Observations for Cosmology and Structure Formation - Part 1

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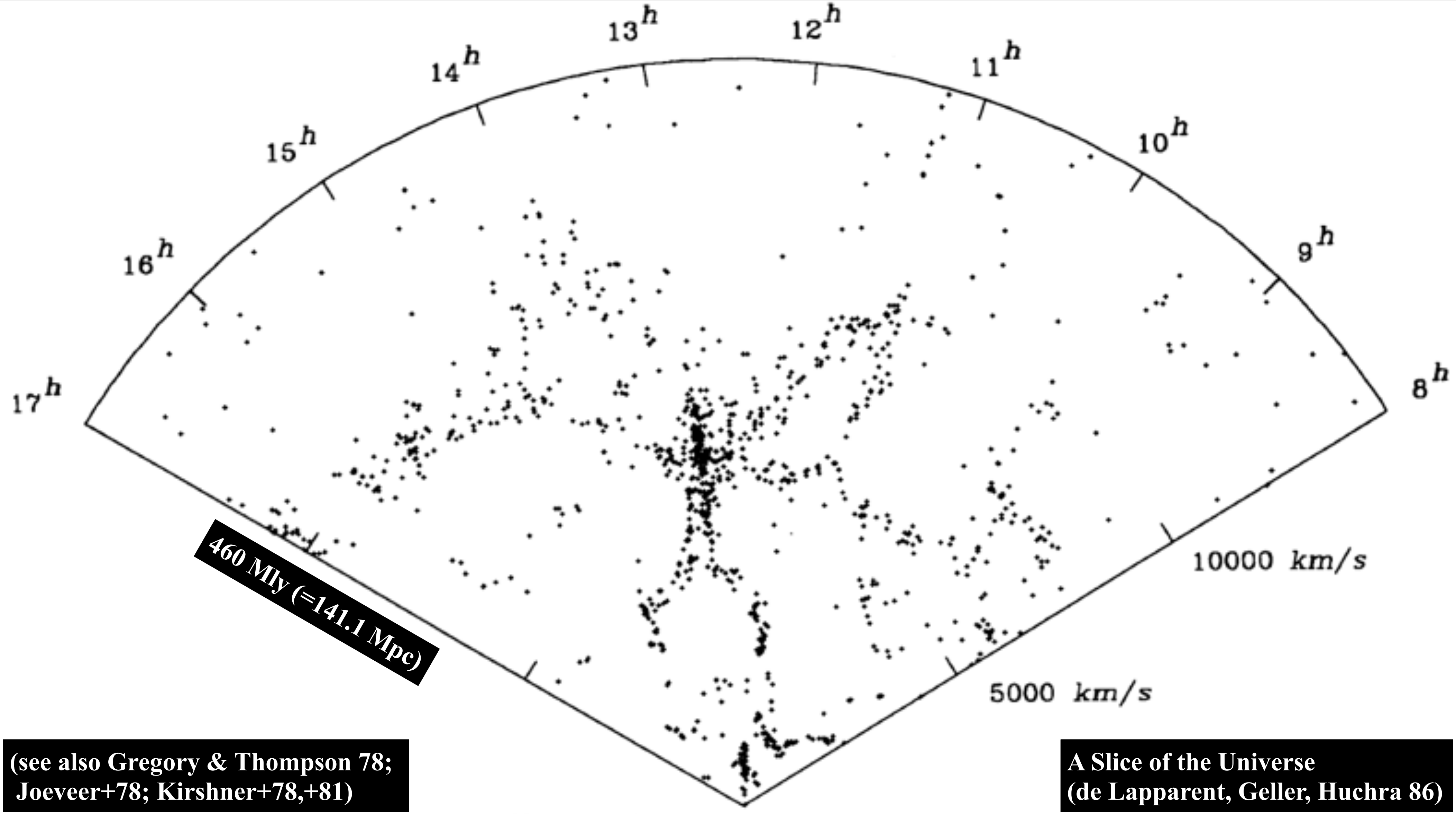
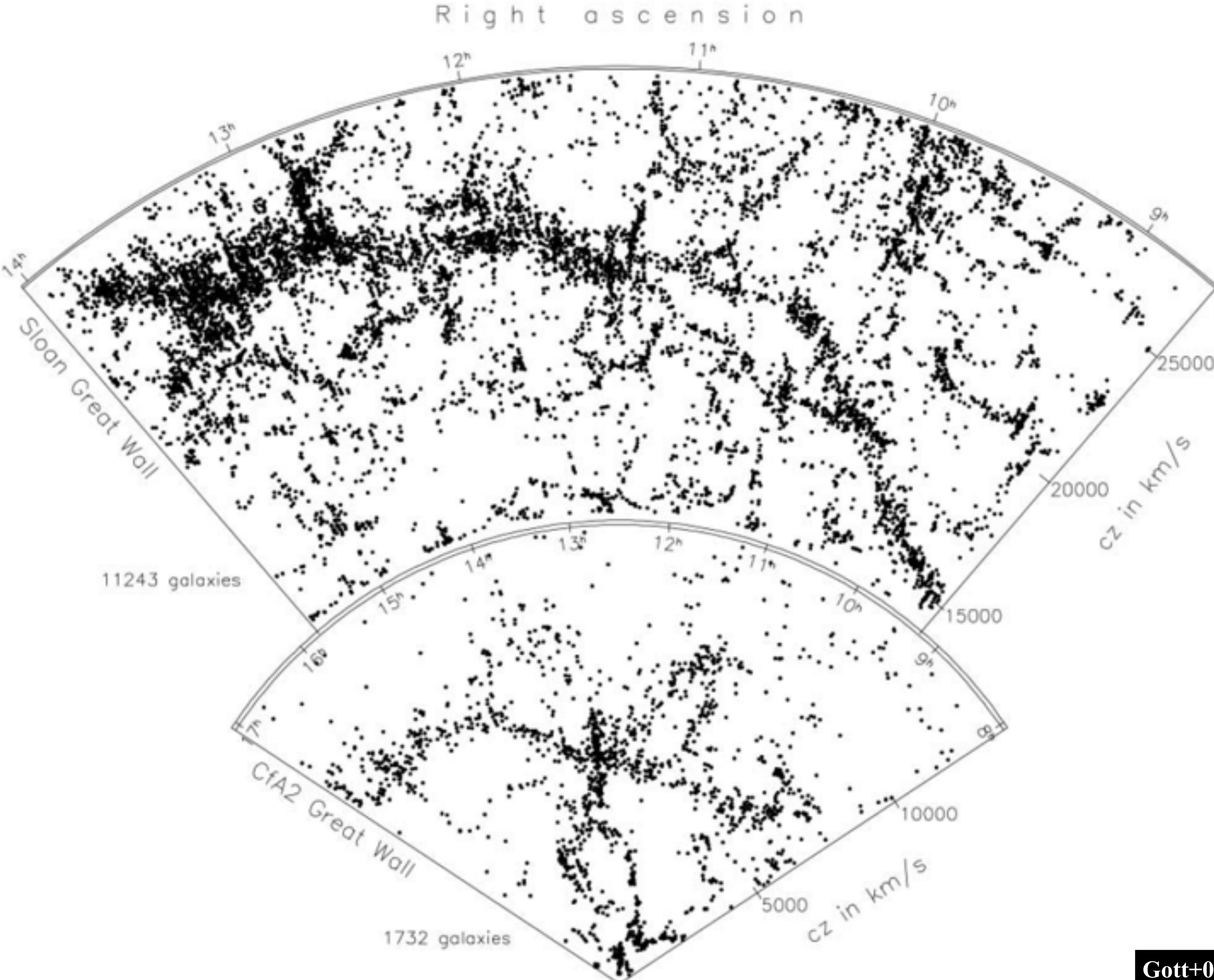
(KIAS)

2015 July 27
Pyeong-Chang Summer Institute 2015



(see also Gregory & Thompson 78; Joeveer+78; Kirshner+78,+81)

A Slice of the Universe
(de Lapparent, Geller, Huchra 86)

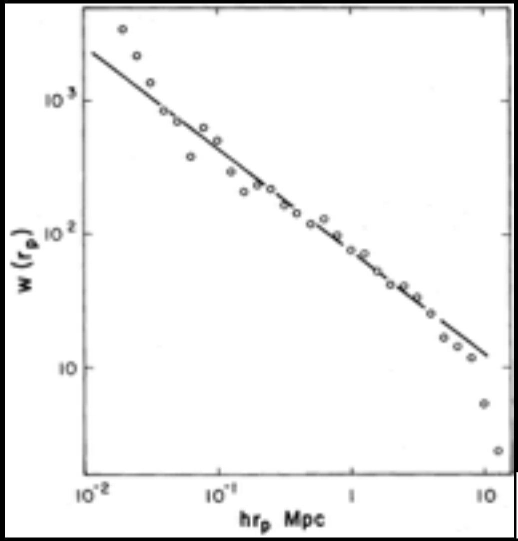


Right ascension
14h
13h
12h
11h
10h
9h
Sloan Great Wall
11243 galaxies
25000
20000
15000
cz in km/s
16h
15h
14h
13h
12h
11h
10h
9h
8h
7h
CfA2 Great Wall
1732 galaxies
10000
5000
cz in km/s

Gott+05

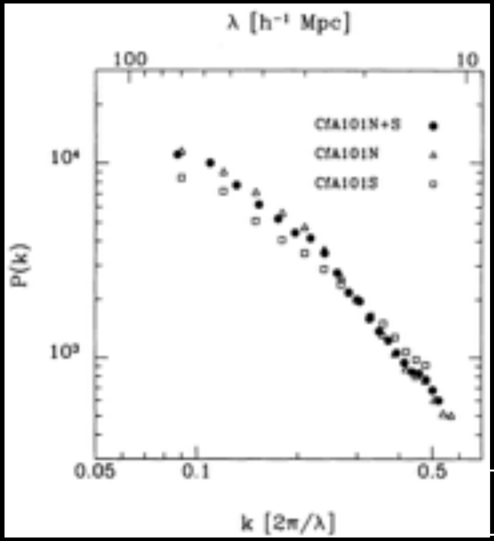
With Galaxy Redshift Survey data

➢ Two-point Correlation Function



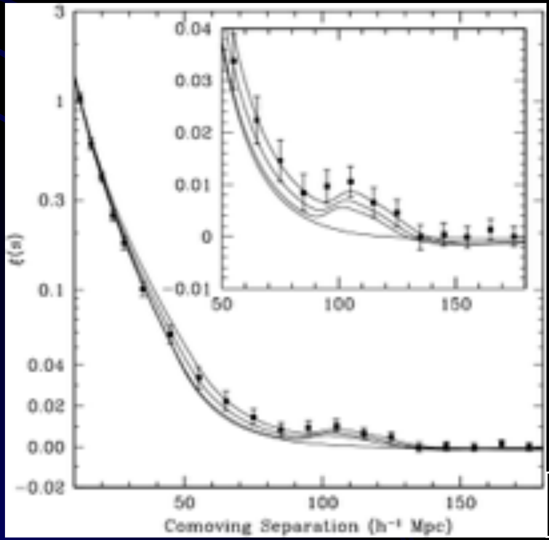
Davis & Peebles (82)

➢ Power Spectrum



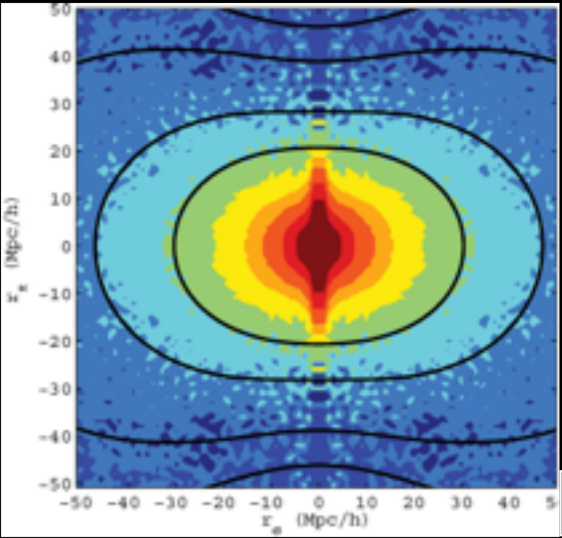
Park+94

➢ Baryon Acoustic Oscillation



Eisenstein+05

➢ Redshift-Space Distortion



Reid+12

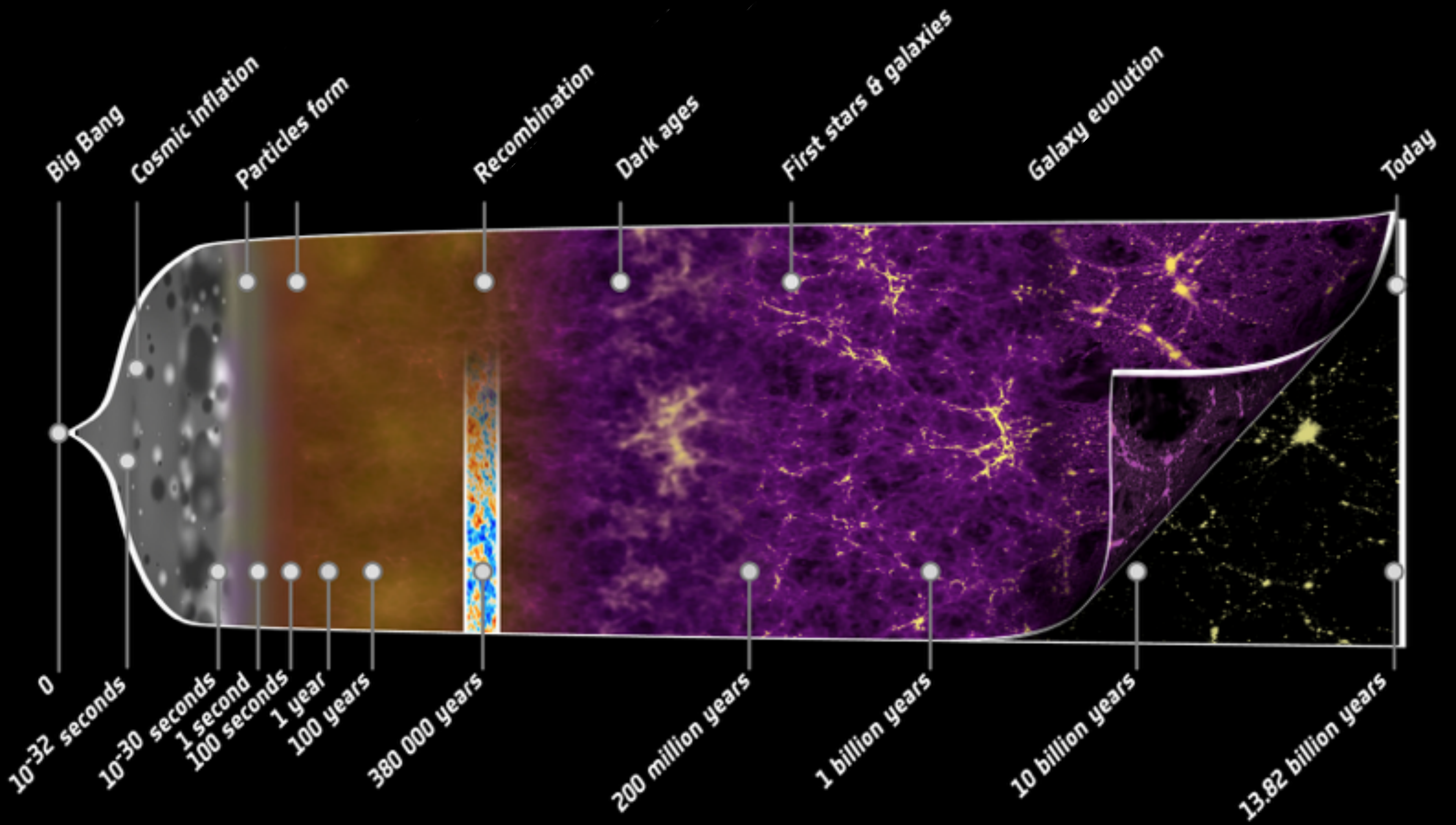
Contents

- **Goal:**

Understand how to obtain scientific results from observational data (redshift survey)

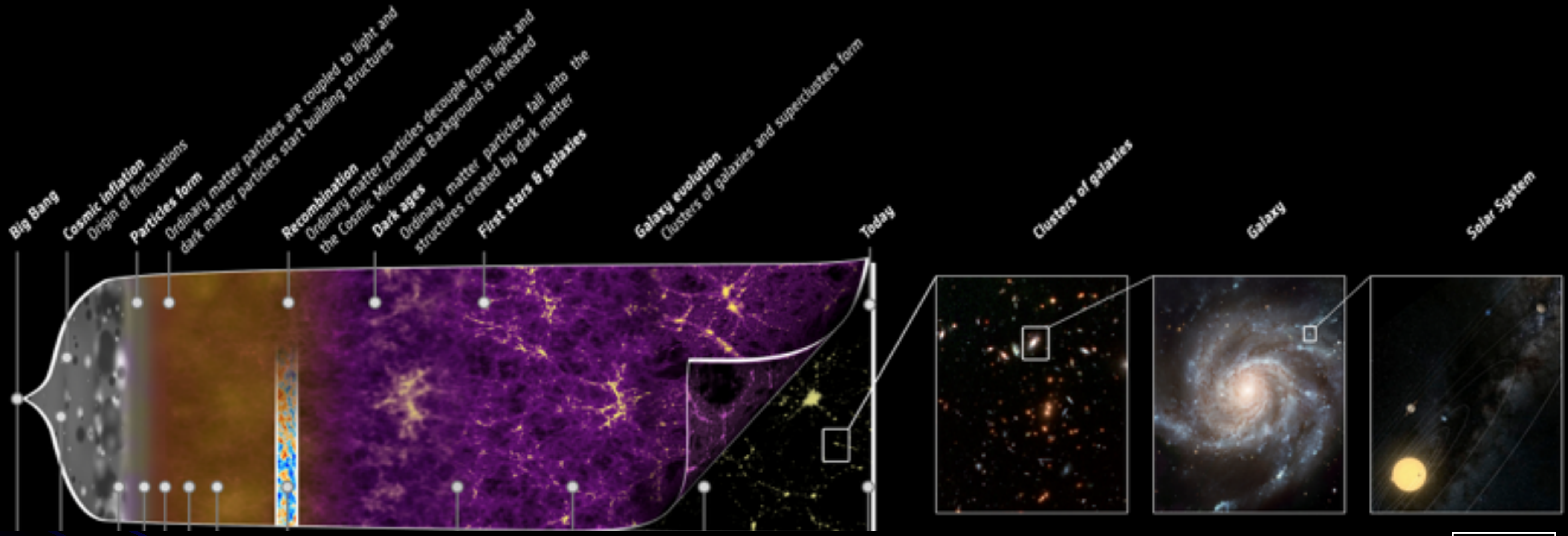
- **Part 1:**
  - **Extragalactic Distance Indicators**
  - **Optical Spectroscopy**
  - **Redshift Space Distortion**
- **Part 2:**
  - **Voids**
  - **Photometric Redshifts (K-correction)**
  - **Cosmology with High-z Objects**
  - **Peculiar Velocity (Large-Scale Structure Near Local Group)**
- **Part 3:**
  - **Current/Future Redshift Surveys**

History of the Universe



Planck

History of the Universe



Planck

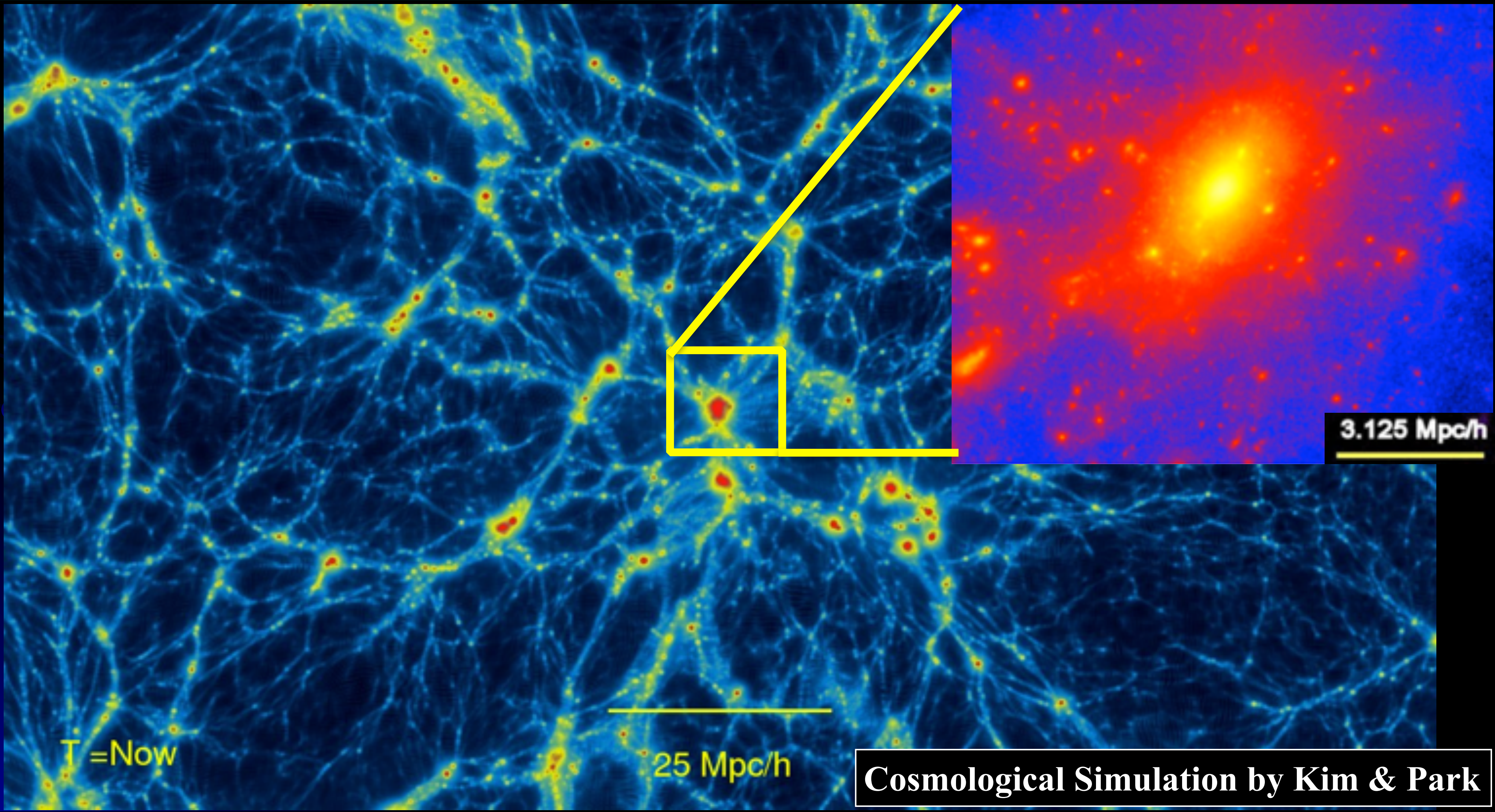
A2744 @ z=0.3
(Merten+11)

What is Large-Scale Structure of the Universe?

- Structure larger than Galaxy Clusters

- Over-density Structure
  - Filament, Chain
  - Wall, Pancake, Sheet

- Under-density Structure
  - Tunnel
  - Void, Cell, Bubble



Cosmological Simulation by Kim & Park

Why Large-Scale Structure of the Universe?

- ➢ Large Structures :
  grew from small initial fluctuations after the inflation

- ➢ Smaller structures form first, larger structures form later:
  we can study the formation of structure in action

- ➢ Physical properties of large-scale structure depend on
  - ➢ cosmological parameters
  - ➢ physics of galaxy formation

←Strong Constraints

Extragalactic Distance Indicators

Extragalactic distance scale (Cosmological Distance Ladder)

- Absolute Distance (known intrinsic properties)
  - Known Candles: luminosity
  - Known Rulers: size

- Relative Distance

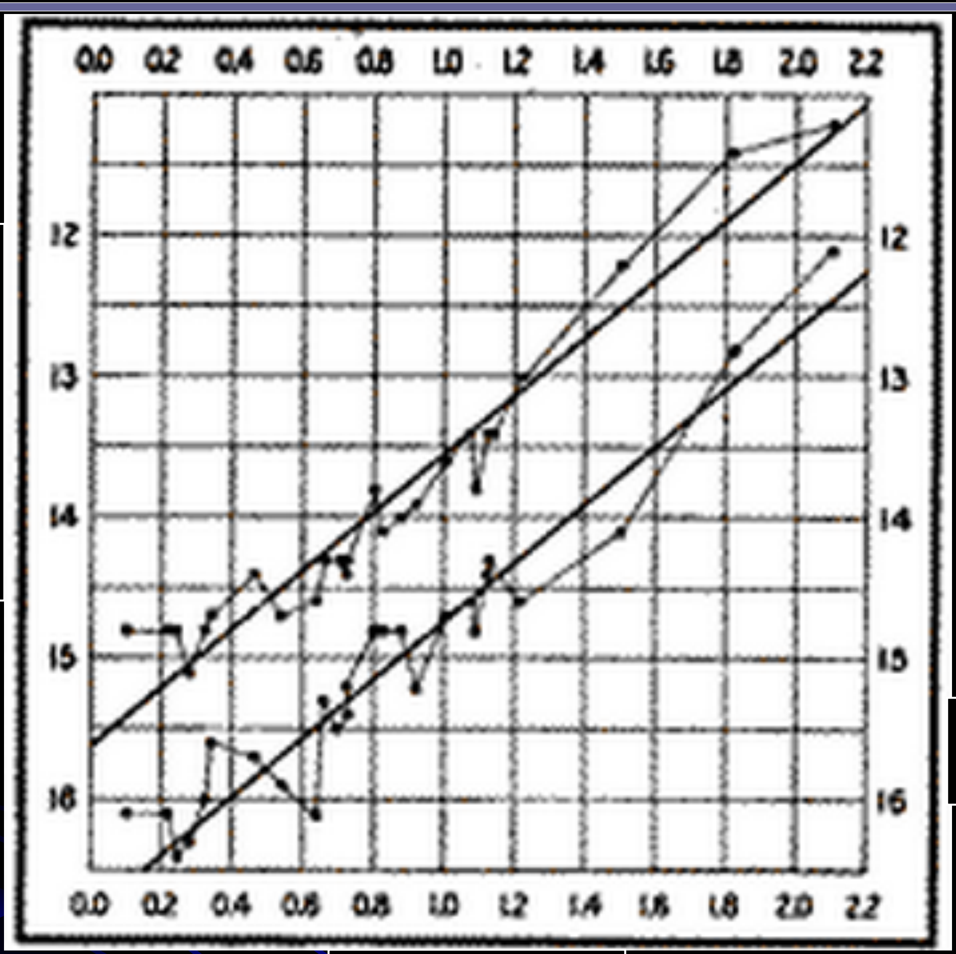
(Secondary Distance Indicators; objects with standardized properties)
  - Standard Candles
  - Standard Rulers

Extragalactic distance scale (Cosmological Distance Ladder)

- **Absolute Distance (known intrinsic properties)**
  - Trigonometric Parallax
  - Statistical Parallax
  - Moving Cluster Method

- **Relative Distance (objects with standardized properties)**
  - Main Sequence Fitting
  - Cepheids: Leavitt's Law (Period-luminosity Relation)
  - RR Lyraes
  - Globular Cluster Luminosity Function (GCLF)
  - Planetary Nebula Luminosity Function (PNLF)
  - Tip of the Red Giant Branch
  - Novae
  - Supernovae Type Ia
  - Surface Brightness Fluctuations
  - Redshift
  - Tully-Fisher Relation
  - D_n - σ Relation
  - Brightest Cluster Galaxies Technique
  - Sunyaev-Zel'dovich Effect
  - Gravitational Lens Time Delays

Leavitt's Law (Period-luminosity Relation)



