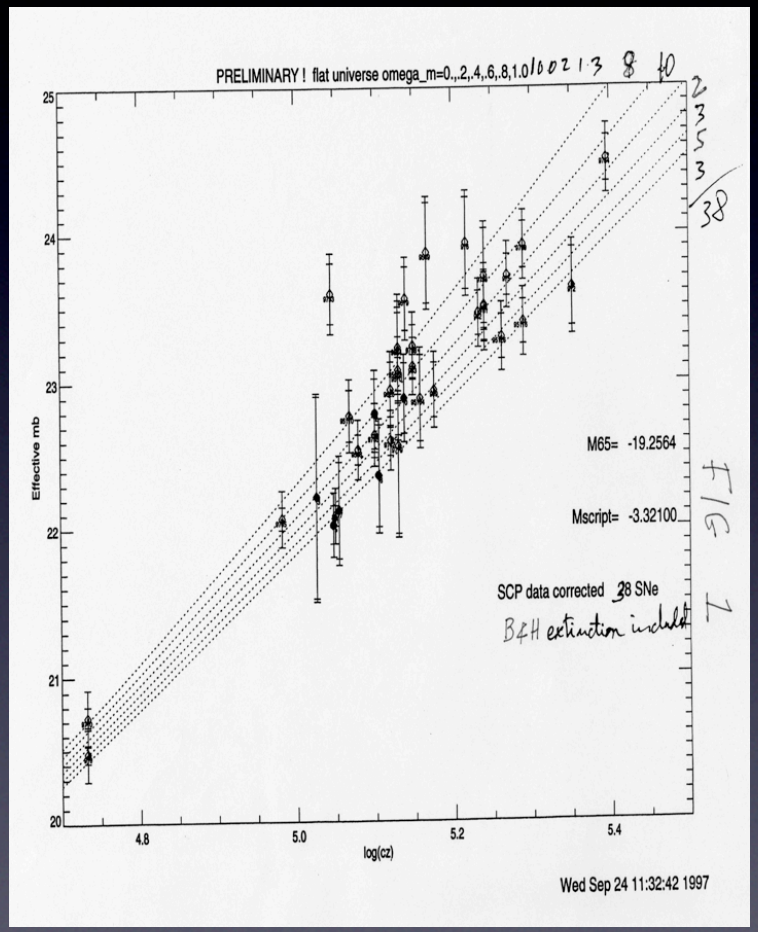
Dark Energy Business Today and Future

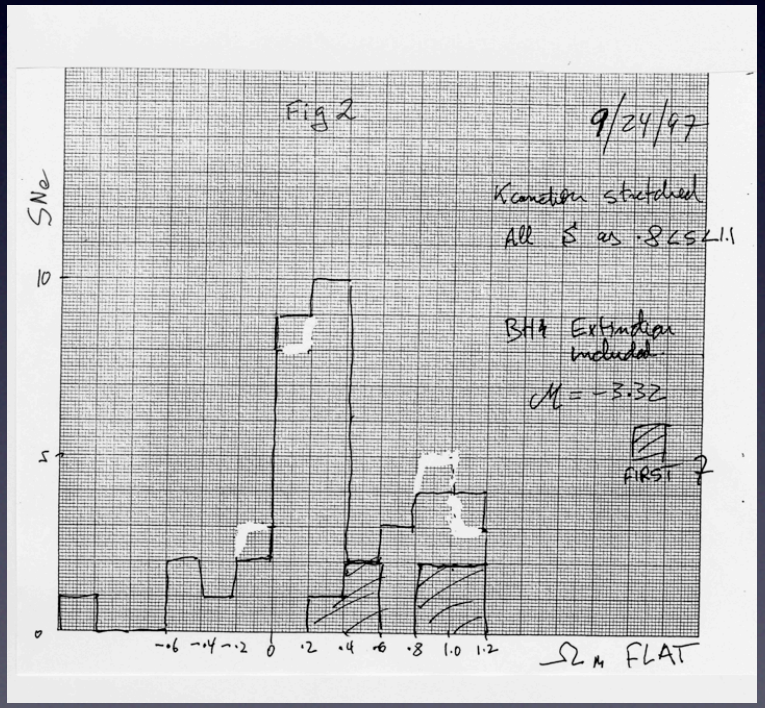
- Nao Suzuki (nsuzuki@lbl.gov)
  Lawrence Berkeley National Lab:
  Supernova Cosmology Project +
  BOSS (Quasar Template, LyAF Science)

- Past Experience : Quasar (BH), Quasar Absorption Line D/H (Baryon Asymmetry), AP Test
- Dark Energy Today in 2010
- Quasar Ly alpha Forest Science
  1) BAO ($2.2 < z < 4.0$)
  2) Growth Factor Measurement

Discovery of Dark Energy (SCP 1997)



Gerson Goldhaber reported non-zero Λ in Sep '97

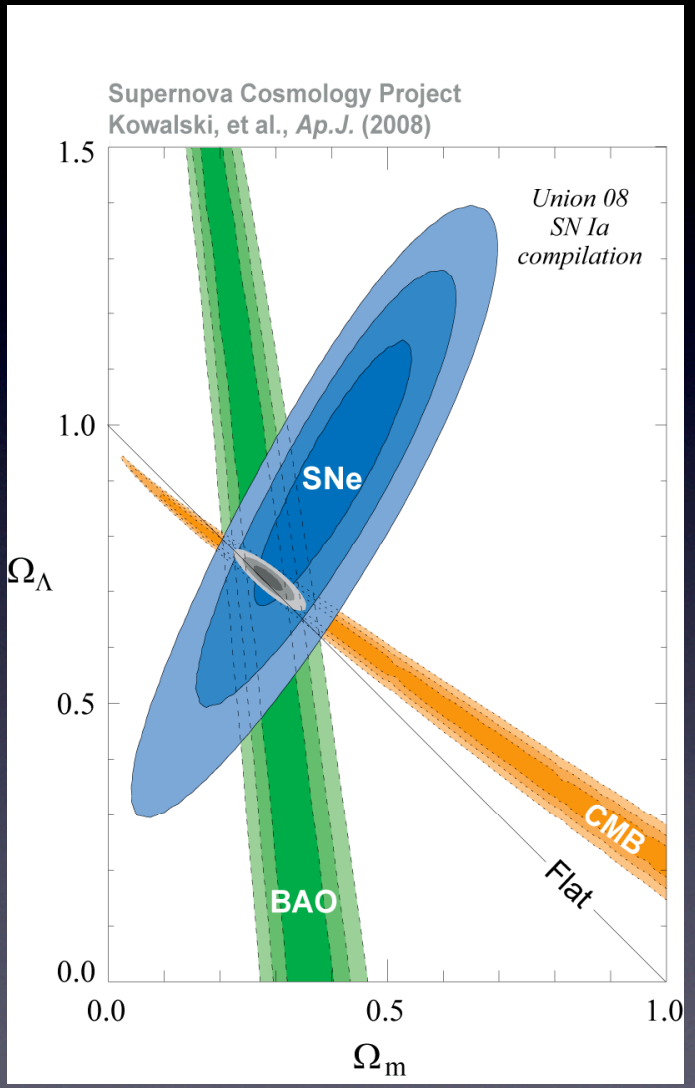


Λ Today

Combination of SNe with:
BAO (Percival et. al., 2009)
CMB (WMAP-7 year data, 2010)
For a flat Universe:
… and with curvature:

$\Omega_m = 0.274 \pm 0.016(\text{stat}) \pm 0.012(\text{sys})$
$\Omega_m = 0.285 \pm 0.020(\text{stat}) \pm 0.010(\text{sys})$
$\Omega_k = -0.001 \pm 0.010(\text{stat}) \pm 0.005(\text{sys})$

Amanullah et al (SCP, 2010)



w=P/ρ : Equation of State today
(statistical err < systematic err)

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

- w=-1 : cosmological constant
- w=0 : matter
- w=1/3: radiation

SNe + BAO + CMB

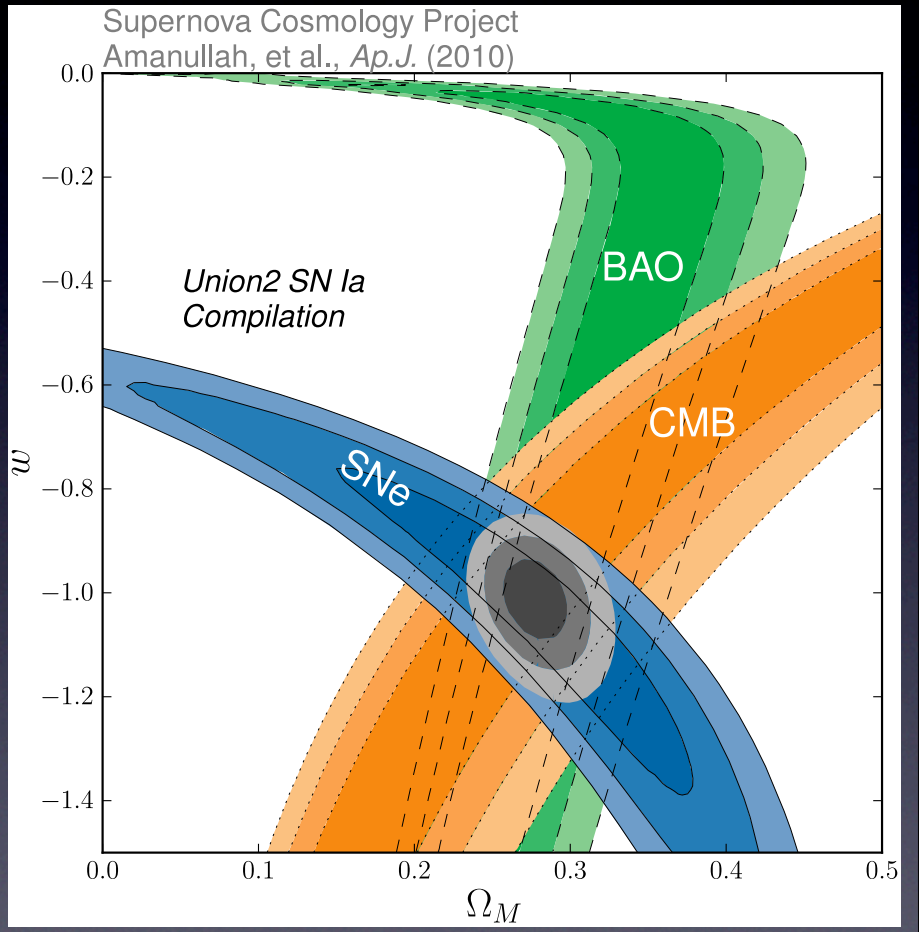
For a flat universe:

w = -0.997 ± 0.052(stat) ± 0.082(sys)

For a non-flat universe

w = -1.038 ± 0.056(stat) ± 0.093(sys)

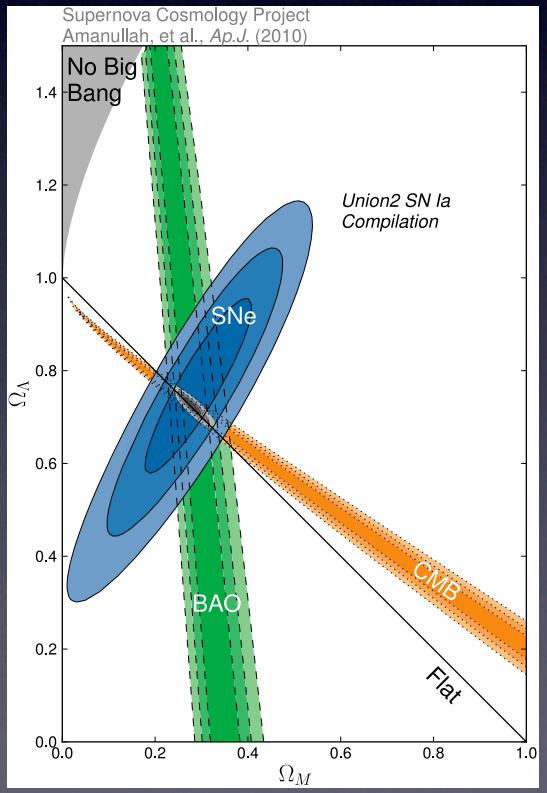
SCP UNION2 Amanullah et al. 2010

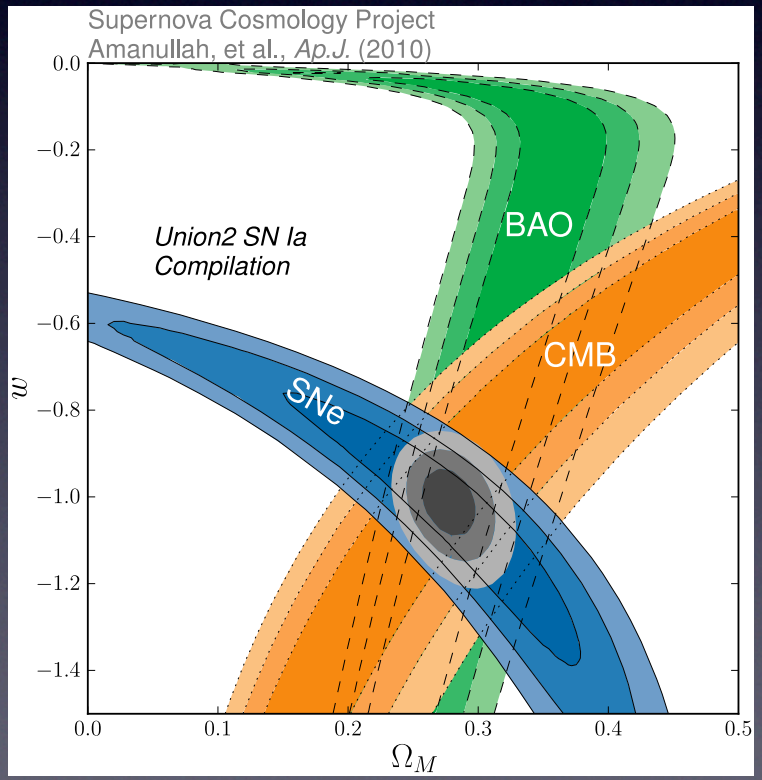


Λ Business : Market Values 2010

ΛCDM : w=−1, k=0 wCDM : w≠−1, k=0

Ω_m ~ 0.27 (~ 5% stat) w ~ −1 (~ 5% stat)

