Lecture XIII: Galaxy Surveys, Part 1

Physics 8803

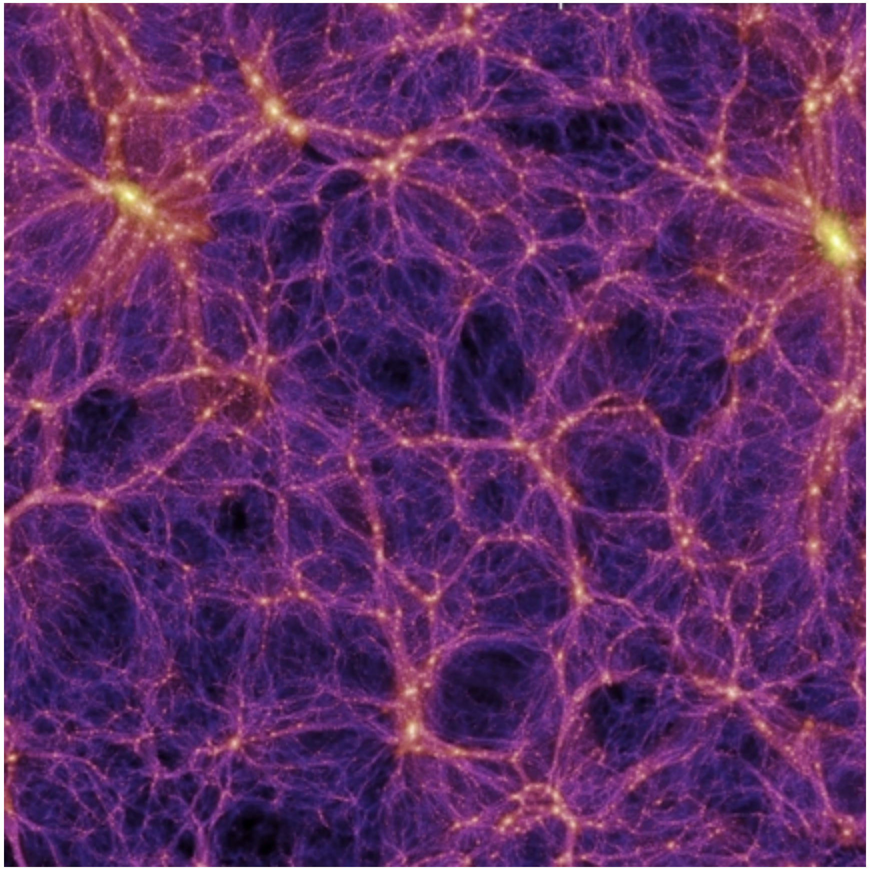
April 10, 2019

Contents

- Theory of galaxy clustering
- Observational aspects of optical surveys

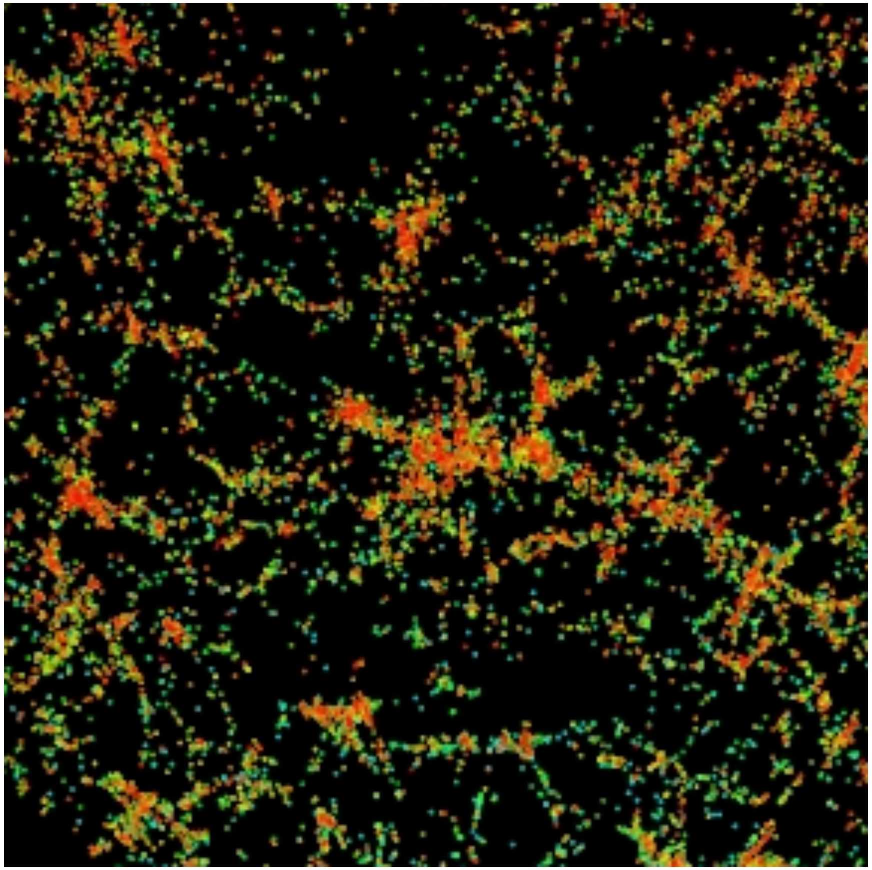
The “biasing” problem

Theory gives “clean” predictions for the matter distribution …



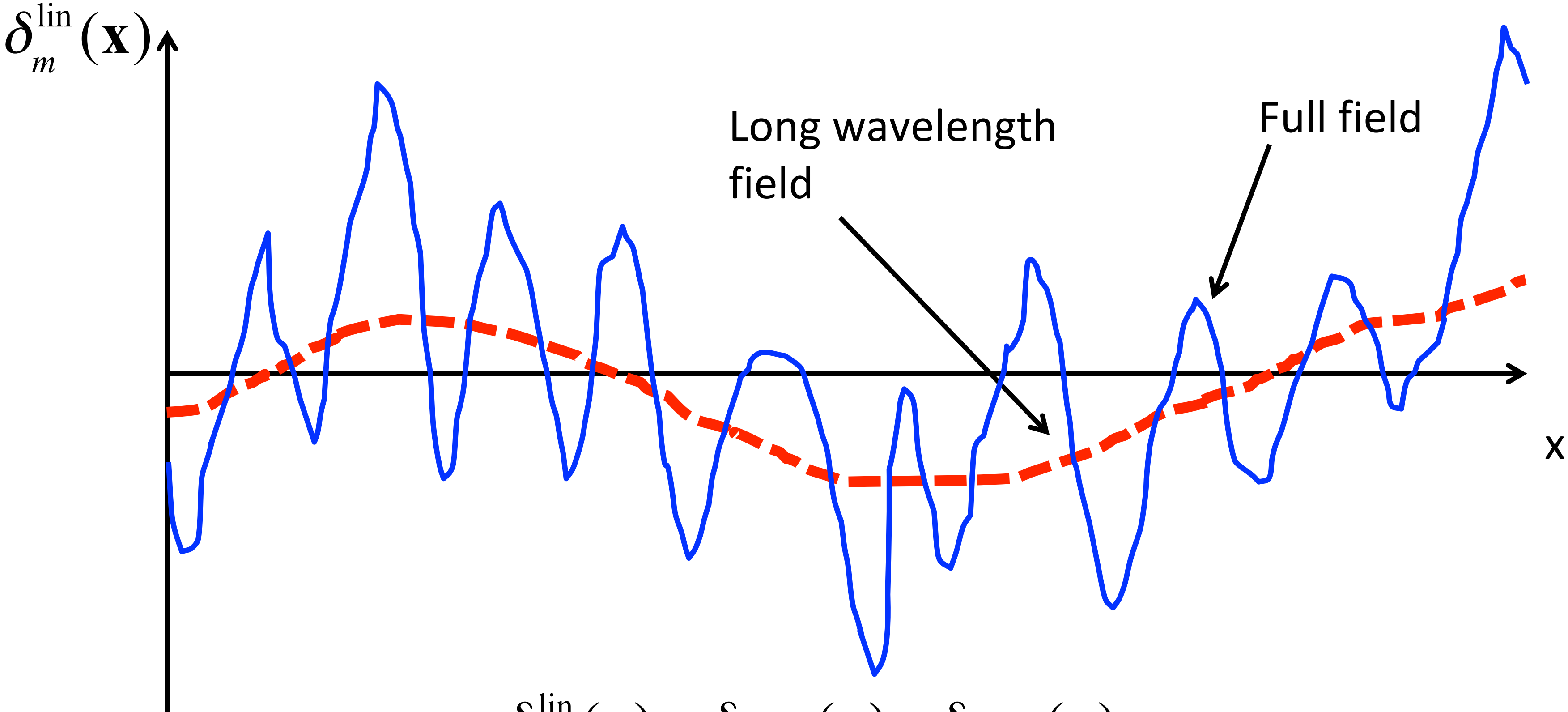
Simulation (Springel et al. 2005)