Apparent Magnitudes

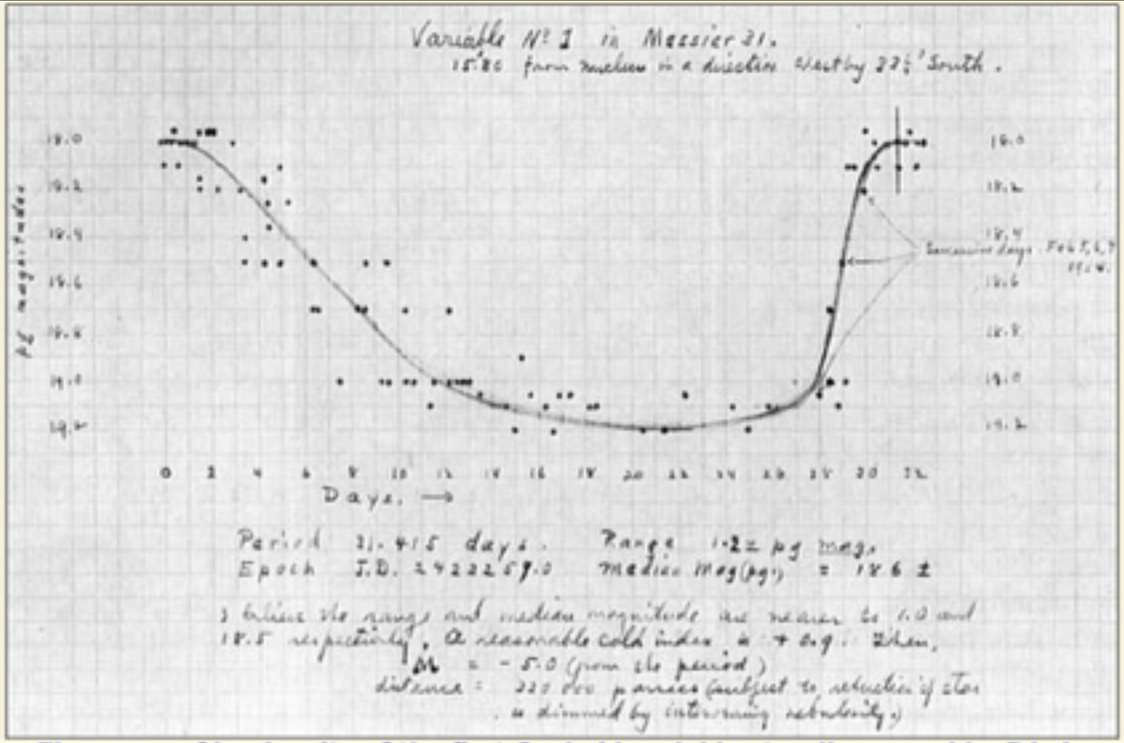
log (Period/days)

Cepheids in SMC (d~61 kpc)
Leavitt (1912)

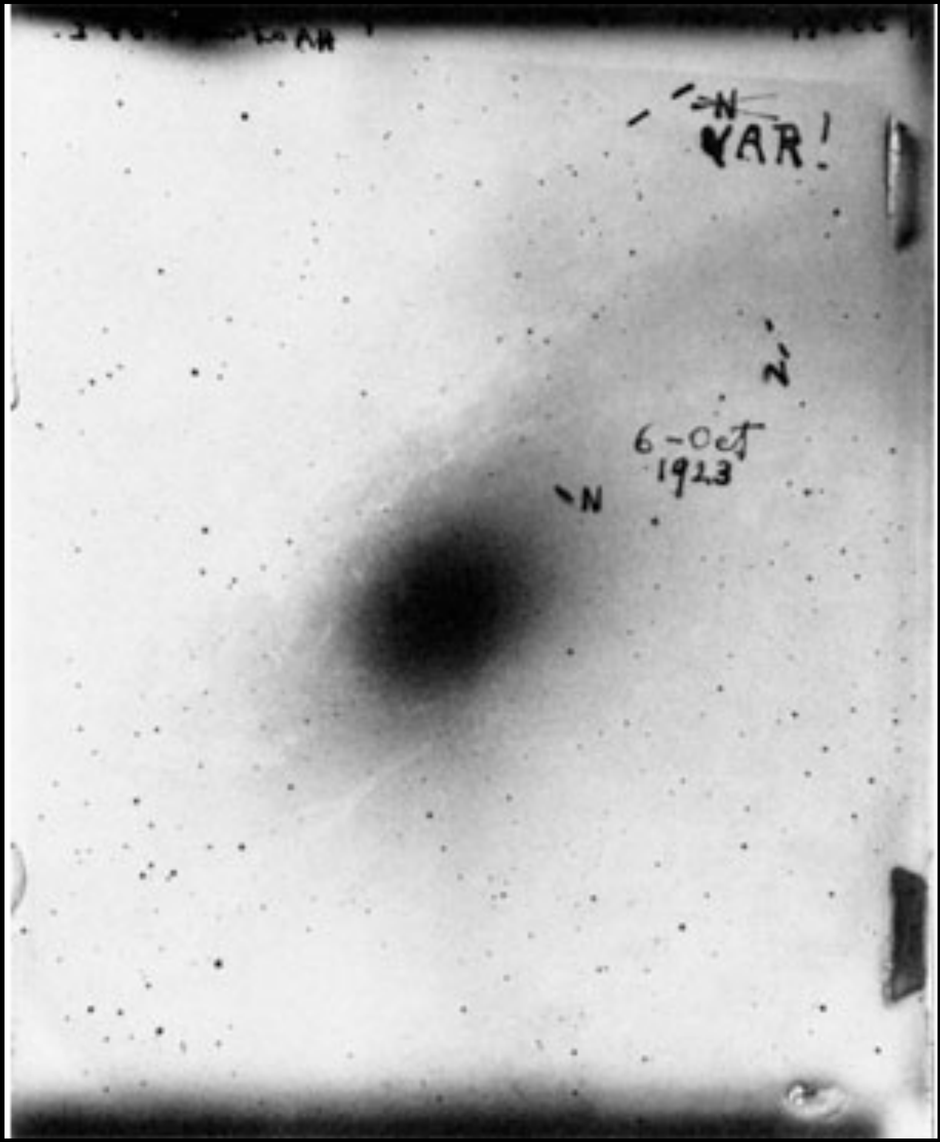
Henrietta Leavitt (1868-1921)

- m = a + b log(P) → M = a + b log(P) where m-M = 5 log D - 5
- Absolute Calibration by
  - Hertzsprung (1913) with secular parallax, and later by Shapley (1918)
- Cepheids (supergiant stars)
  - Bright & Simple: Just need to measure the period

Hubble's Andromeda



The curve of luminosity of the first Cepheid variable star discovered by Edwin Hubble in the Andromeda Nebula, M31. Using this he could determine the nebula's distance. Hubble included this graph in his 19 February 1924 letter to Harlow Shapley.

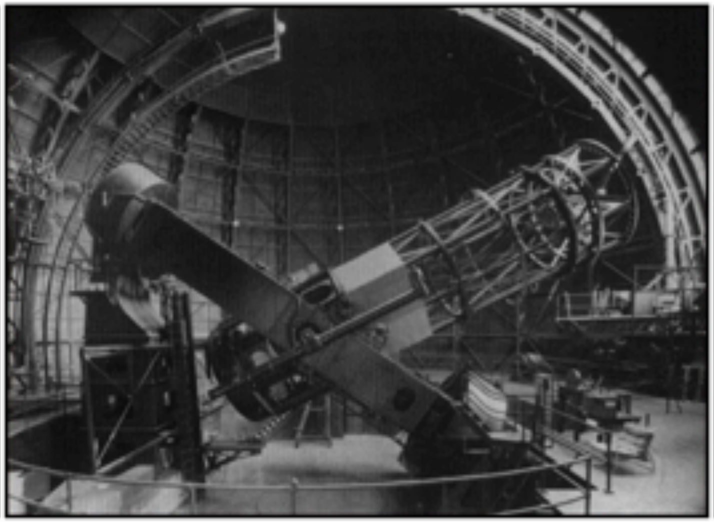


NGC 6822 (Hubble 1925)
M33 (Hubble 1926)
M31 (Hubble 1926, d=276 kpc → 778kpc)

Shapley said to a person in his office: "Here is a letter that has destroyed my universe" (1924)

Expansion of the Universe

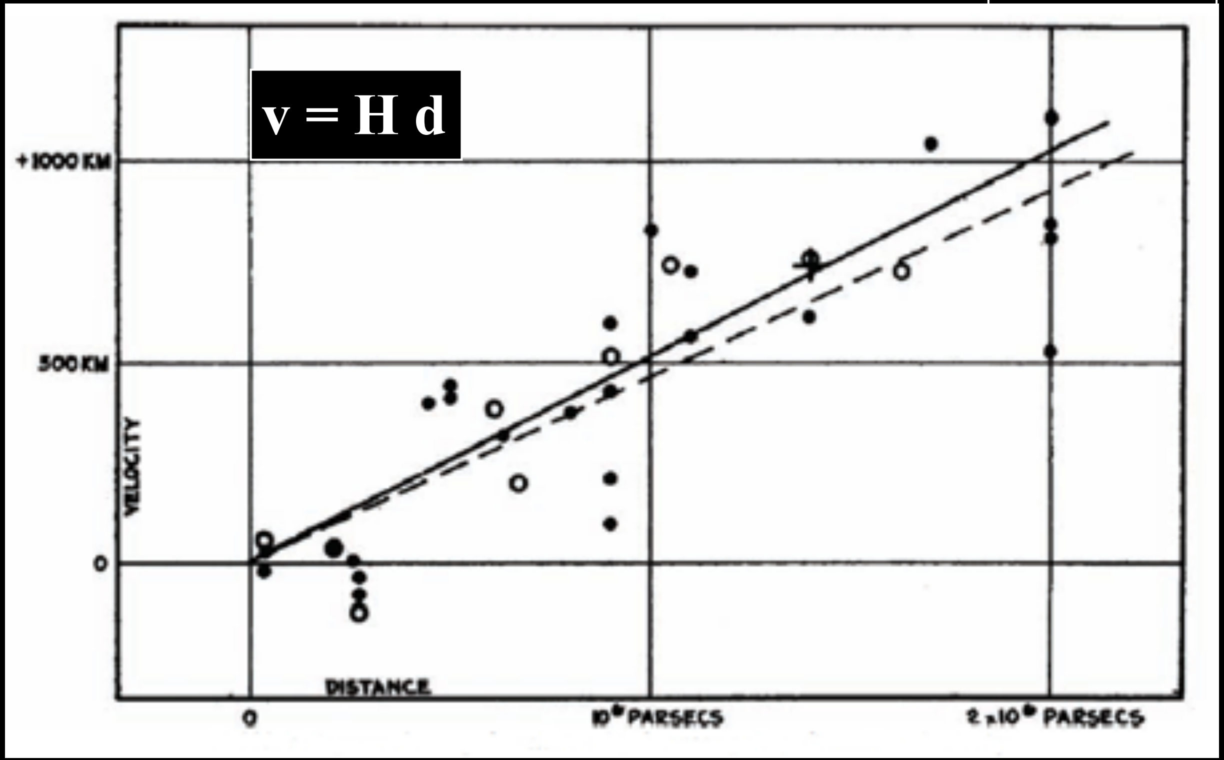
Edwin Hubble
1889 – 1953



100 inch Mt Wilson Telescope

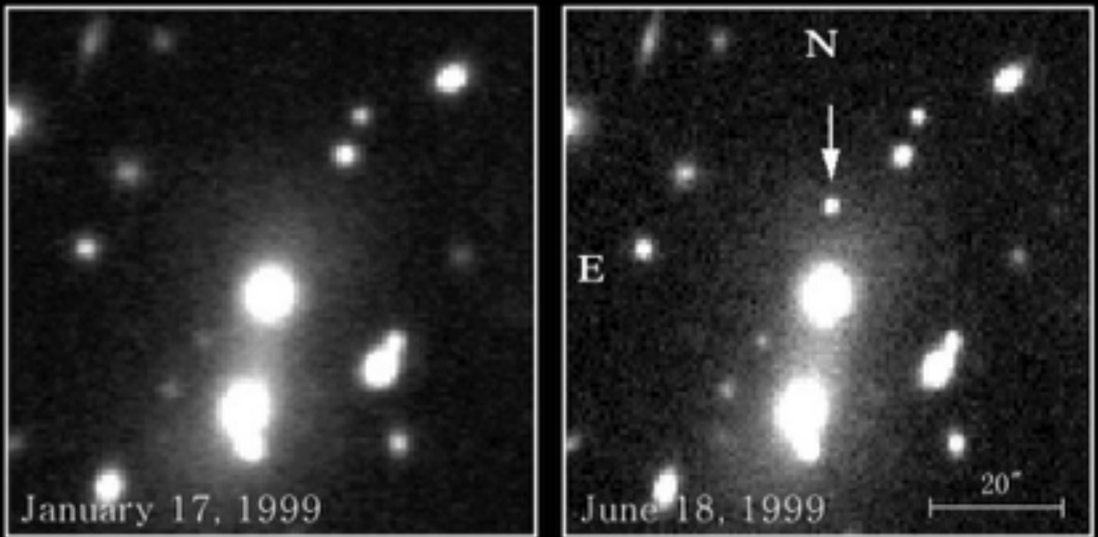
Milton Humason
1891 – 1972

Hubble 1929

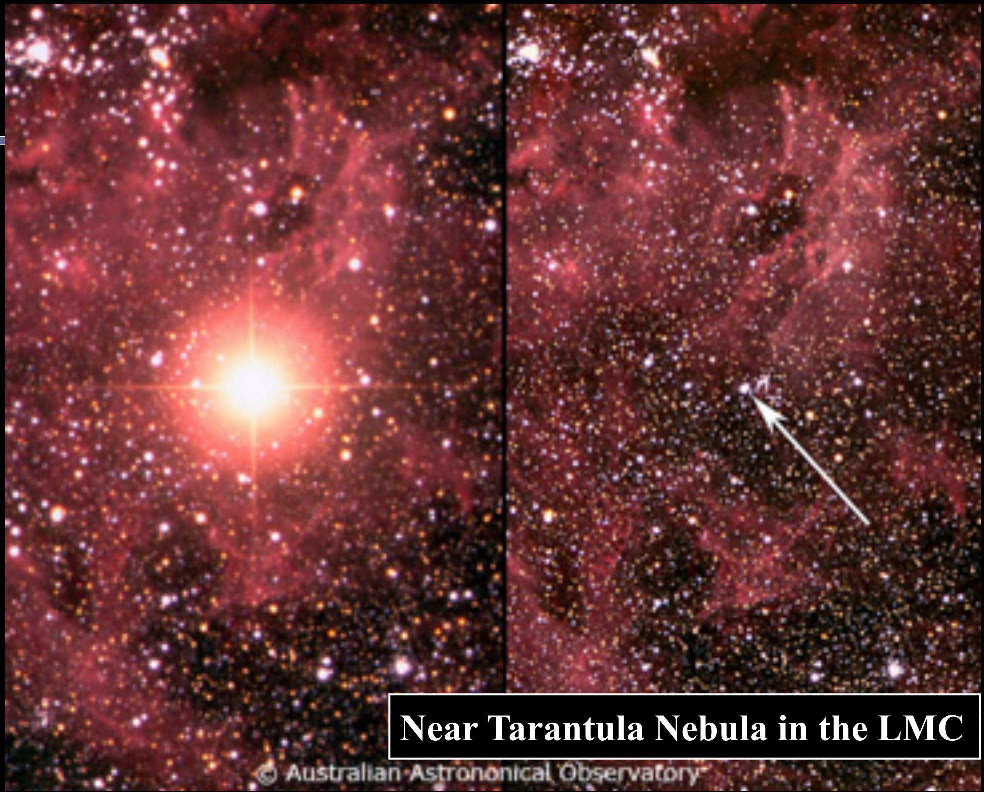


- ➢ **Redshift (v=cz) as galaxy's distance**

Supernovae



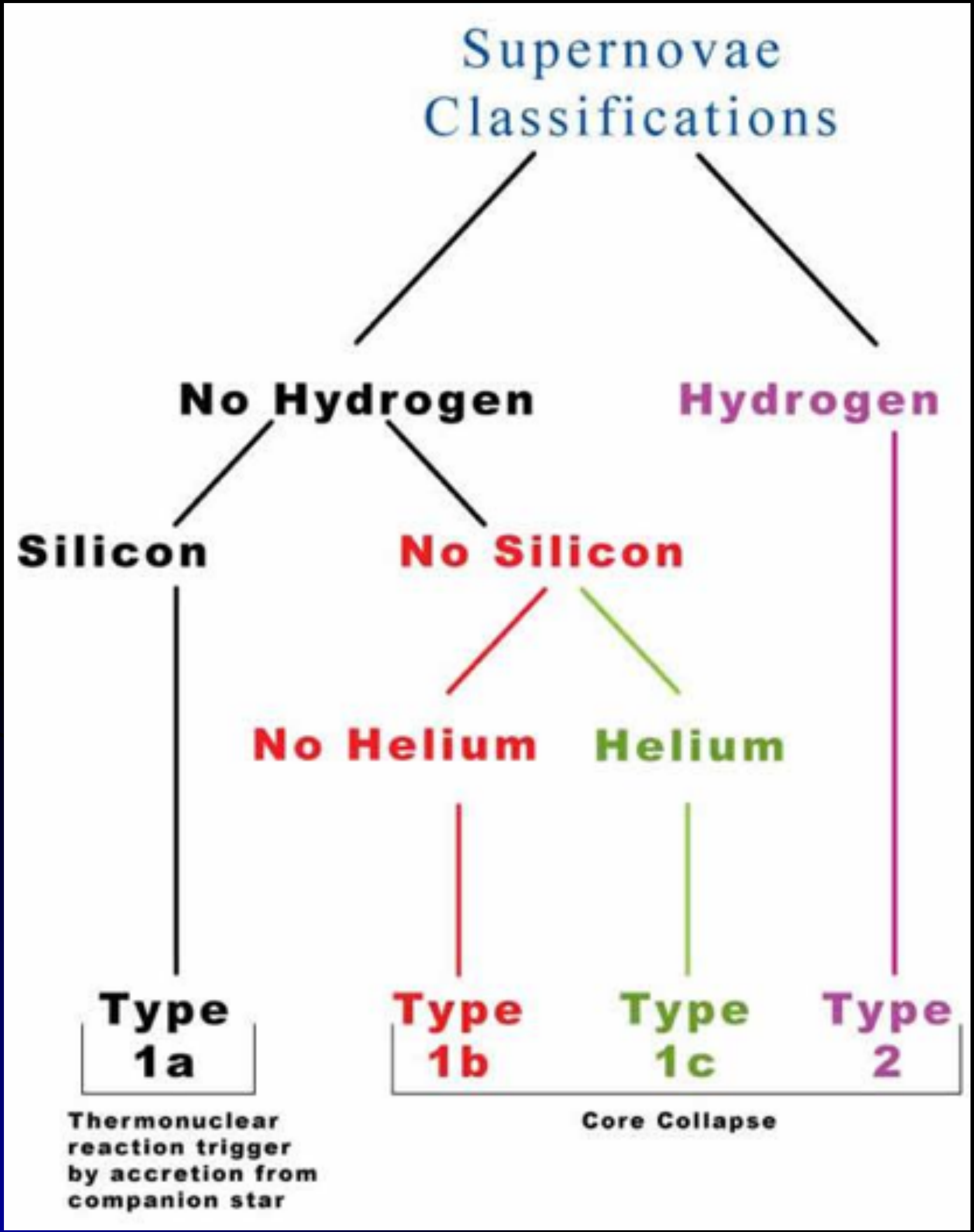
SN 1999dm in BOAO 1.8 m
Galaxy Cluster Abell 2065
Department of Astronomy, Seoul National University - July 7, 1999



Supernova 1987A • November 28, 2003
Hubble Space Telescope • ACS

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC04-09a

Supernovae



Supernova 1987A • November 28, 2003
Hubble Space Telescope • ACS

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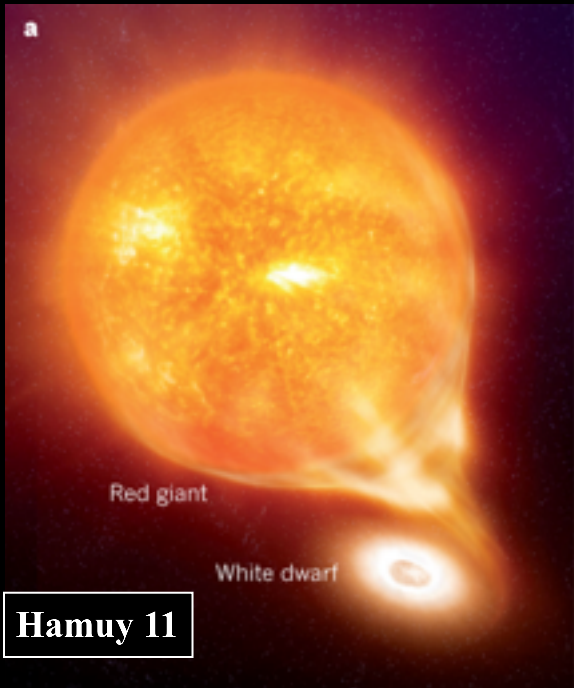
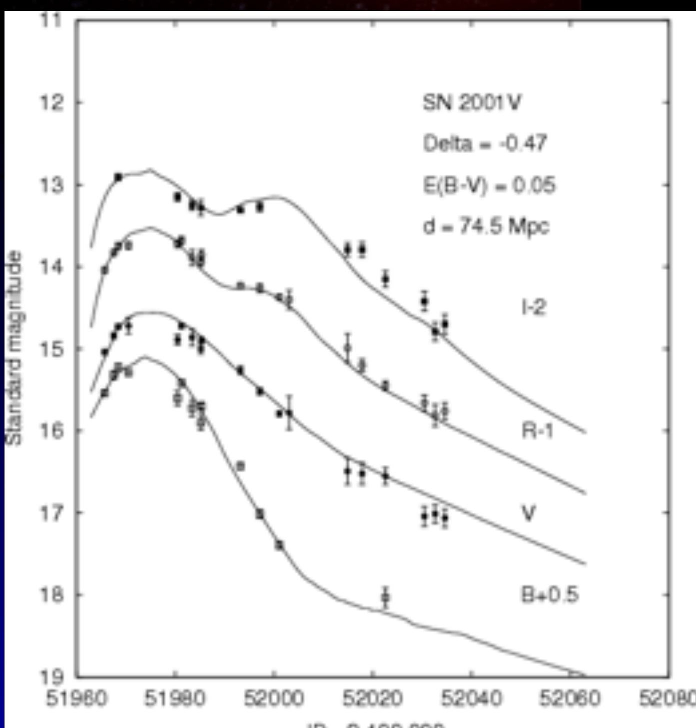
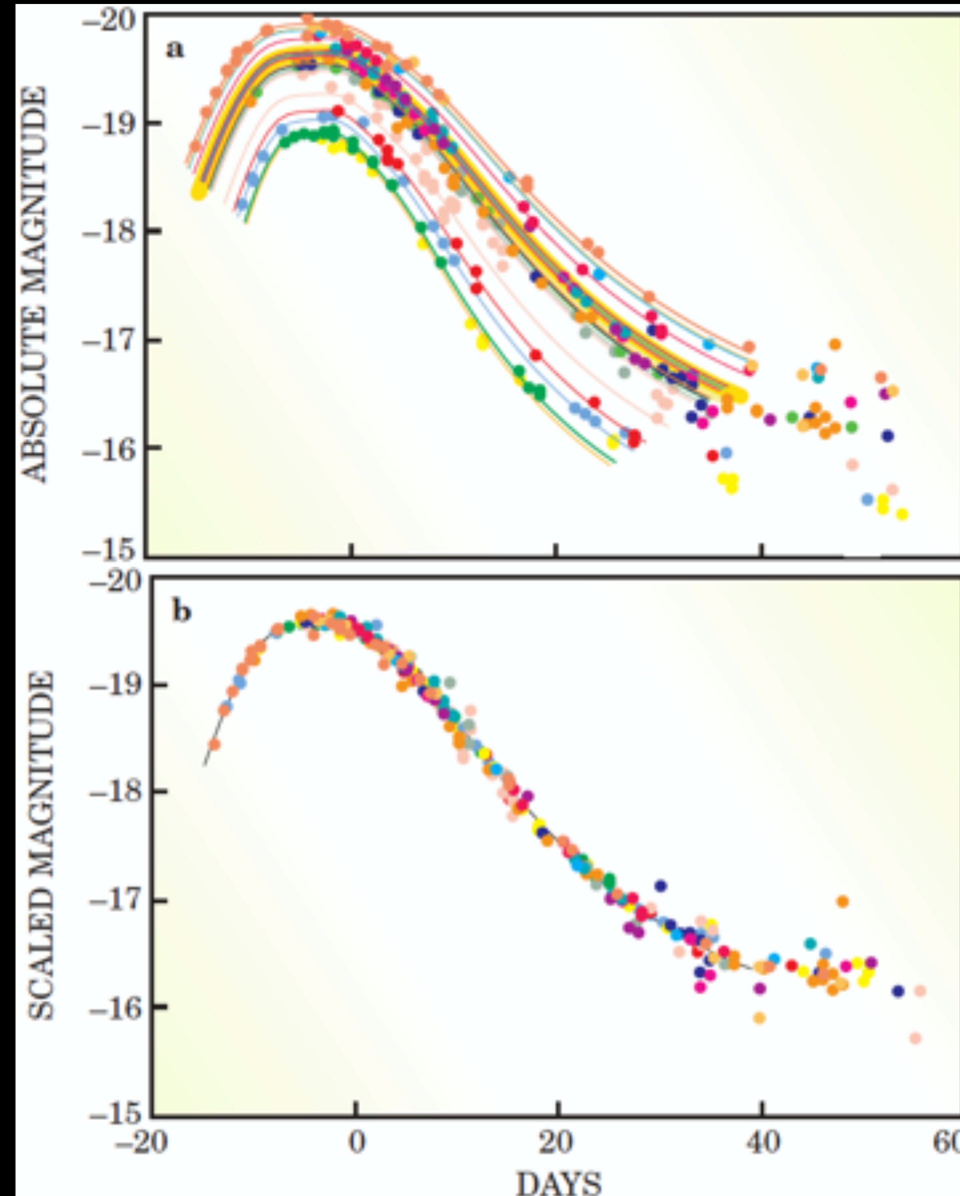
Type 1a Standardized Candles