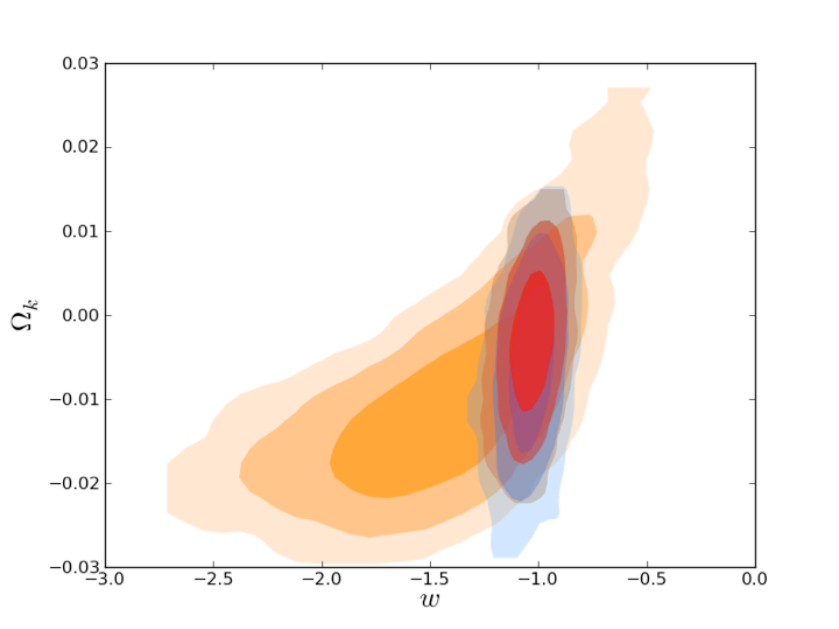




Λ Business Market Values in 2010

owCDM : w≠−1, k≠0

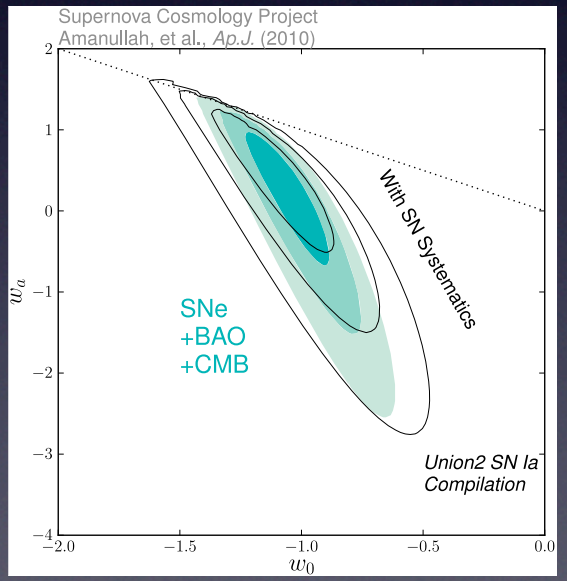
Ω_k ~ 0.0 (~ 1% stat)



$w_a w_0$CDM :

