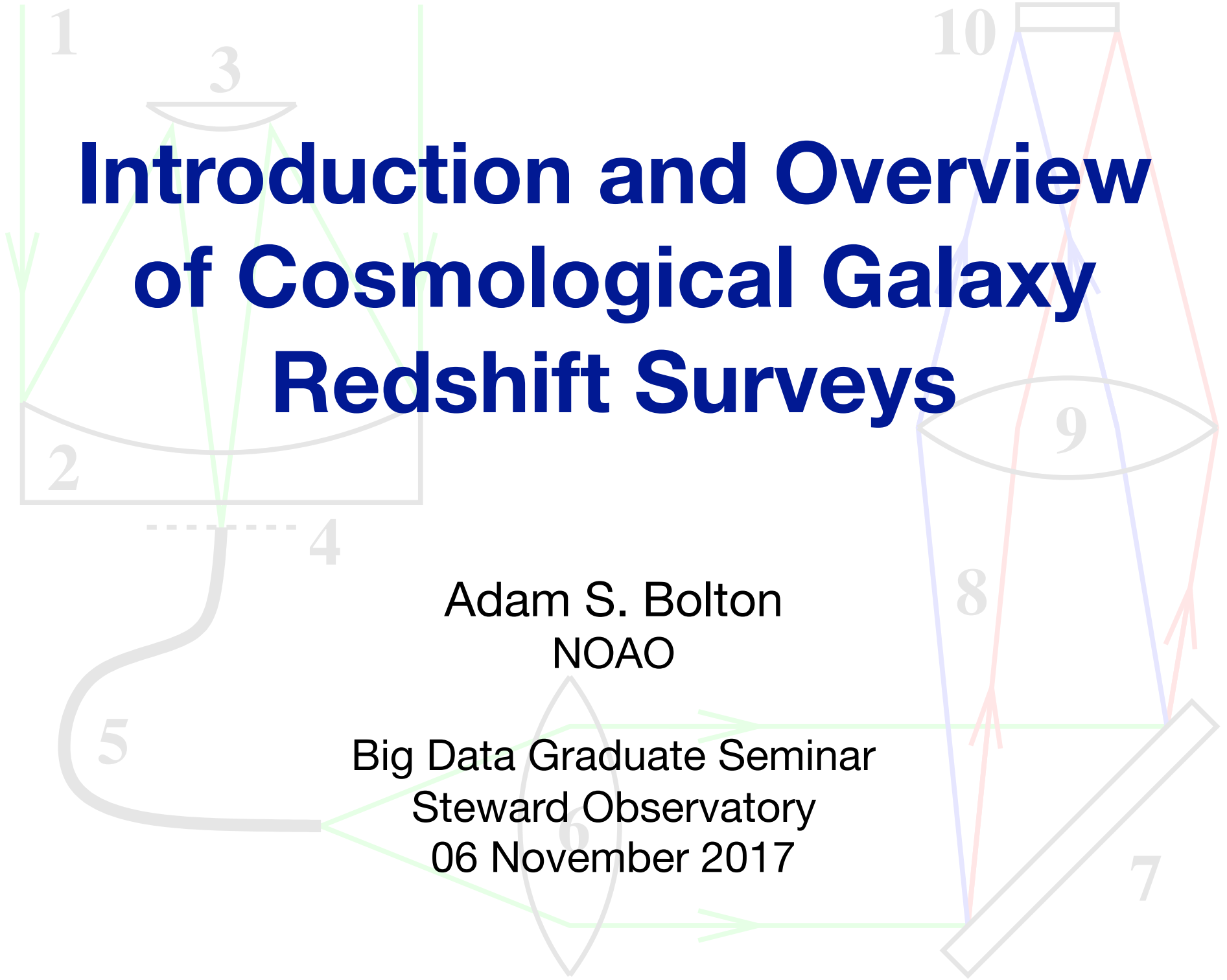

Introduction and Overview of Cosmological Galaxy Redshift Surveys

Adam S. Bolton
NOAO

Big Data Graduate Seminar
Steward Observatory
06 November 2017

Outline

- Introduction
- Galaxies and redshift surveys
- SDSS-III / BOSS
- Spectroscopic Data Pipelining
- *Extra:* Observational cosmology and dark energy
- *Extra:* Baryon acoustic oscillations (BAO)

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Note on contents of this presentation

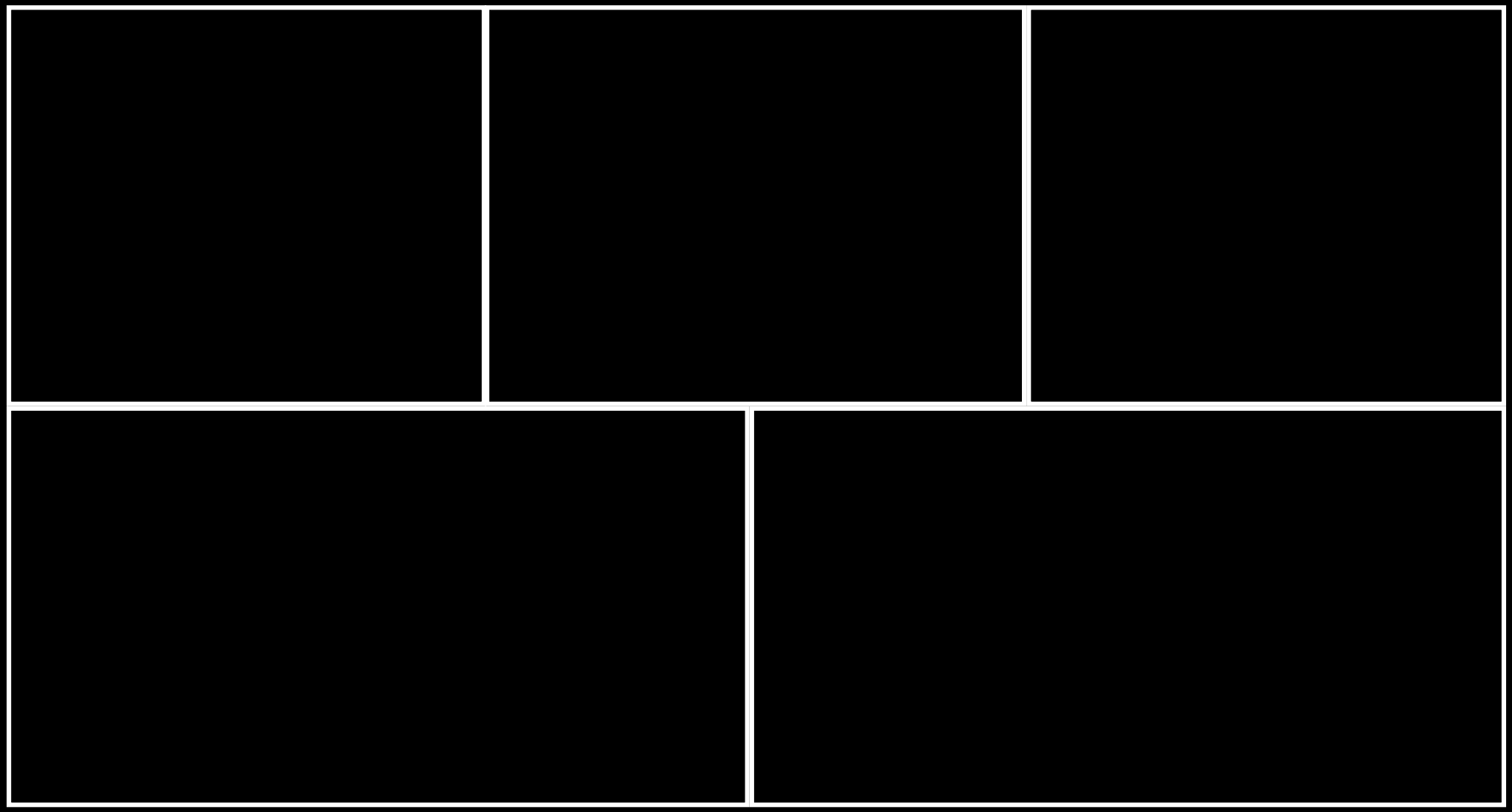
This presentation was assembled primarily from materials that are 3-4 years old.

The concepts are all still current and relevant.

Some published results have since been superseded.

Some technical development has progressed further.

Cartoon History of the Universe in 5 Panels



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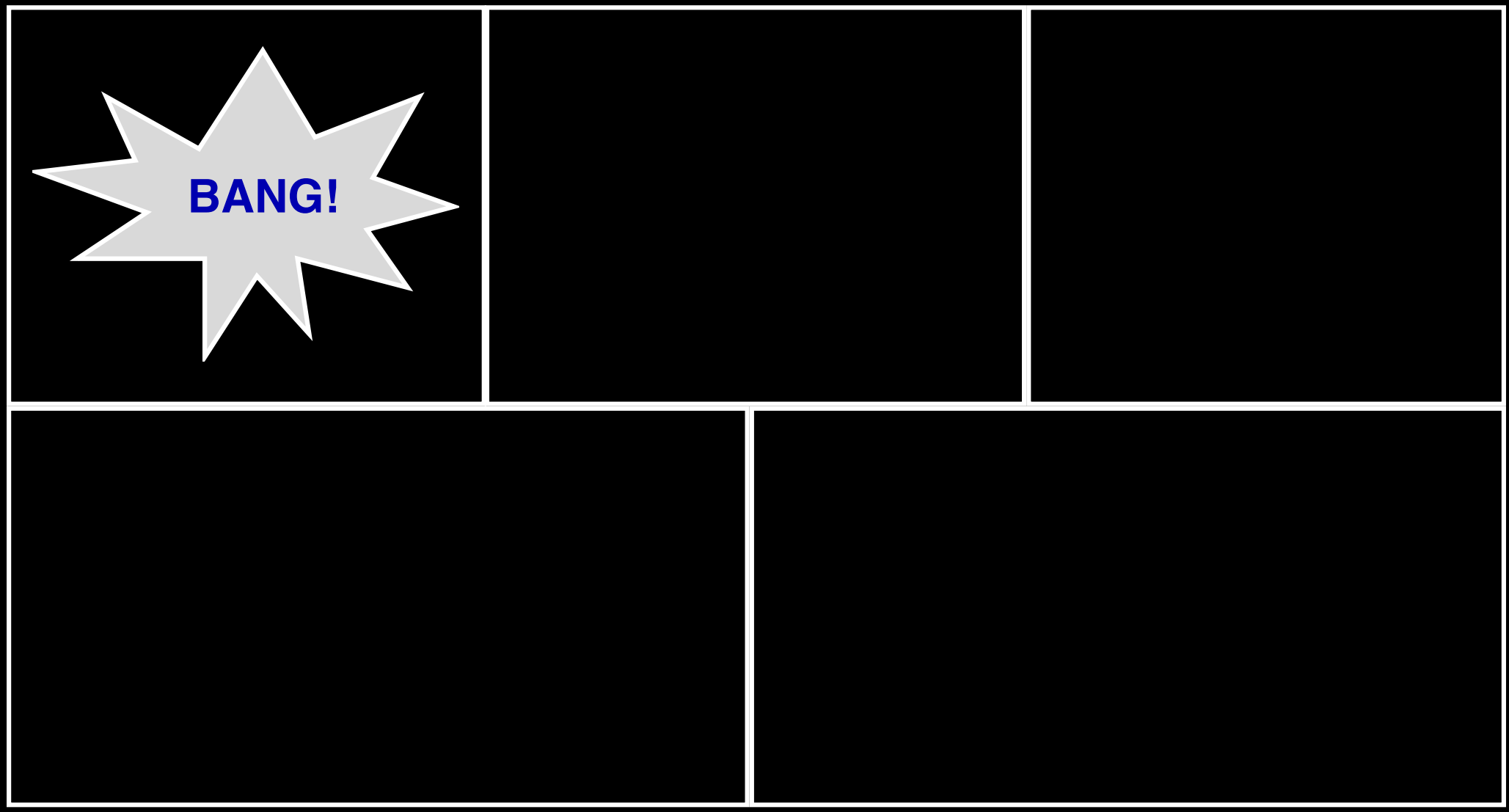

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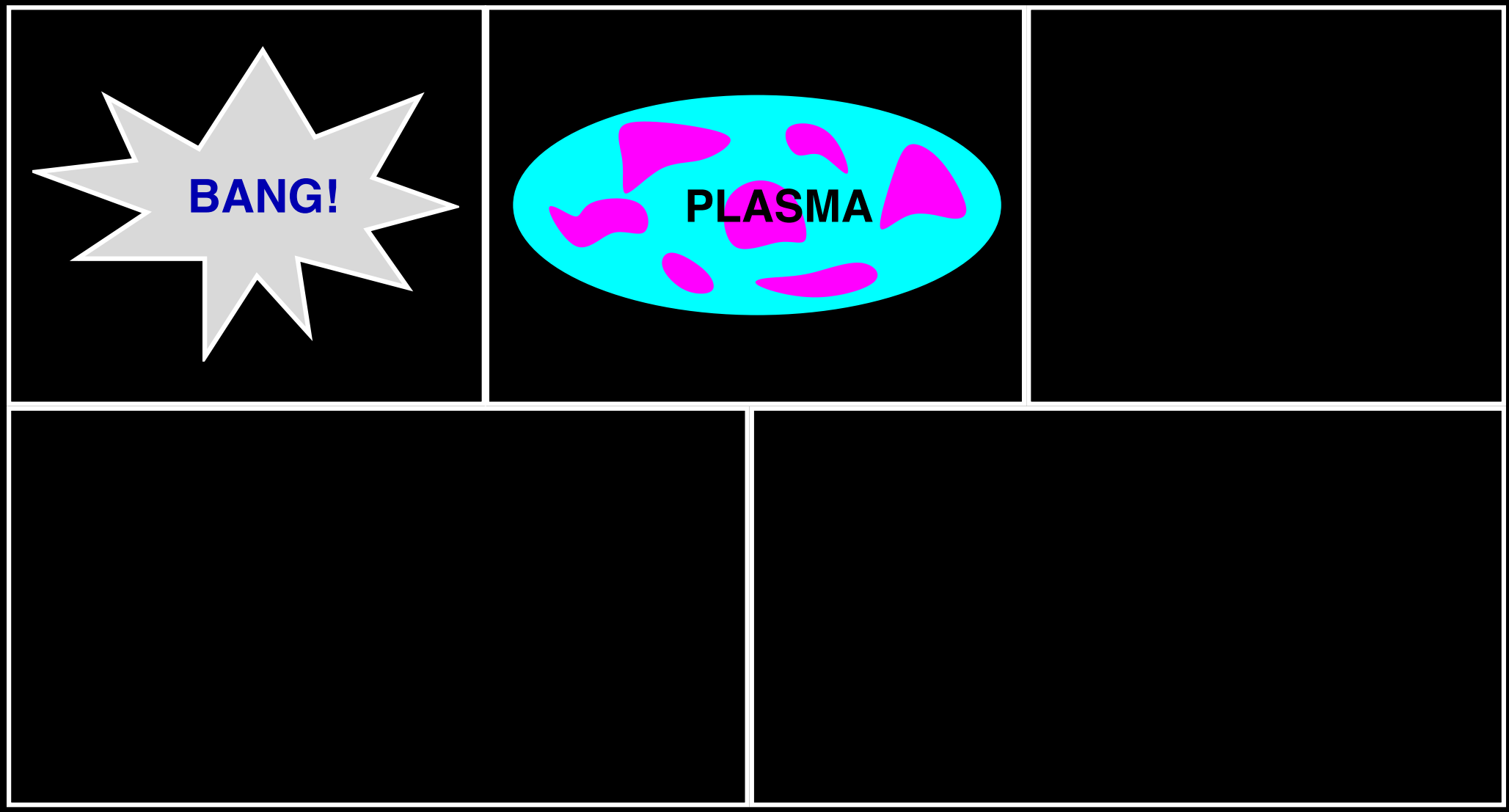

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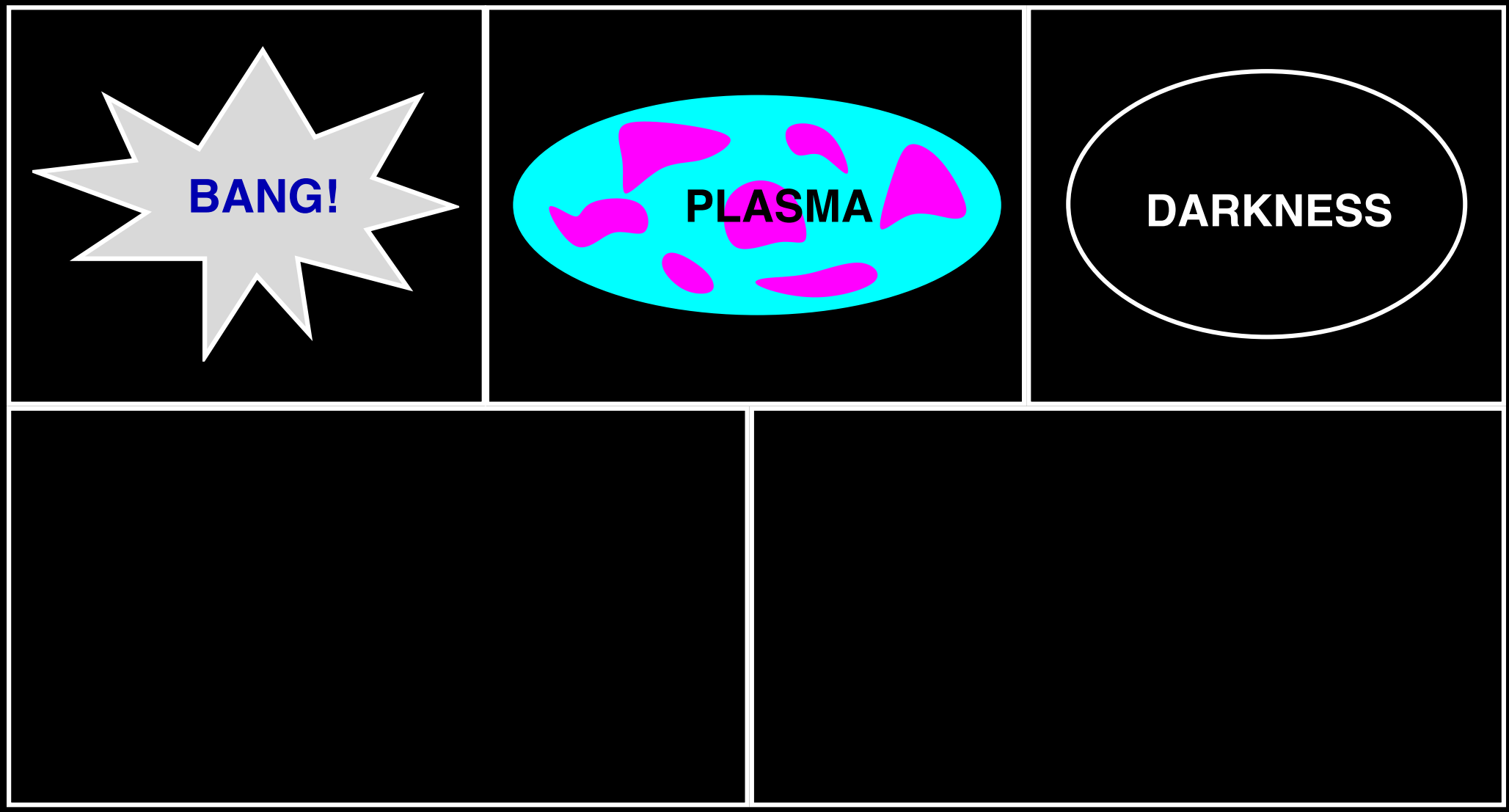

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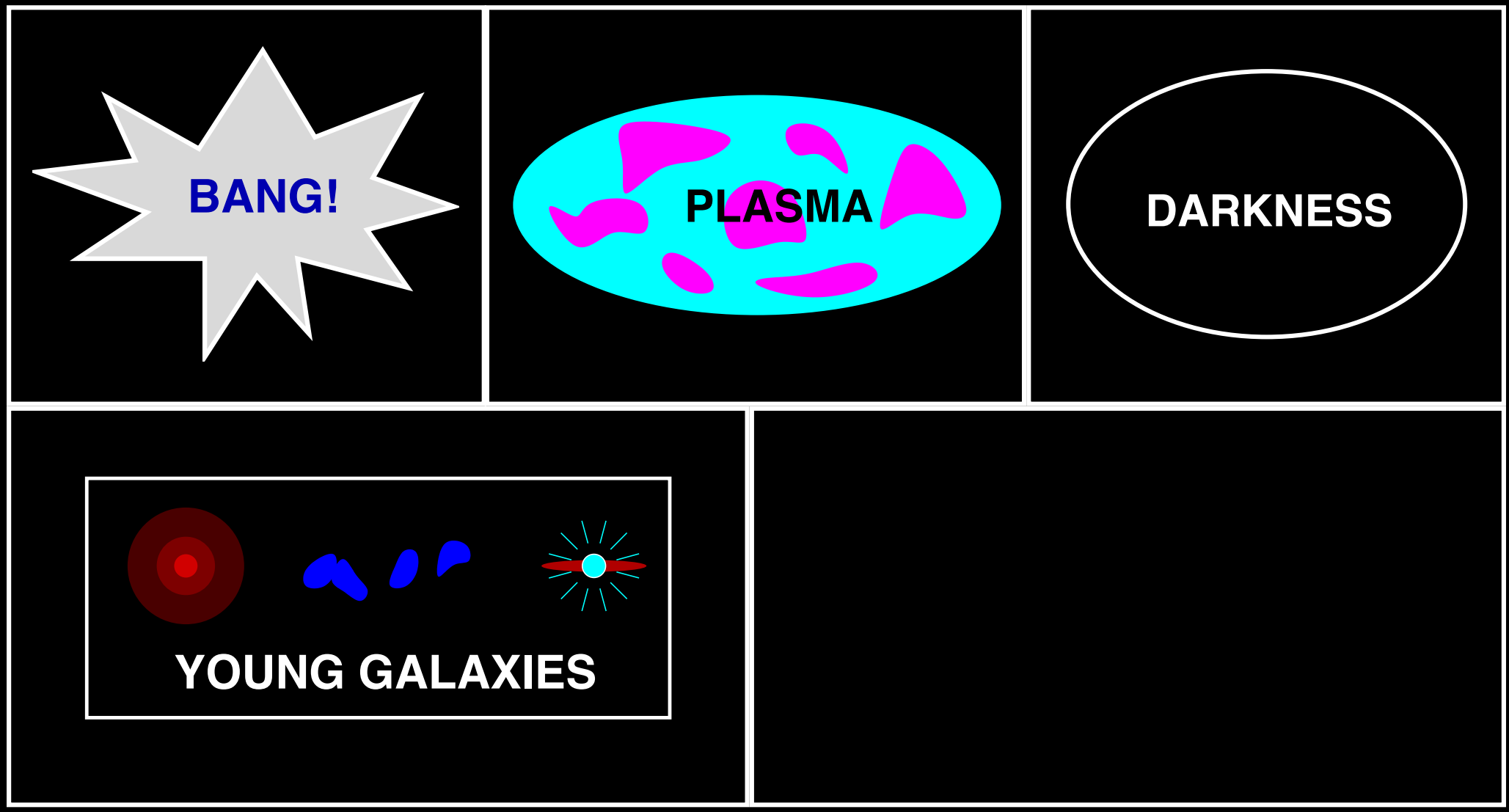

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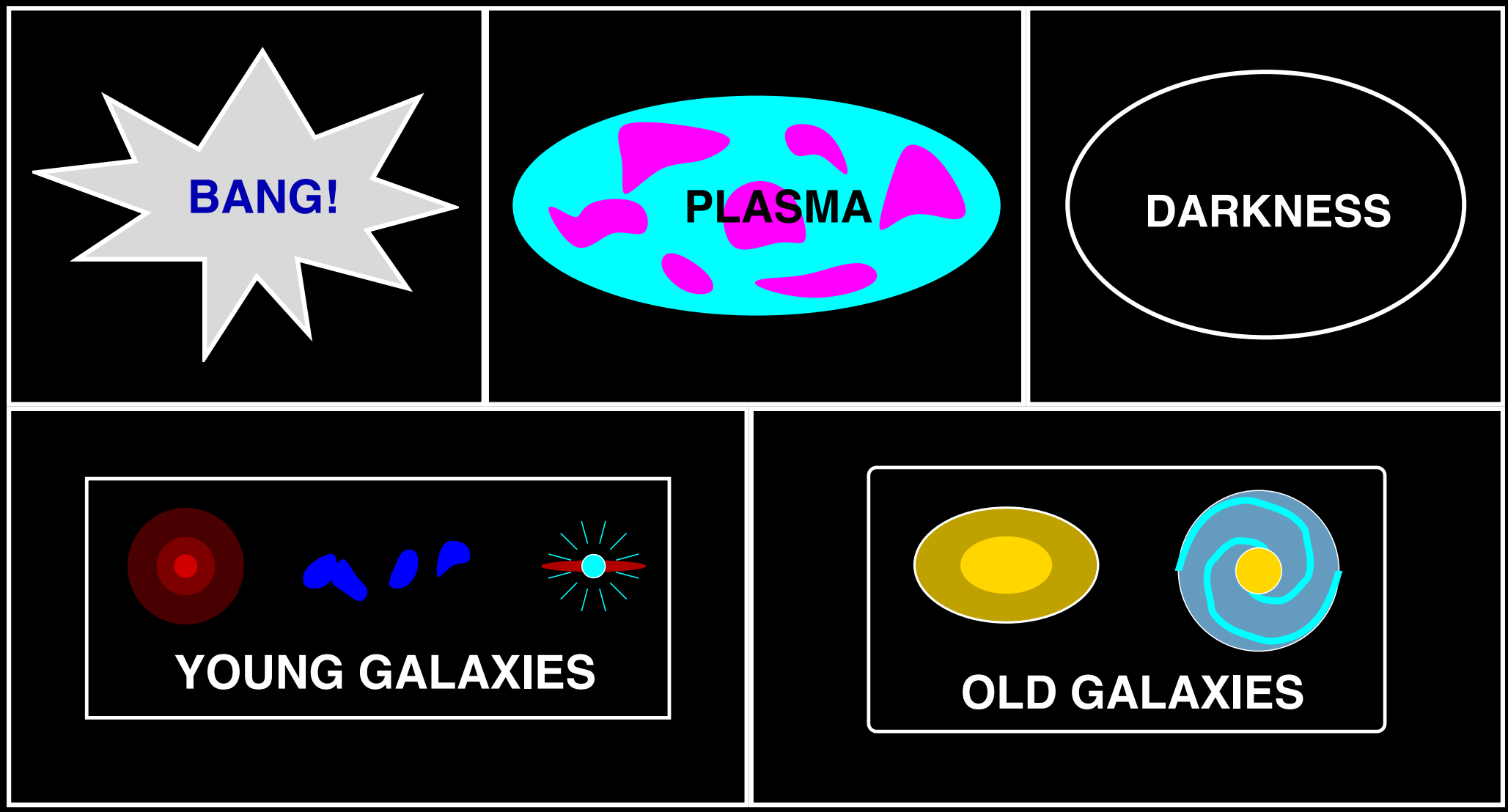

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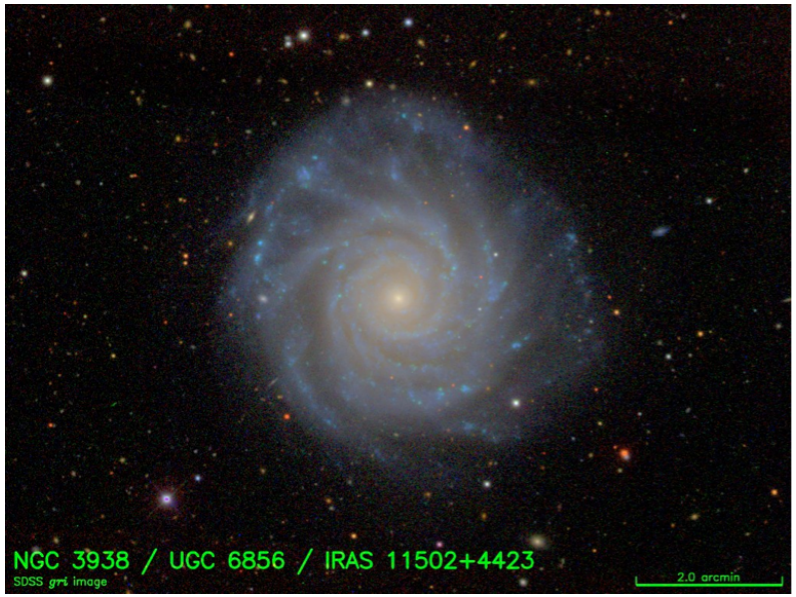
What is a galaxy?