Hamuy 11

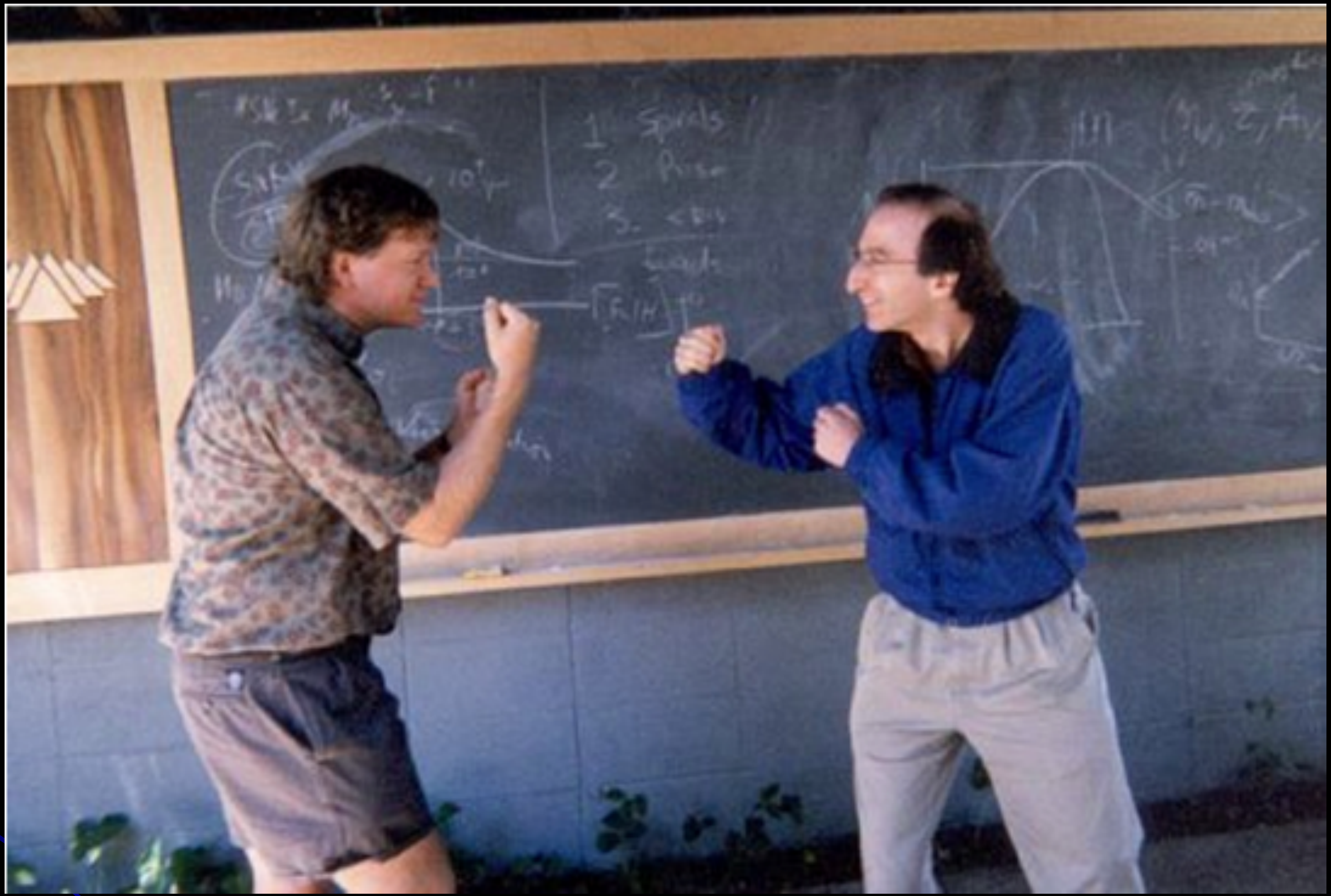


Multi-color light curve shape method (MLCS, Riess+96)



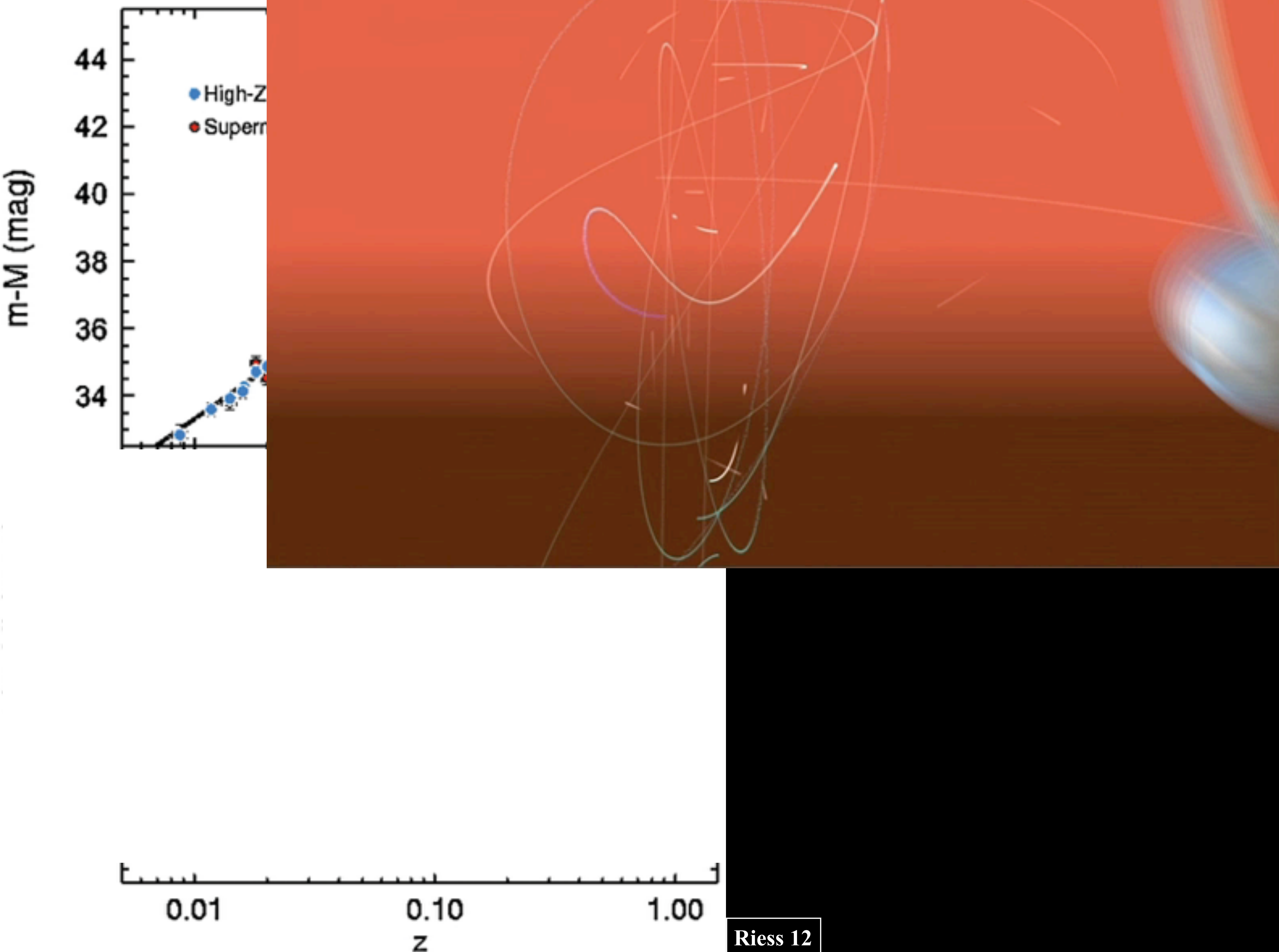
Stretch method (Perlmutter+97;03)

Accelerating Universe



- **High-Z Supernova Search Team**
- **P.I.: B. Schmidt (Harvard)**
- **Started late (94), but publish early (March 98→01)**

- **Supernova Cosmology Project**
- **P.I.: S. Perlmutter (Berkeley)**
- **Started early (88), but publish late (Sept. 98→01)**



Riess 12

2015: 100th Anniversary of General Relativity

Einstein's Field Equation (1915)

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Friedmann Equations (1922)

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2 R_0^2}$$

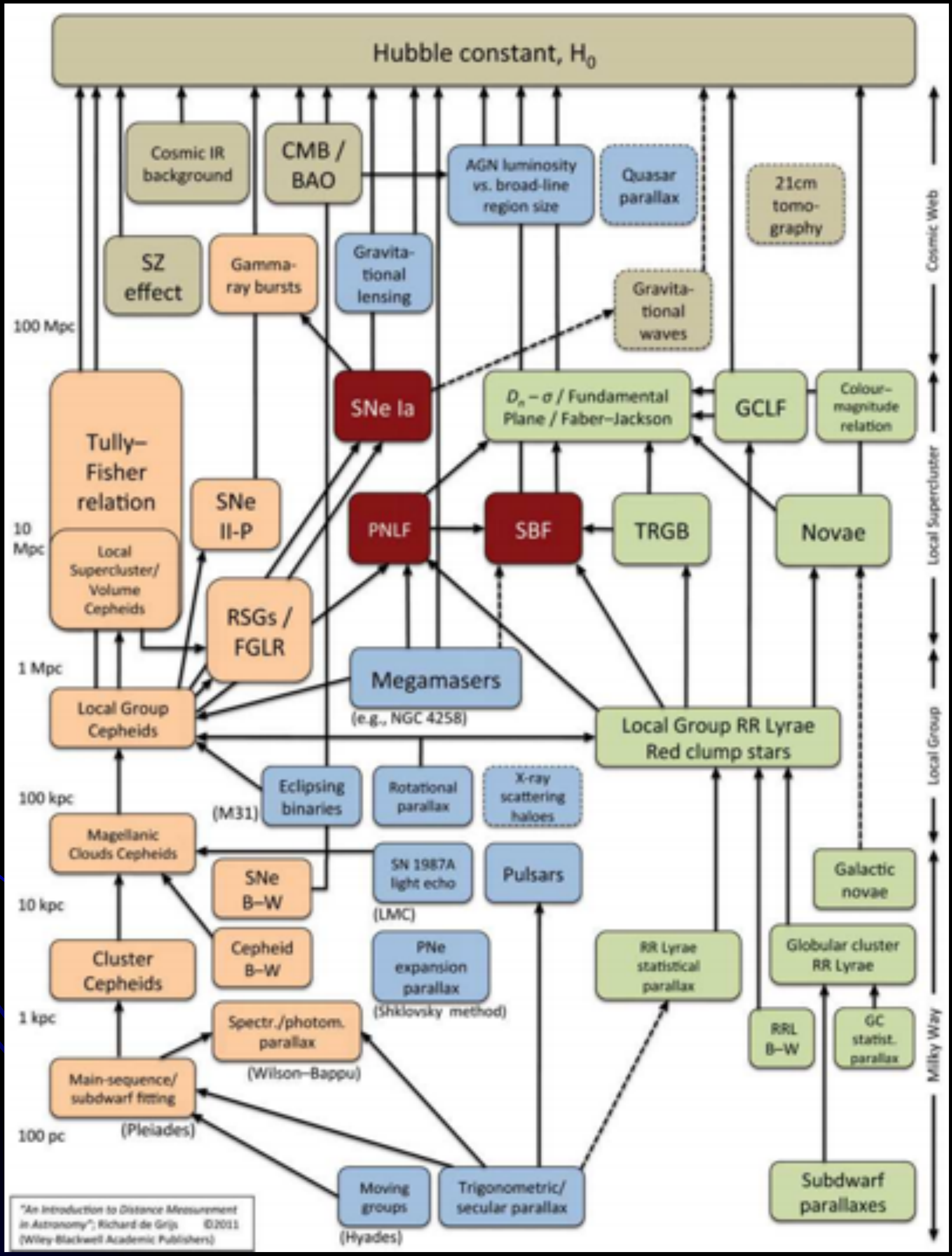
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$$H^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2 R_0^2}$$

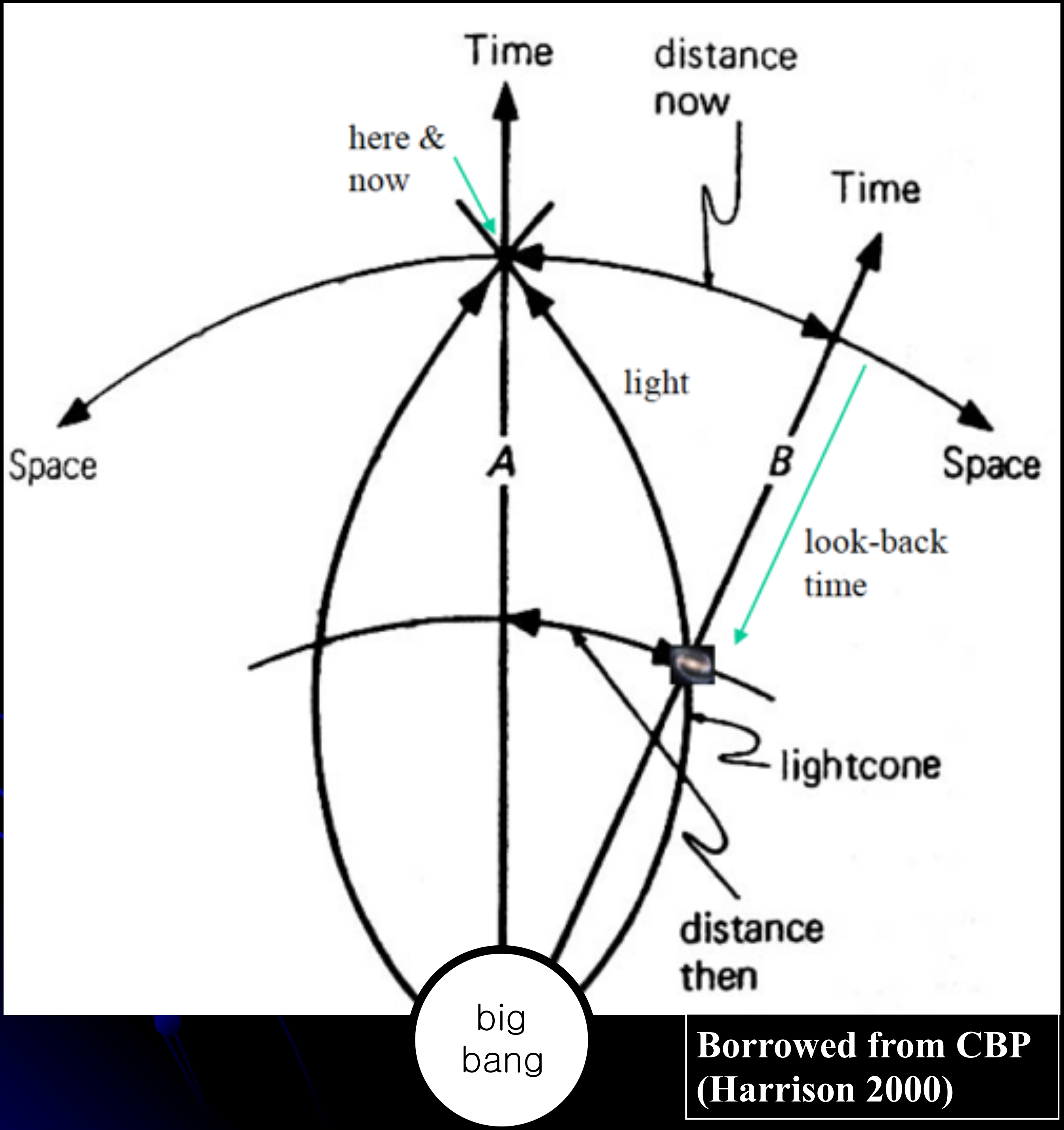
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

static $(\dot{a} = 0)$ solutions

Extragalactic distance scale (Cosmological Distance Ladder)



What Distance?



Borrowed from CBP (Harrison 2000)

What Distance? Connection to Observables

Hogg 00; Peebles 93; Weinberg 08

- **Redshift**

$$\frac{\lambda_0}{\lambda_e} = 1 + z = \frac{a(t_0)}{a(t_e)}$$

- **Comoving Distance (line of sight): From Robertson-Walker metric,**

$$ds^2 = dt^2 - R^2[dr^2 + S^2\ (d\theta^2 + \sin^2\theta\ d\phi^2)]$$

$$r = \int_t^{t_0} \frac{dt}{R} = \frac{1}{R_0}\int_0^z \frac{dz}{H}$$

$$H = H_0[\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda]$$

$$D_C = D_H \int_0^z \frac{dz'}{E(z')}$$

$$D_H \equiv \frac{c}{H_0} = 3000\,h^{-1}\ \mathrm{Mpc} = 9.26 \times 10^{25}\,h^{-1}\ \mathrm{m}$$

$$E(z) \equiv \sqrt{\Omega_M\,(1+z)^3 + \Omega_k\,(1+z)^2 + \Omega_\Lambda}$$

- **Proper Distance: $D_C \times a(t) = D_C\,/\,(1+z)$**

What Distance? Connection to Observables

Hogg 00; Peebles 93; Weinberg 08

- **Angular Diameter Distance:**

$$d_A \equiv \frac{D}{\delta\theta} = \frac{D_M}{1+z}$$

$$D_M = \begin{cases} D_H \frac{1}{\sqrt{\Omega_k}} \sinh\left[\sqrt{\Omega_k}\, D_C/D_H\right] & \text{for } \Omega_k > 0 \\ D_C & \text{for } \Omega_k = 0 \\ D_H \frac{1}{\sqrt{|\Omega_k|}} \sin\left[\sqrt{|\Omega_k|}\, D_C/D_H\right] & \text{for } \Omega_k < 0 \end{cases}$$

where D_M is the transverse coming distance

- **Luminosity Distance**

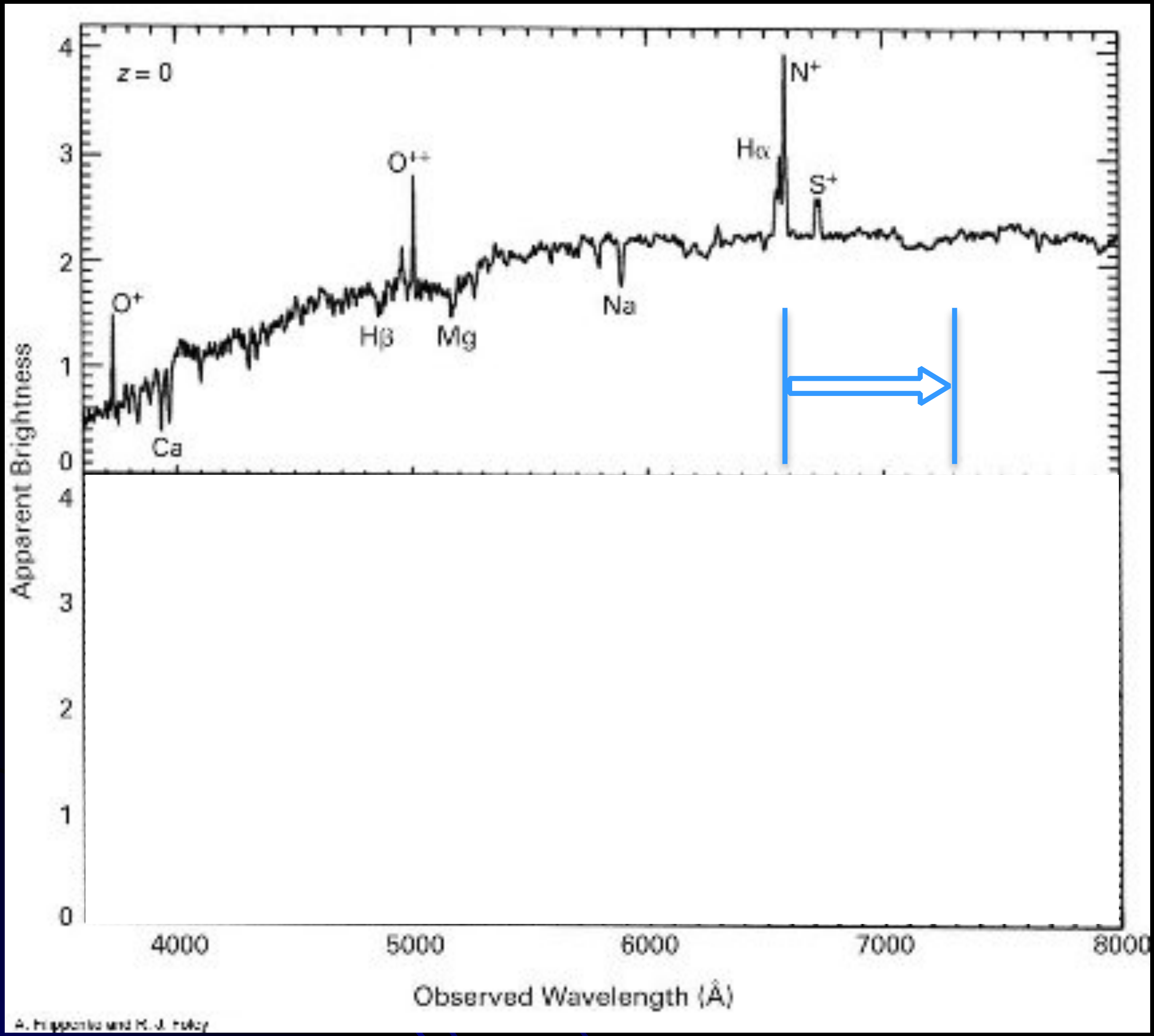
$$D_L \equiv \sqrt{\frac{L}{4\pi S}} = (1+z)\, D_M = (1+z)^2\, D_A$$

- **Lookback Time → Age of the Universe**

$$t_L = t_H \int_0^z \frac{dz'}{(1+z')\, E(z')}$$

$$t_H \equiv \frac{1}{H_0} = 9.78 \times 10^9\, h^{-1}\ \text{yr} = 3.09 \times 10^{17}\, h^{-1}\ \text{s}$$

From Galaxy Spectra to Galaxy Distance

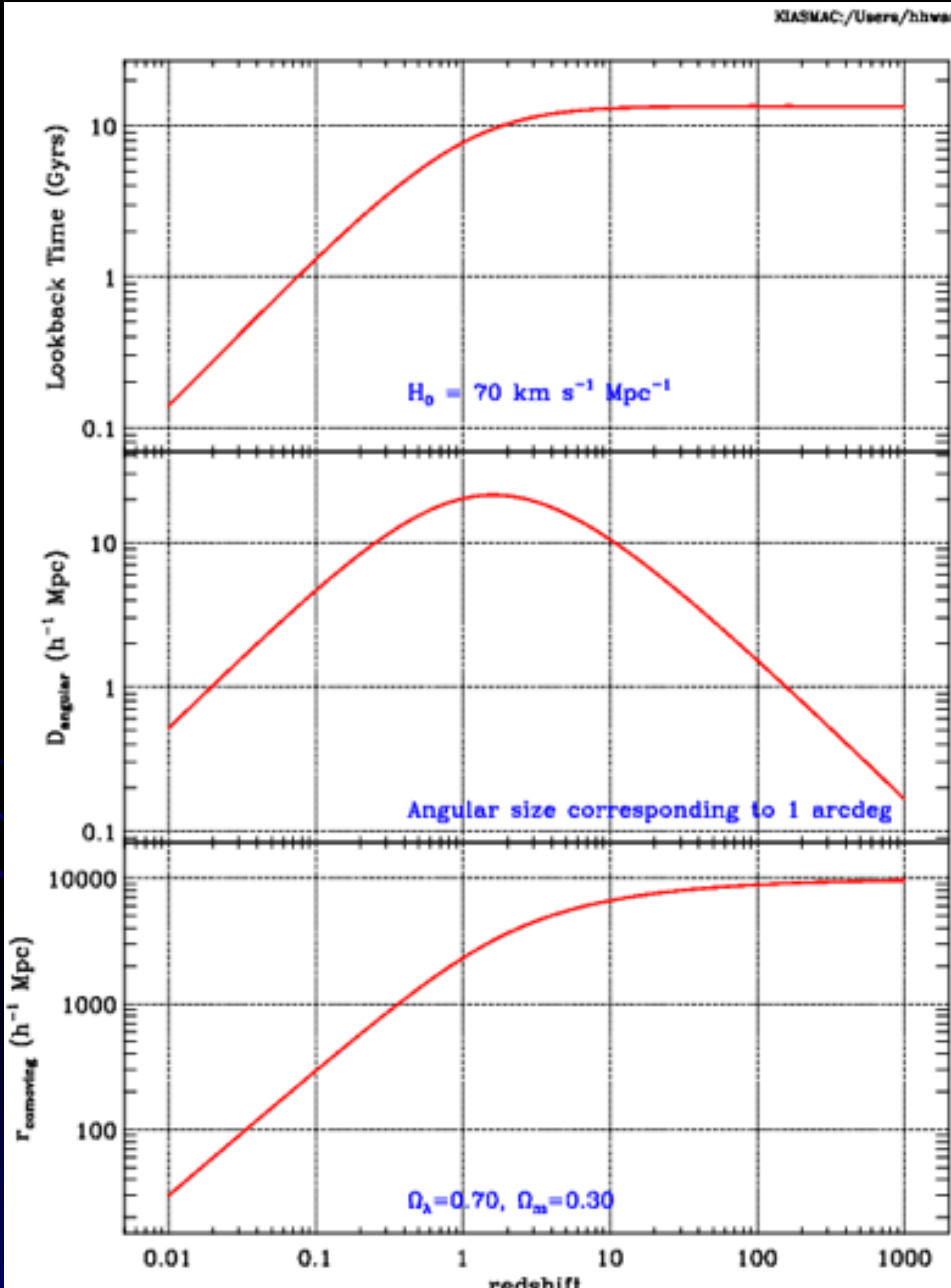


$$\frac{\lambda_0}{\lambda_e} = 1 + z = \frac{a(t_0)}{a(t_e)}$$

$$c\,z = H_0\,D + v$$

$$D_C = D_H \int_0^z \frac{dz'}{E(z')}$$

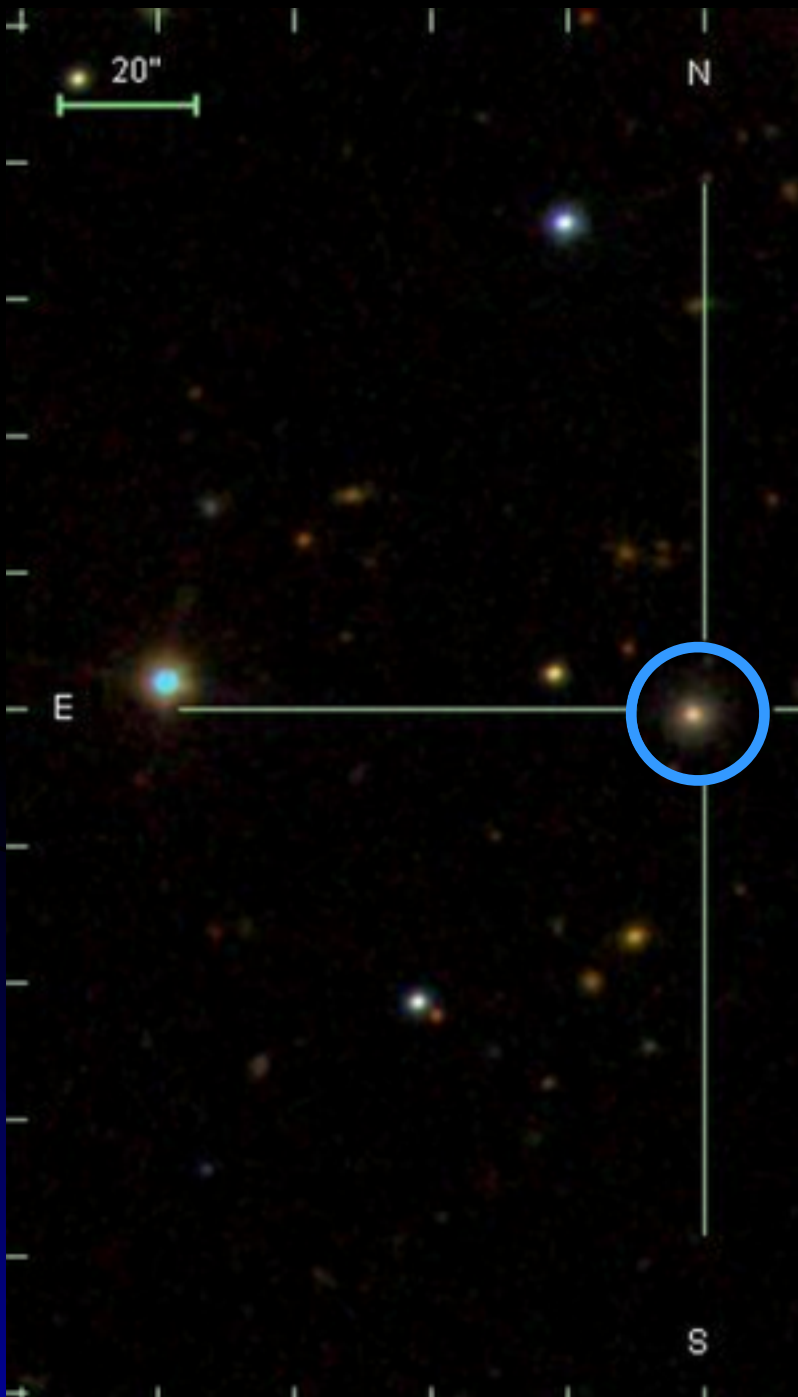
Some Quantities as a function of redshift



z	r_{com}	D_{ang}	Age
0.1	292	4.6	12.2
0.2	571	8.3	11.0
0.5	1322	15.4	8.4
1.0	2312	20.2	5.8
2.0	3625	21.1	3.2
6.0	5772	14.4	0.9
10.0	6608	10.5	0.5
20.0	7519	6.2	0.2
1091.0	9577	0.2	3.8E−4