$w(a)=w_0+(1-a)$

w_0 ~-1 w_a ~0



HST Cluster SN Survey

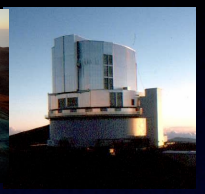
Nao Suzuki & SCP
PI: Saul Perlmutter

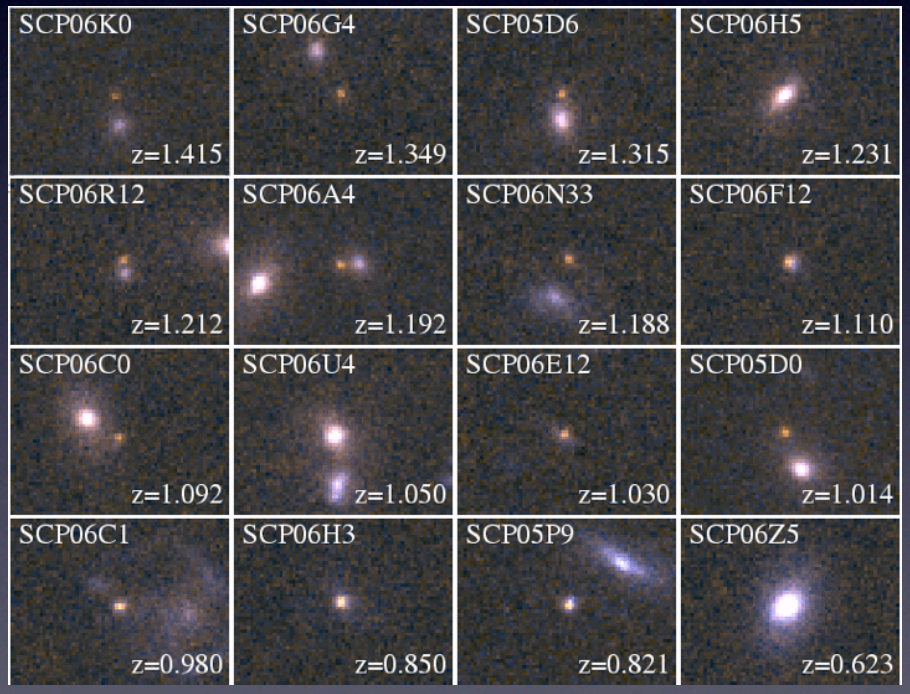
HST

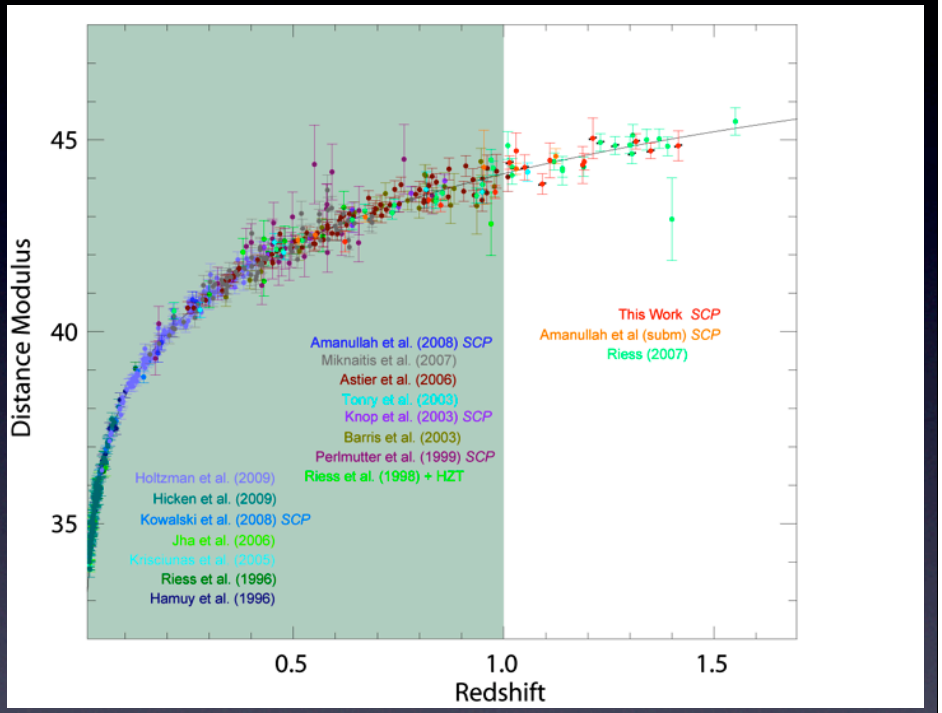
Keck

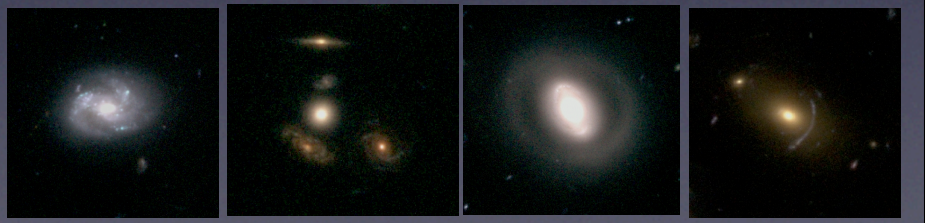
VLT

Subaru





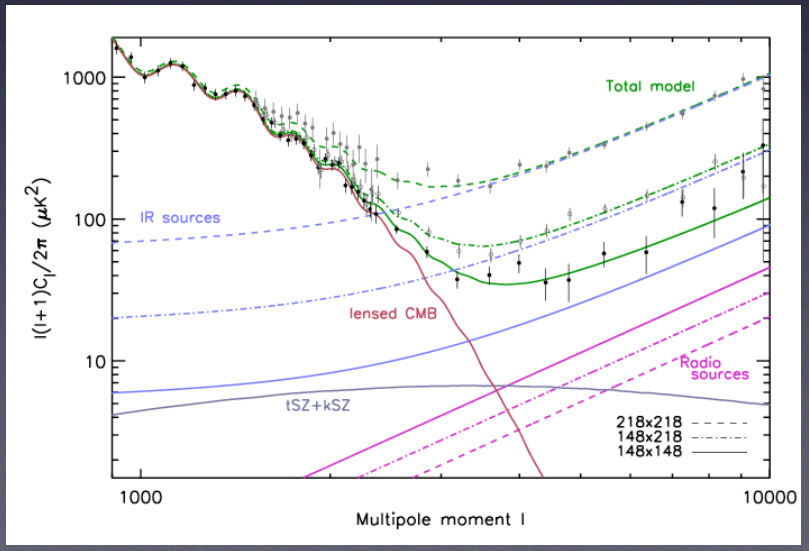




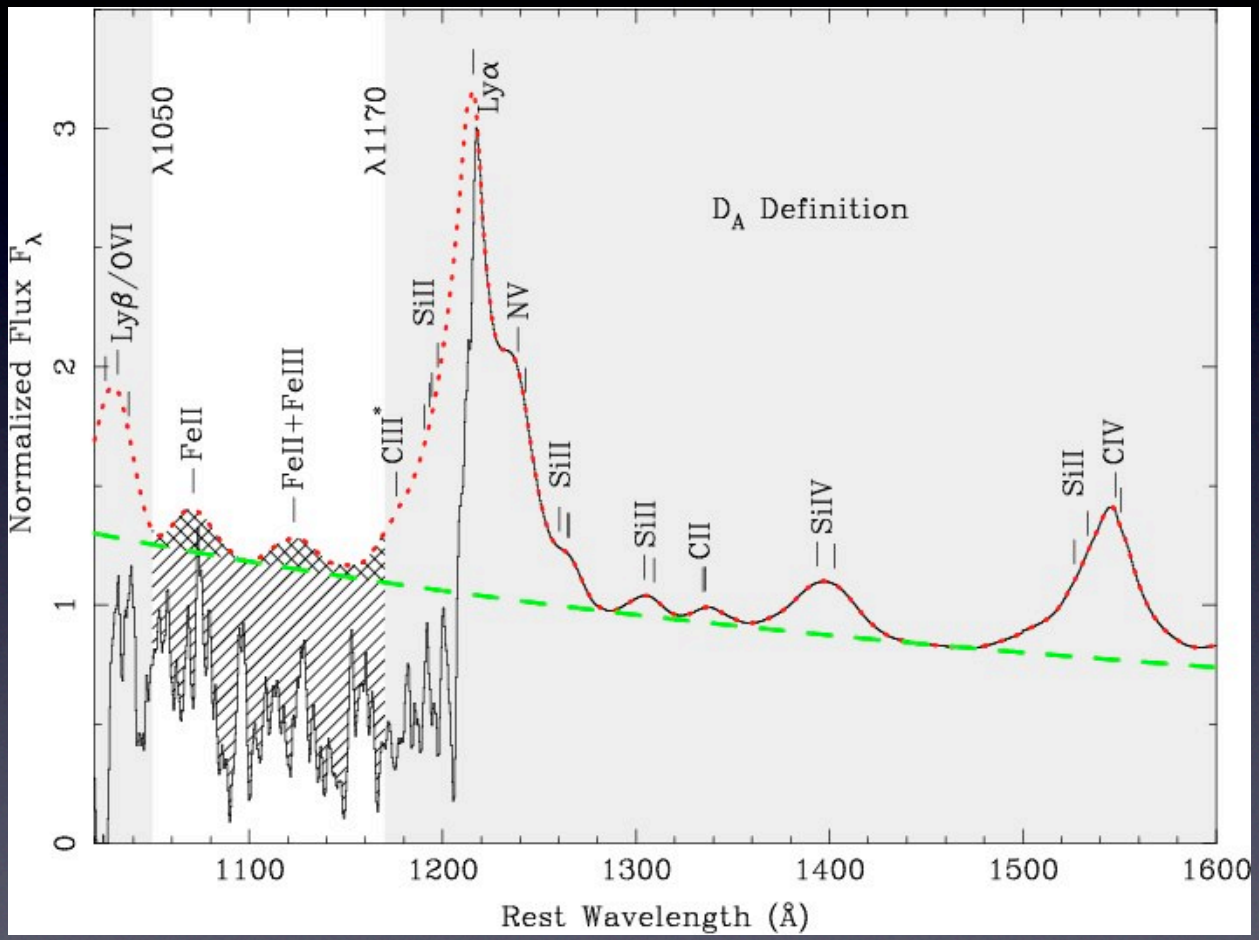
Dark Energy Business enters 1% in the near future

- HST Cluster SN Survey (SCP, high-z SNe)
- HST MCT GOODS SNe (2010-2013)
- SNLS 3 year Data Release
  (Fall 2010, 300 SNe : $0.2 < z < 0.9$)
- Pan-Starr, DES
- CMB: ACT, Planck

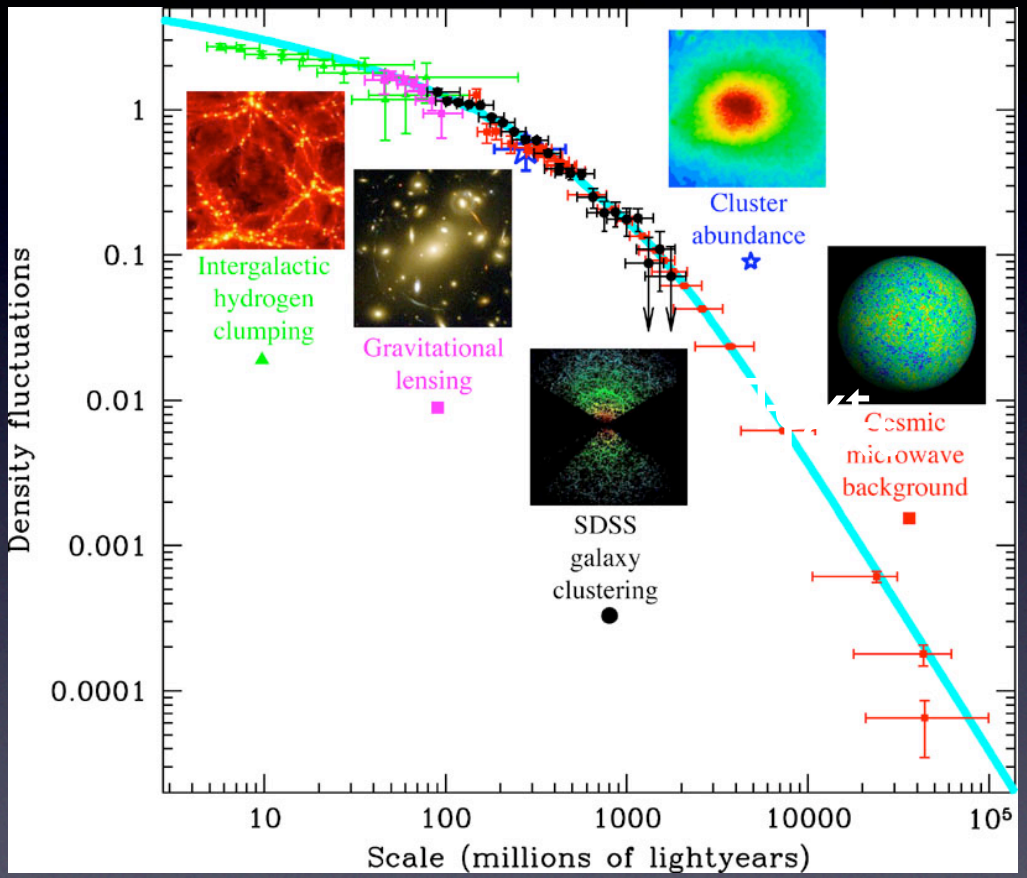
Dunkley et al 2010
Das et al 2010



Quasar Ly alpha Forest



Quasar Ly alpha Forest Science



Max Tegmark

- BAO
- Growth Factor
- Small Scale Power Spectrum
- Slope n

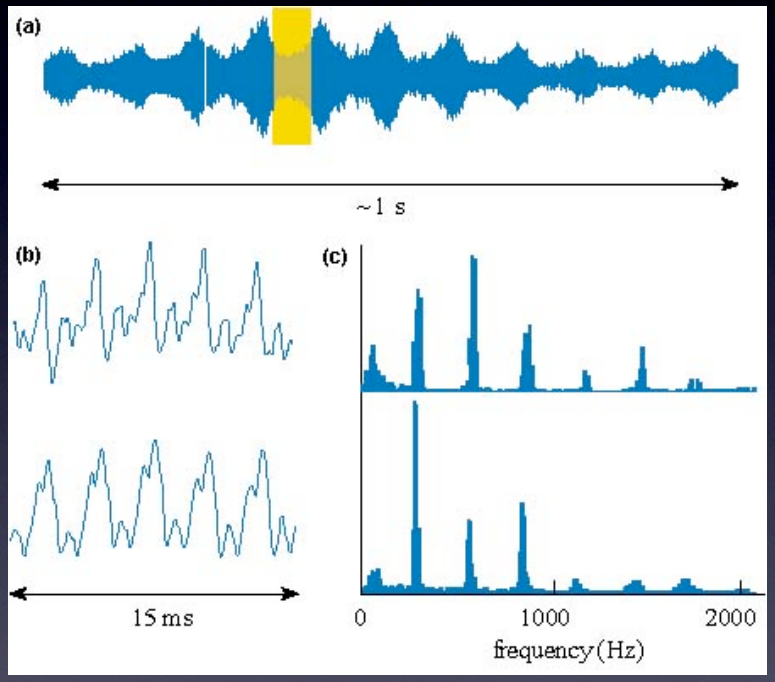
e-foldings of Inflation

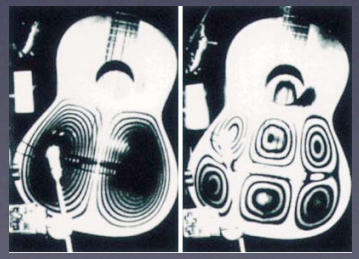
- Upper limit of

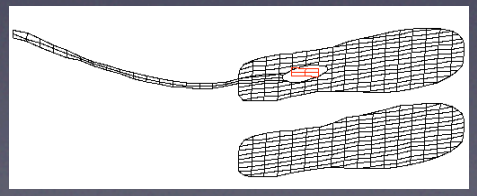
Neutrino Mass

- Chemical Evolution in IGM

Instrument vibrates! : Harmonics in Cosmos





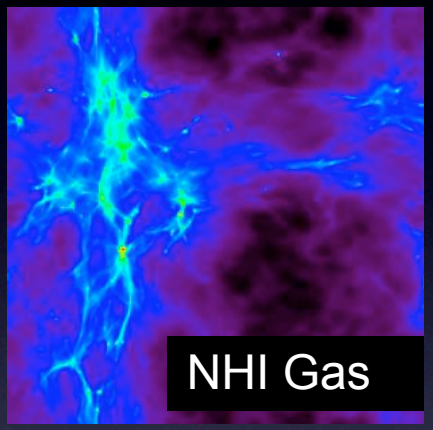


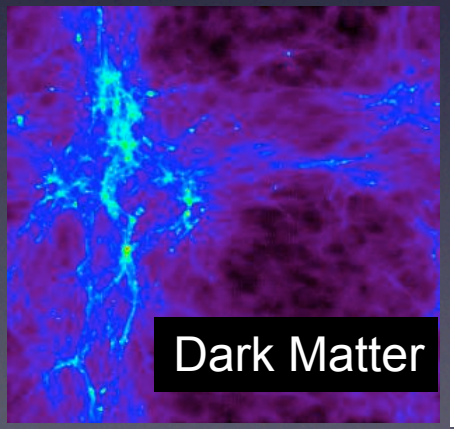
In Cosmos:
x-axis : Frequency(Hz)
=> Distance (Mpc)

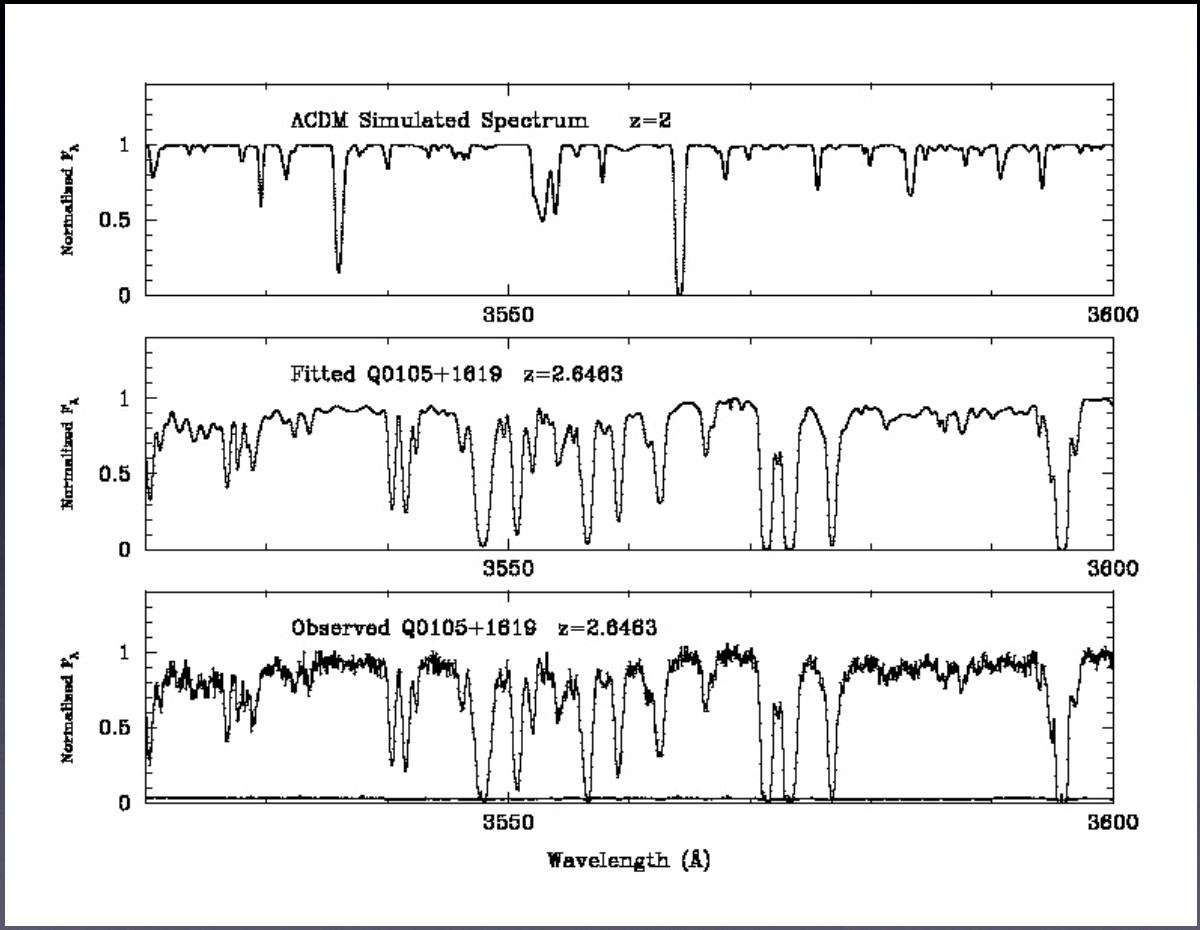
y-axis: Amplitude (Volume)
=>P(k) : Mass Fluctuation
=>CMB : Temp Fluctuation
Ly alpha Forest
=>$P_F(k)$: Flux Fluctuation