A distinct object composed of stars, gas, and dark matter, all bound together by their mutual gravity

"Spiral" galaxy



"Elliptical" galaxy

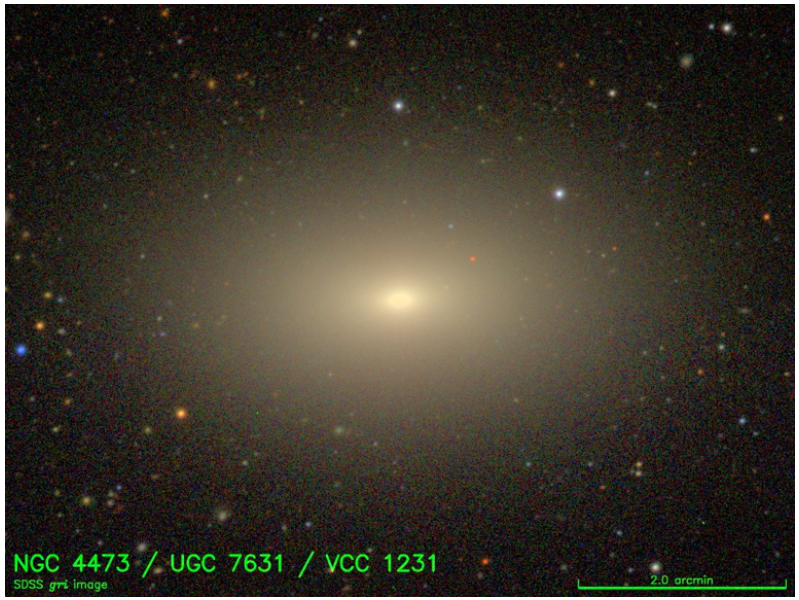


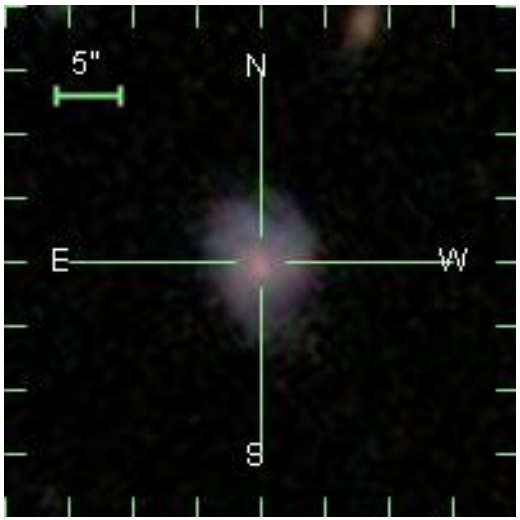
Image credits: Hogg & Blanton for SDSS

First classified by Edwin Hubble in 1926

Galaxies viewed from a distance

Morphology is strongly correlated with color

"Blue" galaxy



"Red" galaxy

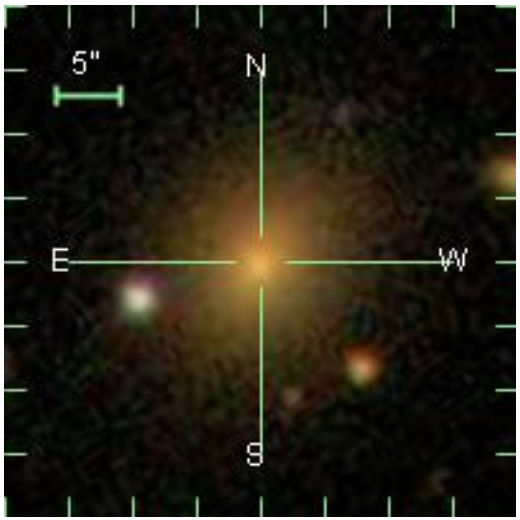


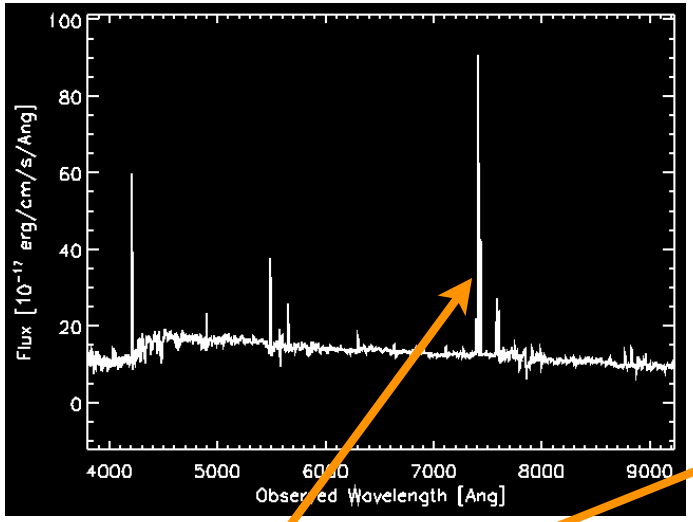
Image credit: SDSS

Strong correlation of color with stellar populations

Galaxy spectroscopy

Detailed galaxy physics revealed by measuring energy distribution as a function of wavelength

"Starforming" galaxy



"Passive" galaxy

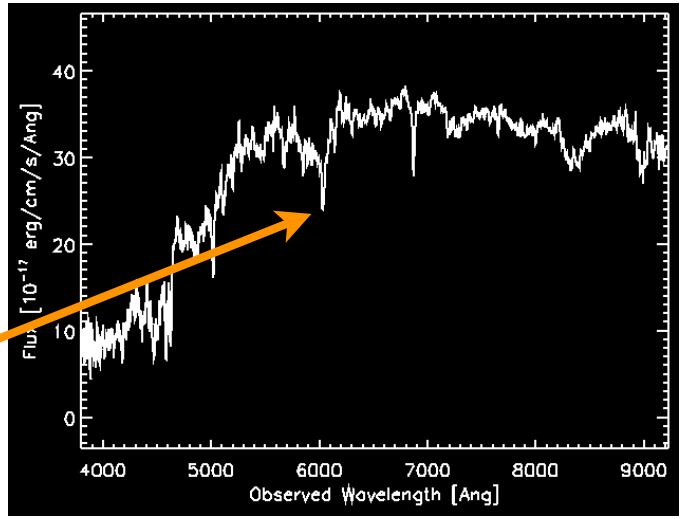
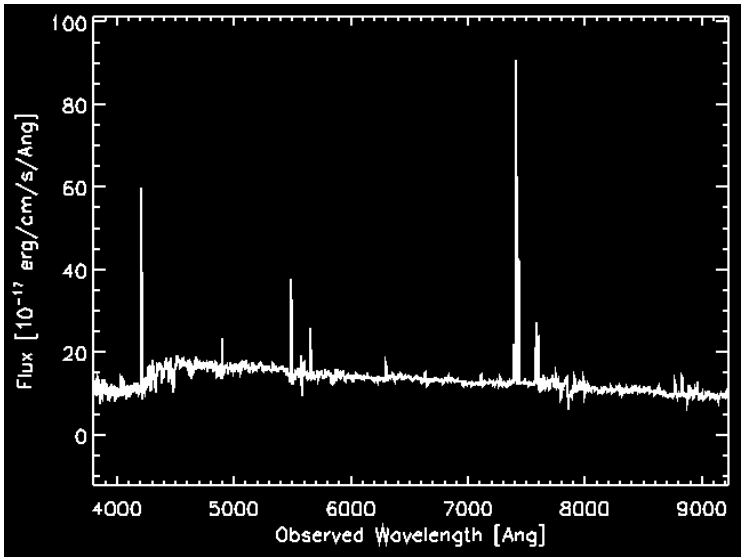


Image credit: SDSS

Features correspond to quantum transitions with known rest wavelengths

“Redshift” *z* defined



$$\frac{\lambda_{\rm observed}}{\lambda_{\rm emitted}} \equiv 1 + z$$

In the limit of small radial velocities *v*, redshift is related to Doppler shift by:

$$z \simeq v/c$$

Redshift, Hubble expansion, big bang

The Universe is expanding

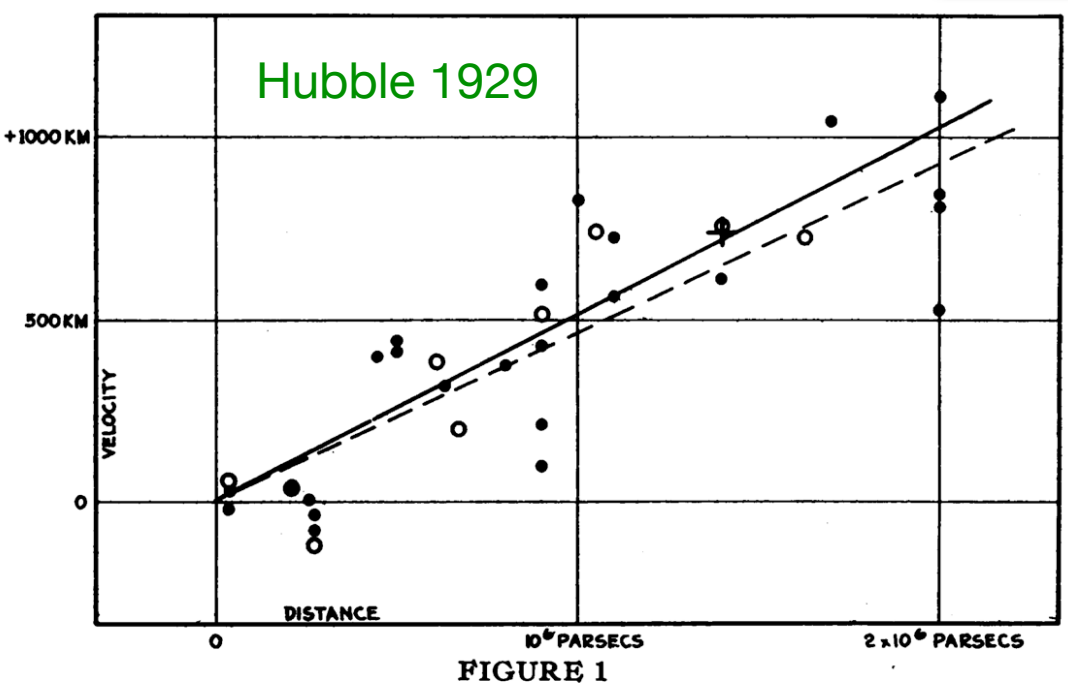
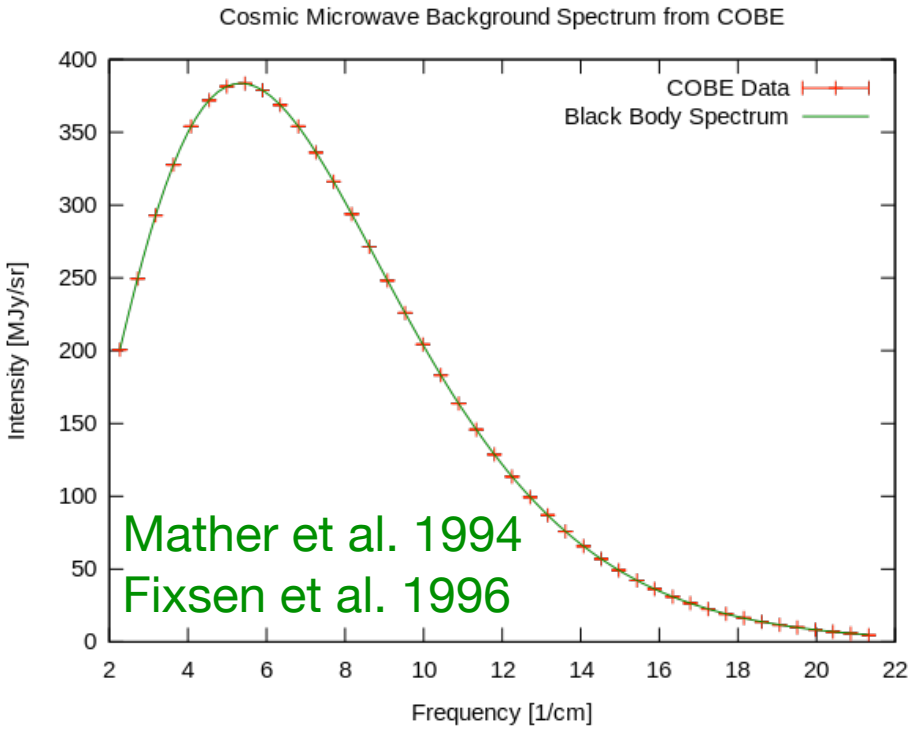


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

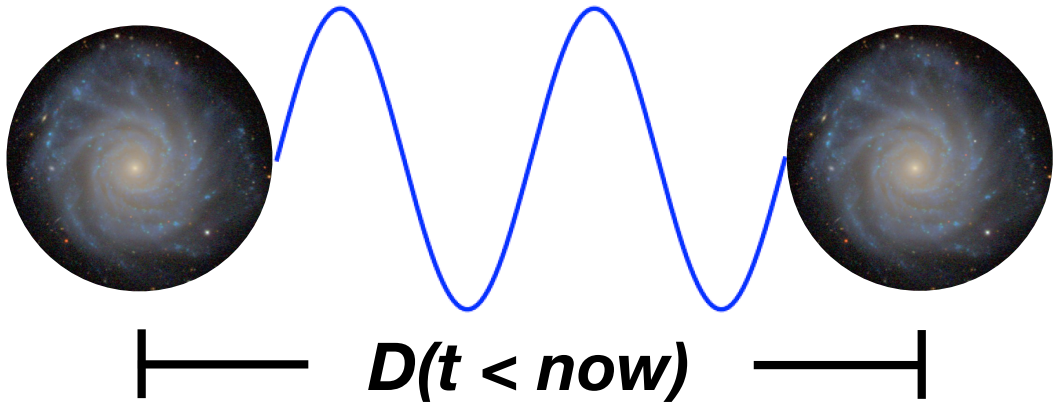
Seen in cosmological distance--redshift relation of galaxies

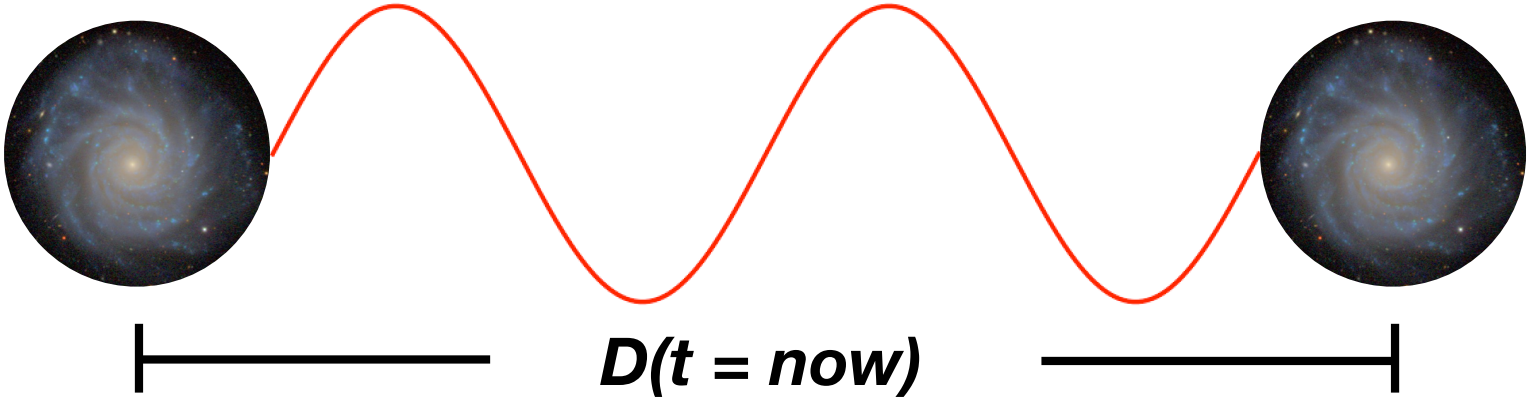
We see the afterglow of the big bang



Seen in cosmic microwave background radiation

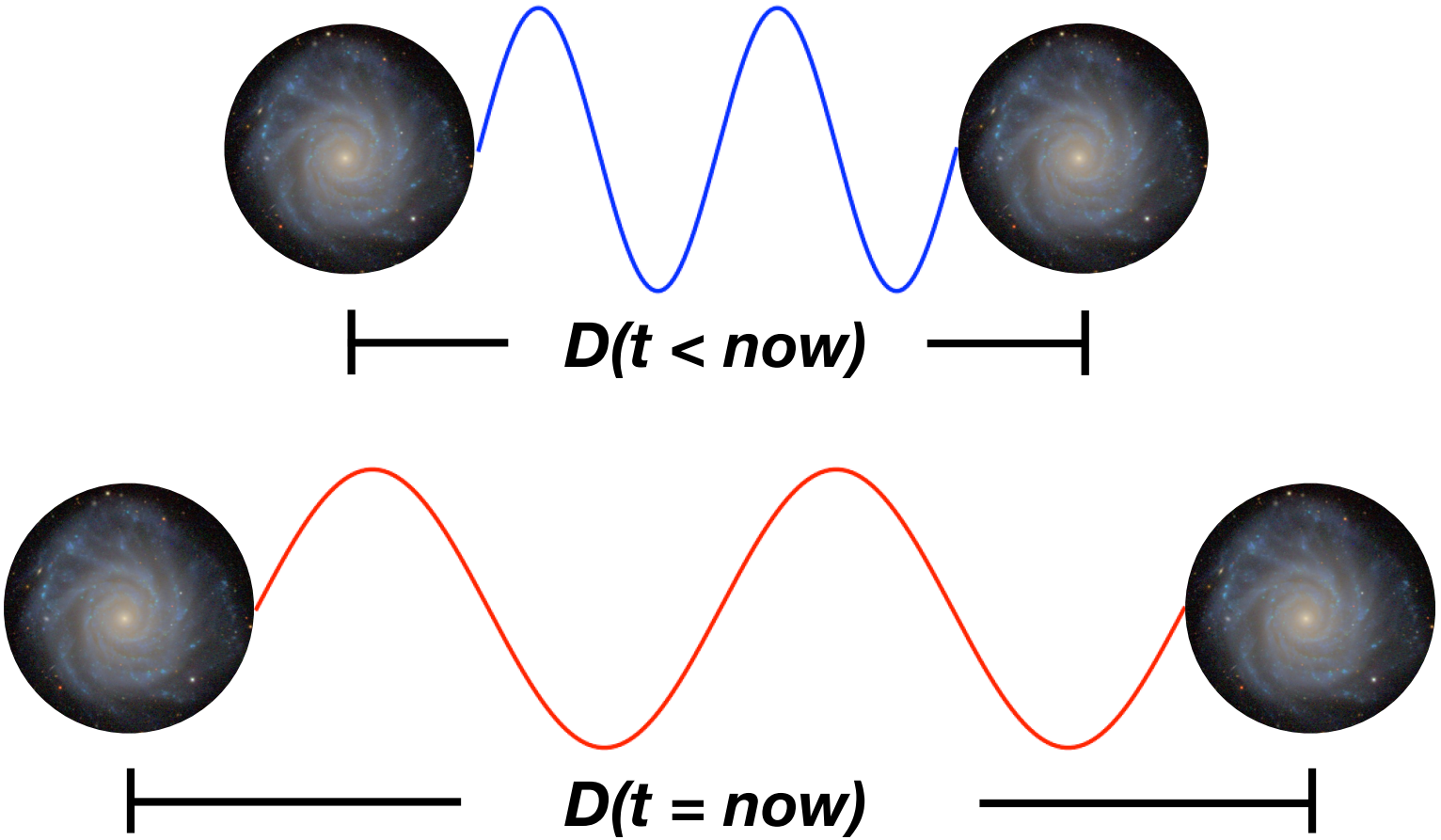
Redshift and scale factor





$$a(t) \equiv \frac{D(t < \mathrm{now})}{D(t = \mathrm{now})} = \frac{\lambda_{\mathrm{emitted}}}{\lambda_{\mathrm{observed}}} = \frac{1}{1+z}$$

Redshift and scale factor



Redshift serves as observable proxy for distance and time in cosmology

What is a galaxy redshift survey?

- An observational project to measure the three-dimensional distribution of a large number of ***galaxies*** in the universe
- Imaging observations provide the first two dimensions
- Spectroscopic ***redshifts*** provide the third dimension
- A fundamentally *statistical* experiment, or ***survey***!

Why conduct galaxy redshift surveys?

- Astronomy & Astrophysics:
  - Map the large-scale structure of the universe
  - Study galaxy population demographics
  - Study galaxy evolution over cosmic time
  - Learn relationship between galaxies and dark matter
- Cosmology
  - Measure expansion history of universe
  - Test Einstein's general theory of relativity
  - Infer the contents of the universe
  - Constrain the nature of those contents
- ***Signatures of dark energy are imprinted on galaxy distribution over cosmic time (see "extra" slides.)***

Partial (quasi-chronological) list of past & present galaxy redshift surveys

- Davis, Huchra, Latham, & Tonry
- Southern Sky Redshift Survey
- Center for Astrophysics (CfA) Redshift Survey
- Canada-France Redshift Survey (CFRS)
- Las Campanas Redshift Survey
- Two-degree Field Galaxy Redshift Survey (2dFGRS)
- Sloan Digital Sky Survey (SDSS)
- DEEP2 Redshift Survey
- VIMOS VLT Deep Survey (VVDS)
- zCOSMOS
- Gemini Deep Deep Survey
- Prism Multi-Object Survey (PRIMUS)
- WiggleZ
- SDSS-III Baryon Oscillation Spec. Survey (BOSS)
- SDSS-IV extended BOSS (eBOSS)

Coming up next: Dark Energy Spectroscopic Instrument (DESI)

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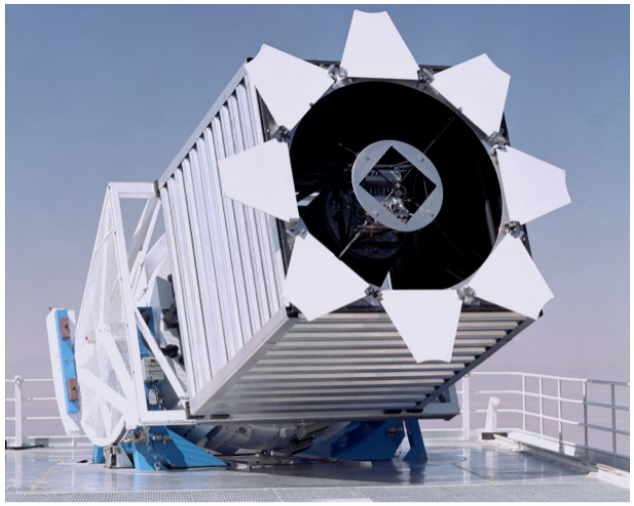
SDSS-III BOSS project

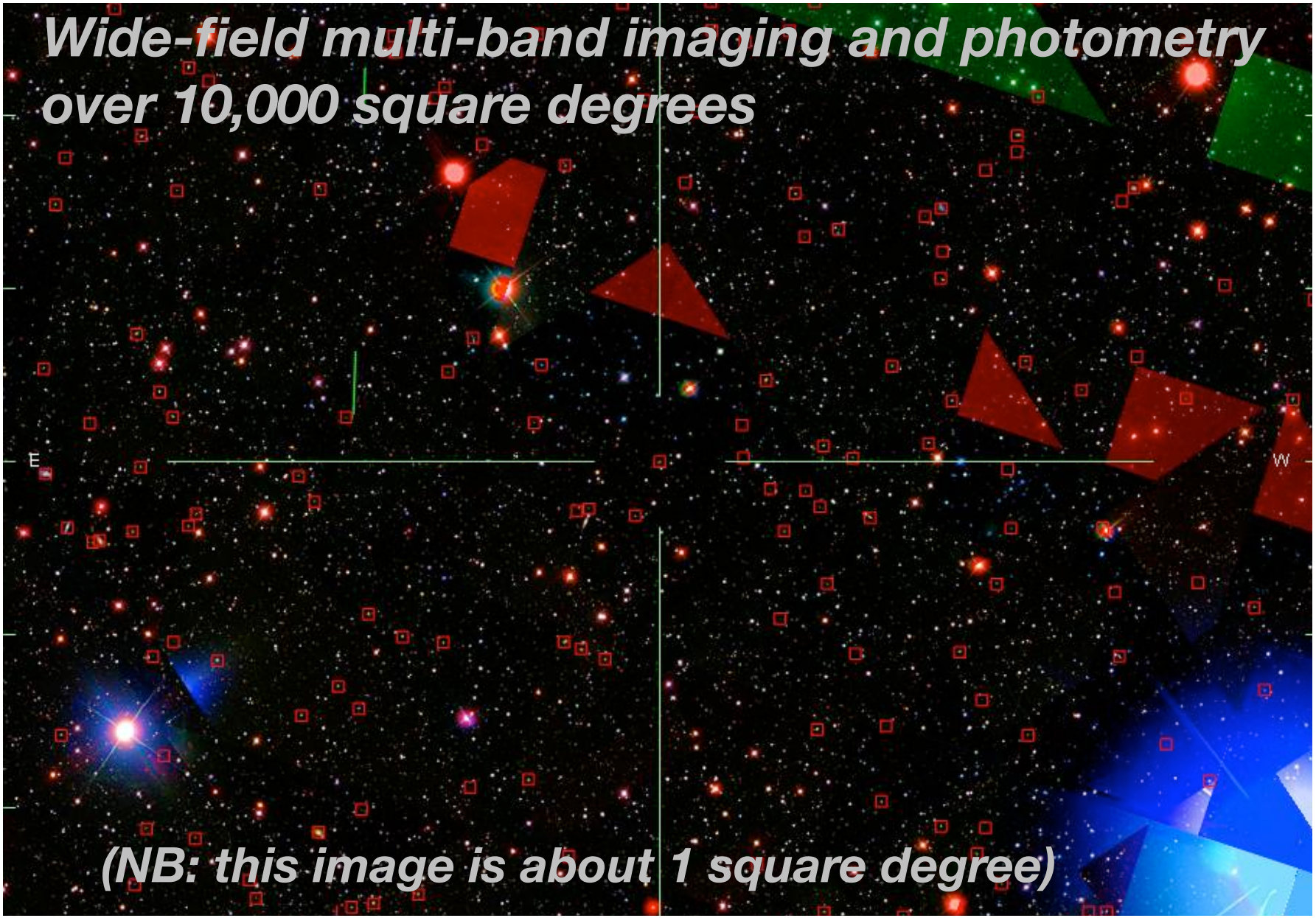
To measure the properties of dark energy, we map the three-dimensional structure of the universe on the largest scales.