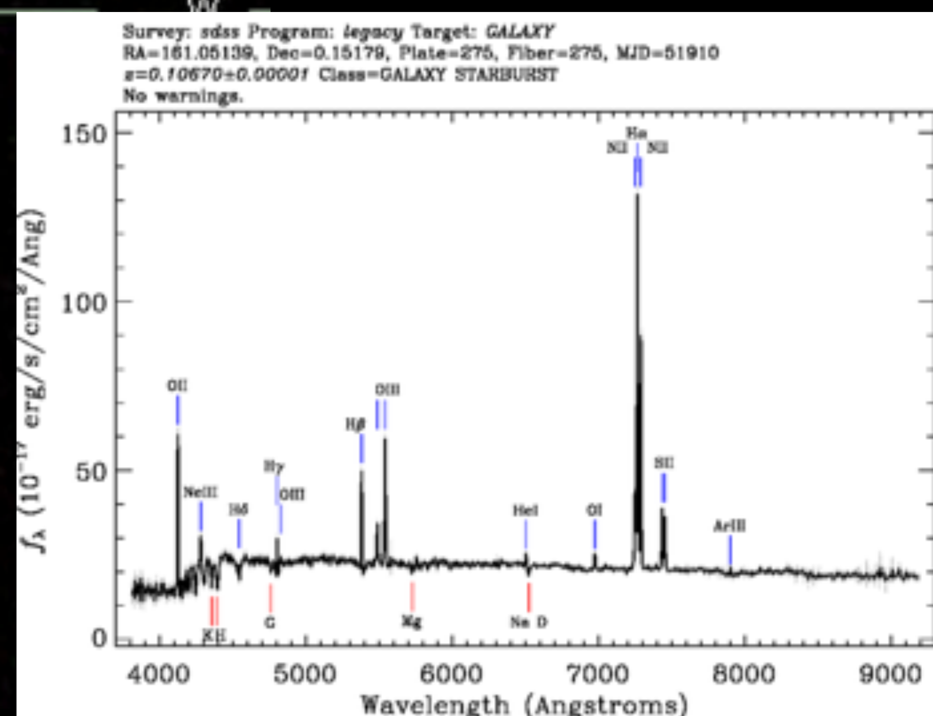
Optical Spectroscopy

Photometry vs. Spectroscopy



$$mag = constant - 2.5 \log_{10} (flux)$$

$$m_R = -2.5 \log_{10} \left[\frac{\int \frac{d\nu_o}{\nu_o} f_\nu(\nu_o) R(\nu_o)}{\int \frac{d\nu_o}{\nu_o} g_\nu^R(\nu_o) R(\nu_o)} \right]$$

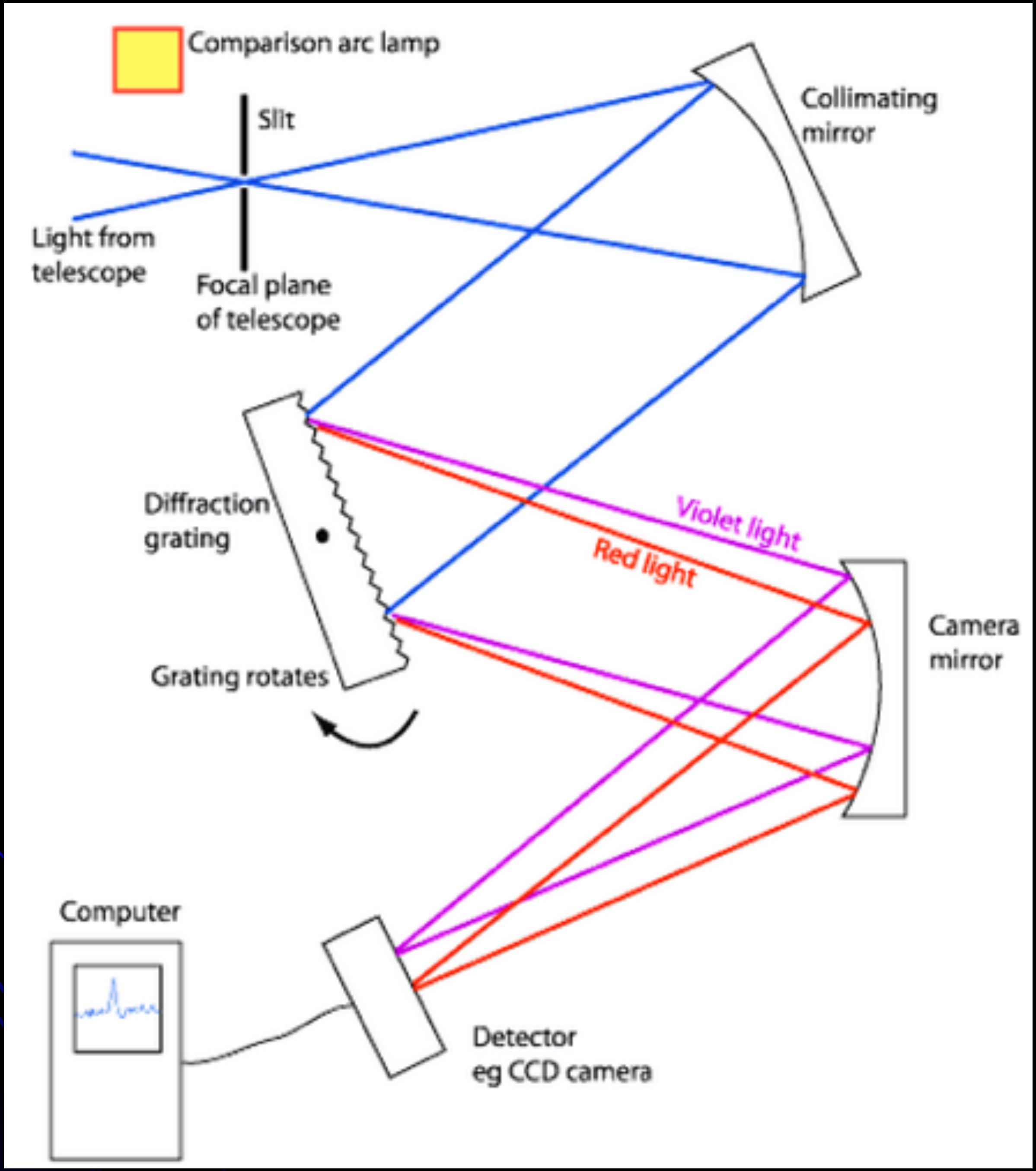


Australian Government

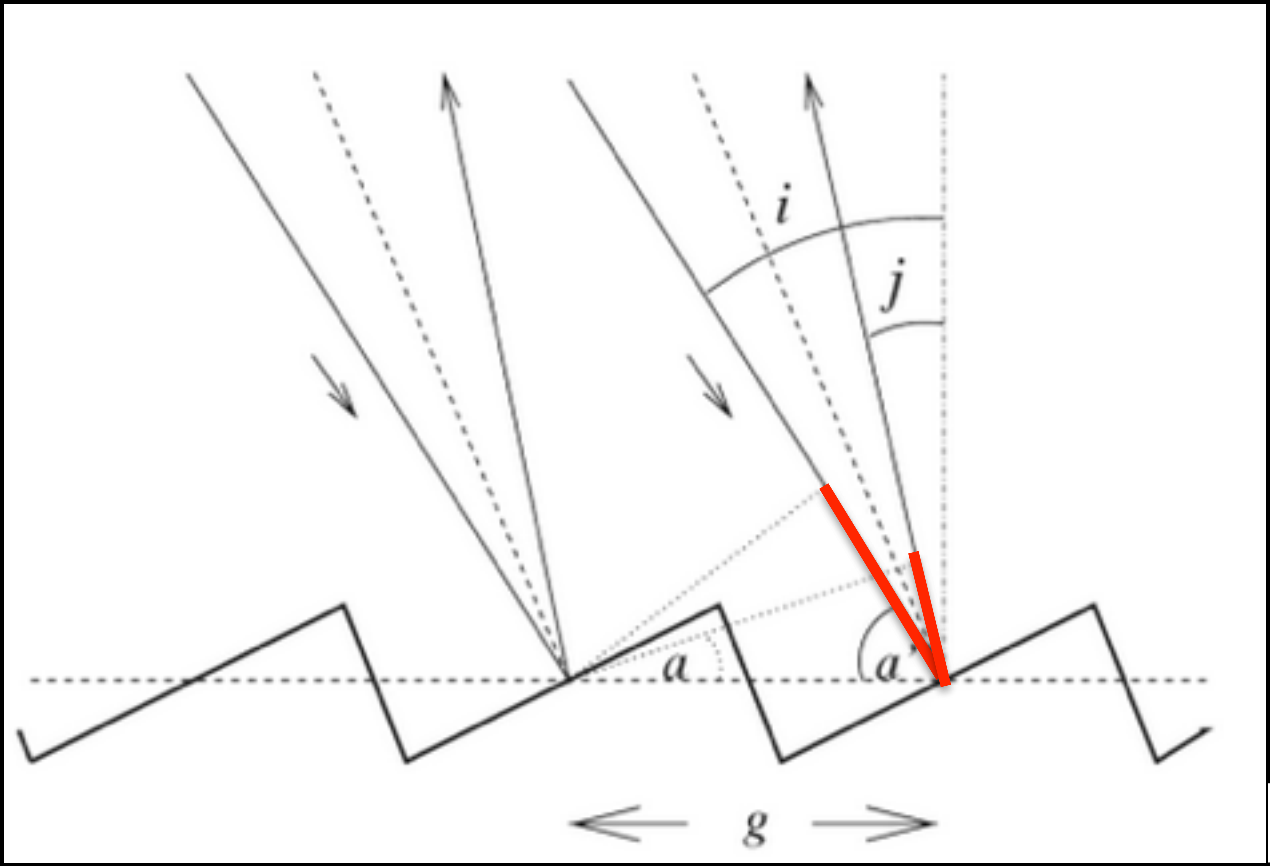
Department of Industry and Science

AAO

Structure of a Spectrograph



Structure of a Spectrograph - Grating Equation



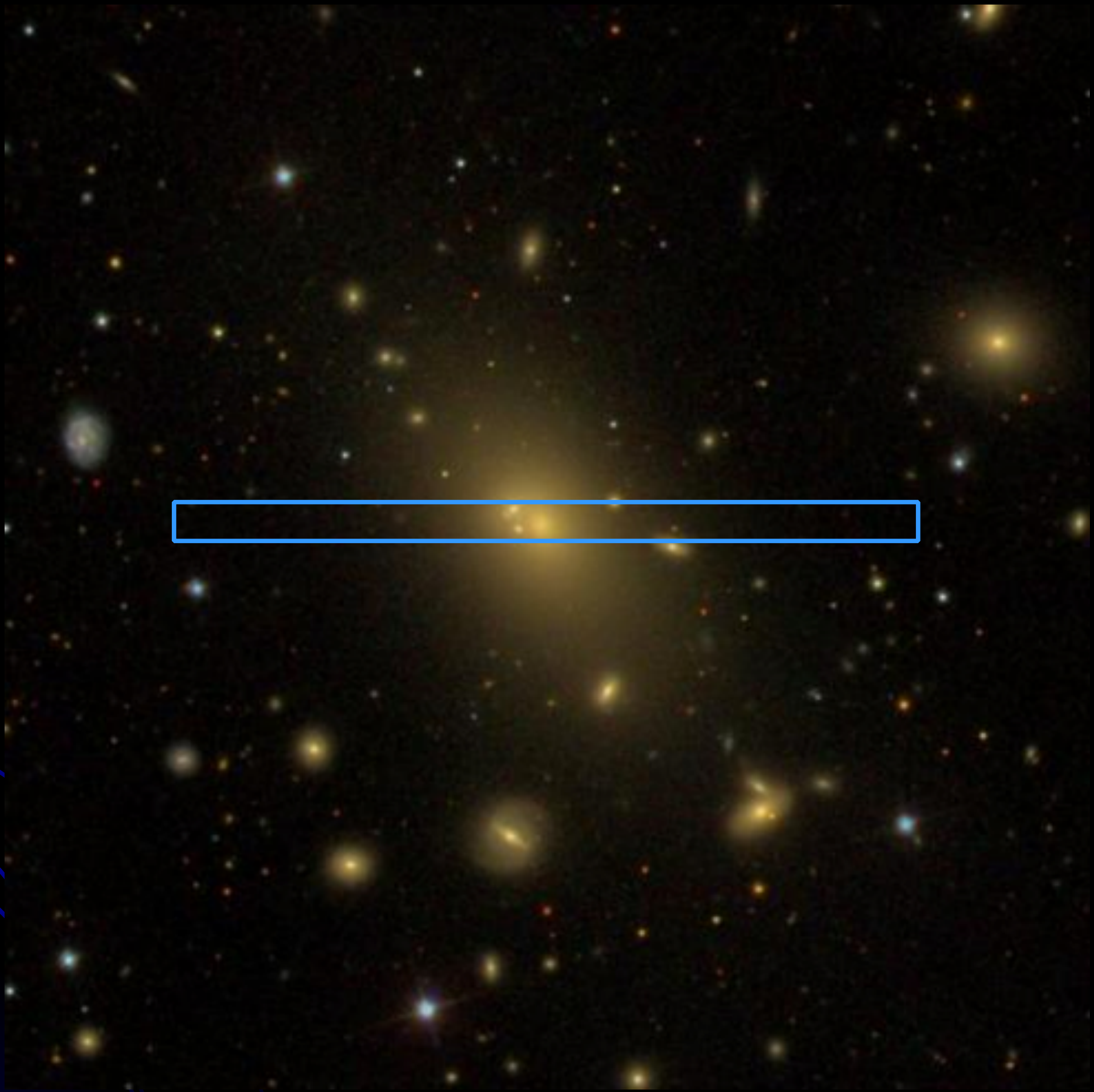
Appenzeller (13)

- **Grating eq:** $l = g(\sin i + \sin j) = m\,\lambda.$
- **Spectral Resolution:** $R = \frac{\lambda}{\Delta\lambda} = m\,N = \frac{G}{\lambda}(\sin i + \sin j),$ $G = N\,g$ total width of the grating.

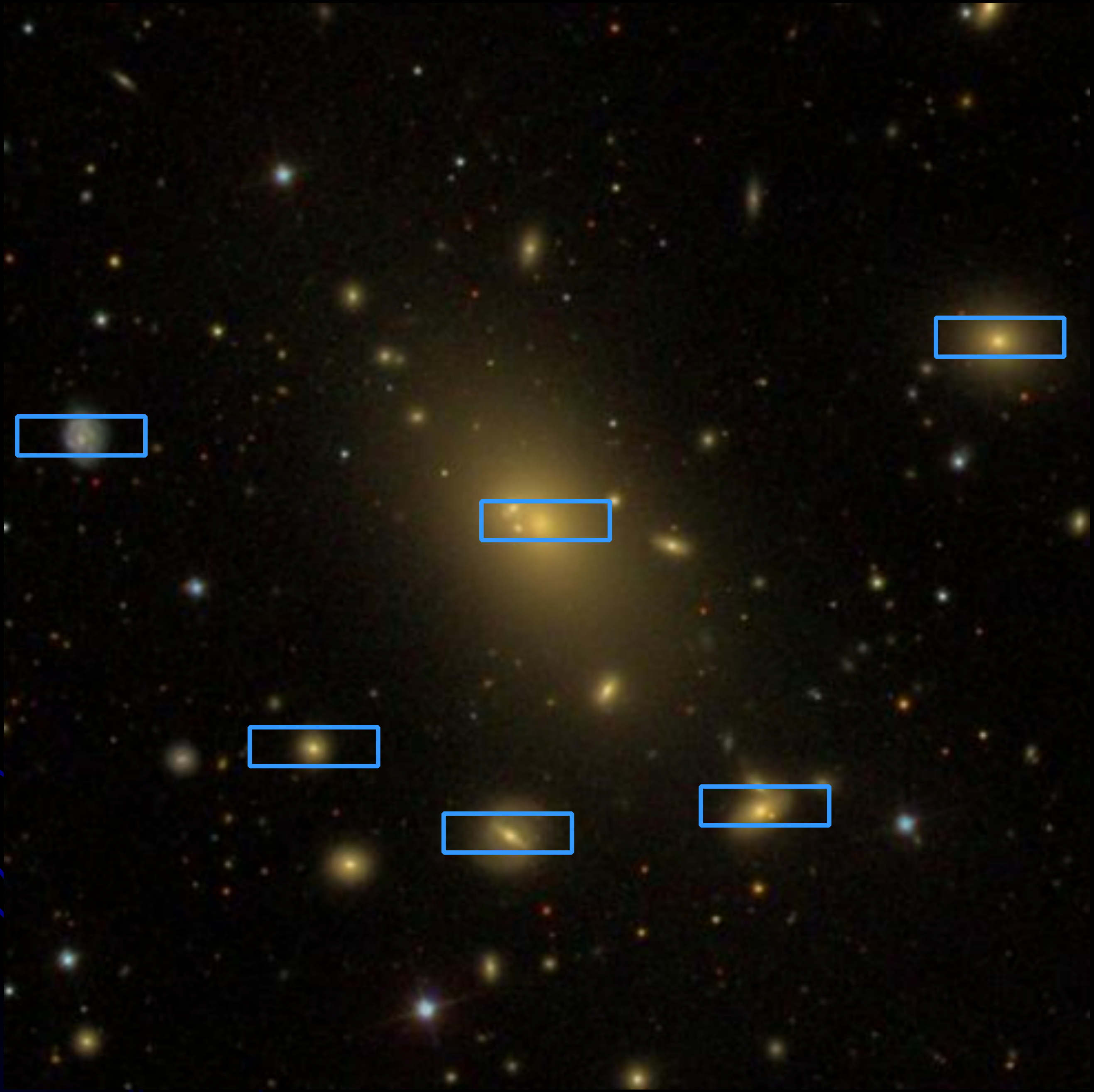
$$\mathrm{FWHM} = (d\lambda^2_{(slits)} + d\lambda^2_{(resolution)} + d\lambda^2_{(line)})^{1/2}$$

- **Dispersion:** $dj/d\lambda = m/(g \cos j)$

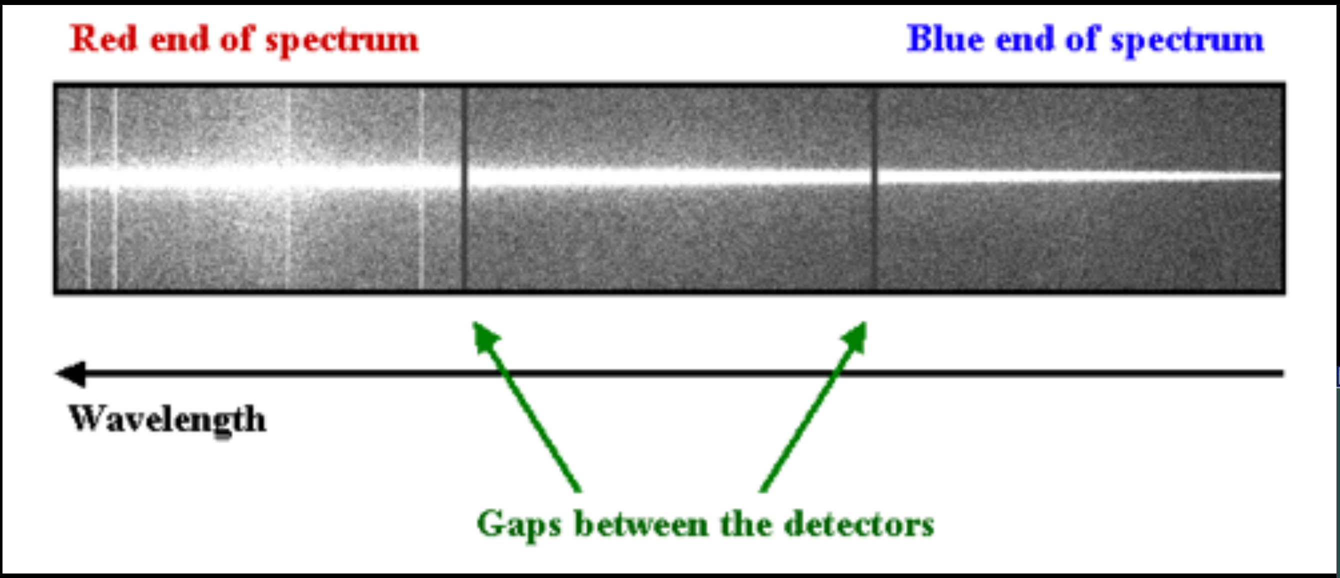
Spectroscopy with Longslit

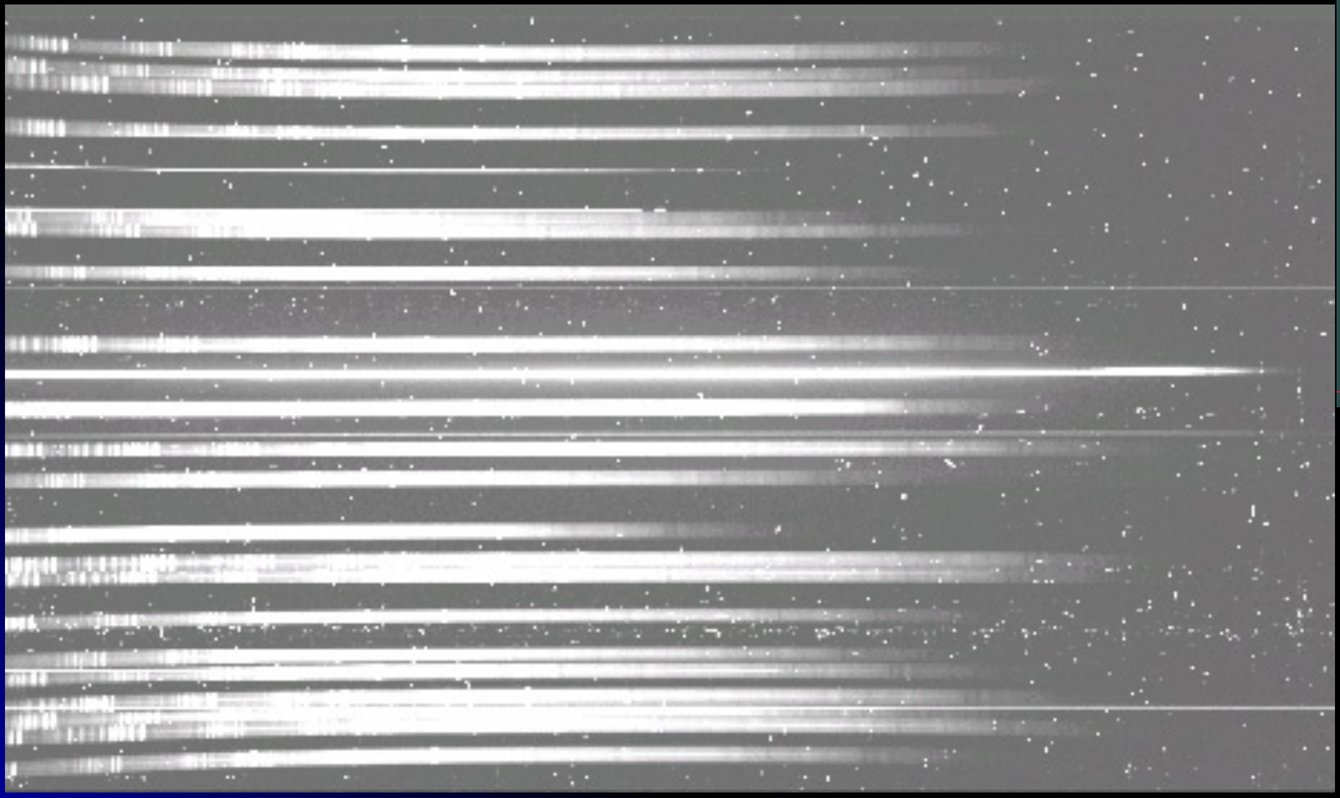


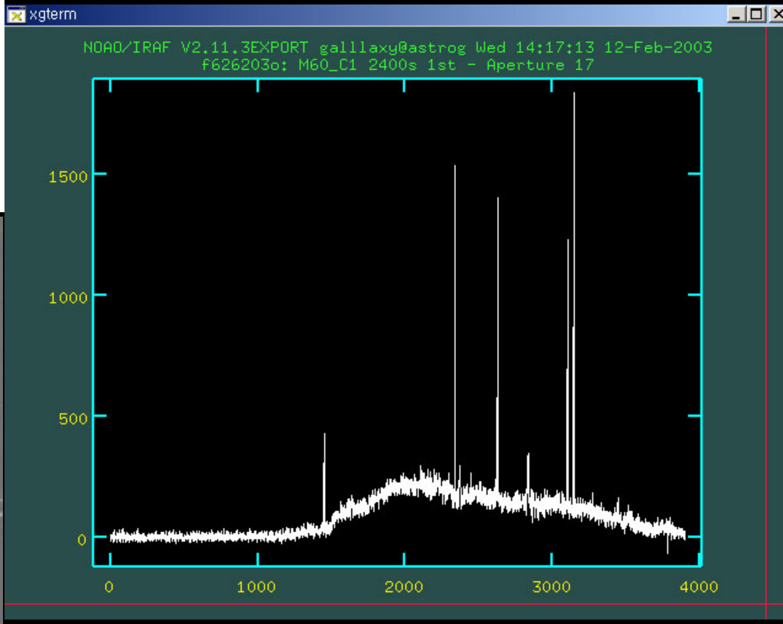
Spectroscopy with Multi Object Spectrograph