… **but we (mostly) see the galaxies: the most complicated regions of the Universe!**



Data (SDSS)

Biasing theory



$$\delta_m^{\mathrm{lin}}(\mathbf{x}) = \delta_{\mathrm{Long}}(\mathbf{x}) + \delta_{\mathrm{Short}}(\mathbf{x})$$

"Long wavelength" field = smoothed on a scale that is **linear**.
For Gaussian initial conditions, δ_{Long} and δ_{Short} are independent (different Fourier modes, zero covariance).

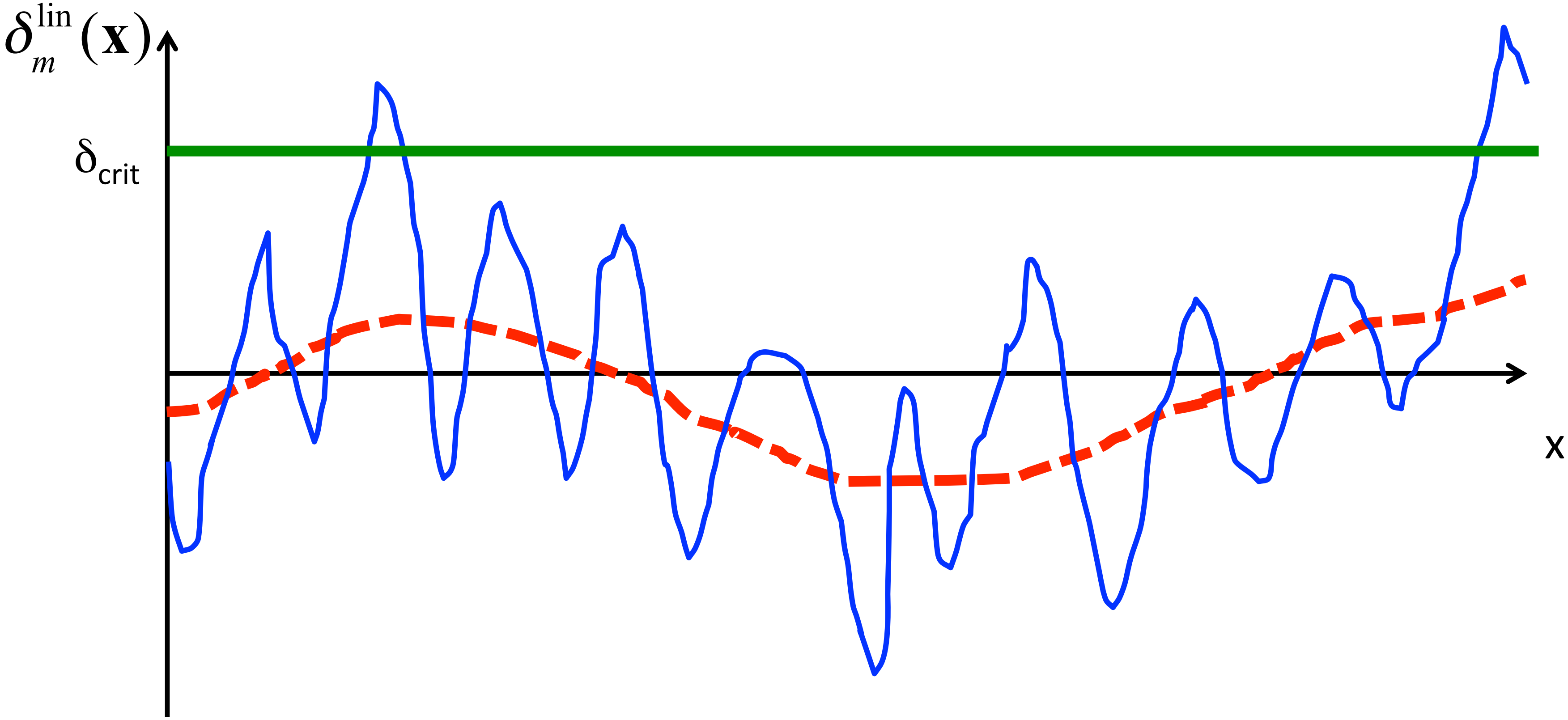
Biasing theory

- Imagine a region of space goes non-linear and collapses if the linear theory density perturbation exceeds some threshold δ_{crit} of order unity (1.69 in spherical collapse model).
- Then some probability for collapse at mass scale M:

$$P_{\mathrm{collapse}} \approx \int_{\delta_{\mathrm{crit}}}^{\infty} \frac{1}{\sqrt{2\pi}\ \sigma(M)} e^{-(\delta-\delta_{\mathrm{Long}})^2/2\sigma^2(M)}\ \mathrm{d}\delta$$

- Collapse probability for halos of mass M depends on:
  - Standard deviation at mass scale M, σ(M) (smaller for larger M)
  - Long-wavelength overdensity, δ_{Long}.
- See: Press & Schechter (1974), Bond et al. (1991), etc.

Biasing theory



Predictions

- Cosmic mean abundance of halos:

$$n(M) \sim \frac{\bar{\rho}_m}{M} P_{\text{collapse}}\Big|_{\delta_{\text{Long}}=0} \approx \frac{\bar{\rho}_m}{M} \int_{\delta_{\text{crit}}}^{\infty} \frac{1}{\sqrt{2\pi}\ \sigma(M)} e^{-\delta^2/2\sigma^2(M)}\ \mathrm{d}\delta$$