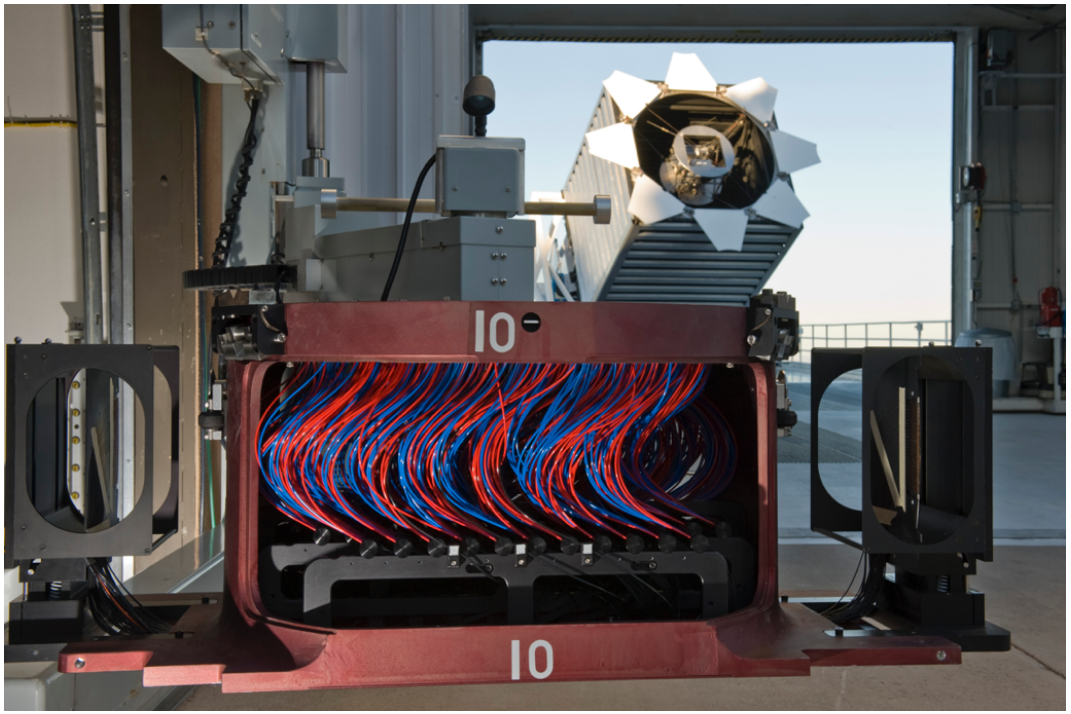
- BOSS = Baryon Oscillation Spectroscopic Survey
- Part of the Sloan Digital Sky Survey III, 2009-2014
- The best dark energy experiment to date
- Mapping large-scale structure with ~1.5 million galaxies and ~200,000 quasar lines of sight

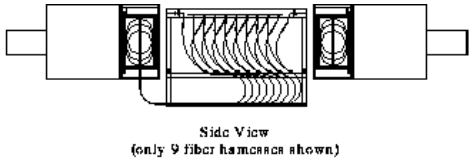
Dawson et al. 2013

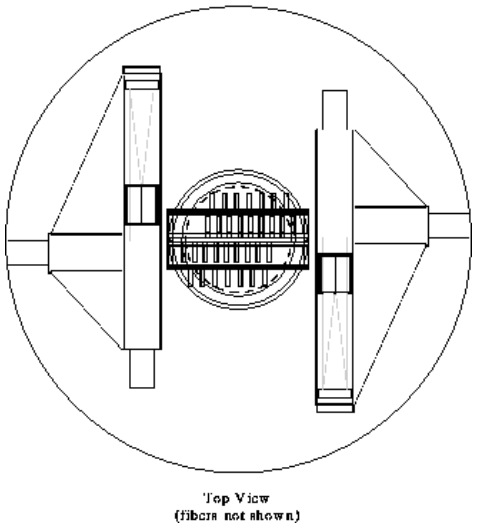
Imaging dimensions 1 and 2



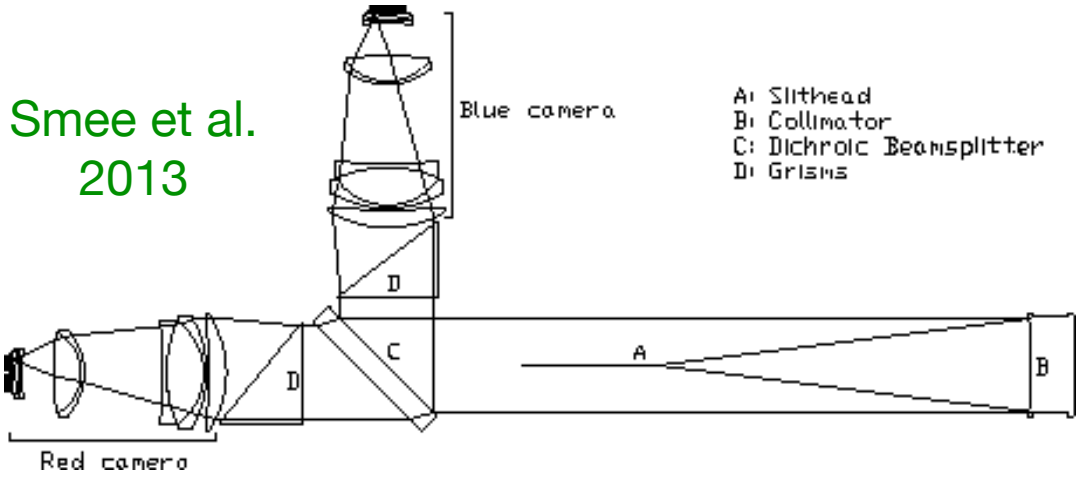
Spectroscopy for dimension 3

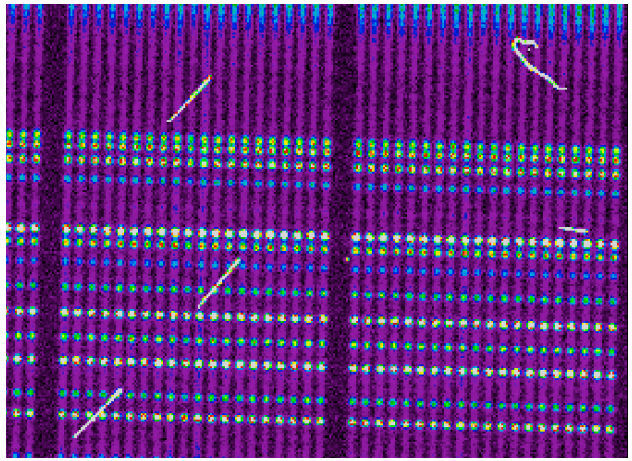






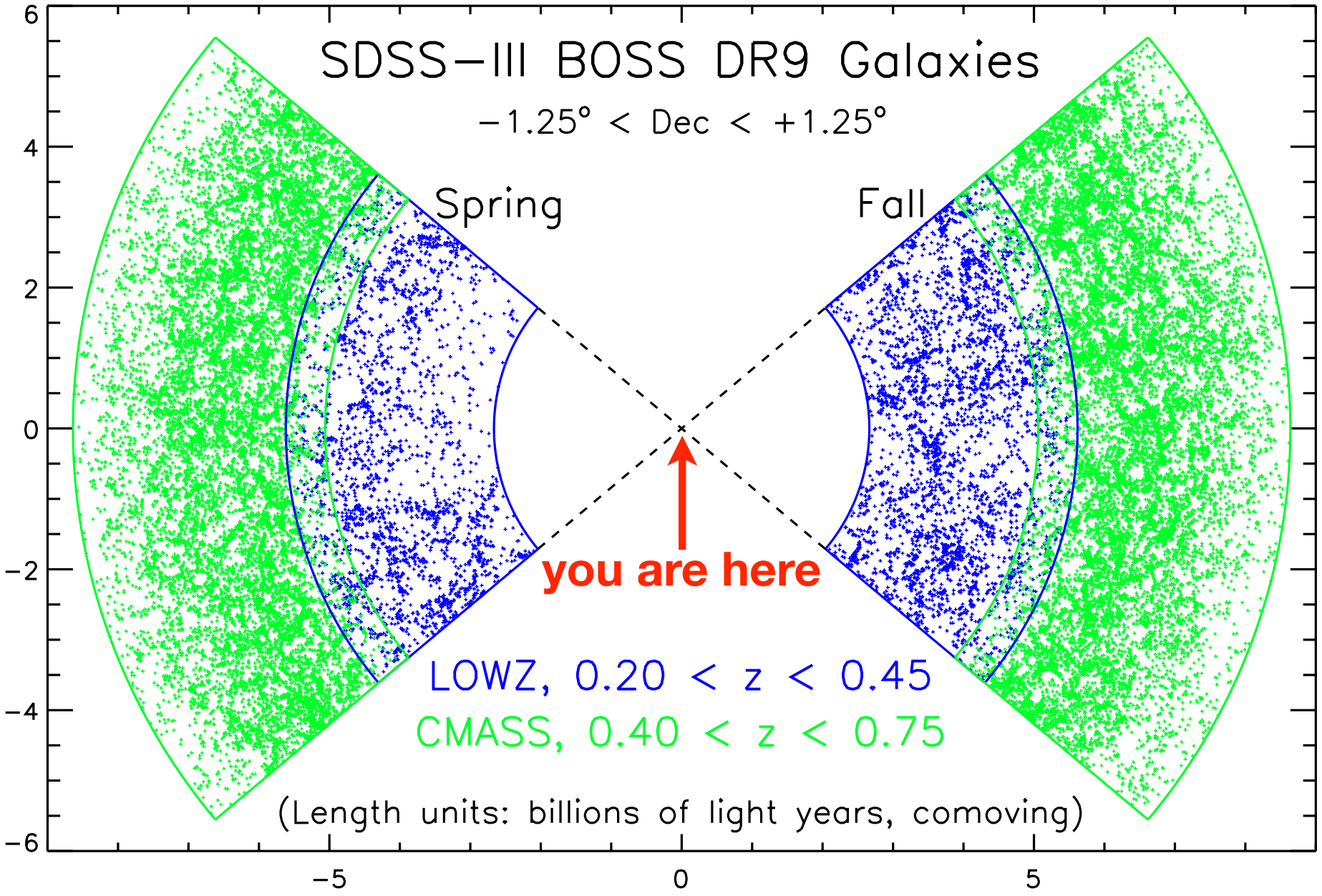
Smee et al. 2013





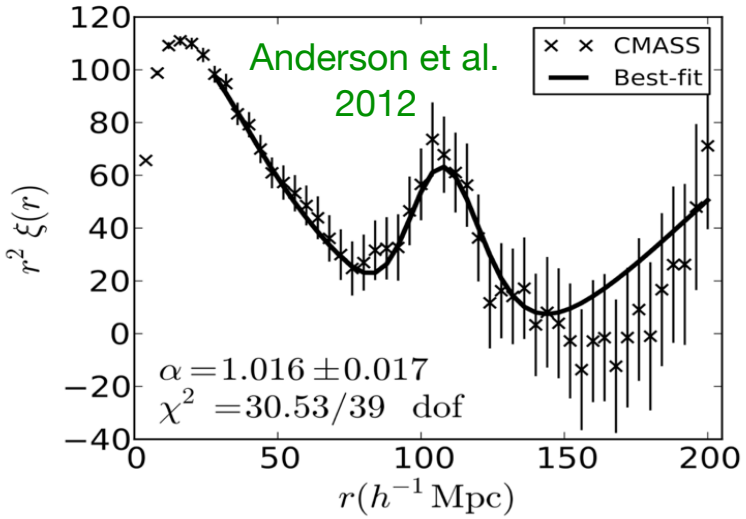
Bolton & Schlegel 2010

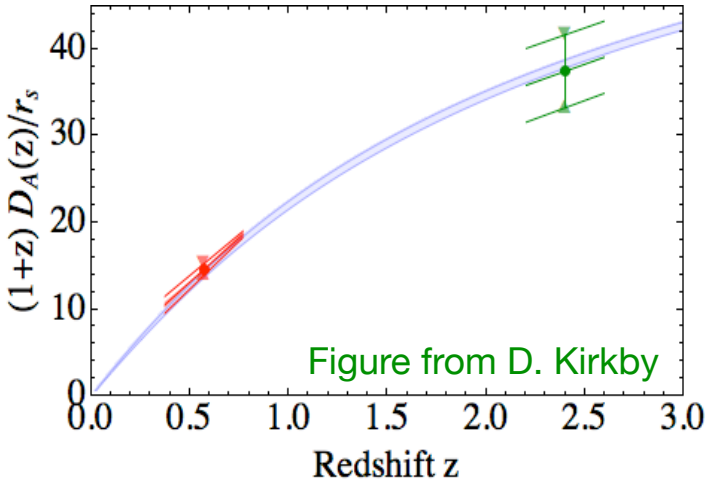
The universe in three dimensions

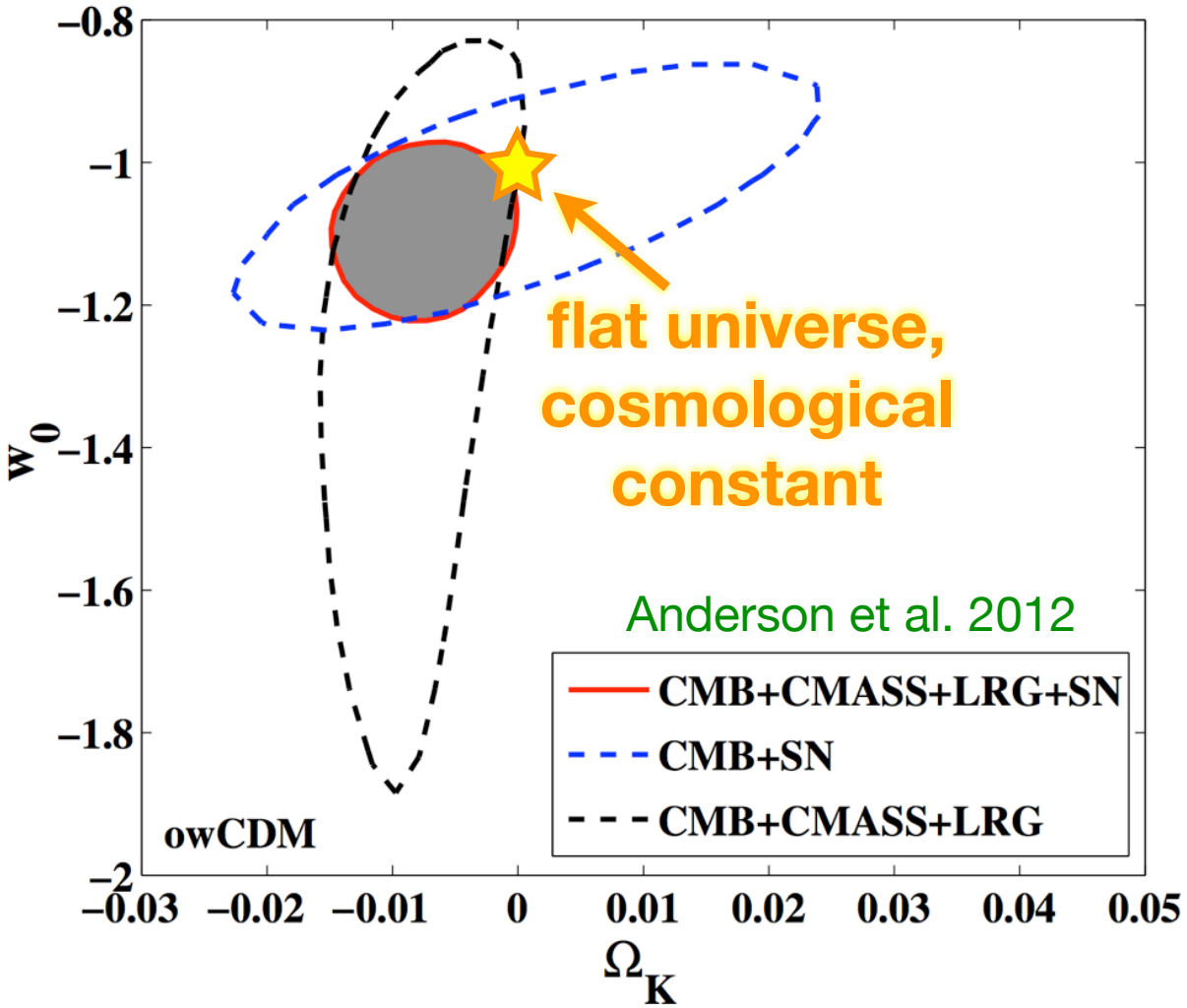


Dark energy physics from galaxy maps

Baryon acoustic feature measurement from BOSS Data Release 9



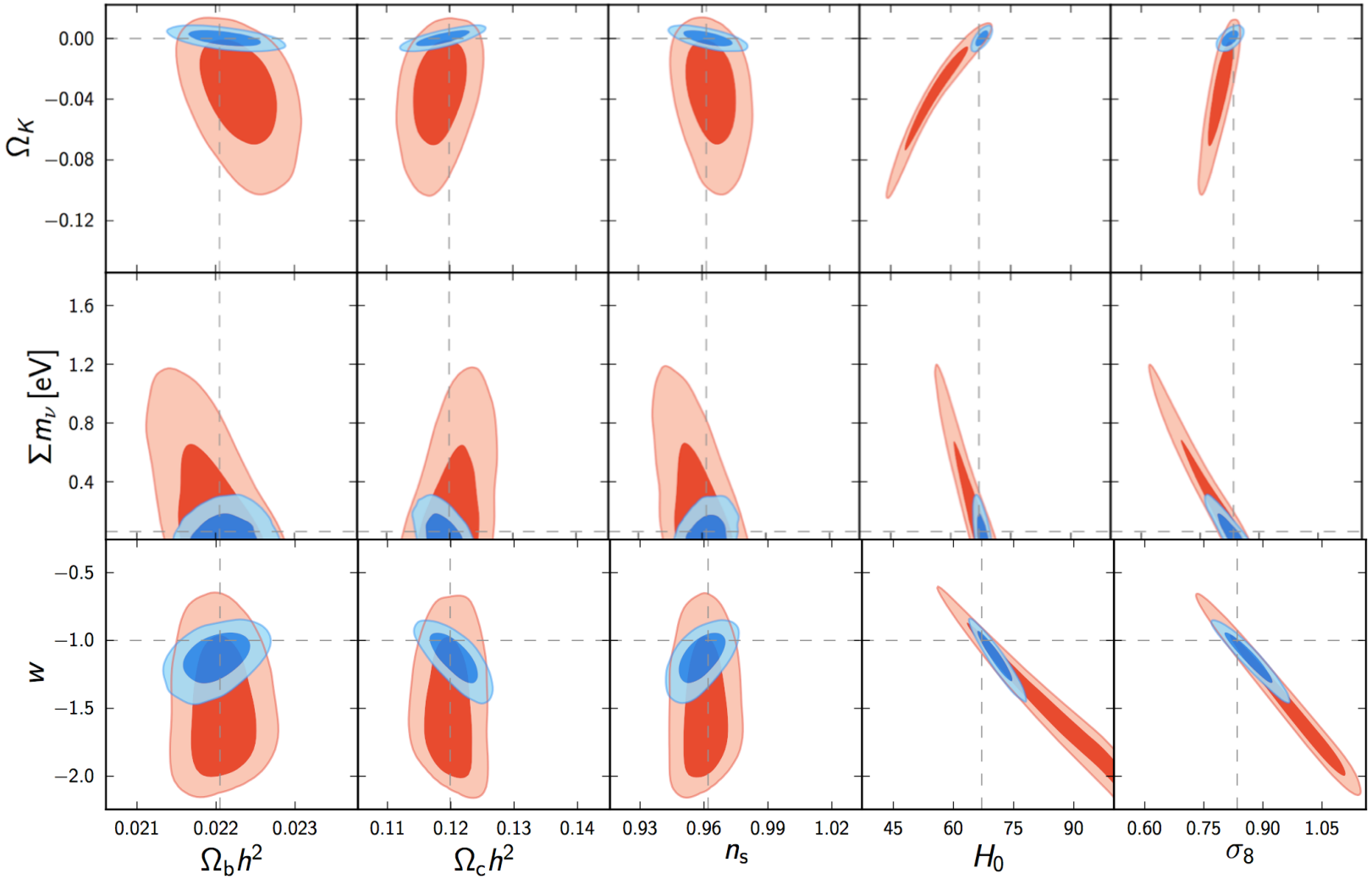




Dark energy physics from galaxy maps

Cosmological parameter constraints from:

- *Microwave background alone*
- *BAO plus microwave background*



Planck XVI, 2013

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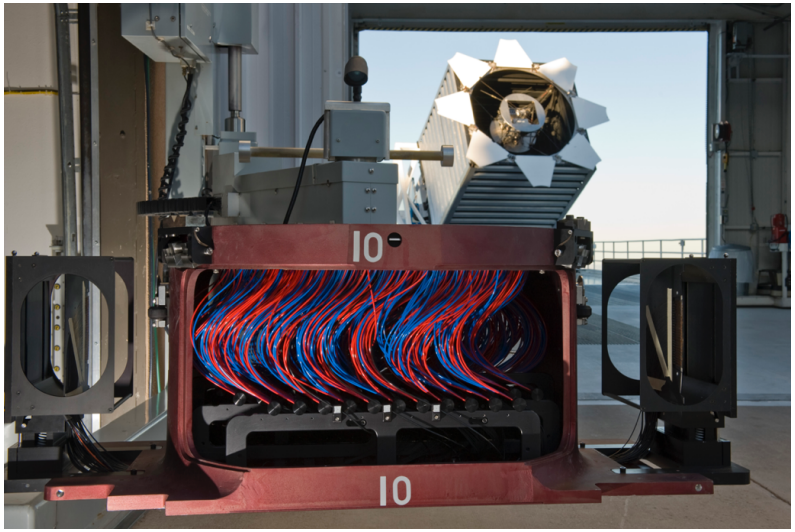
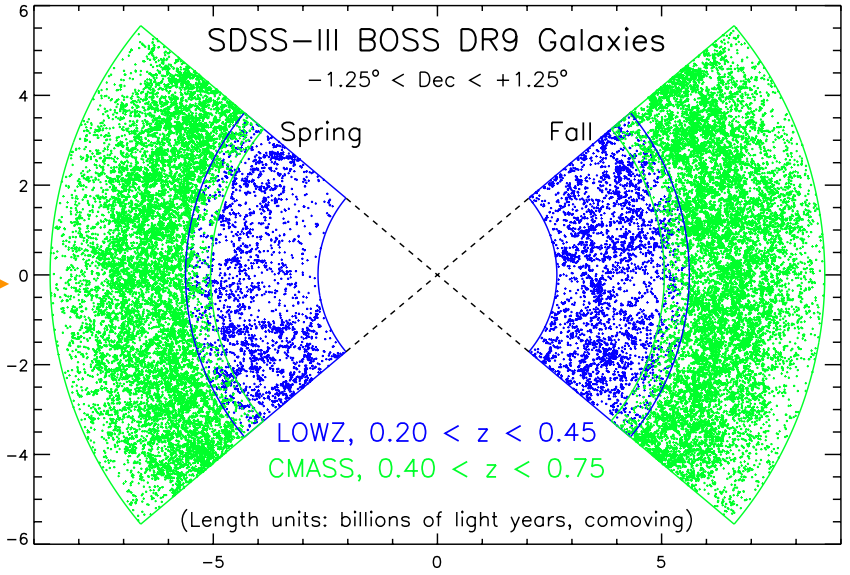
What really goes on in this step?