Spectrum on Chips

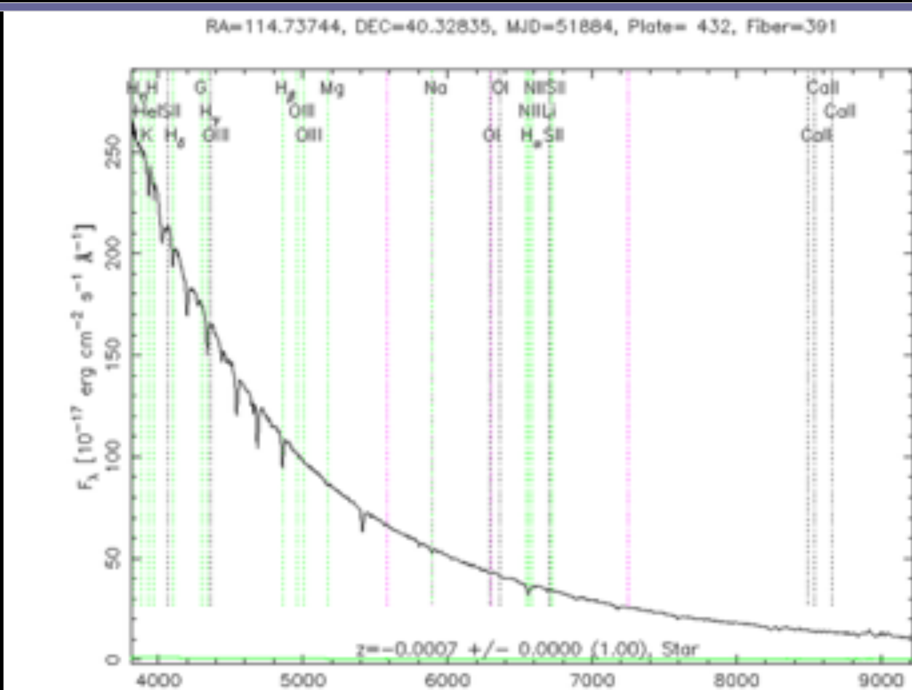




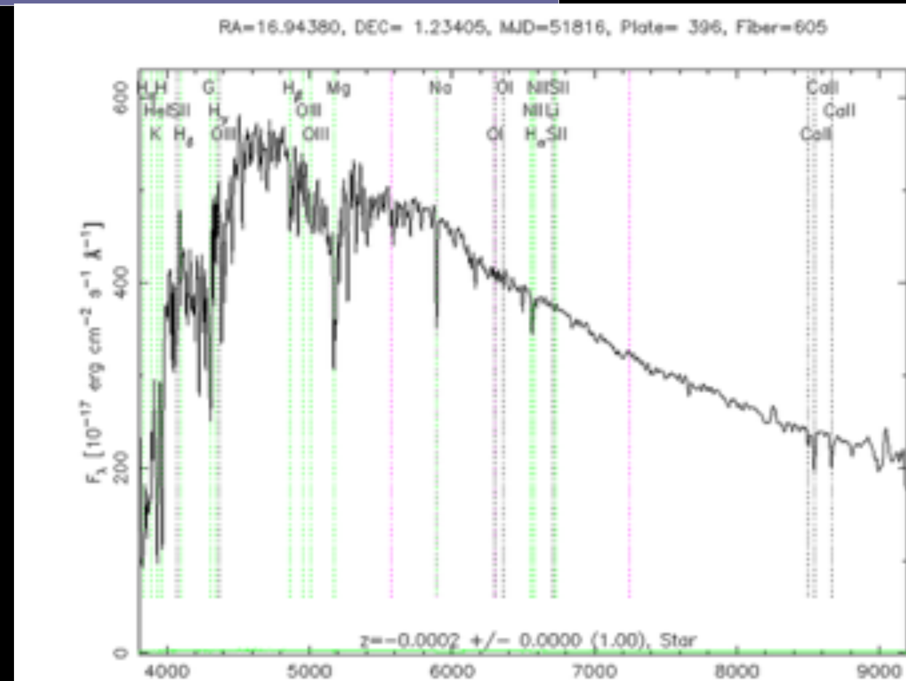


Spectra of Stars

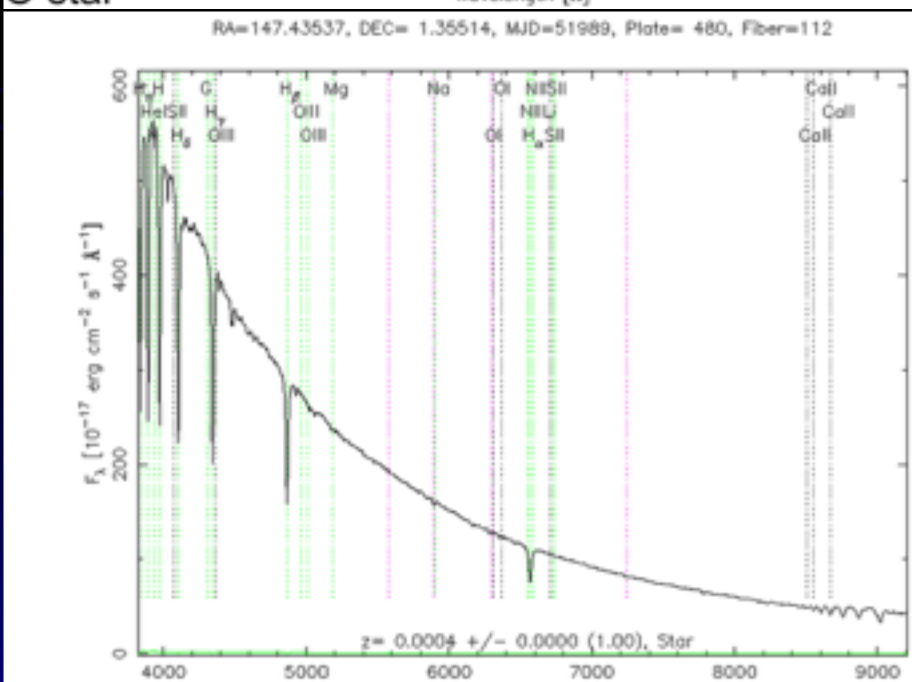
http://www.sdss.org/dr7/algorithms/spectemplates/



O star



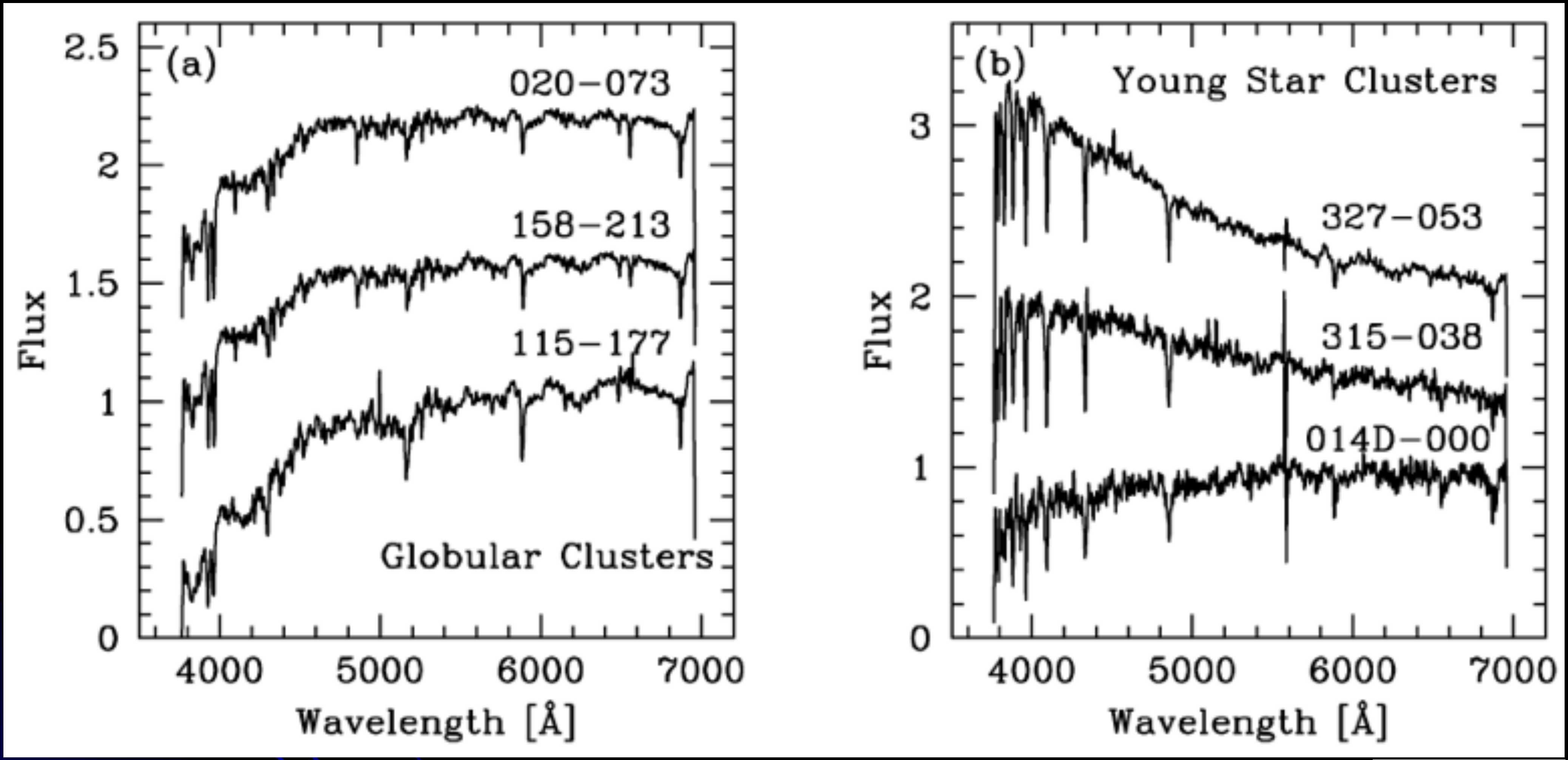
K star



A star

M1 star (Late-type star, M or later)

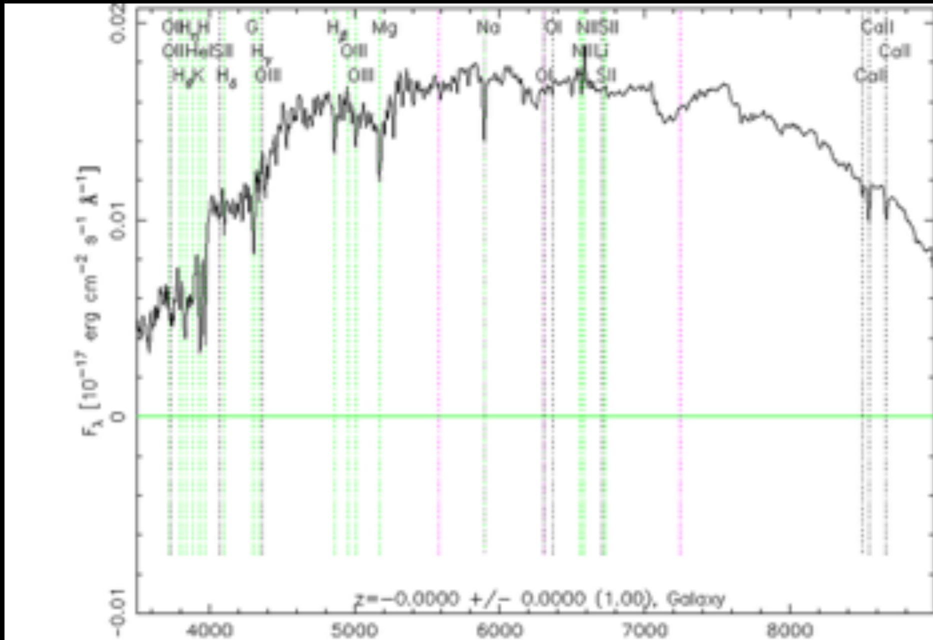
Spectra of Star Clusters



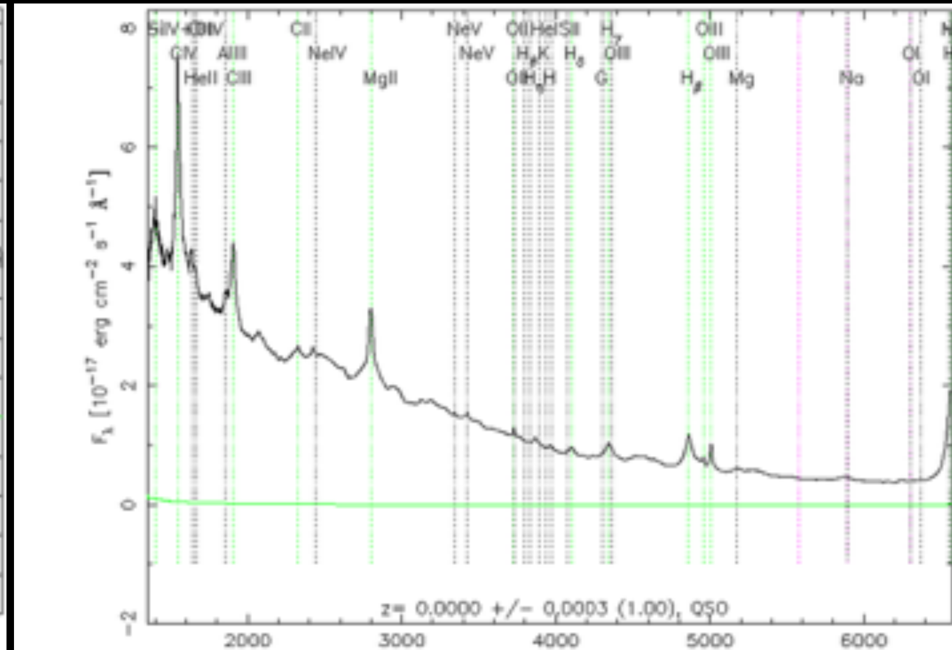
KimSC+07

Spectra of Galaxies and QSOs

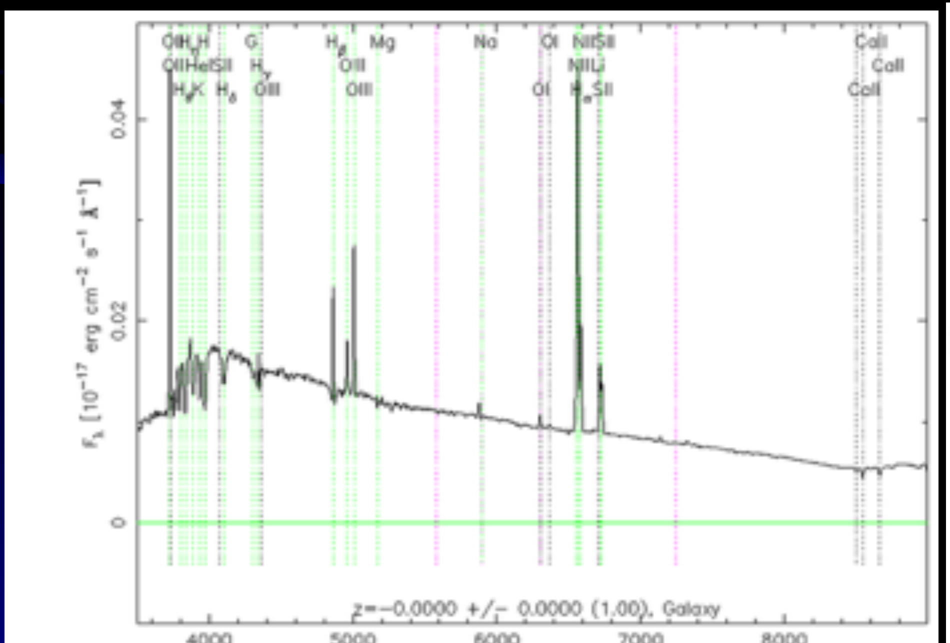
http://www.sdss.org/dr7/algorithms/spectemplates/



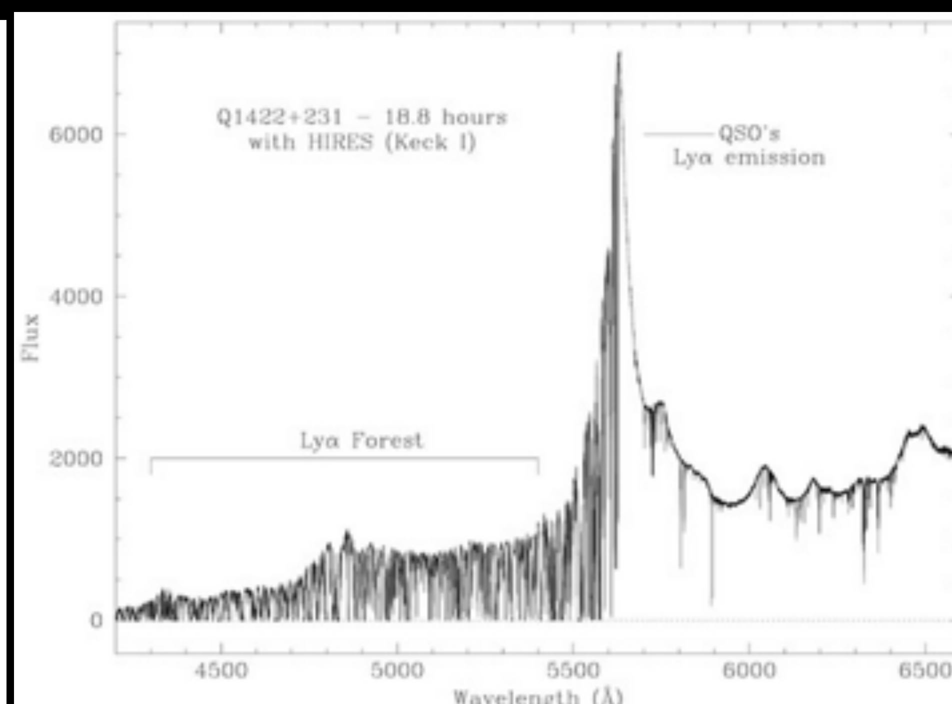
Early-type galaxy



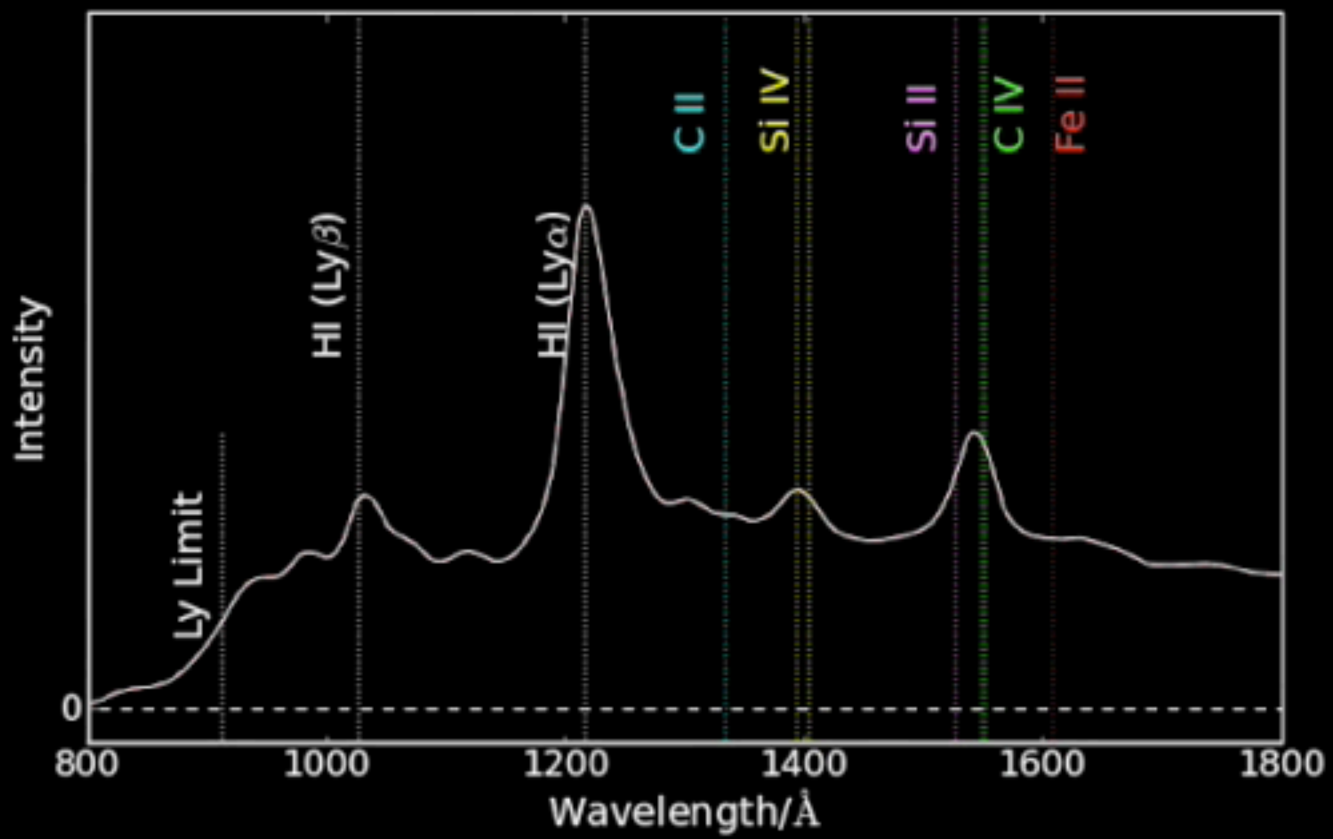
High-luminosity QSO (QSO)



