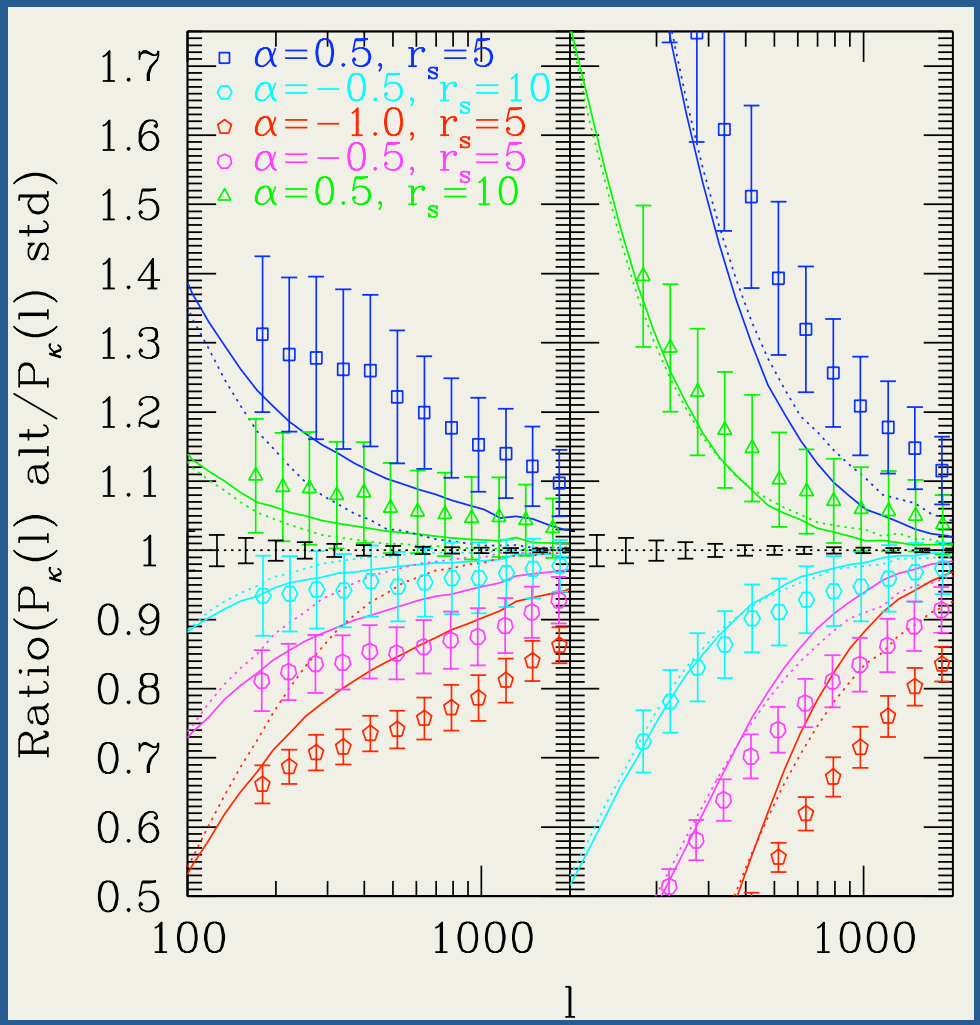
- Convergence power spectrum

$$P_\kappa(l) \propto \int_0^{\chi_H} d\chi W^2(\chi) k^4 P_{\Phi+\Psi}\left(k=\frac{l}{\chi},\chi\right)$$

$$\propto \int_0^{\chi_H} d\chi W^2(\chi) f^2(k,t) P_\delta\left(k=\frac{l}{\chi},\chi\right)$$