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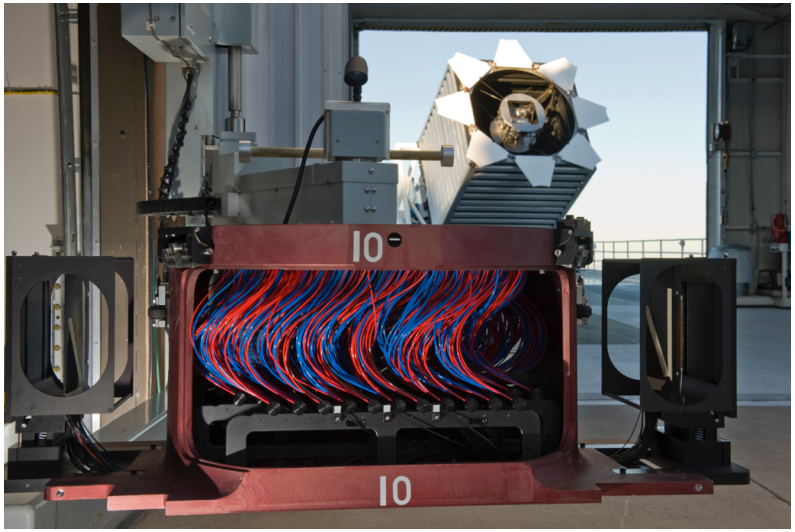
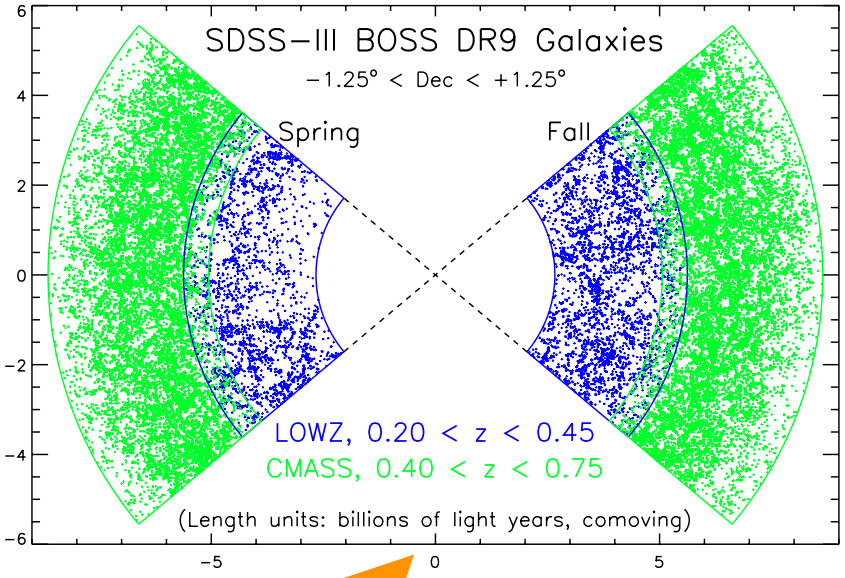




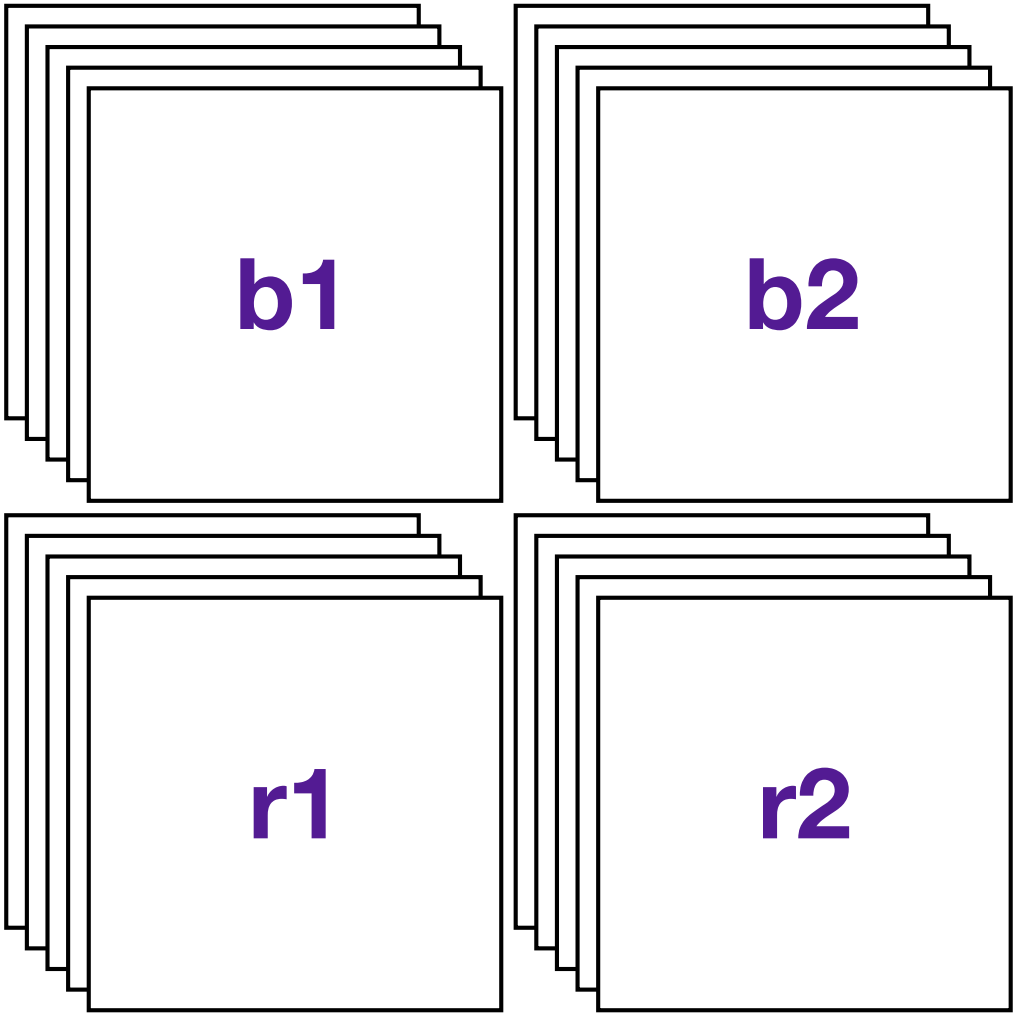
BOSS SPECTROSCOPIC PIPELINE

BOSS Spectroscopic Pipeline Overview

- Fully automated IDL software pipeline
- Inherited & modified from SDSS-I/II
- Cluster-parallelized by plates of 1000 fibers
- Extensive execution logging and QA plot generation
- Raw pixel errors estimated from first principles
- Errors propagated to redshifts and classifications
- Exceeds BOSS redshift science requirements
- Schlegel et al. in prep, Bolton et al. 2012, AJ, 144, 144

Science Frames

~5 exposures X 4 cameras X ~4,000x4,000 pixels



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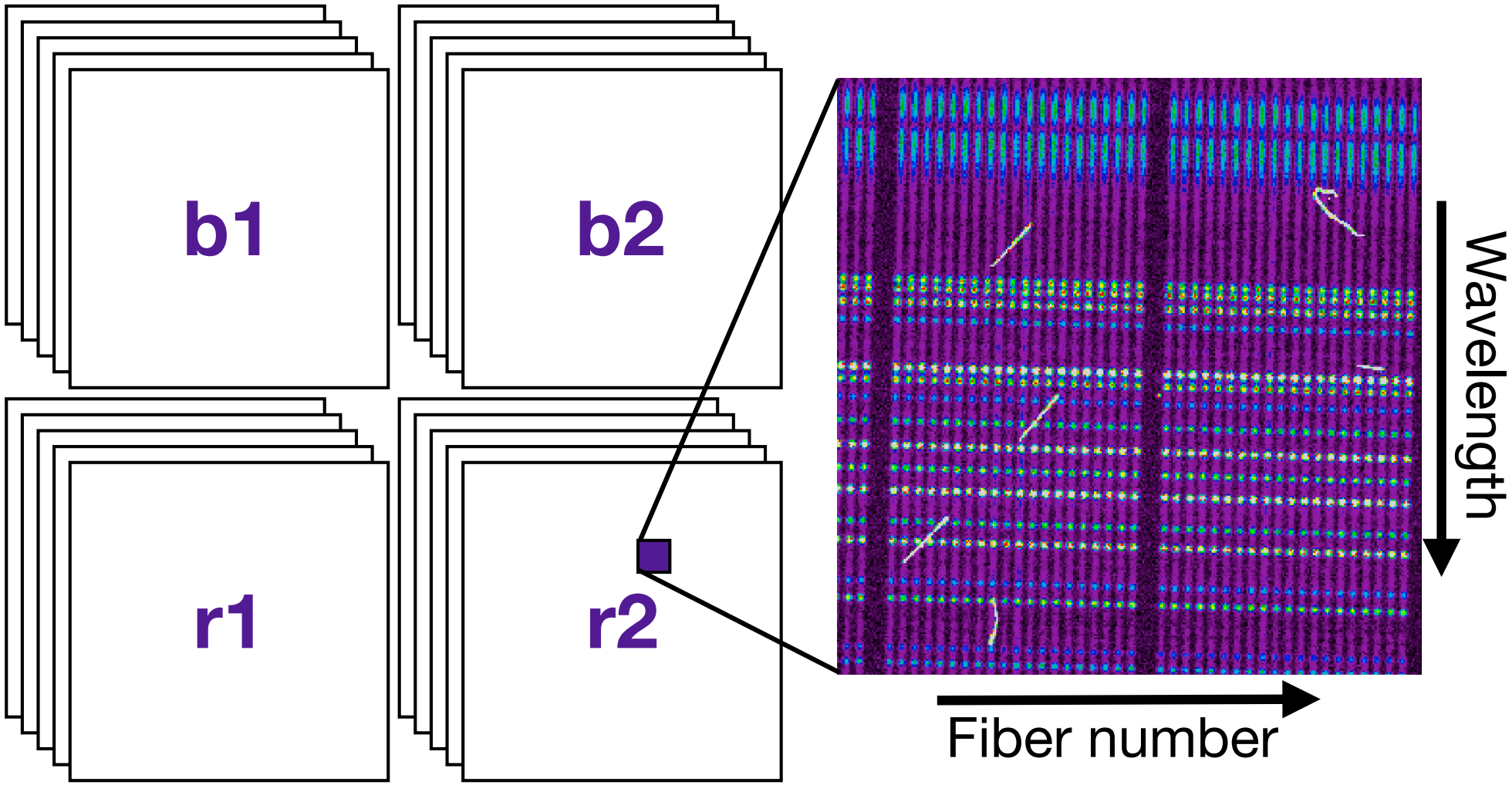
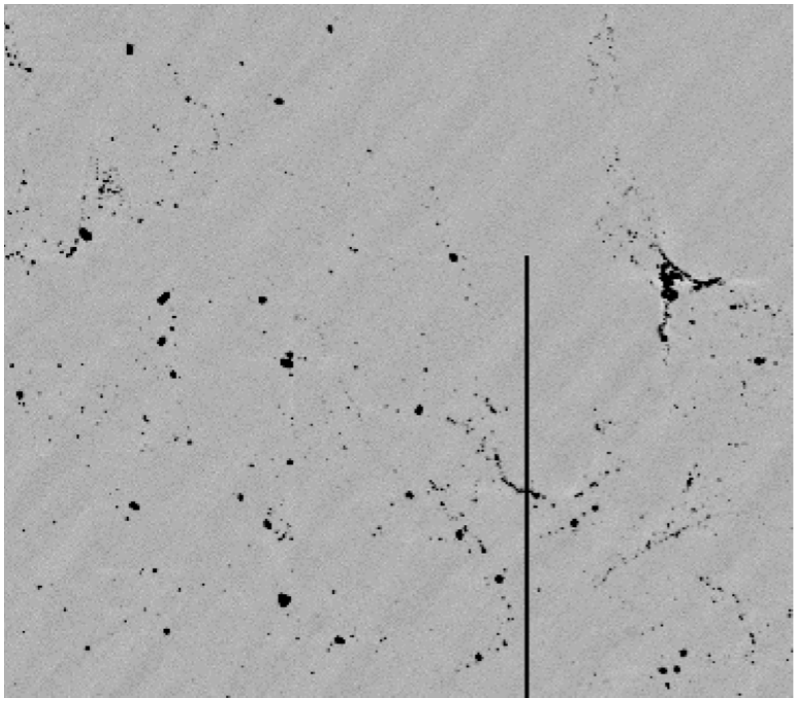
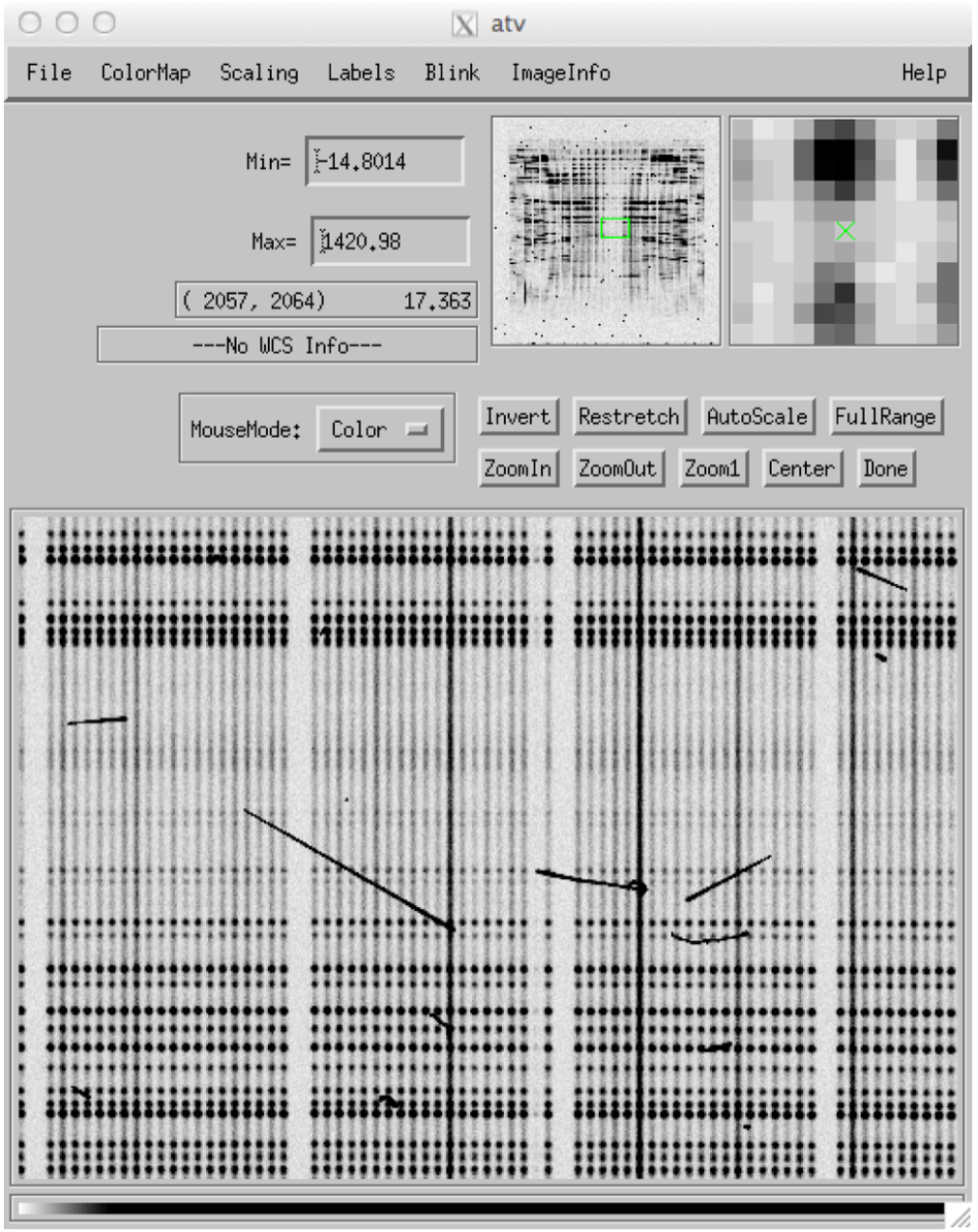


Most counts are night-sky photons!

Calibration, Part 1

bias subtraction,
gain correction,
pixel-response correction,
bad-column masking,
cosmic-ray rejection,
pixel error estimation





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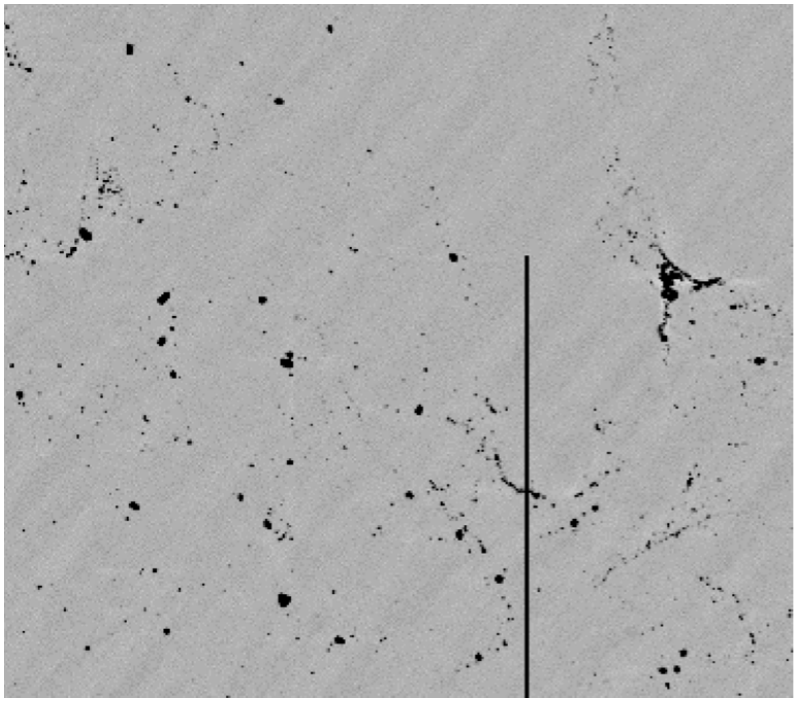
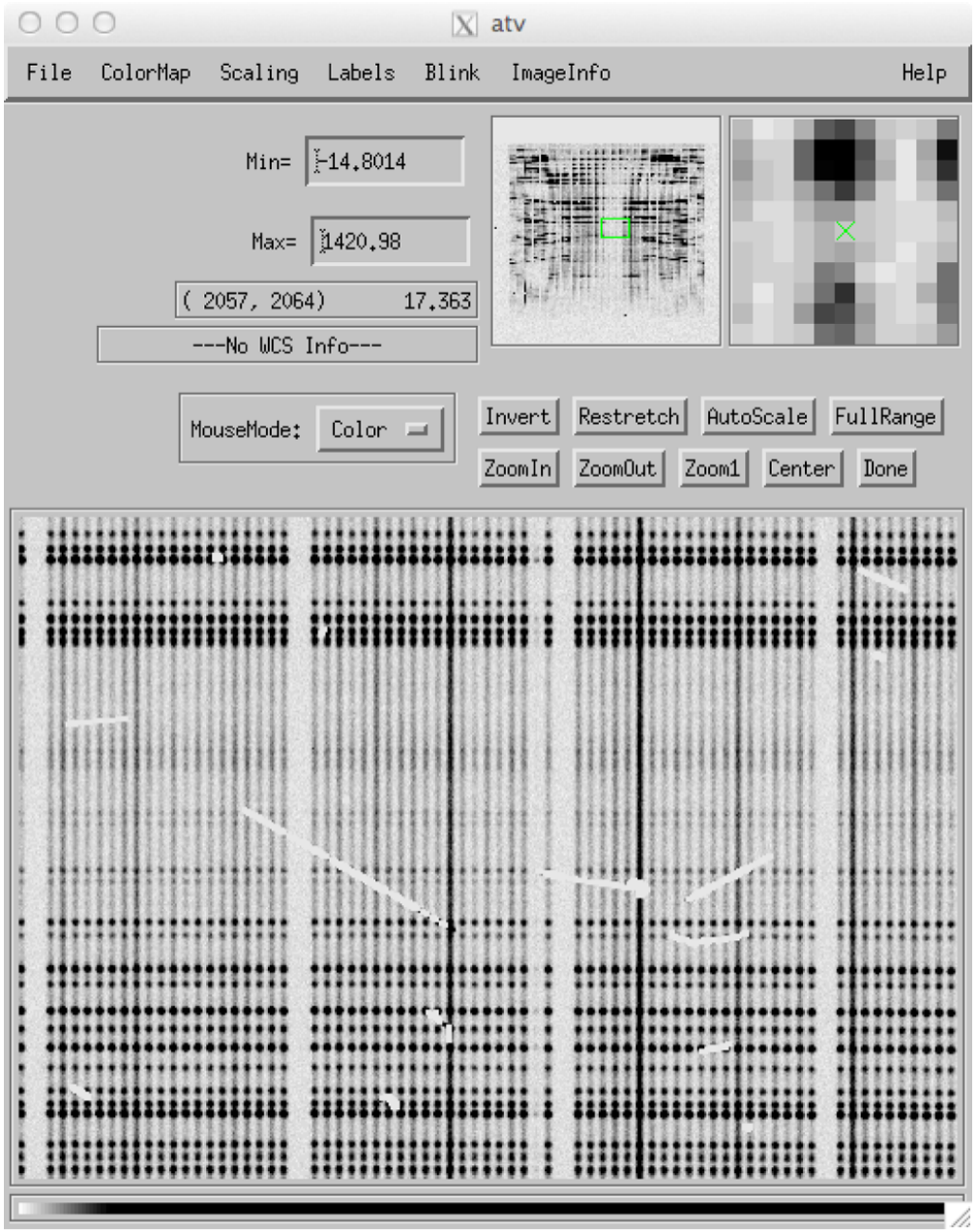
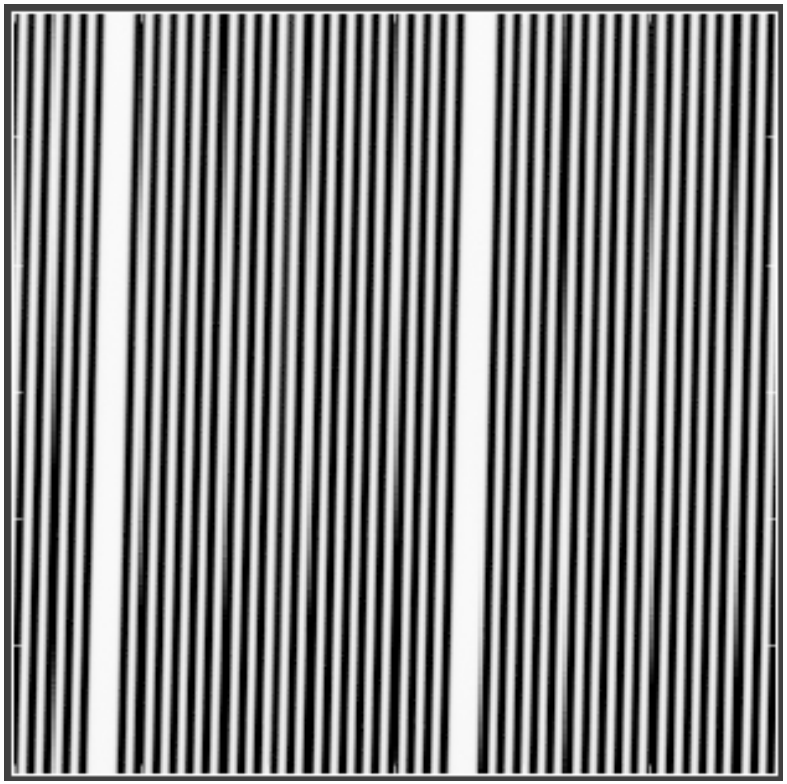