Late-type galaxy

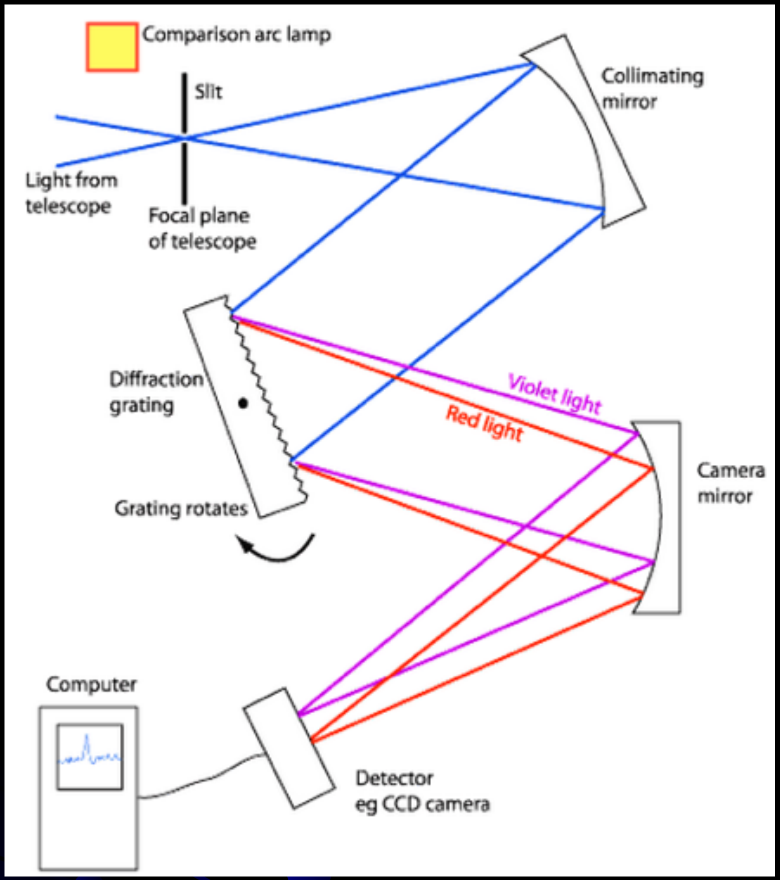


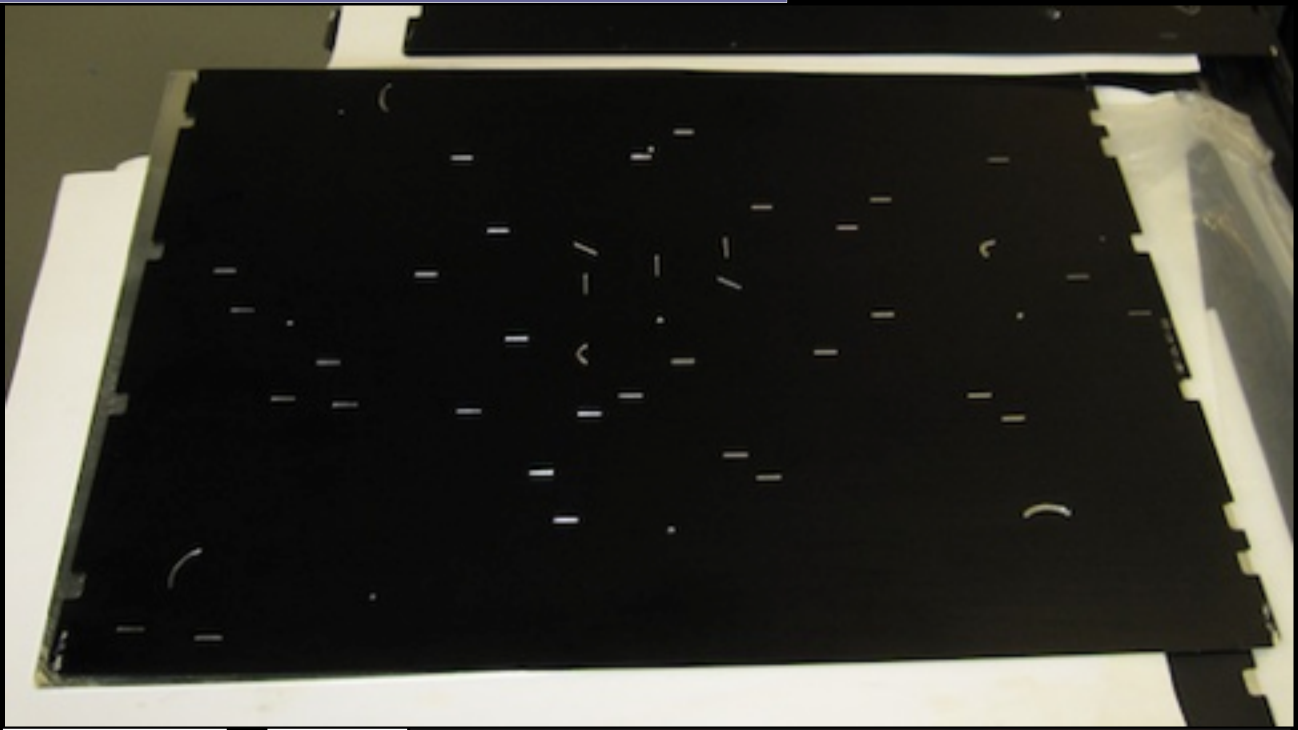
QSO with Lyman α Forest



Andrew Pontzen

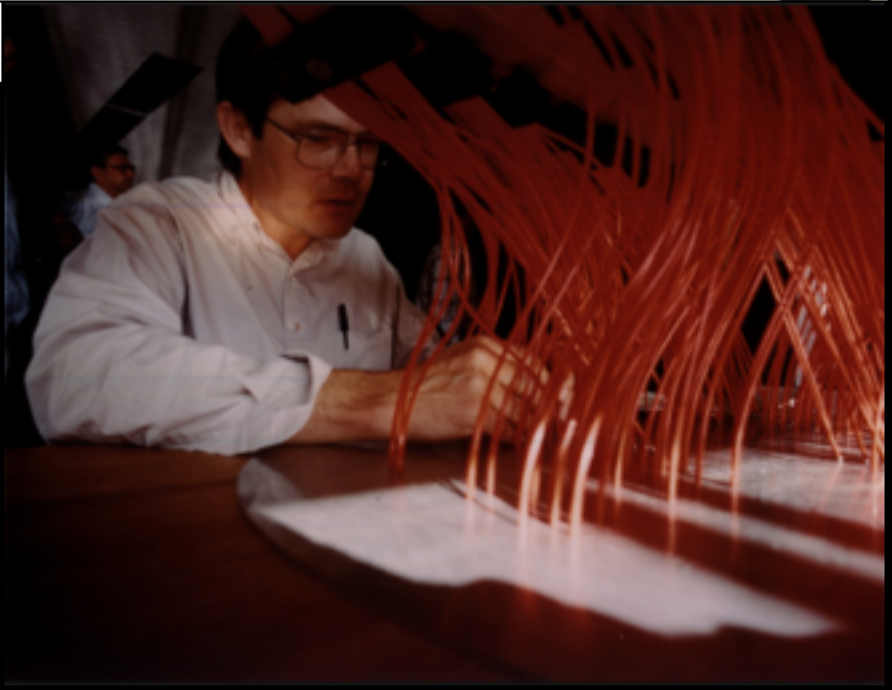
Multi Object Spectrograph



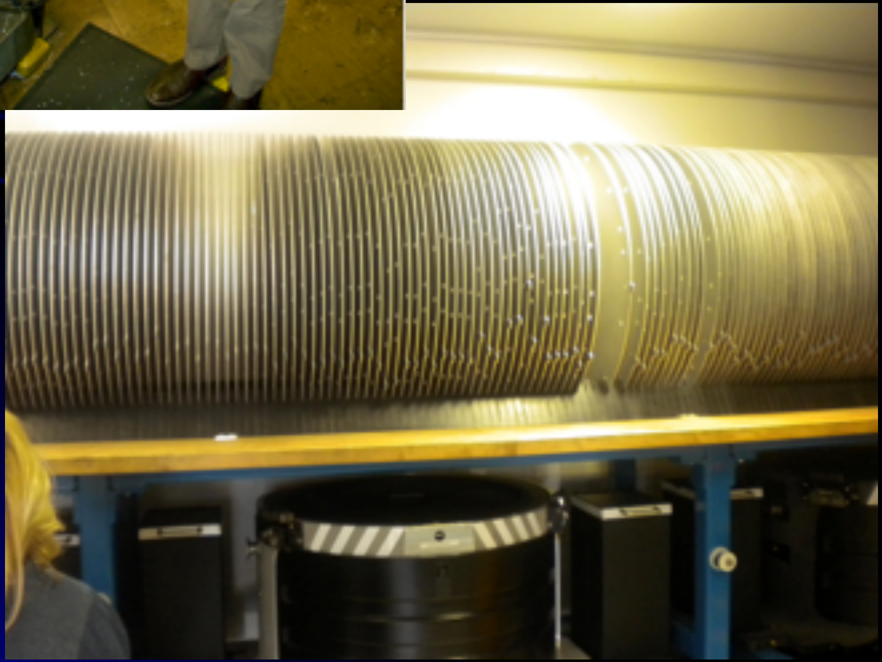


Slit Mask

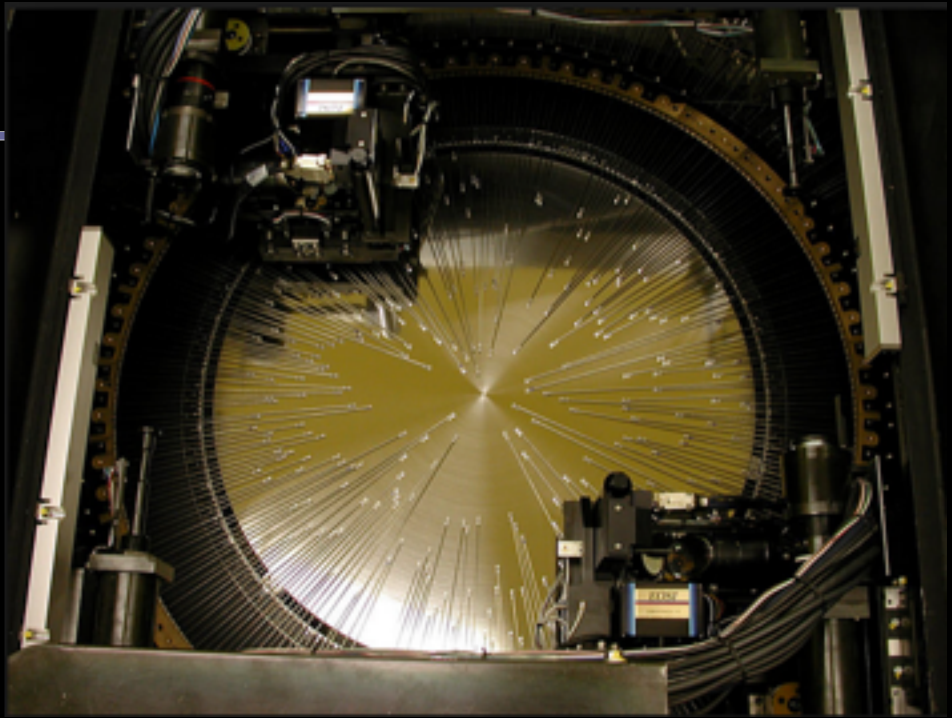
Fiber



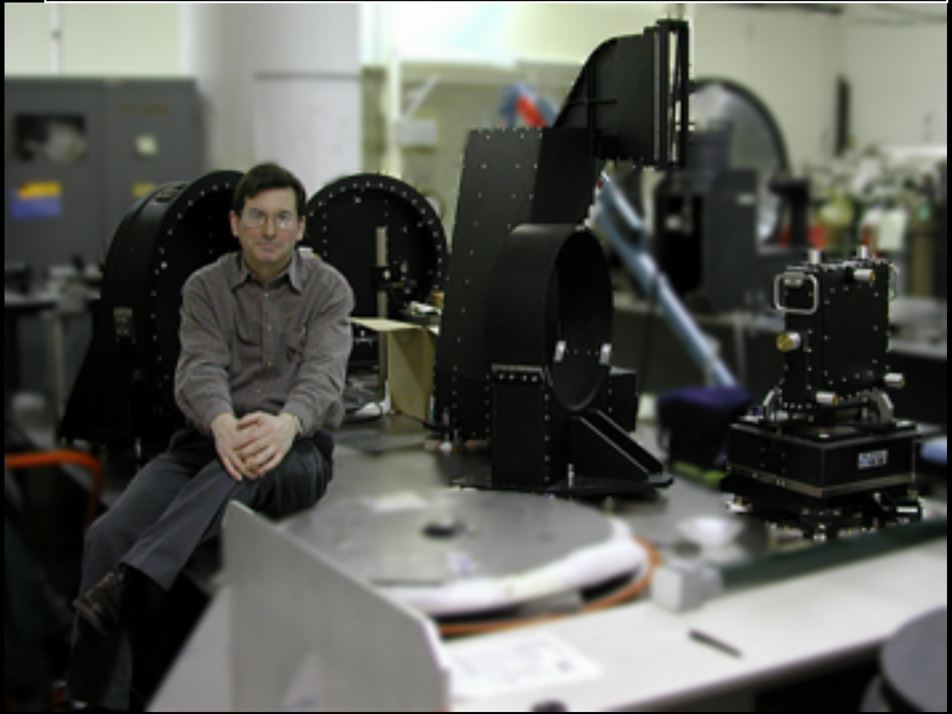
Multi Object Spectrograph

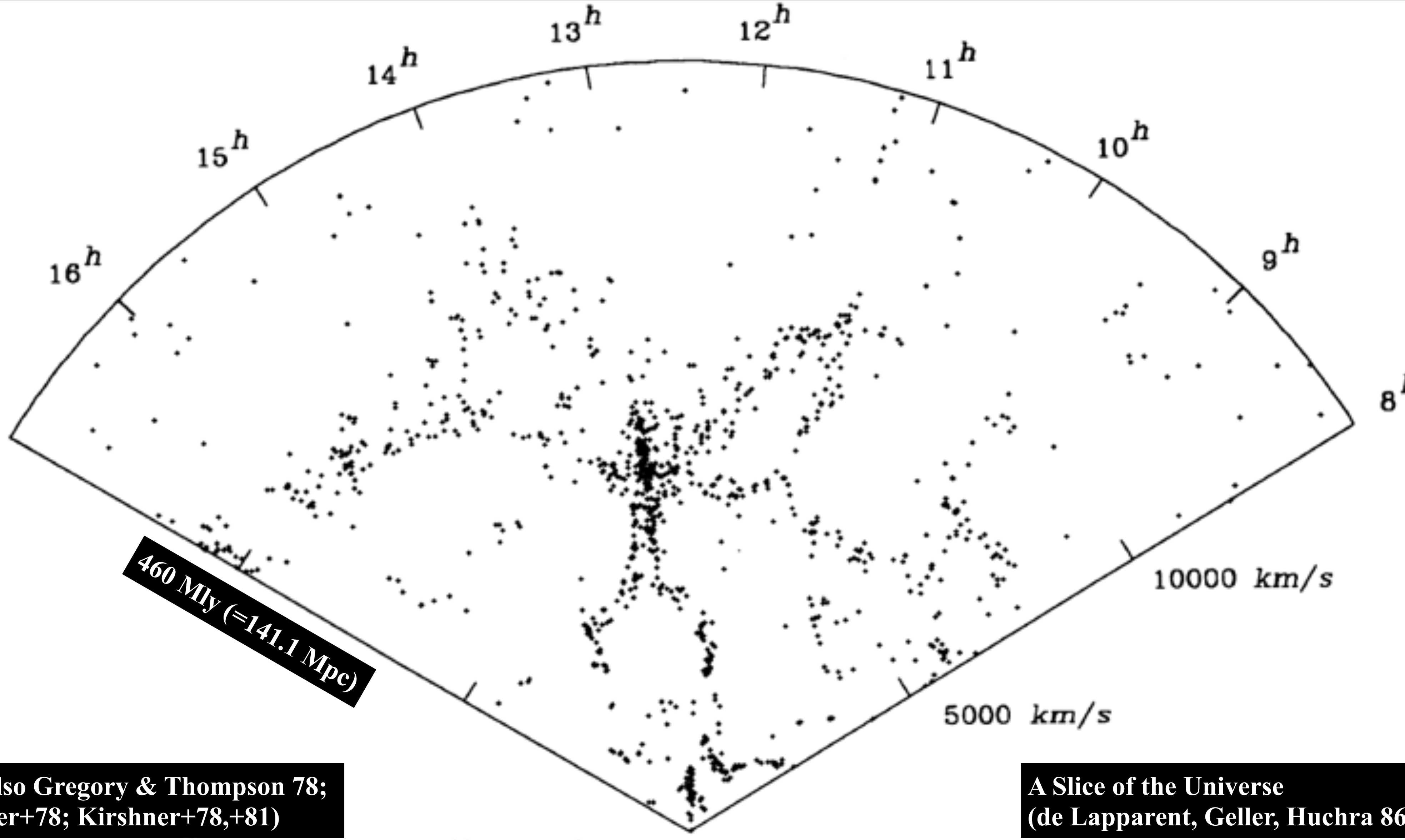


SDSS plates



Hectospec's optical fiber robotic positioner





(see also Gregory & Thompson 78;
Joeveer+78; Kirshner+78,+81)

A Slice of the Universe
(de Lapparent, Geller, Huchra 86)

The Astrophysical Journal, 470:172–188, 1996 October 10

THE LAS CAMPANAS REDSHIFT SURVEY

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First zSurvey with Multi-object Spectrograph

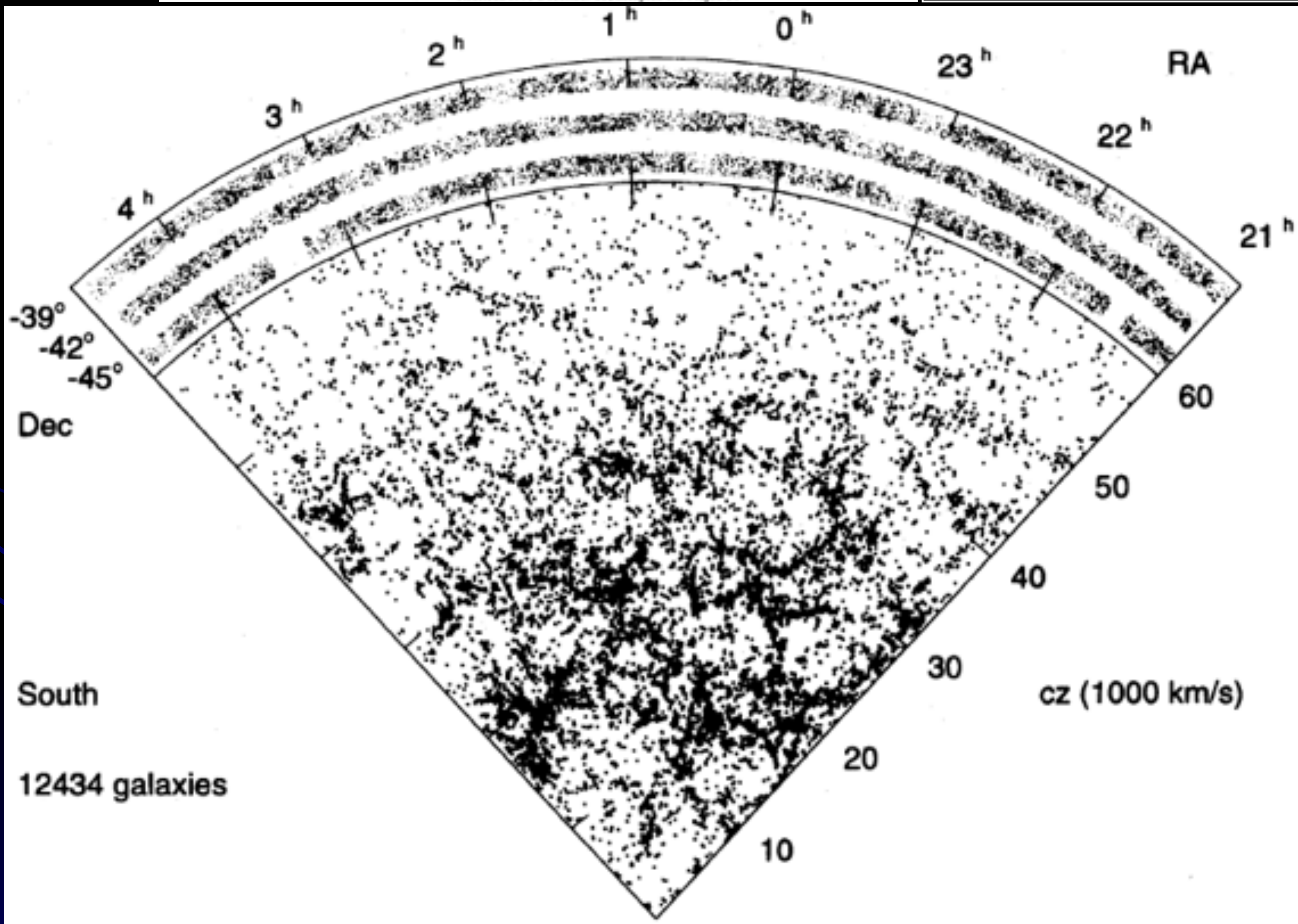


FIG. 8*h*

Slit vs. Fiber

- Advantages
  - High throughput
  - Can choose slit width and length
  - Good sky subtraction
  - Can place slits close together

- Disadvantages
  - No flexibility at the telescope other than to change exposure times
  - Setup time for such masks is non-negligible (~15-20 min)
  - Wavelength coverage will vary from slitlet to slitlet

- CFHT/MOS, Gemini/GMOS

Slit vs. Fiber

- Advantages
  - Large fields
  - Uniform wavelength coverage
  - High Stability (needed for precision velocity)
  - Not suffer flexure as the telescope is moved
  - Additional “scrambling” of the light
    (exact placement of a target is needed for slitlets)

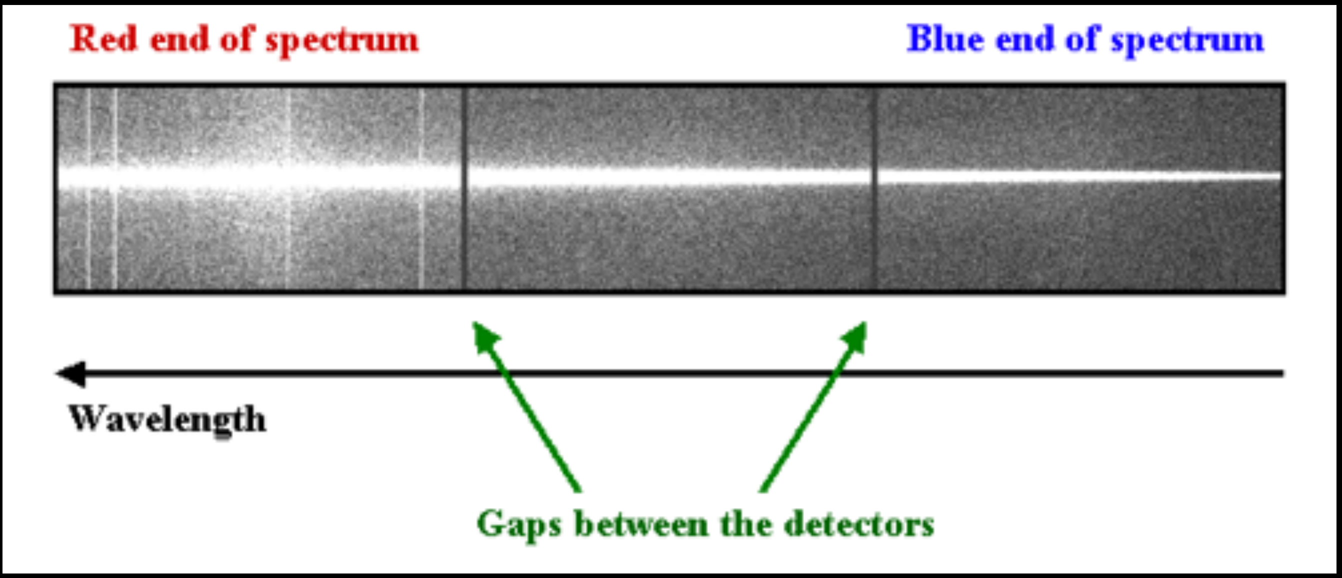
- Disadvantages
  - Light loss within the fiber
  - Fiber collision - Minimal spacing between fibers
  - Sky subtraction is never “local”

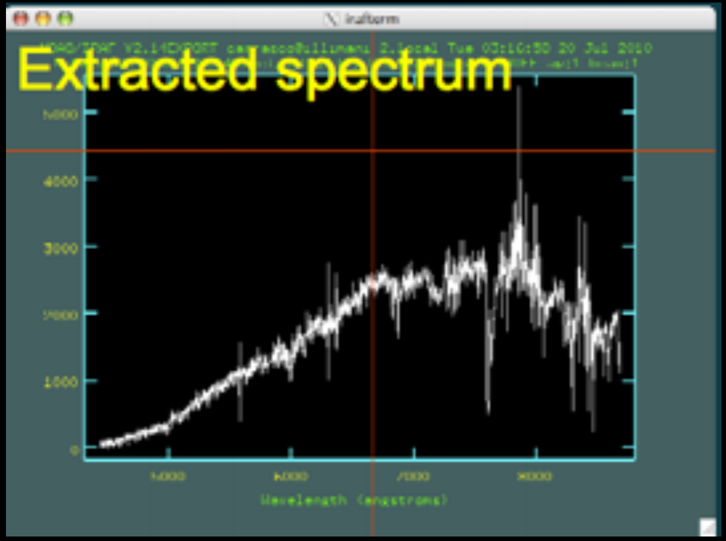
- MMT/Hectospec, SDSS

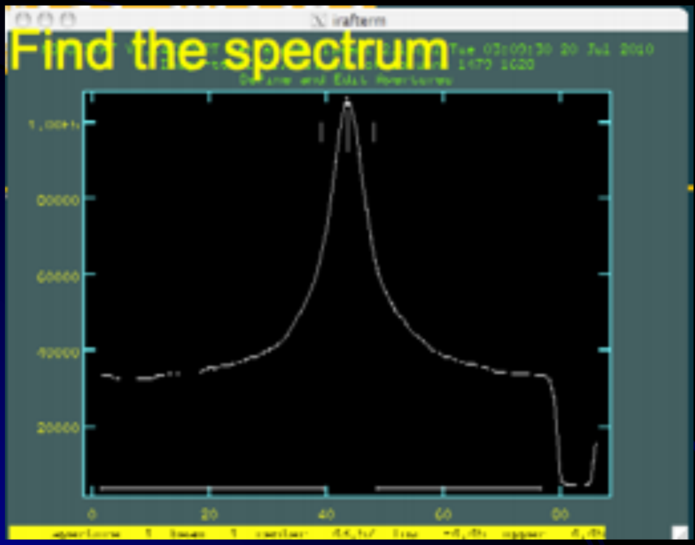
Slit vs. Fiber

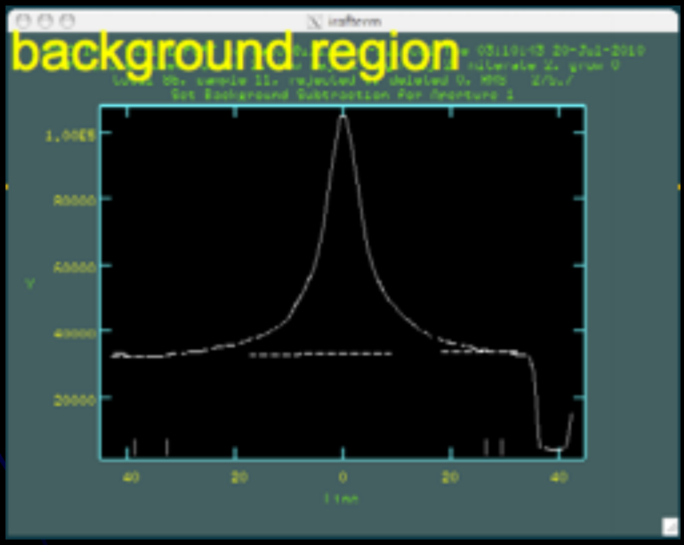
MOS	Mode	FOV	Grating	Resolution $(R\sim\lambda/d\lambda)$	Wavelength (Angstrom)	N per field
MMT(6.5m)/Hectospec	Fiber	D~1 deg	270 gpm 600 gpm	1000 2000	3650-9200 5300-7800	300
Magellan(6.5m)/ IMACS LDSS3 M2FS (PI inst.: Mateo)	 Slit Prism Fiber	 27'x27' 27'x27' D~30'	 150-1200 300-1090 (Grism) LoRes	 500-20000 800-1900 1500-2700	 4300-9300 4300-9300 3700-10000	 300 2500 256
Gemini(8m)/GMOS	Slit	5.5'x5.5'	R150 R831	150 4396	4500-10000 5500-10000	<50
Subaru(8m)/FMOS	Fiber	D~30'	600ZD- 1200G	600-2200	9000-18000	400
VLT(8m)/VIMOS	Slit	4x7'x8'	Grism	200-2500	3600-10000	40-200
Keck(10m)/DEIMOS	Slit	16.7'x5.0'	600ZD- 1200G	<6000	4100-11000	<130
GMT(25m)/GMACS (Manifest)	Slit	4'x8'		100-3000	4000-9000	100

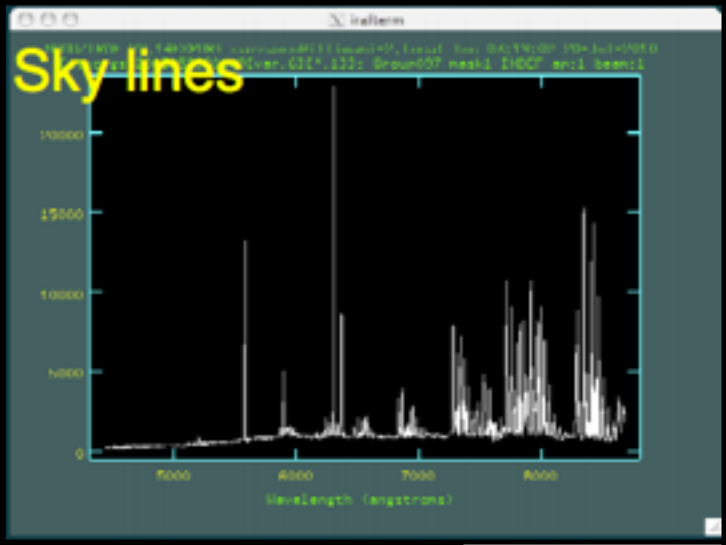
Practical Observation - 1) Nod & Shuffle





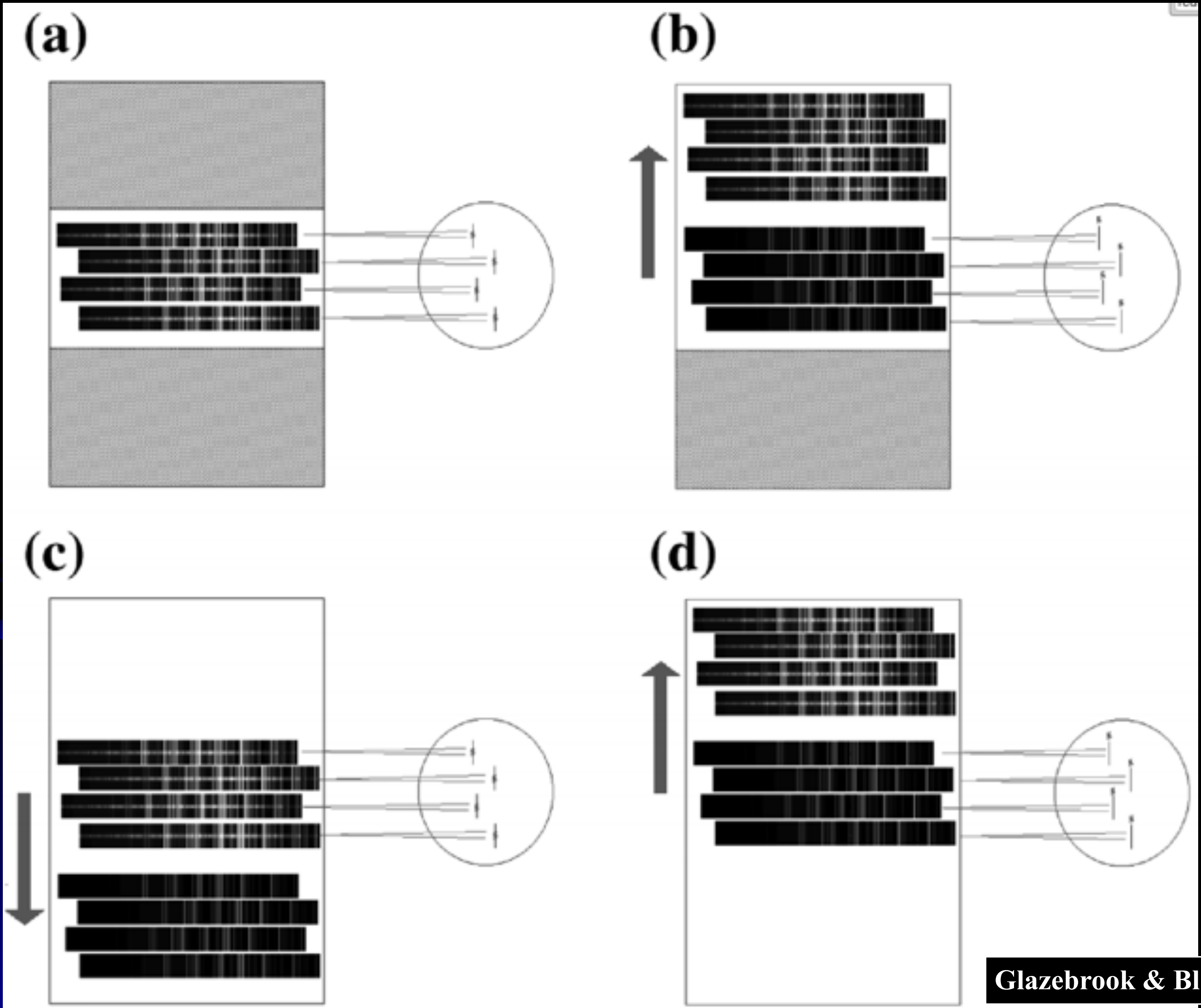






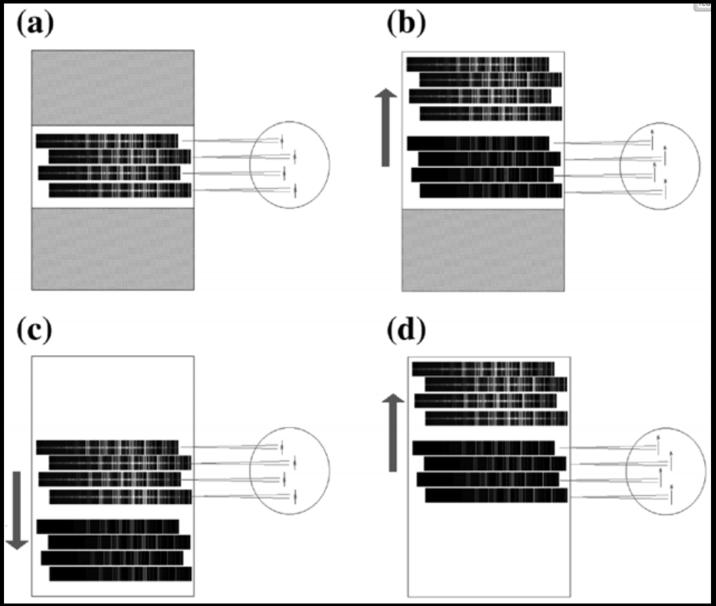
Schiavon (11)