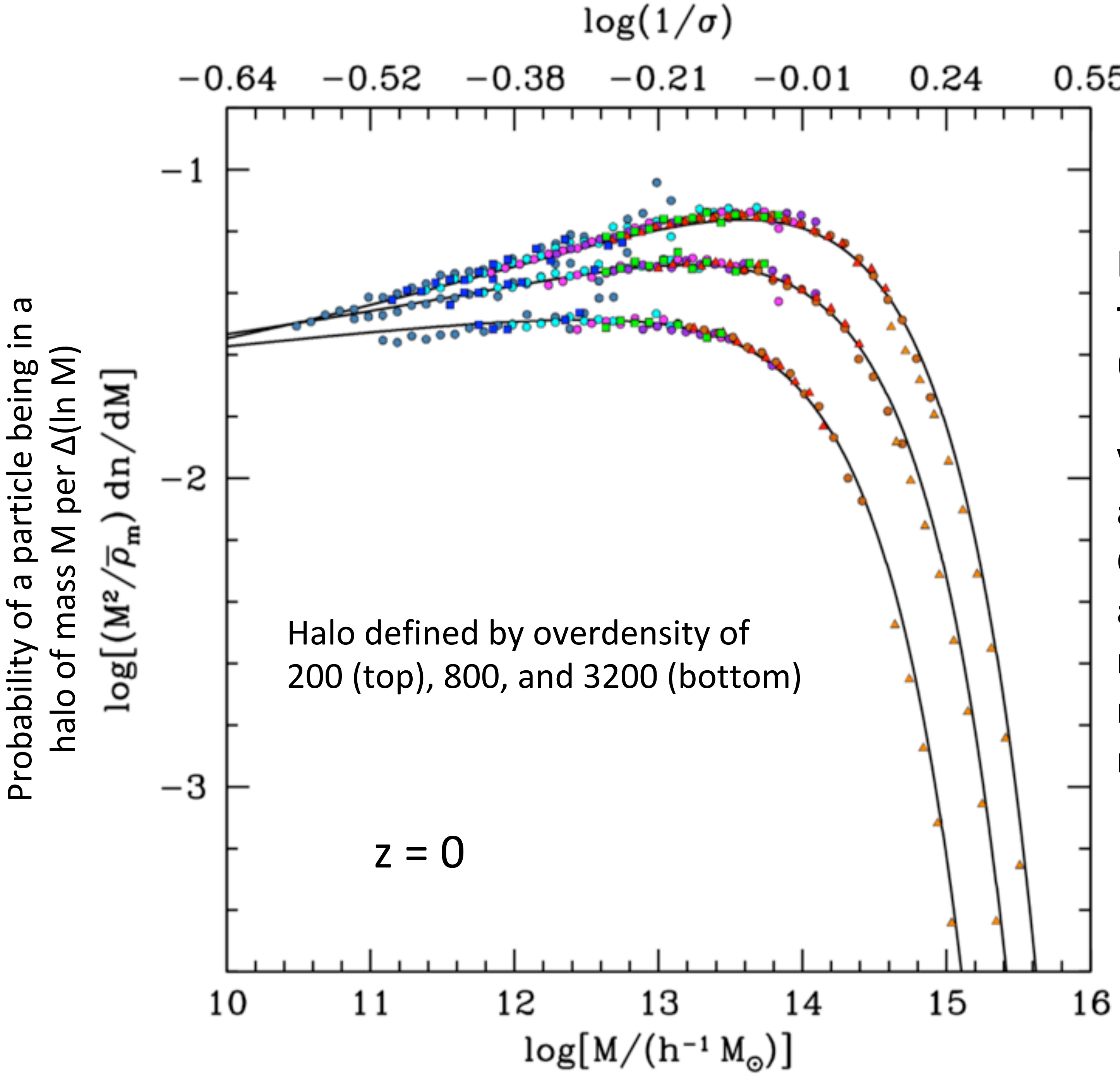
decreases as a function of M (tail of Gaussian, width σ(M)).

- Local overdensity of halos:

$$\delta_{\text{halo}} = b(M)\delta_m$$

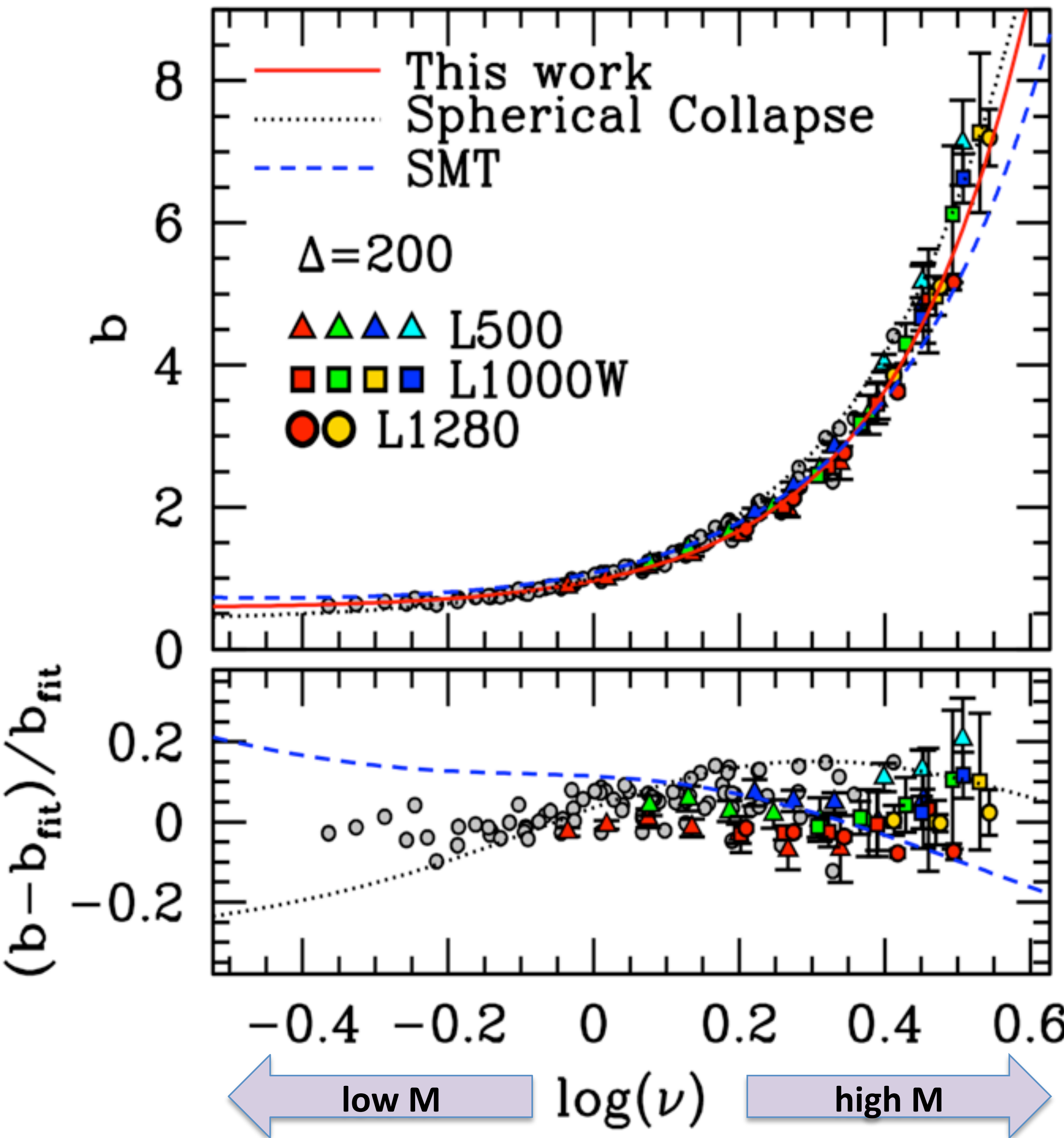
$$b(M) \sim 1 + \frac{d \ln P_{\text{collapse}}}{d\delta_m}\Bigg|_{\delta_{\text{Long}}=0} \approx \frac{d}{d\delta_{\text{Long}}} \ln \int_{\delta_{\text{crit}}}^{\infty} \frac{1}{\sqrt{2\pi}\ \sigma(M)} e^{-(\delta-\delta_{\text{Long}})^2/2\sigma^2(M)}\ \mathrm{d}\delta$$

- b(M) = bias factor, **increases** as a function of M
- Simple analytic formulae give guidance, but need simulations for accurate results.



Halo mass function from simulations (Tinker et al. 2008)

Very massive halos are rare (small σ). Can use their abundance as a measure of $\sigma(M)$ <u>if</u> mass can be measured.