Extracting Cosmological Parameters

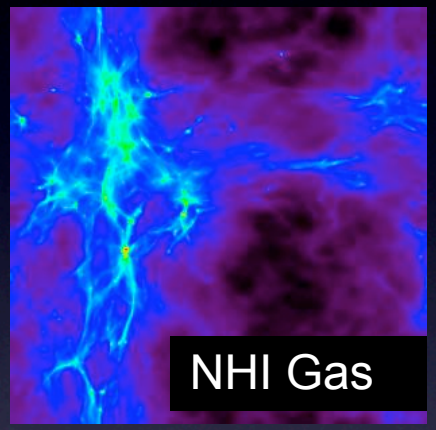
Simulation vs. Observation

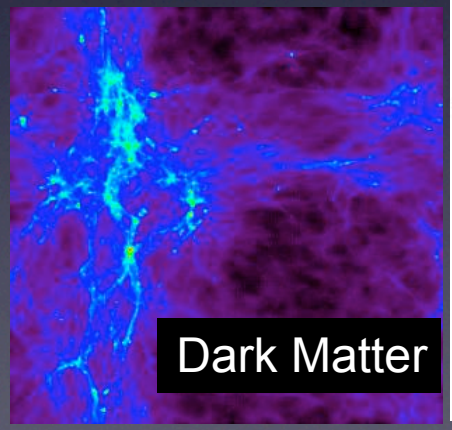




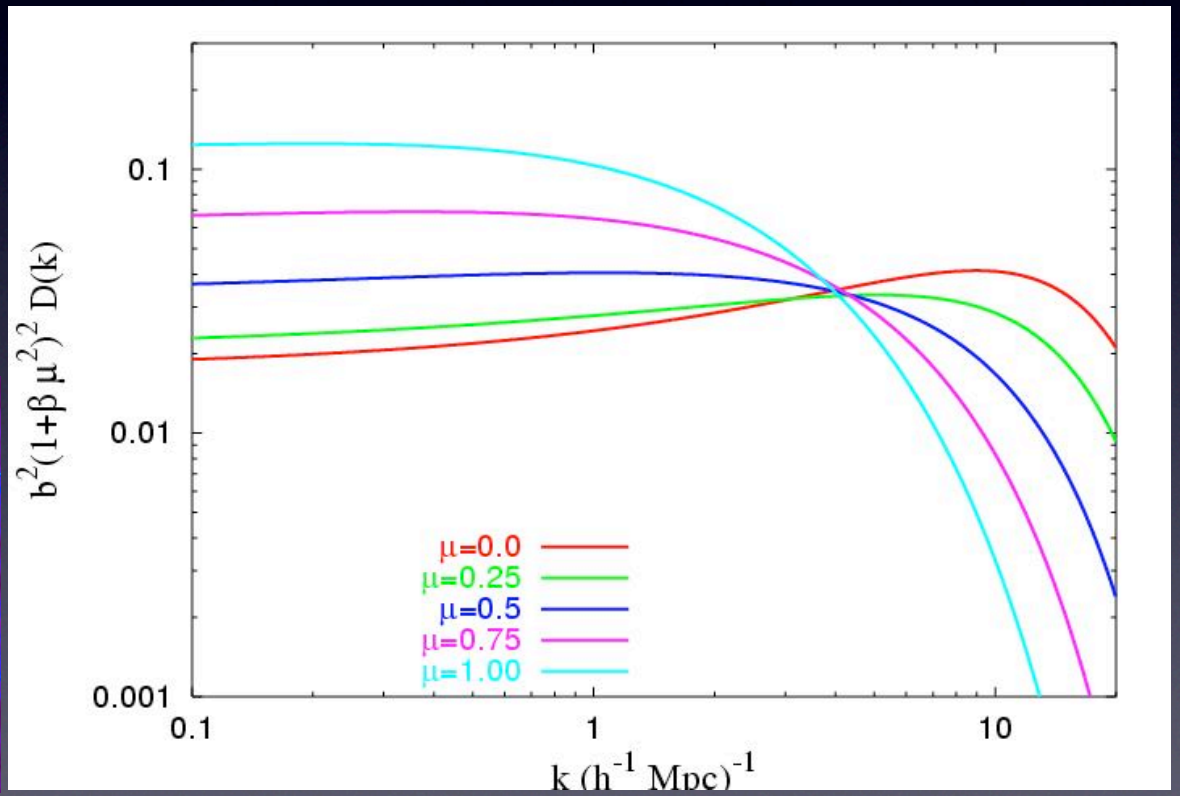


Mass Power <=> Flux Power
(Simulation: bias <= translator)

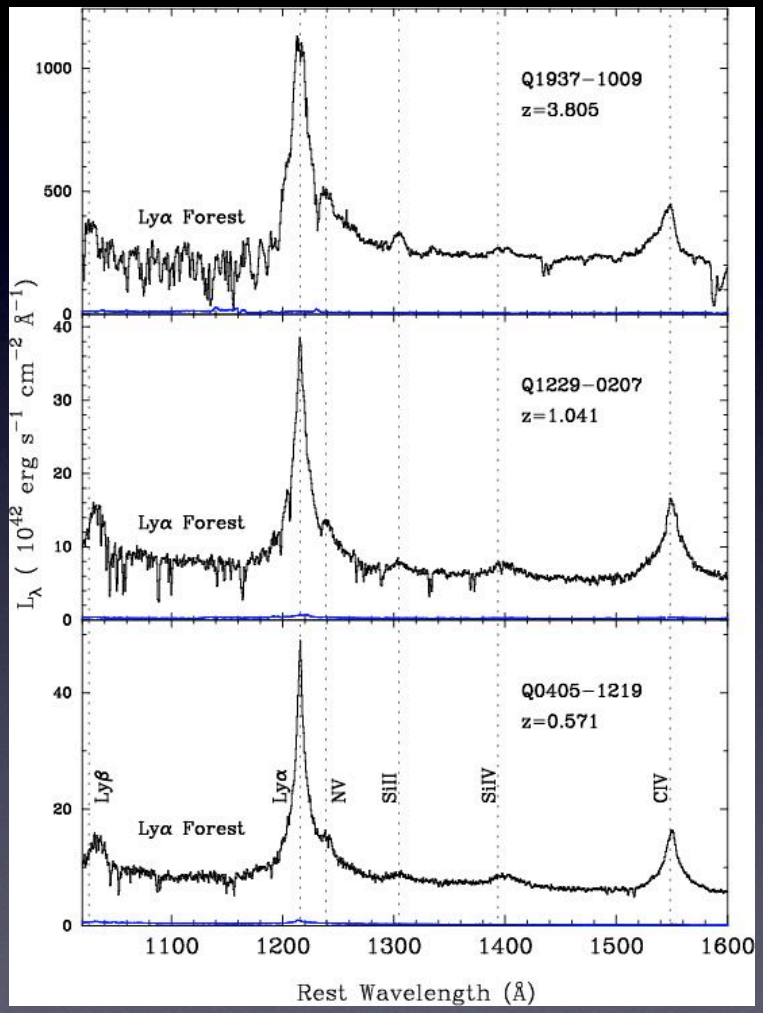


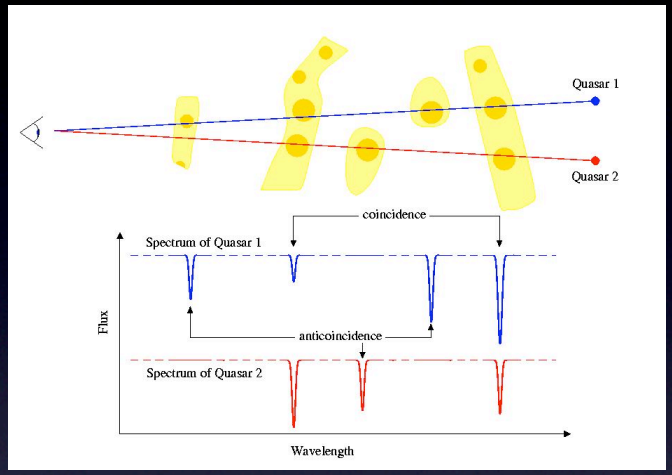


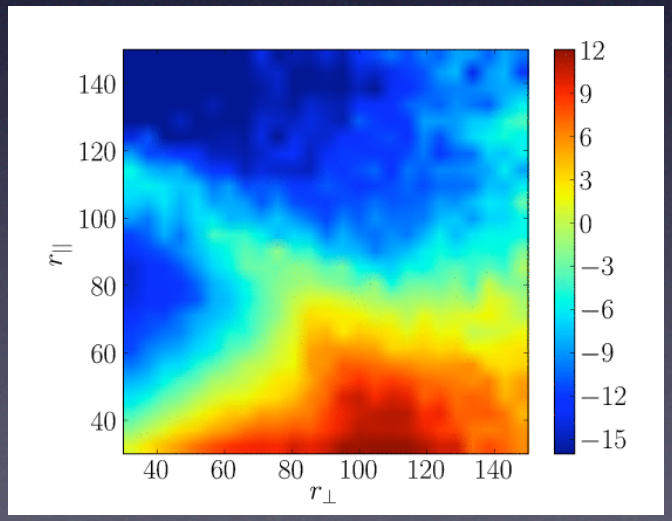
$$P_F(k,\mu) = b^2(1+\beta\mu^2)^2 P_L(k) D(k,\mu)$$