Practical Observation - 1) Nod & Shuffle



Glazebrook & Bland-Hawthorn 01

Practical Observation - 1) Nod & Shuffle



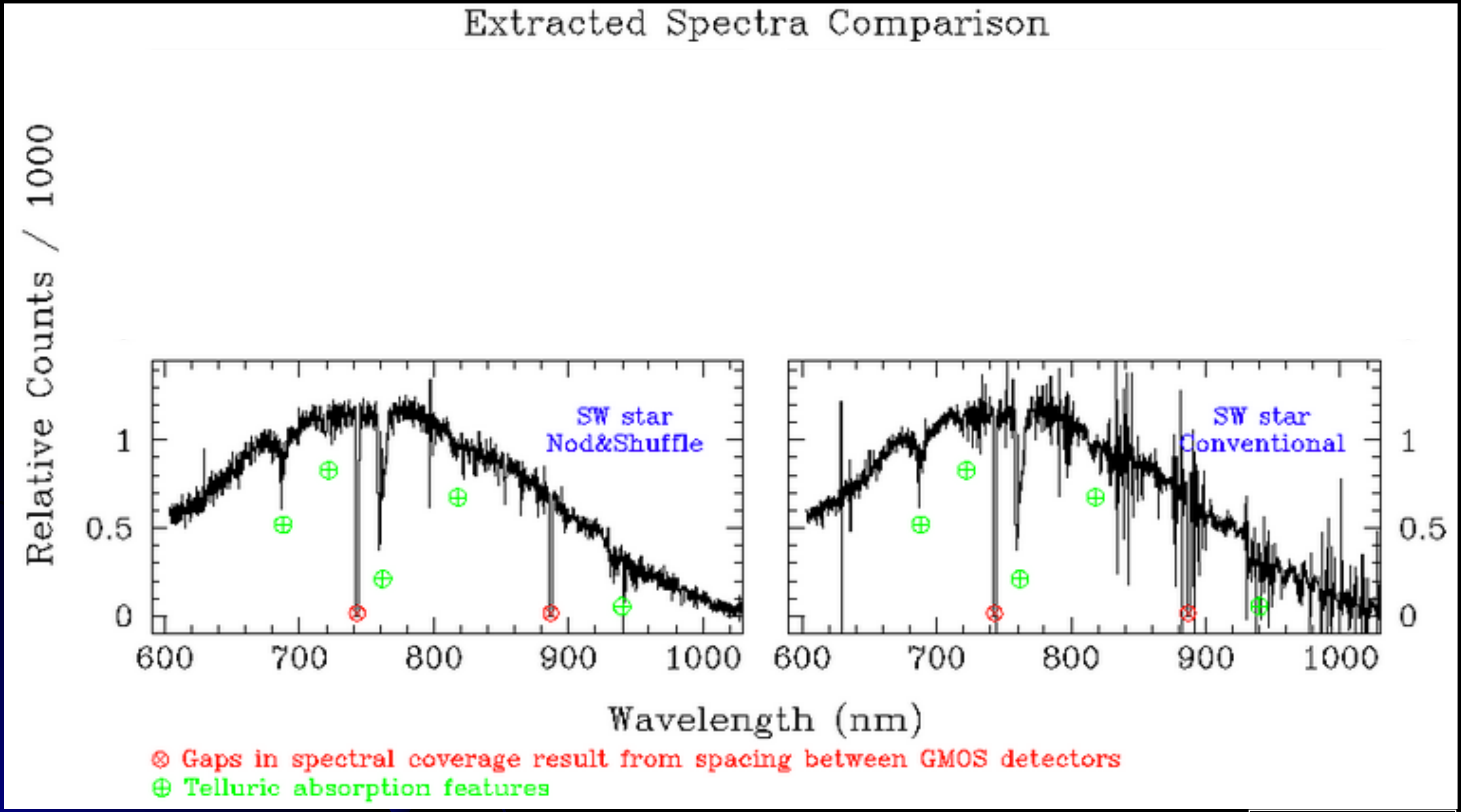
- Nod: Telescope Motion on the Sky
- Shuffle: Charge shift up/down the detector

- Advantage: Lower Sky-line residuals
  - Sky measured from the same pixels → Direct Subtraction of Sky
  - Make slits small → More slits
  - Good for high-z galaxy spectroscopy

- Disadvantage: Higher Overheads
  - Need more observing time
  - Storage regions in CCD needed → decrease total sky coverage

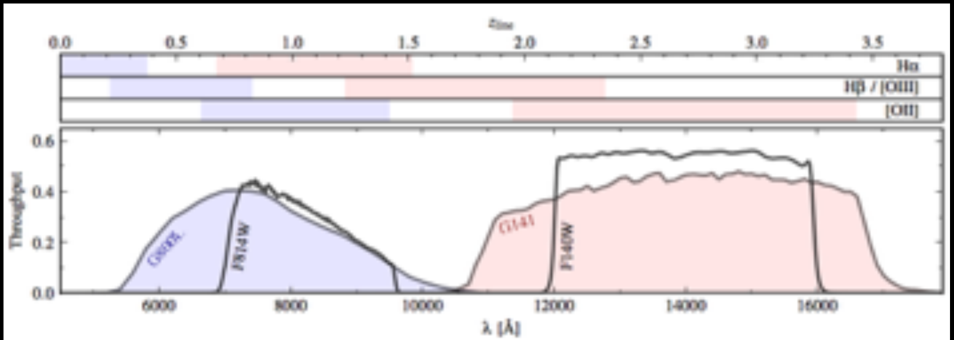
Glazebrook & Bland-Hawthorn 01

Practical Observation - 1) Nod & Shuffle

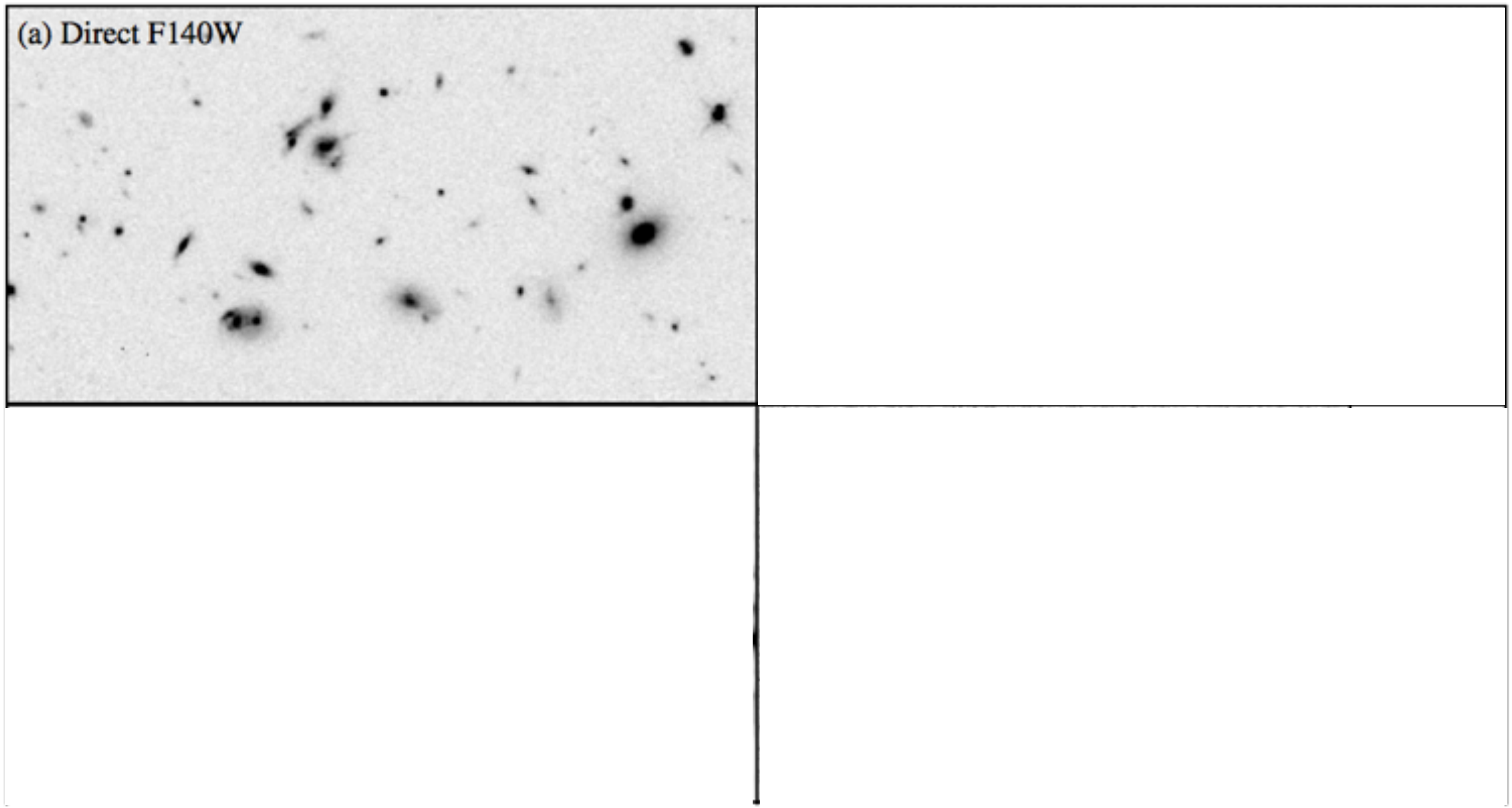


Gemini Website

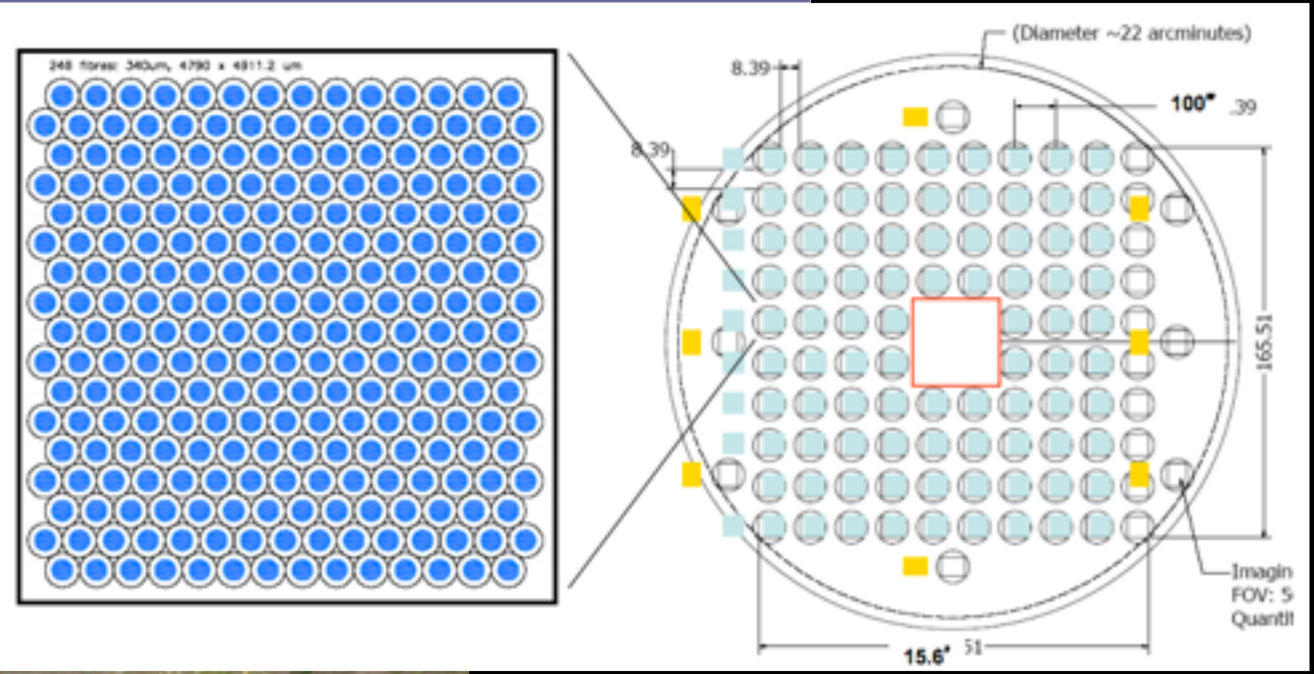
Practical Observation - 2) HST Slitless Spectroscopy



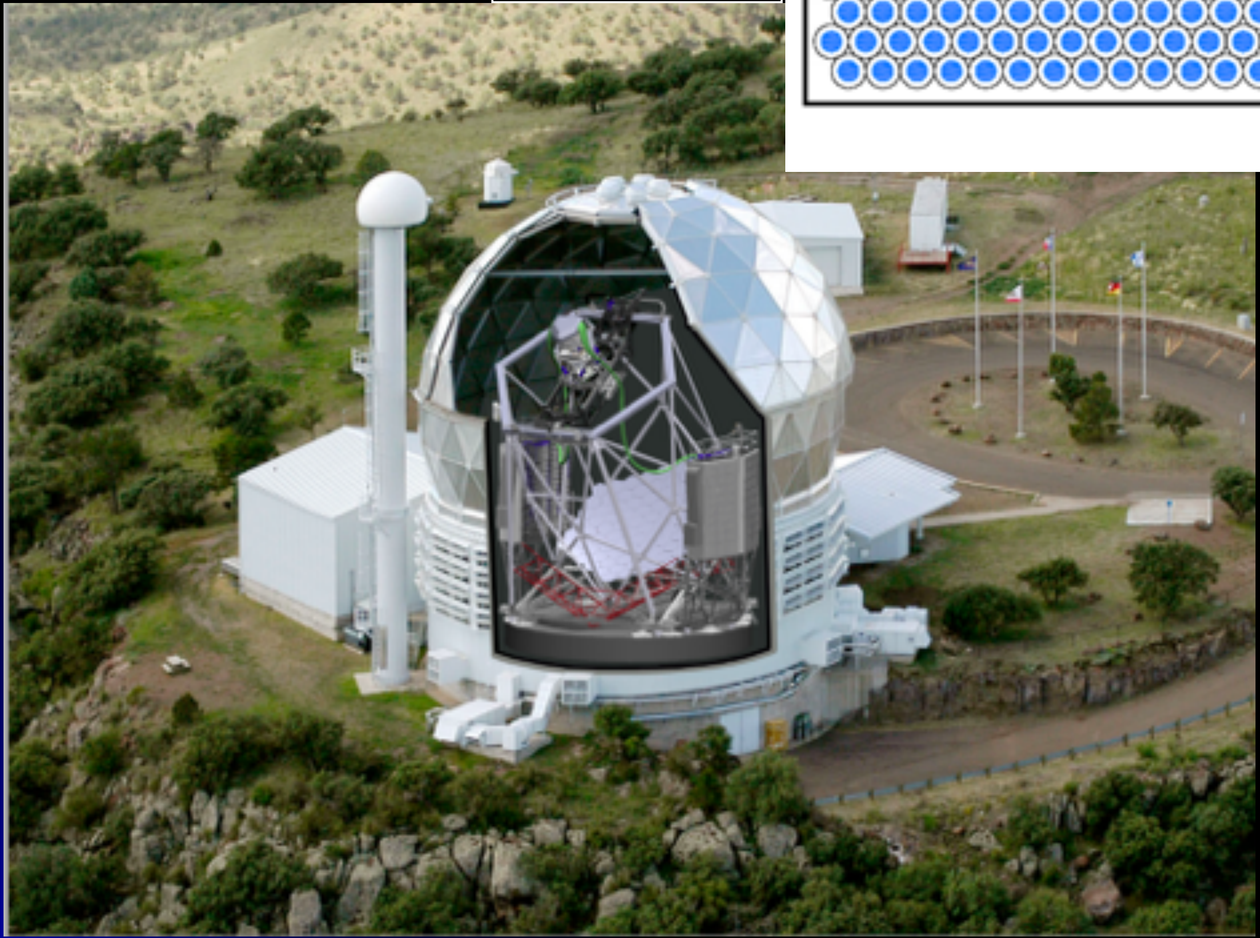
3D-HST (Brammer+12)



Practical Observation - 3) HETDEX IFU+MOS Survey



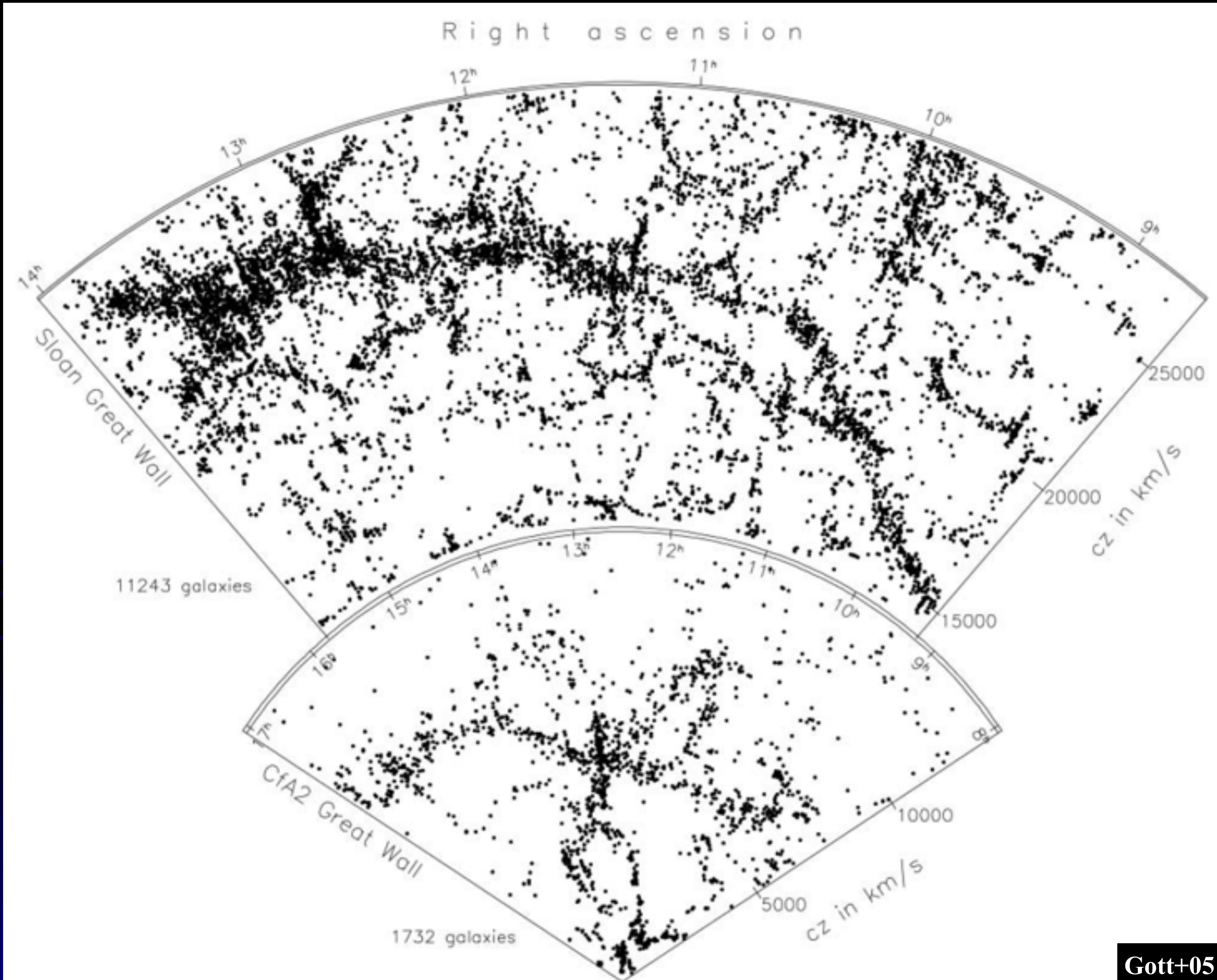
HETDEX team



- Hobby-Eberly Telescope: 9.2m
- 75 IFUs (each 448 1.5” fibres) in Diameter of 22’
- L = 3500 - 5500A and R~800
- Targets: 800,000 LAEs at 1.9<z<3.5
- 420 deg^2 in 140 nights over 3 years

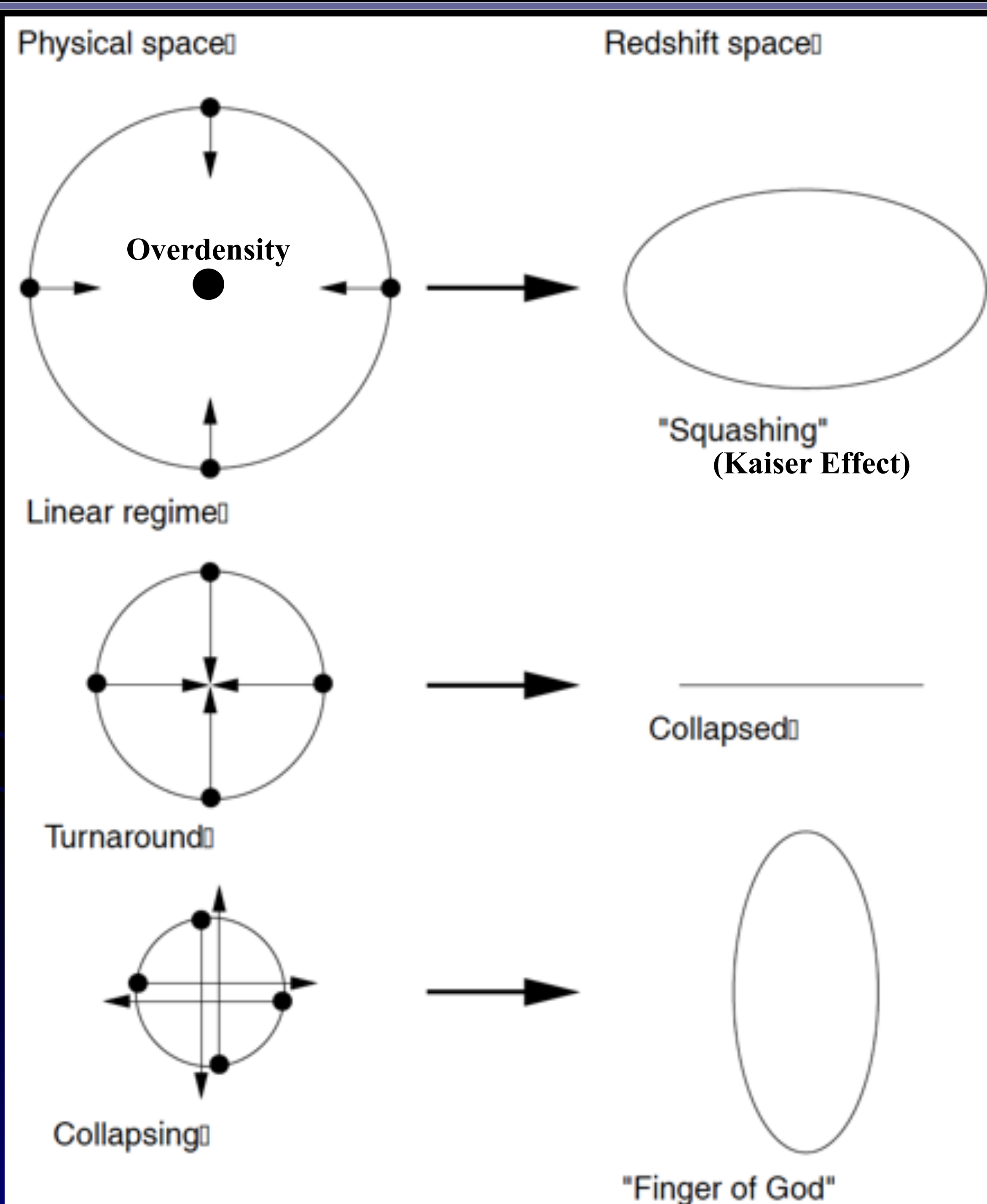
Redshift Space Distortion

Working on Redshift Space

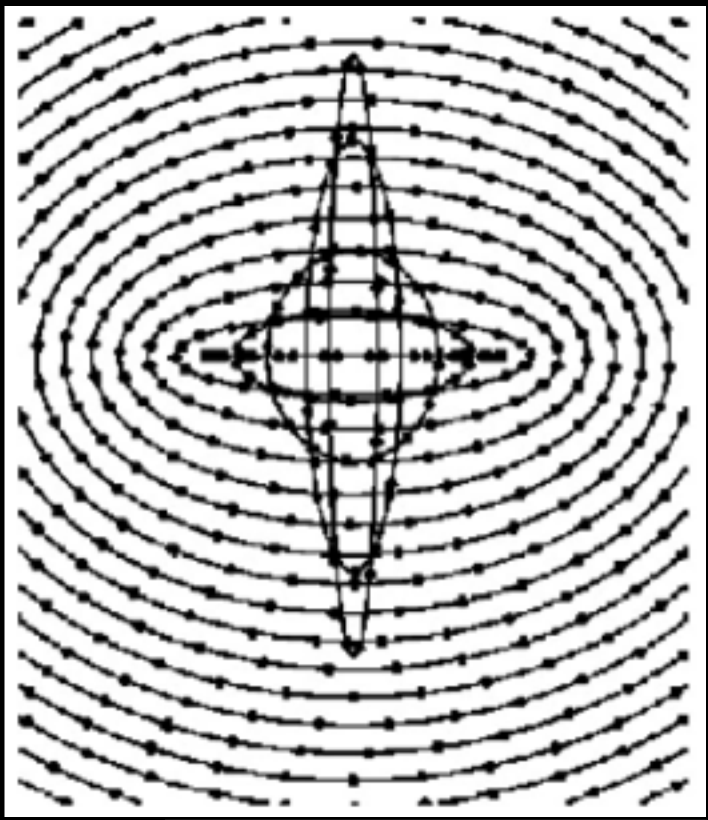


Gott+05

Spherical Infall: Real vs. Redshift Space



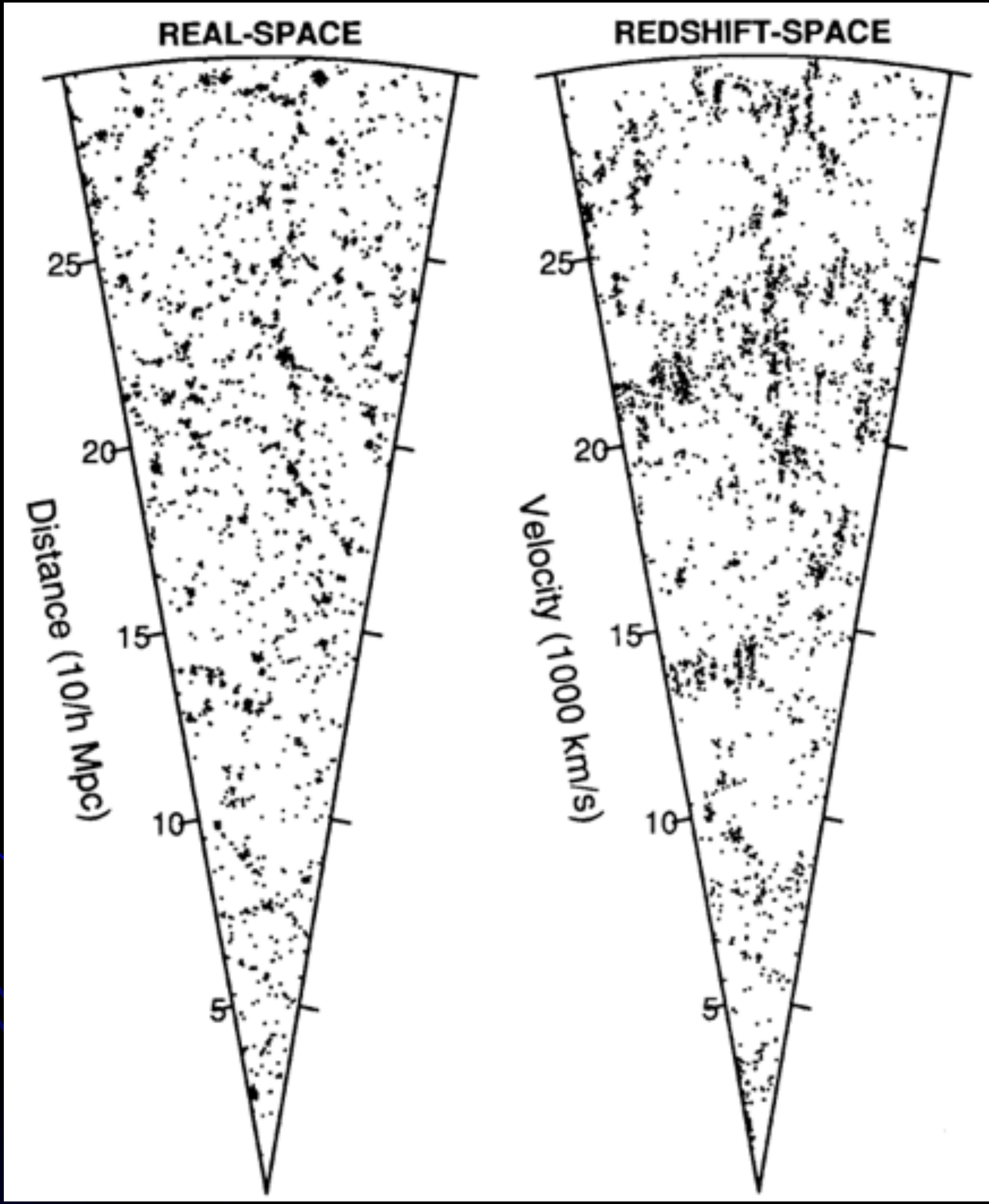
Line of Sight



Positions of galaxies (points) in redshift space, in reality located on spherical shells.