Bias of dark matter halos in N-body simulations

Tinker et al. (2009)

$$\nu = \frac{1.69}{\sigma(M)}$$

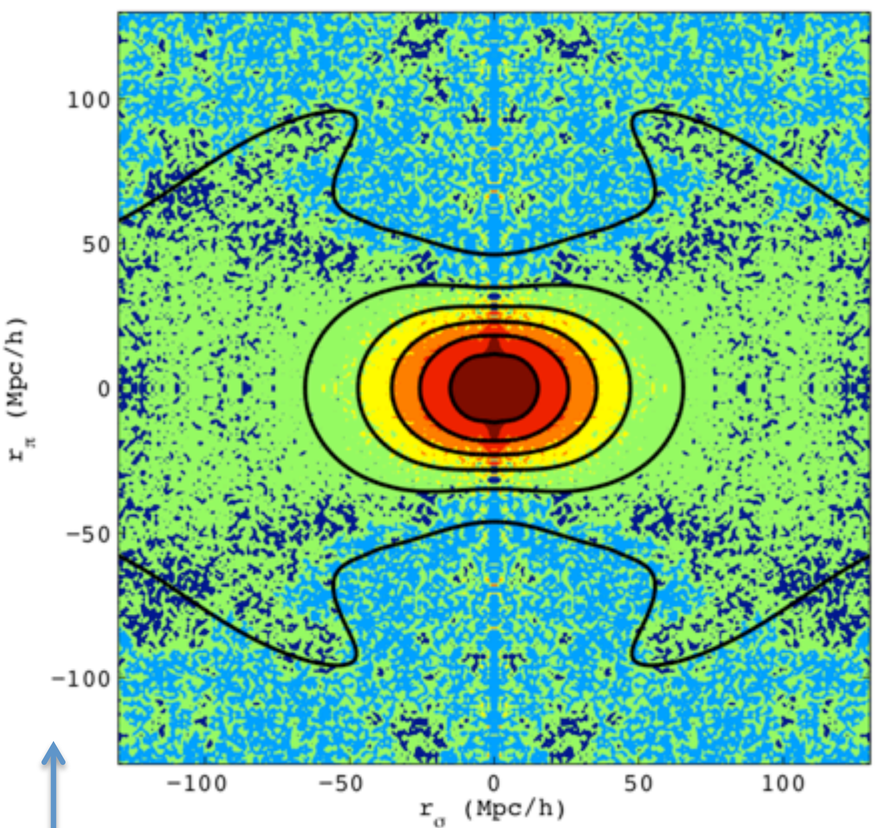
Most massive halos are most biased!

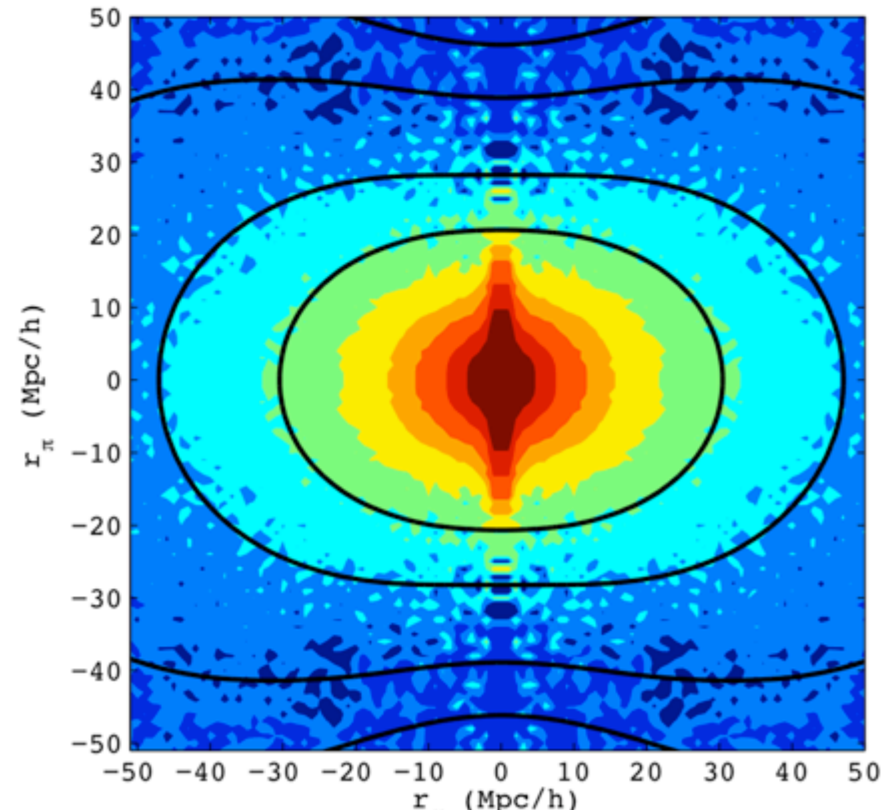
Redshift space distortions

Galaxy correlation function is **anisotropic** in observed space, since the "observed" position of a galaxy depends on its velocity.

$$\mathbf{r}_{\mathrm{obs}} = \mathbf{r}_{\mathrm{true}} + \frac{v_3}{aH}\hat{\mathbf{e}}_3$$

(distant observer approximation)





$\hat{\mathbf{e}}_3$

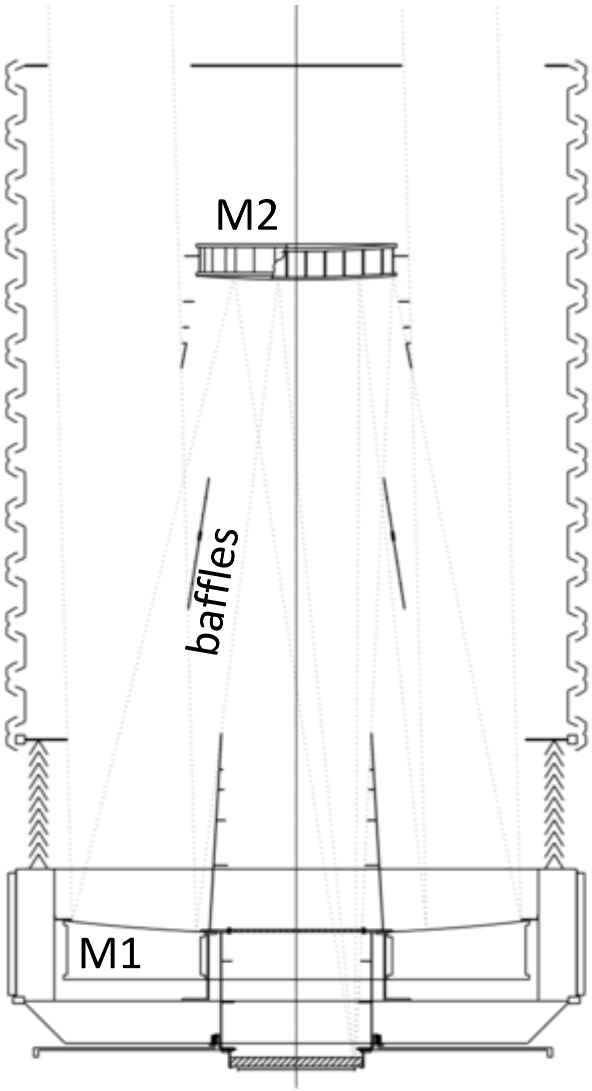
Reid et al. 2012

Observational Aspects

- **Imaging surveys:**
  - Can go fainter/get more objects in a given amount of telescope time
  - Colors only, not “real” redshifts (but photo-z’s)
  - But morphological information (e.g., shapes for weak lensing)

- **Spectroscopic surveys:**
  - Most precise redshifts
  - Spectral diagnostics of galaxies (line widths, ratios of intensities …)
  - But very expensive and sample sizes are smaller
  - (Usually) “target” objects identified in imaging surveys

Imaging Surveys



Use optical telescope − may be:

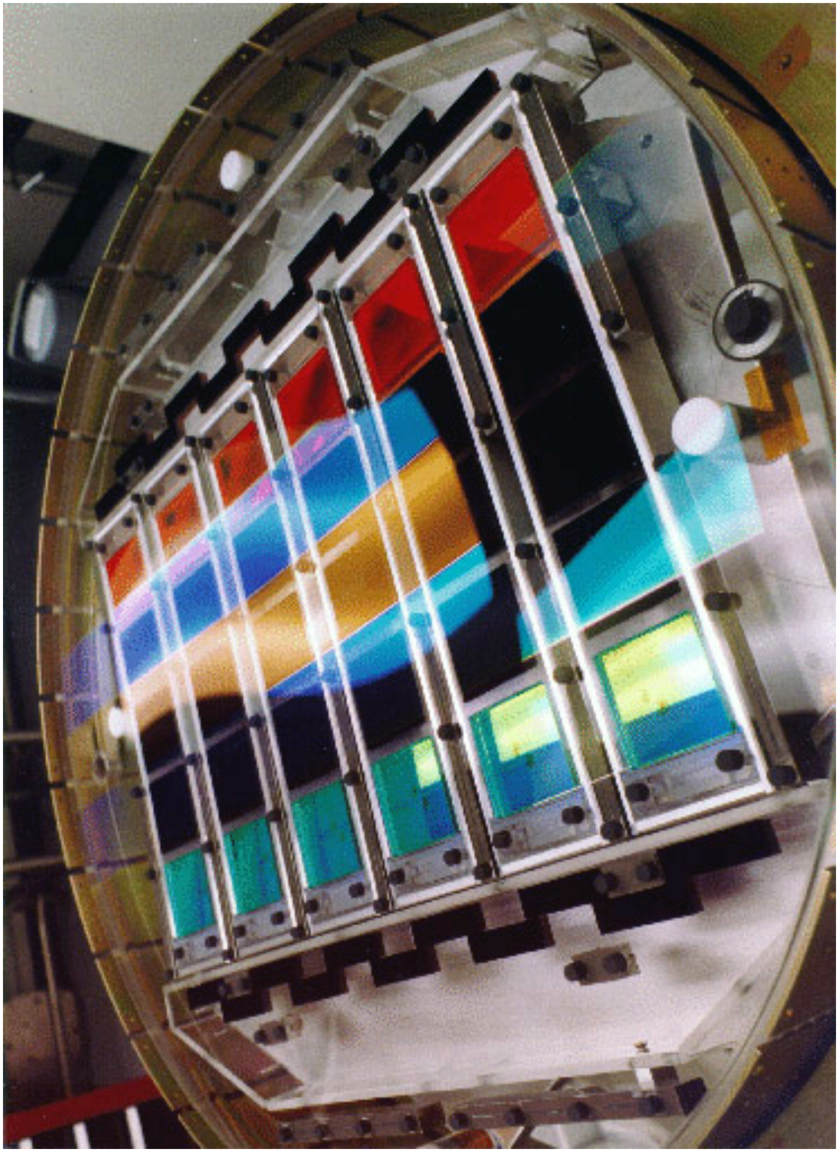
- 1 mirror + multi-lens corrector (DECam, HSC)
- 2 mirror + smaller corrector (SDSS)
- 3 mirror, no refractive elements with substantial power (LSST, WFIRST, Euclid Visible channel)

Choice often based on desired pixel scale and engineering considerations.

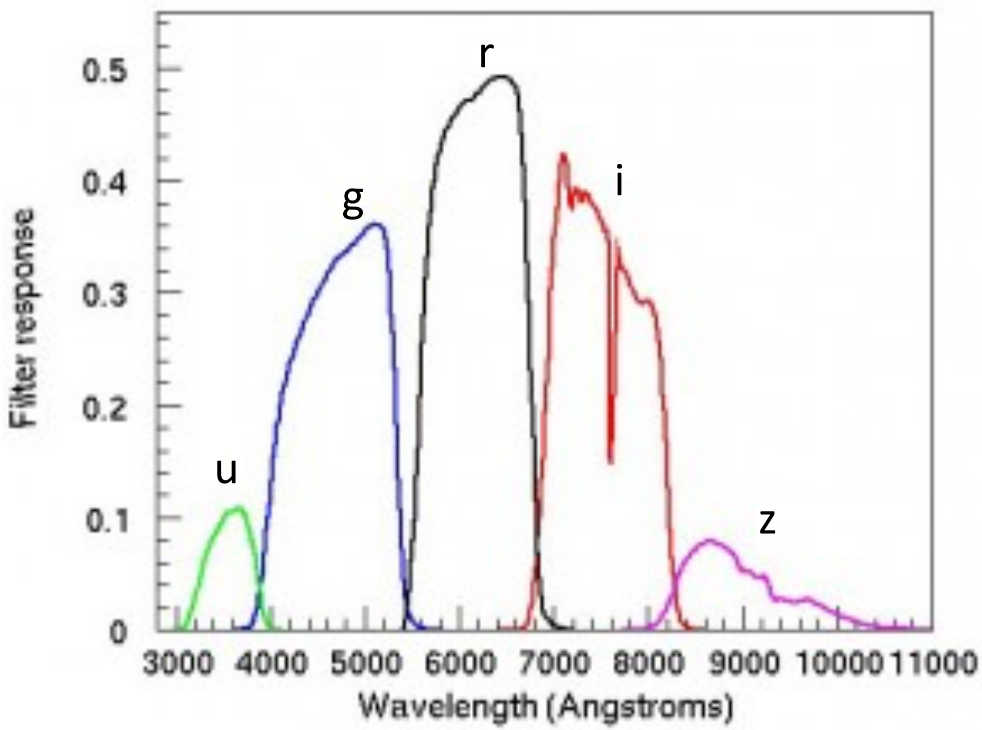
Detectors in focal plane − usually CCDs in visible (HgCdTe hybrid detectors in NIR)

SDSS telescope (Gunn et al. 2006)

Cameras



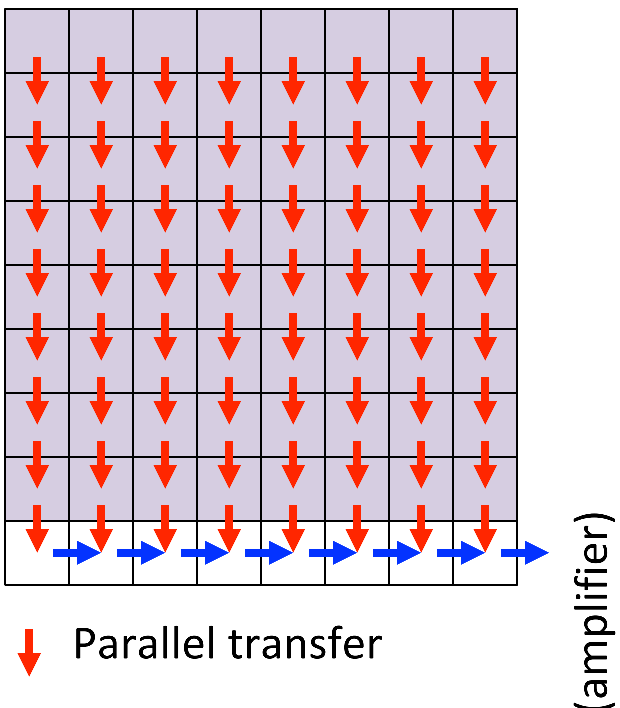
Multi-layer interference filters may be fixed (e.g., SDSS at left) or on a mechanical filter changer or wheel (most surveys)



SDSS Mosaic Camera

Silicon CCDs

Incoming photon, hν>1.1 eV
→ electron-hole pair
→ Electron (usually) collected in "pixel" (potential minimum)
→ Transferred to amplifier