Convergence Power Spectra





Cosmological Timeline

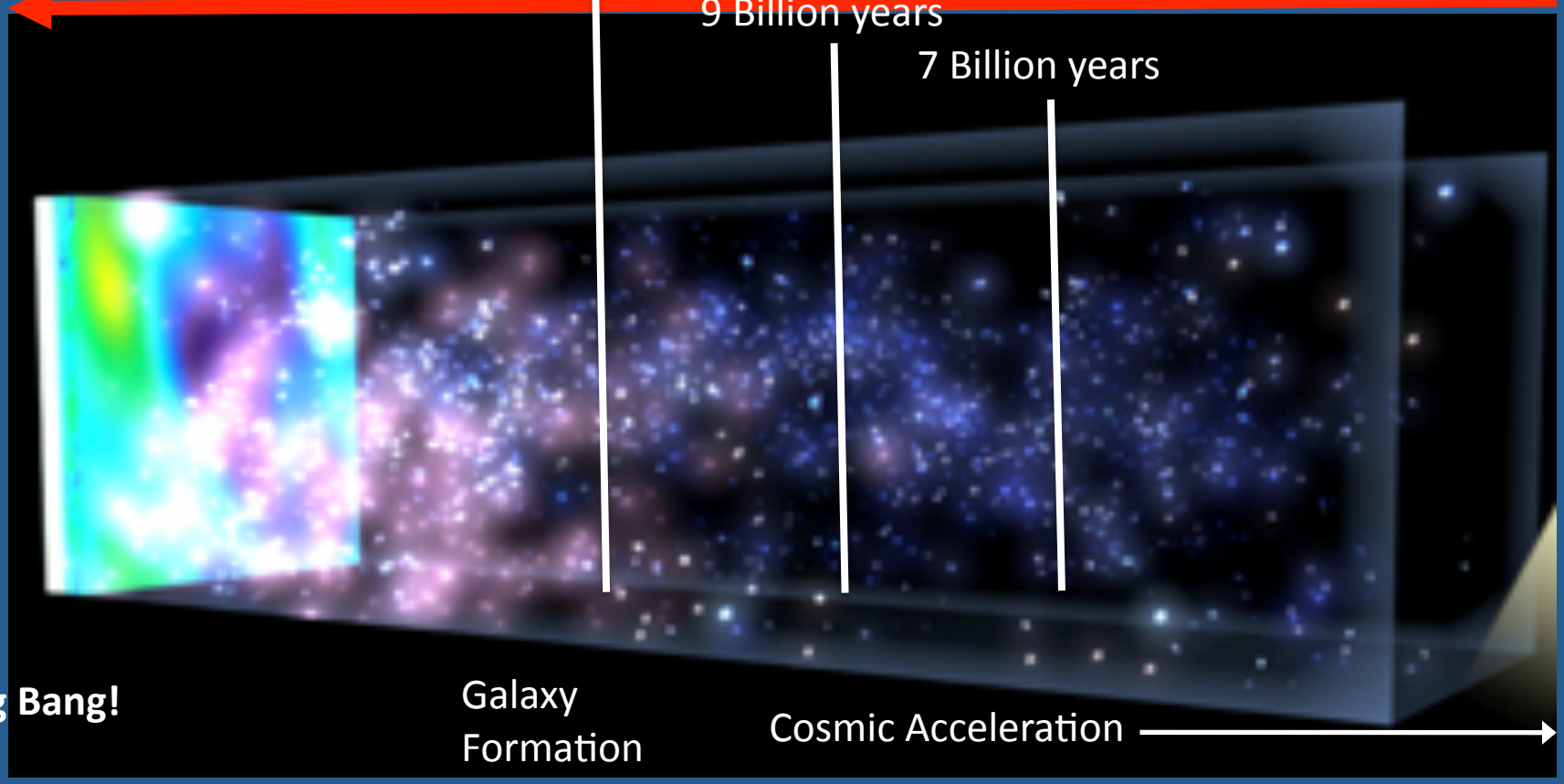
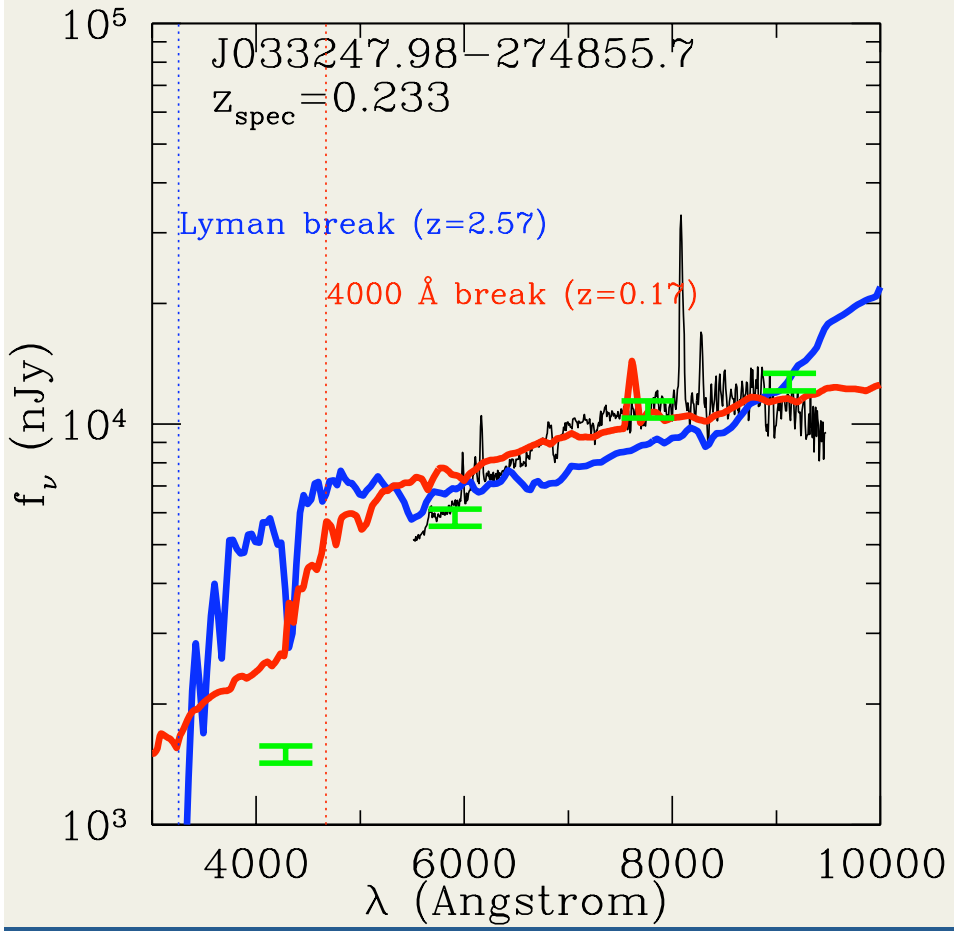