Kaiser 87; Hamilton 92

Real Space vs. Redshift Space



Praton+97

Two-point Correlation Function (Peebles 80)

- If n_bar is the average number density of galaxies,
  the probability of finding a galaxy in a volume element dV around x

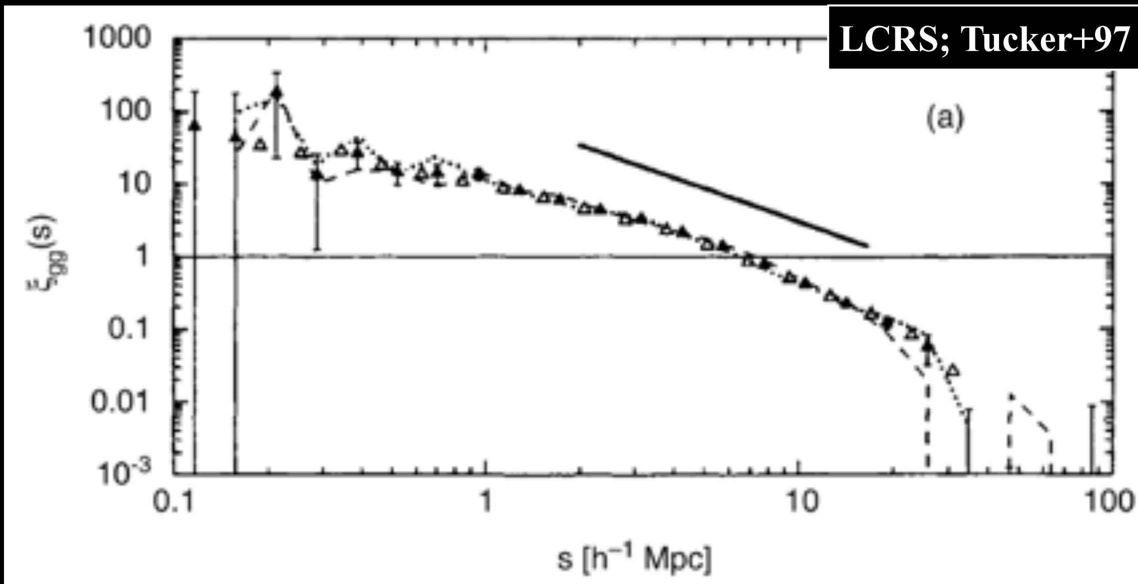
$$P_1 = \overline{n}\,\mathrm{d}V$$

- The probability of
  finding a galaxy in a volume element dV at location x
  and at the same time
  finding a galaxy in the volume element dV at location y

$$P_2 = (\overline{n}\,\mathrm{d}V)^2\left[1+\xi_{\mathrm{g}}(x,y)\right]$$

- ξ_g is the two-point correlation function of galaxies

Two-point Correlation Function

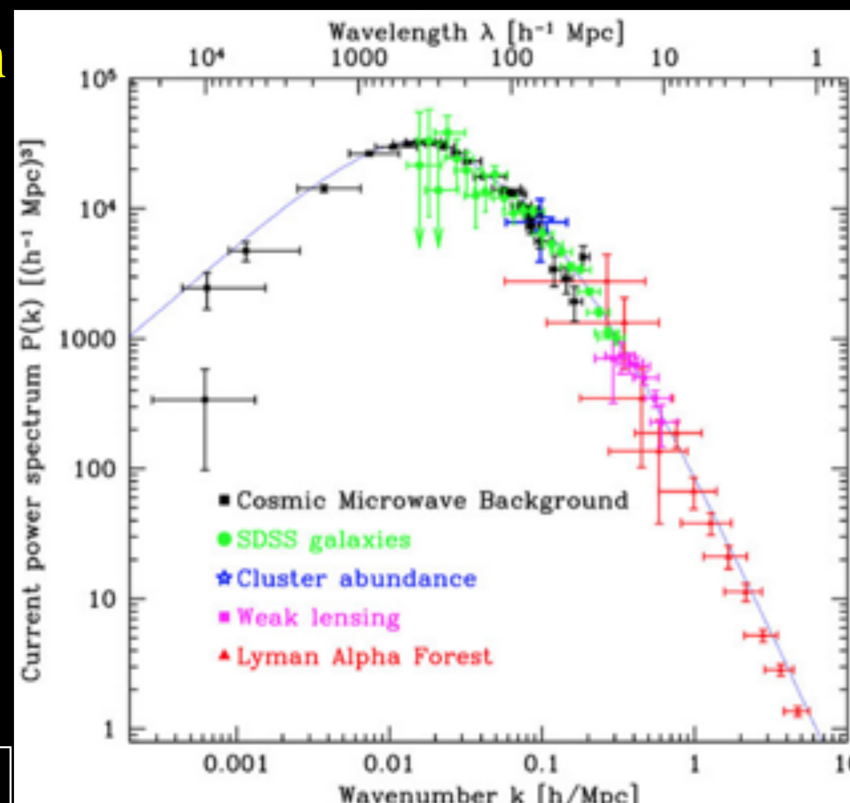


LCRS; Tucker+97

$$\xi_g(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

- Power law with
  - r_0: correlation length ($5h^{-1}$ Mpc)
  - gamma = 1.5-1.8
- Application to Power Spectrum

$$P(k) = 2\pi \int_0^\infty \mathrm{d}r\, r^2 \frac{\sin kr}{kr} \xi(r)$$



Tegmark+04

The Astrophysical Journal, 633:560–574, 2005 November 10

DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

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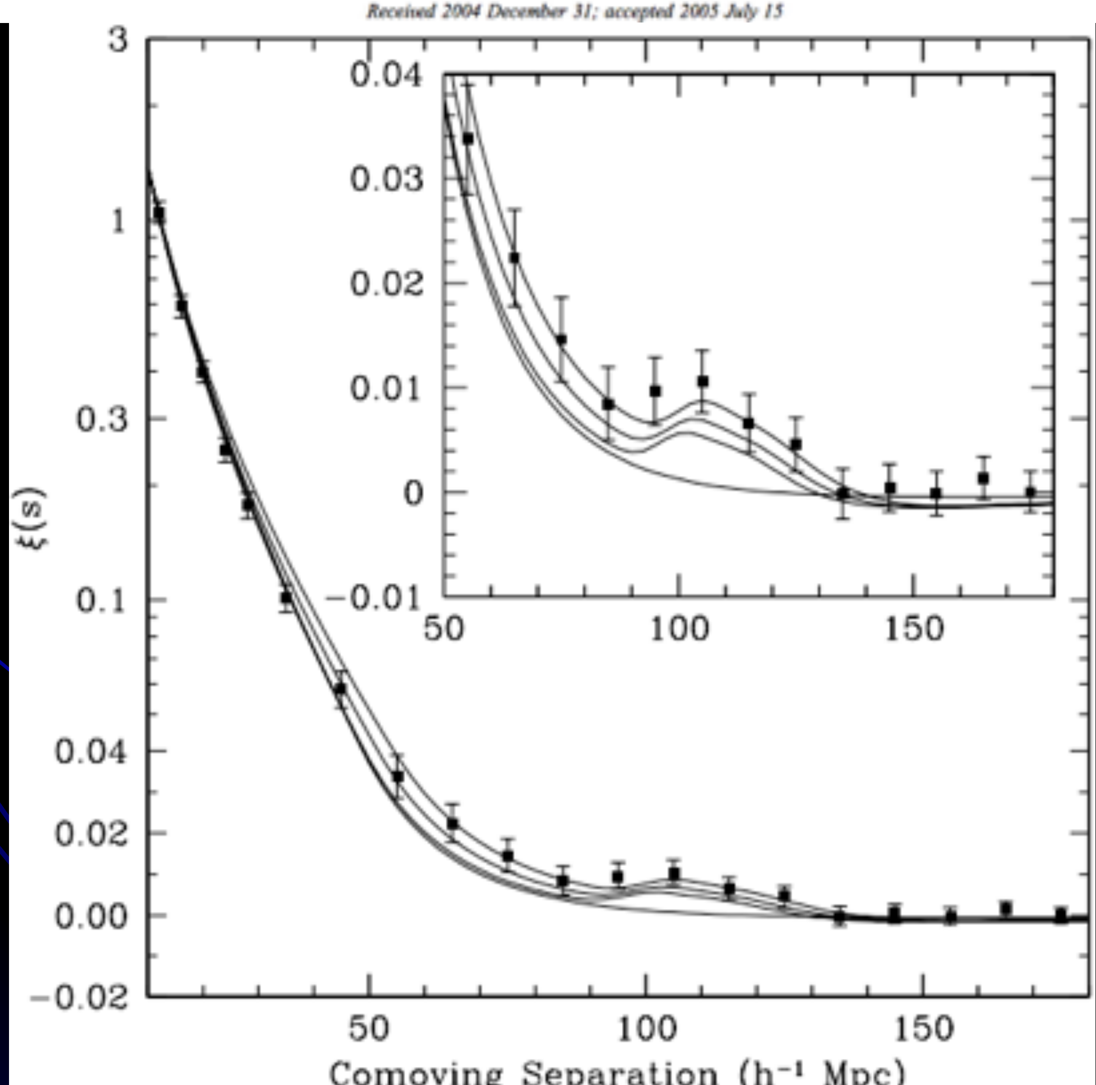
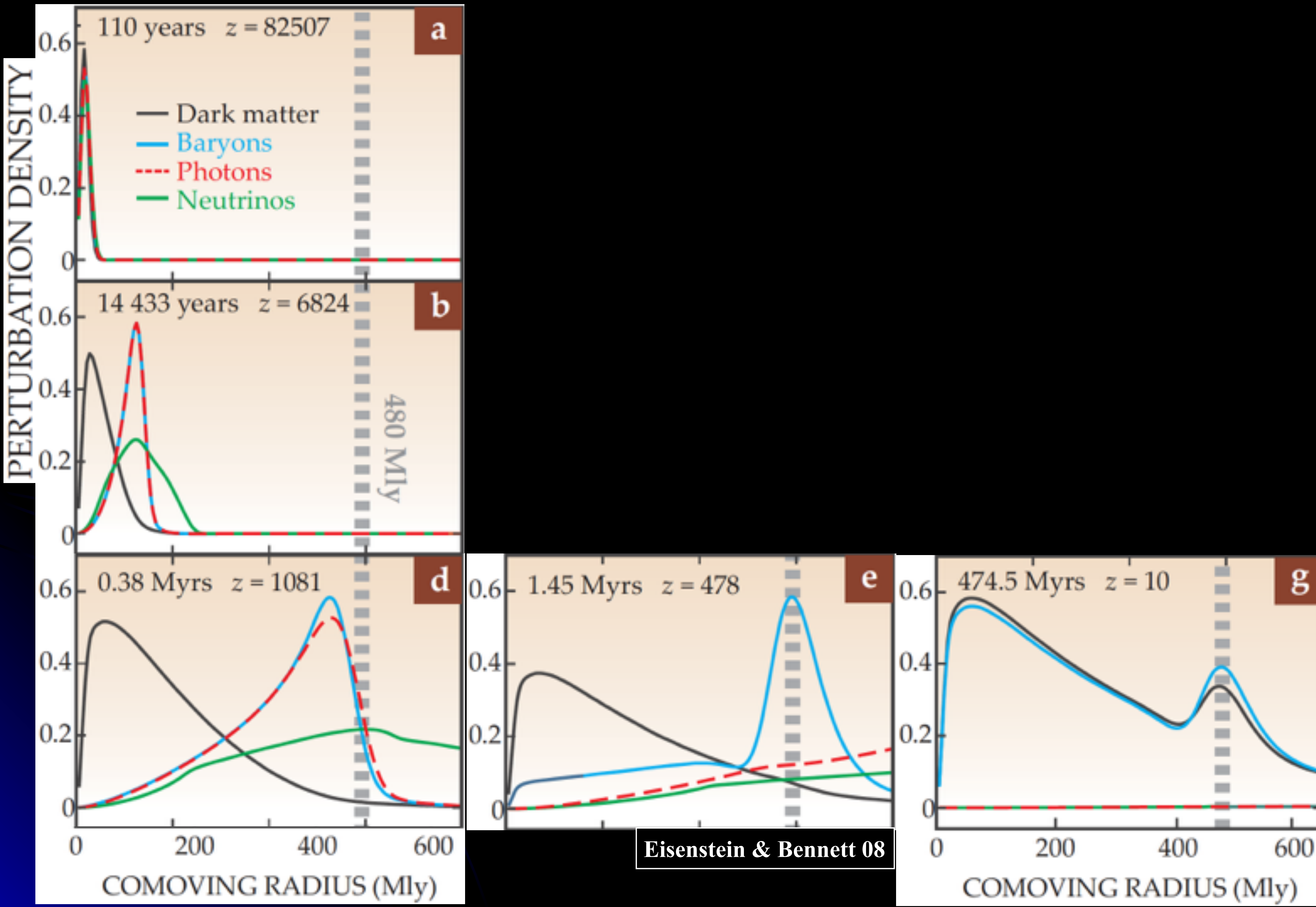
Received 2004 December 31; accepted 2005 July 15



See also Cole+05 from 2dFGRS

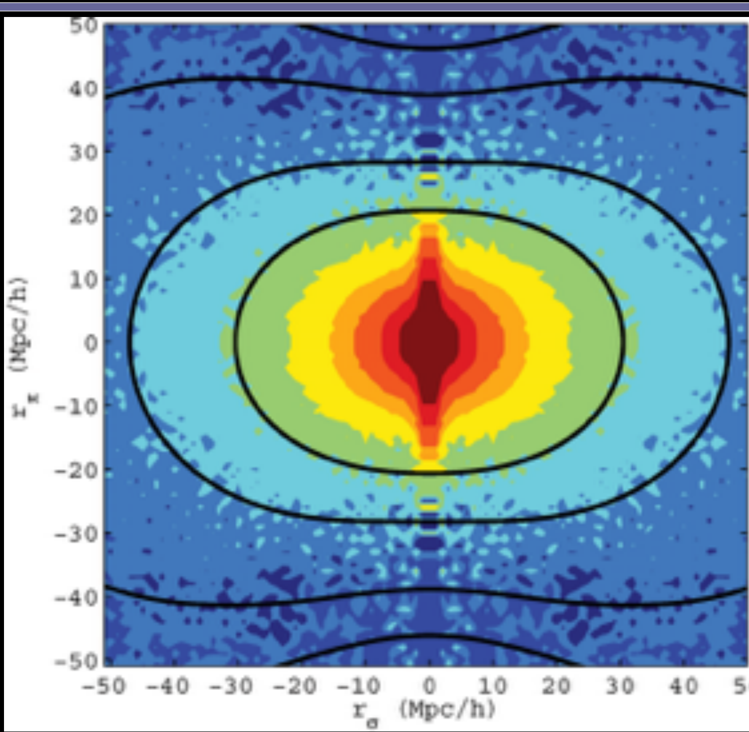
BAO

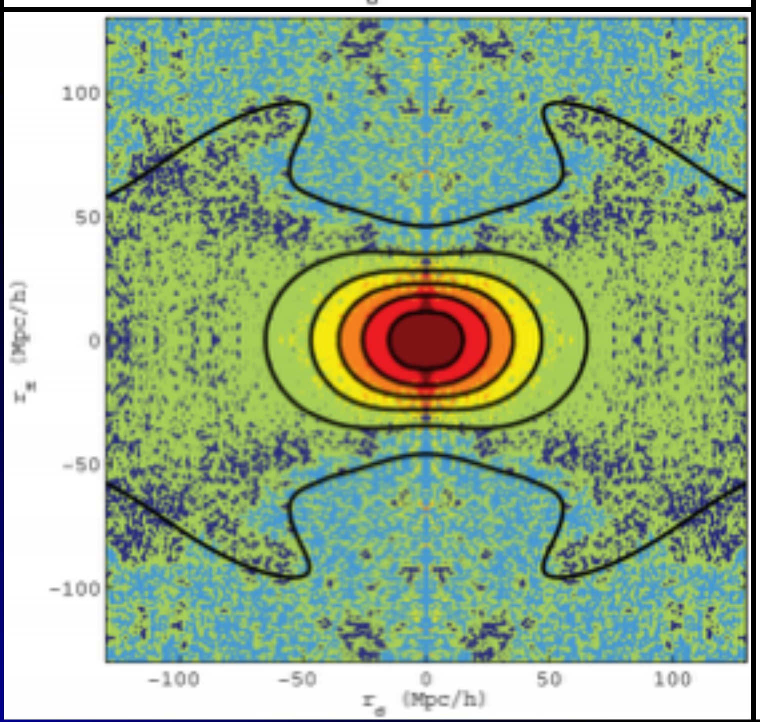


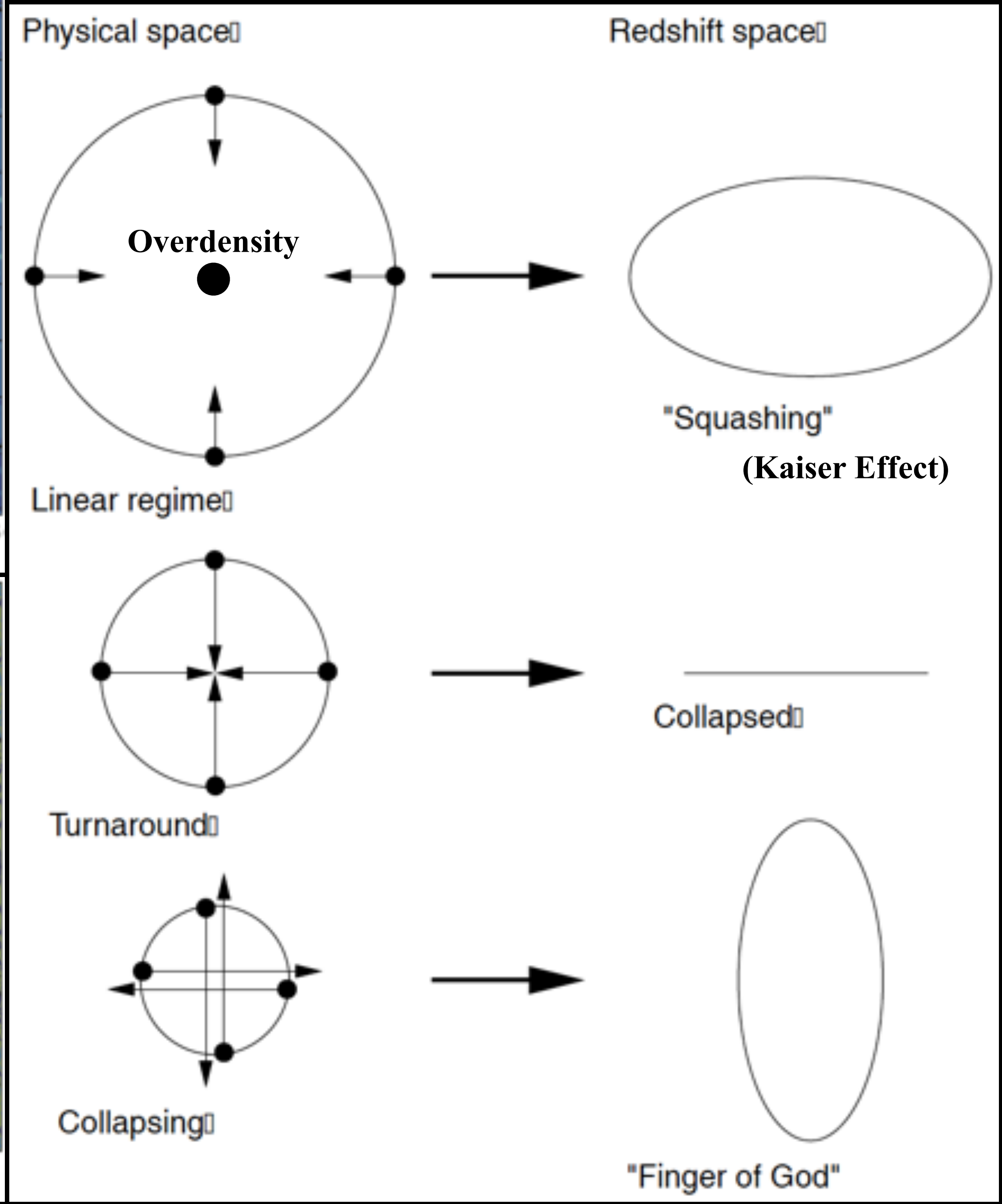
Eisenstein & Bennett 08

Two-point Correlation Function in 2D

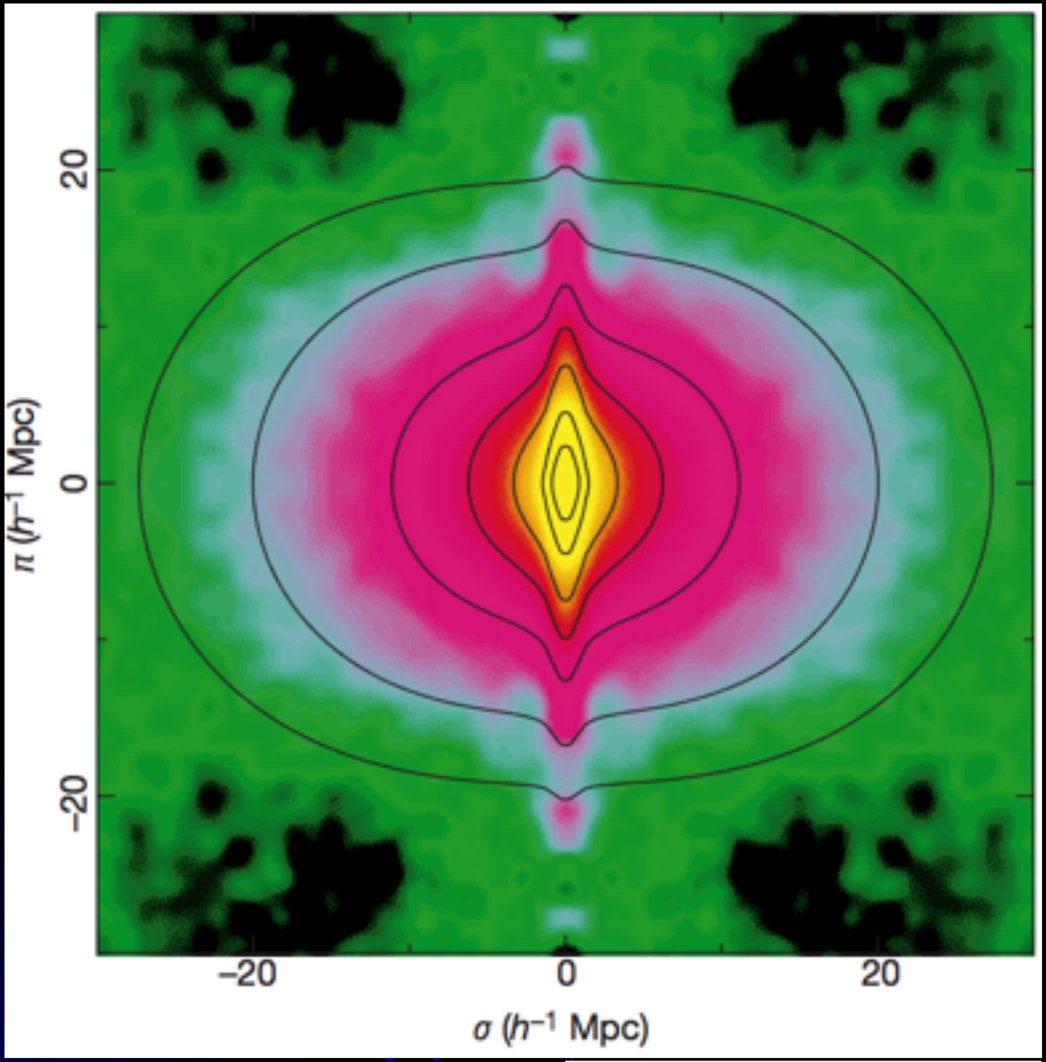
2D correlation function of DR9 CMASS galaxies (Reid+12)







Two-point Correlation Function in 2D

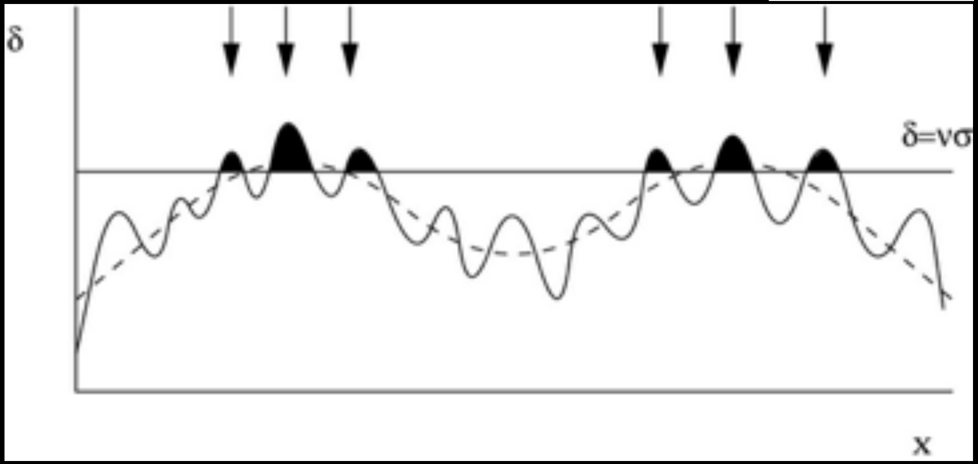


From 2dFGRS (Peacock 01)

- Flattening: gravitational infall → depending on Ω_m (Kaiser 87) : $\beta \equiv \Omega_m^{0.6}/b$

$$\left.\frac{\delta\rho}{\rho}\right|_{galaxies} = b \left.\frac{\delta\rho}{\rho}\right|_{mass}$$

Peacock 03



- Using 2dFGRS (Peacock +01), $\beta = 0.43 \pm 0.07 \rightarrow \Omega_m \sim 0.3$ {b from the ratio of galaxy and mass(CMB) power spectra}

Contents

- **Goal:**

Understand how to obtain scientific results from observational data (redshift survey)

- **Part 1:**
    - **Extragalactic Distance Indicators**
    - **Optical Spectroscopy**
    - **Redshift Space Distortion**
- **Part 2:**
    - **Voids**
    - **Photometric Redshifts (K-correction)**
    - **Cosmology with High-z Objects**
    - **Peculiar Velocity (Large-Scale Structure Near Local Group)**
- **Part 3:**
    - **Current/Future Redshift Surveys**