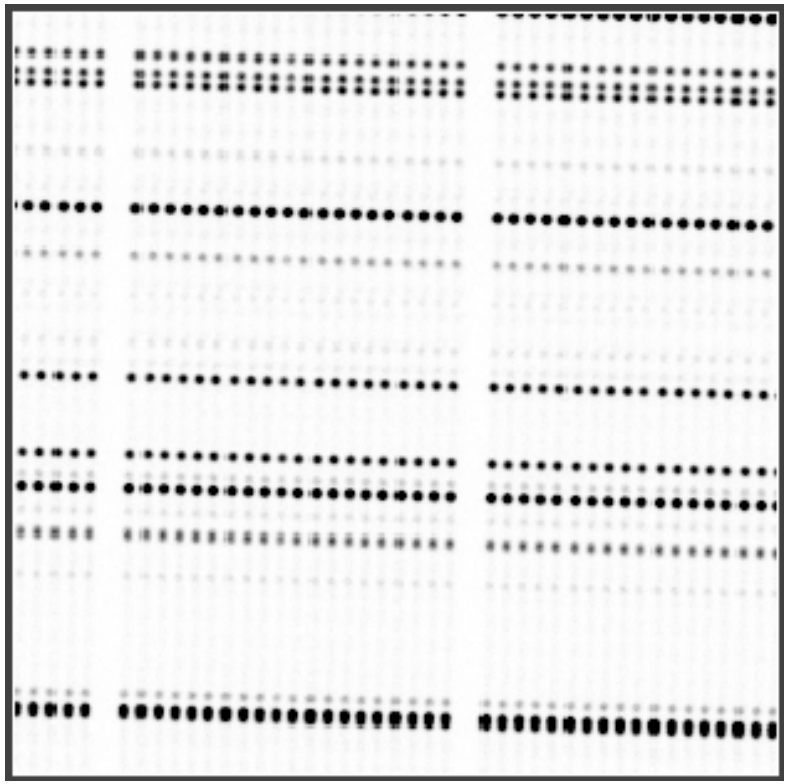
Calibration, Part 2

Flat Frames



trace positions
fiber-to-fiber throughput
cross-sectional profile

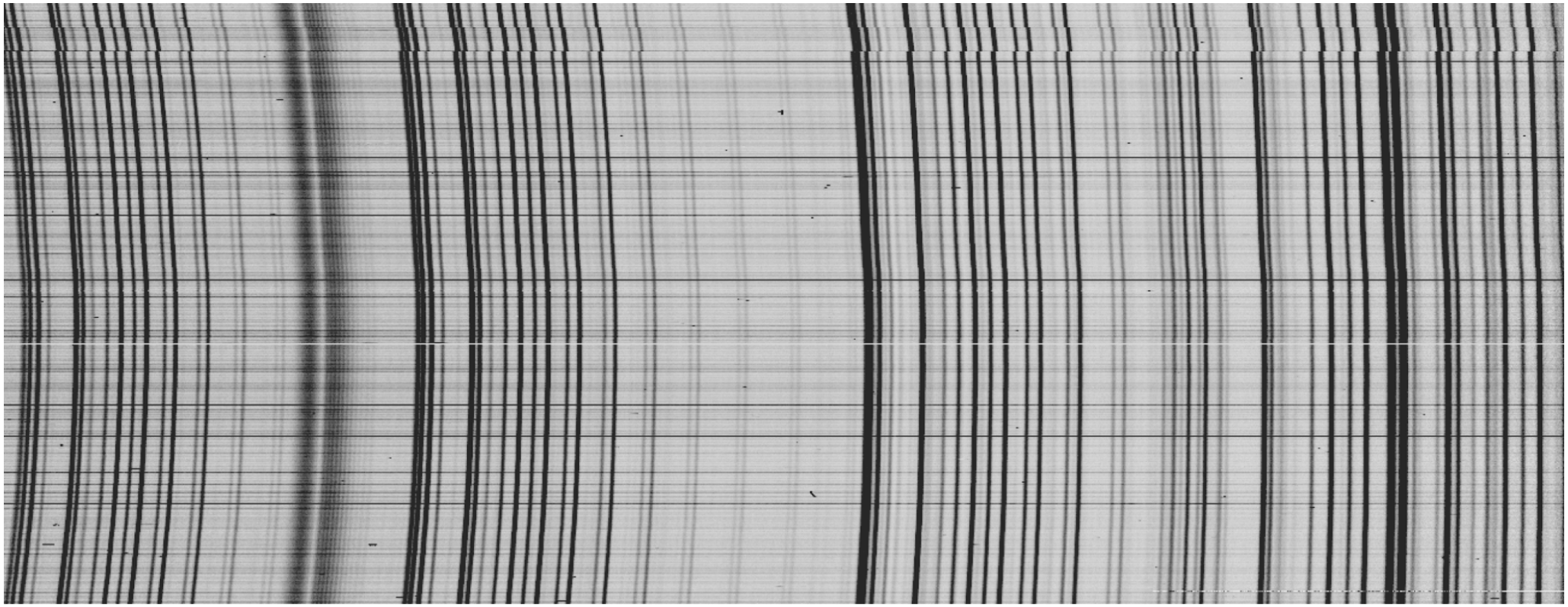
Arc Frames



wavelength solution
spectral resolution

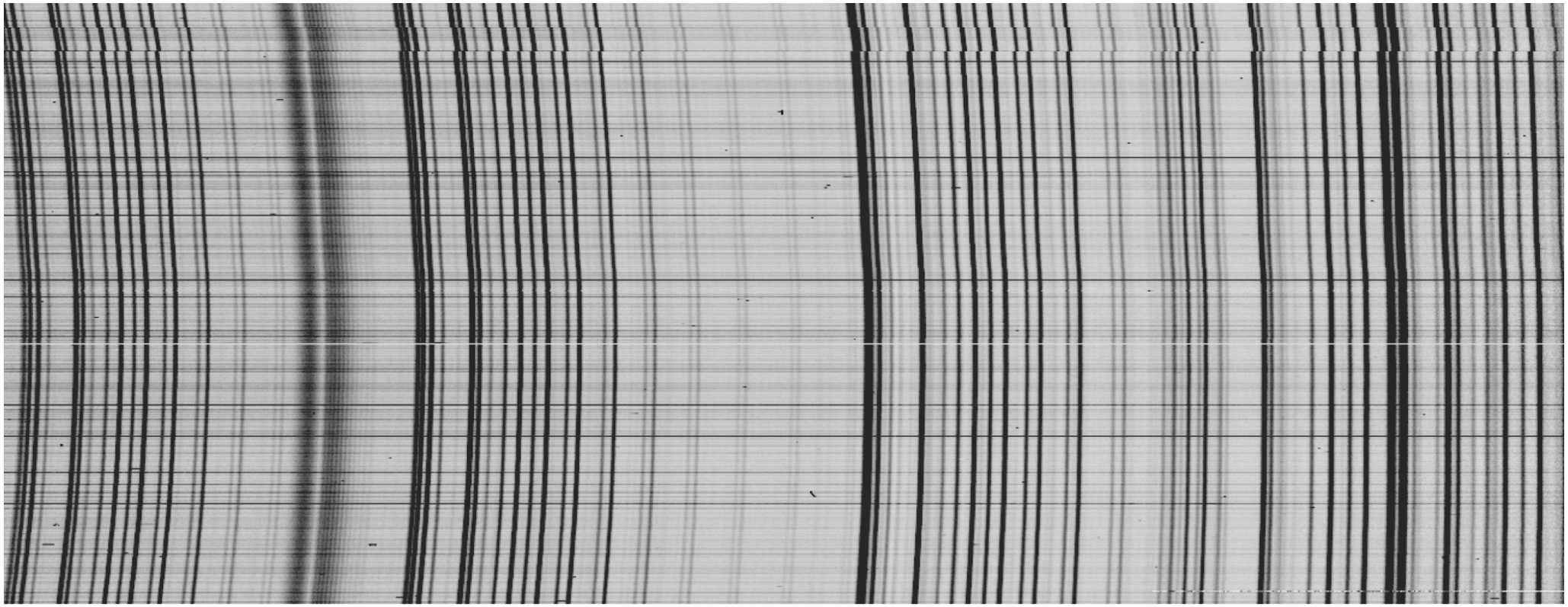
Extraction

Profile fitting “optimal extraction”, a la Horne 1986



Sky Subtraction

B-spline sky model in un-rebinned pixel space



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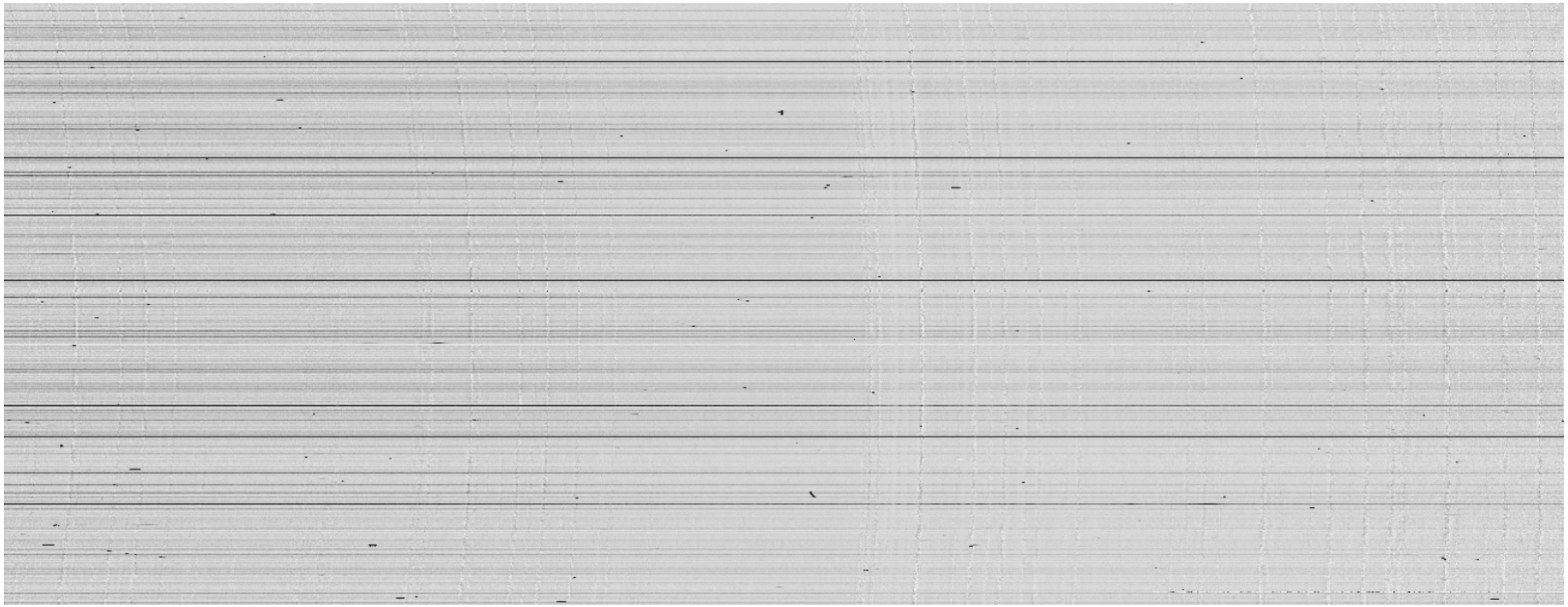
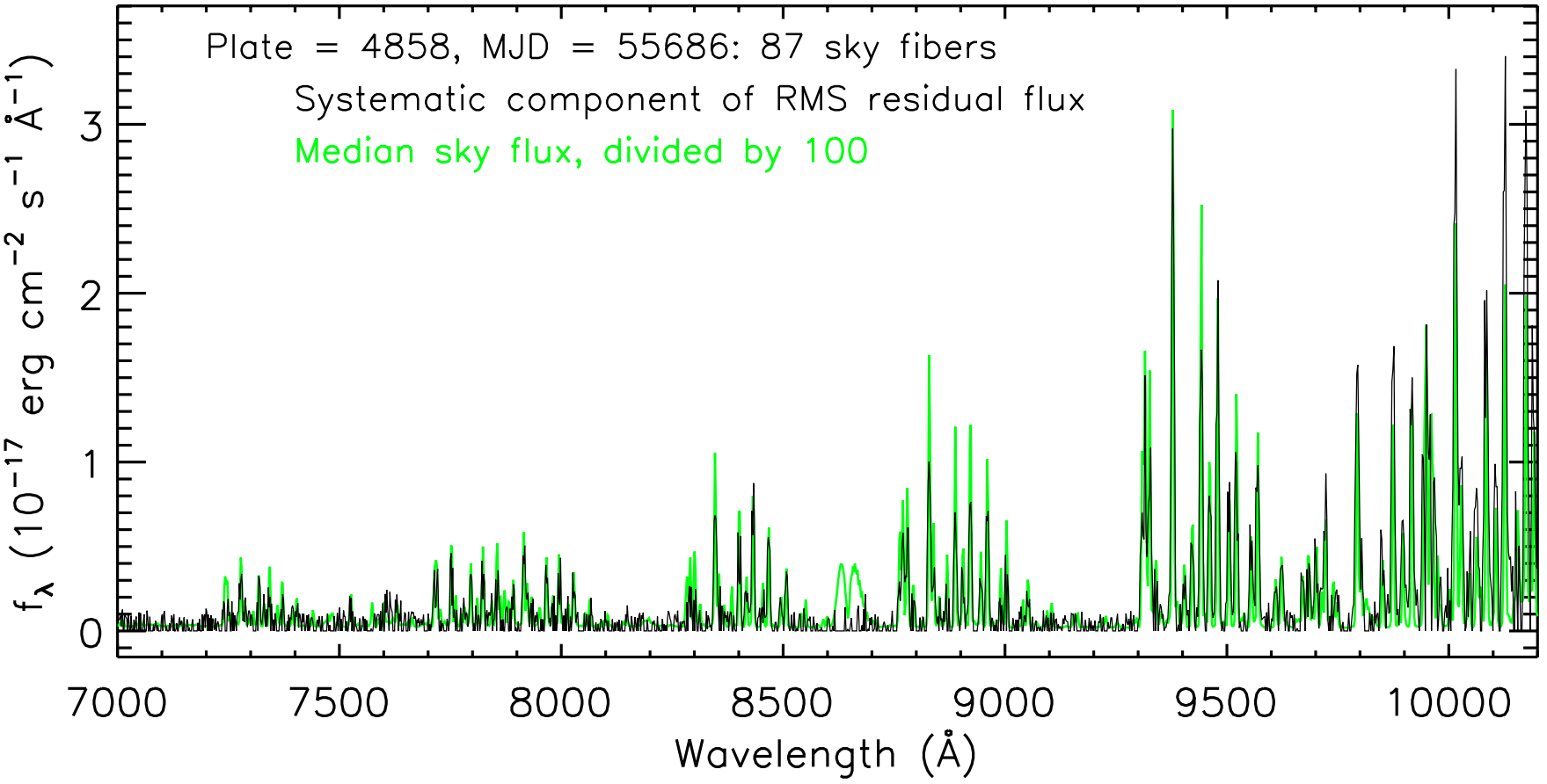


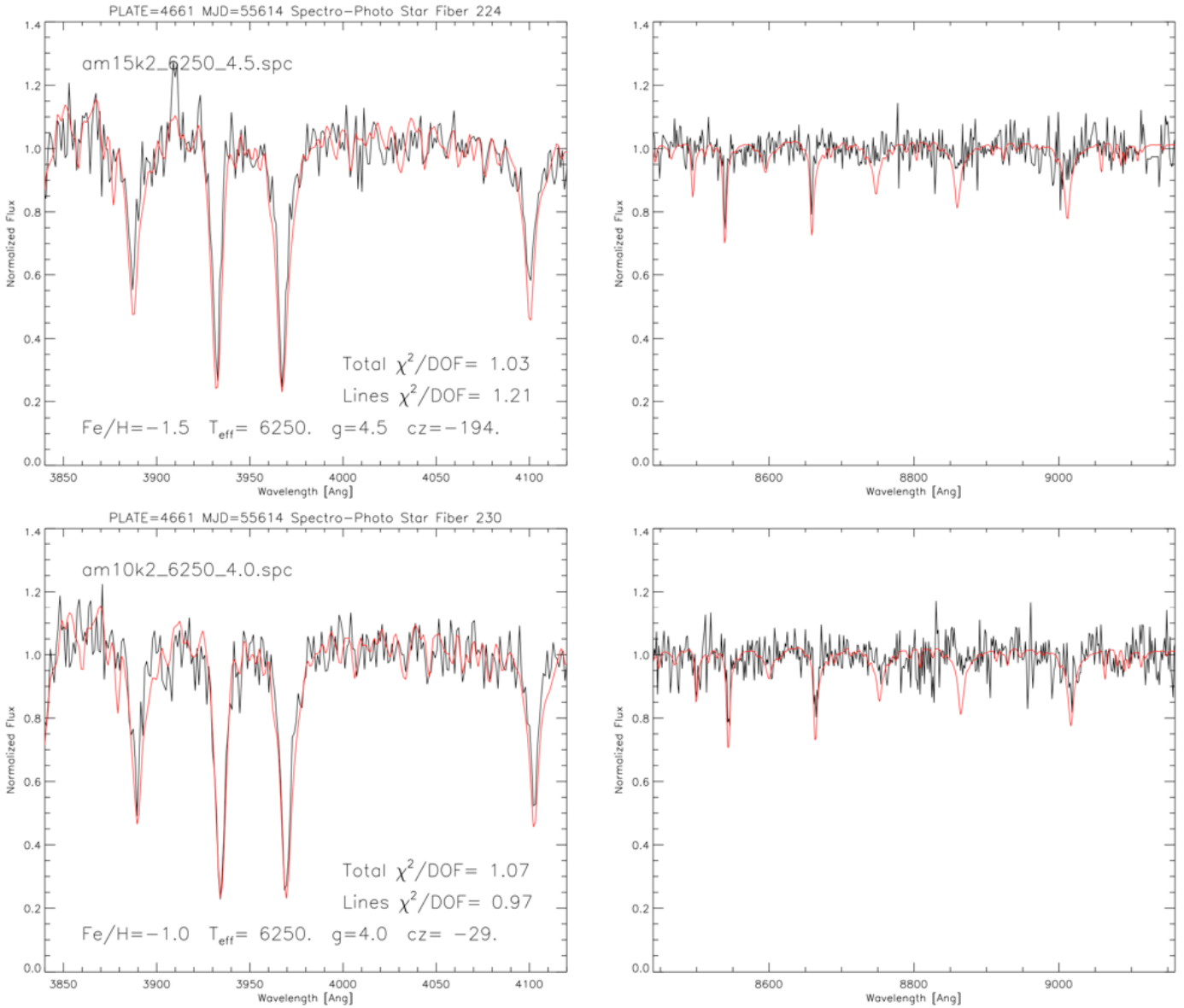
Sky Subtraction Quality

Systematic residuals < ~ 1% even on sky lines



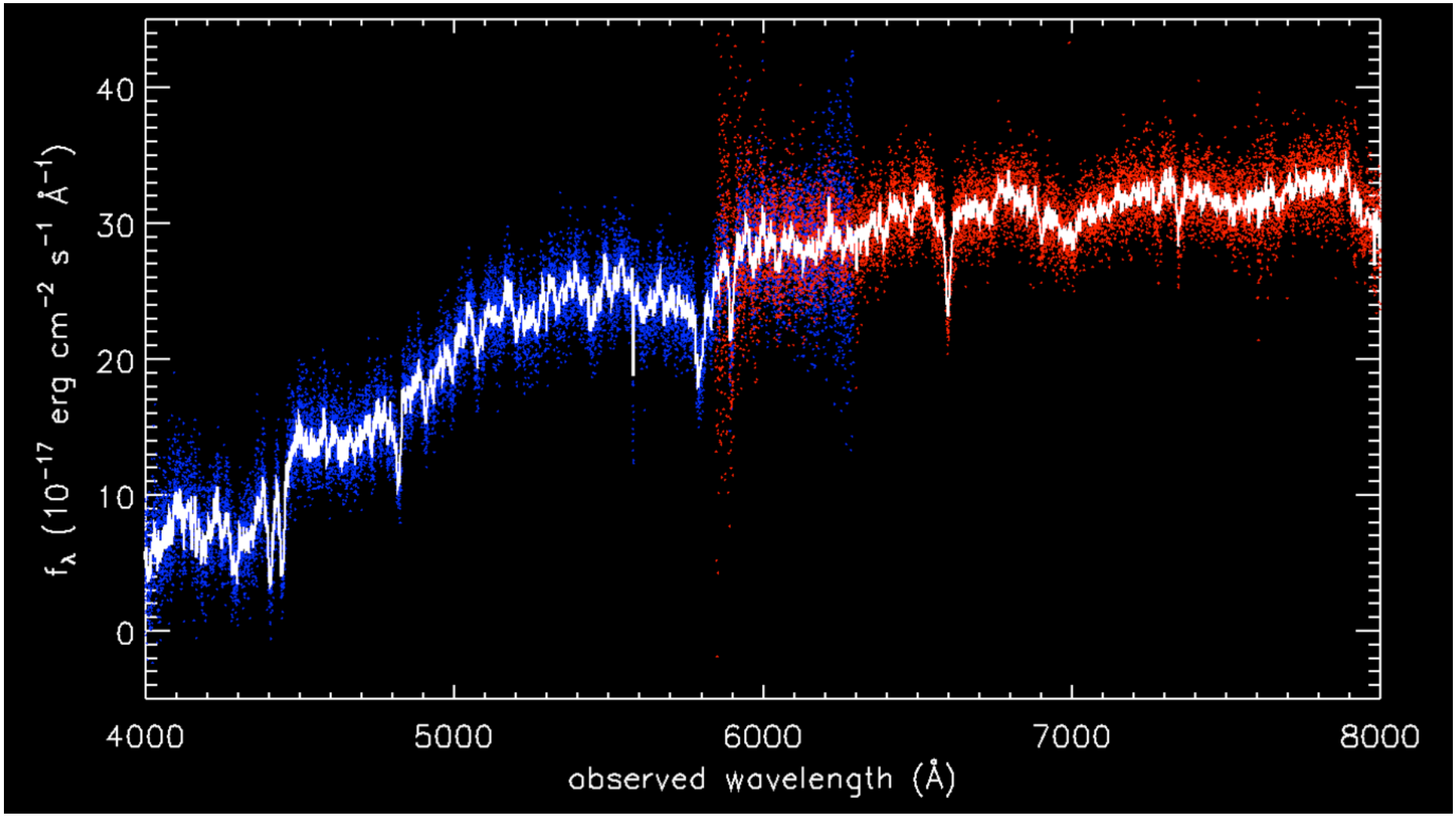
Calibration Part 3: Spectrophotometry

F-star model atmospheres selected by line fitting



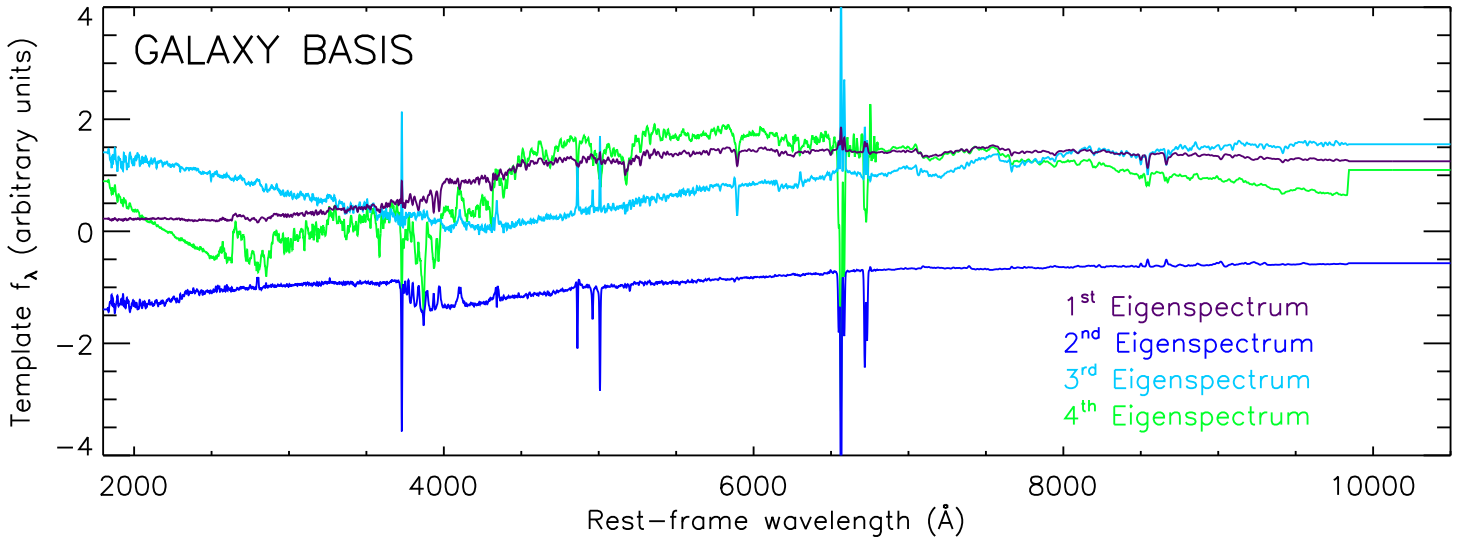
Coaddition

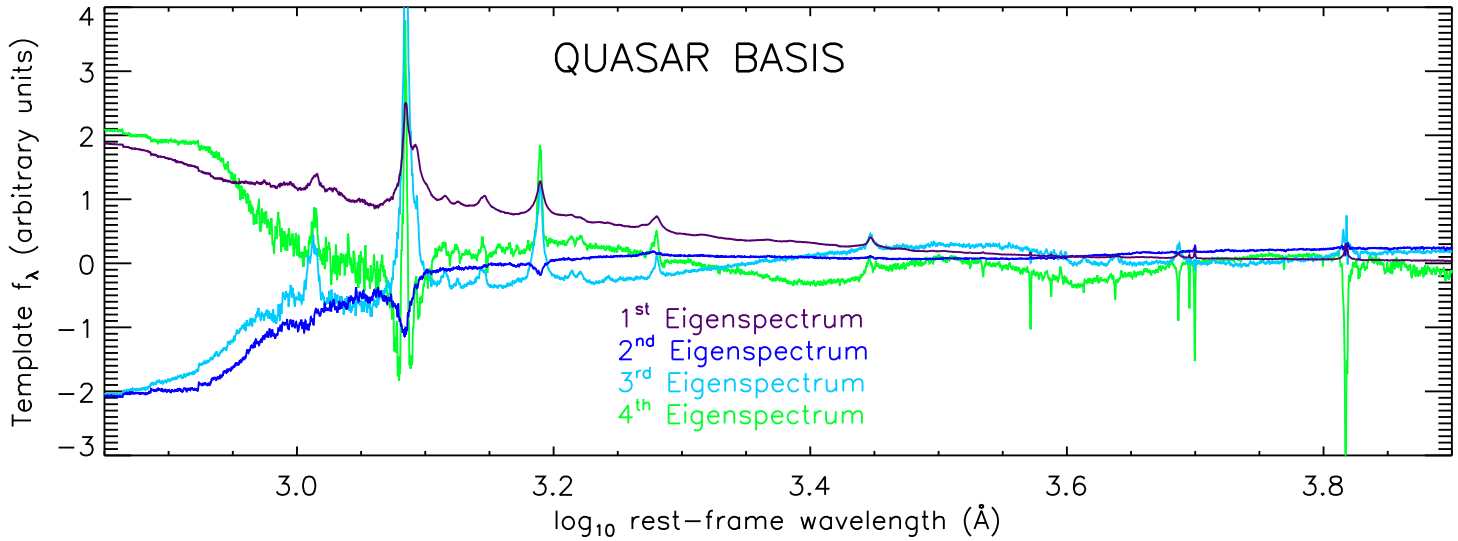
B-spline model for output coadd:
fitted to all fluxed frames,
evaluated at dlogλ = 10^{-4}