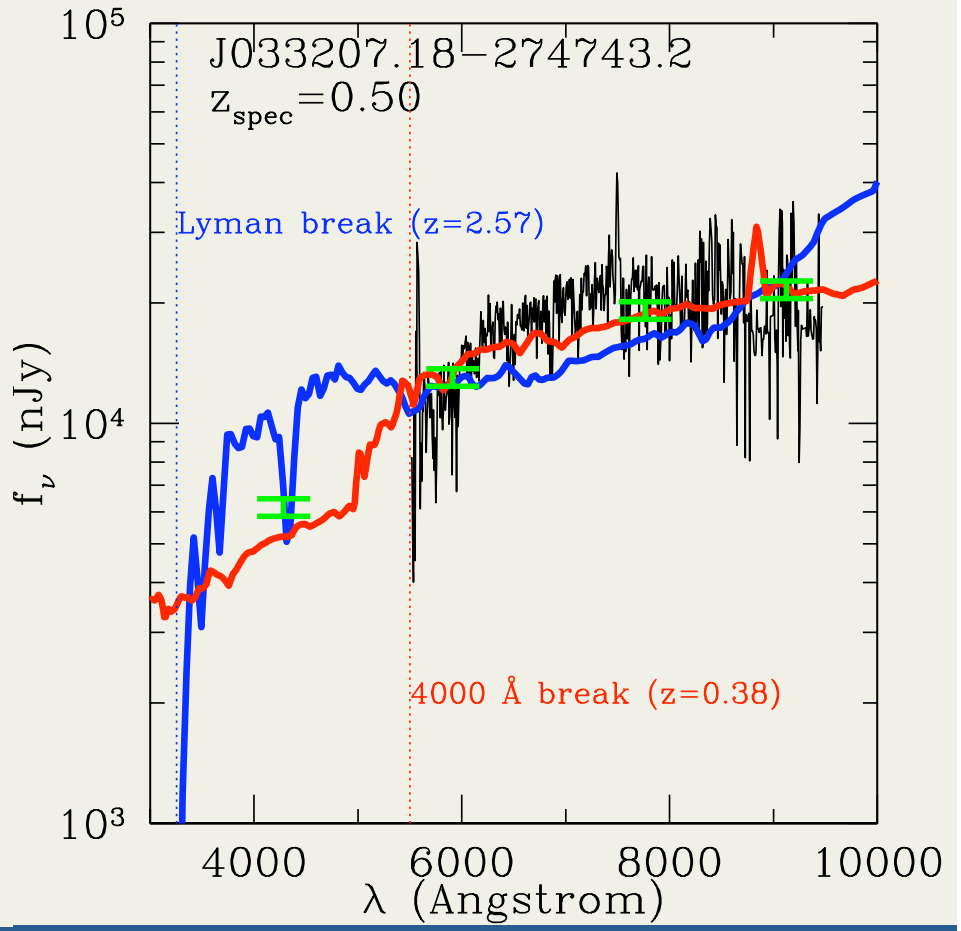
Figure from WMAP Website

Photometric Redshifts

- Unbiased galaxy redshifts are important for:
  - Weak Lensing (e.g. Jain, Connolly, Takada '06, Mandelbaum et al. '07)
  - Large-scale structure (3D galaxy surveys)
  - Cluster lensing
  - Astrophysics: SFR(z)
- Need too many for spectra

Color-Redshift Degeneracy





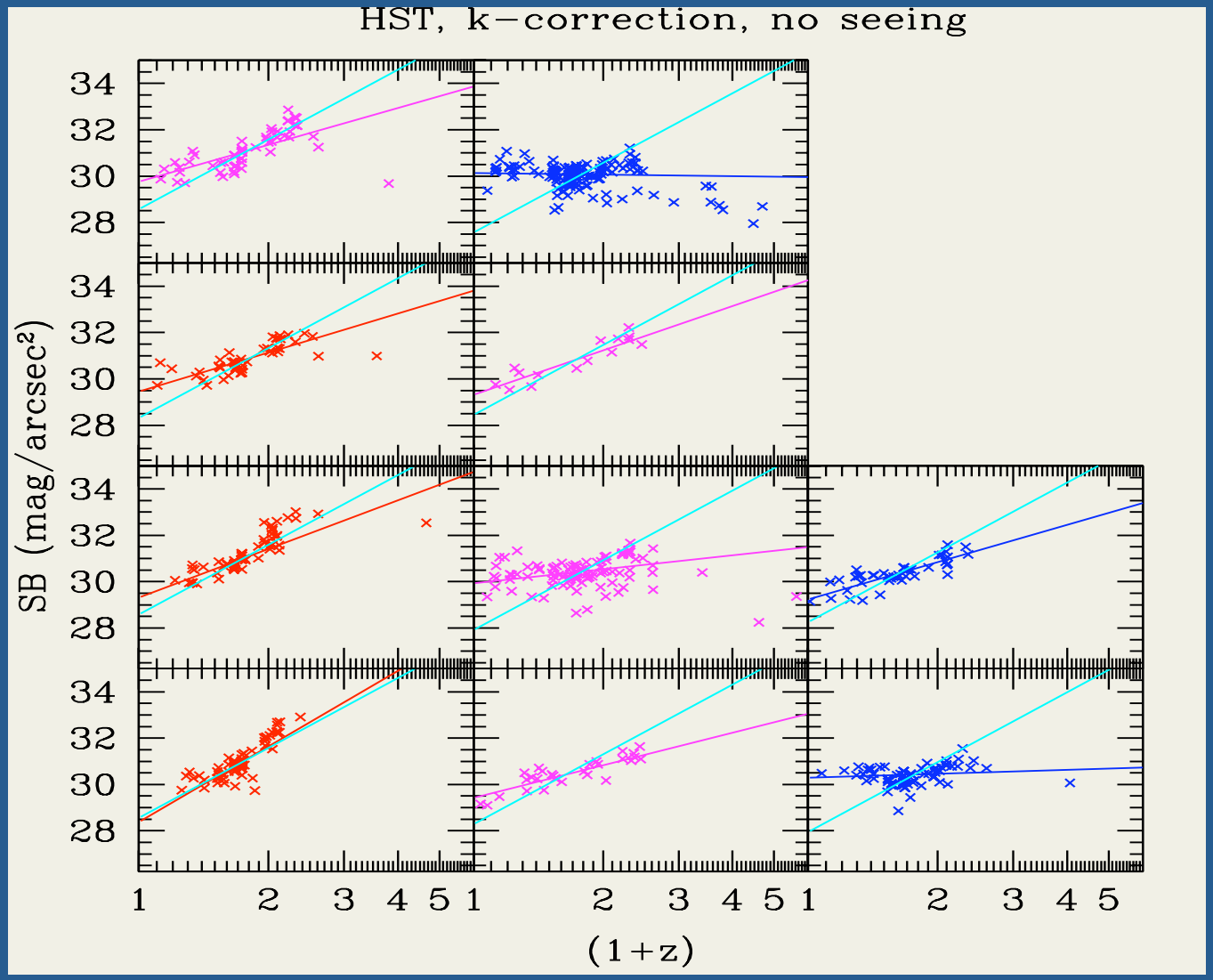
Surface Brightness and Redshift

- Break the color-redshift degeneracy:

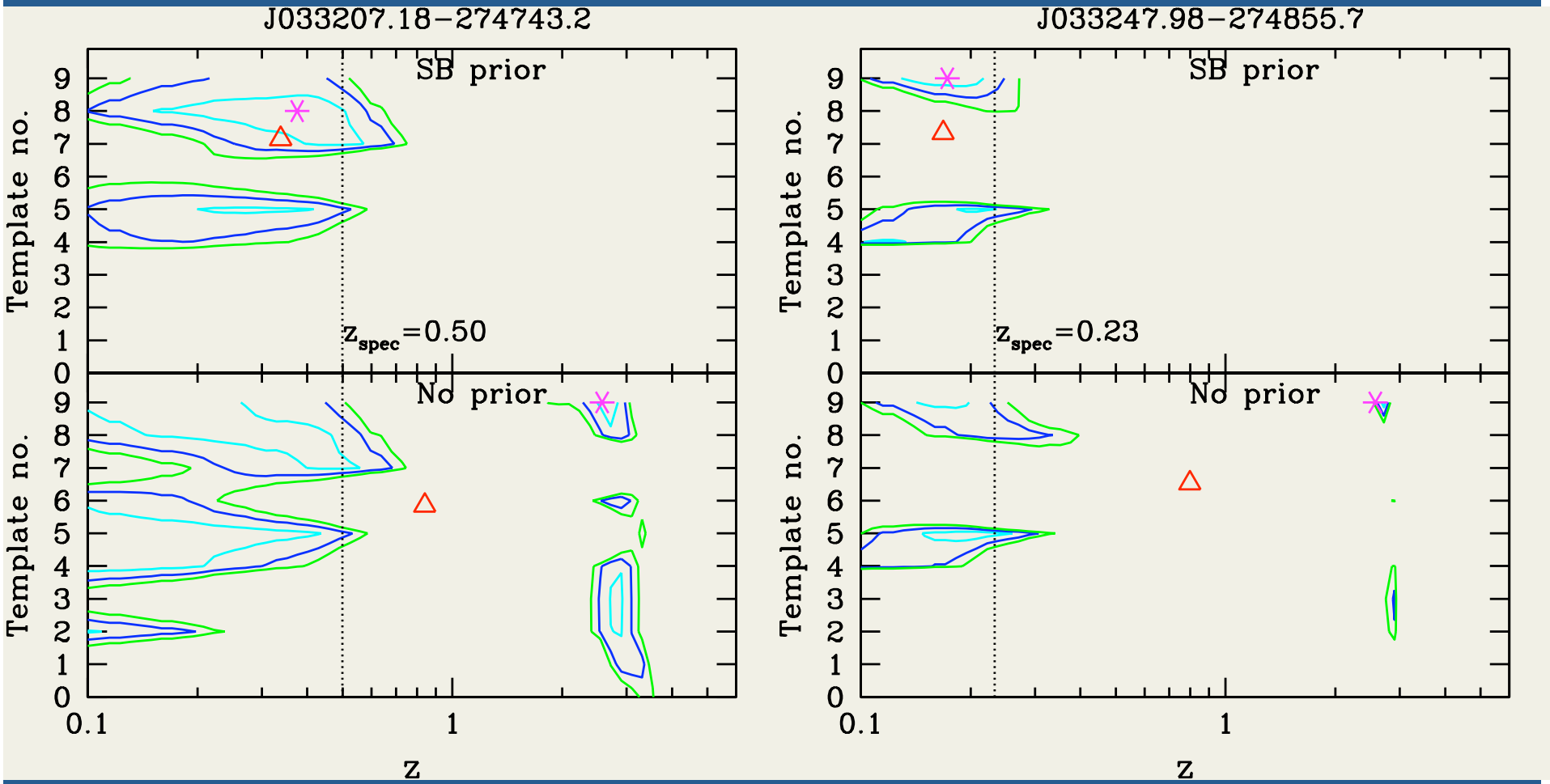
$$
\begin{aligned}
\mathrm{SB} &\equiv m + 2.5 \log A \\
&= \left[-2.5 \log \frac{L}{4\pi D_L^2(z)} \right] + \left[2.5 \log \frac{R_p^2}{D_A^2(z)} \right] + \mathrm{const.} \\
&= \left[5 \log (1+z) \cdot \chi(z) \right] + \left[5 \log \frac{(1+z)}{\chi(z)} \right] + \mathrm{const.} \\
&= 10 \log (1+z) + \mathrm{const.}
\end{aligned}
$$

- Independent of cosmology
- Lensing conserves SB

GOODS-N SB(z)