Quasar Absorption Lines: Lyα Forest

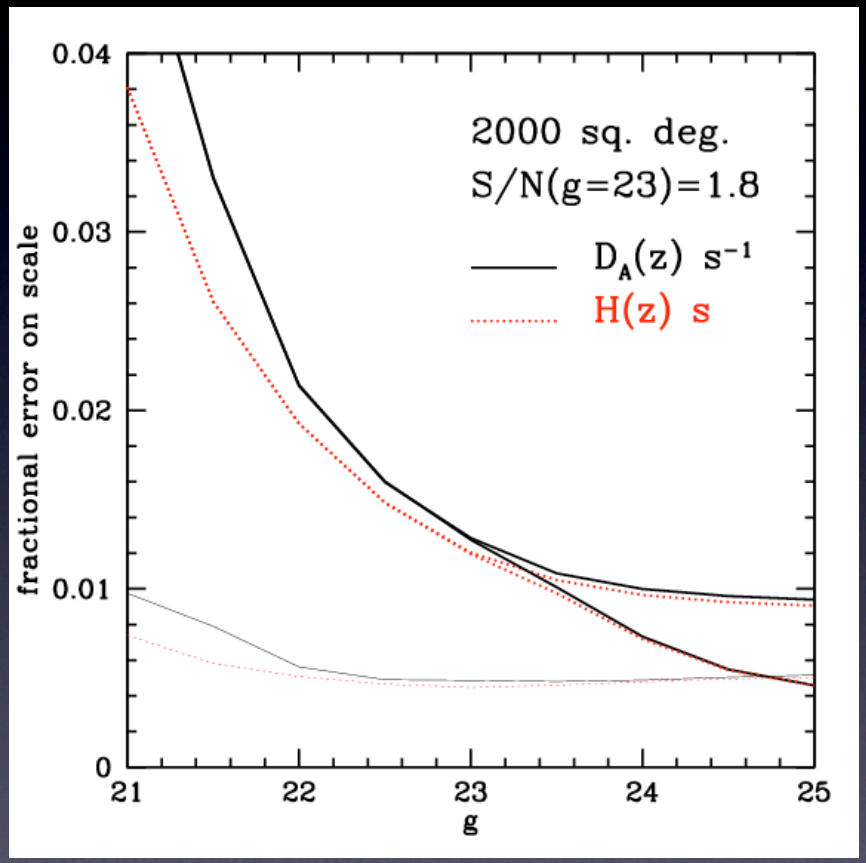


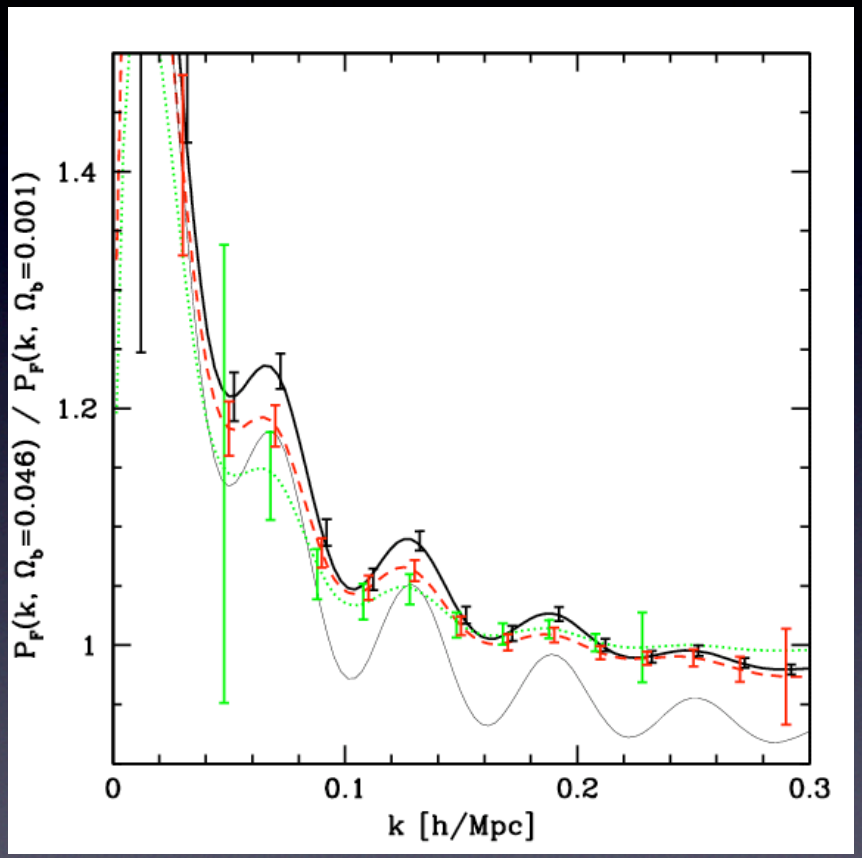




Slosar et al. 2009

BAO from the Ly alpha Forest



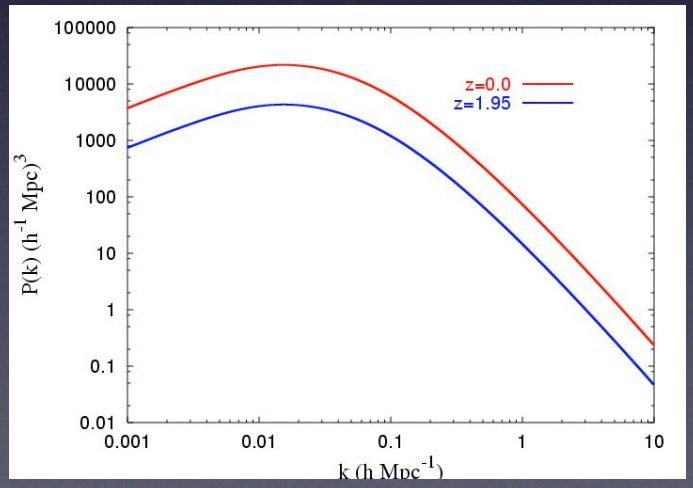


- McDonald & Eisenstein (astroph/0607122)

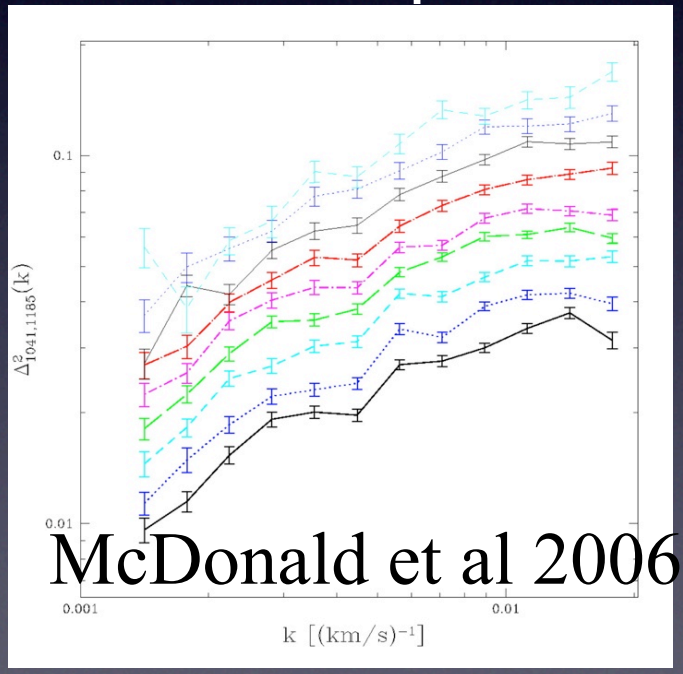
Flux Power Amplitude Measurement
Mass Power Spectrum

$$\frac{\delta\tau}{\tau} = \delta(x) \qquad \delta(k) = \frac{1}{2\pi}\int \delta(x) e^{-2\pi i k x} dx$$

$$P(k) =< \delta^2(k) >$$

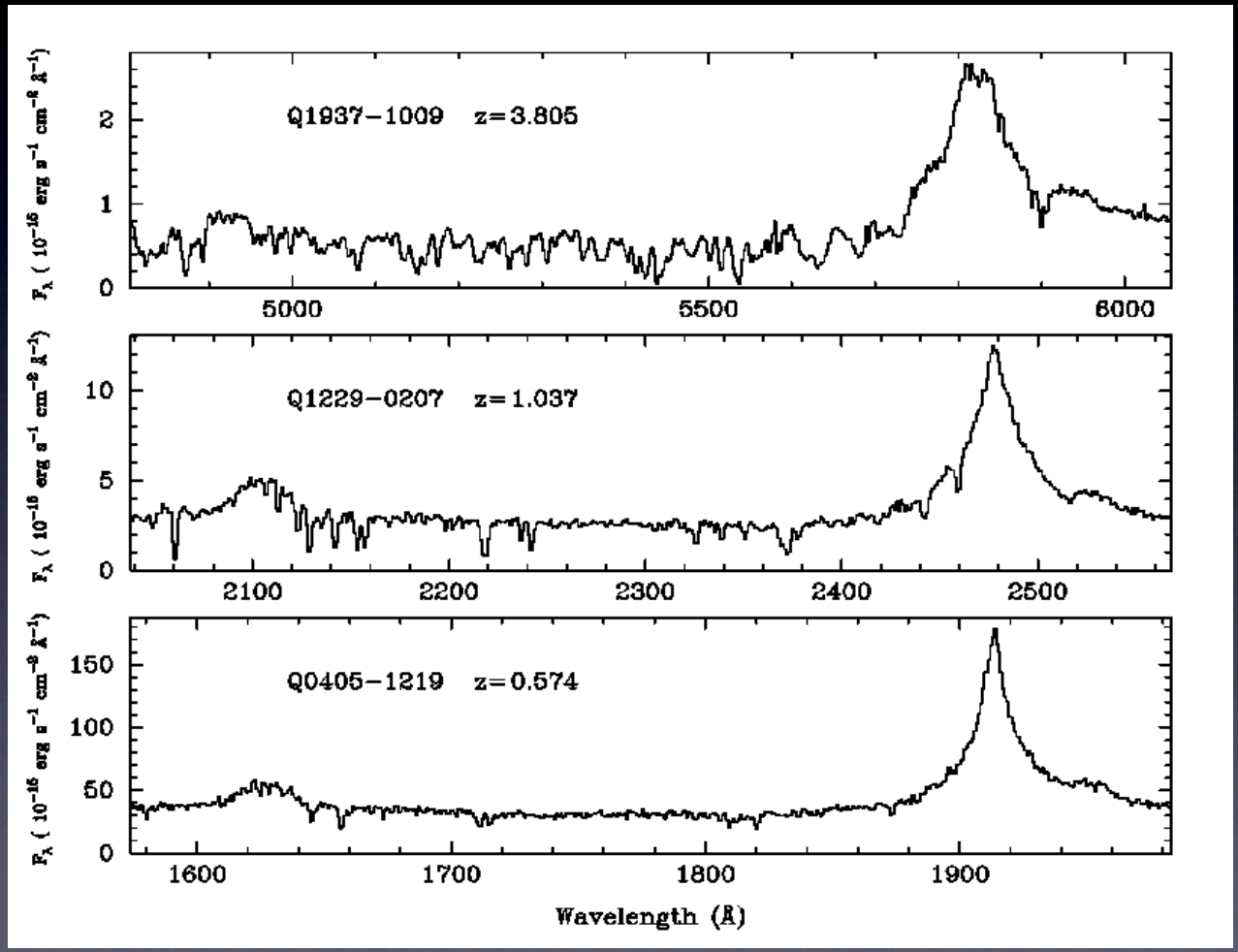


Flux Power Spectrum



McDonald et al 2006

Ly alpha Forest Evolution



IGM Physics

$$n_{HI}\Gamma = n_p n_e \alpha_{rr}(HI, T)$$

$$X_{HI} = \frac{n_{HI}}{n} \qquad n \sim n_p \sim n_e \sim \delta\rho$$

$$\overline{\rho} \propto (1+z)^3$$

$$X_{HI} = \frac{n\alpha_{rr}}{\Gamma} \qquad \frac{\delta\rho}{\overline{\rho}} \propto g(z) \sim \frac{1}{(1+z)}$$

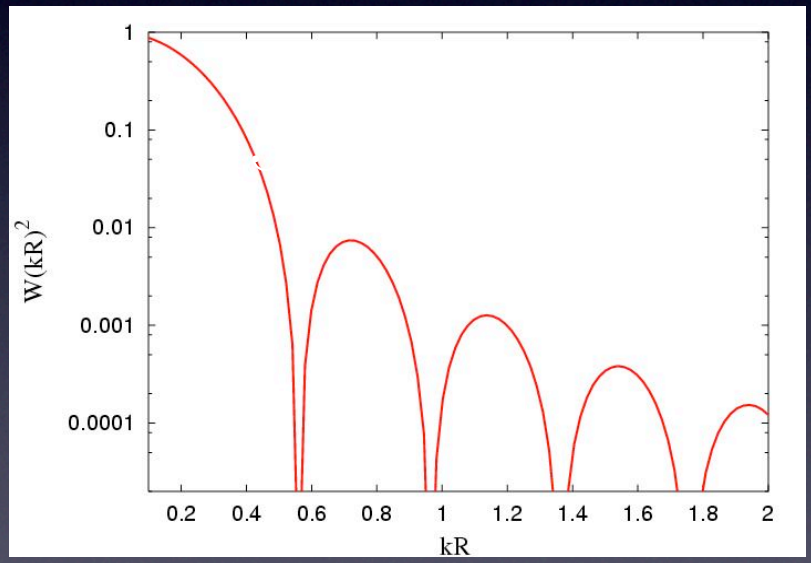
$$X_{HI} = \frac{\alpha_{rr}}{\Gamma}(1+z)^3 g(z) \sim \frac{\alpha_{rr}}{\Gamma}(1+z)^2$$

Flux Power Amplitude

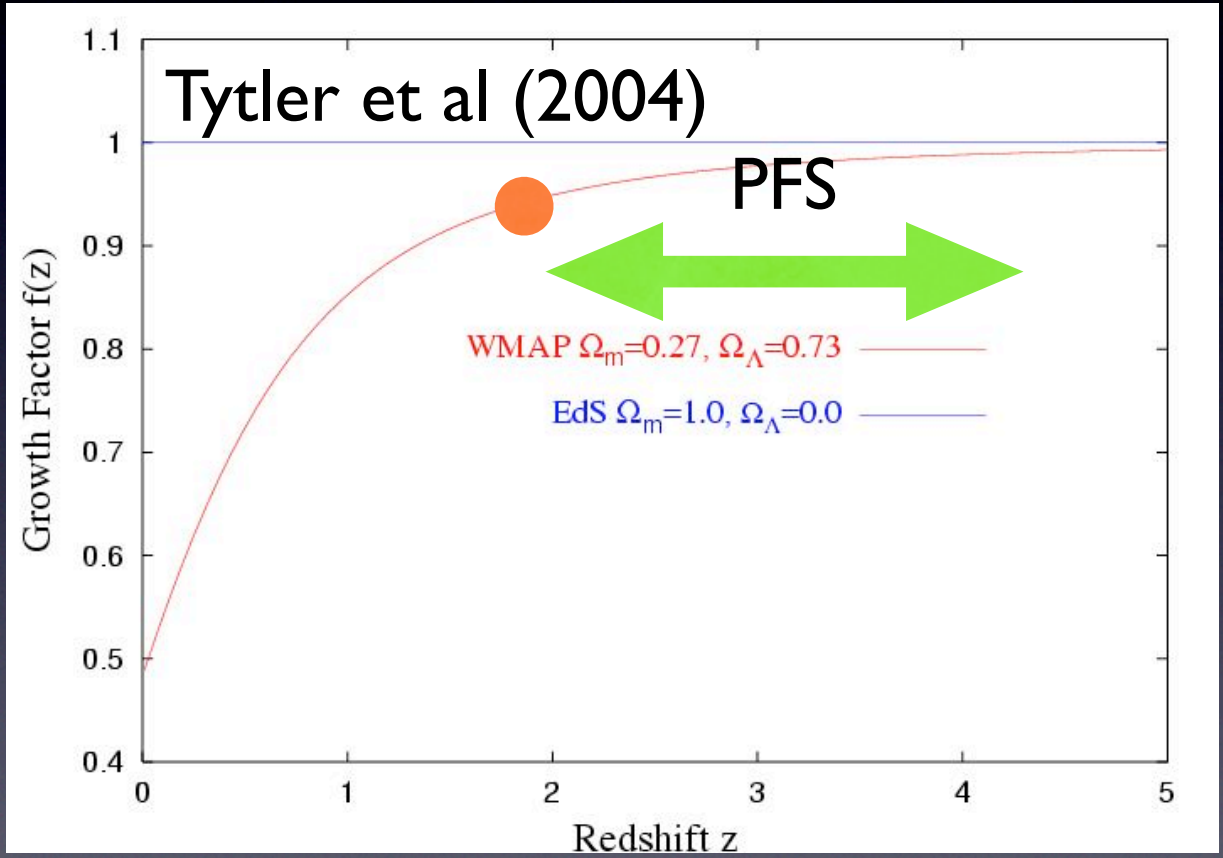
$$\sigma = \frac{< F >^2}{2\pi} = \int P(k) W^2(kR) dk$$