Redshift Measurement and Classification

Fitting done using bases of PCA Eigenspectra

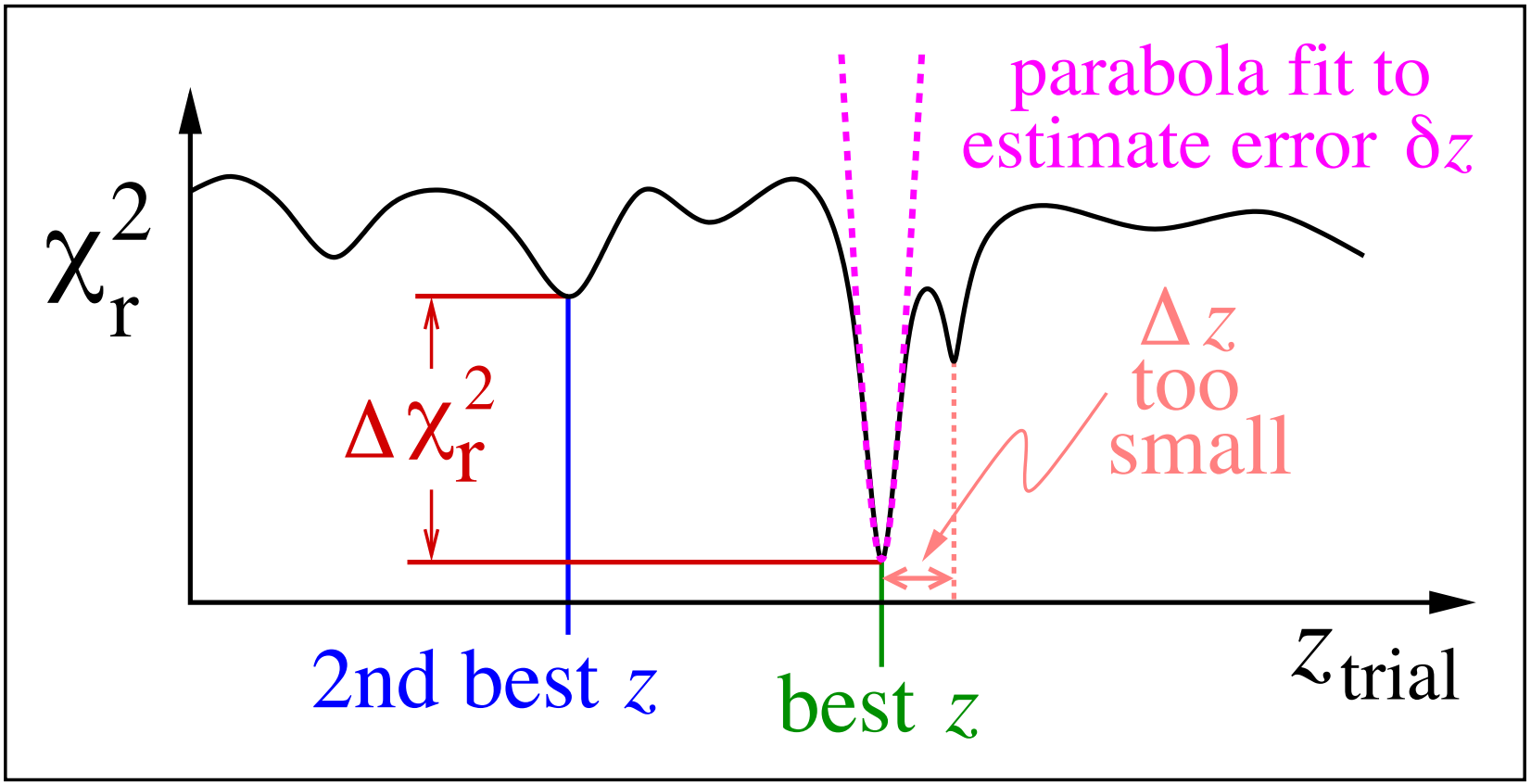




Plus: stellar archetype spectra

Redshift Measurement and Classification

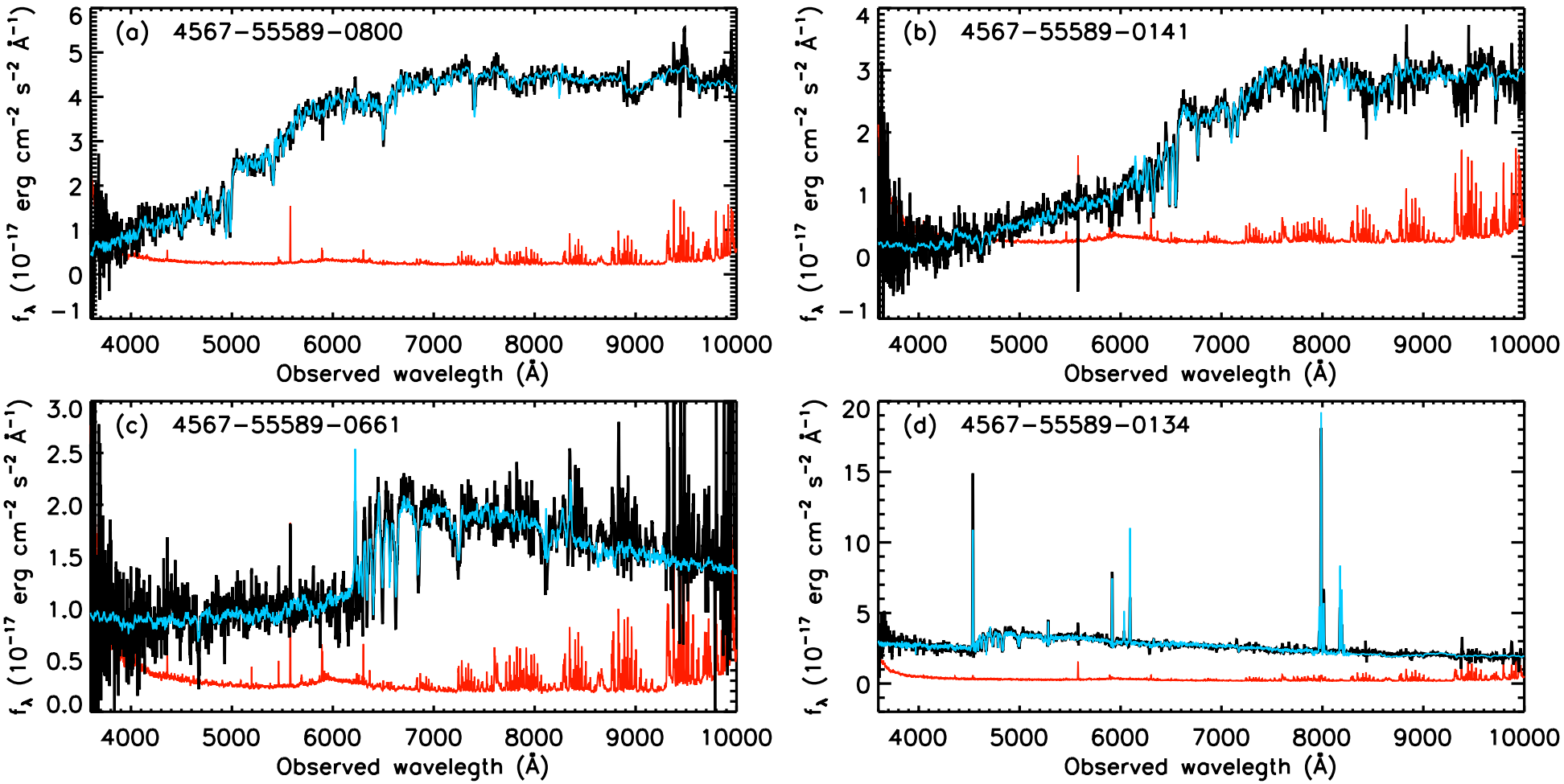
Schematic illustration of the algorithm



Forward modeling allows objective model comparison and error estimation

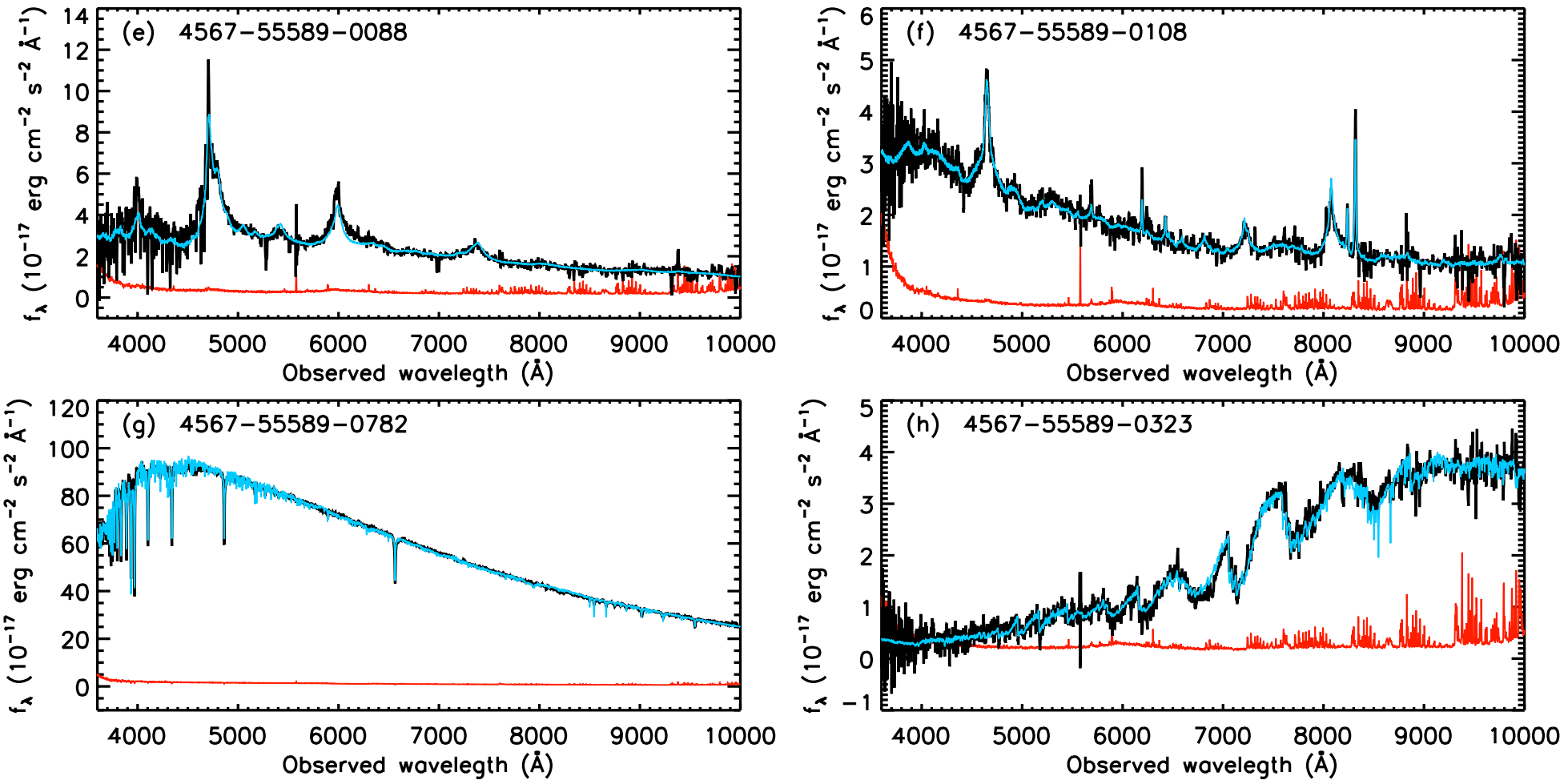
Redshift Measurement and Classification

Example redshift model fits: galaxies



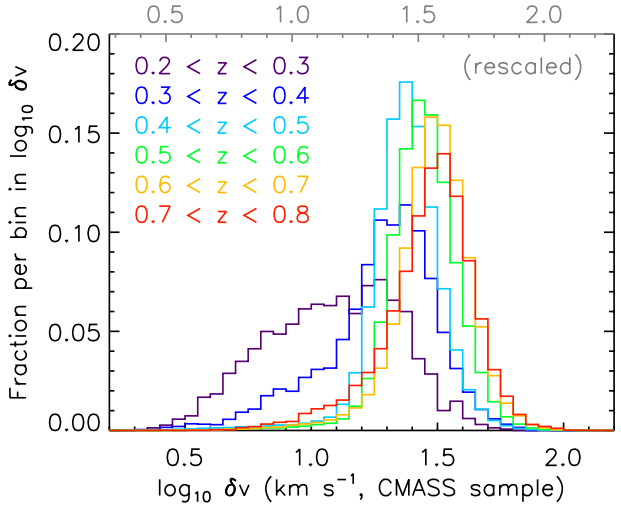
Redshift Measurement and Classification

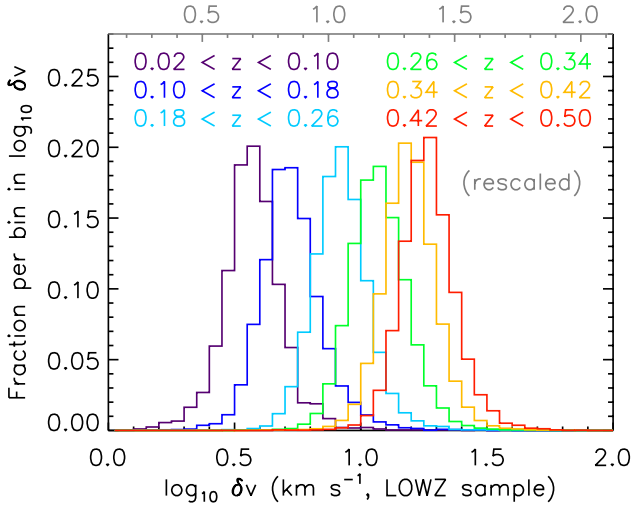
Example redshift model fits: quasars and stars

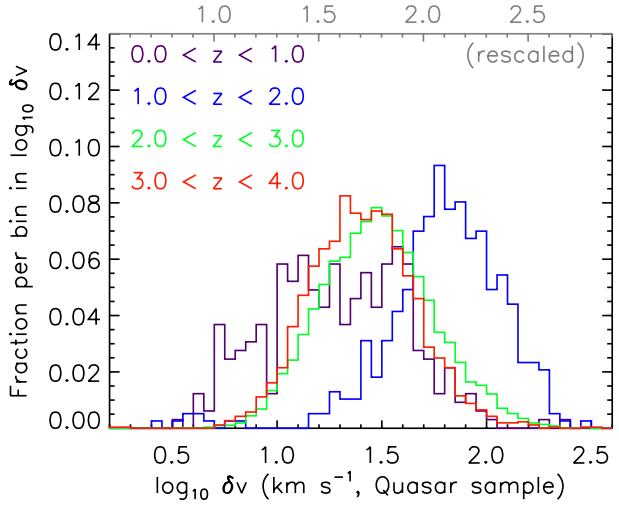


Redshift Measurement Precision

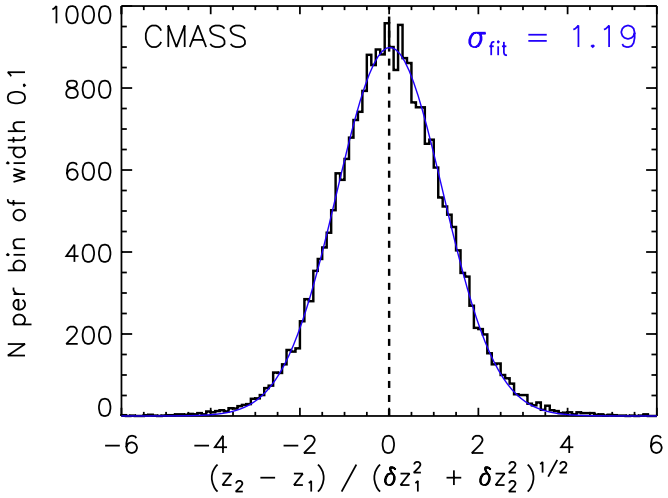
Typical redshift errors: few tens of km/s (statistical):

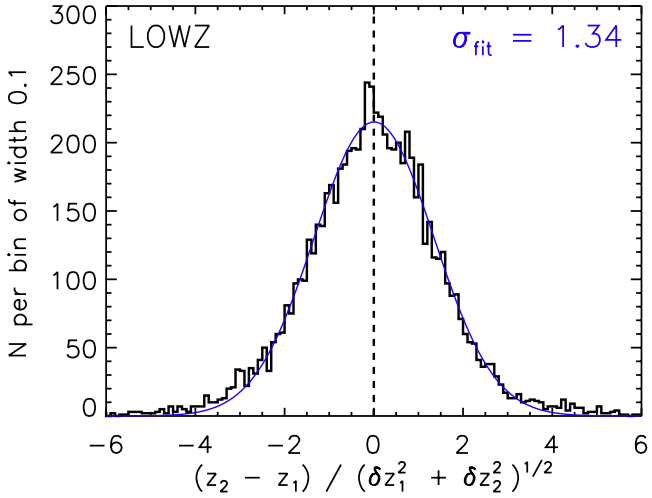


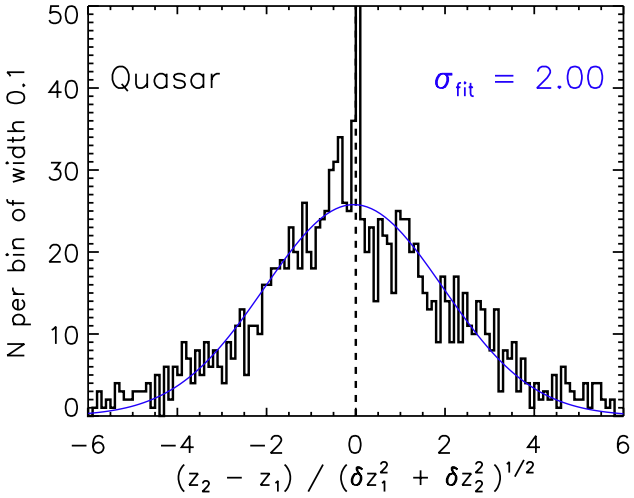




Statistical error estimates substantially accurate:



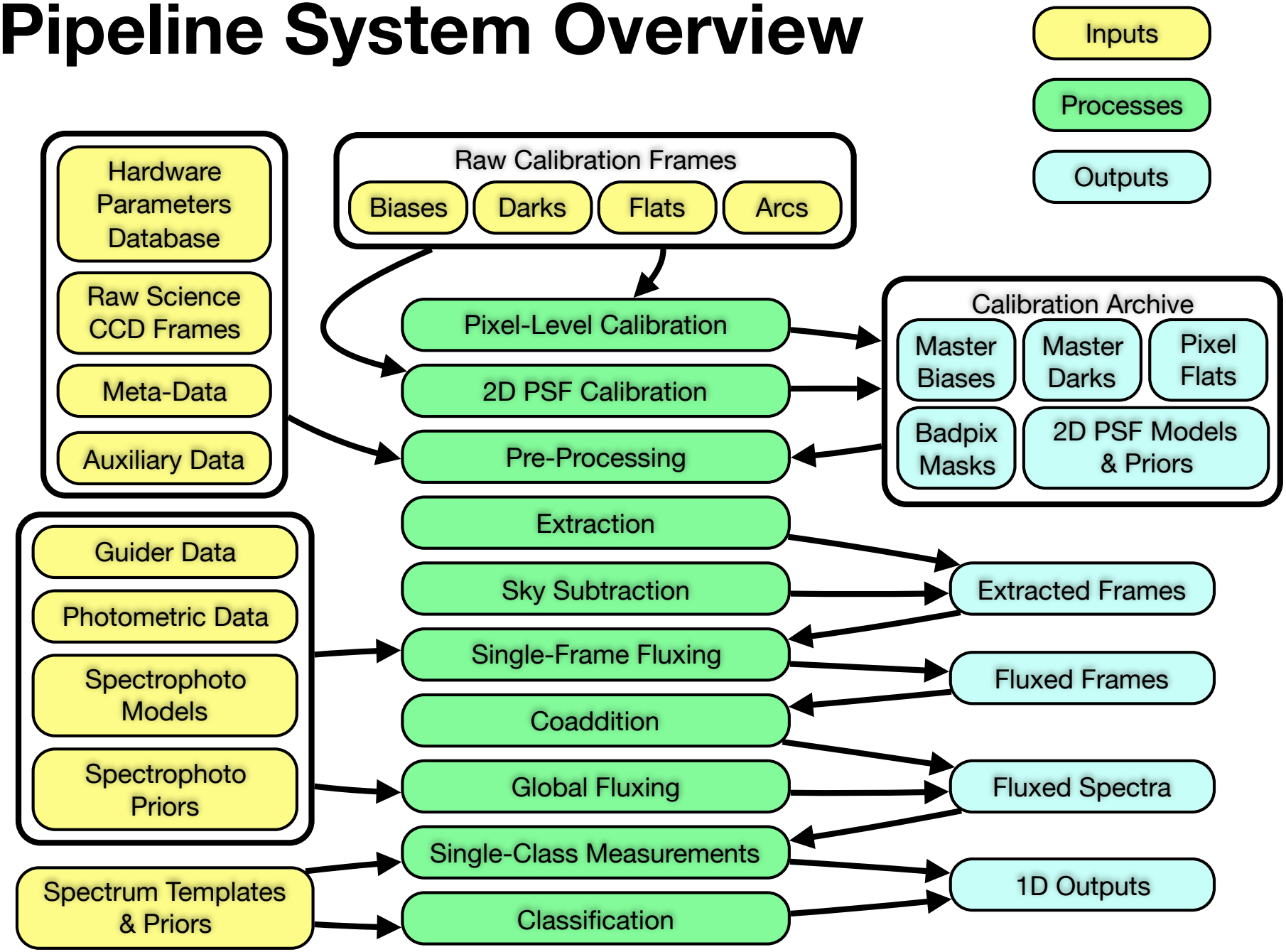




BOSS Pipeline Performance Statistics

Target Sample	CMASS	LOWZ	QSO (2.2 < z < 3.5)
Sample classification success rate	98.7%	99.9%	79%
Target object confirmation rate	95.4%	99.2%	33.6%
Completeness vs. visual inspections	99.6%	100%	98.3%
Purity vs. visual inspections	99.8%	100%	99.4%

Pipeline System Overview



Current and Future Developments

- Archetype-based redshift measurement
- More flexible template-class management
- Joint fit to spectroscopic and photometric data
- Unifying redshift and parameter measurement
- Hierarchical Bayesian priors for redshift distribution and physical parameter distributions
- Greater quasar redshift accuracy control
- Performance analysis and optimization for emission-line galaxy (ELG) target class
- Next-generation extraction algorithms

(See, e.g., Bolton & Schlegel 2010; Hutchinson et al. 2017)

(Notebook interaction goes here)

Outline

- Introduction
- Galaxies and redshift surveys
- SDSS-III / BOSS
- Spectroscopic Data Pipelining
- ***Extra:*** **Observational cosmology and dark energy**
- *Extra:* Baryon acoustic oscillations (BAO)

Observational cosmology

What are the contents, physics, and history of the universe on the largest scales?

Expansion history is connected to contents and their physics through Einstein's general relativity:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

determines expansion

function of contents

observe this...