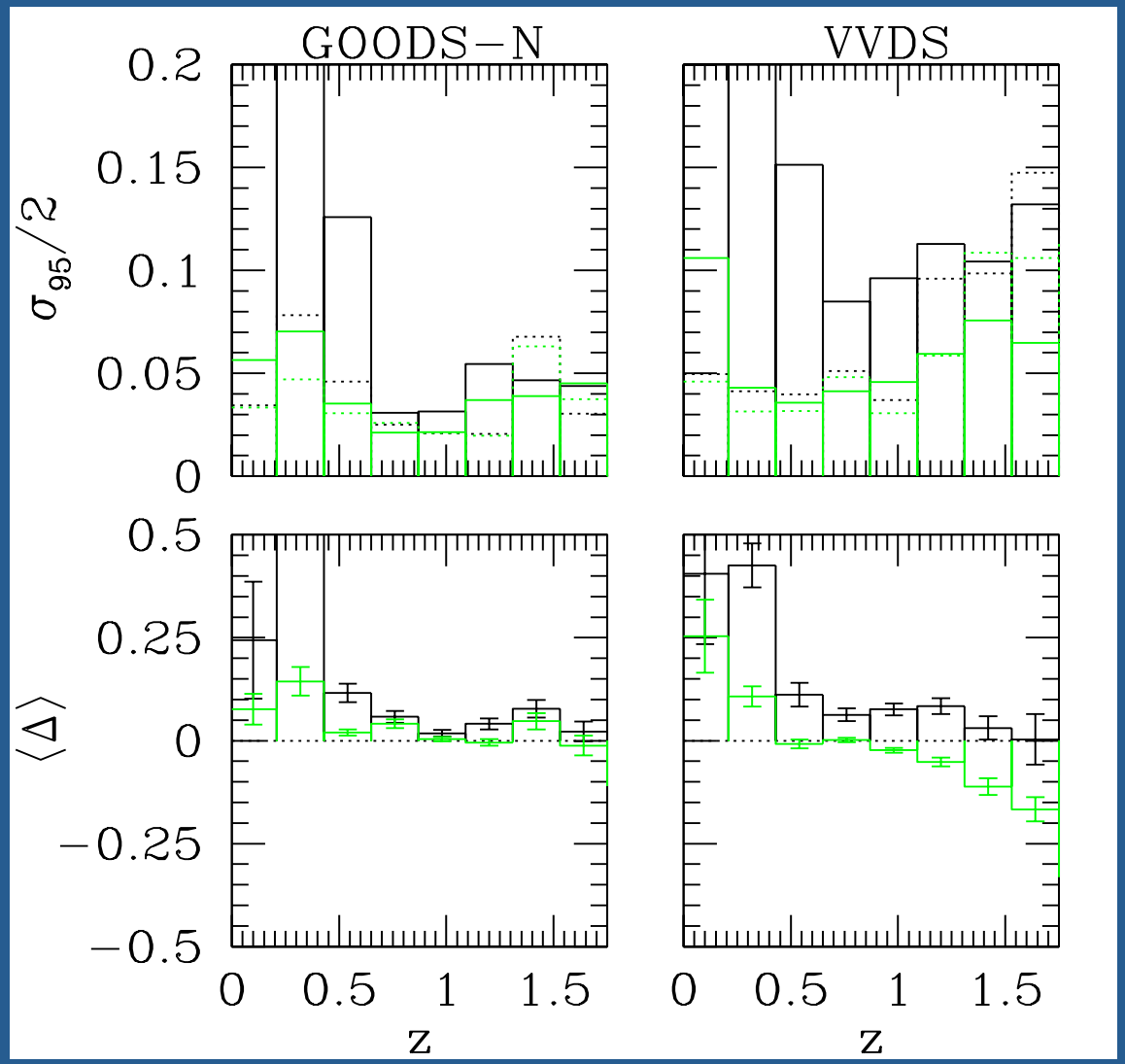
Priors


J033207.18−274743.2
J033247.98−274855.7
SB prior
No prior
z_{spec}=0.50
z_{spec}=0.23
Template no.
z
0.1
1

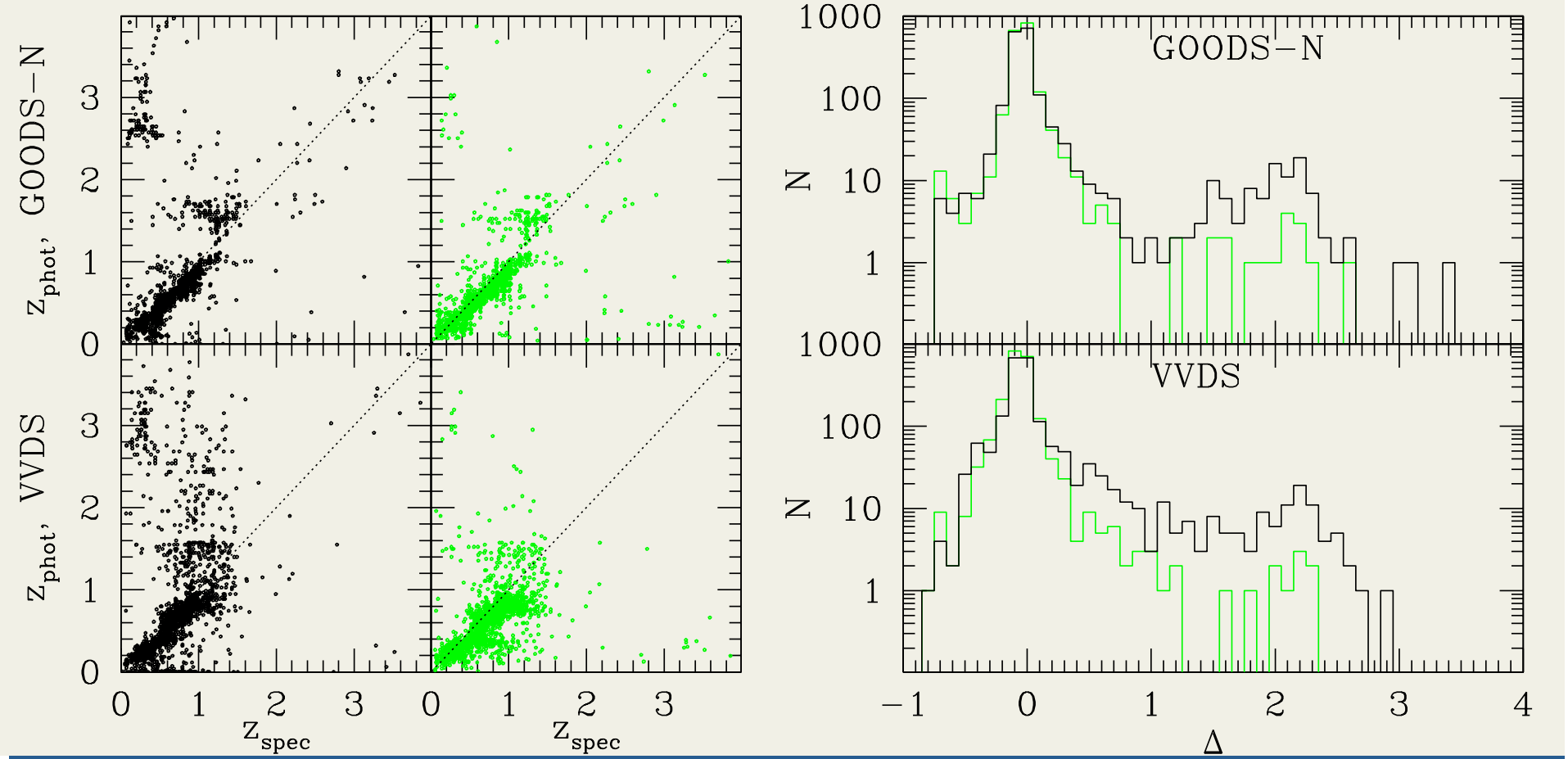
Calibration and Test Data

- Space-based data:
  - GOODS-S (calibration sample): 603 spectra
  - GOODS-N (test sample): 1814 spectra
  - 0.05” seeing
- Ground-based data:
  - VVDS: 4180 spectra, 0.5 deg^2
  - 0.5-1” seeing
- We use half for calibration and half for testing
- Demand ≥ 95% confidence for spectro-z's
- Almost all galaxies have $z \leq 1.5$

Bias(z) and Scatter(z)