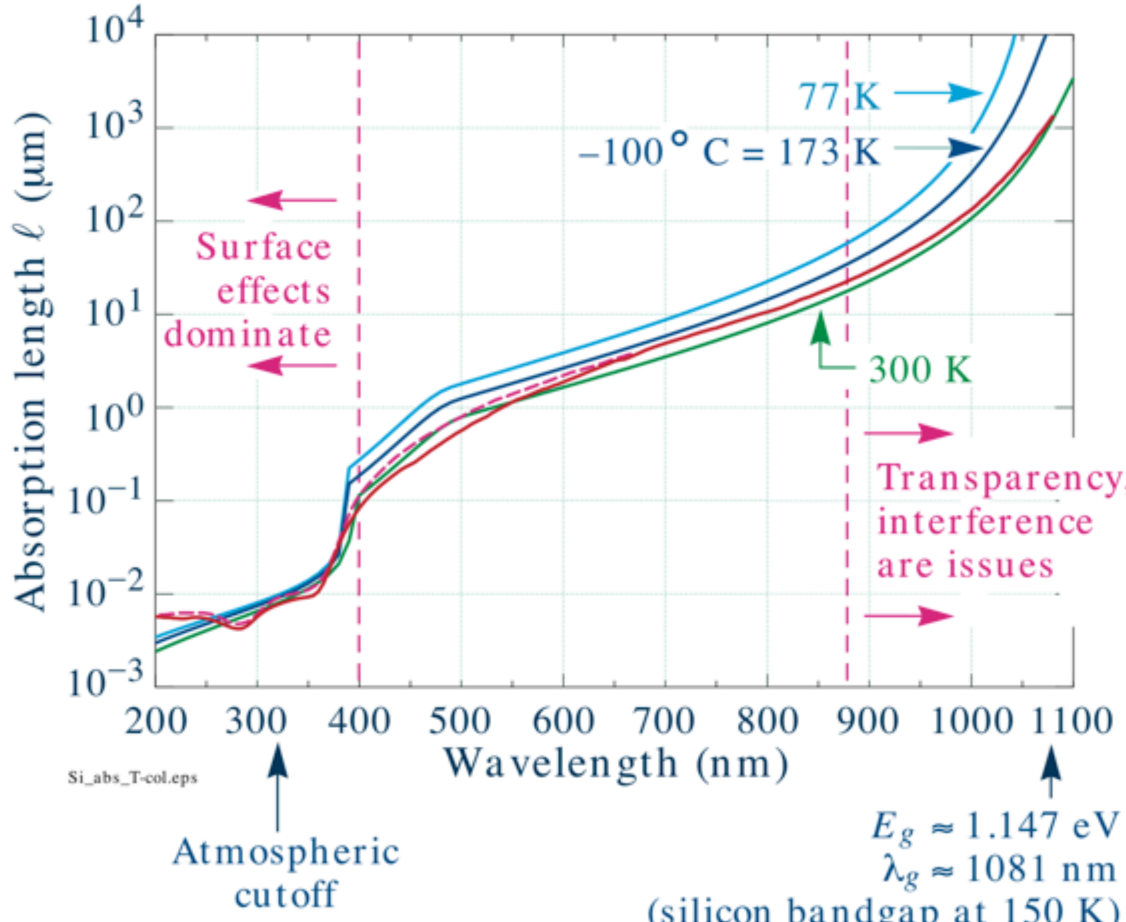


Parallel transfer

Serial transfer

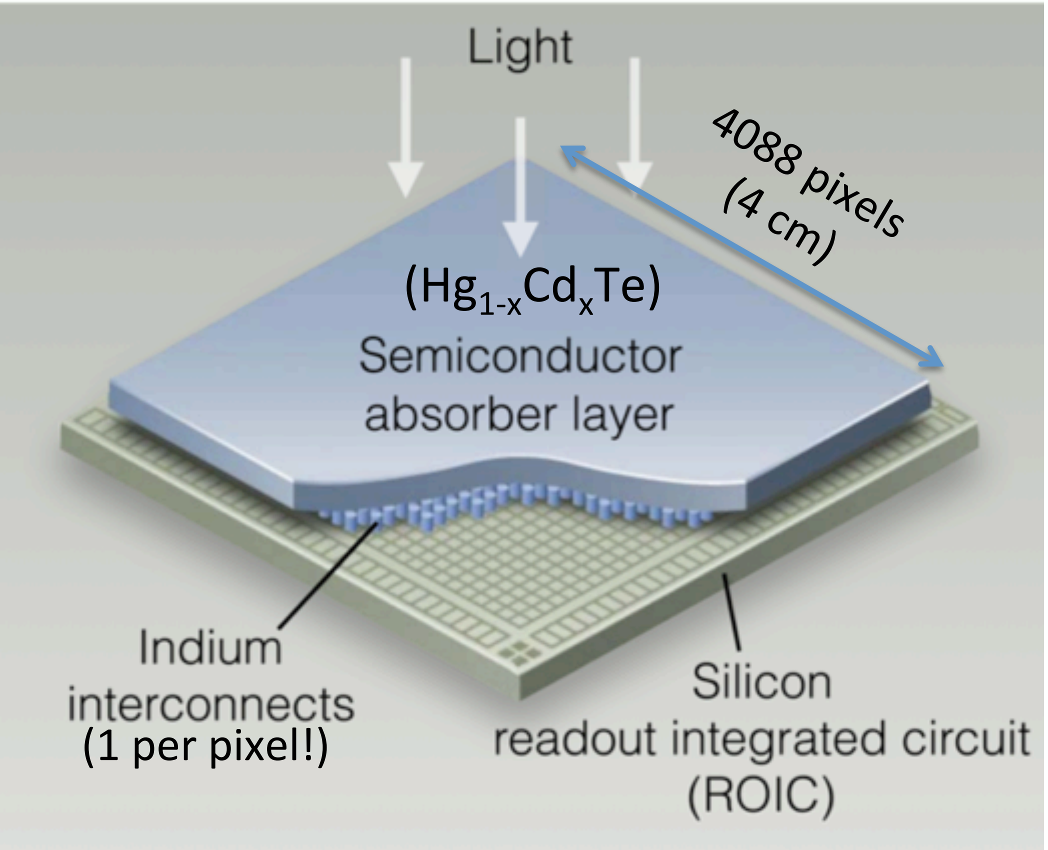
Pixel

Historically sensitive to λ ~ 800 nm, now ~1000 nm ("thick" CCDs)



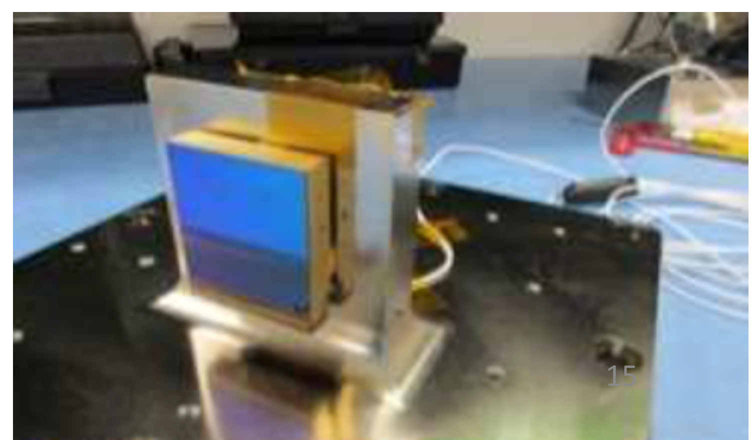
Groom et al. (1999)