... infer that

Connecting expansion to contents

Universe expansion rate versus redshift in GR:

"Hubble Constant", typically in km/s per Megaparsec

$$H(z) = H_0\sqrt{\Omega_{\rm R}(1+z)^4 + \Omega_{\rm M}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda}$$

Radiation density parameter

Matter density parameter

Curvature density parameter

Vacuum density parameter

$$\Omega_k = 1 - \Omega_{\rm R} - \Omega_{\rm M} - \Omega_\Lambda$$

Connecting expansion to contents

Universe expansion rate versus redshift in GR:

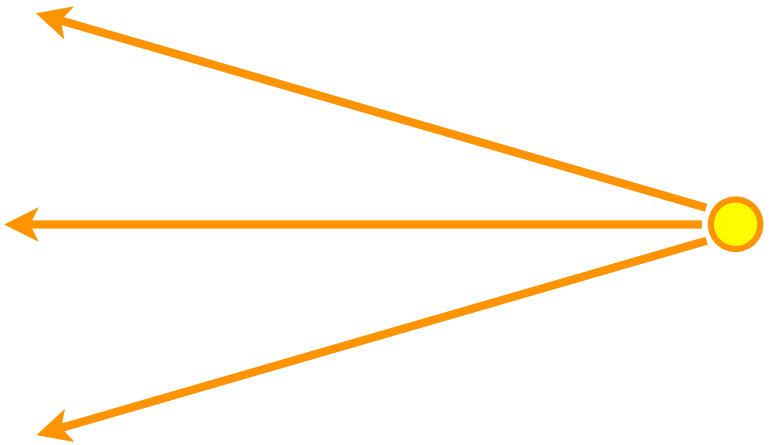
$$H(z) = H_0 \sqrt{\Omega_{\rm R}(1+z)^4 + \Omega_{\rm M}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda}$$

Suitable integration of this expansion rate (see exercise) yields the predicted distance--redshift relationship for a given mix of cosmological density components

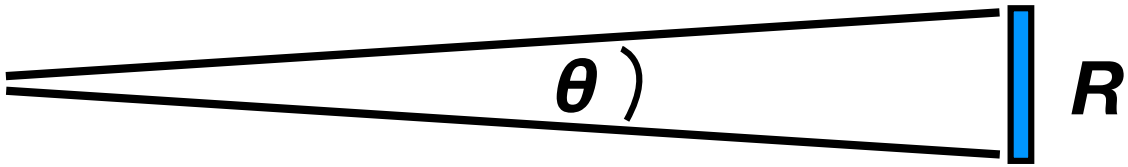
Measuring distances

"Standard candles" (L) or "standard rulers" (R) allow observational determination of distances (D)

$S = L/(4\pi D^2)$

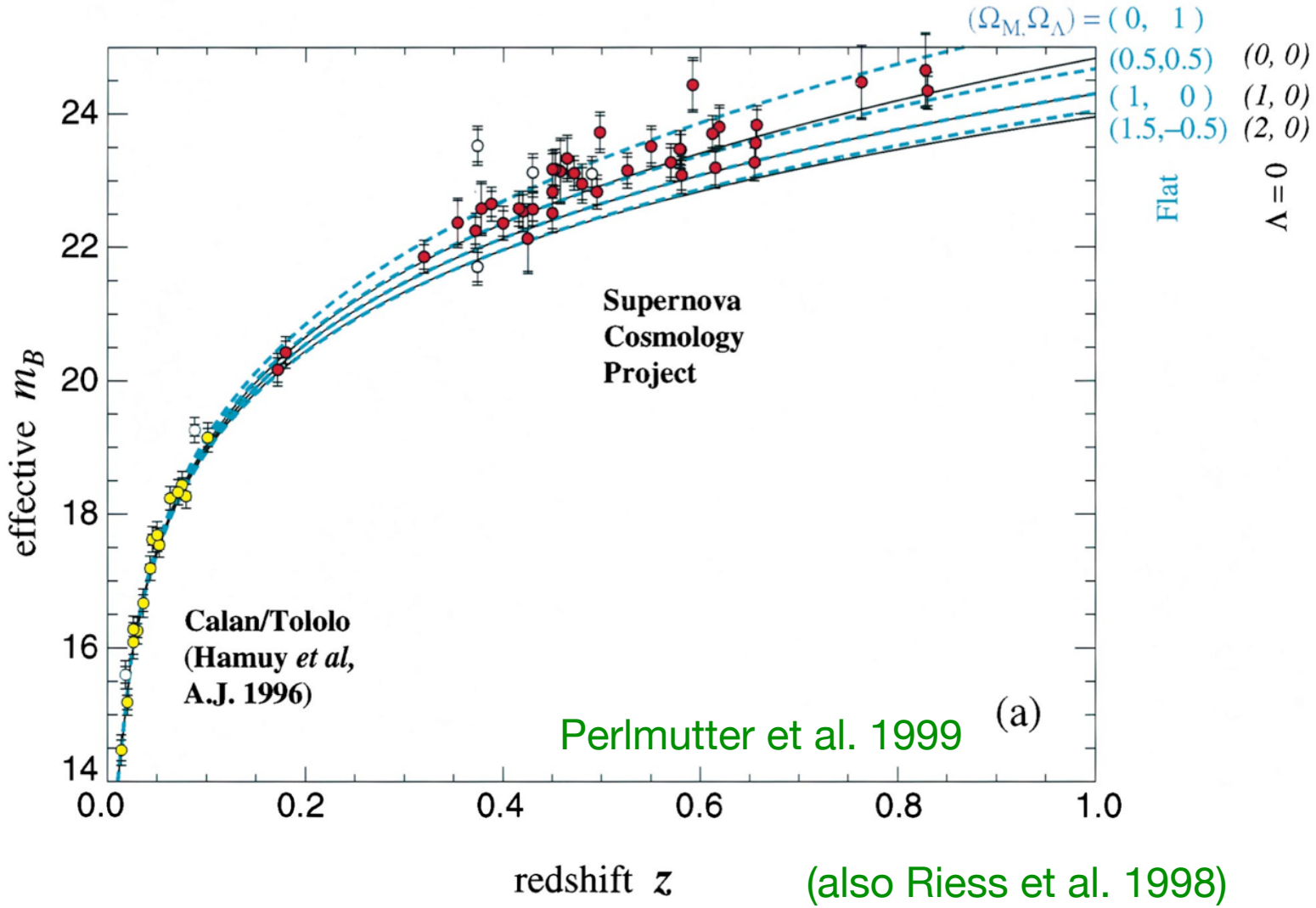


$\theta = R / D$



Constraining cosmology with data

Central tool: the modern Hubble diagram

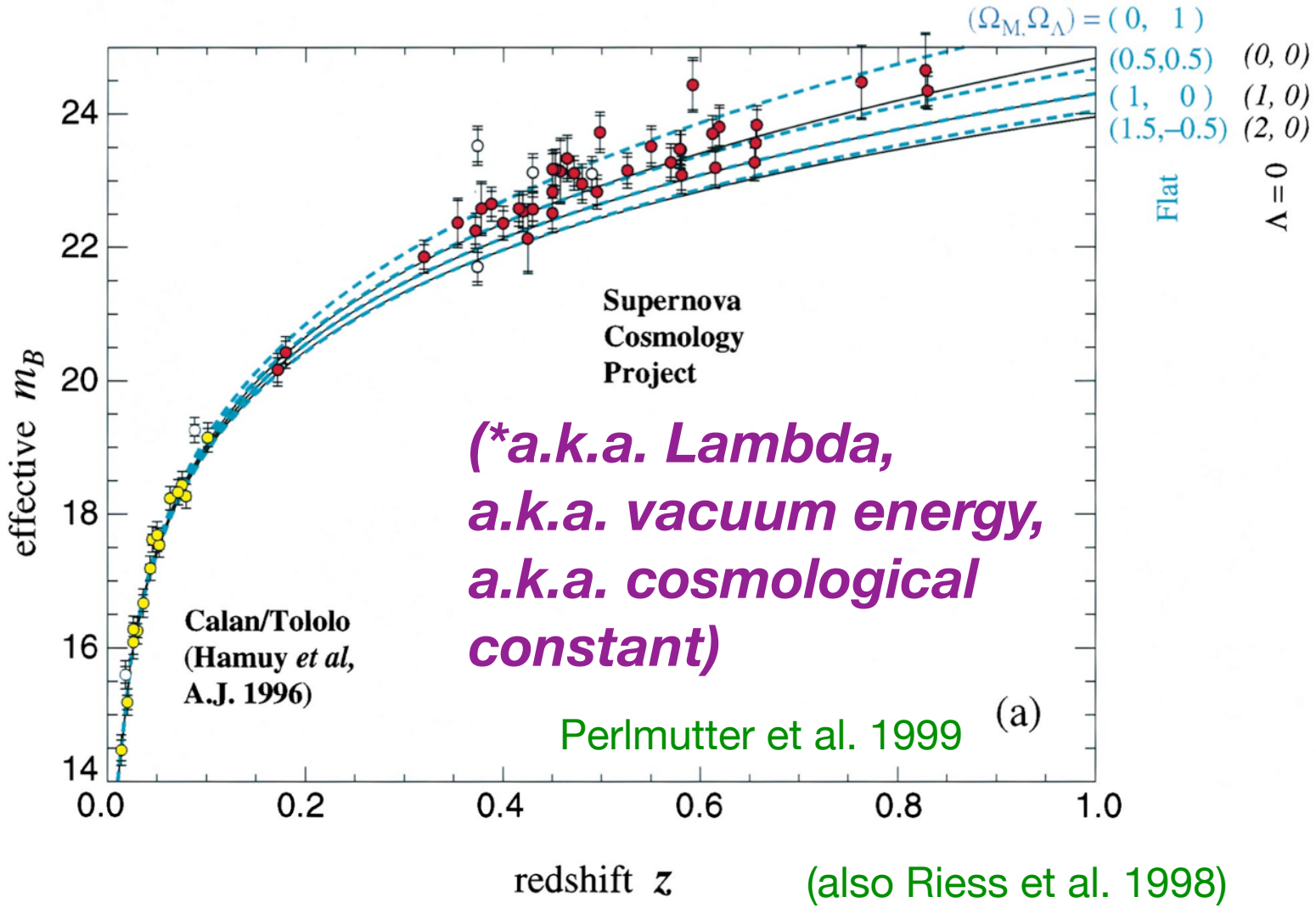


Perlmutter et al. 1999

(also Riess et al. 1998)

Constraining cosmology with data

Observational evidence shows that recent expansion is accelerating, driven by a form of "dark energy*"

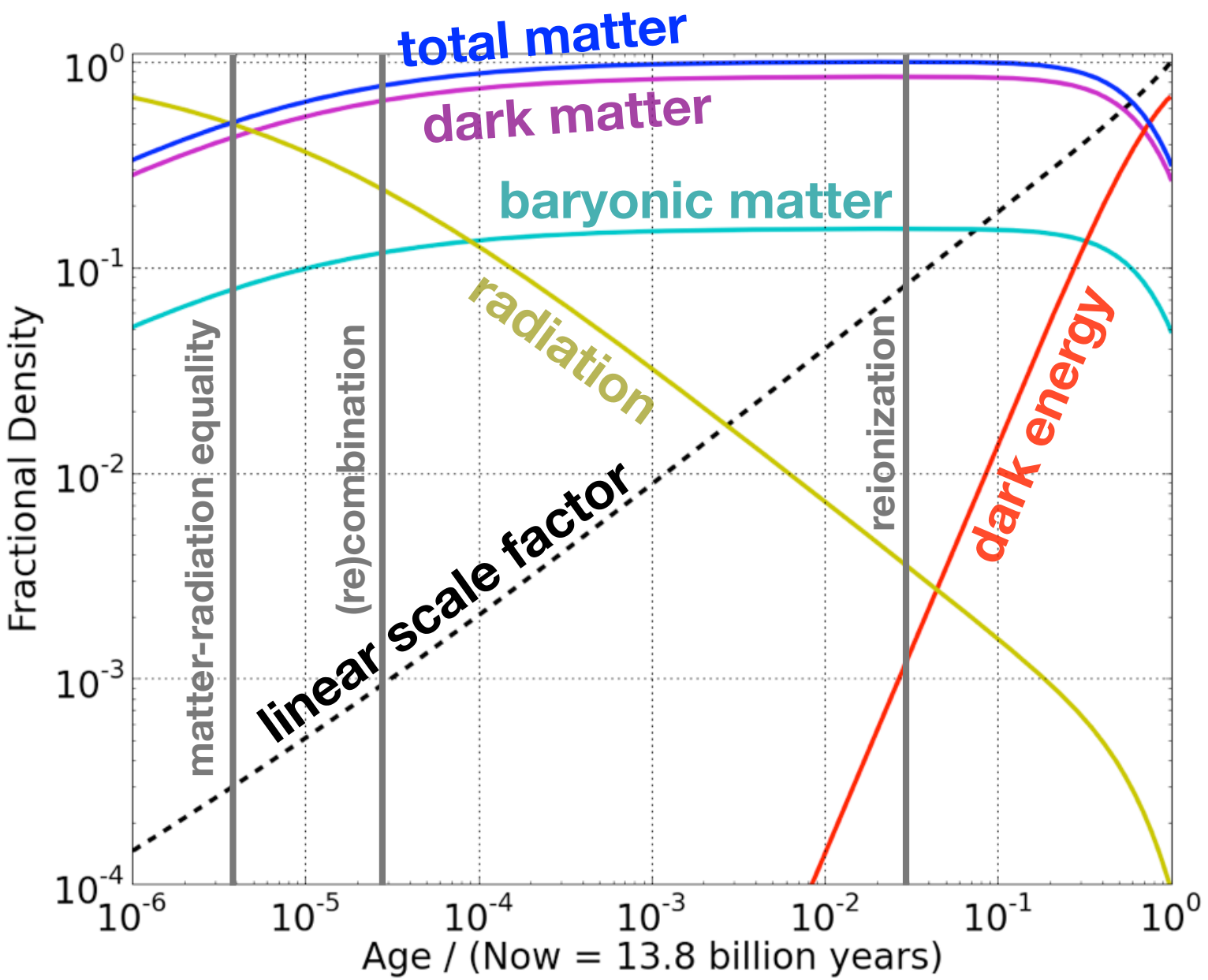


(*a.k.a. Lambda, a.k.a. vacuum energy, a.k.a. cosmological constant)

Perlmutter et al. 1999

(also Riess et al. 1998)

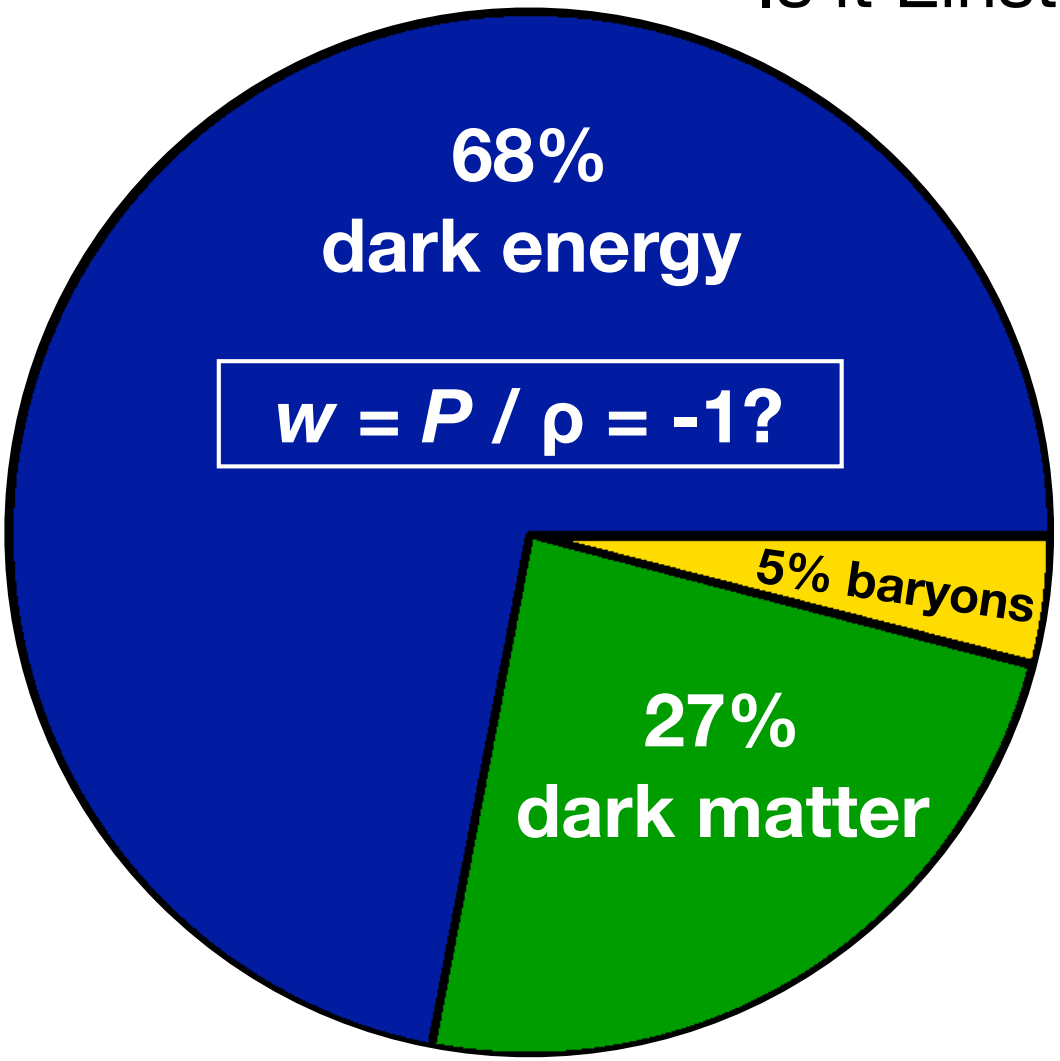
One-dimensional history of the universe



Where we are now: dark energy

Biggest Question: ***What is dark energy?***
Is it Einstein's cosmological constant?
Or does it evolve in time?
Or is it a failure of GR?

e.g. Albrecht et al. 2006



The best experimental prospect for answering this question is via the ***baryon acoustic feature*** seen in ***surveys of the large-scale distribution of galaxies, quasars, and intergalactic gas***

Outline

- Introduction
- Galaxies and redshift surveys
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- Spectroscopic Data Pipelining
- *Extra:* Observational cosmology and dark energy
- ***Extra:*** **Baryon acoustic oscillations (BAO)**

Baryon acoustic what?

The ***baryon acoustic feature*** is the "echo" of primordial sound waves that propagated in the early universe.

Also known as ***baryon acoustic oscillations (BAO)***.

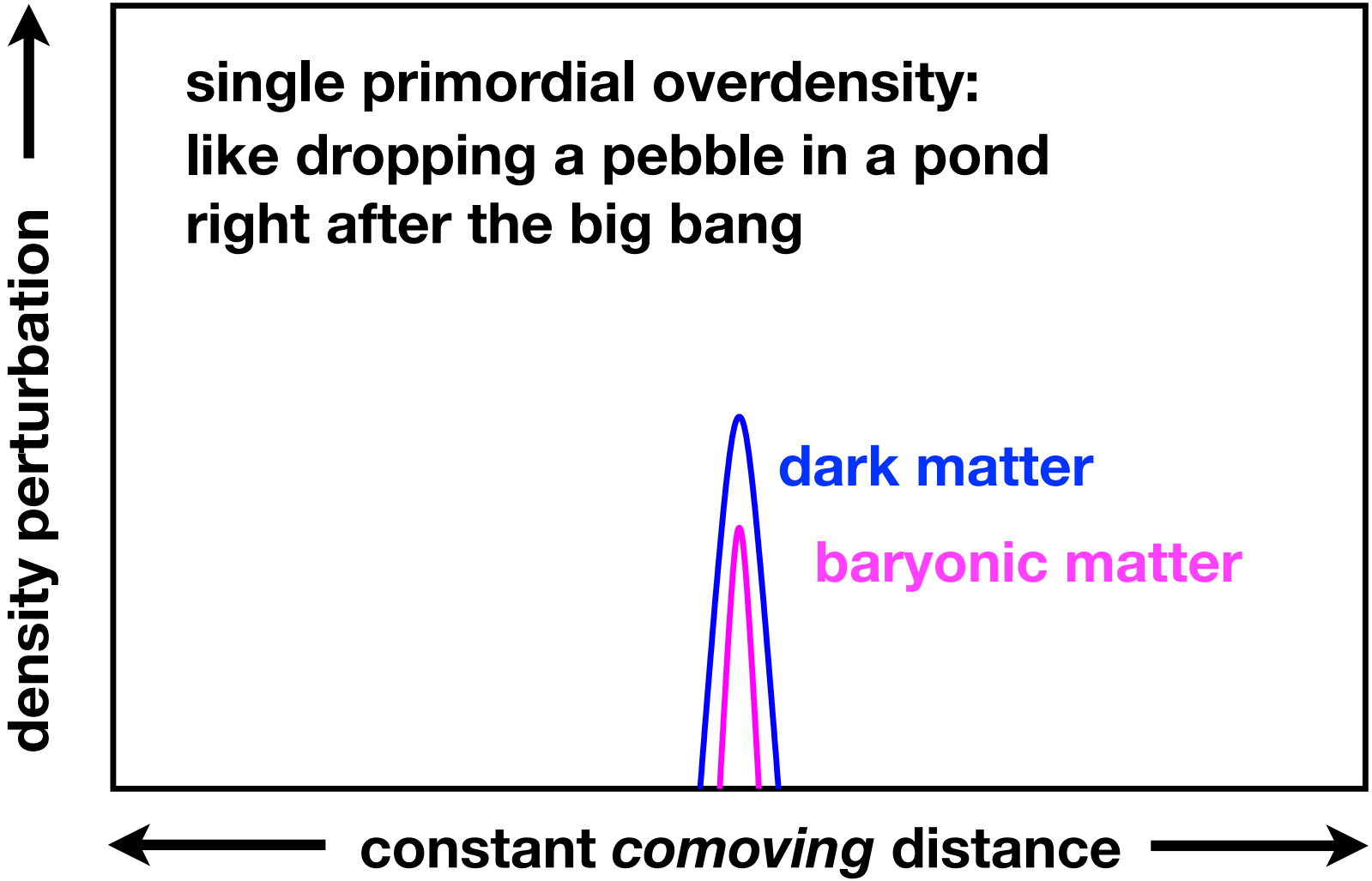
It is imprinted on the spatial distribution of matter on large scales in the universe.

The BAO length scale can be calibrated to observations of the microwave afterglow of the big bang.

BAO provides a cosmological "standard ruler" that lets us map the distance-redshift relation and constrain the physics of dark energy.

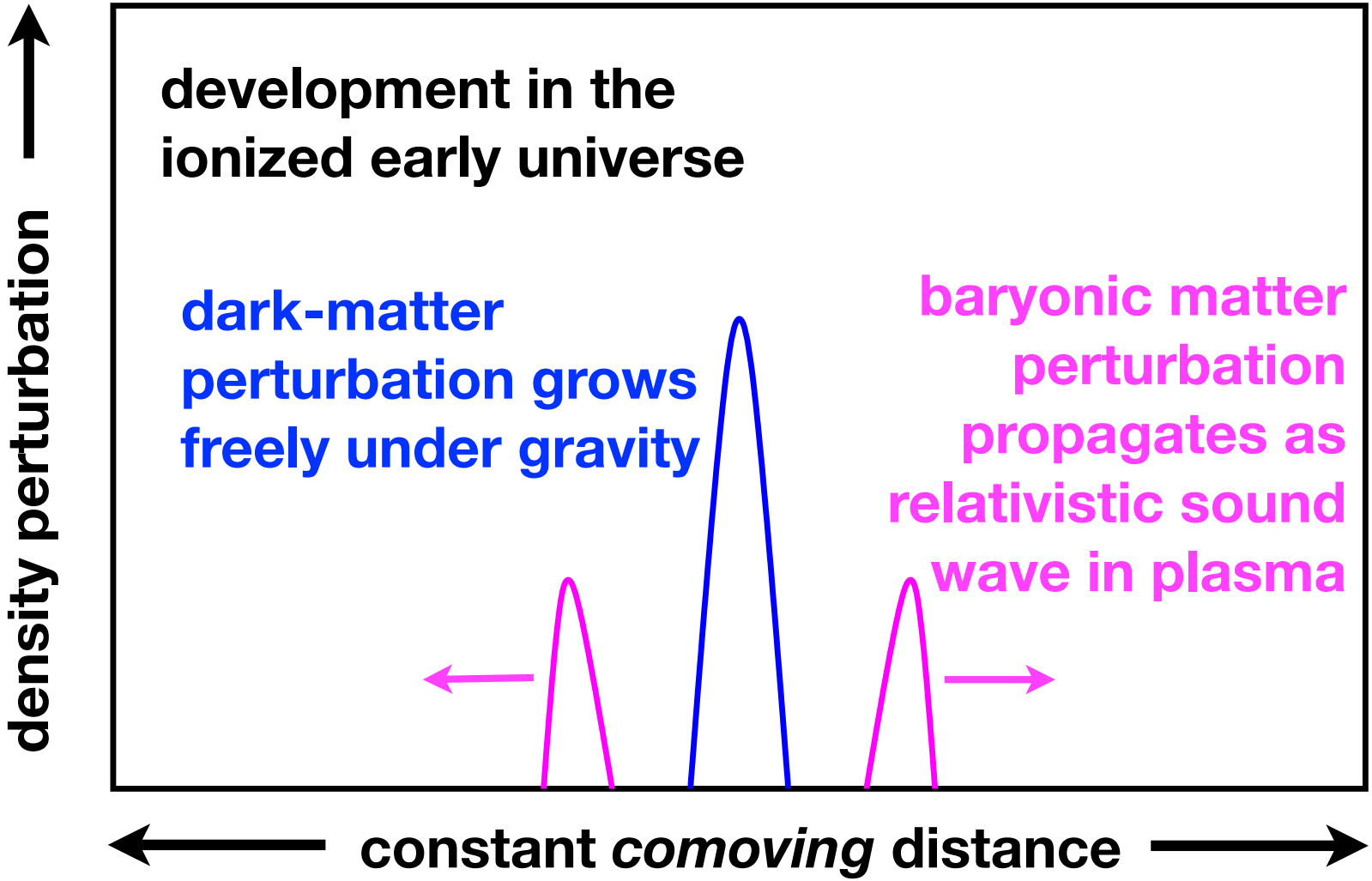
e.g., Eisenstein & Hu 1998, Eisenstein et al. 2005, Weinberg et al. 2012

The echo of primordial sound

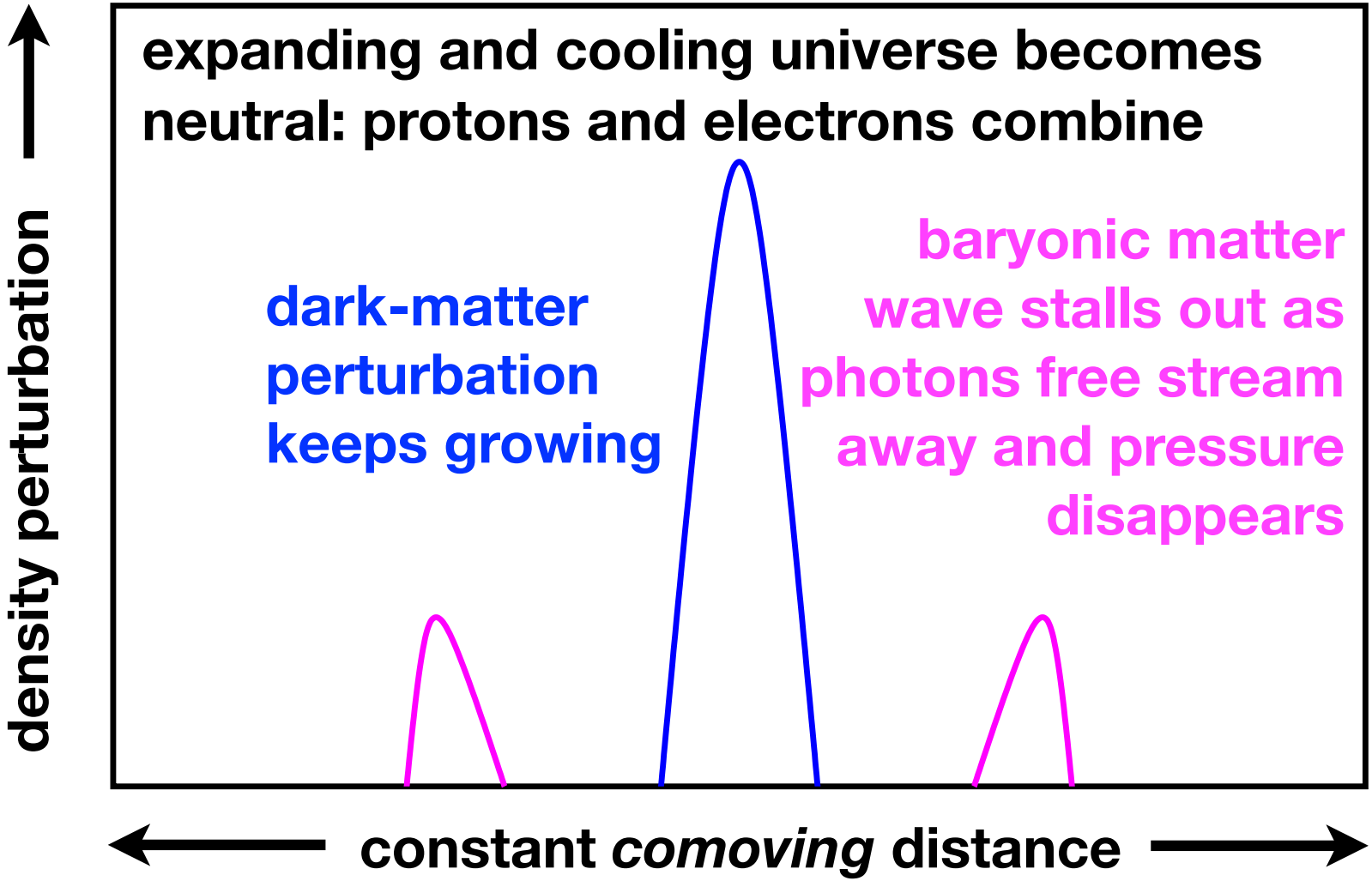


(following M. White)