Error distributions

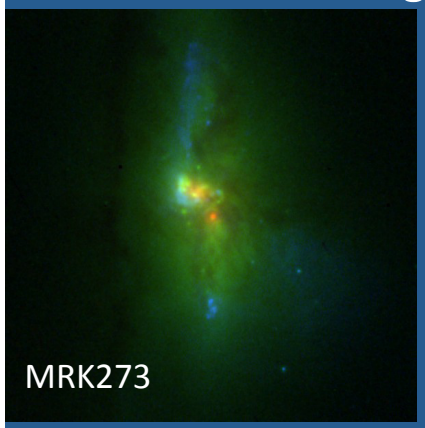


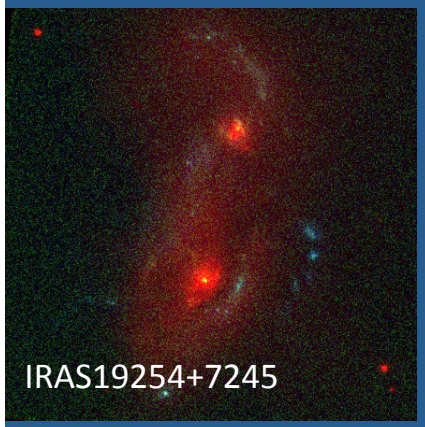
Ultra-Luminous Infrared Galaxies

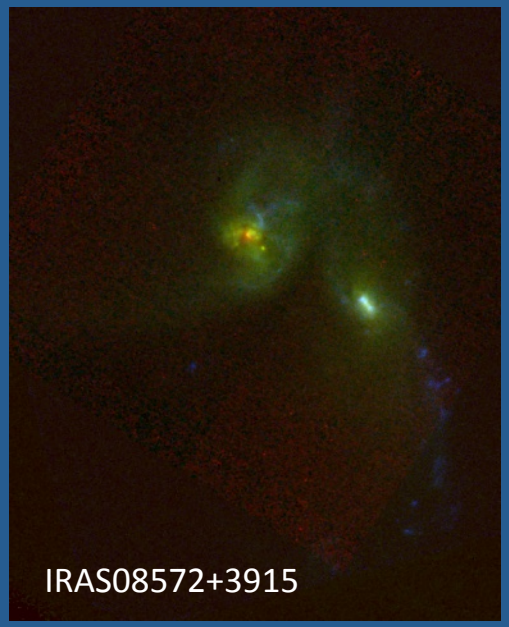
Discovered by IRAS in 1980's

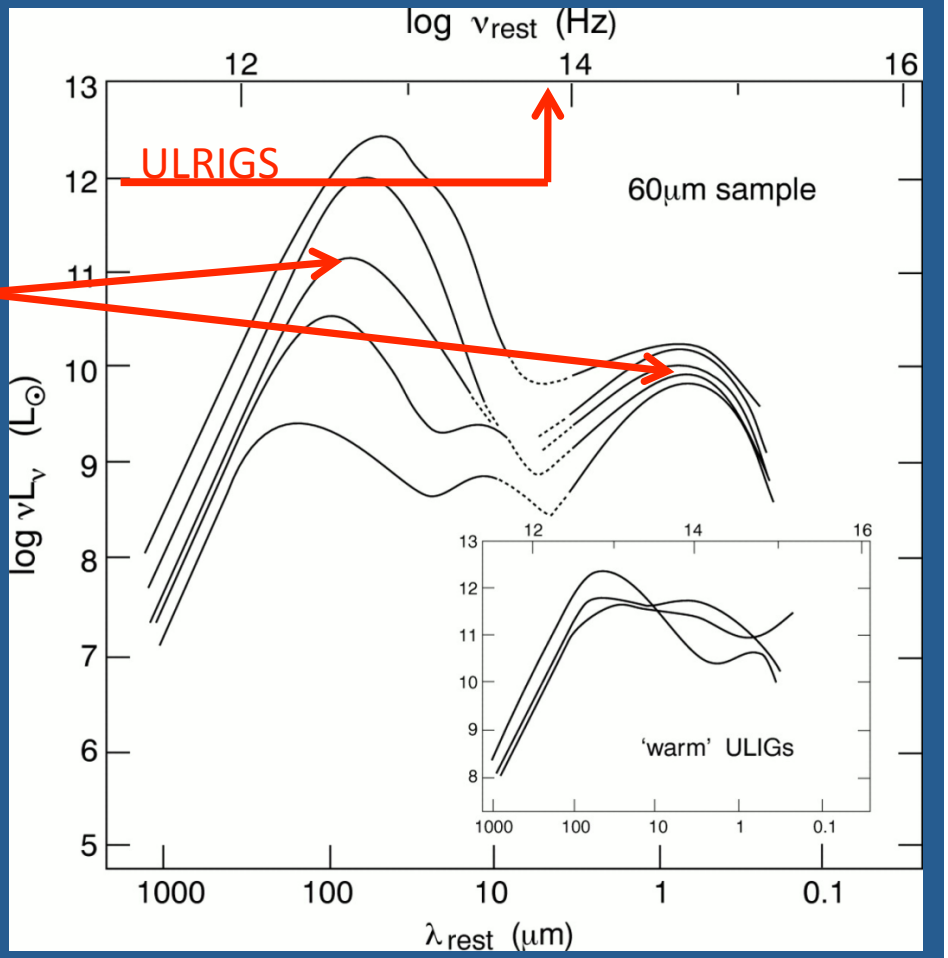
Increasing bolometric luminosity

Higher FIR/Optical ratio









Sanders and Mirabel 1996

Major mergers trigger massive star formation leading to high luminosities.