$$W^2(kR) = \frac{2(1 - cos(kR))}{(kR)^2}$$

$$R = 150 Mpc \quad \sigma_{150}$$



Growth Factor



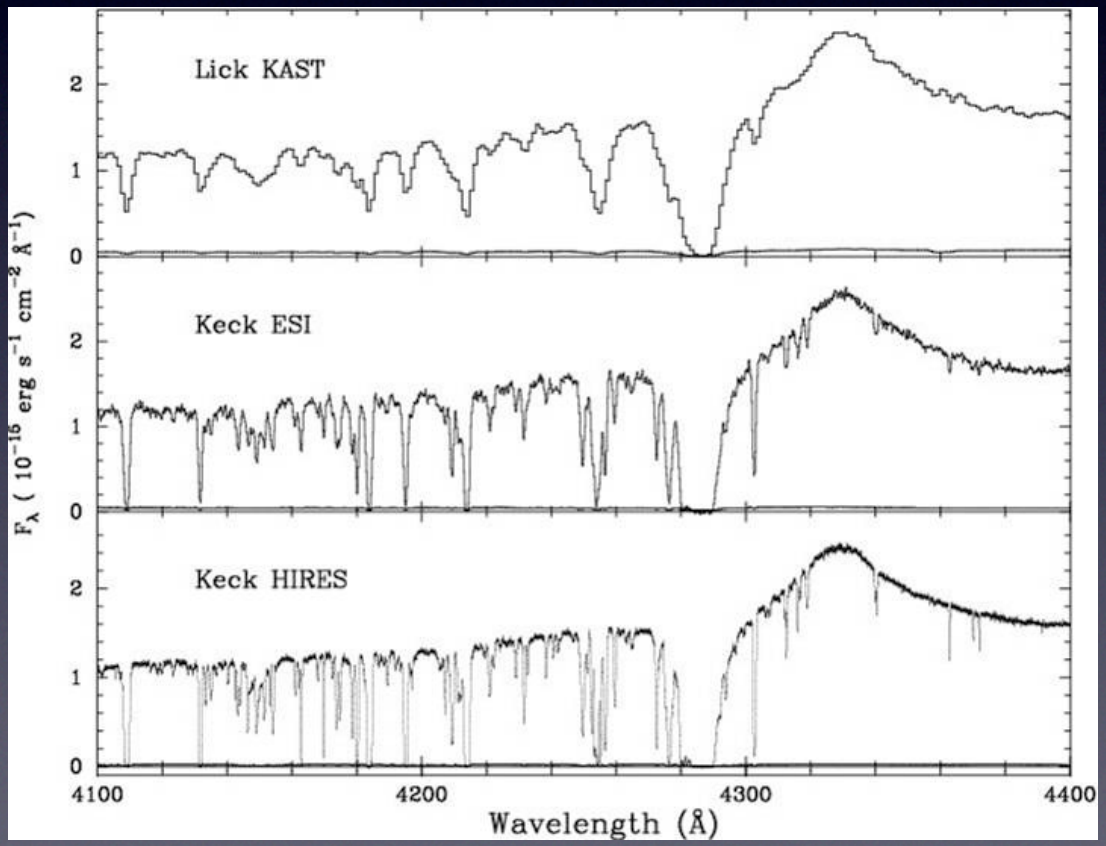
LyAF Wish List

- Wavelength Coverage=> Blue Side!
  λ3800-10000 (2.2 < z < 4)
  λ3200-10000 (1.6 < z < 4)
  Note: Missing Range (BOSS): 1.6 < z < 2.2
- Fiber:
  20-40 quasars/deg^2 (mag dependent)
  Success Rate: 50%
  70-150 fibers/ 1.8 deg^2
- Resolution:
  R=2000 (v=150km/s) Good for LyAF BAO
  R=4000 (v=75km/s) Metal Line Studies

Basics of Spectroscopy

$$R = \frac{\lambda}{\Delta\lambda}$$

$$v = \frac{\Delta\lambda}{\lambda} c$$



- SDSS R=2,000 v=150km/s
- LRIS R=3,000 v=100km/s
- ESI R=4,200 v=72km/s
- HIRES R=37,500 v=8km/s

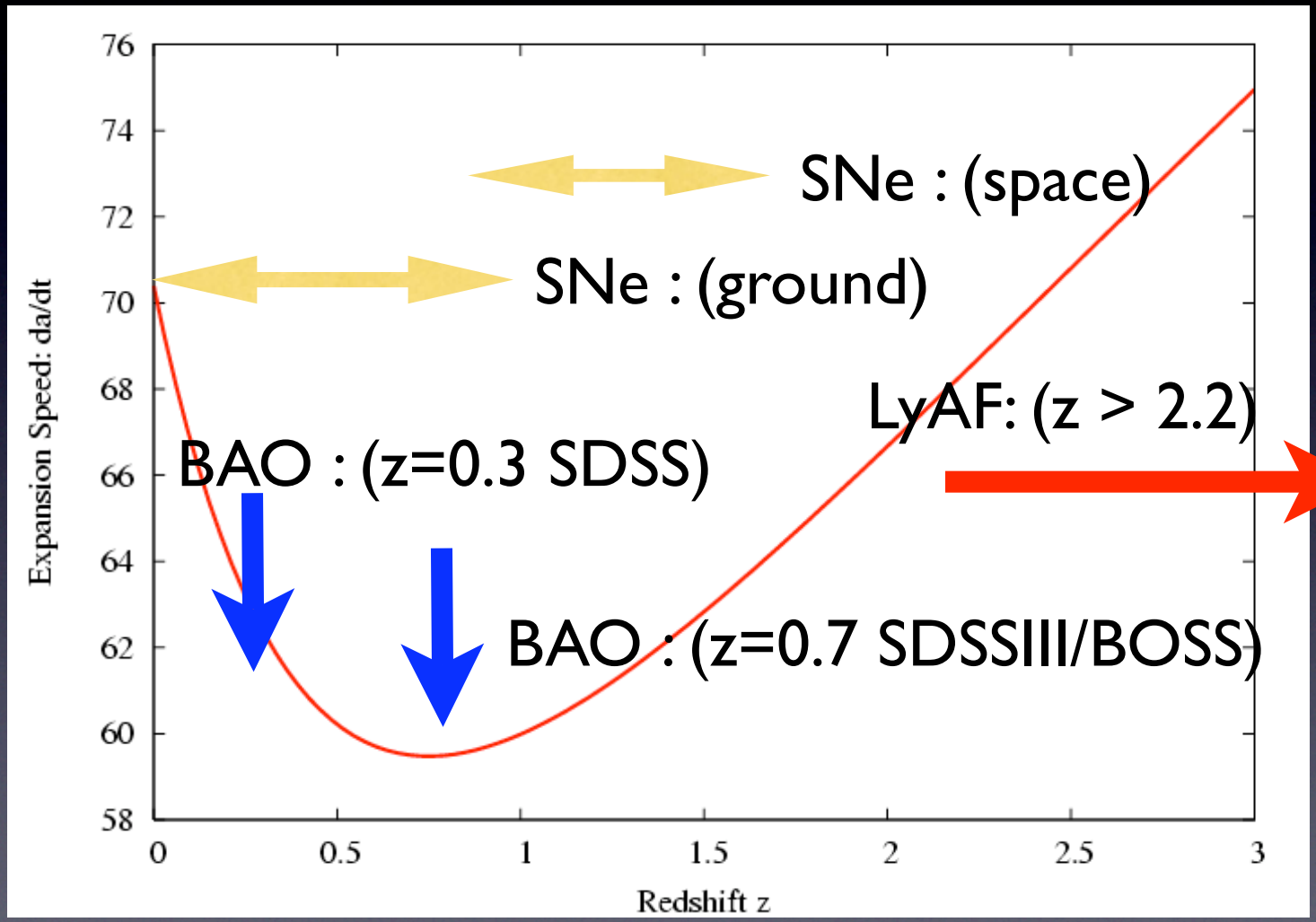
My Personal Note I

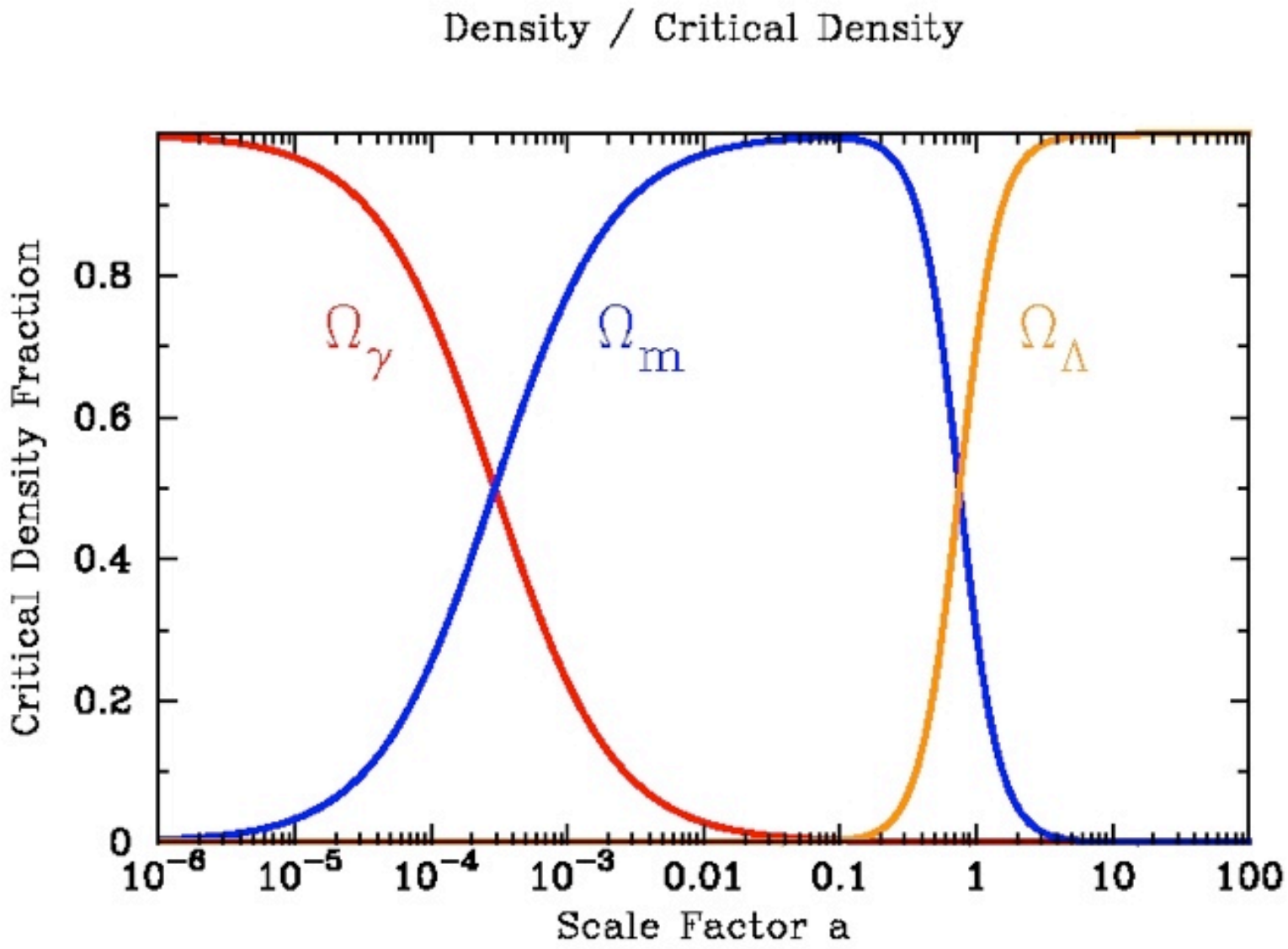
- Dark Energy : The Biggest Discovery regarding Gravity in the last 400 years!
- It is urgent to reduce systematic errors
- Wish to know w(z)
- LyAF science has synergy to Quasar Science
- PFS will be the most important instrument in JWST/LSST/TMT/WFIRST era
- PFS is the demand from the world and time!
- 「世界」の要請、「時代」の要求！