Infrared detector arrays



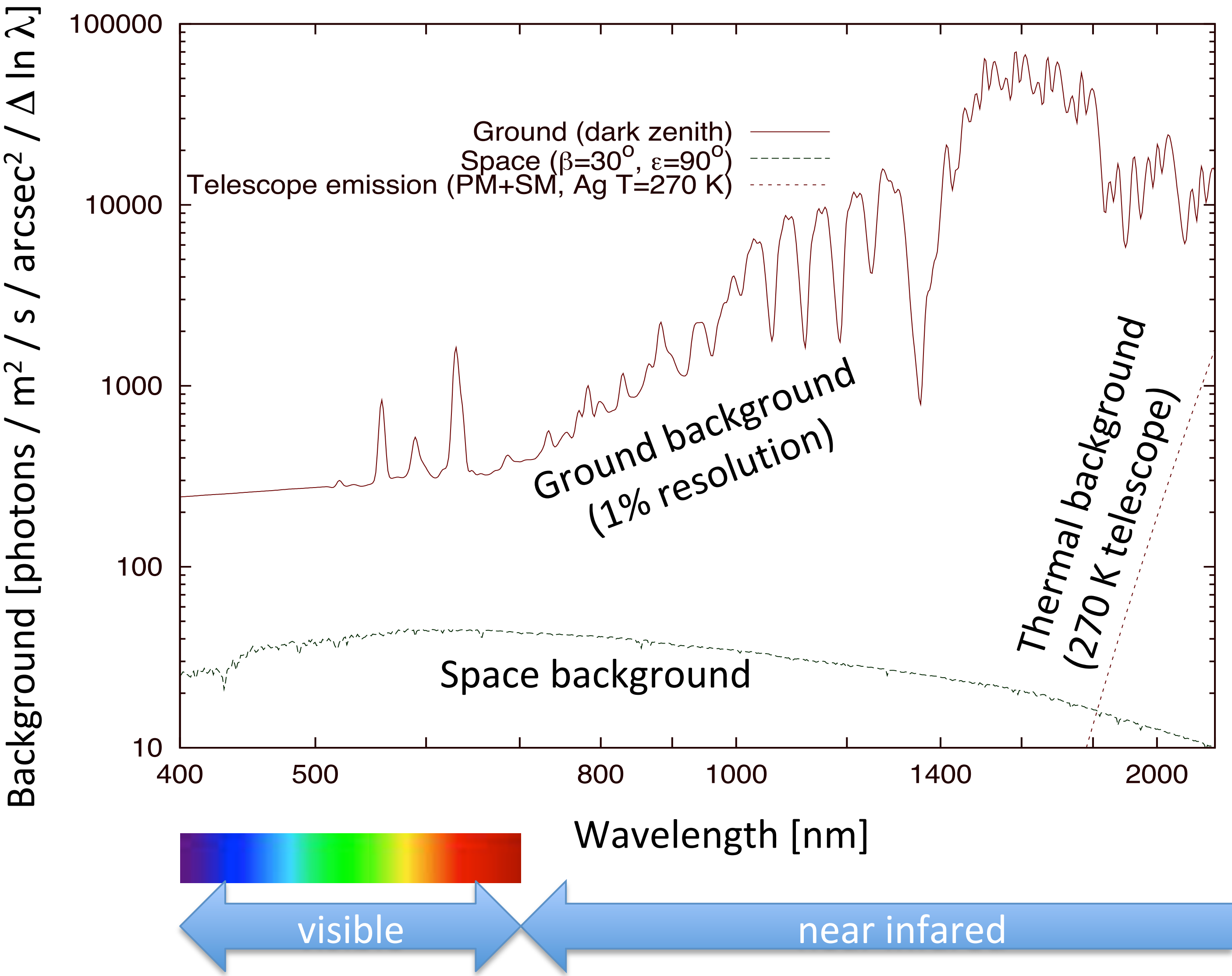
- Silicon is not a good light sensing material at wavelengths > 1.06 μm
- Usually use a photodiode array in a narrow-gap semiconductor, and connect to a silicon readout circuit
- Material of choice for NIR astronomy is mercury cadmium telluride ($Hg_{1-x}Cd_xTe$)

(Modified figure by Bernie Rauscher, based on a similar figure by Jim Beletic)



Detector array on vibration fixture
(WFIRST IR Technology Milestone Report #5)