HST Images of ULIRGs from http://www.pha.jhu.edu/~meurer/research/uvlirgs.html

Slide Credit: M. Devlin

BLAST

Balloon-borne **L**arge-**A**perture **S**ubmillimeter **T**elescope

Antarctica 2006:

First Extra-galactic Survey Results

Mark Devlin

University of Pennsylvania

UBC
Ed Chapin
Mark Halpern
Gaelen Marsden
Douglas Scott

CDF (France)
Guillaume Patanchon

U of T
Peter Martin
Barth Netterfield
Marco Viero
Don Wiebe

JPL
Jamie Bock

UPenn
Simon Dicker
Jeff Klein
Marie Rex
Chris Semisch
Matt Truch

Brown University
Greg Tucker

U of Miami
Josh Gundersen
Nick Thomas

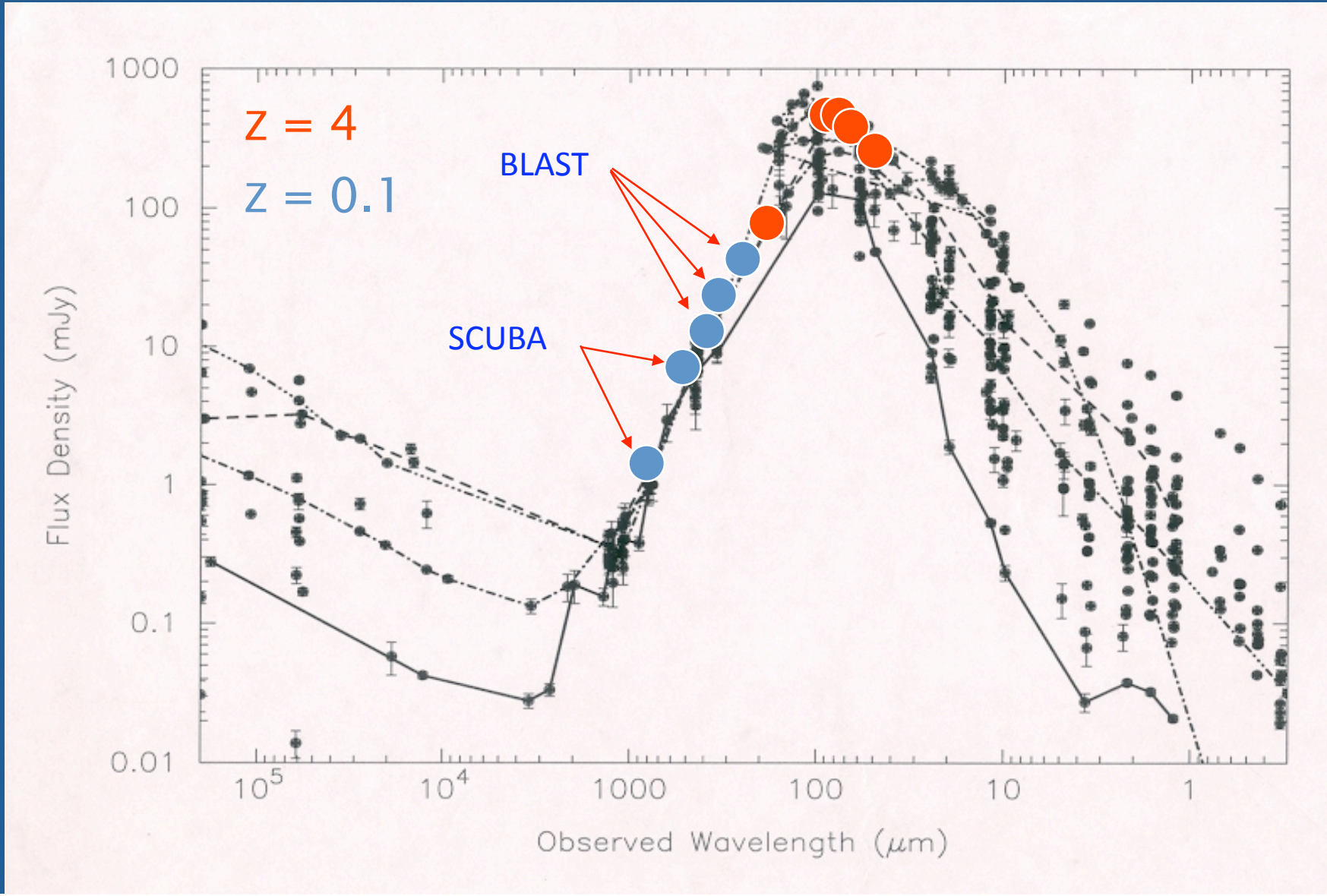
INAOE (Mexico)
David Hughes
Itziar Aretxaga

U Puerto Rico
Luca Olmi

Cardiff University
Peter Ade
Matt Griffin
Peter Hargrave
Phil Mauskopf
Carole Tucker
Enzo Pascale