My Personal Note II

- BAO => Quantity > Quality
- Potentials for New Science (Lepton Asymmetry, Direct Expansion measurement)
- High Resolution (R > 3000) may help reducing metal line contamination for LyAF BAO
- Join SDSSIII as Japan Participation Group (JPG) and learn lessons from BOSS, SEGUE, APOGEE, MARVELS
- High Quality Imaging + High Quality Spectroscopy = Winning Formula (J. Gunn)

From Deceleration to Acceleration

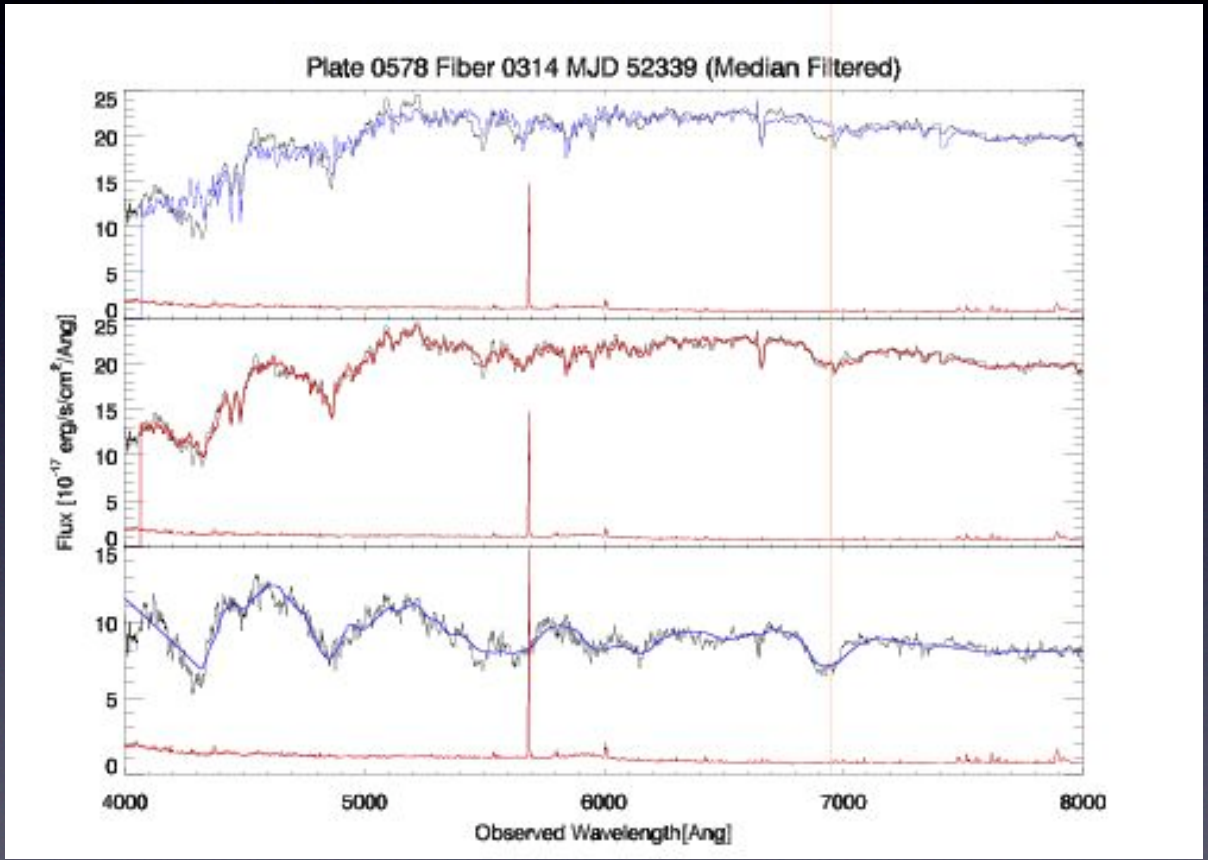


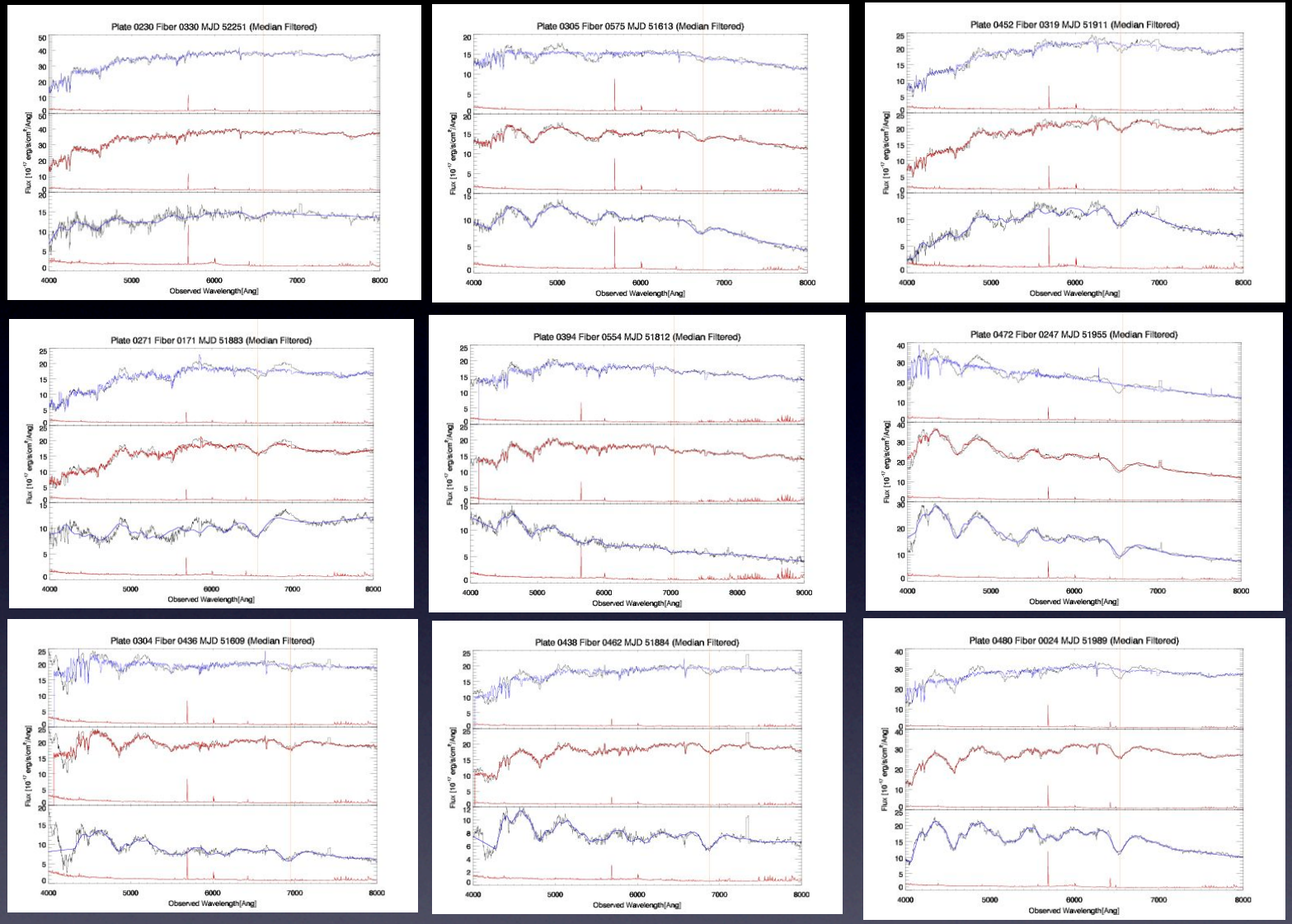

Density / Critical Density
Critical Density Fraction
0
0.2
0.4
0.6
0.8
Ω_γ
Ω_m
Ω_Λ
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
10
100
Scale Factor a

Back-up Slides

Supernova Ia from SDSS DR7

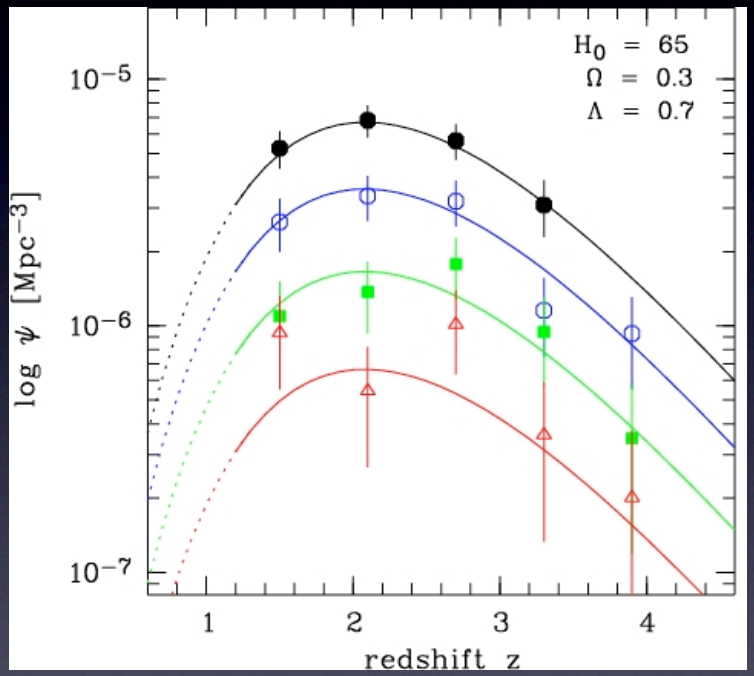
Janos Botyanszki, Kimberly Aller,
Josh Meyers (code), Nao Suzuki(eigen spectra)

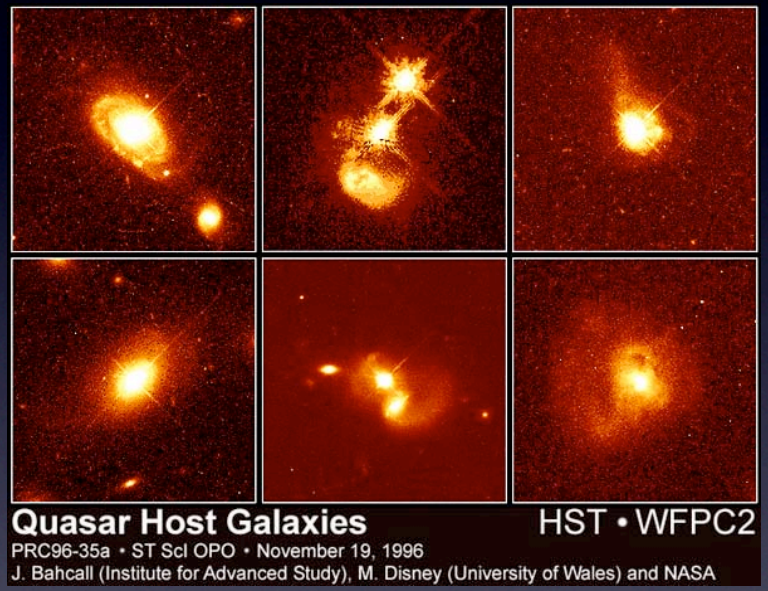




SDSS DR7 : 1 SNIa / 6000 Galaxies

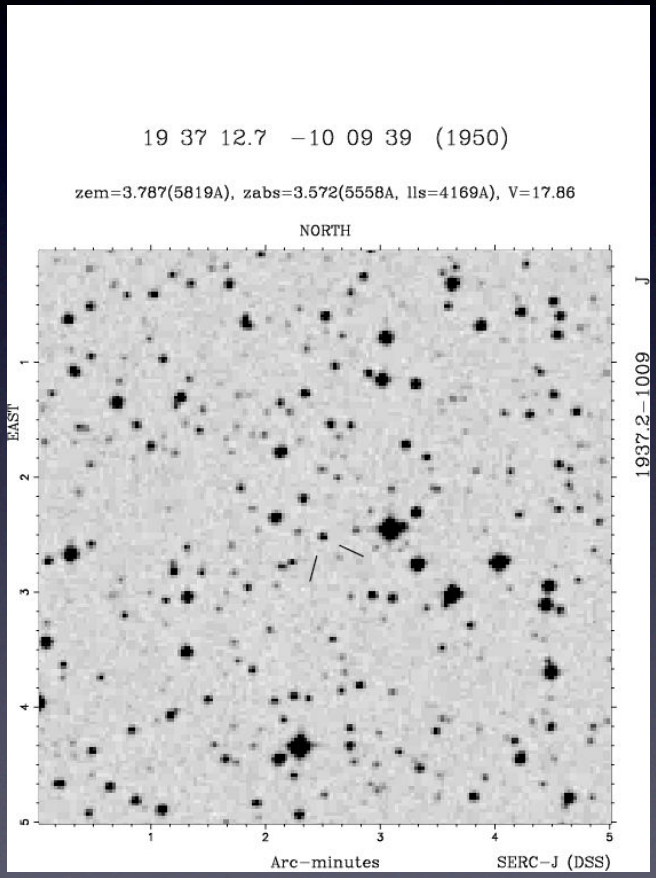
Quasar Basics 1: Number Density Evolution