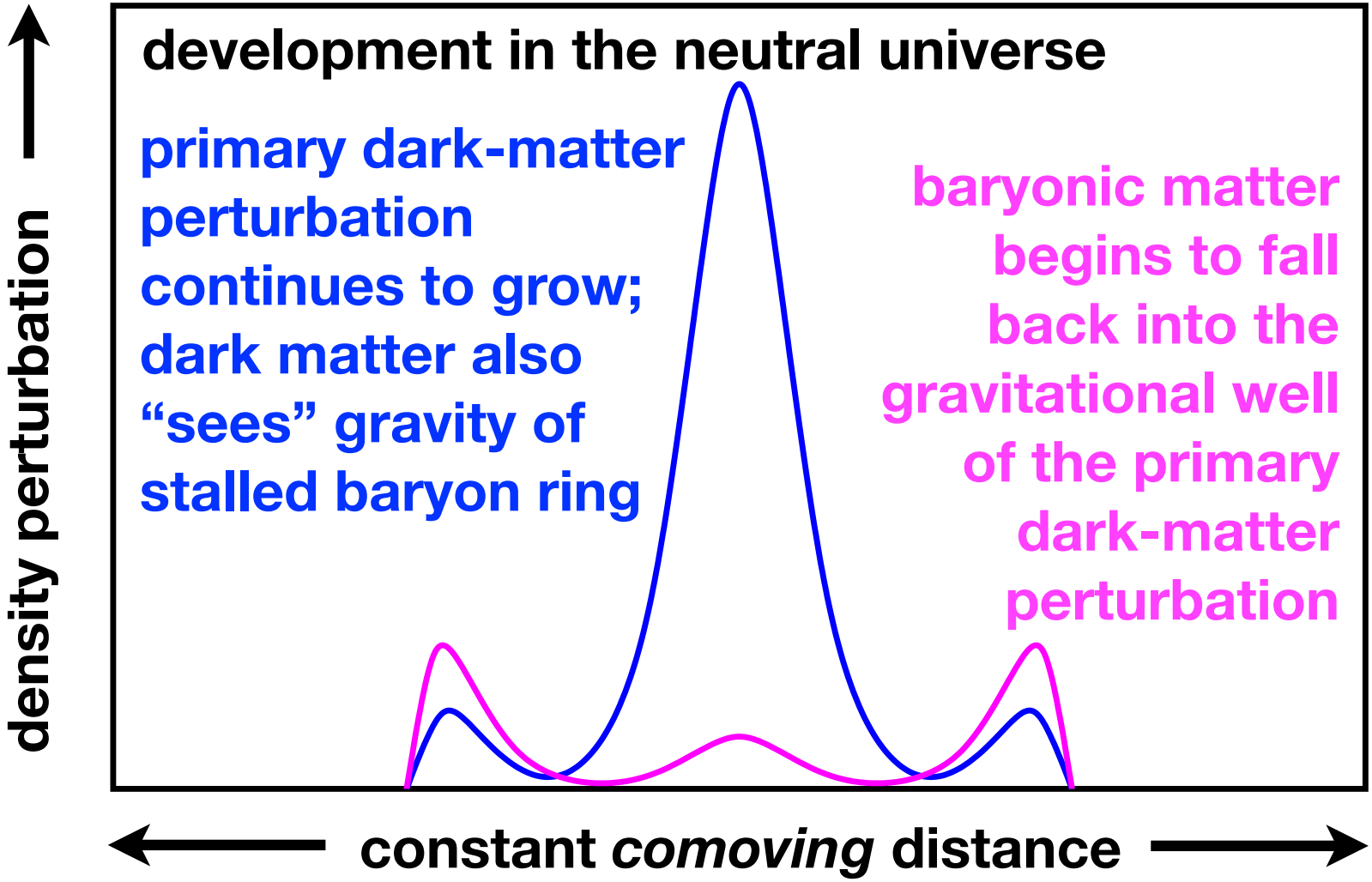
The echo of primordial sound



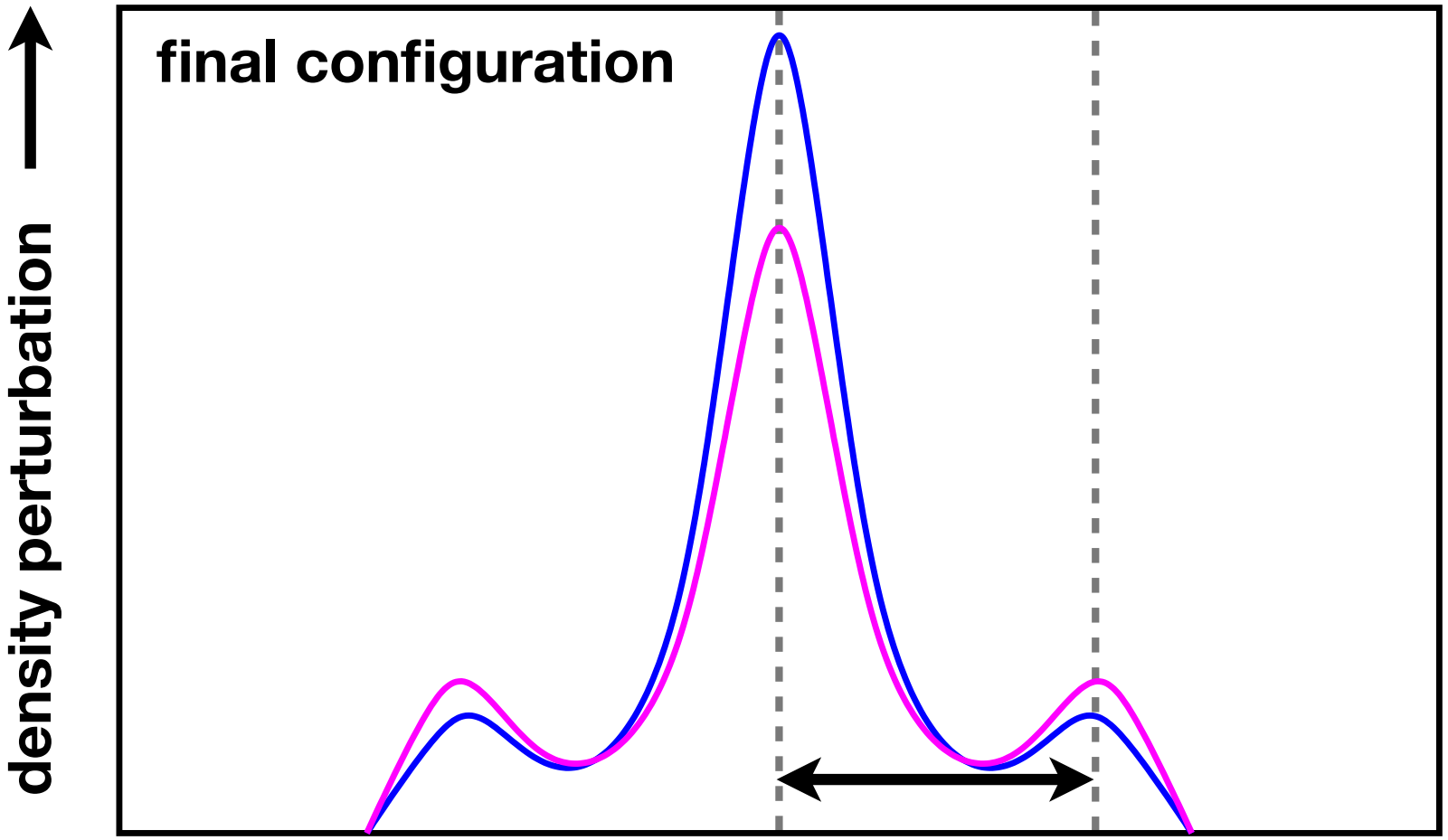
The echo of primordial sound



The echo of primordial sound

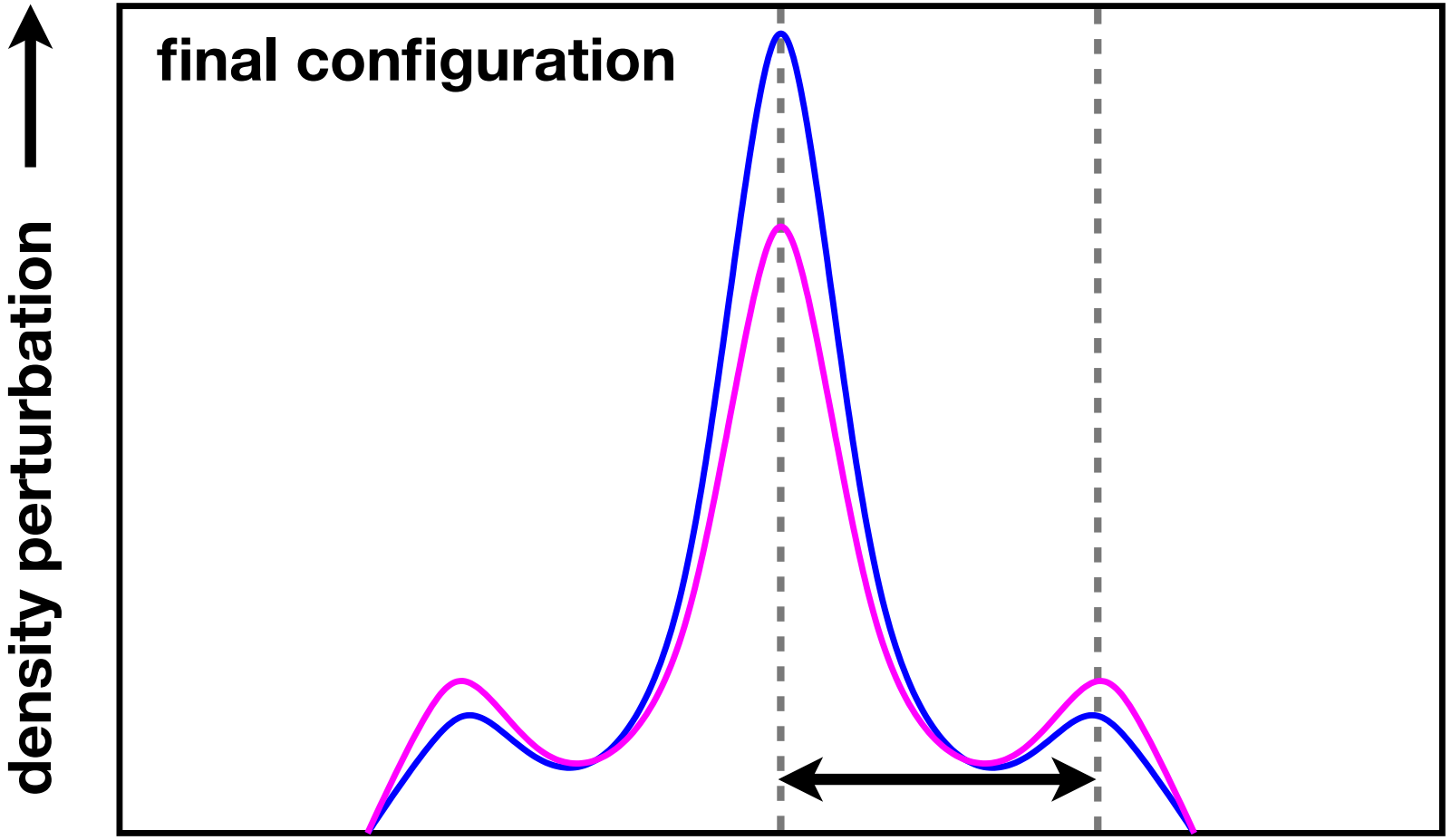


The echo of primordial sound



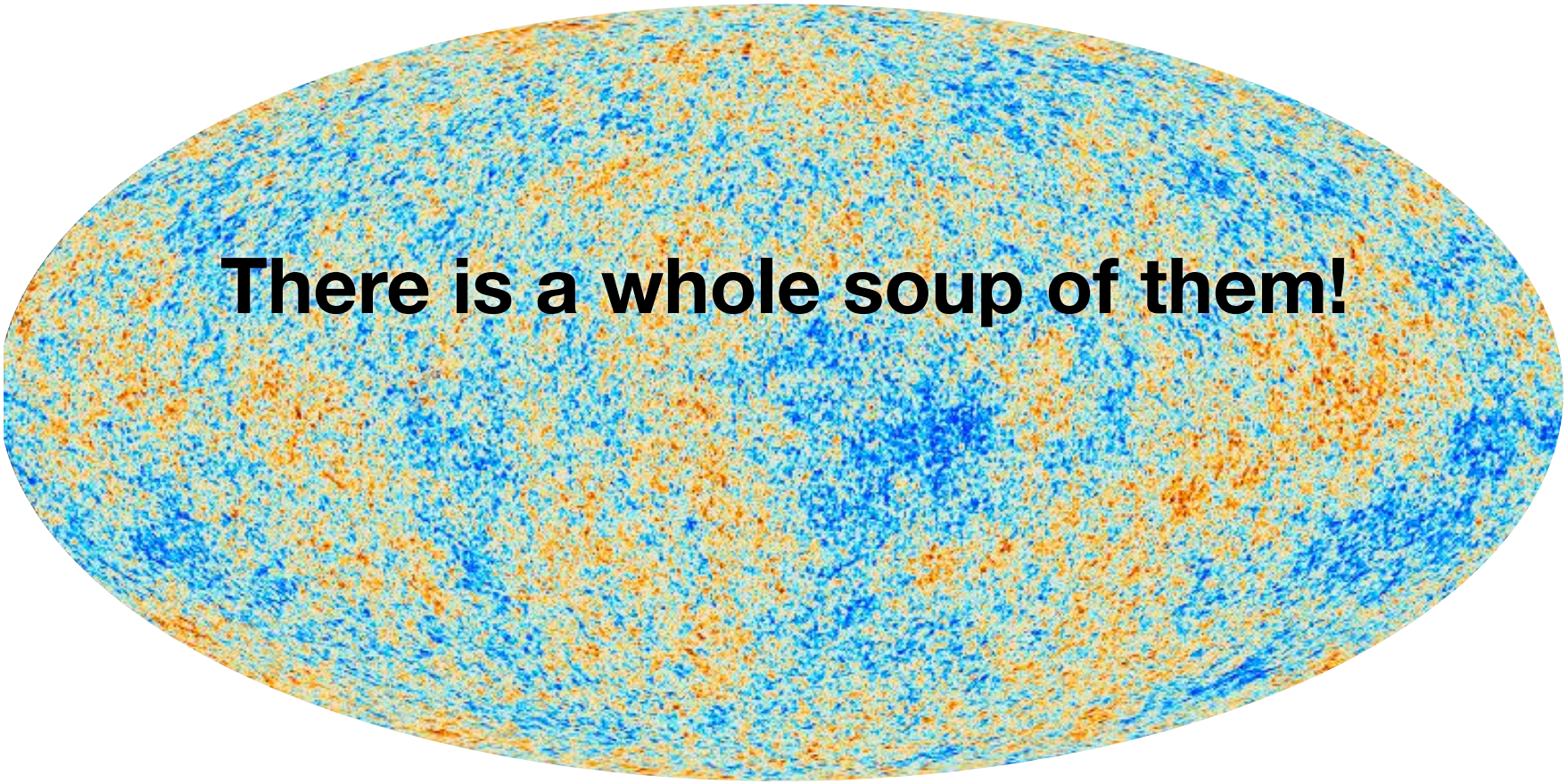
Characteristic separation scale of about 500 million light years in today's universe

The echo of primordial sound



But of course, there is more than one single primordial density perturbation...

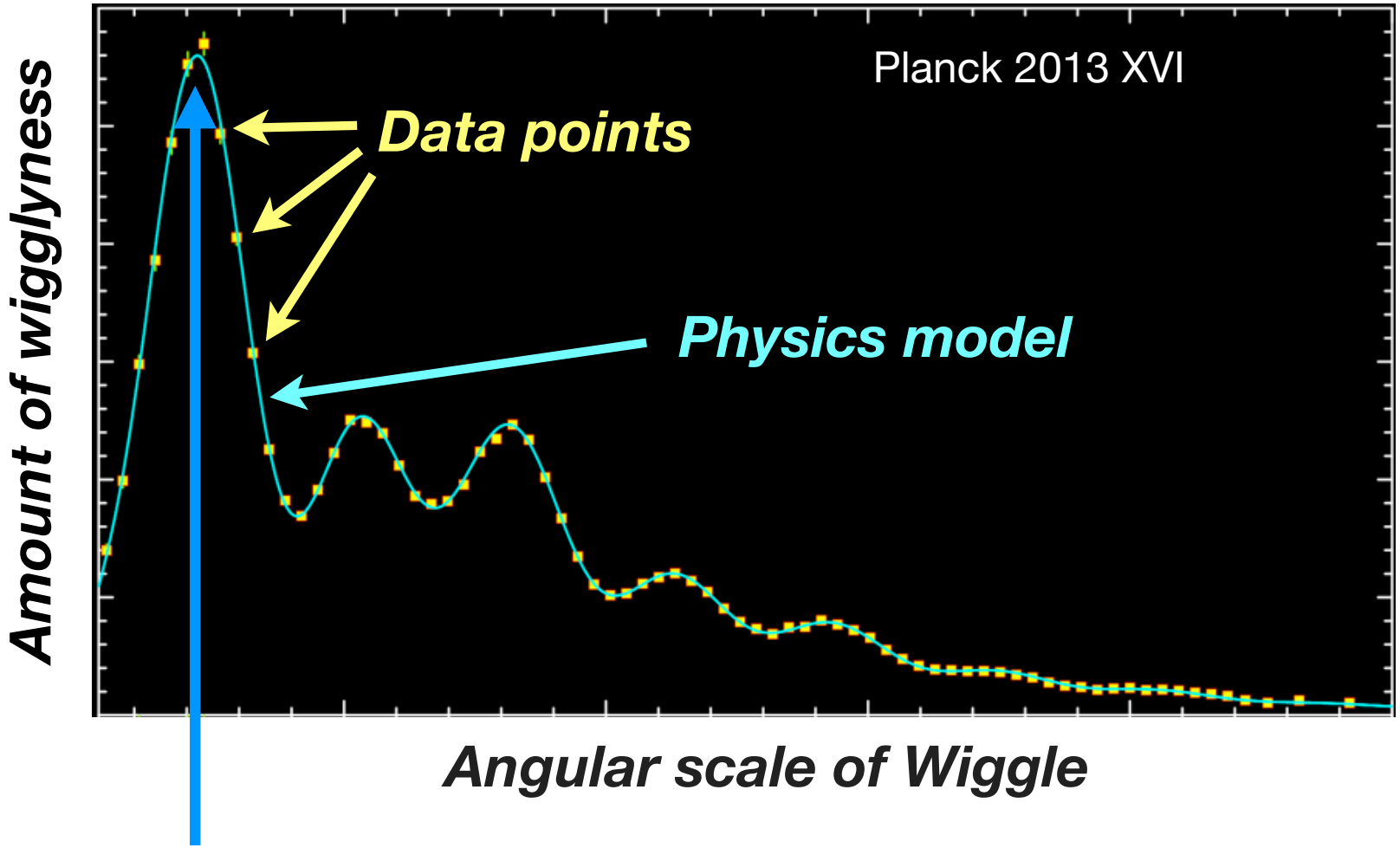
The echo of primordial sound



Cosmic microwave background anisotropy map
ESA Planck satellite, 2013

The echo of primordial sound

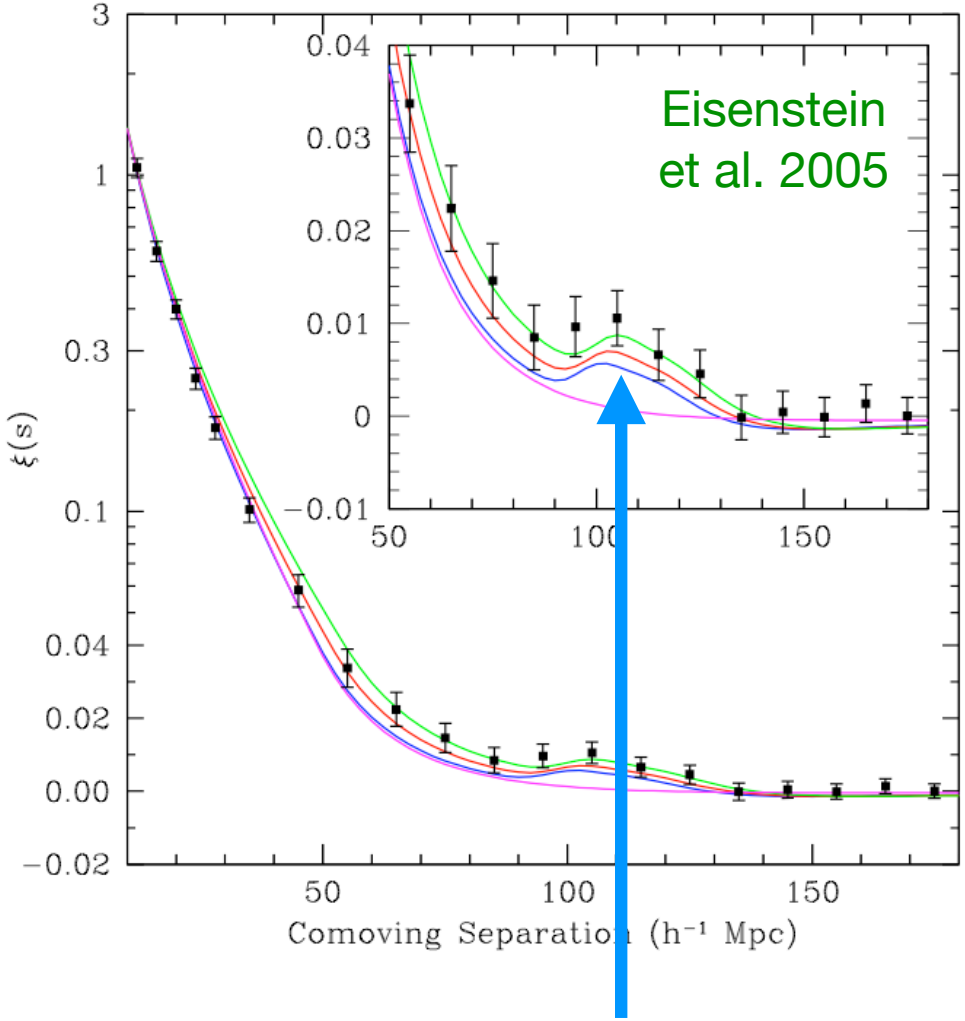
Cosmic microwave background anisotropy spectrum

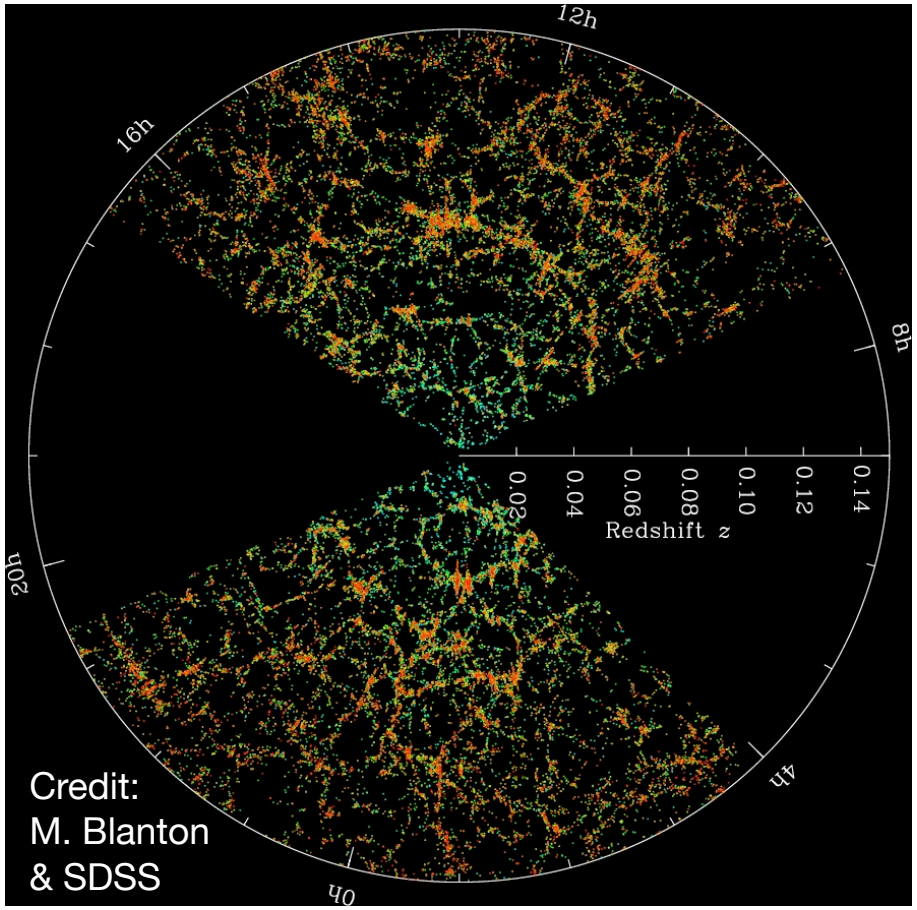


Scale of longest sound wavelength in early universe

The echo of primordial sound

2-point correlation function of galaxies





Same feature, imprinted on the distribution of galaxies