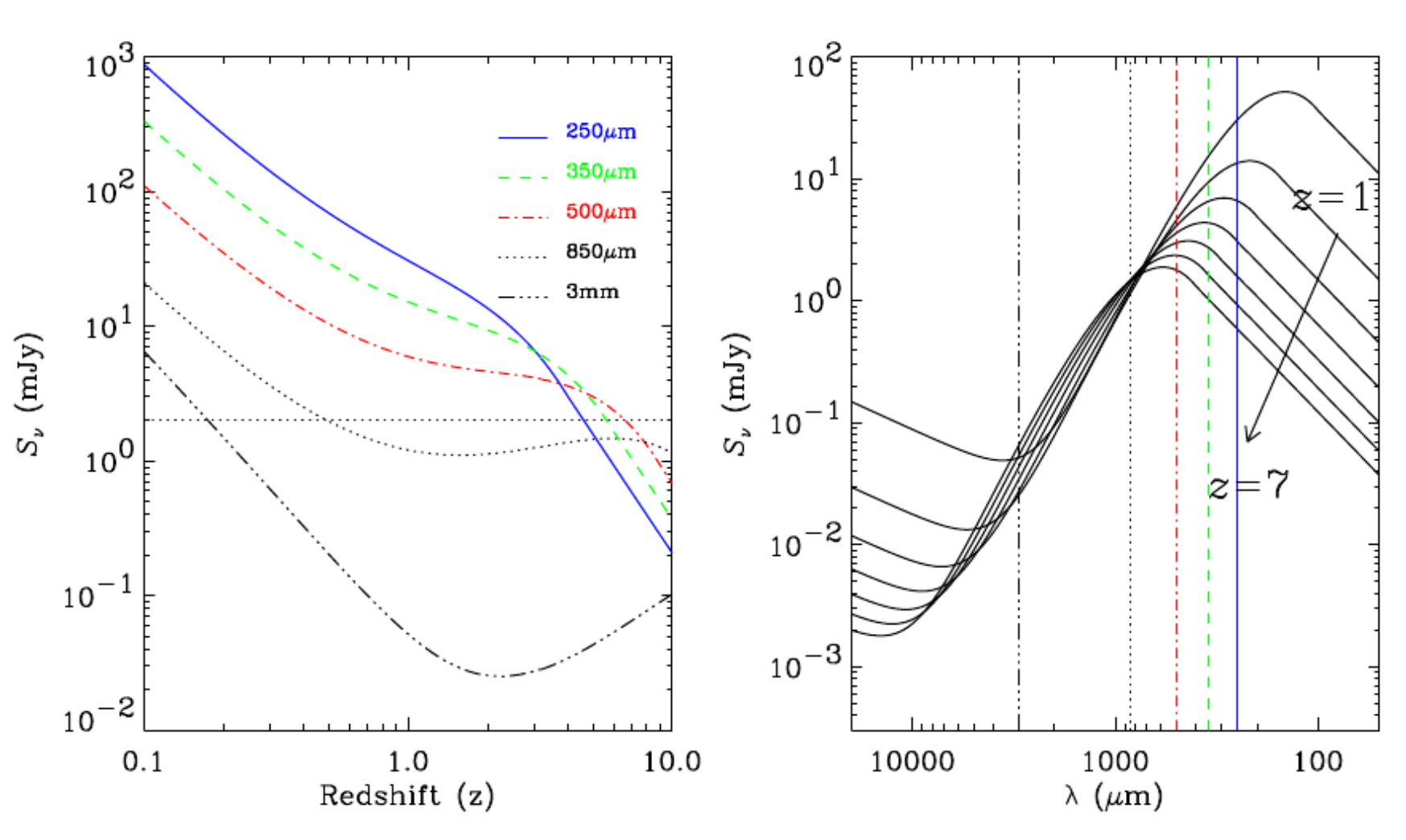
Photo: Mark Halpern

Submillimeter Photo-zs

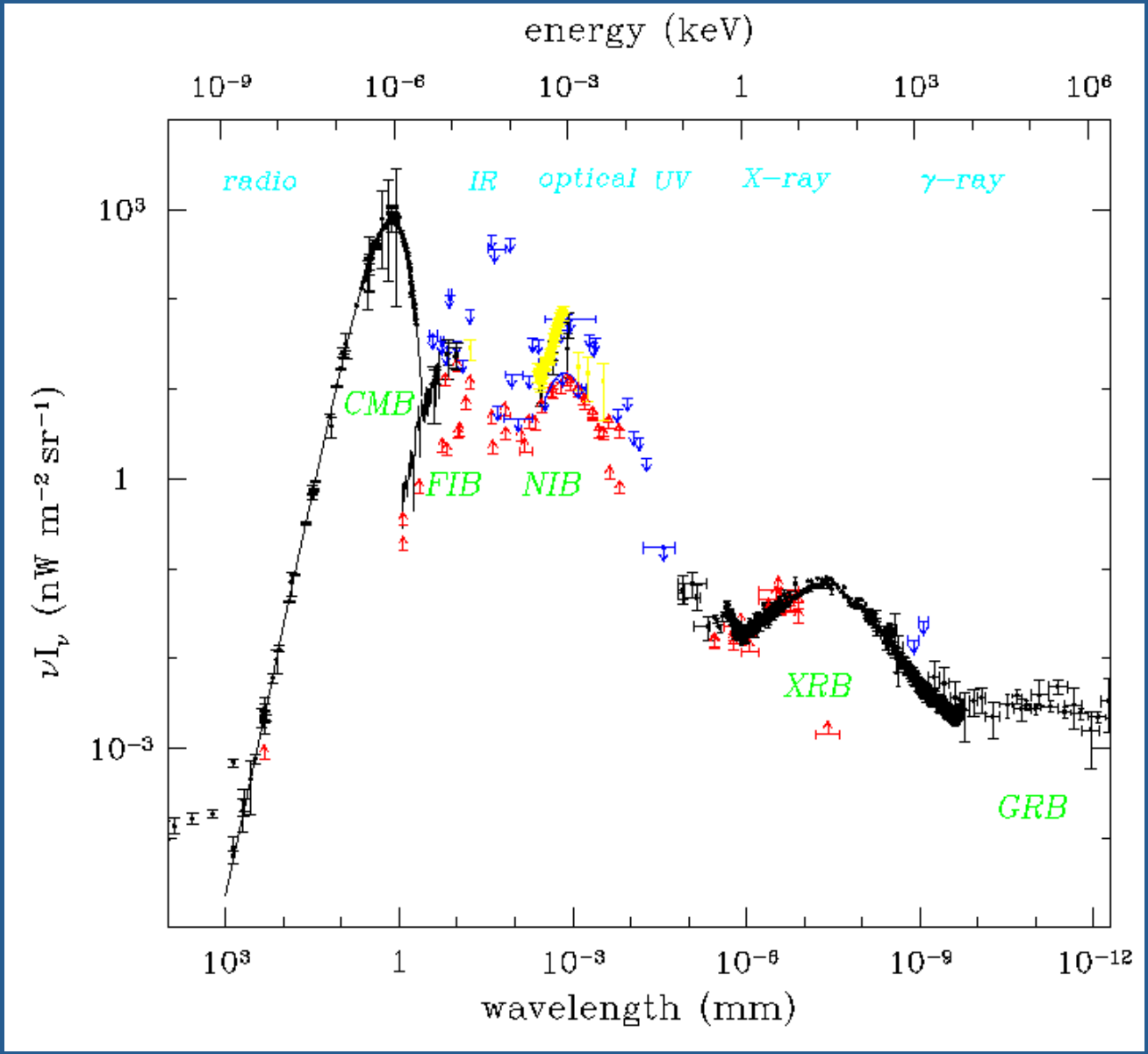


Submillimeter K-Correction

ULIRGs ARE DETECTABLE AT LARGE REDSHIFTS IN SUBMM



Cosmic Infrared Background



Conclusion

- Cosmic acceleration: DE or AG
- Simulated an approximate AG model
  - Computed lensing observables
- Photo-z's are important for observations
  - SB(z) helps constrain them
- In progress: BLAST analysis
  - ULIRGs and the far-IR background
  - SFR(z)