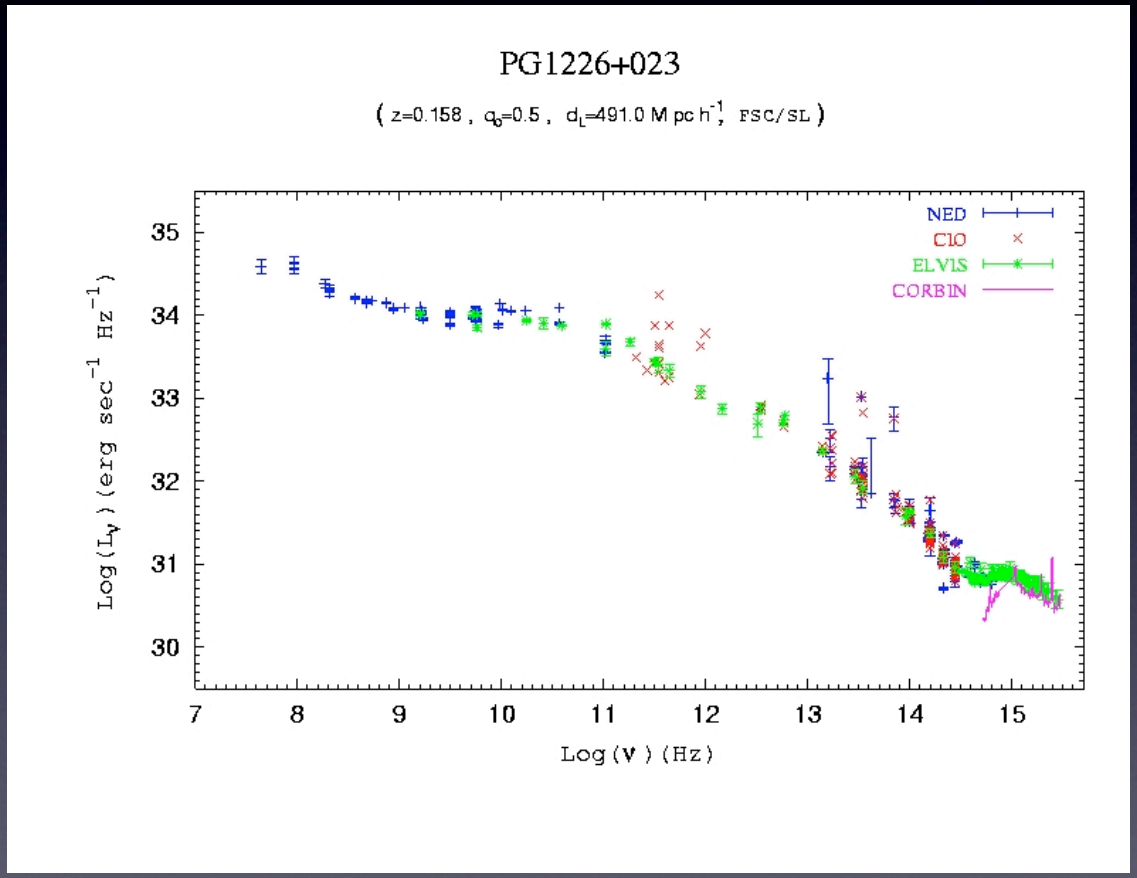




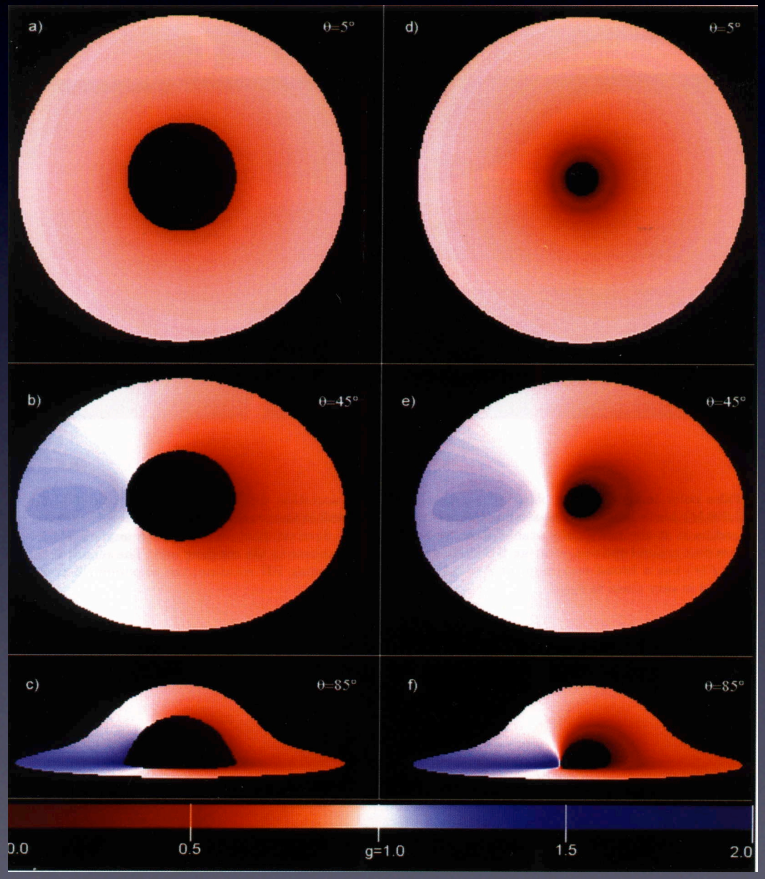
- Red (M < -27) Green (M < -26) Blue (M< -25) Black (M < -24) : Combo-17 Survey (MPG/ESO 2.2 m : Wolf et al. 2003)

Quasar Basics 2 : SED
UV Excess



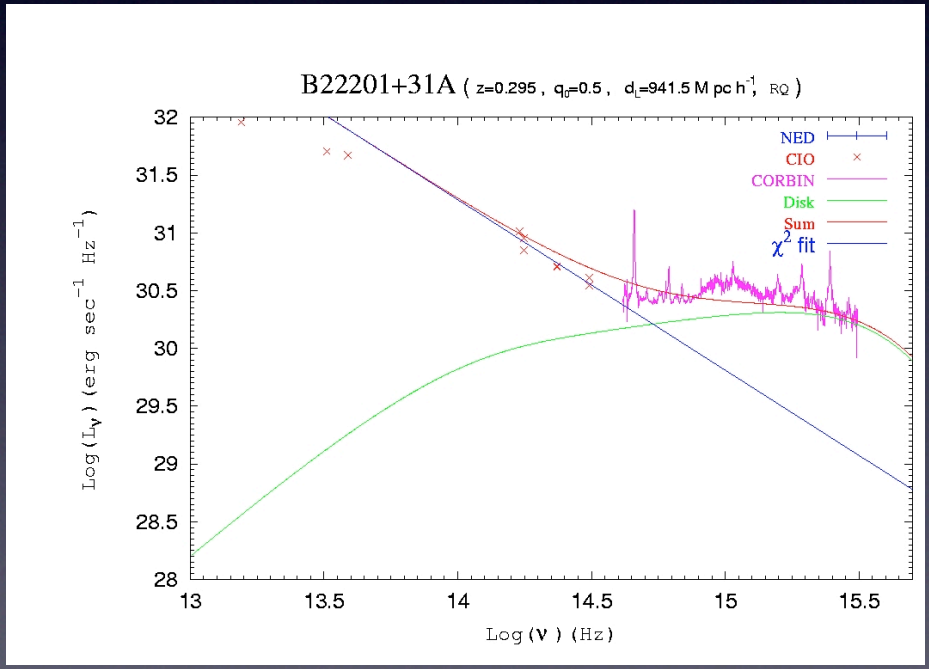


Physics of UV Excess

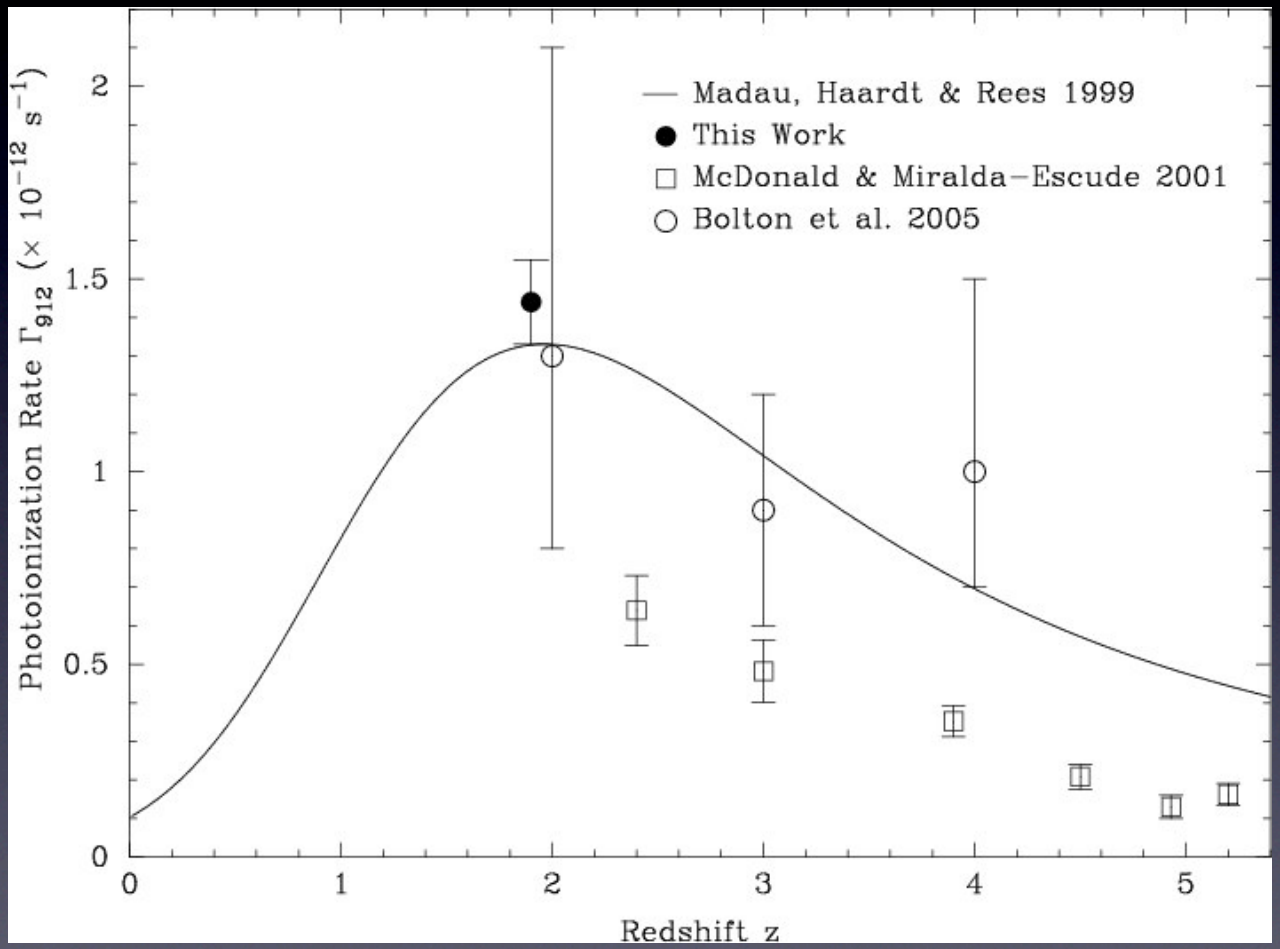


Accretion disk surrounds the super massive black hole

SED(Mass, Accretion Rate)



Ionization Rate : 5 years ago



Ionization Rate : 2009

Dall'Aglio et al 2009