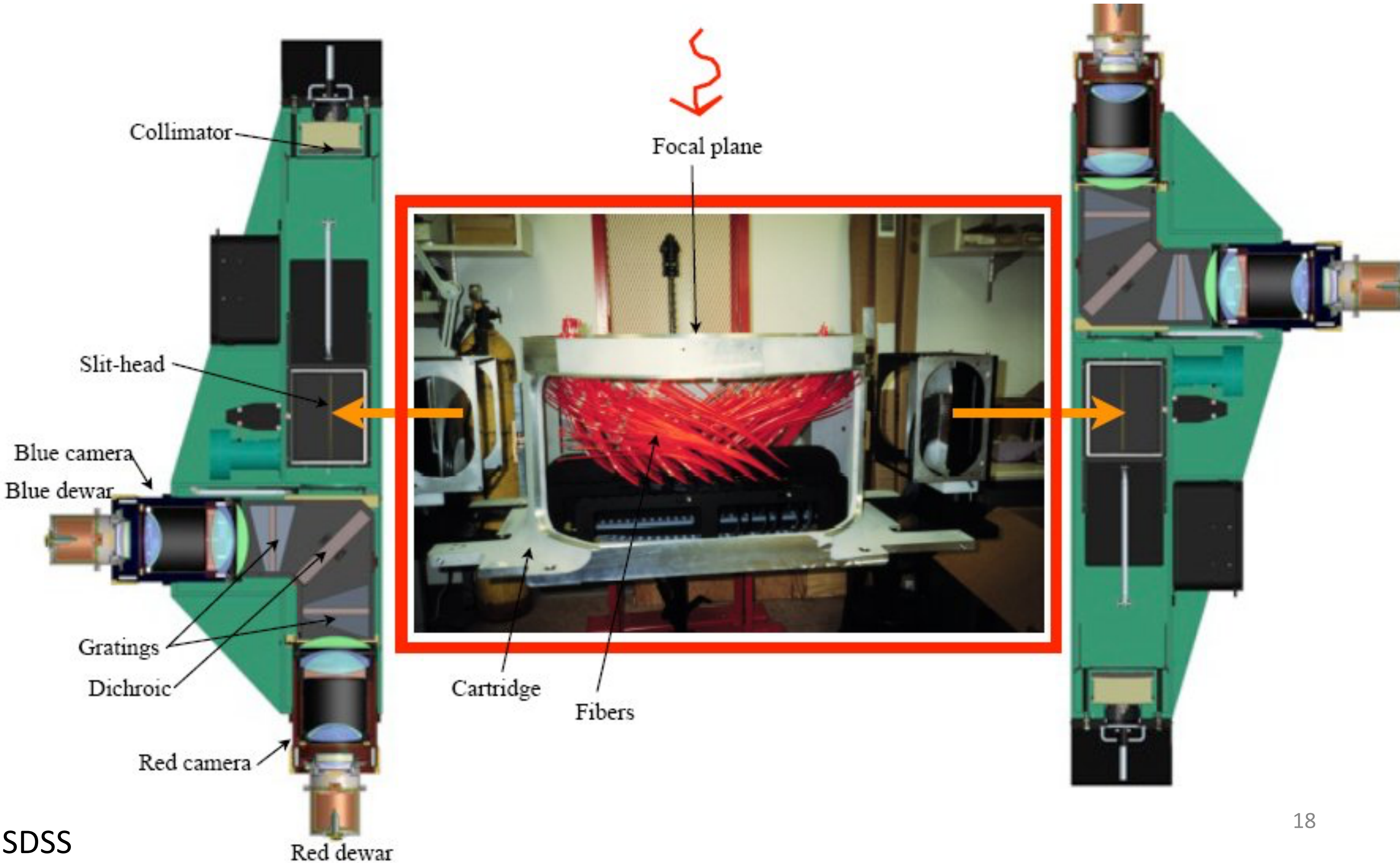
Working in the Near Infrared



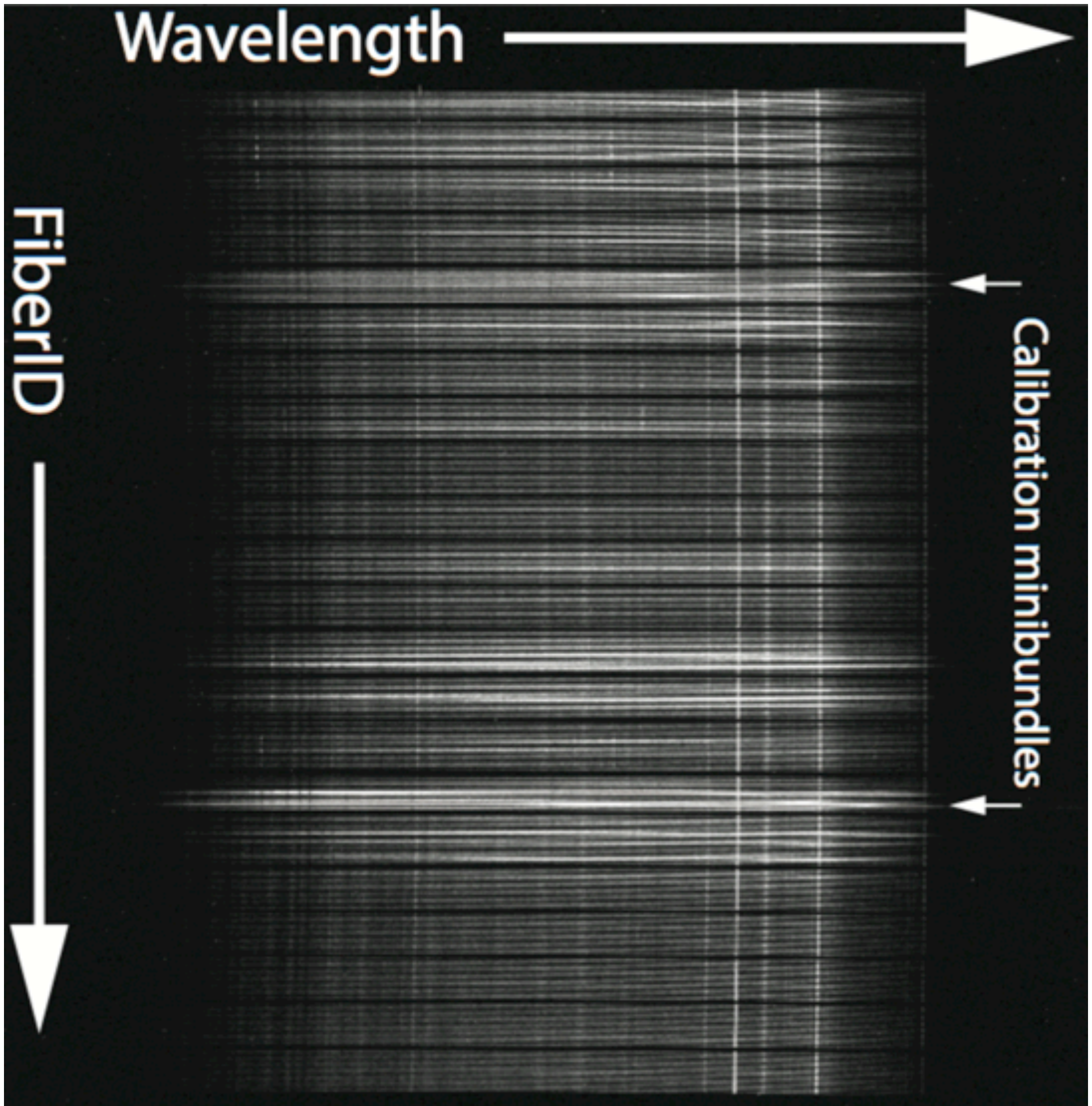
Fiber Spectrographs

- Used for most large ground-based surveys: SDSS, BOSS/eBOSS, DESI, PFS, 4MOST, …
- “Targets” are identified from a prior imaging survey
- Every instrument is unique, but generally have:
  - **Focal plane** – feed light into fibers, placed at positions of targets (old: plug plate with holes; in the future, with robotic positioners)
  - **Fiber run** to spectrograph entrance slit – here fibers are formatted in a vertical column
  - **Collimator** to put image of fibers at ∞ (light from 1 fiber is all parallel)
  - **Diffraction gratings** to spread light horizontally
  - (optional) **Dichroic(s)** to split light into wavelength bands (e.g., blue vs. red channels) to go into optimized cameras
  - **Camera** (set to image source at ∞)
  - **Detectors** (in camera focal plane)

BOSS Spectrograph

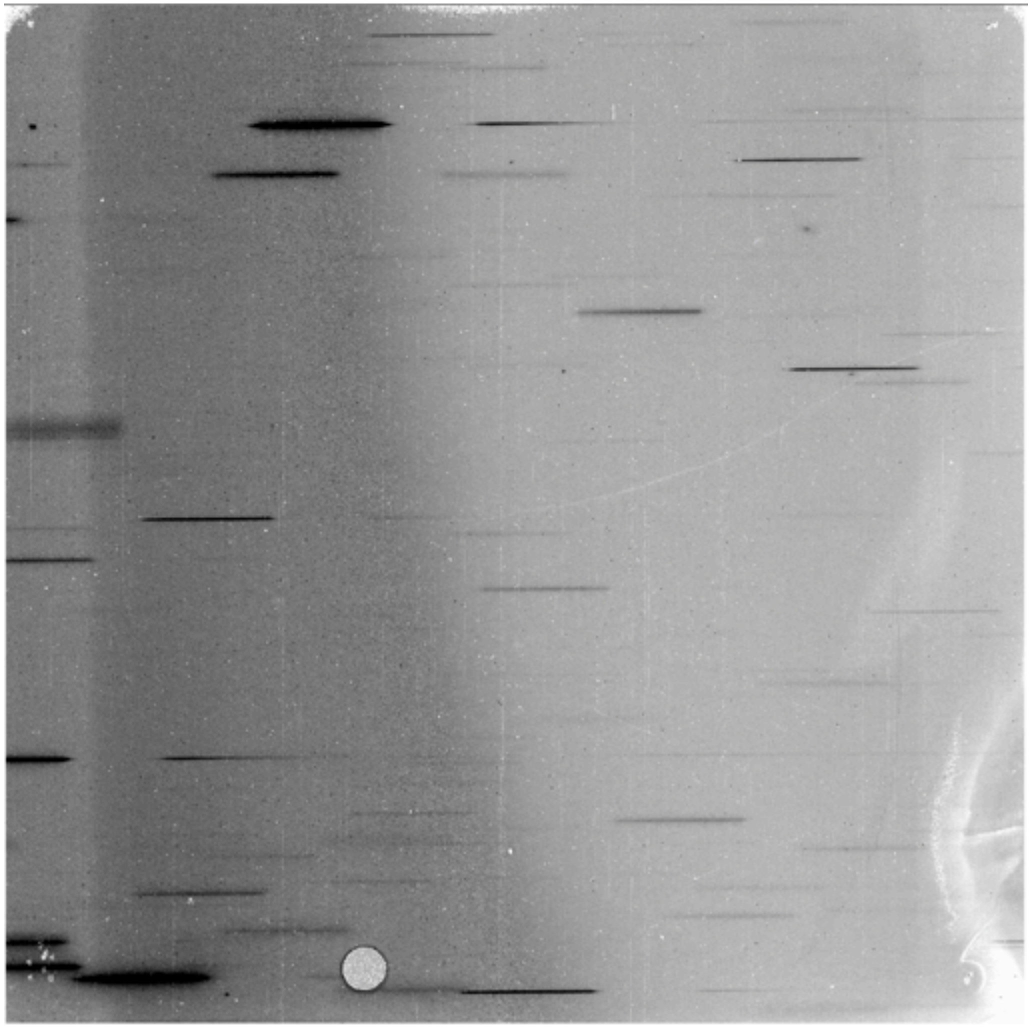


“2D” Spectrograph Data



… example from MaNGA survey (Law et al. 2016)

Alternative − Slitless Spectroscopy



Example of grism image from Hubble (STScI)

- Put a grating in front of the detector instead of (only) a filter − no fiber system, collimator, camera optics
- Disadvantages − much more sensitive to sky background; “collisions” of spectra
- But mechanically **so** simple − usually used in space where sky background is already low and we don’t want moving parts.
- Planned for NIR spectroscopy with Euclid, WFIRST